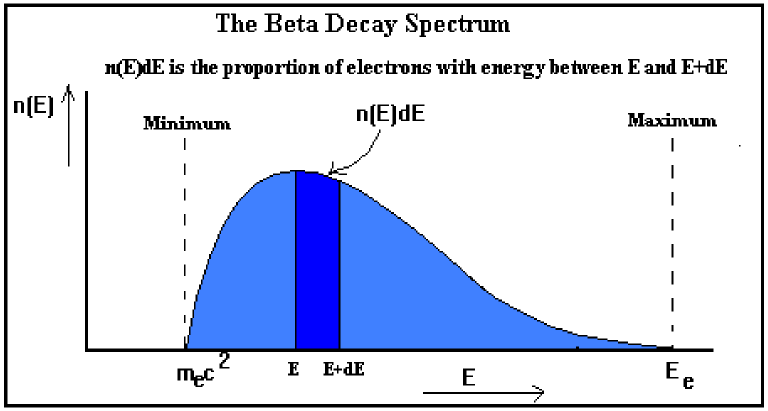
Neutrinos: the dark side of the light fermions

- missing energy: neutrino discovered
- missing particles: neutrino oscillations
- missing people: from Majorana to Gamow, to Pontecorvo
- missing mass: dark matter
- missing symmetries and leptogenesis
- missing fundamental theory

concentrate on the **dark side:** singlet (right-handed) neutrinos

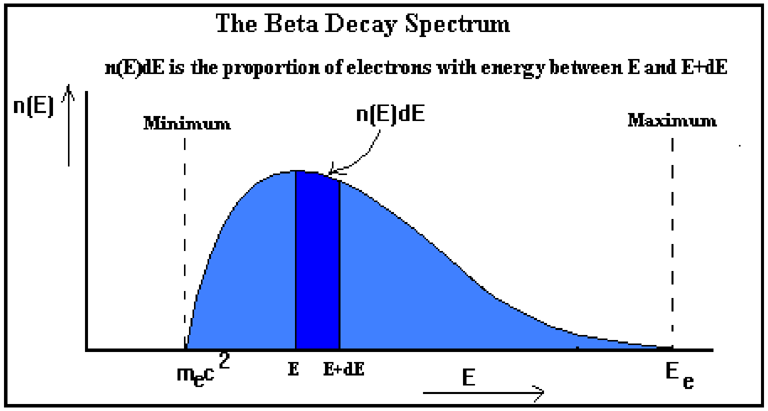
Missing energy in β-decays



$$A_1 \longrightarrow A_2 + e^-$$

Why is the electron energy not equal the mass difference between the two nuclei? Is the energy conserved?

Missing energy in β-decays



$$A_1 \longrightarrow A_2 + e^-$$

Why is the electron energy not equal the mass difference between the two nuclei? Is the energy conserved?

$$A_1 \longrightarrow A_2 + e^- + \text{new particle}$$

Pauli's letter (December 4, 1930)

Dear Radioactive Ladies and Gentlemen,
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, **the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons**, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

Your humble servant W. Pauli

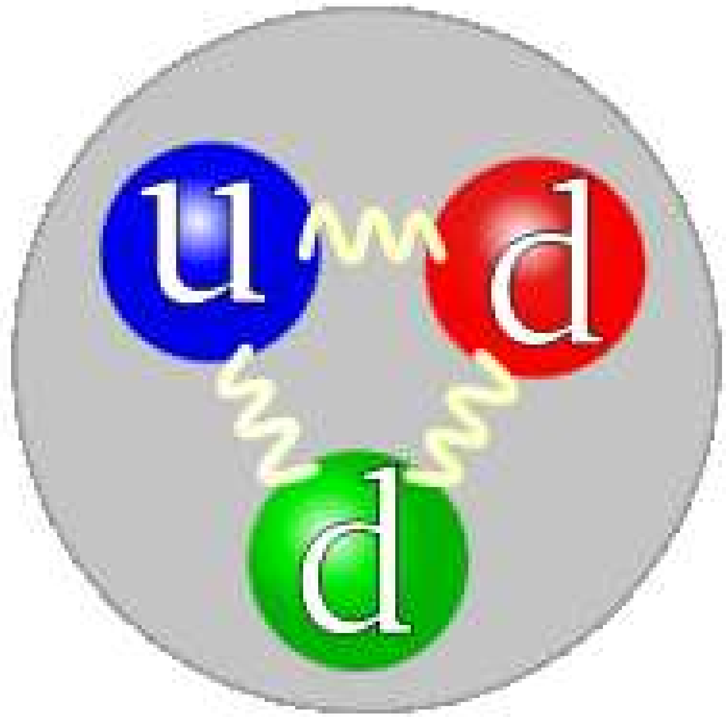
Pauli's letter (December 4, 1930)

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call **neutrons**, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. **The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.** The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

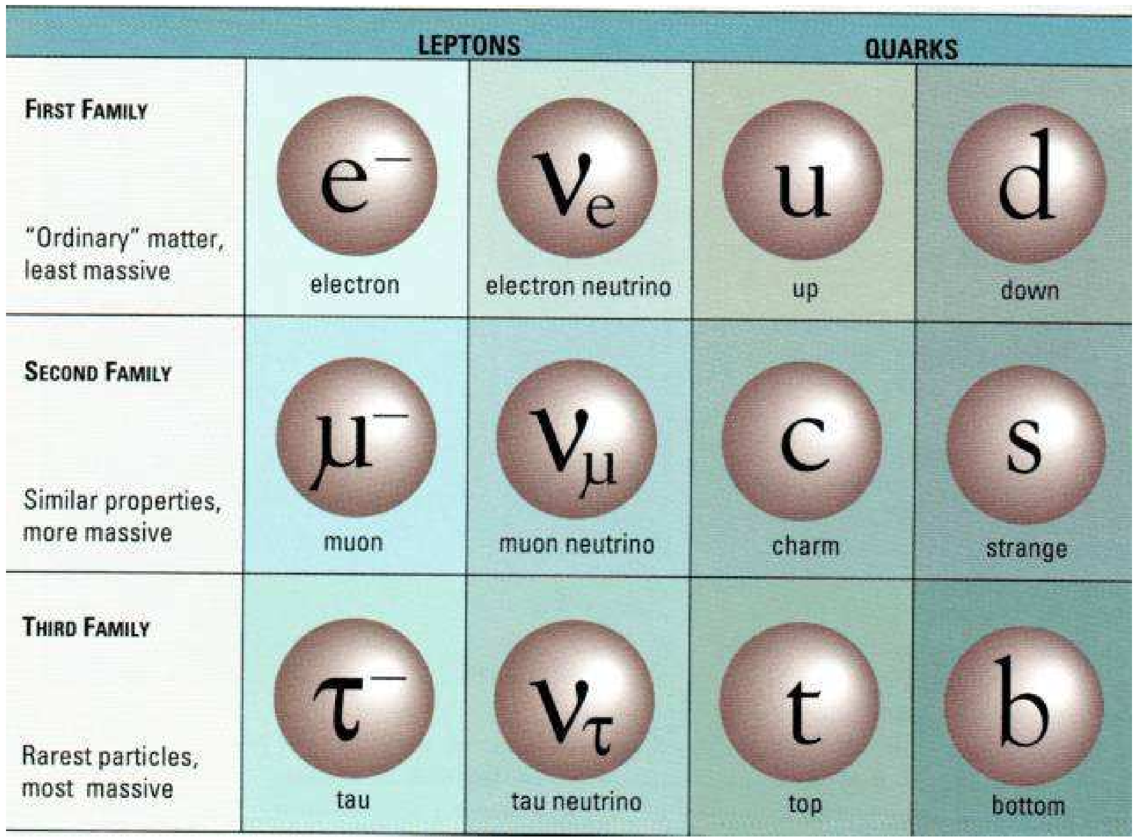
Your humble servant W. Pauli

In 1932 Chadwick discovered the neutron.



In 1933 Enrico Fermi develops a theory of beta decay, including neutrino, and gives it the name.

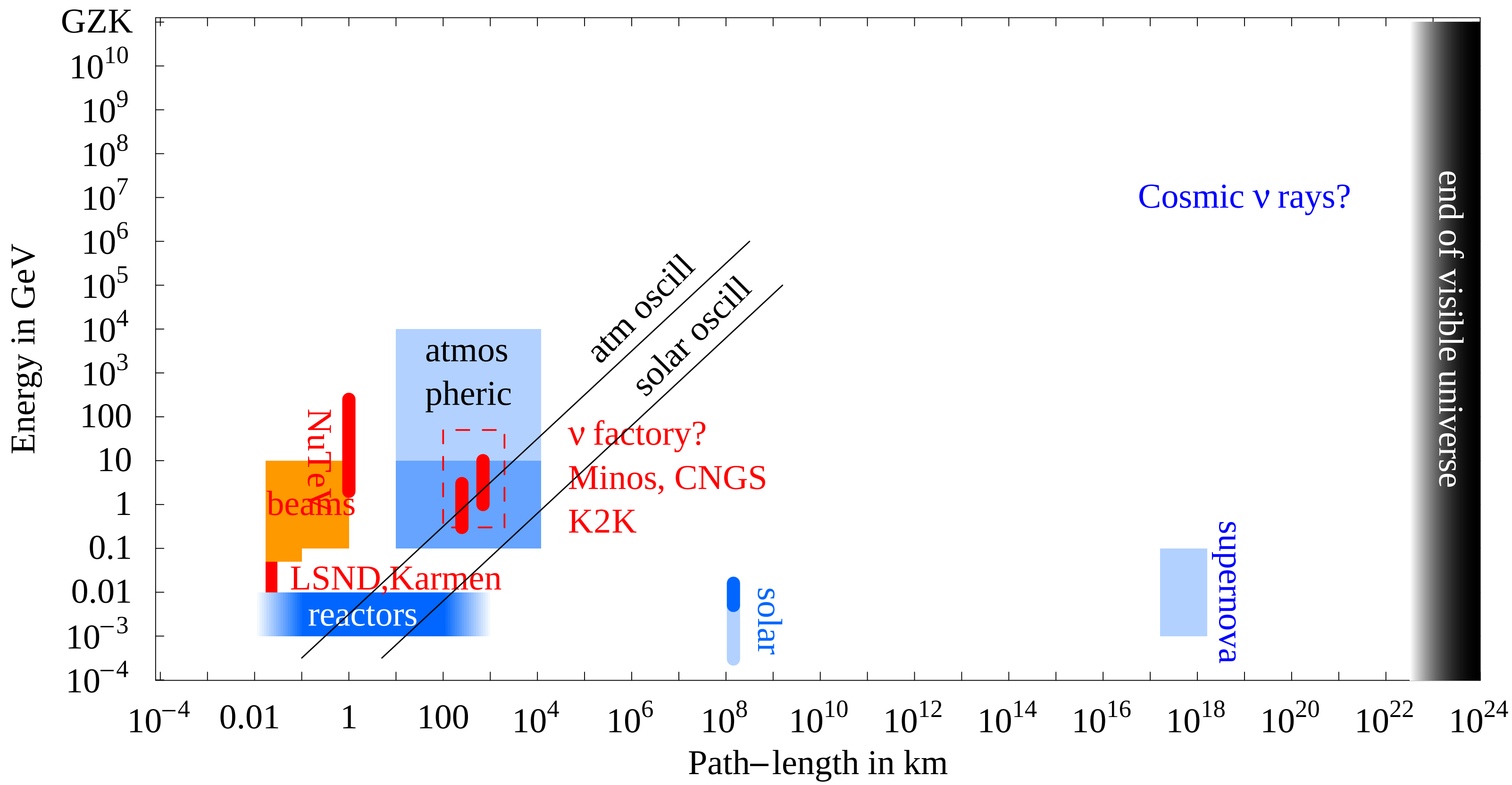
Thee families of fermions



Astrophysical neutrinos are flying at us!

- Neutrinos from stars, including Sun
- Neutrinos from supernovae, including 1987A
- Relic neutrinos from Big Bang (have not seen)
- Ultrahigh-energy neutrinos (ANITA, Ice Cube, etc.)

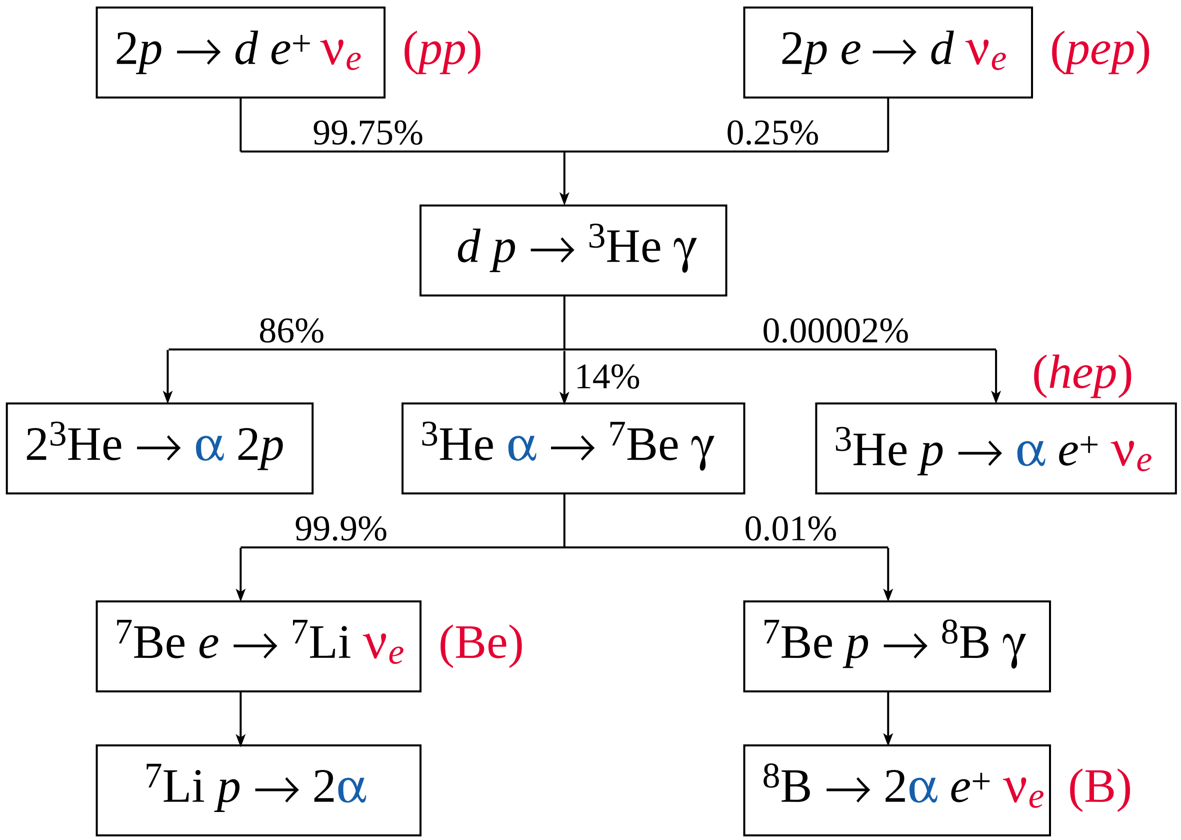
Neutrinos available: natural (blue) and man-made (red)



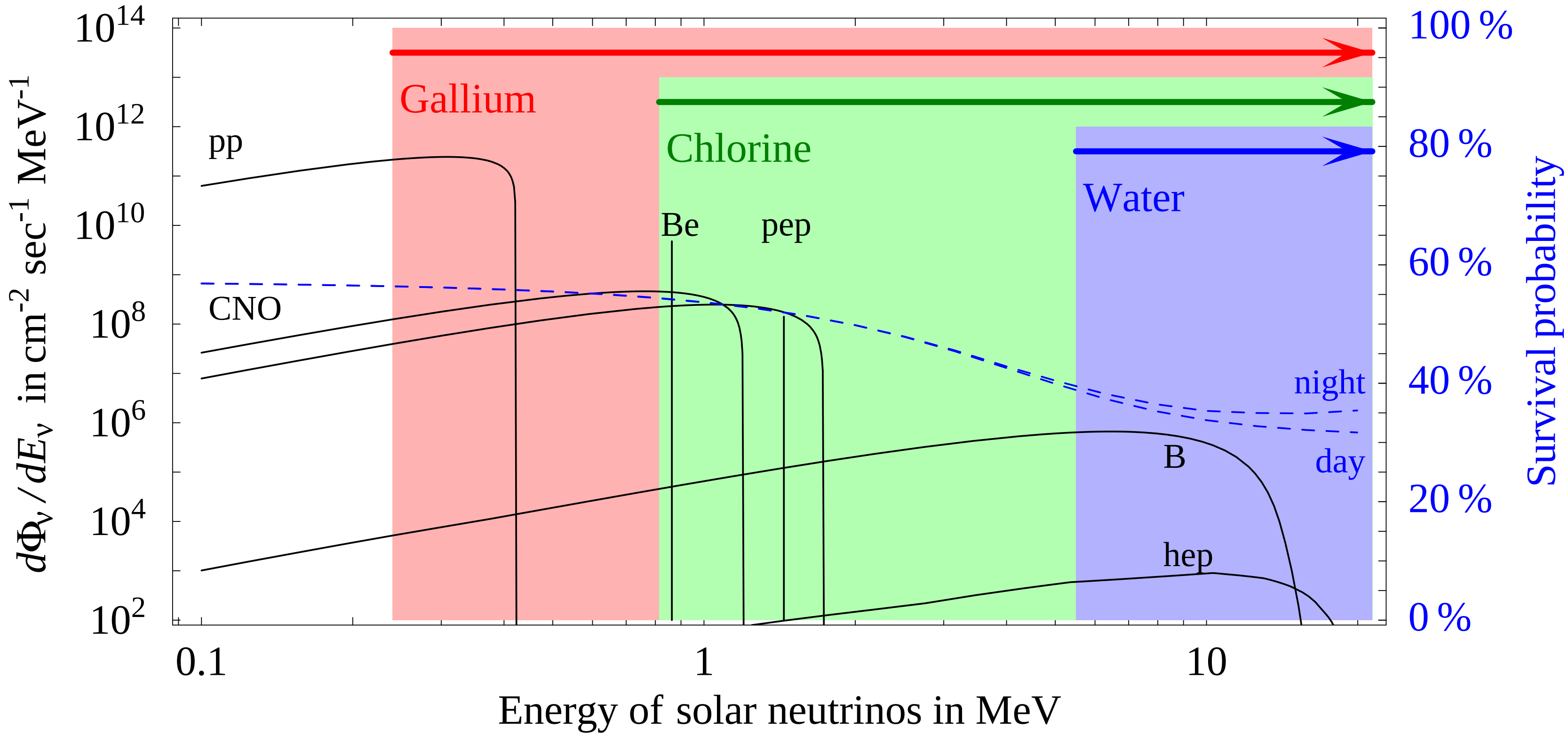
Solar neutrinos

Neutrinos in the Sun are produced by nuclear reactions (which also power the Sun).
[Bethe, Fowler, Bahcall, Ulrich]

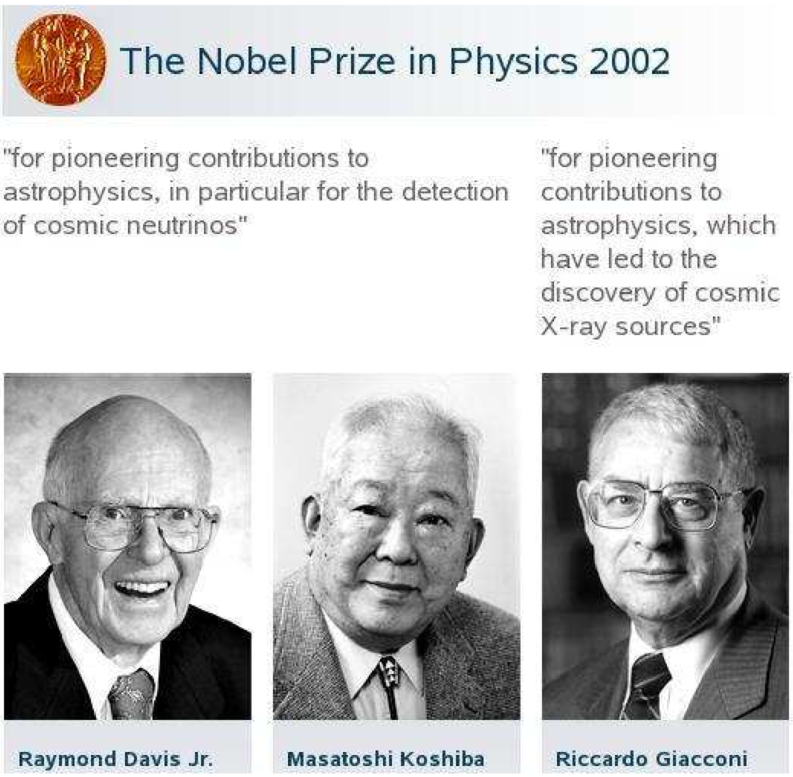
Solar neutrinos



Solar neutrinos



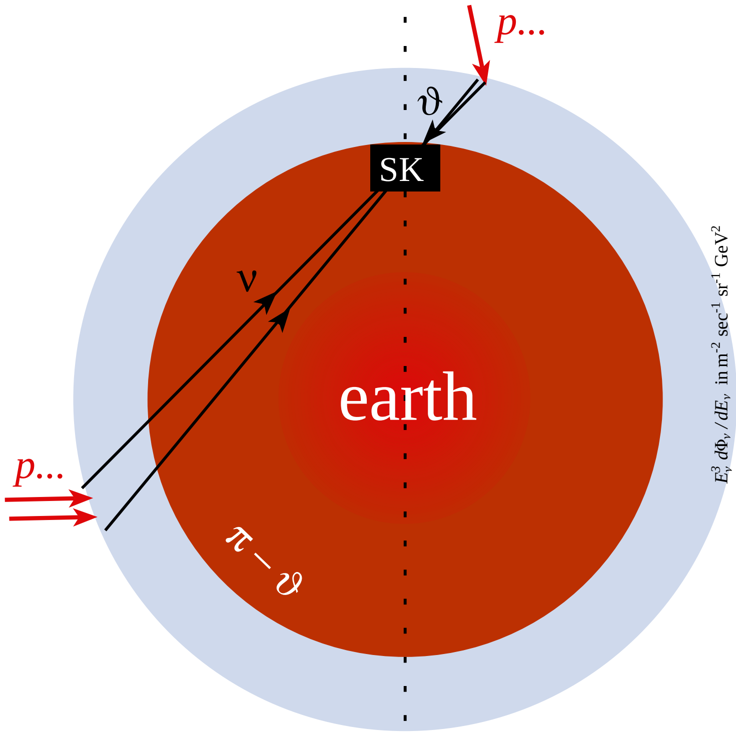
Solar neutrinos discovered

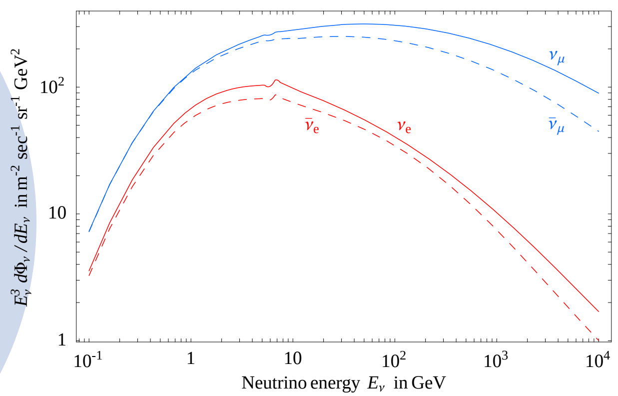


Missing neutrinos

The deficit of solar neutrinos indicated new physics, most likely, neutrino oscillations

Atmospheric neutrinos





Neutrino oscillations

If neutrinos have masses, their mass eigenstates need not be the same as their weak eigenstates:

$$\begin{cases} |\nu_1\rangle = \cos\theta|\nu_e\rangle - \sin\theta|\nu_\mu\rangle \\ |\nu_2\rangle = \sin\theta|\nu_e\rangle + \cos\theta|\nu_\mu\rangle \end{cases} \tag{1}$$

In general, for three neutrinos,

$$\left|\nu_i^{(\mathrm{mass})}\right\rangle = U_{i\alpha}\left|\nu_\alpha^{(\mathrm{weak})}\right\rangle$$

Oscillations in vacuum

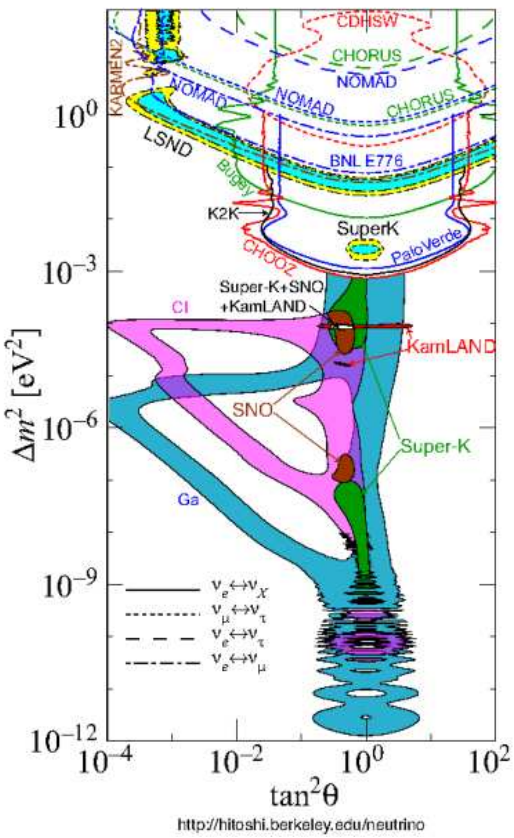
Weak eigenstates are produced in the electroweak interactions, $|\nu_\alpha\rangle$ ($\alpha = e, \mu, \tau$). What propagates through space is mass eigenstates (irreps of the Poincaré group), $|\nu_i\rangle$ ($i = 1, 2, 3$). In a two-neutrino case, if ν_e is produced at some point x,

$$|\nu(x)\rangle = e^{ip_1 x} \cos\theta |\nu_1\rangle + e^{ip_2 x} \sin\theta |\nu_2\rangle .$$

The probability of ν_μ *appearance* at distance $x \approx L$ is

$$\begin{aligned} \boldsymbol{P(\nu_e \longrightarrow \nu_\mu)} \quad &= \quad \boldsymbol{|\langle \nu_\mu | \nu(L) \rangle|^2} = \\ & \sin^2 2\theta \quad \sin^2 \frac{(p_2 - p_1)L}{2} \simeq \sin^2 2\theta \quad \sin^2 \frac{\boldsymbol{\Delta m^2_{12}} L}{4E} . \end{aligned}$$

Neutrino oscillations imply neutrino masses



Two possibilities: "normal" or "inverted" hierarchy

Neutrion oscillations probability, e.g., $P(\nu_e \to \nu_\mu) \simeq \sin^2 2\theta \quad \sin^2 \frac{\Delta m^2_{12} L}{4E}$ is not sensitive to the sign of Δm^2.

Neutrino oscillations in matter

The interactions with matter are described by

$$H = \frac{G_F}{\sqrt{2}} \bar{\nu}_e \gamma^\mu (1-\gamma_5)\nu_e \, \bar{e}\gamma_\mu (1-\gamma_5) e$$

For the electrons at rest, only $\gamma_\mu = \gamma_0$ contributes, and $\bar{e}\gamma_0(1-\gamma_5)e$ is the number density. Matter introduces an effective interaction:

$$H = \sqrt{2} G_F n_e$$

$$p^2 - m^2 = (E-V)^2 \approx E^2 - 2EV$$

Thus, the matter adds to the *mass squared* the equivalent of

$$m^2 = 2EV = 2\sqrt{2} G_F n_e$$

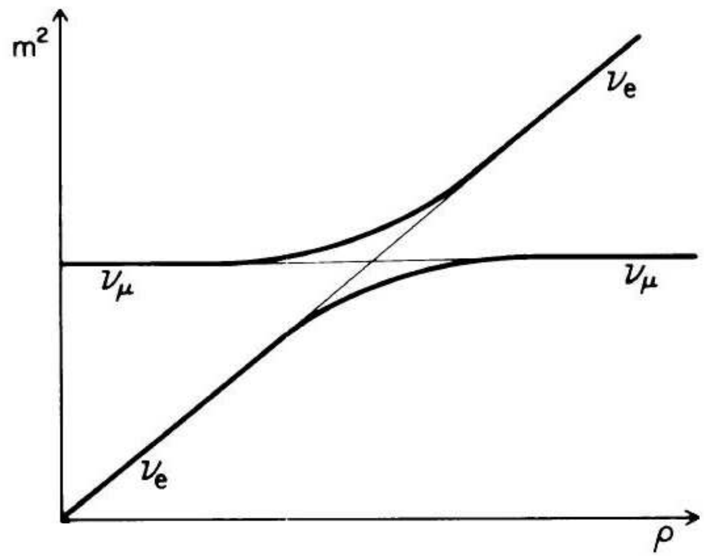
2008 J. J. Sakurai Prize for Theoretical Particle Physics

Alexei Smirnov
Stanislav Mikheyev

"For pioneering and influential work on the enhancement of neutrino oscillations in matter, which is essential to a quantitative understanding of the solar neutrino flux."

Neutrino oscillations in matter: MSW resonance

When $m_1^2 - m_2^2 = 2E$,
or $\frac{m_1^2 - m_2^2}{2E} = V$,
$\Rightarrow$ **level crossing**



The resonance condition is

$$\frac{m_i^2}{2k} \cos 2\theta_{ij} + V(\nu_i) = \frac{m_j^2}{2k} \cos 2\theta_{ij} + V(\nu_j) \tag{2}$$

Here V is the forward scattering amplitude.

Neutrino oscillations

- change the flavor composition of the detected neutrino signal
- indicate that the mass eigenstates are not the same as the weak eigenstates
- have a typical length scale

$$\lambda = \frac{4\pi E}{\Delta m^2} = 2.48\,\mathrm{km}\left(\frac{E}{\mathrm{GeV}}\right)\left(\frac{\mathrm{eV}^2}{\Delta m_{ij}^2}\right)$$

.

- for a resonance to occur, need (i) adiabaticity, (ii) weak damping.

Need a theory of the neutrino masses!

Neutrino masses: Majorana, Dirac

- one Weyl spinor ν_L enough

$\bar{\nu}_L^c \nu_L$

- SU(2) triplet in SM

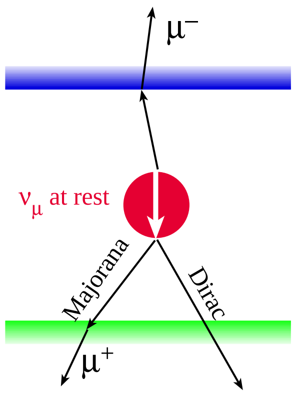
- need two Weyl spinors, ν_L, ν_R,

$(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$

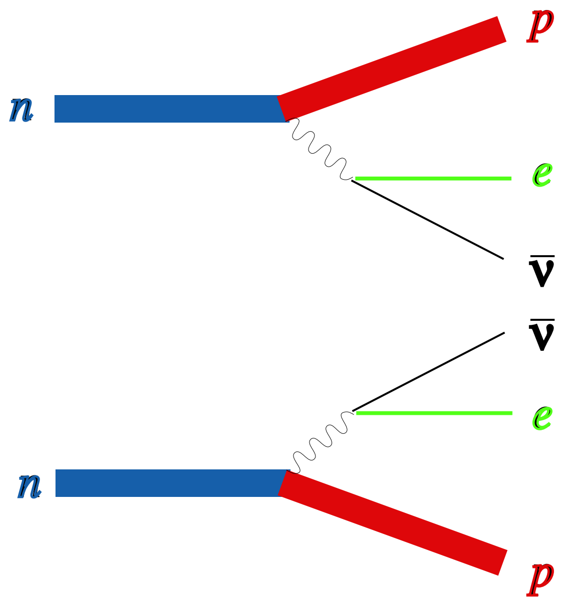
- SU(2) doublet in SM

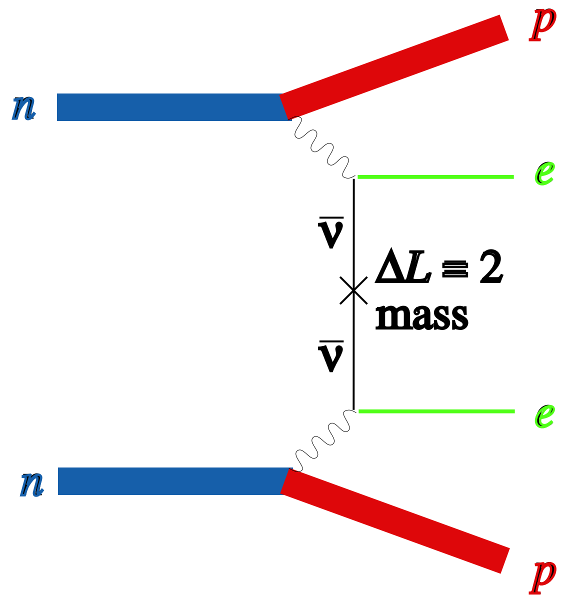
Majorana or Dirac?

A gedanken experiment. A neutrino, initially at rest, accelerated to a high energy in the upward direction would always produce a μ^-. However, if accelerated downward, it would produce either μ^+ or nothing at all in CC interactions.

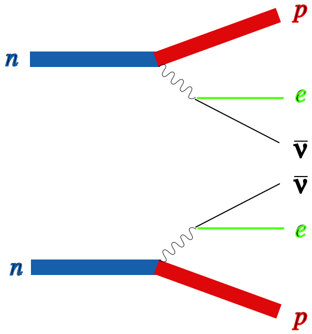


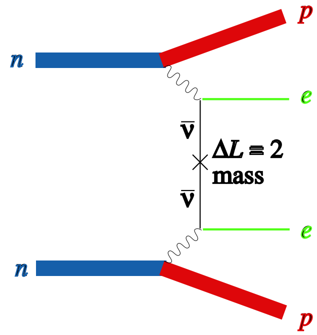
Neutrinoless double-beta decay

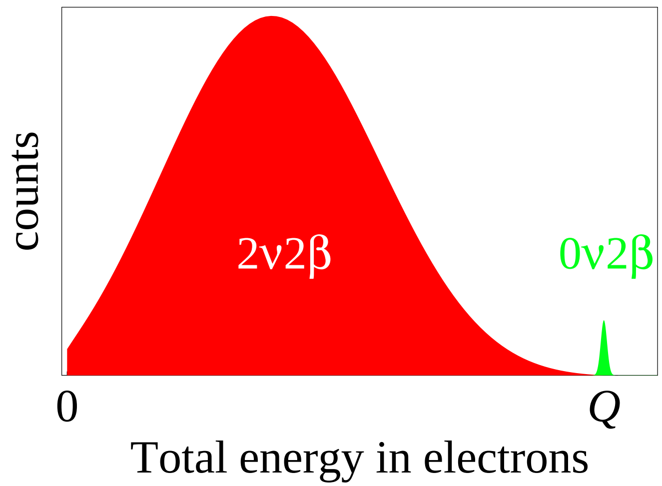




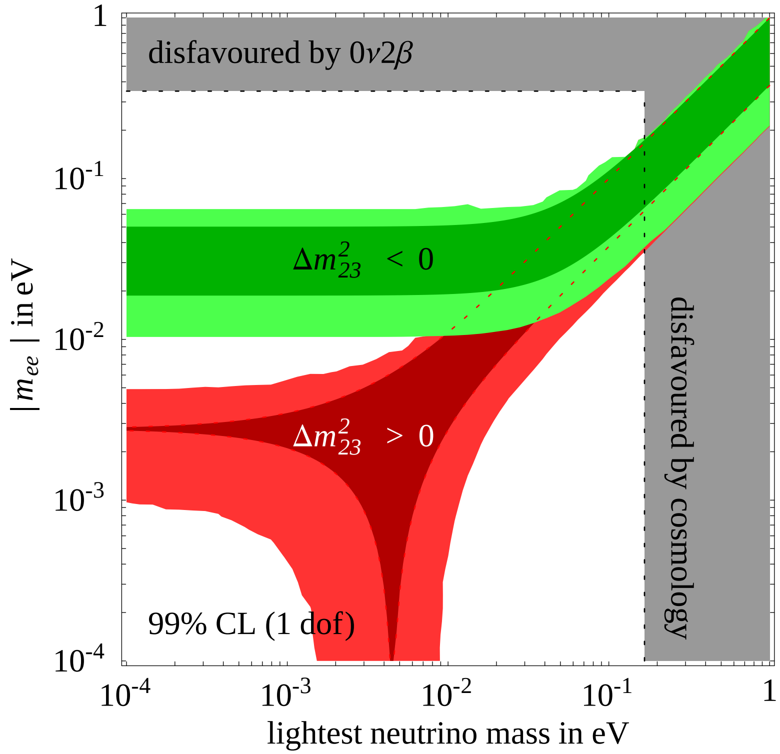
Neutrinoless double-beta decay







Neutrinoless double-beta decay



If inverted hierarchy, can measure in the near future

Neutrino masses

Discovery of neutrino masses implies a plausible existence of right-handed (sterile) neutrinos. Most models of neutrino masses introduce sterile states

$$\{\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \ldots, \nu_{s,N}\}$$

The number of **dark-side** neutrinos is unknown: **minimum two**
These states may have some additional gauge interactions that can be discovered at LHC. **[PQ Hung]**

Sterile neutrinos

The name "sterile" was coined by **Bruno Pontecorvo** in a paper [JETP, **53**, 1717 (1967)], which also discussed

- lepton number violation
- neutrinoless double beta decay
- rare processes (e.g. $\mu \longrightarrow e\gamma$)
- vacuum neutrino oscillations
- detection of neutrino oscillations
- astrophysical neutrino oscillations

Pontecorvo: neutrino oscillations can *"convert potentially active particles into particles that are, from the point of view of ordinary weak interactions,* **sterile**, *i.e. practically unobservable, since they have the "incorrect" helicity"* [JETP, **53**, 1717 (1967)]

Neutrino masses

Discovery of neutrino masses implies a plausible existence of right-handed (sterile) neutrinos. Most models of neutrino masses introduce sterile states

$$\{\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \ldots, \nu_{s,N}\}$$

and consider the following lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a}\left(i\partial_\mu \gamma^\mu\right)\nu_{s,a} - y_{\alpha a} H\, \bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2}\,\bar{\nu}^c_{s,a}\nu_{s,b} + h.c.\,,$$

where H is the Higgs boson and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublets. The mass matrix:

$$M = \begin{pmatrix} 0 & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{pmatrix}$$

What is the *natural* scale of M?

Seesaw mechanism

In the Standard Model, the matrix D arises from the Higgs mechanism:

$$D_{ij} = y_{ij} \langle H \rangle$$

Smallness of neutrino masses **does not** imply the smallness of Yukawa couplings. For large M,

$$m_\nu \sim \frac{y^2 \langle H \rangle^2}{M}$$

One can understand the smallness of neutrino masses even if the Yukawa couplings are $y \sim 1$ [Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra, Senjanović].

Is $y \sim 1$ better than $y \ll 1$?

Depends on the model.

- If $y \approx \text{some intersection number}$ in string theory, then $y \sim 1$ is natural
- If y comes from wave function overlap of fermions in models with extra-dimensions, then it can be exponentially suppressed, hence, $y \ll 1$ can be natural.

In the absence of theory of the Yukawa couplings, one is evokes some naturalness arguments.

Is $\epsilon \ll 1$ natural?

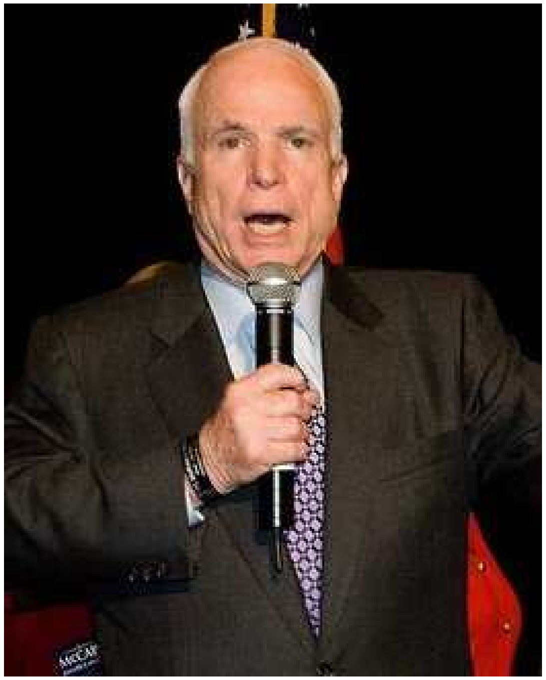
$50\% \pm \epsilon$ $\qquad\qquad$ $50\% \pm \epsilon$

Symmetry: the two candidates are similar

$\Rightarrow \epsilon \ll 1$ is natural!

Is $\epsilon \ll 1$ natural?

$50\% \pm \epsilon$



$50\% \pm \epsilon$

No obvious symmetry: the two candidates are very different

$\Rightarrow \epsilon \ll 1$ is not natural!

't Hooft's naturalness criterion

Small number is natural if setting it to zero increases the symmetry

Small breaking of the symmetry $\Rightarrow$ small number

- Pion masses are small because the massless pions correspond to exact chiral symmetry **natural**
- Gauge hierarchy problem: small $\boldsymbol{M}_{\text{Higgs}}/\boldsymbol{m}_{\text{Planck}}$ is **not natural in the Standard Model** because setting $\boldsymbol{M}_{\text{Higgs}} = \mathbf{0}$ does not increase the symmetry. In a supersymmetric extension, $\boldsymbol{M}_{\text{Higgs}} \approx \boldsymbol{M}_{\text{Higgsino}}$, and setting $\boldsymbol{M}_{\text{Higgsino}} = 0$ increases the overall (chiral) symmetry. Hence, a light Higgs is **natural in SUSY models**.
- Cosmological constant problem: $\Lambda \to 0$ does not increase the symmetry. Hence, **not natural**.

What if we apply this criterion to sterile neutrinos? Symmetry increases for $M \to 0$, namely, the chiral symmetry of right-handed fields.

Small M is technically **natural**.

Clues from cosmology?

Baryon asymmetry of the universe could be generated by **leptogenesis**

However, leptogenesis can work for both $M \gg 100$ GeV and $M < 100$ GeV:

- For $M \gg 100$ GeV, heavy sterile neutrino decays can produce the lepton asymmetry, which is converted to baryon asymmetry by sphalerons [Fukugita,Yanagida]
- For $M < 100$ GeV, neutrino oscillations can produce the lepton asymmetry, which is converted to baryon asymmetry by sphalerons [Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov]
- If the neutrino mass is generated through the Higgs mechanism, the extended Higgs sector allows new possibilities for baryogenesis. [Essey, Petraki, AK, work in progress]

Over the years, neutrino physics has shown many theoretical prejudices to be wrong: neutrinos were expected to be massless, neutrinos were expected to have small mixing angles, etc.

Since the fundamental theory of netrino masses is lacking, one should

consider all allowed values
for the singlet/sterile neutrino masses

in the following lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a} \left(i \partial_\mu \gamma^\mu \right) \nu_{s,a} - y_{\alpha a} H \, \bar{L}_\alpha \nu_{s,a} - \frac{M_{aa}}{2} \, \bar{\nu}^c_{s,a} \nu_{s,a} + h.c. \, ,$$

where M is can be small or large

Dark side at work: leptogenesis

- offers an explanation of baryon asymmetry of the universe
- makes an intriguing connection with the neutrino physics

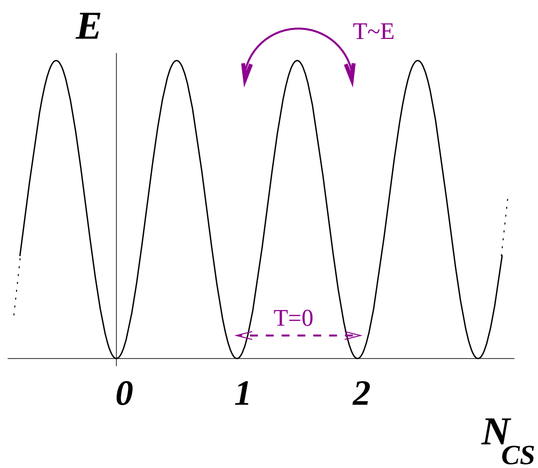
Baryon asymmetry

Observations, WMAP, nucleosynthesis, *etc.*:
matter-antimatter asymmetry is

$$\eta \equiv \frac{n_B}{n_\gamma} = 6 \times 10^{-10}$$

Baryogenesis

Topology of vacuum: $B - L = \mathrm{const}$, but not $B + L$



Vacua with different Chern-Simons (baryon) numbers are separated by a high barrier. At zero temperature,

tunneling is suppressed $\sim \exp\{-2\pi/\alpha\}$

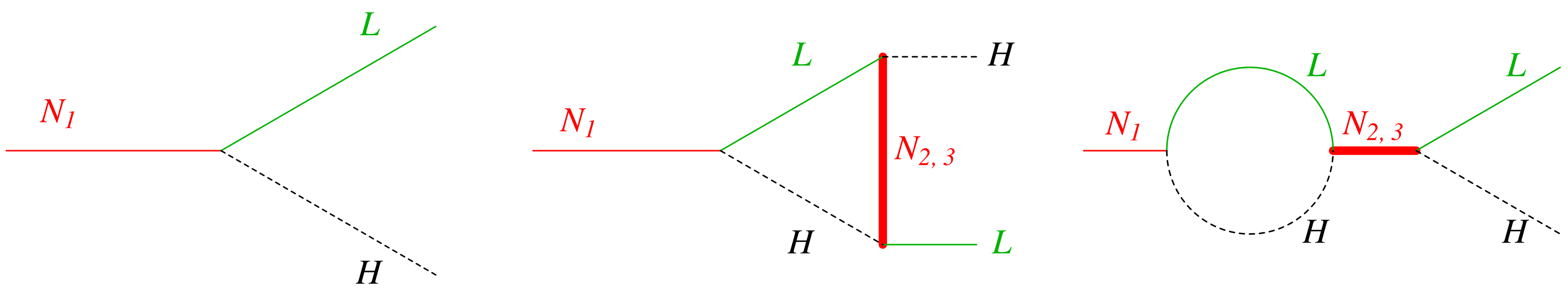
In the early universe, at $T \gtrsim 10^2$ GeV, these transitions are allowed.

Thermal leptogenesis (seesaw with a high-scale Majorana mass)

Consider again the following lagrangian for heavy $N \equiv \nu_s$:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i\partial_\mu\gamma^\mu\right) N_a - y_{\alpha a} H\, \bar{L}_\alpha N_a - \frac{M_{aa}}{2}\, \bar{N}_a^c N_a + h.c.\,,$$

Out-of-equilibrium decays with CP violation (from interference):



An asymmetry is proportional to the imaginary parts of the Yukawa couplings of the N's to the Higgs:

$$\epsilon = \frac{\Gamma(N_1 \to \ell H_2) - \Gamma(N_1 \to \bar{\ell}\bar{H}_2)}{\Gamma(N_1 \to \ell H_2) + \Gamma(N_1 \to \bar{\ell}\bar{H}_2)} \tag{3}$$

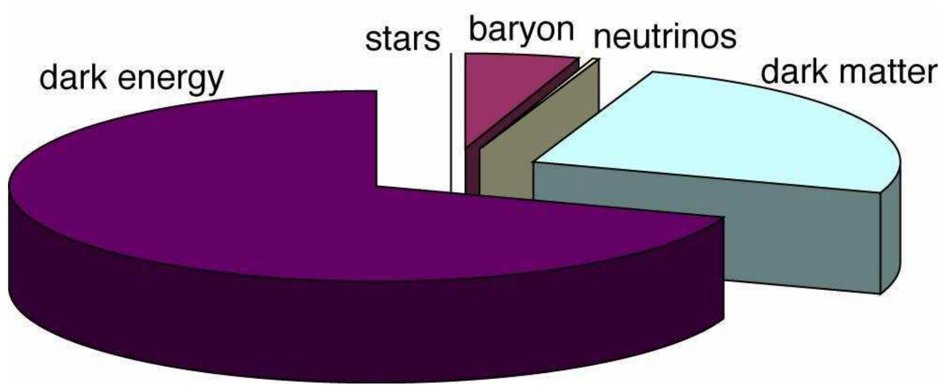
$$= \frac{1}{8\pi}\frac{1}{hh^\dagger}\sum_{i=2,3} \mathrm{Im}[(h_\nu h_\nu^\dagger)_{1i}]^2 f\left(\frac{M_i^2}{M_1^2}\right) \tag{4}$$

where f is a function that represents radiative corrections. For example, in the Standard Model $f = \sqrt{x}[(x-2)/(x-1) + (x+1)\ln(1+1/x)]$, while in the MSSM $f = \sqrt{x}[2/(x-1) + \ln(1+1/x)]$.

This asymmetry can lead to an acceptable lepton number asymmetry, which is converted into the baryon asymmetry by sphalerons.

For light sterile neutrinos, replace decays with oscillations: it works!

The universe



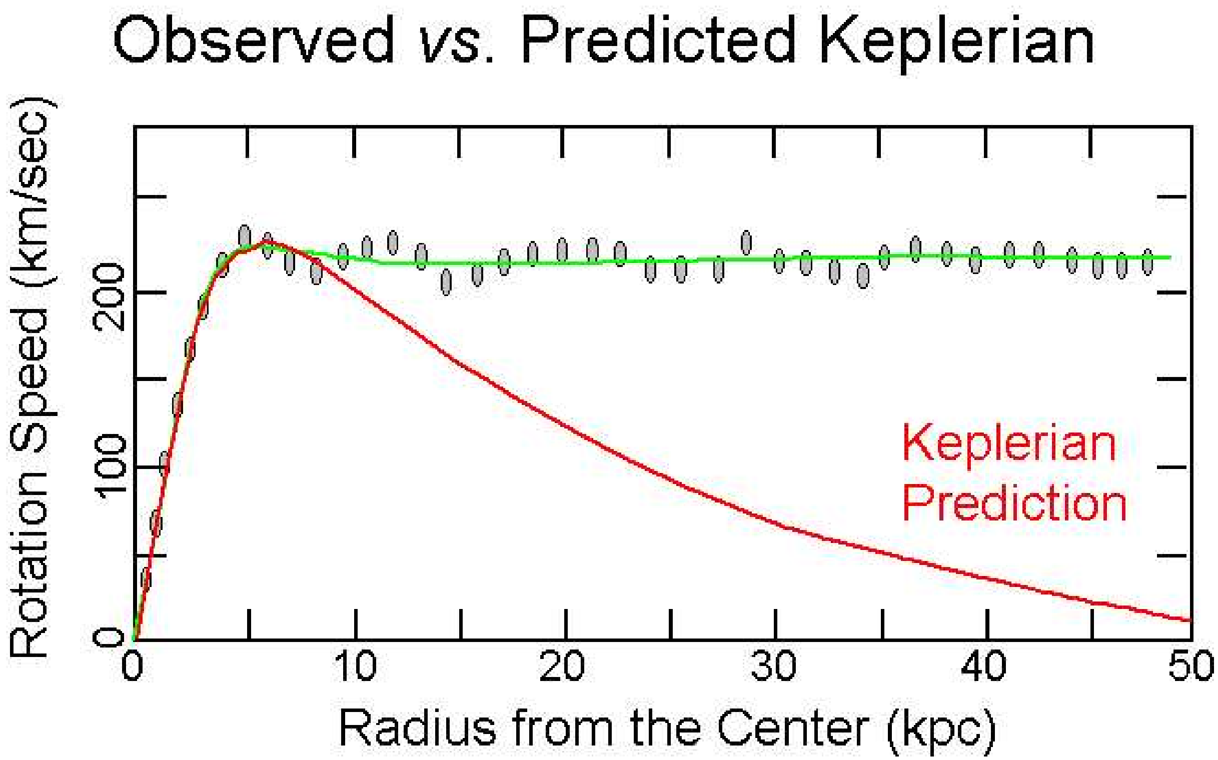
Dark matter

The only data at variance with the Standard Model

The evidence for dark matter is very strong:

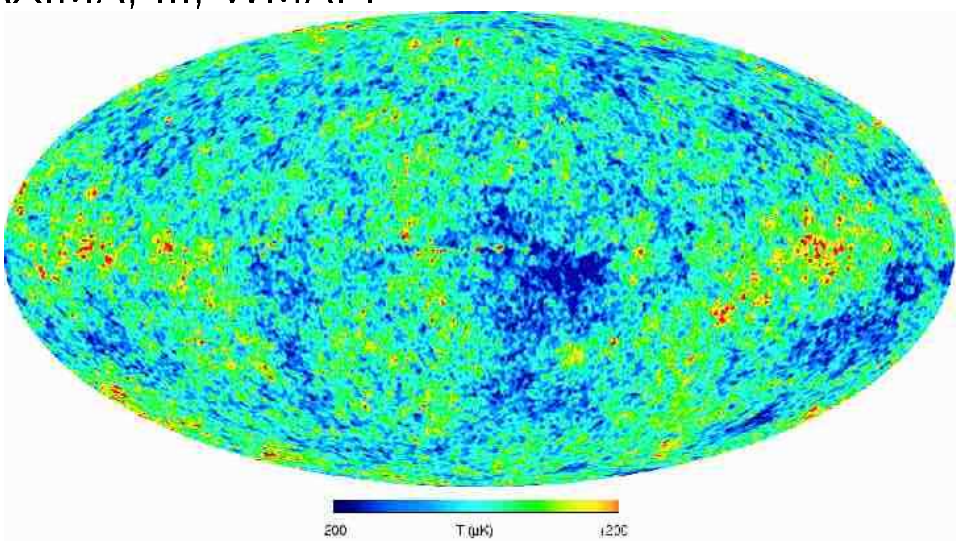
- galactic rotation curves cannot be explained by the disk alone
- cosmic microwave background radiation
- gravitational lensing of background galaxies by clusters is so strong that it requires a significant dark matter component.
- clusters are filled with hot X-ray emitting intergalactic gas (without dark matter, this gas would dissipate quickly).
- neat: 1E0657-56 shows separation of ordinary matter (gas) from dark matter

Galactic rotation curves

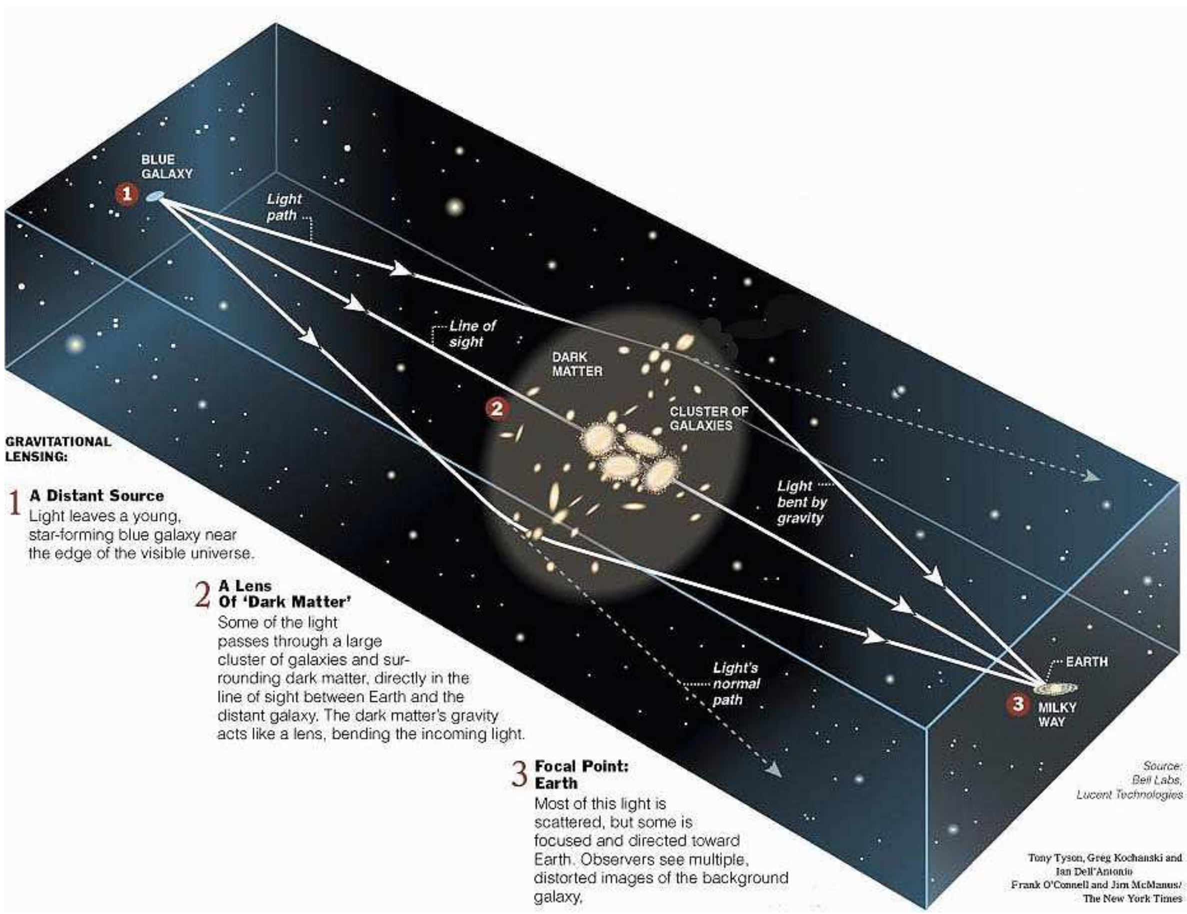


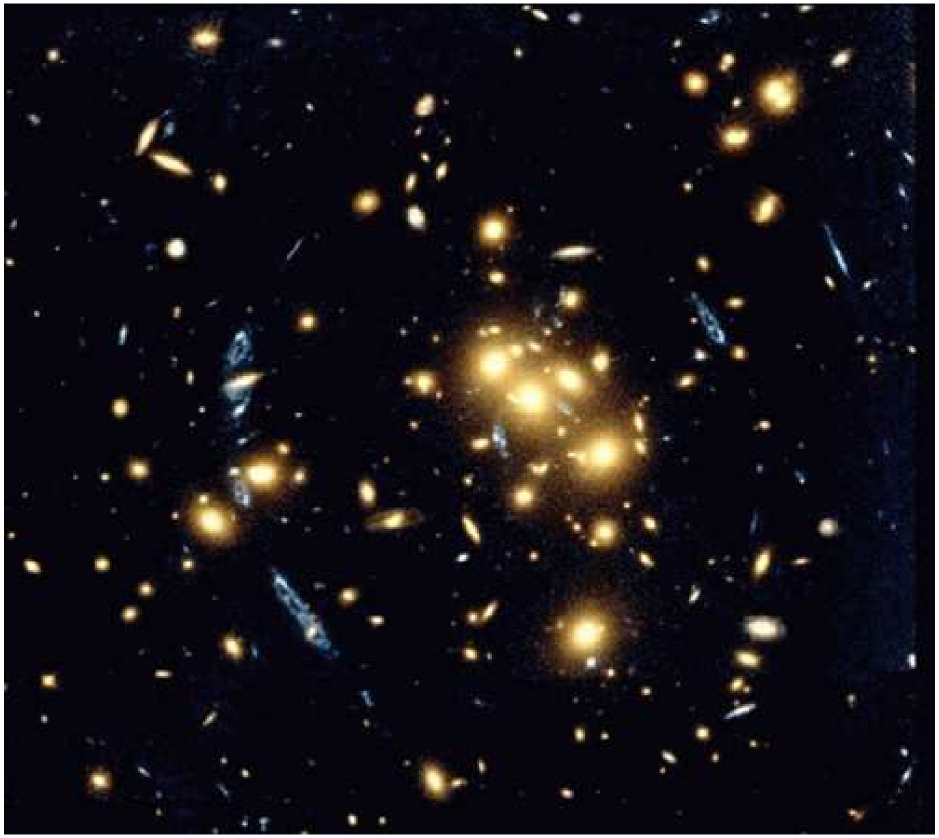
Cosmic microwave background radiation (CMBR)

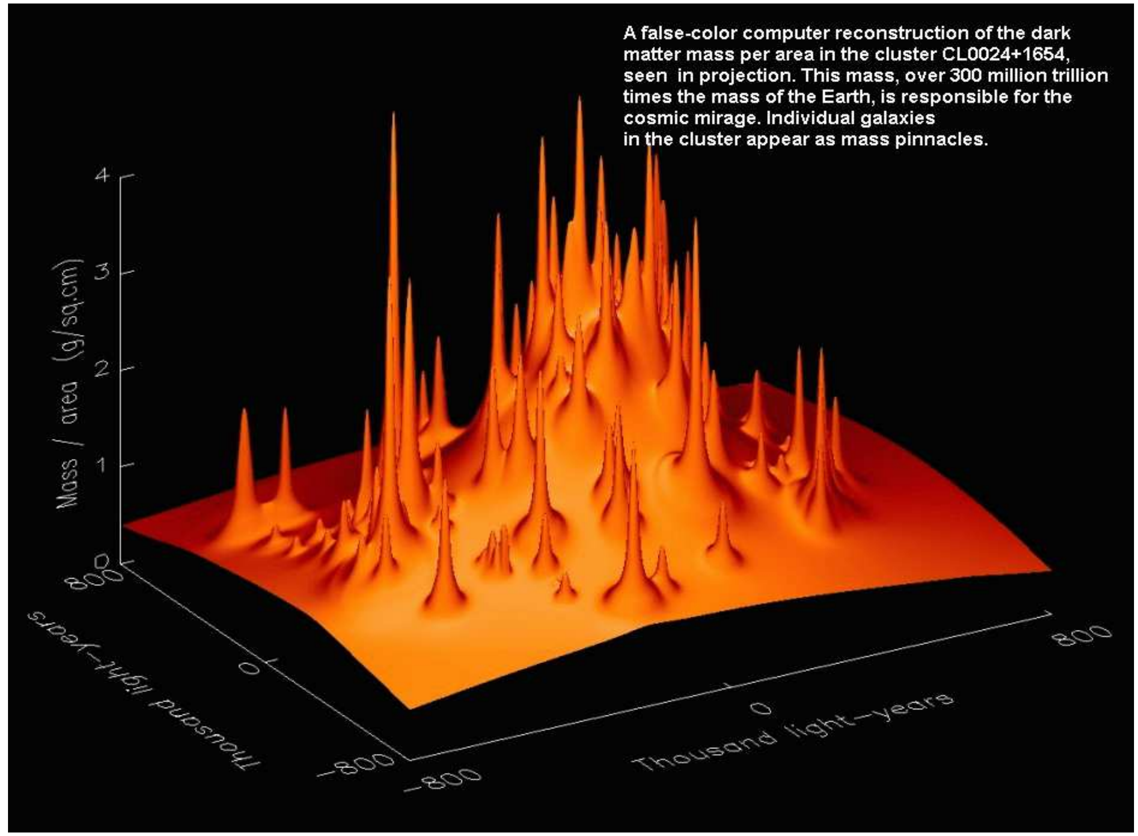
At redshift $z_{\text{dec}} = 1089 \pm 1$, the atoms formed and the universe became transparent to radiation. Radiation emitted at that time, $t_{\text{dec}} = (379 \pm 8)$ kyr, has been red-shifted into the microwave range. Fluctuations have been measured first by COBE, and later by BOOMERANG, MAXIMA, ..., WMAP:



Gravitational lensing: seeing the invisible

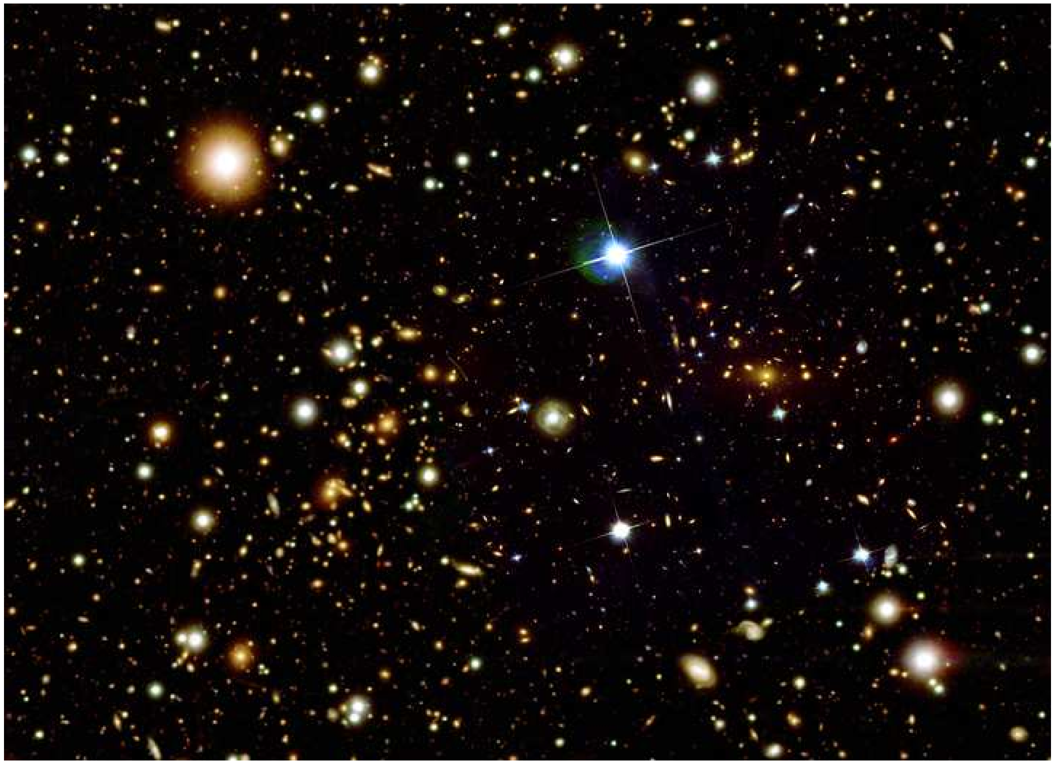




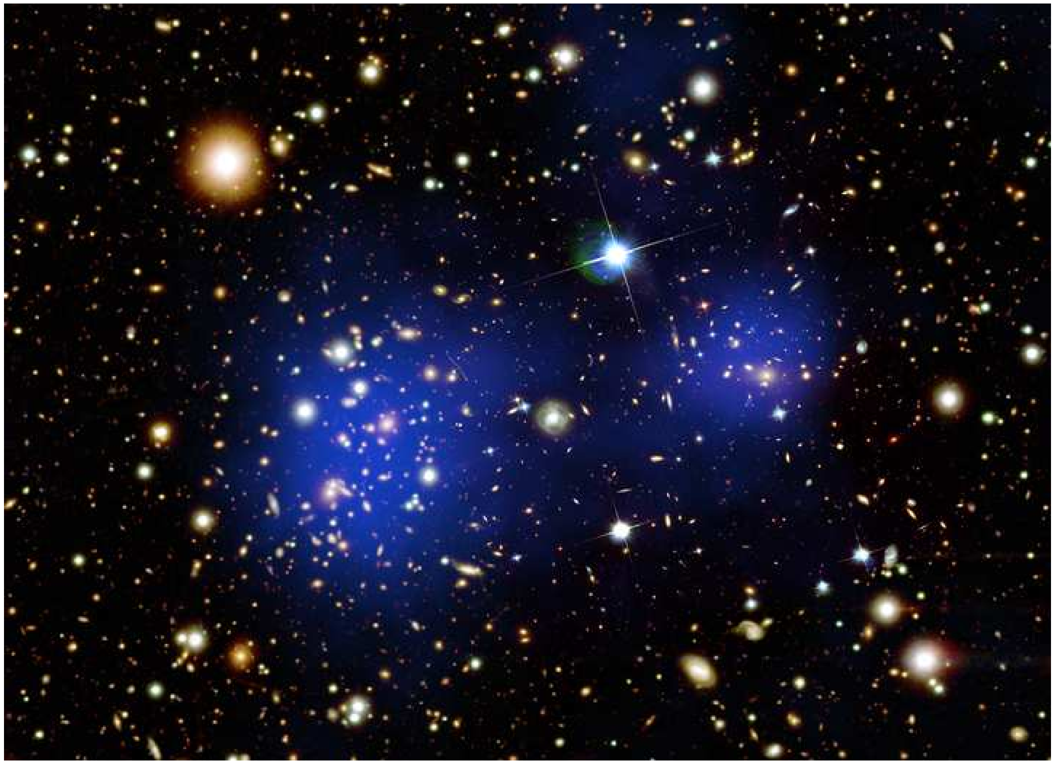


Foreground cluster CL0024+1654 produces multiple images of a blue background galaxy in the HST image (left). Mass reconstruction (right).

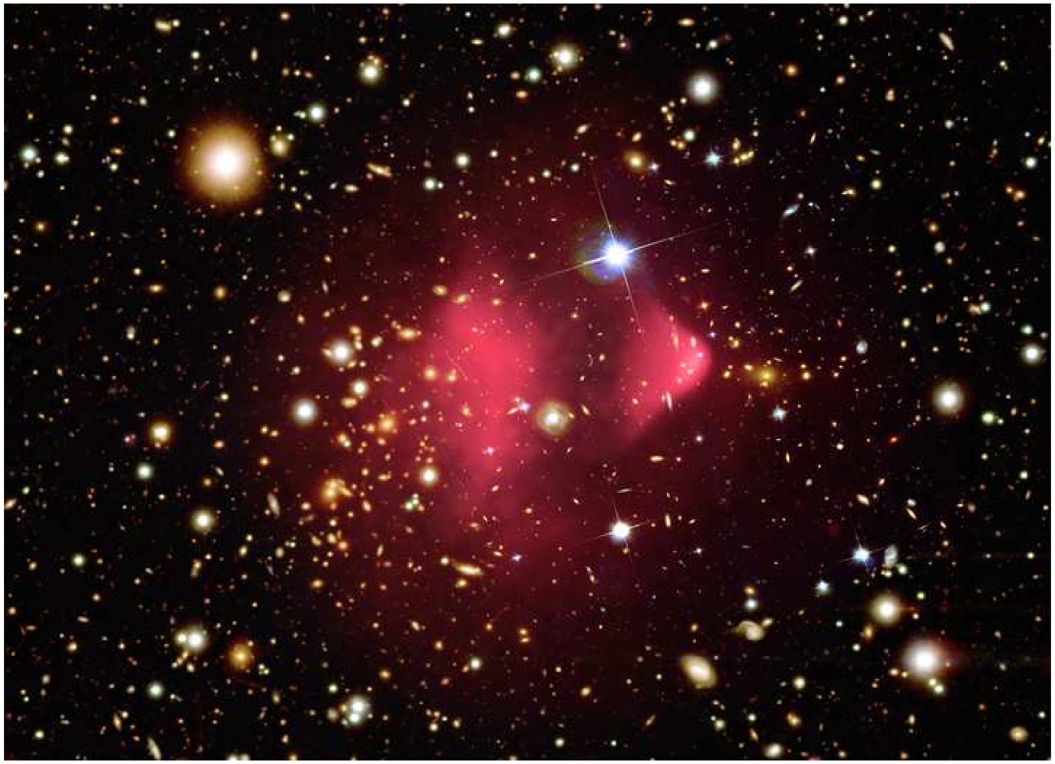
Merging clusters: optical image of 1E 0657-56



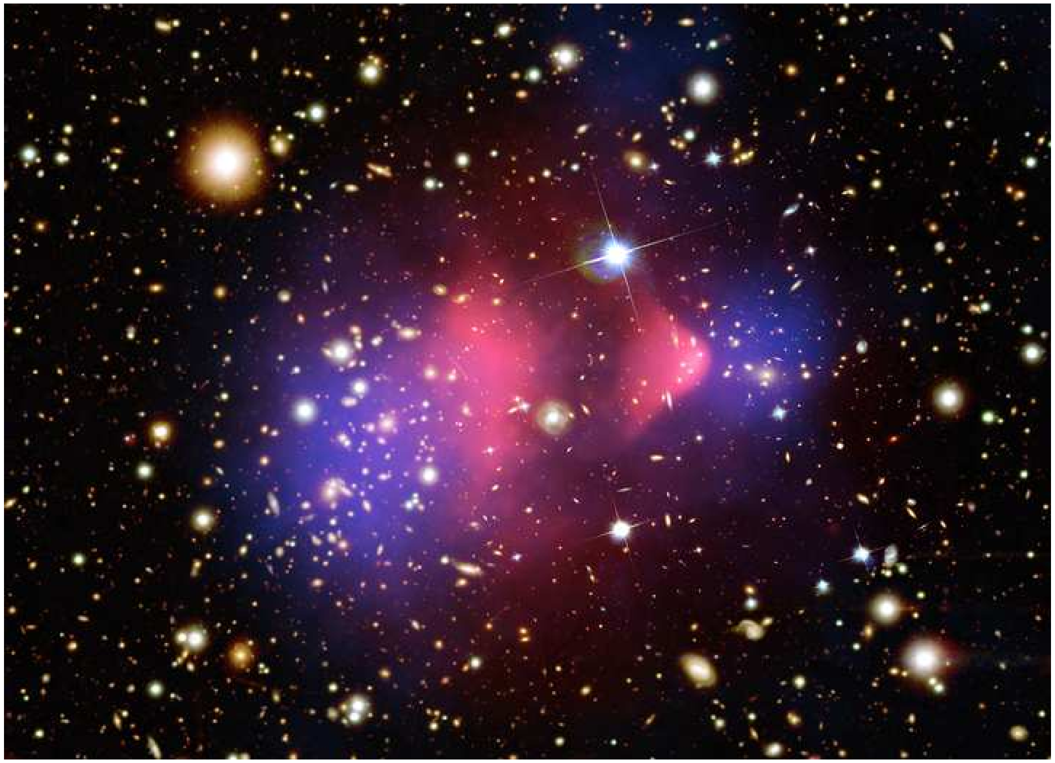
Merging clusters: grav. lensing image of 1E 0657-56



Merging clusters: Chandra x-ray image of 1E 0657-56



Merging clusters: image of 1E 0657-56



Gass, dark matter separated.

Dark matter: what we know

We know:

- dark matter exists
- dark matter is not usual atoms
- cold or warm, not "hot"

We don't know:

- dark matter composition
- dark matter interactions
- cold or warm?

Dark matter: what we know

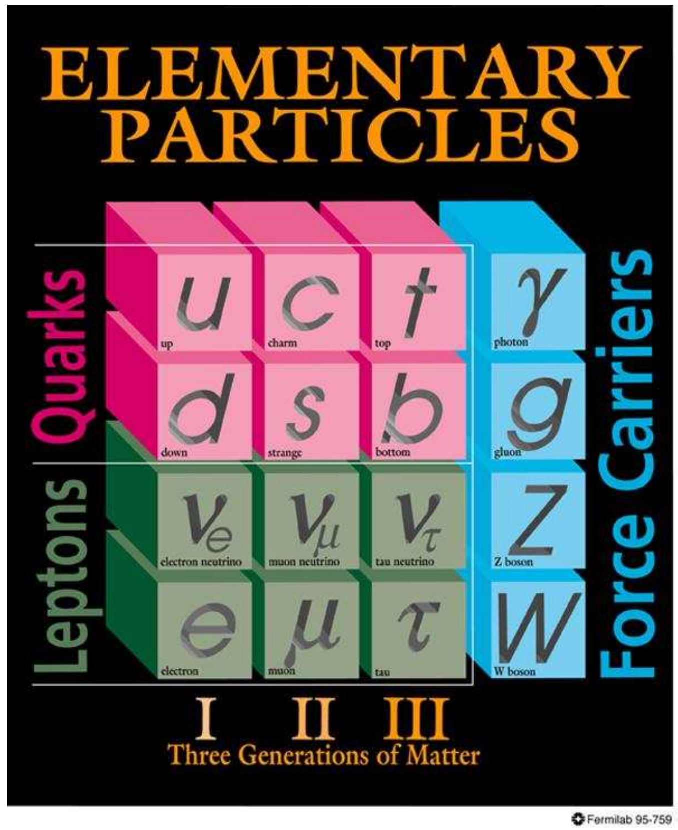
We know:

- dark matter exists
- dak matter is not usual atoms
- cold or warm, not “hot”

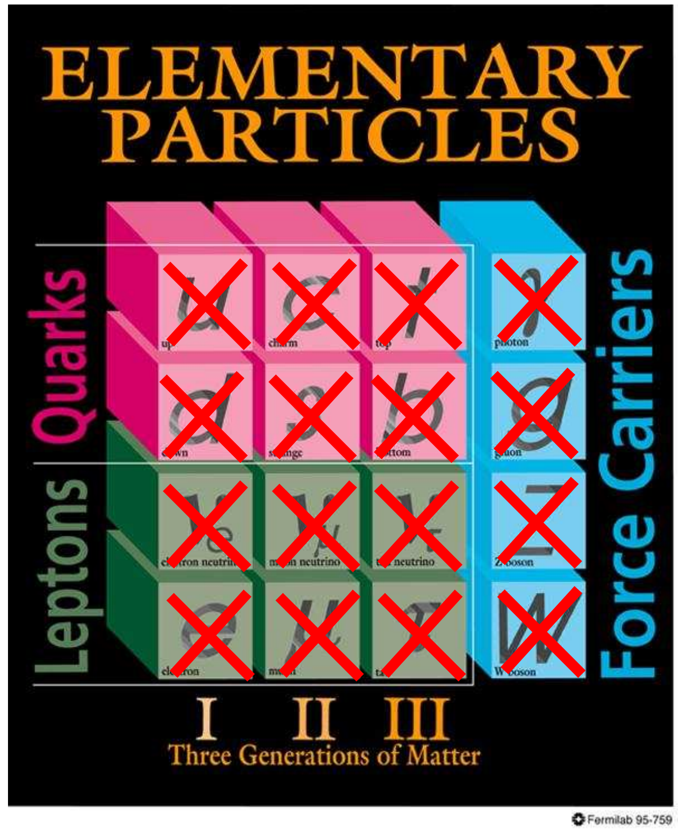
We don’t know:

- D.M. composition (dark matter experiments)
- D. M. interactions (dark matter experiments)
- cold or warm? (astronomy [colloquium by Rosie Wyse])

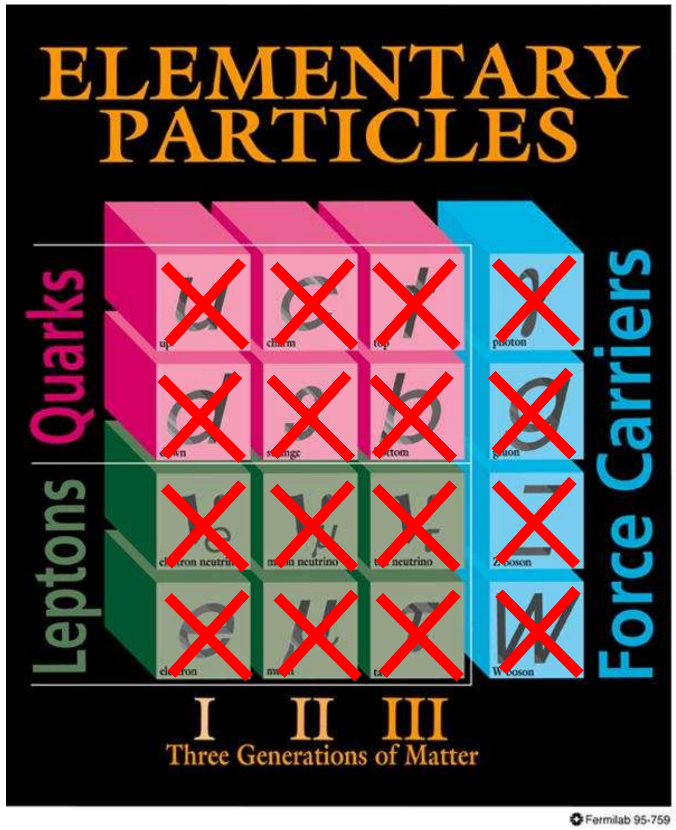
None of the known particles can be dark matter



None of the known particles can be dark matter



Dark matter $\Rightarrow$ new physics (at least one new particle)



The early universe: relic neutrinos and dark matter

Ordinary (active) neutrinos contribute a negligible amount to dark matter.

$$\sum_j m(\nu_j) < \Omega_{\nu\bar{\nu}} h^2 (94\,\mathrm{eV}) < \Omega_{\mathrm{matter}} h^2 (94\,\mathrm{eV}) \approx 13\,\mathrm{eV} \tag{5}$$

[Gerstein + Zeldovich]

Experiments suggest much smaller masses.

Therefore, neutrinos make a negligible contribution to matter density of the universe, unless some of the assumptions used in deriving the Gerstein-Zeldovich bound are violated.

Sterile neutrinos with small mixing to active neutrinos

- can be produced through neutrino oscillations
- can be produced from other mechanisms, for example, from Higgs decays
- perhaps, a minimal extension of the Standard Model consistent with dark matter

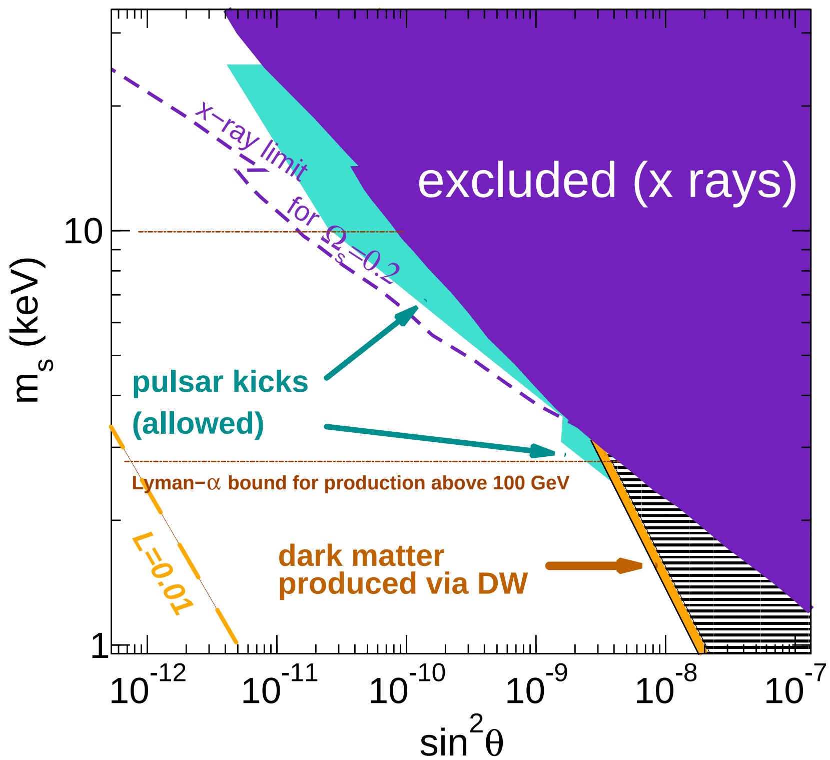
Sterile neutrinos with small mixing to active neutrinos

$$\begin{cases} |\nu_1\rangle = \cos\theta_m|\nu_e\rangle - \sin\theta_m|\nu_s\rangle \\ |\nu_2\rangle = \sin\theta_m|\nu_e\rangle + \cos\theta_m|\nu_s\rangle \end{cases} \tag{6}$$

The almost-sterile neutrino, $|\nu_2\rangle$ was never in equilibrium. Production of ν_2 is through oscillations.

The resulting density of relic sterile neutrinos [Dodelson, Widrow]:

$$\Omega_{\nu_2} \sim 0.3 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{\text{keV}}\right)^2$$

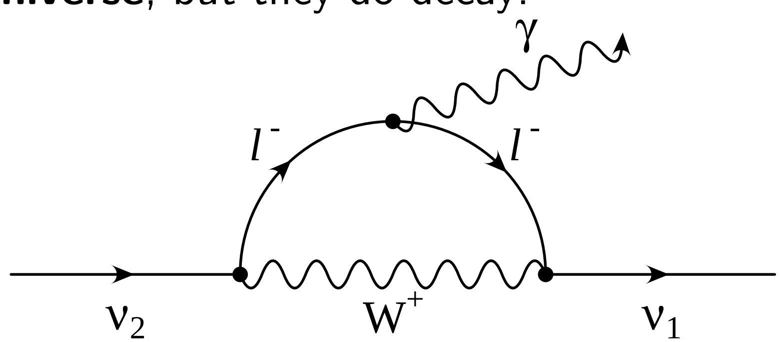


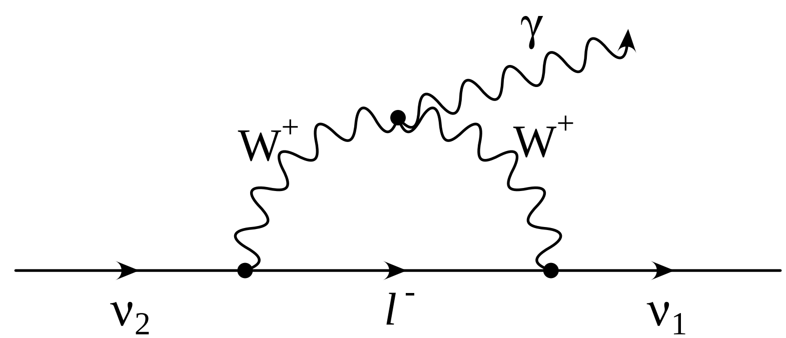
Different production mechanisms possible (e.g. neutrino oscillations, Higgs decays, etc.)

Kallia Petraki, AK study these production mechanisms: can produce dark matter for smaller mixing angles

Radiative decay

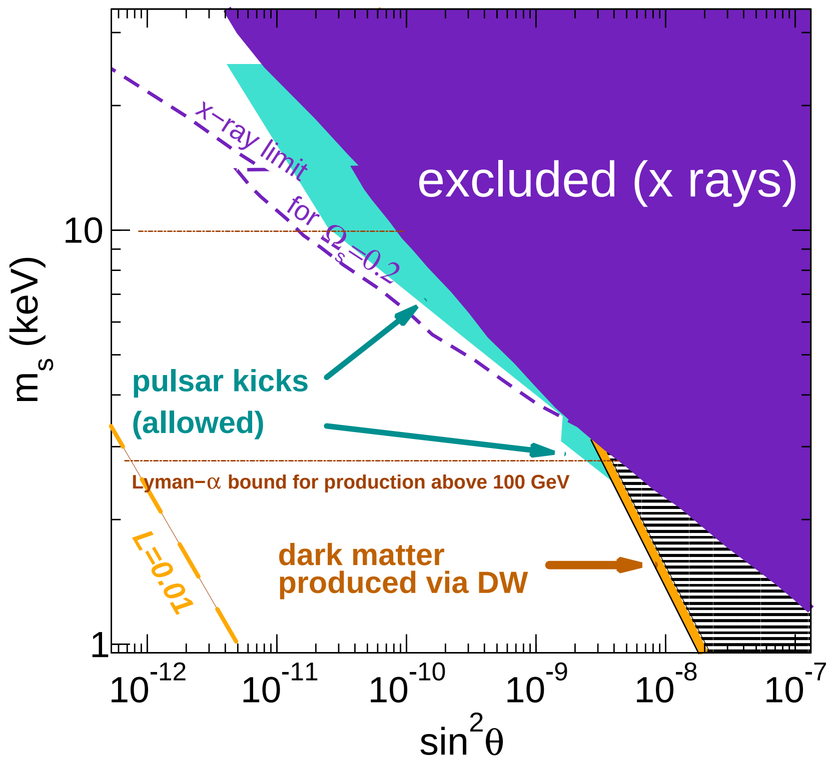
Sterile neutrino in the mass range of interest have lifetimes **longer than the age of the universe**, but they do decay:



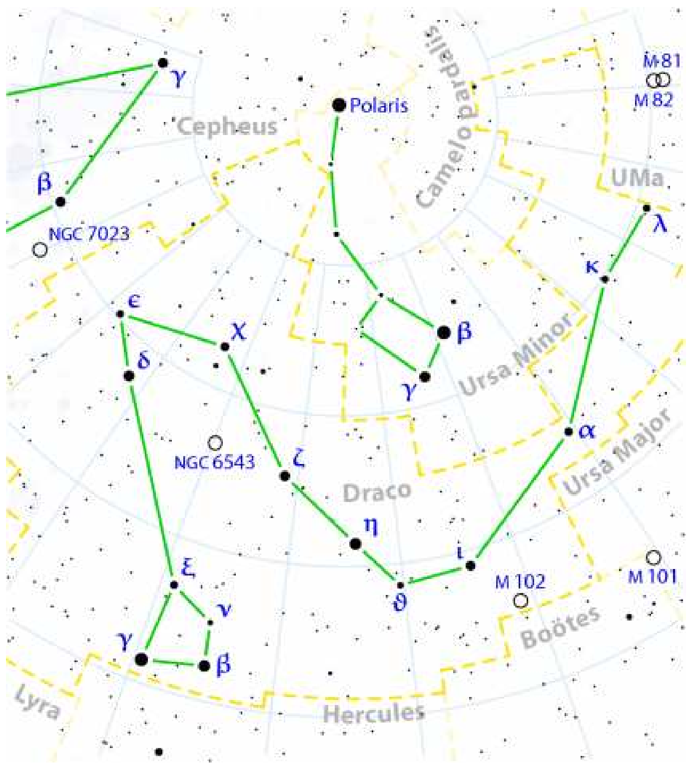


Photons have energies $m/2$: X-rays. Large lumps of dark matter emit some X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

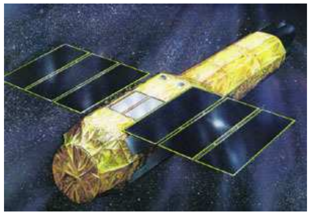
X-ray observations: the current limits

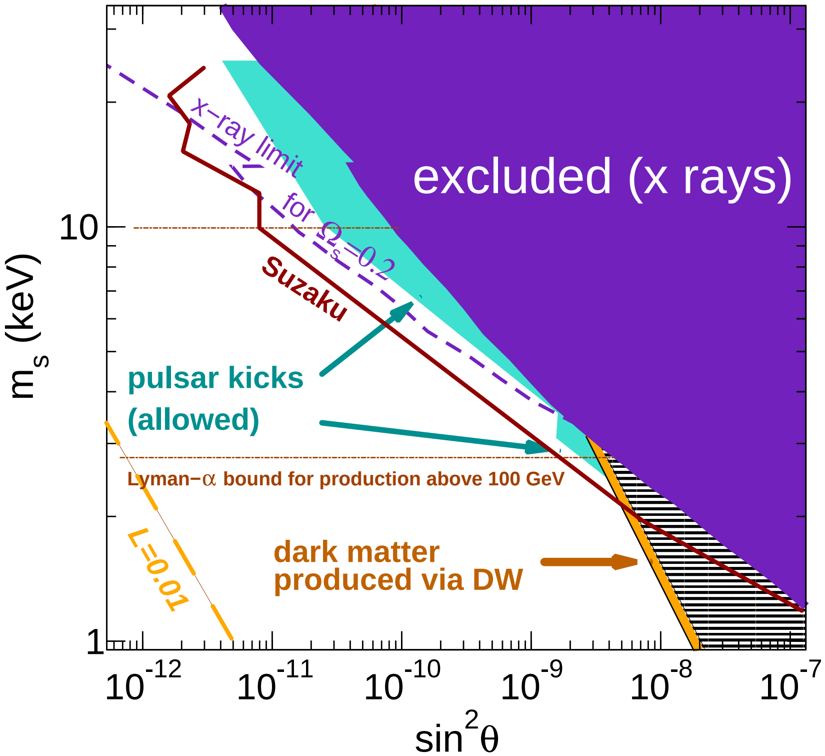


X-ray observations: Draco and Ursa Minor



X-ray observations: Suzaku reach





[Loewenstein, Biermann, AK]

Astrophysical clues: supernova

- Sterile neutrino emission from a supernova is anisotropic due to
  1. asymmetries in the urca cross sections
  2. magnetic effects on neutrino oscillations
- Sterile neutrinos with masses and mixing angles consistent with dark matter can explain the pulsar velocities

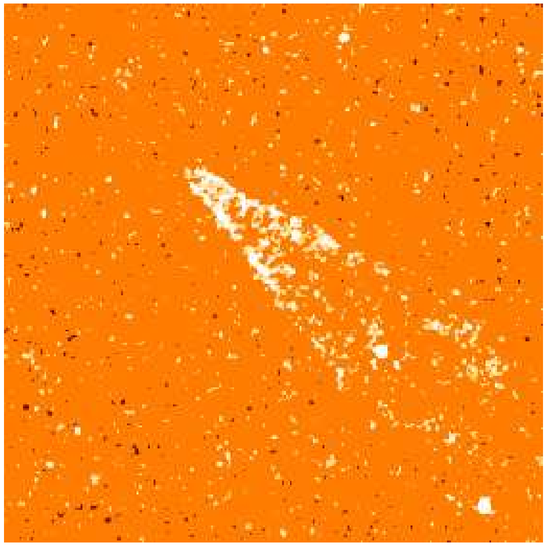
[AK, Segrè; Fuller, AK, Mocioiu, Pascoli; Barkovich, D'Olivo, Montemayor]

The pulsar velocities.

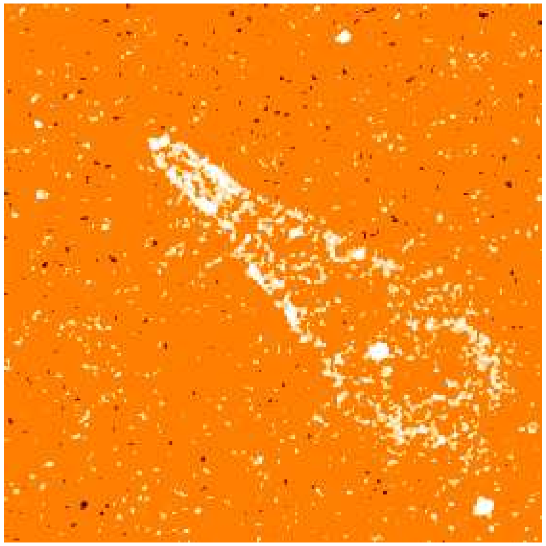
Pulsars have large velocities, $\langle v \rangle \approx \mathbf{250 - 450\ km/s}$.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

A significant population with $v > \mathbf{700\ km/s}$,
about **15 %** have $v > \mathbf{1000\ km/s}$, up to $\mathbf{1600\ km/s}$.
[Arzoumanian *et al.*; Thorsett *et al.*]

A very fast pulsar in Guitar Nebula

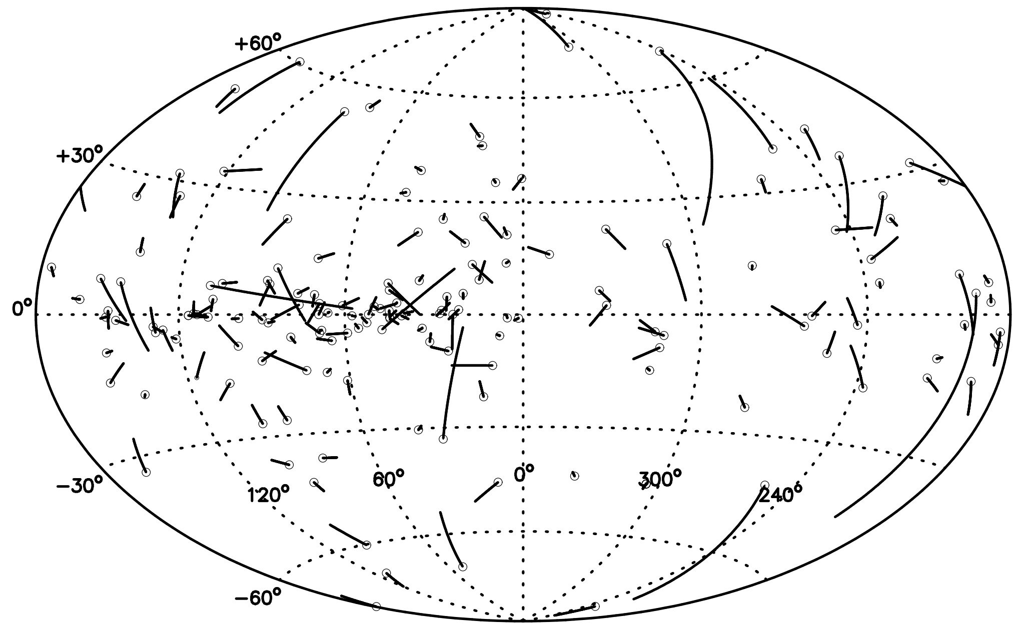


HST, December 1994



HST, December 2001

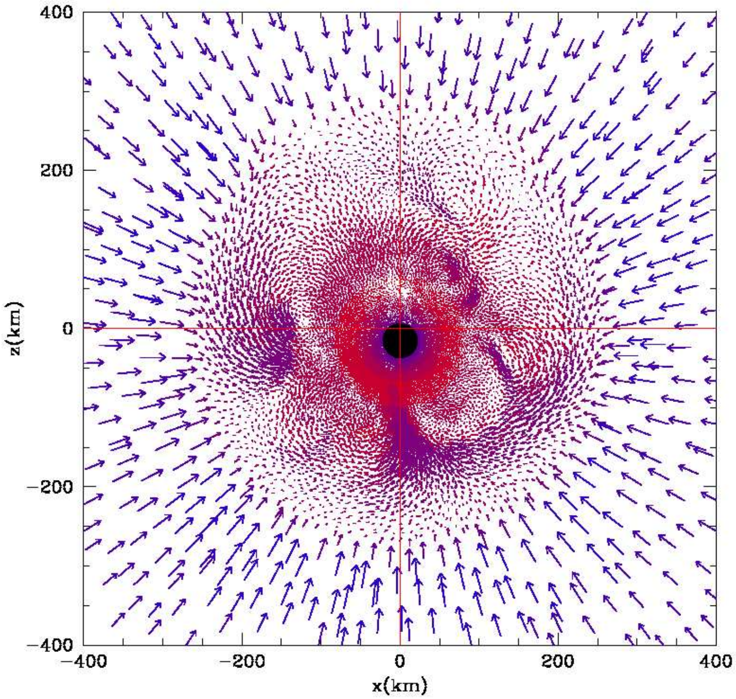
Map of pulsar velocities

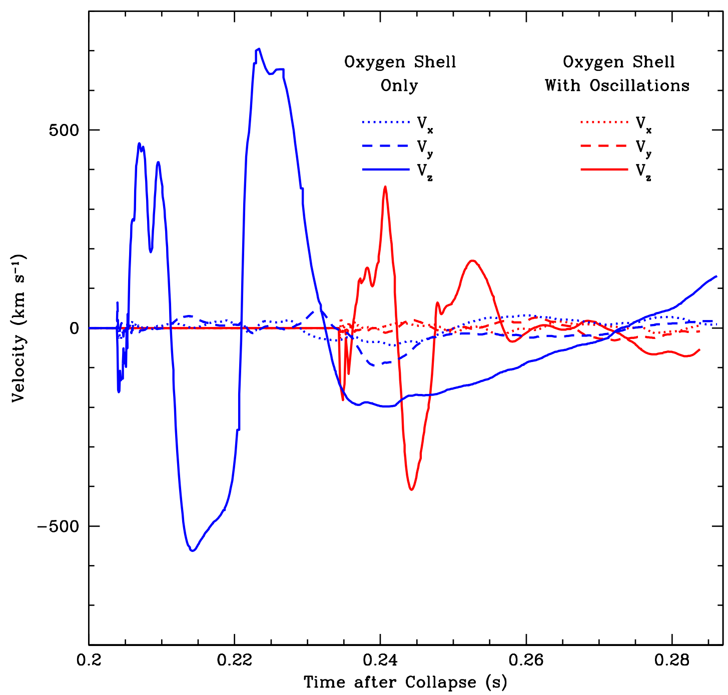


Proposed explanations:

- asymmetric collapse [Shklovskii] (small kick)
- evolution of close binaries [Gott, Gunn, Ostriker] (not enough)
- acceleration by EM radiation [Harrison, Tademaru] (kick small, predicted polarization not observed)
- asymmetry in EW processes that produce neutrinos [Chugai; Dorofeev, Rodinov, Ternov] (asymmetry washed out)
- "cumulative" parity violation [Lai, Qian; Janka] (it's *not* cumulative)
- various exotic explanations
- explanations that were "not even wrong"...

Asymmetric collapse





"...the most extreme asymmetric collapses
do not produce final neutron star velocities above 200km/s" [Fryer '03]

Supernova neutrinos

Nuclear reactions in stars lead to a formation of a heavy iron core. When it reaches $M \approx 1.4 M_\odot$, the pressure can no longer support gravity. $\Rightarrow$ collapse.

Energy released:

$$\Delta E \sim \frac{G_N M^2_{\text{Fe core}}}{R} \sim 10^{53}\text{erg}$$

99% of this energy is emitted in neutrinos

Pulsar kicks from neutrino emission?

Pulsar with $v \sim 500$ km/s has momentum

$$\boldsymbol{M_{\odot} v \sim 10^{41}} \text{ g cm/s}$$

SN energy released: 10^{53} erg $\Rightarrow$ in neutrinos. Thus, the total neutrino momentum is

$$\boldsymbol{P_{\nu;\,\mathrm{total}} \sim 10^{43}} \text{ g cm/s}$$

a **1% asymmetry** in the distribution of **neutrinos**

is sufficient to explain the pulsar kick velocities

But what can cause the asymmetry??

Magnetic field?

Neutron stars have large magnetic fields. A typical pulsar has surface magnetic field $B \sim 10^{12} - 10^{13}$ **G**.

Recent discovery of *soft gamma repeaters* and their identification as *magnetars*

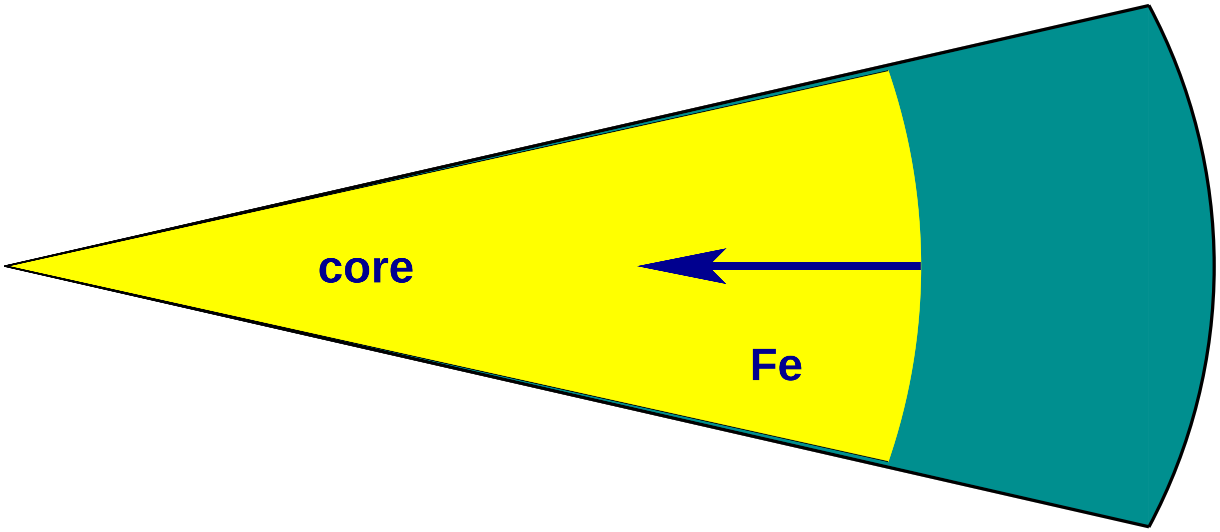
$\Rightarrow$ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16}$ **G**.

$\Rightarrow$ **magnetic fields inside can be $10^{15} - 10^{16}$ G.**

Neutrino magnetic moments are negligible, but the **scattering of neutrinos off polarized electrons and nucleons** is affected by the magnetic field.

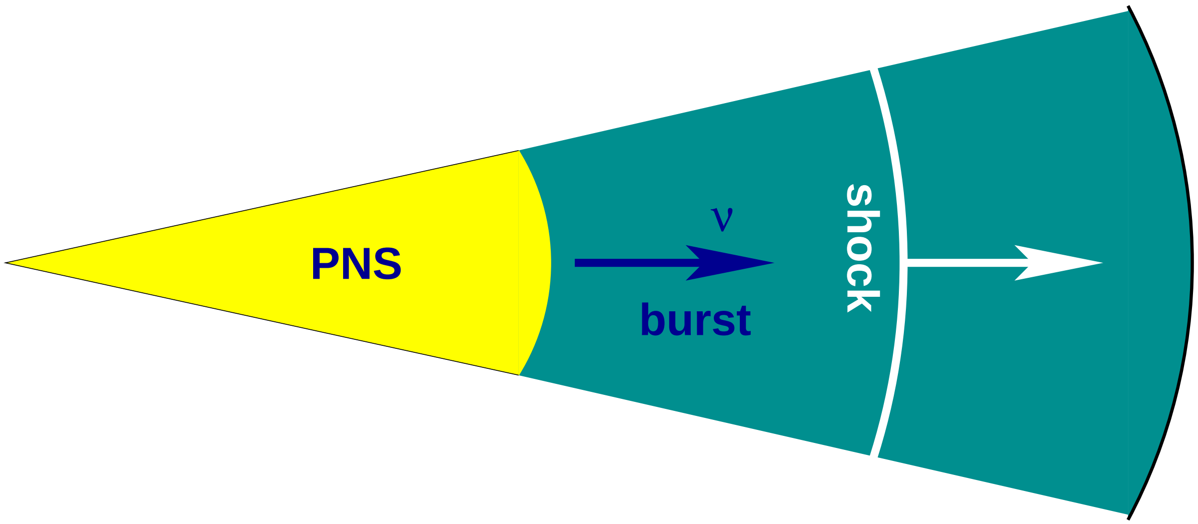
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

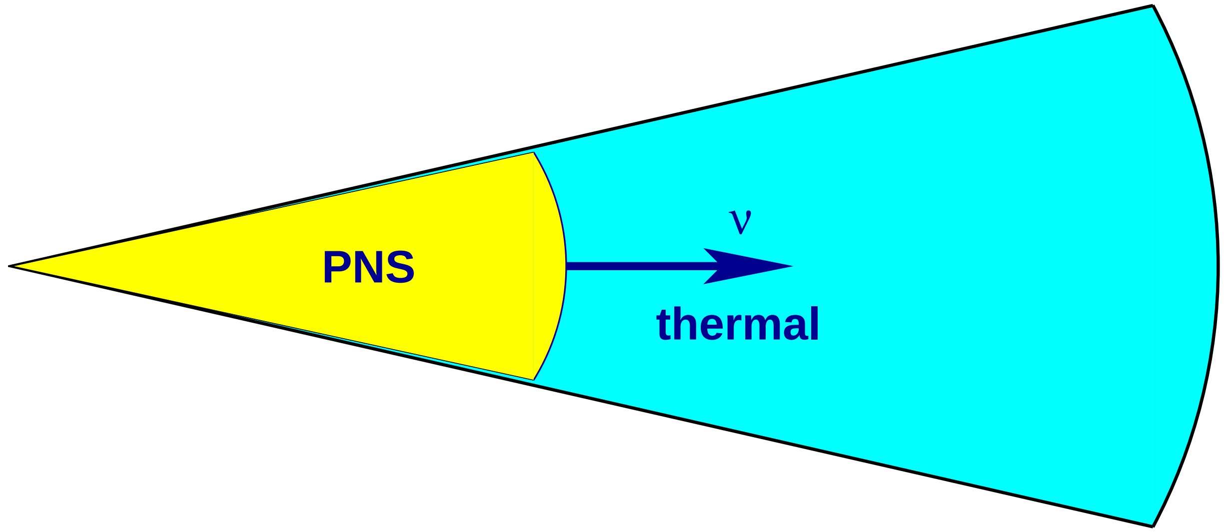
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



Protoneutron star formed. Neutrinos are trapped. The shock wave breaks up nuclei, and the initial neutrino come out (a few %).

Core collapse supernova

Thermal cooling: $t = 10 - 15$ s



Most of the neutrinos emitted during the cooling stage.

Electroweak processes producing neutrinos (**urca**),

$$p + e^- \rightleftharpoons n + \nu_e \quad n + e^+ \rightleftharpoons p + \bar{\nu}_e, \ldots$$

George Gamow

Electroweak processes producing neutrinos (urca),

$$p + e^- \rightleftharpoons n + \nu_e \qquad n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

have an asymmetry in the production cross section, depending on the spin orientation.

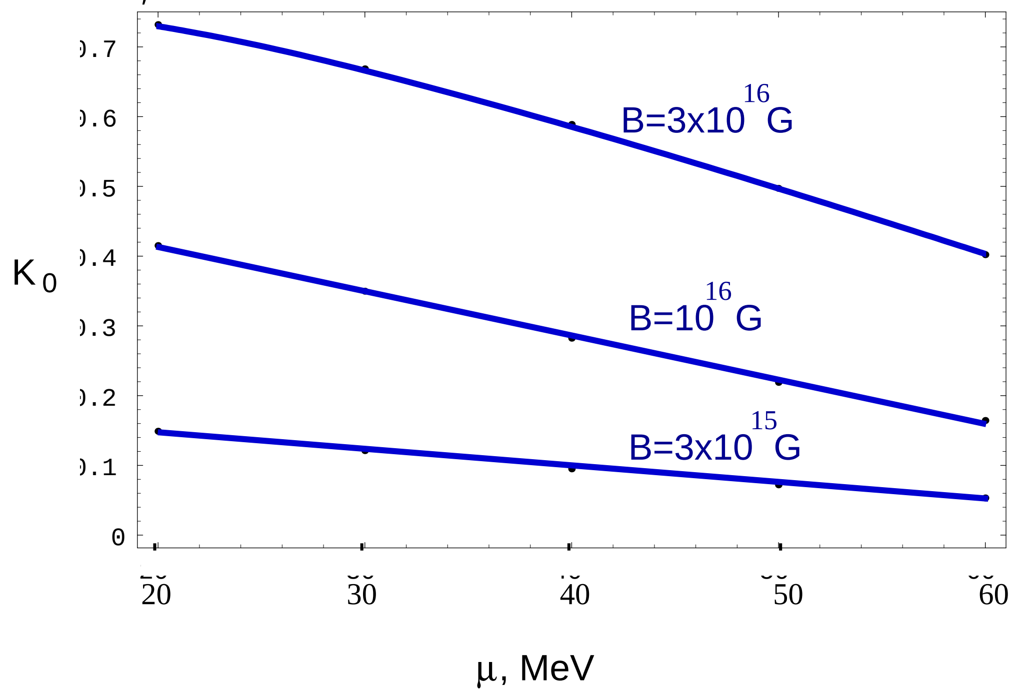
$$\sigma(\uparrow \quad e^-, \uparrow \quad \nu) \neq \sigma(\uparrow \quad e^-, \downarrow \nu)$$

The asymmetry:

$$\tilde{\epsilon} = \frac{g_V^2 - g_A^2}{g_V^2 + 3g_A^2} k_0 \approx 0.4\, k_0,$$

where k_0 is the fraction of electrons in the lowest Landau level.

In a strong magnetic field,



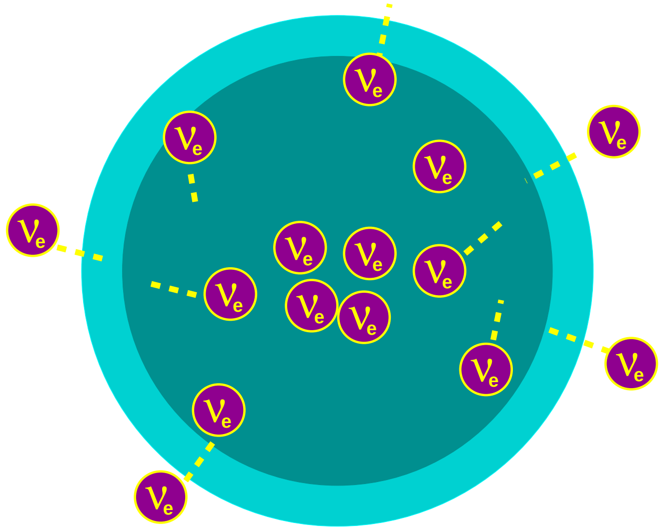
k_0 is the fraction of electrons in the lowest Landau level.

Pulsar kicks from the asymmetric production of neutrinos?

[Chugai; Dorofeev, Rodionov, Ternov]

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

No



Neutrinos are trapped at high density.

Can the weak interactions asymmetry cause an anisotropy in the flux of neutrinos due to a large magnetic field?

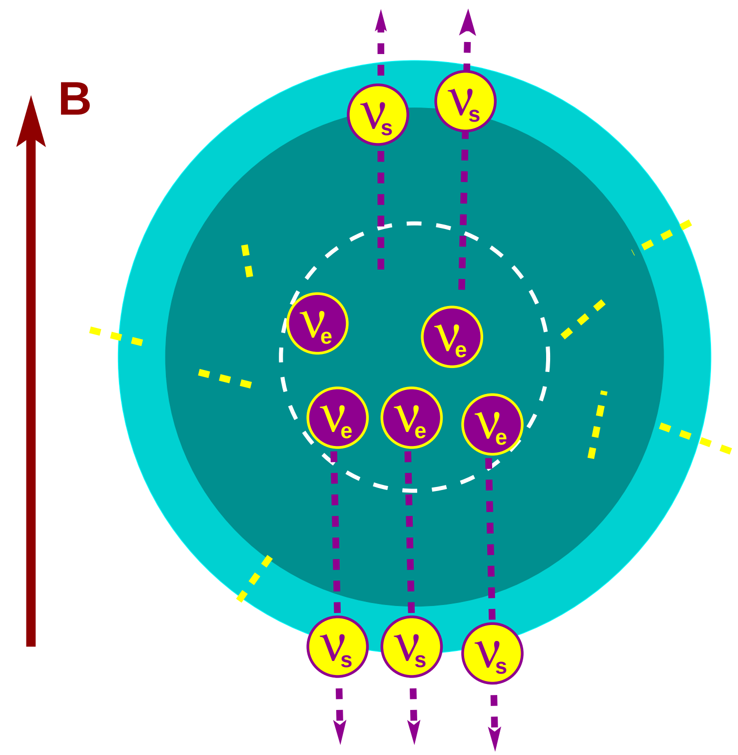
No

Rescattering washes out the asymmetry

In approximate thermal equilibrium the asymmetries in scattering amplitudes do not lead to an anisotropic emission [Vilenkin,AK, Segrè]. Only the outer regions, near neutrinospheres, contribute, but the kick would require a mass difference of $\sim 10^2$ eV [AK,Segrè].

However, if a weaker-interacting <u>sterile neutrino</u> was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

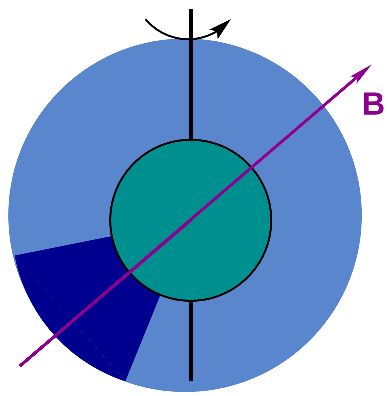
[AK, Segrè; Fuller, AK, Mocioiu, Pascoli]



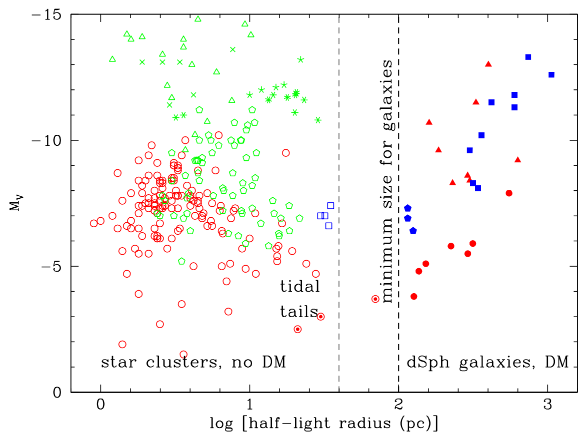
The mass and mixing required for the pulsar kick are consistent with dark matter.

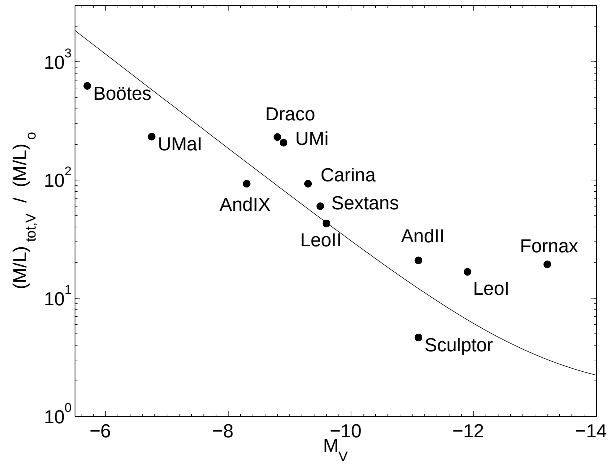
Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK]
- **No $B - v$ correlation** expected because
  - the magnetic field *inside* a hot neutron star during the *first ten seconds* is very different from the surface magnetic field of a cold pulsar
  - rotation washes out the x, y components
- **Directional $\vec{\Omega} - \vec{v}$ correlation** is expected (and observed!), because
  - the direction of rotation remains unchanged
  - only the z-component survives

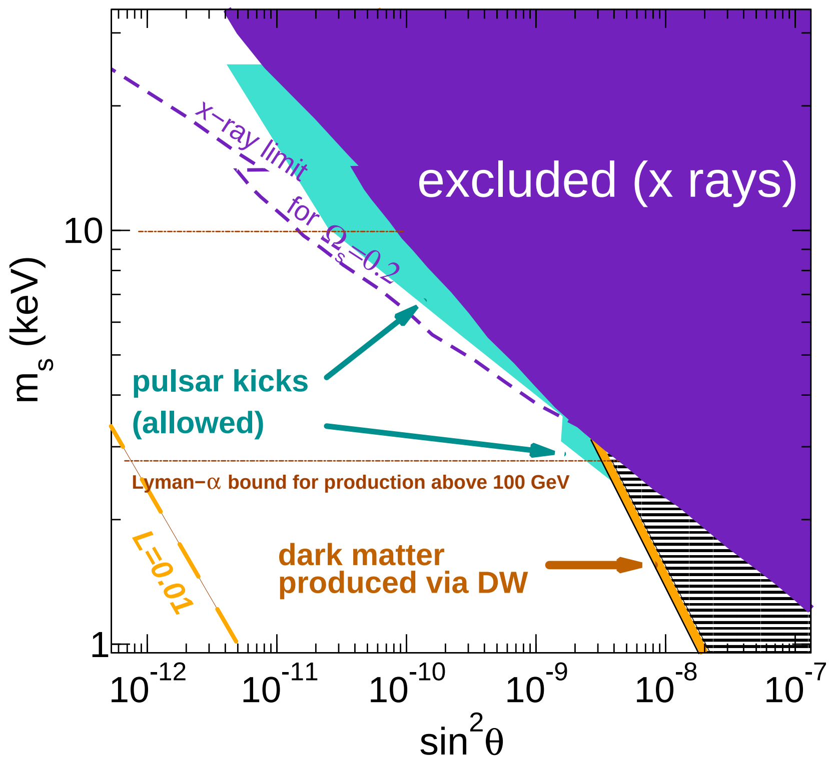


Astrophysical clues: warm dark matter





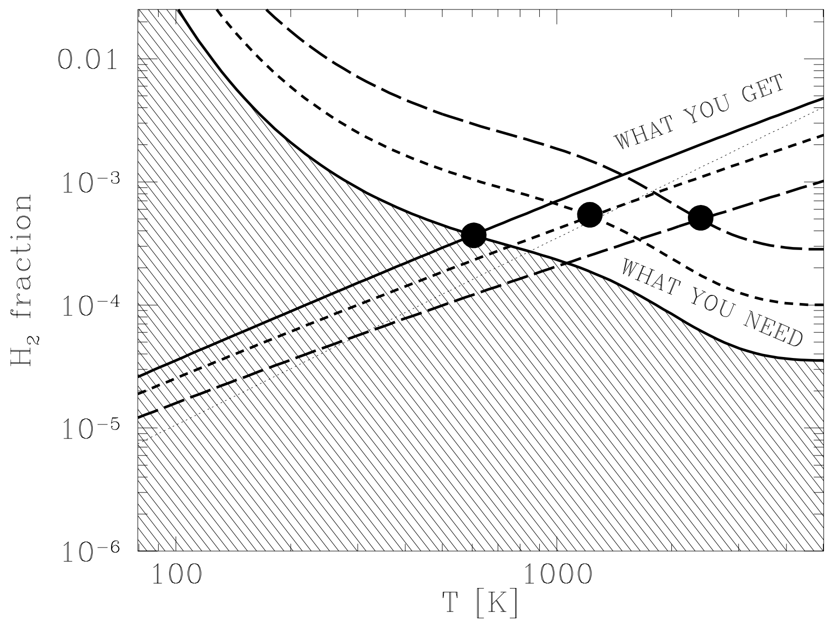
Observations of dwarf spheroids suggest a non-vanishing free-streaming length [Gilmore, Wyse]



Free-streaming length depends on mass, production mechanism **[Kalliopi Petraki, AK]**

Astrophysical clues: star formation and reionization

Molecular hydrogen is necessary for star formation



[Tegmark, et al., ApJ **474**, 1 (1997)]

Molecular hydrogen

$$\boldsymbol{H} + \boldsymbol{H} \longrightarrow \boldsymbol{H_2} + \boldsymbol{\gamma} \quad - \text{ very slow!}$$

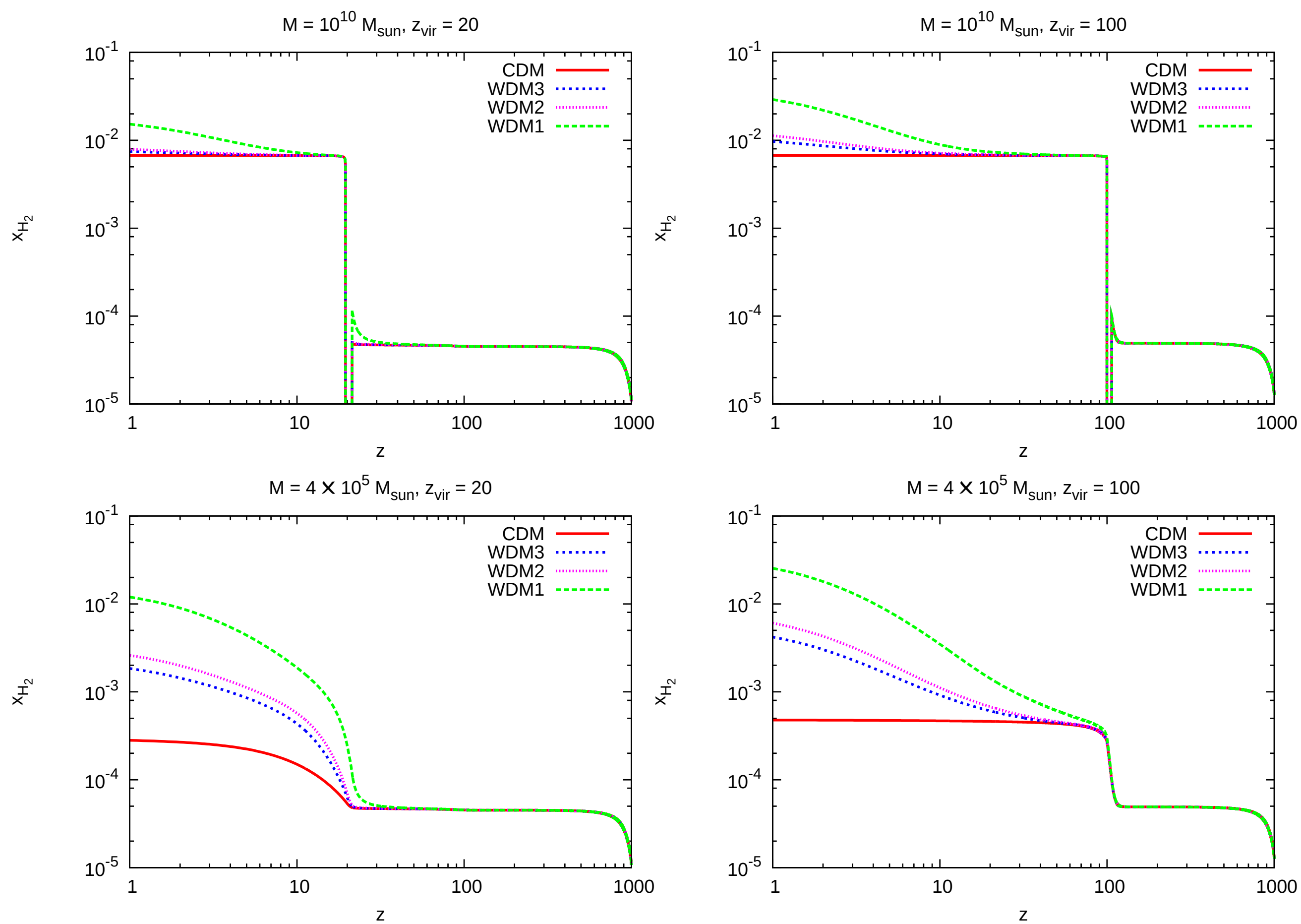
In the presence of ions the following reactions are faster:

$$\begin{aligned} \boldsymbol{H^+} + \boldsymbol{H} &\longrightarrow \boldsymbol{H_2^+} + \boldsymbol{\gamma}, \\ \boldsymbol{H_2^+} + \boldsymbol{H} &\longrightarrow \boldsymbol{H_2} + \boldsymbol{H^+}. \end{aligned}$$

H^+ catalyze the formation of molecular hydrogen

[Biermann, AK, PRL **96**, 091301 (2006)]

[Stasielak, Biermann, AK, ApJ.654:290 (2007)]



[Biermann, AK; Stasielak, Biermann, AK]