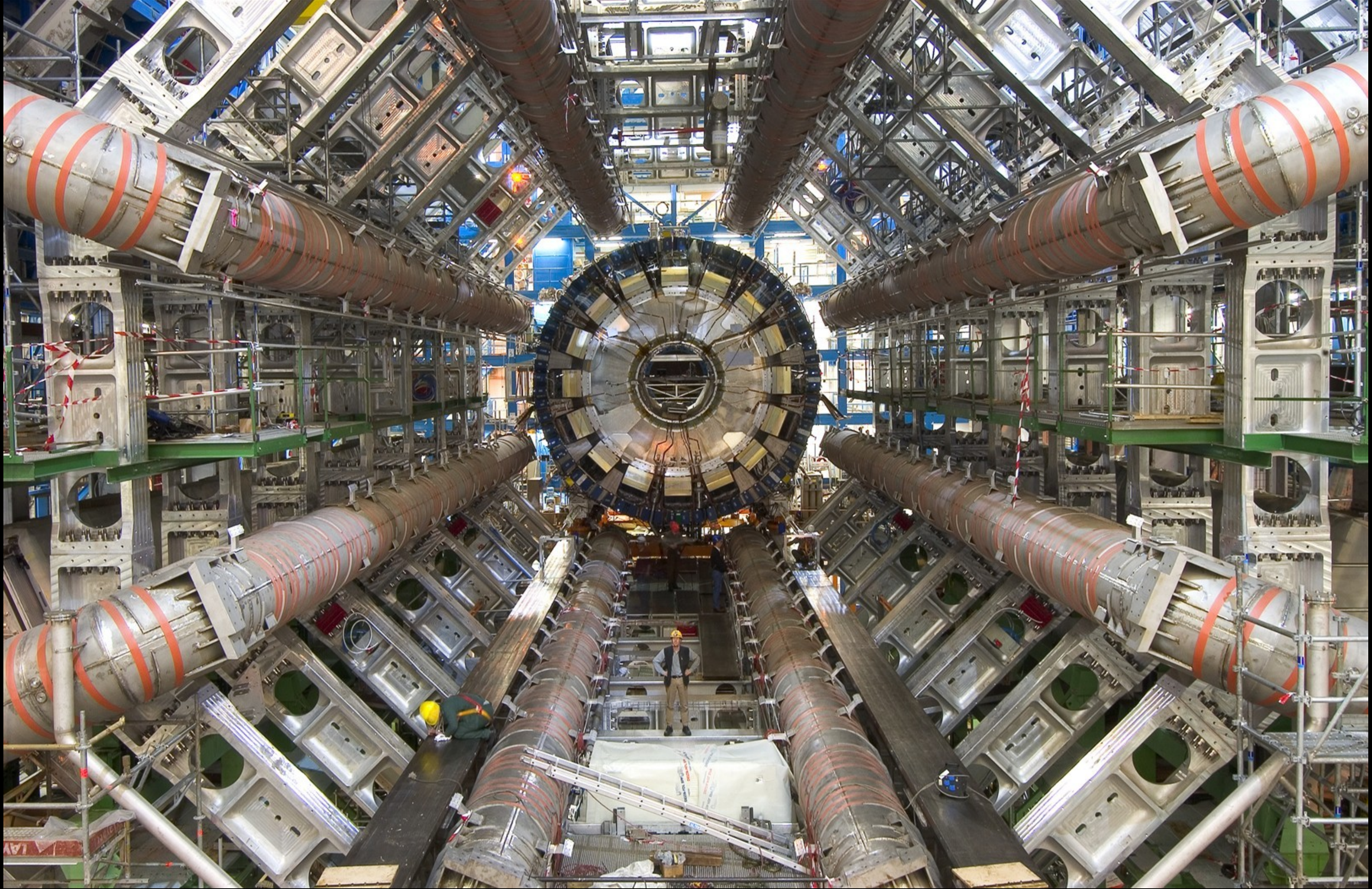
Introduction to high-energy astrophysical neutrinos 1/3

Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

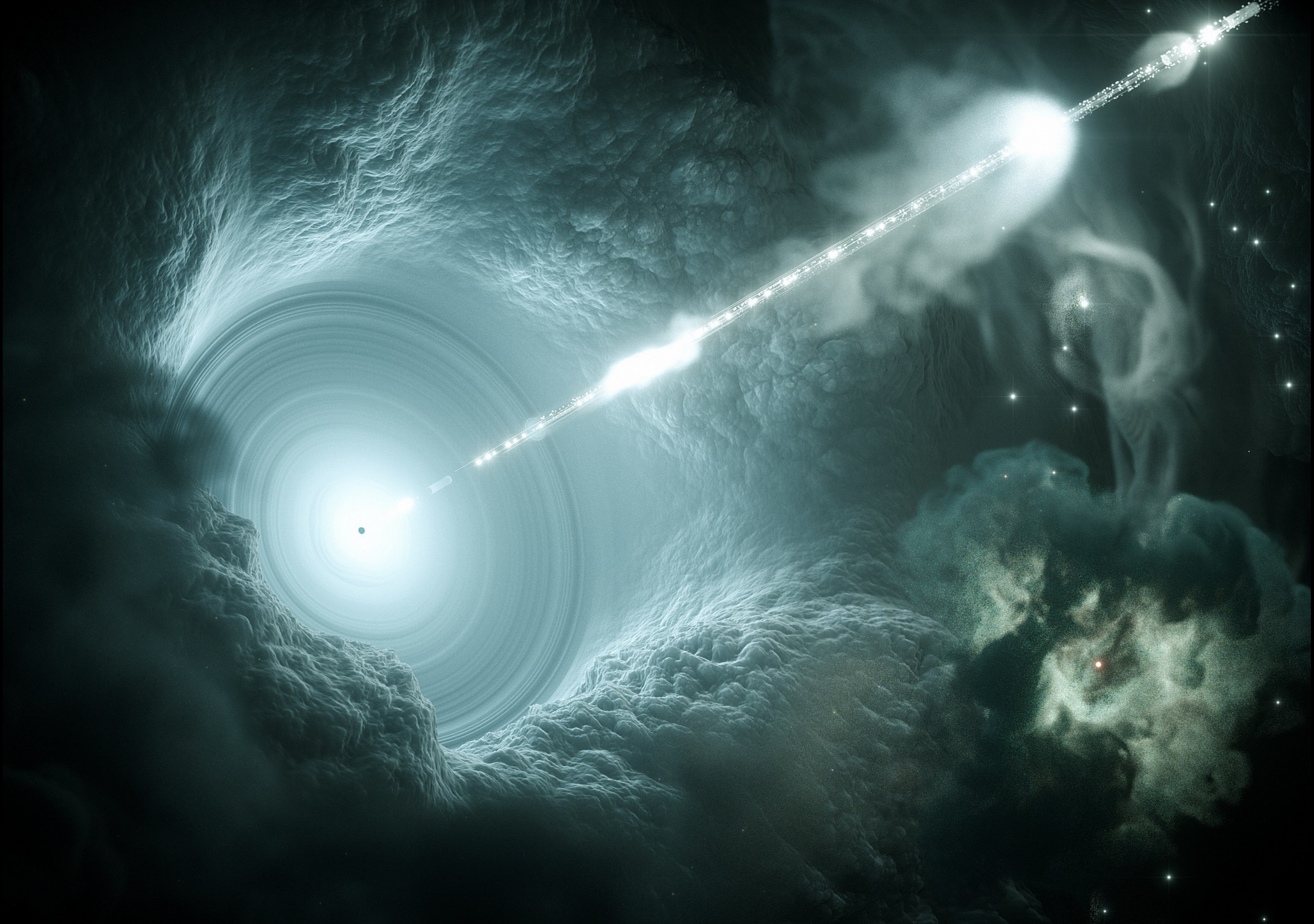
EuCAPT Astroneutrino Theory Workshop
Prague, September 16–20, 2024

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

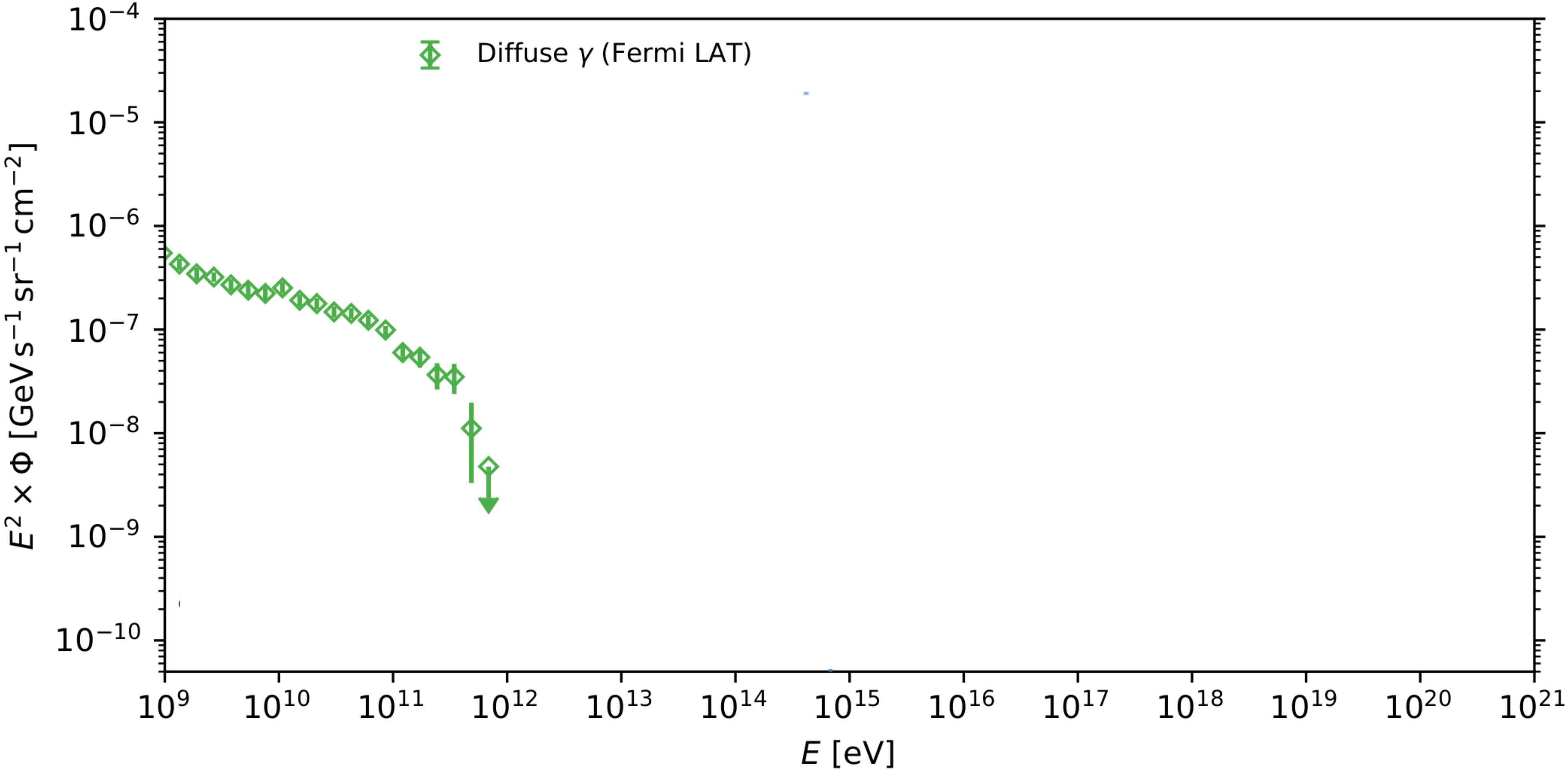


ATLAS

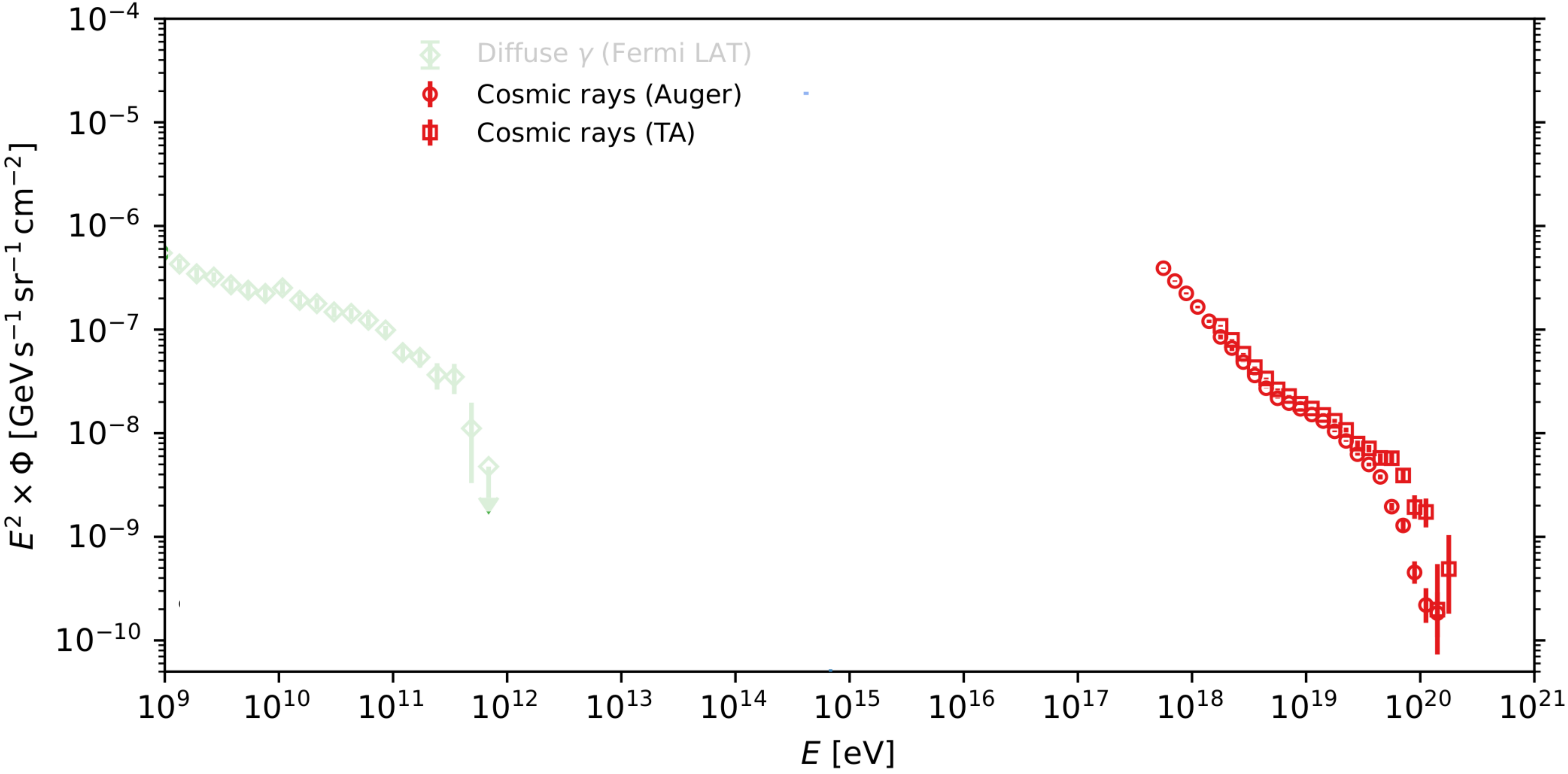


DESY

Gamma rays Neutrinos Cosmic rays



M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]



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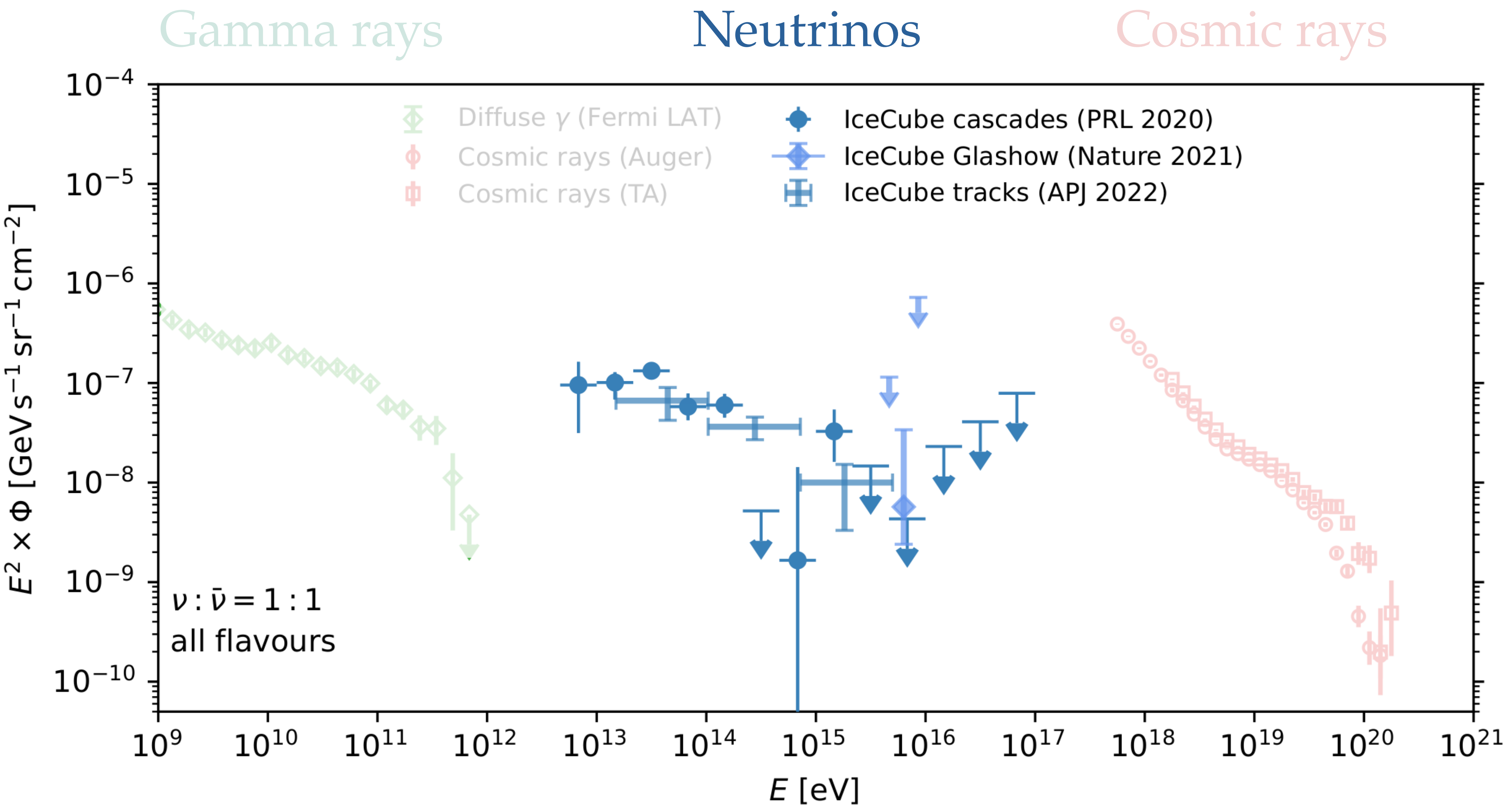

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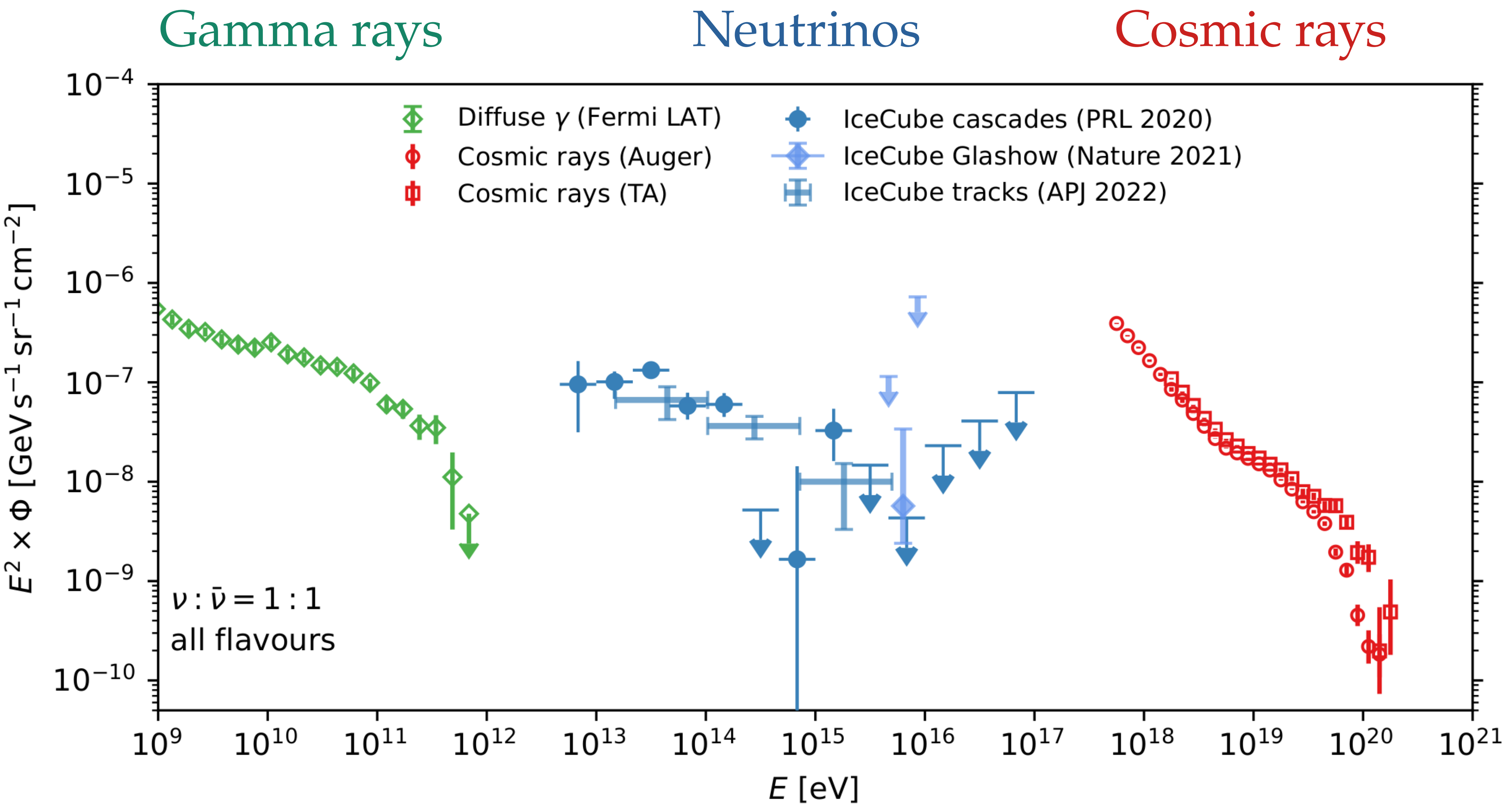

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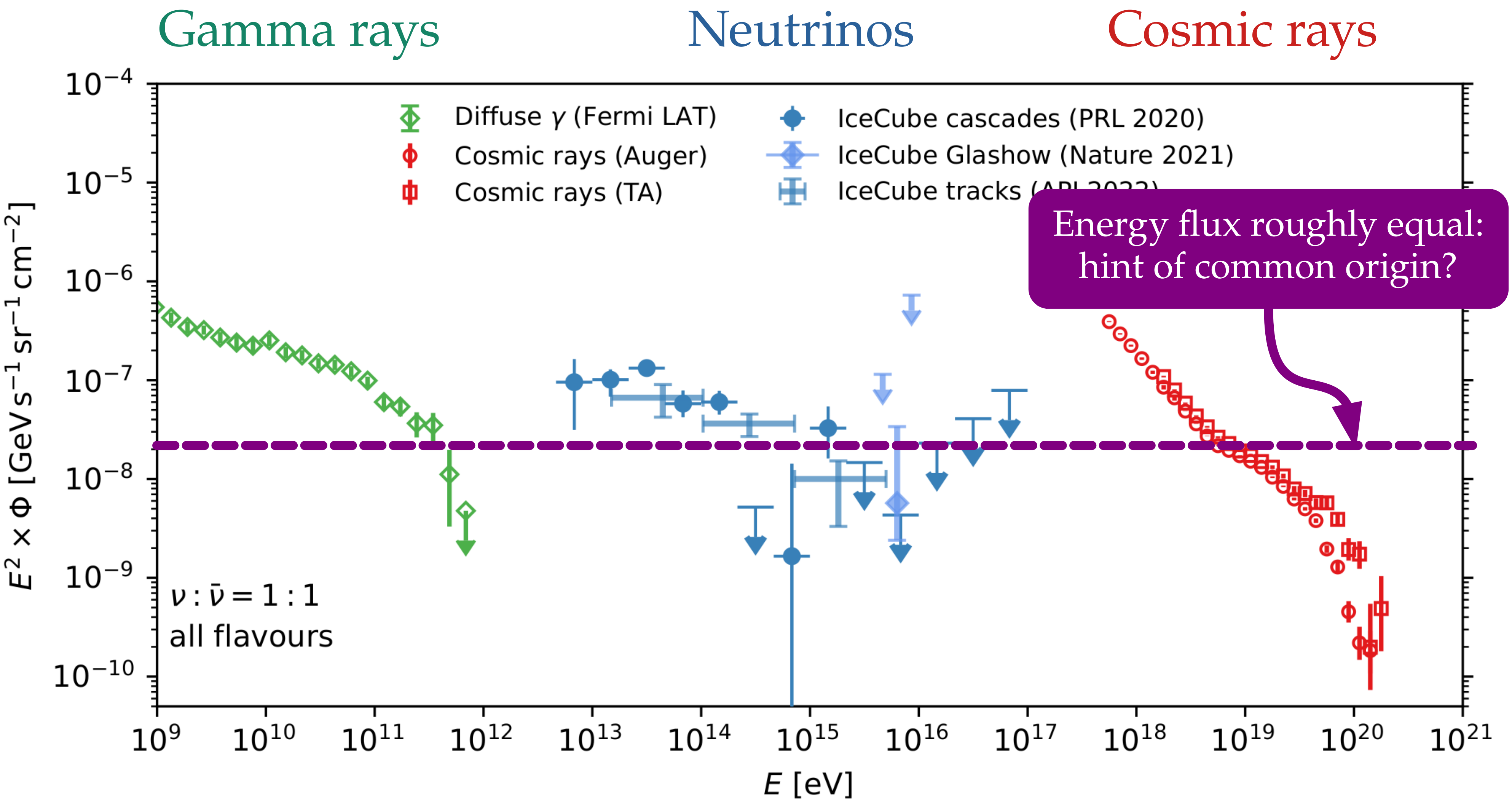

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The multi-messenger connection: a simple picture

$$p + \gamma_{\text{target}} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

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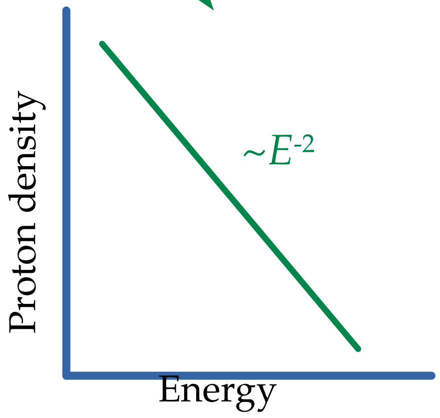

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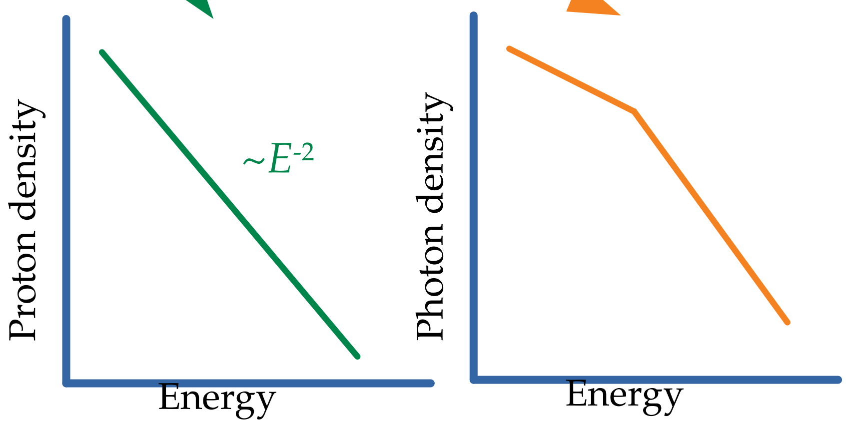

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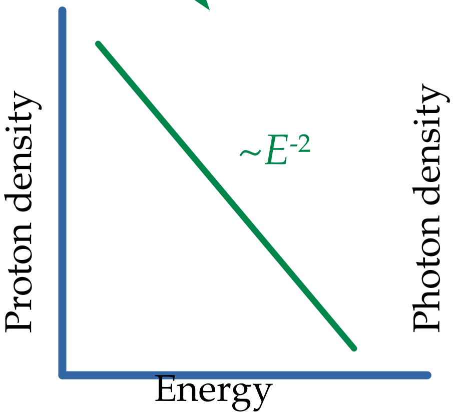
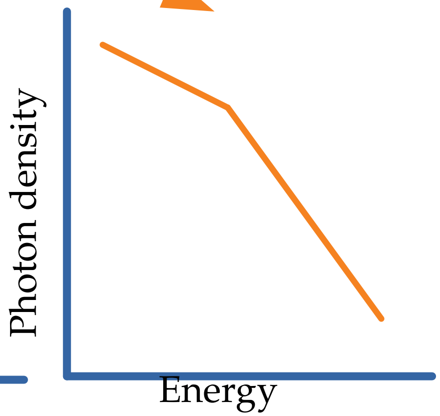
$$\pi^{0} \rightarrow \gamma + \gamma$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow \bar{\nu}_{\mu} + e^{+} + \nu_{e} + \nu_{\mu}$$

$$n \text{ (escapes)} \rightarrow p + e^{-} + \bar{\nu}_{e}$$





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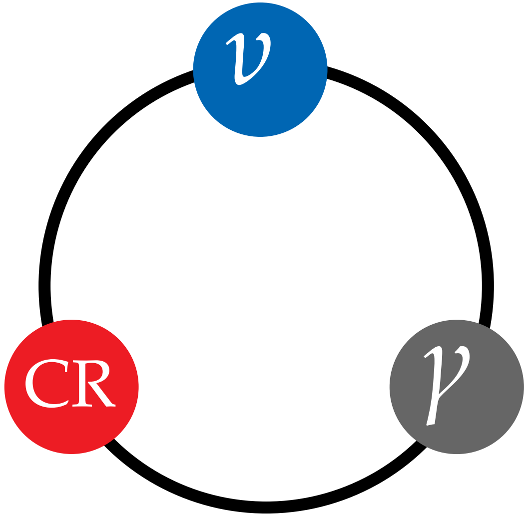

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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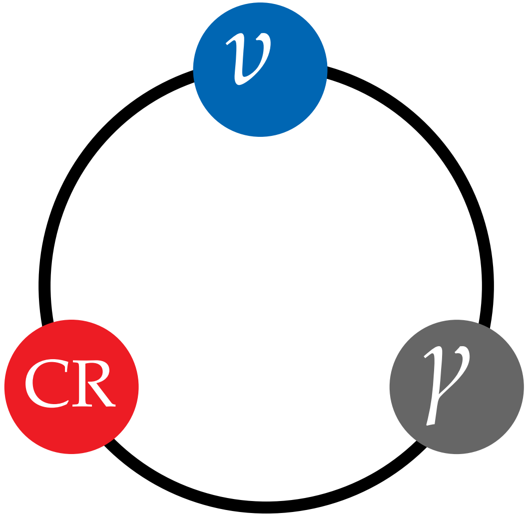

1 PeV 20 PeV

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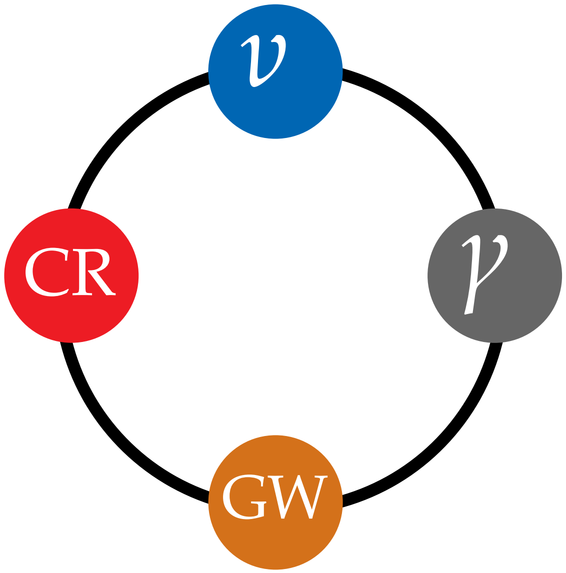

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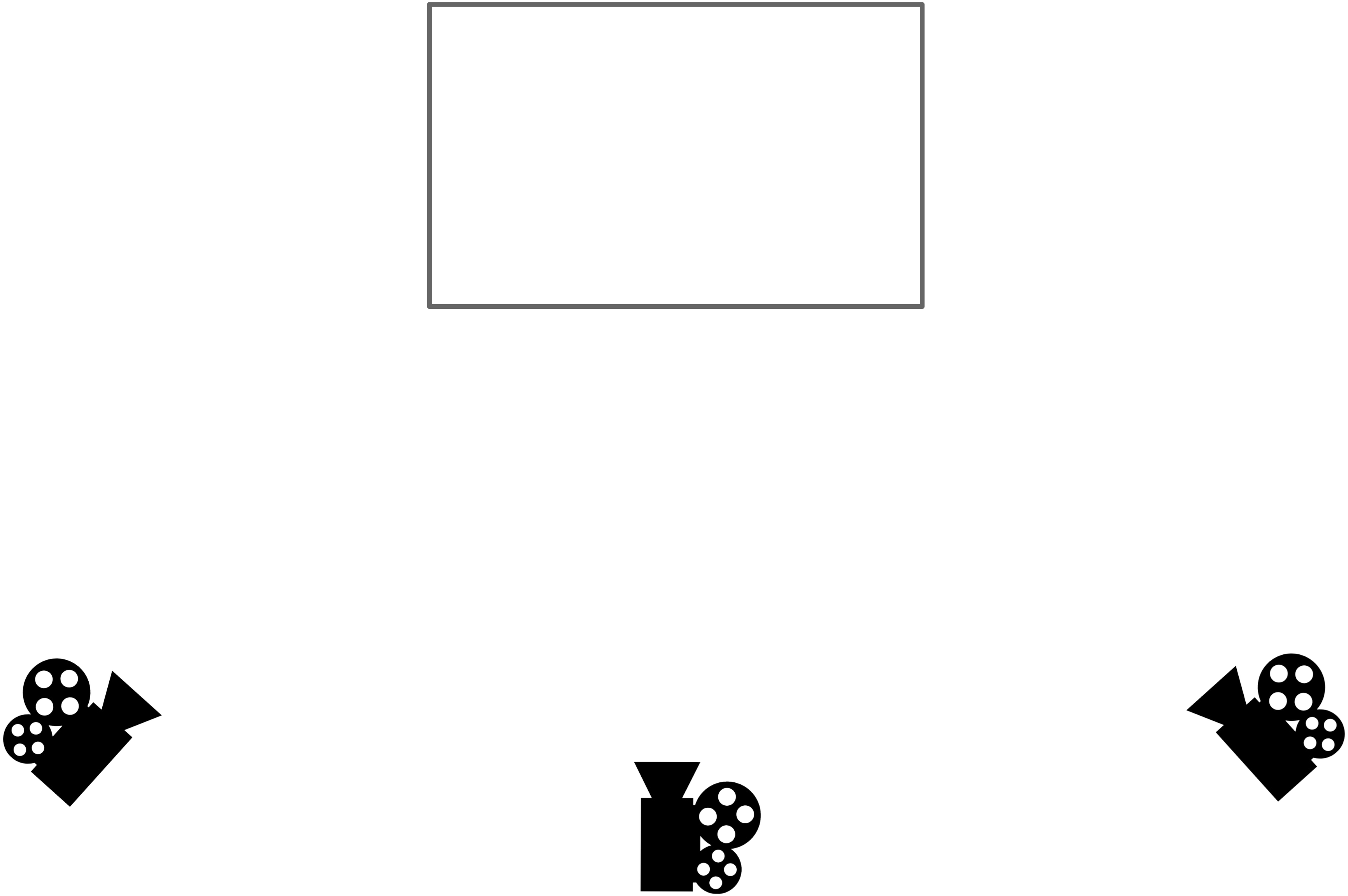
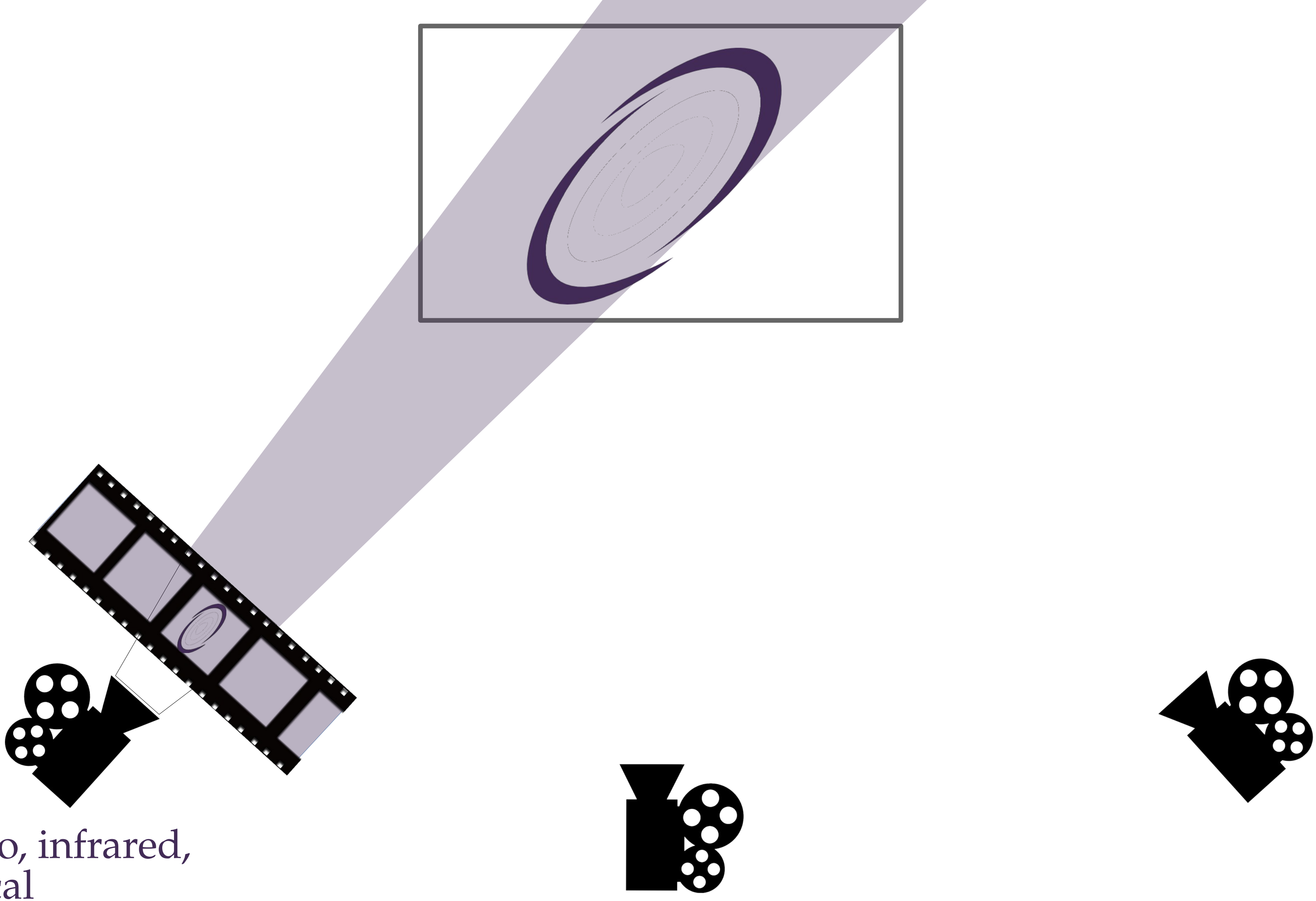
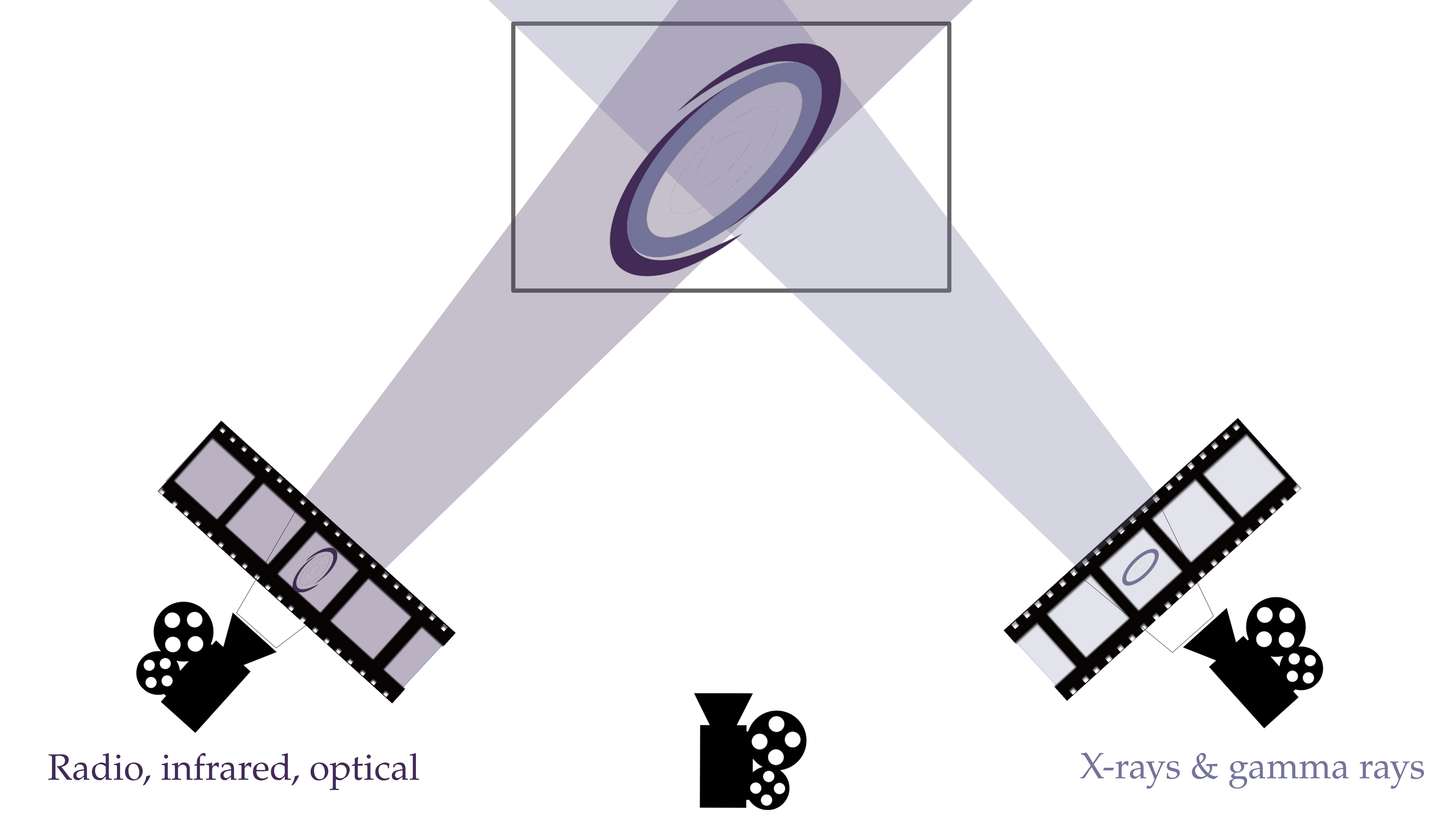
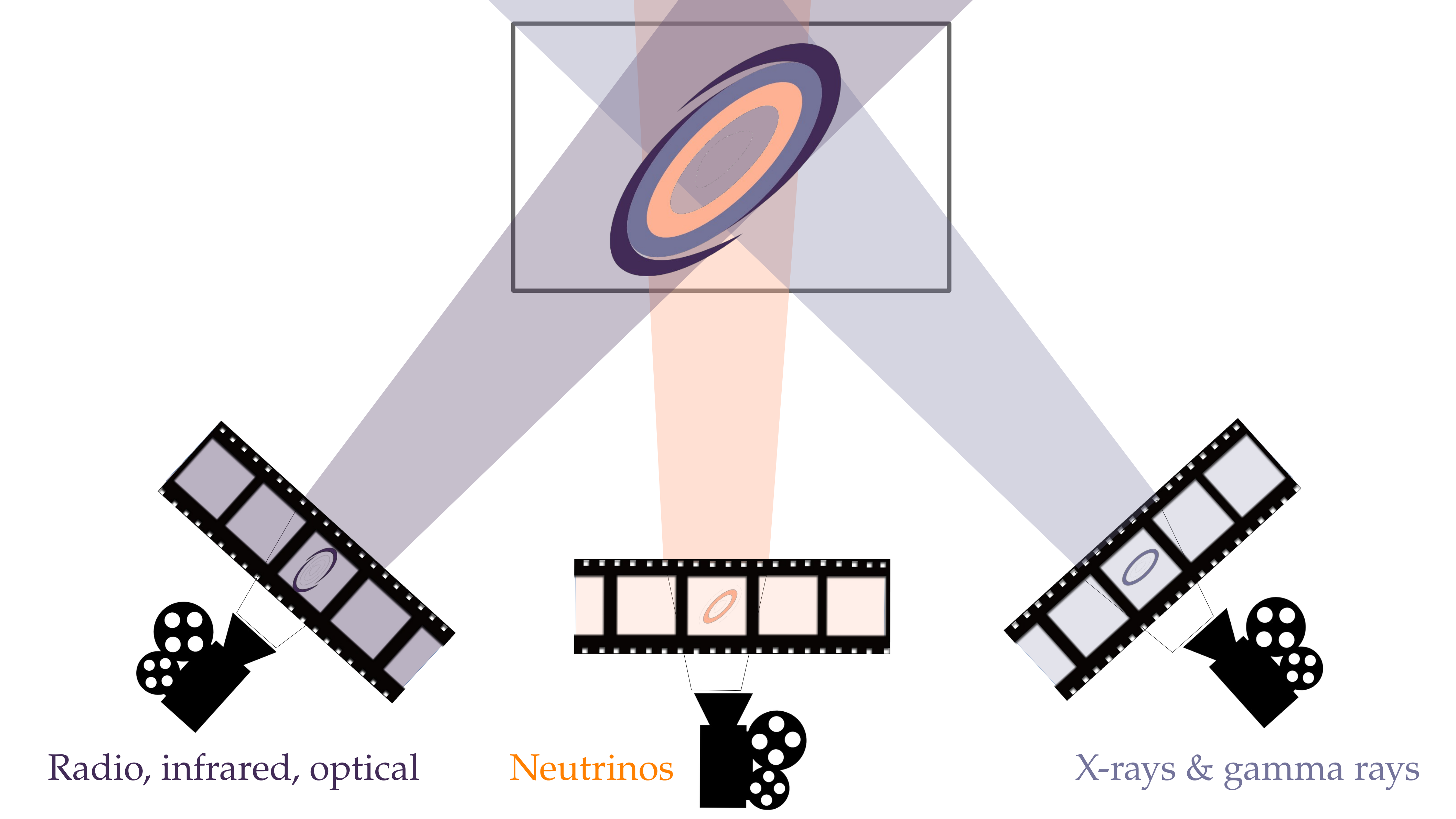




Radio, infrared,
optical


Radio, infrared, optical
X-rays & gamma rays


Radio, infrared, optical
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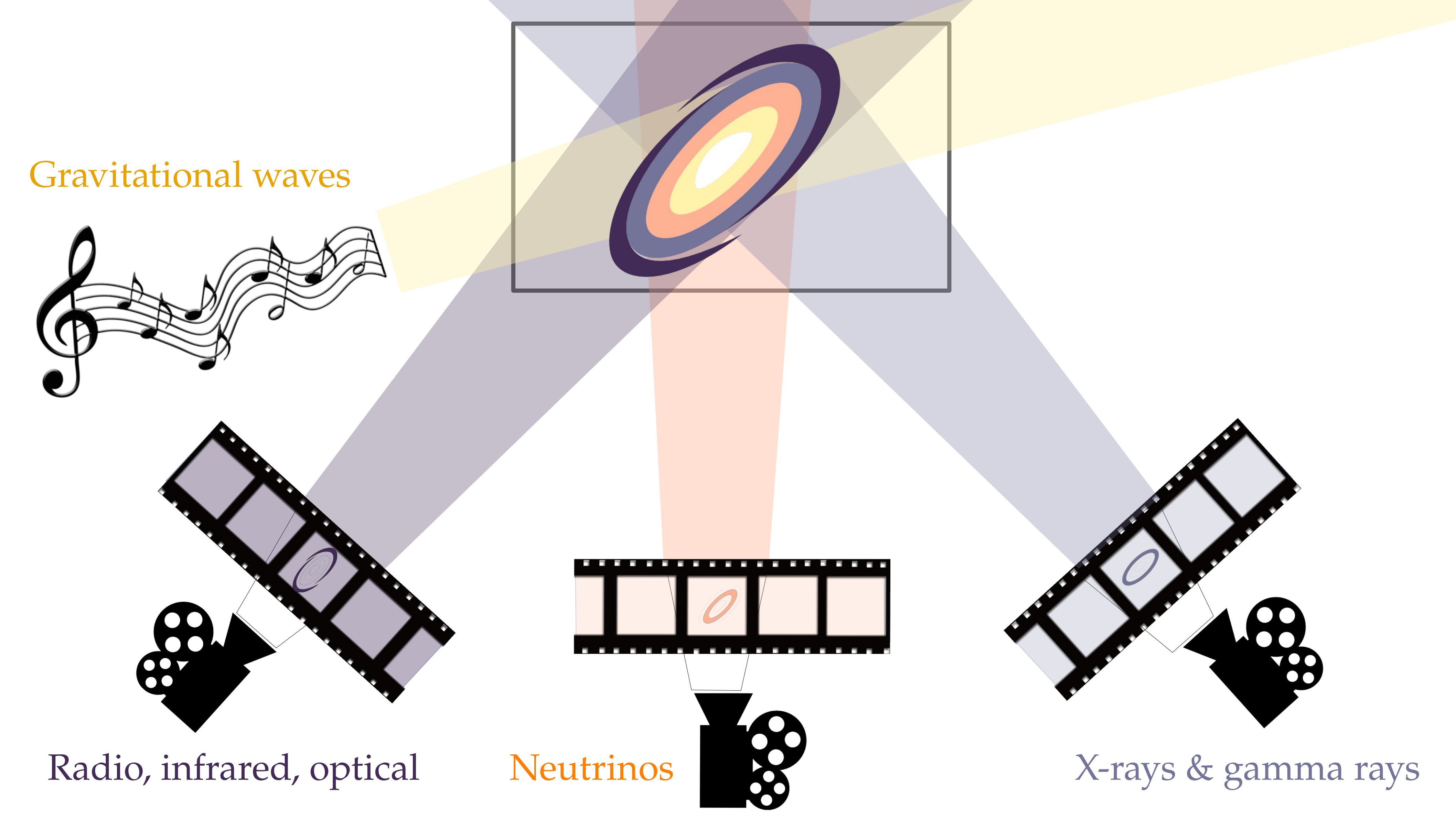
Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays

Ultra-high-energy cosmic rays

1962: First cosmic rays with >10^{20} eV

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2023: We are getting close to finding what is making them!

A story more than 100 years old

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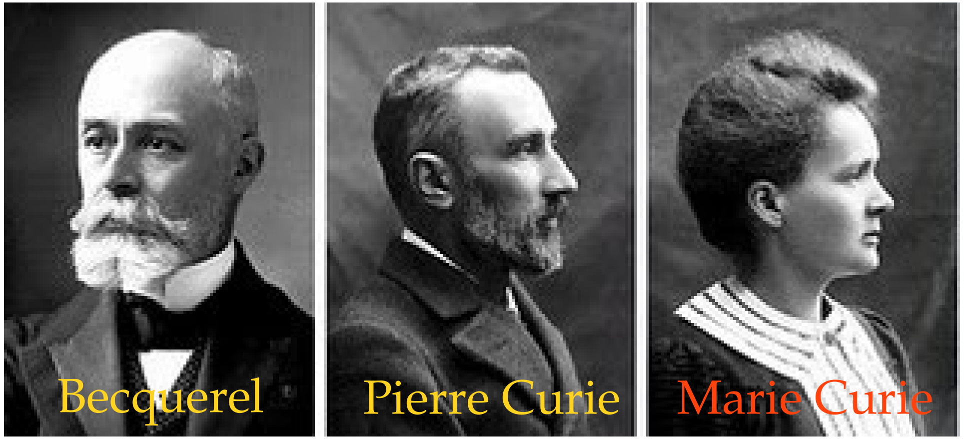
1896: radioactivity discovered (uranium, radium)



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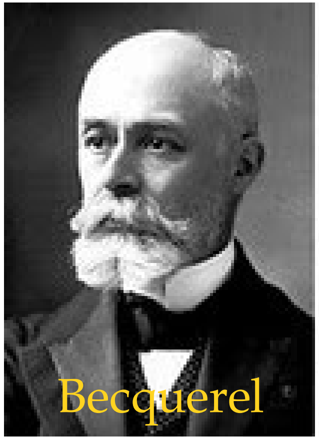

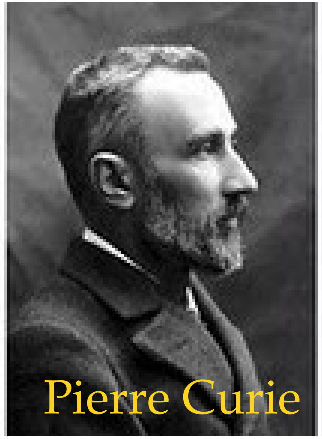

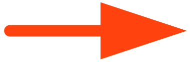

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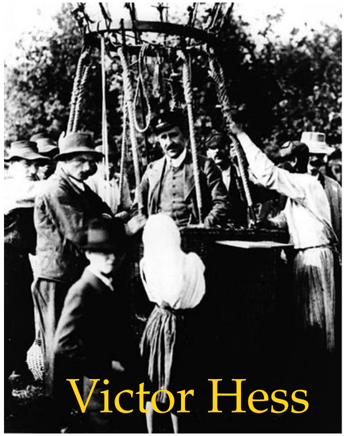

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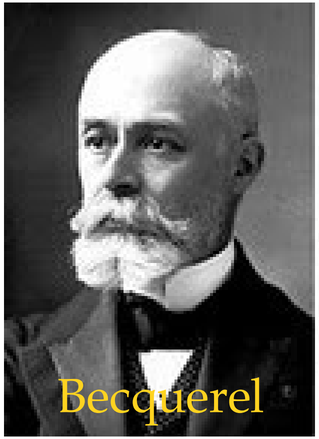

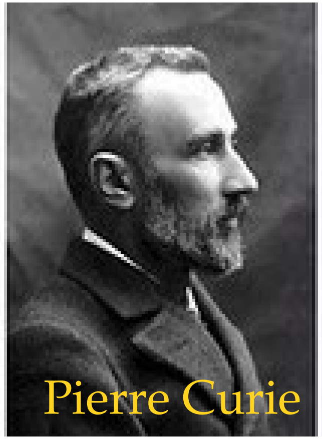

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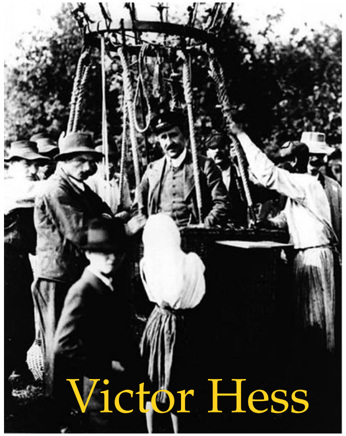
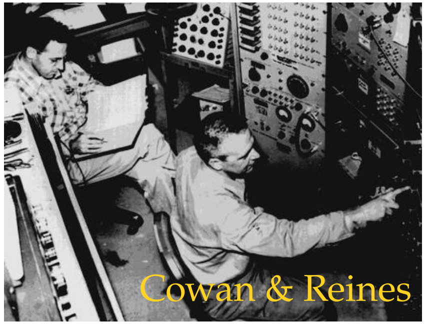


1956: neutrino discovered



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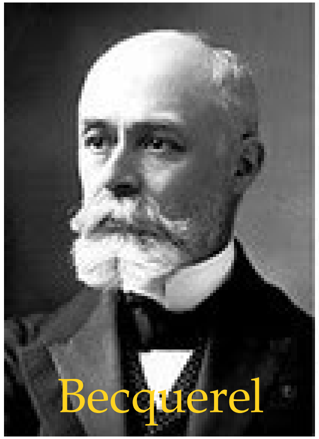

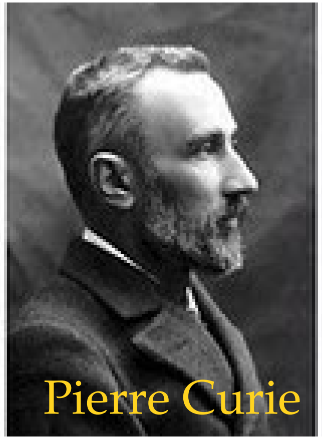

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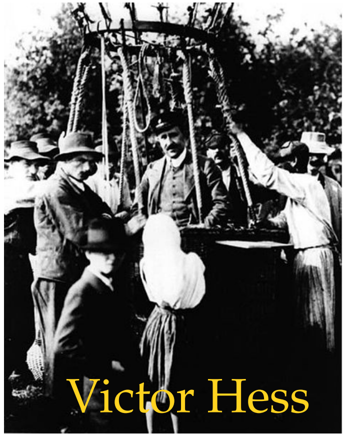

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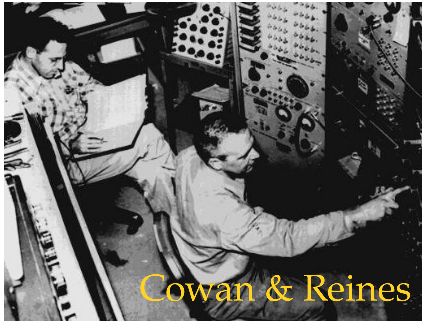

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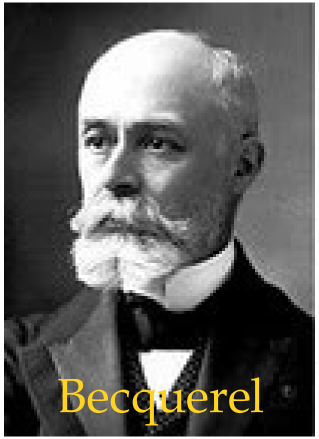

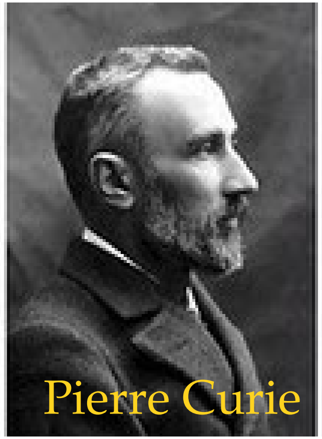

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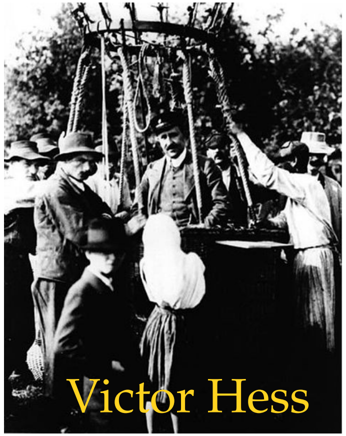

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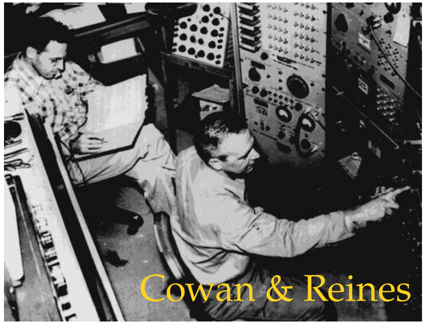

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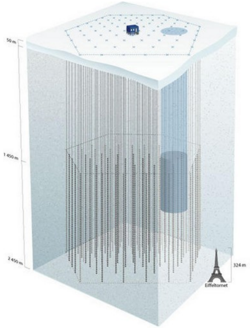
2013: high-energy neutrinos



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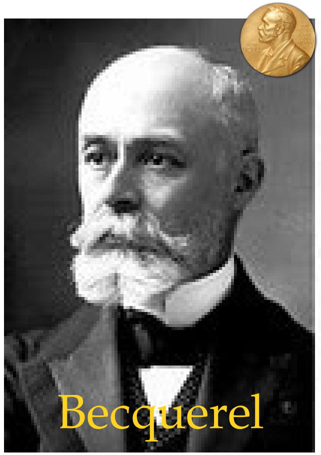

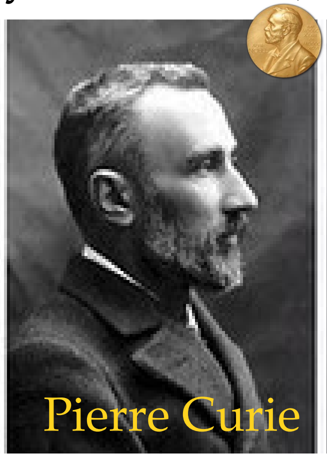

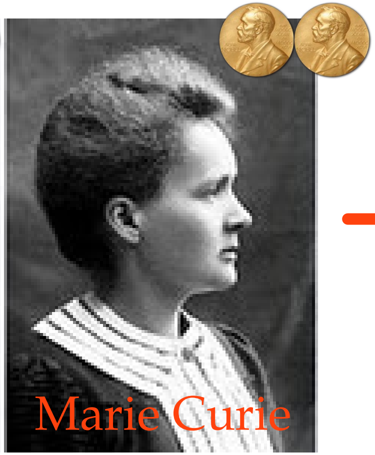

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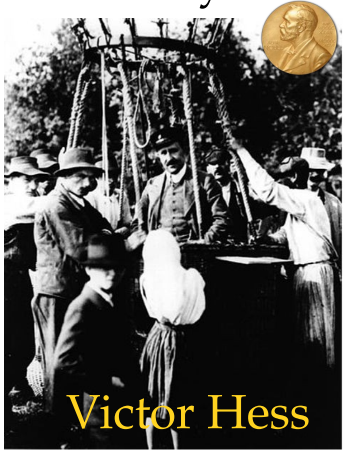

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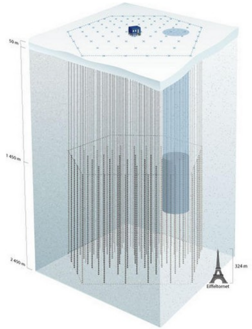

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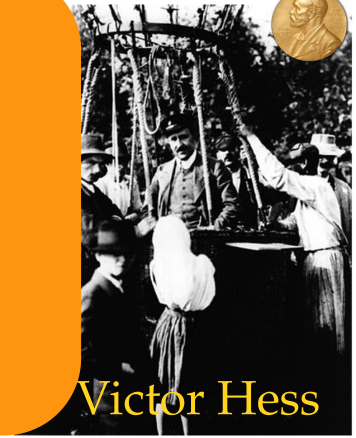
1896: radioactivity discovered (uranium, radium)

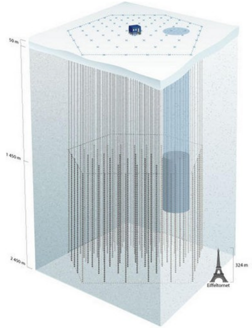
1911: cosmic rays discovered

These are the **most energetic** particles
in the known Universe

Where do they come from?



2013: high-energy neutrinos



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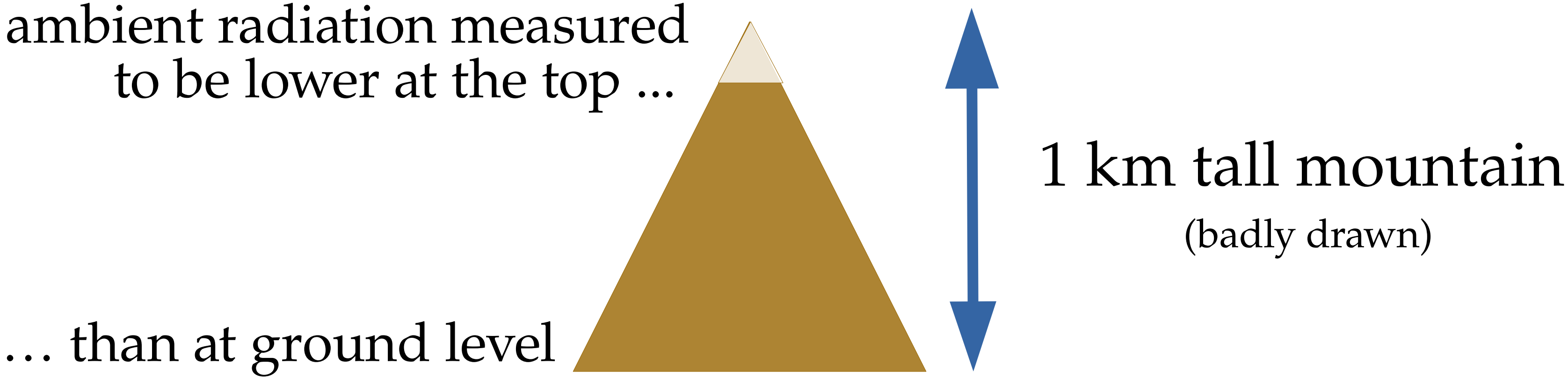
Cosmic rays discovered

The state at the beginning of the 20th century:

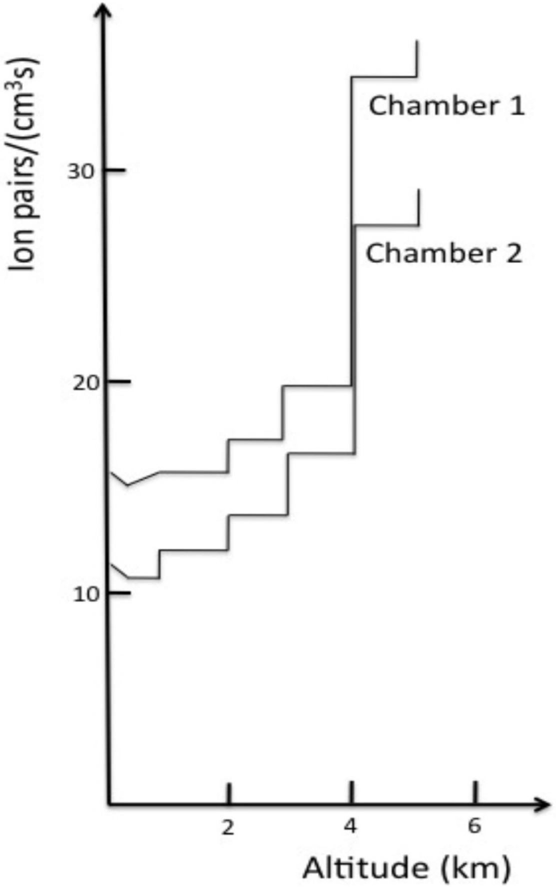
(1) ambient radiation was already known to exist
(2) believed to be mainly coming from the ground



Problem: they had measured *only* up to ~1 km of altitude

Physics is a risky business

Victor Hess – 1911-1913, balloon flights up to 5.3 km



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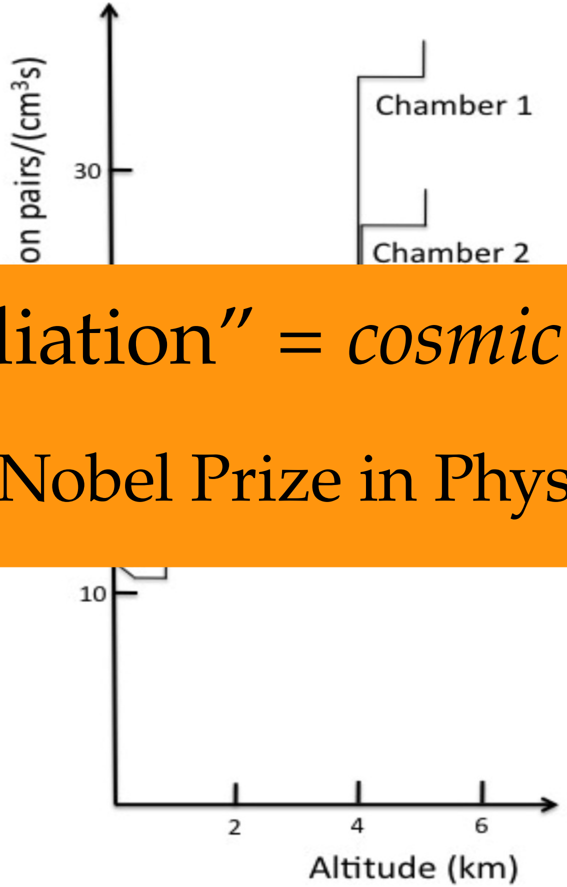
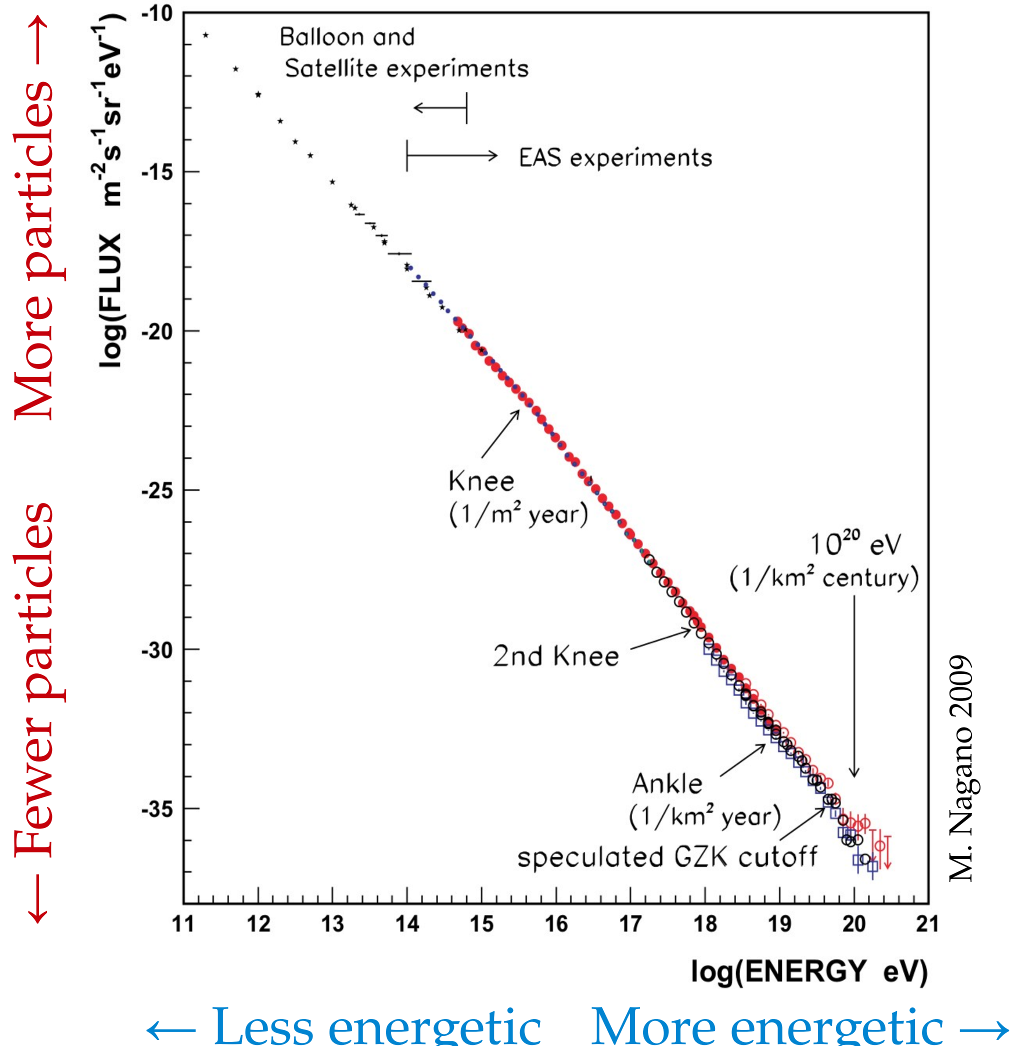


"Unknown penetrating radiation" = *cosmic rays*

… and that's one way to get a Nobel Prize in Physics

The cosmic ray spectrum at Earth



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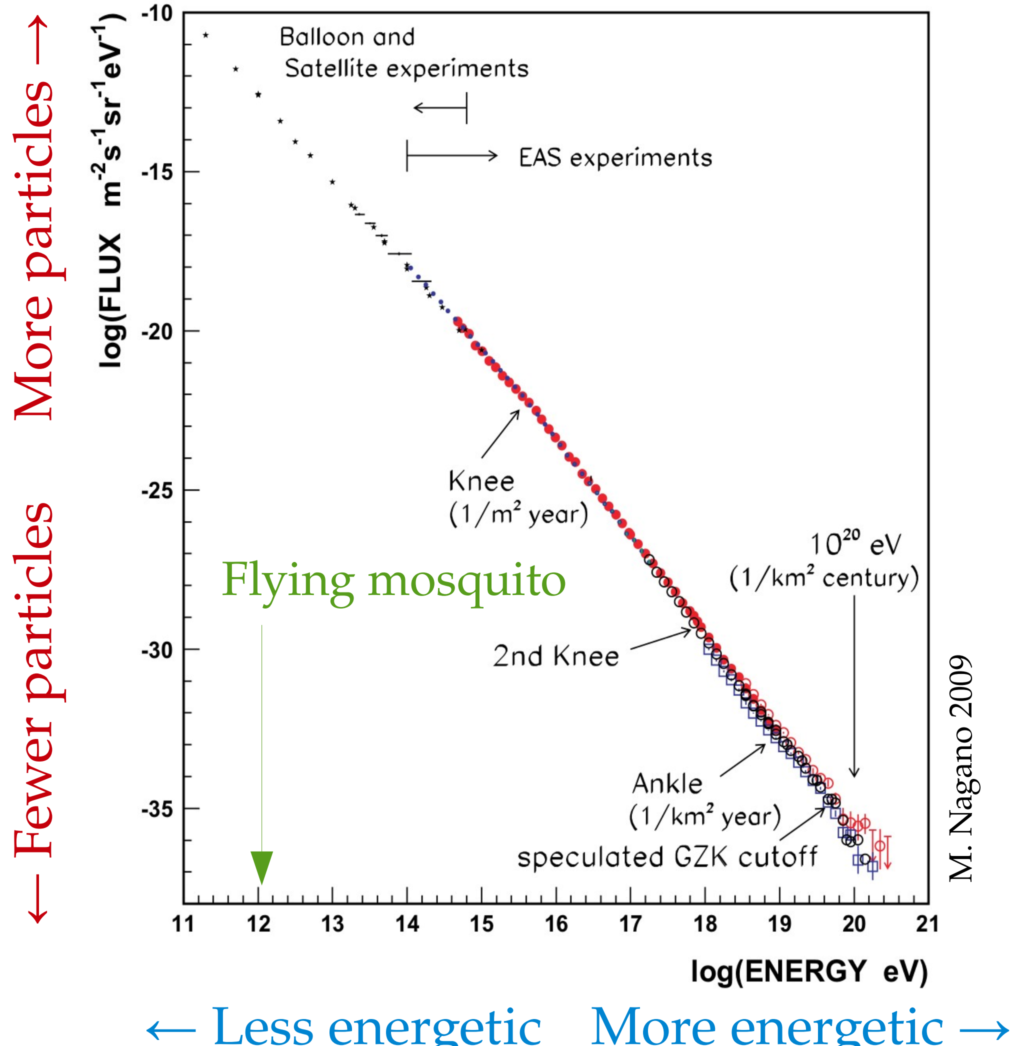

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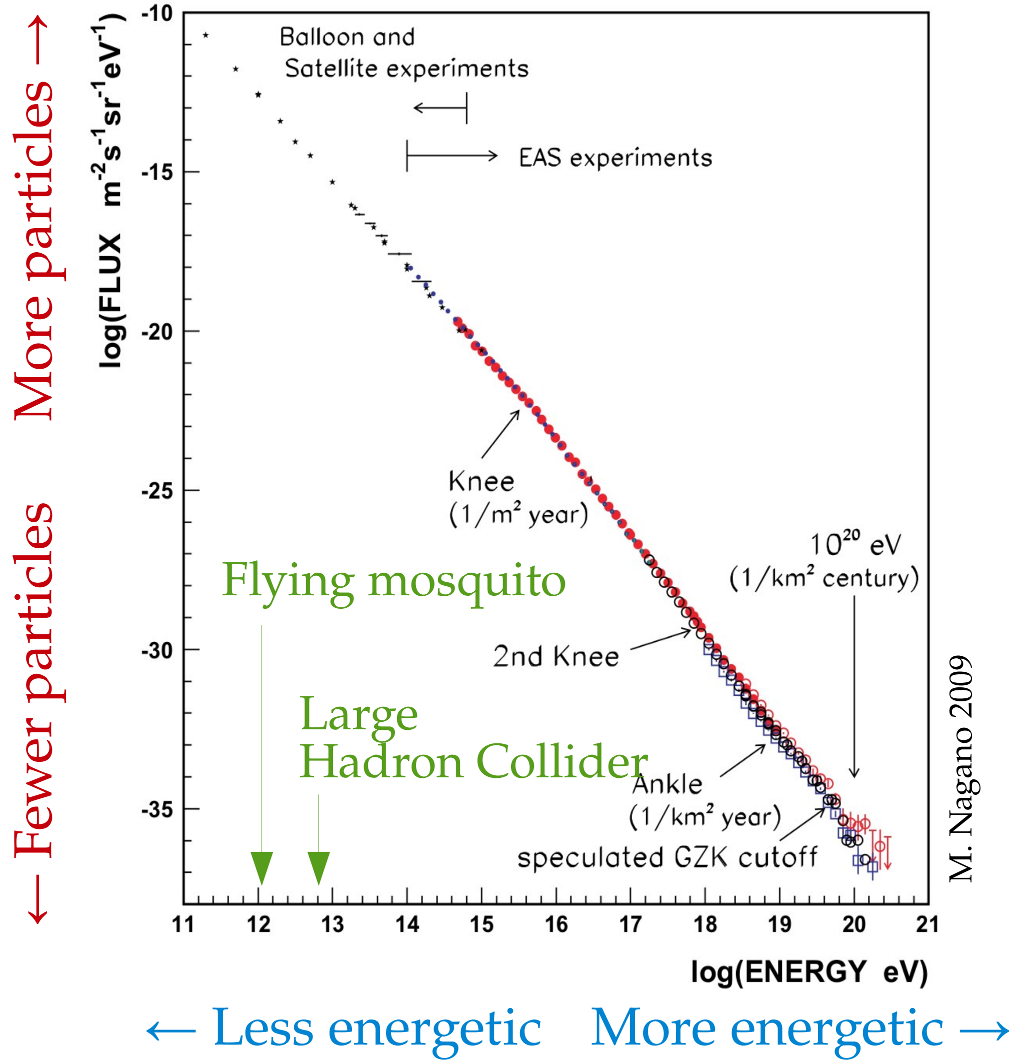
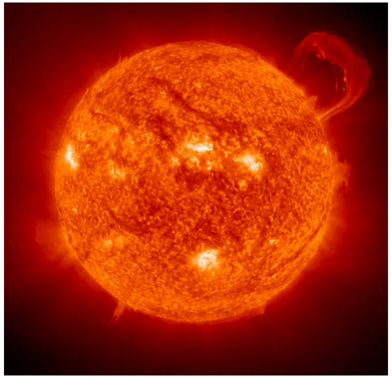


So what *are* cosmic rays?

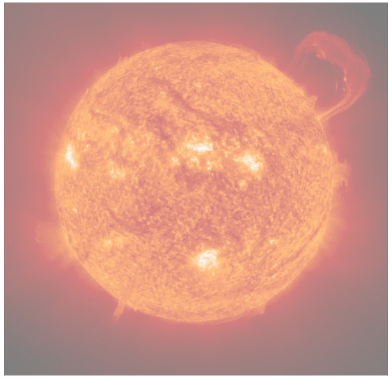


Low energies: from the Sun
– mostly electrons + protons

Higher energies: from supernovae inside the Milky Way
– protons and nuclei

Highest energies: from beyond the Milky Way
– protons + heavier nuclei

So what *are* cosmic rays?



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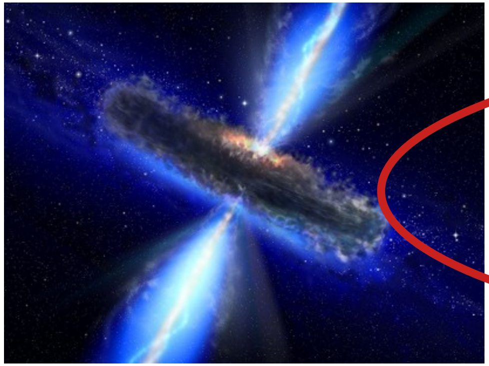
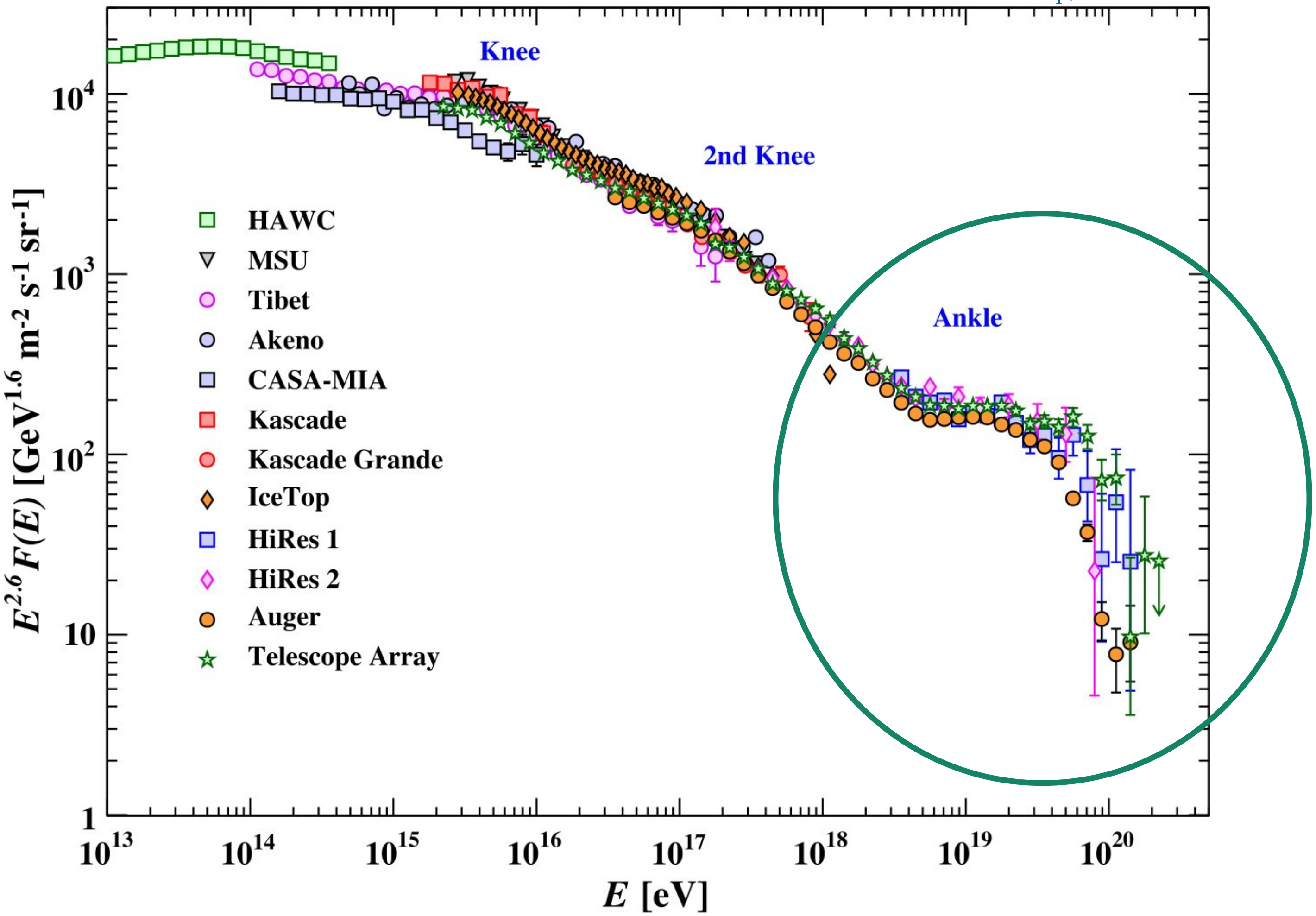
We will talk about these



Highest energies: from beyond the Milky Way
– protons + heavier nuclei

The UHECR all-particle spectrum

Particle Data Group, *PTEP* 2022



Let's talk about these energies

What are they?

Protons and nuclei with energies above 10^{17} eV

Is that a lot?

Yes.

10^5–10^8 times higher than LHC protons

A 10^{20}-eV proton has the kinetic energy of a kicked football

We know no particles more energetic than UHECRs

So what's making them?

Good question. We don't know.

Whatever it is, it is one of the most violent processes in the Universe

(Ok, fine: extragalactic non-thermal astrophysical sources that act as cosmic particle accelerators)

Why is it so hard?

UHECRs don't travel in straight lines

(the Universe is magnetized)

+

UHECRs are rare

(the Universe is opaque to them)

Are we getting closer?

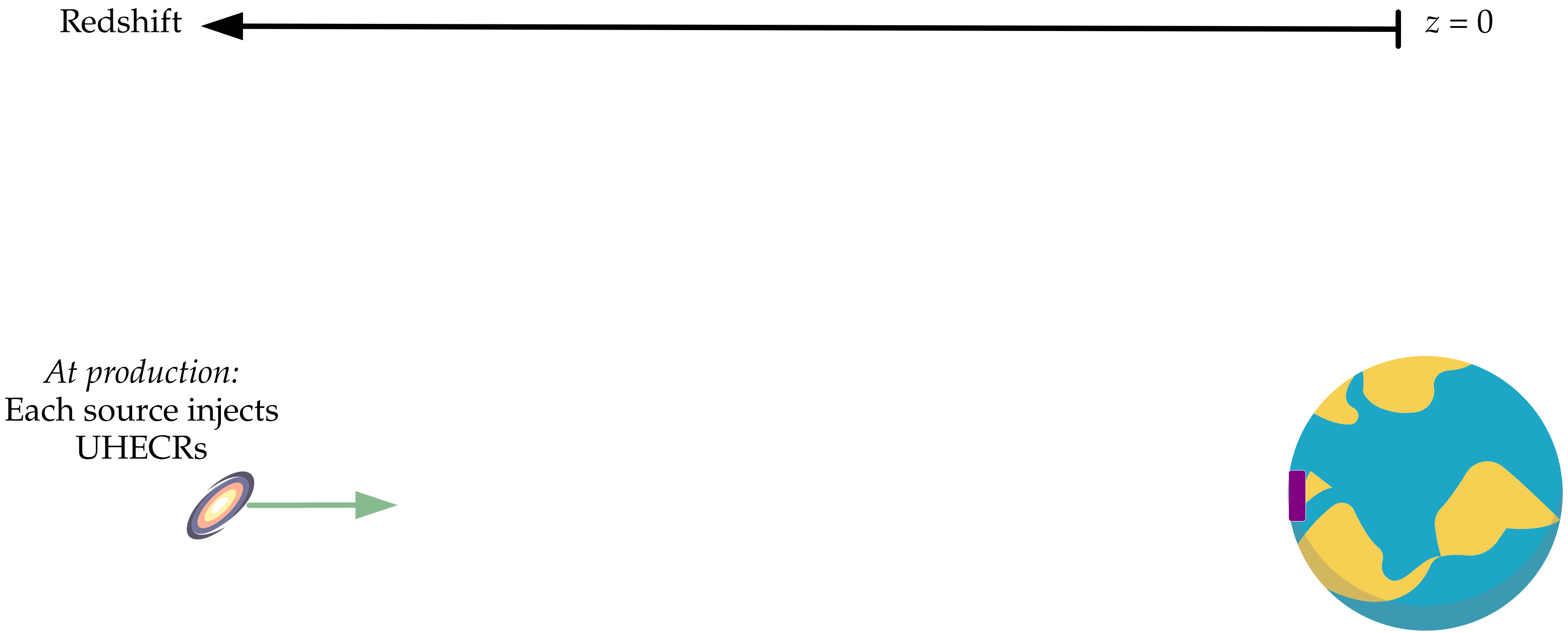
Yes.

We detect a growing number of UHECRs

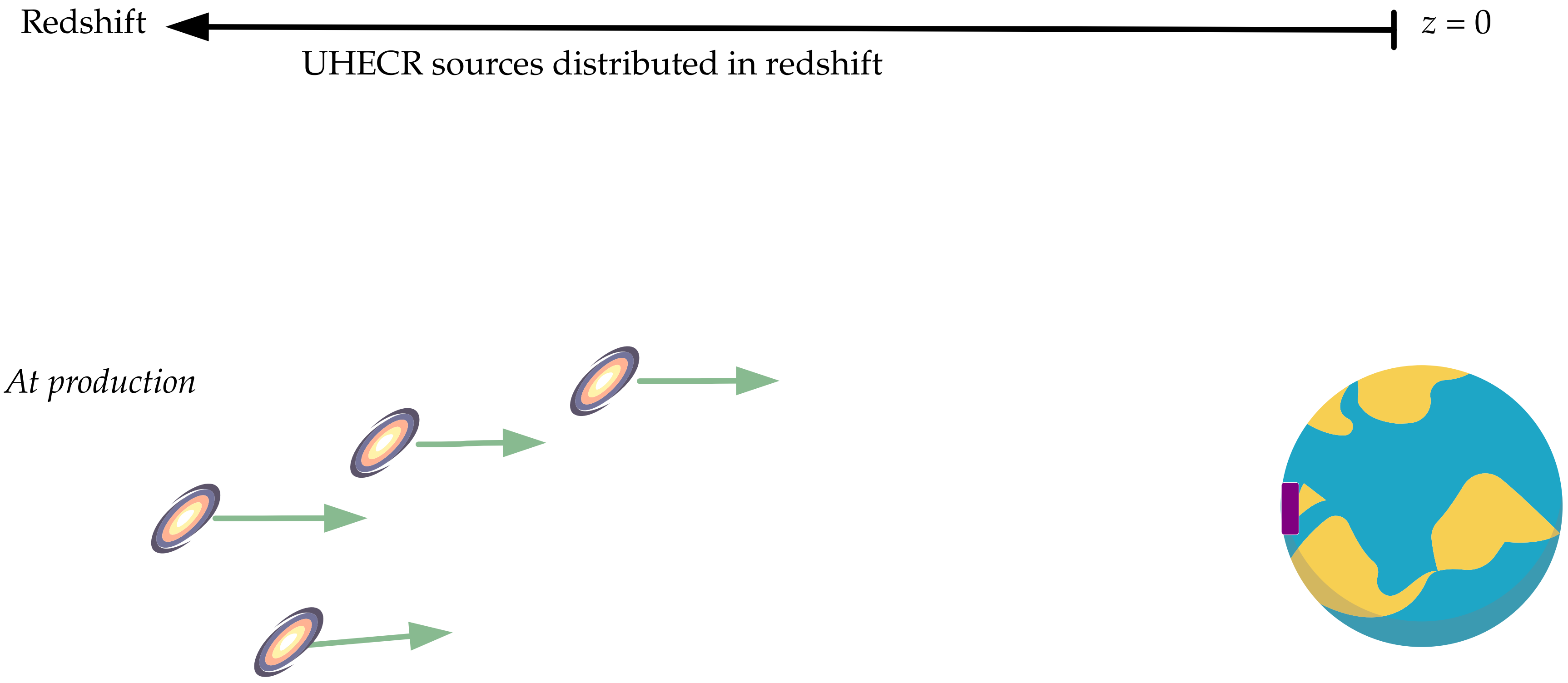
and

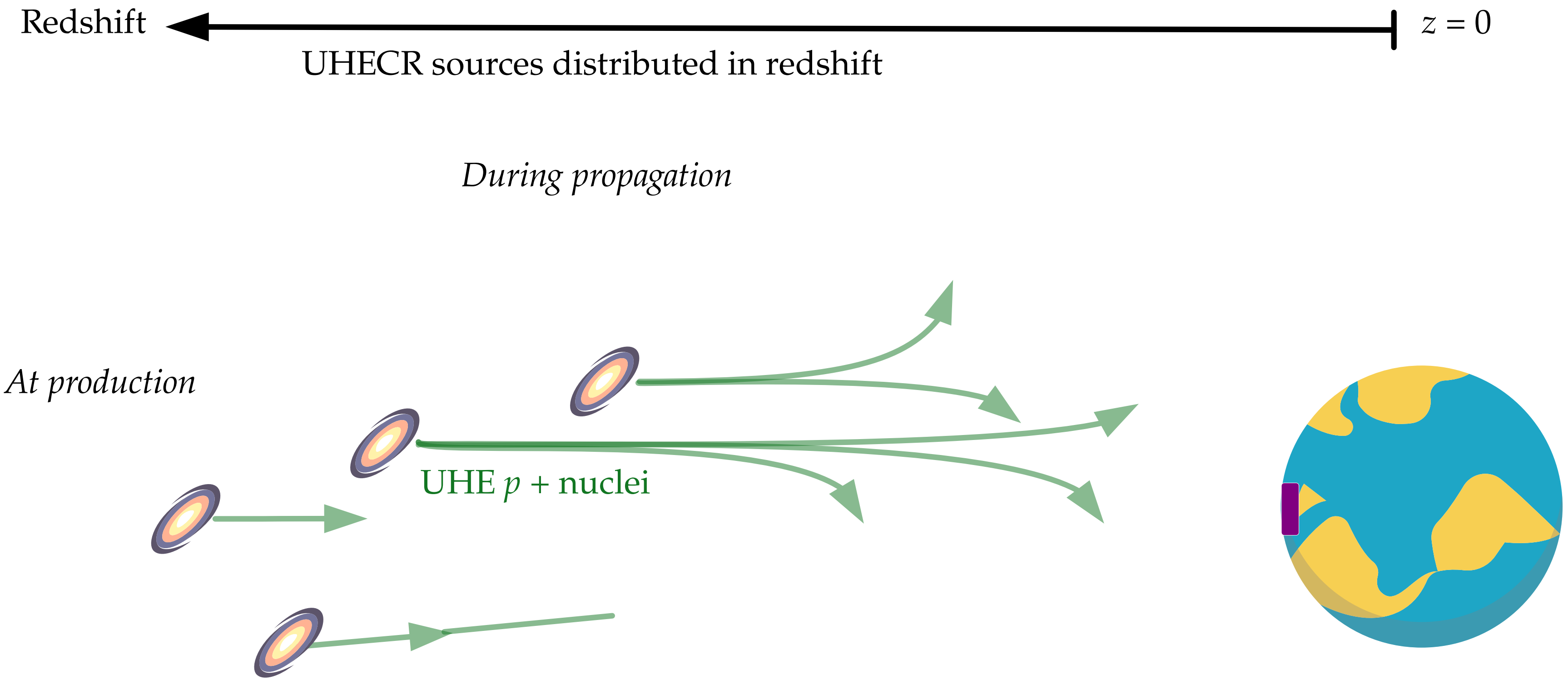
we can use neutrinos, too

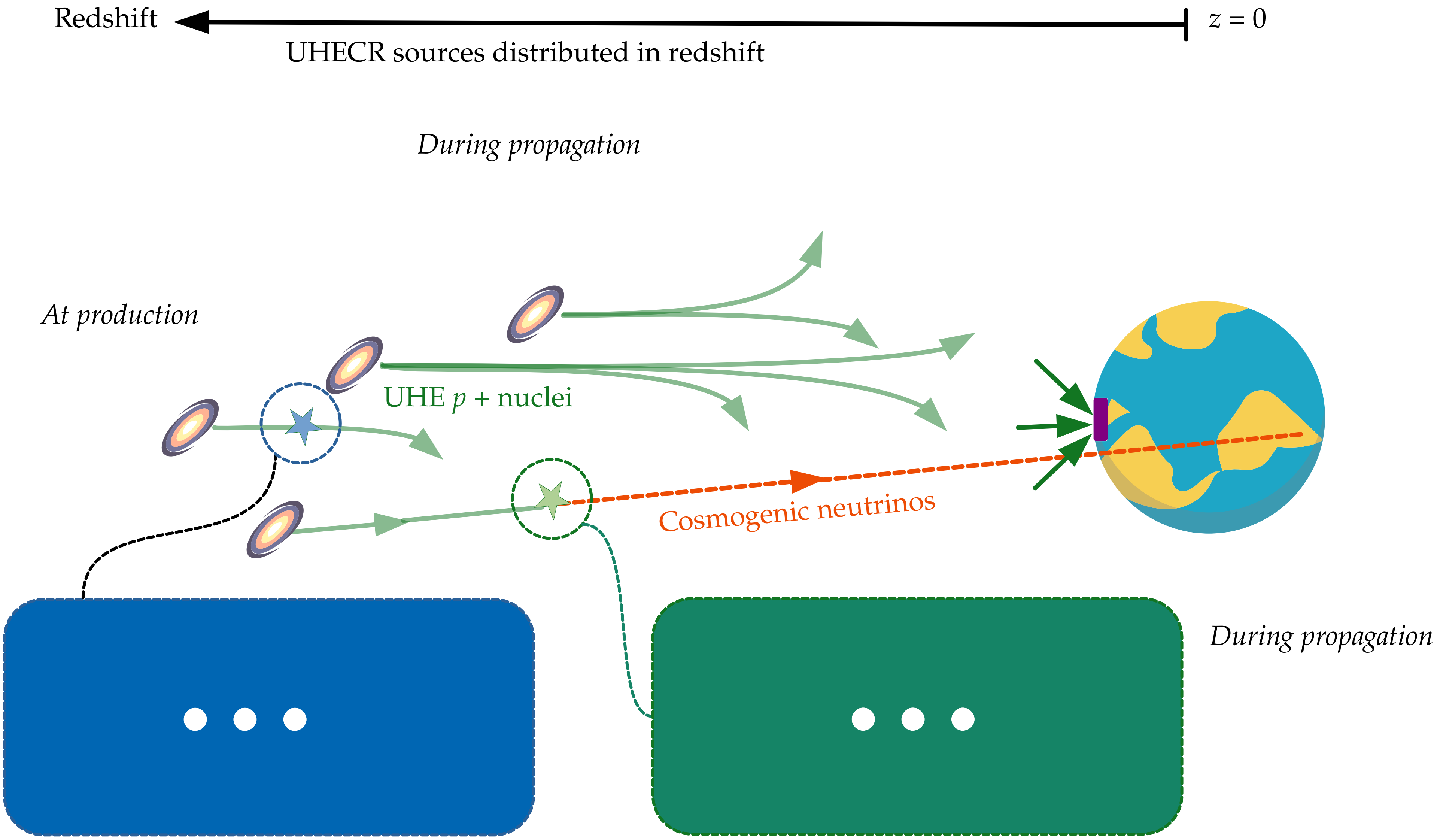
(more on this later)



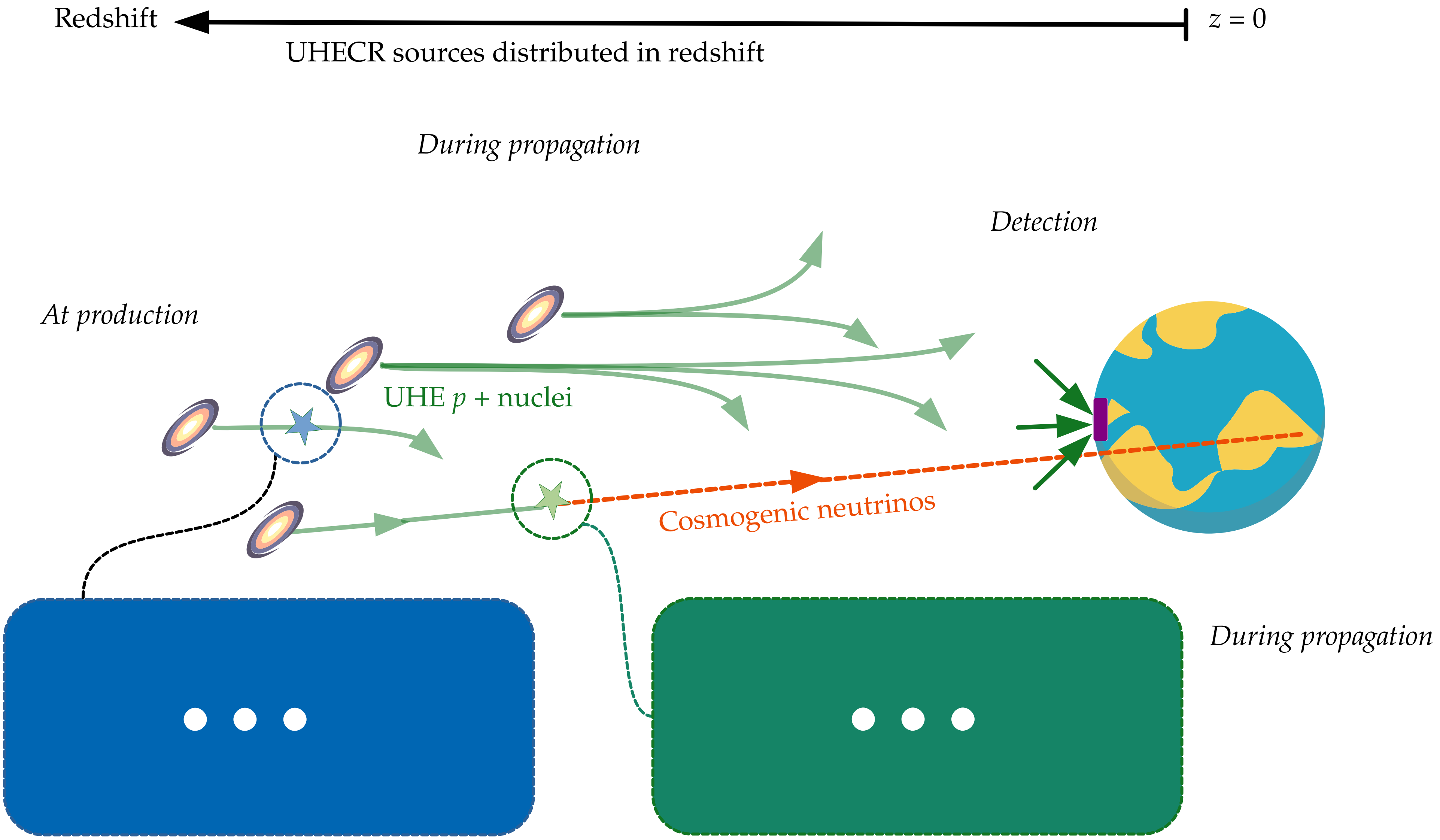
Redshift
$z = 0$
At production:
Each source injects
UHECRs


Redshift
$z = 0$
UHECR sources distributed in redshift
At production


Redshift
z = 0
UHECR sources distributed in redshift
During propagation
At production
UHE p + nuclei



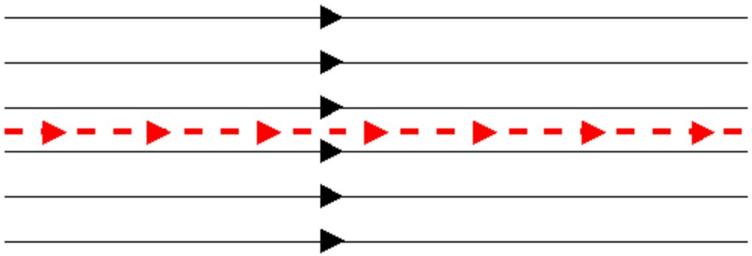
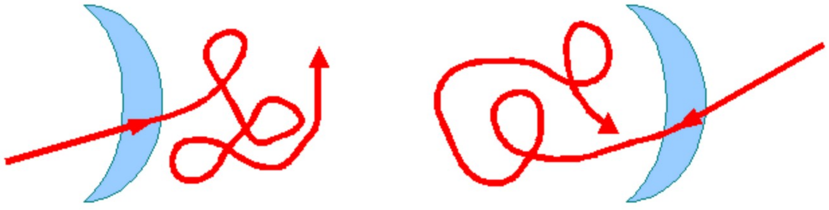
Redshift
$z = 0$
UHECR sources distributed in redshift
During propagation
At production
UHE p + nuclei
Cosmogenic neutrinos
During propagation



Redshift
z = 0
UHECR sources distributed in redshift
During propagation
Detection
At production
UHE p + nuclei
Cosmogenic neutrinos
During propagation

UHECR production

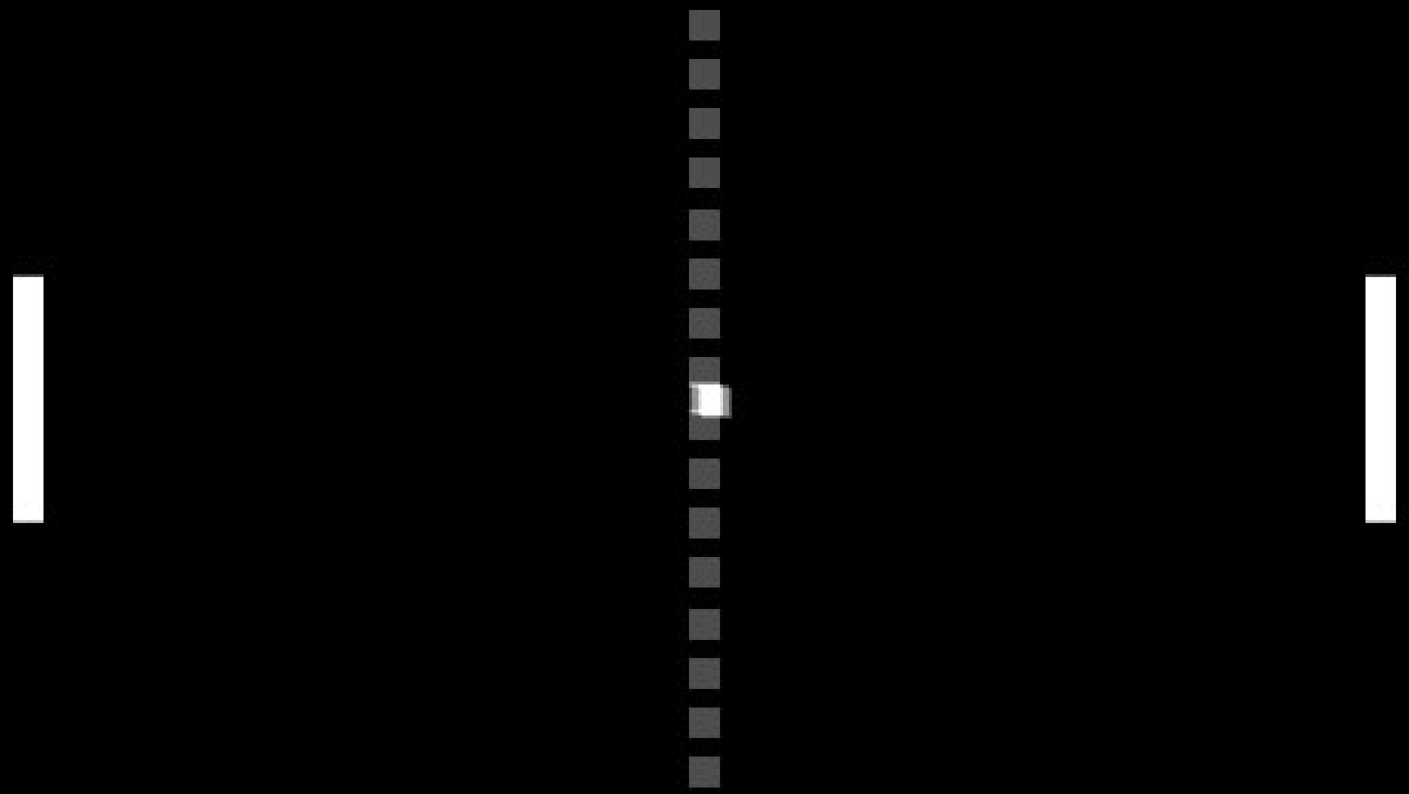
UHECR sources are messy

	Man-made accelerators	Astrophysical accelerators
		
Acceleration	In vacuum	In a medium
E.m. fields	Ordered	Messy
Beam dumps	Precisely regulated	Fully unregulated

Astrophysical accelerators *inevitably* make high-energy secondaries

How are cosmic rays made?

How are cosmic rays made?



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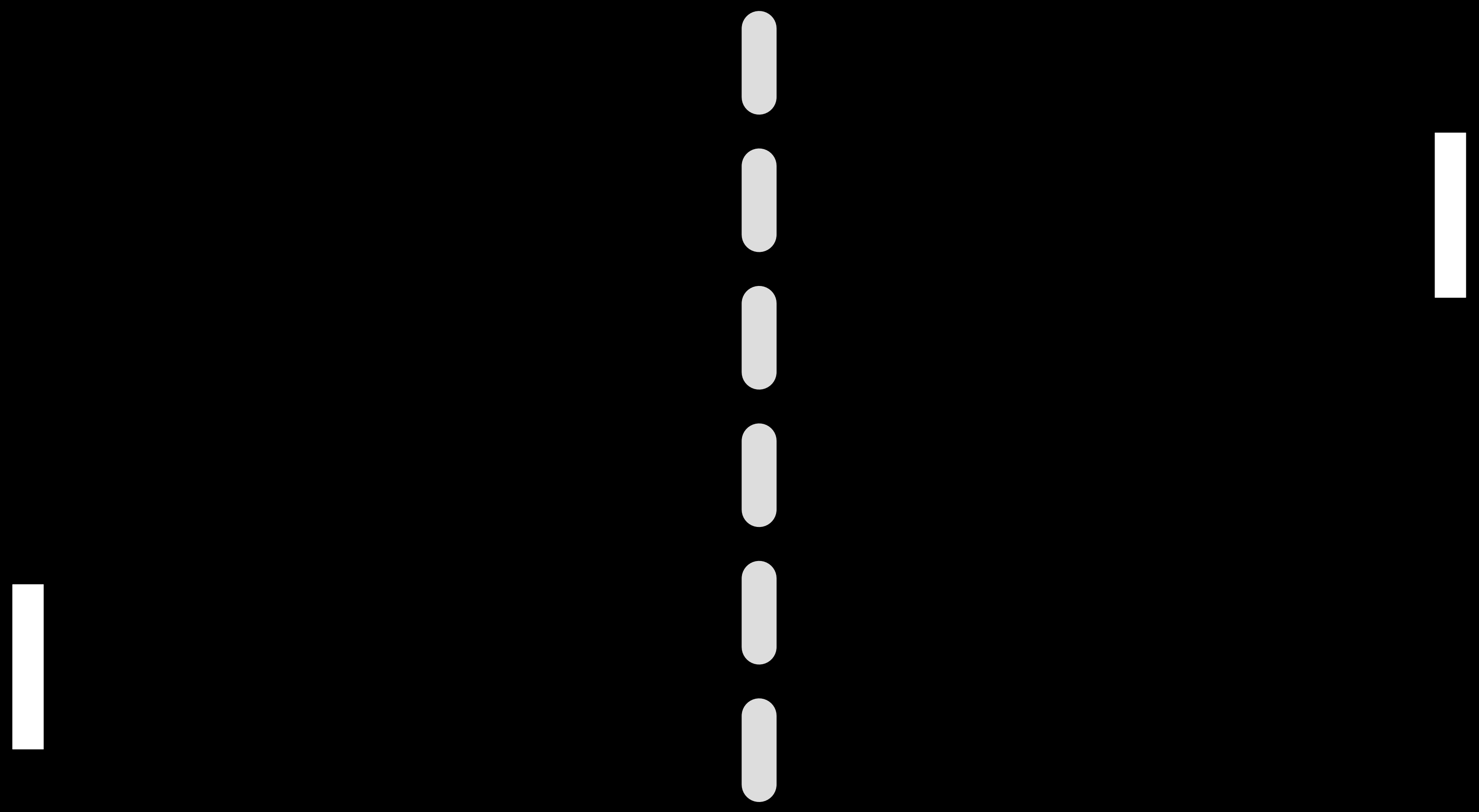

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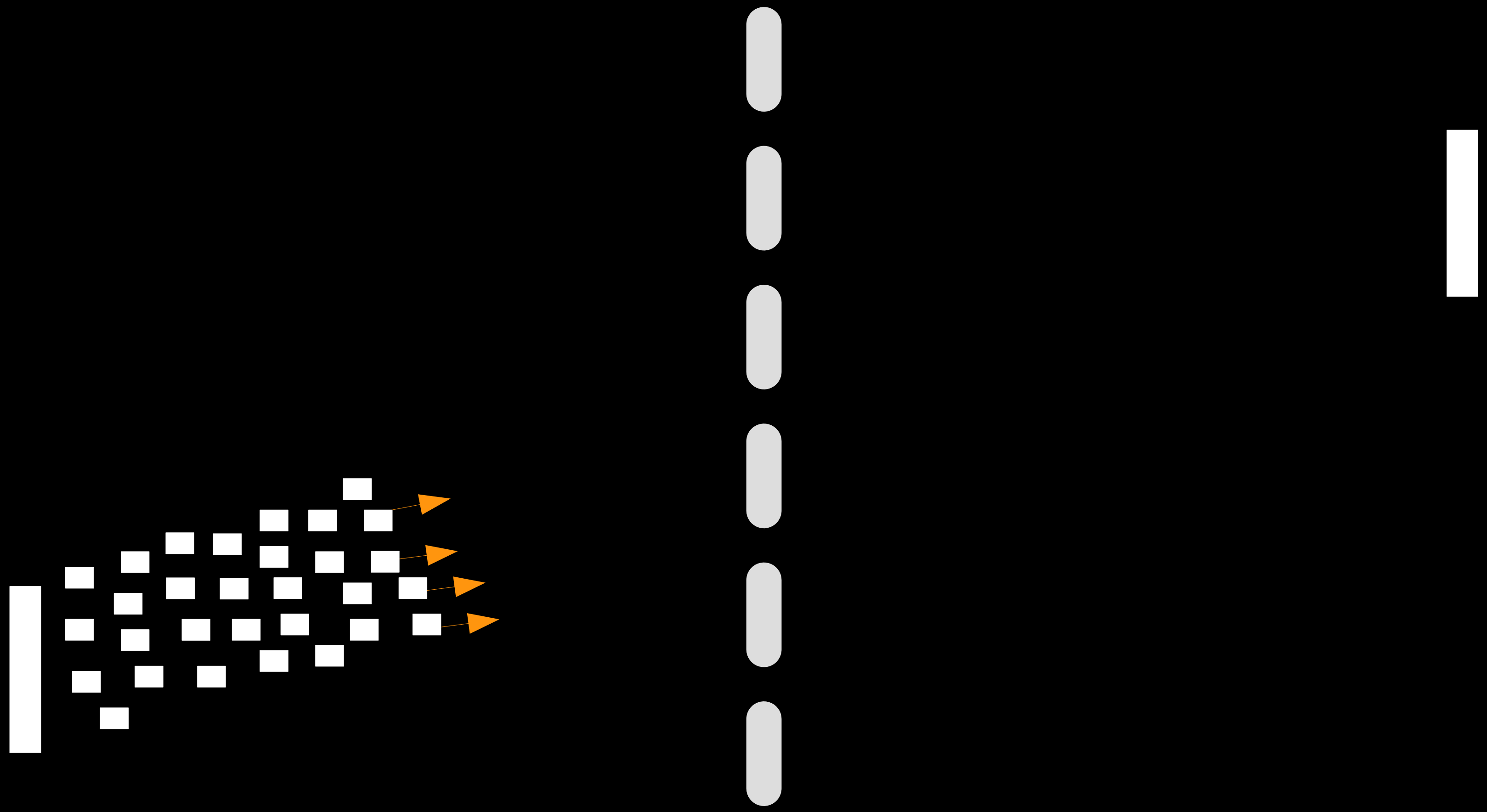

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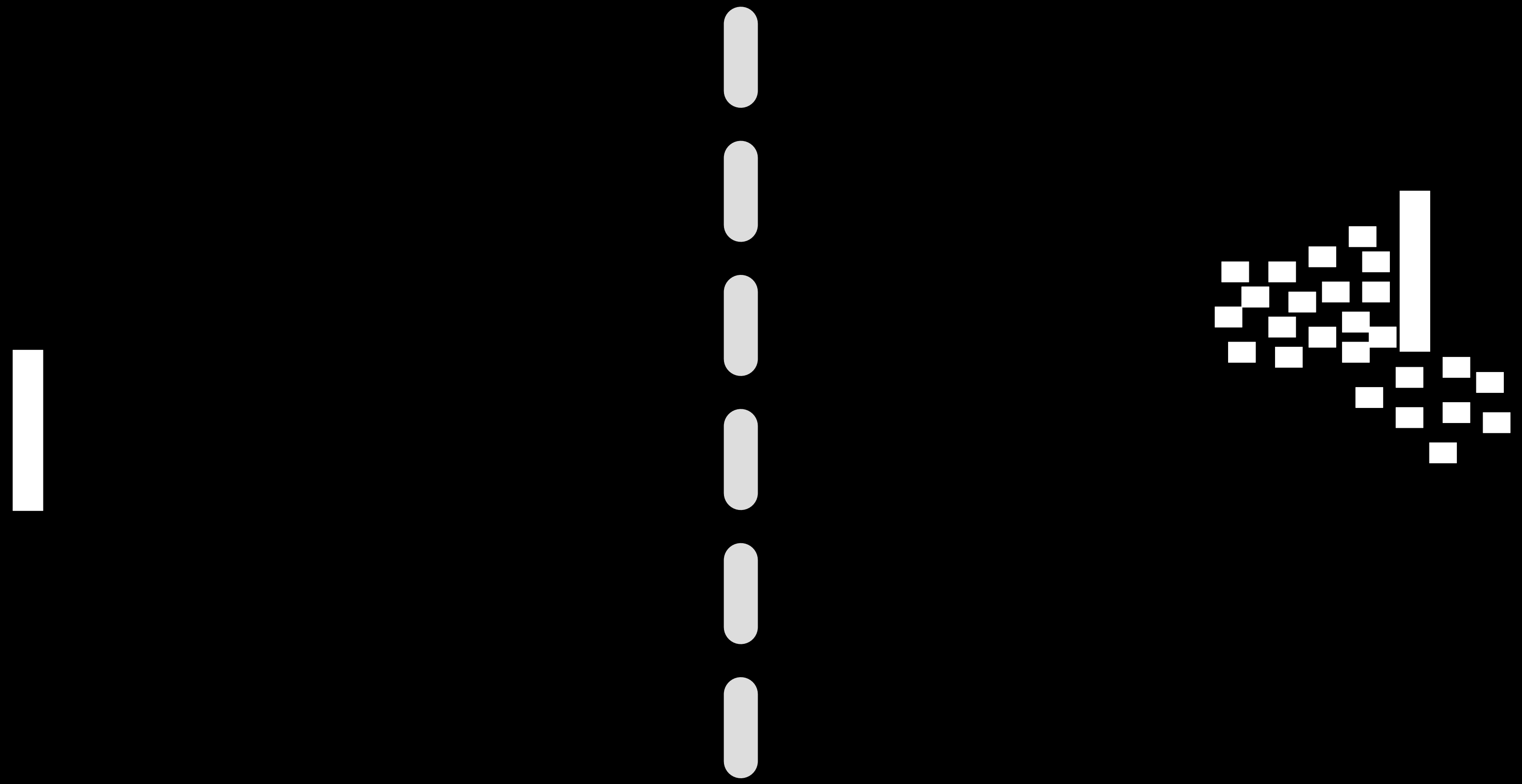

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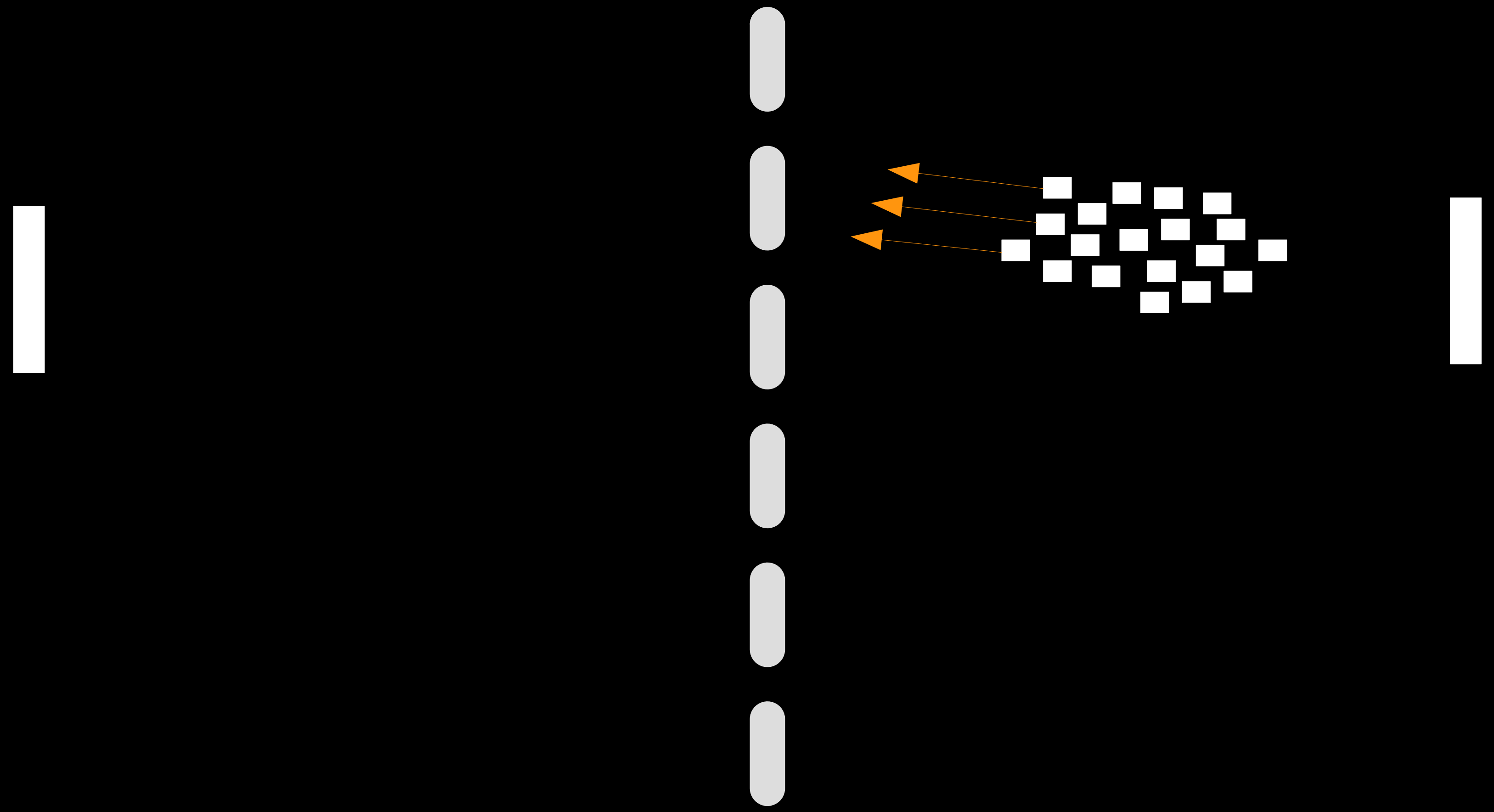
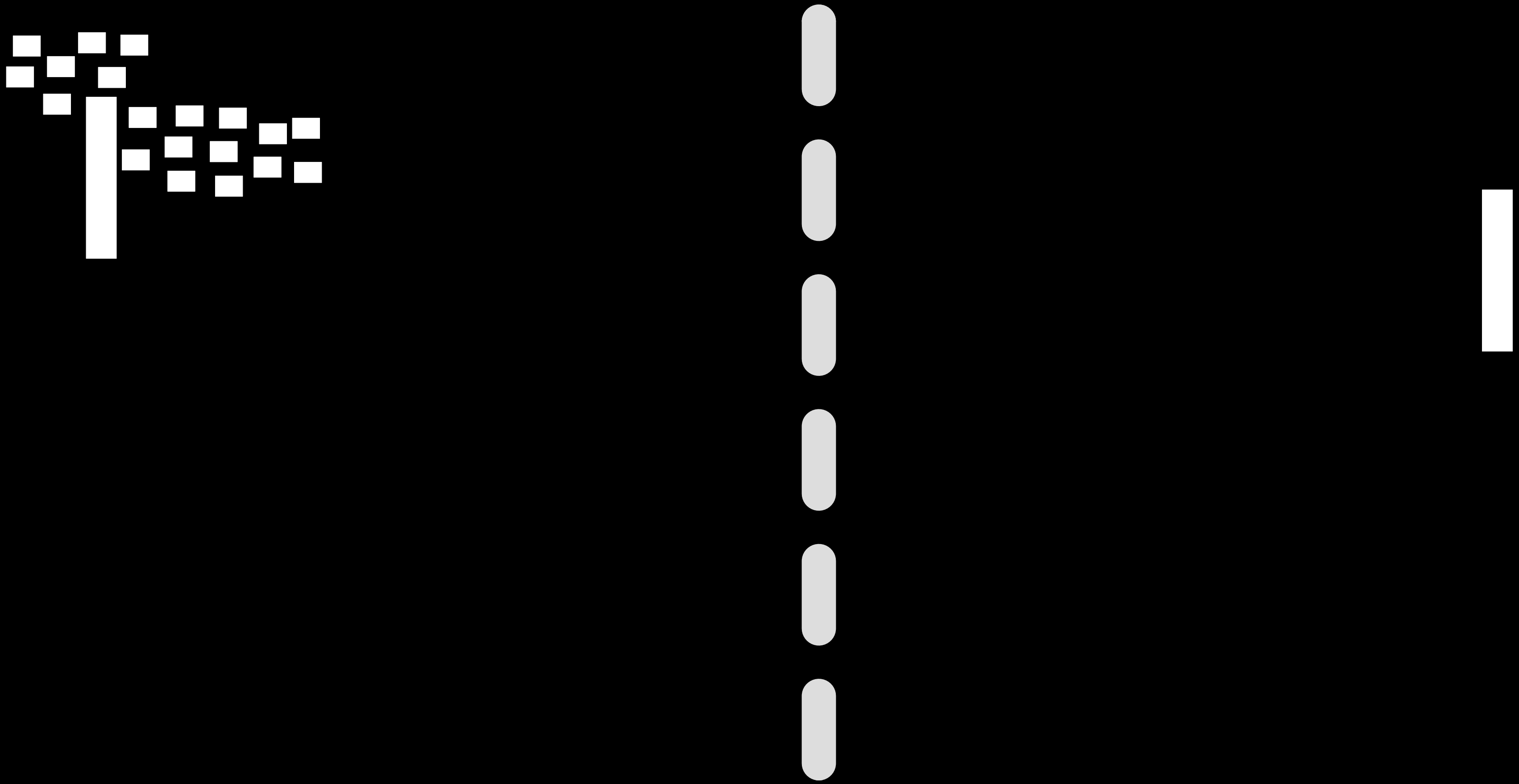
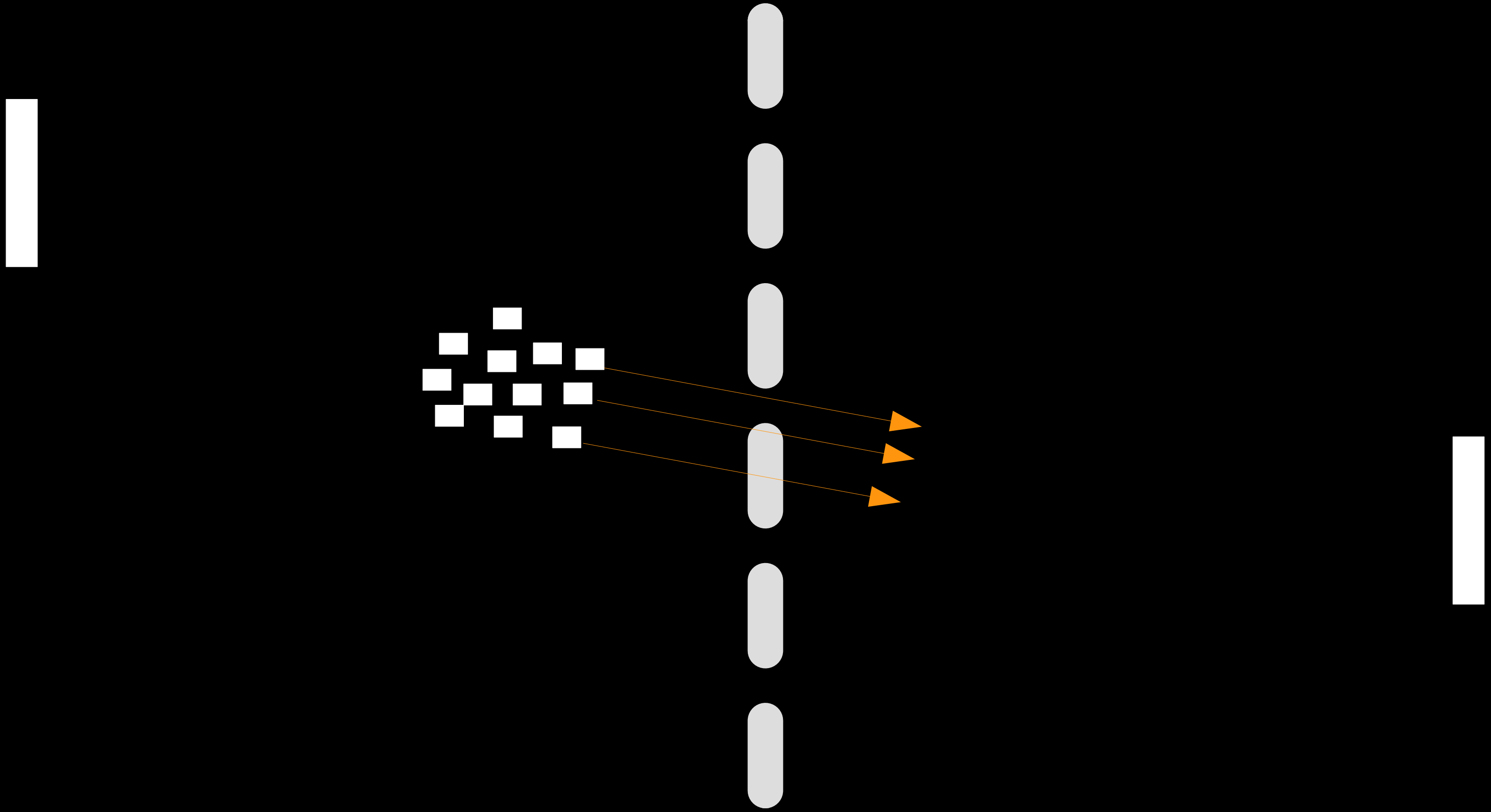
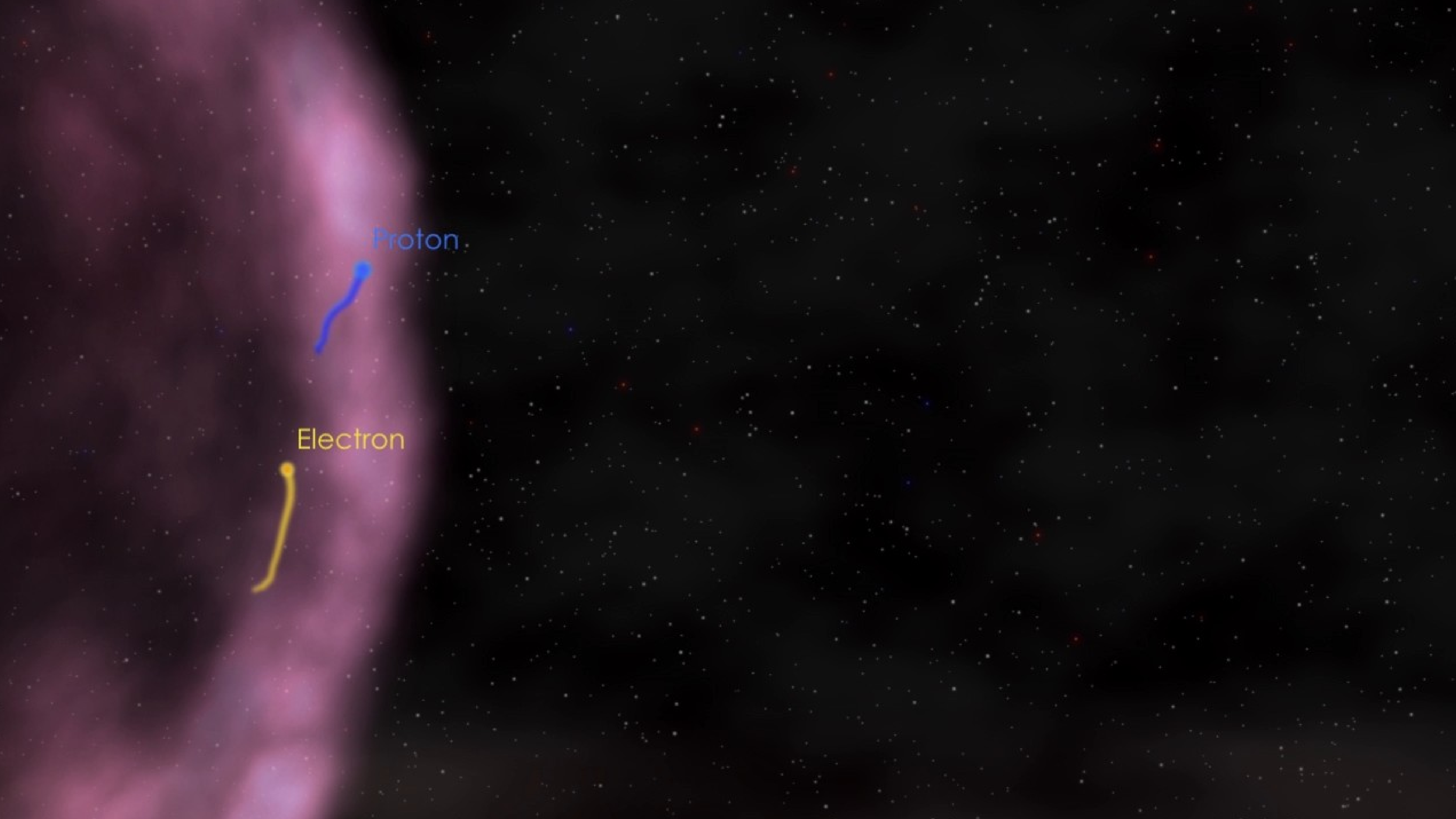


How are cosmic rays made?



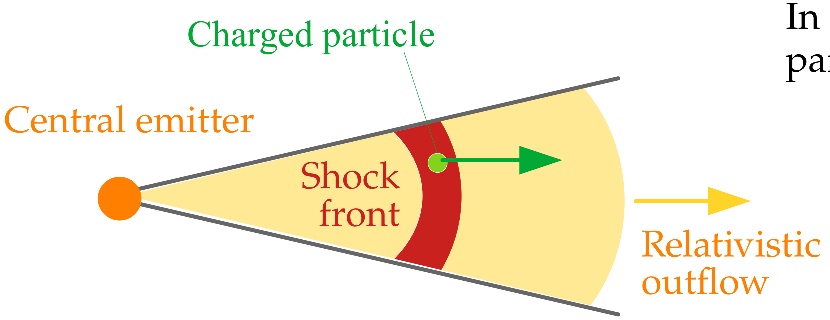
How are cosmic rays made?




Proton
Electron

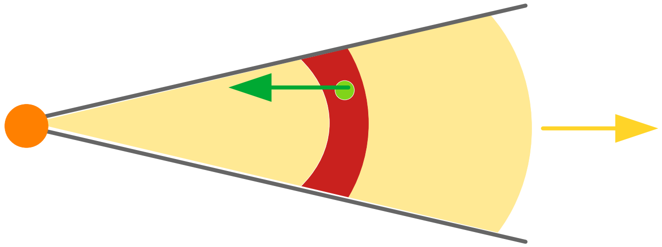
Fermi acceleration

Upstream to downstream



Downstream to upstream

In each crossing, the particle gains energy $\Delta E \propto v_{\text{shock}}$



Average energy of a particle after one crossing: $E = k\, E_0$

Probability that the particle remains in the acceleration region after one crossing: P

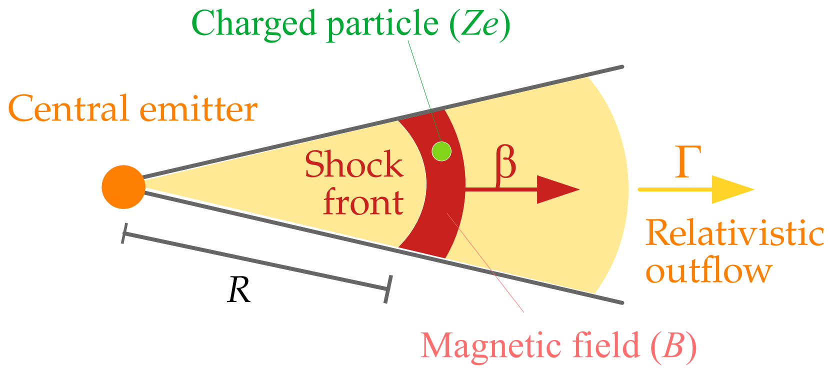
After n collisions, $N = N_0\, P^n$ particle remain, with energy $E = E_0\, k^n$

Energy spectrum: $N(E)dE \propto E^{-1+\frac{\ln P}{\ln k}} dE$

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\left(\frac{v}{c}\right) \quad \text{and} \quad P = 1 - P_{\text{esc}} = 1 - \frac{4}{3}\left(\frac{v}{c}\right) \Rightarrow N(E)dE \propto E^{-2}dE$$

Hillas criterion

A necessary condition to accelerate charged particles is confinement within the acceleration region.



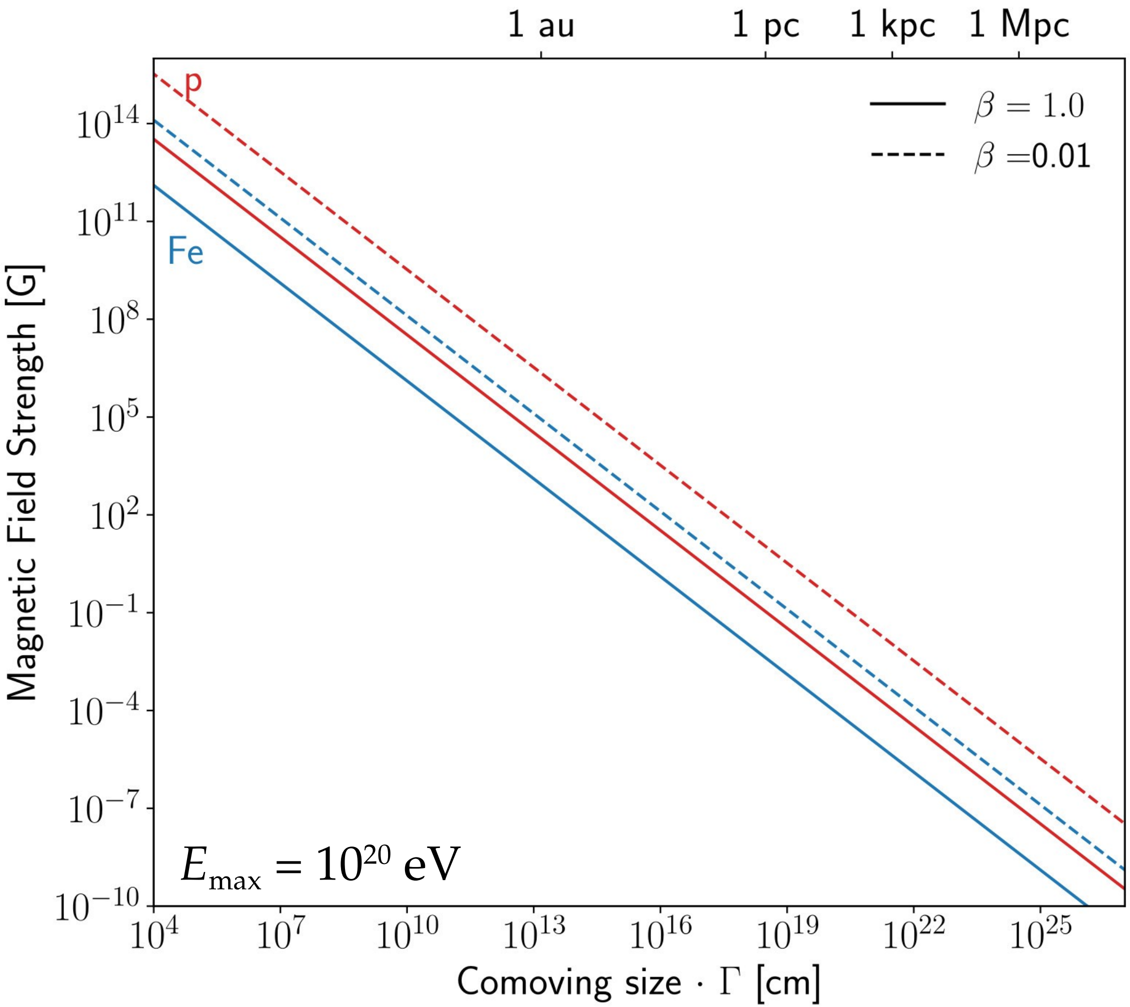
Confinement holds until

Larmor radius (R_L) = Size of region (R)

$$\frac{E_{\rm max}}{ZeB} = \beta\Gamma R$$

$$\Rightarrow E_{\rm max} = \eta^{-1}\beta\Gamma ZeBR$$

Acceleration efficiency



Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

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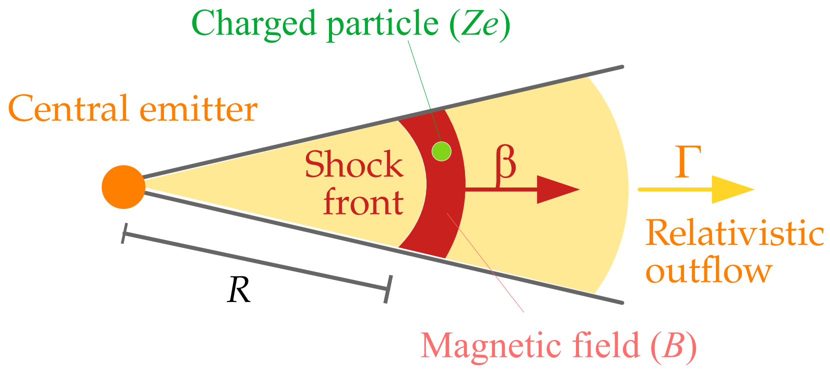

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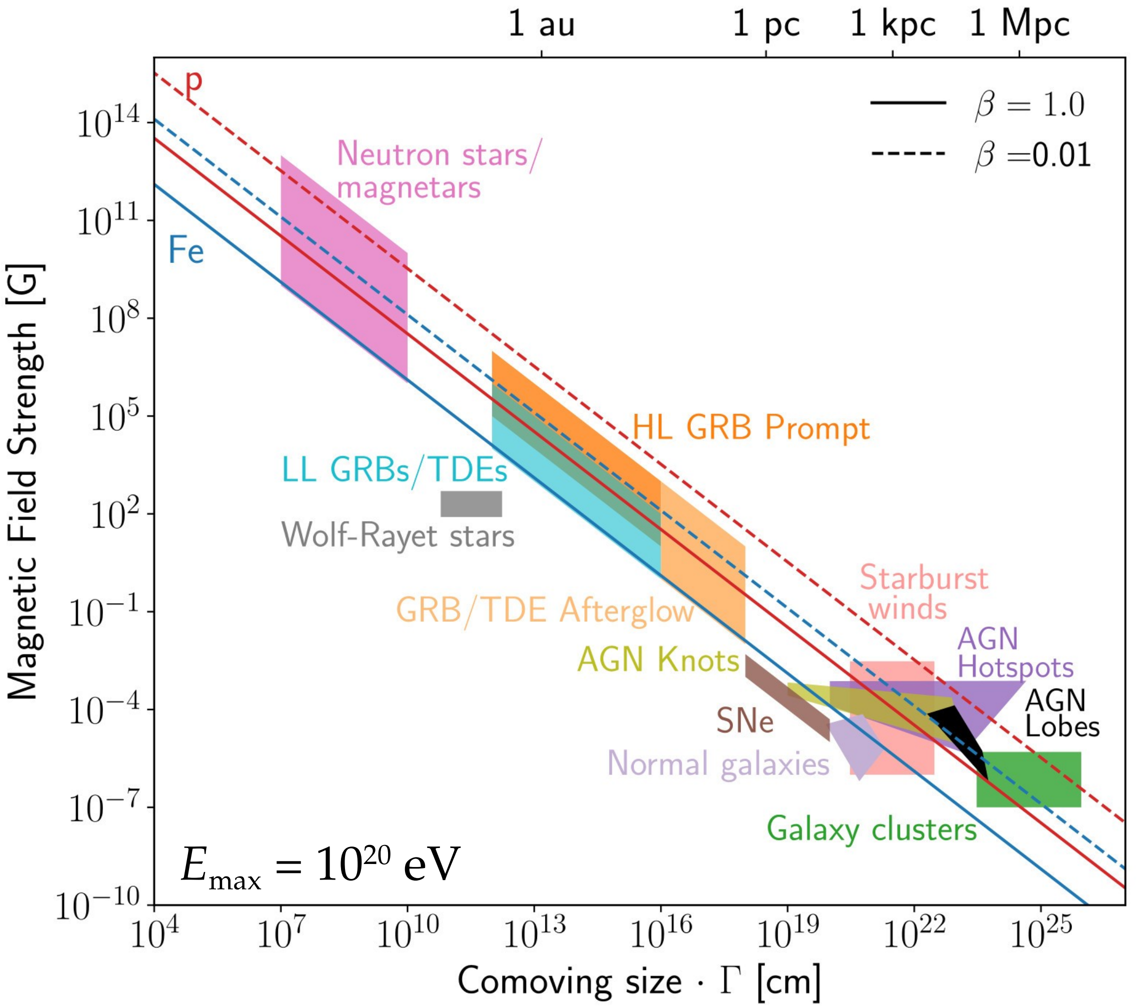


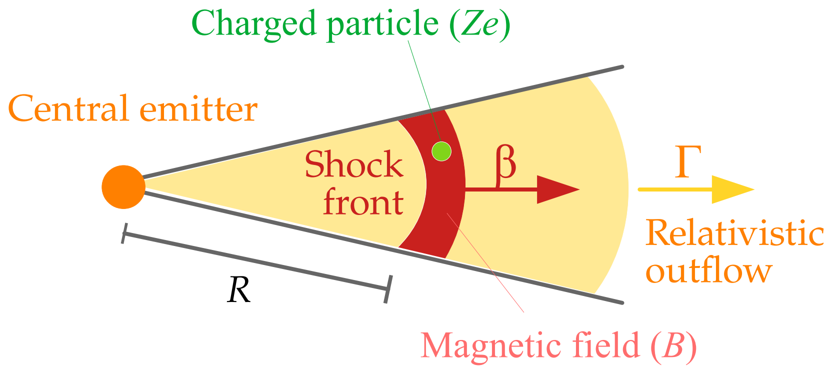
Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

Hillas criterion

But not sufficient!

A necessary condition to accelerate charged particles is confinement within the acceleration region



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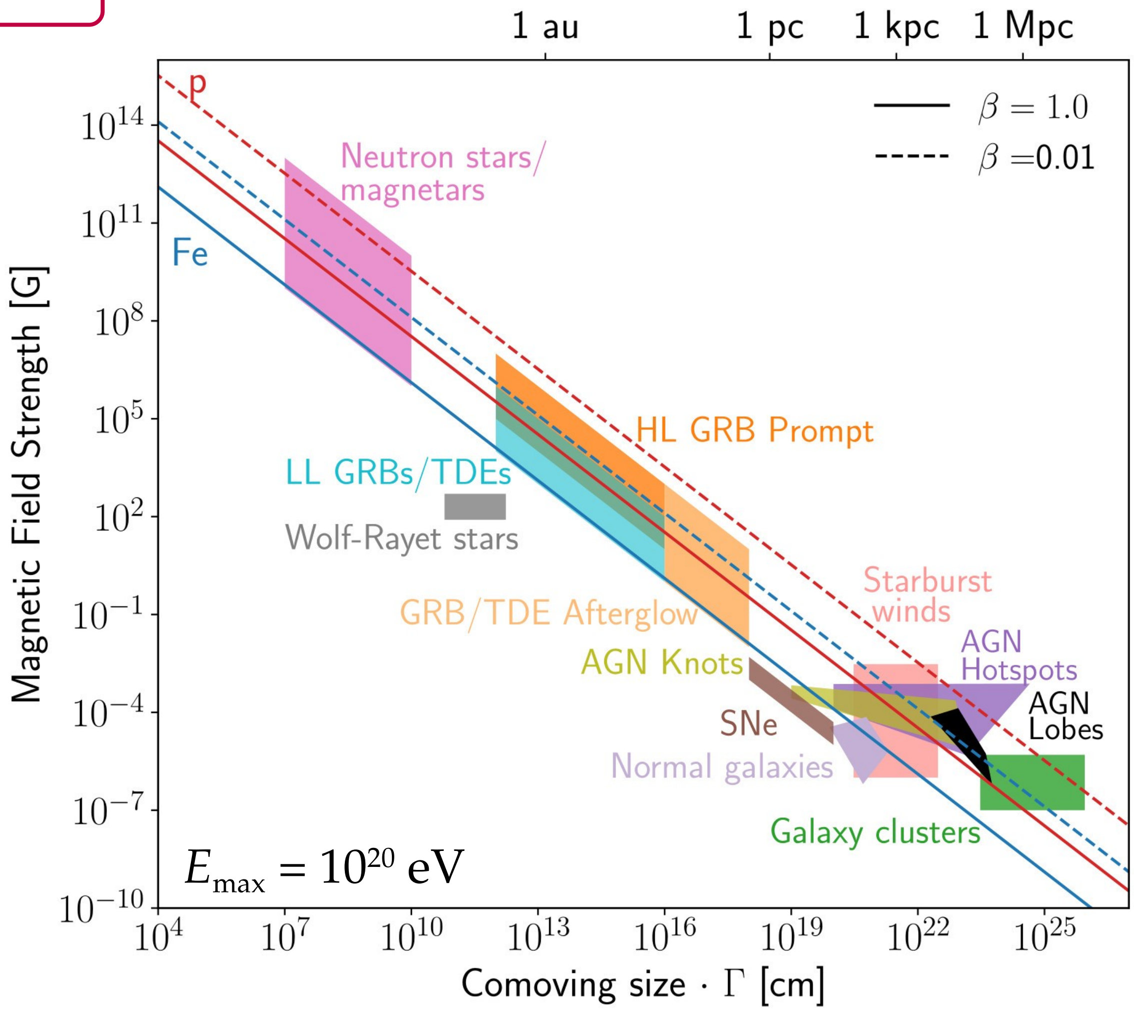

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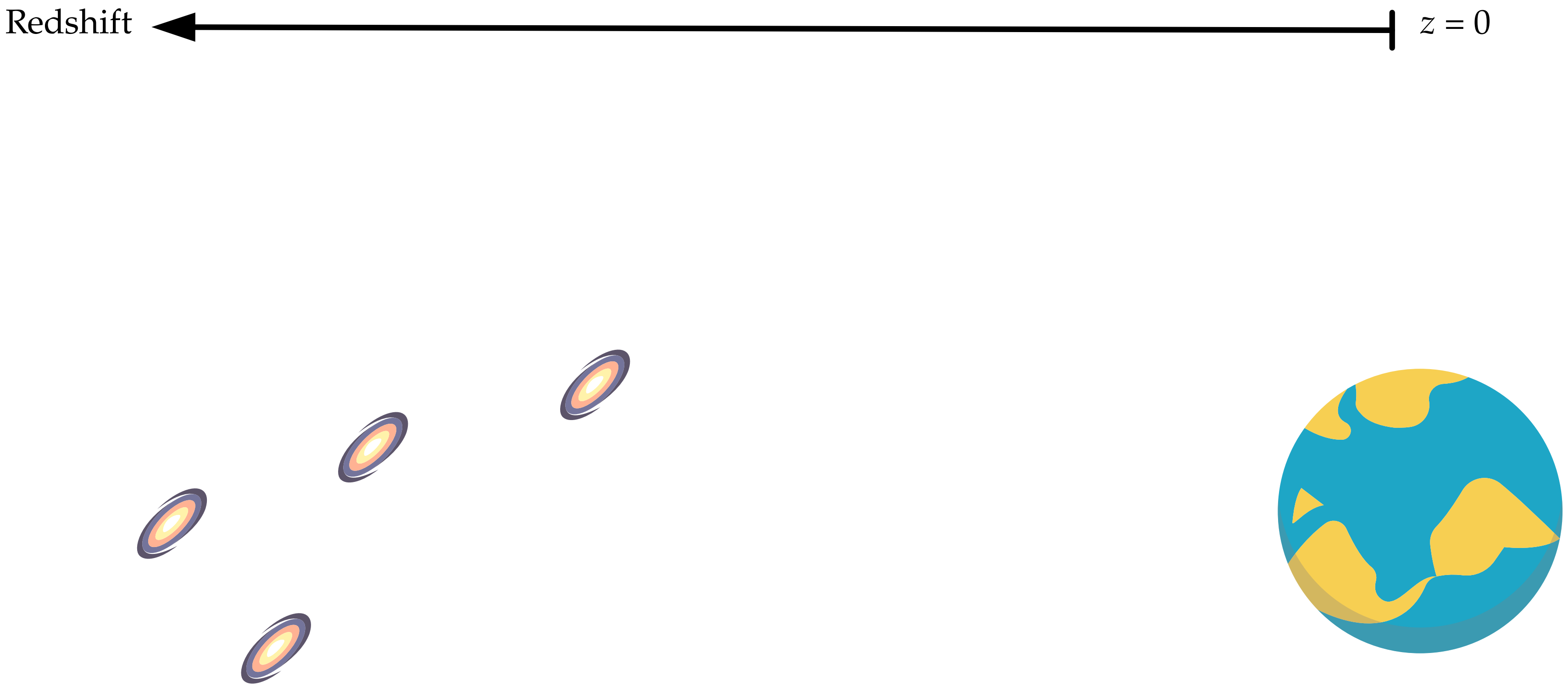
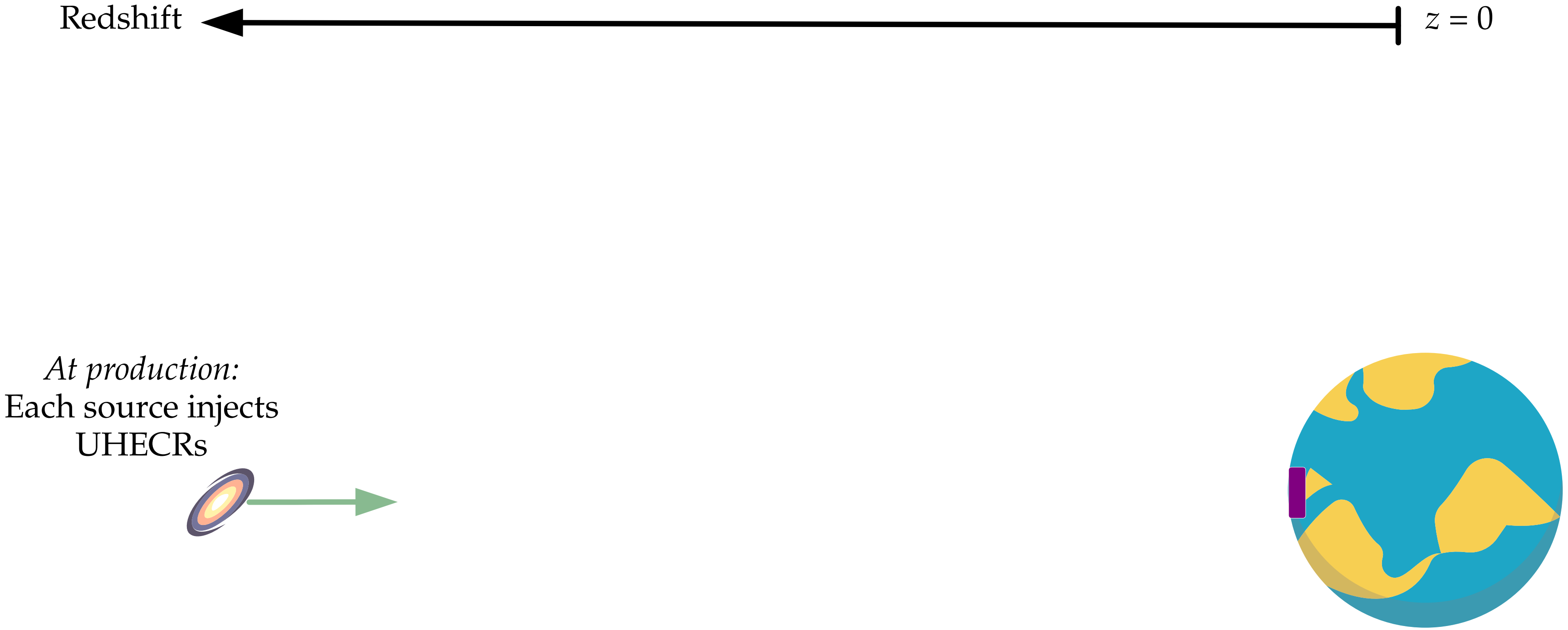
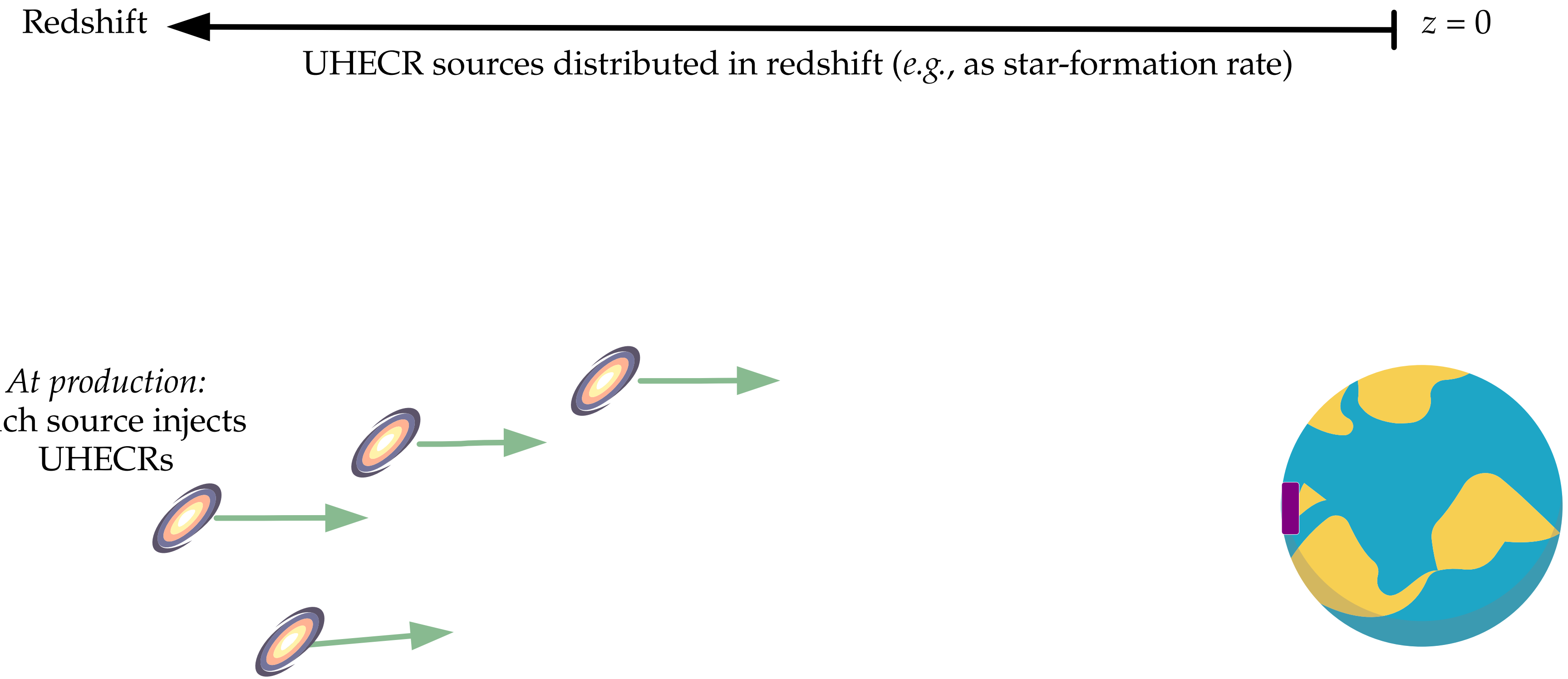
Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

UHECR propagation

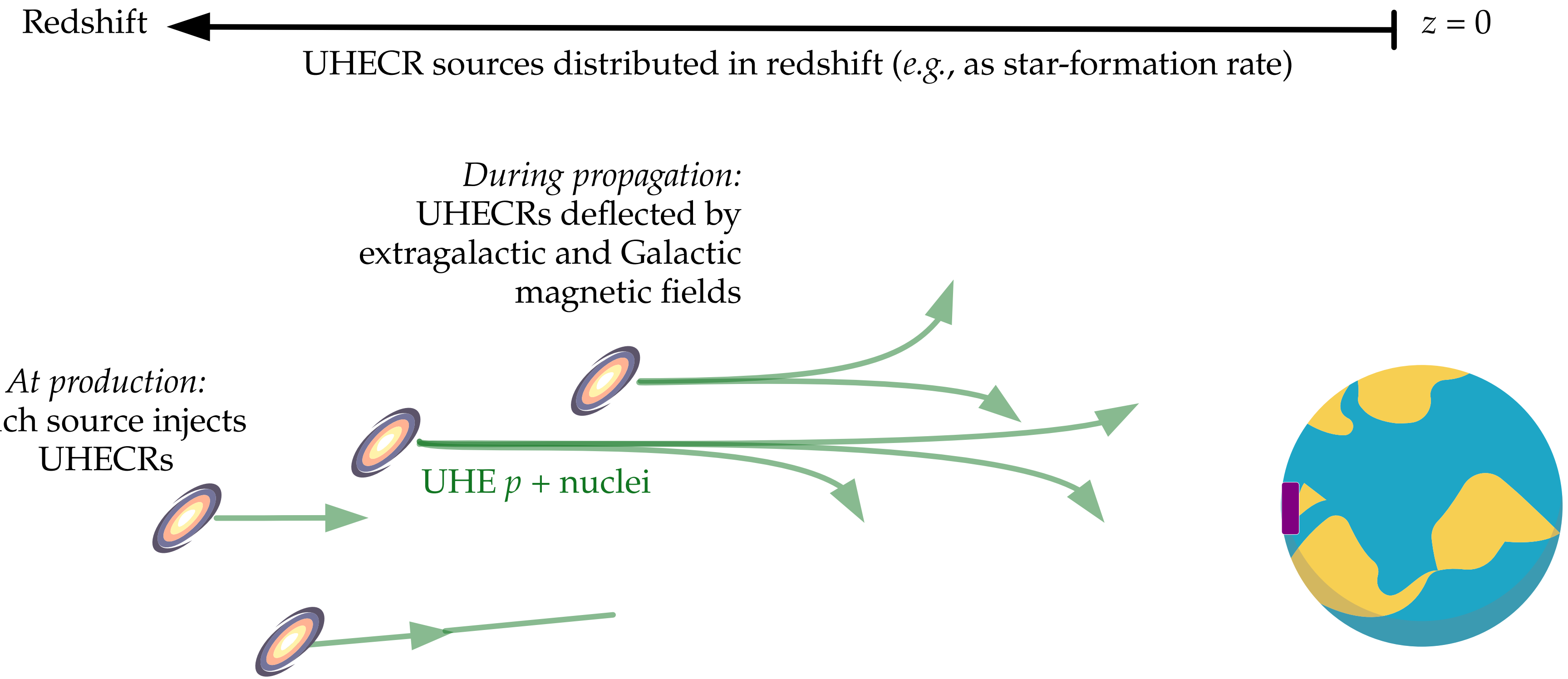
Calculating the UHECR flux at Earth

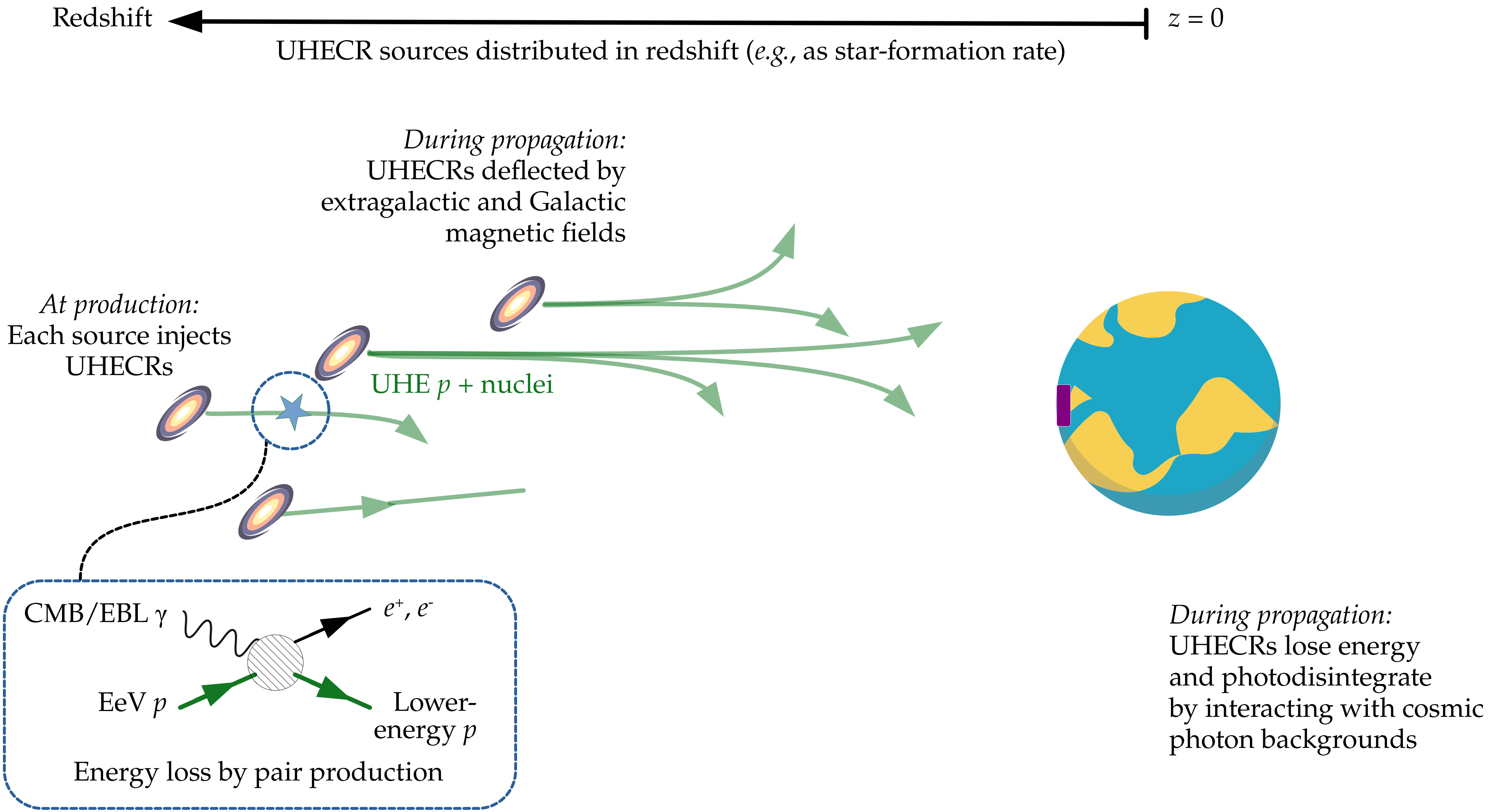

Redshift
$z = 0$


Redshift
$z = 0$
At production:
Each source injects
UHECRs



Redshift
z = 0
UHECR sources distributed in redshift (e.g., as star-formation rate)
At production:
Each source injects
UHECRs


Redshift
z = 0
UHECR sources distributed in redshift (e.g., as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
At production:
Each source injects
UHECRs
UHE p + nuclei


Redshift
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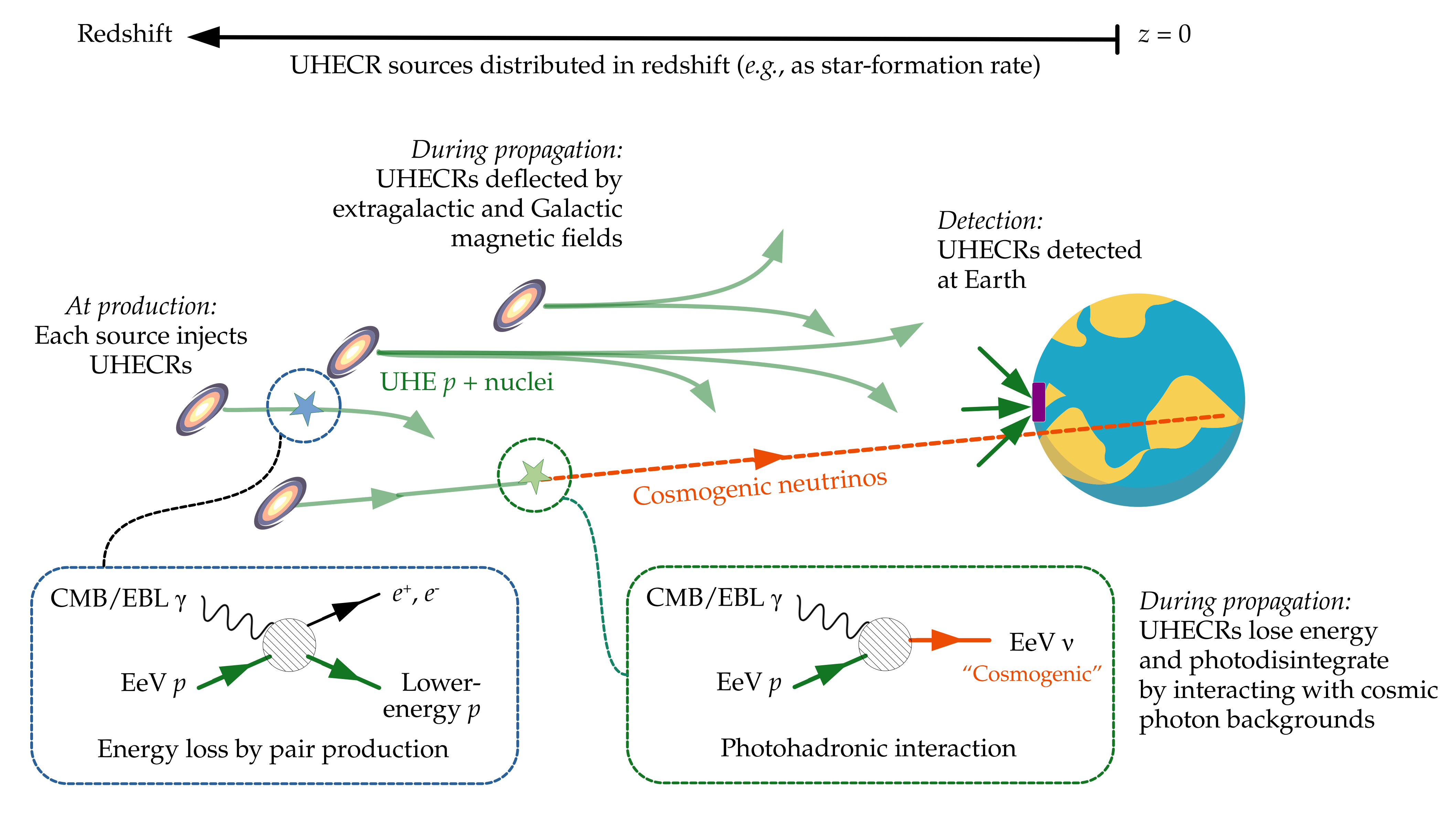
UHECR sources distributed in redshift (*e.g.*, as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
At production:
Each source injects
UHECRs
UHE p + nuclei
CMB/EBL γ
e^+, e^-
EeV p
Lower-
energy p
Energy loss by pair production
During propagation:
UHECRs lose energy
and photodisintegrate
by interacting with cosmic
photon backgrounds


Redshift
$z = 0$
UHECR sources distributed in redshift (*e.g.*, as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
Detection:
UHECRs detected
at Earth
At production:
Each source injects
UHECRs
UHE p + nuclei
Cosmogenic neutrinos
CMB/EBL γ
e^+, e^-
EeV p
Lower-energy p
Energy loss by pair production
CMB/EBL γ
EeV ν
"Cosmogenic"
EeV p
Photohadronic interaction
During propagation:
UHECRs lose energy
and photodisintegrate
by interacting with cosmic
photon backgrounds

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z)n_p(E,z) = \frac{1}{(1+z)^3}n_p(E,z)$

Calculating the UHECR flux at Earth

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n_p: Real number density

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Solve a propagation equation:

$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\rm CR}$$

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Energy loss due to adiabatic cosmological expansion

Calculating the UHECR flux at Earth

a: Scale factor

n_p: Real number density

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Solve a propagation equation:

Energy loss rates: $b \equiv -\frac{dE}{dt}$

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Energy loss due to adiabatic cosmological expansion

Energy loss due to pair production:
$p + \gamma \rightarrow p + e^+ + e^-$

Calculating the UHECR flux at Earth

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Energy loss due to adiabatic cosmological expansion

Energy loss due to pair production:
$p + \gamma \rightarrow p + e^+ + e^-$

Energy loss due to photohadronic int.:
$p + \gamma \rightarrow p + \pi^0$
$p + \gamma \rightarrow n + \pi^+$
+ other process
+ n beta-decay into p

Calculating the UHECR flux at Earth

a: Scale factor

n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z)\, n_p(E,z) = \frac{1}{(1+z)^3} n_p(E,z)$

Solve a propagation equation:

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$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\rm CR}$$

Energy loss due to adiabatic cosmological expansion

Energy loss due to pair production:
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Energy loss due to photohadronic int.:
$p + \gamma \rightarrow p + \pi^0$
$p + \gamma \rightarrow n + \pi^+$
+ other process
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Cosmic-ray injection by UHECR sources

Calculating the UHECR flux at Earth

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Recast in terms of redshift using

$$\frac{dz}{dt} = -(1+z)H(z)$$

with Hubble parameter

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

Calculating the UHECR flux at Earth

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$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)}\{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\rm CR}(E,z)\}$$

Calculating the UHECR flux at Earth

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Solve a propagation equation:

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Evolve this equation from $z_{\mathrm{max}} \sim 4$ to Earth ($z = 0$)

Calculating the UHECR flux at Earth

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\rm CR}(E,z)\}$$

Cosmic-ray injection by UHECR sources

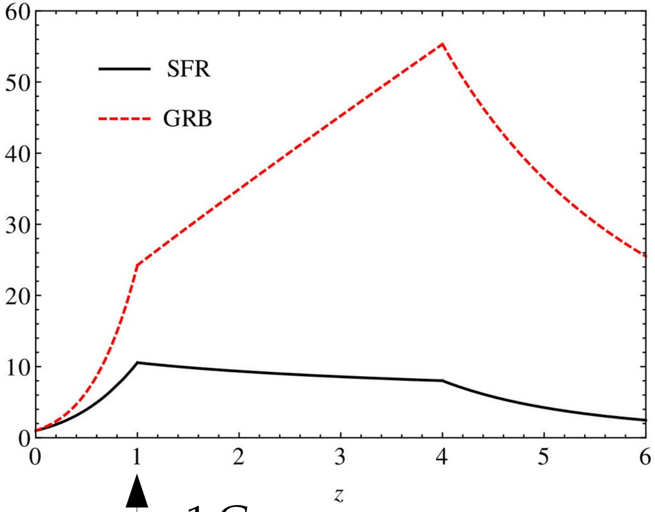
Each source injects UHECRs with a spectrum (GeV^{-1} s^{-1})

$$Q_{\rm CR}(E) \propto E^{-\gamma} e^{-E/E_{\max}}$$

$$\mathcal{L}_{\rm CR} = Q_{\rm CR}(E(1+z))\mathcal{H}_{\rm CR}(z)$$

The number density of sources evolves with redshift (Mpc^{-3})

$\mathcal{H}_{\rm CR}(z)$



~1 Gpc

Calculating the UHECR flux at Earth

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

Adiabatic cosmological expansion

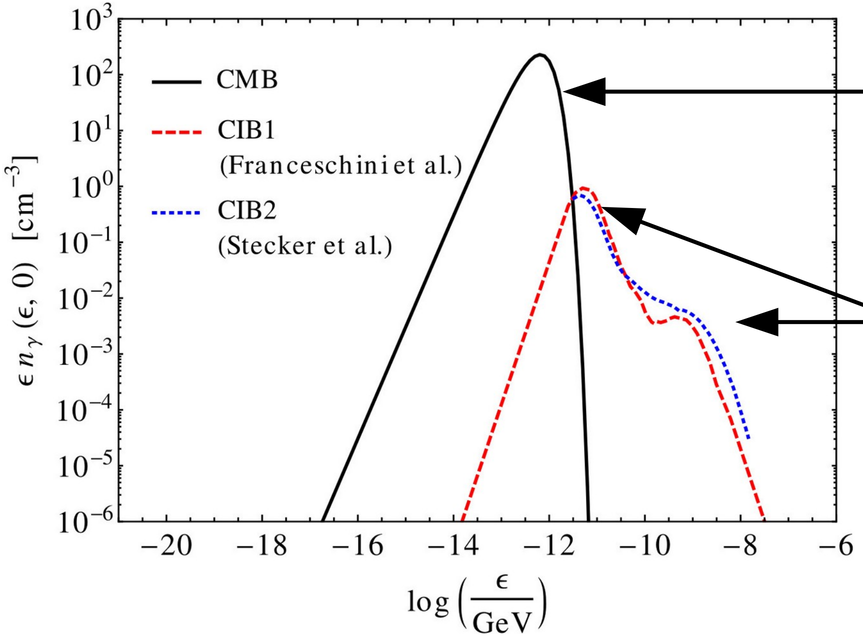
$$\text{Energy at Earth} = \frac{\text{Energy at production}}{1+z}$$

Calculating the UHECR flux at Earth

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\rm CR}(E,z)\}$$

Interaction with cosmological backgrounds
(pair production + photohadronic)

$p + \gamma \to \Delta$



Blackbody spectrum

Optical/UV emission from stars, reprocessed into infrared by dust

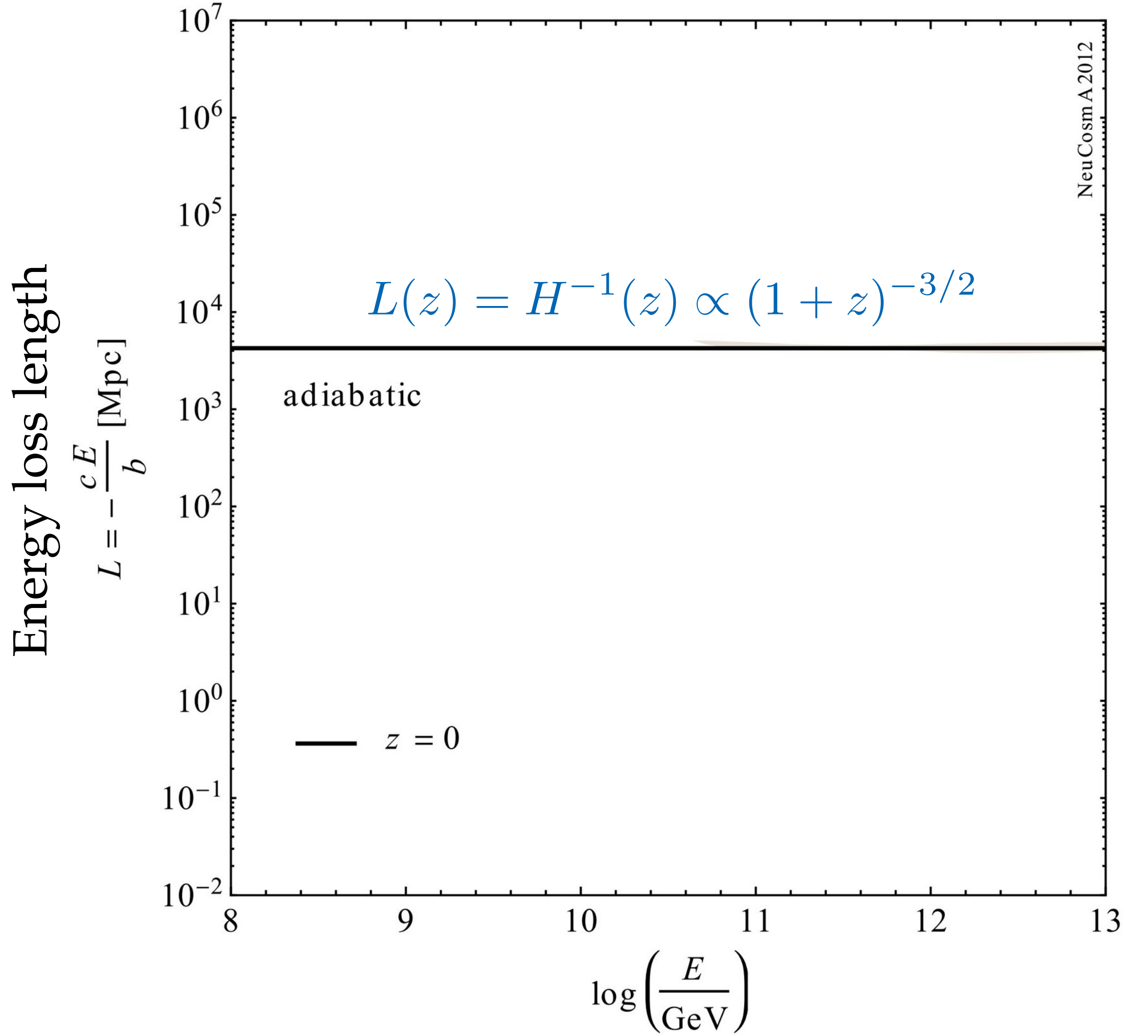
Energy threshold to produce a Δ(1232) resonance:

$$p_p + p_\gamma = p_\Delta$$

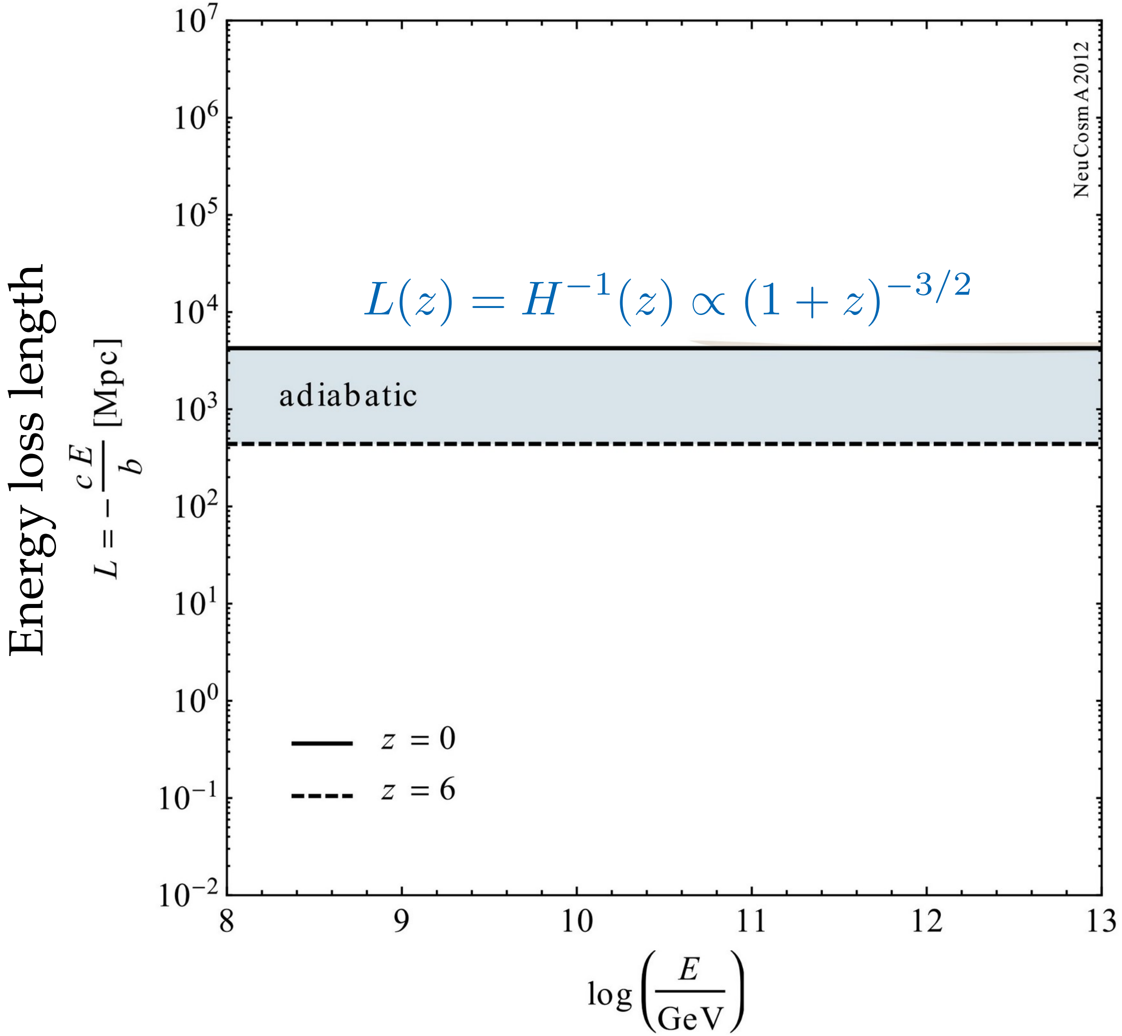
$$E_p E_\gamma \approx 0.16~\text{GeV}^2$$

(We will use this later, too)

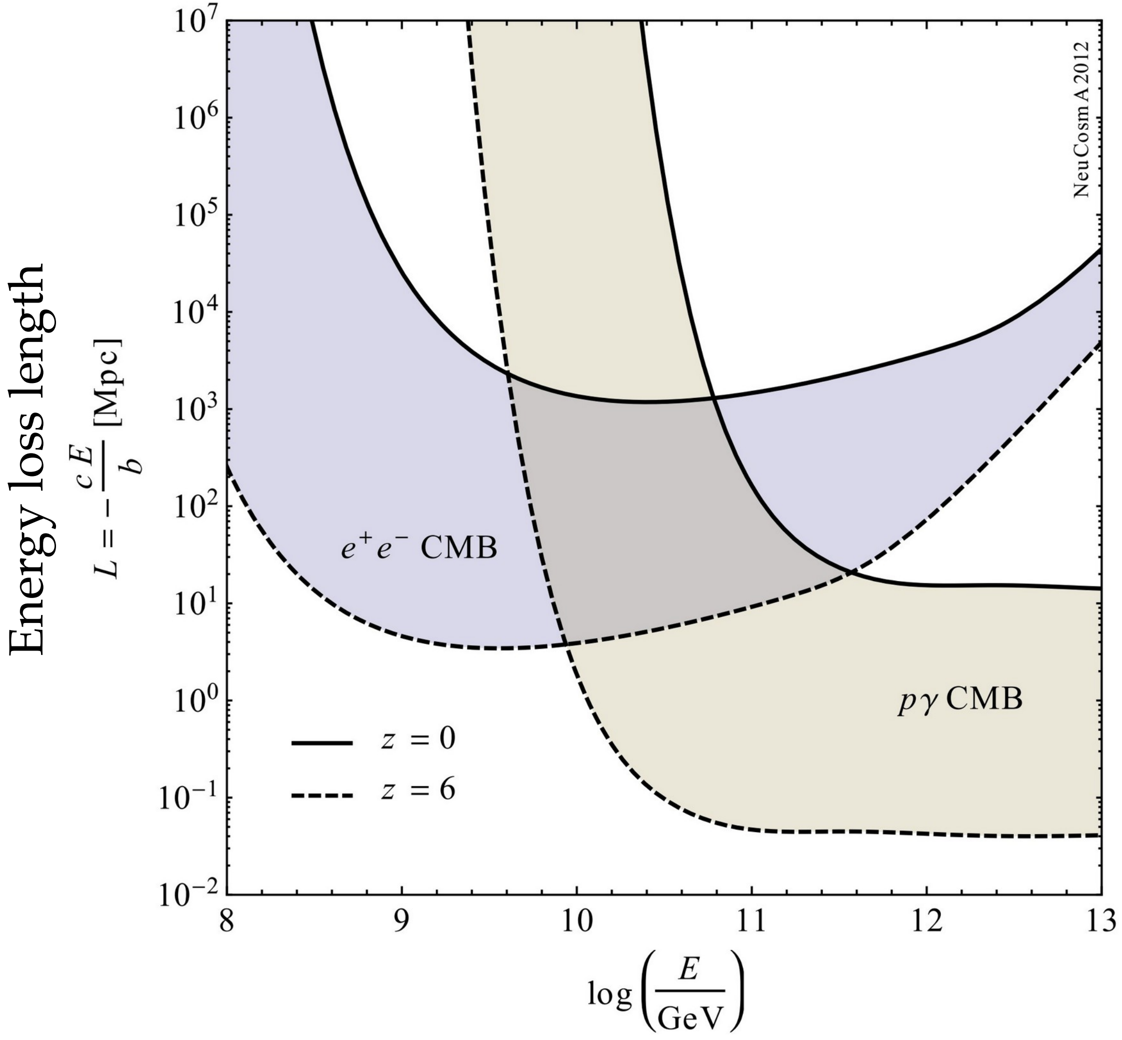
Calculating the UHECR flux at Earth



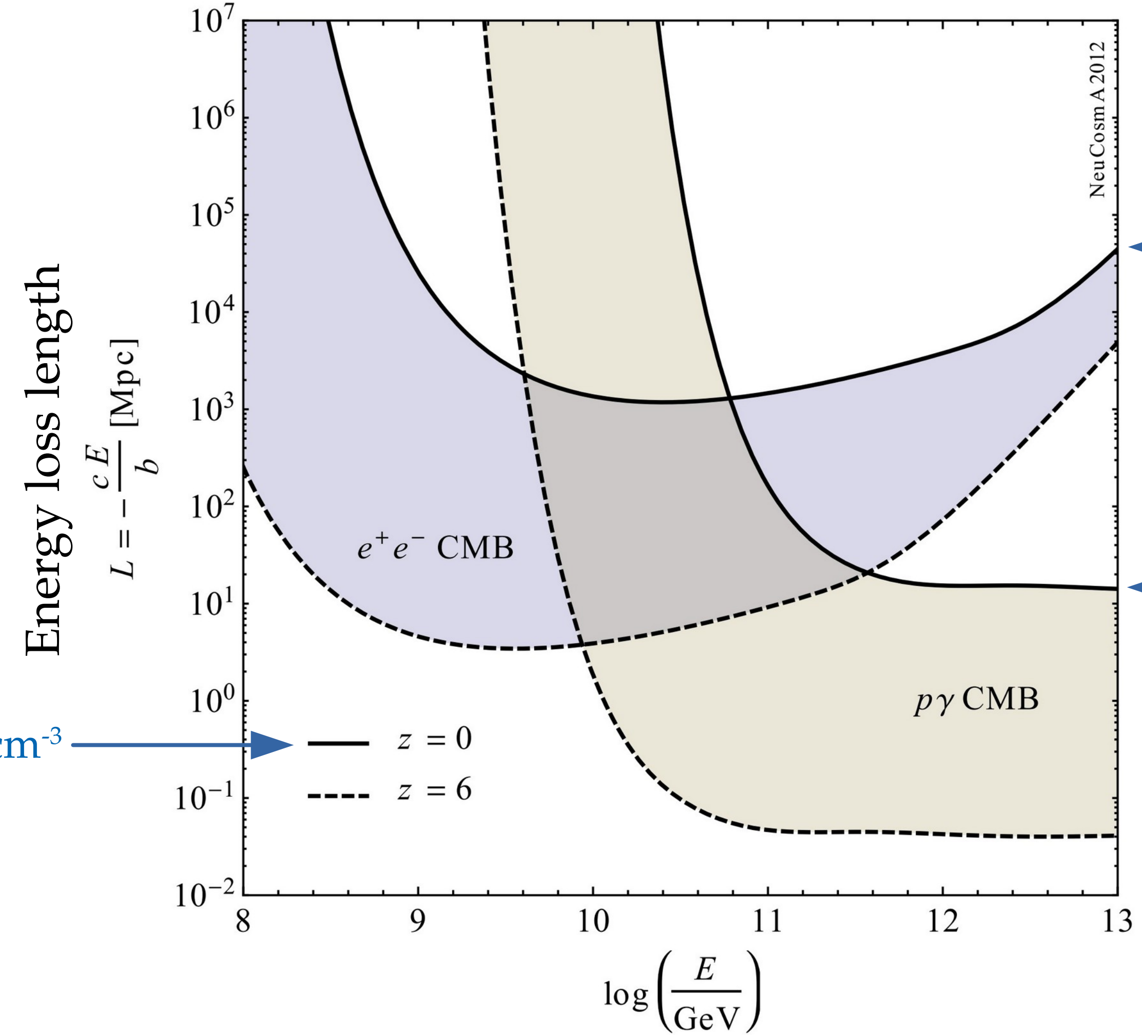
Calculating the UHECR flux at Earth



Calculating the UHECR flux at Earth

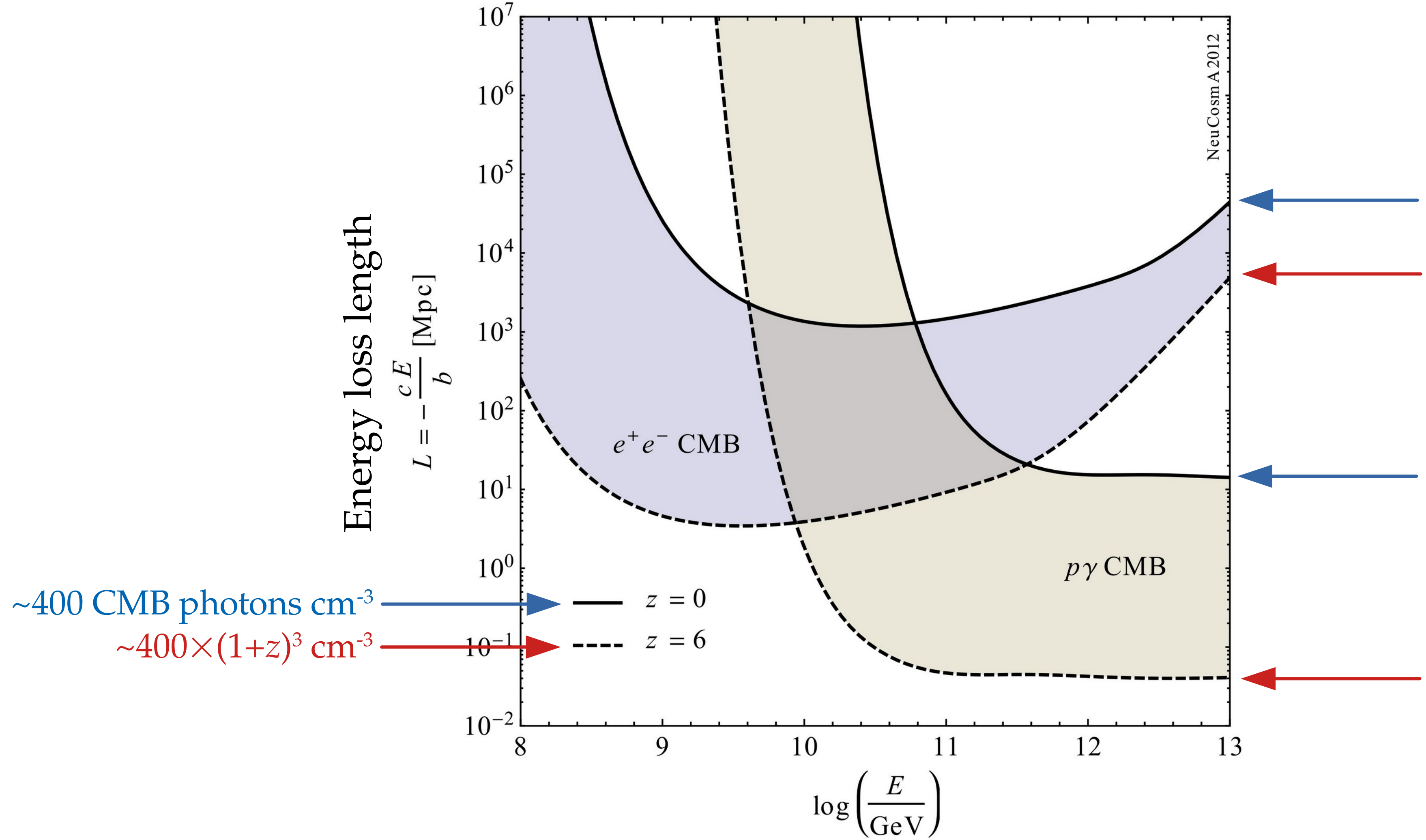


Calculating the UHECR flux at Earth

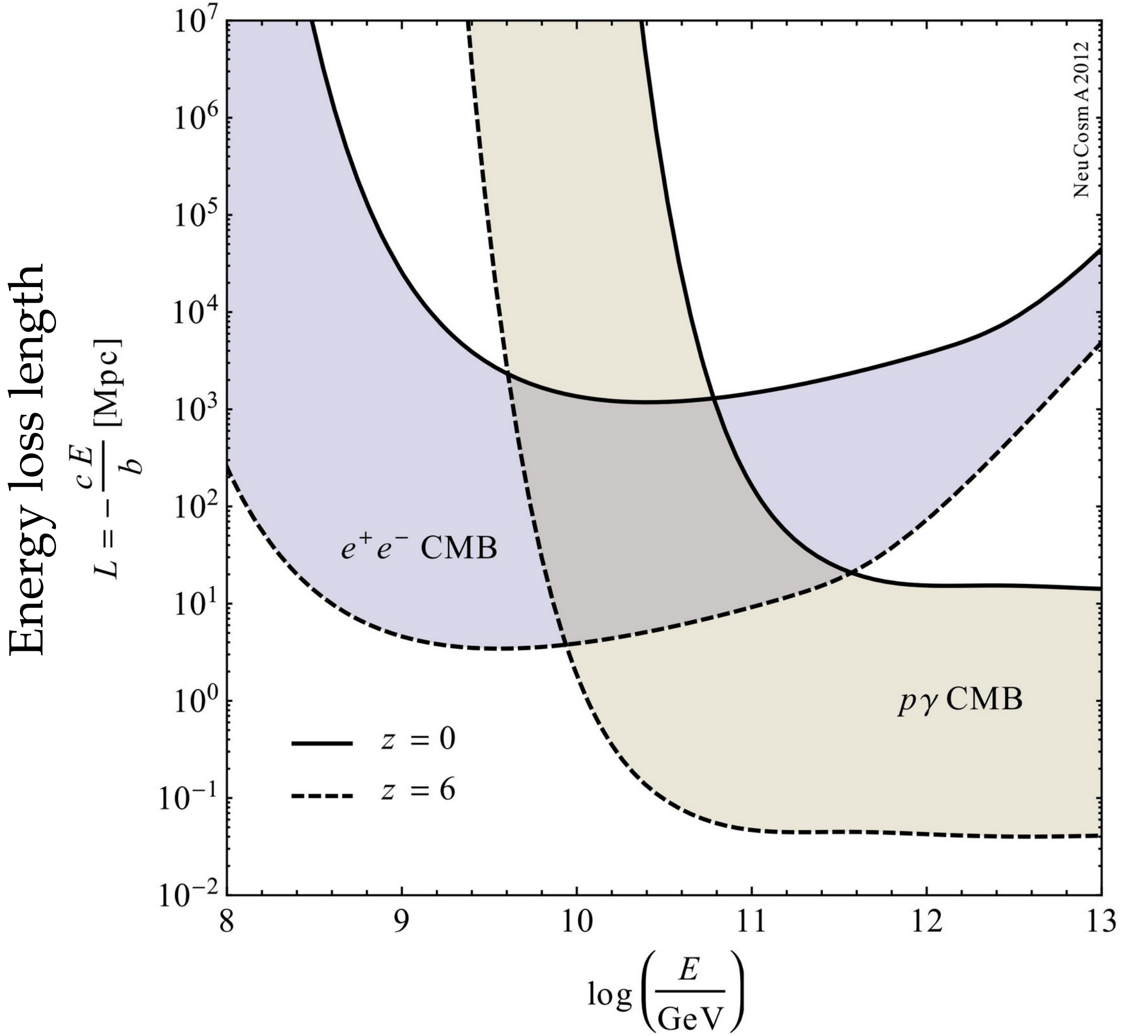


~400 CMB photons cm^{-3}

Calculating the UHECR flux at Earth



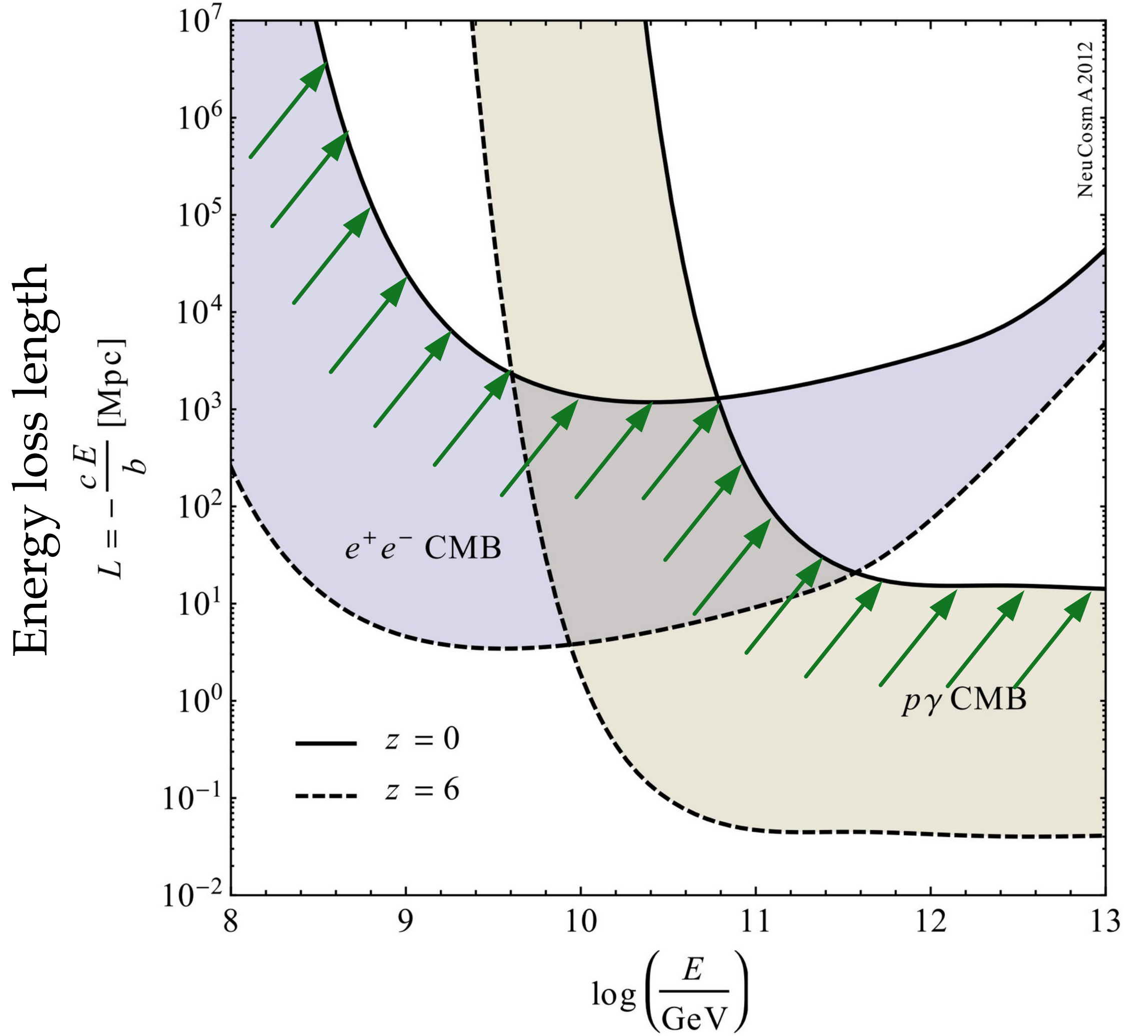
Calculating the UHECR flux at Earth



1

The shorter the energy loss length, the faster the UHECR proton loses energy during propagation

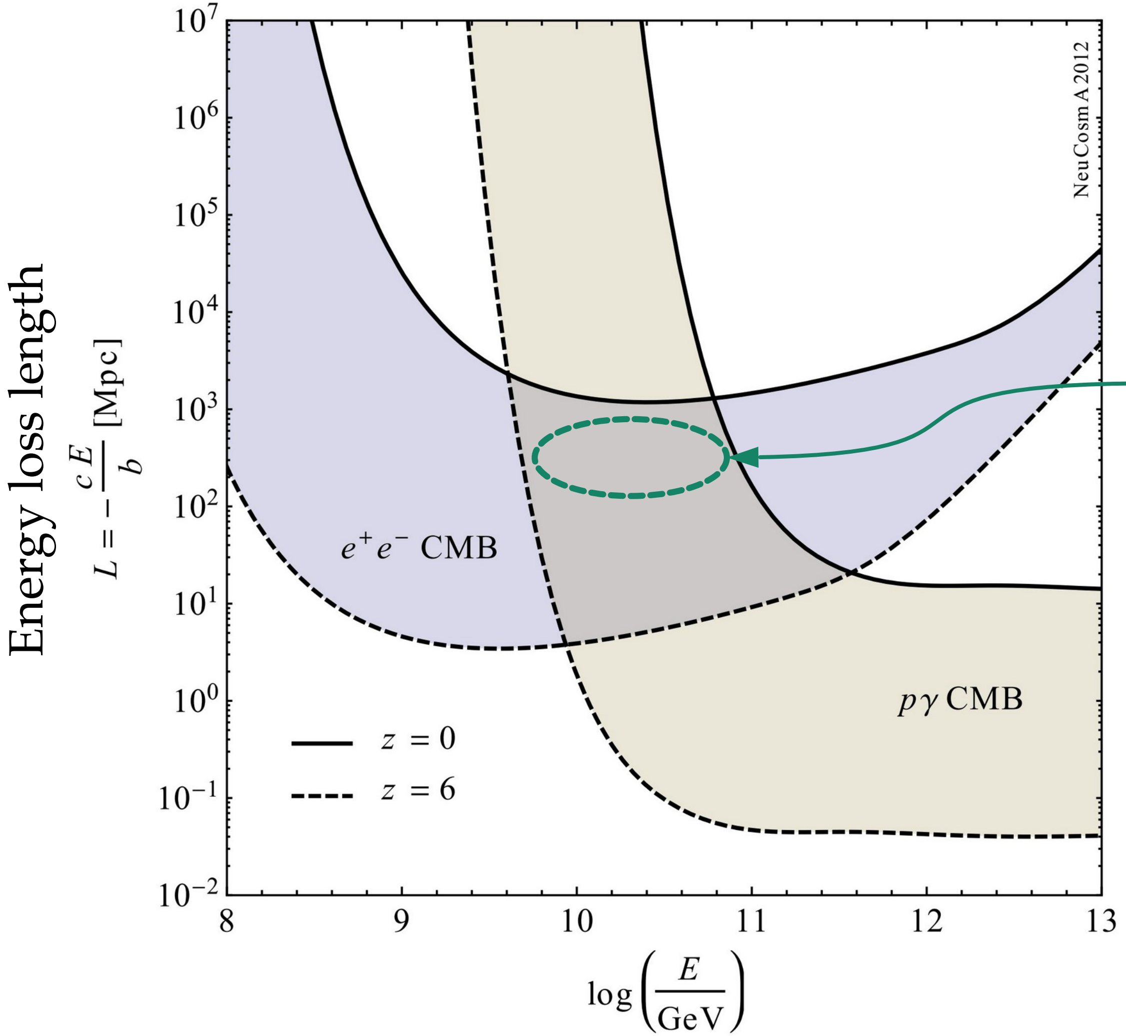
Calculating the UHECR flux at Earth



2

At each energy, the energy loss length is dominated by the fastest energy-loss process

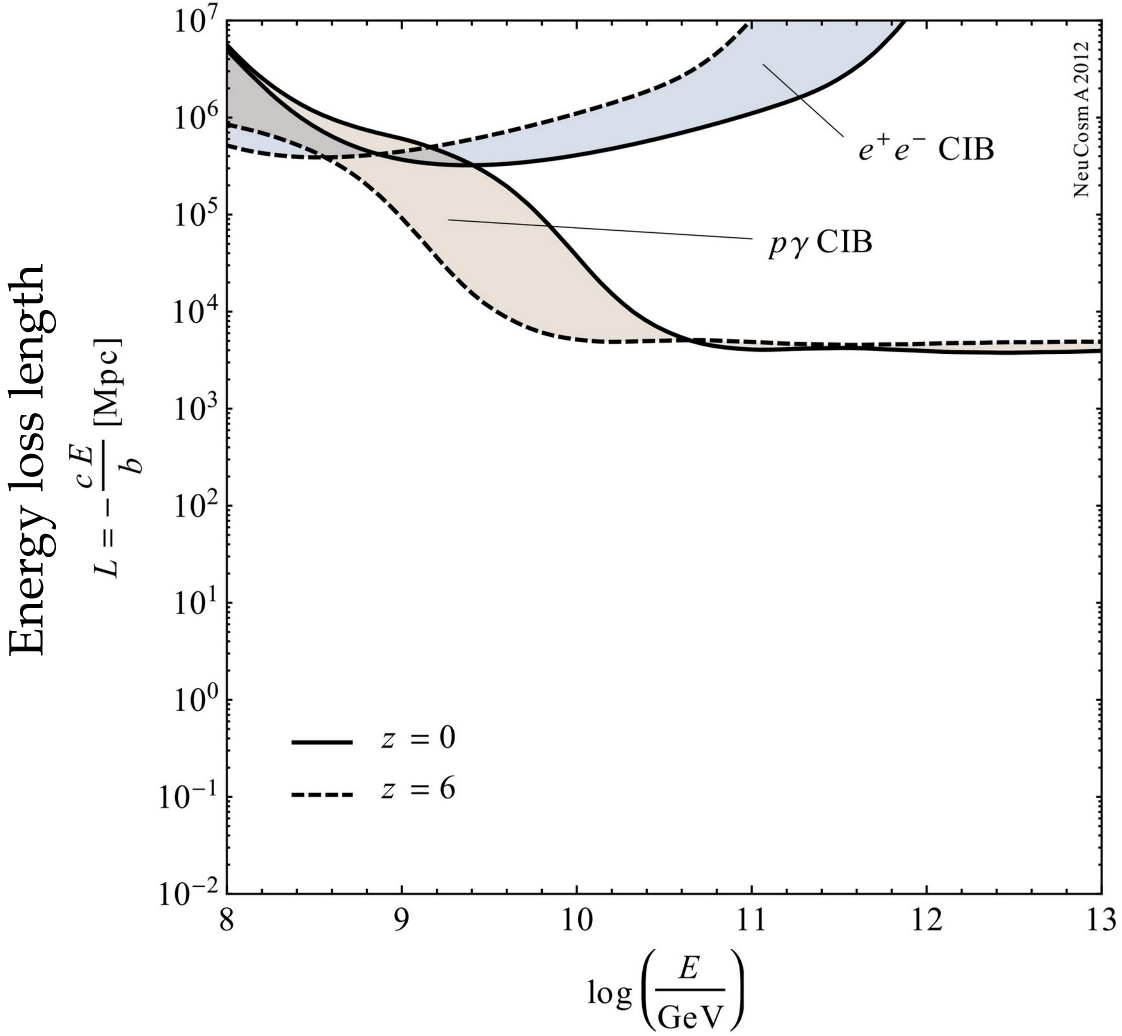
Calculating the UHECR flux at Earth



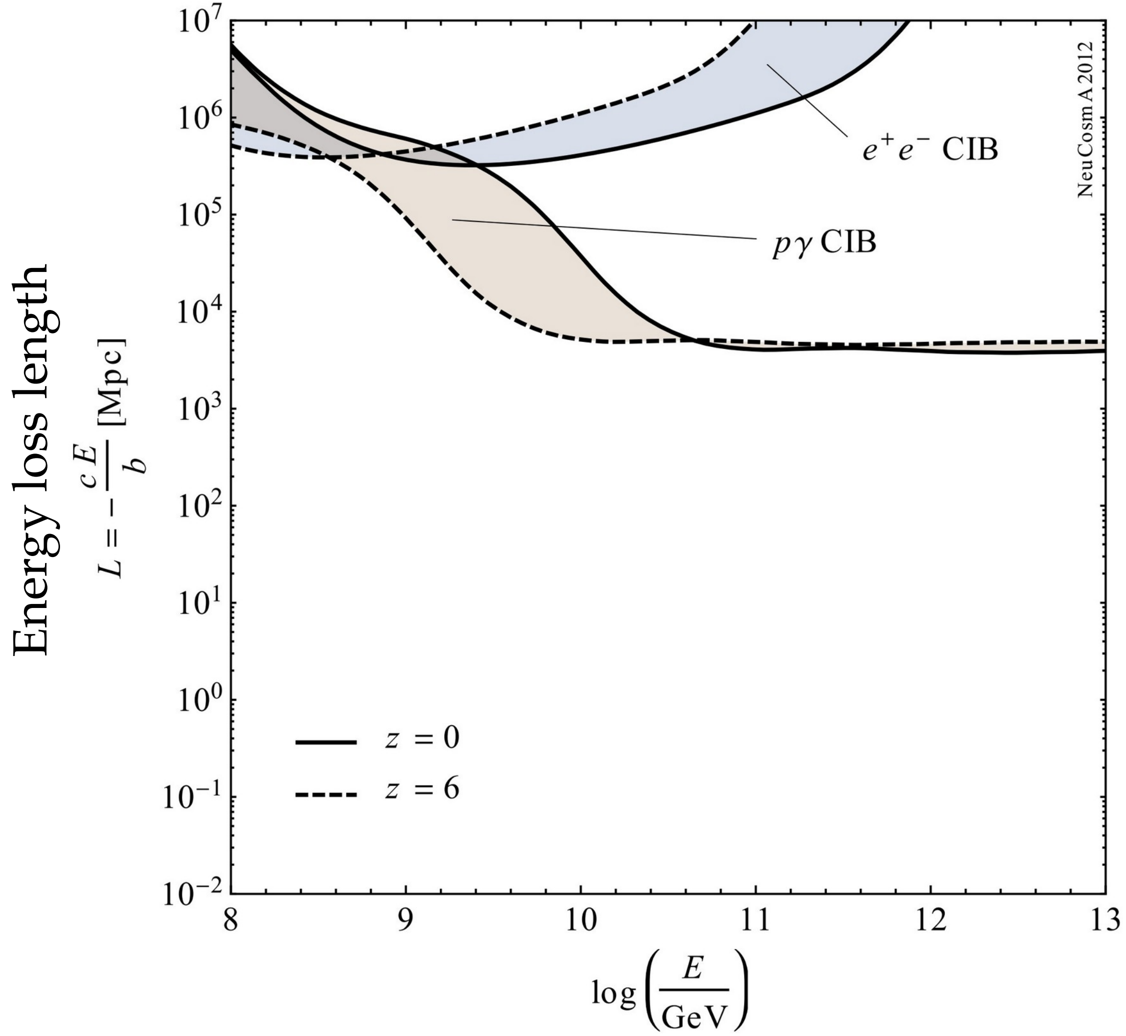
3

Greisen-Zatsepin-Kuzmin (GZK) cut-off is ~100 Mpc

Calculating the UHECR flux at Earth



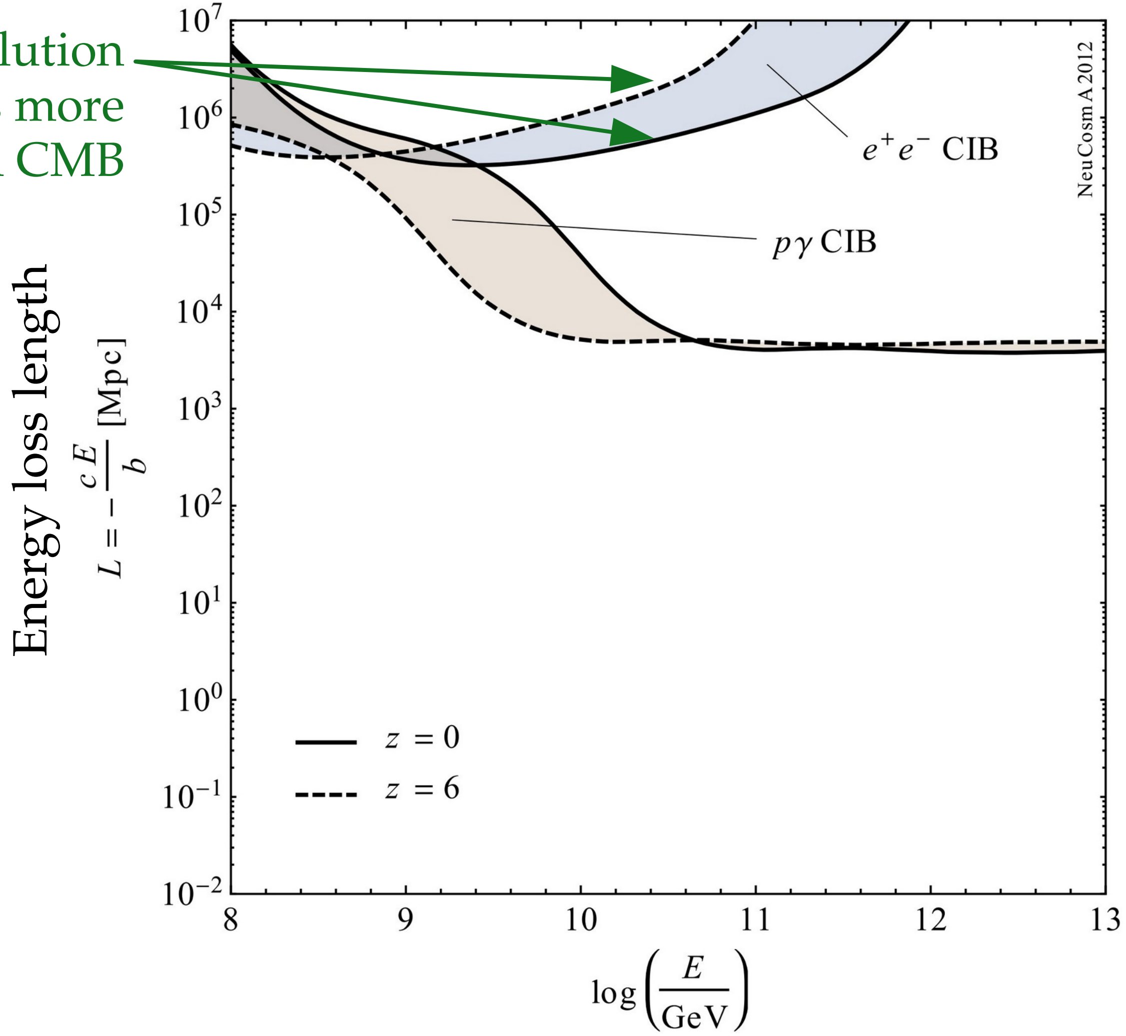
Calculating the UHECR flux at Earth



CIB number density is $\ll$ CMB number density, so there are fewer UHECR interactions on CIB photons ($b_{\rm CIB} \ll b_{\rm CMB}$)

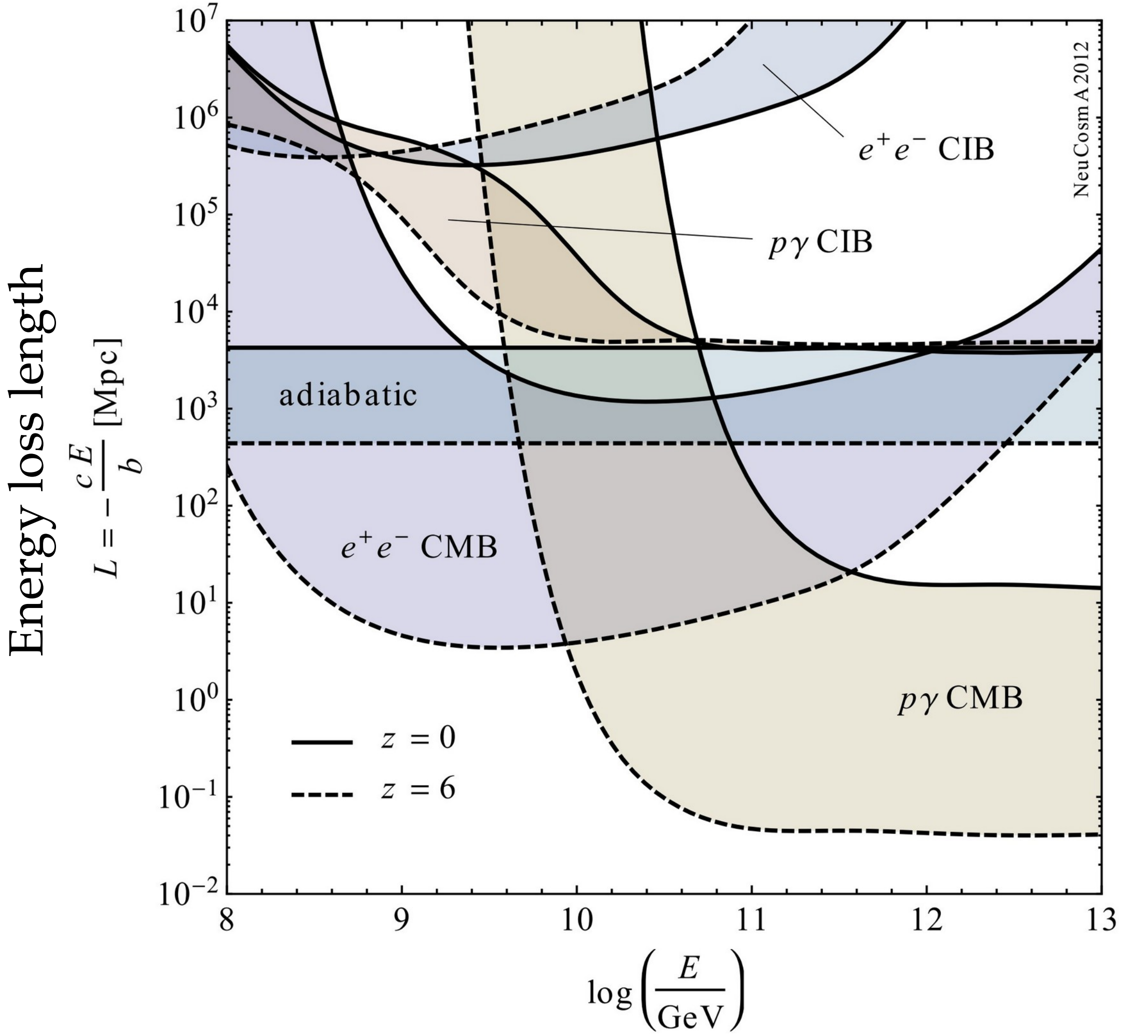
Calculating the UHECR flux at Earth

The redshift evolution of CIB is more complex than CMB

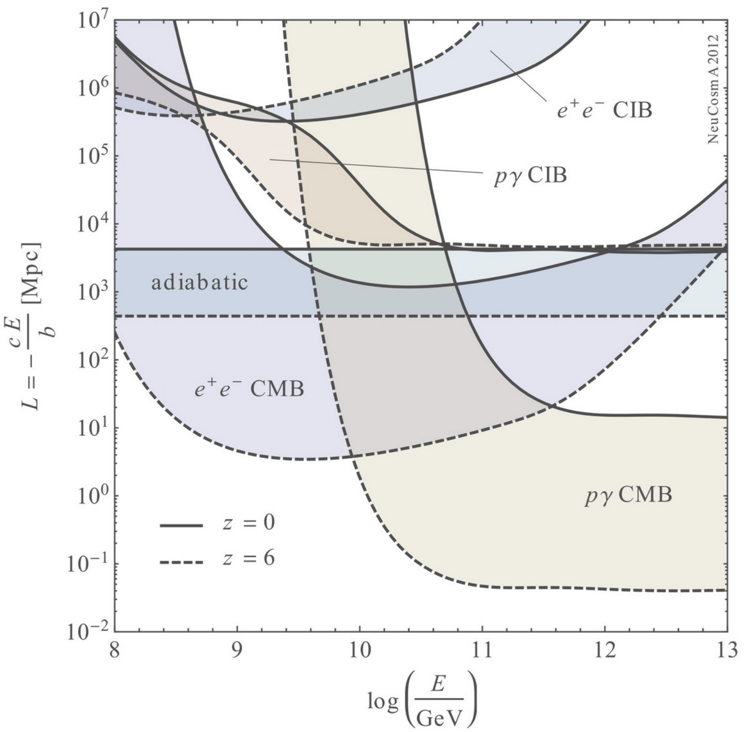


CIB number density is $\ll$ CMB number density, so there are fewer UHECR interactions on CIB photons ($b_{\text{CIB}} \ll b_{\text{CMB}}$)

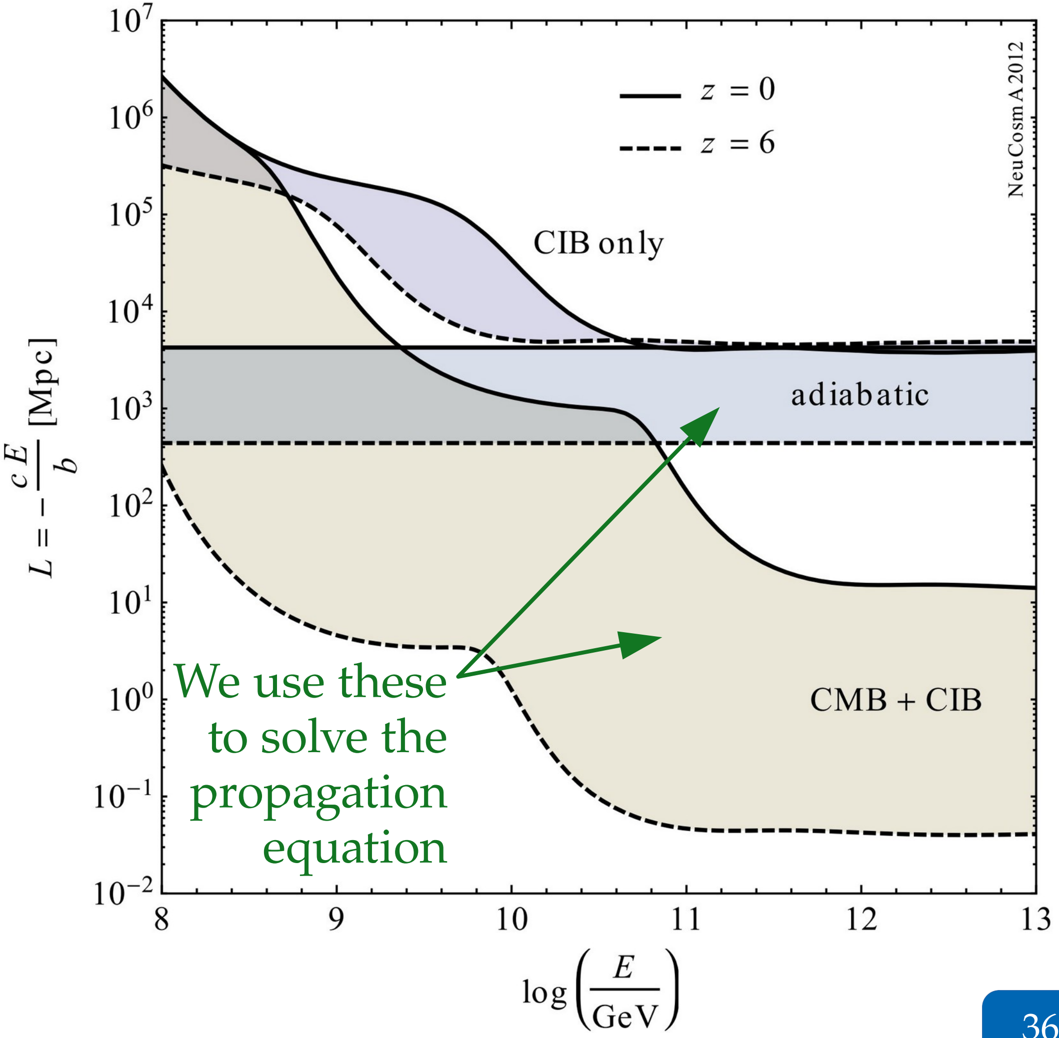
Calculating the UHECR flux at Earth



Calculating the UHECR flux at Earth



Faster energy-loss process dominates



We use these to solve the propagation equation

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \quad (\rightarrow \gamma + \gamma) \\ n + \pi^+ \quad (\rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+) \end{cases}$$

Pair production:

$$p + \gamma \rightarrow p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

$$E_p \approx \frac{0.16\ \mathrm{GeV}^2}{0.66\ \mathrm{meV}} \approx 2 \cdot 10^{11}\ \mathrm{GeV}$$

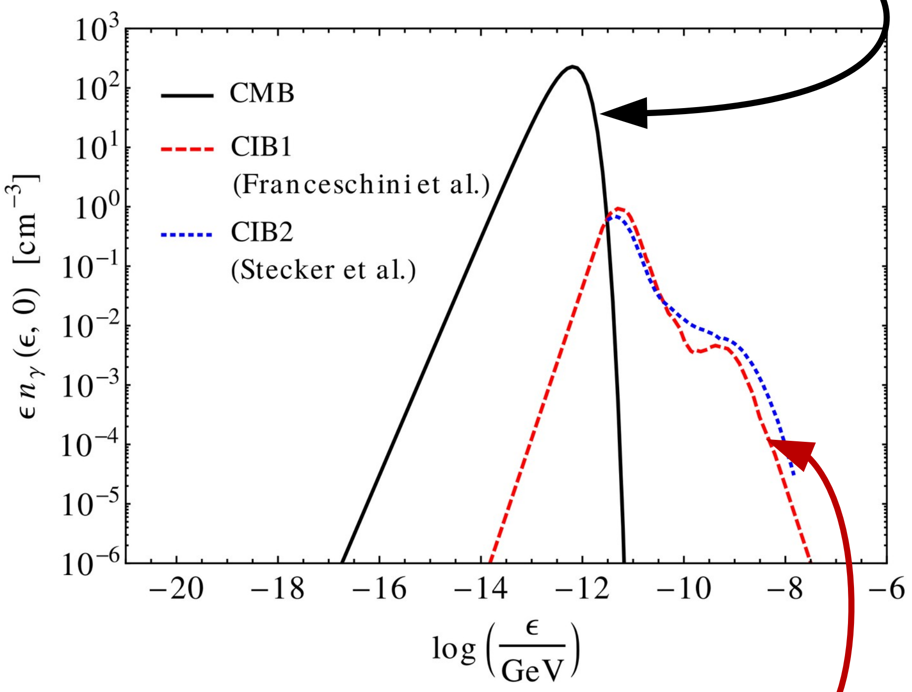
(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

$$E_p \approx 5 \cdot 10^{10}\ \mathrm{GeV}$$

Target photon spectra (at $z = 0$):

CMB: Microwave (black body, <ϵ> ~ 0.66 meV)



CIB: optical (stars) + infrared (dust remission)

$n_\gamma(z) = (1+z)^3\, n_\gamma(z=0)$ (exact only for CMB)

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

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(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

$$E_p \approx 5 \cdot 10^{10}\ \mathrm{GeV}$$

Mean free path:

$$(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} = (413\ \mathrm{cm}^{-3} \times 200\ \mu\mathrm{barn})^{-1} \approx 10^{25}\ \mathrm{cm} \approx 4\ \mathrm{Mpc}$$

Energy-loss scale:

$$L = (E/\Delta E)(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} \approx (1/0.2) \times 4\ \mathrm{Mpc} \approx 20\ \mathrm{Mpc}$$

A more detailed calculation yields

$$L_{\mathrm{GZK}} \approx 100\ \mathrm{Mpc}$$

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \quad \hookrightarrow \gamma + \gamma \\ n + \pi^+ \quad \hookrightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{cases}$$

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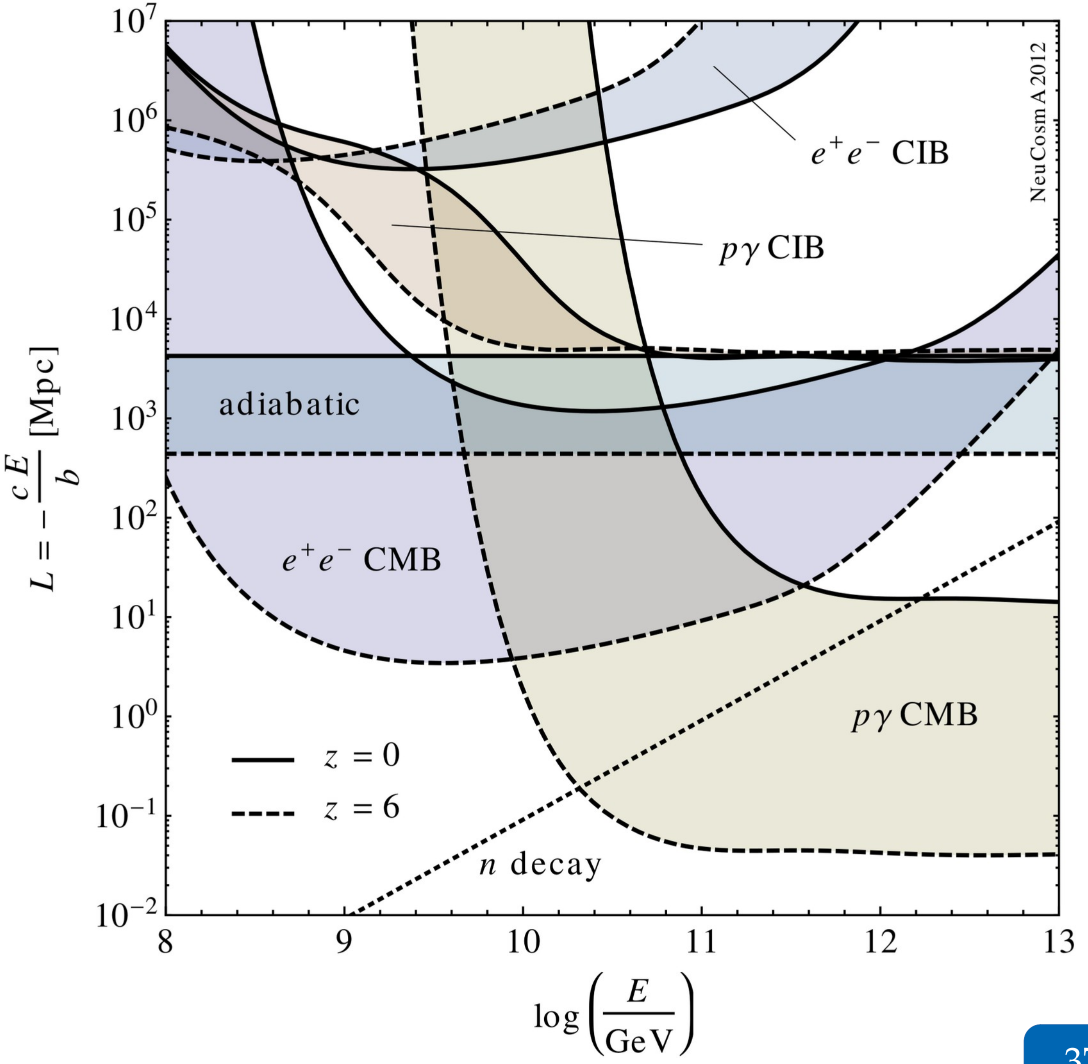
(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width

$$E_p \approx 5 \cdot 10^{10} \text{ GeV}$$



Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is *also* opaque to PeV gamma rays

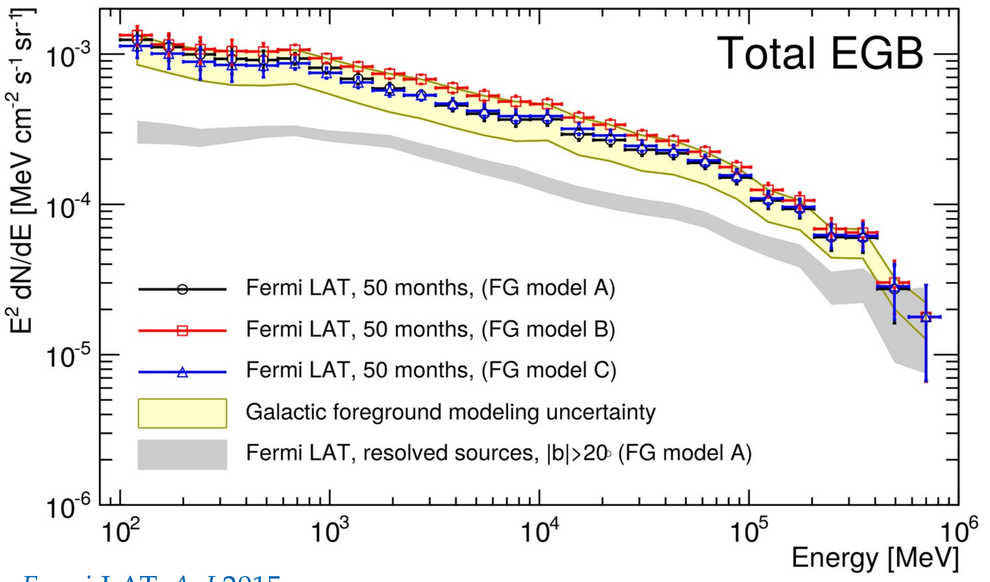
Pair production:

$\gamma_{astro} + \gamma_{cosmo} \rightarrow e^- + e^+$

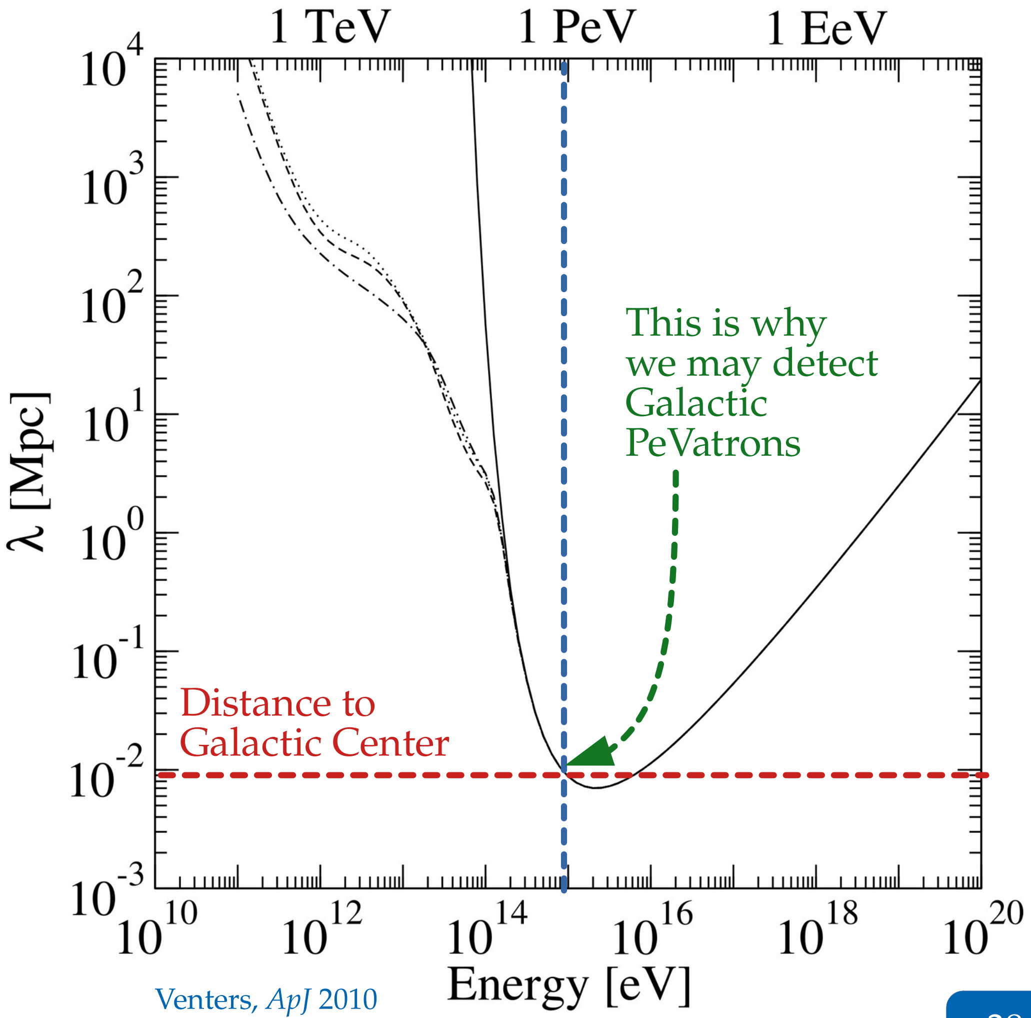
Inverse Compton scattering:

$e^{\pm} + \gamma_{cosmo} \rightarrow e^{\pm} + \gamma$

PeV gamma rays cascade down to MeV–GeV:



Fermi-LAT, *ApJ* 2015



Venters, *ApJ* 2010

Calculating the UHECR flux at Earth

Putting it all together…

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\rm CR}(E,z)\}$$

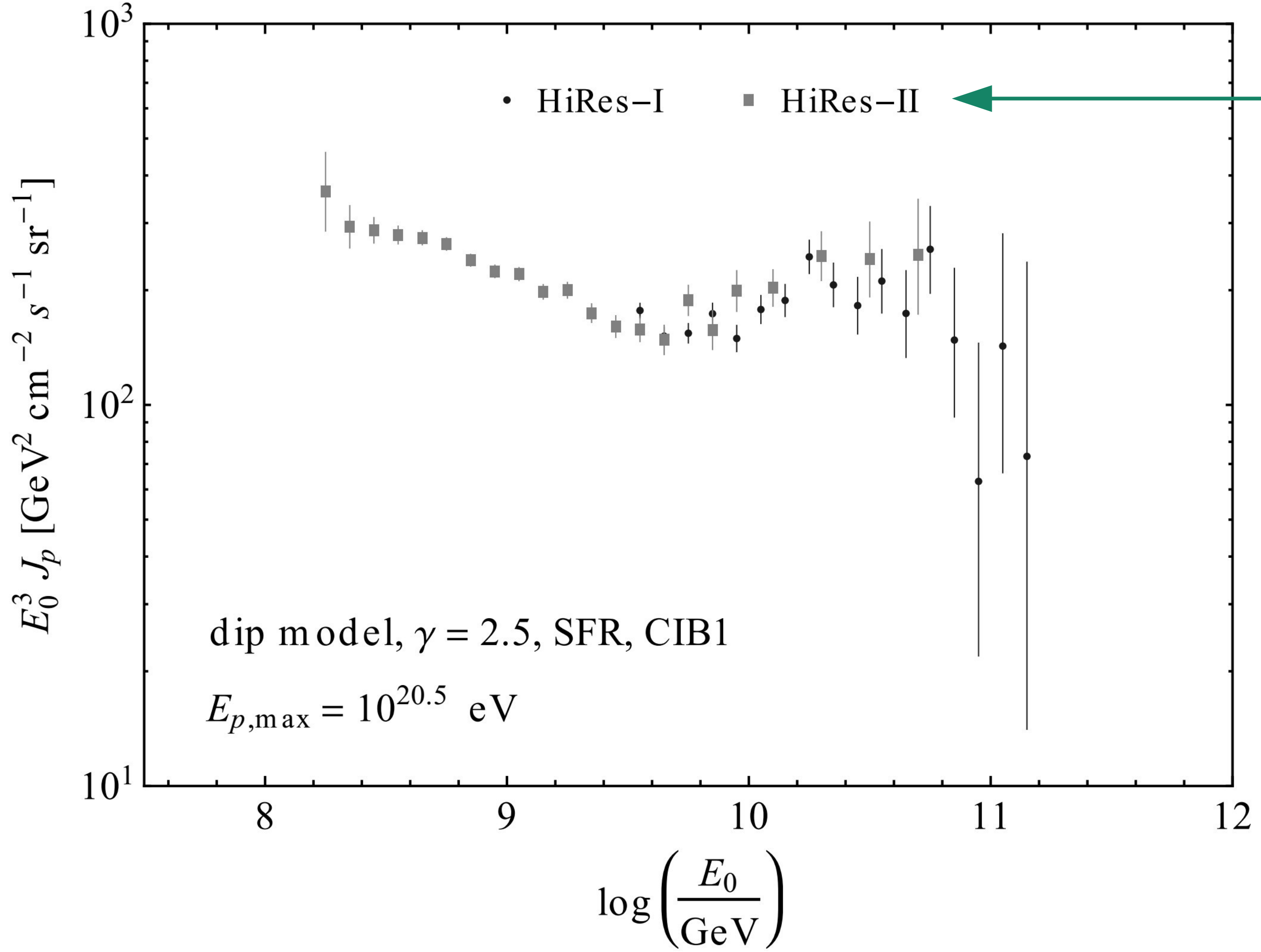
Evolve numerically from $z_{\rm max} \sim 4$ to Earth ($z = 0$)

Diffuse UHECR proton flux at Earth ($\mathrm{GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$):

$$J_p(E) = \underbrace{\frac{c}{4\pi}} n_p(E, z=0)$$

This factor converts density to flux

Calculating the UHECR flux at Earth



Old UHECR data (just as example)

Calculating the UHECR flux at Earth

Compare our predicted flux to the measured flux:

Flux normalization

Flux data points

$$\chi^2(J_{p,0}, \delta_E) = \sum_i^{\text{data}} \left(\frac{E^3 J_p(J_{p,0}) - \left(E^3 J_p\right)_i^{\text{HiRes}}}{\sigma_i} \right)^2 + \left(\frac{\delta_E}{\sigma_E} \right)^2$$

Energy shift (nuisance)

Uncertainty of *i*-th data point

Systematic energy uncertainty

Minimize the function with respect to $J_{p,0}$ and δ_E

Note: This is a simplified setup; in reality, many flux parameters are jointly varied

Calculating the UHECR flux at Earth

Compare our predicted flux to the measured flux:

Flux normalization

Flux data points

"Pull term"

$$\chi^2(J_{p,0}, \delta_E) = \sum_i^{\text{data}} \left(\frac{E^3 J_p(J_{p,0}) - \left(E^3 J_p\right)_i^{\text{HiRes}}}{\sigma_i} \right)^2 + \left(\frac{\delta_E}{\sigma_E}\right)^2$$

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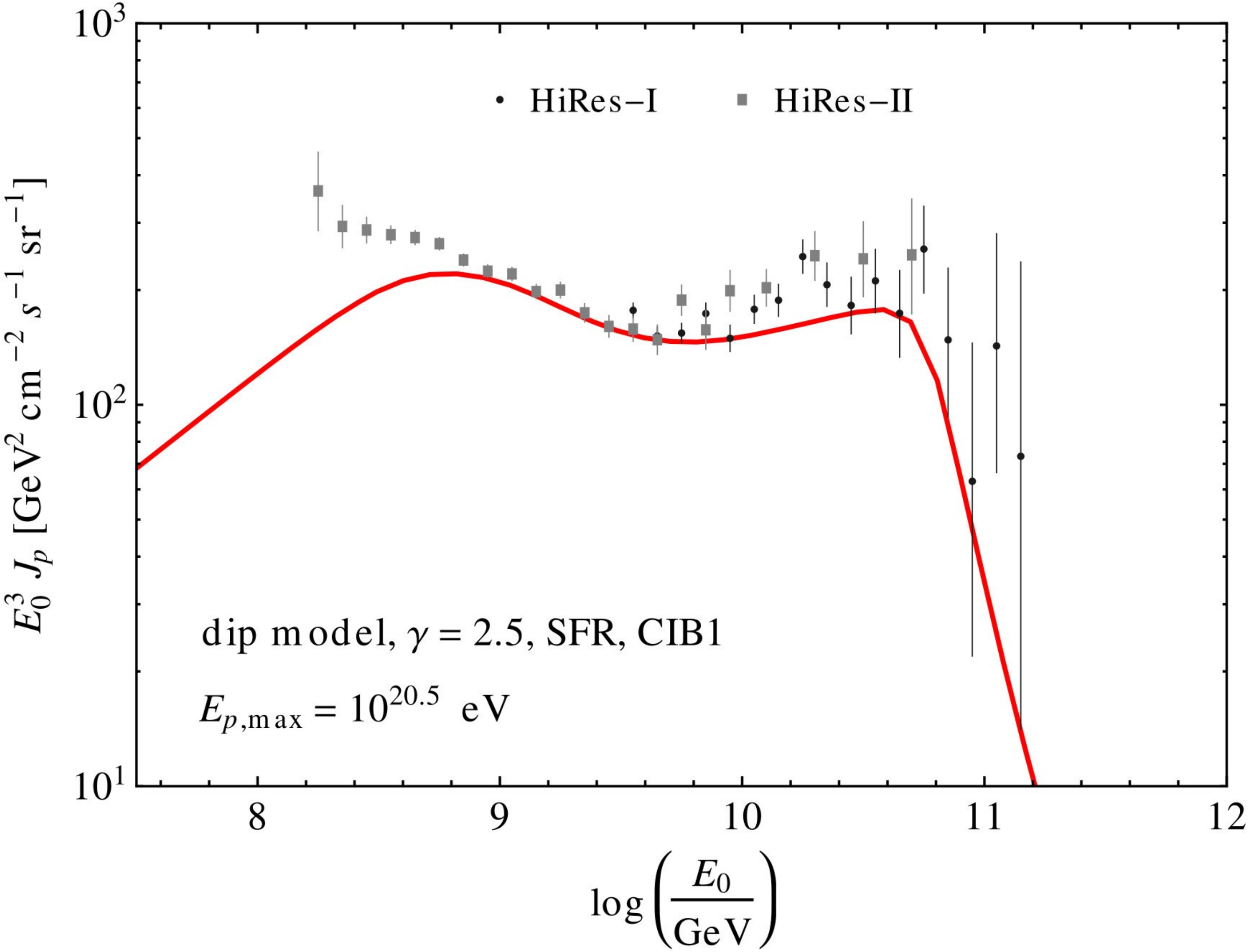
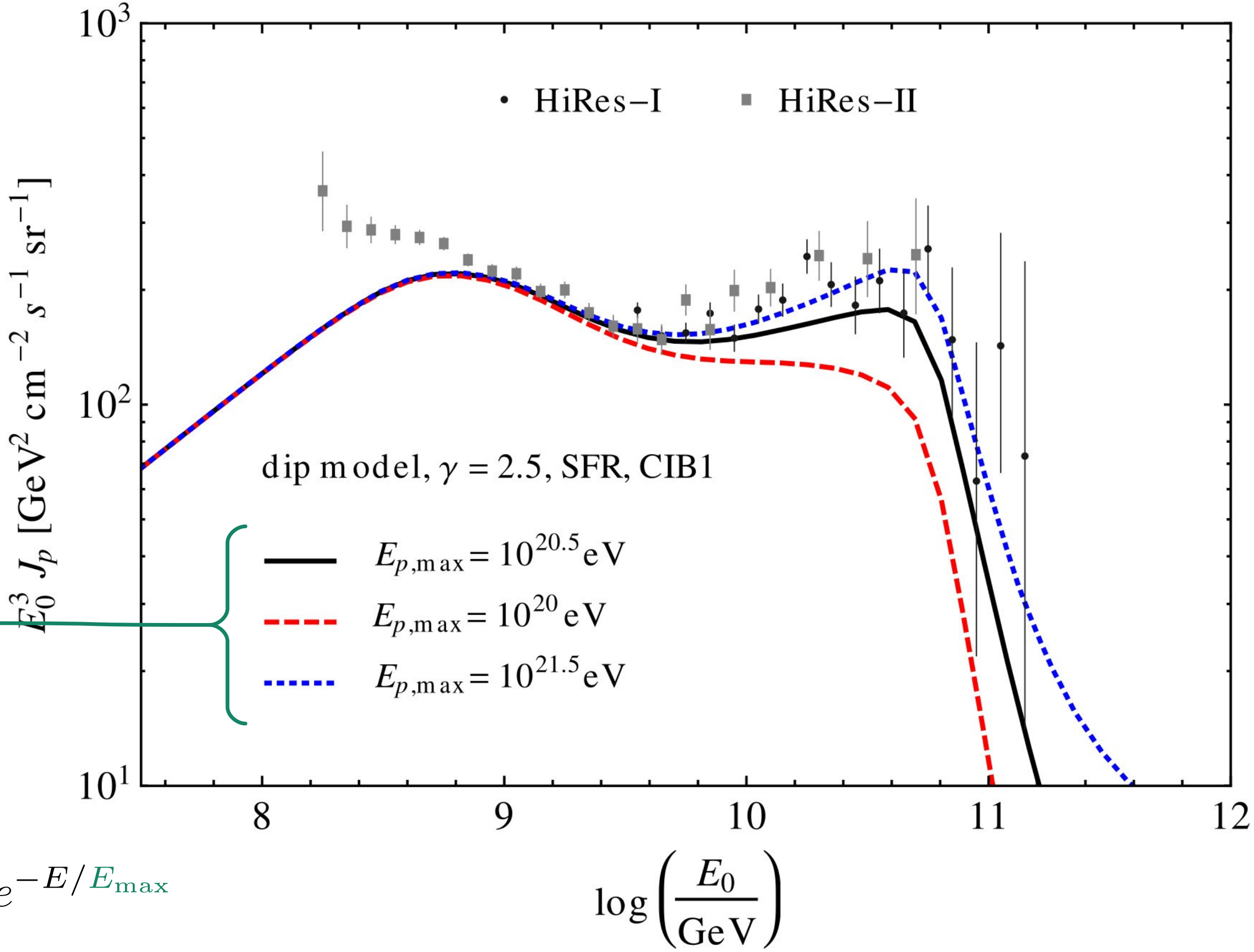
Calculating the UHECR flux at Earth



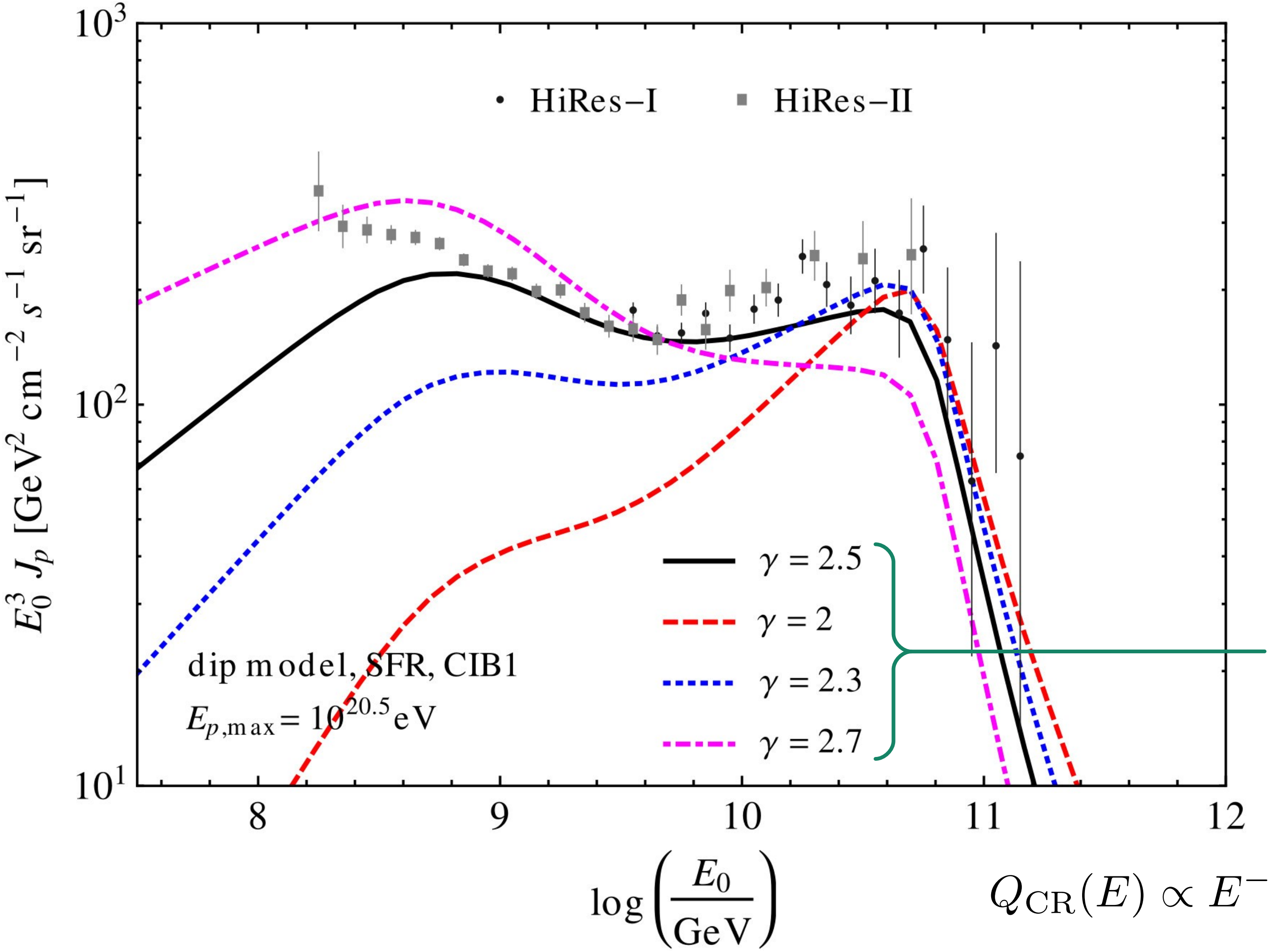
Calculating the UHECR flux at Earth



Varying the maximum proton energy

$$Q_{\mathrm{CR}}(E) \propto E^{-\gamma} e^{-E/E_{\max}}$$

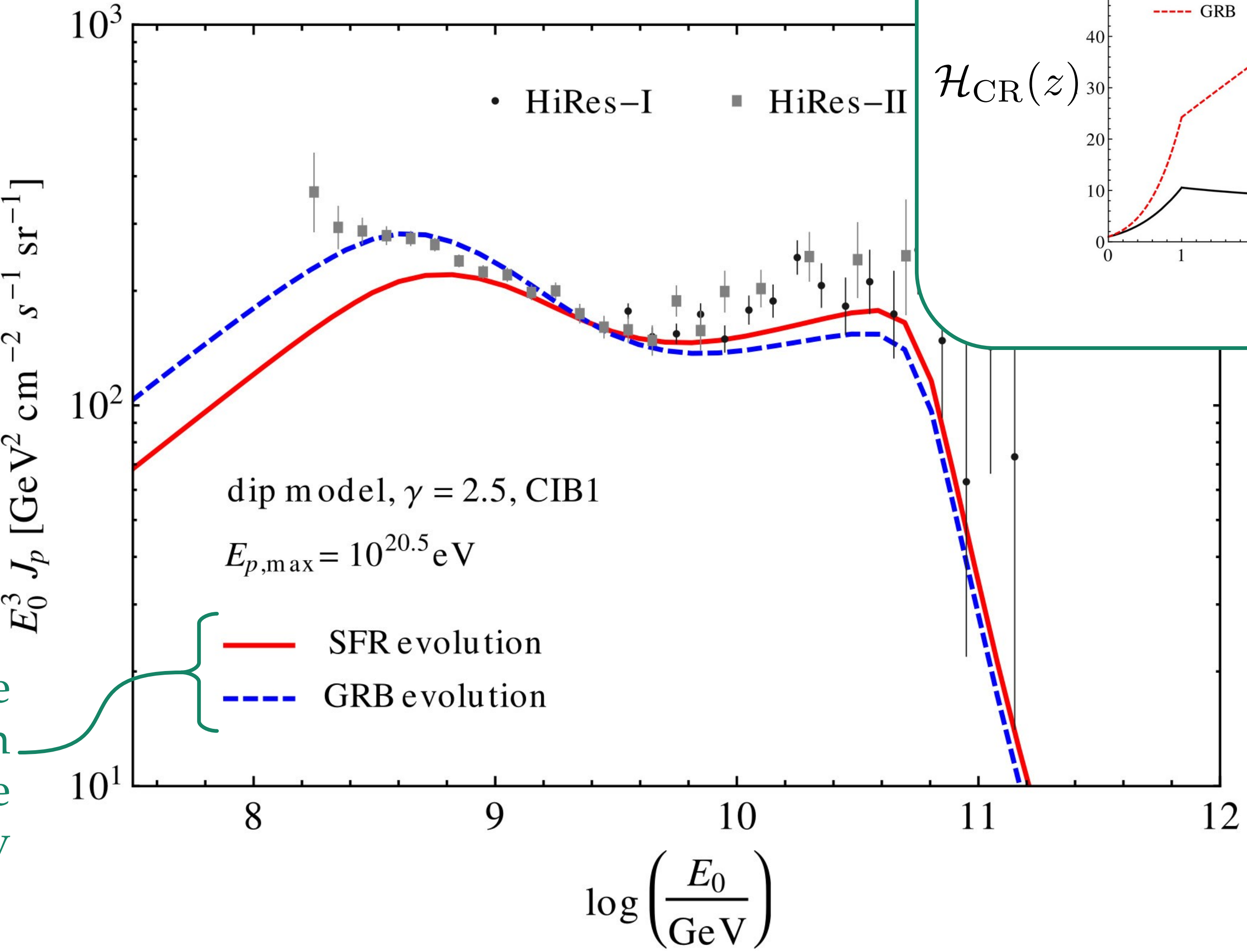
Calculating the UHECR flux at Earth

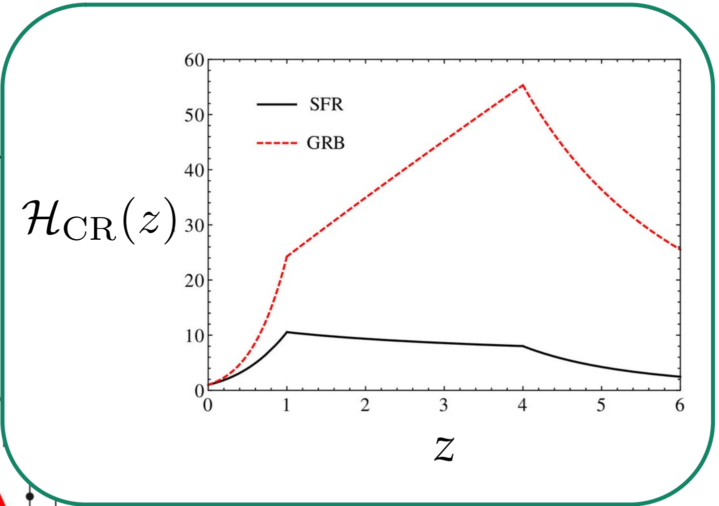


Varying the proton spectral index

$$Q_{\rm CR}(E) \propto E^{-\gamma} e^{-E/E_{\max}}$$

Calculating the UHECR flux at Earth

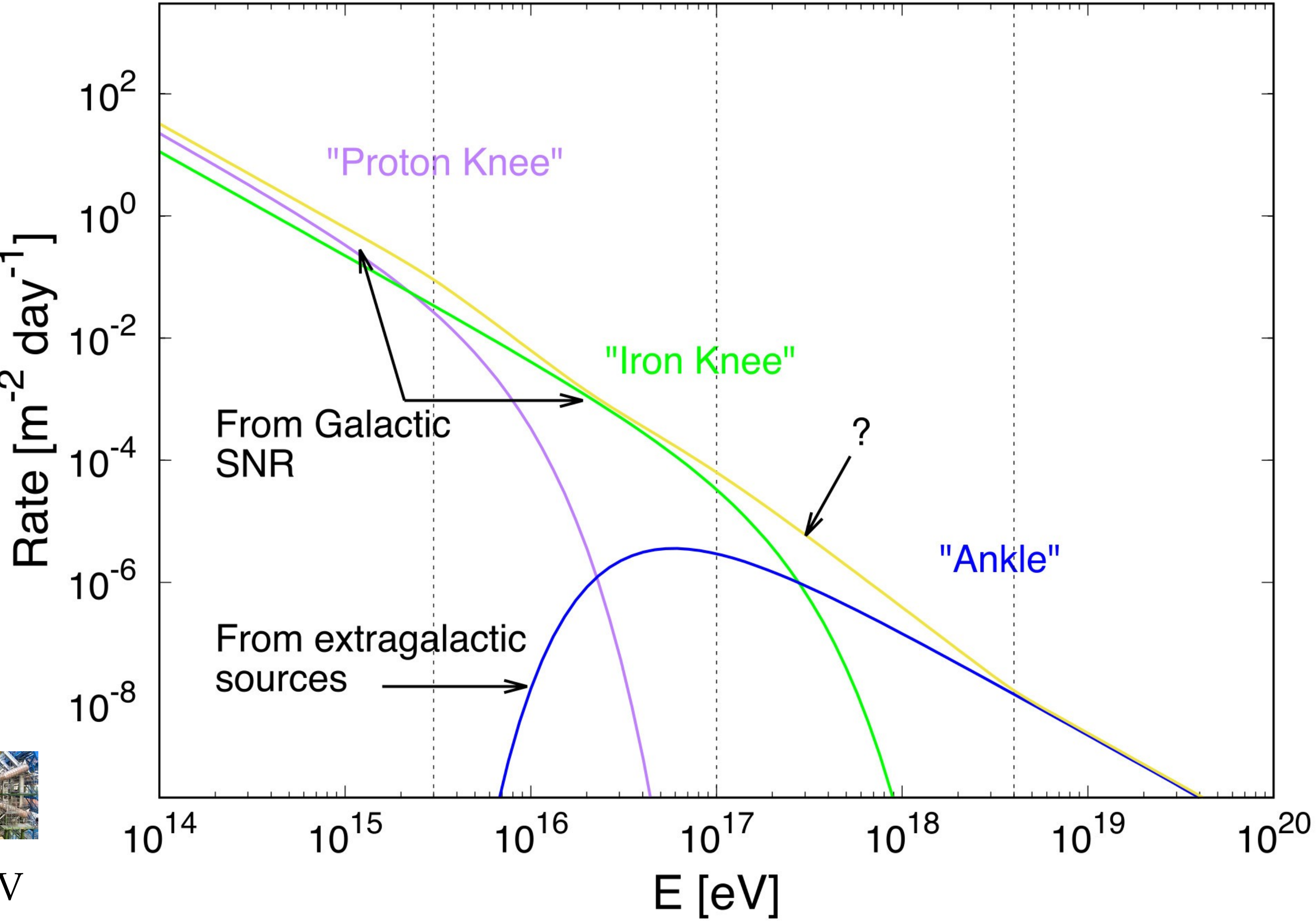




Varying the redshift evolution of the source number density

The UHECR all-particle spectrum

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019



1 eV ≈ 10^{-19} J

10^{12} eV

10^{13} eV

6×10^{20} eV

The UHECR all-particle spectrum

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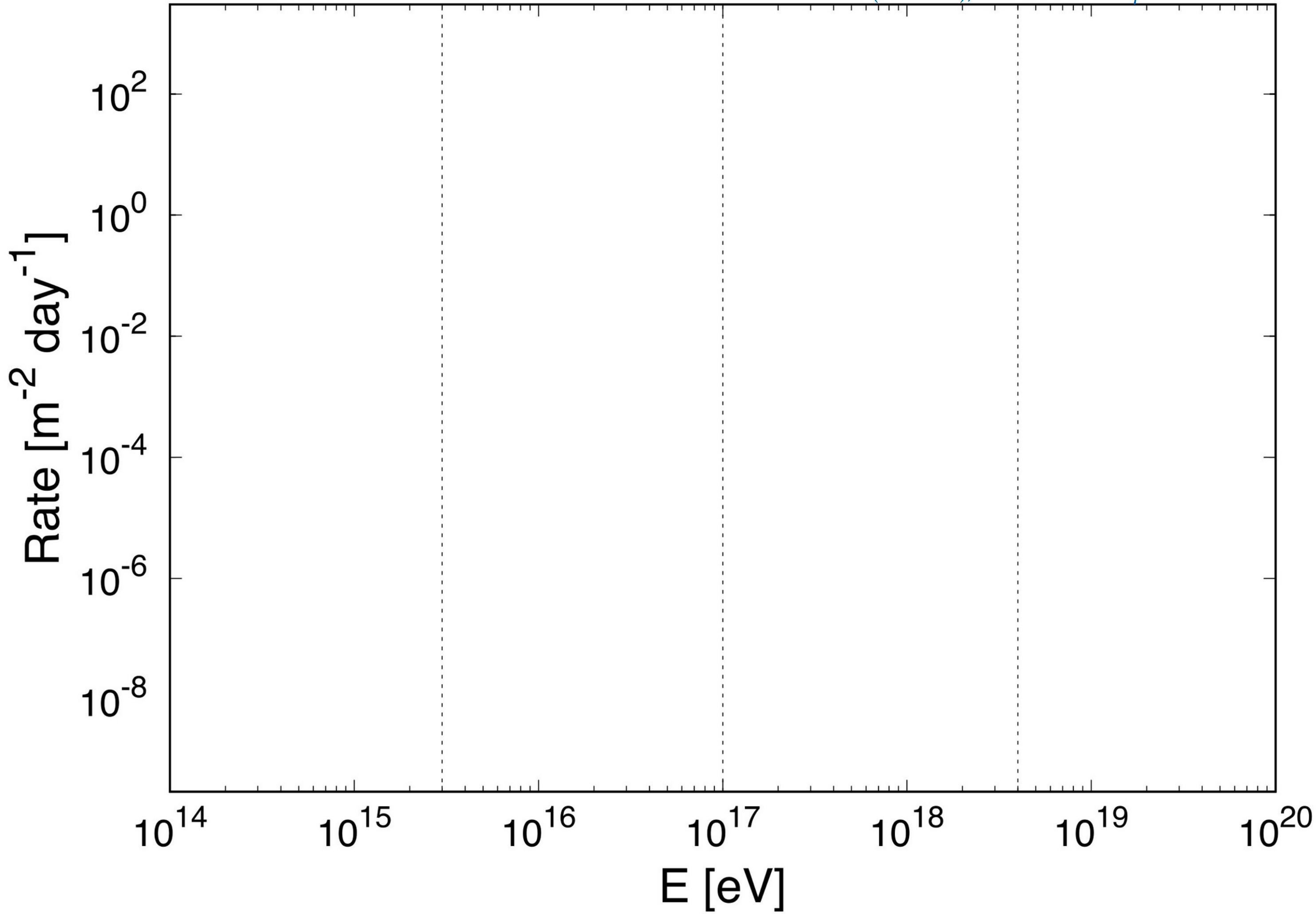

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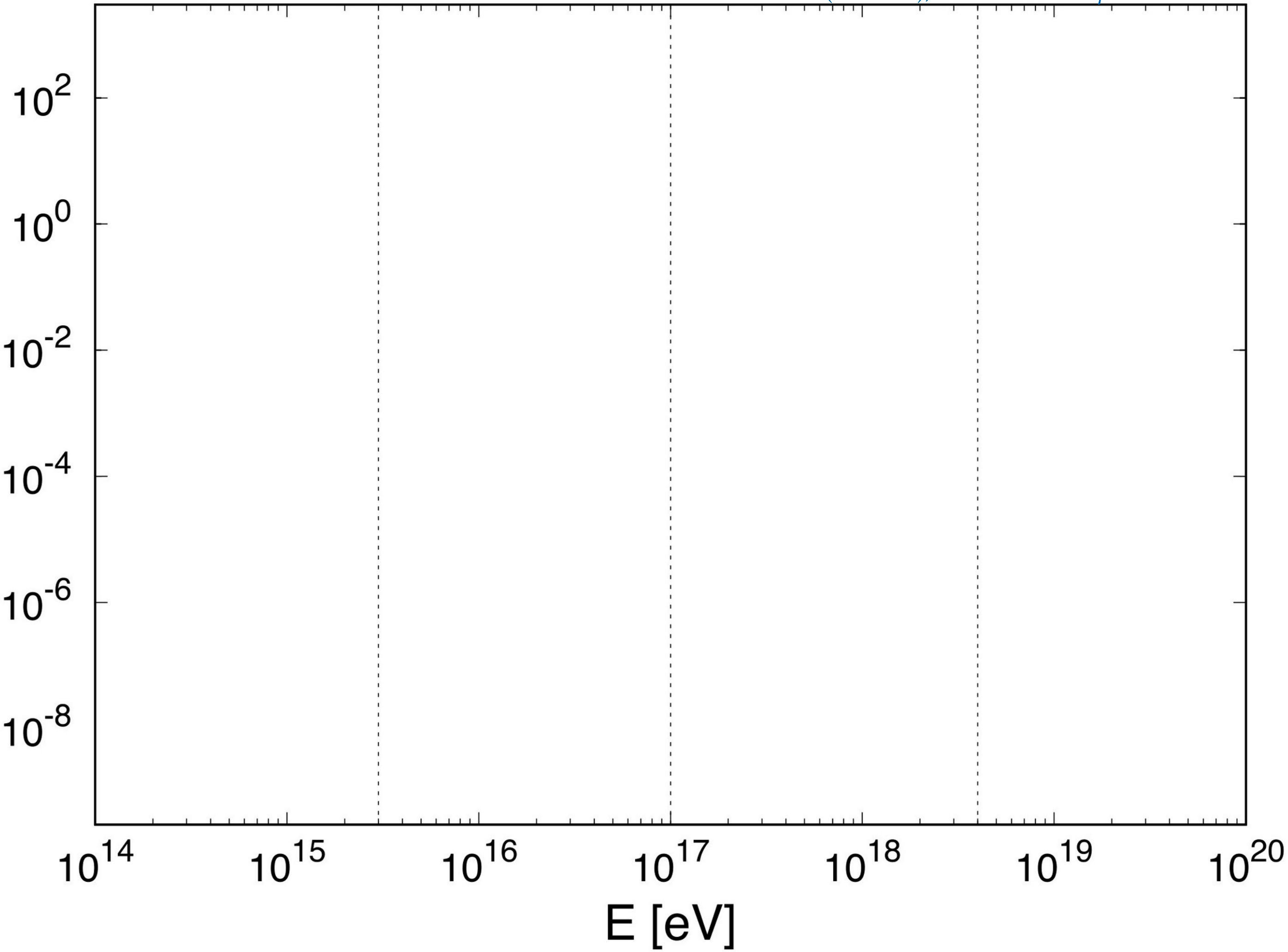

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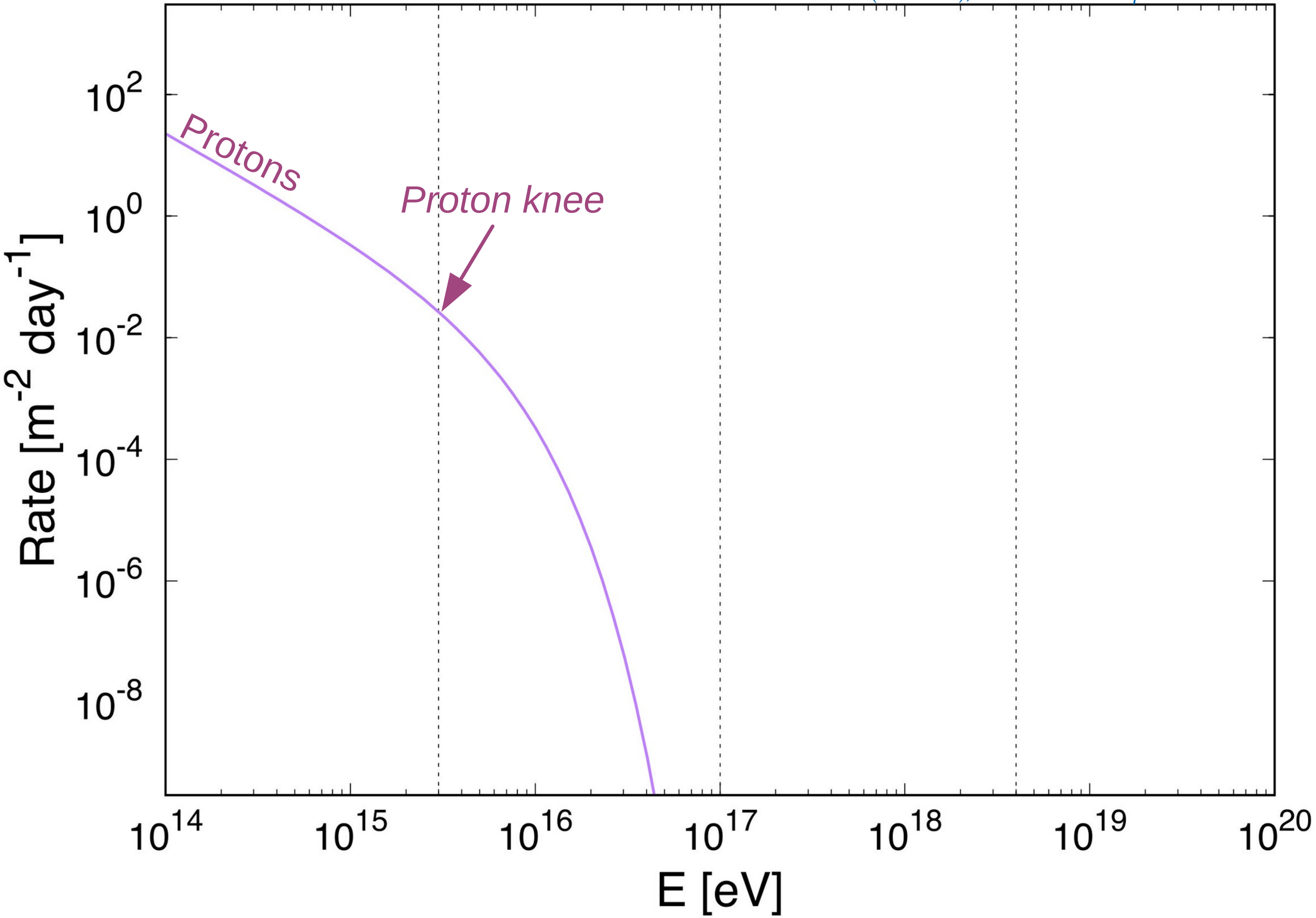

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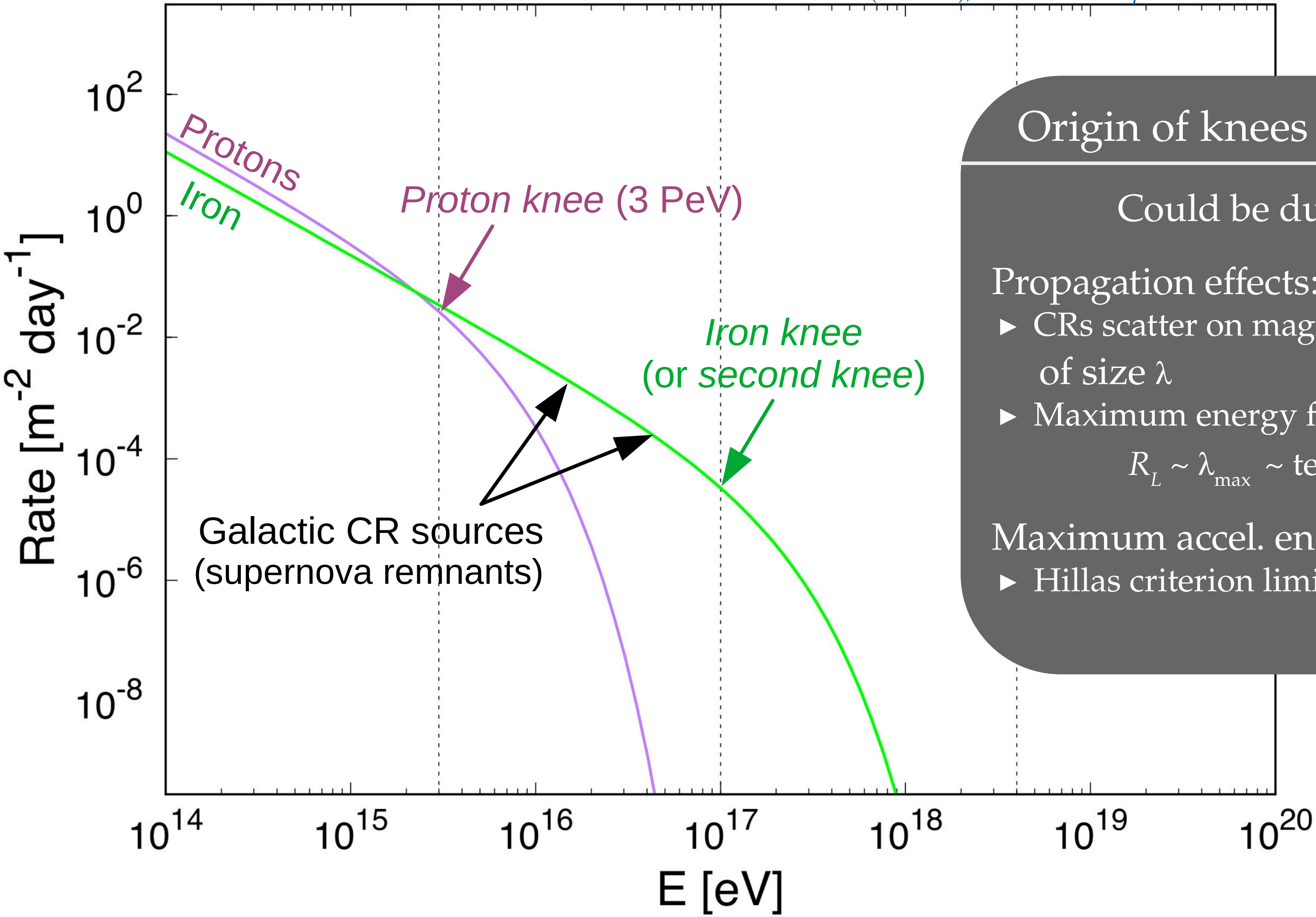


Origin of knees is unknown

Could be due to…

Propagation effects:

- CRs scatter on magnetic turbulence of size λ
- Maximum energy from

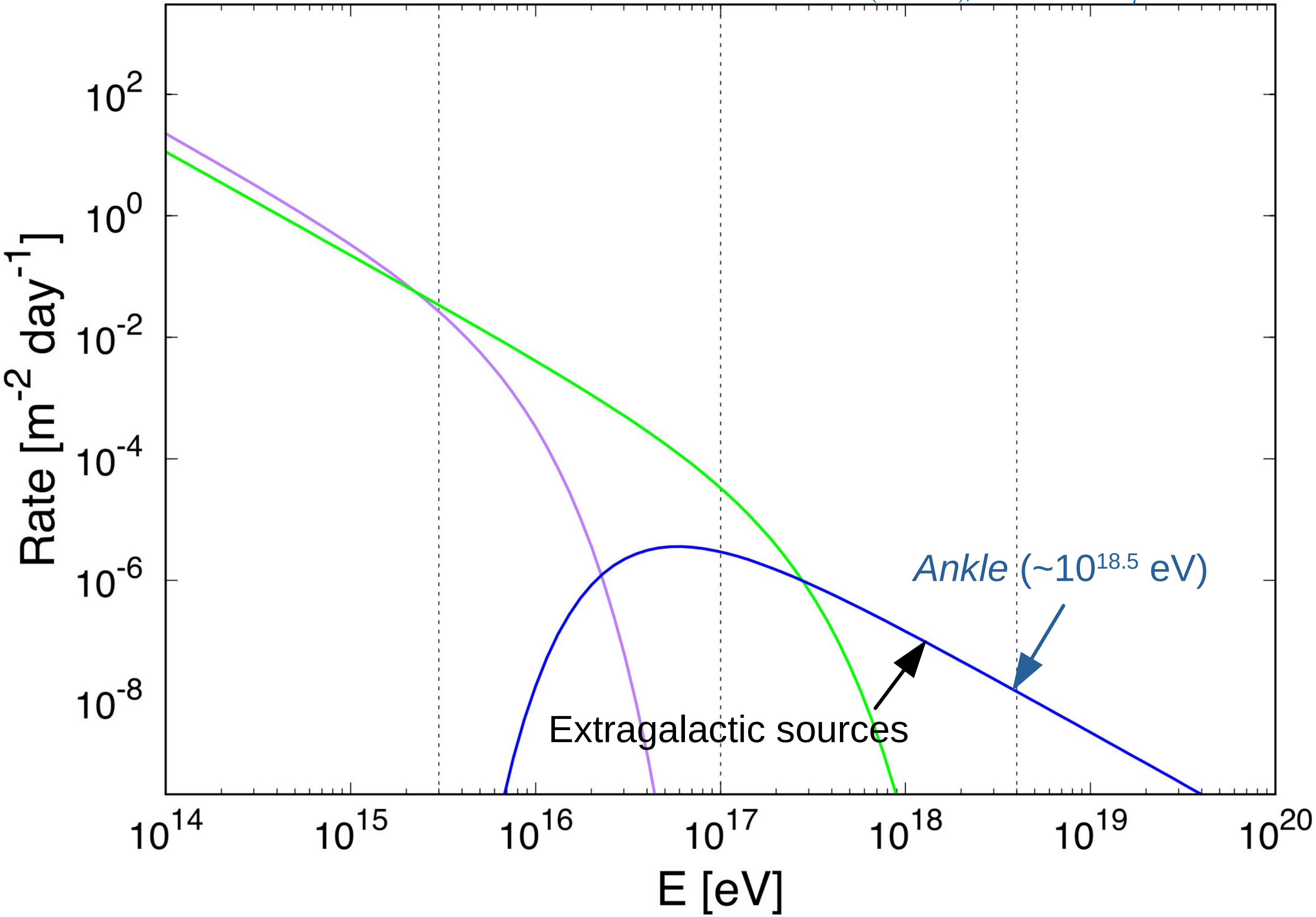
$$R_L \sim \lambda_{max} \sim \text{tens of pc}$$

Maximum accel. energy:

- Hillas criterion limits acceleration

The UHECR all-particle spectrum

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019



The UHECR all-particle spectrum

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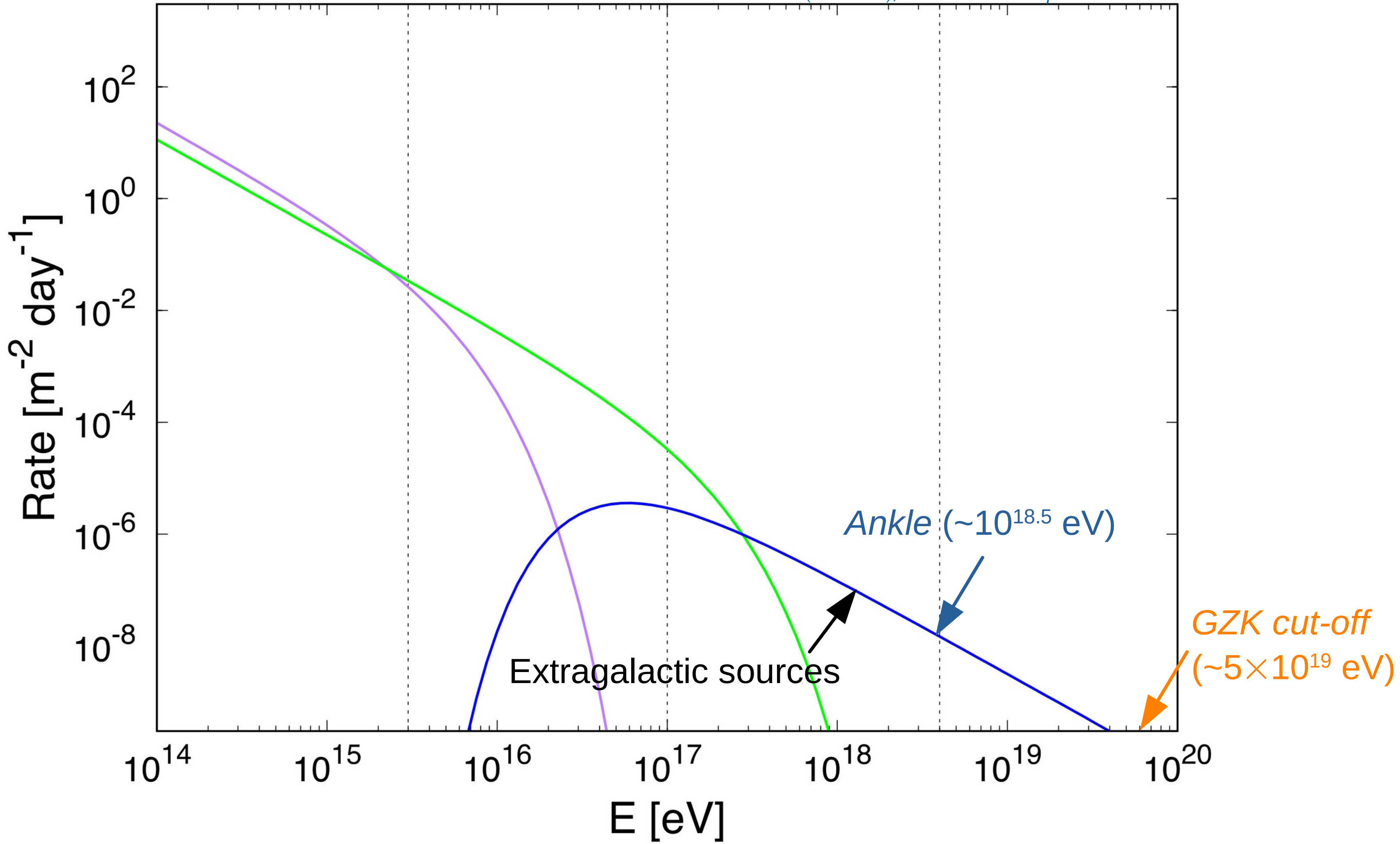

The UHECR all-particle spectrum

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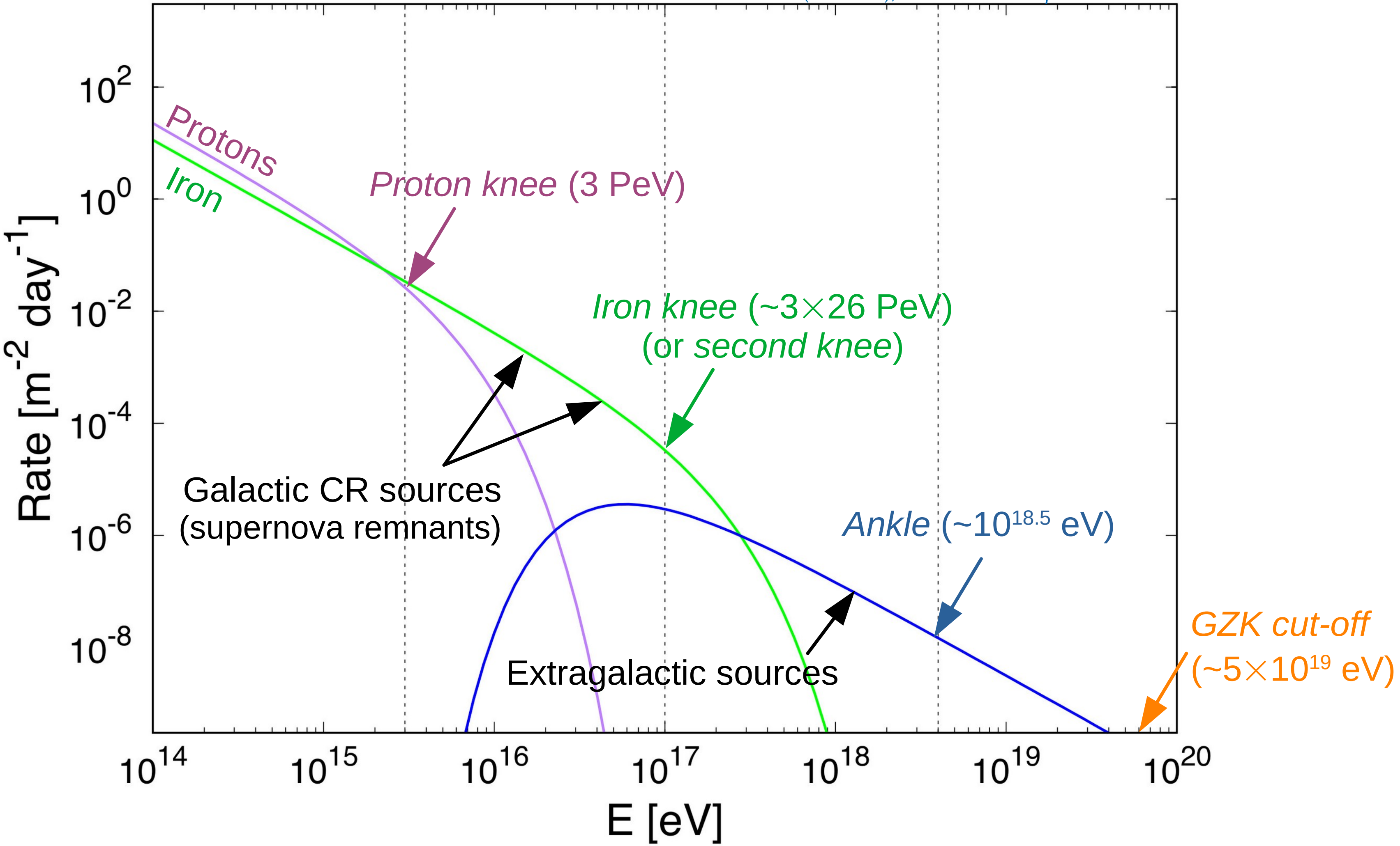

The UHECR all-particle spectrum

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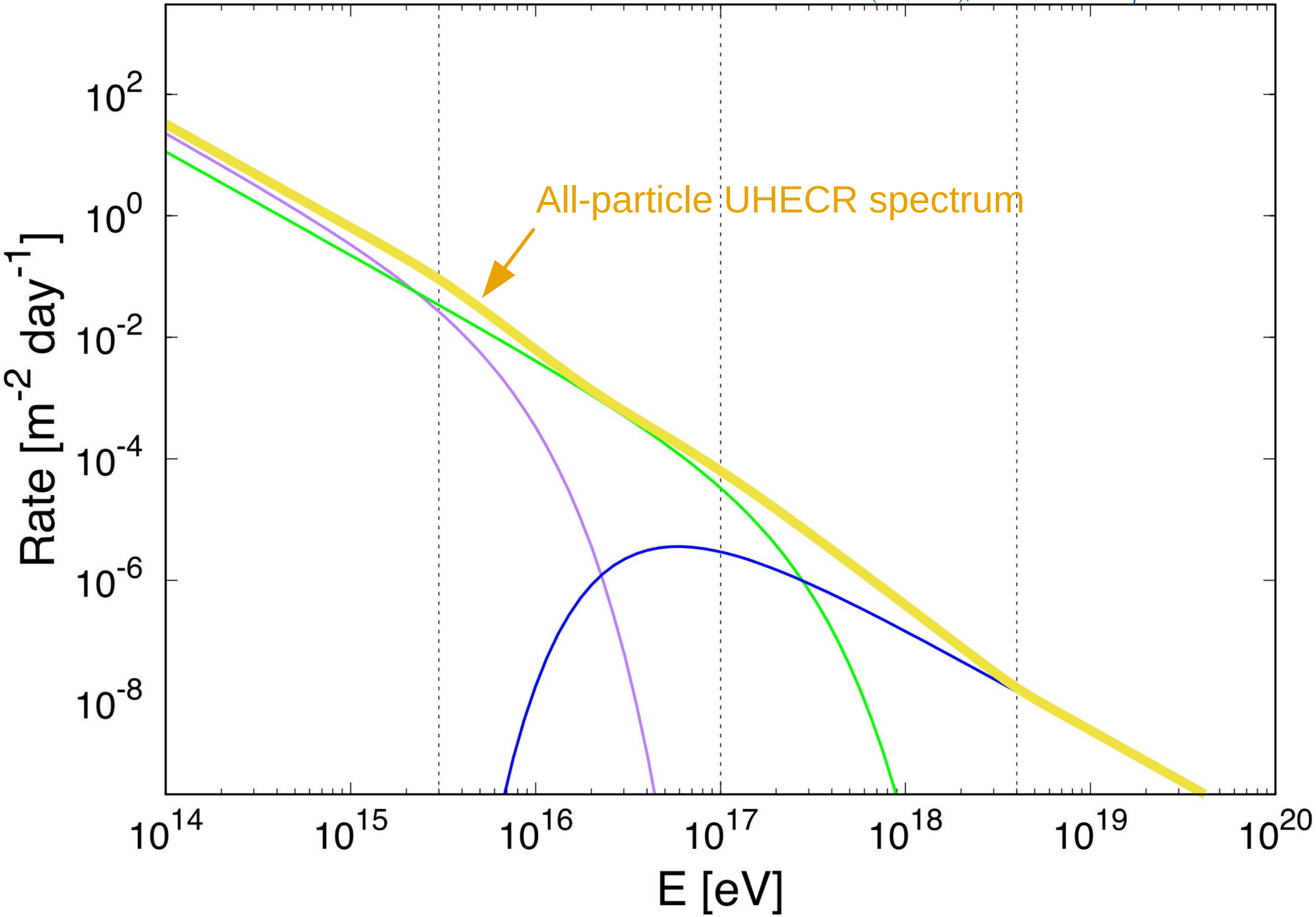
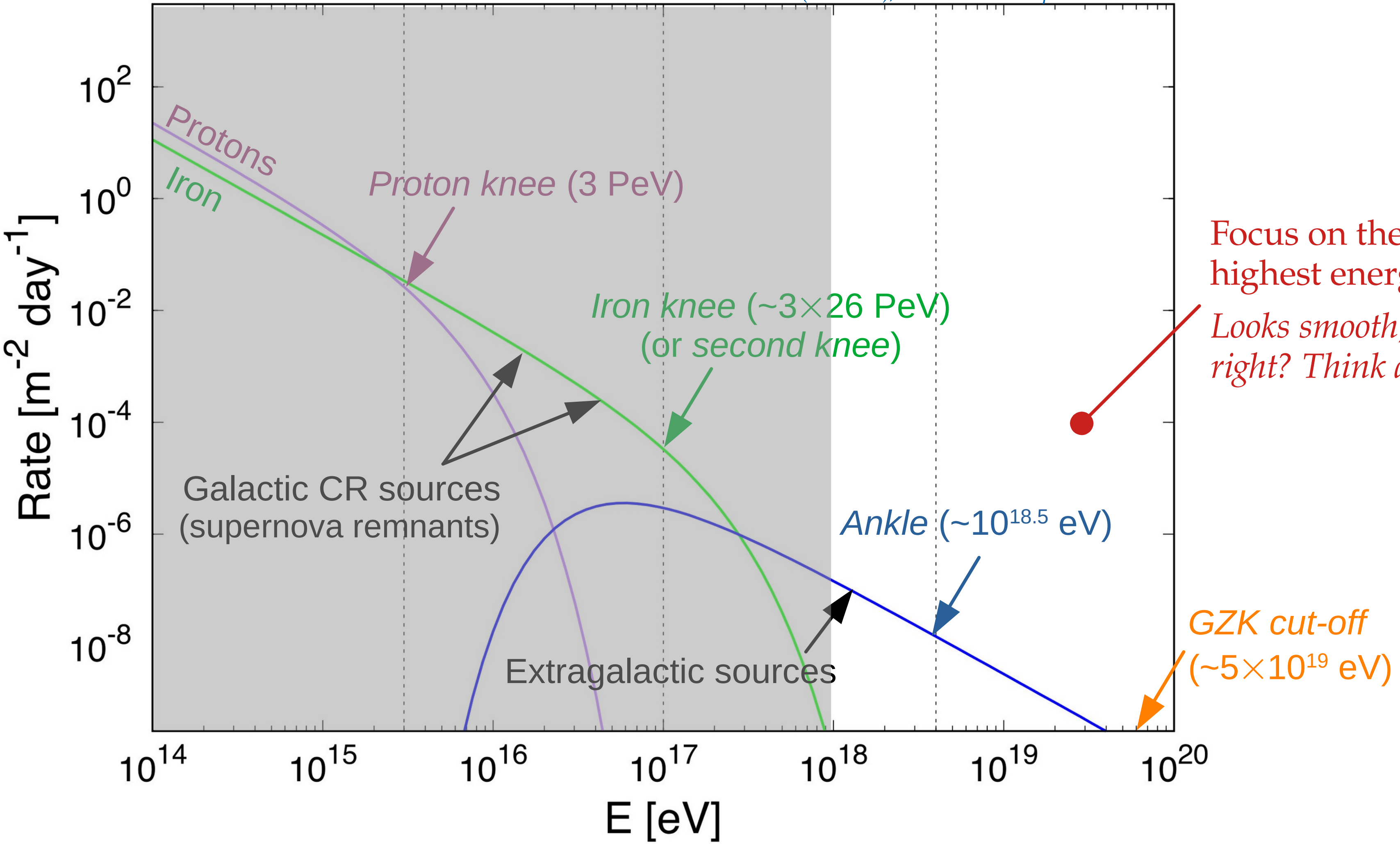


The UHECR all-particle spectrum – more features!

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019



Focus on the highest energies

Looks smooth, right? Think again!

The UHECR all-particle spectrum – more features!

15 years of Auger data (2004–2019)!

~215k events above 2.5×10^{18} eV

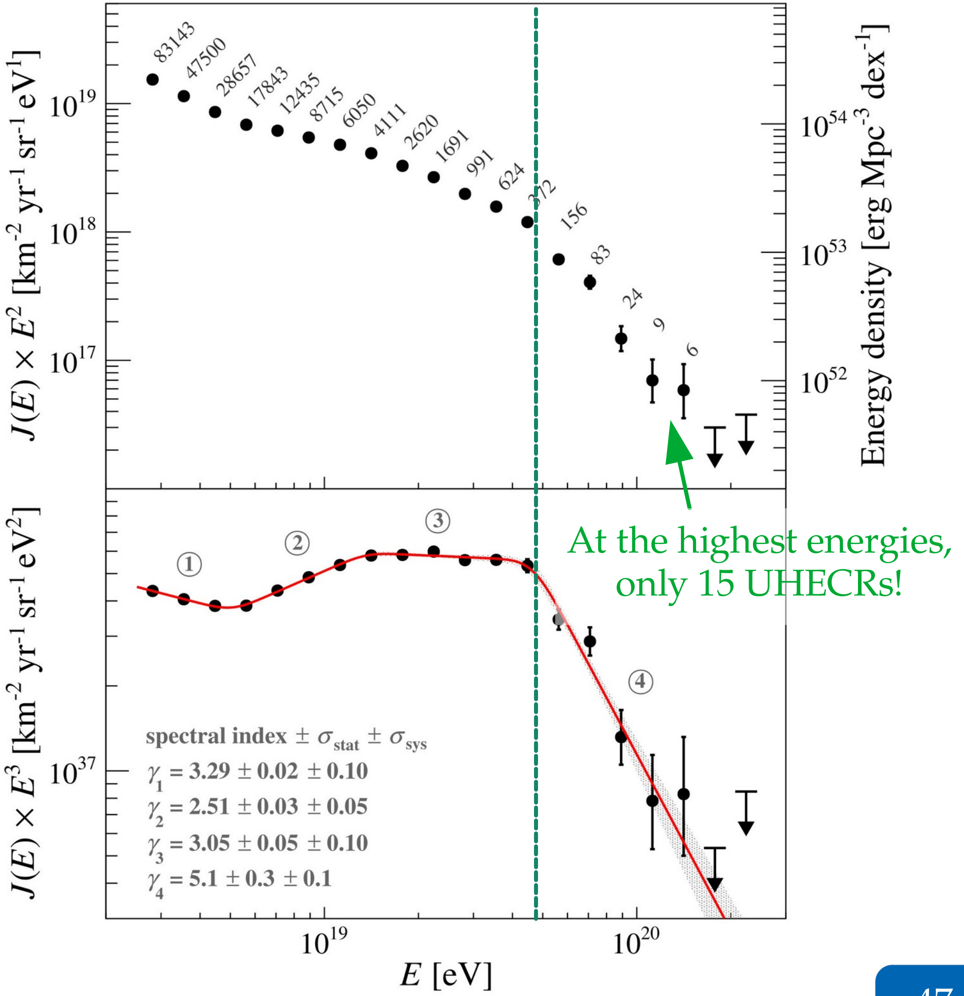
Use *hybrid* events detected by surface + fluorescence detectors to calibrate
—Allows us to measure energies of other events robustly

CR luminosity density above 5×10^{18} eV:

6×10^{44} erg Mpc^{-3} yr^{-1}

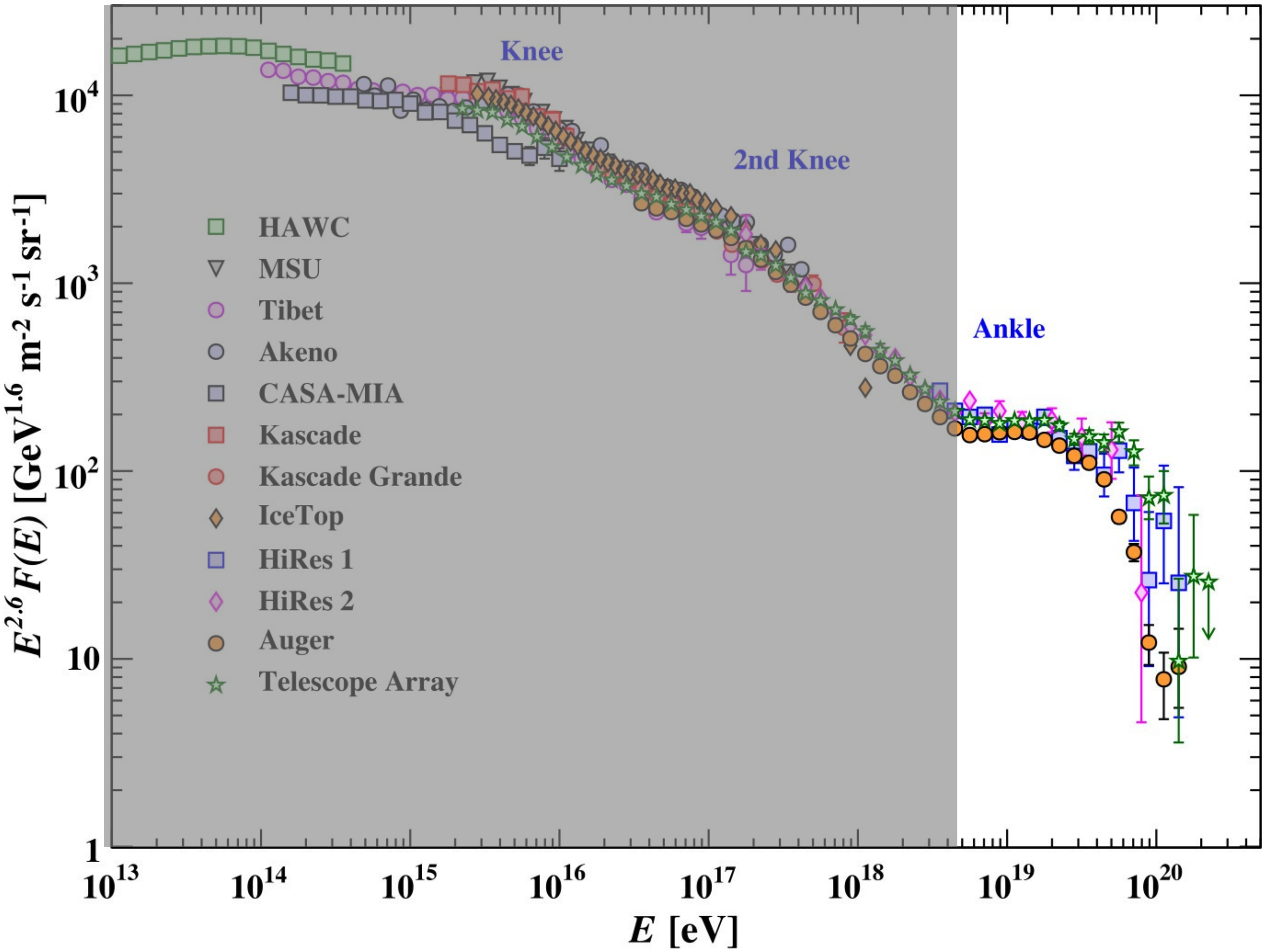
(could be AGN or starburst galaxies)

$$\ln(10)\frac{4\pi}{c}E^2 J(E)$$

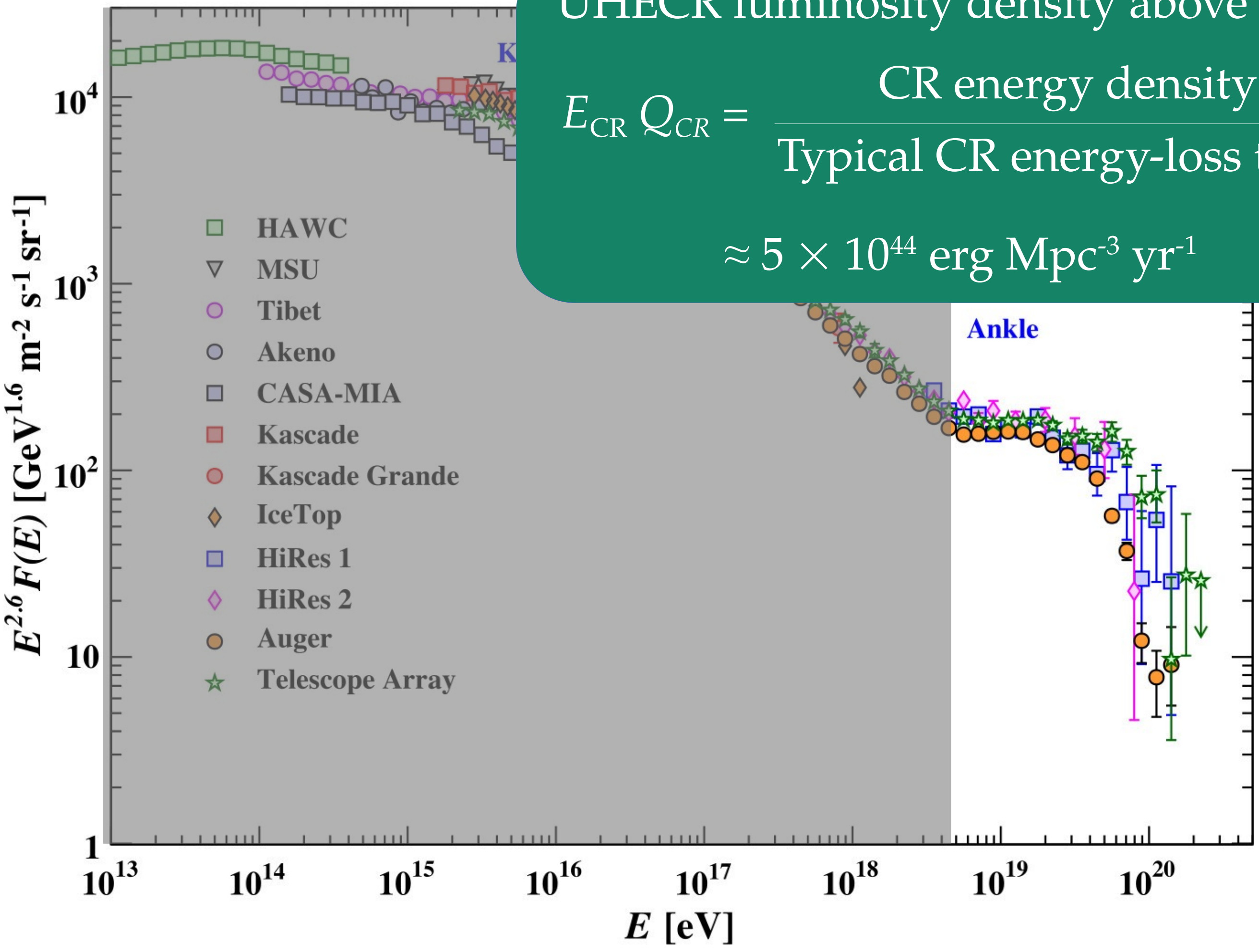


Auger Collab., *PRL* 2020
See also: Auger Collab., PRD 2020

Luminosity density of UHECR sources



Luminosity density of UHECR sources

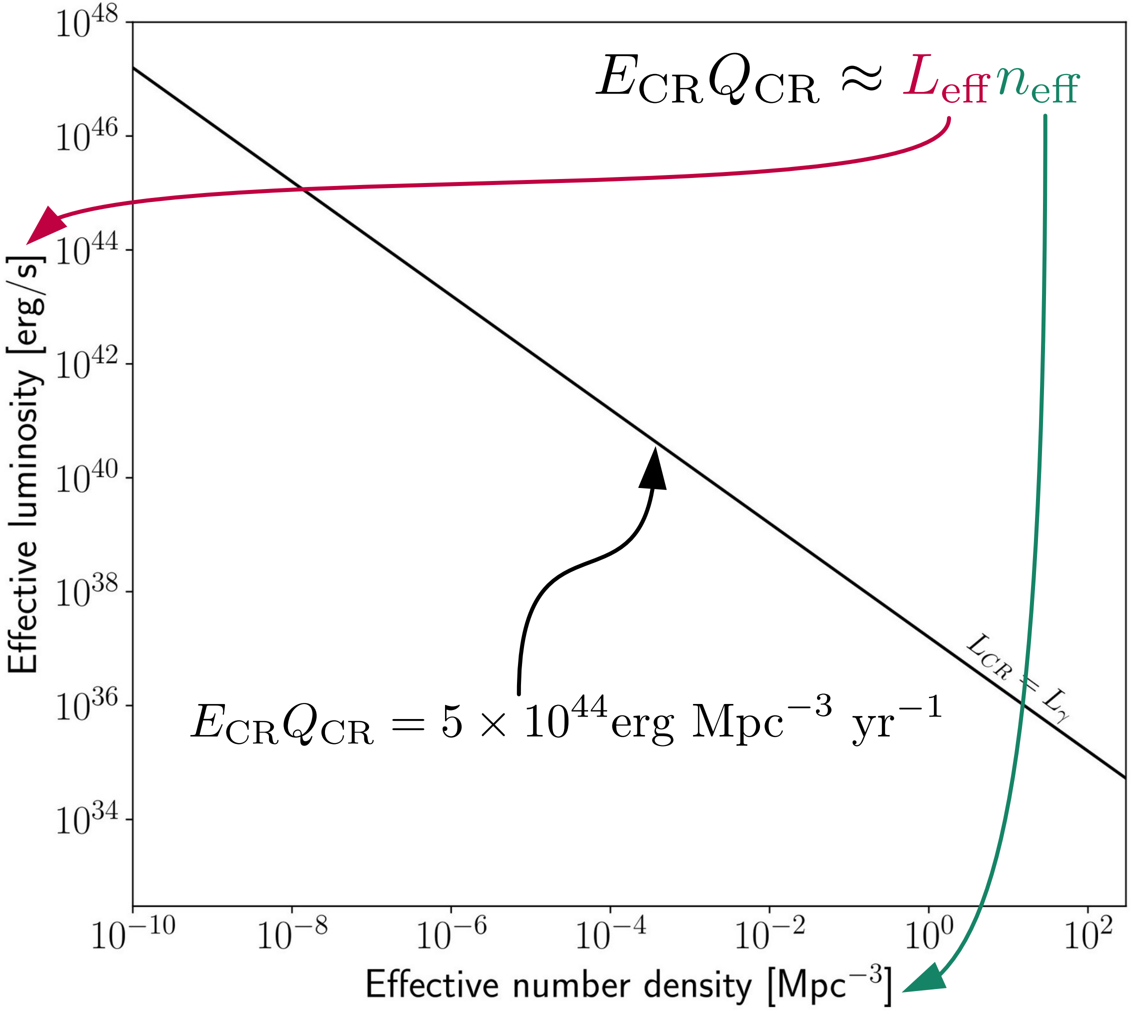


UHECR luminosity density above 5×10^{18} eV:

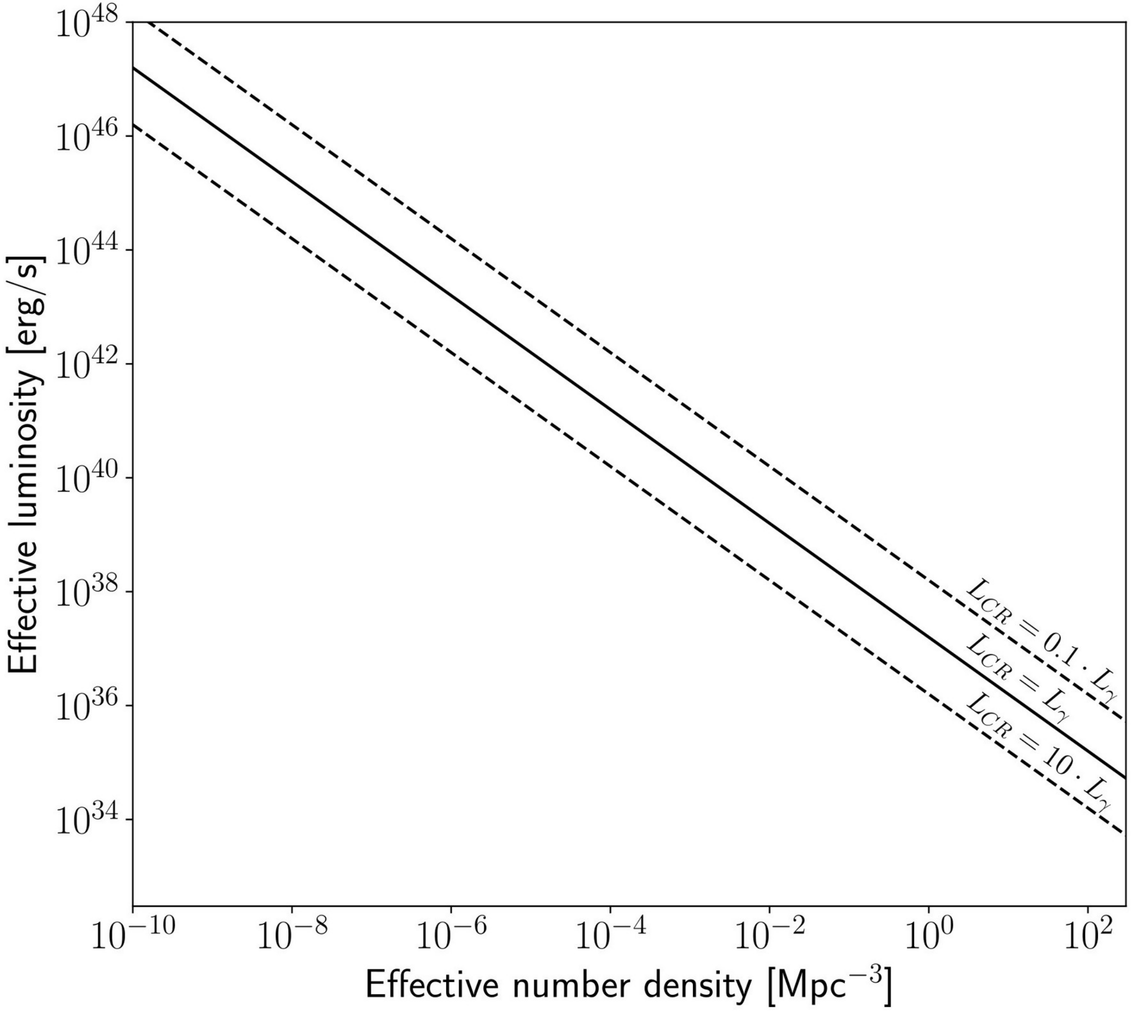
$$E_{CR}\, Q_{CR} = \frac{\text{CR energy density (measured)}}{\text{Typical CR energy-loss time (estimated)}}$$

$\approx 5 \times 10^{44}$ erg Mpc^{-3} yr^{-1}

Luminosity density of UHECR sources



Luminosity density of UHECR sources



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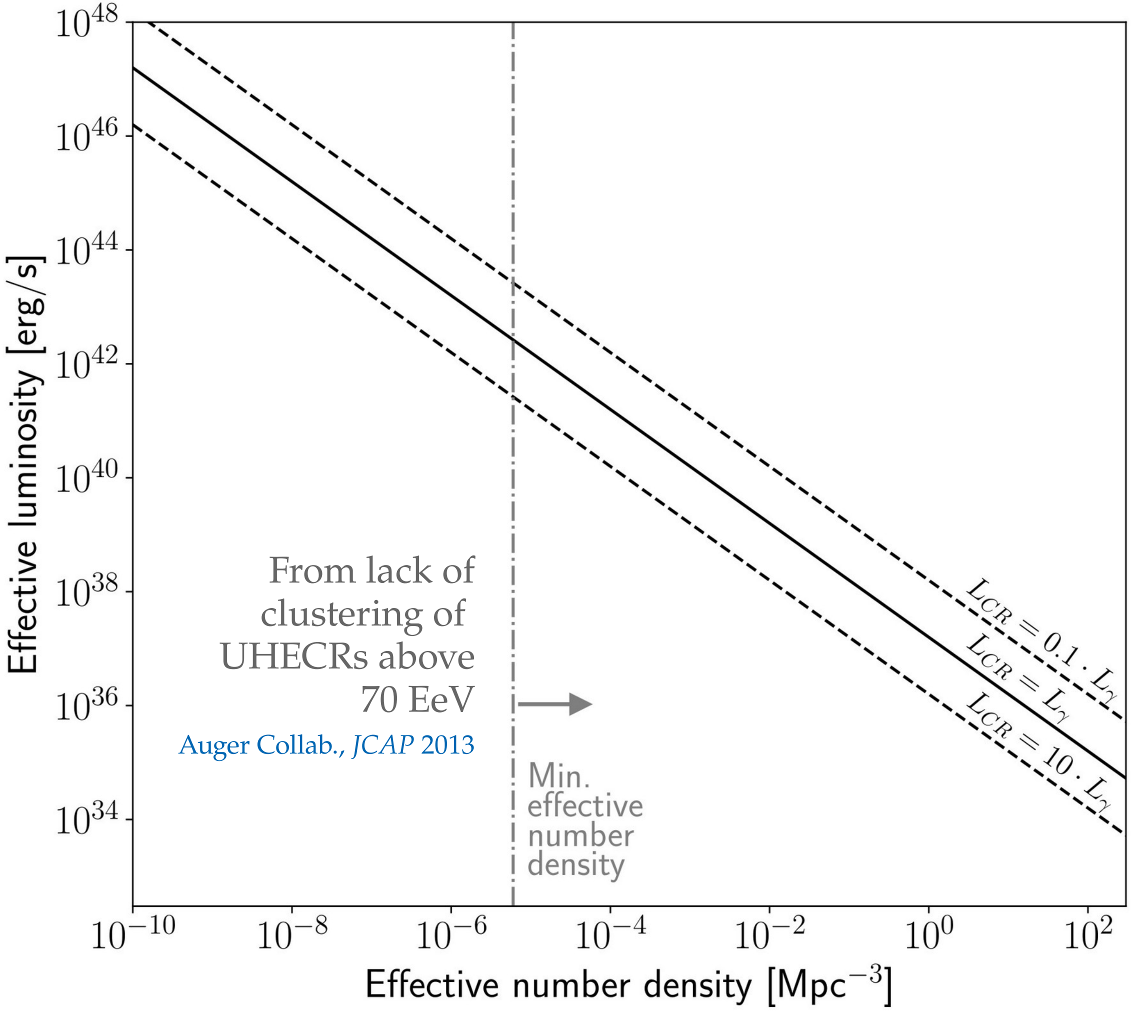

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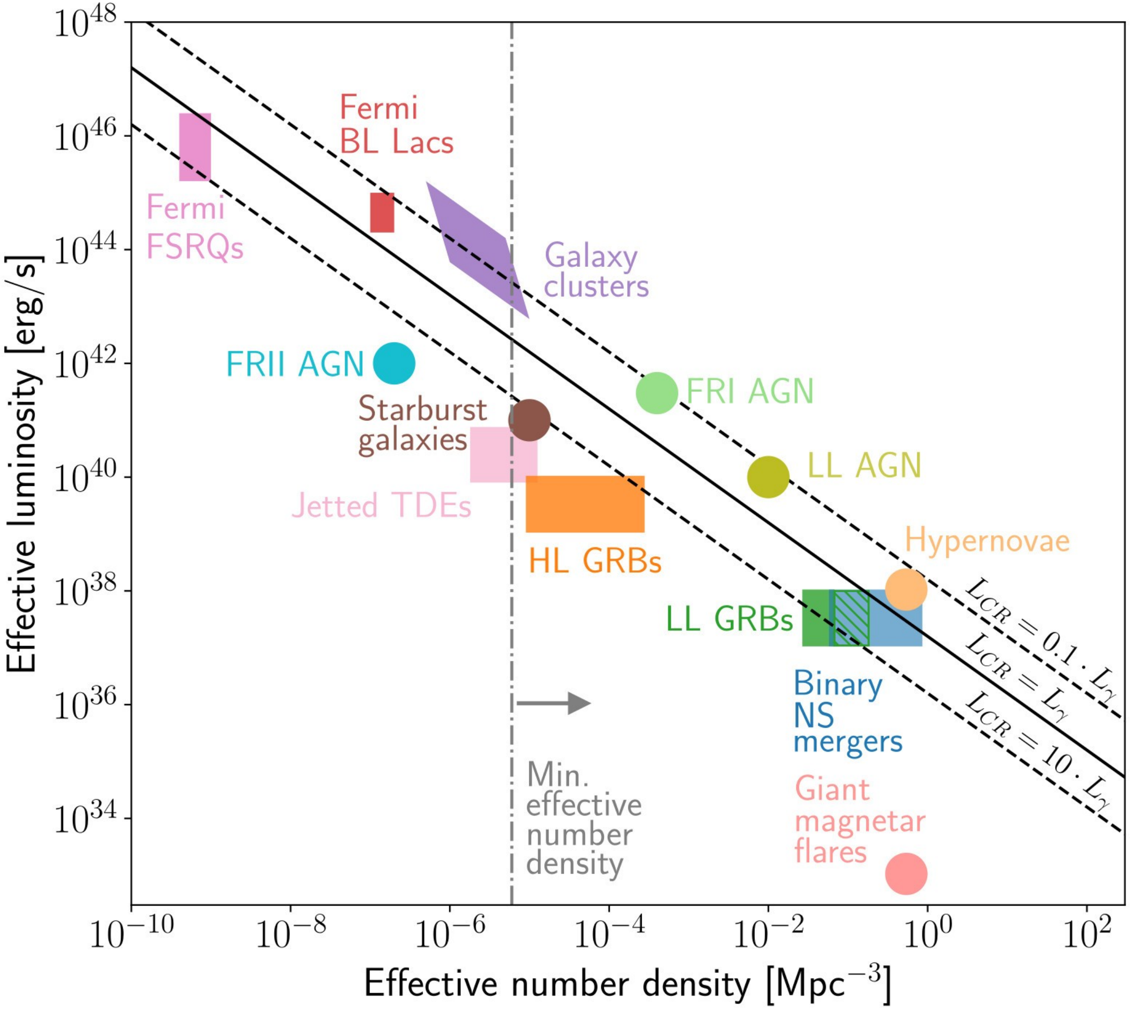
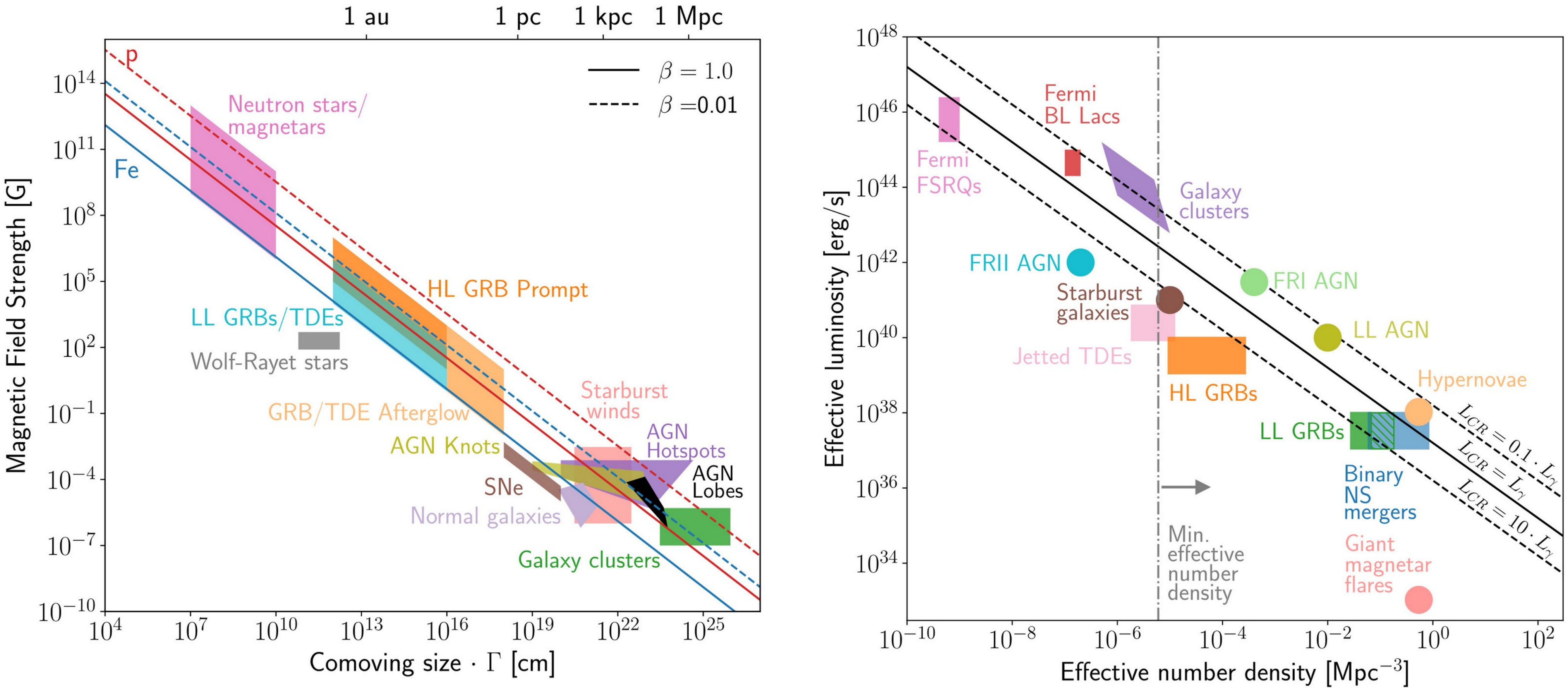


Relation between UHECR and e.m. emission is uncertain and model-dependent

Luminosity density of UHECR sources

Two complementary criteria to constrain potential UHECR source classes—



Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

Luminosity density of UHECR sources

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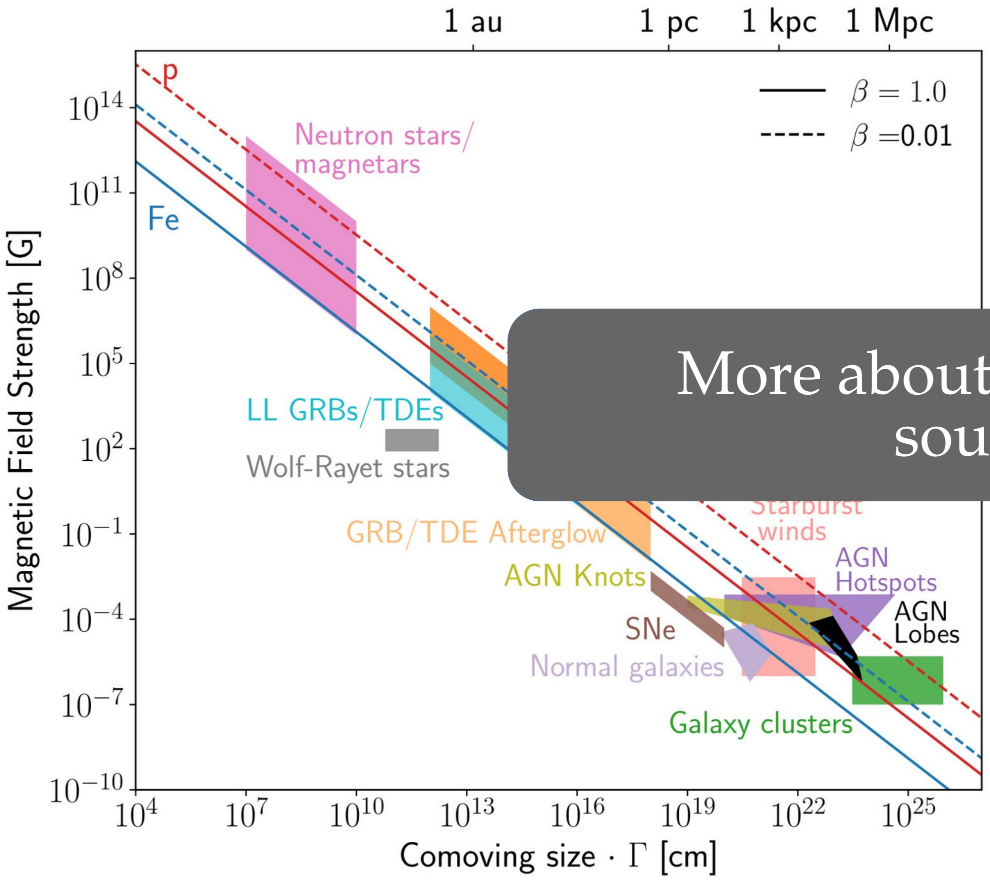
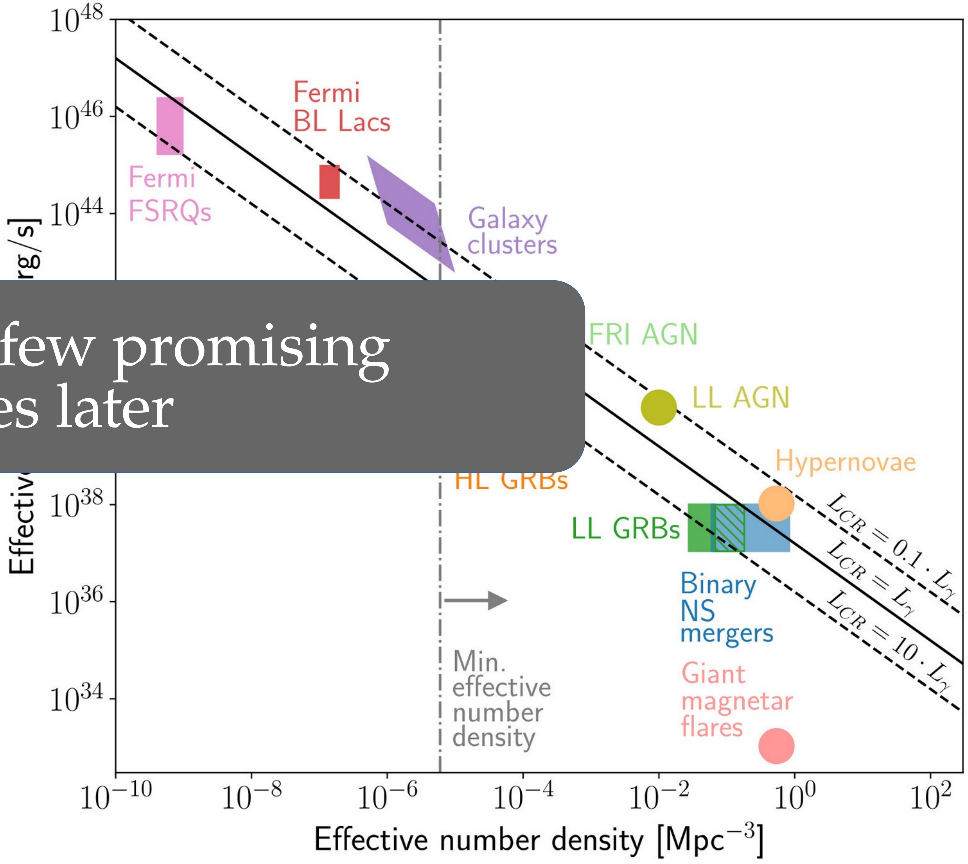
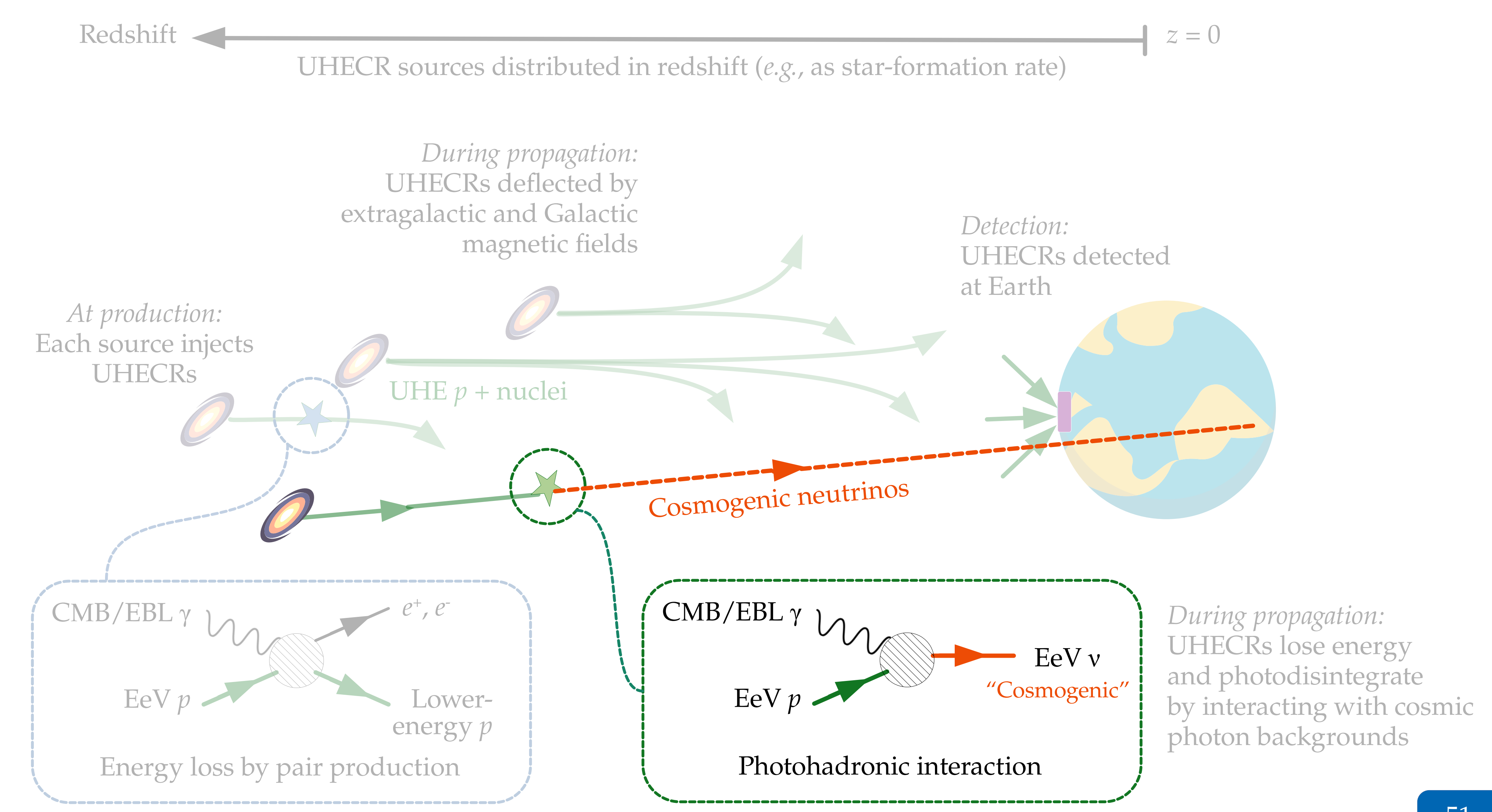




More about a few promising sources later

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019



Redshift
z = 0
UHECR sources distributed in redshift (e.g., as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
Detection:
UHECRs detected
at Earth
At production:
Each source injects
UHECRs
UHE p + nuclei
Cosmogenic neutrinos
CMB/EBL γ
e+, e-
EeV p
Lower-
energy p
Energy loss by pair production
CMB/EBL γ
EeV ν
"Cosmogenic"
EeV p
Photohadronic interaction
During propagation:
UHECRs lose energy
and photodisintegrate
by interacting with cosmic
photon backgrounds

What about the cosmogenic neutrinos?

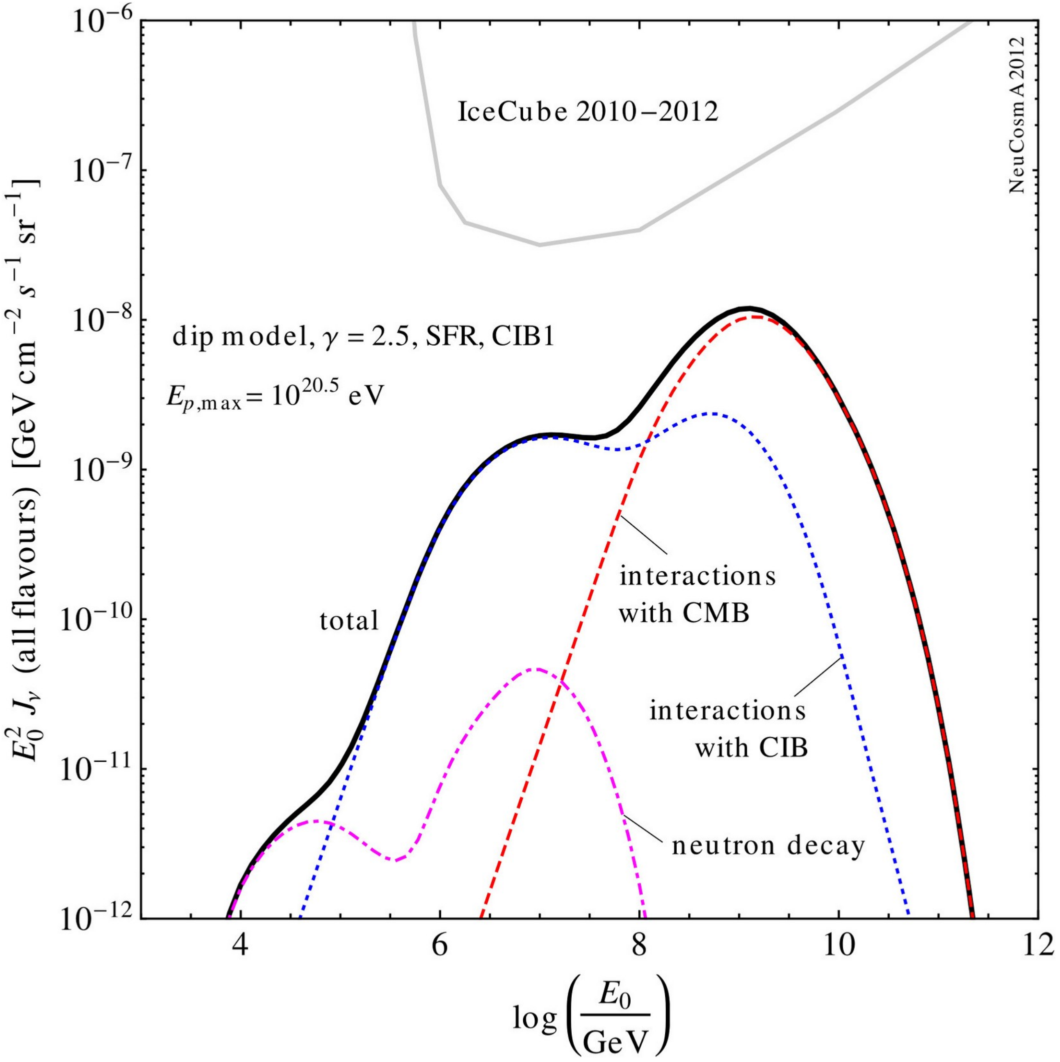
Co-evolve UHECRs and cosmogenic neutrinos:

UHECRs: $$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\rm CR}(E,z)\}$$

Neutrinos: $$\partial_z Y_\nu(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_\nu(E,z)) + \mathcal{L}_\nu(E,z)\}$$

Note: We can propagate gamma rays by adding an additional equation for them

Cosmogenic neutrinos



The position of the ν bump is determined by the Δ-resonance production threshold,

$$E_p E_\gamma \approx 0.2 \text{ GeV}^2 \ ,$$

and the relation between neutrino energy and proton energy,

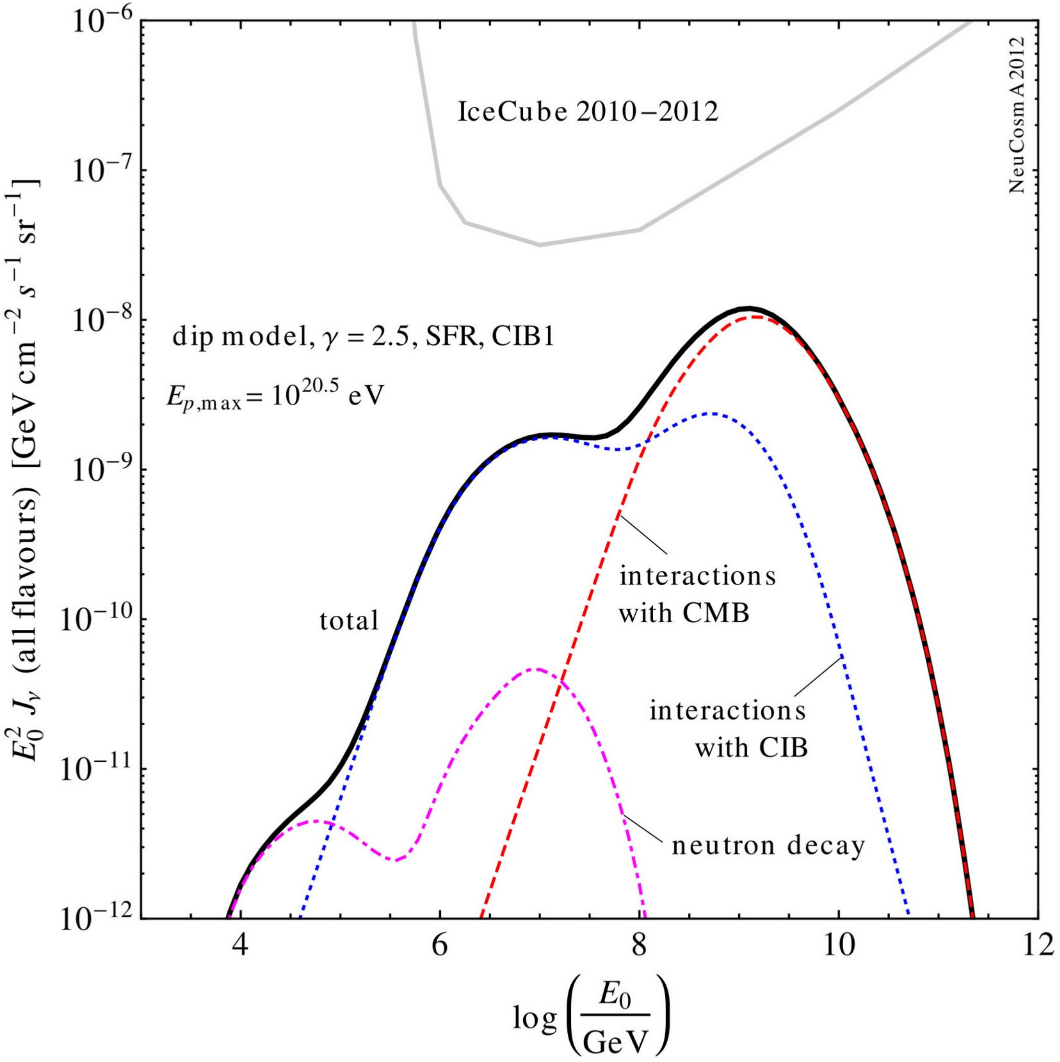
$$E_\nu \approx E_p/20 \, .$$

So the neutrino spectrum peaks at

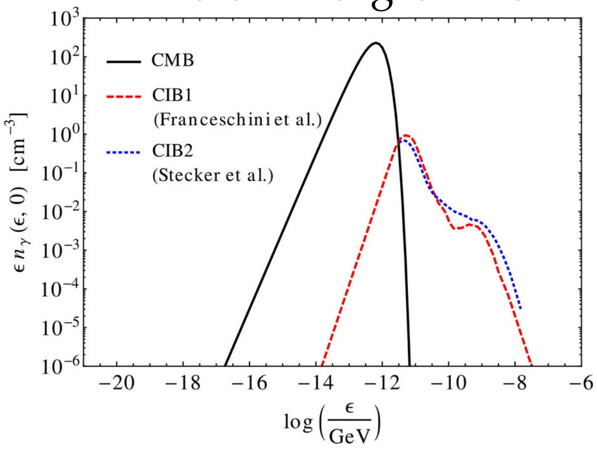
$$E_\nu \approx \frac{0.01 \text{ GeV}}{E_\gamma/\text{GeV}}$$

Let's put this to test ▸

Cosmogenic neutrinos



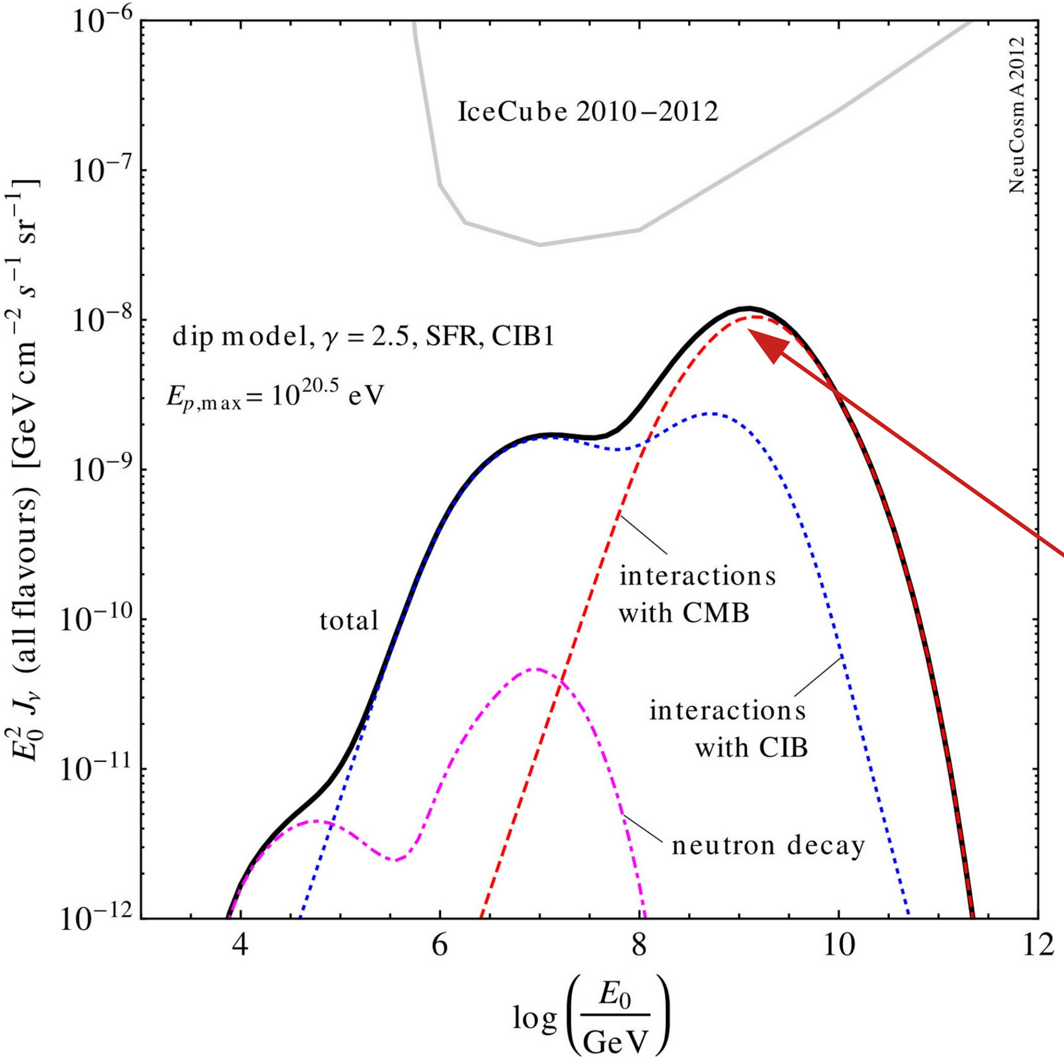
Photon backgrounds



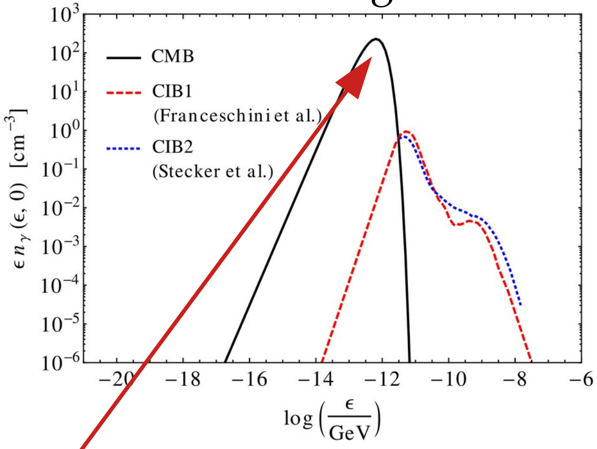
Position of the ν bump from $p\gamma$:

$$E_\nu \approx \frac{0.01\ \text{GeV}}{E_\gamma/\text{GeV}}$$

Cosmogenic neutrinos



Photon backgrounds

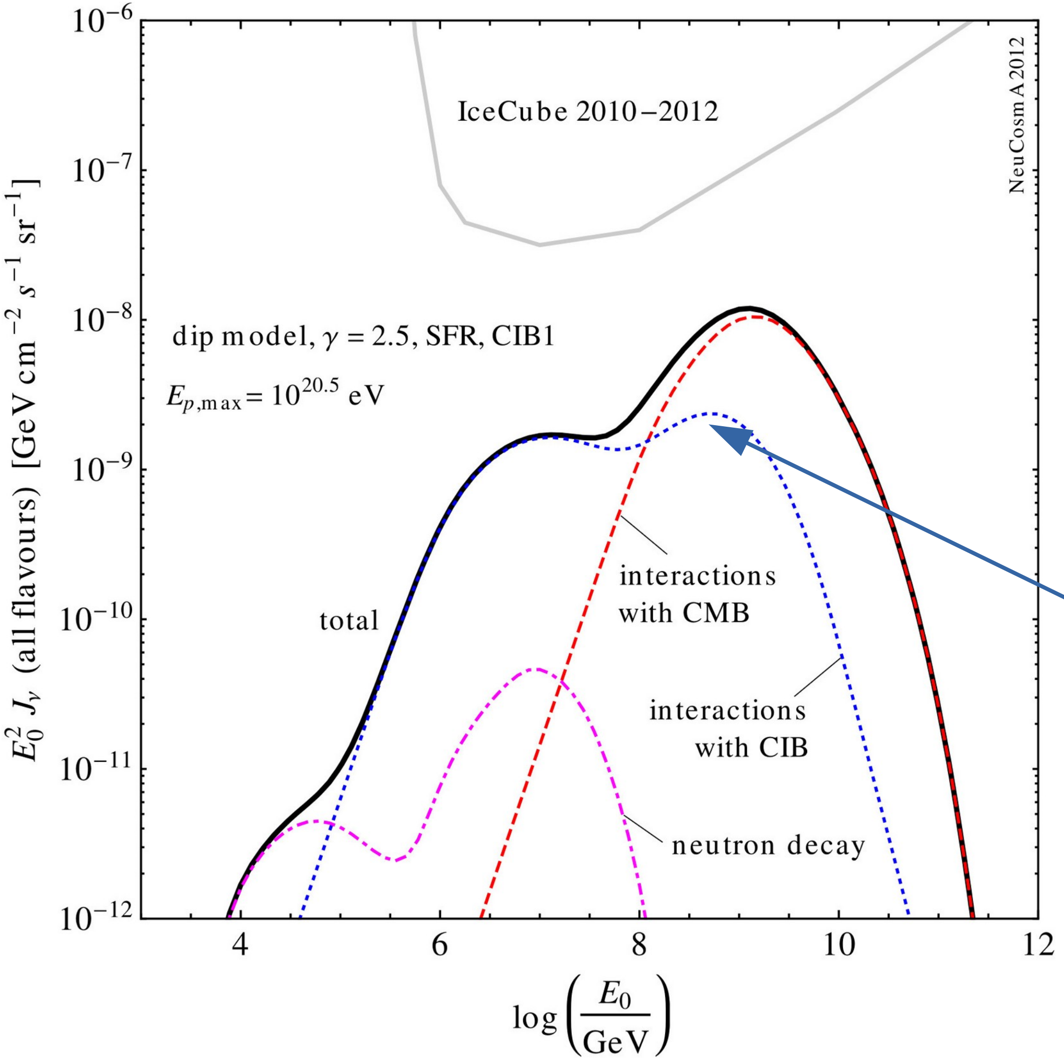


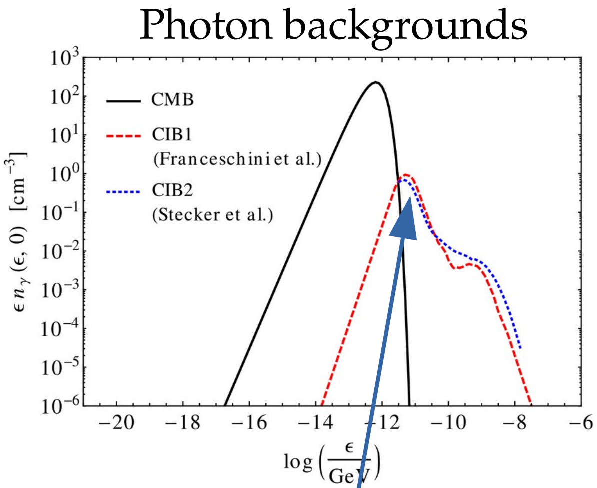
Position of the ν bump from $p\gamma$:

$$E_\nu \approx \frac{0.01 \text{ GeV}}{E_\gamma/\text{GeV}}$$

ν from CMB: $E_\nu \approx \frac{0.01 \text{ GeV}}{10^{-12}} = 10^{10}$ GeV

Cosmogenic neutrinos





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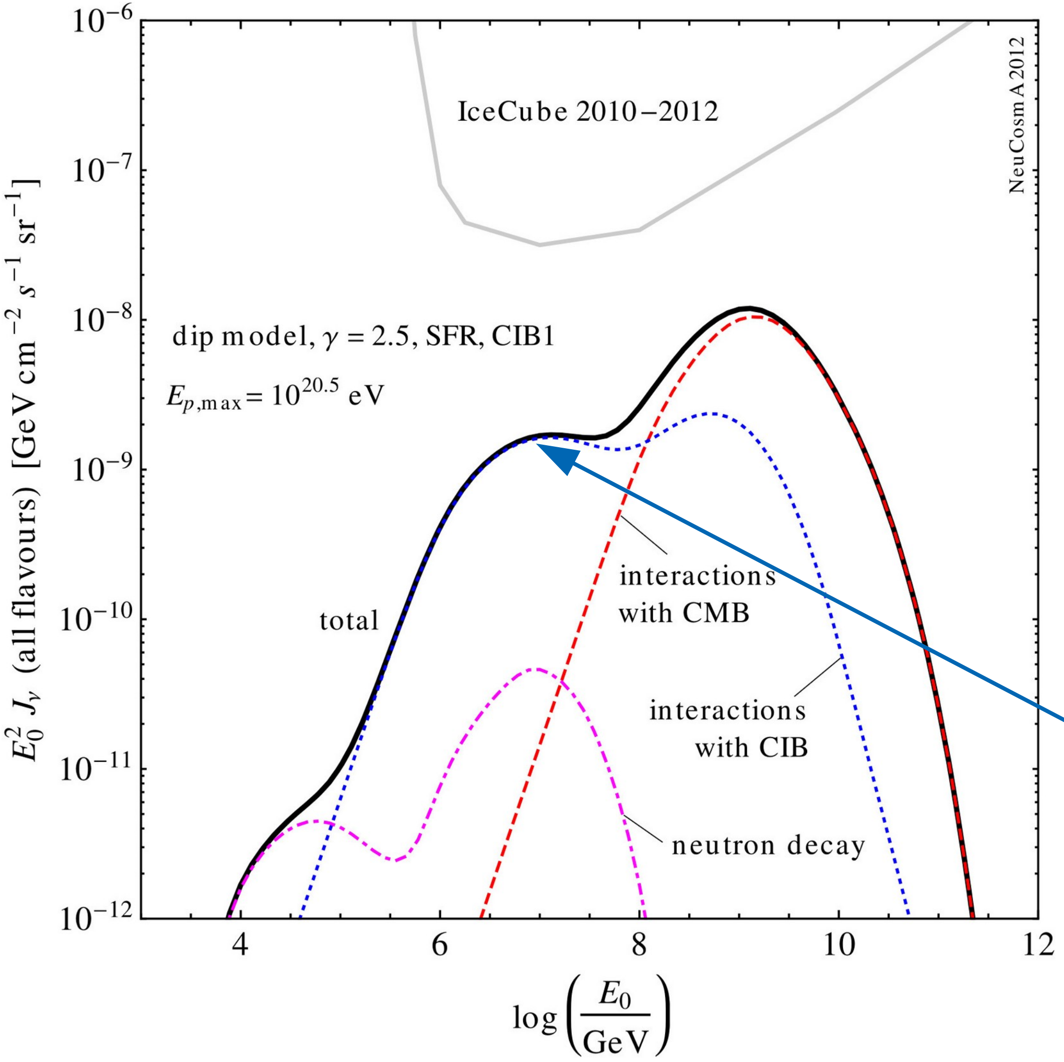
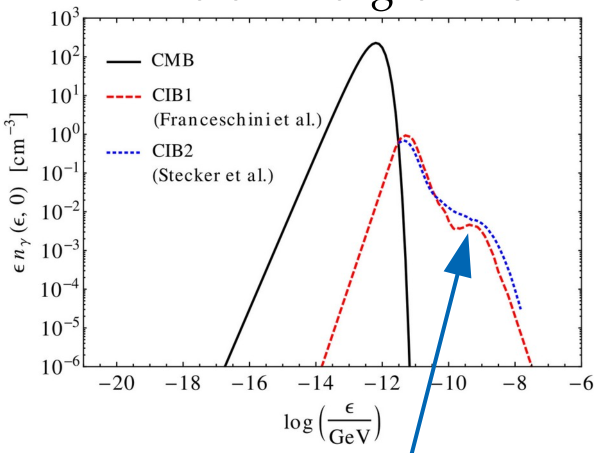
Cosmogenic neutrinos



Photon backgrounds



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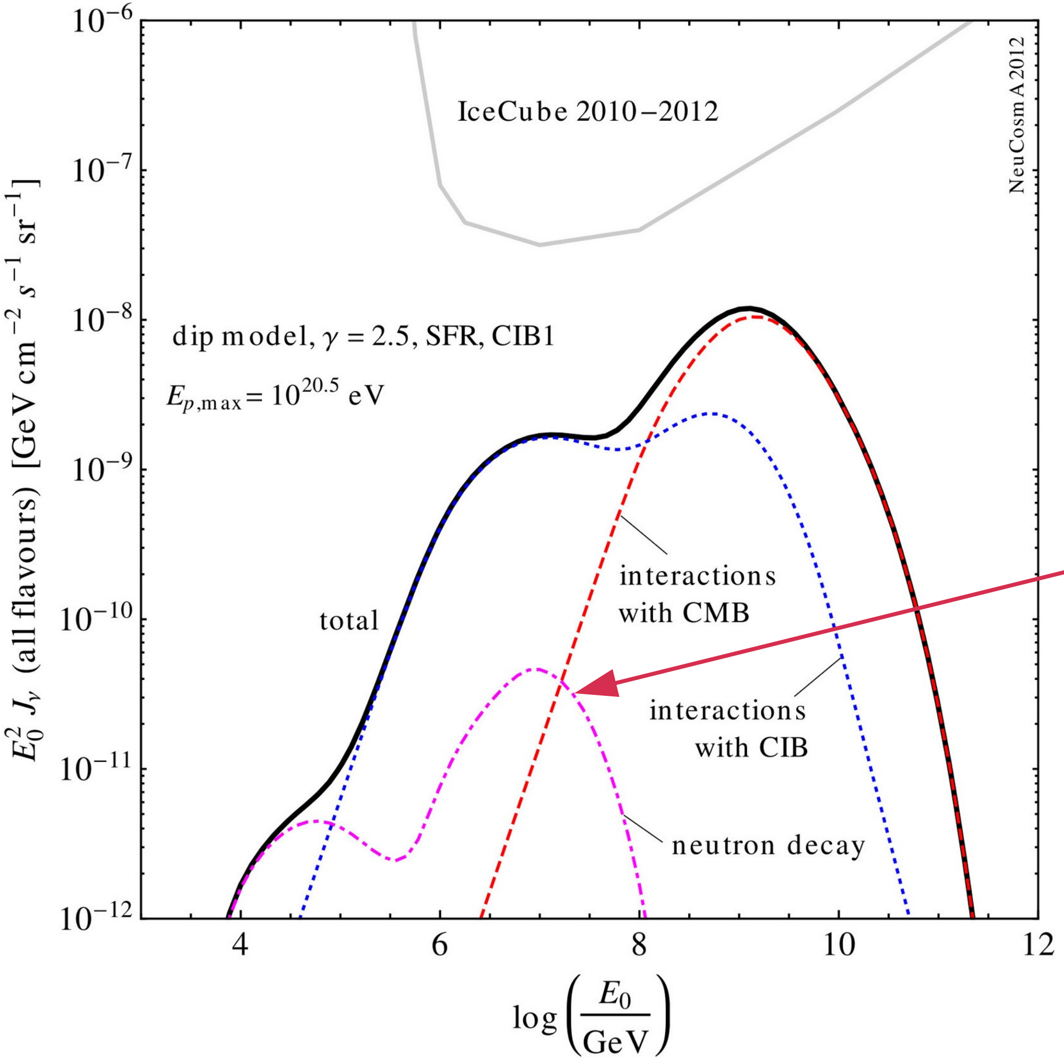
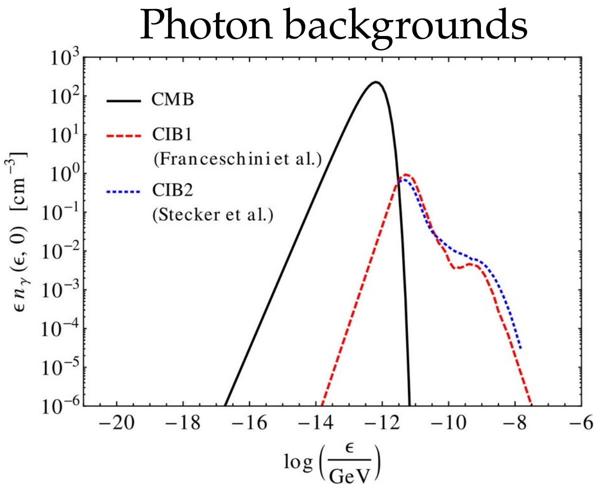
$$E_\nu \approx \frac{0.01 \text{ GeV}}{10^{-11}} = 10^{9} \text{ GeV}$$

$$E_\nu \approx \frac{0.01 \text{ GeV}}{10^{-9}} = 10^{7} \text{ GeV}$$

Cosmogenic neutrinos





Position of the ν bump from $p\gamma$:

$$E_\nu \approx \frac{0.01 \text{ GeV}}{E_\gamma/\text{GeV}}$$

Why are ν from n decay lower-energy?

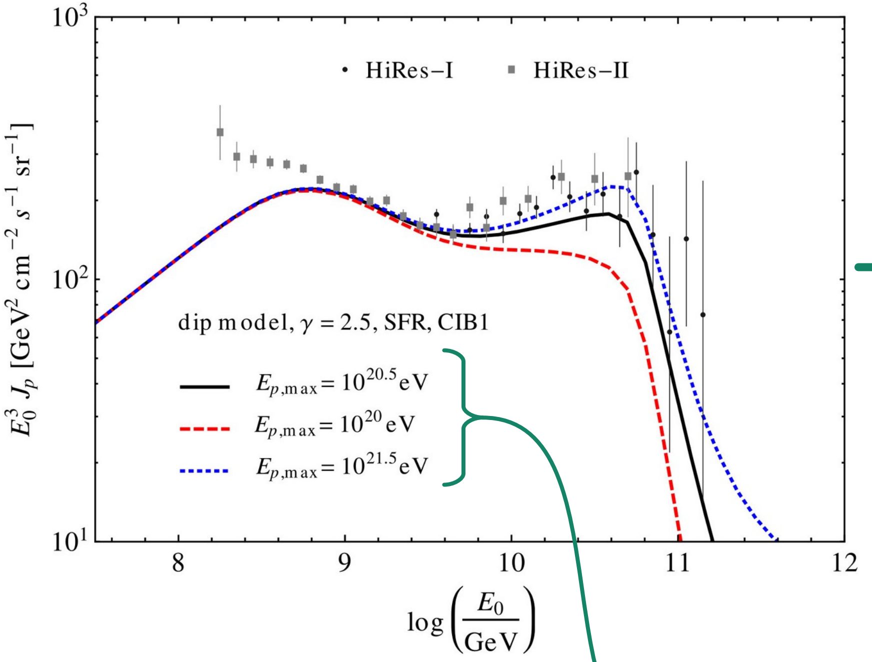
$$n \to p + e^- + \bar{\nu}_e$$

The n and p mass are very similar …

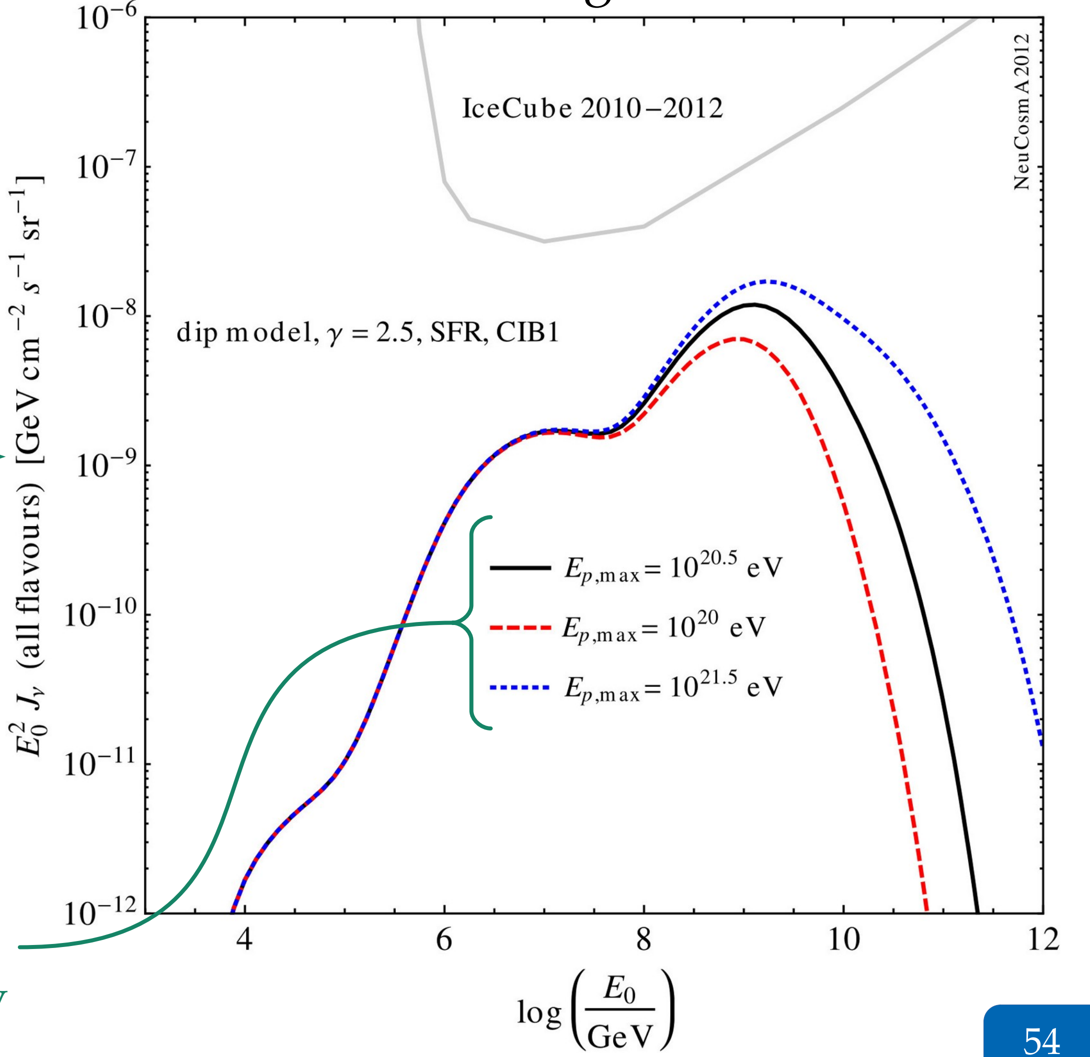
… so there is little energy left for e, ν

Cosmogenic neutrinos

UHECRs



Cosmogenic ν

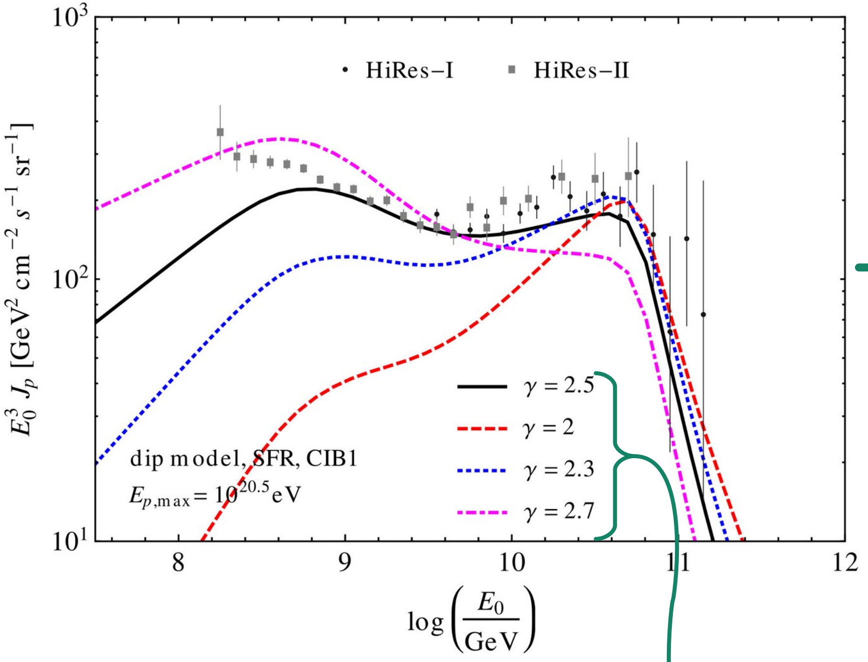


Varying the maximum proton energy

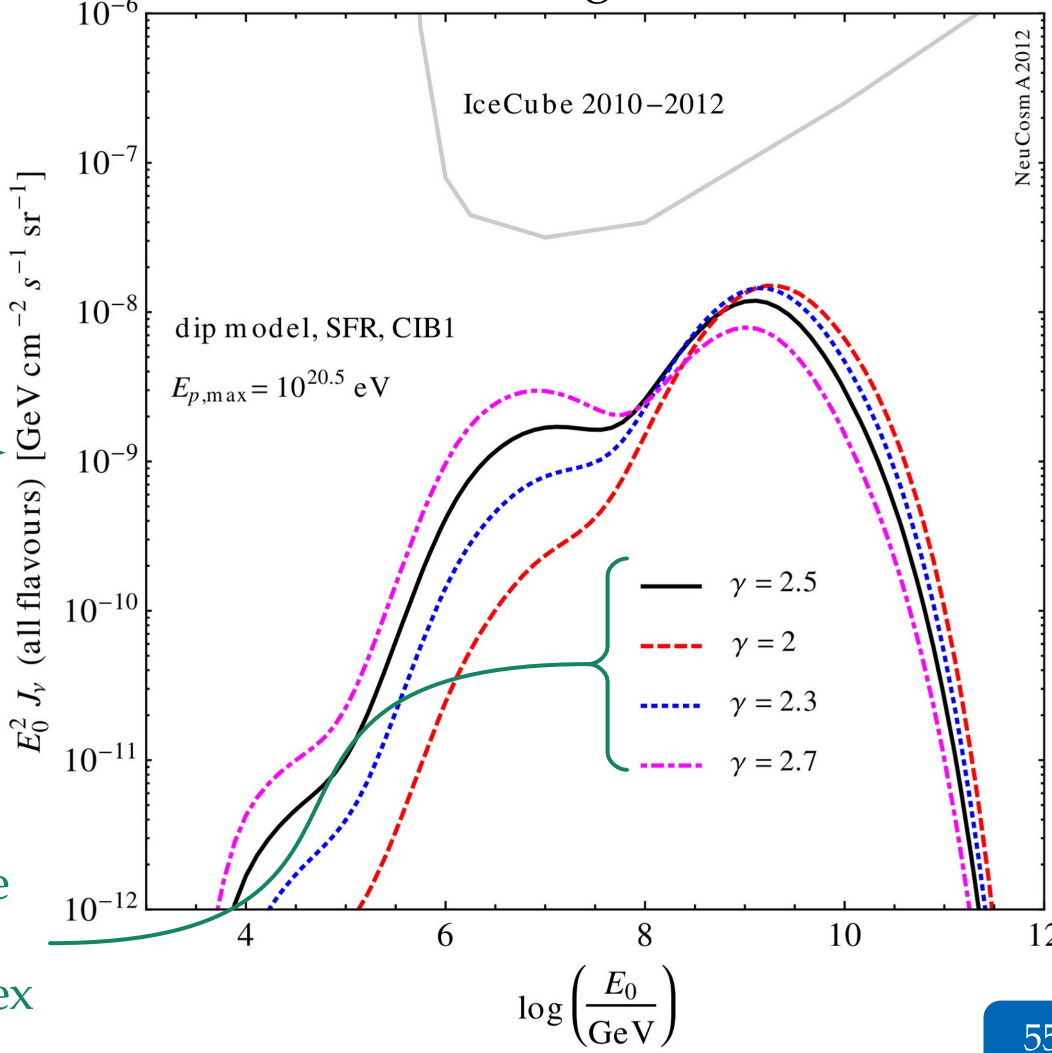
$$Q_{\rm CR}(E) \propto E^{-\gamma} e^{-E/E_{\max}}$$

Cosmogenic neutrinos

UHECRs



Cosmogenic ν

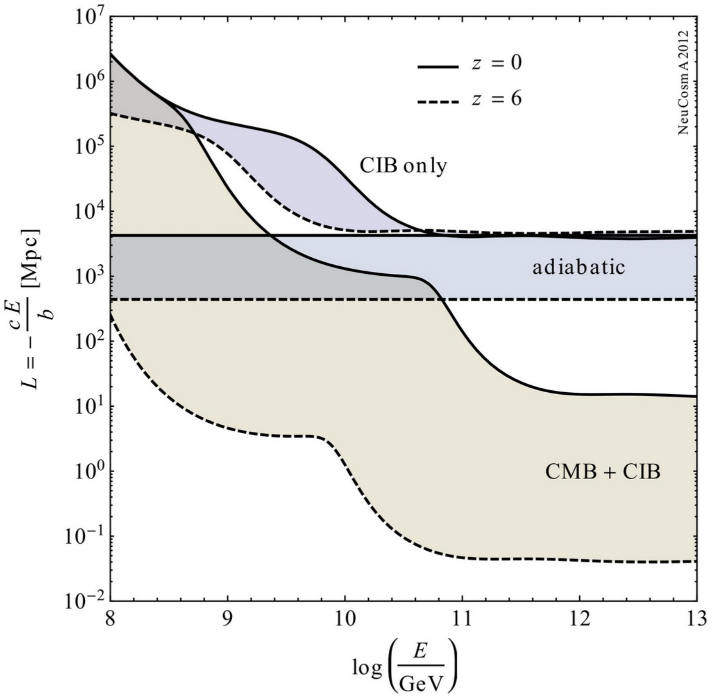


Varying the cosmic-ray spectral index

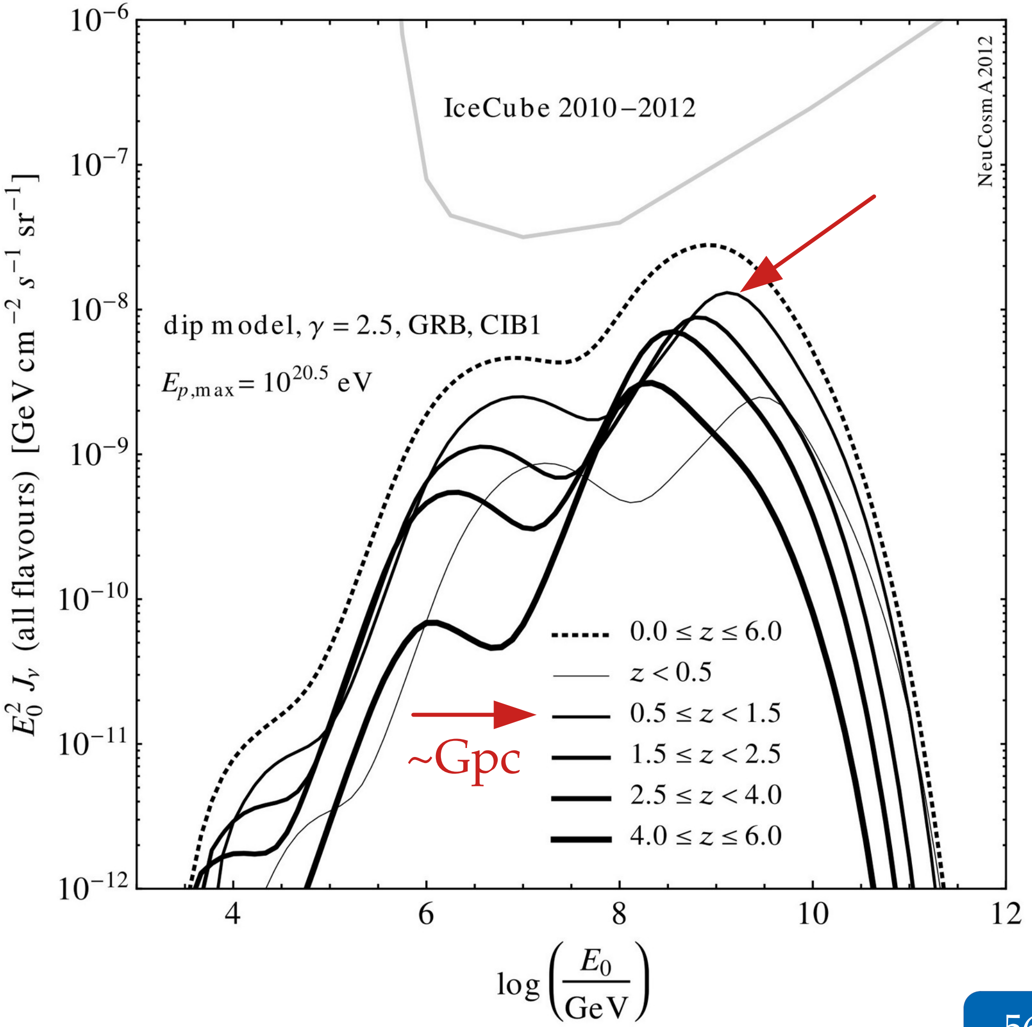
$$Q_{\rm CR}(E) \propto E^{-\gamma} e^{-E/E_{\max}}$$

Cosmogenic neutrinos—they come from afar

UHECRs cannot travel farther than the GZK horizon (~100 Mpc)



But neutrinos can!



UHECRs: no cosmogenic neutrinos means no pure protons

Use more recent data:
UHECR flux measured by Telescope Array

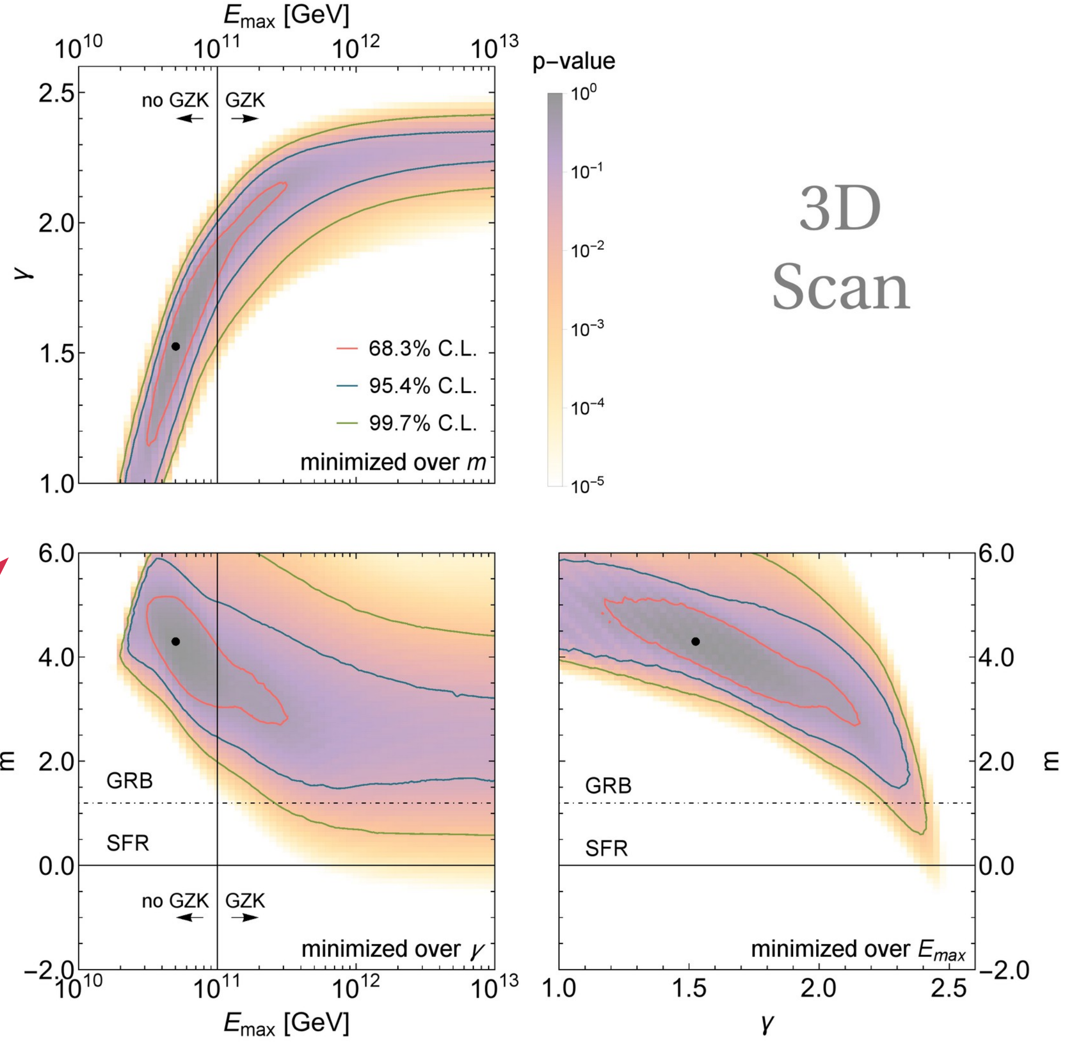
Assume pure-proton flux:
UHECR injected spectrum is

$$Q_{\rm CR}(E) \propto E^{-\gamma} e^{-E/E_{\rm max}}$$

Source number density:
Evolves with redshift as

$$\mathcal{H}_{\rm CR}(z) \propto (1+z)^m$$

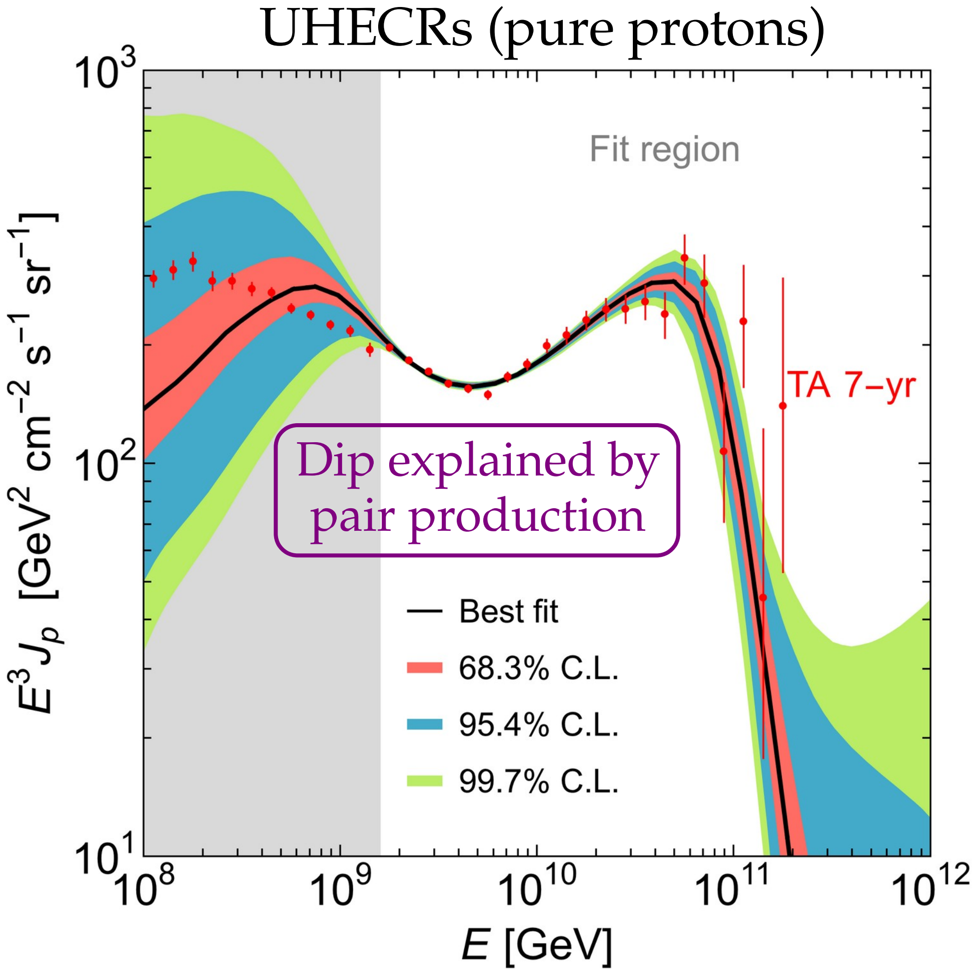
Minimize χ^2 function over γ, E_{max}, and m



3D Scan

Heinze, Boncioli, **MB**, Winter, *ApJ* 2015

UHECRs: no cosmogenic neutrinos means no pure protons



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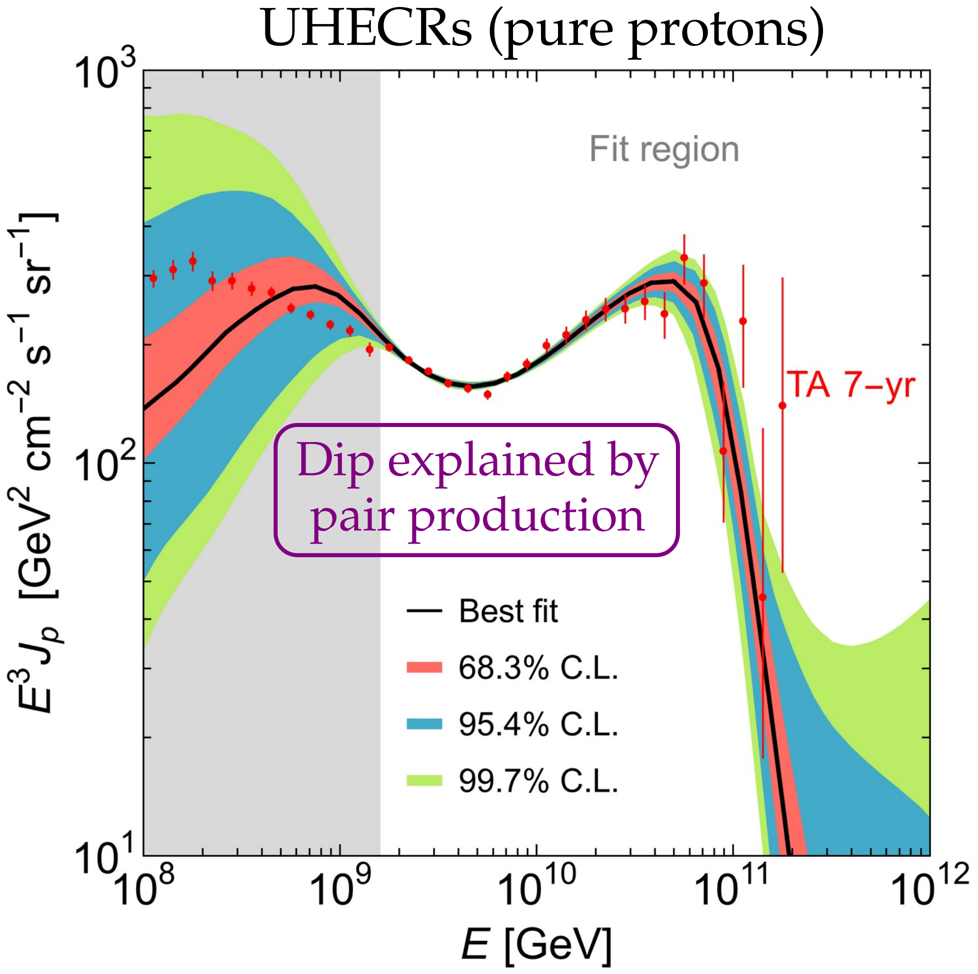

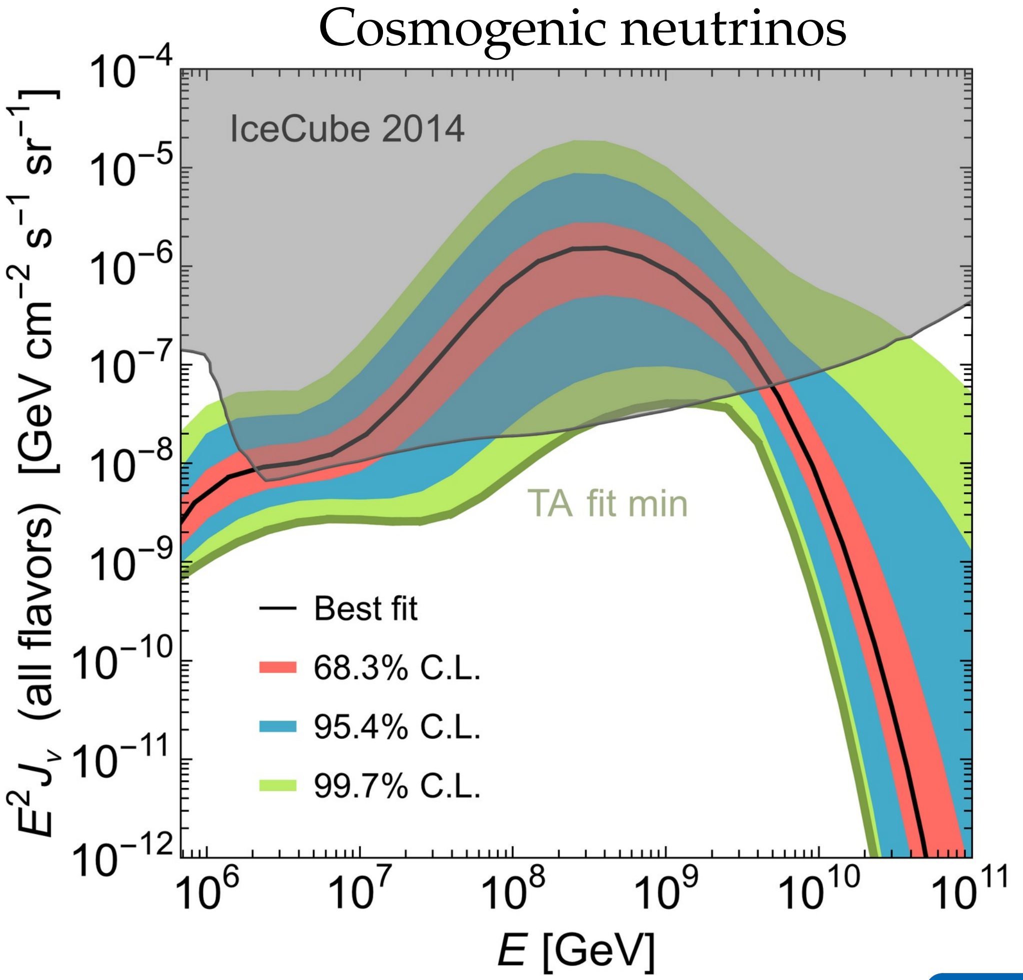

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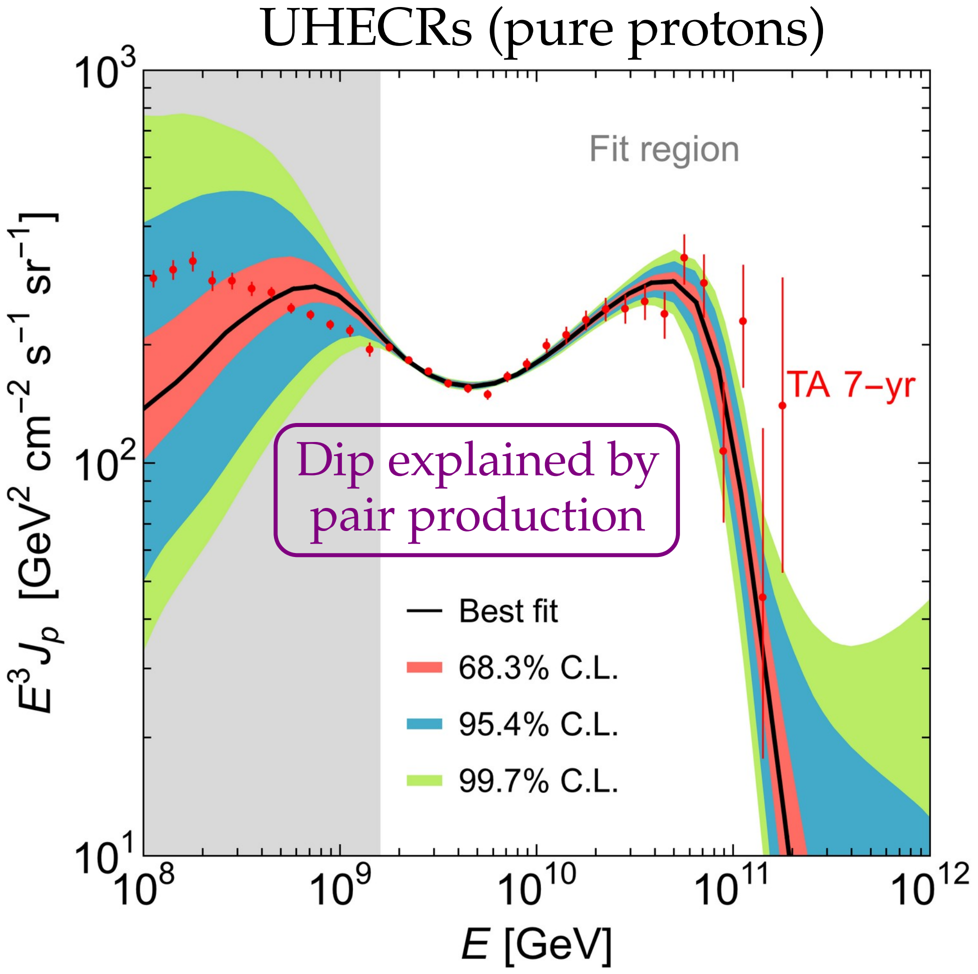
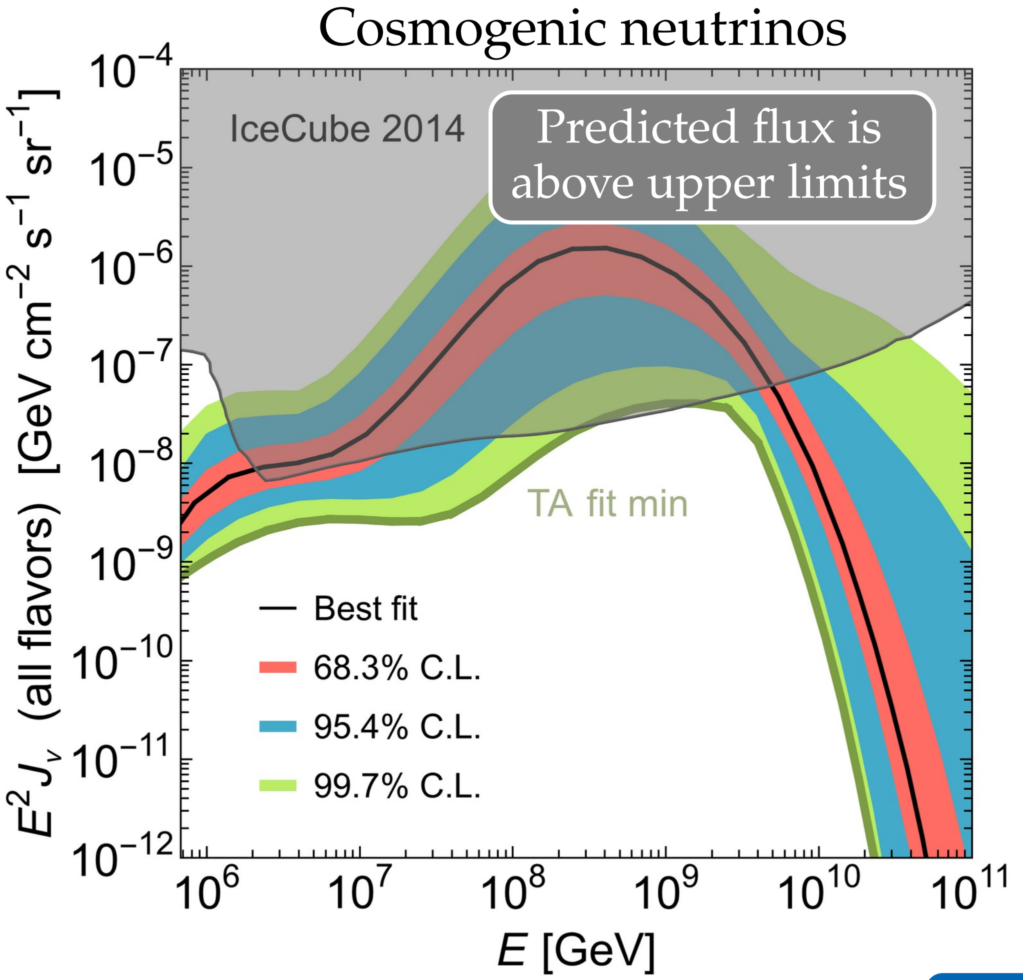
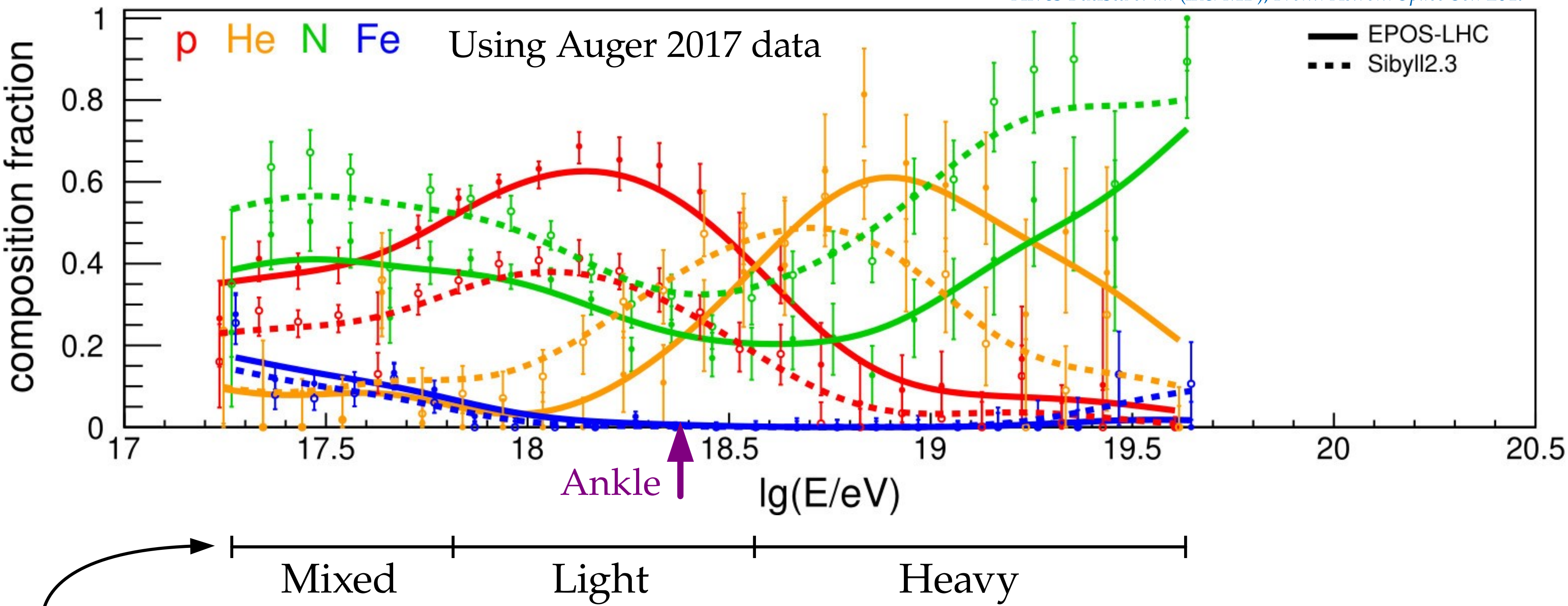




Heinze, Boncioli, **MB**, Winter, *ApJ* 2015

X_{max} and UHECR mass composition

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019



These are general trends, but there are large variations due to systematic and statistical errors (also other experiments differ, *e.g.*, Telescope Array)

UHECRs: more sophisticated models

Use more data:
Spectrum + mass composition ($X_{\rm max}$)

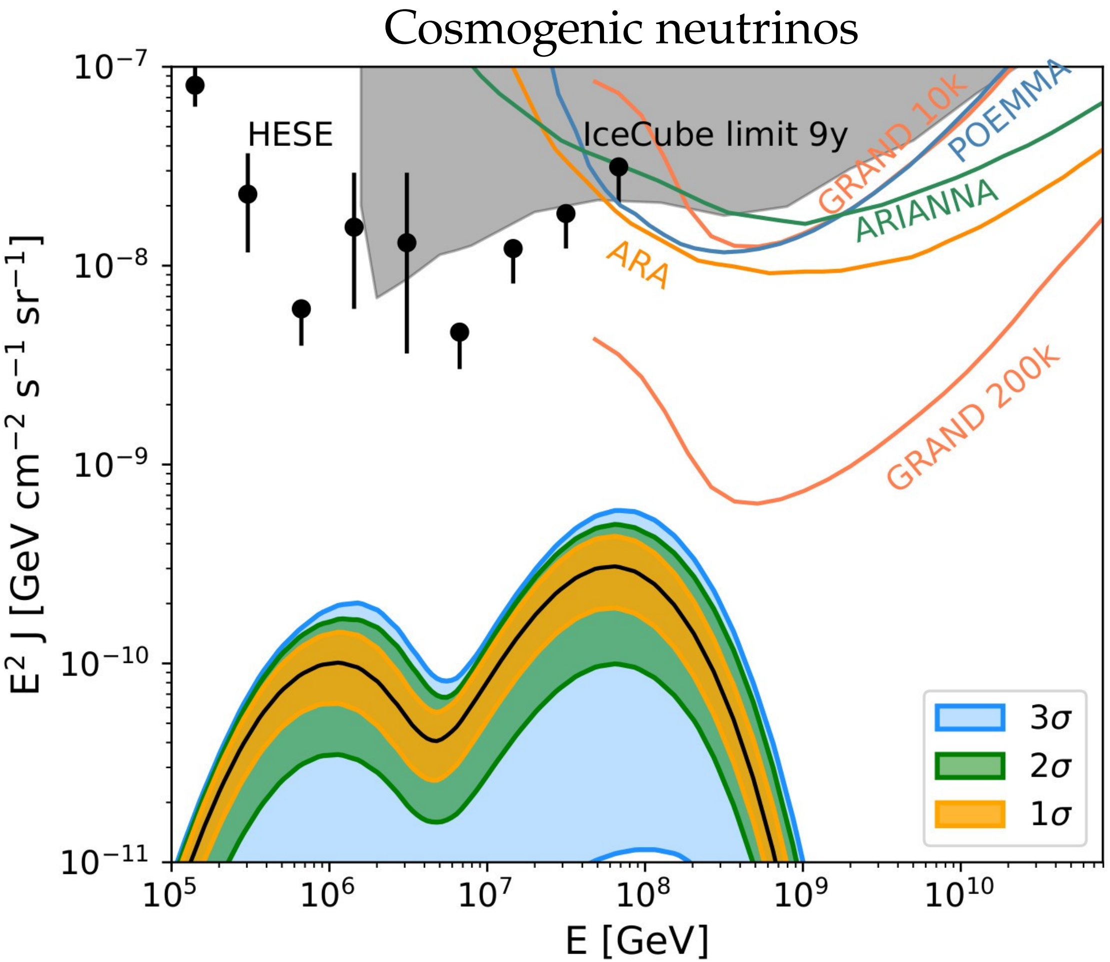
Five mass groups:
H, He, N, Si, Fe

Common maximum rigidity:
Max. rigidity is $R_{\rm max} = E_{\rm max}/Z$

$$Q_Z(E) \propto E^{-\gamma} e^{-E/(ZR_{\rm max})}$$ ← "Peters c

Add nuclei photodisintegration:
During propagation, interaction of nuclei on CMB or EBL breaks them up,

$$A + \gamma \to (A-1) + \gamma$$



See also: Romero-Wolf & Ave, *JCAP* 2018
Alves Batista, Almeida, Lago, Kotera, *JCAP* 2019

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Peters (

Add nuclei photodisintegration:
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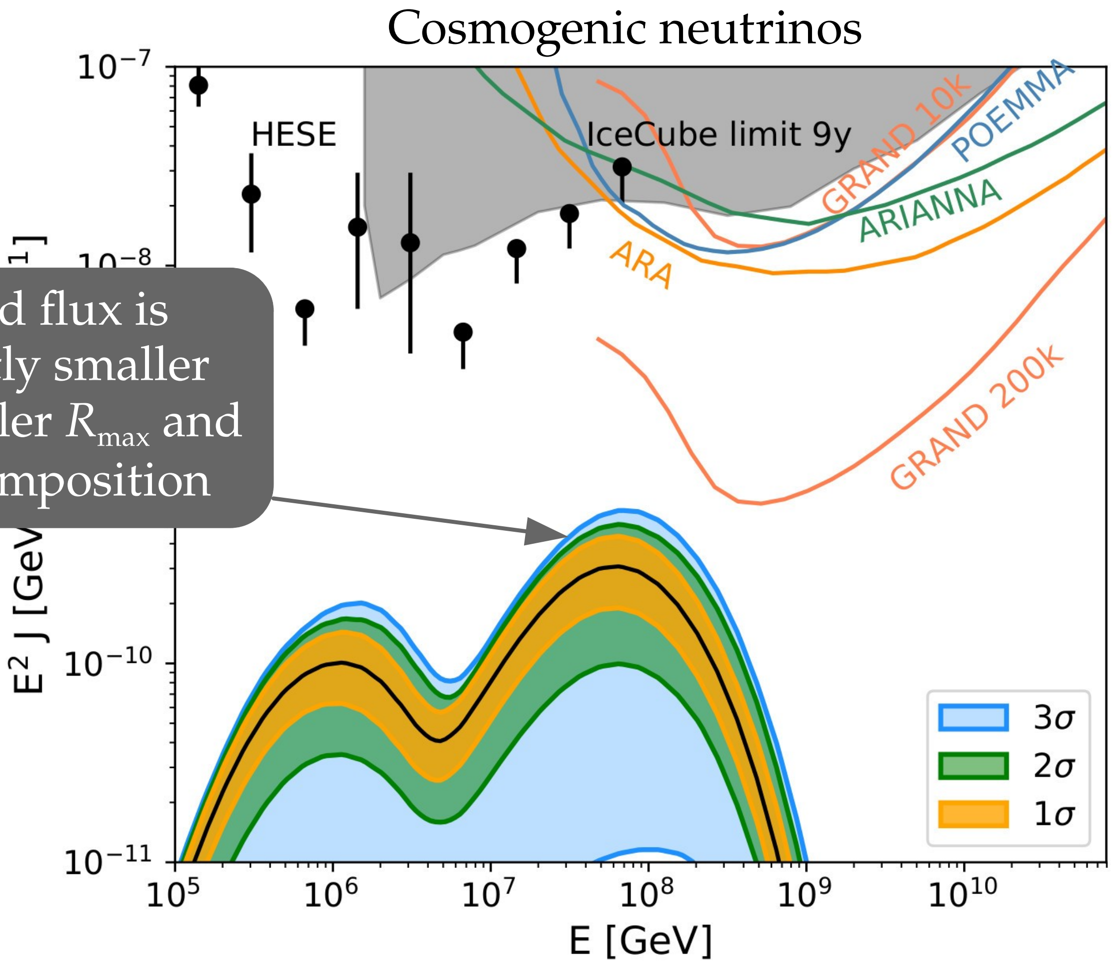
Predicted flux is significantly smaller due to smaller R_{max} and heavier composition



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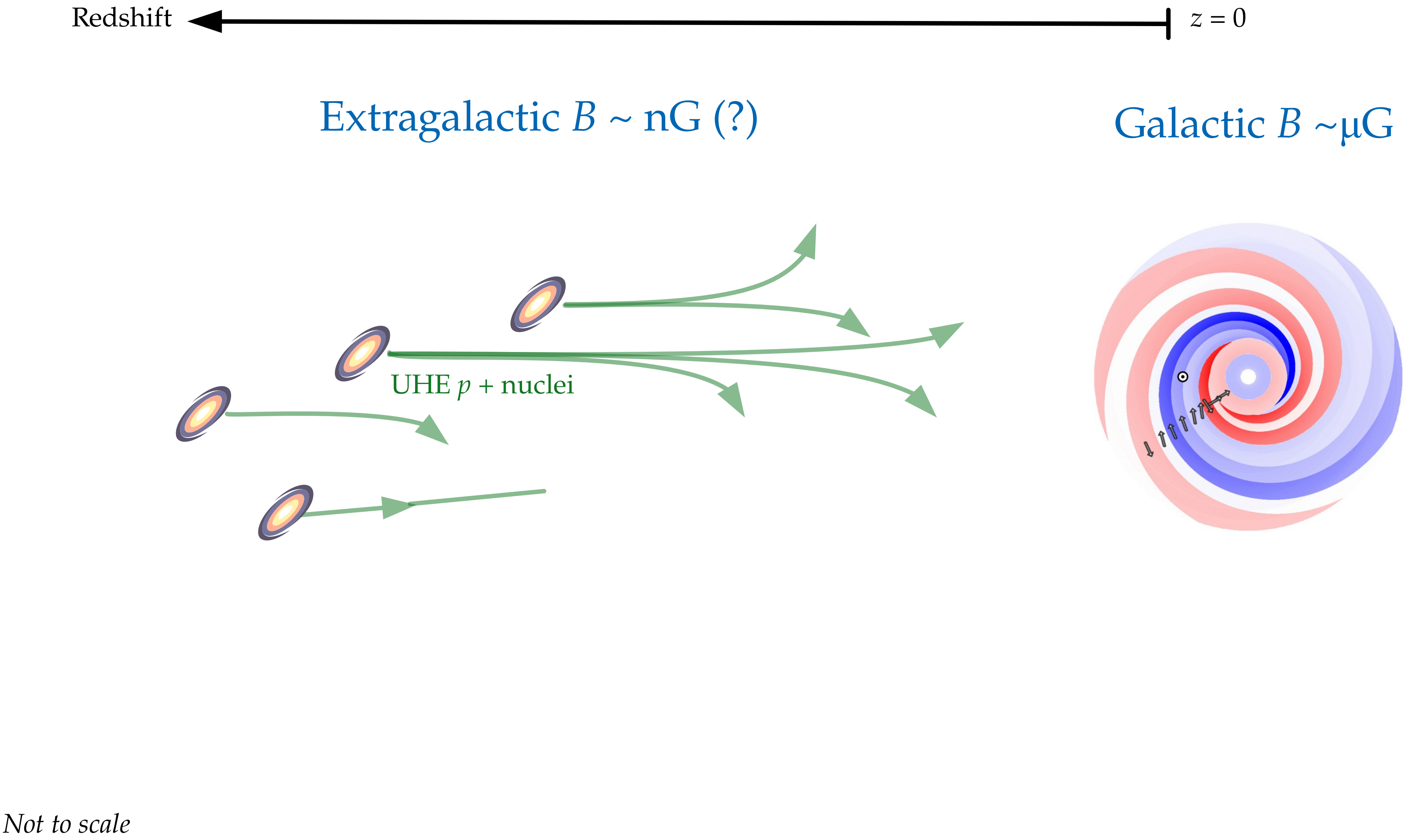
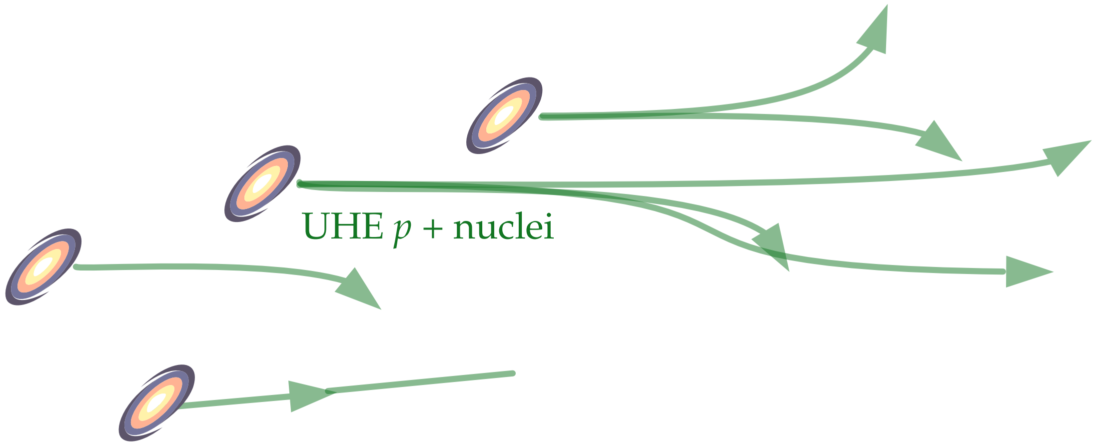
Backup slides



Redshift
$z = 0$
Extragalactic B ~ nG (?)
Galactic B ~μG
UHE p + nuclei
Not to scale

Redshift ← $z = 0$

Extragalactic $B \sim$ nG (?)



Larger charge bends more

Longer trajectories bend more

Magnetic field intensity

$$\delta_{\rm rms} \approx 0.8^\circ \, Z \left(\frac{10 \text{ EeV}}{E} \right) \left(\frac{L}{10 \text{ Mpc}} \right)^{1/2} \left(\frac{L_c}{\text{Mpc}} \right)^{1/2} \left(\frac{B_{\rm rms}}{n\text{G}} \right)$$

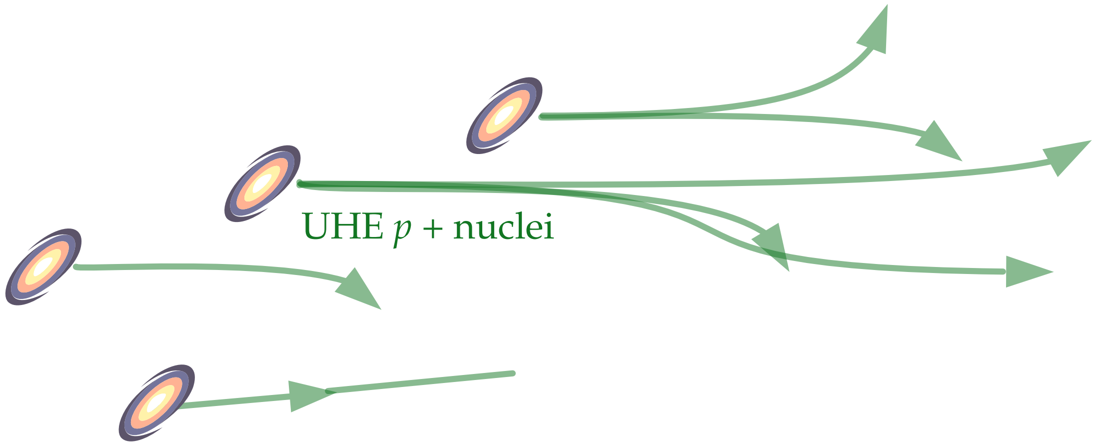
Larger charge bends more

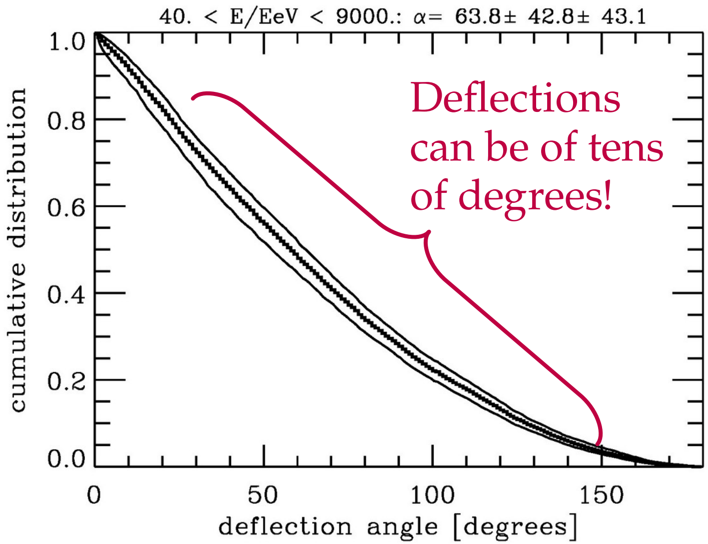
L_c: field coherence length

Sigl, Miniati, Ensslin, *PRD* 2004

Redshift ← $z = 0$

Extragalactic $B \sim$ nG (?)





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Larger charge bends more

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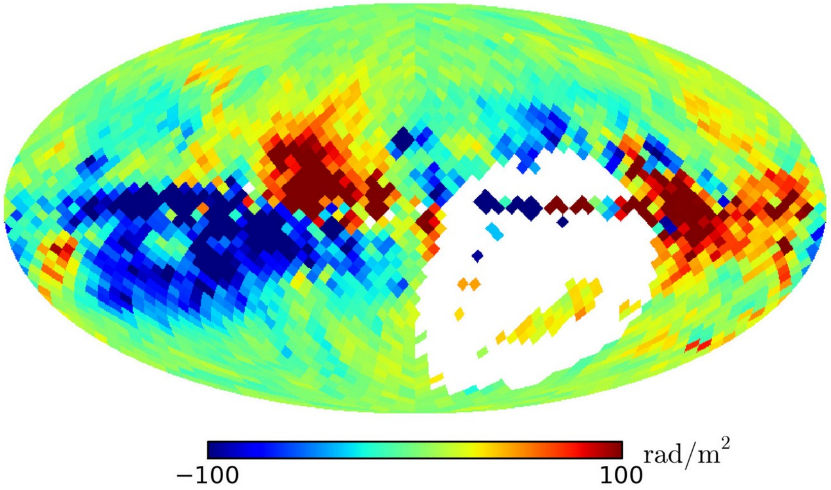
Sigl, Miniati, Ensslin, *PRD* 2004

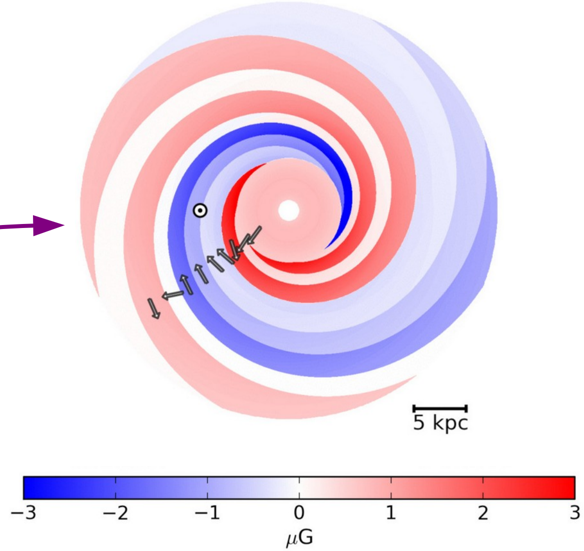
Scattering on magnetic fields

Faraday rotation: Polarization of e.m. waves by magnetized plasma

$$\Delta\Psi = \mathrm{RM} \cdot \lambda^2$$



Galactic B ~μG



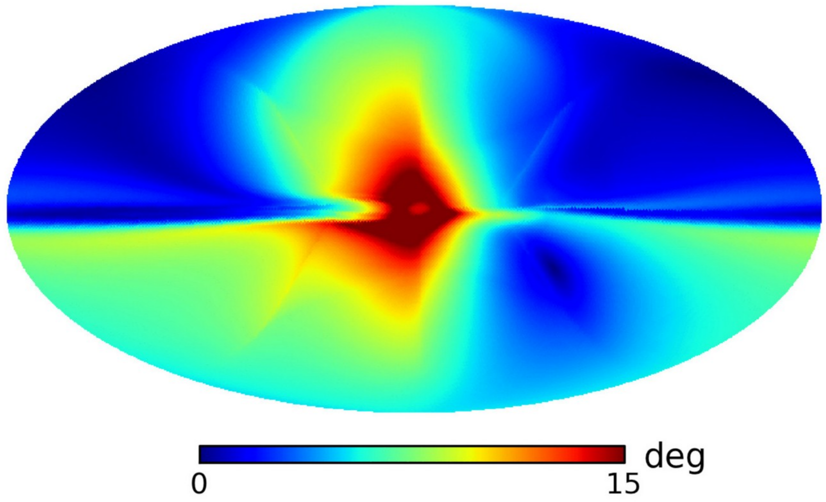
Milky Way electron density

$$\mathrm{RM} \simeq 0.81 \int_0^L \left(\frac{n_e(l)}{\mathrm{cm}^{-3}}\right) \left(\frac{B(l)}{\mu\mathrm{G}}\right) \left(\frac{dl}{\mathrm{pc}}\right)$$

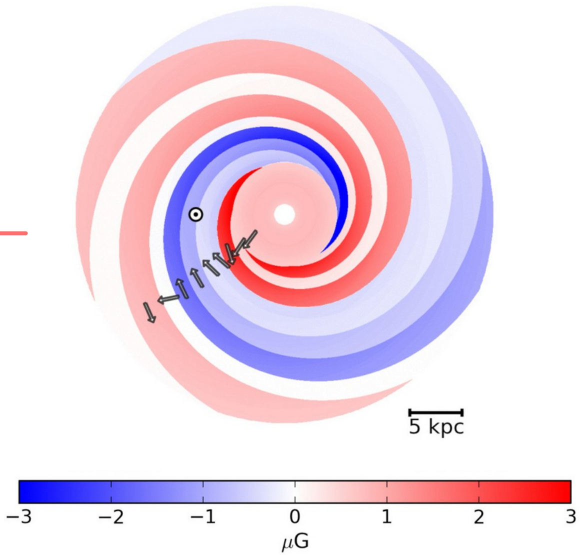
Jansson & Farrar, *ApJ* 2012

Scattering on magnetic fields

Galactic deflections of 60-EeV protons



Galactic B ~μG



$$\delta \approx 16^\circ Z \left(\frac{20 \text{ EeV}}{E}\right) \int_0^L \frac{dL}{3 \text{ kpc}} \left(\frac{B}{2\ \mu\text{G}}\right)$$

Auger Collab., *Astropart. Phys.* 2007

Jansson & Farrar, *ApJ* 2012

Practical matters

How to compute the UHECR spectrum, mass composition, anisotropy?

Write your own code from scratch: Great for learning, gets complicated fast

PriNCe: Fast solver of the transport equation of UHECRs + cosmogenic neutrinos
github.com/joheinze/PriNCe

SimProp: Original Monte-Carlo propagator of UHECRs and secondaries, updated
augeraq.sites.lngs.infn.it/SimProp

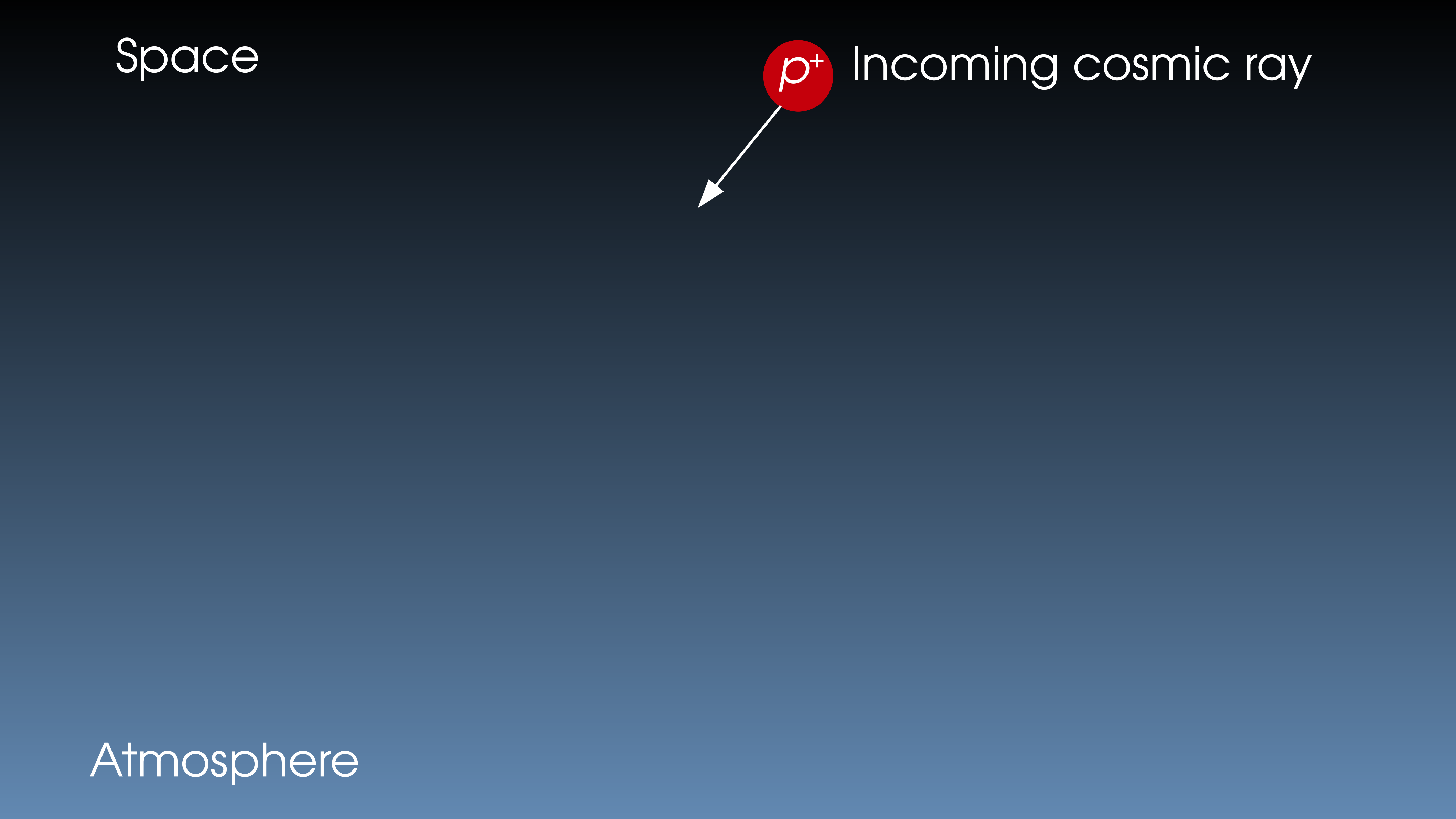
CRPropa: Widely used Monte-Carlo propagator of UHECRs, neutrinos, gamma rays, including magnetic deflection
crpropa.desy.de

Others: Hermes (arXiv:1305.4364), TransportCR (sourceforge.net), …

UHECR detection

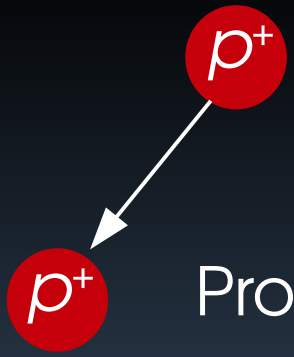
Space

Atmosphere


Space
p^+
Incoming cosmic ray
Atmosphere

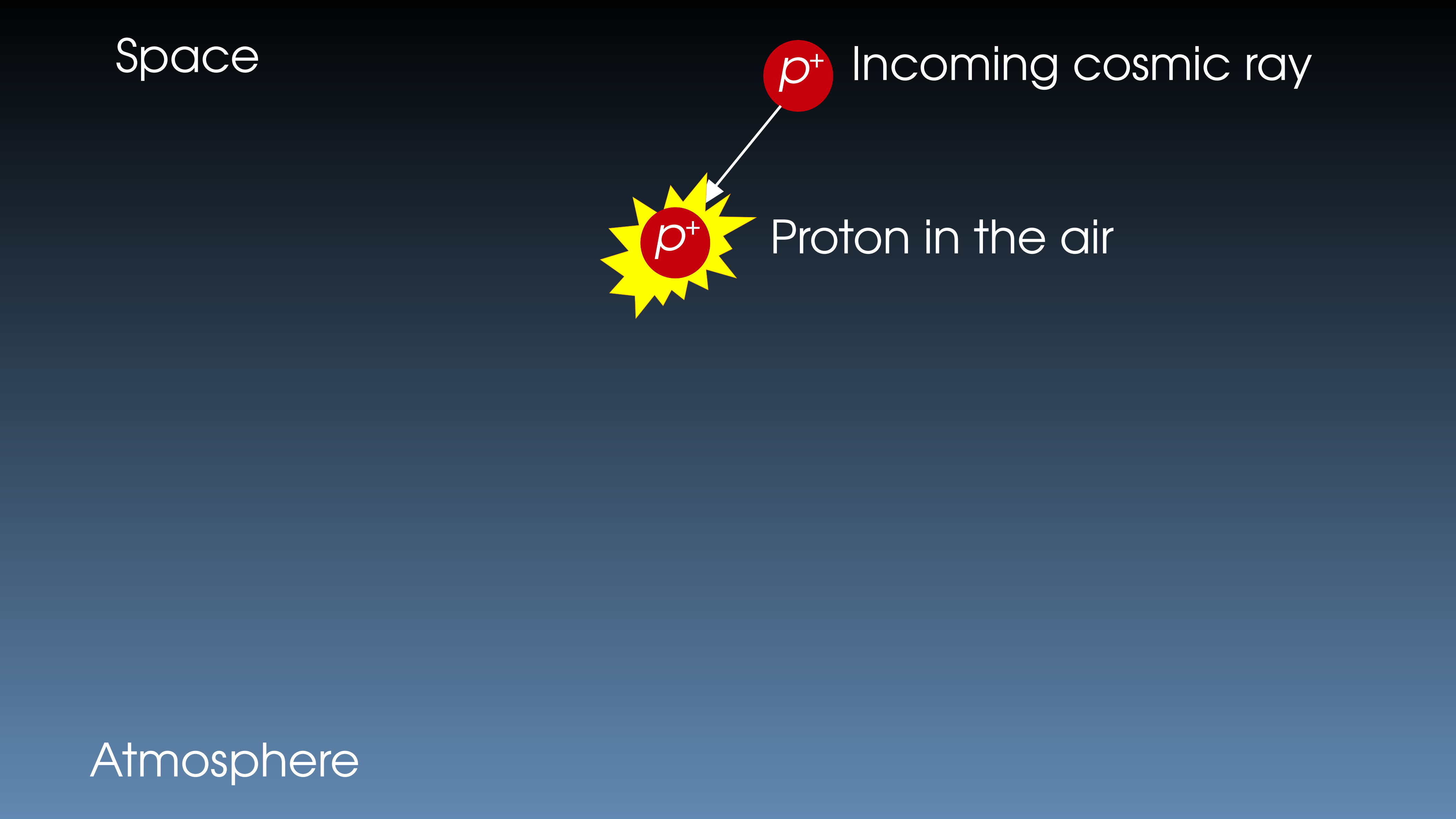
Space

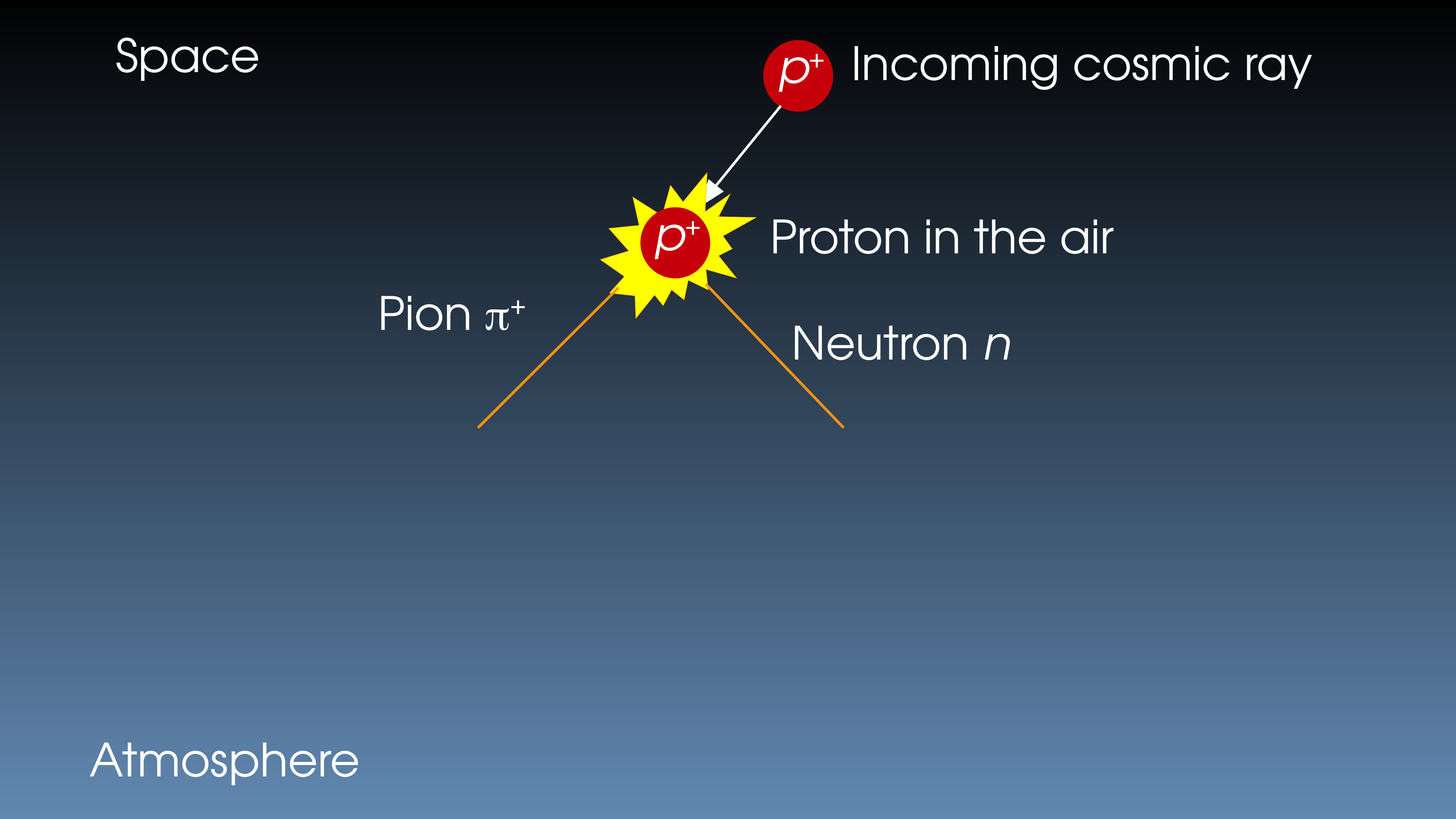
Incoming cosmic ray

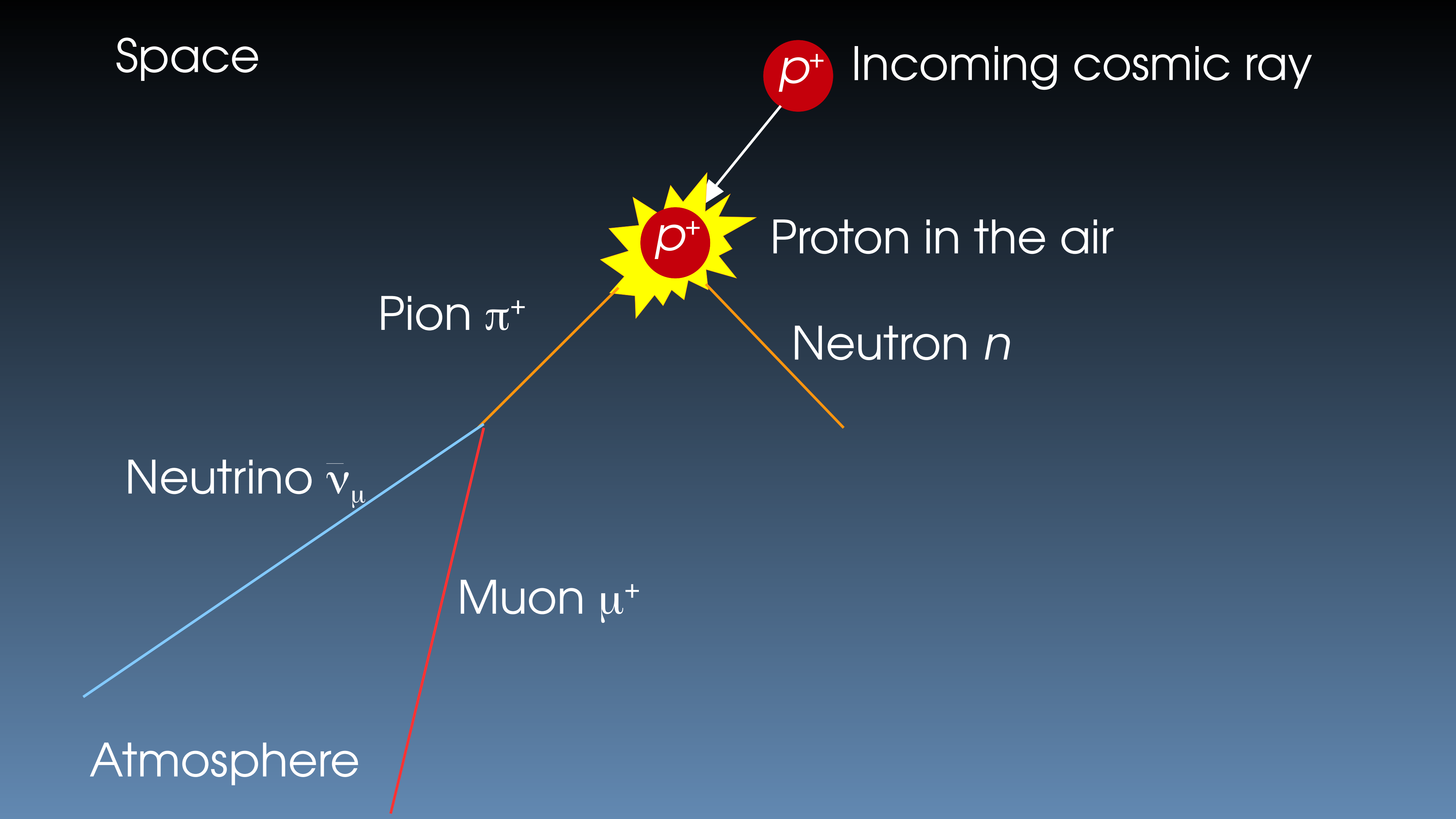


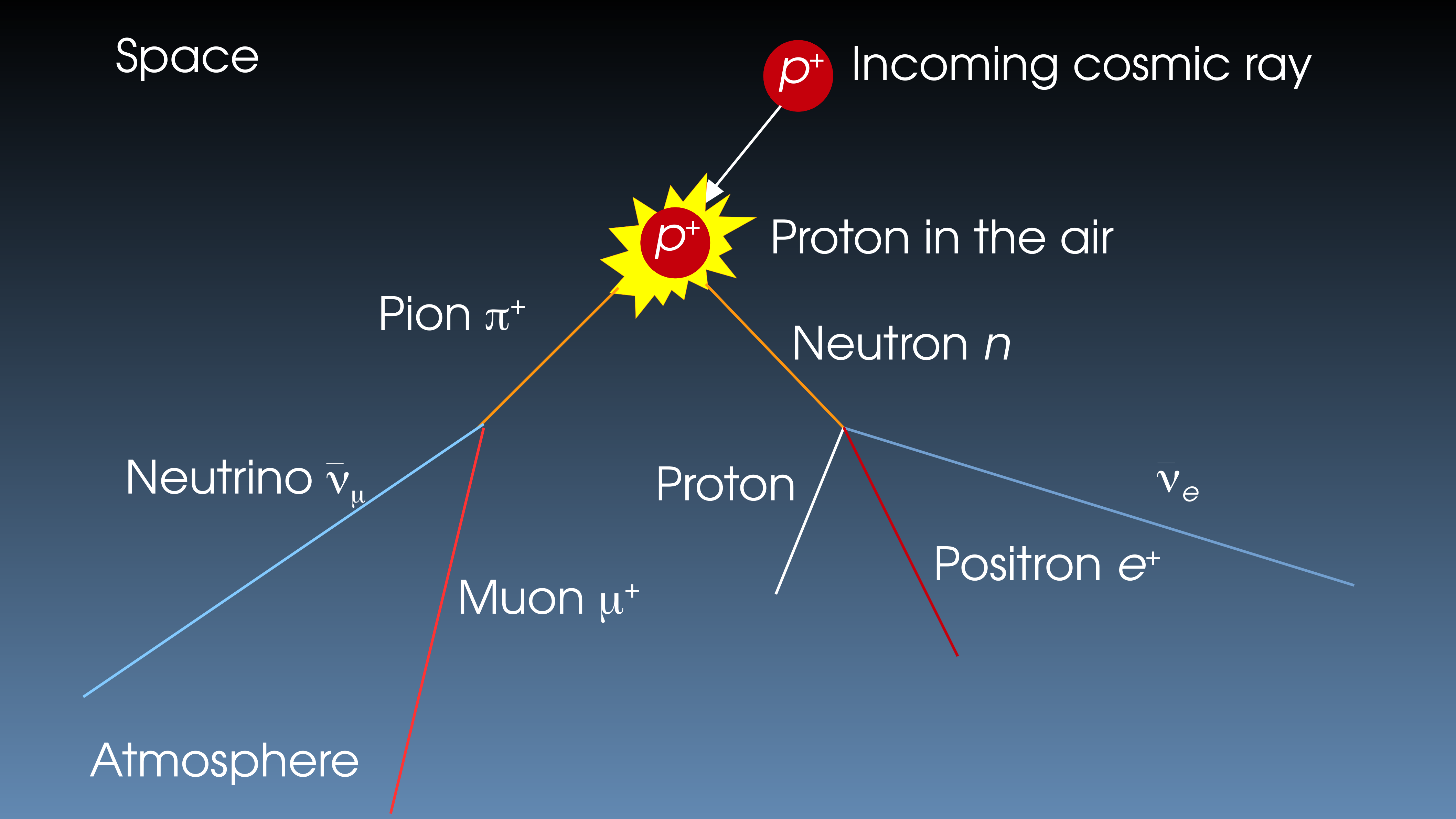
Proton in the air

Atmosphere

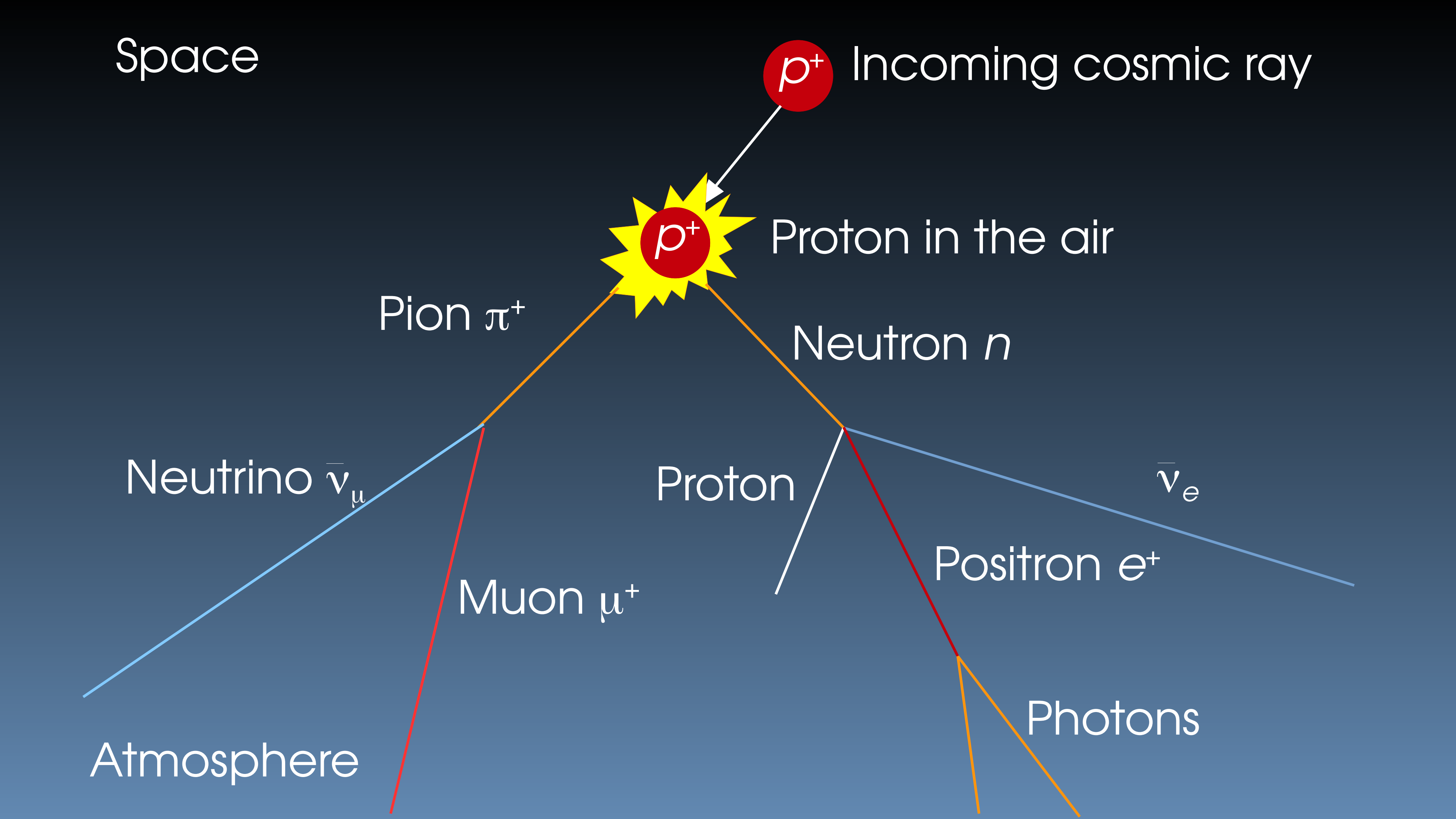

Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Atmosphere


Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Atmosphere


Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Muon μ^+
Atmosphere



Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Atmosphere


Space
p^+
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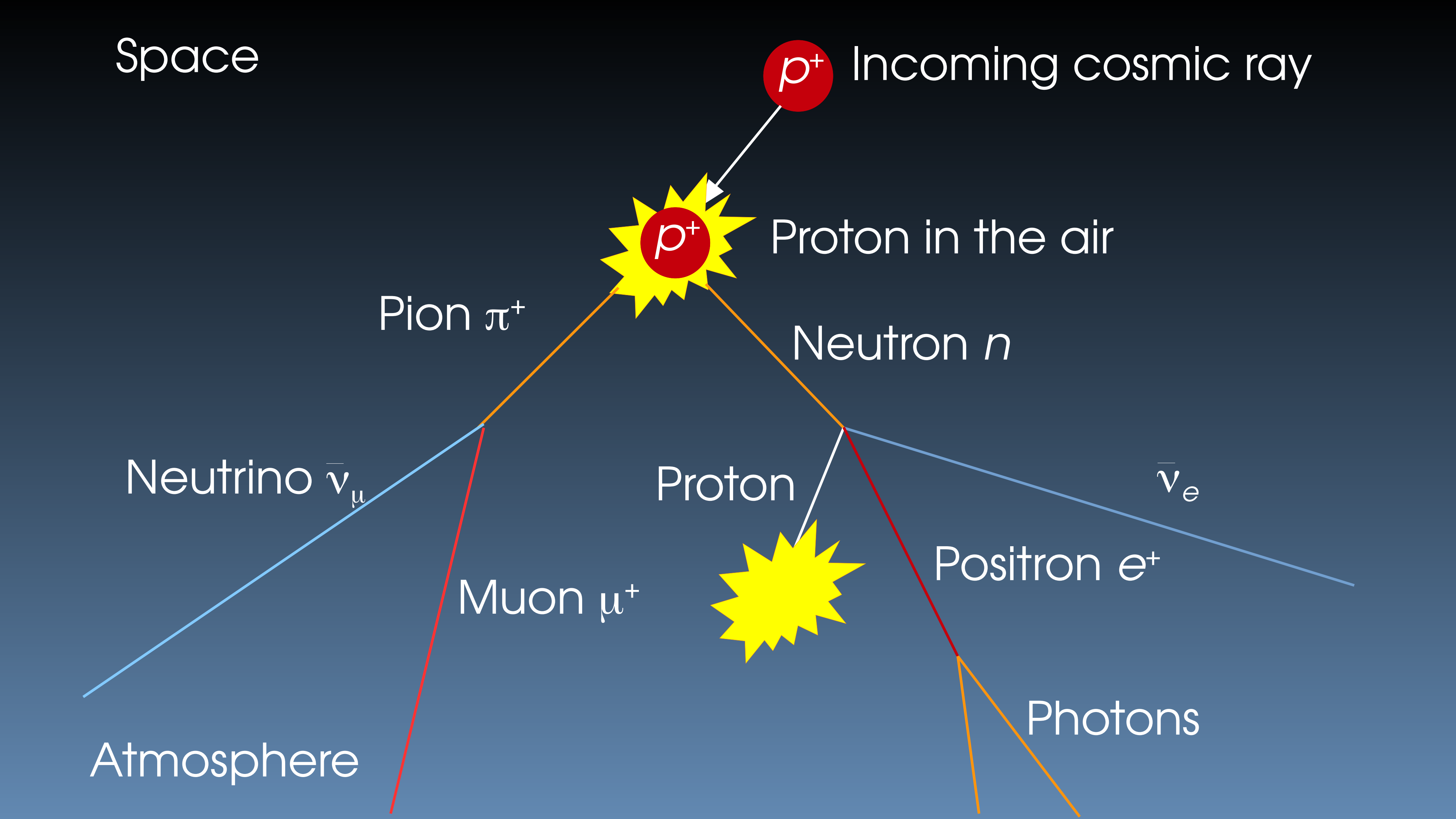
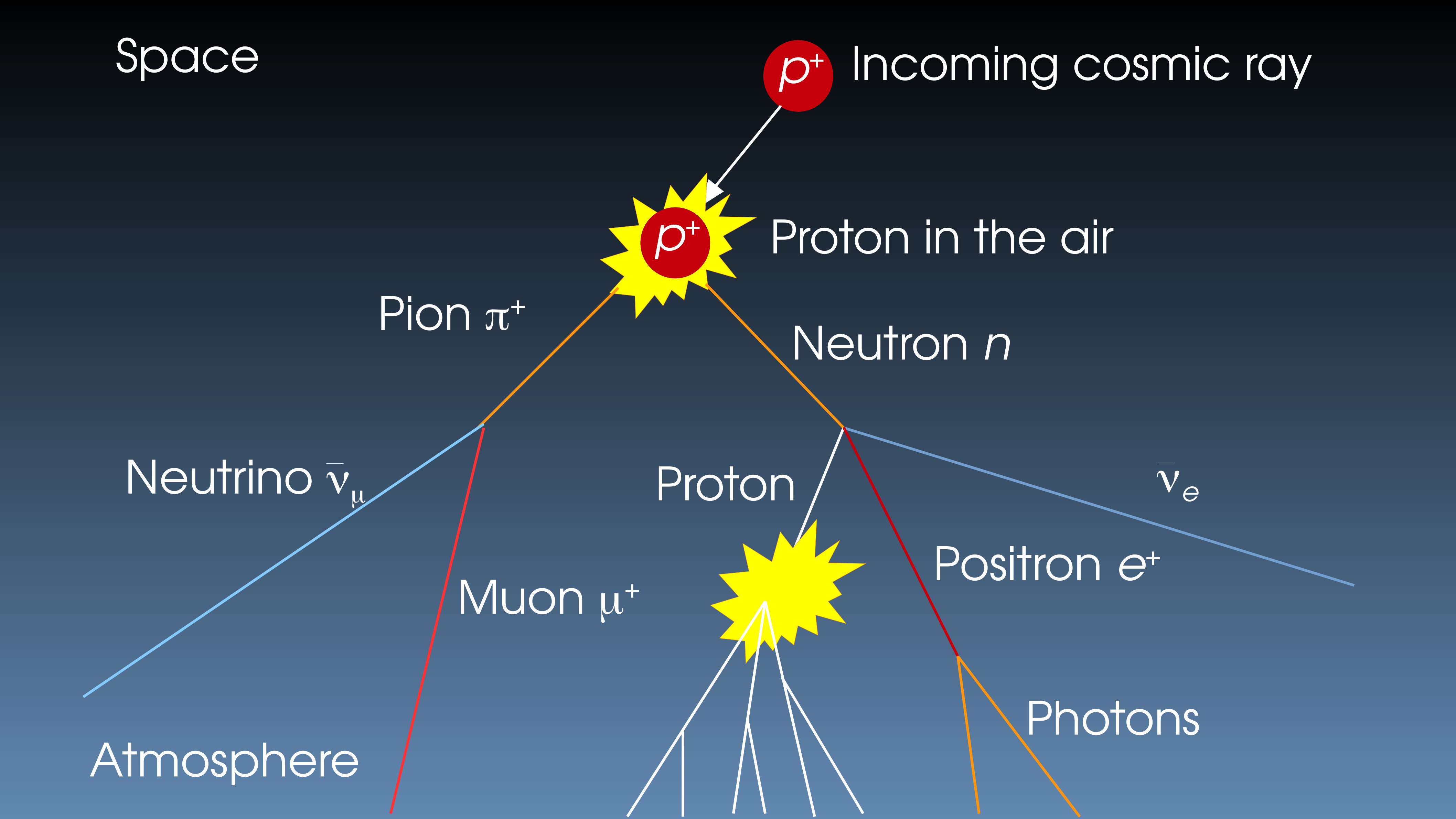
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere



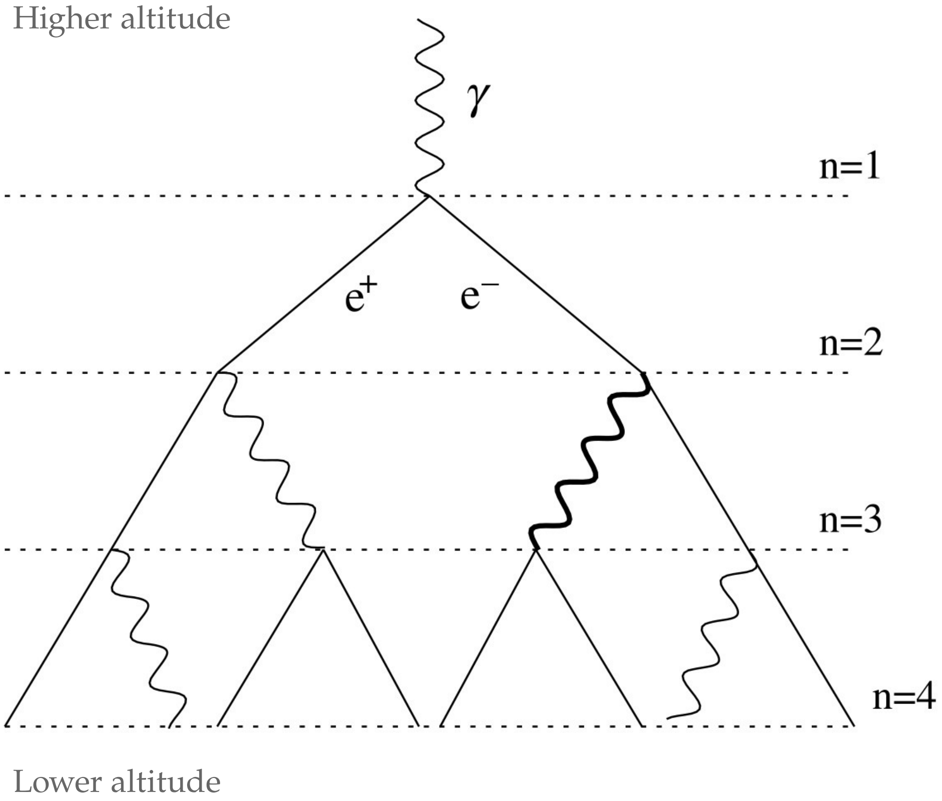
Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere



Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere

Shower development in the atmosphere

Heitler model—simple, but illustrative:



Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

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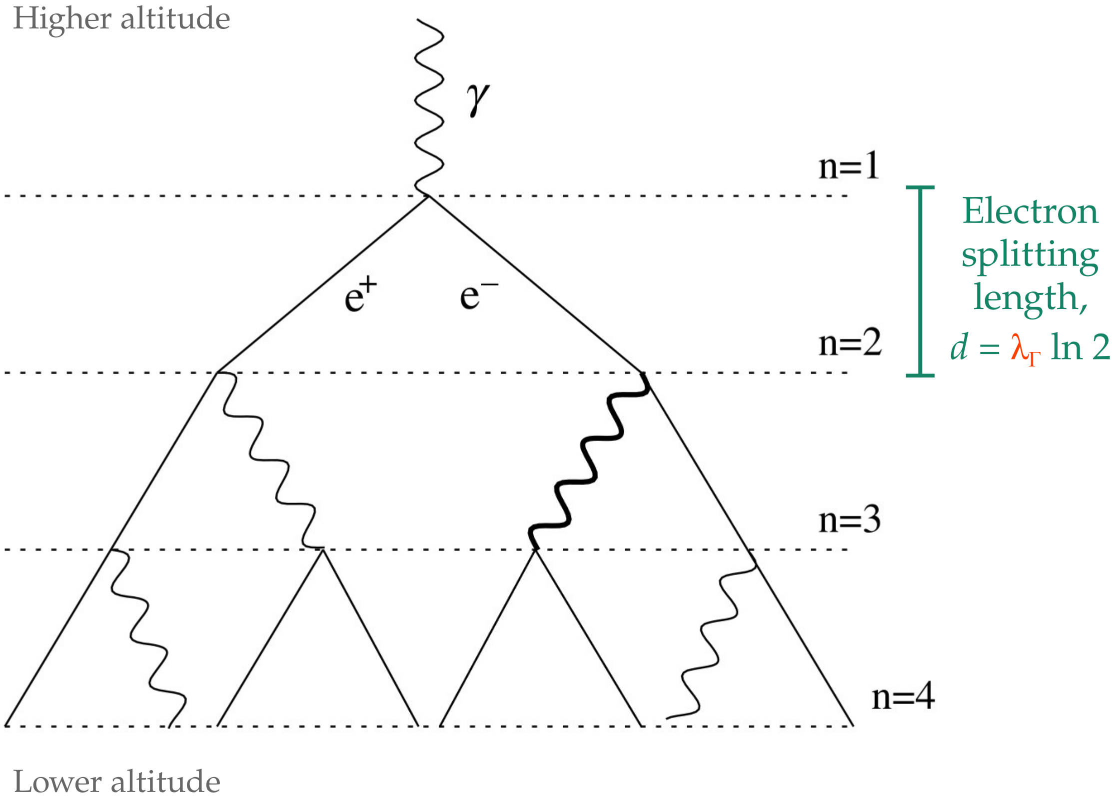

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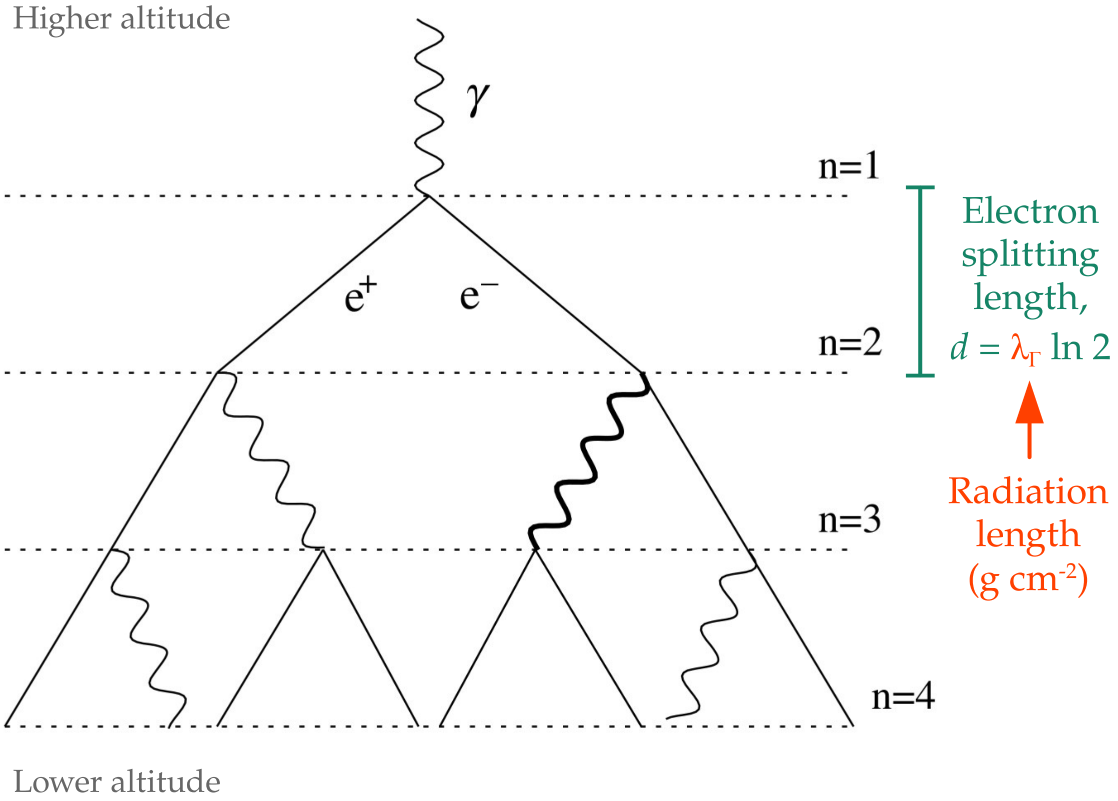

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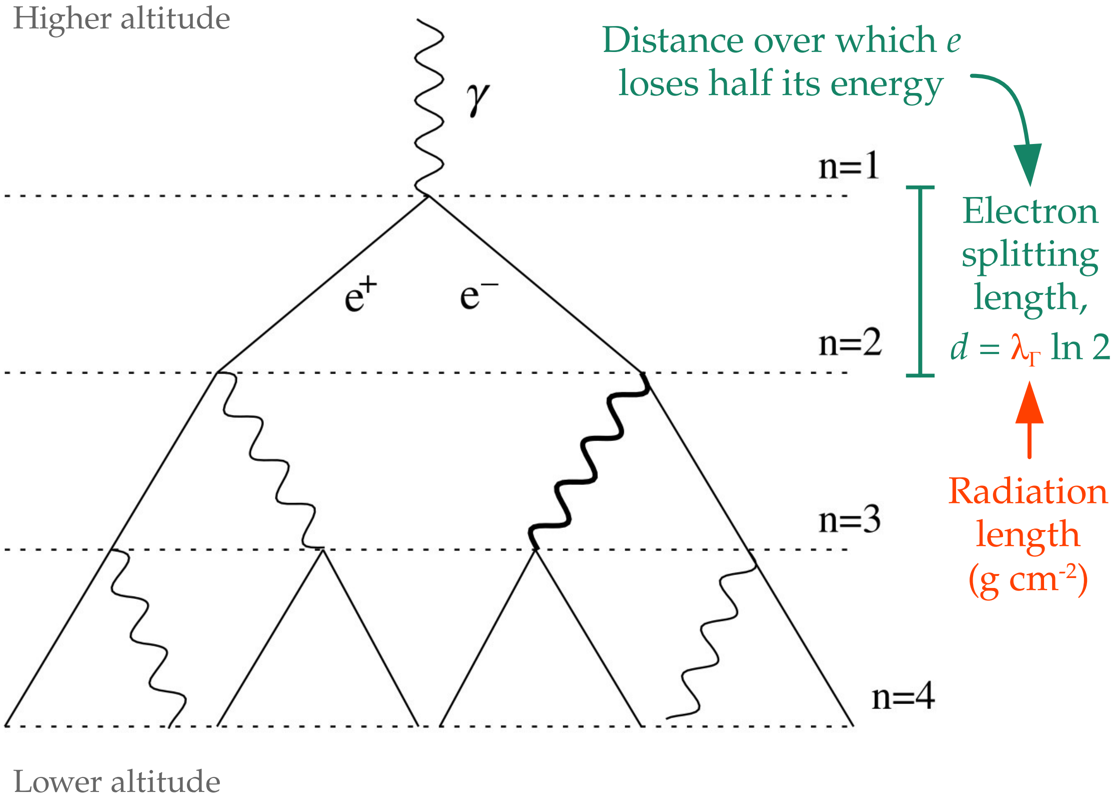
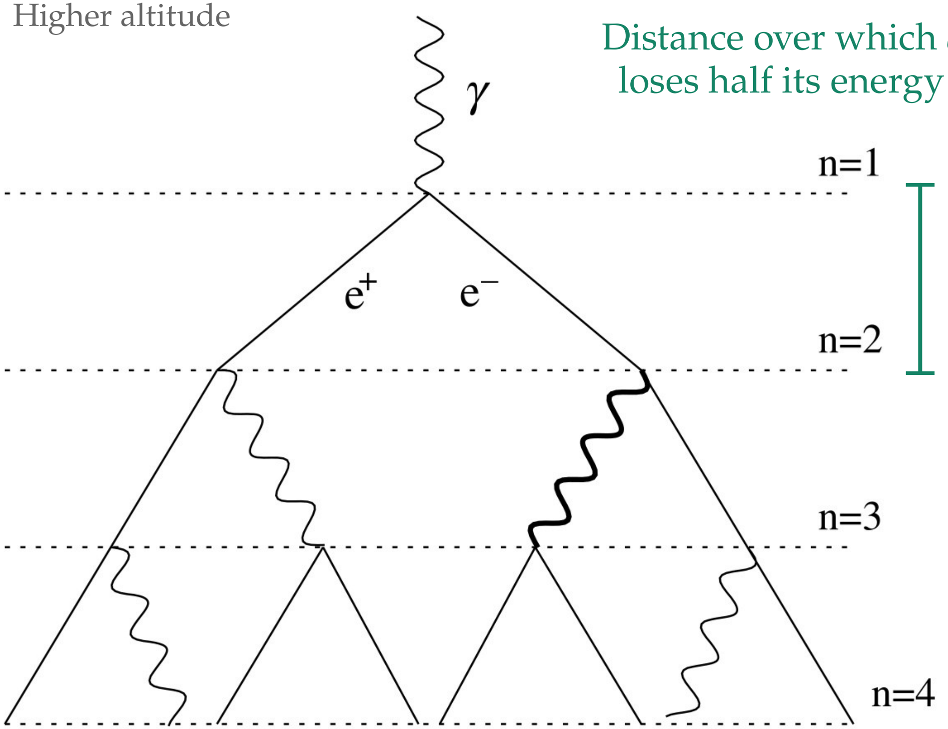


Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:

Higher altitude



Lower altitude

Distance over which *e* loses half its energy

Electron splitting length, $d = \lambda_\Gamma \ln 2$

Radiation length (g cm^{-2})

After *n* splitting lengths,

Depth traveled: $x = n\,\lambda_\Gamma \ln 2$

Number of particles (e + γ): $N = 2^n = e^{x/\lambda_\Gamma}$

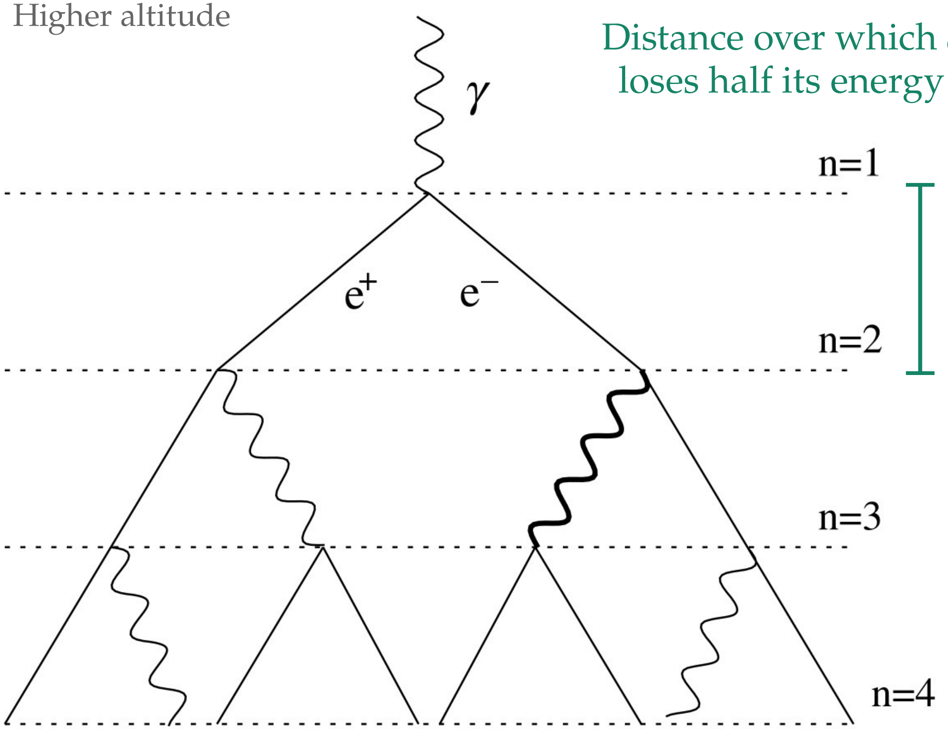
Heitler, *The Quantum Theory of Radiation*, 1954

Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:

Higher altitude



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Radiation length (g cm^{-2})

After n splitting lengths,

Depth traveled: $x = n\,\lambda_\Gamma \ln 2$

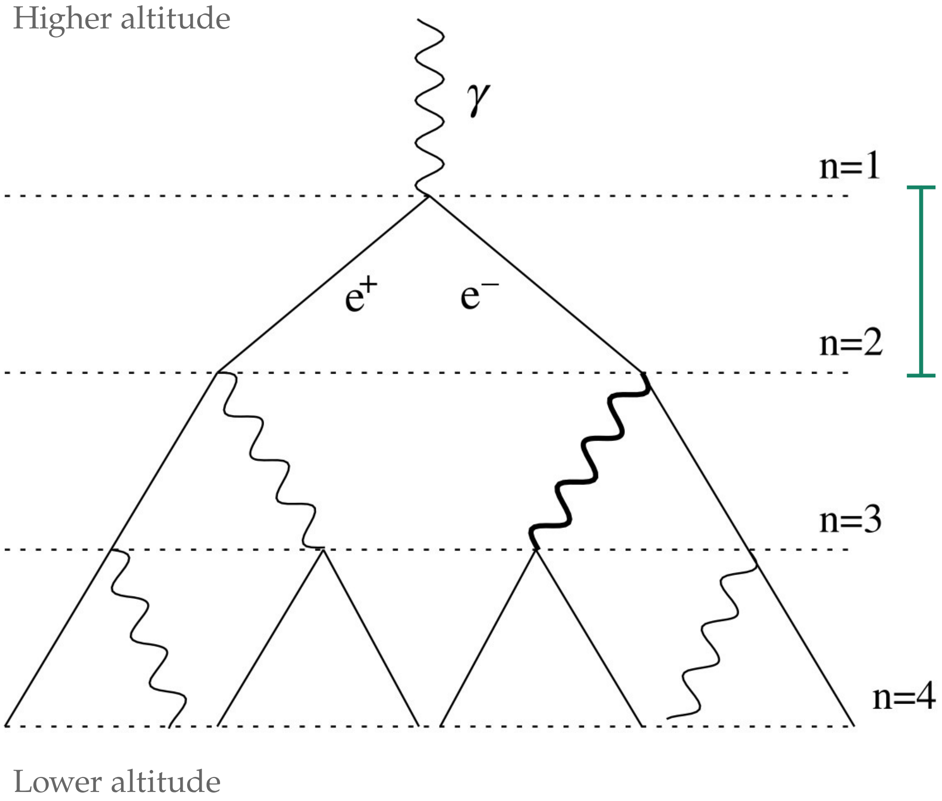
Number of particles ($e + \gamma$): $N = 2^n = e^{x/\lambda_\Gamma}$

Cascade development stops after n_C splittings, when the particle energies are too low for pair production or bremsstrahlung

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:



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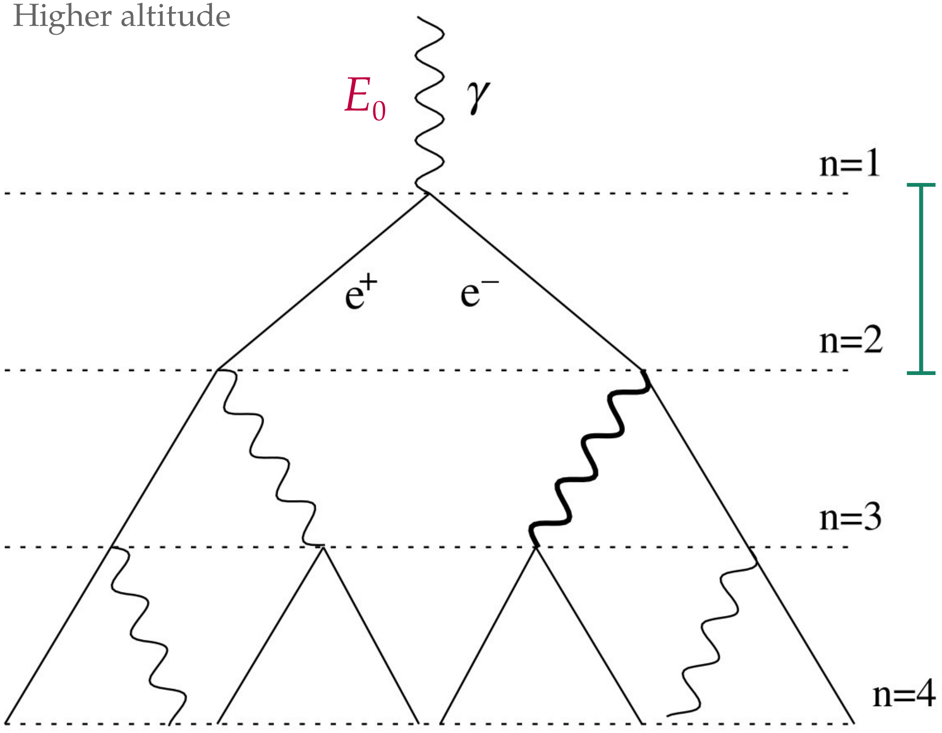
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:



Lower altitude

Each particle: E_C
($\approx$ 85 MeV in air)

Electron splitting length,
$d = \lambda_\Gamma \ln 2$

Radiation length
(g cm^{-2})

After n splitting lengths,

Depth traveled:
$x = n\,\lambda_\Gamma \ln 2$

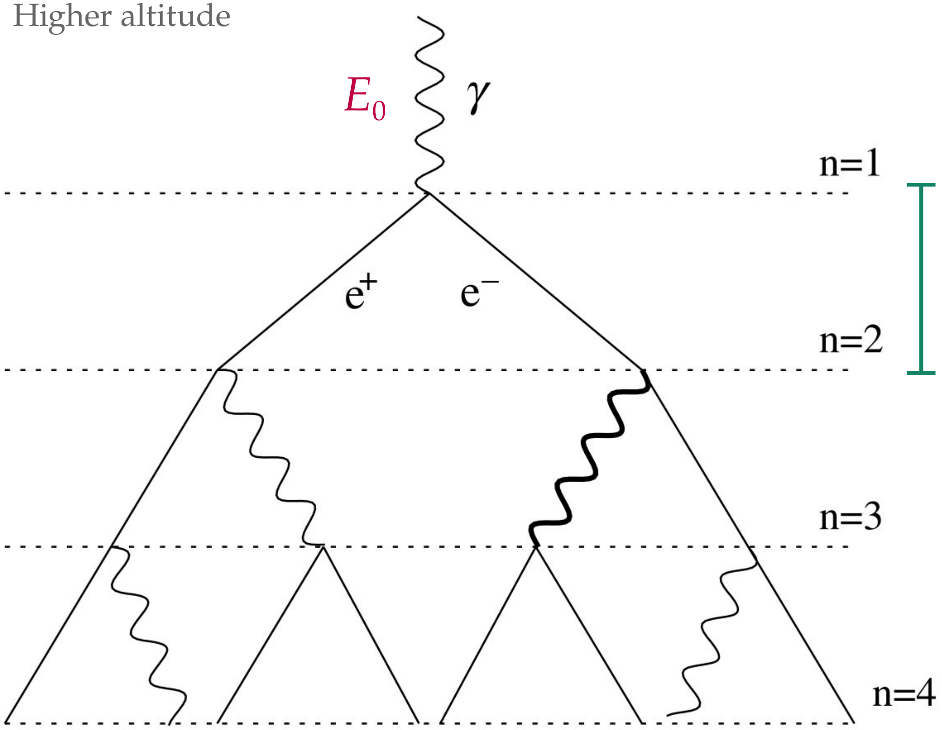
Number of particles ($e + \gamma$):
$N = 2^n = e^{x/\lambda_\Gamma}$

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:

Higher altitude



Lower altitude

Each particle: E_C
($\approx$ 85 MeV in air)

Electron splitting length, $d = \lambda_\Gamma \ln 2$

Radiation length (g cm^{-2})

After n splitting lengths,

Depth traveled: $x = n\,\lambda_\Gamma \ln 2$

Number of particles ($e + \gamma$): $N = 2^n = e^{x/\lambda_\Gamma}$

The cascade reaches its maximum size $N = N_{max}$ when all particles have energy E_C so that

$$E_0 = E_C\, N_{max}\ .$$

But $N_{max} = 2^{n_C}$, so

$$n_C = \ln(E_0/E_C)/\ln 2$$

And $X_{max} = n_C\, d$ is

$$X_{max} = \lambda_\Gamma \ln(E_0/E_C)$$

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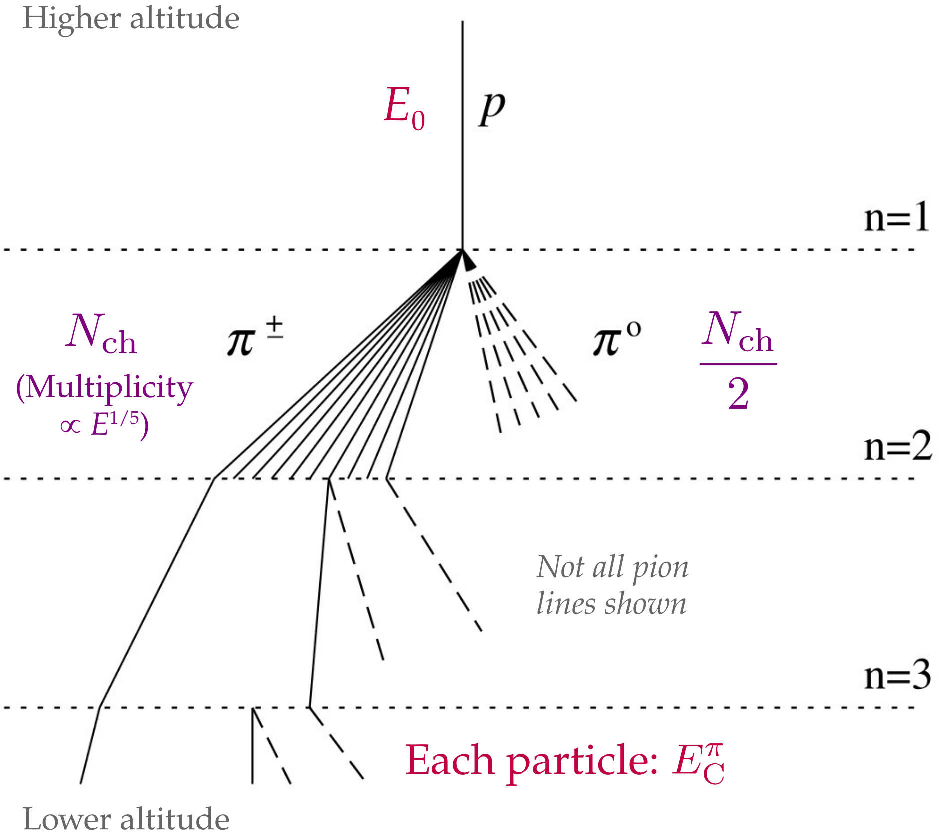

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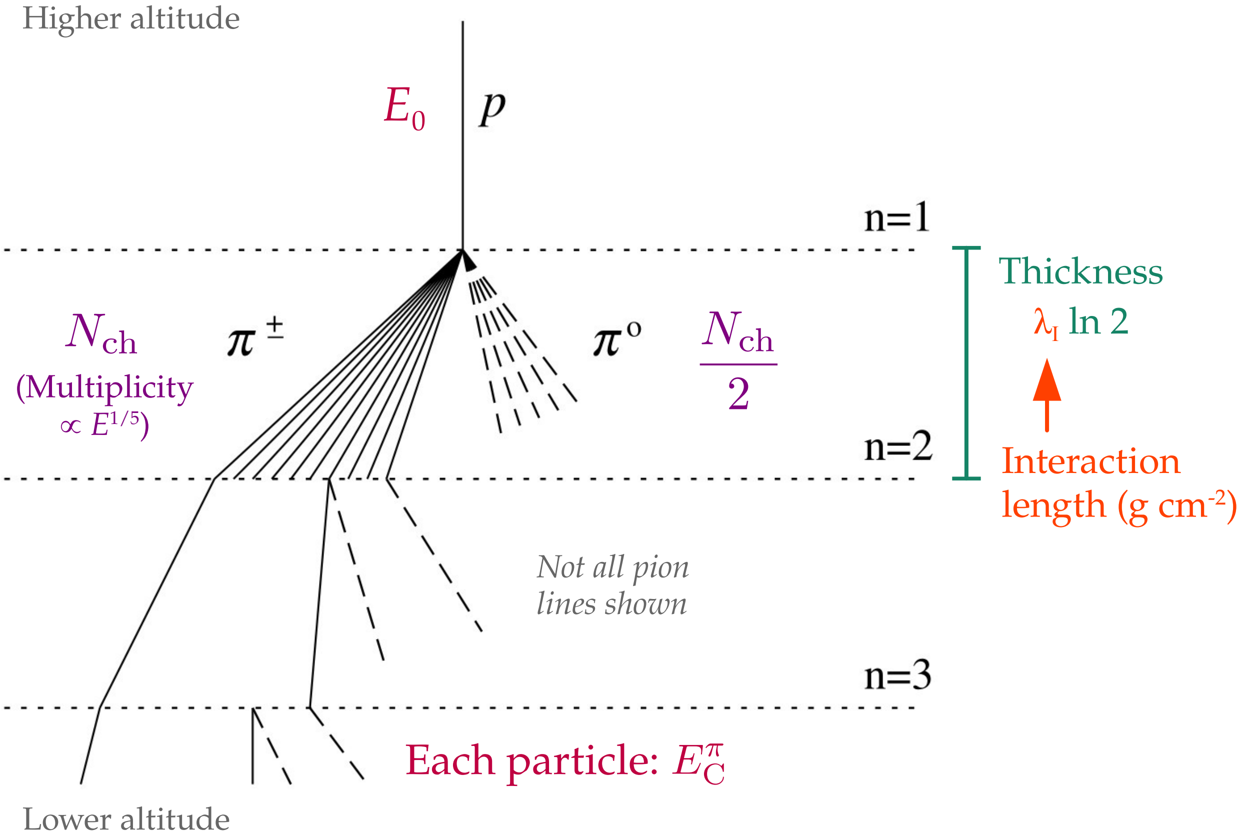

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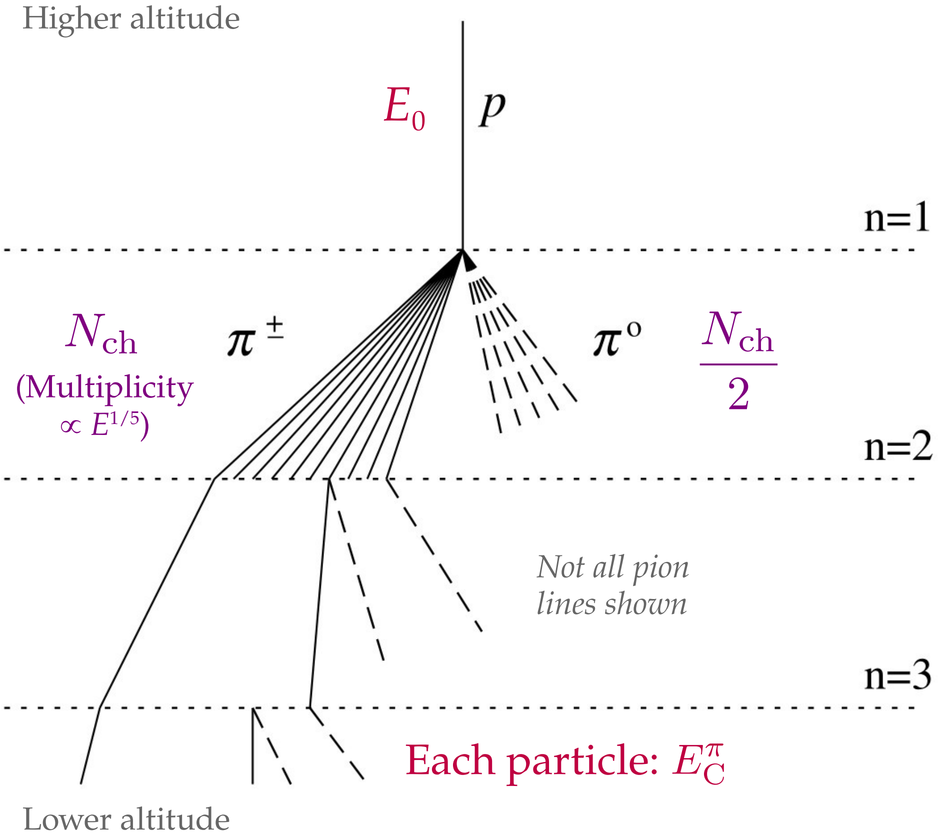

Thickness $\lambda_I \ln 2$

Interaction length (g cm^{-2})

After n lengths,

Number of $\pi^{\pm}$:

$$N_\pi = N_{ch}^n$$

Total energy in $\pi^{\pm}$:

$(2/3)^n E_0$

Per $\pi^{\pm}$:

$$E_\pi = \frac{E_0}{\left(\frac{3}{2}N_{ch}\right)^n}$$

Heitler, *The Quantum Theory of Radiation*, 1954
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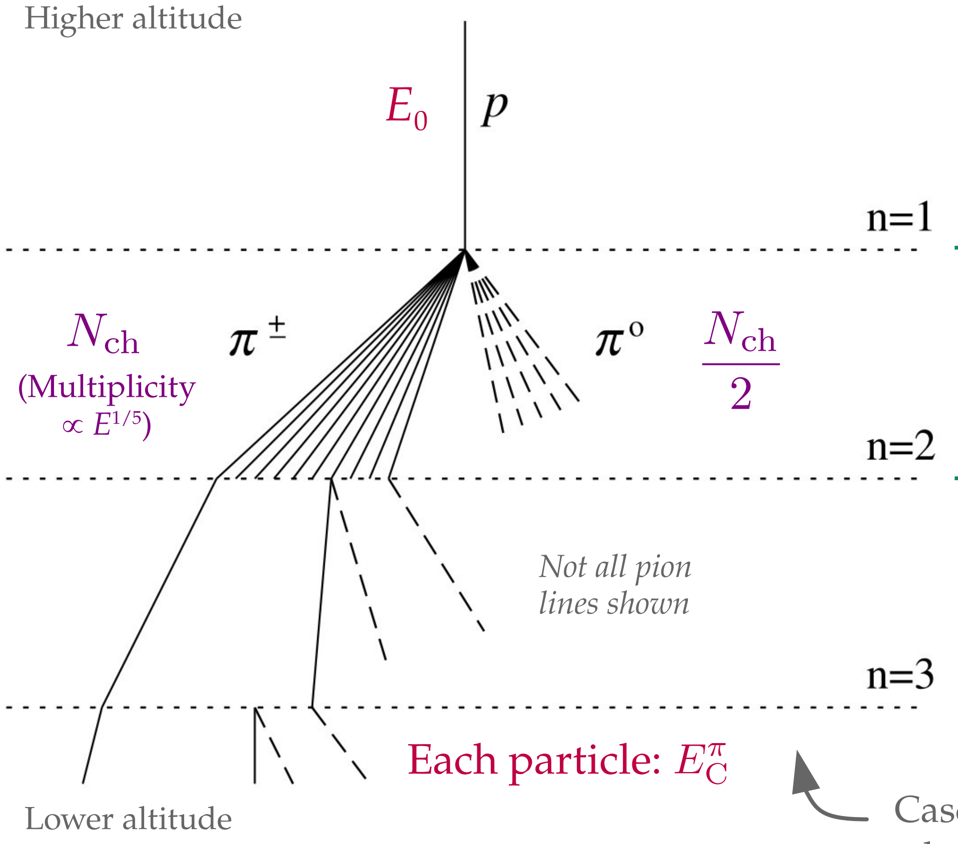

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Cascade development stops after n_C lengths, when the average pion energy E_C is such that the decay length of $\pi^{\pm}$ is < λ_I

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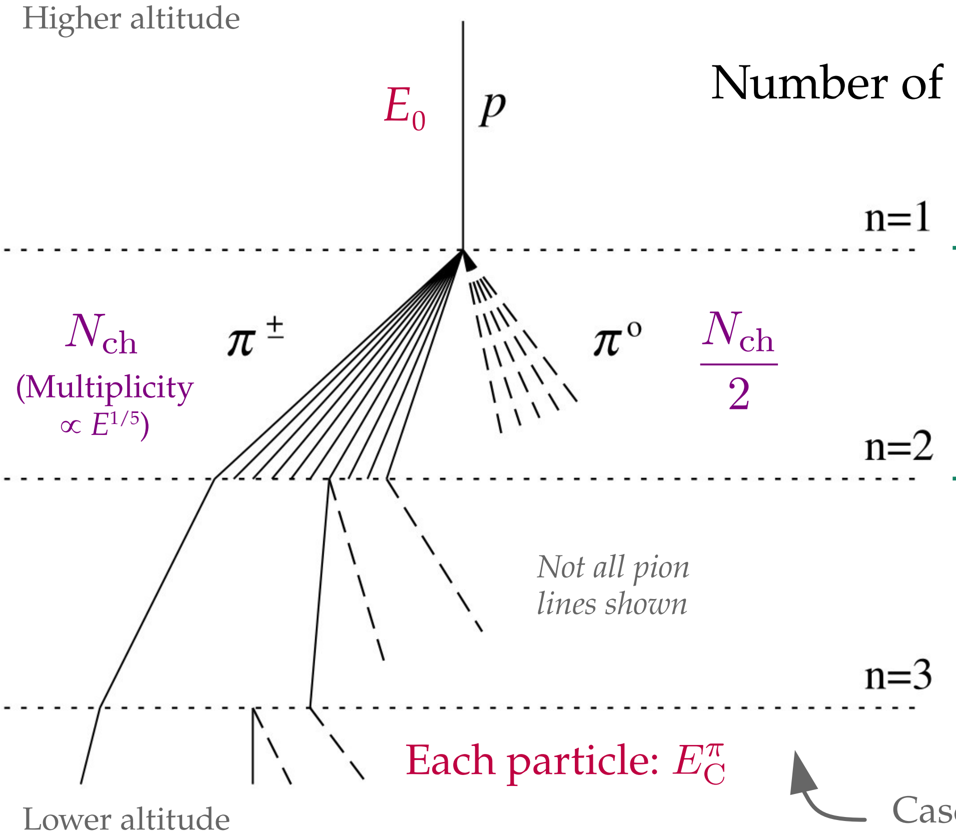
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Heitler model—simple, but illustrative:



Number of interactions to reach $E_\pi = E_C^\pi$: $n_C = \dfrac{\ln(E_0/E_C^\pi)}{\ln(\frac{3}{2}N_{ch})}$

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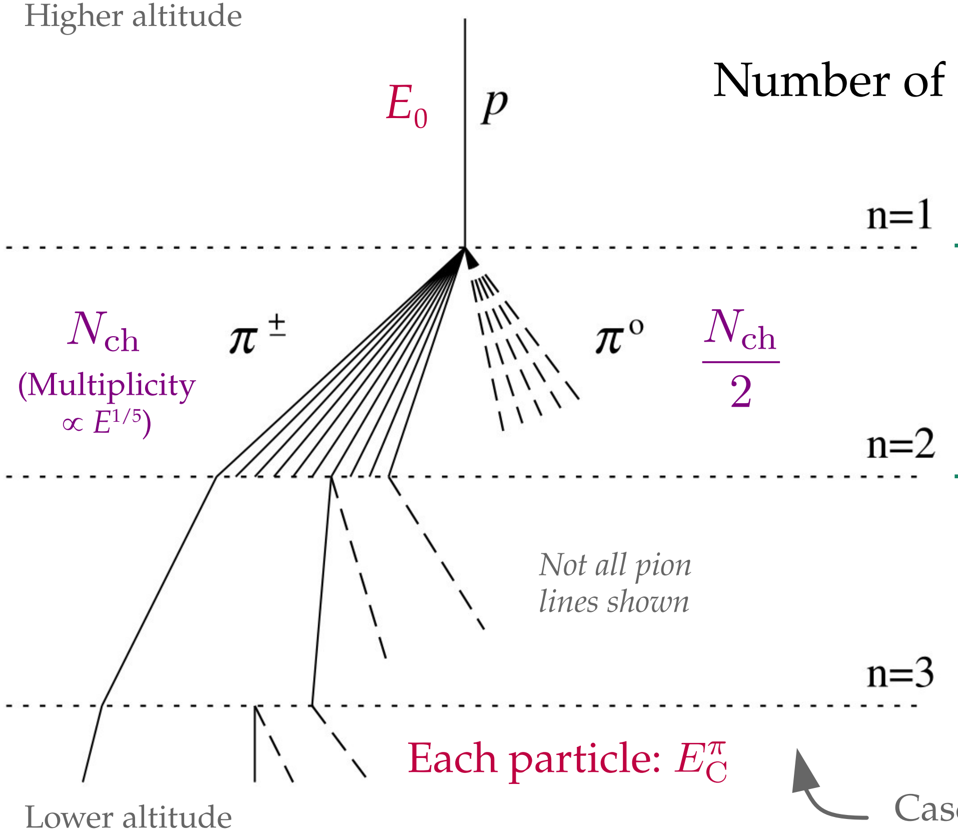

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$(2/3)^n E_0$

Per $\pi^{\pm}$:

$E_\pi = \frac{E_0}{\left(\frac{3}{2}N_{ch}\right)^n}$

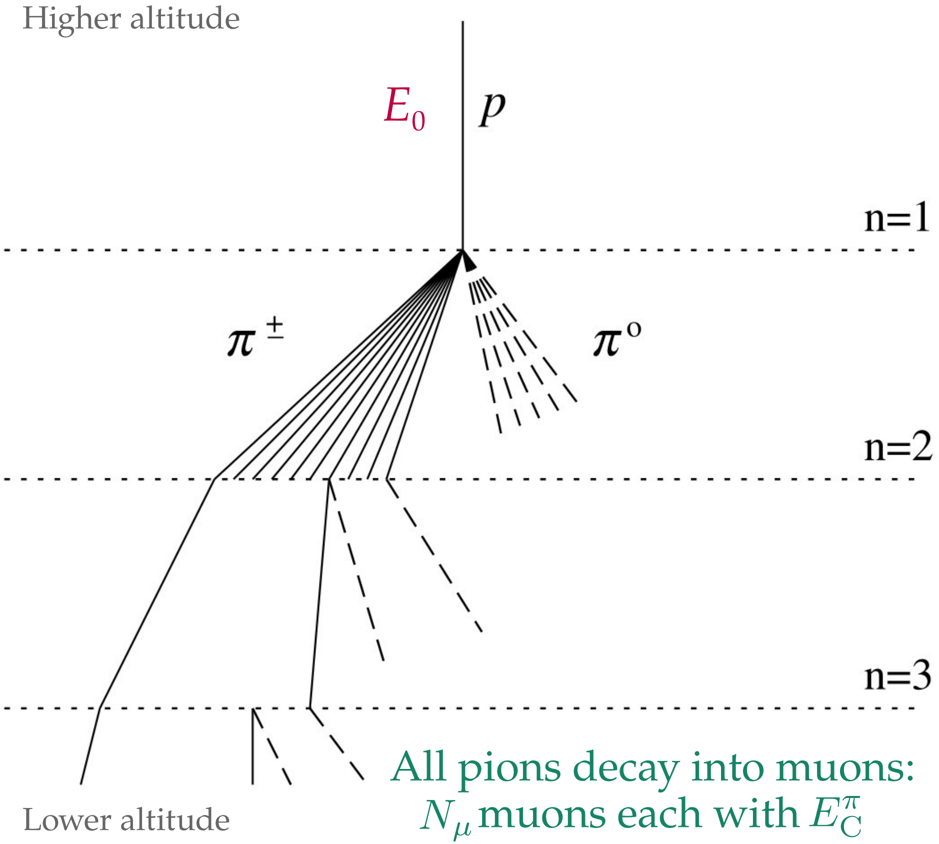
Let's put this all together to infer E_0 and X_{max} from measured quantities (*simplified calculations*)

Cascade development stops after n_C lengths, when the average pion energy E_C is such that the decay length of $\pi^{\pm}$ is < λ_I

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring the primary UHECR energy:



All pions decay into muons:
N_μ muons each with E_C^π

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

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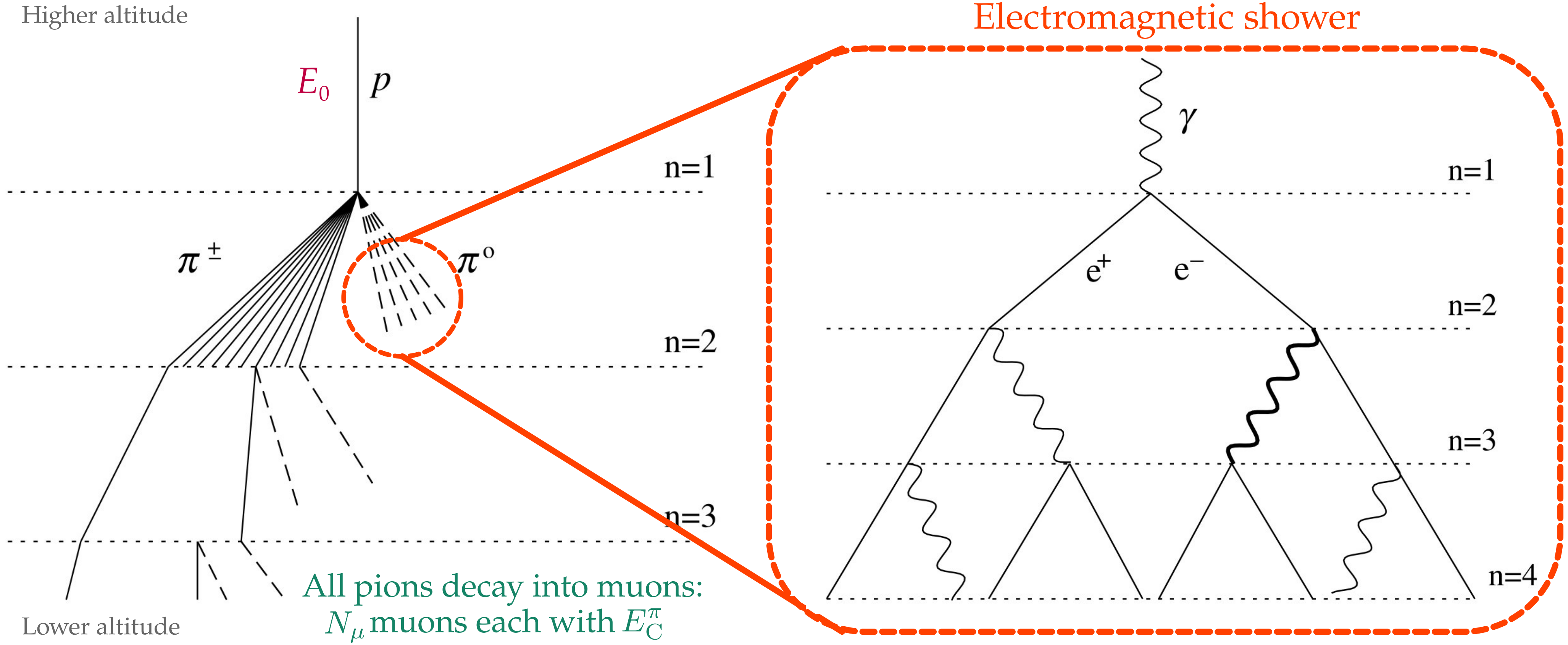


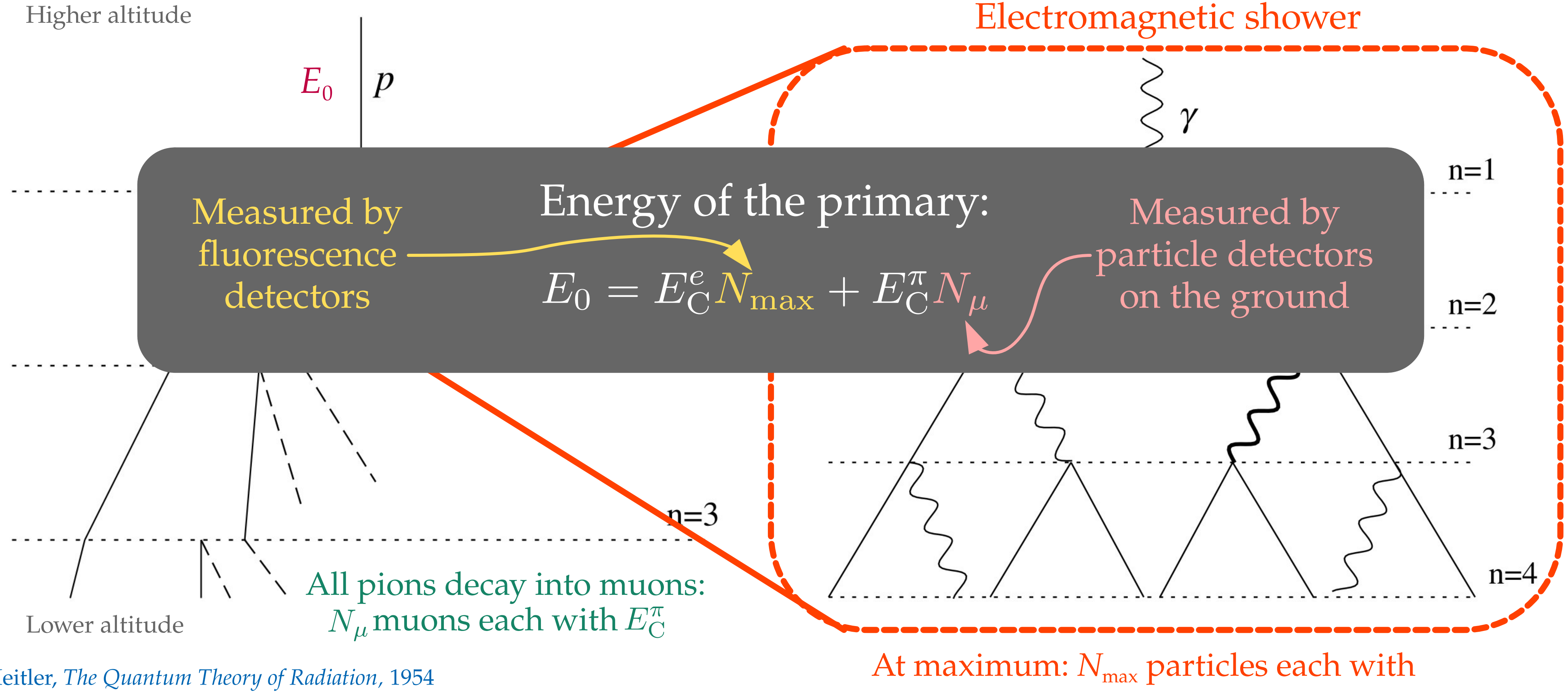
All pions decay into muons: N_μ muons each with E_C^π

At maximum: $N_{\max}$ particles each with E_C^π

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere

Inferring the primary UHECR energy:

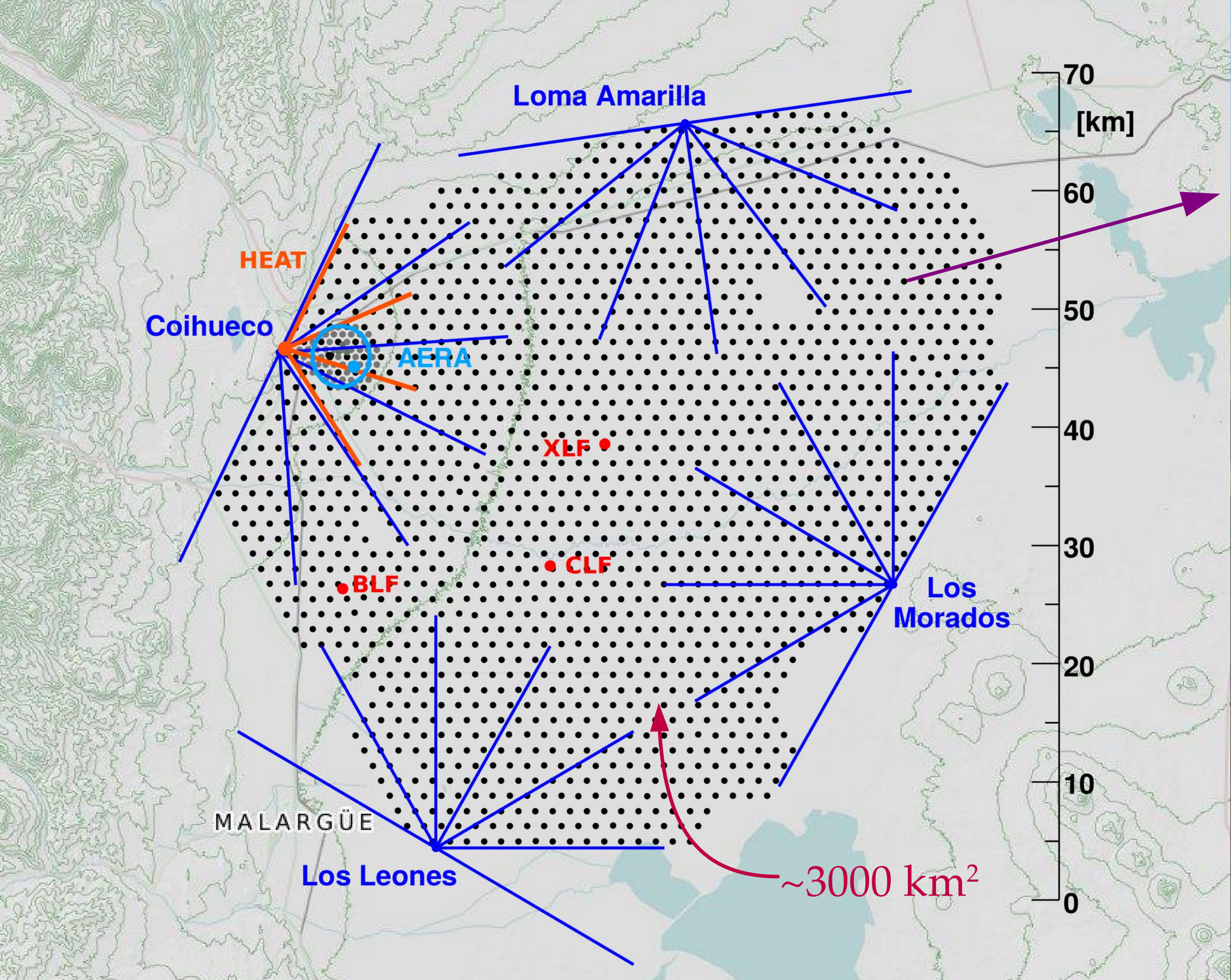


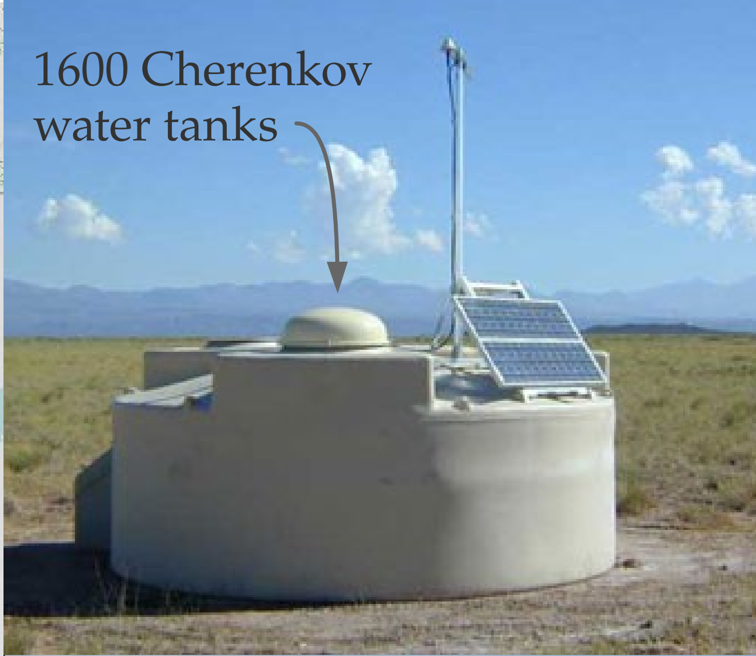
Energy of the primary:

$$E_0 = E_C^e N_{max} + E_C^\pi N_\mu$$

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Pierre Auger Observatory (Malargüe, Argentina)





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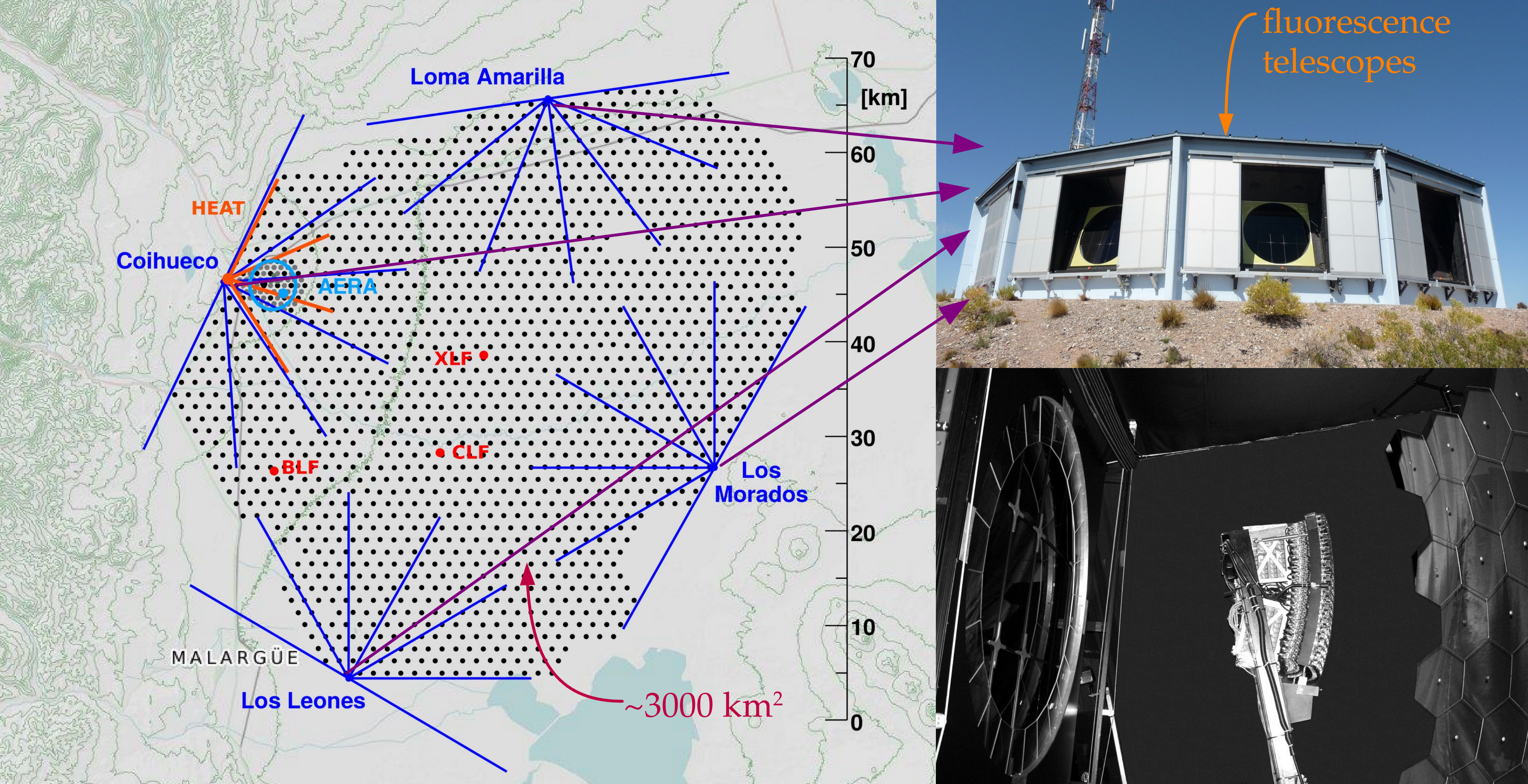
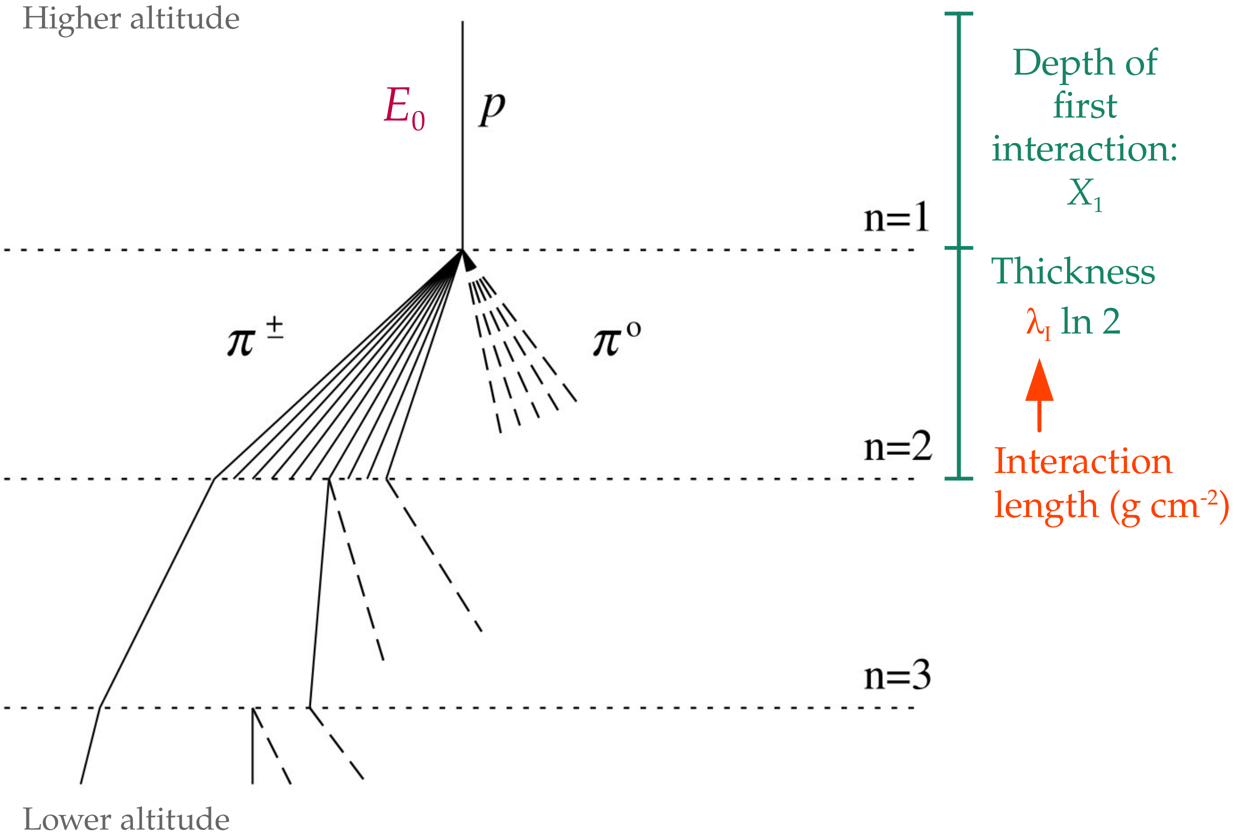


Shower development in the atmosphere

Inferring $X_{\max}$:



Proton-air interaction length:

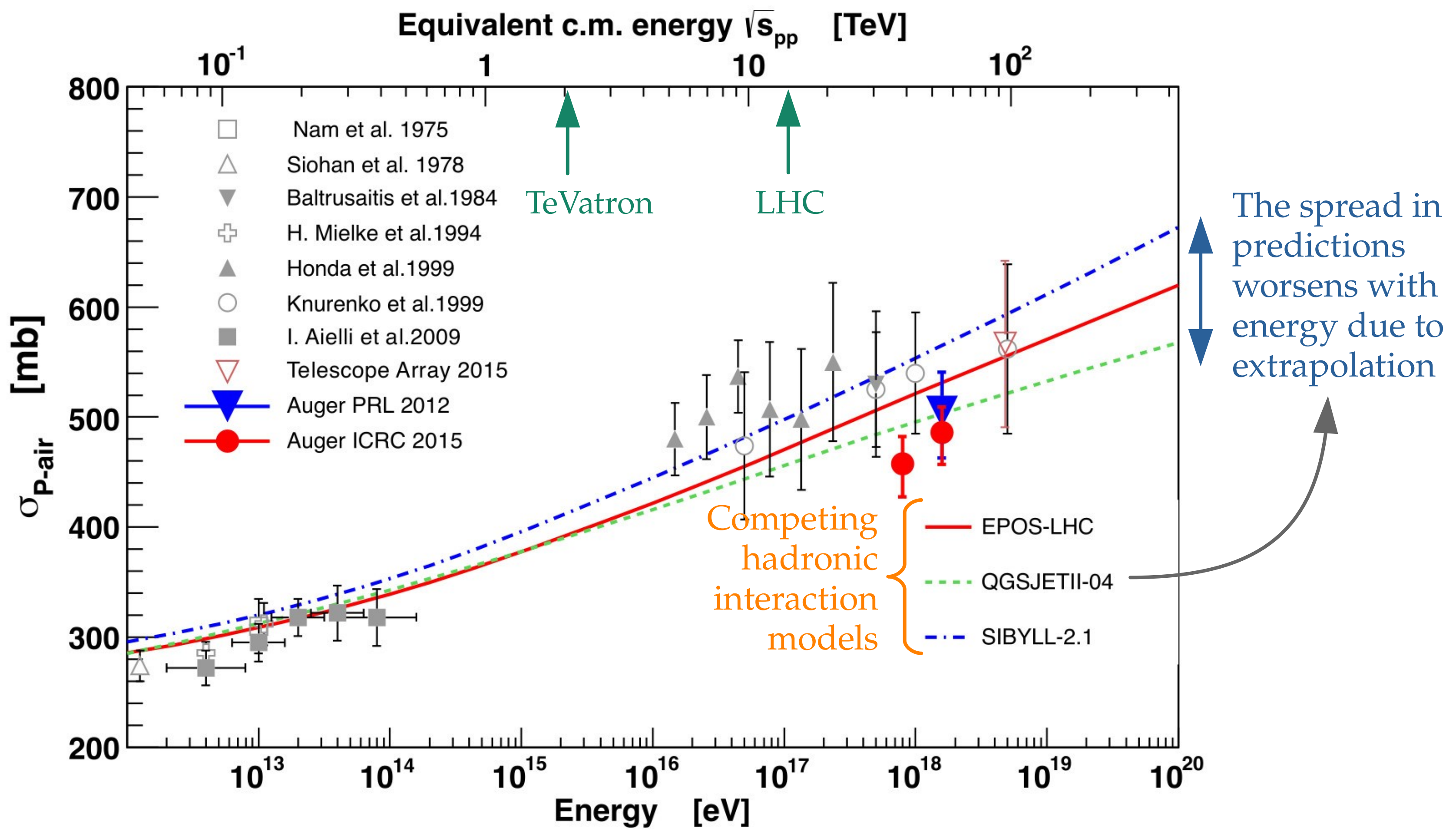
$$\lambda_{\mathrm{I}} = \sigma_{p-\mathrm{air}} \langle m_{\mathrm{air}} \rangle$$

Hard: High-energy proton-air cross section

Easy: Average target mass of air (needs model of density profile of atmosphere)

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

Shower development in the atmosphere



Ulrich (for Auger Collab.), *PoS* ICRC2015

Shower development in the atmosphere

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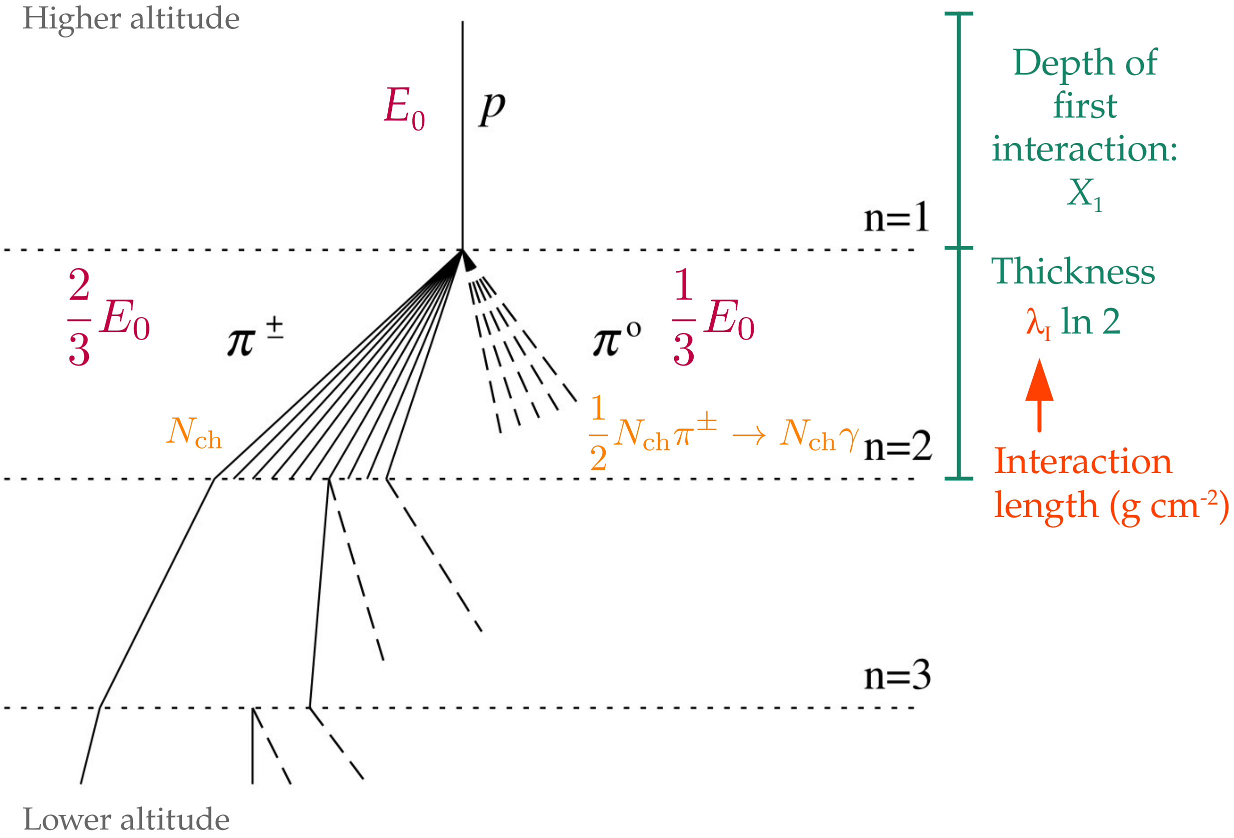

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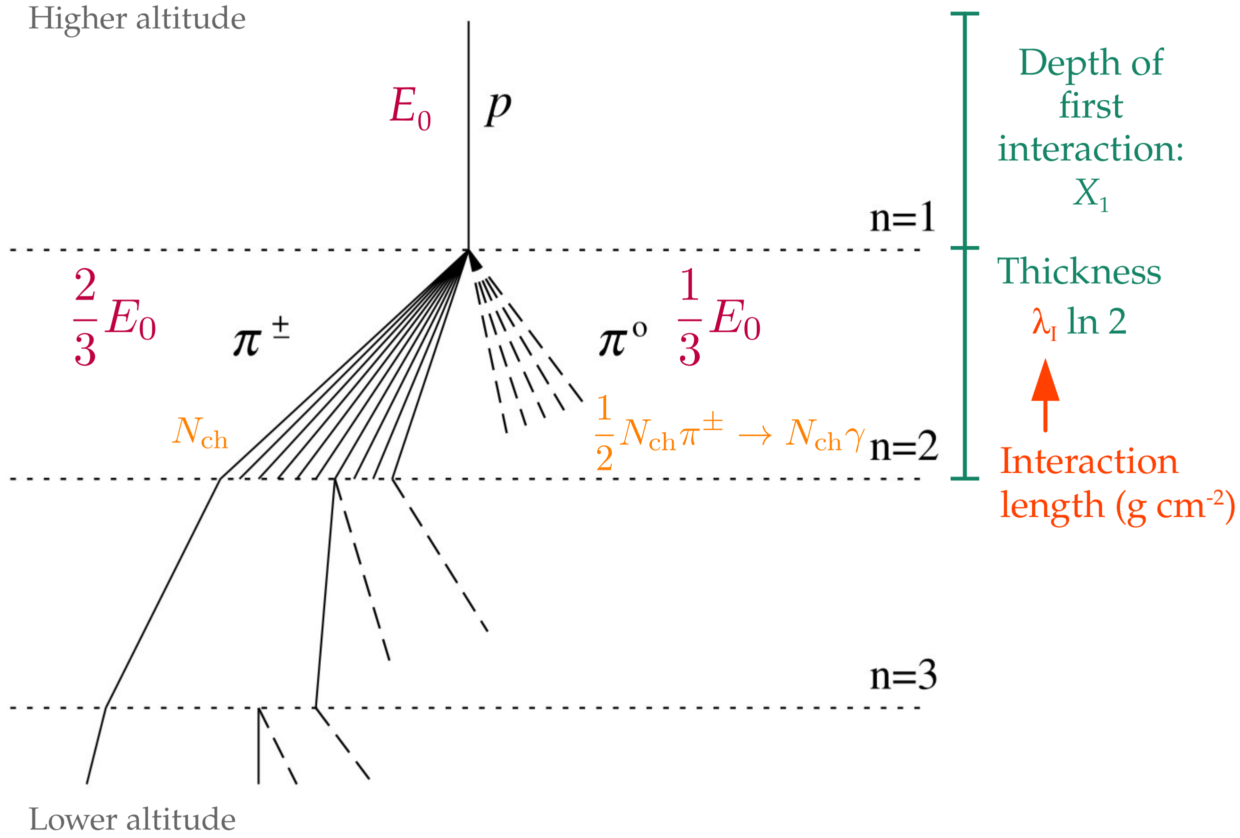

Proton-air interaction length:

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Depth of first interaction:

$$X_1 = \lambda_{\mathrm{I}} \ln 2$$

Heitler, *The Quantum Theory of Radiation*, 1954
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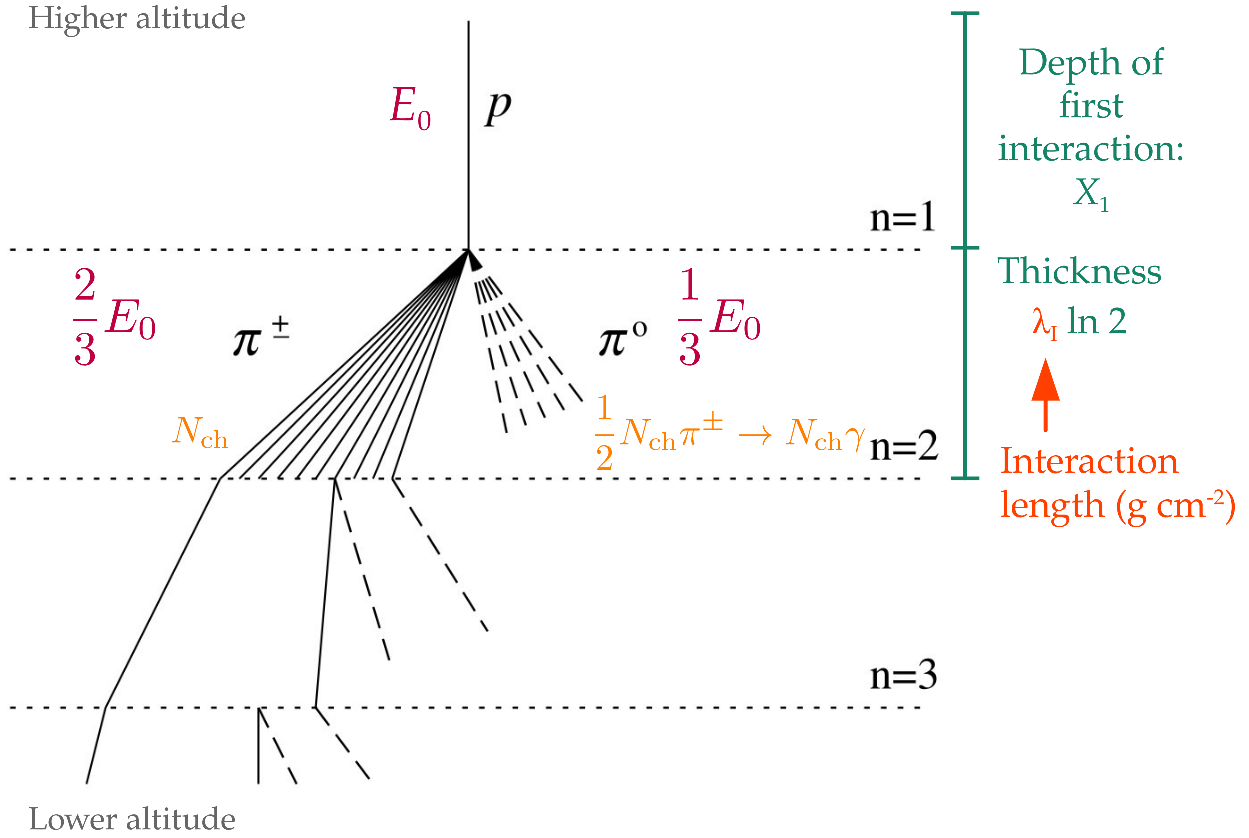
Shower development in the atmosphere

Inferring X_{max}:



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Each photon from π^0 decay starts a shower of energy $(E_0/3)/N_{ch}$

Heitler, *The Quantum Theory of Radiation*, 1954
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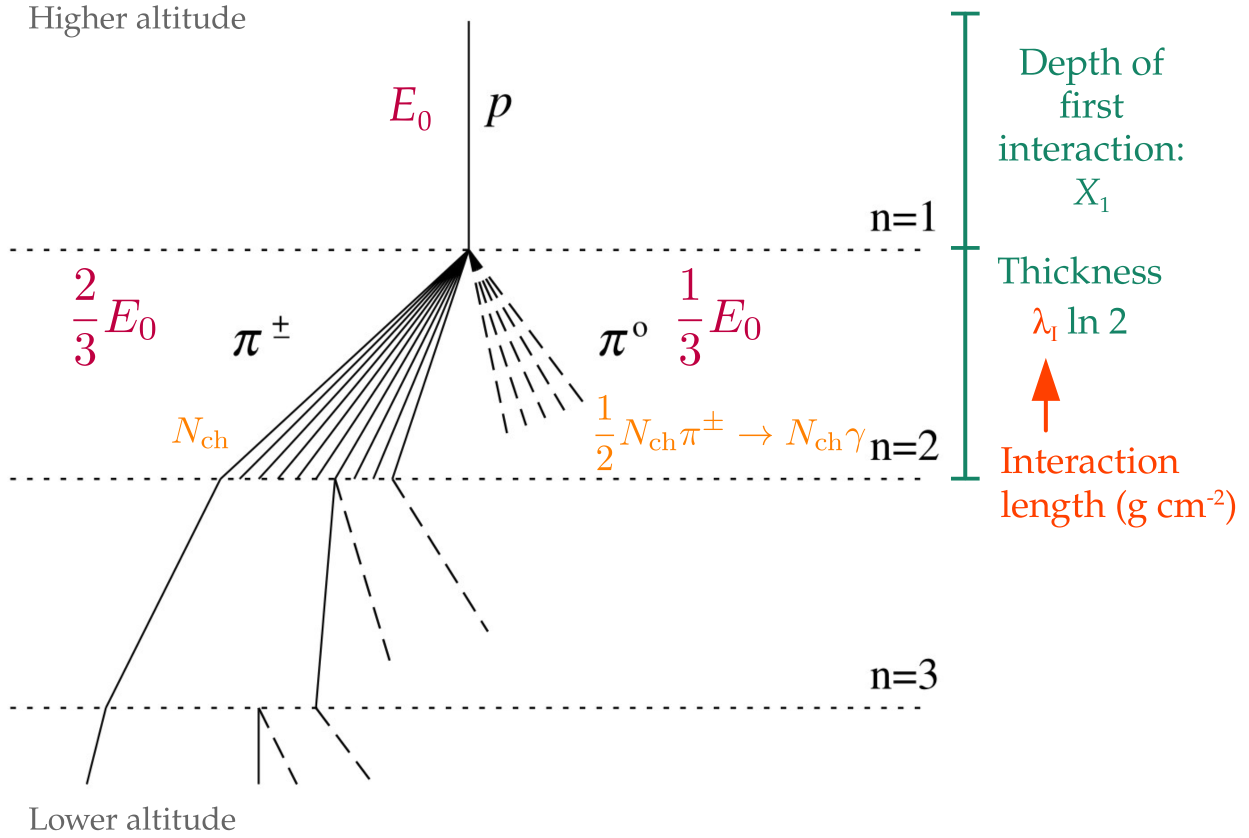
Shower development in the atmosphere

Inferring $X_{\max}$:



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Each e.m. shower reaches maximum at $\lambda_\Gamma \ln[E_0/(3N_{\text{ch}})/E_{\text{C}}^e]$

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Shower development in the atmosphere

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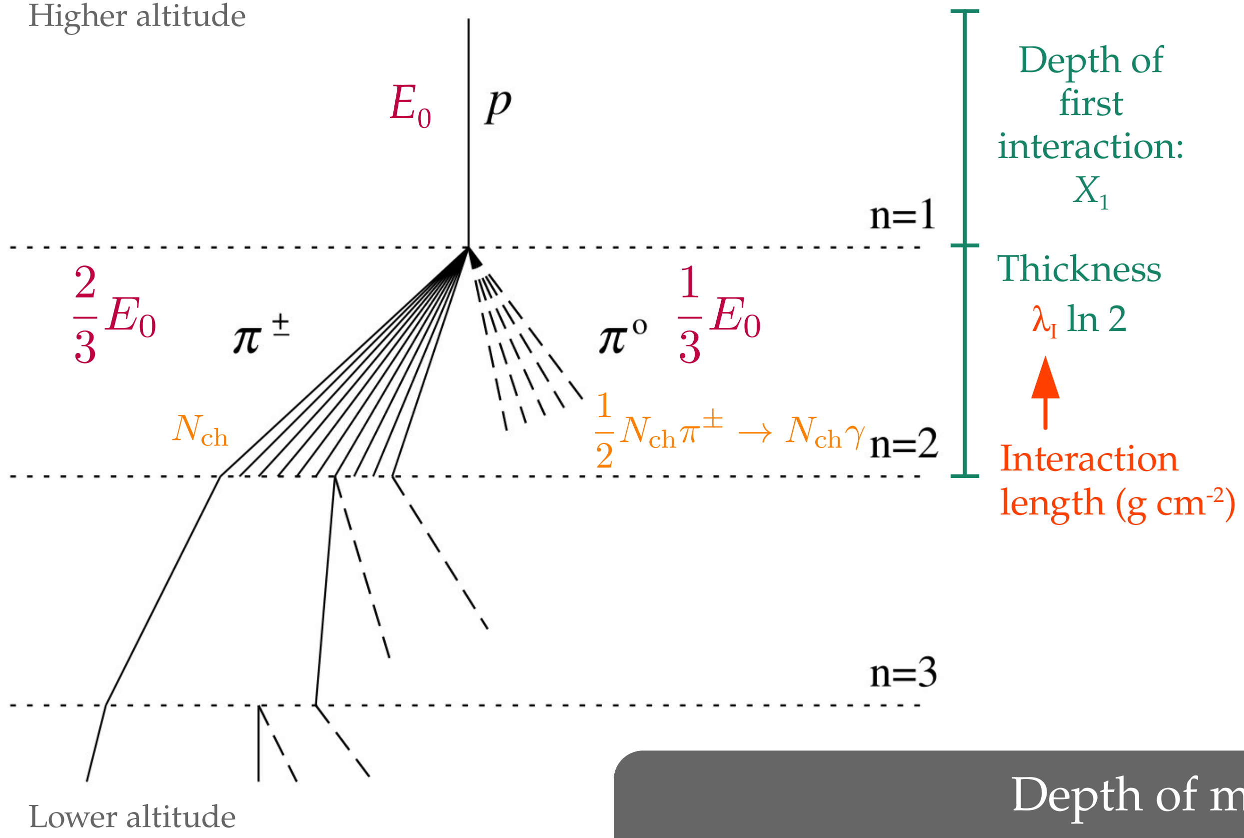

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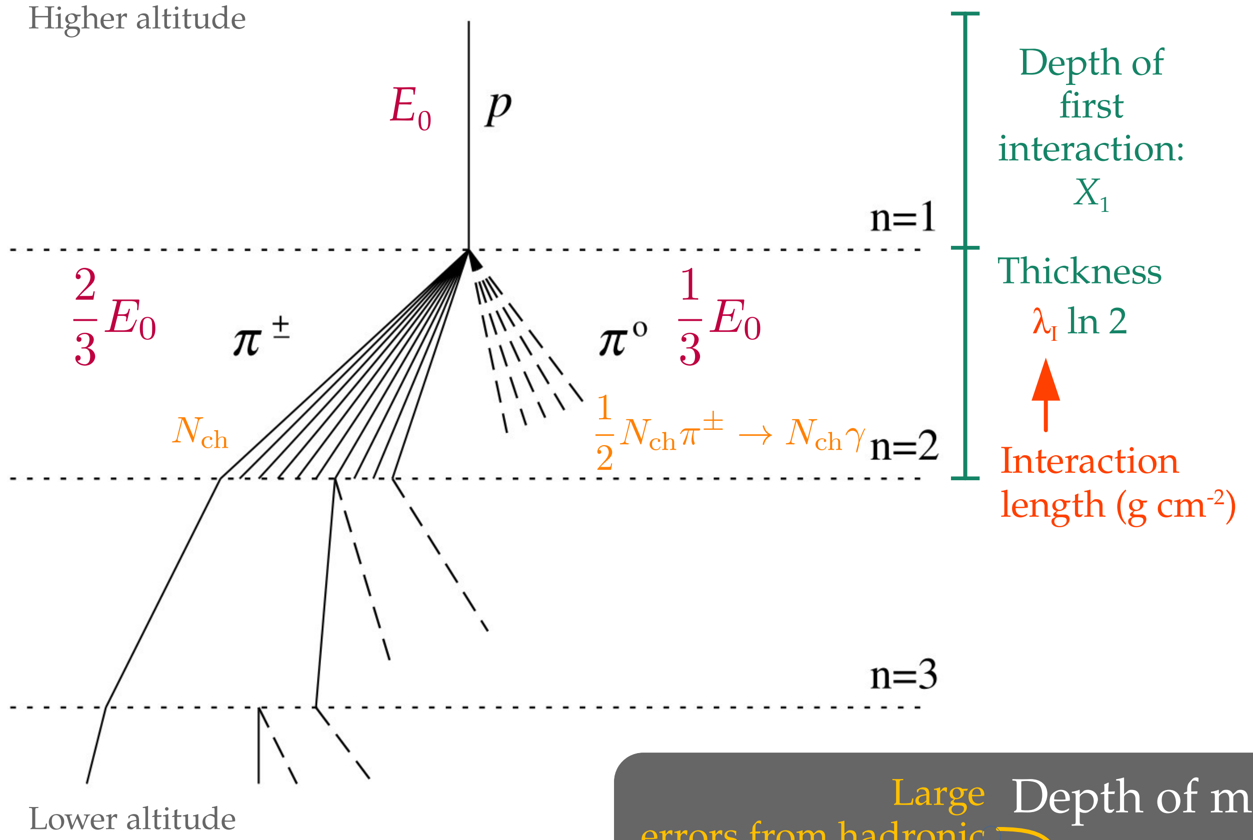
Depth of maximum of the p-initiated shower:

$$X^p_{max} = X_1 + \lambda_\Gamma \ln[E_0/(3N_{ch}E^e_C)]$$

Shower development in the atmosphere

Inferring X_{max}:



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Depth of maximum of the p-initiated shower:

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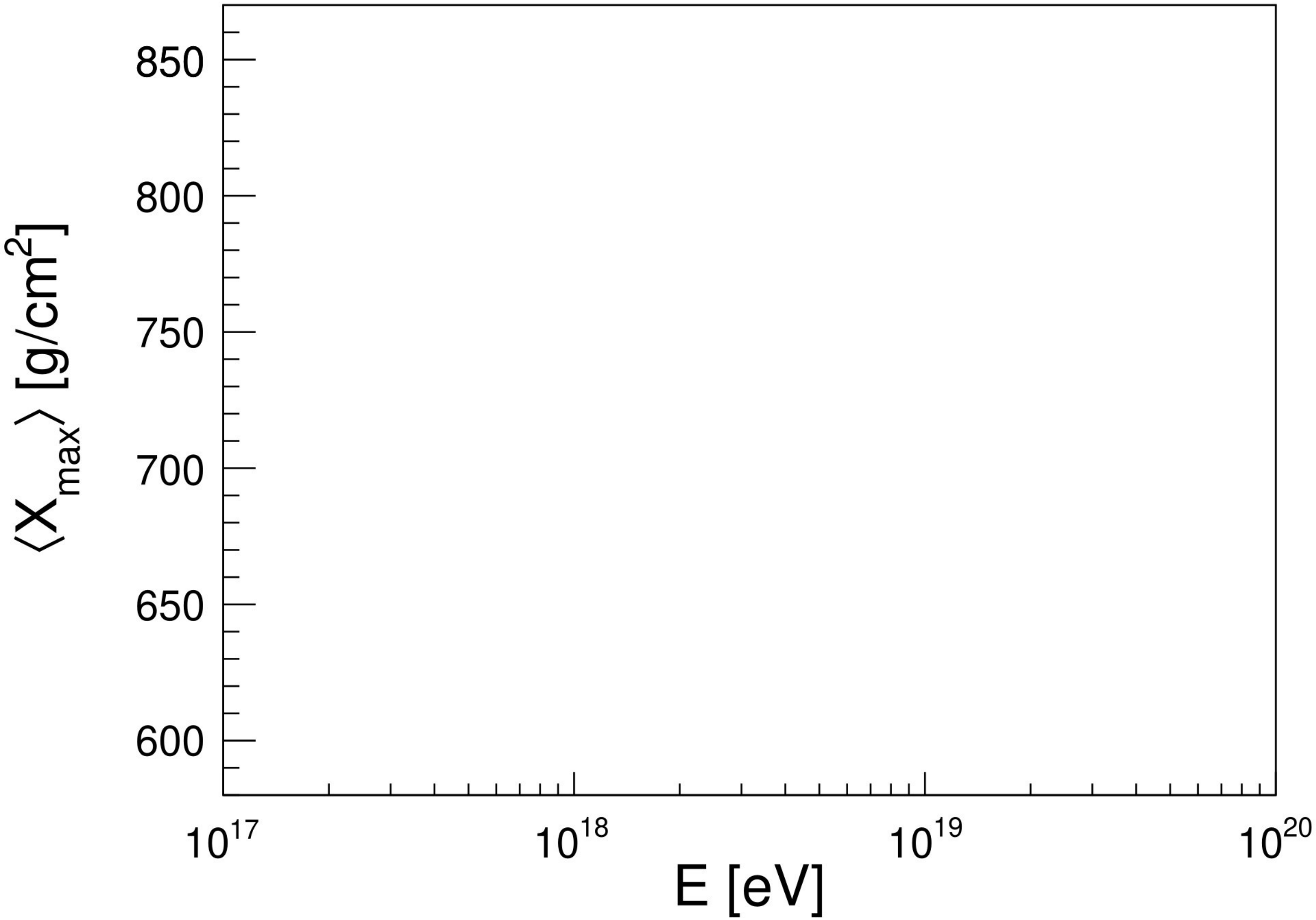
Large errors from hadronic interaction models

Heitler, *The Quantum Theory of Radiation*, 1954
Matthews, *Astropart. Phys.* 2005

X_{max} and UHECR mass composition



Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

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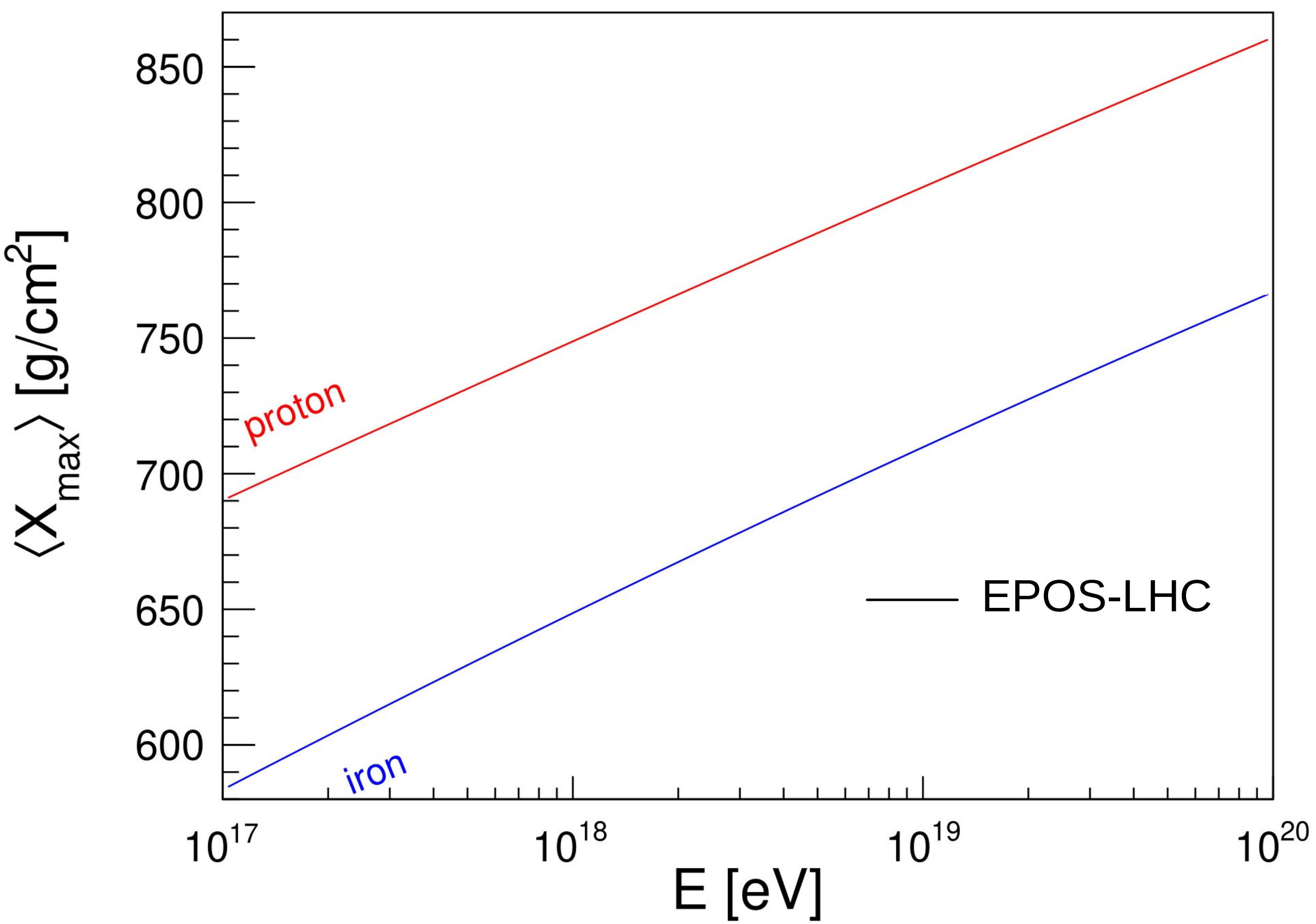

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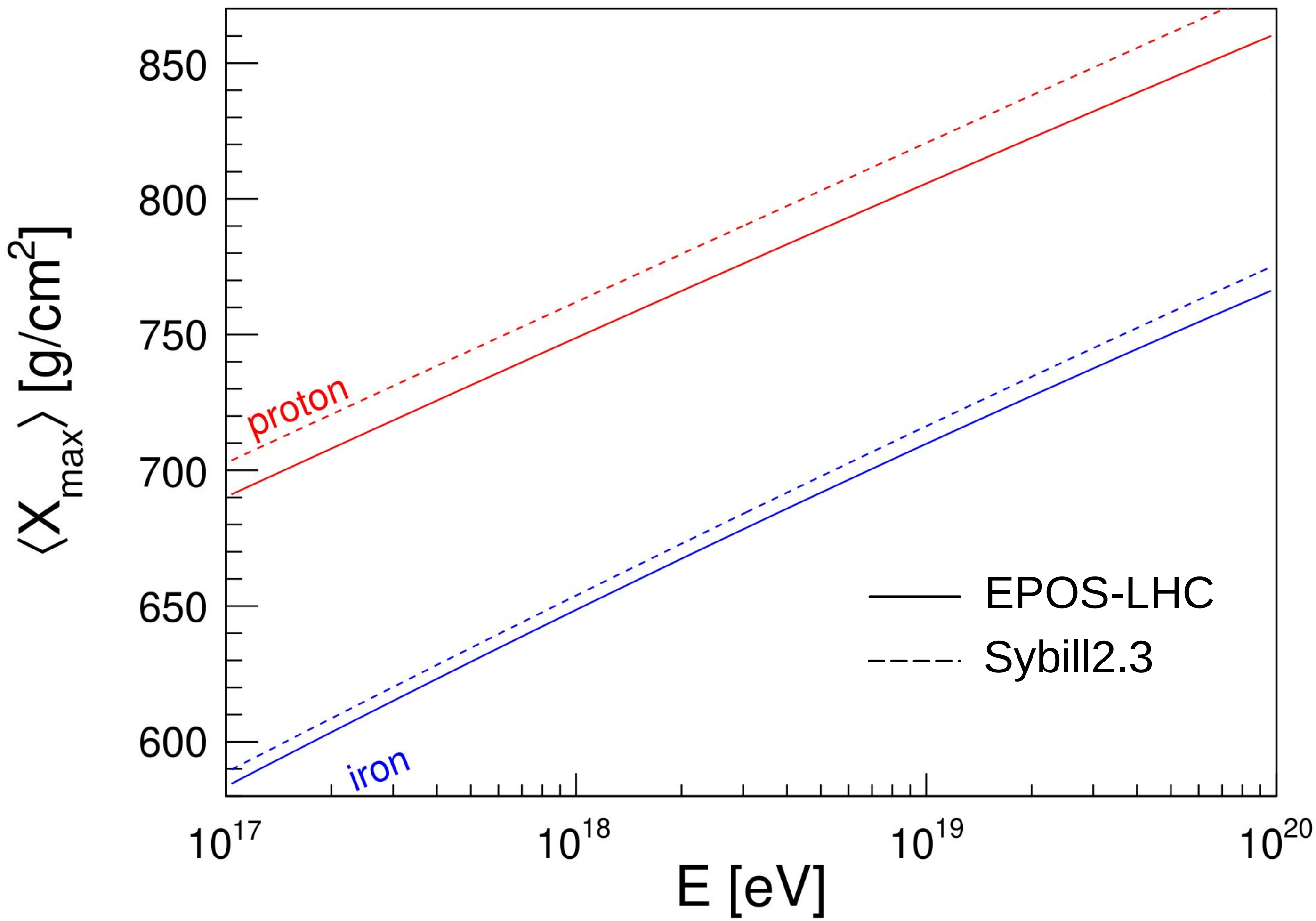

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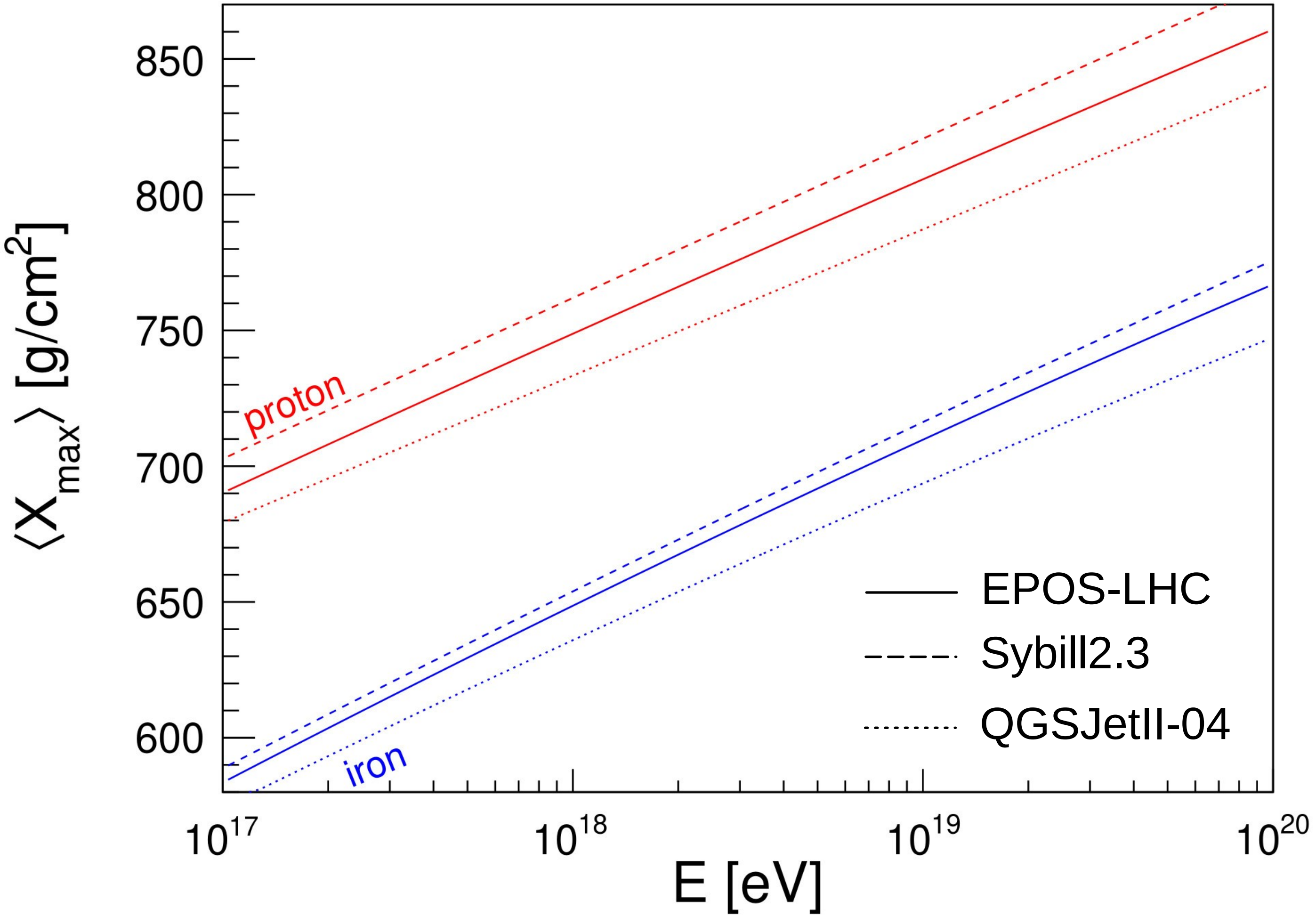

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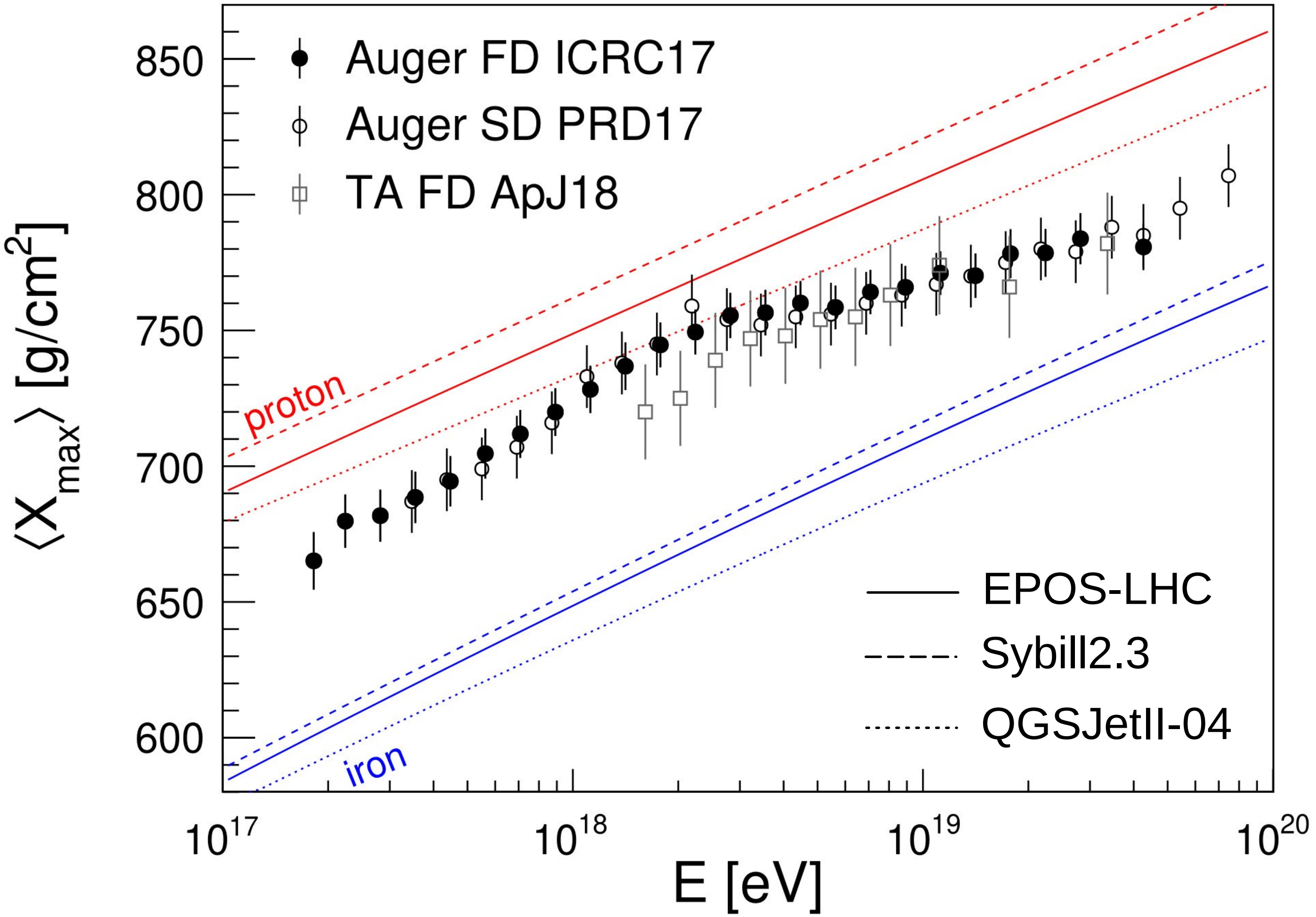

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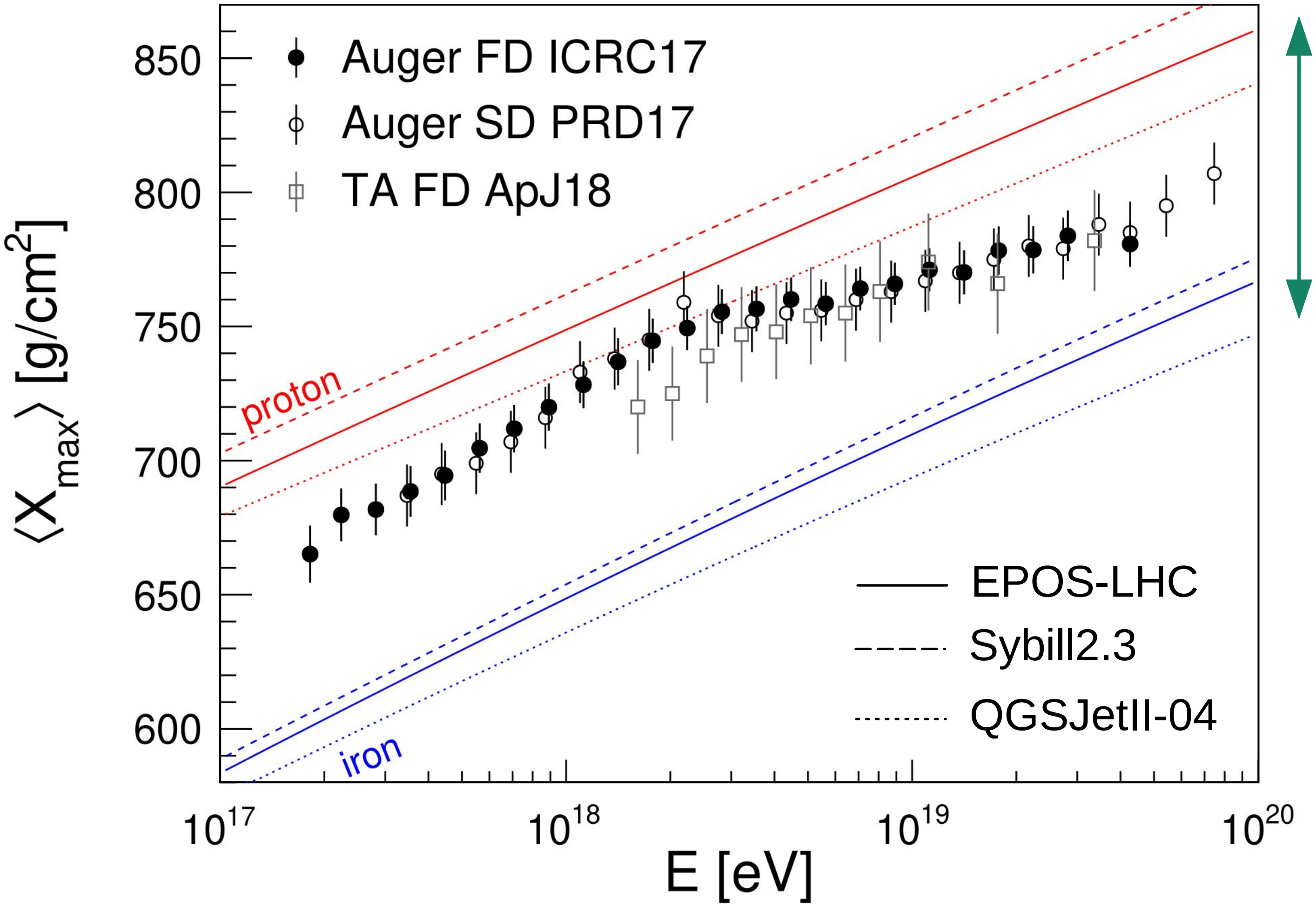

Other mass groups lie within this band (He, N, Si)

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

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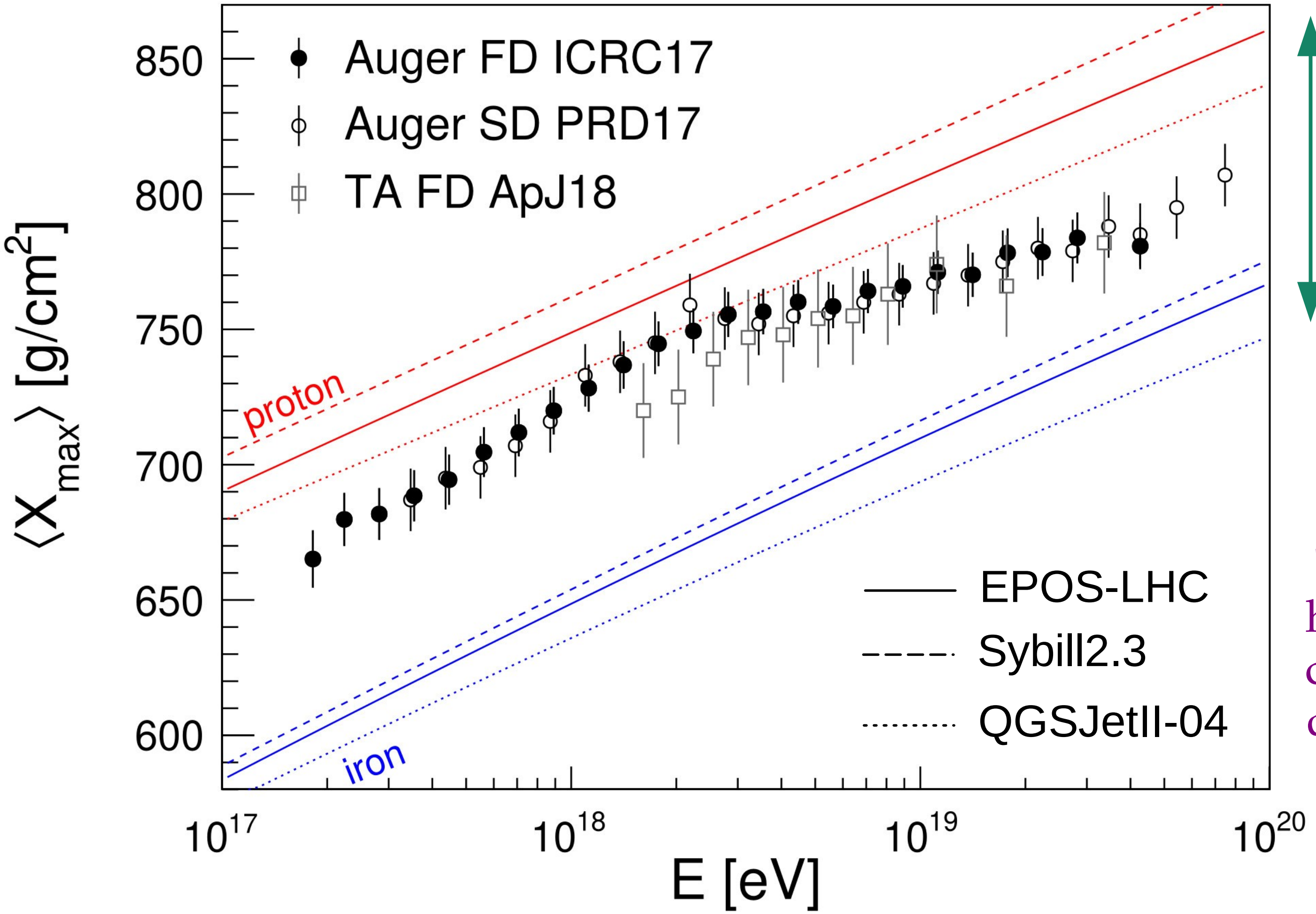

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This is why it's hard to suss out contributions of different nuclei!

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

UHECRs: more sophisticated models

Use more data:
Spectrum + mass composition ($X_{\max}$)

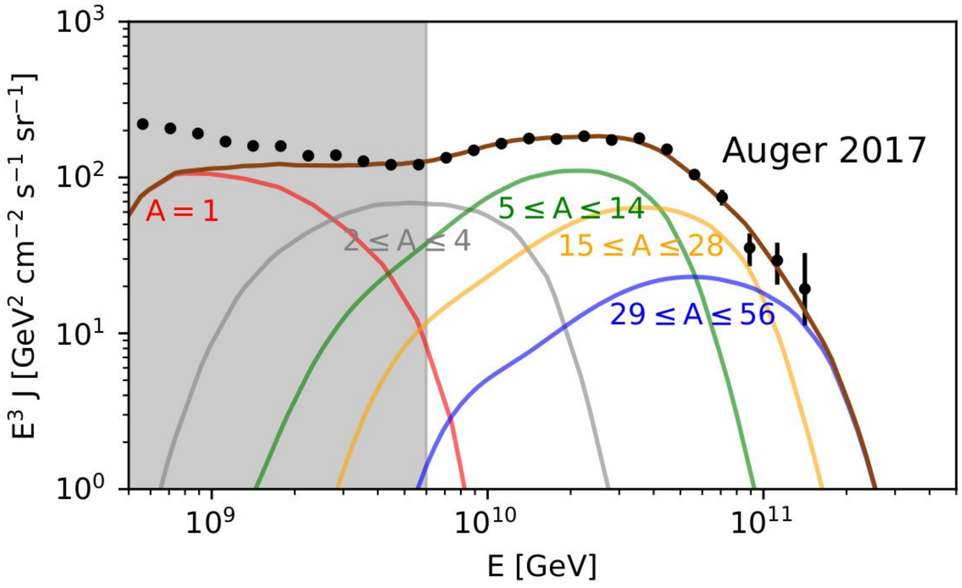
Five mass groups:
H, He, N, Si, Fe

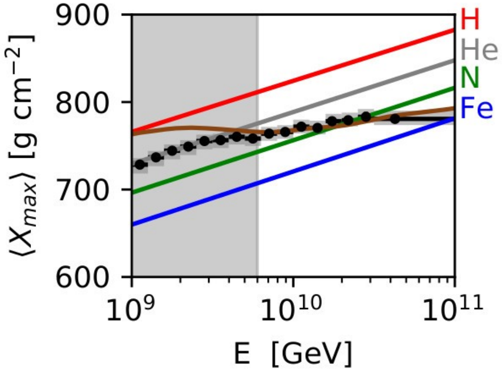
Common maximum rigidity:
Max. rigidity is $R_{\max} = E_{\max}/Z$

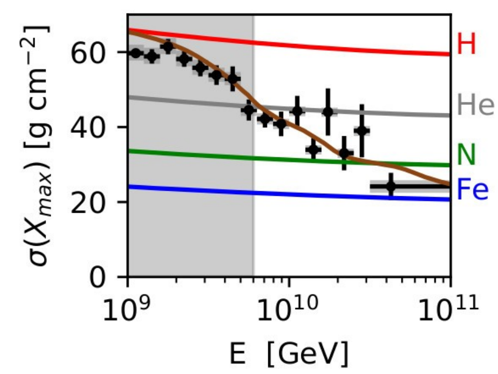
$$Q_Z(E) \propto E^{-\gamma} e^{-E/(ZR_{\max})}$$

Add nuclei photodisintegration:
During propagation, interaction of nuclei on CMB or EBL breaks them up,

$$A + \gamma \to (A-1) + \gamma$$







Heinze, Fedynitch, Boncioli, Winter, *ApJ* 2019
See also: Romero-Wolf & Ave, *JCAP* 2018
Alves Batista, Almeida, Lago, Kotera, *JCAP* 2019

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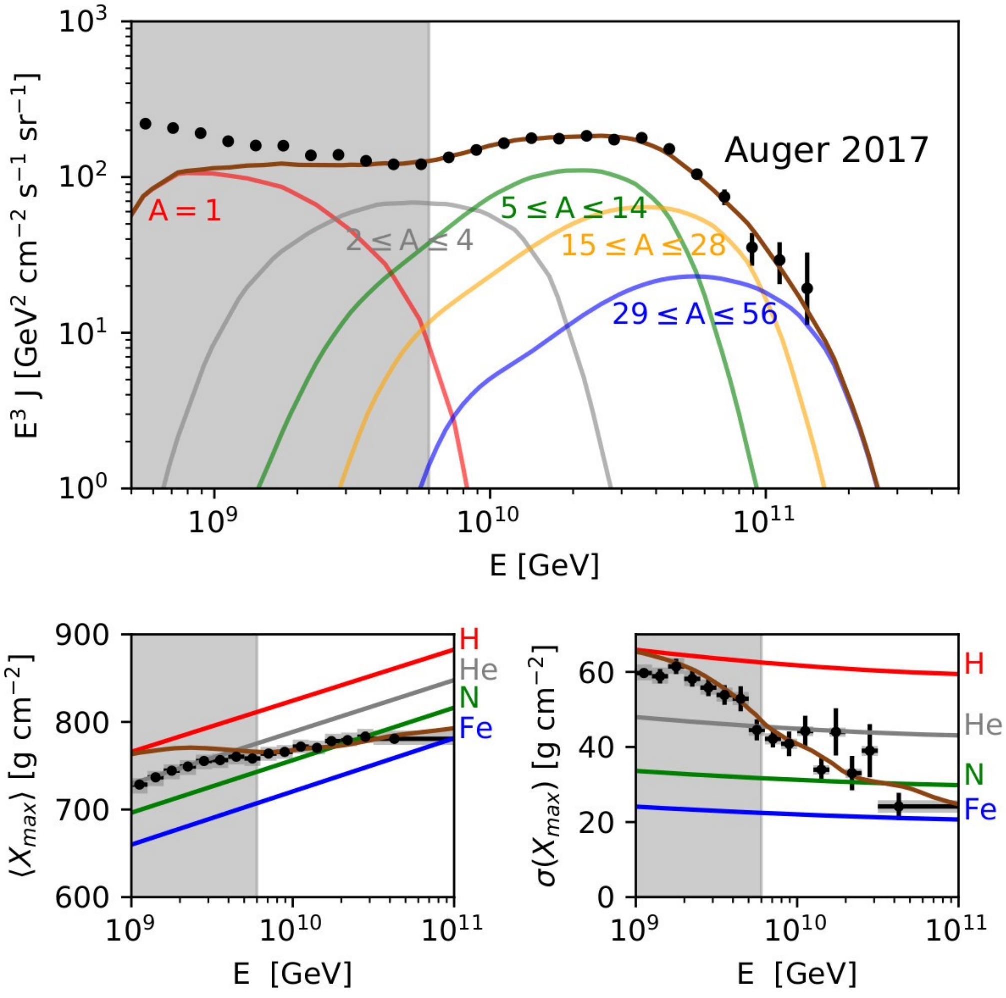

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Fedynitch, Boncioli, Winter, *Sci. Rep.* 2017

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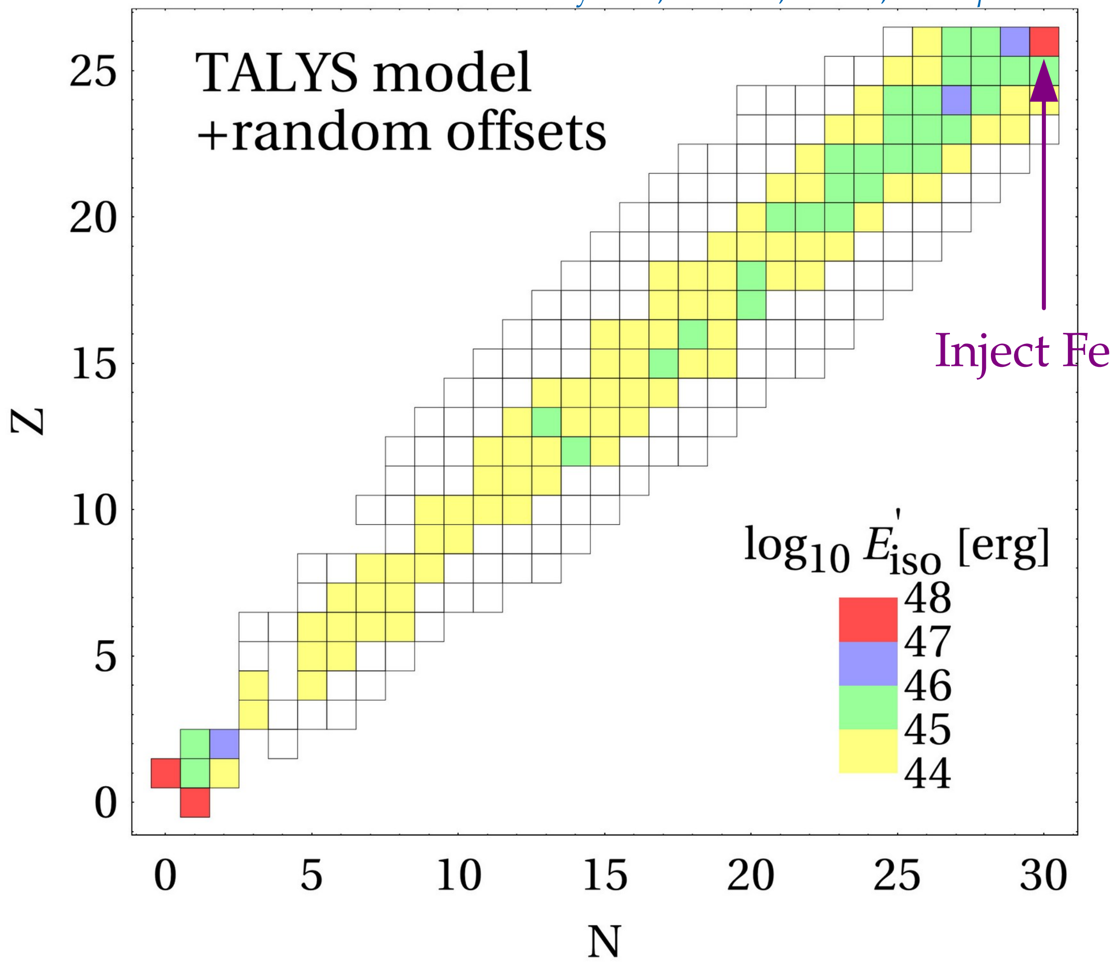


See also: Romero-Wolf & Ave, *JCAP* 2018
Alves Batista, Almeida, Lago, Kotera, *JCAP* 2019

UHECR anisotropy

How do we know that UHECRs have an extragalactic origin?

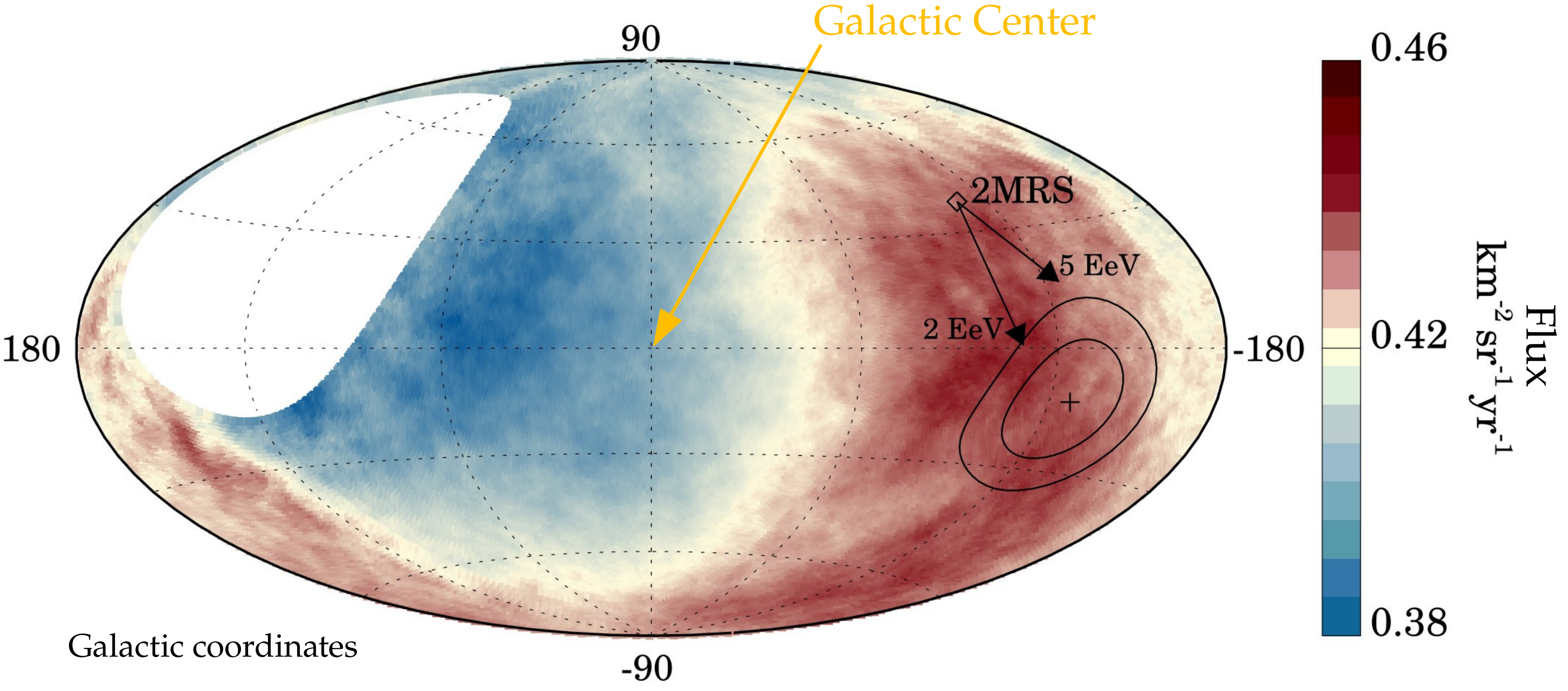
1. Their energies are so large that their Larmor radius cannot be contained by the Milky Way

$$R_L = \frac{E_p}{eB} \approx \frac{10^{18}\ \mathrm{eV}}{e \times 1\ \mu\mathrm{G}} \gg 100\ \mathrm{kpc}$$

2. We can look at the distribution of arrival directions of UHECRs

UHECR anisotropy

Flux of UHECRs > 8 EeV (Auger, 12 years of data!):



Auger Collab., *Science* 2017

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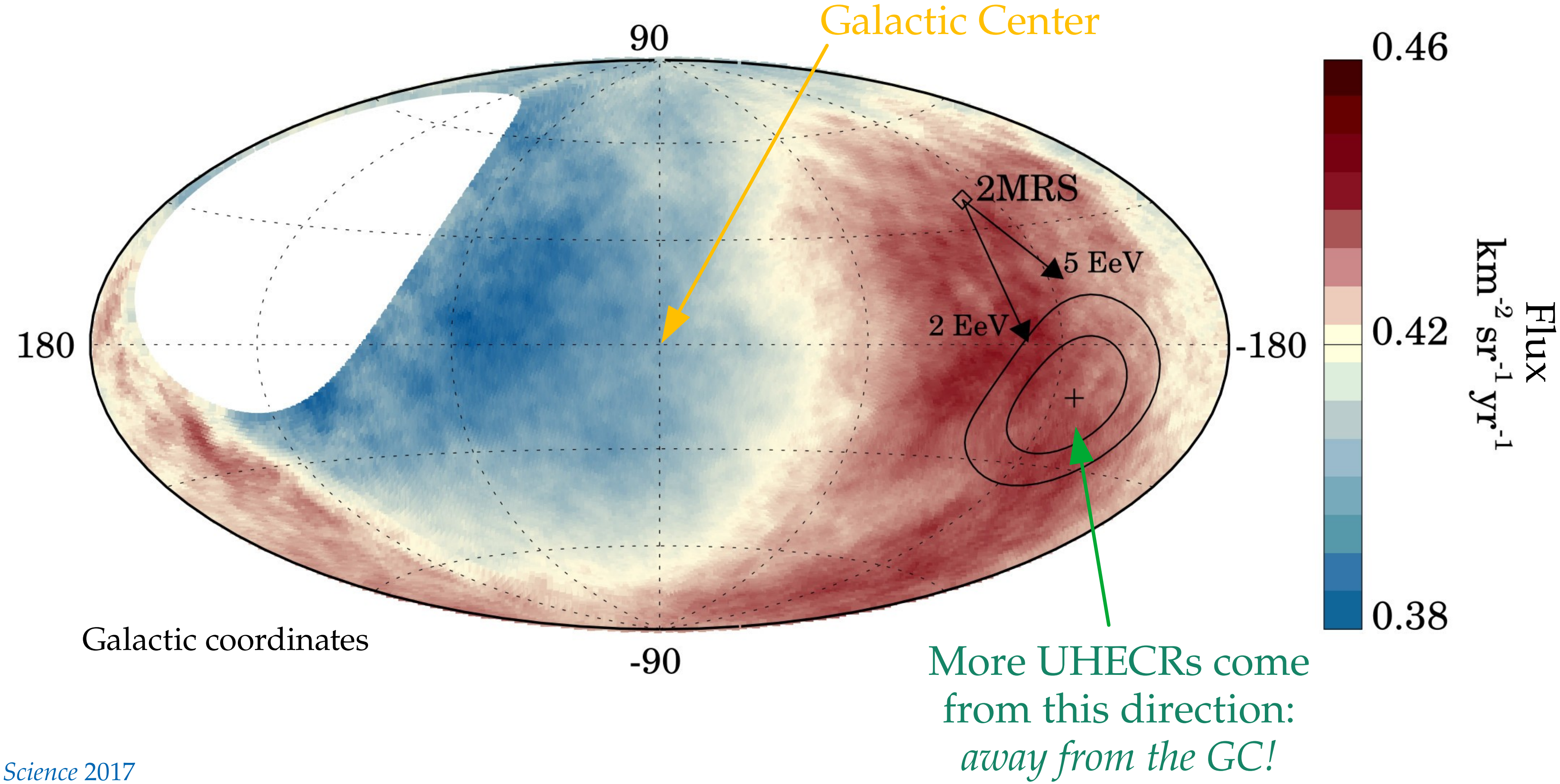

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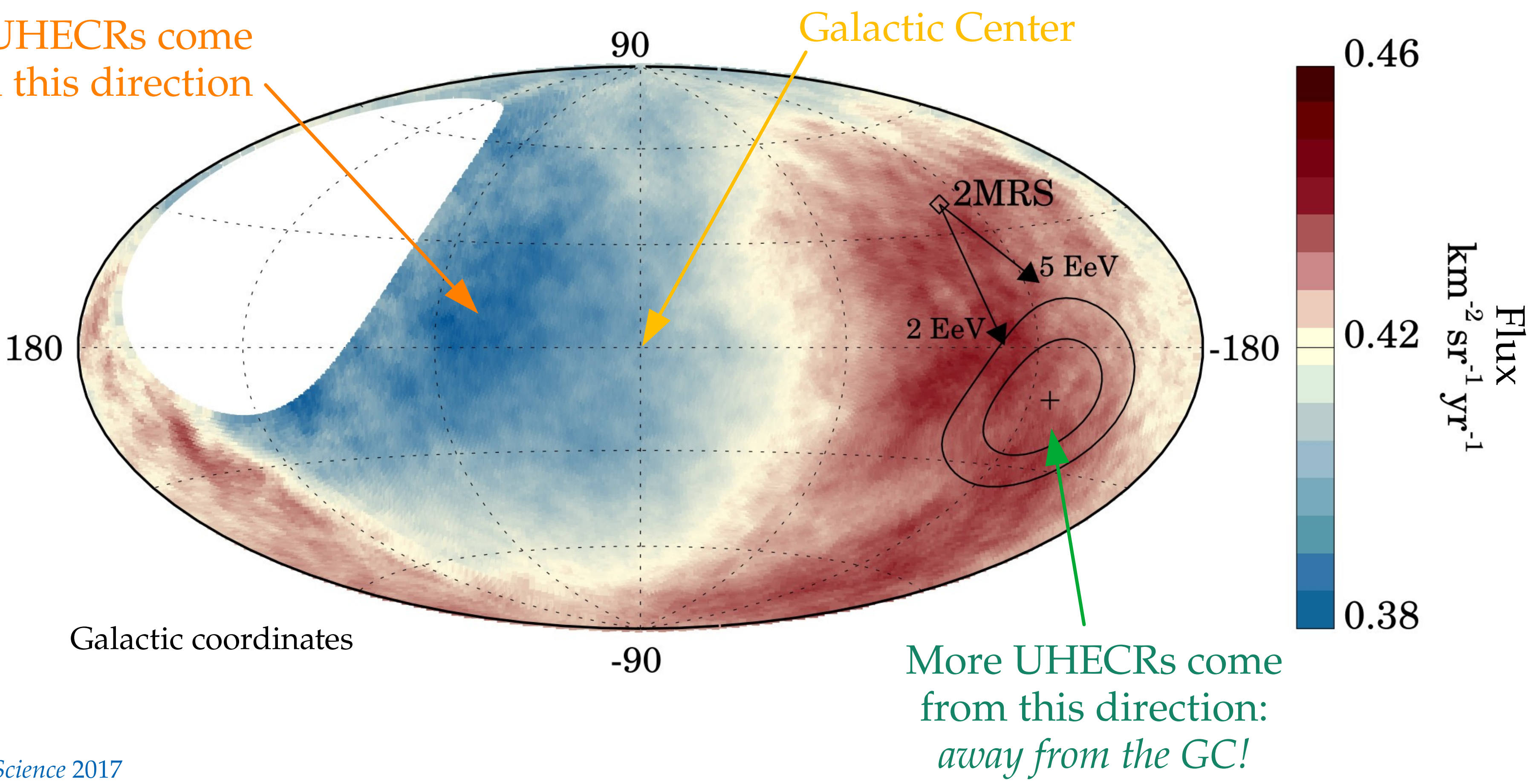

Auger Collab., *Science* 2017

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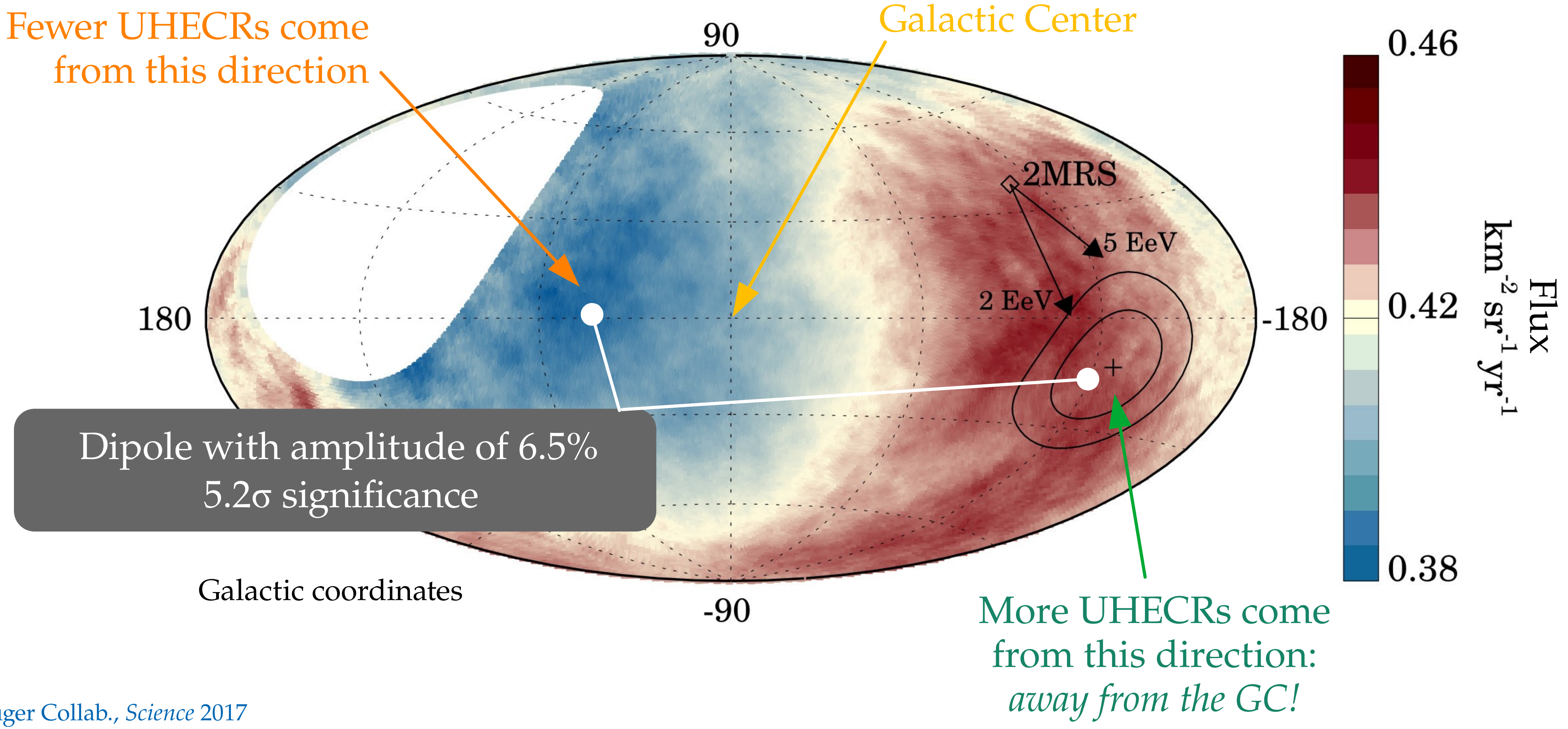

Auger Collab., *Science* 2017