

# *Neutrinos with a mass of $0.4 \text{ eV}/c^2$ Columbus' egg ?*

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## *Outline :*

- Relic neutrinos in an expanding Universe
- Current properties
- Consequences of the Pauli principle
  - *Large scale structure*
  - *Accelerated expansion*
- Intriguing features of the cosmic ray spectrum
  - *Dark matter*
- Conclusions

*Part 1 (9/27)*

*Part 2 (9/29)*

# Part 1

*Neutrinos in an expanding Universe*

# Big Bang Relics

- *Relic photons*

- When Universe was  $\sim 300,000$  years old ( $T \sim 3,000$  K):
  - End of thermal equilibrium  $\gamma + H \rightleftharpoons p + e$
  - $\gamma$ 's decouple from matter, stable atoms form
  - Start of *matter dominated* era
- 1964: Cosmic Microwave Background Radiation (Penzias, Wilson)
- 2002:  $T = 2.725$  K (WMAP), with local temperature variations at the mK level  
 $\gamma/baryon\ ratio = 1.5 - 1.8 \cdot 10^9$

- *The Leptonic Era ( $t < 1$  second)*

- Thermal equilibrium  $\gamma + \gamma \rightleftharpoons e^+ + e^-$ ,  $\bar{\nu}_e + p \rightleftharpoons n + e^+$ ,  $\nu_e + n \rightleftharpoons p + e^-$
- $\sim 1$  second ( $T \sim 1$  MeV):
  - Neutron production energetically impossible →  $p/n$  asymmetry
  - Shortly afterwards: Lifetime of  $\nu_e, \bar{\nu}_e$  longer than age Universe (density!)
    - $\nu_e, \bar{\nu}_e$  decouple from matter
    - $n/p$  ratio frozen, determines cosmological He/H ratio ( $\approx 0.24$ )
    - End of leptonic era

# Properties of Relic Neutrinos (*then*)

- *Spectrum* described by relativistic Fermi-Dirac distribution function

$$N(p) \sim \frac{p^2}{\exp(pc/kT_\nu) + 1} \cdot g_s$$

$$\begin{aligned} kT_\nu &\sim 1 \text{ MeV} \\ p_\nu &\sim 1 \text{ MeV}/c \end{aligned}$$

$g_s$ : # of possible spin states (2 for  $\nu_{\text{Majorana}}$ , 4 for  $\nu_{\text{Dirac}}$ )

- *Number density*  $n_\nu = \int_0^\infty N(p) dp$

→ During Leptonic Era (thermal equilibrium with photons):

$$\frac{n_\nu}{n_\gamma} = \frac{3}{4} \text{ (Majorana)}, \frac{6}{4} \text{ (Dirac)}$$

→ After  $t \sim 10$  s ( $kT = 511$  keV):  $e^+ e^- \rightarrow \gamma\gamma$

Entropy conservation →  $(\frac{n_\nu}{n_\gamma})' = \frac{n_\nu}{n_\gamma} \cdot \frac{4}{11} = -\frac{3}{11} (\nu_M), \frac{6}{11} (\nu_D)$

# Properties of Relic Neutrinos (*now*)

*What happened to the relic (anti-)neutrinos?*

- Their **wavelengths expanded** with the Universe

$$p_\nu = h/\lambda \propto R^{-1}$$

- Relativistic Fermi-Dirac spectrum, *momentum redshifted*

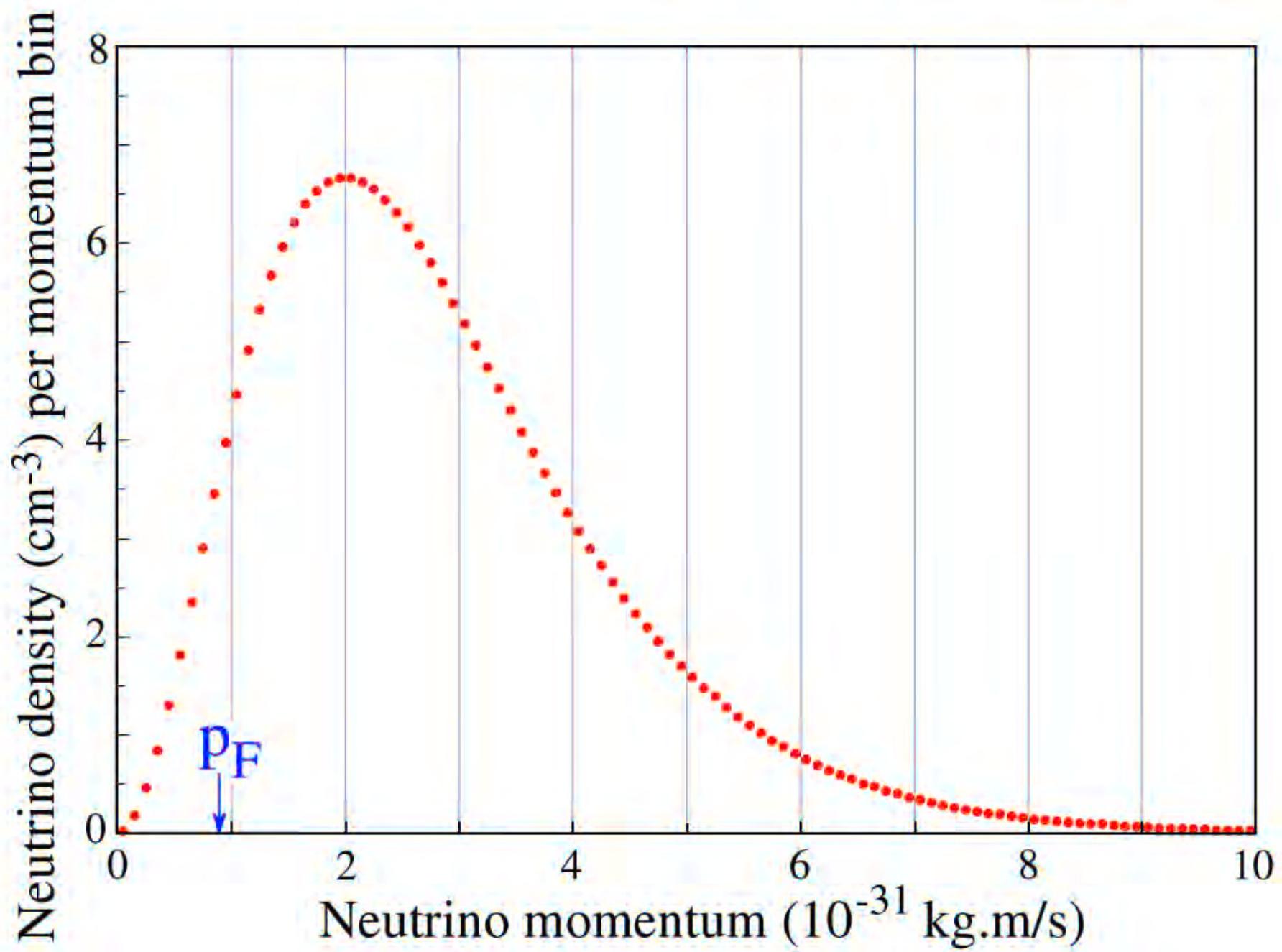
- At present:

$$N(p) \sim \frac{p^2}{\exp(pc/kT_\nu) + 1}$$

with  $T_\nu \sim 1.95 \text{ K} (= \sqrt[3]{4/11} T_\gamma) \rightarrow kT_\nu = 1.68 \cdot 10^{-4} \text{ eV}$

- $n_\gamma = 411/\text{cm}^3 \rightarrow n_\nu \sim 110/\text{cm}^3$  (Majorana),  $\sim 220/\text{cm}^3$  (Dirac)  
*for each flavor*
- *There are thus  $\mathcal{O}(10^{87})$  relic neutrinos in the observable Universe*  
*These outnumber baryons by  $\mathcal{O}(10^{10})$*

# Fermi-Dirac relic neutrino spectrum at $T_V = 1.95$ K



# The neutrino mass

## Measurements

- Most restrictive *upper* limits from  ${}^3\text{H} \rightarrow {}^3\text{He}$   $\beta$ -decay:  $m_{\nu_e} < 1.1 \text{ eV}/c^2$  (KATRIN, 2019)
- Superkamiokande: Zenith-angle dependence of  $\nu_e/\nu_\mu$  ratio  
 $0.0015 < \Delta m^2 < 0.006 \text{ (eV)}^2 \rightarrow$  At least one  $\nu$  mass  $> 0.04 \text{ eV}/c^2$

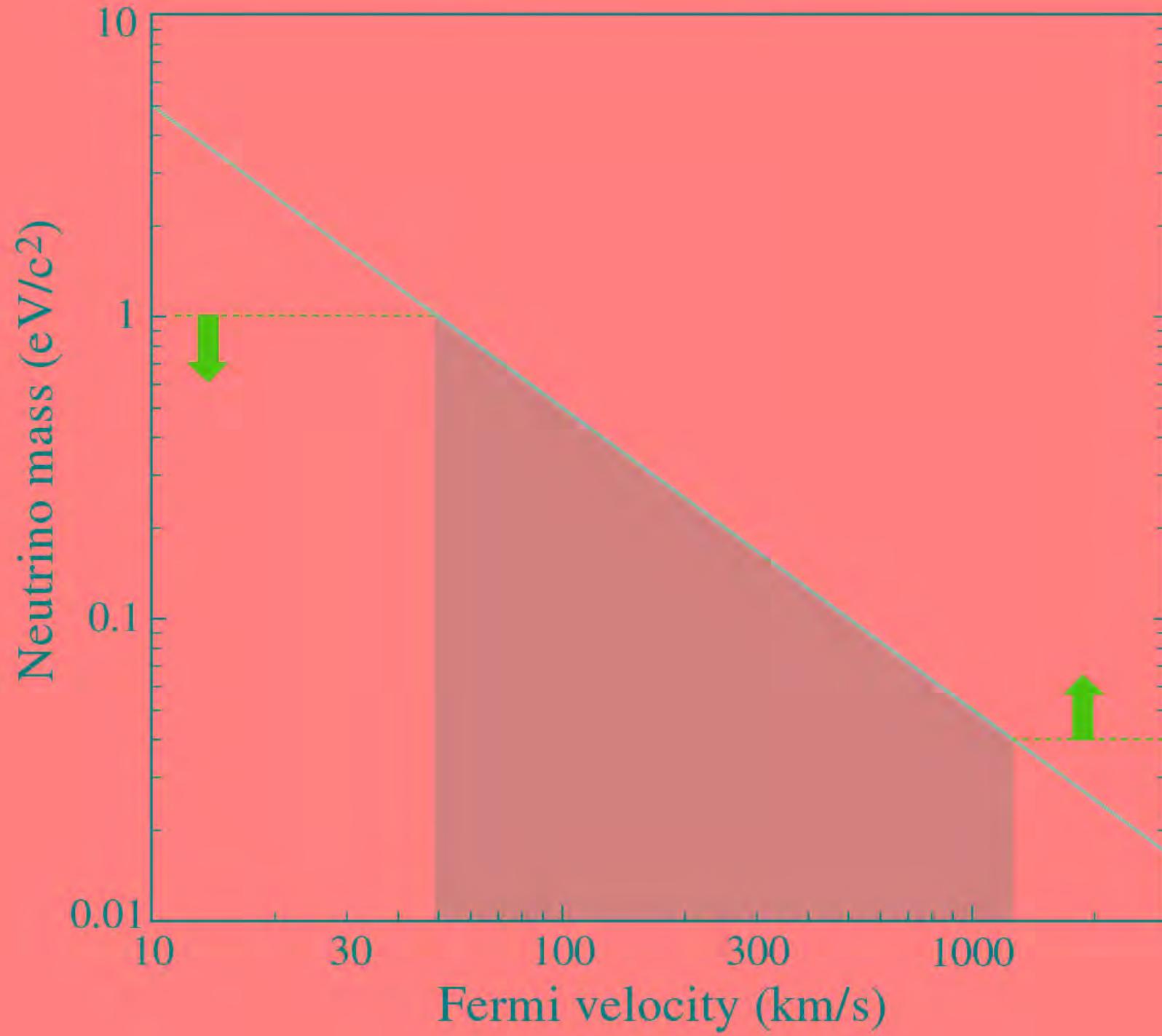
## Interpretations

- Neutrinoless  $\beta\beta$  decay  ${}^{76}\text{Ge}$  (?):  $0.24 < m_\nu < 0.58 \text{ eV}/c^2$  ( $3\sigma$ )  
Phys. Lett. B586 (2004) 198, Nucl. Instr. Meth. A522 (2004) 371
- PeV features of cosmic-ray spectra:  $m_{\nu_e} = 0.5 \pm 0.2 \text{ eV}/c^2$   
Astroparticle Phys. 19 (2003) 379
- Cosmology (WMAP *etc.*):  $\sum_i m_{\nu_i} < 1 - 2 \text{ eV}/c^2$

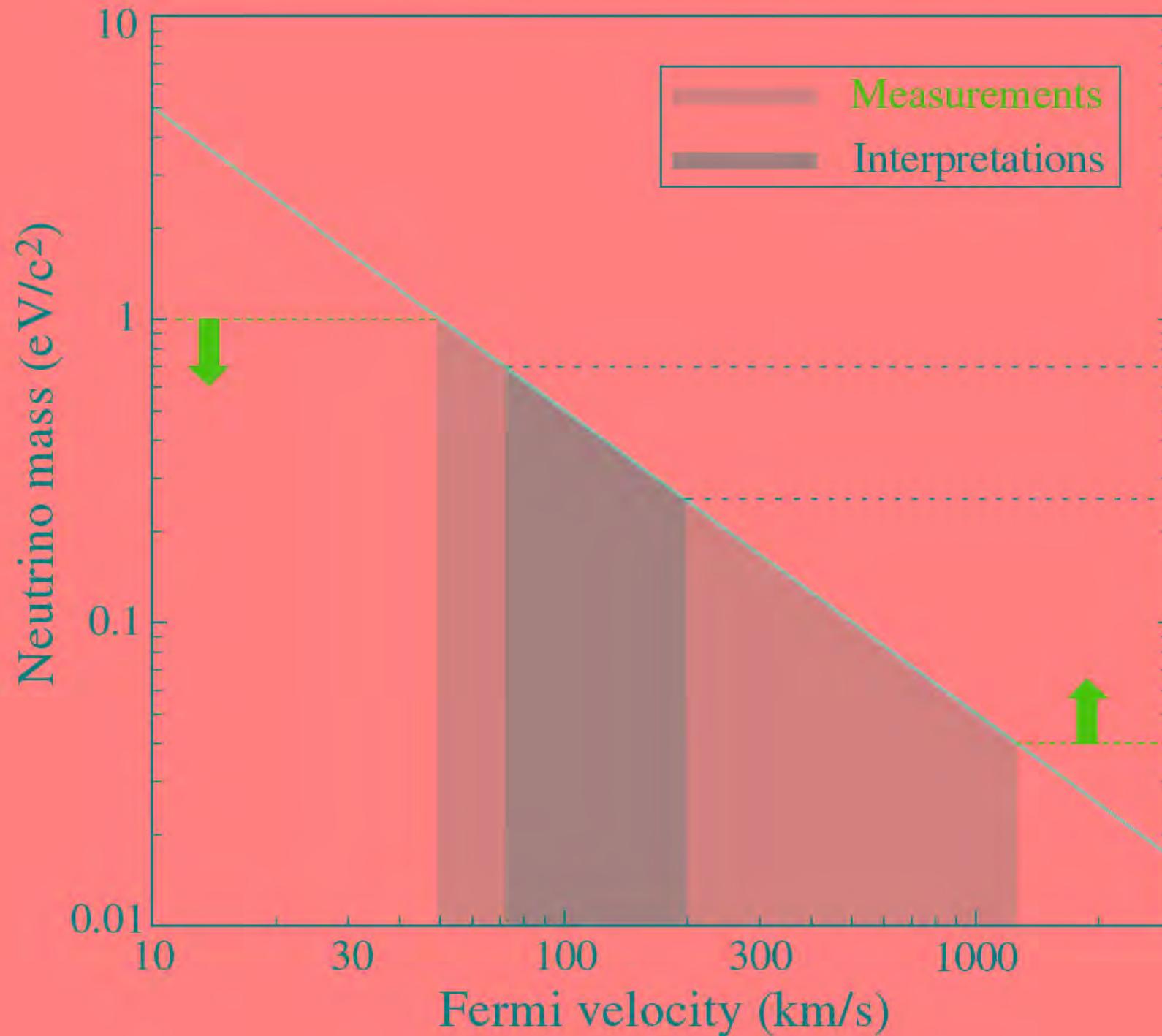
## Velocities of massive relic neutrinos

- Fermi momentum of relic neutrinos:  $p_F = \frac{kT_\nu}{c} = 1.68 \cdot 10^{-4} \text{ eV}/c$   
Momenta are redshifted by a factor  $10^{10}$  since decoupling  
(from  $1 \text{ MeV}/c \rightarrow 10^{-4} \text{ eV}/c$ )
- If restmass  $= 1 \text{ eV}/c^2 \rightarrow v_F = 1.68 \cdot 10^{-4} c$  (50 km/s)
  - Massive relic neutrinos may thus be **very slow!**  
(i.e. compatible with escape velocity of galaxies)

# Mass/velocity relationship relic neutrinos



# Mass/velocity relationship relic neutrinos



# Pauli, Heisenberg and fermion density

- Pauli's Exclusion Principle: *One fermion per quantum state* (e.g. atomic structure, specific heat of metals, etc.)

- Heisenberg's Uncertainty Principle:

Every quantum state occupies  $\hbar^3$  in phase space

Phase volume of 1 fermion =  $4\pi p^2 dp$

- Maximum number of fermions with momentum between  $p, p + \Delta p$  in volume  $V$ :

$$dn = V \frac{4\pi p^2 dp}{\hbar^3}$$

Maximum fermion density

$$\left[ \frac{n}{V} \right]_{\max} = \frac{4\pi}{3} \left( \frac{p_{\max}}{\hbar} \right)^3 \quad \times 2 \text{ (spin)}$$

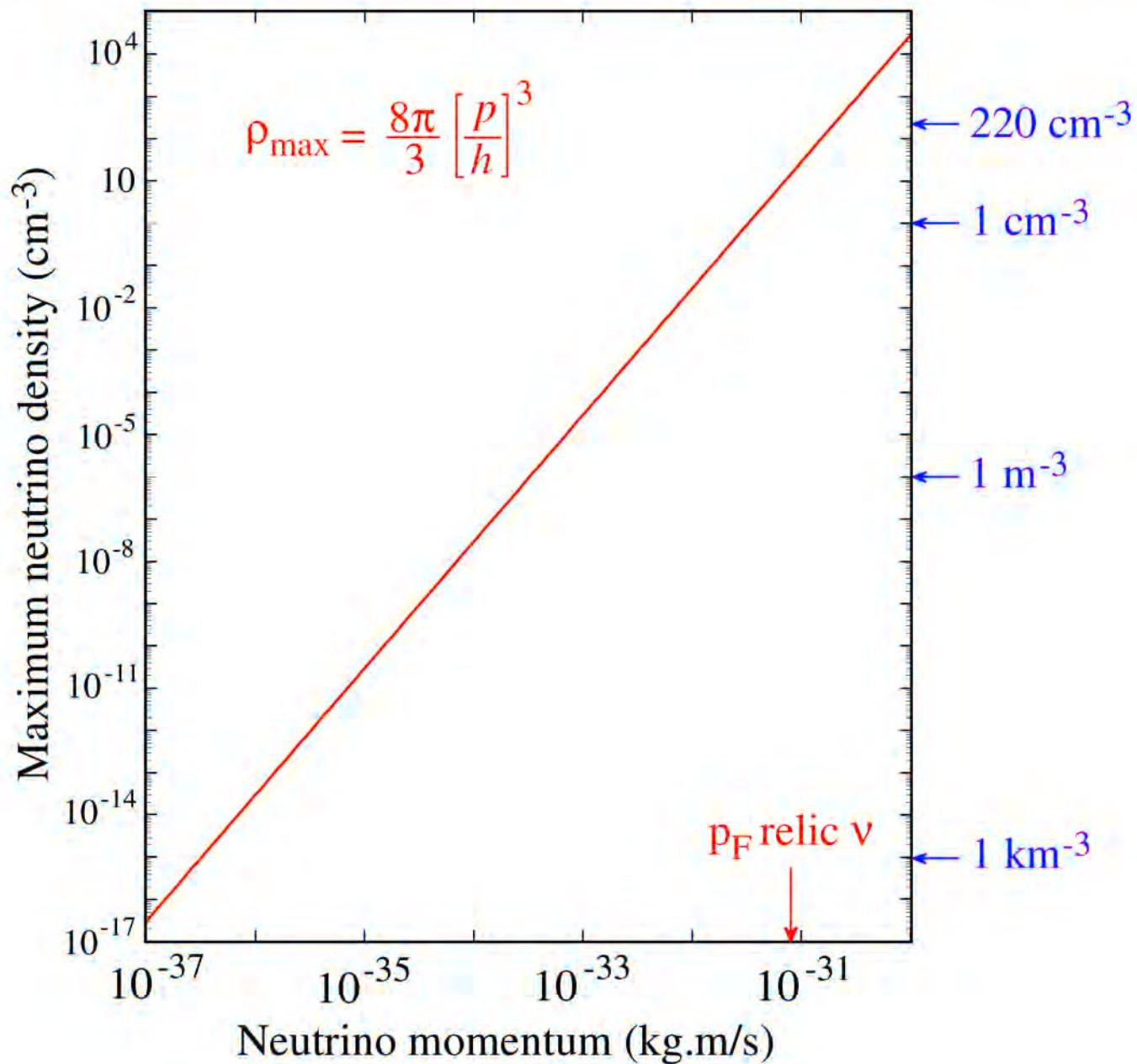
- This density *cannot be exceeded*

Prevented by the *fermion degeneracy pressure*

# Fermion degeneracy pressure

- Well-known phenomenon in astrophysics
  - For example:
    - Prevents gravitational collapse of White Dwarfs (fermions = electrons) or neutron stars (fermions = neutrons)
  - Maximum fermion density  $\rho_f \text{ (max)} = \frac{8\pi}{3} \left(\frac{p}{h}\right)^3$
  - White Dwarf:  $p \sim \text{MeV}/c$   
Neutron star:  $p \sim \text{GeV}/c$
- Relic neutrinos:  $p \sim 10^{-4} \text{ eV}/c$
- Maximum relic neutrino density is **30 (!)** orders of magnitude smaller than the electron density in White Dwarfs

# Maximum neutrino density according to Pauli



## Fermion degeneracy and the relic neutrinos

- The *relic neutrinos form a degenerate fermion gas* at  $T = 1.95 \text{ K}$   
The number of fermions with momentum between  $p, p + \Delta p$  in volume  $V$ :

$$dn = V \frac{4\pi p^2 dp}{h^3} \frac{2}{\exp(pc/kT) + 1}$$

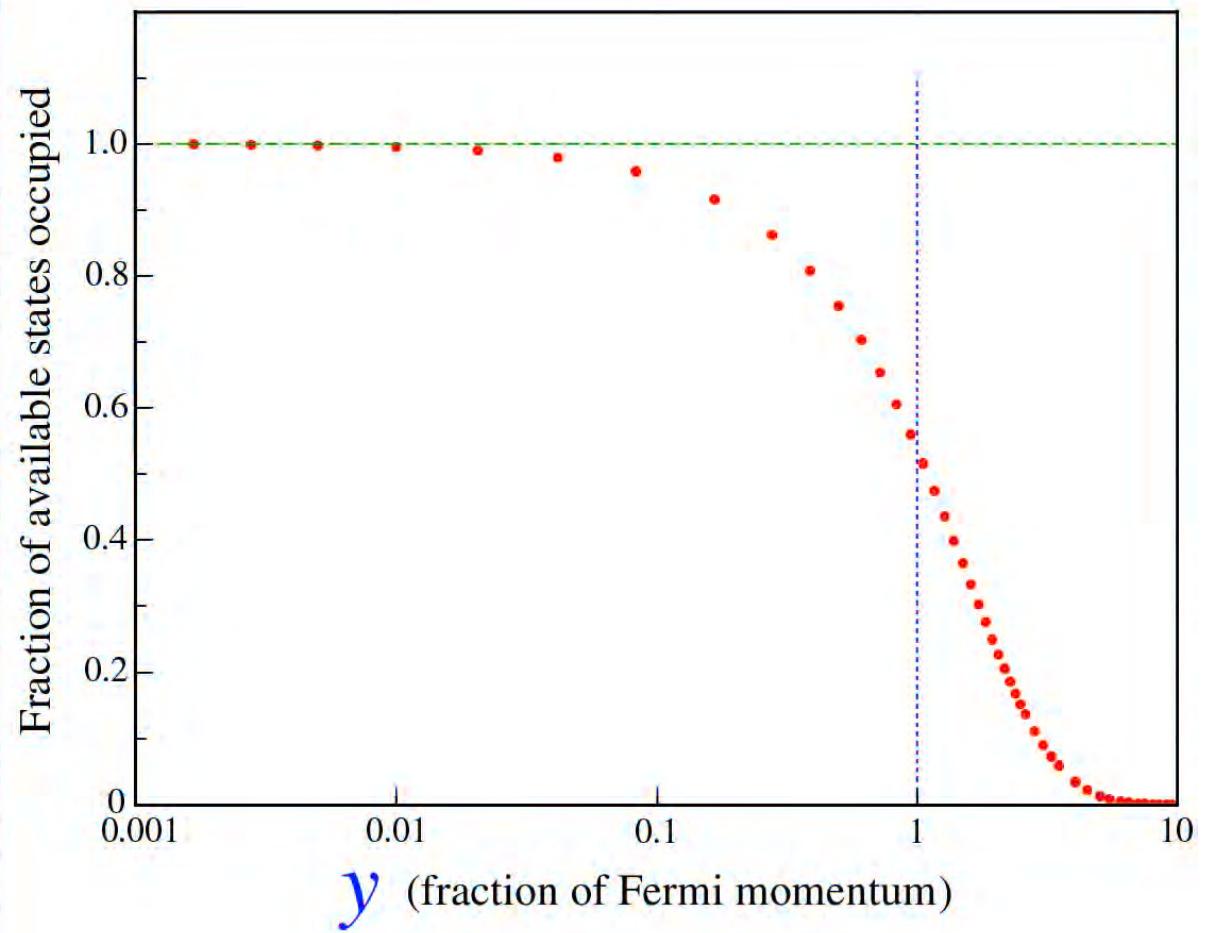
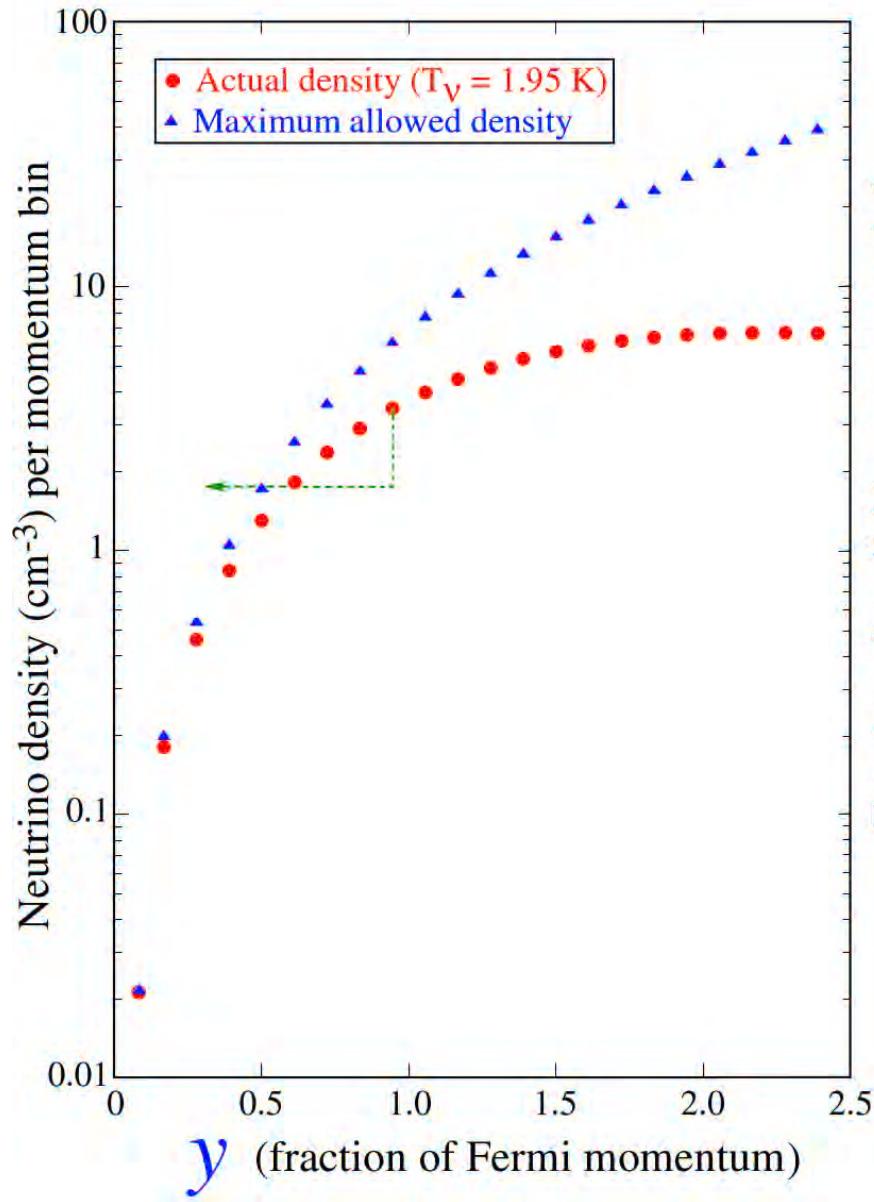


F-D factor: Describes occupancy of available quantum states

- Define  $y = \frac{p}{p_F} = \frac{cp}{kT_v}$

*Quantum states with  $y < 1$  are almost completely filled*

# Relic neutrinos: A degenerate fermion gas ( $T = 1.95$ K)



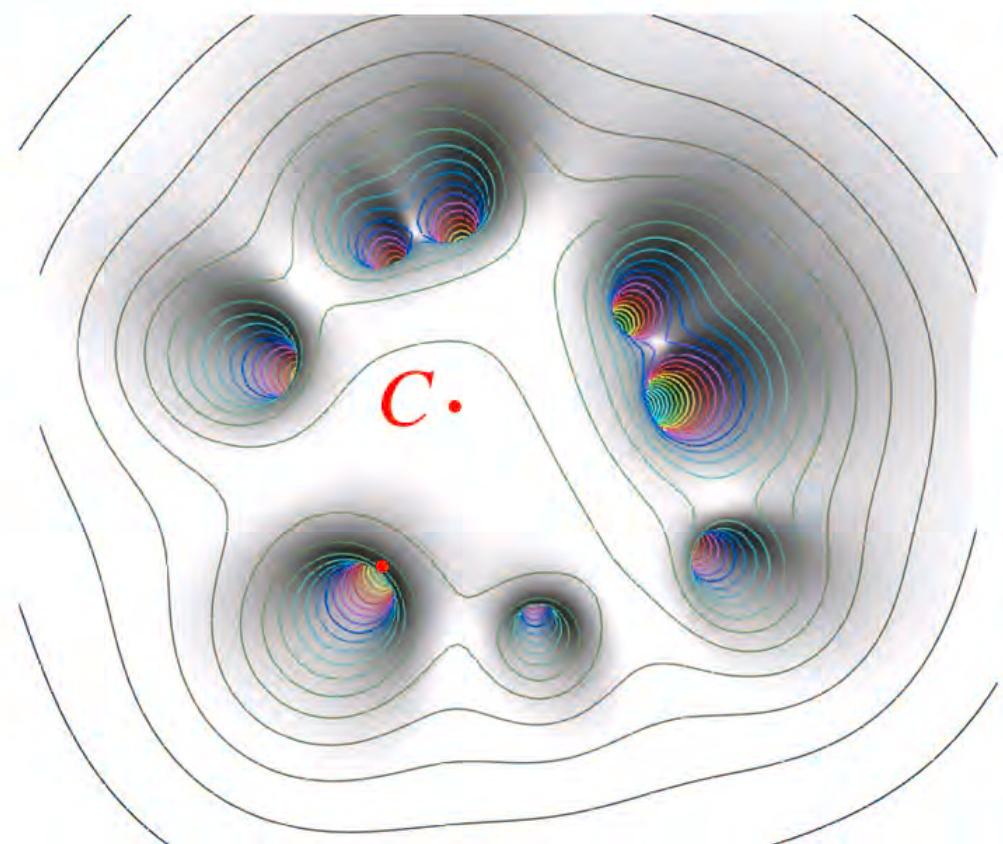
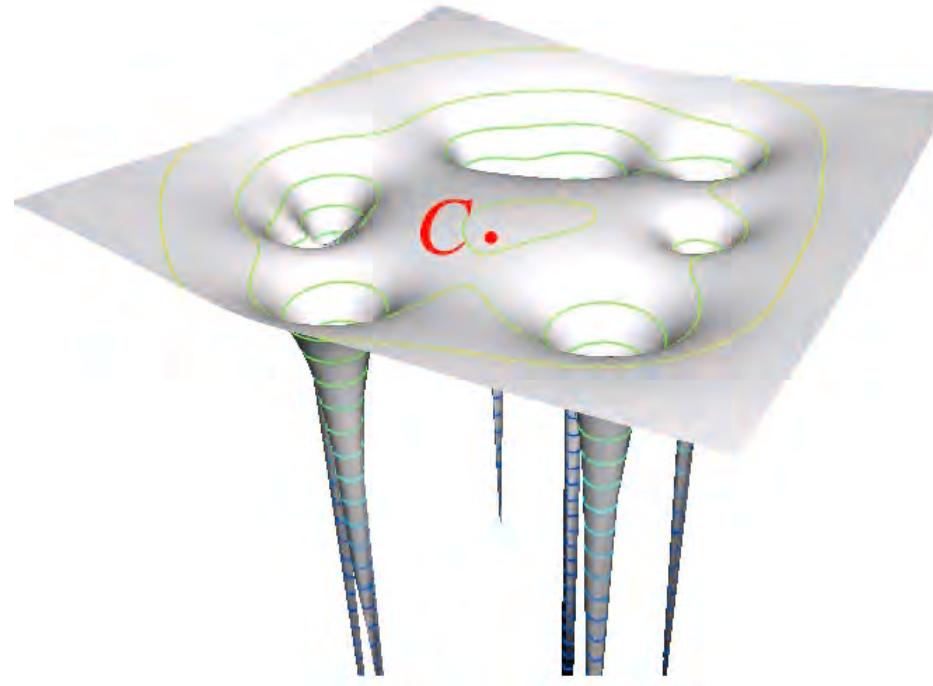
## Fermion degeneracy and the relic neutrinos (2)

- The relic neutrinos form a degenerate fermion gas
- *The expansion of the Universe does not change that fact*  
$$\begin{aligned} p_\nu &= h/\lambda \propto R^{-1} \\ \rho_\nu(\text{max}) &\propto p_\nu^3 \end{aligned} \quad \Rightarrow \quad V \times \rho_\nu(\text{max}) = \text{constant}$$
$$V \times \rho_\nu = \text{constant} \quad \Rightarrow \quad \frac{\rho_\nu}{\rho_\nu(\text{max})} \quad \text{independent of volume}$$
- The relic neutrinos have thus *always* formed a degenerate fermion gas  
*Quantum states with  $y < 1$  are almost completely filled, regardless of  $T_v$*
- $Rp_v = \text{constant} = \frac{RkT_v}{c} \quad \longrightarrow \quad RT_v = \text{constant}$

# Gravitation and the neutrino spectrum

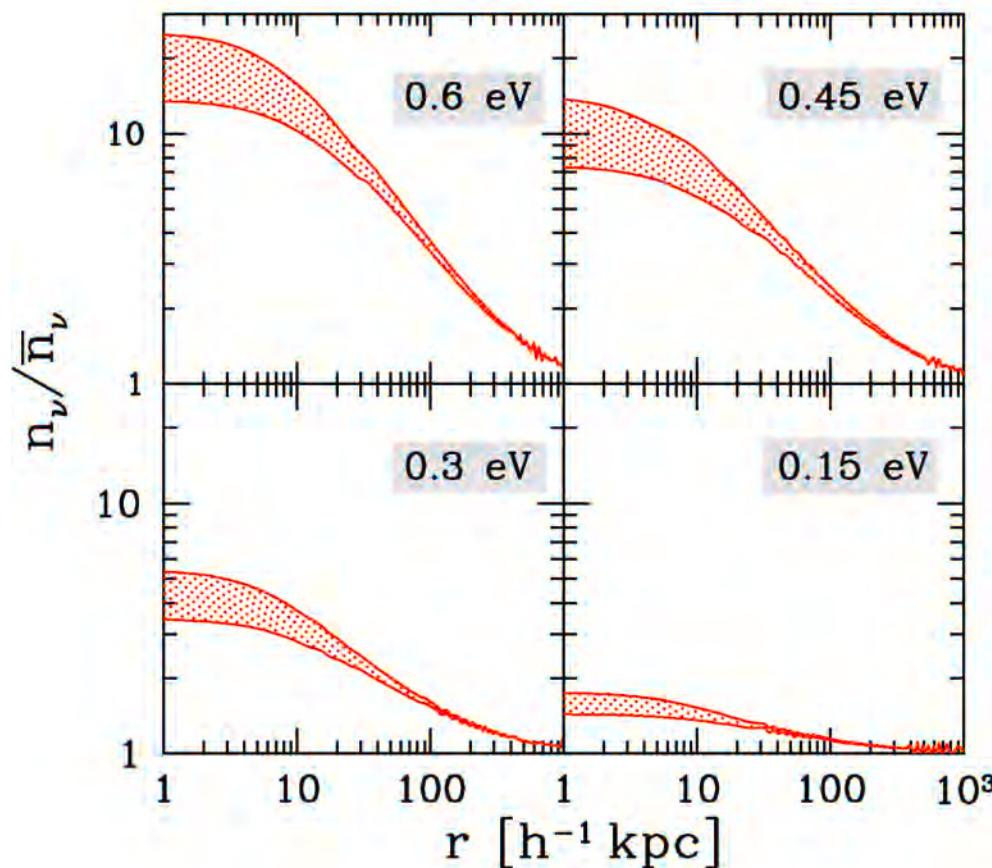
- $z \sim 1100$ : Gravitation becomes the dominating force in the Universe  
Matter is very uniformly distributed  
The expansion of the Universe decelerates (*gravitational slowdown*)
- $z \sim 10$ : Galaxy formation starts (typical distance between galaxies 100 kpc)  
Matter is no longer uniformly distributed → **Gravitation** is *no longer* a *uniform* force
- Consequences for relic neutrinos:  
Some fraction are *accelerated*, others *decelerated* by gravitational forces
- *Gravitation modifies (broadens) the relic ν spectrum*

Galaxies form: Gravitational fields become non-uniform

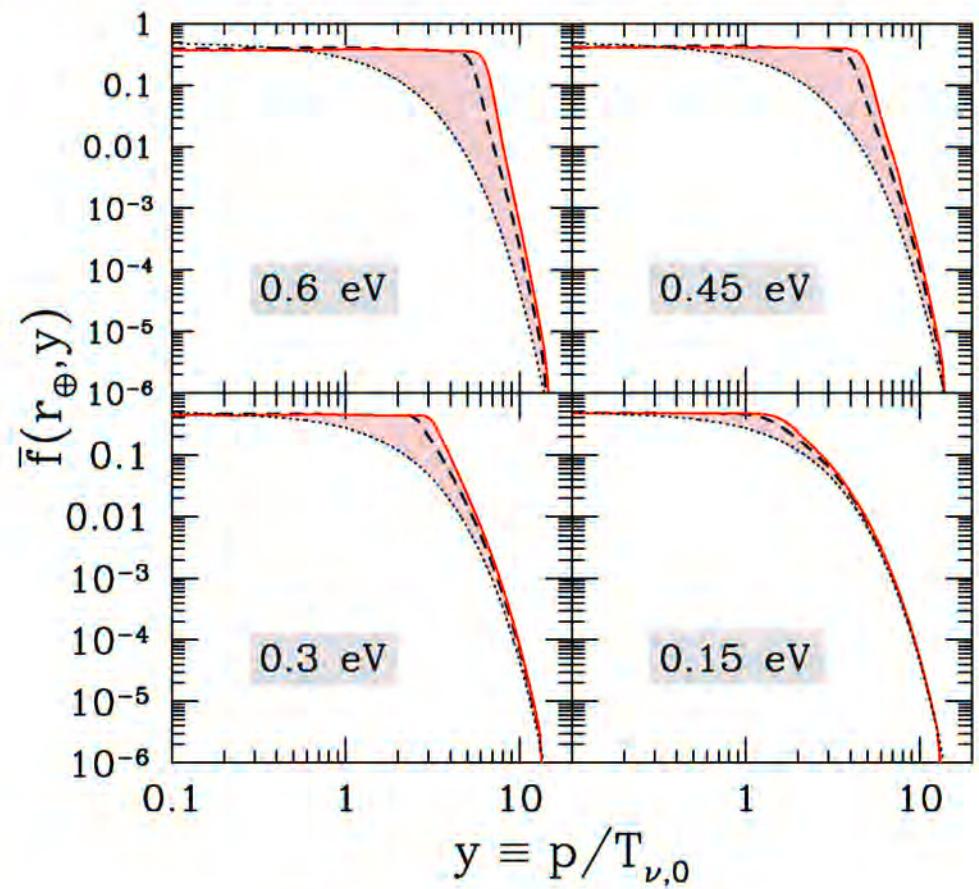


# Gravitational clustering of massive $\nu$ in Milky Way galaxy

(From: A. Ringwald & Y. Wong, hep-ph/0408241)

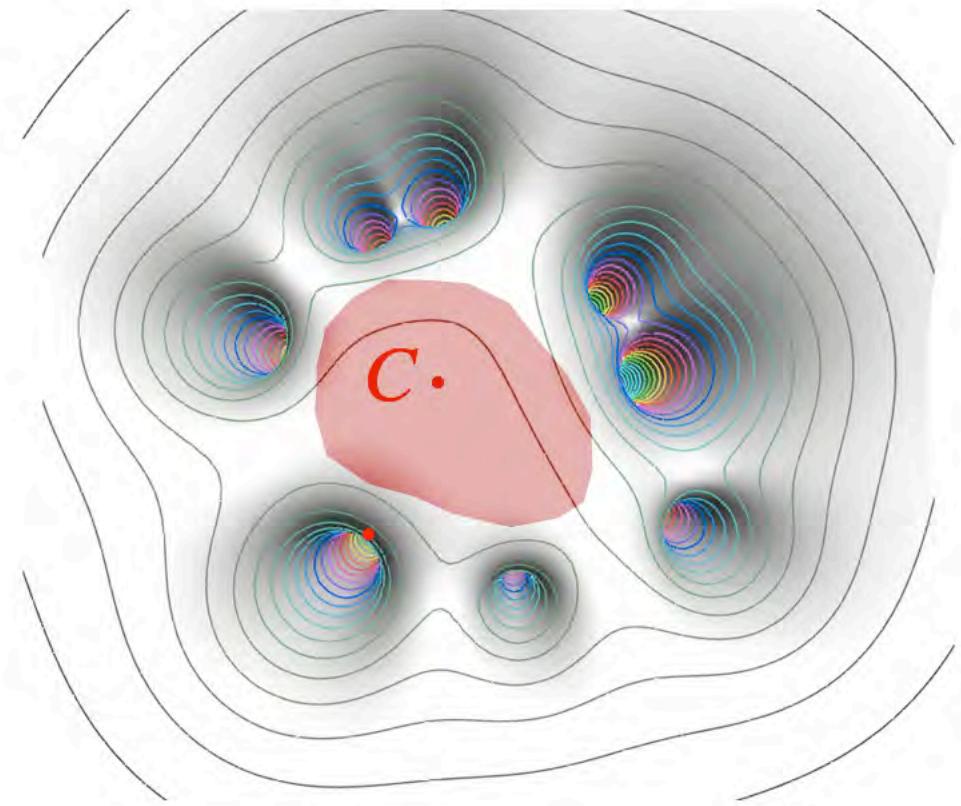
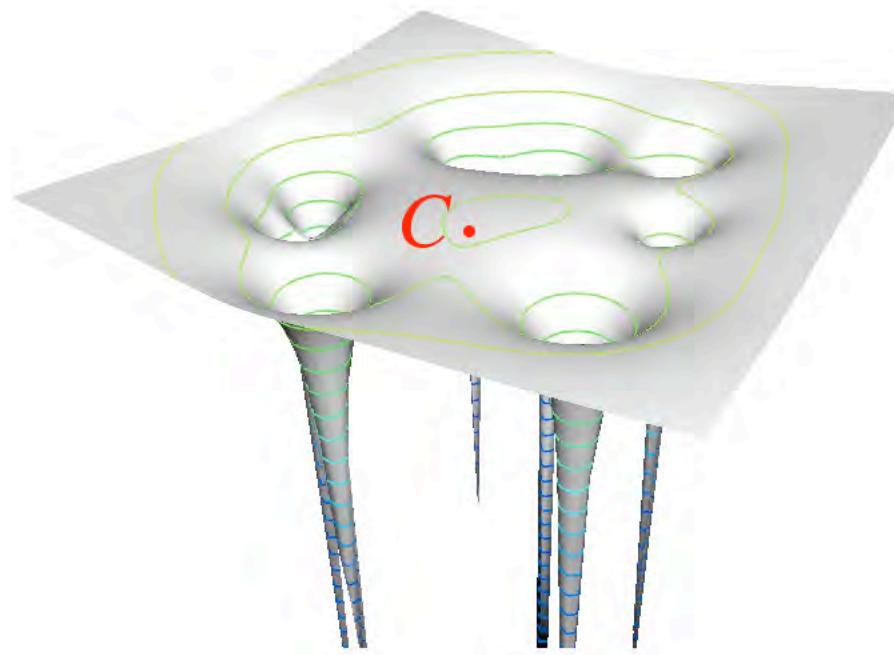


Neutrino *density*



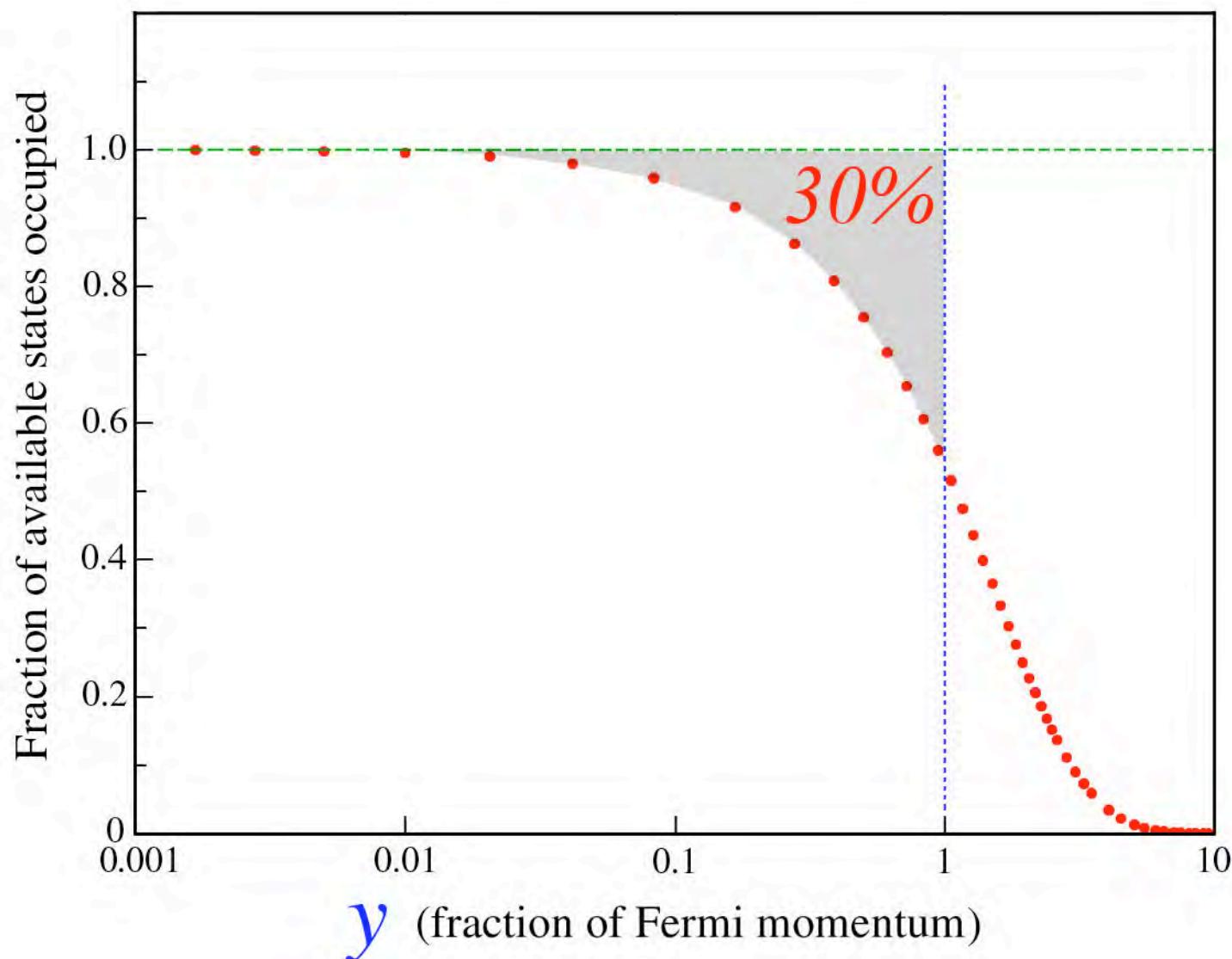
Neutrino *spectrum*

# Galaxies form: Gravitational fields become non-uniform



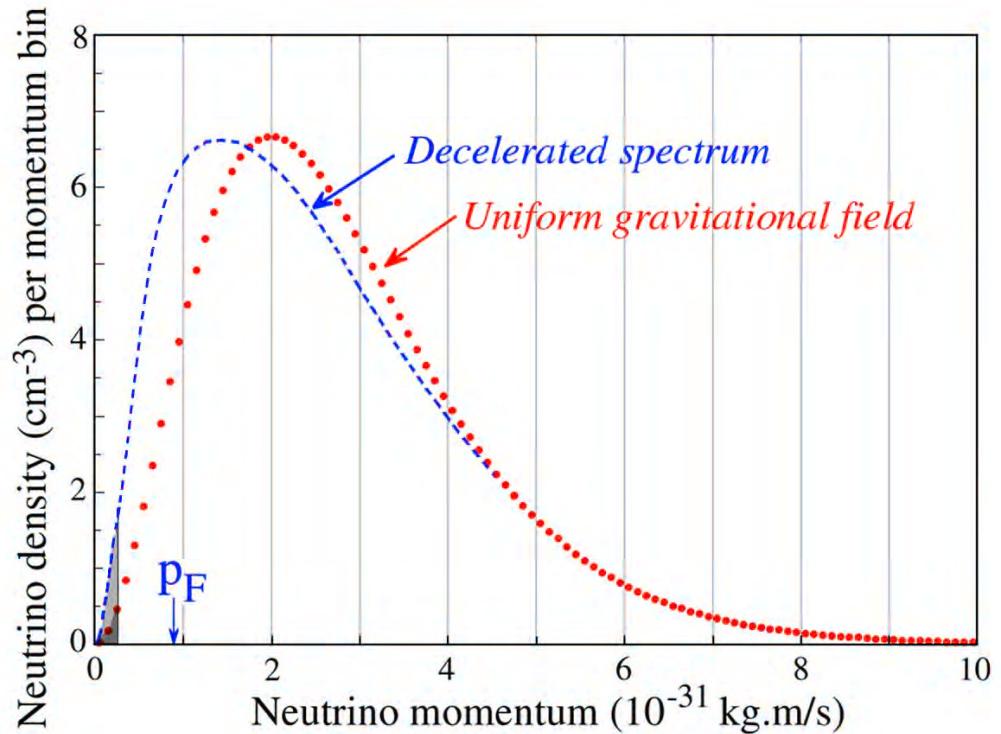
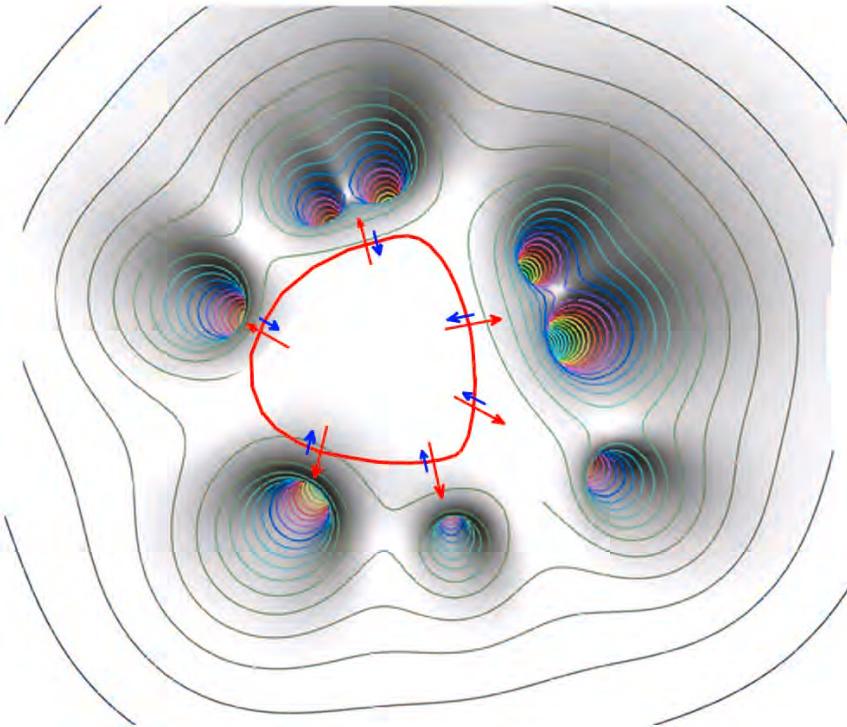
$T_v$  in red area *decreases* (gravitational cooling)  
→ *There may not be enough quantum states  
to accommodate the neutrinos  
(violation of Pauli principle)*

# Relic neutrinos: Violation of Pauli Principle



*if  $\rho_\nu$  ( $y < 1$ ) increases by more than 30%*

# The Pauli acceleration



- The neutrino temperature in the box *drops* (just as it *increases* near galaxies)

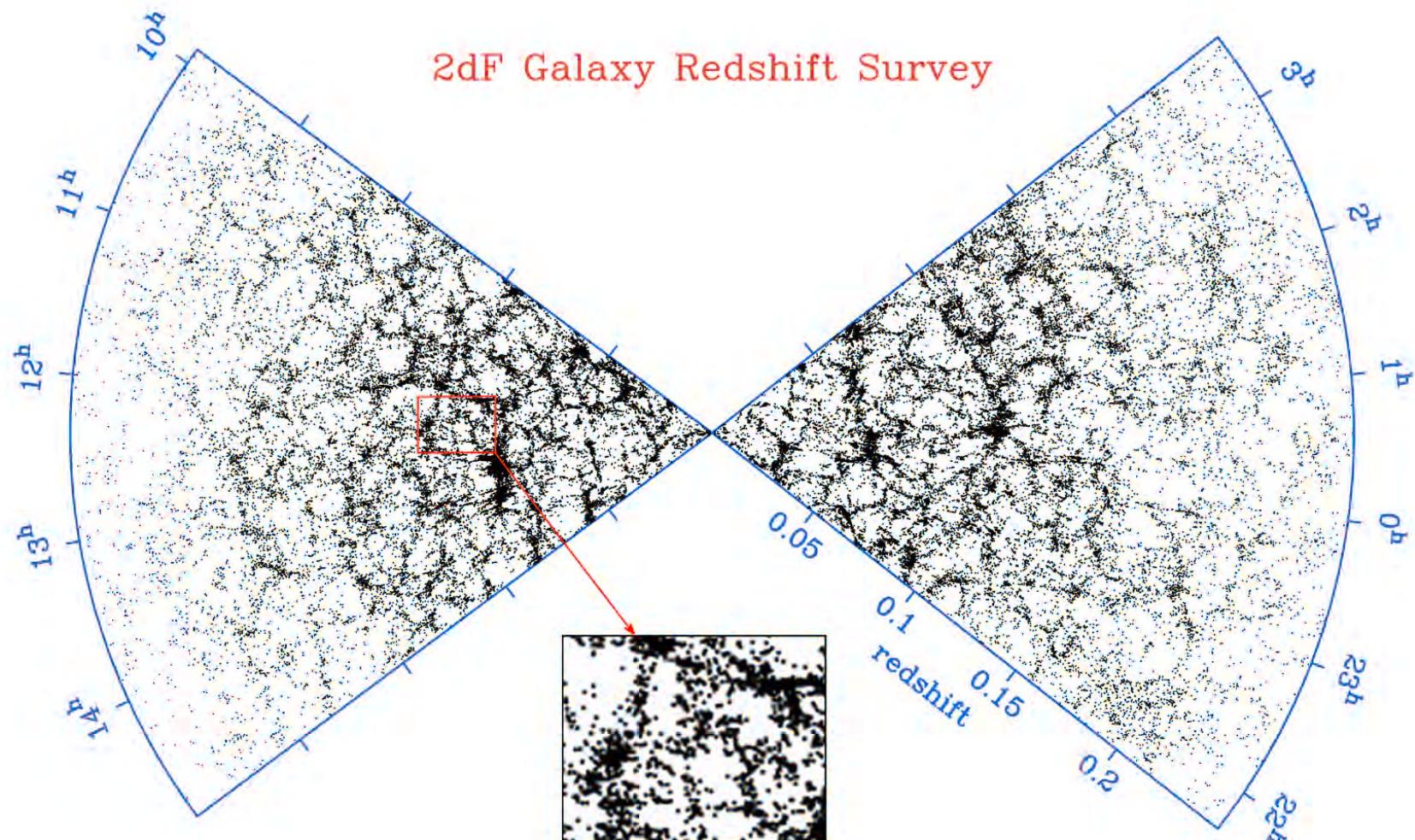
$RT_v = \text{constant} \rightarrow R \text{ has to increase}$

*The box thus has to expand to avoid violation of the Pauli principle*

- The degree of degeneracy does *not* change in this process

*The void will thus continue to expand*

# Large-scale structure in the Universe



# The Pauli acceleration

## *How does this mechanism work?*

- In White Dwarfs, neutron stars violation of Pauli principle prevented by *fermion degeneracy pressure*  
Motion of electrons (neutrons) in highly excited states generates the pressure that is needed to prevent gravitational collapse
- However, *neutrinos cannot translate kinetic energy into pressure*  
*Their only option to save the Pauli principle is gravitation*
- *General Relativity: Massive objects curve space-time*  
e.g.  $10^{56}$  hydrogen atoms cluster to form a star and curve space-time in its vicinity  
*Positive curvature* → Star acts as a *converging* gravitational lens

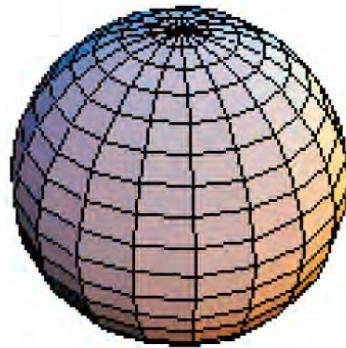
*Here:  $10^{76}$  cooling neutrinos curve space-time around the center-of-mass of a developing galaxy cluster such as to prevent violation of the Pauli principle*

*Negative curvature* → Center acts as a *diverging* gravitational lens

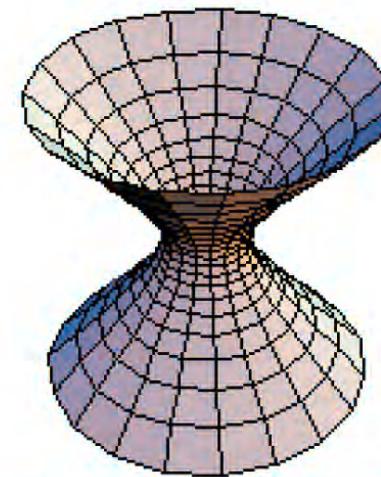
## The Pauli acceleration (2)

### *How does this mechanism work?*

- Space around center ( $C$ ) of developing galaxy cluster has *negative curvature*  
 $C$  acts as a *diverging* gravitational lens



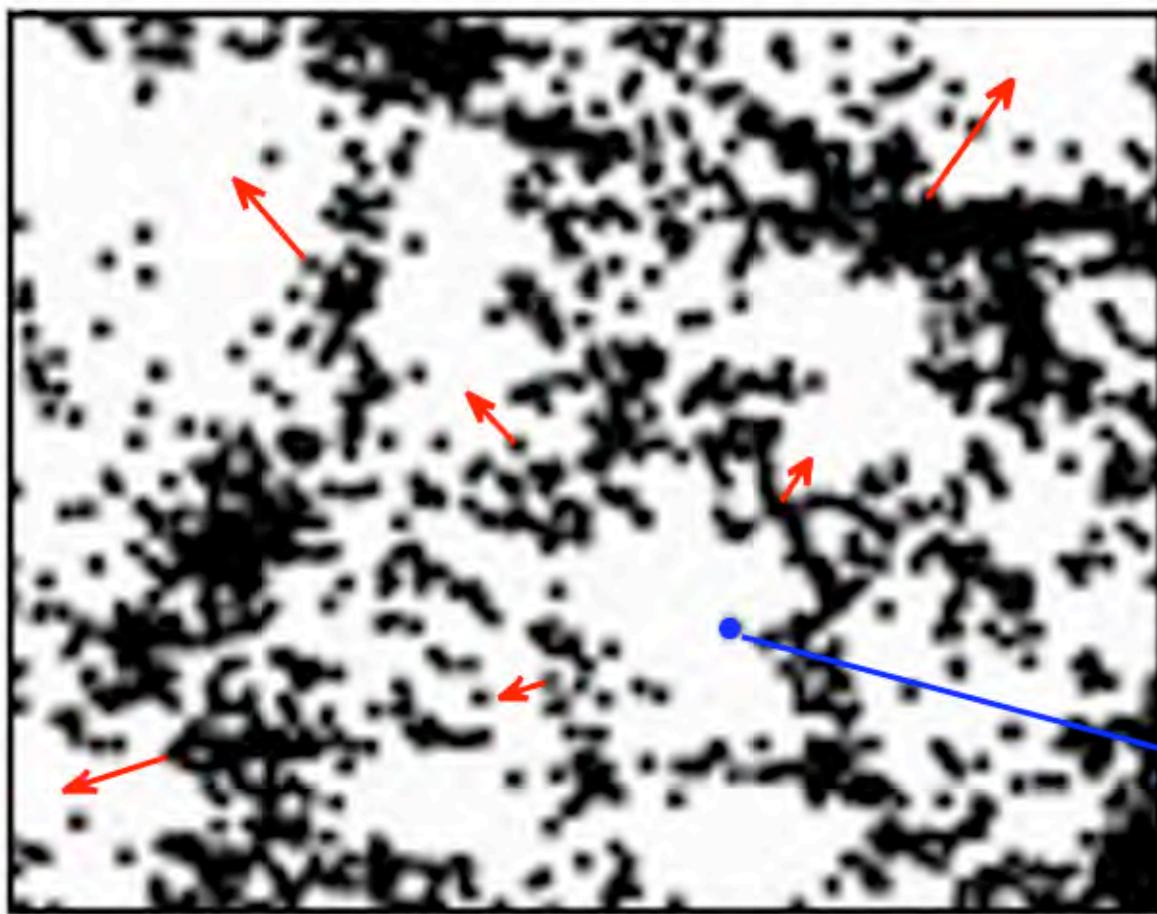
*A sphere has constant **positive** curvature.*



*A hyperboloid has constant **negative** curvature.*

- All massive objects in this region are thus *accelerated away from  $C$*  (neutrinos, galaxies...)
  - A *negative mass* placed in  $C$  would have the same effect  
*Equivalence Principle:* Impossible to distinguish
- *The cluster galaxies feel a force driving them away from  $C$*

## Pauli acceleration: Superposition effects



*observer*

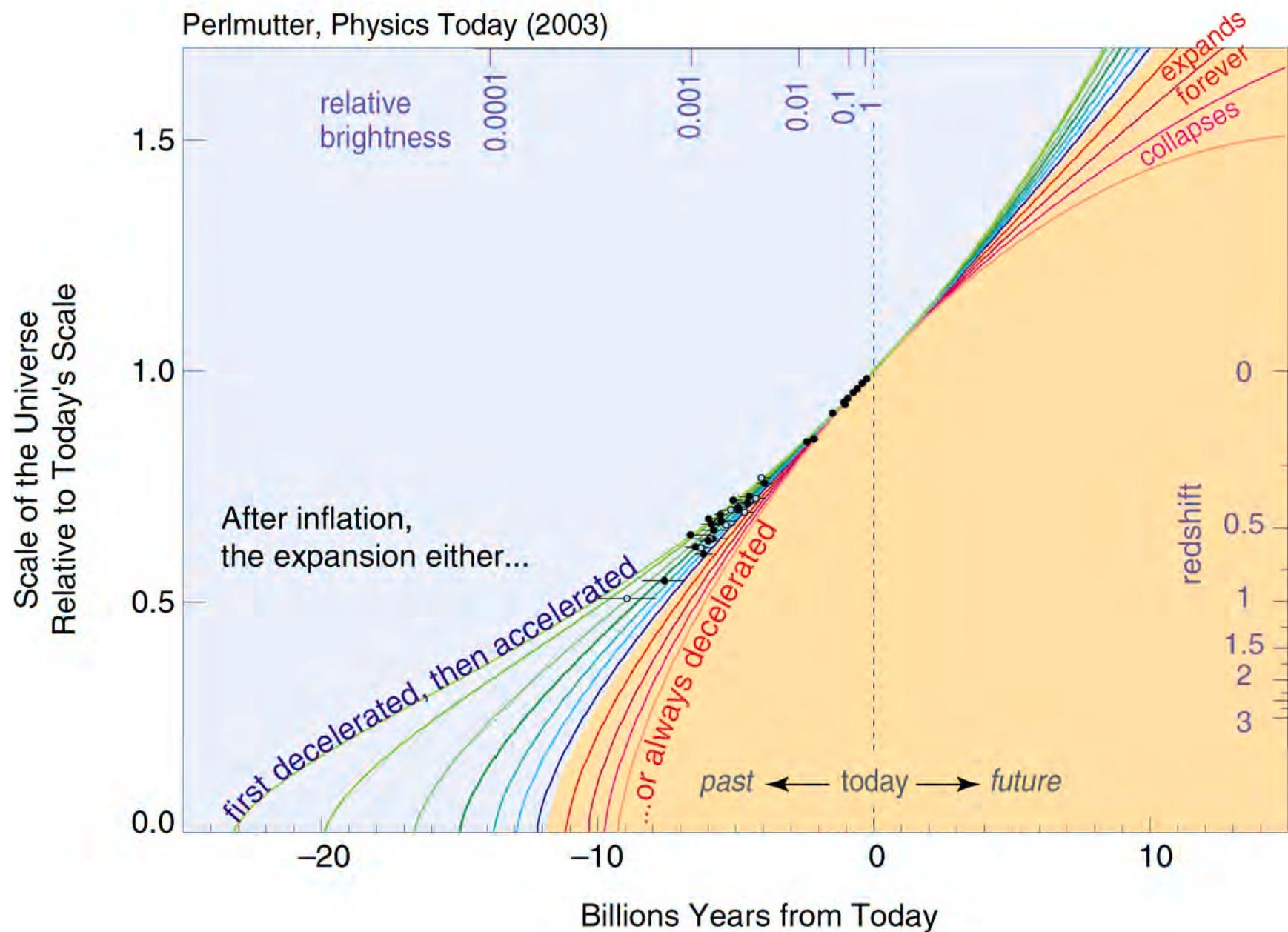
## Implications of Pauli Acceleration Model

### 1) No need for "dark energy"

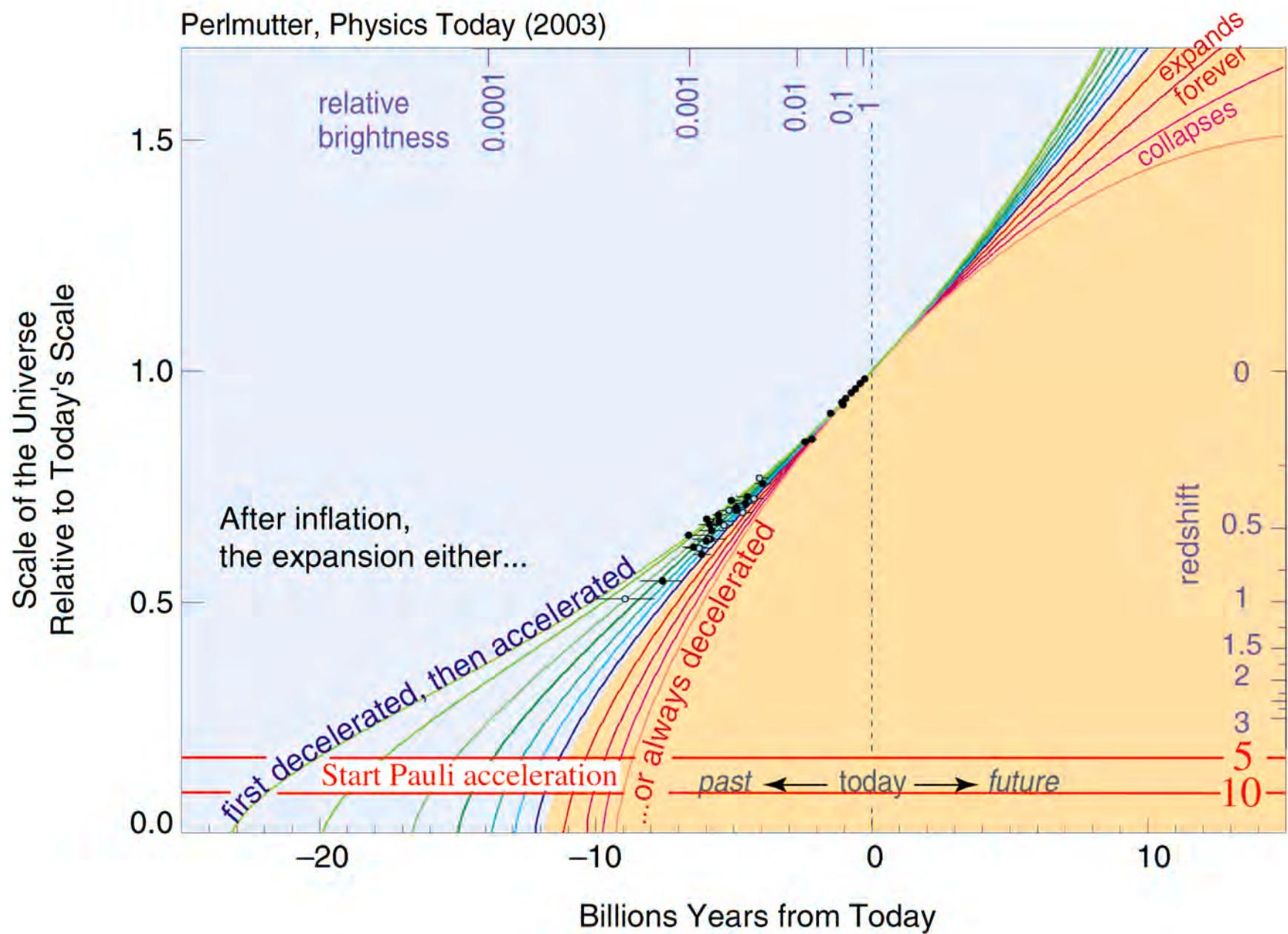
The model provides a very natural explanation for the deceleration, followed by an acceleration of the expansion.

No need to speculate about new physics.

# Supernovae Type Ia and the expansion of the Universe



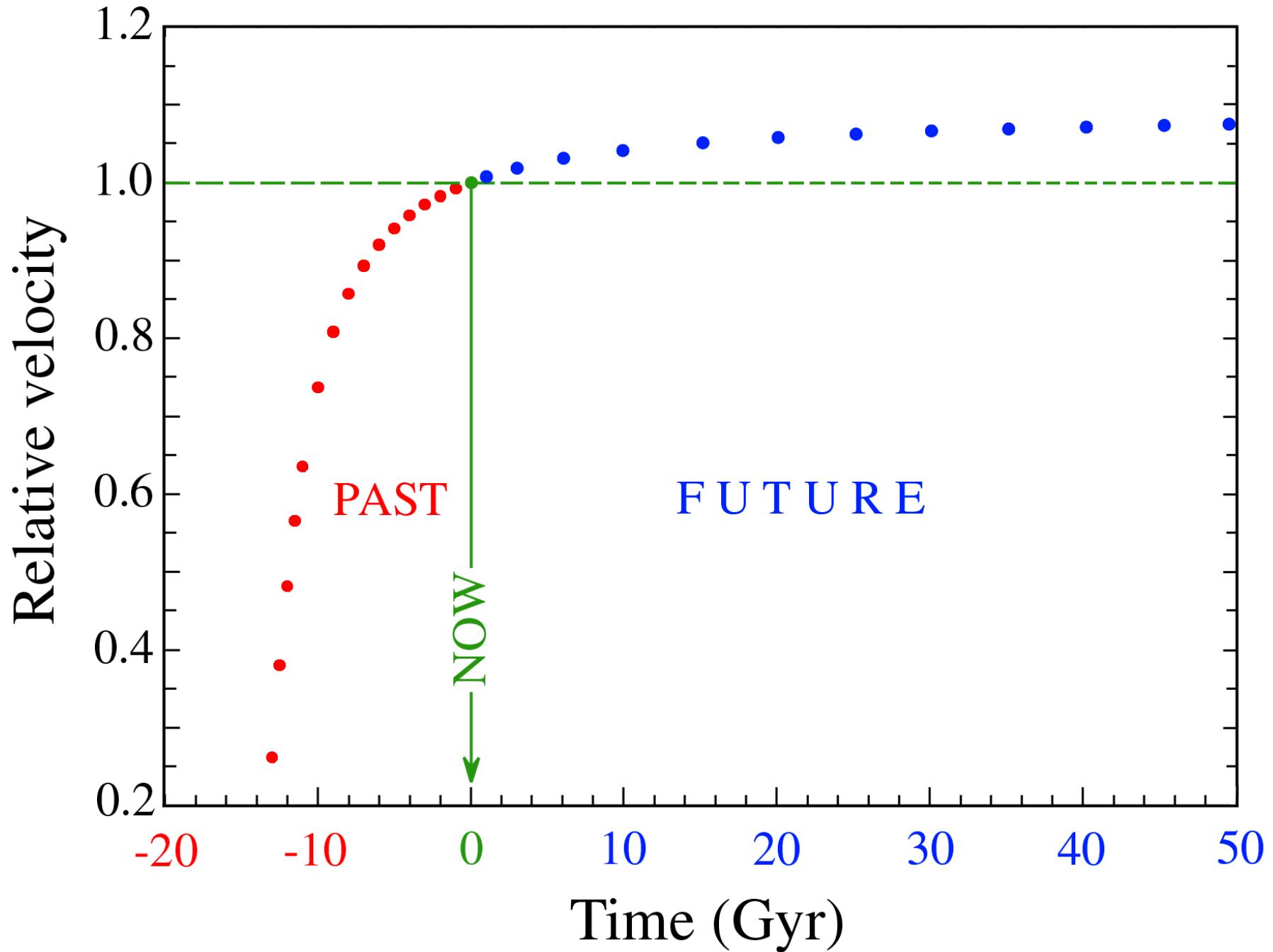
# Supernovae Type Ia and the expansion of the Universe



## Implications of Pauli Acceleration Model

- 1) No need for "dark energy"
- 2) Expansion will continue forever, regardless of the value of  $\Omega$   
The mechanism that drives the expansion does not go away  
 $\rightarrow$  *No correspondence between geometry and energy density*  
 $(k \geq 0 \not\leftrightarrow \Omega \geq 1)$

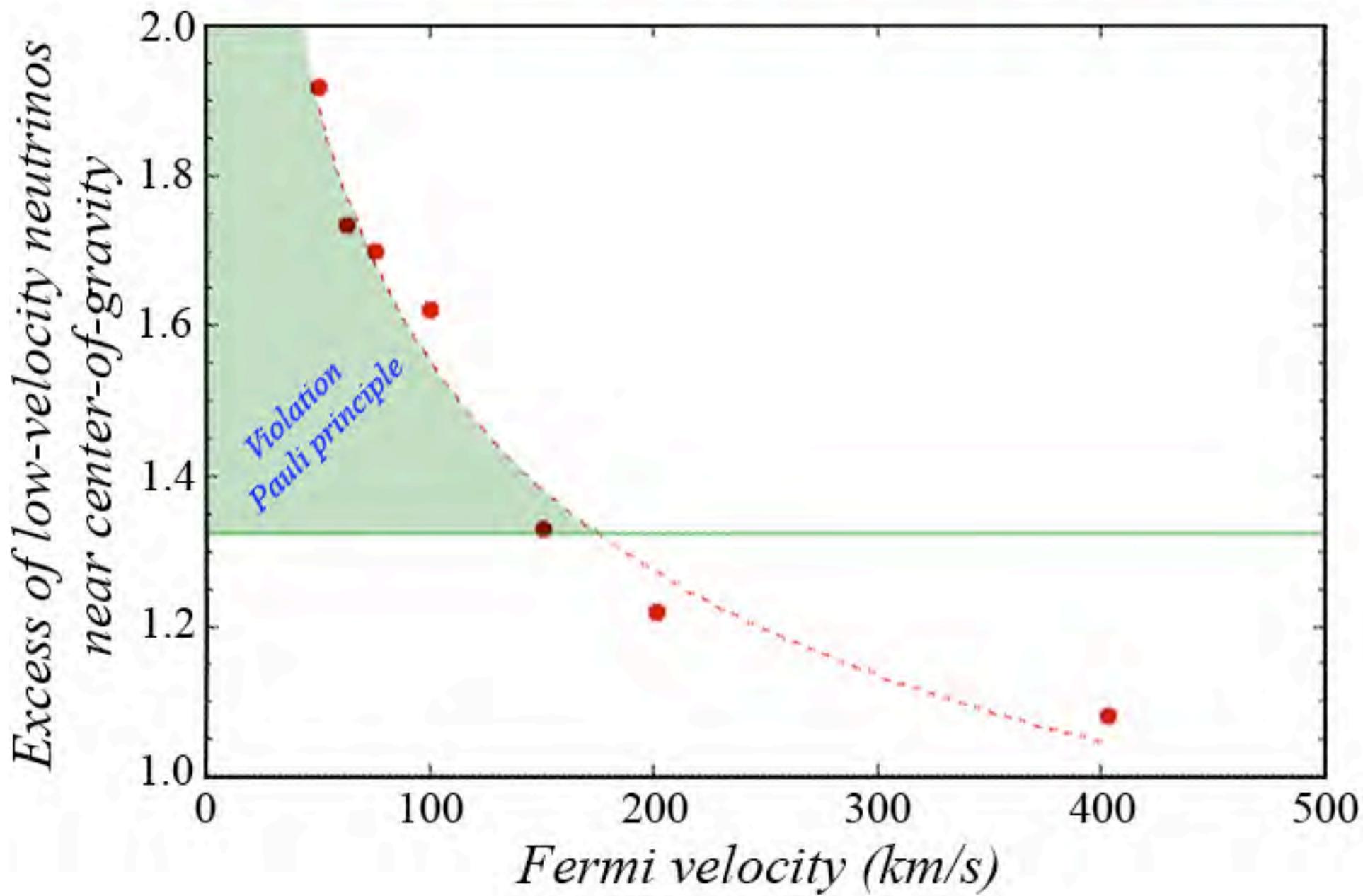
# Past and future evolution of the expansion rate



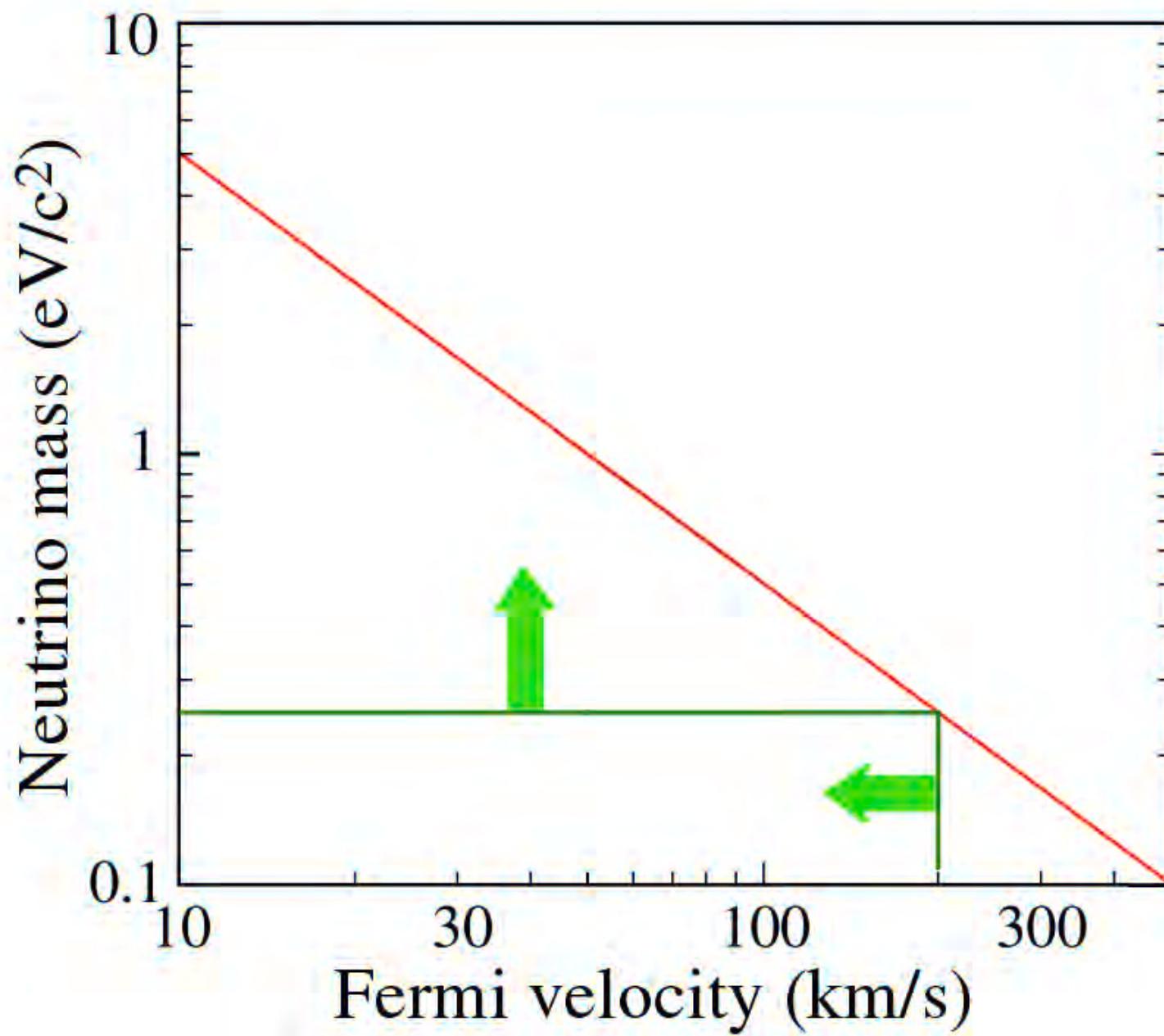
## Implications of Pauli Acceleration Model

- 1) No need for "dark energy"
- 2) Expansion will continue forever, regardless of the value of  $\Omega$
- 3) Neutrino mass: Lower limit
  - Relic neutrinos need to lose significant fraction of momentum by gravitational deceleration, in order to violate Pauli principle  
*e.g.* > 40% for the fastest 95% ( $v > 0.82 v_F$ )
  - Neutrinos with  $v < 165$  km/s meet this condition  $\rightarrow v_F < 200$  km/s  
 $\rightarrow m_\nu > 0.25 \text{ eV/c}^2$  (95% c.l.)

# Pauli violation & neutrino velocity



# Mass/velocity relationship relic neutrinos



## *Conclusions, part 1*

- Relic neutrinos form a *degenerate* Fermi-Dirac gas.  
Typical velocities are  $\sim 100 \text{ km/s}$
- Gravitationally decelerated neutrinos may violate the *Pauli principle* in the low-field region *near the center-of-gravity of galaxy clusters*
- To avoid this, a *local expansion of space* is needed in this region.  
Such an expansion could lead to the observed *Large-Scale Structure*
- This mechanism could also explain the *high-z Supernova data* without the need for "*dark energy*"

# Neutrinos in an expanding Universe

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**Abstract.** The Universe contains several billion neutrinos for each nucleon. In this paper, we follow the history of these relic neutrinos as the Universe expanded. At present, their typical velocity is a few hundred km/s and, therefore, their spectra are affected by gravitational forces. This may have led to a phenomenon that could explain two of todays great mysteries: The large-scale structure of the Universe and the increasing rate at which it expands.

## 1. Introduction

According to the Big Bang model, large numbers of neutrinos and antineutrinos have been around since the earliest stages of the evolving Universe. During the Leptonic Era, the density was so large that the (anti-)neutrinos were in thermal equilibrium with the other particles that made up the primordial soup: photons, electrons, positrons and nucleons. When the Universe was about 1 second old, the neutrinos decoupled and thus turned into relics of the Big Bang. Since that time, they have behaved like a gas of free particles. They are now the most abundant species, outnumbering baryons by more than 9 orders of magnitude. Yet, despite their enormous abundance (estimated at  $\mathcal{O}(10^{87})$  for the observable Universe), relic neutrinos have until now escaped direct detection. Their extremely small kinetic energy makes it all but impossible to find a process through which they might reveal themselves as individual particles.

In this paper, we follow the relic neutrinos throughout the history of the Universe. In Section 2, their properties are briefly reviewed. In Section 3, the effects of gravitational acceleration and deceleration on the spectra and local densities of massive neutrinos are studied. It turns out that the density may exceed the maximum density allowed by the Pauli principle in the field-free region around the center-of-mass of galaxy clusters. In Section 4, we discuss the mechanism that prevents this from happening and analyze some of the consequences of this mechanism. Conclusions are presented in Section 5.

## 2. Properties of relic neutrinos

### 2.1. Spectra and densities

During the Leptonic Era, neutrinos and antineutrinos were in thermal equilibrium with the other constituents of the Universe. They converted protons into neutrons and vice versa. However, when the Universe was  $\approx 1$  second old and the temperature (or rather  $kT$ ) had dropped to  $\sim 1$  MeV, this thermal equilibrium ceased to exist, for two reasons. First, the production of neutrons through the reactions  $\bar{\nu}_e + p \rightarrow n + e^+$  and  $e^- + p \rightarrow \nu_e + n$  became energetically impossible, whereas the reverse reactions still occurred. This led to the proton/neutron asymmetry. Second, the density dropped to the point where the average lifetime of the neutrinos and antineutrinos became longer than the age of the Universe (*i.e.*, 1 second at that time).