Discovering dark matter in space

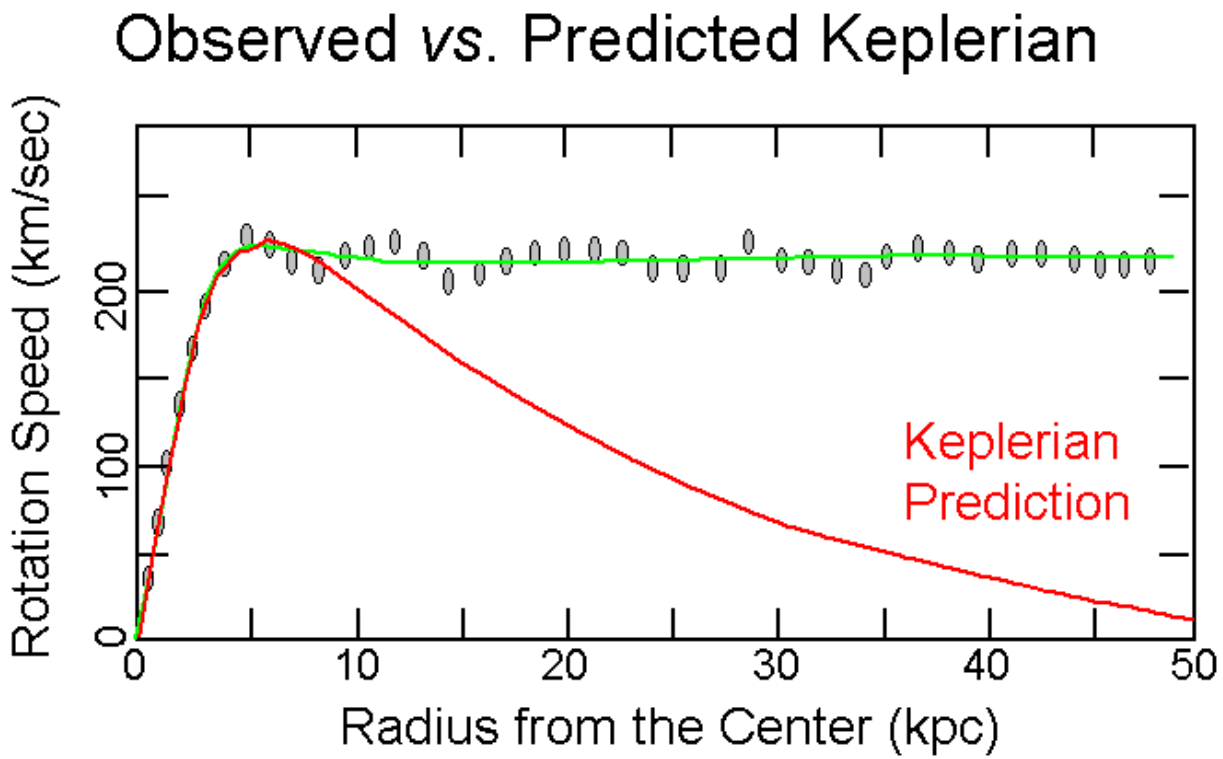
- The evidence for dark matter
- The candidates, and the detection strategies
- The opportunities in space
- Sterile neutrinos as dark matter:

Dark matter

The evidence for dark matter is very strong:

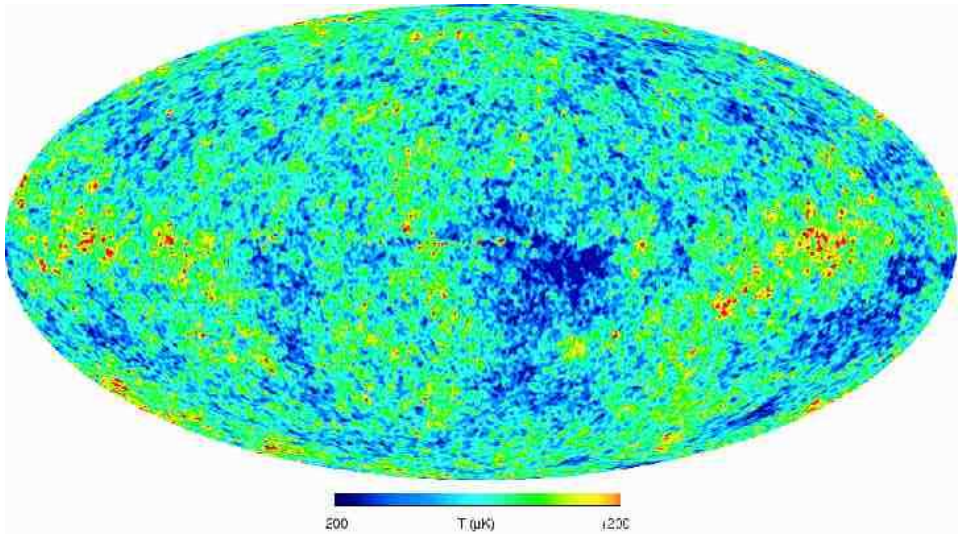
- galactic rotation curves cannot be explained by the disk alone
- cosmic microwave background radiation
- gravitational lensing of background galaxies by clusters is so strong that it requires a significant dark matter component.
- clusters are filled with hot X-ray emitting intergalactic gas; some (merging) clusters show displacement of dark and baryonic matter

Galactic rotation curves



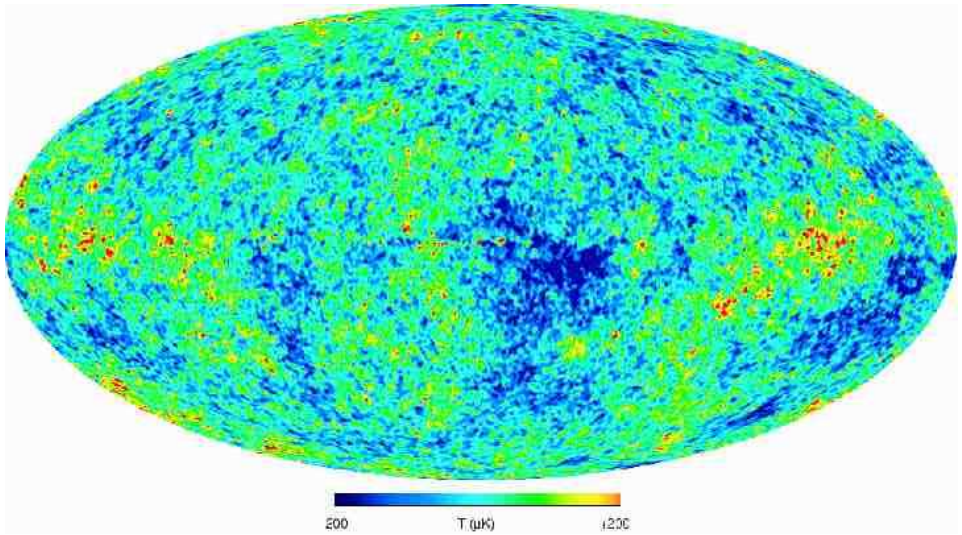
Cosmic microwave background radiation (CMBR)

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



Cosmic microwave background radiation (CMBR)

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



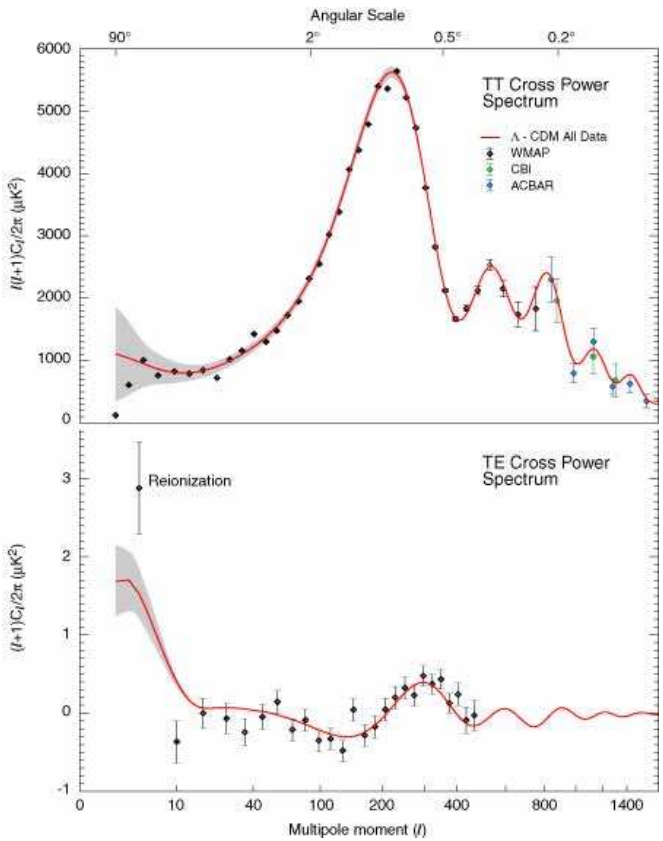
These fluctuations can be represented in the form of a power spectrum C_l. First, one expands in spherical harmonics:

$$\frac{\Delta T}{T} = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi)$$

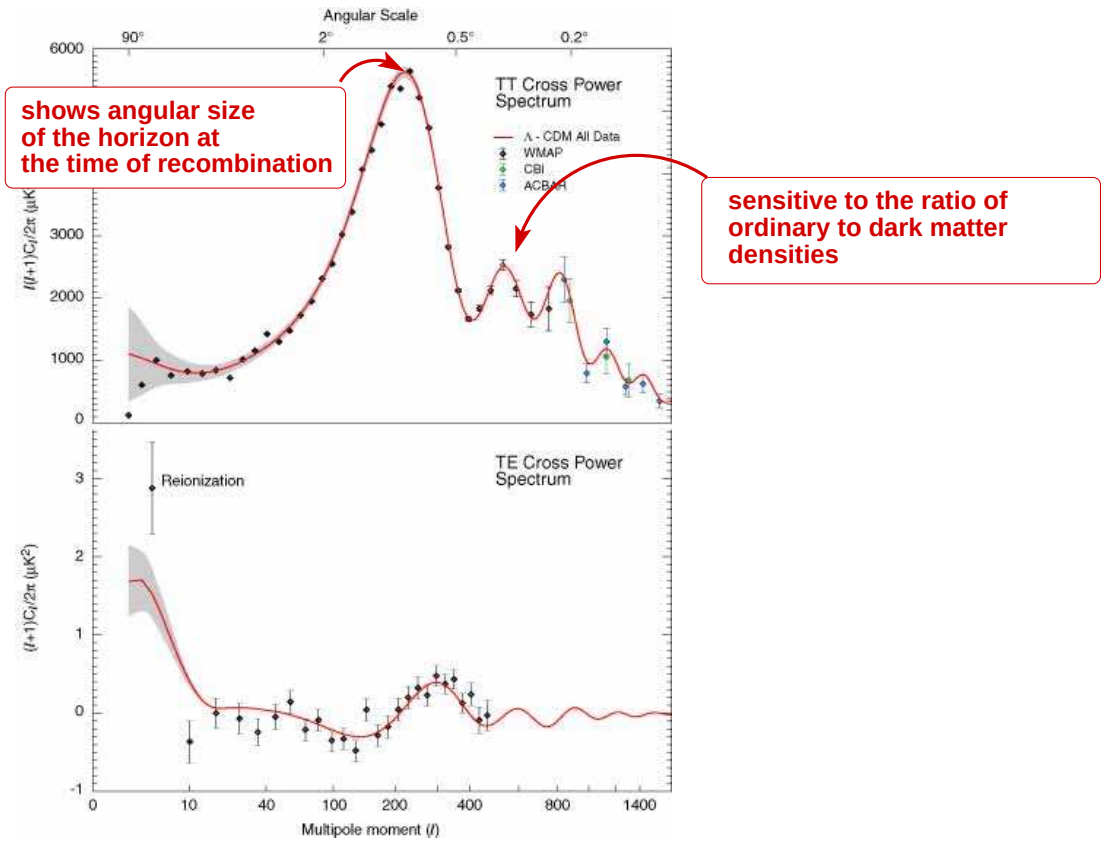
And then one plots

$$C_l \equiv \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

Power spectrum measured by WMAP

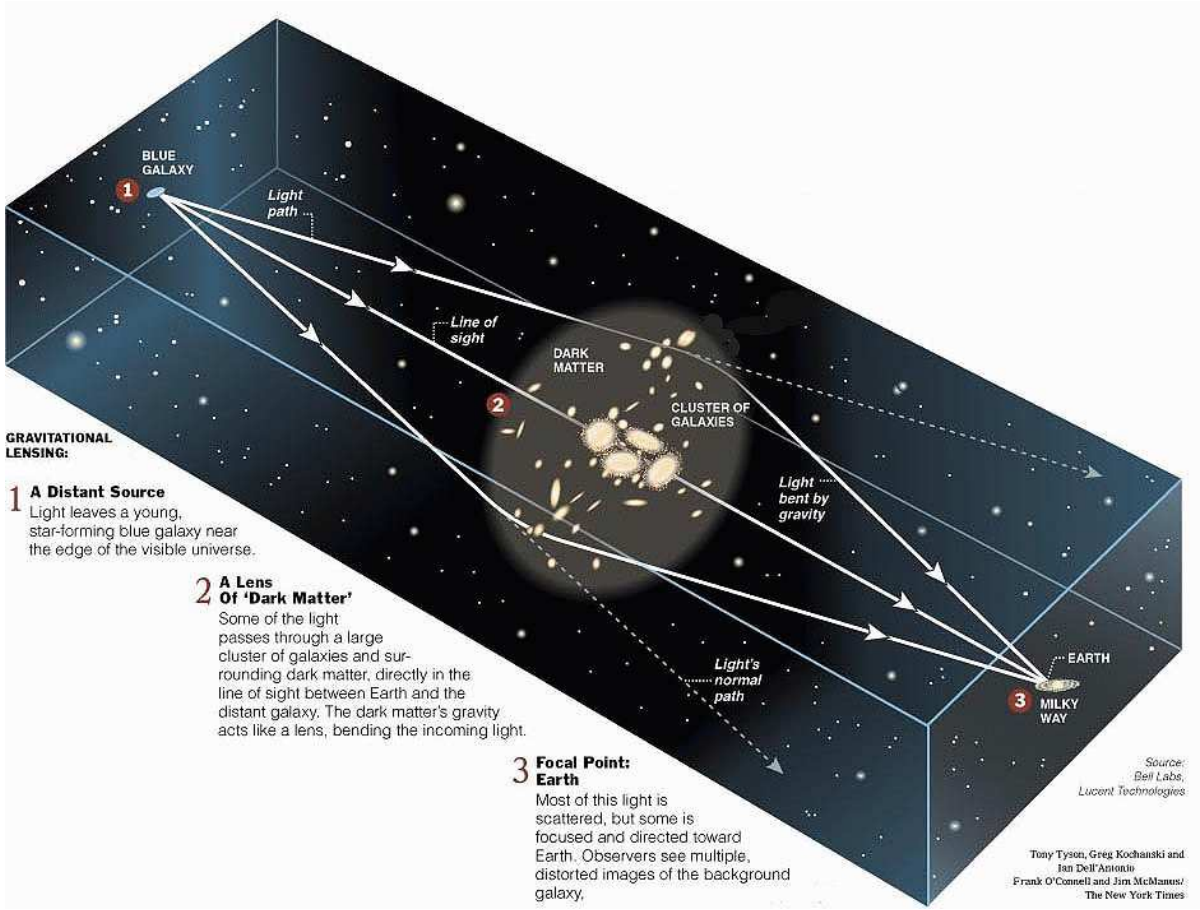


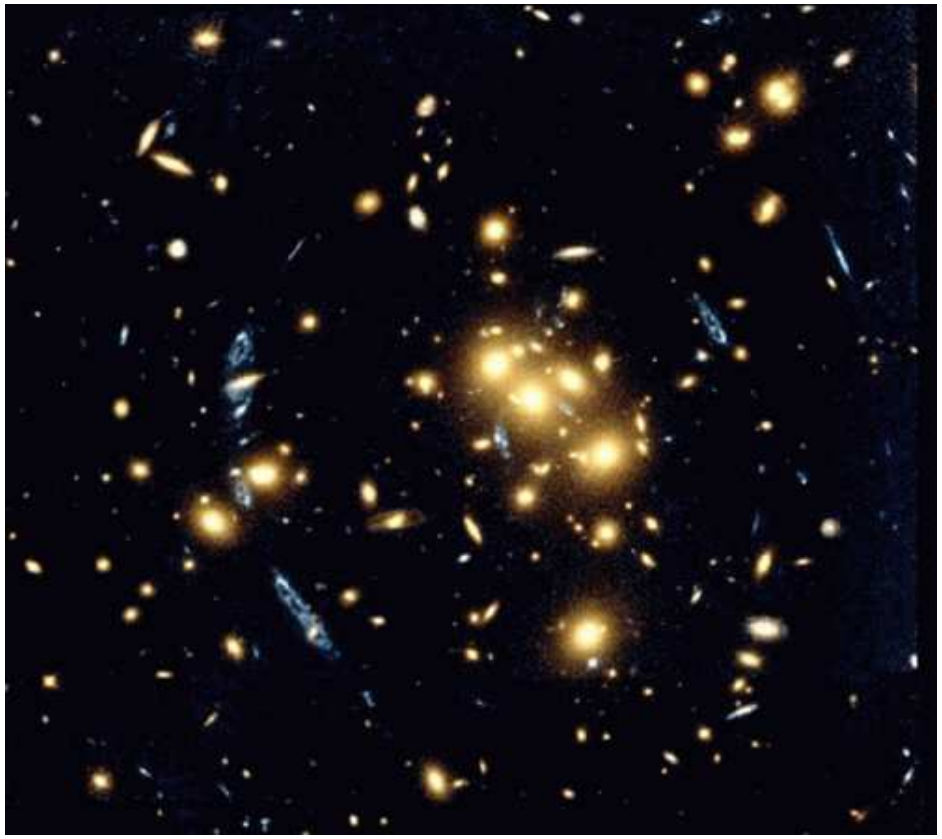
Power spectrum measured by WMAP

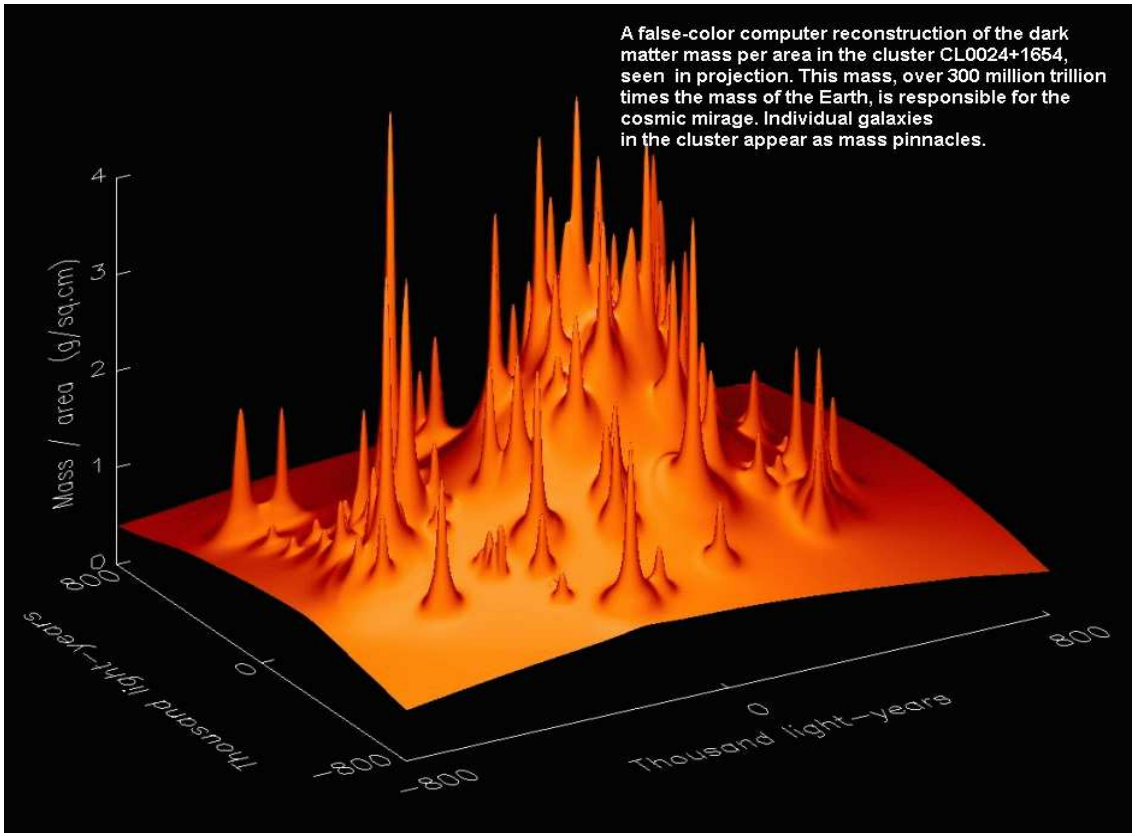


WMAP: $\Omega_{\rm matter} = 0.234 \pm 0.035; \;\; \Omega_{\rm b} = 0.0446 \pm 0.0016$

Gravitational lensing: seeing the invisible

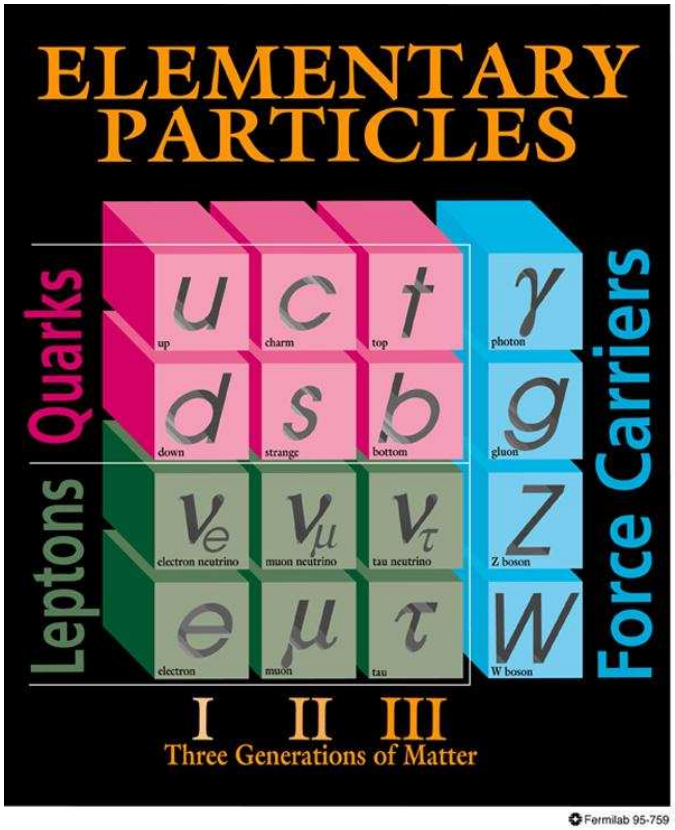




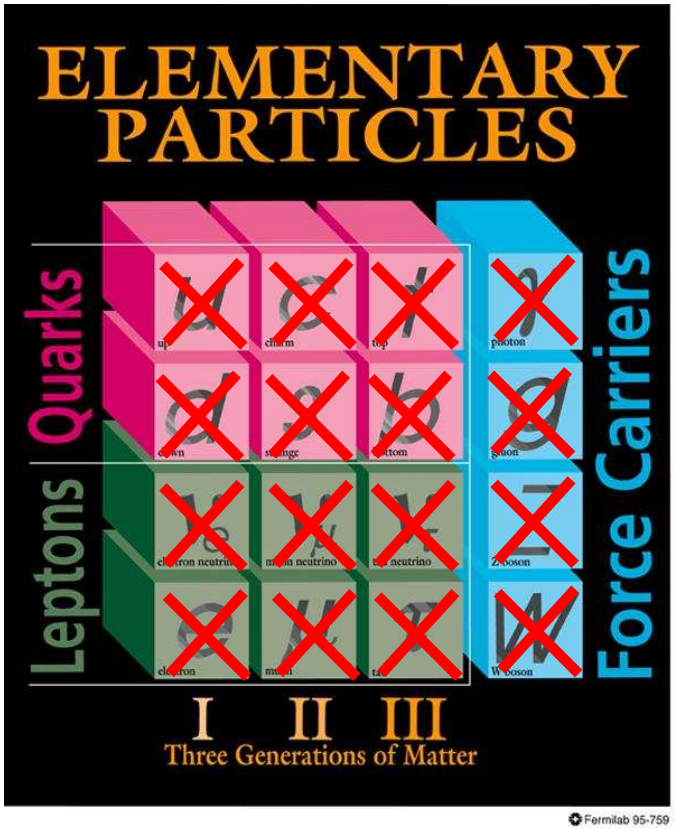


Foreground cluster CL0024+1654 produces multiple images of a blue background galaxy in the HST image (left). Mass reconstruction (right).

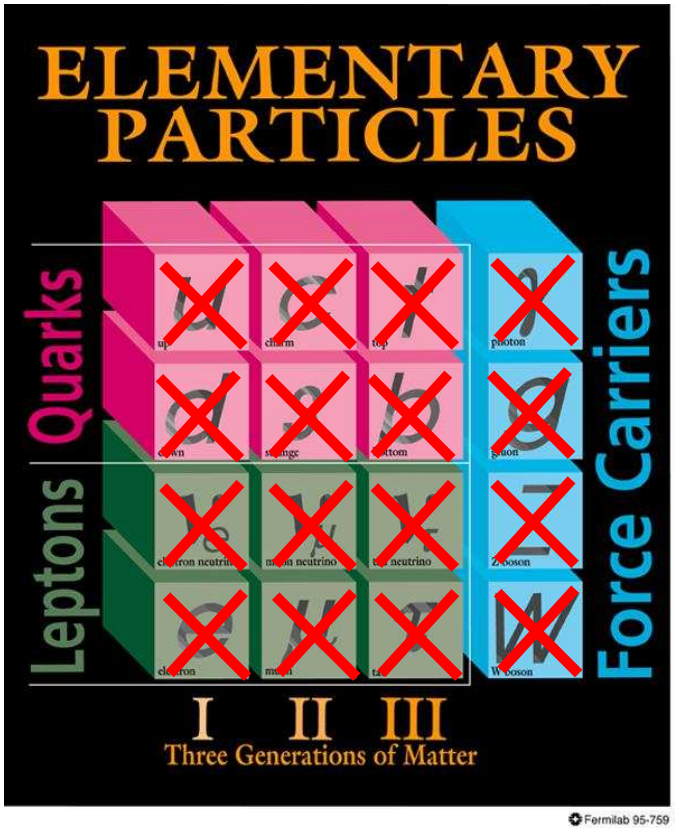
None of the known particles can be dark matter



None of the known particles can be dark matter



Dark matter ⇒ new physics



Dark matter: what is it?

Can take guesses based on...

- ...compelling theoretical ideas
- ...simplicity
- **...observational clues**

Dark matter properties determine the detection strategy

Dark matter: compelling theoretical ideas

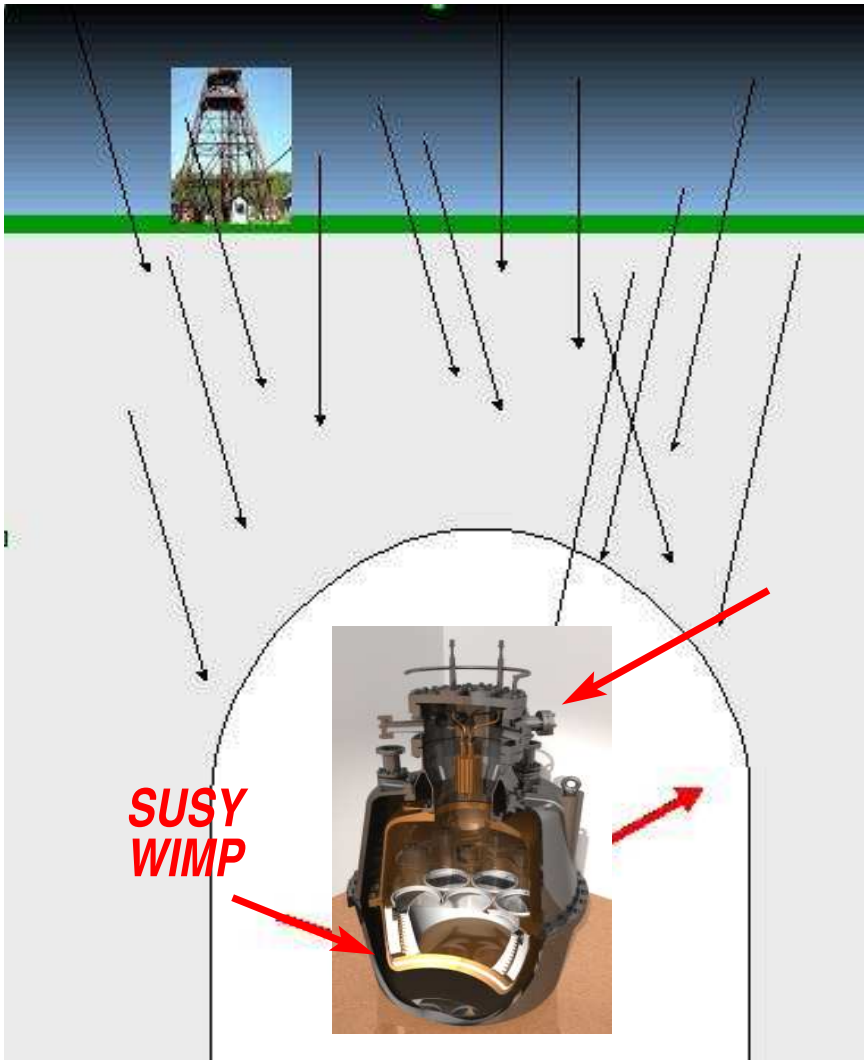
SUSY is an appealing theoretical idea

Dark matter comes as part of the package as one of the following:

- **Lightest supersymmetric particle**, stable because of **R-parity**
  - **neutralino**
  - **gravitino**
  - **axino**
- **SUSY Q-balls**, stable for gauge-mediated SUSY breaking, thanks to the **baryon number and energy conservation**.

Theoretically motivated! Mass vs cross section OK, even **"natural"**.

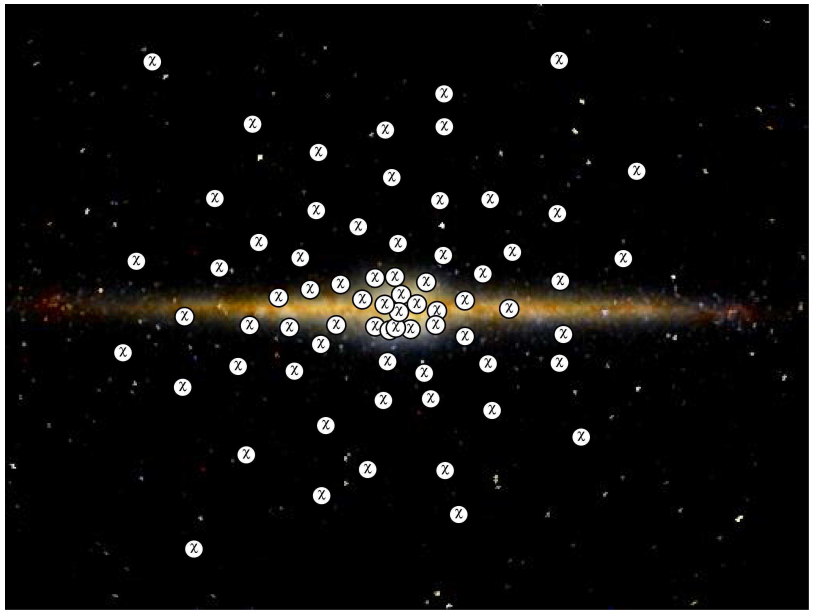
By no means minimal. No experimental evidence so far, but the search is under way.



Direct detection

Weakly interacting particles (WIMP) can penetrate through rock; they can be detected in underground detectors, such as **Zeplin** and others, screened by the rock from cosmic rays (unwanted background)

Indirect detection of WIMPs



Annihilations of WIMPs in the center of MW galaxy can be detected by gamma ray and x-ray telescopes in space

Axion

Strong CP problem: QCD vacuum is a superposition $|\theta\rangle = \sum_n \exp\{-in\theta\}|n\rangle$ of topologically distinct vacuum states $|n\rangle$.

$$\mathcal{L}_{QCD} = \mathcal{L}_{\rm pert} + \theta \frac{g^2}{32\pi^2} F\tilde{F}$$

$$\bar{\theta} = \theta + \arg\det M$$

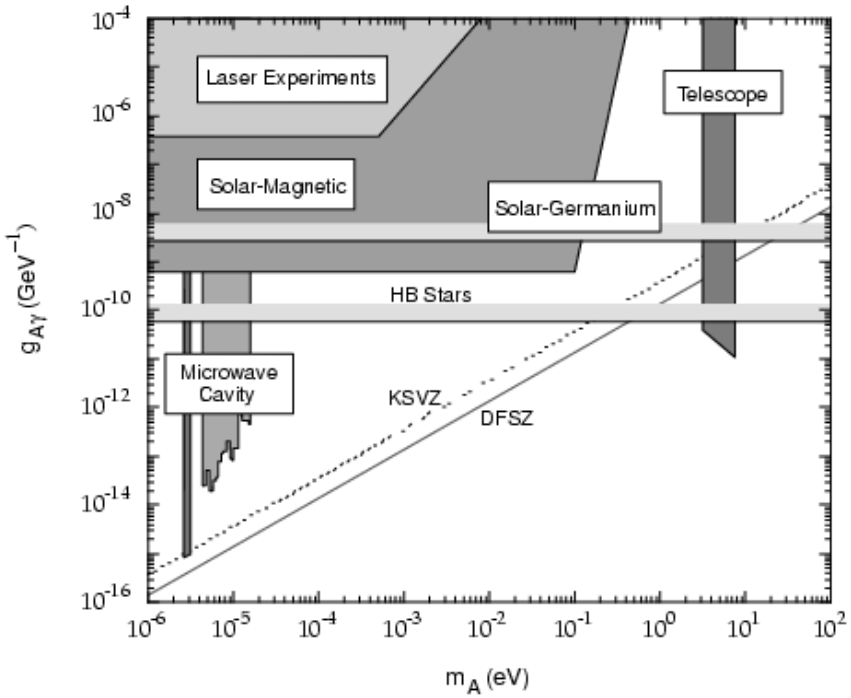
Experiment: $|\bar{\theta}| \ll 10^{-10}$!

Possible solution: Peccei-Quinn symmetry

An elegant solution: $\bar{\theta}$ relaxes to zero dynamically, by a VEV of the **axion** . Additional U(1) symmetry, **Peccei-Quinn symmetry** is spontaneously broken by instantons $\Rightarrow$ axion has small mass.

Axion is a weakly interacting particle $\Rightarrow$ **dark matter**

Axion dark matter



Axion dark matter

Various searches:

- axion-photon conversion in magnetic field
- detection of solar axions
- long-range forces; possible advantage in space: **drag-free environment**

Sterile dark matter: a simple (minimalist) solution

Need **one** particle $\Rightarrow$ add just **one** particle
If a fermion, must be gauge singlet (anomalies)
Interactions only through mixing with neutrinos

$\Rightarrow$ **sterile neutrino**

Small mass and, therefore, **stability!** No symmetries required.

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. $\mu \to e\gamma$)
- 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)]

Sterile neutrinos with a small mixing to active neutrinos

$$\begin{cases} |\nu_1\rangle = \cos\theta|\nu_e\rangle - \sin\theta|\nu_s\rangle \\ |\nu_2\rangle = \sin\theta|\nu_e\rangle + \cos\theta|\nu_s\rangle \end{cases} \quad (1)$$

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

The coupling of ν_2 to weak currents is also suppressed, and $\sigma \propto \sin^2\theta$.

The probability of $\nu_e \to \nu_s$ conversion in presence of matter is

$$\langle P_{\rm m}\rangle = \frac{1}{2}\left[1 + \left(\frac{\lambda_{\rm osc}}{2\lambda_{\rm s}}\right)^2\right]^{-1} \sin^2 2\theta_m, \quad (2)$$

where $\lambda_{\rm osc}$ is the oscillation length, and $\lambda_{\rm s}$ is the scattering length.

Sterile neutrinos in the early universe

Sterile neutrinos are produced in primordial plasma through

- off-resonance oscillations. [Dodelson, Widrow; Abazajian, Fuller; Dolgov, Hansen; Shaposhnikov et al.]

- oscillations on resonance, if the lepton asymmetry is non-negligible [Fuller, Shi]

Mixing is suppressed at high temperature [Dolgov, Barbiieri; Stodolsky]

$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V(T))^2}, \quad (3)$$

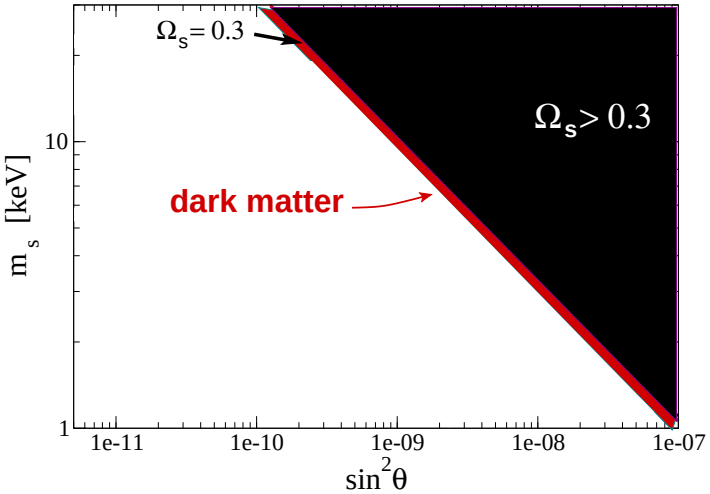
For small angles,

$$\sin 2\theta_m \approx \frac{\sin 2\theta}{1 + 0.79 \times 10^{-13} (T/\mathrm{MeV})^6 (\mathrm{keV}^2/\Delta m^2)} \quad (4)$$

Production of sterile neutrinos peaks at temperature

$$T_{\max} = 130\,\mathrm{MeV} \left(\frac{\Delta m^2}{\mathrm{keV}^2}\right)^{1/6}$$

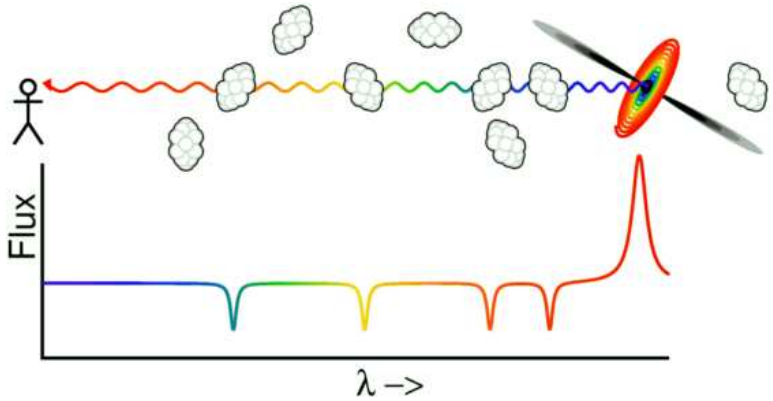
The resulting density of relic sterile neutrinos in conventional cosmology, in the absence of a large lepton asymmetry:

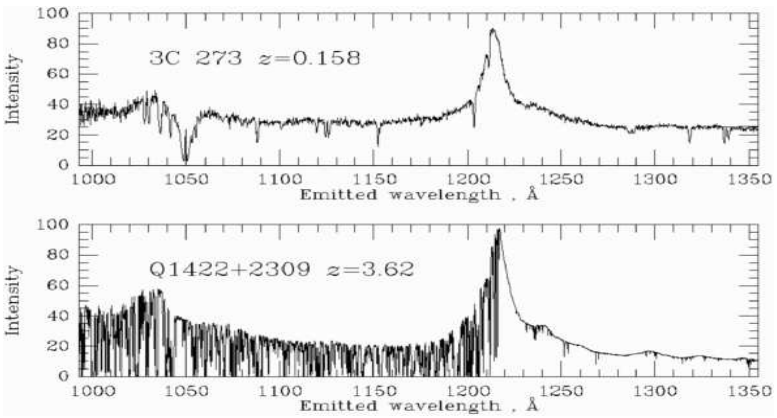


$$\Omega_{\nu_2} \sim 0.3 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{\mathrm{keV}}\right)^2$$

[Dodelson, Widrow; Dolgov, Hansen; Fuller, Shi; Abazajian, Fuller, Patel]

Lyman-α forest: a look at the small-scale structure

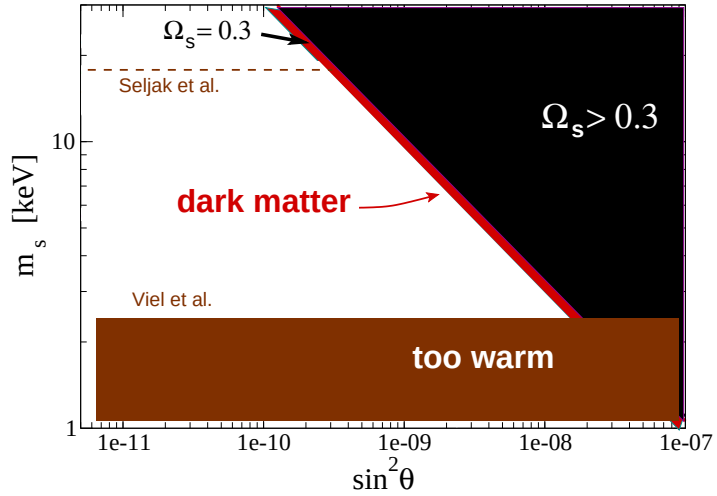




The resulting density of relic sterile neutrinos in conventional cosmology, in the absence of a large lepton asymmetry:

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

Lyman-α forest clouds show significant structure on small scales. Dark matter must be cold enough to preserve this structure.



Cold or warm dark matter?

CDM works well, but...

There are problem problems with cold dark matter on small scales

Some CDM problems eliminated by WDM

- overproduction (by an order of magnitude!) of the satellite halos for galaxies of the size of Milky Way.

- WDM can reduce the number of halos in low-density voids. [Peebles]

- observed densities of the galactic cores (from the rotation curves) are lower than what is predicted based on the ΛCDM power spectrum. [Dalcanton et al.; van den Bosch et al.; Moore; Abazajian]

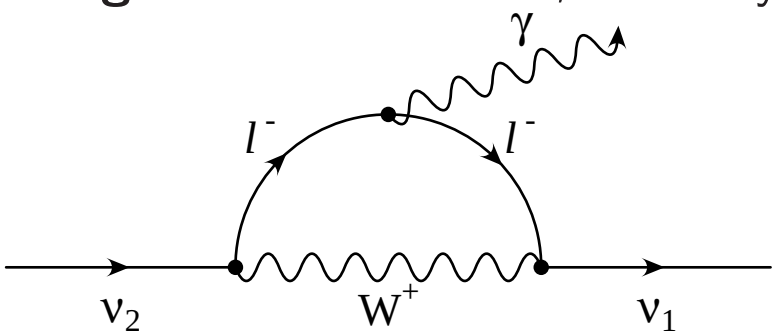
- The "angular-momentum problem": in CDM halos, gas should cool at very early times into small halos and lead to massive low-angular-momentum gas cores in galaxies. [Dolgov]

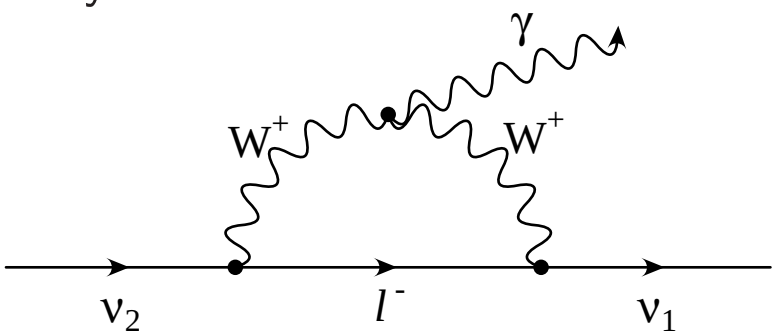
- disk-dominated (pure-disk) galaxies are observed, but not produced in CDM because of high merger rate. [Governato et al.; Kormendy et al.]

- observations of dwarf spheroidal galaxies $\Rightarrow$ $m \sim$ keV [Gilmore et al.]

Radiative decay

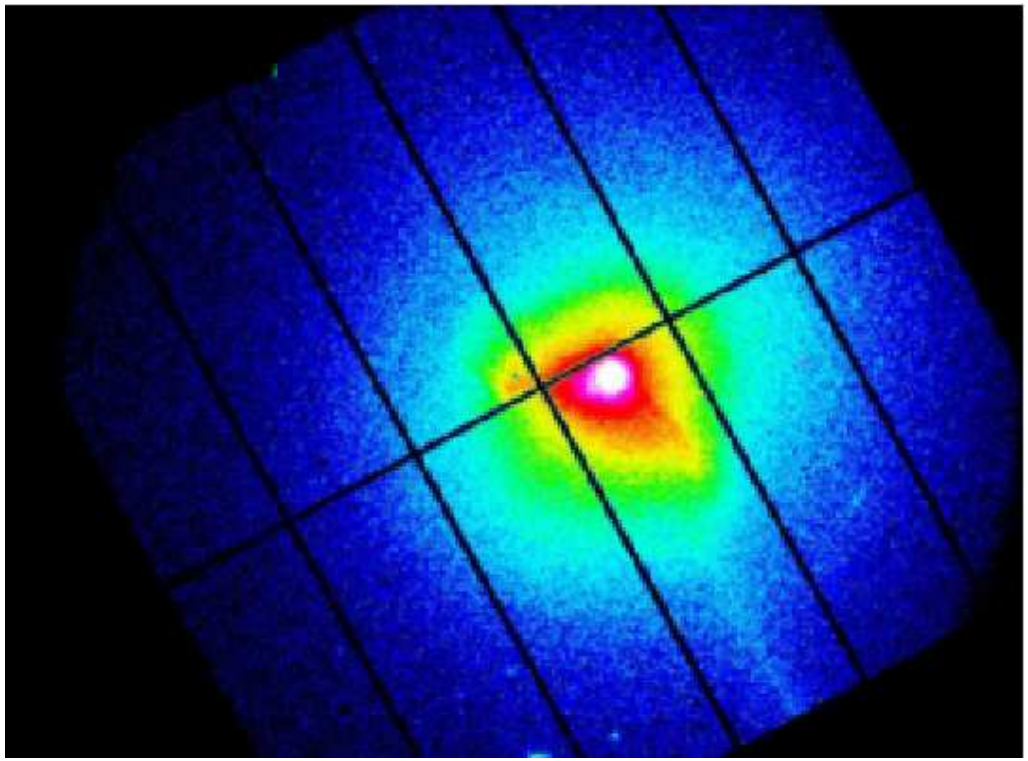
Sterile neutrino in the mass range of interest have lifetimes **longer than the age of the universe**, but they do decay:





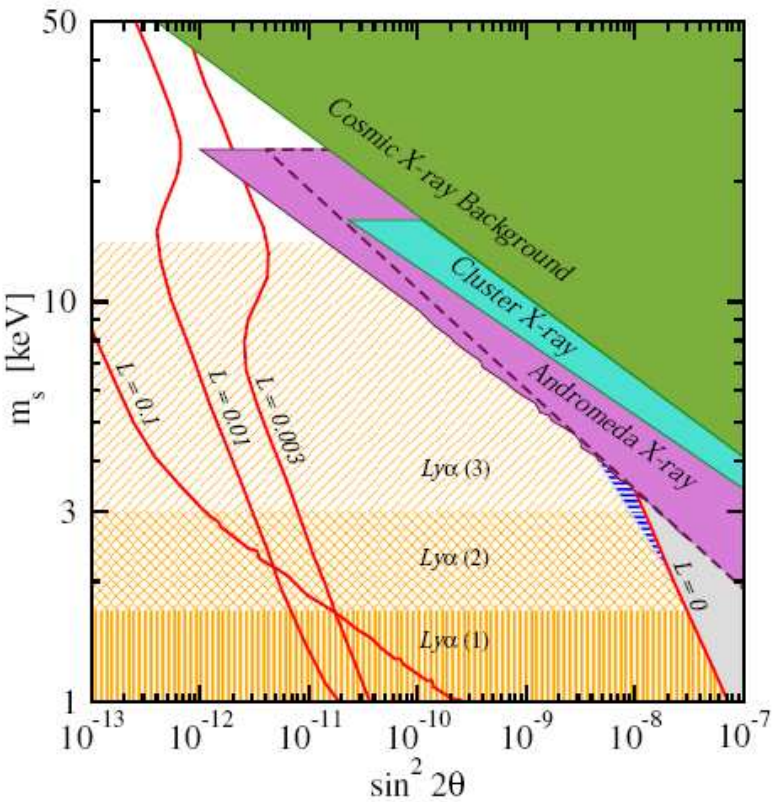
Photons have energies $m/2$: X-rays. Large lumps of dark matter emit some X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

X-ray observations



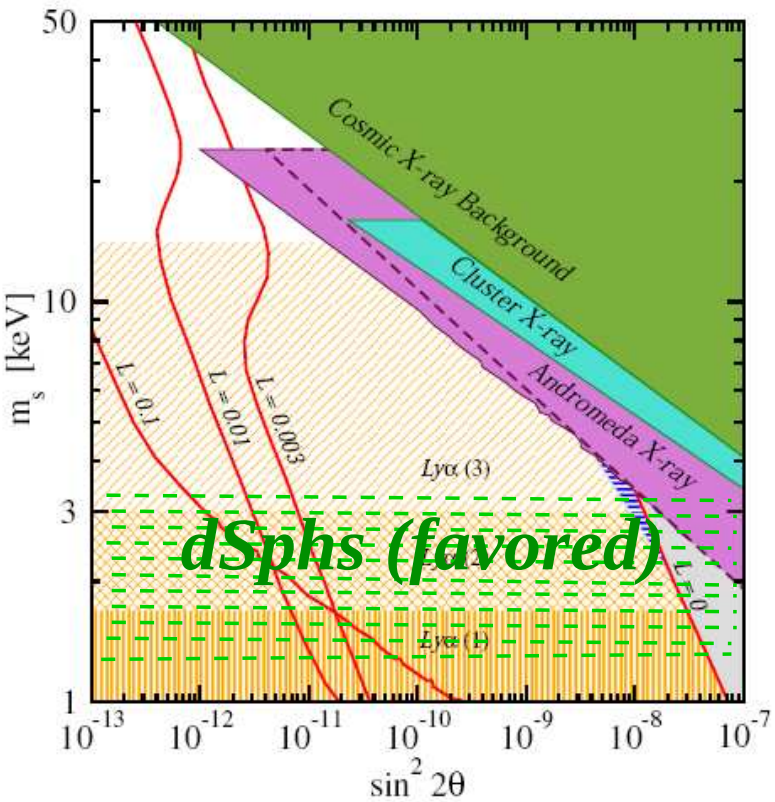
Virgo cluster image from XMM-Newton

Chandra, XMM-Newton can see photons: $\nu_s \longrightarrow \nu_e \gamma$



[Abazajian et al; Hansen et al.; Boyarsky et al.; Watson et al.]

Chandra, XMM-Newton can see photons: $\nu_s \longrightarrow \nu_e \gamma$



[Abazajian et al; Hansen et al.; Boyarsky et al.; Watson et al.]

Emission of sterile neutrinos from a supernova

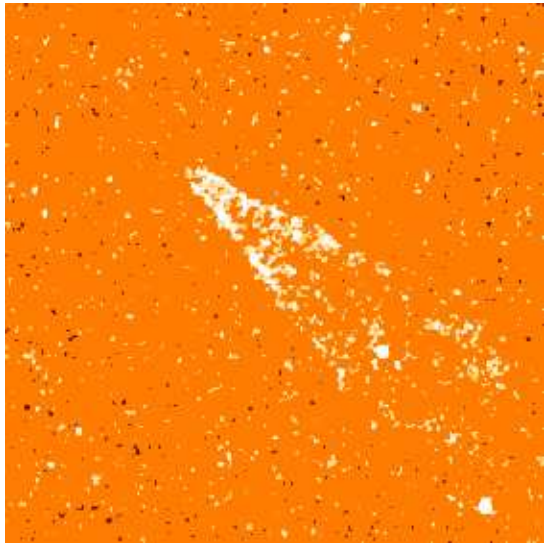
- Sterile neutrino emission from a supernova is anisotropic
- Sterile neutrinos with masses and mixing angles consistent with dark matter can explain the pulsar velocities

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

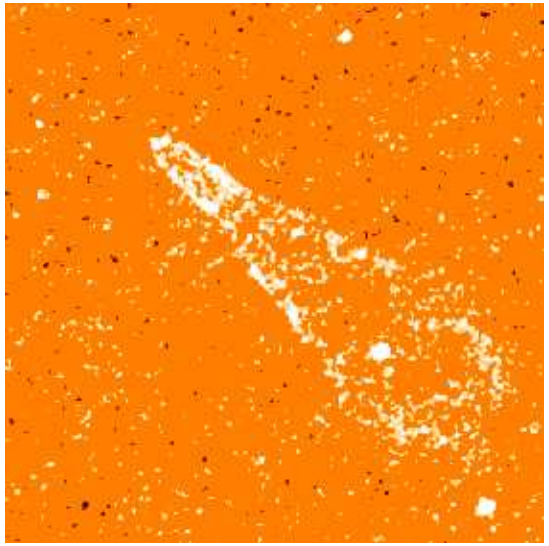
The pulsar velocities.

Pulsars have large velocities, $\langle v \rangle \approx 250 - 450$ km/s.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]
A significant population with $v > 700$ km/s,
about **15 %** have $v > 1000$ km/s, up to 1600 km/s.
[Arzoumanian *et al.*; Thorsett *et al.*]

A very fast pulsar in Guitar Nebula

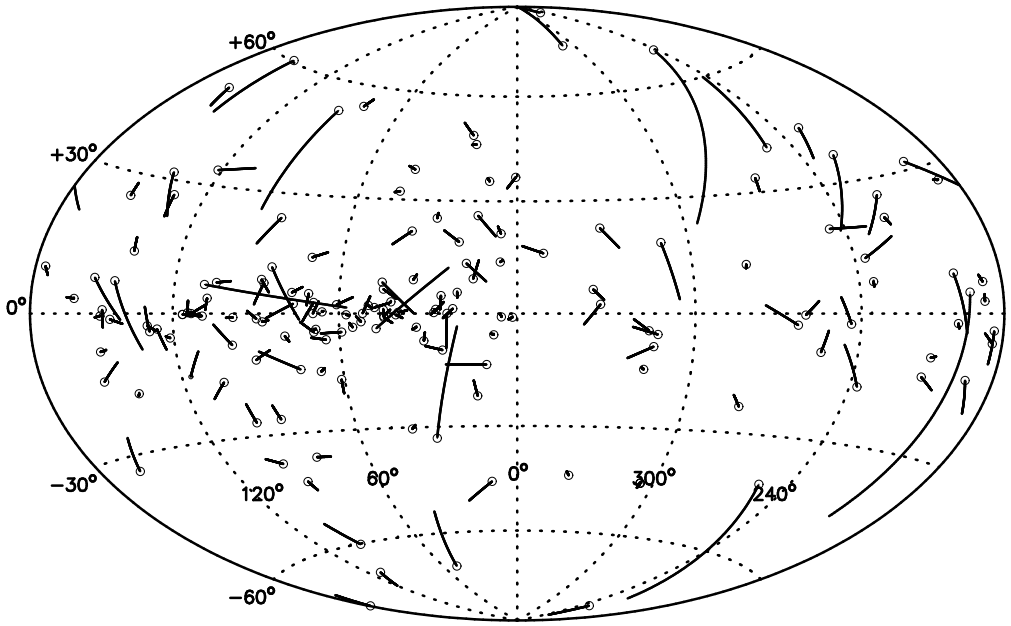


HST, December 1994



HST, December 2001

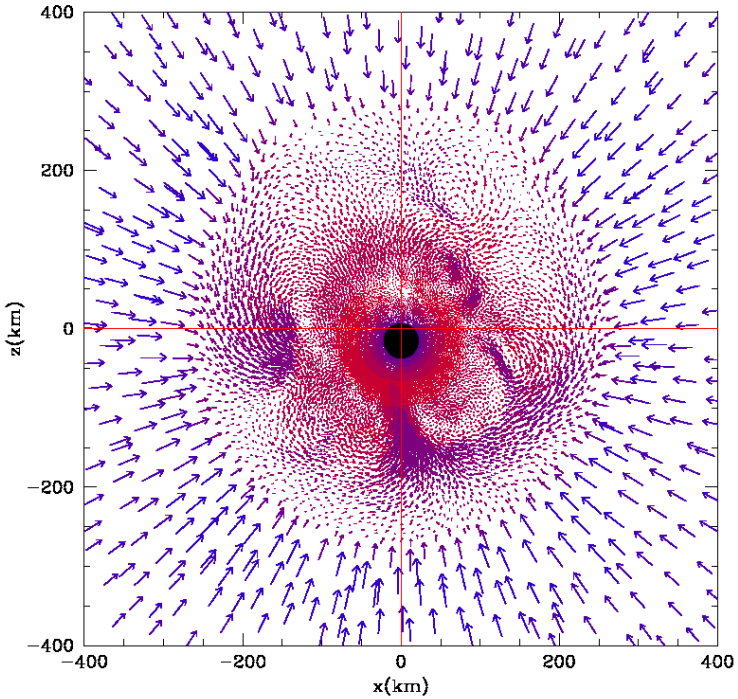
Map of pulsar velocities

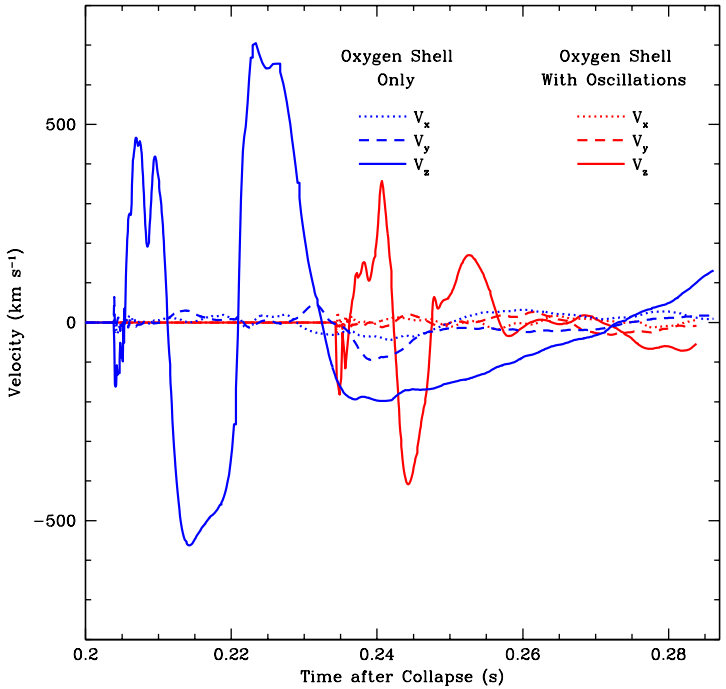


Proposed explanations:

- 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)

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:

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

99% of this energy is emitted in neutrinos

Pulsar kicks from neutrino emission?

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

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

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

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

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*

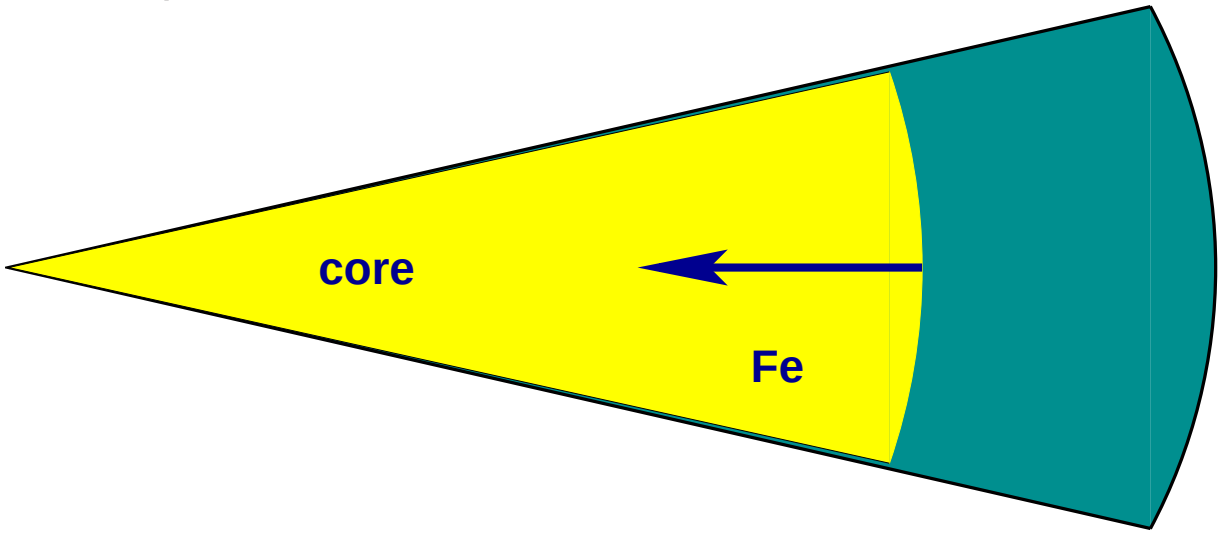
$\Rightarrow$ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16}$ **G**.

$\Rightarrow$ **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.

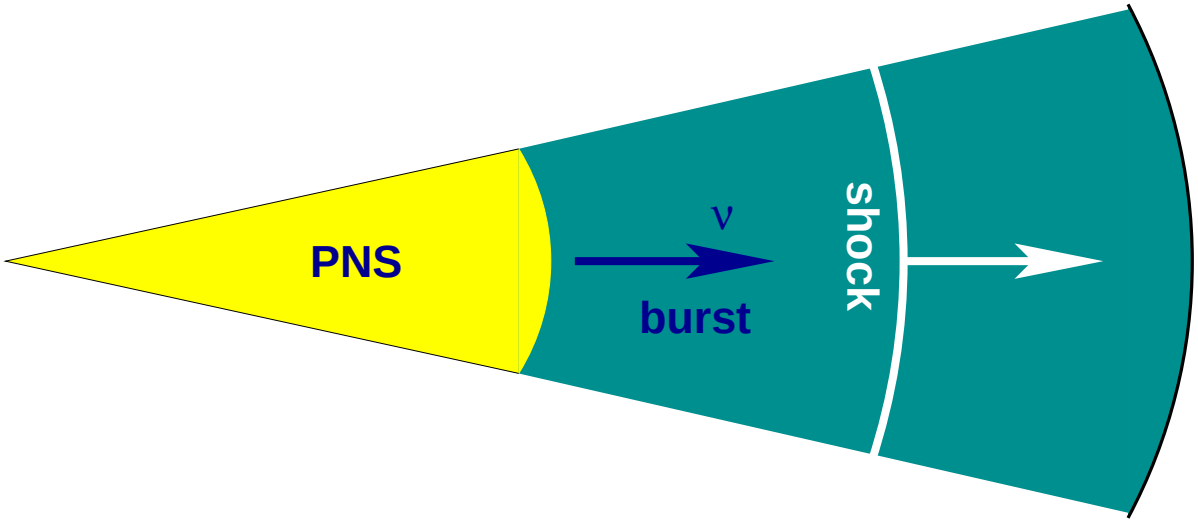
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

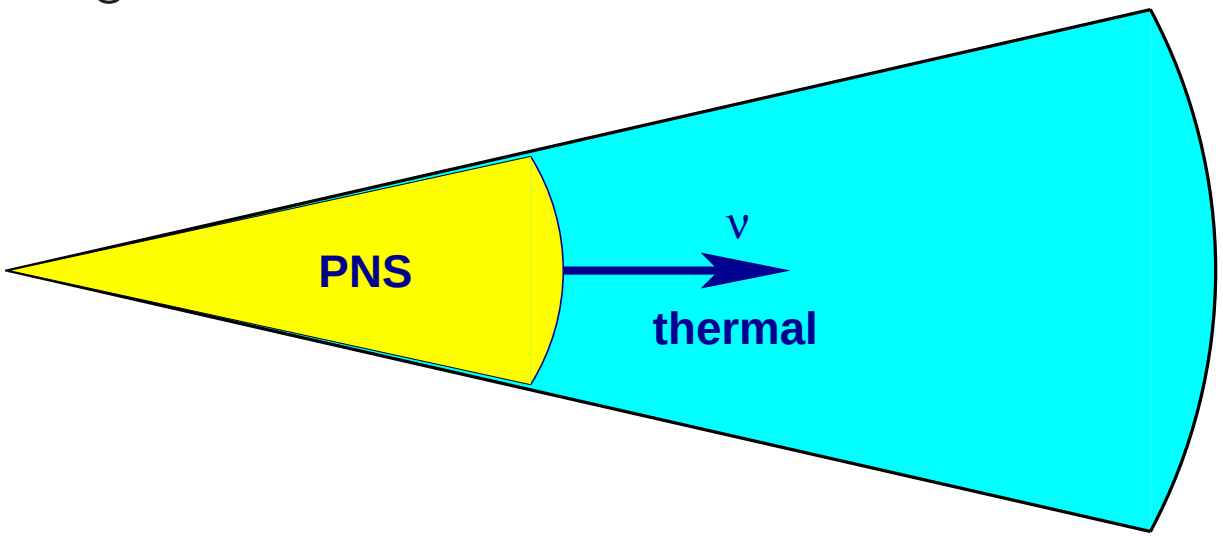
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



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),

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

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

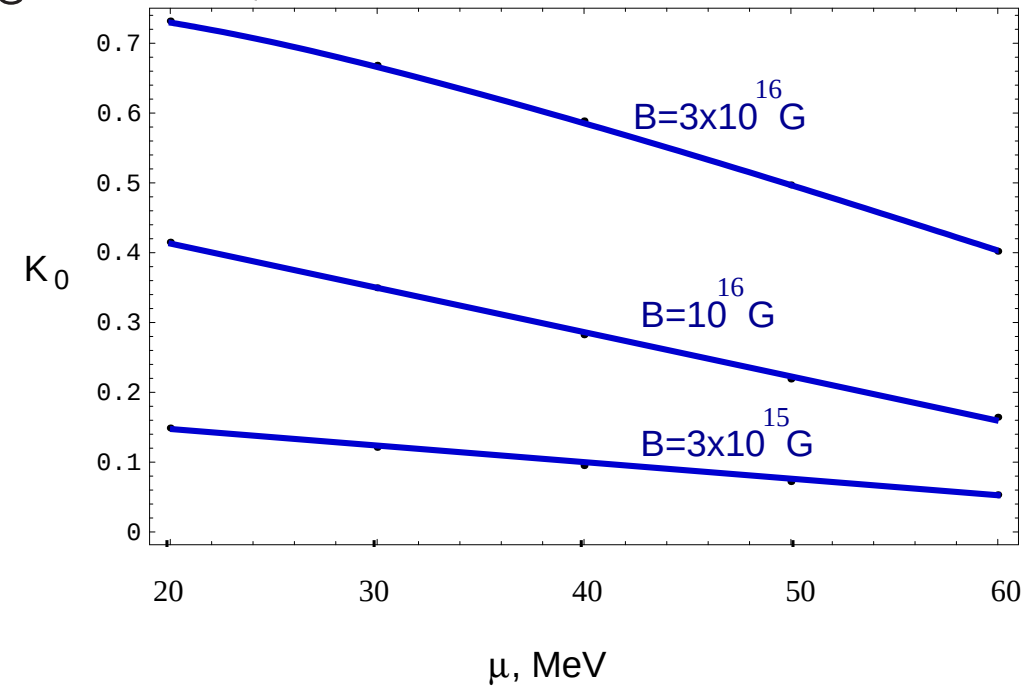
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

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,

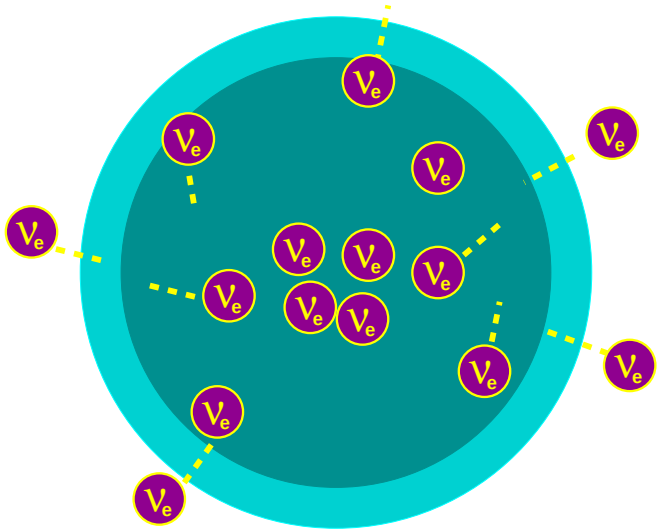


k_0 is the fraction of electrons in the lowest Landau level.

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?

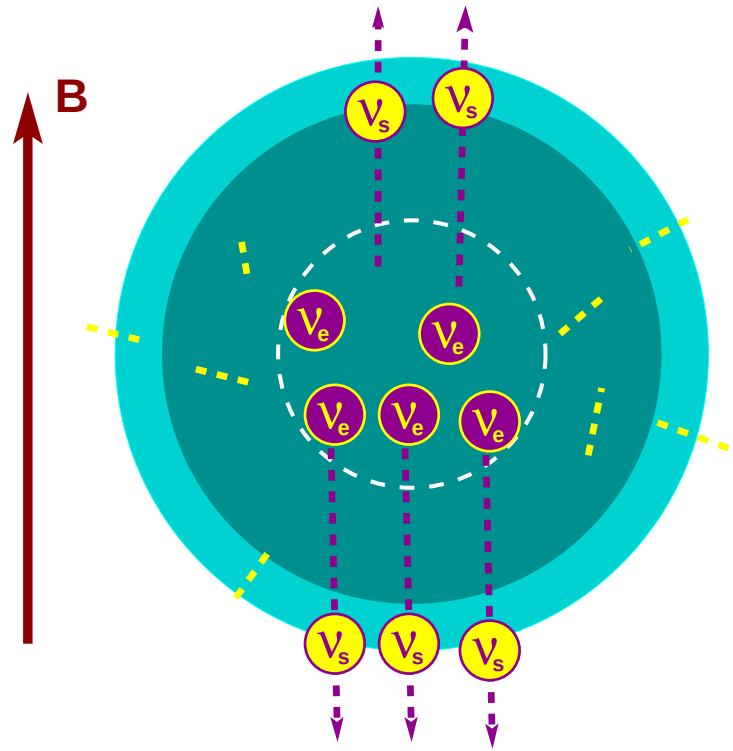
No

Rescattering washes out the asymmetry

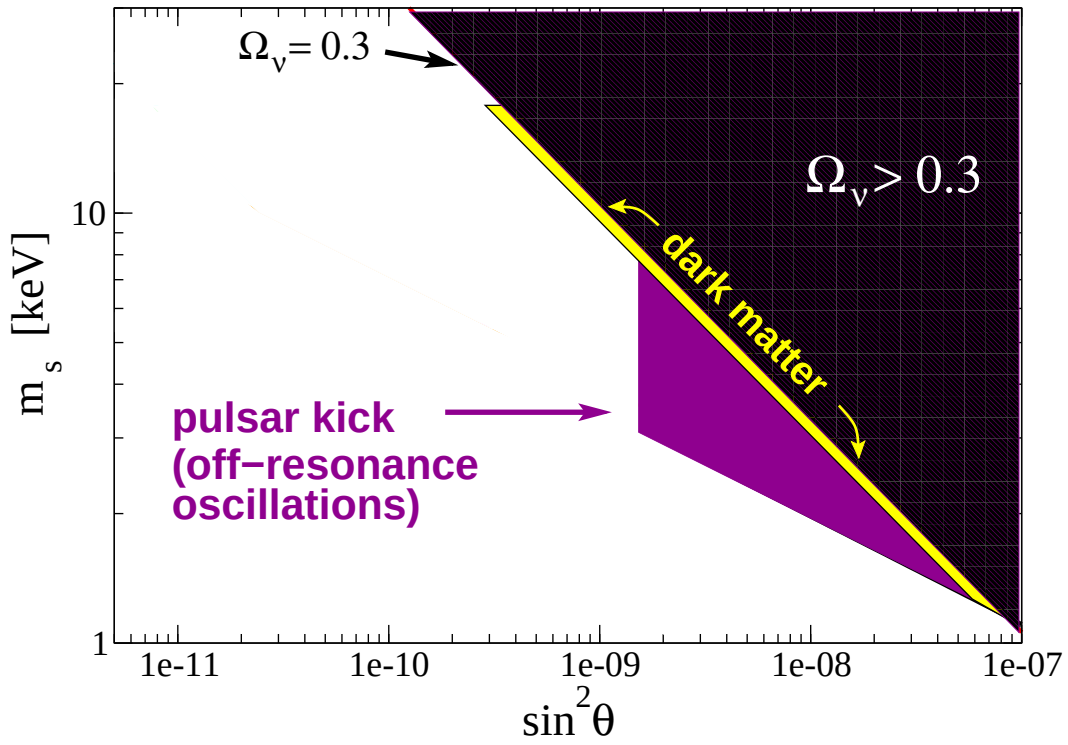
In approximate thermal equilibrium the asymmetries in scattering amplitudes do not lead to an anisotropic emission. Only the outer regions, near neutrinospheres, contribute (a negligible amount). [Vilenkin,AK, Segrè]

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

Sterile neutrinos leave the star without scattering. Hence, they give the pulsar a kick.



Allowed range of parameters (time scales, fraction of total energy emitted):



[Fuller, AK, Mocioiu, Pascoli]

Resonant active-sterile neutrino conversions in matter

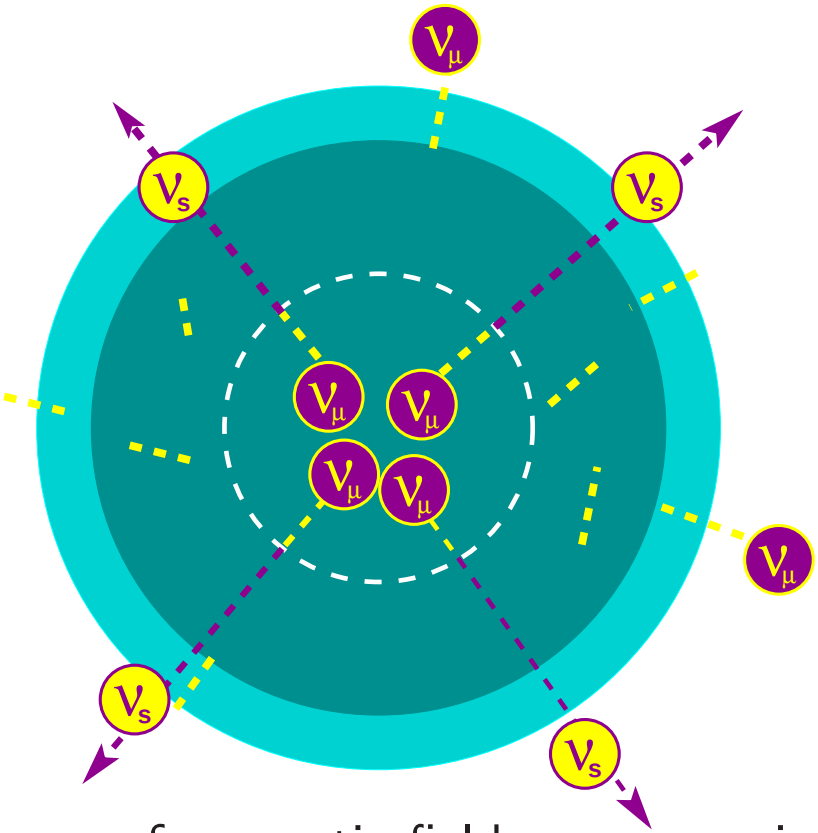
Matter potential:

$$
\begin{aligned}
V(\nu_s) &= 0 \\
V(\nu_e) &= -V(\bar{\nu}_e) = V_0\,(3\,Y_e - 1 + 4\,Y_{\nu_e}) \\
V(\nu_{\mu,\tau}) &= -V(\bar{\nu}_{\mu,\tau}) = V_0\,(Y_e - 1 + 2\,Y_{\nu_e}) \;+\; c_L^Z\,\frac{\vec{k}\cdot\vec{B}}{k}
\end{aligned}
$$

$$
c_L^Z = \frac{eG_F}{\sqrt{2}}\left(\frac{3N_e}{\pi^4}\right)^{1/3}
$$

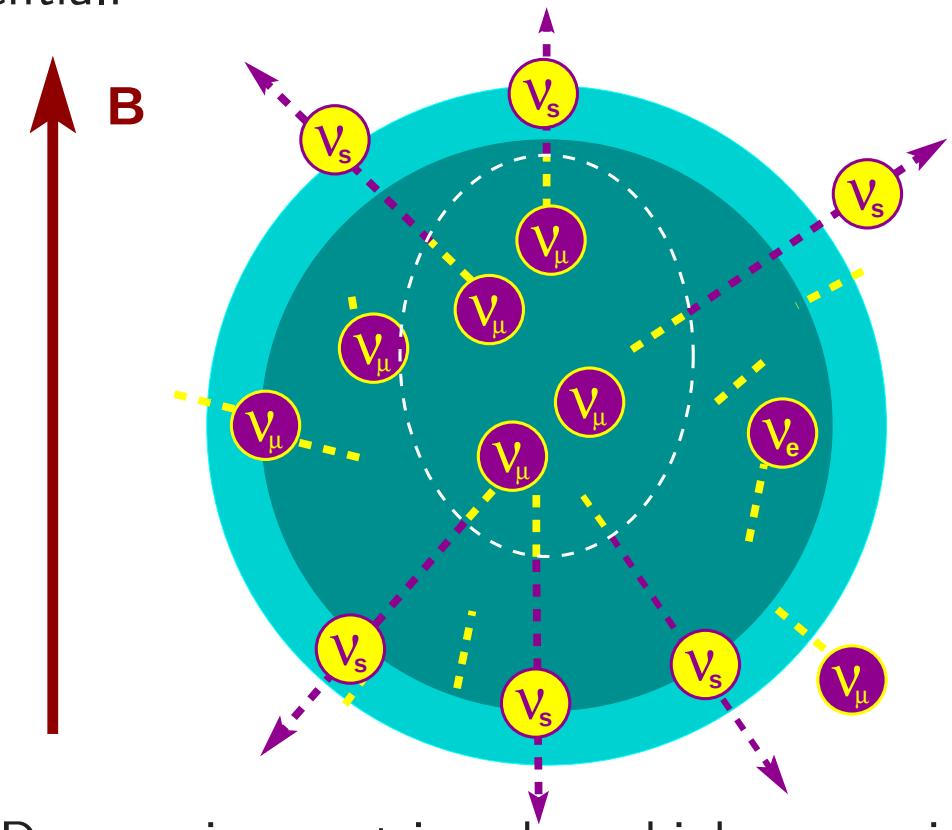
[D'Olivo, Nieves, Pal]

The magnetic field shifts the position of the resonance because of the $\frac{\vec{k}\cdot\vec{B}}{k}$ term in the potential:



In the absence of magnetic field, ν_s escape isotropically

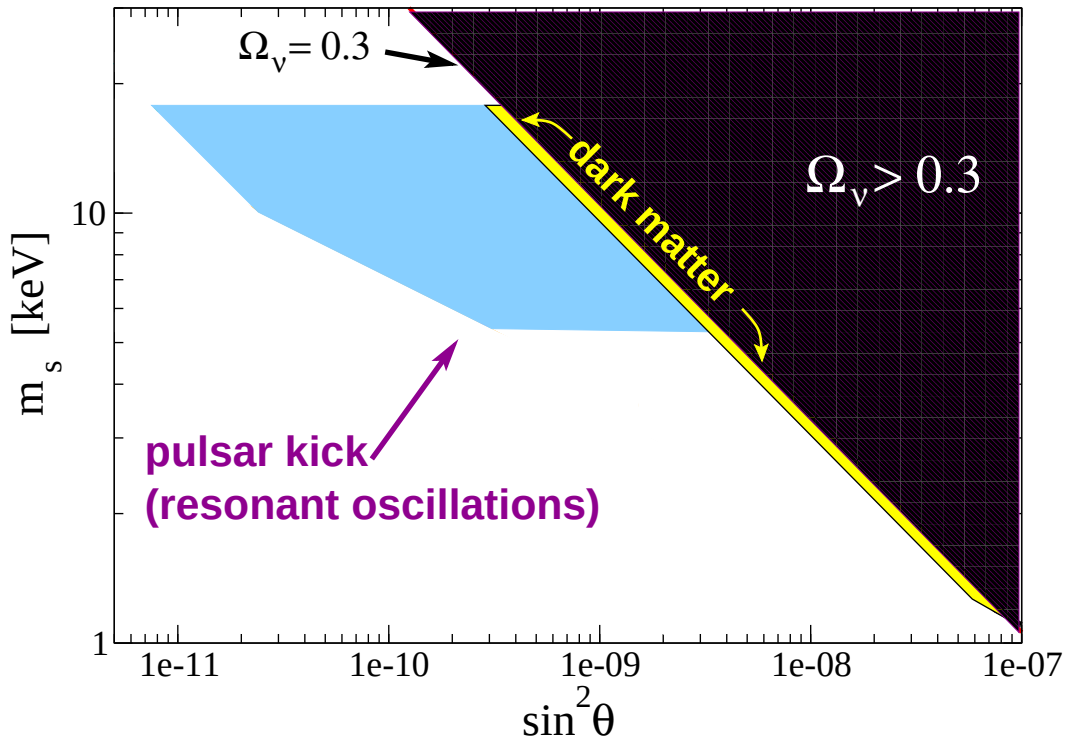
The magnetic field shifts the position of the resonance because of the $\frac{\vec{k}\cdot\vec{B}}{k}$ term in the potential:



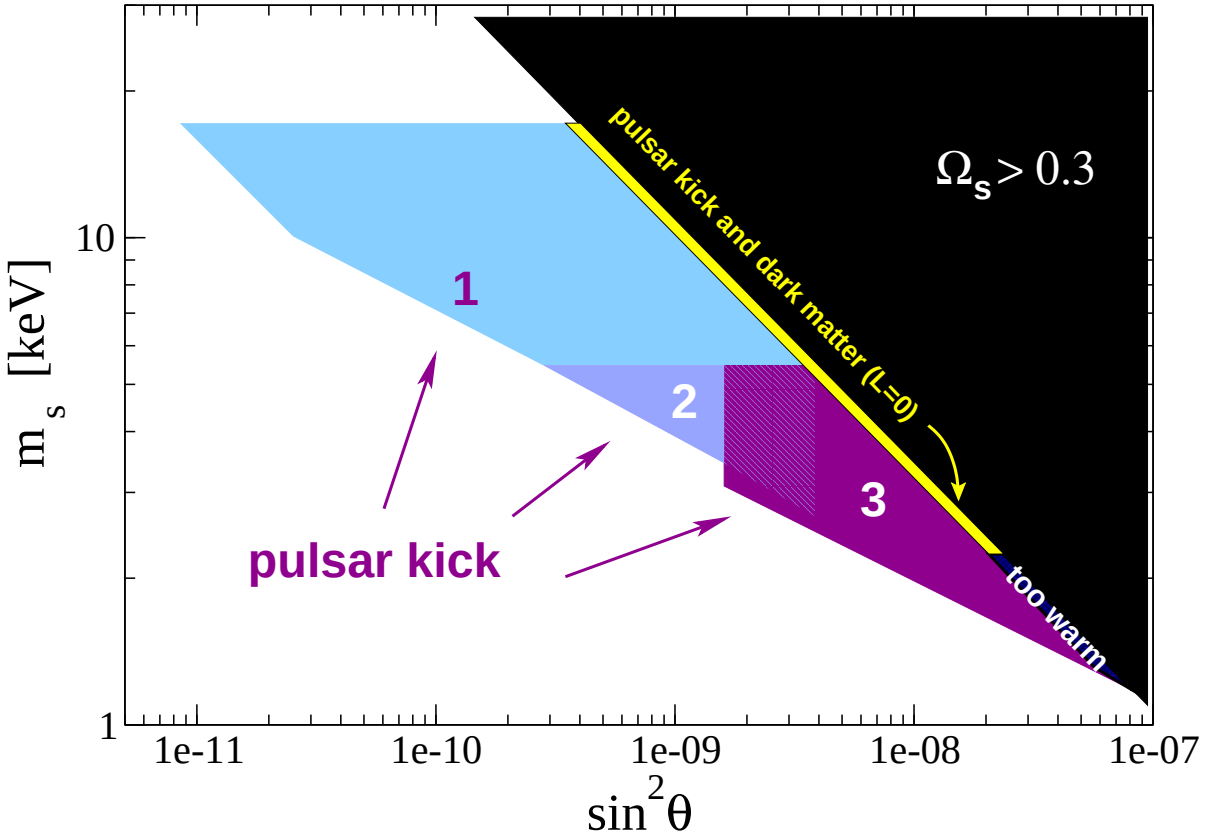
Down going neutrinos have higher energies

of the

The range of parameters (resonance, adiabaticity, weak damping):



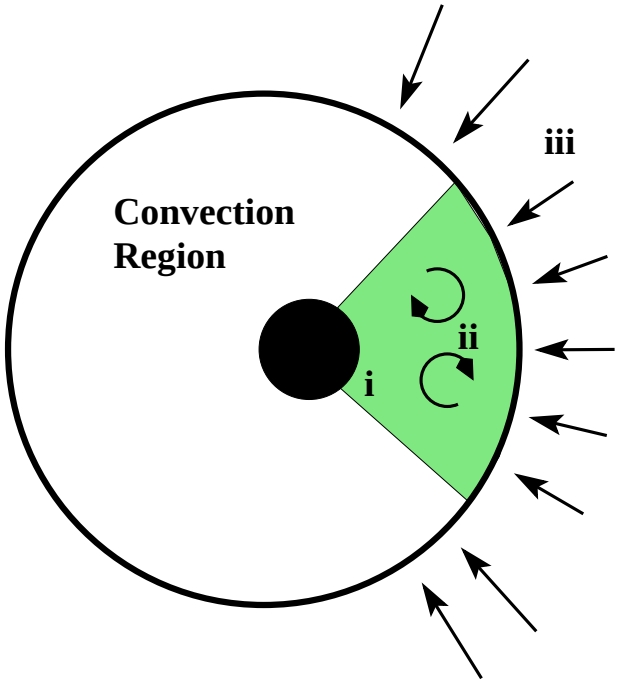
Resonance & off-resonance oscillations



[A.K., Segrè, PL **B396**, 197 (1997); Fuller, A.K.,Mocioiu,Pascoli, PR **D 68**, 103002 (2003)]

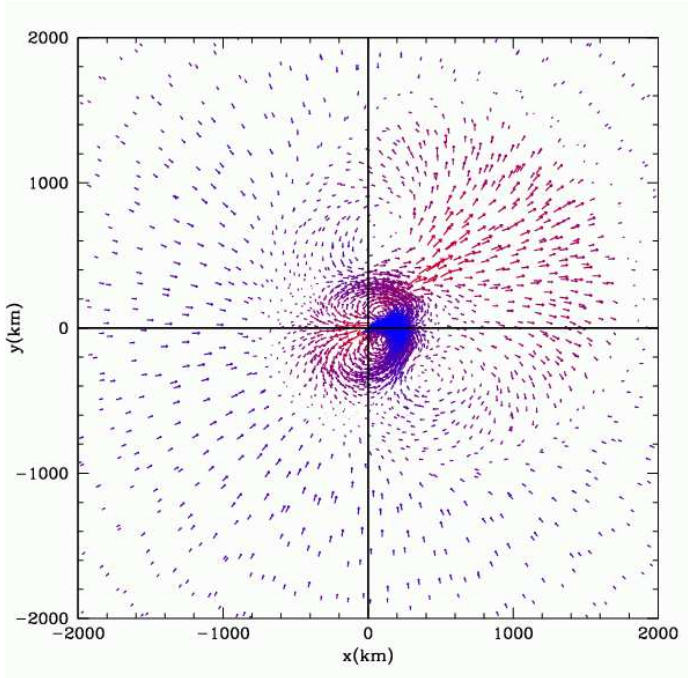
Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK, ApJ, in press; astro-ph/0512033]



Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK, ApJ, in press; astro-ph/0512033]

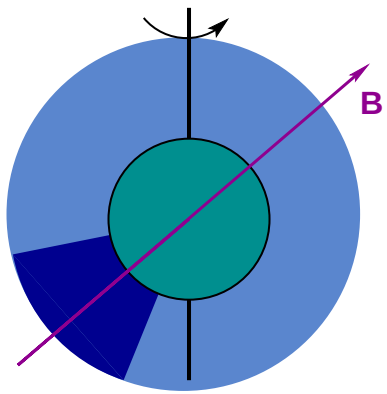


Other predictions of the pulsar kick mechanism

- Stronger supernova shock [Fryer, AK, ApJ, in press; astro-ph/0512033]

- **No $B - v$ correlation** is 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, because
  - the direction of rotation remains unchanged
  - only the z-component survives



Reionization

WMAP, three years of data, reionization redshift: $z_{\rm r} = 10.9^{+2.7}_{-2.3}$.
(This improves the one-year WMAP result, $z_{\rm r} = 17 \pm 5$.)
Observations of distant quasars: reionization must be completed by $z = 6$.
First stars can ionize gas, but can they form so early?
WMAP 3 yrs $\Rightarrow$ new challenge: can one end reionization by $z = 6$ without exceeding the optical depth $\tau_{\rm WMAP} = 0.10 \pm 0.03$?
Small halos collapse first and start ionizing gas. If reionization is to be completed by $z = 6$, small halos shine to early, too bright, and exceed $\tau_{\rm WMAP}$.

Need suppression of star formation in small halos by an order of magnitude: [Haiman, Bryan, astro-ph/0603541]

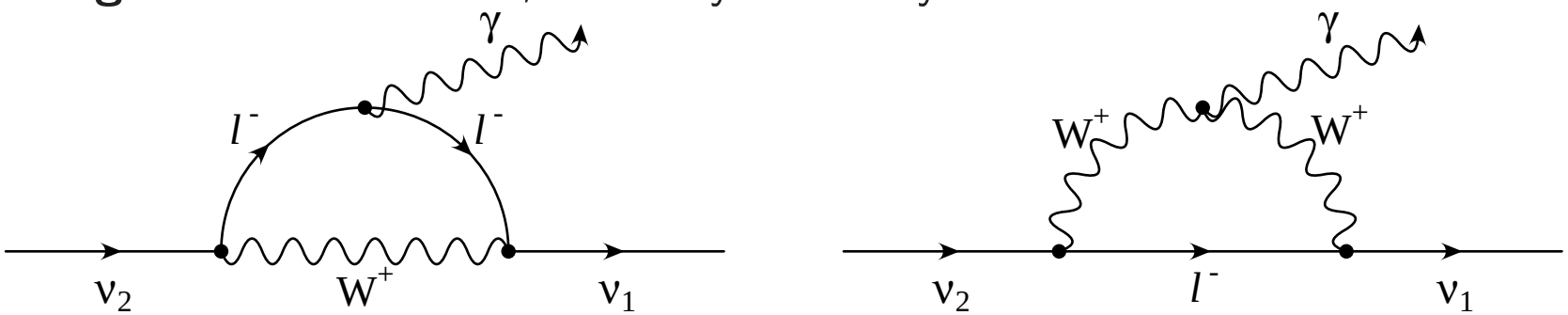
Warm dark matter (**gravitinos**) could suppress small structure and but they would also delay the star formation.

What about sterile neutrinos?

- they are warm $\Rightarrow$ small halos suppressed
- they decay and produce x-rays, and x-rays can ionize gas!

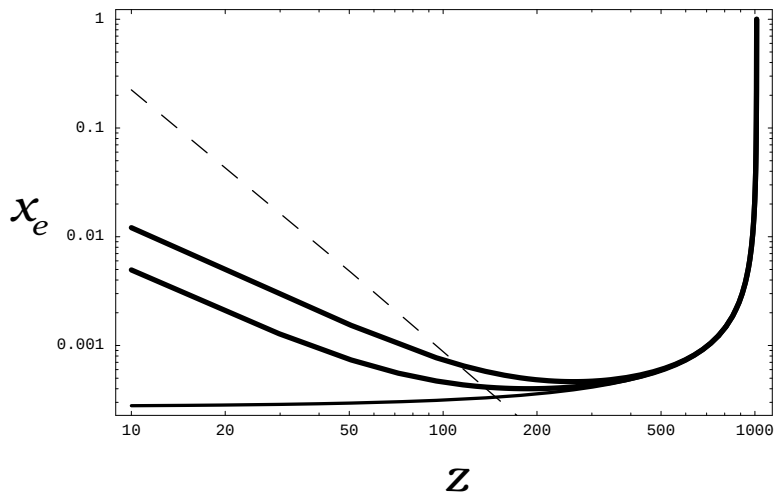
Photons from radiative decays

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. X-rays can ionize gas.

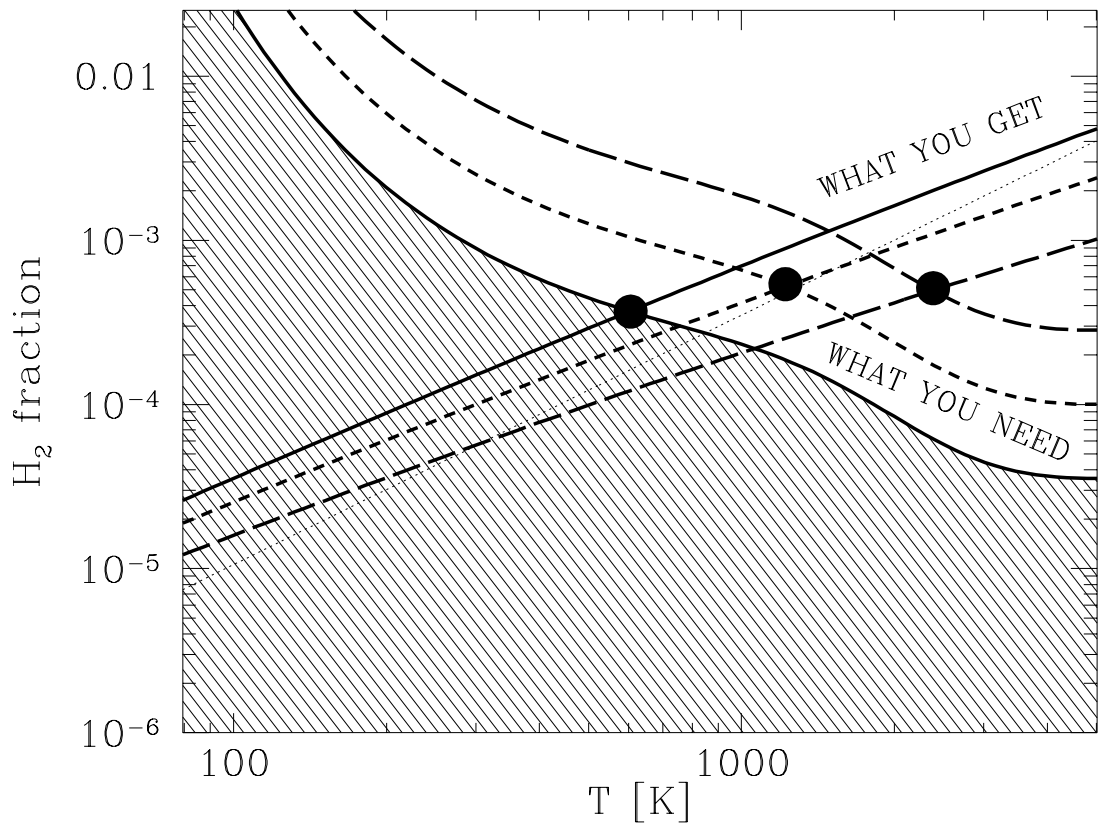
Sterile neutrino decays: an increase in ionization fraction



The ions too few to explain the WMAP results [Ferrara, Mapelli]...

...but it's a much higher fraction than in the absence of sterile neutrinos. Ionization catalyzes formation of molecular hydrogen [AK; P.L. Biermann]...

production of molecular hydrogen speeds up gas cooling, halo collapse and star formation



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

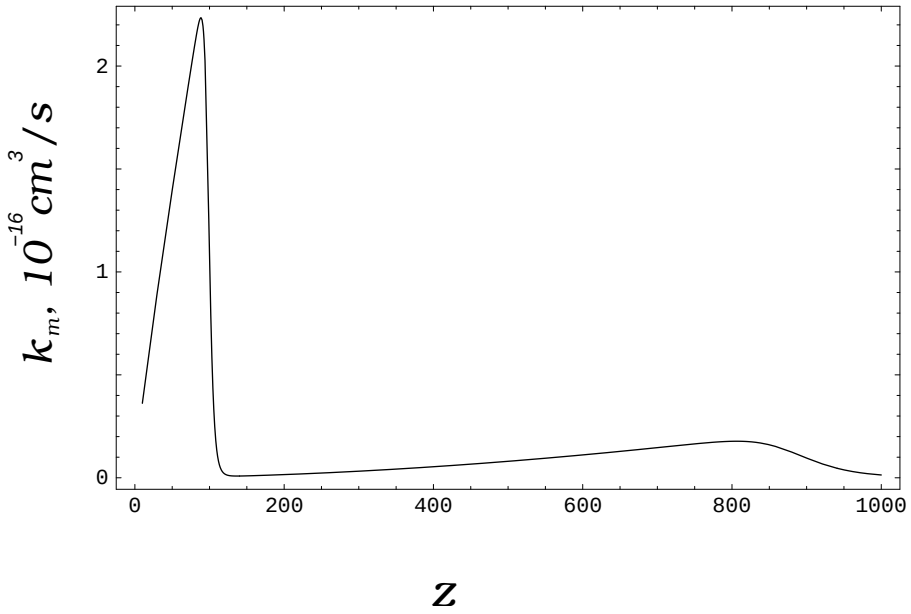
Molecular hydrogen

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

In the presence of ions the following reactions are faster:

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

H^+ catalyze the formation of molecular hydrogen!
[Biermann, AK, PRL **96**, 091301 (2006)]



The fraction of molecular hydrogen f

$$\dot{f} \approx k_m(t)\, n_H(t)\, x_e(t),$$

where k_m is the rate shown

End result: H_2 production is enhanced at $z \sim 100$

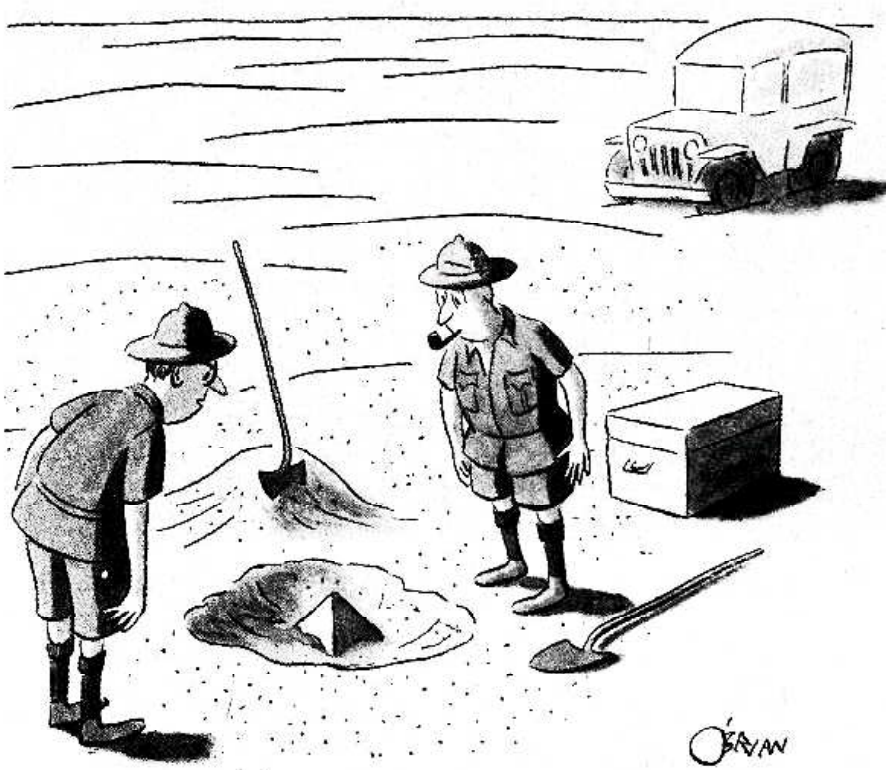
Sterile neutrino decays can precipitate the early star formation. Stars can reionize the universe by redshif $z_r = 11 \pm 3$ (WMAP) while avoiding the minihalo problem

Clues of sterile neutrinos

The sterile neutrinos can explain:

- the light neutrino masses
- dark matter
- baryon asymmetry via **leptogenesis** [Asaka, Shaposhnikov; Akhmedov et al.]
- pulsar kicks
- reionization

Clues of sterile neutrinos



This could be the greatest discovery of the century. Depending, of course, on how far down it goes.

Summary

- **Dark matter** is out there and needs to be discovered!
- NASA can make the discovery in space using x-ray and gamma-ray telescopes
- A sterile neutrino with keV mass is a viable dark matter candidate, free of CDM problems, consistent with dSphs observations.
- The same neutrino is emitted from a supernova with a sufficient anisotropy to explain the pulsar velocities
- The same neutrino can boost the production of molecular hydrogen and precipitate a rapid early star formation.
- A rather minimal extension of the Standard Model, the addition of three **sterile neutrinos** explains all the present data, including **dark matter**, the **baryon asymmetry** of the universe, the **pulsar velocities**, and **reionization**