Neutrinos in an Expanding Universe

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Università di Cagliari, May 12, 2005

Outline :

- Relic neutrinos
- Current properties
- Pauli Acceleration Model
  - *- Large-scale Structure*
  - *- Accelerating Expansion*
- Other applications: H_0, m_ν
- Conclusions

Big Bang Relics

- *Relic photons*

- When Universe was $\sim 500,000$ years old ($T \sim 3{,}000$ K):
  - $\rightarrow$ End of thermal equilibrium $\gamma + H \rightleftharpoons p + e$
  - $\rightarrow$ γ's decouple from matter, stable atoms form
  - $\rightarrow$ 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

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

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

Properties of Relic Neutrinos *(then)*

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

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

g_s: # of possible spin states (2 for ν_{Majorana}, 4 for ν_{Dirac})

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

➡ During Leptonic Era (thermal equilibrium with photons):

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

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

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

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:

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

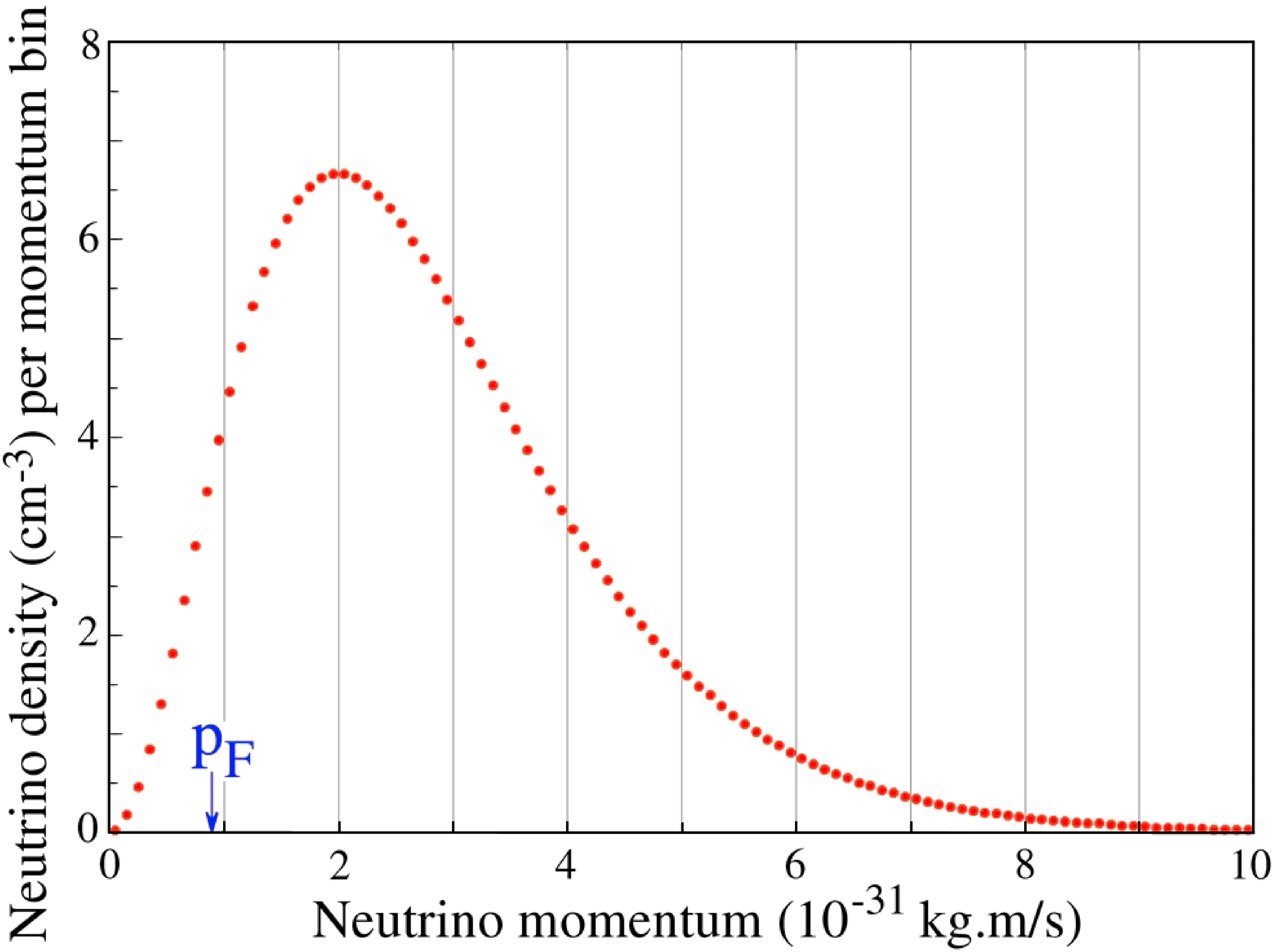
with $T_\nu \sim 1.95$ K $(= \sqrt[3]{4/11}\ T_\gamma) \to kT_\nu = 1.68 \cdot 10^{-4}$ eV

- $n_\gamma = 411/\mathrm{cm}^3 \longrightarrow n_\nu \sim 110/\mathrm{cm}^3$ (Majorana), $\sim 220/\mathrm{cm}^3$ (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 $T_\nu = 1.95$ K



The neutrino mass

Measurements

- Most restrictive *upper* limits from $^3H \to ^3He$ β-decay: $m_{\nu_e} < 2.2\ eV/c^2$

- Superkamiokande: Zenith-angle dependence of ν_e/ν_μ ratio
  $0.0015 < \Delta m^2 < 0.006\ (eV)^2$ ➡ At least one ν mass $> 0.04\ eV/c^2$

Interpretations

- Neutrinoless $\beta\beta$ decay ^{76}Ge (?): $0.24 < m_\nu < 0.58\ eV/c^2$ (3σ)

  Phys. Lett. B586 (2004) 198, Nucl. Instr. Meth. A522 (2004) 371

- PeV features of cosmic-ray spectra: $m_{\nu_e} = 0.5 \pm 0.2\ eV/c^2$

  Astroparticle Phys. 19 (2003) 379

- Cosmology (WMAP *etc.*): $\sum_i m_{\nu_i} < 1 - 2\ eV/c^2$

Velocities of massive relic neutrinos

- Fermi momentum of relic neutrinos: $p_F = \frac{kT_\nu}{c} = 1.68 \cdot 10^{-4}\,\mathrm{eV}/c$

  Momenta are redshifted by a factor 10^{10} since decoupling

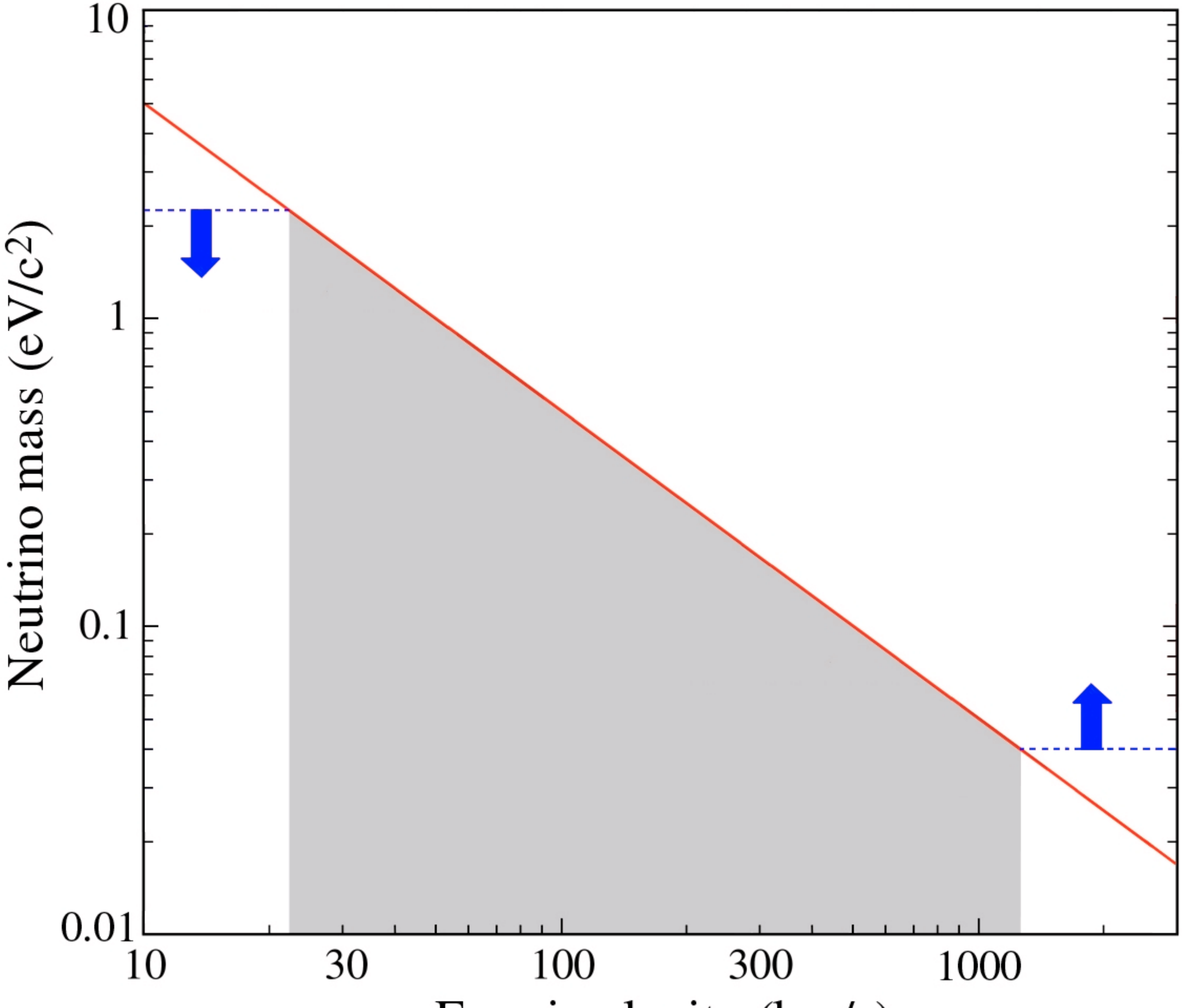
  (from $1\ \mathrm{MeV}/c \rightarrow 10^{-4}\ \mathrm{eV}/c$)

- If restmass $= 1\ \mathrm{eV}/c^2 \rightarrow v_F = 1.68 \cdot 10^{-4} c$ (50 km/s)

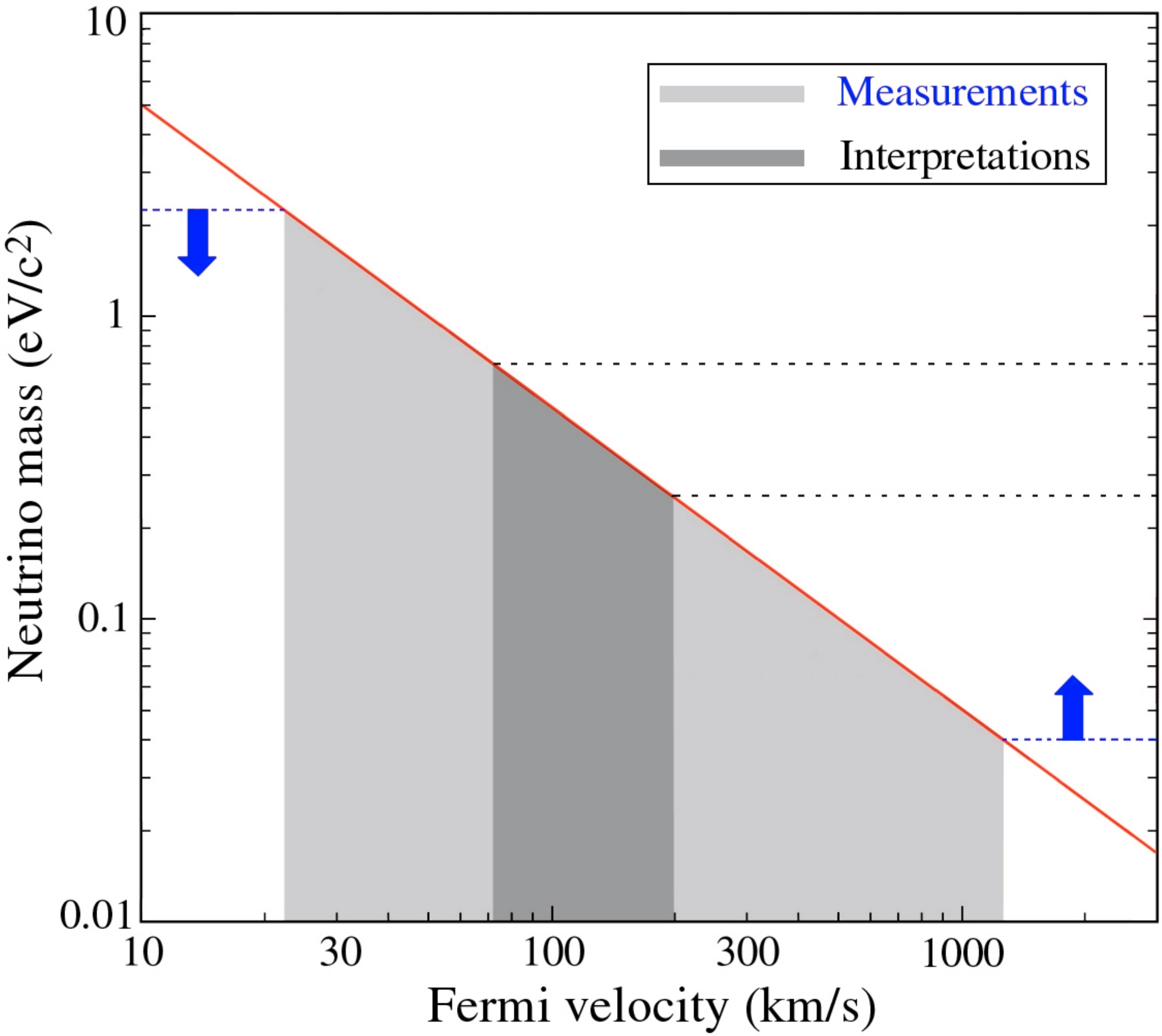
  ➡ Massive relic neutrinos may thus be ***very slow!***

  (*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 h^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:

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

Maximum fermion density

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

- 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)

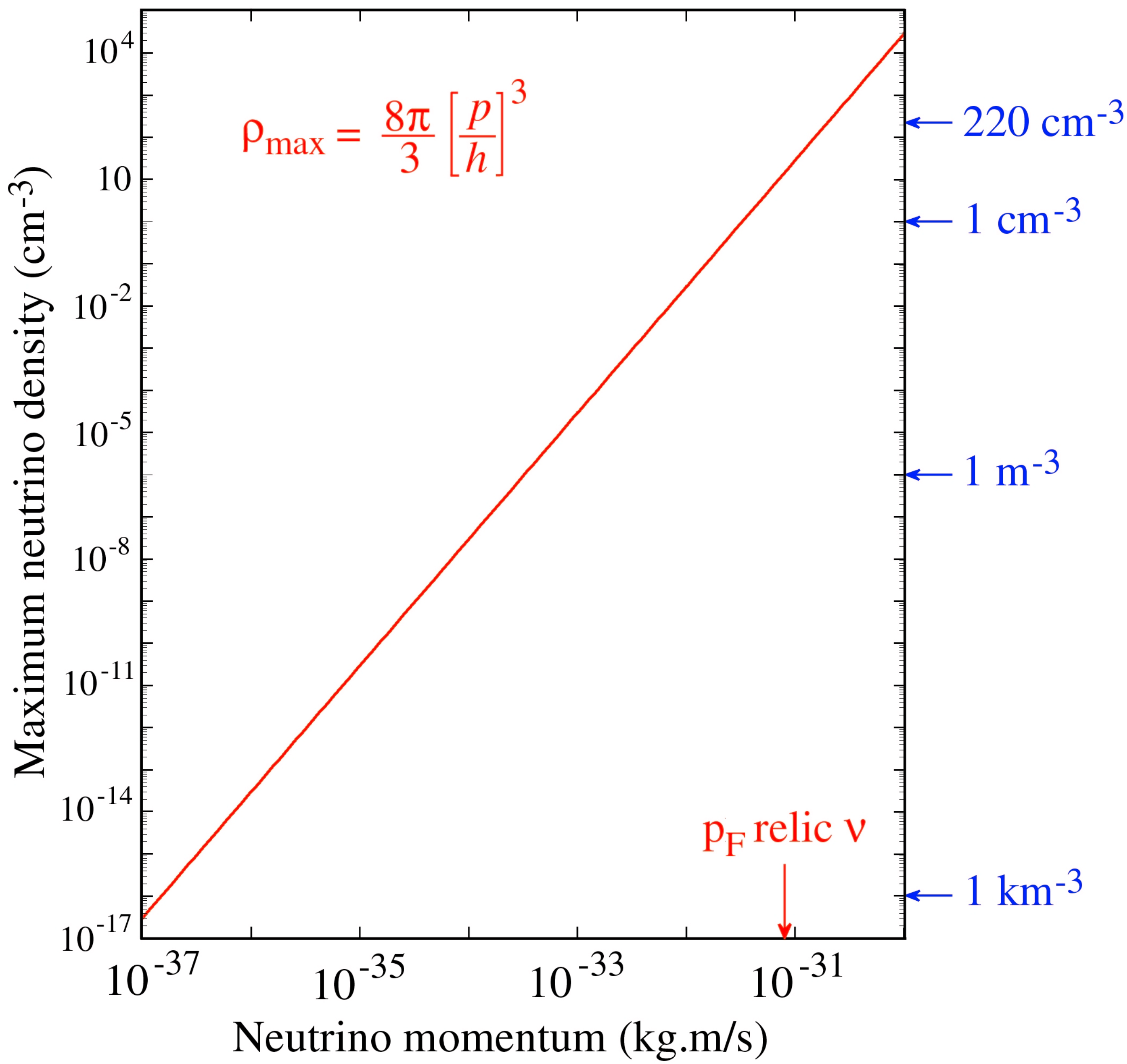
- Maximum fermion density $\rho_f \text{ (max)} = \frac{8\pi}{3}\left(\frac{p}{h}\right)^3$

- 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 $T = 1.95$ K

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

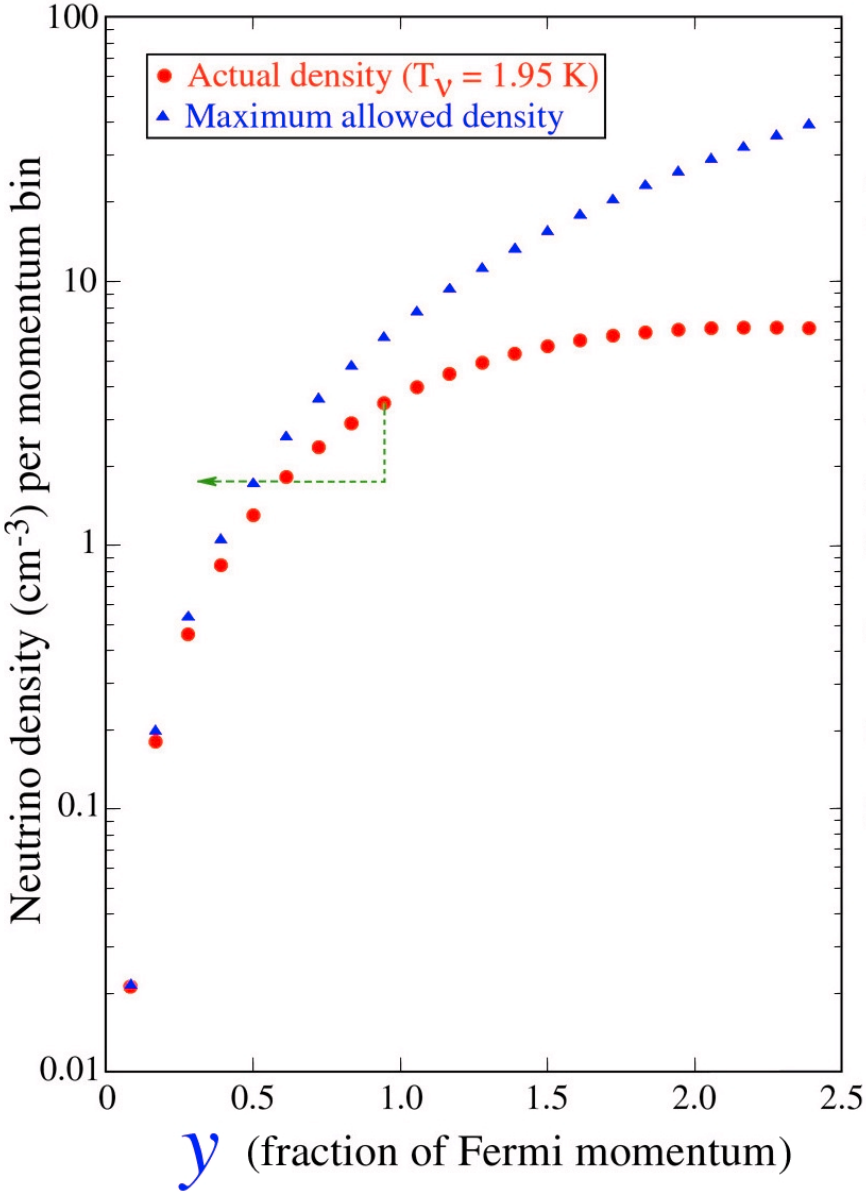
$$dn = V \frac{4\pi p^2 dp}{h^3} \frac{2}{\exp(pc/kT) + 1}$$

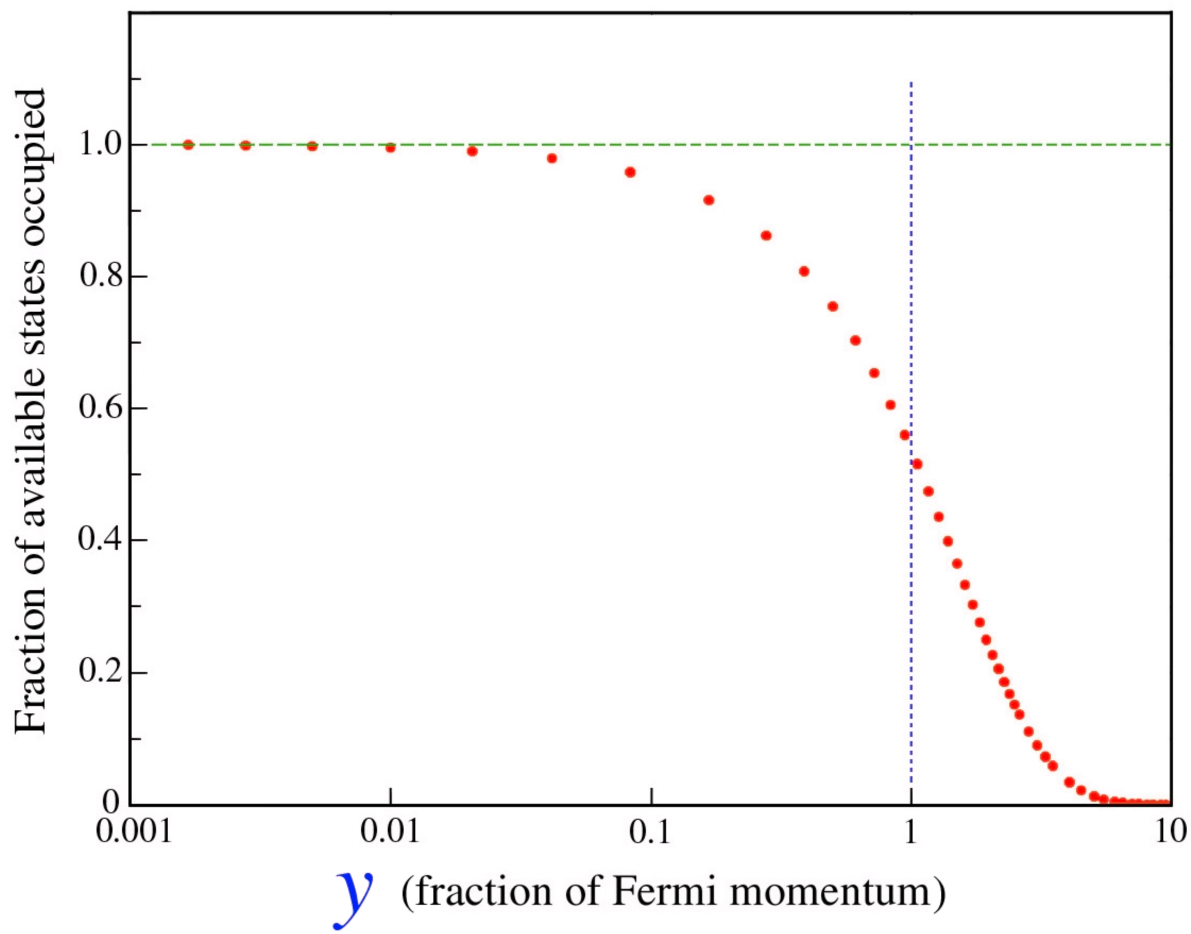
  F-D factor: Describes occupancy of available quantum states

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

  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*

$$p_\nu = h/\lambda \propto R^{-1}, \quad \rho_\nu(\max) \propto p_\nu^3 \;\rightarrow\; V \times \rho_\nu(\max) = \text{constant}$$

$$V \times \rho_\nu = \text{constant} \;\rightarrow\; \frac{\rho_\nu}{\rho_\nu(\max)} \text{ independent of volume}$$

- The relic neutrinos have thus *always* formed a degenerate fermion gas

  Quantum states with y < 1 are almost completely filled, regardless of T_ν

- $$R p_\nu = constant = \frac{R k T_\nu}{c} \longrightarrow R T_\nu = constant$$

Gravitation and the neutrino spectrum

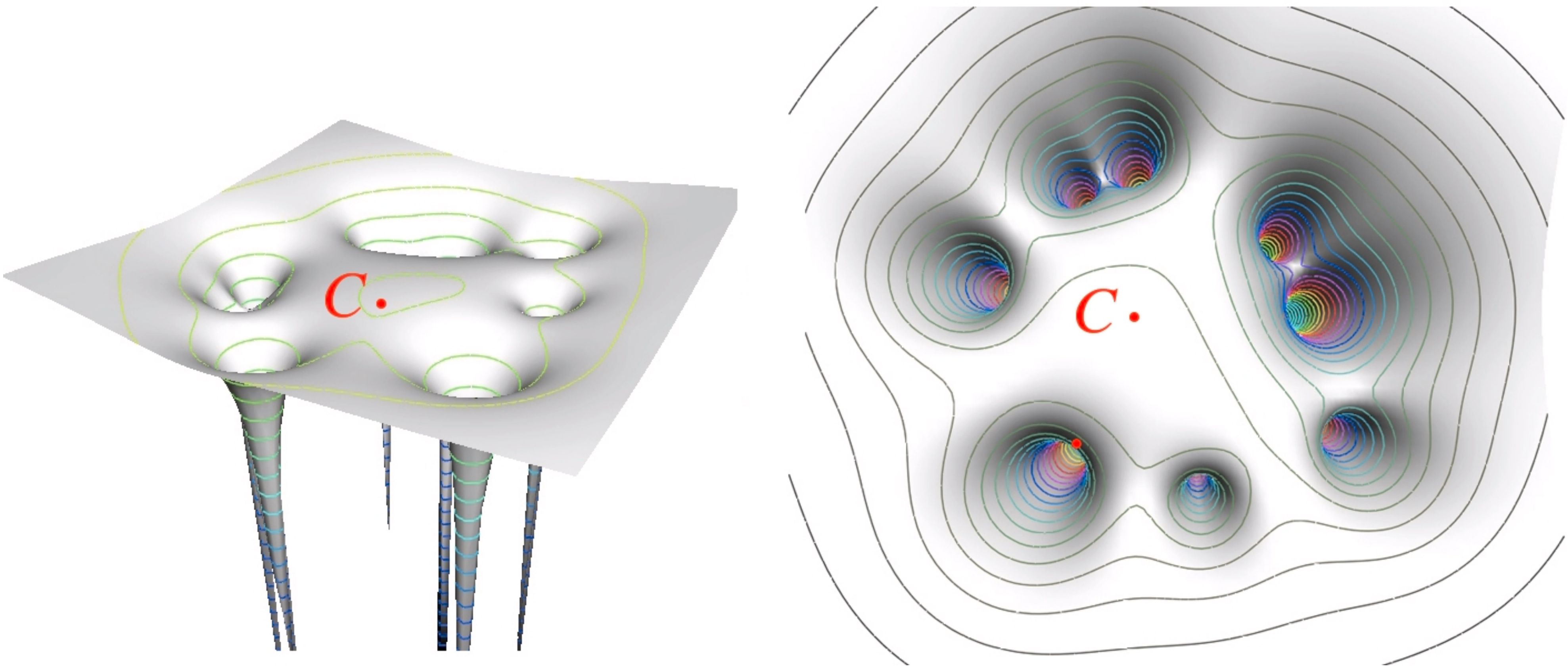
- $z \sim 1100$: Gravitation becomes the dominating force in the Universe
  Matter is very uniformly distributed
  The expansion of the Universe decelerates *(gravitational slowdown)*

- $z \sim 10$: 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

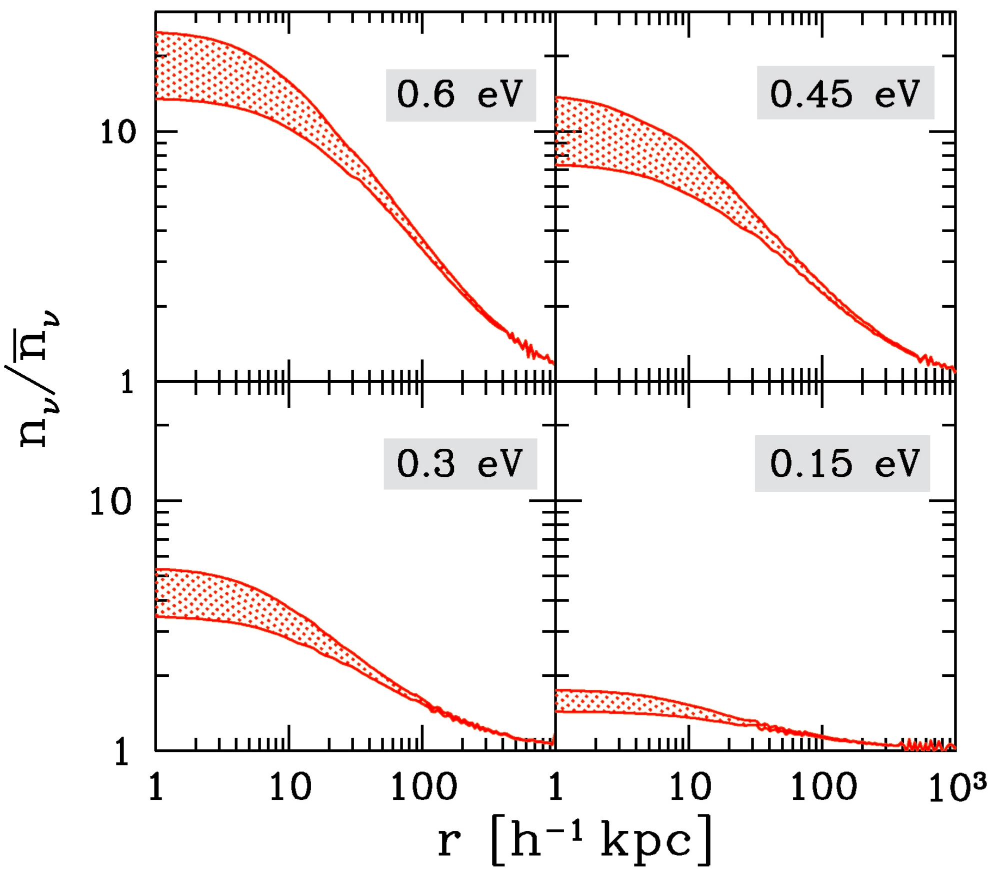
- *Gravitation modifies (broadens) the relic ν spectrum*

Galaxies form: Gravitational fields become non-uniform

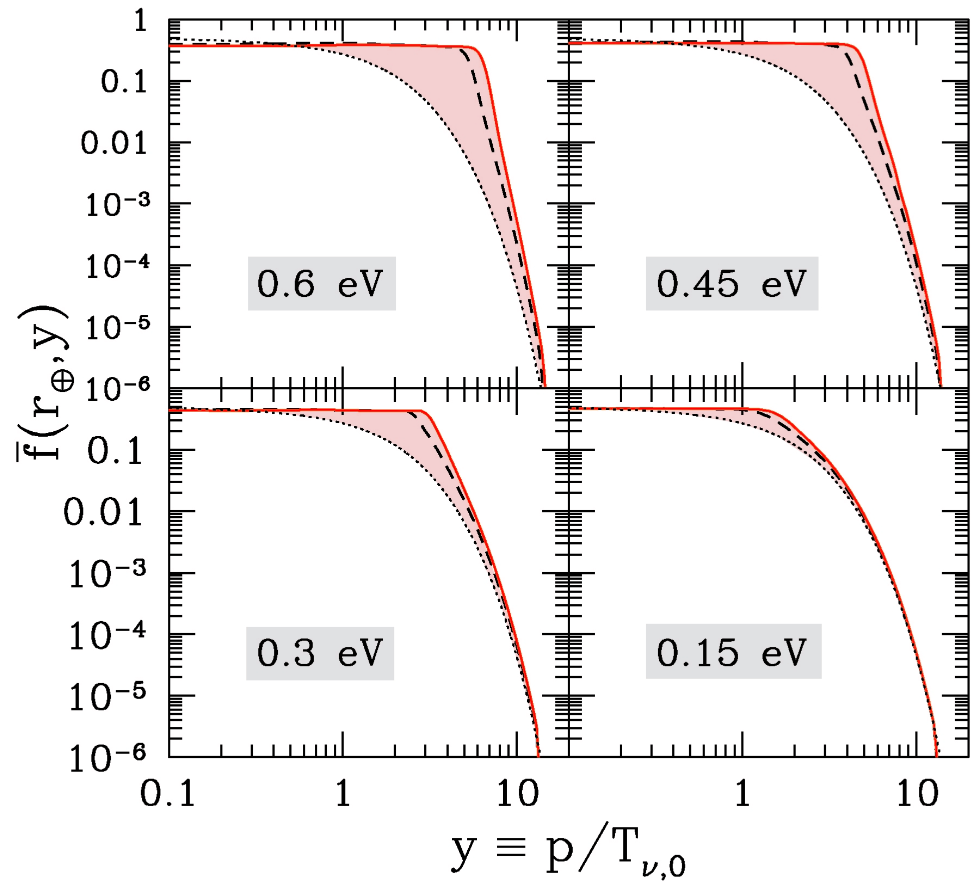


Gravitational clustering of massive ν in Milky Way galaxy

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

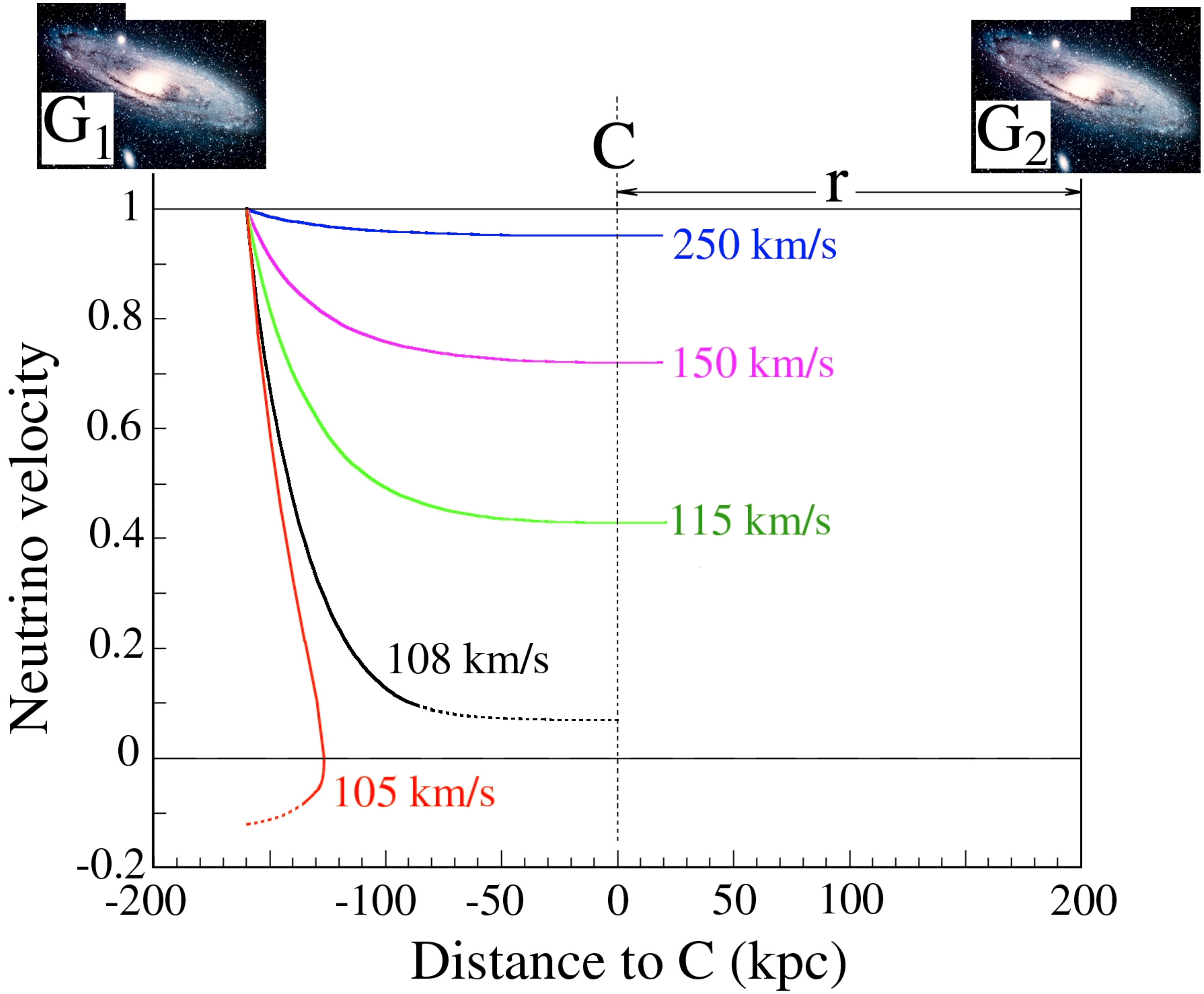


Neutrino *density*

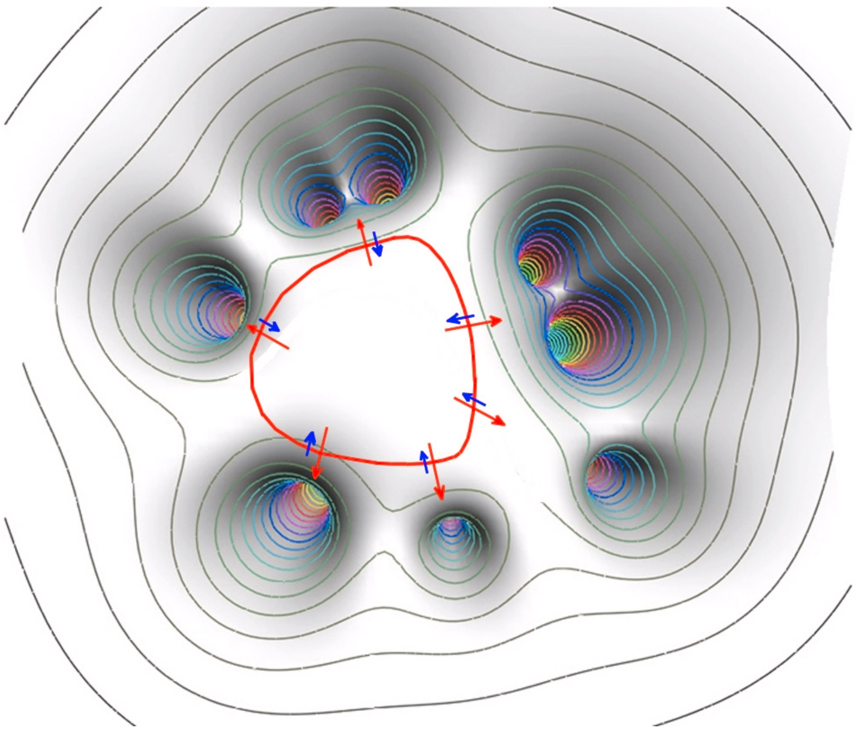


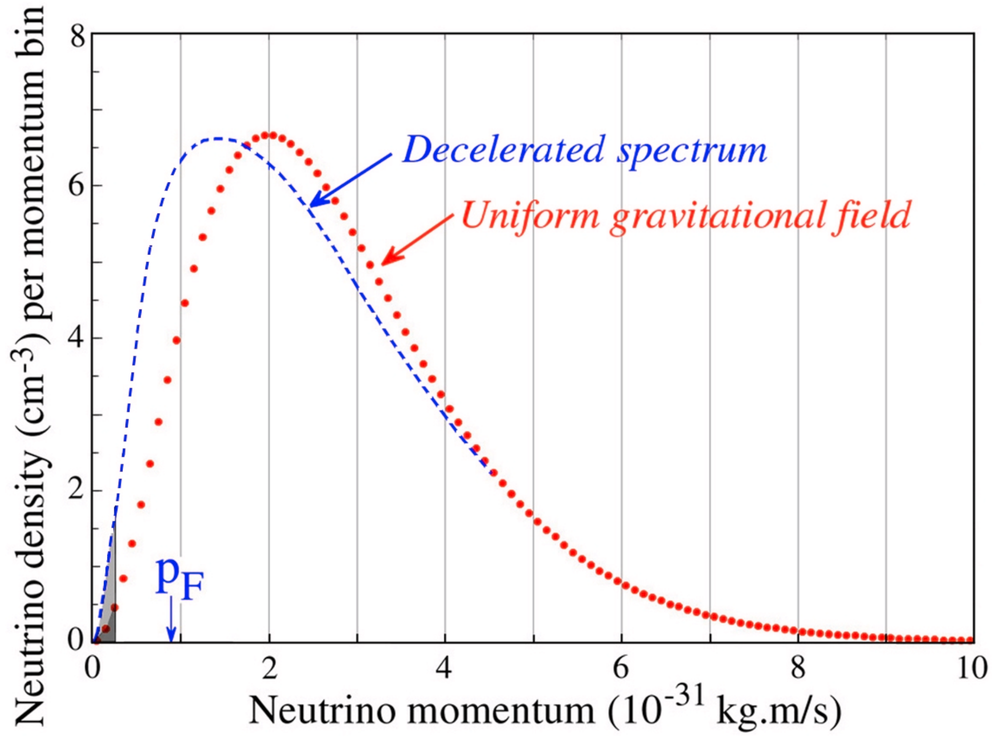
Neutrino *spectrum*

Gravitational slowdown of relic neutrinos



The Pauli acceleration





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

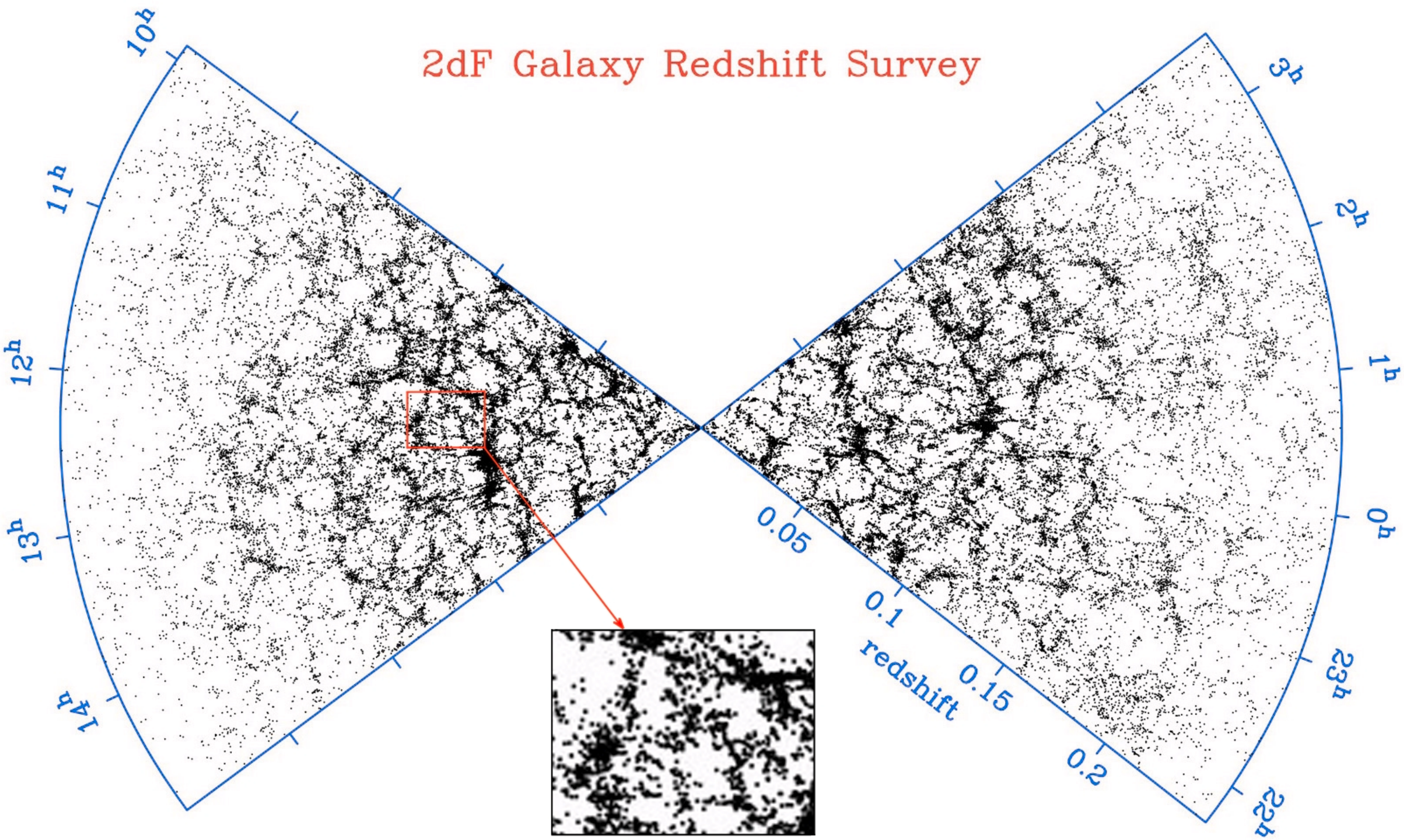
  RT_ν = *constant* ⟶ *R has to increase*

  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

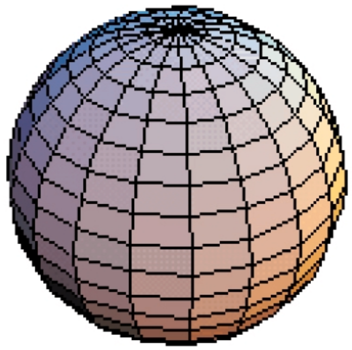
Here: 10^{76} *cooling neutrinos curve space-time around the center-of-mass of a developing galaxy cluster such as to prevent violation of the Pauli principle*

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

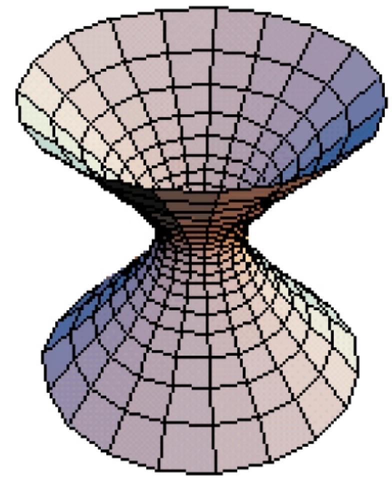
The Pauli acceleration (2)

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.

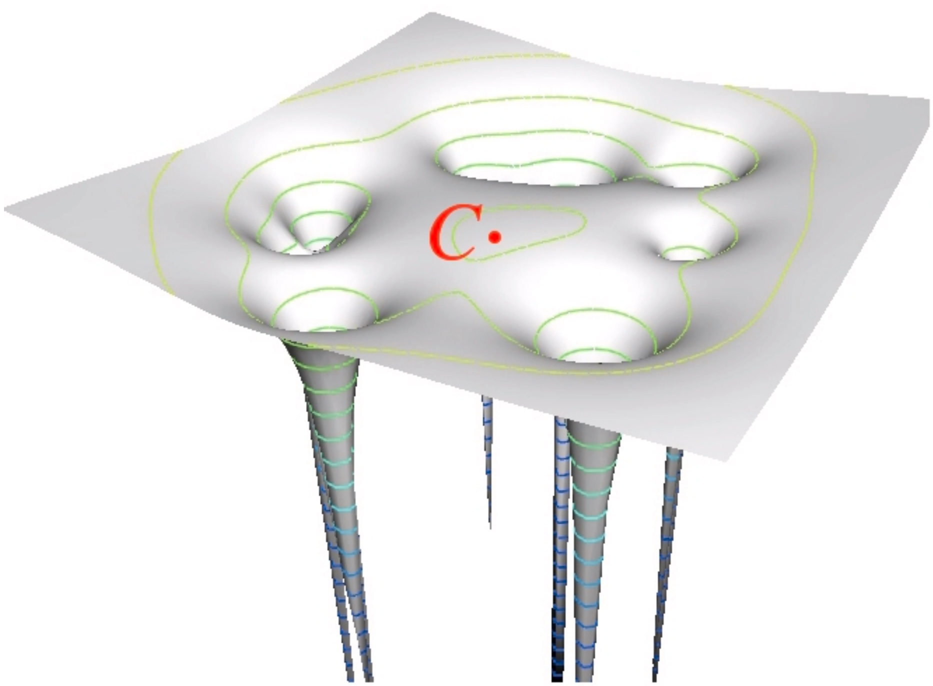


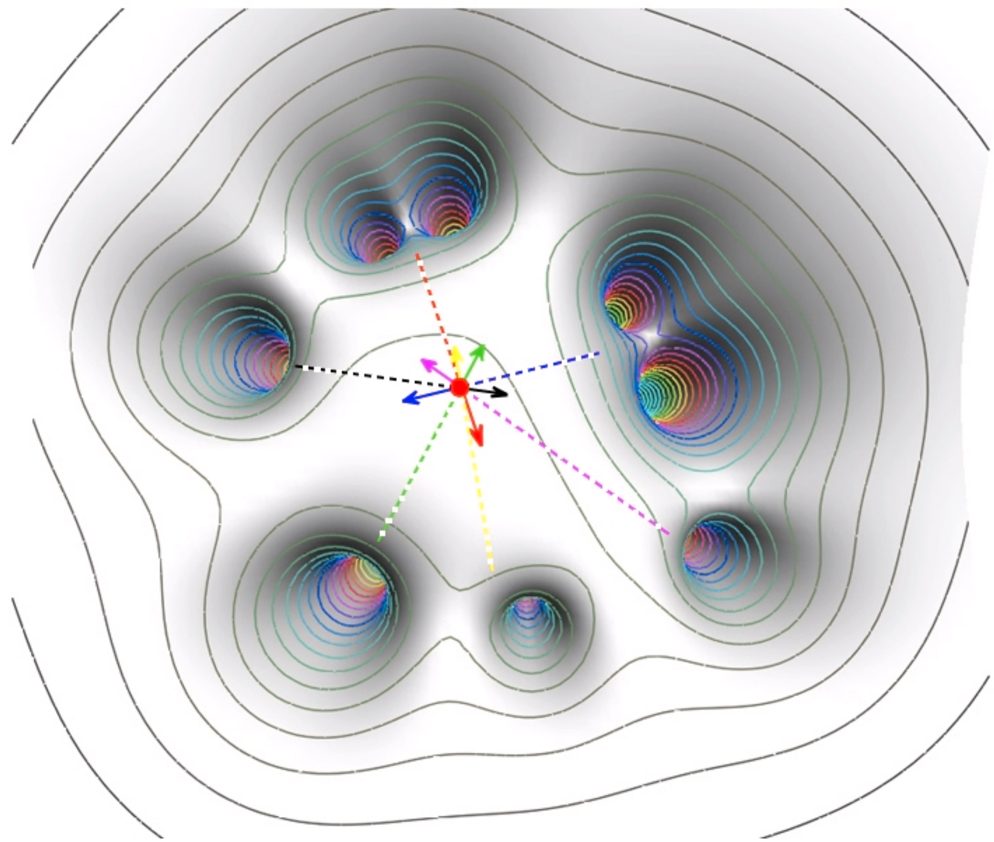
A hyperboloid has constant negative curvature.

- *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*

Galaxies form: Start of the Pauli acceleration





Pauli acceleration (3)

How large is the Pauli acceleration?

- Pauli violation is caused by decelerating neutrinos

  → *Pauli acceleration neutralizes this effect*

  $$\vec{a}_P = \frac{GM}{r_C^2}\hat{\mathbf{r}} \qquad \begin{array}{l} M = \text{mass galaxy} \\ r_C = \text{distance to } C \end{array}$$

  Typical value of a_P $(M = 5 \cdot 10^{10} M_\odot,\ r_C = 0.1\ \text{Mpc})$: $\sim 10^{-12}\ \text{m/s}^2$

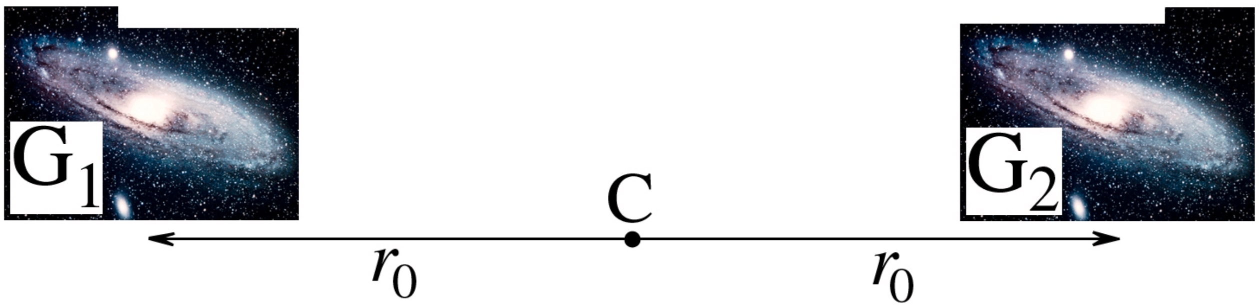
  → Δv = 1 km/s in 300 million years

- The *gravitational deceleration* galaxies experience as a result of the *attractive* force between them *is always smaller* than $|\vec{a}_P|$

  $$\vec{a}_G = -\sum_i \frac{GM_i}{{r_i}^2}\hat{\mathbf{r}}_i \qquad |\vec{a}_G| < |\vec{a}_P|$$

➡ *Galaxies move apart at a gradually increasing speed*

Calculations of the effects of the Pauli acceleration



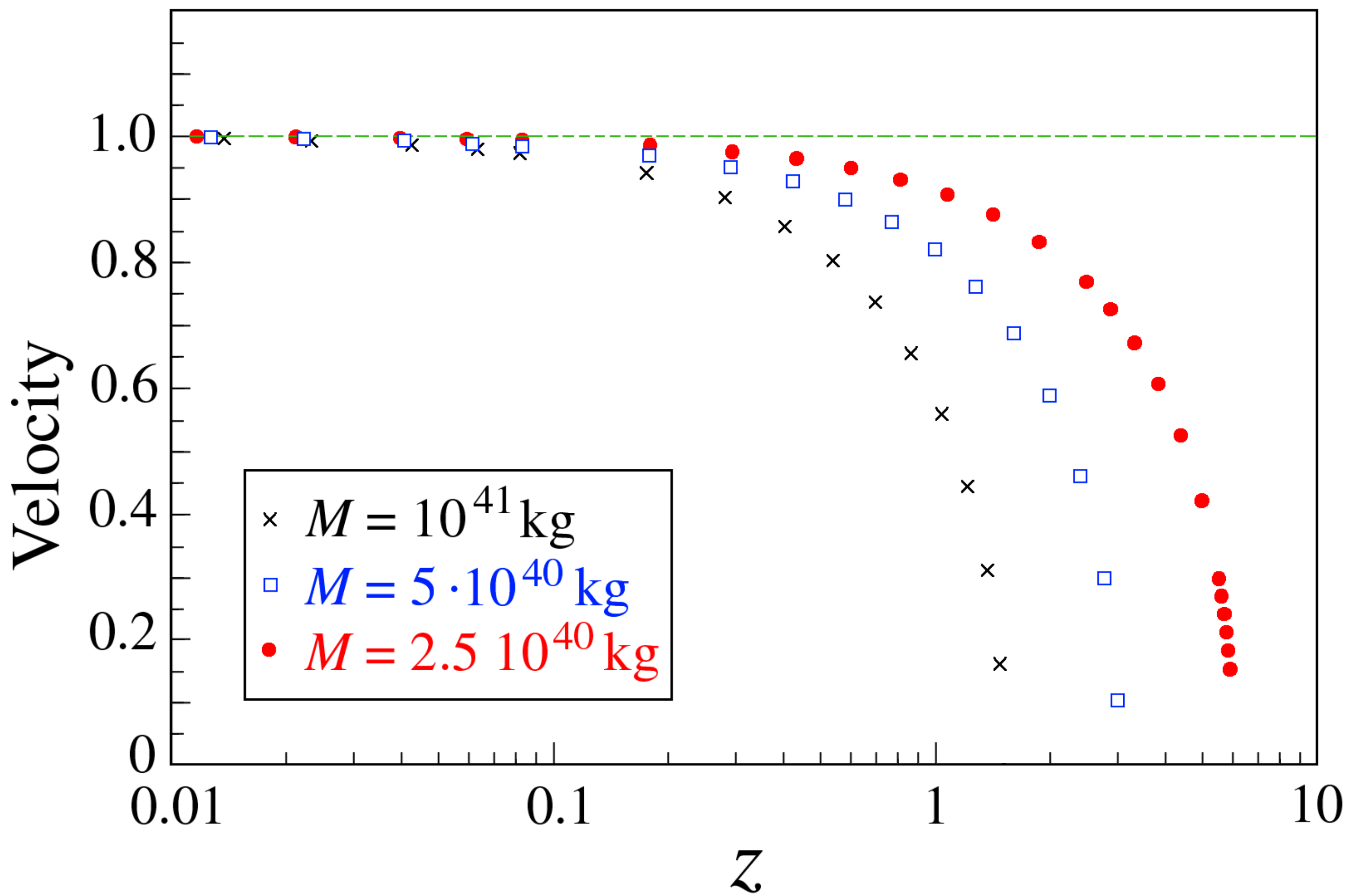
- Take 2 galaxies with mass M each, separated by distance $2r_0$
  These galaxies move away from each other at a speed v_0
  Pauli acceleration increases this speed: $a_P = GMr_0^{-2}$
  Gravitational deceleration decreases this speed: $a_G = -GM(2r_0)^{-2}$
  Take a step back in time (*e.g.* 1 million years), calculate $v(-t)$, $r(-t)$ and $a(-t)$
  Repeat until $v(-t) = 0$

- Parameters used: $2r_0 = 1$ Mpc, $v_0 =$ 73 km/s $(= H_0)$

- Evolution of v sensitive to choice of M and r_0
  This choice determines z value of start Pauli acceleration

$$z = \frac{r_0}{r(-t)} - 1$$

Pauli acceleration: Dependence on galaxy mass



Calculations of the effects of the Pauli acceleration

- Take 2 galaxies with mass M each, separated by distance $2r_0$
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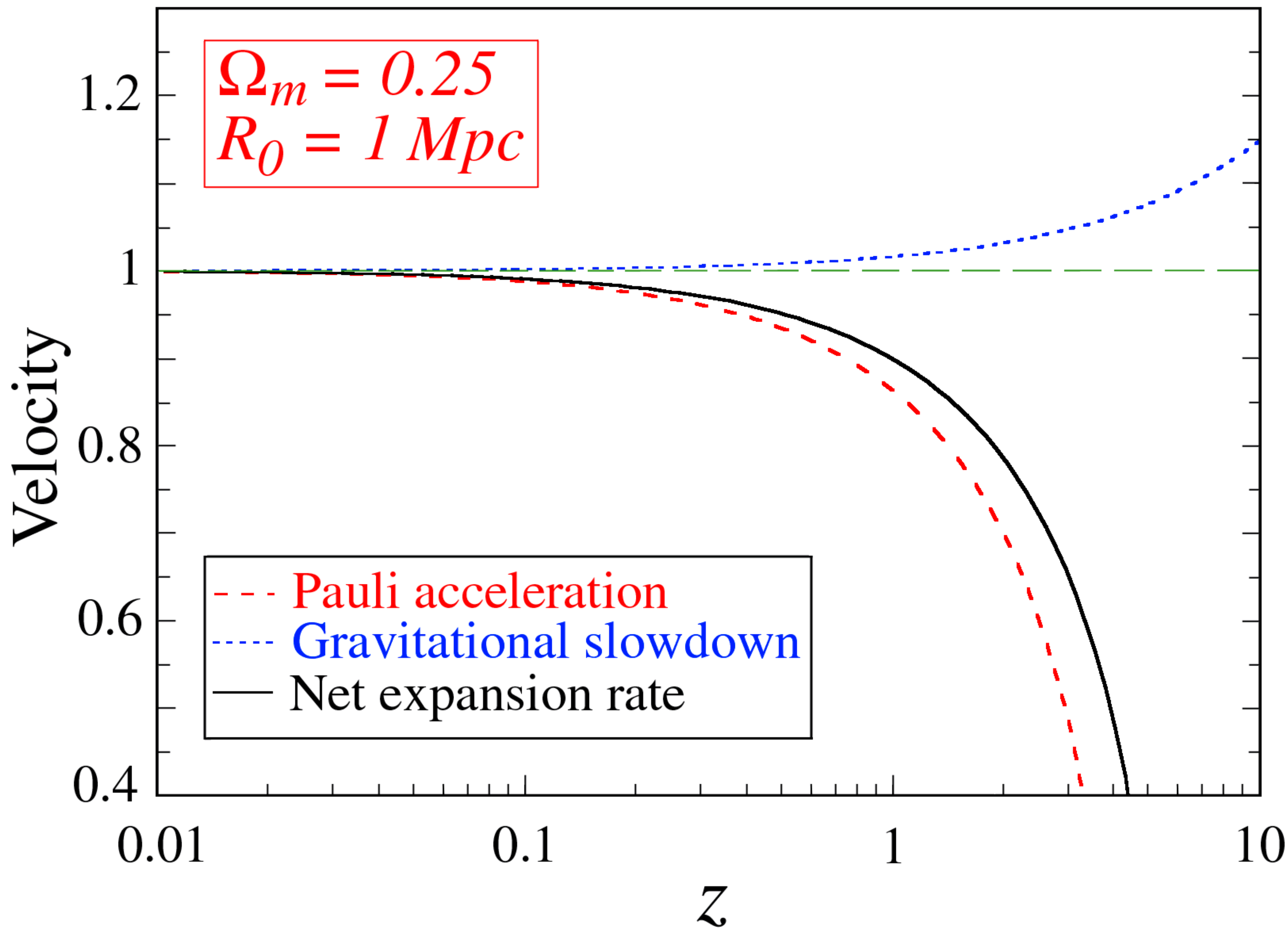
  Repeat until $v(-t) = 0$

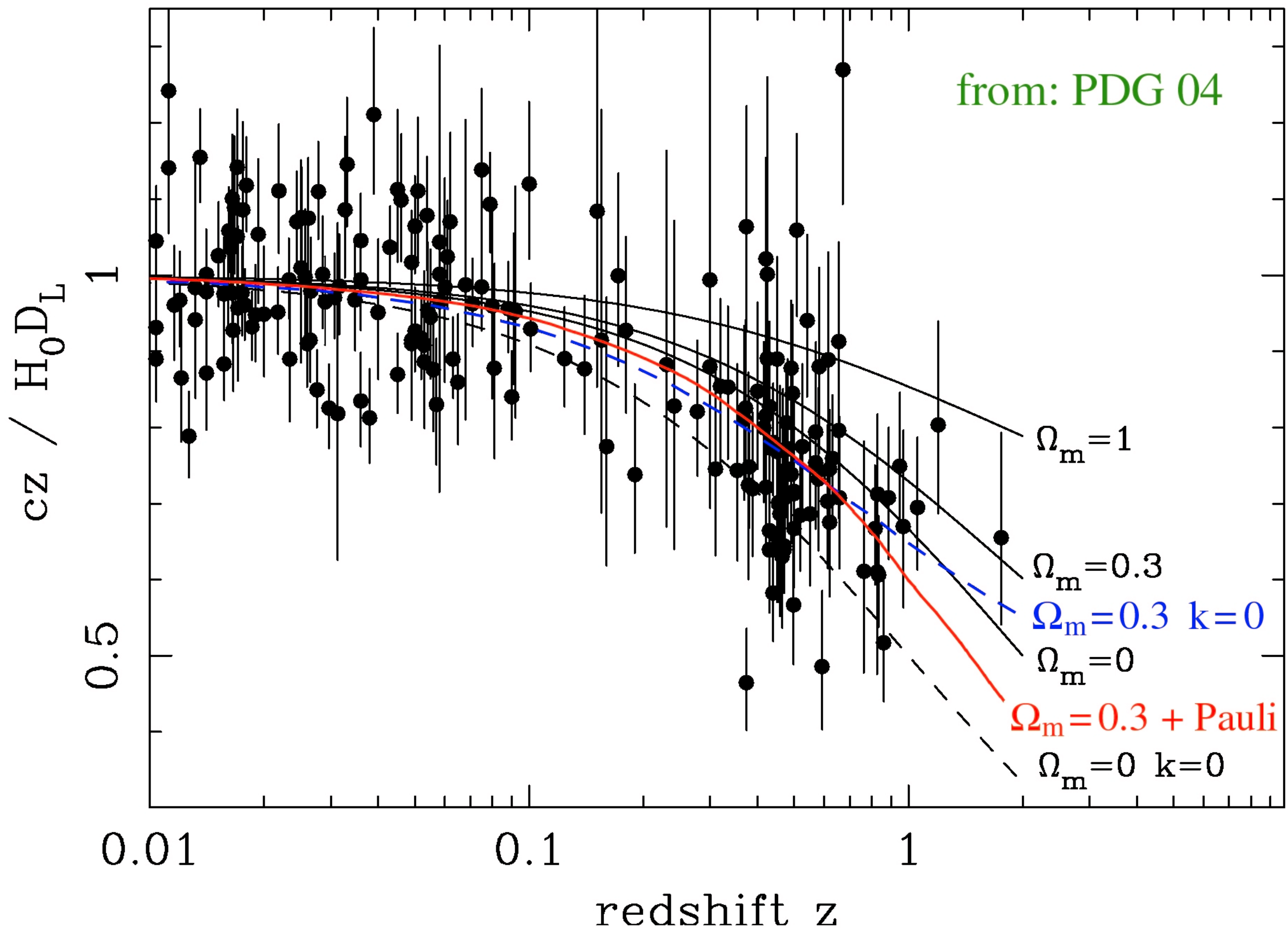
- Parameters used: $2r_0 = 1$ Mpc, $v_0 = 73$ km/s $(= H_0)$

Mass density $\Omega_m = 0.25 \rightarrow$ in sphere with $r = 0.5$ Mpc $M = 4 \cdot 10^{40}$ kg
Pauli acceleration starts around z ~ 6, ~ 13 billion years ago

History of the expansion



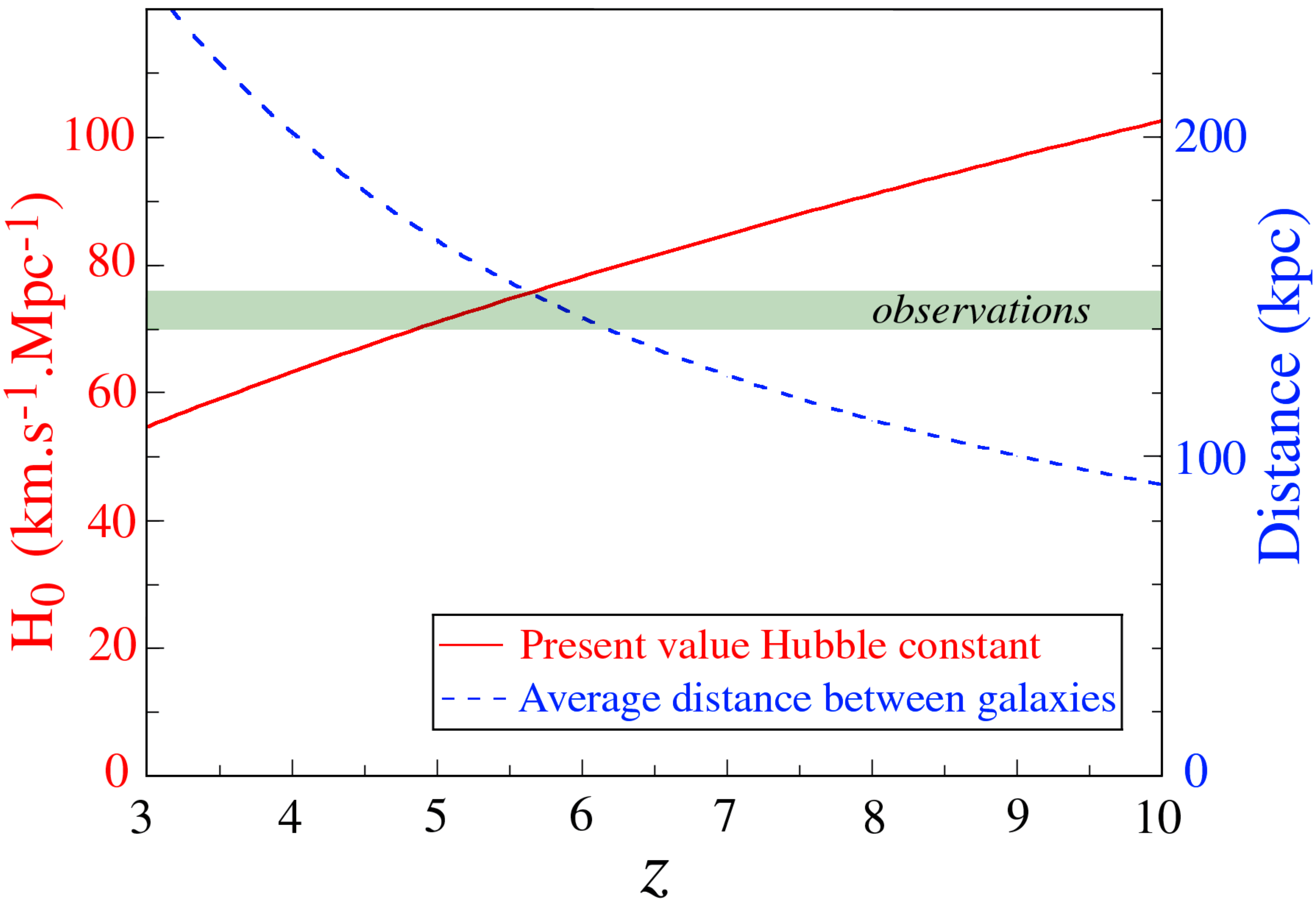
H(z) : Pauli and the Supernova data



Calculations of the effects of the Pauli acceleration

Choose z value at which Pauli acceleration starts
Simulate process *in reverse order*
→ *Calculate H_0*

H_0 and the start of the Pauli acceleration



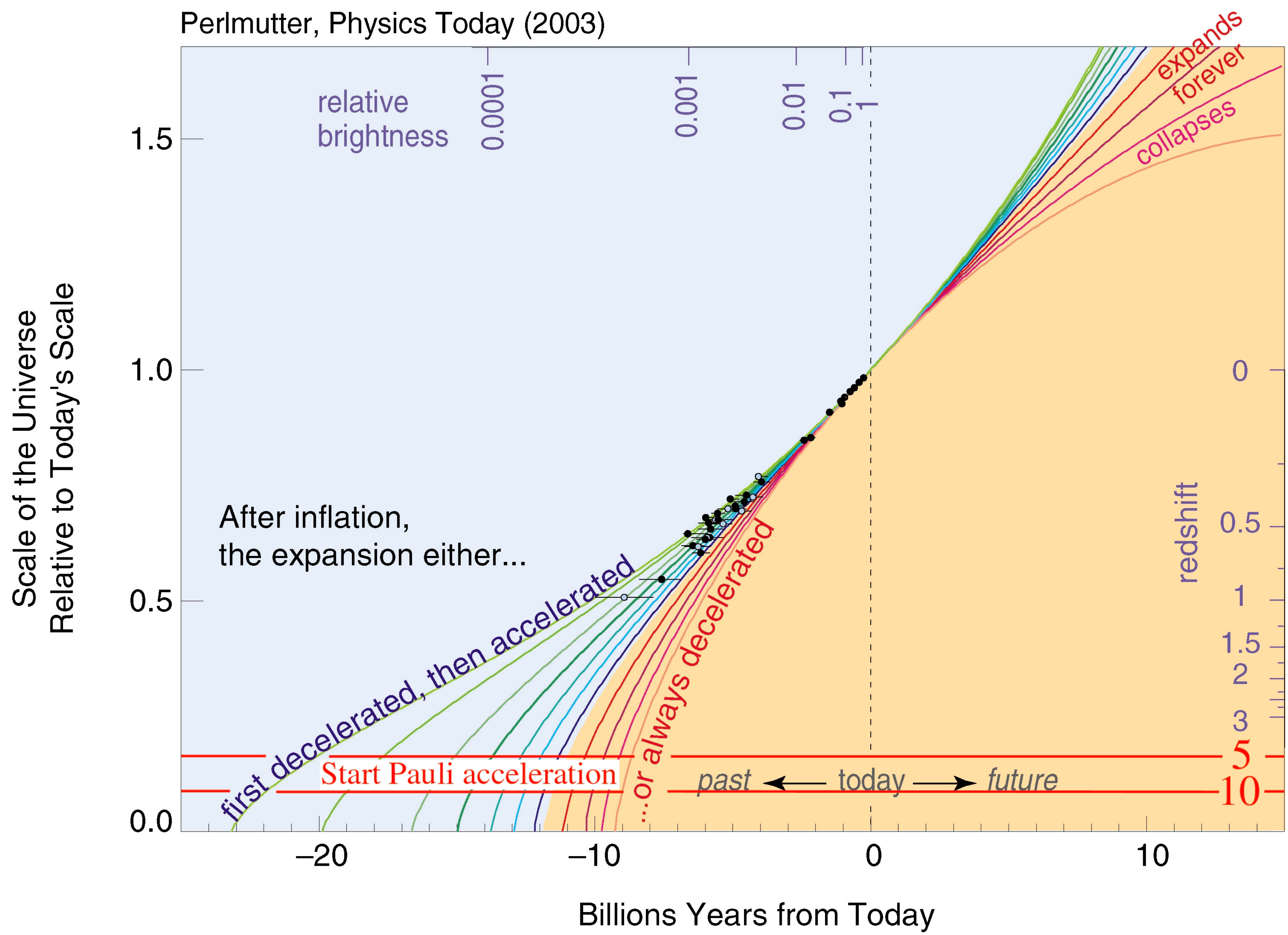
Implications of Pauli Acceleration Model

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



Implications of Pauli Acceleration Model

1) No need for "dark energy"

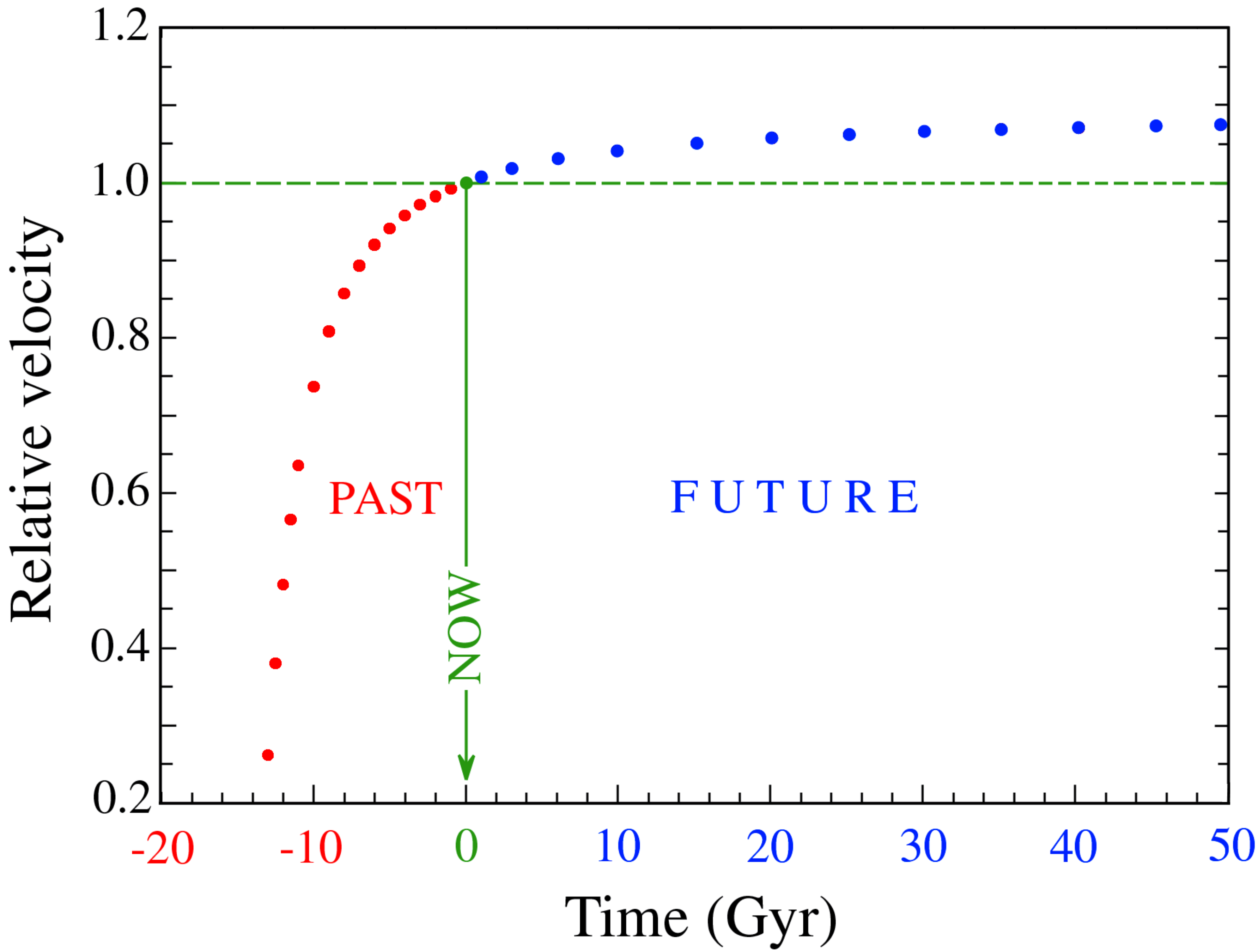
2) Expansion will continue forever, regardless of the value of Ω

The mechanism that drives the expansion does not go away

$\longrightarrow$ *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 Ω

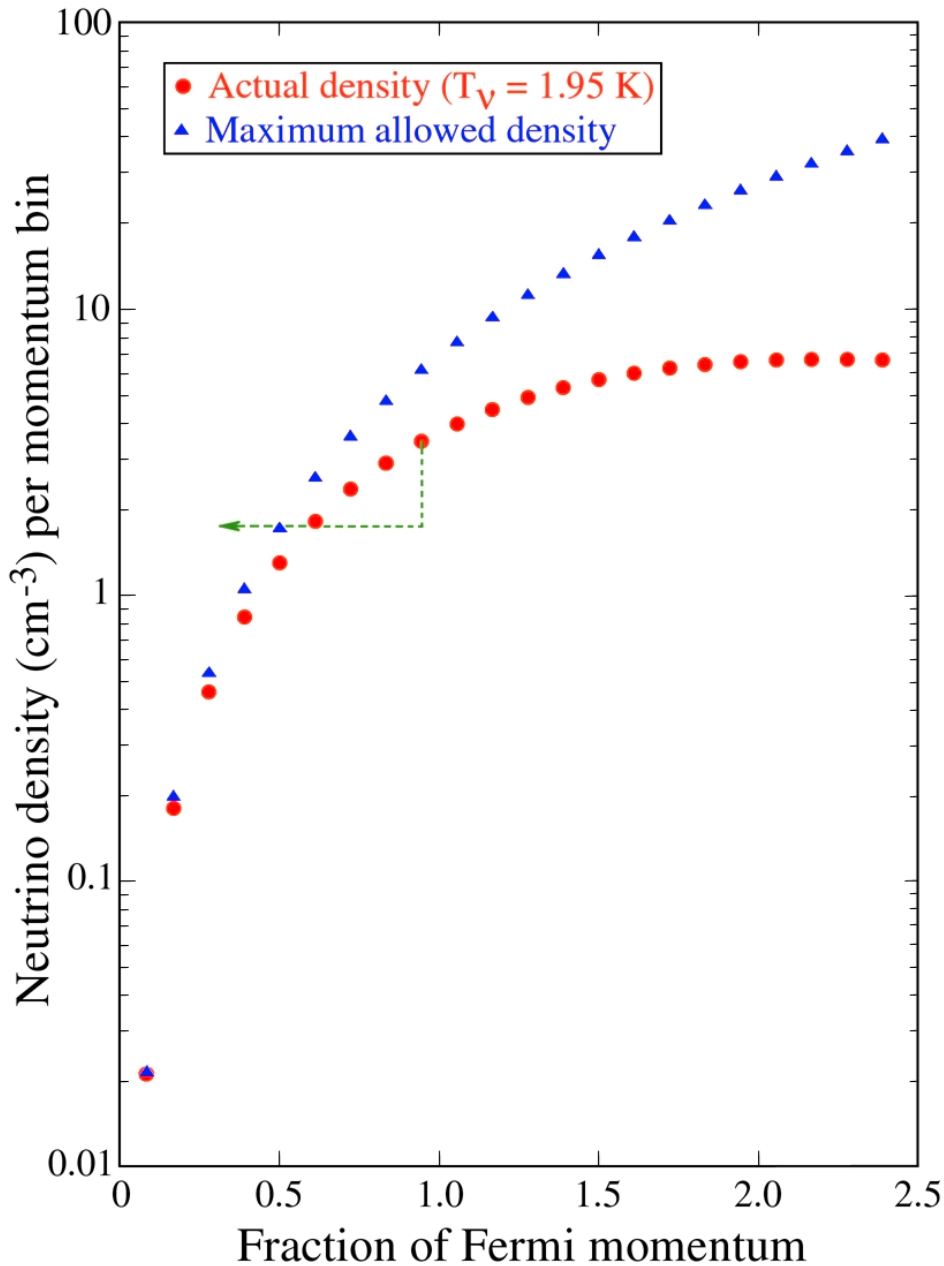
3) Neutrino mass: Lower limit

- 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% ($v > 0.82\ v_F$)

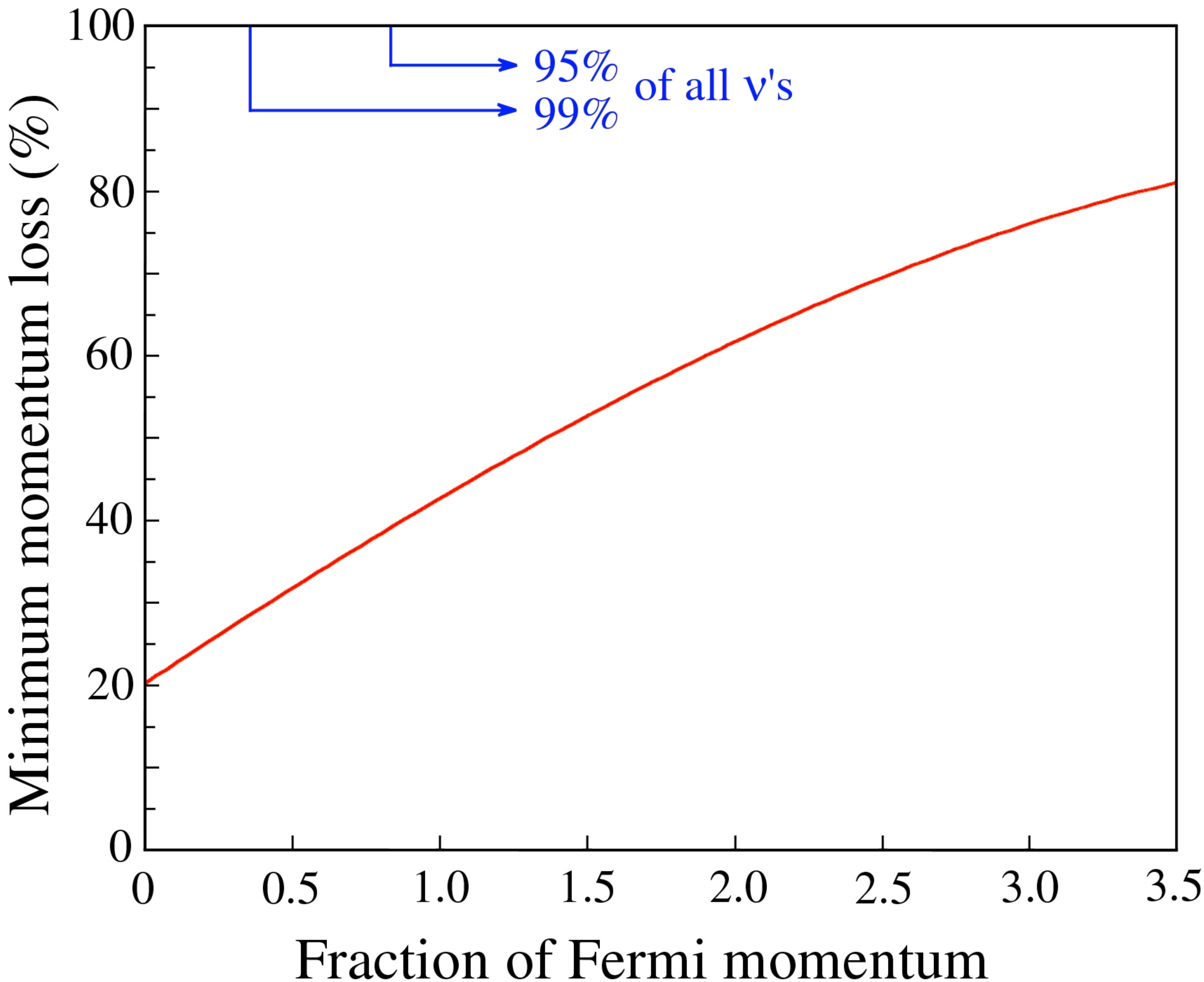
- Neutrinos with $v < 165$ km/s meet this condition $\rightarrow v_F < 200$ km/s

$$\rightarrow m_\nu > 0.25\ \mathrm{eV}/c^2 \quad (95\%\ \mathrm{c.l.})$$

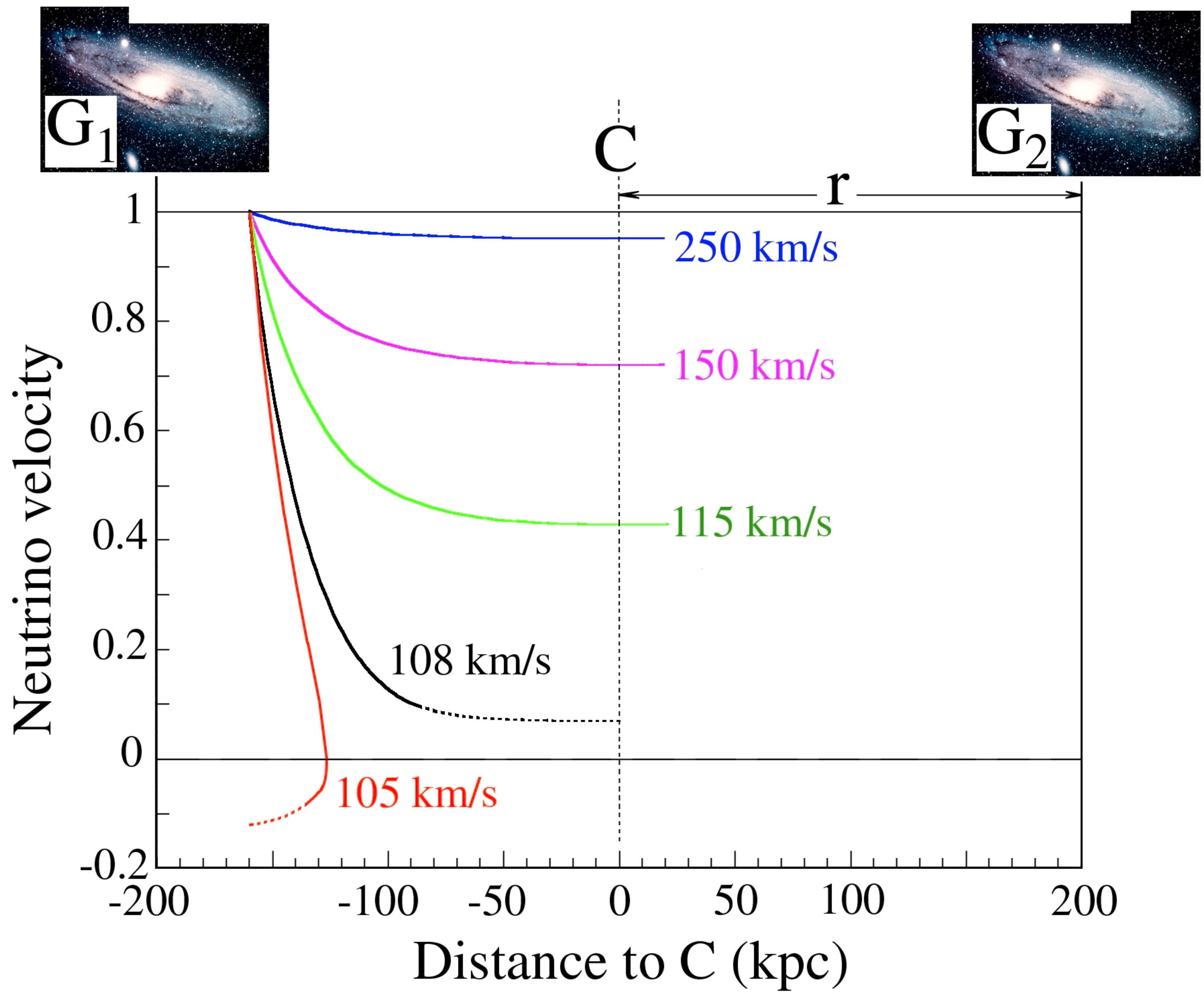
Relic neutrinos: A degenerate fermion gas (T = 1.95 K)



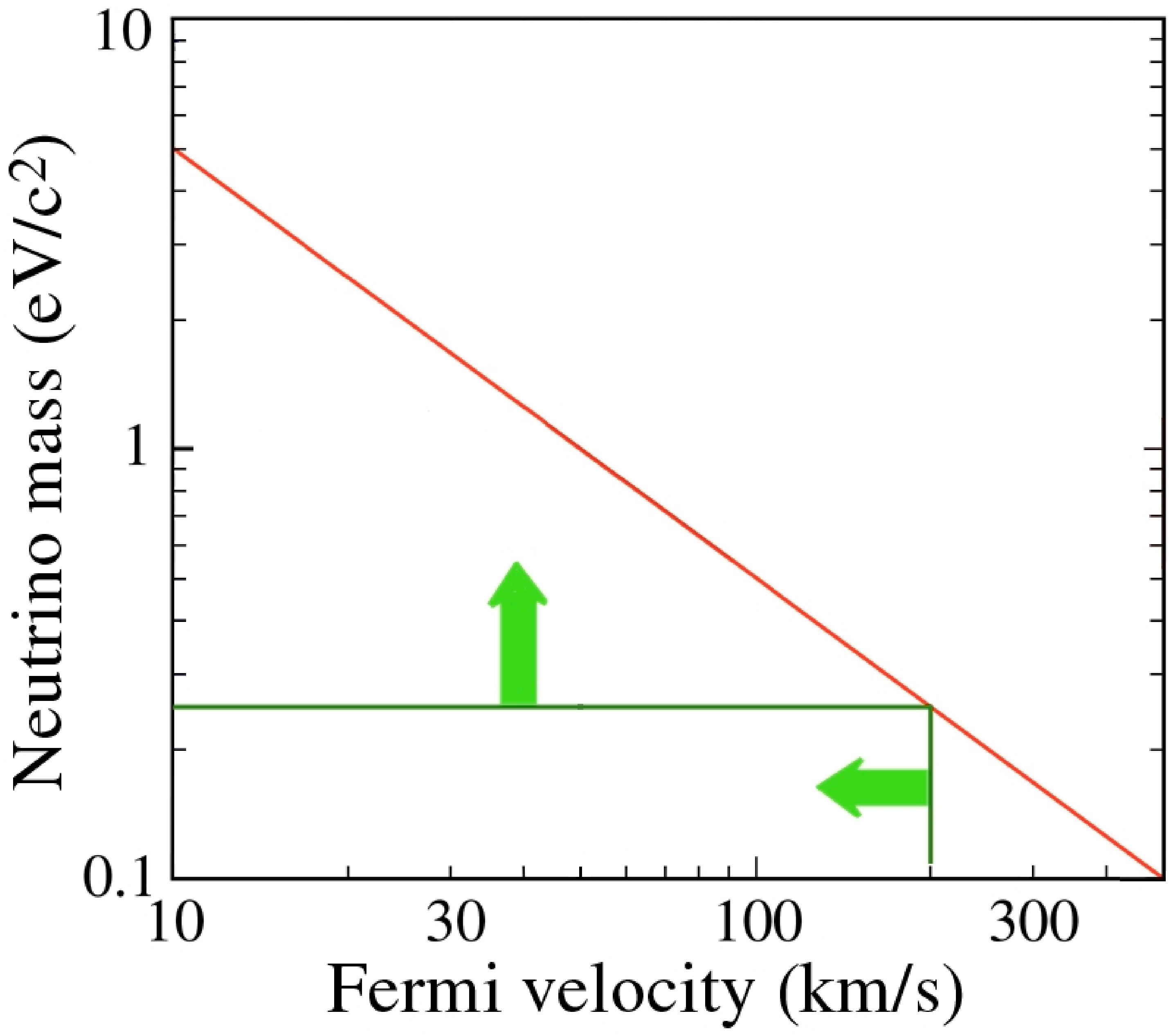
Momentum losses needed to violate Pauli principle



Gravitational slowdown of relic neutrinos



Mass/velocity relationship relic neutrinos



The Status of Modern Cosmology

We live in an unusual time, perhaps the first golden age of empirical cosmology. With advancing technology, we have begun to make philosophically significant measurements. These measurements have already brought surprises. Not only is the universe accelerating, but it apparently consists primarily of mysterious substances. We've already had to revise our simplest cosmological models. Dark energy has now been added to the already perplexing question of dark matter. One is tempted to speculate that these ingredients are add-ons, like the Ptolemaic epicycles, to preserve an incomplete theory. With the next decade's new experiments, exploiting not only distant

S. Perlmutter (SCP)

Summary & Conclusions

- Relic neutrinos form a *degenerate* Fermi-Dirac gas.
  Typical velocities are *~100 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"*
- Fermion degeneracy effects are usually associated with extremely hot/dense conditions inside White Dwarfs and neutron stars.
  They may also play a crucial role in the empty, cold intergalactic space

and finally

If this is all true, then

- *Quantum Mechanics drives the expansion of the Universe!!*
- *We are witnessing Quantum Gravity at work*
- $m_\nu > 0.25\ \mathrm{eV}/c^2 \longrightarrow$ *go find it !*

On the Accelerated Expansion of the Universe

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The Universe is filled with relic neutrinos, remnants from the Leptonic Era. Since the formation of galaxies started, gravitation has modified the Fermi-Dirac momentum distribution of these otherwise decoupled particles. Decelerated neutrinos moving toward the field-free regions between galaxies could violate the Pauli principle. The fermion degeneracy pressure resulting from this leads to an accelerated motion of galaxies away from one another. We show that this model not only offers a natural explanation for the accelerated expansion of the Universe, but also allows a straightforward calculation of the Hubble constant and the time-evolution of this constant. Moreover, it sets a lower limit for the (average) neutrino mass. For the latter, we find $m_\nu > 0.25$ eV/c^2 (95% C.L).

PACS numbers: 14.60.Pq, 98.80.Es

The experimental observation [1,2] that distant Type Ia Supernovae are dimmer than expected seems to lead to the inevitable conclusion that the rate at which the Universe expands has increased since the time when these stellar explosions occurred, 5 - 10 billion years ago. Current cosmological reviews [3] ascribe the responsibility for this phenomenon to anti-gravitational action associated with “dark energy”. However, the nature of this energy and, therefore, the meaning of the non-zero cosmological constant which is needed in the equations that describe the evolution of the Universe is a mystery.

In this letter, we argue that there is another scenario that may explain the experimental observations. This scenario does not invoke new forces or unknown forms of energy. It is based on a well known phenomenon, the *fermion degeneracy pressure*, a consequence of Pauli's Exclusion Principle. This degeneracy pressure is responsible for a variety of astrophysical phenomena, *e.g.,* the characteristics of White Dwarfs and neutron stars. Whereas the fermions involved in these objects are electrons and neutrons, the ones responsible for the degeneracy pressure discussed here are neutrinos. The proposed scenario requires that neutrinos have masses of ~ 1 eV/c^2.

According to the Big Bang model, large numbers of neutrinos and antineutrinos have been around since the earliest stages of the evolving Universe. Since the decoupling that marked the end of the Leptonic Era, the wavelengths of these relic (anti-)neutrinos have been expanding in proportion to the size of the Universe. Their present spectrum is believed to be a momentum-redshifted relativistic Fermi–Dirac distribution, and the number of particles per unit volume in the momentum bin $(p, p + dp)$ is given by

$$N(p)dp \;=\; \frac{8\pi p^2 dp}{h^3[\exp(pc/kT_\nu)+1]}\left(\frac{g_\nu}{2}\right) \qquad (1)$$

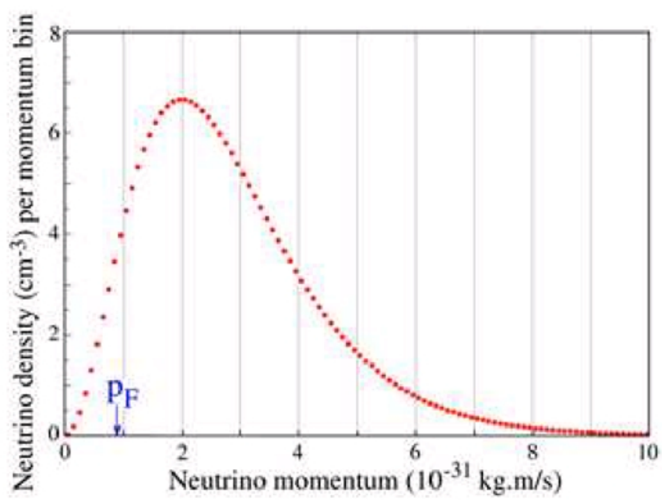

FIG. 1. The momentum distribution of relic neutrinos at a temperature $T_\nu = 1.95$ K. The number of helicity states is assumed to be 2.

where g_ν denotes the number of neutrino helicity states [4]. This momentum spectrum is depicted in Figure 1. The distribution is characterized by a temperature T_ν, which is somewhat lower than that for the relic photons, which were reheated when the electrons and positrons decoupled. Since $(T_\nu/T\;)^3 = 4/11$ and $T\; = 2.725 \pm 0.001$ K [5], T_ν is expected to be 1.95 K. For a neutrino temperature of 1.95 K, the Fermi momentum ($p_F = kT_\nu/c$) is $1.68 \cdot 10^{-4}$ eV/c, or $9.0 \cdot 10^{-32}$ kg.m.s^{-1}.
The present density of these Big Bang relics is estimated at ~ 220 cm^{-3}, for each (Dirac) neutrino avor [6], nine orders of magnitude larger than the density of baryons in the Universe.
It is important to realize that, depending on their mass, these relic neutrinos might be very *nonrelativistic* at the current temperature. Since they decoupled, their momenta have been stretched by a factor of 10^{10}, from 1 MeV/c to 10^{-4} eV/c. If their rest mass were 1 eV/c^2,