Dark matter lighting up the stars

a keV sterile neutrino

- Relic keV sterile neutrinos: the astrophysical hints
  - can be dark matter
  - can explain the pulsar kicks
  - eliminates problems with CDM, agrees with VLT observations (warm is hot!)
  - three sterile neutrinos: dark matter + baryogenesis (by neutrino oscillations)
  - Lighting up the first stars: early star formation and reionization by keV sterile neutrinos [Biermann,Kusenko, PRL, in press]
- Implications for particle physics

Dark matter: what is it?

Can take guesses based on...

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

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 with a small mixing to active neutrinos

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

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

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

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

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

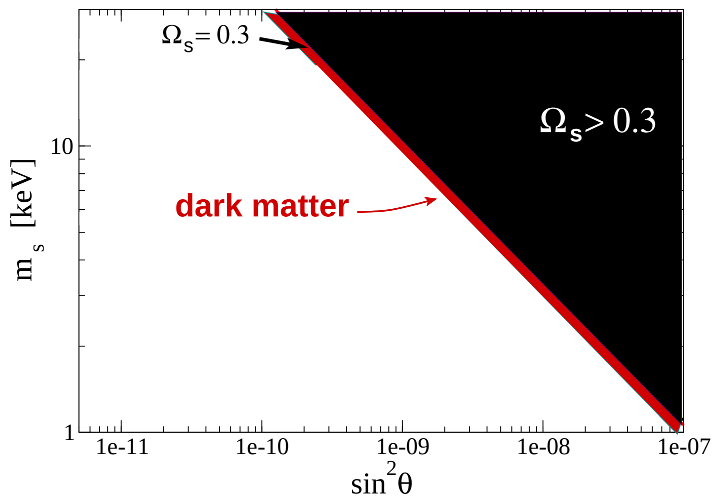
$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V(T))^2}, \quad (3)$$

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

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

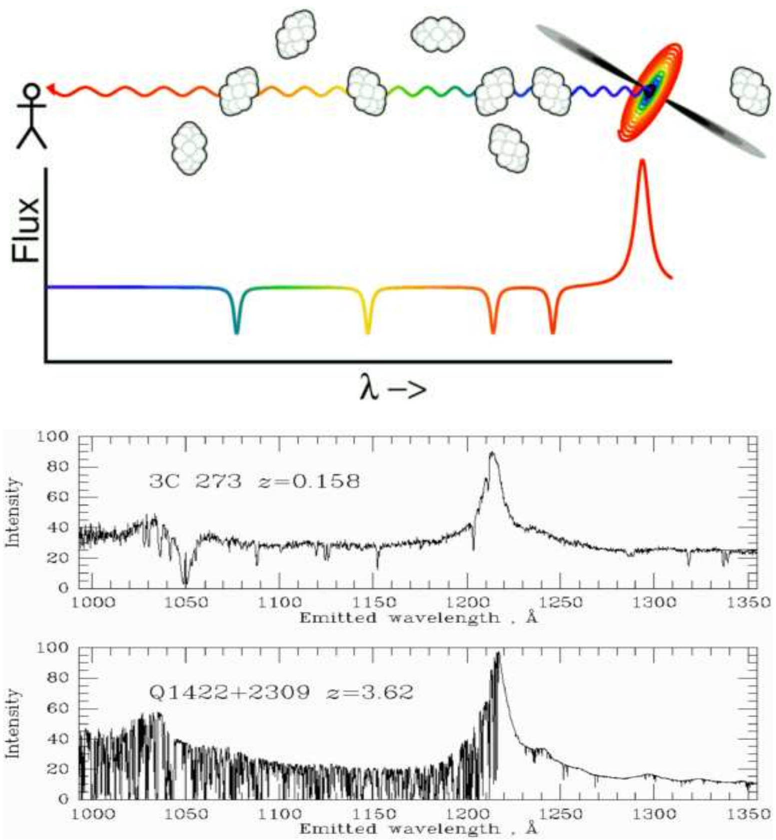


The resulting density of relic sterile neutrinos in conventional cosmology, in the absence of a large lepton asymmetry:

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

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

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



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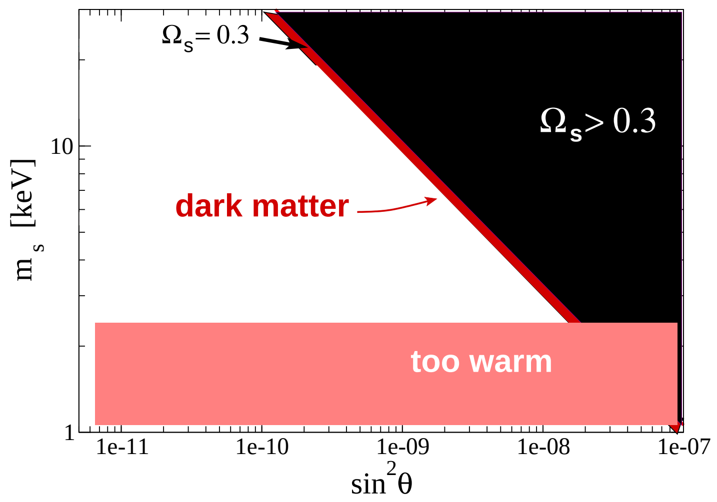
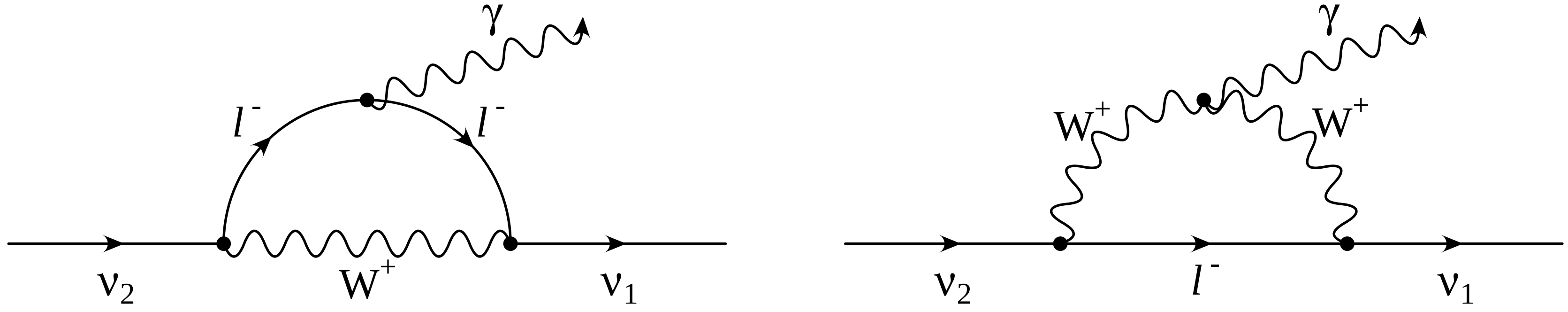
Lyman-α forest clouds show significant structure on small scales. Dark matter must be cold enough to preserve this structure.



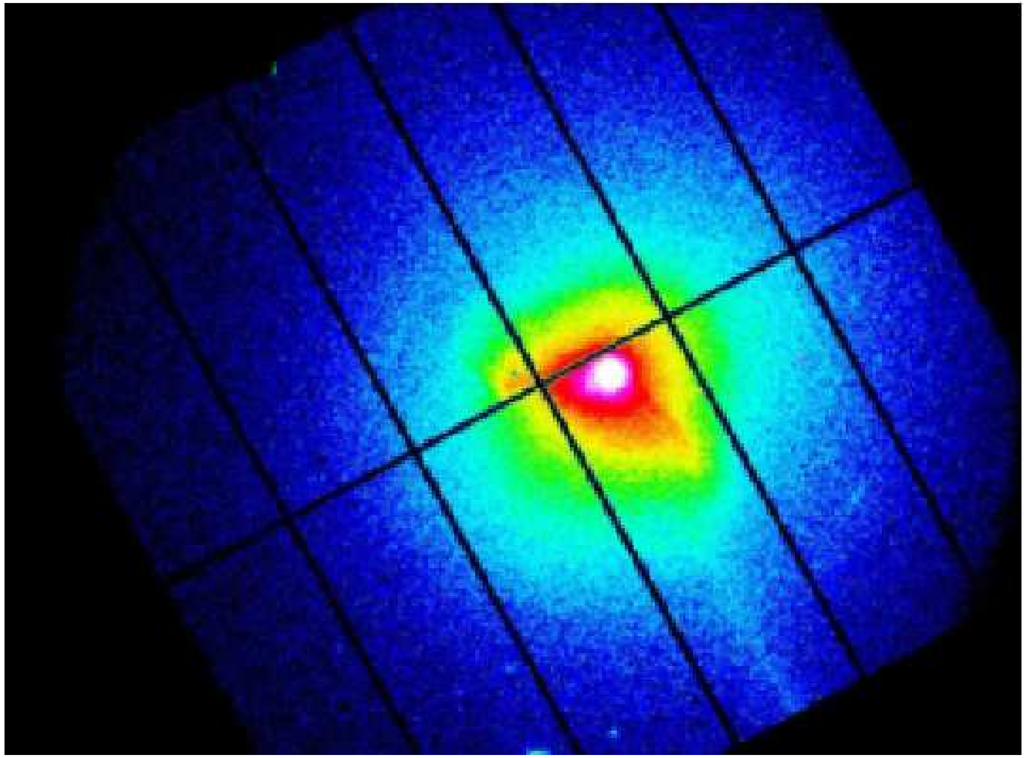
Radiative decay

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



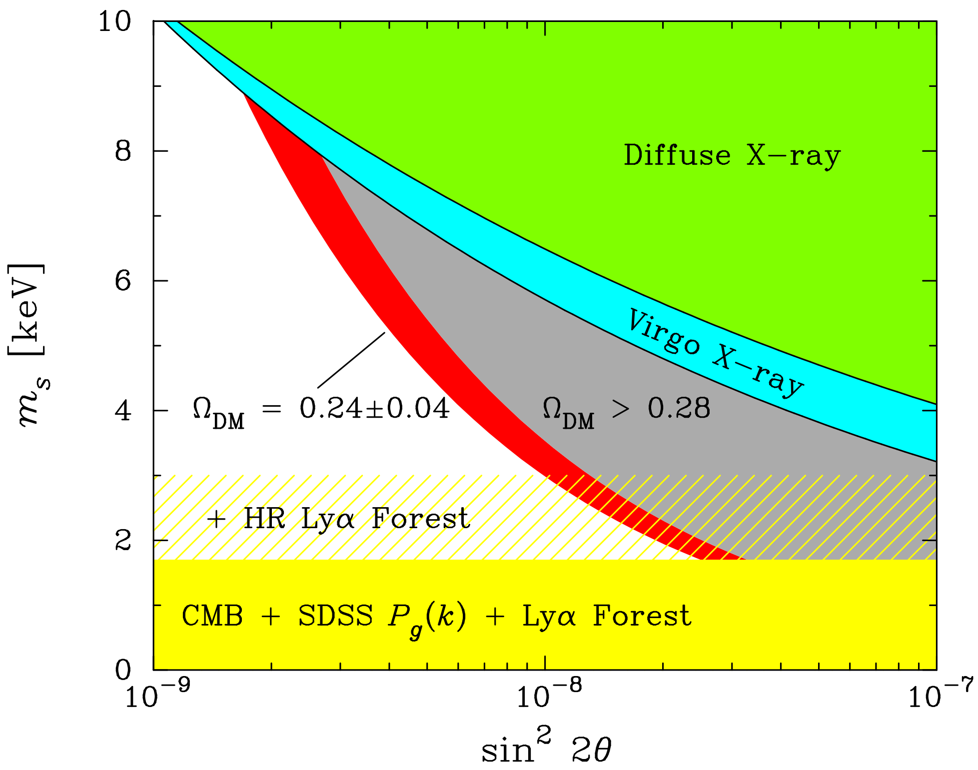
Photons have energies $m/2$: X-rays. Large lumps of dark matter emit some X-rays.

X-ray observations



Virgo cluster image from XMM-Newton

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



Cold or warm dark matter?

CDM works well, but...

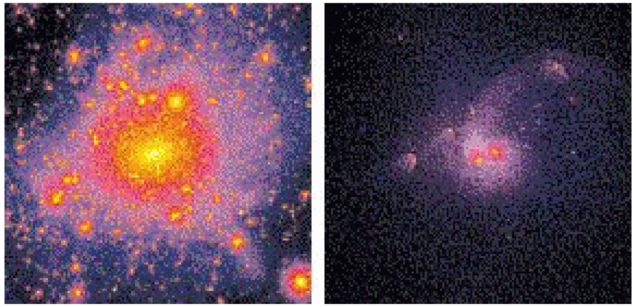
Potential problems with cold dark matter:

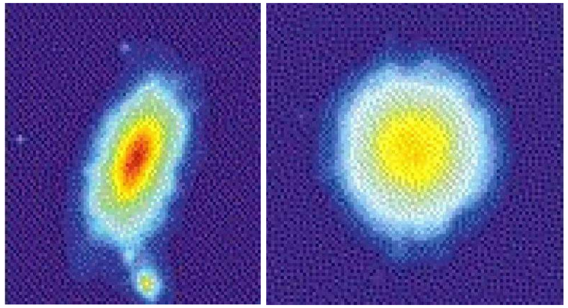
- too much structure on small scales: the self-similar spectrum predicts $\sim \mathbf{10}$ small "satellite galaxies" per galaxy.

- core overdensity, cuspy density profile may be in conflict with observations

  [B. Moore, *et al.*, Ap. J. **524**, L19 (1999)]

Warm dark matter $(m \approx 1 - 5\ \mathrm{keV})$ can offer a solution

the satellites:  [Moore]

the cusp:  [Moore]

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.]

Emission of sterile neutrinos from a supernova

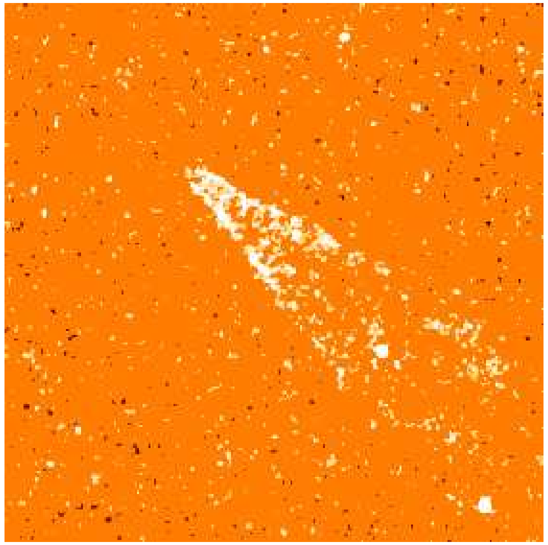
- Sterile neutrino emission from a supernova is anisotropic
- Sterile neutrinos with masses and mixing angles consistent with dark matter can explain the pulsar velocities

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

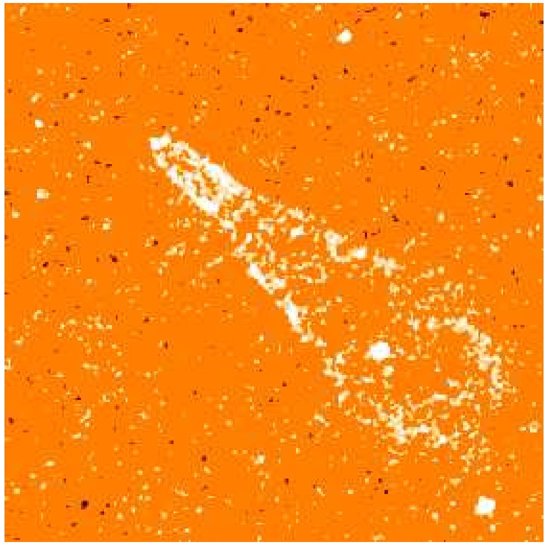
The pulsar velocities.

Pulsars have large velocities, $\langle v \rangle \approx \mathbf{250 - 450\ km/s}$.
[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

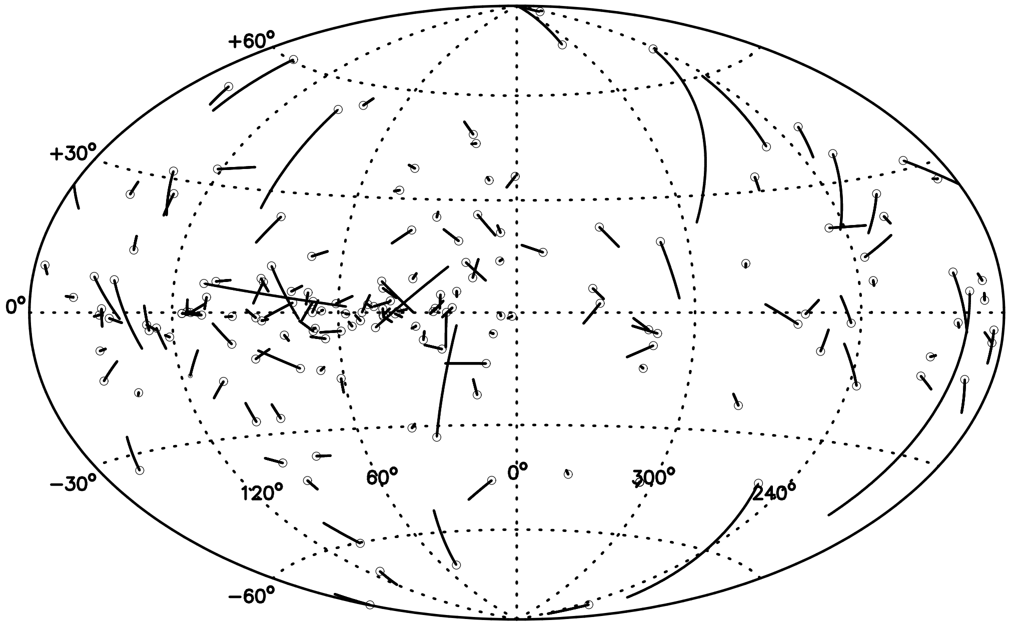


HST, December 1994



HST, December 2001

Map of pulsar velocities



Proposed explanations:

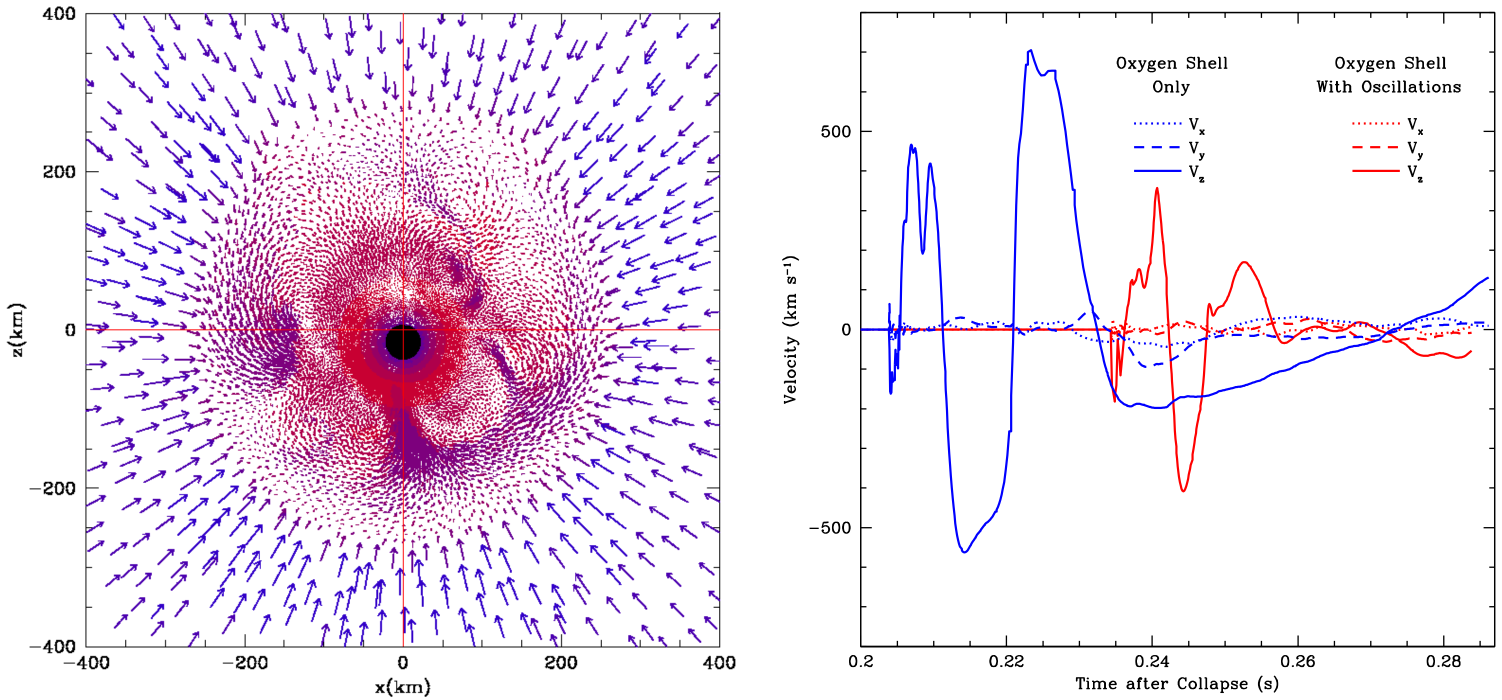
- asymmetric collapse [Shklovskii] (small kick)

- 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)

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:

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

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*

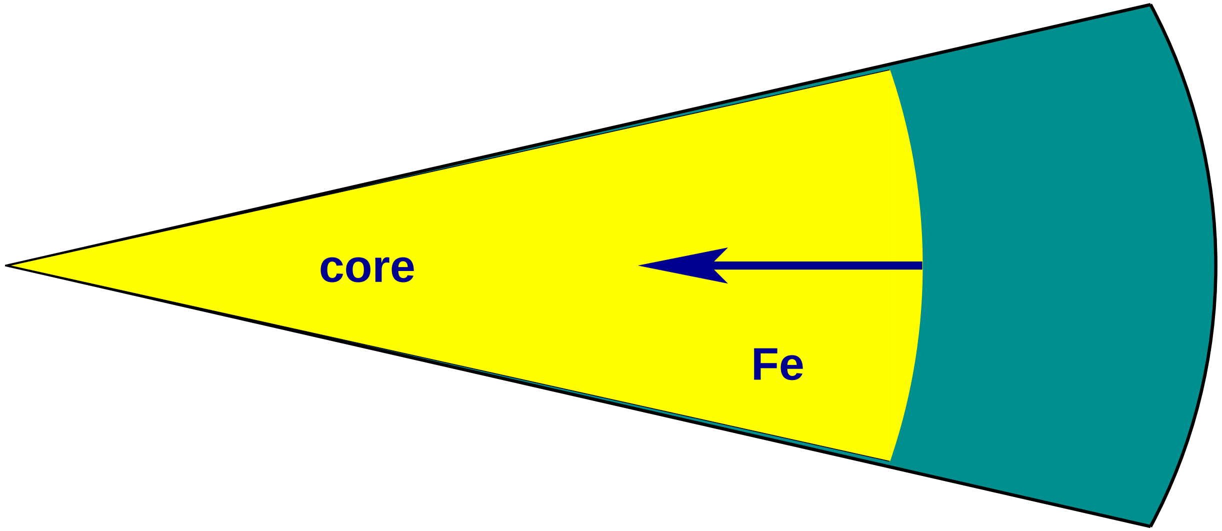
$\Rightarrow$ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16}$ G.

$\Rightarrow$ **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.

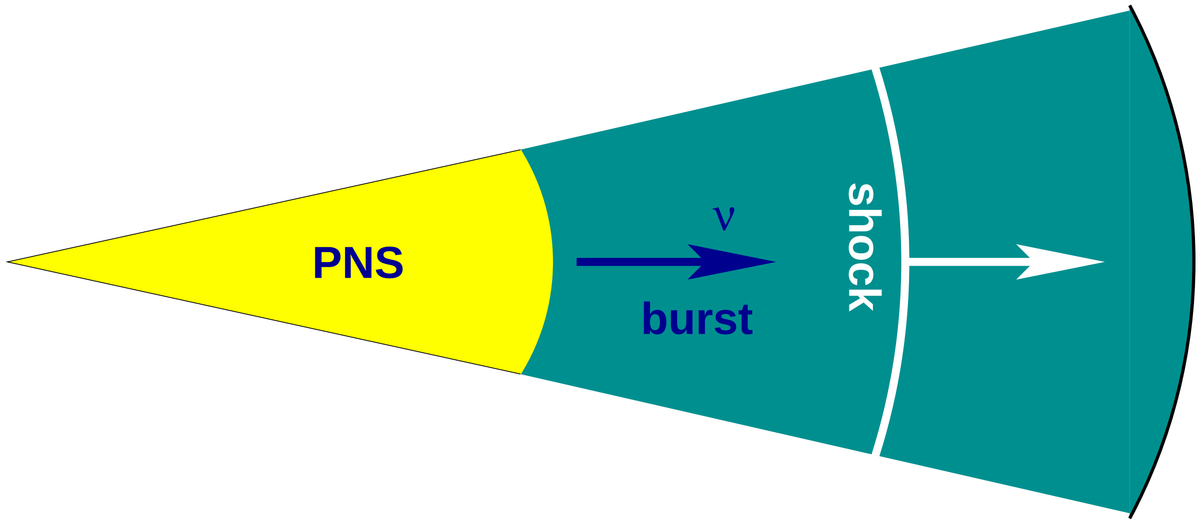
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

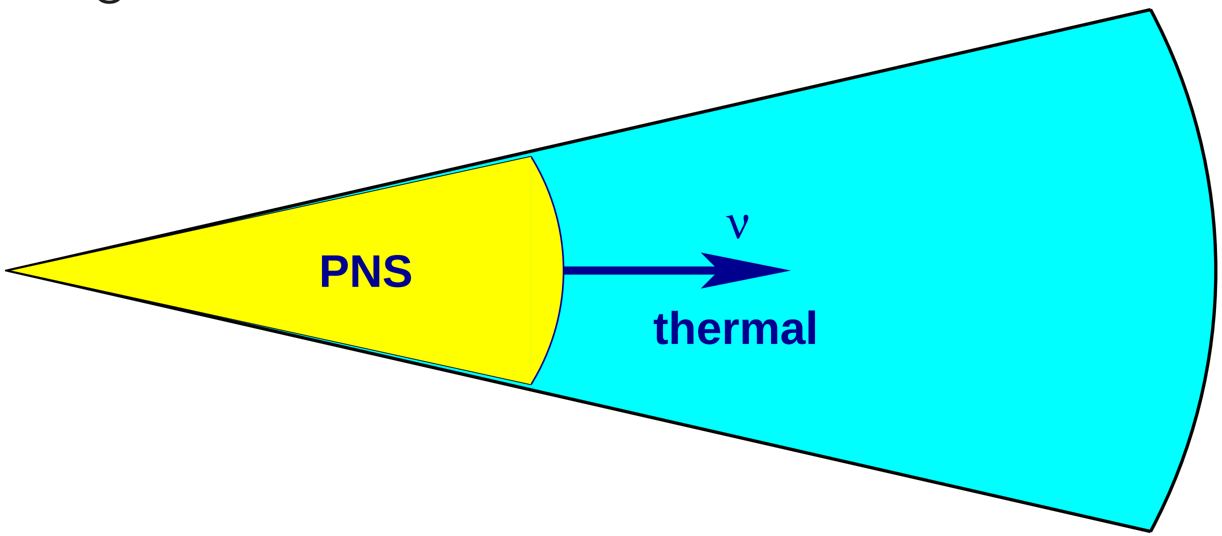
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



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.

Resonant active-sterile neutrino conversions in matter

Matter potential:

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

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

The resonance condition is

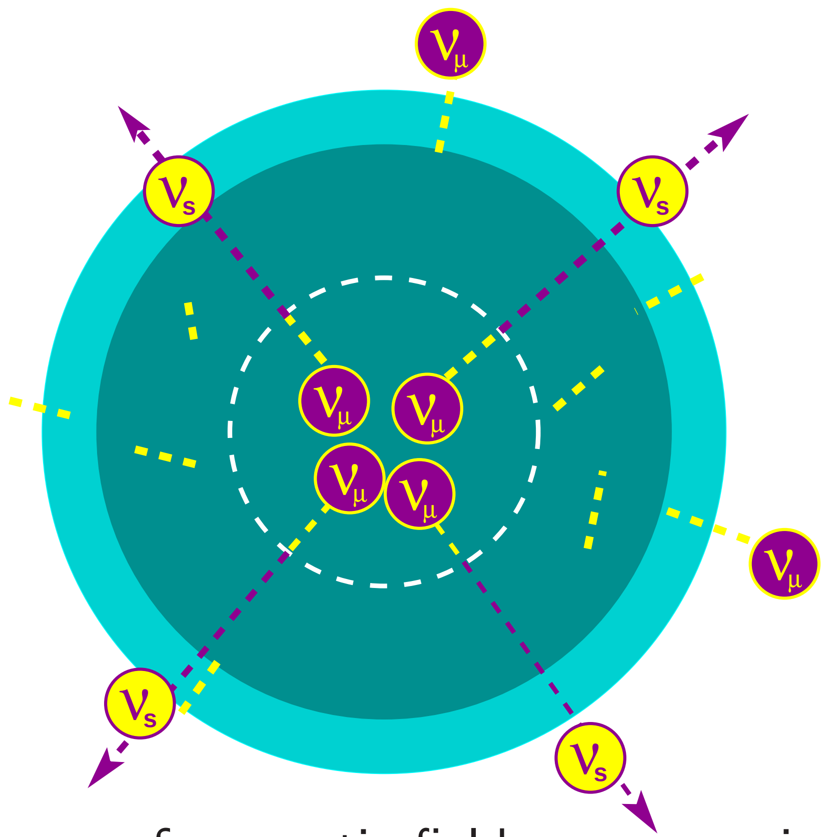
$$\frac{m_i^2}{2k} \cos 2\theta_{ij} + V(\nu_i) = \frac{m_j^2}{2k} \cos 2\theta_{ij} + V(\nu_j) \tag{5}$$

The resonance is affected by the magnetic field and occurs at different density depending on $\vec{k} \cdot \vec{B}$, that is depending on direction.

As a result, the active neutrinos convert to sterile neutrinos at different depths on different sides of the start.

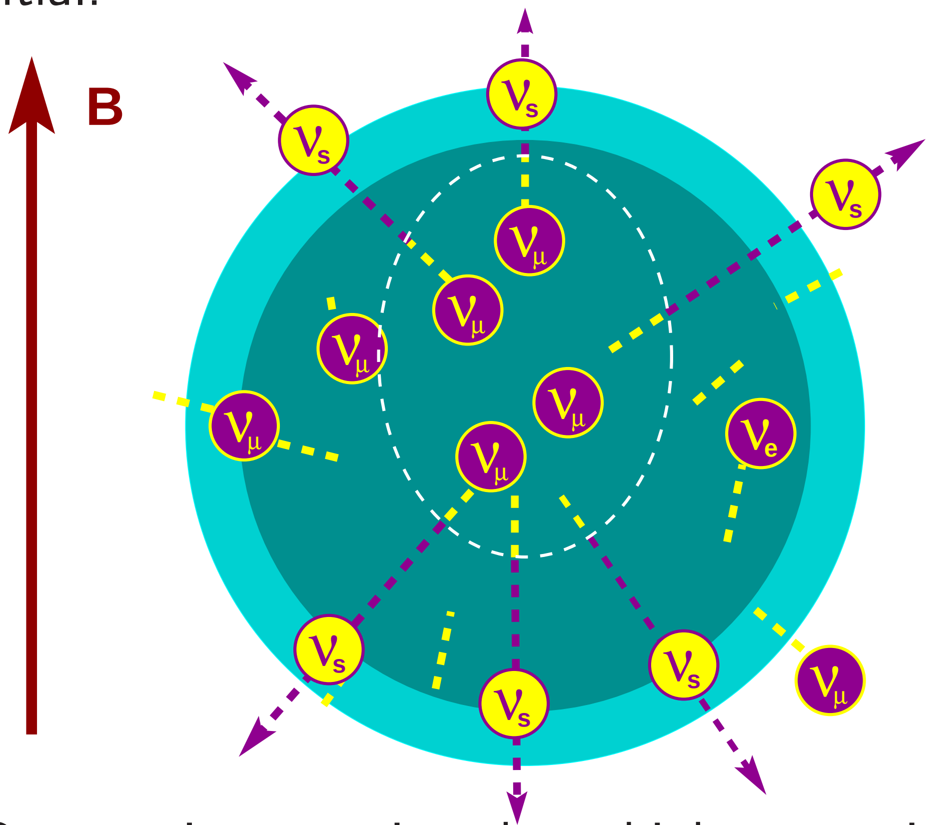
Temperature is a function of r. The energy of an escaping sterile neutrino depends on the temperature of at the point it was produced.

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 asymmetry in the outgoing momentum

$$\frac{\Delta k}{k} \sim 0.01 \left(\frac{B}{10^{15}\mathrm{G}} \right)$$

[AK, Segrè; Barkovich *et al.*]

The core density $\rho \sim 10^{14}$ g/cm^3 determines the $\Delta m^2 \sim (3\,\mathrm{keV})^2$

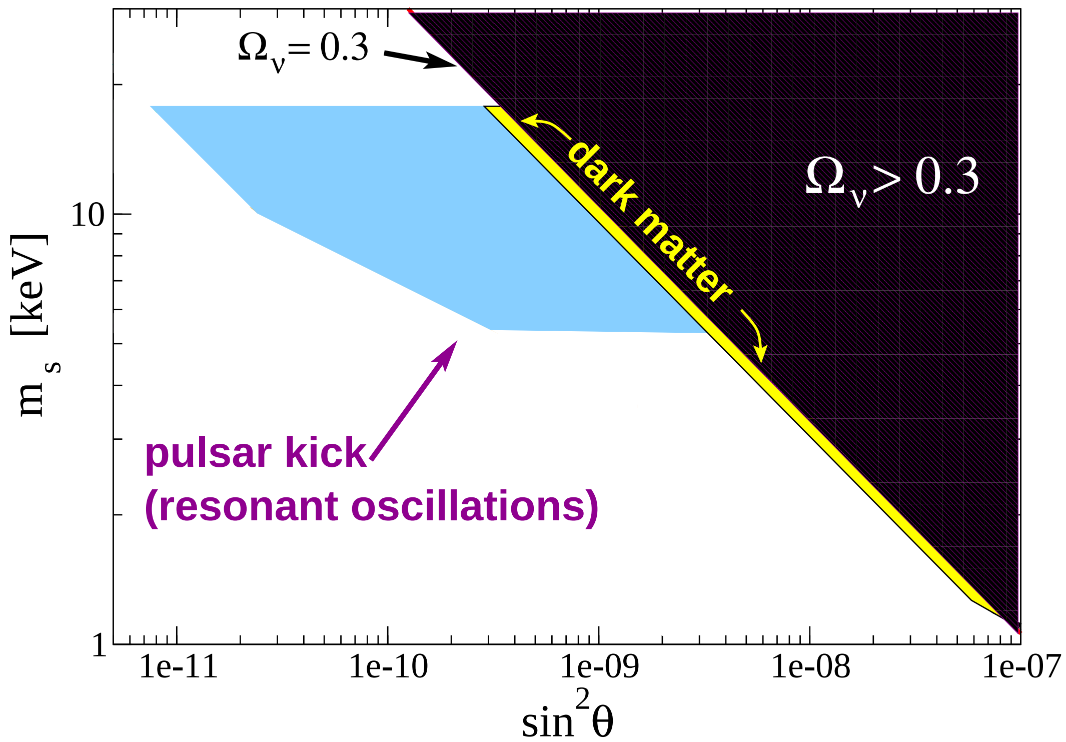
Adiabaticity: the oscillation length

$$\lambda_{\mathrm{osc}} \approx \left(\frac{1}{2\pi} \frac{\Delta m^2}{2k} \sin 2\theta \right)^{-1} \sim \frac{1\,\mathrm{mm}}{\sin 2\theta}.$$

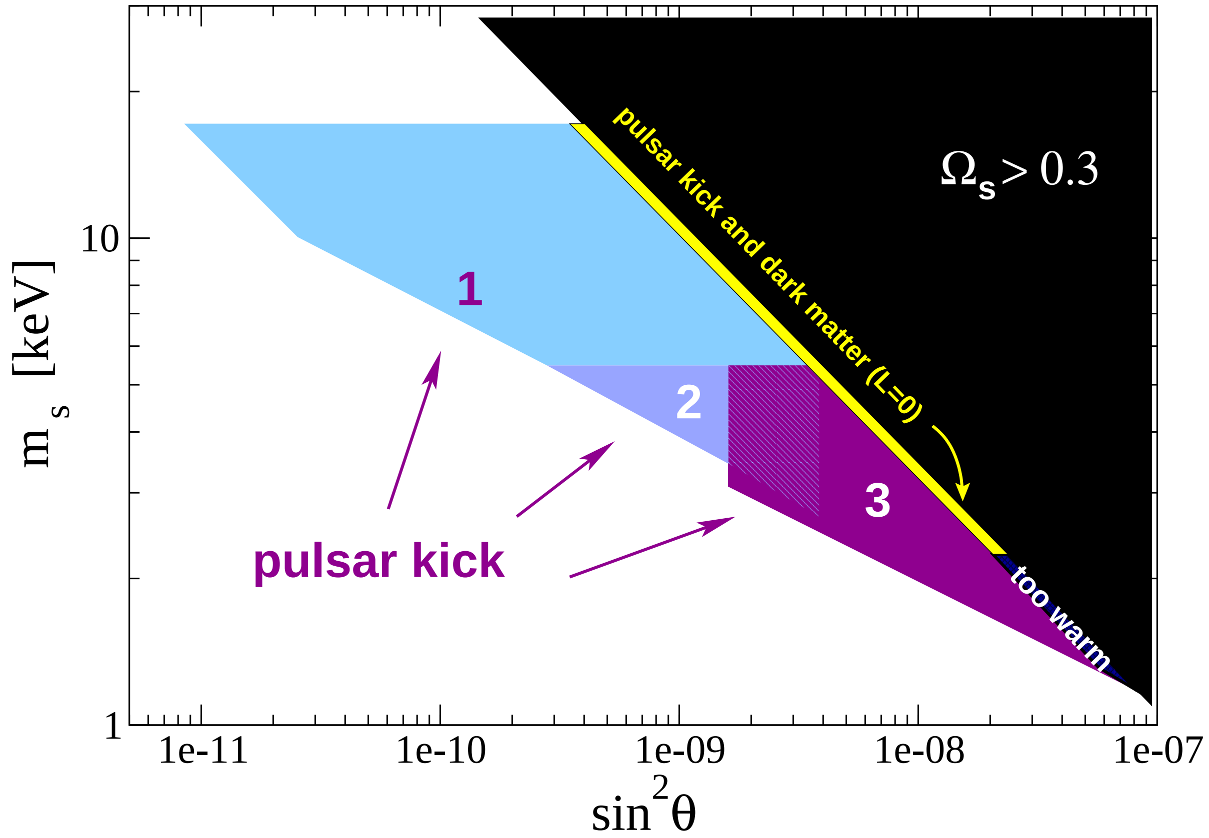
must be smaller than (1) the scale height of density (2) the mean free path of neutrinos. $\Rightarrow$

$$\sin^2\theta \gtrsim 10^{-10}$$

The range of parameters:



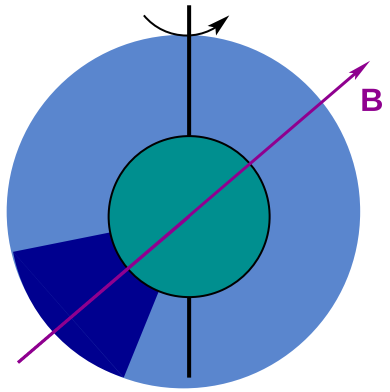
Resonance (MSW) & off-resonance oscillations



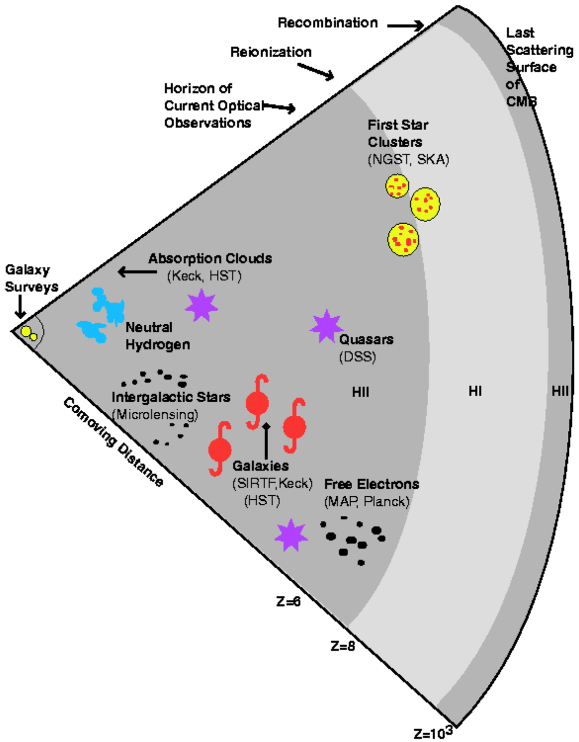
[A.K., Segrè, PL **B396**, 197 (1997); Fuller, A.K.,Mocioiu,Pascoli, PR **D 68**, 103002 (2003)]

Other predictions of the pulsar kick mechanism

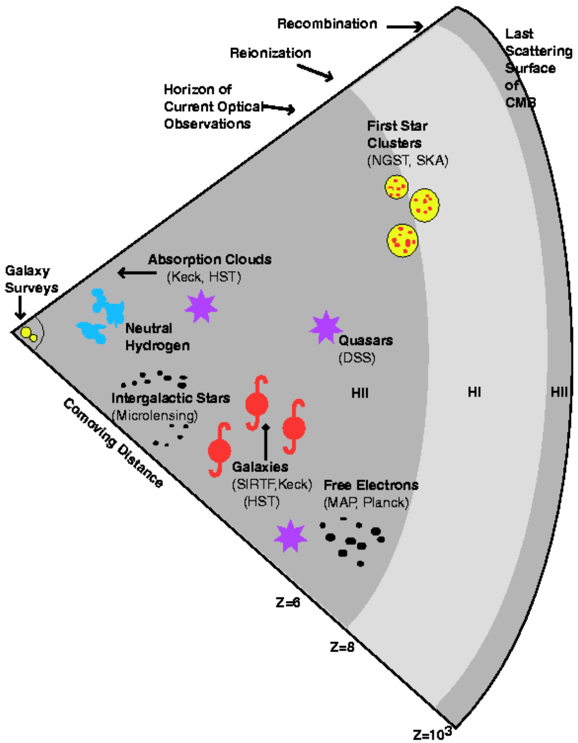
- Stronger supernova shock [Fryer, AK, ApJ, in press; astro-ph/0512033]
- **No $B - v$ correlation** is expected because
  - the magnetic field *inside* a hot neutron star during the *first ten seconds* is very different from the surface magnetic field of a cold pulsar
  - rotation washes out the x, y components
- **Directional $\vec{\Omega} - \vec{v}$ correlation** is expected, because
  - the direction of rotation remains unchanged
  - only the z-component survives

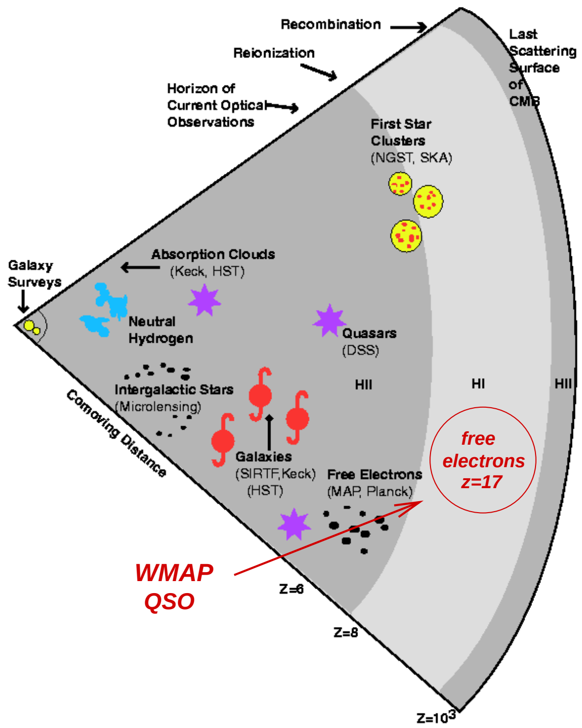


Reionization



Reionization





Reionization

Observations of distant quasars, WMAP: IGM was reionized at red shift $z_r = 17 \pm 5$.
First stars can ionize gas, but it is hard to make stars so early.
Warm dark matter (**gravitinos**) could make matters **worse**:
suppress small structure.

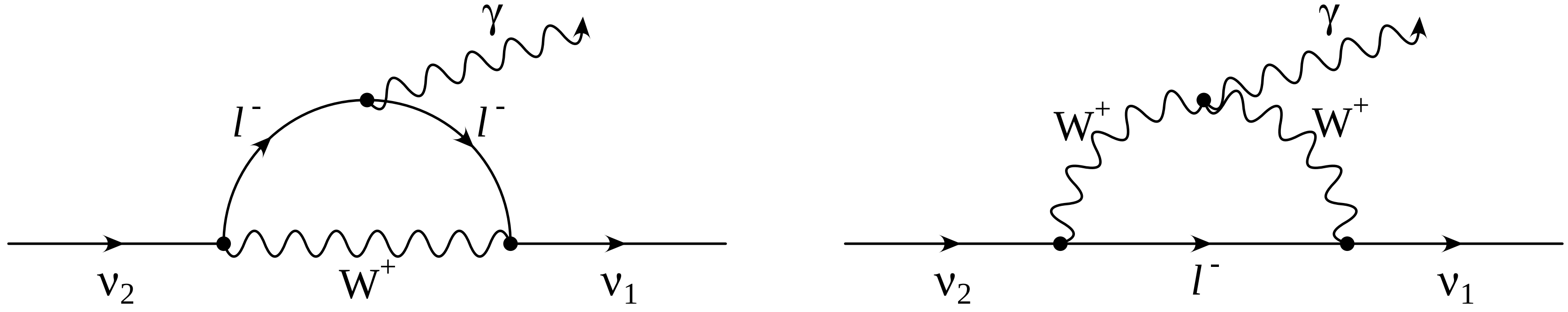
What about sterile neutrinos?

- they are warm, but

- they decay and produce x-rays, and x-rays can ionize gas!

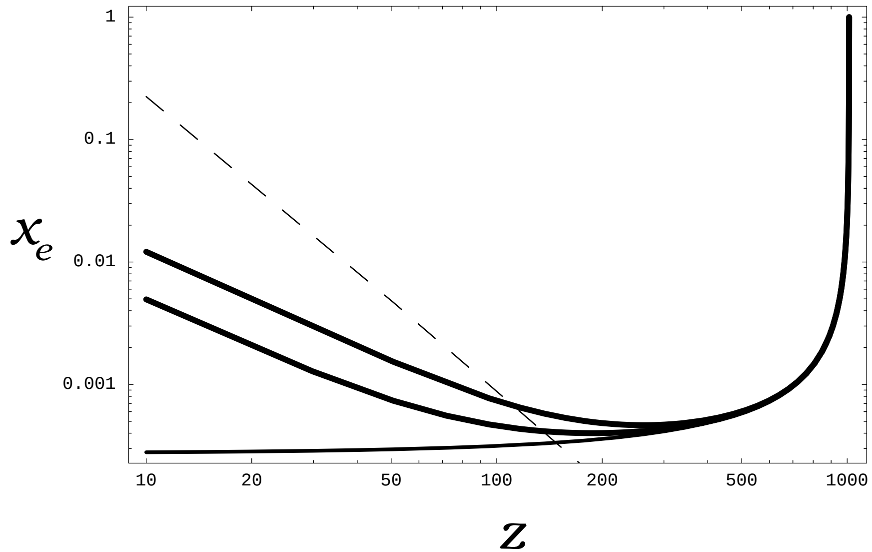
Photons from radiative decays

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.

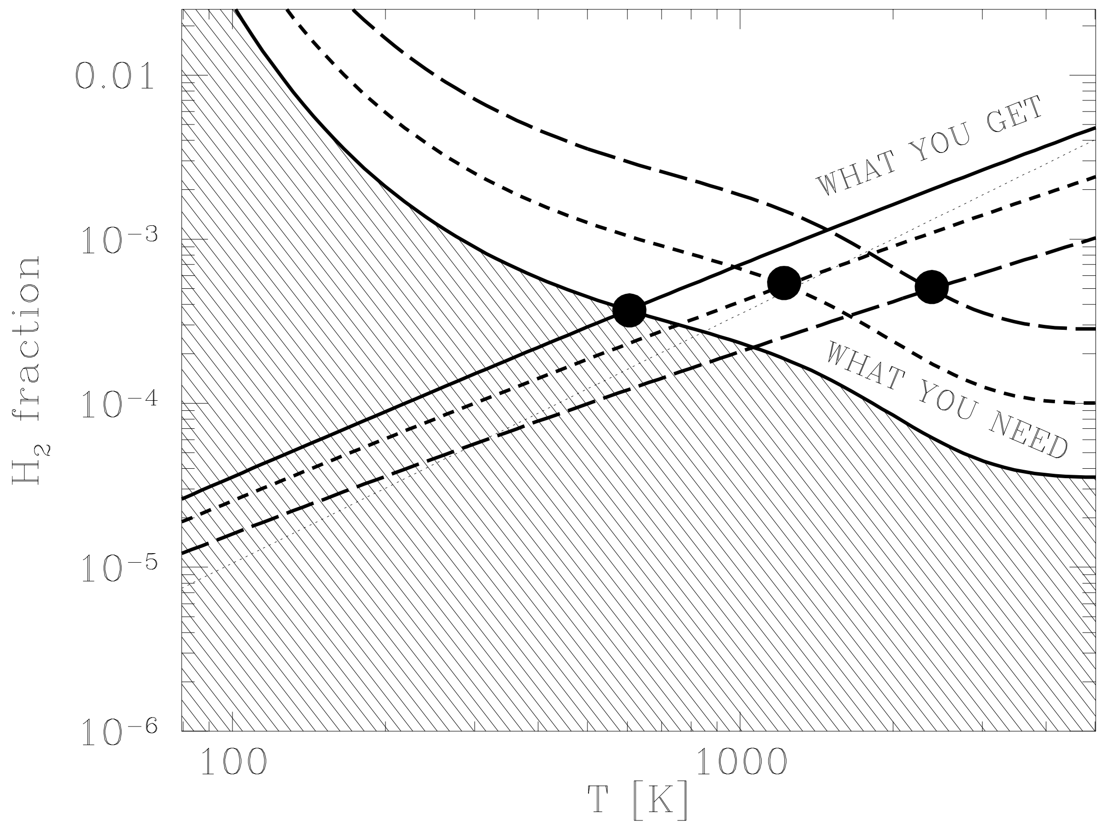
Sterile neutrino decays: a discouraging estimate



The fraction of ions is too small to explain the WMAP results...

...but it's a much higher fraction than in the absence of sterile neutrinos. Ionization catalyzes formation of molecular hydrogen

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



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

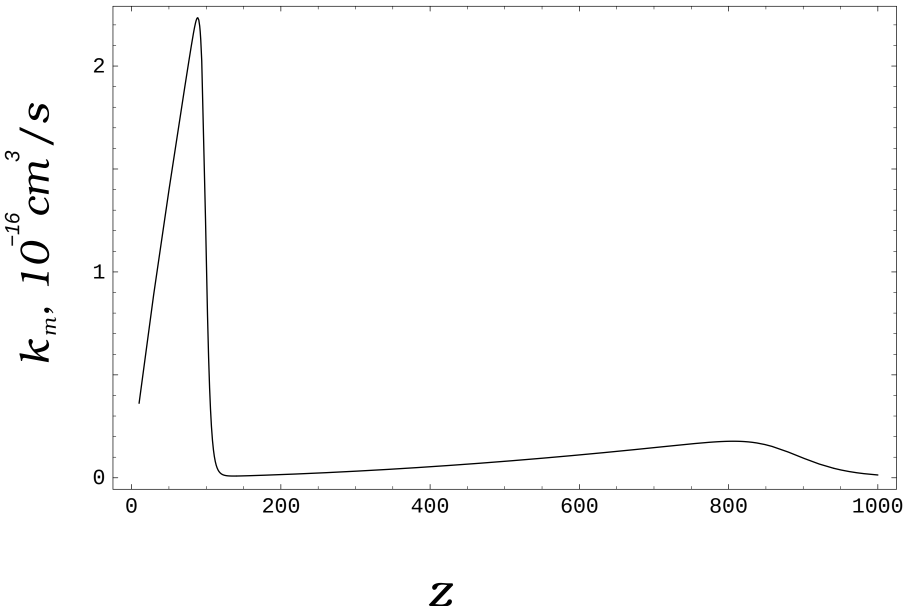
Molecular hydrogen

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

In the presence of ions the following reactions are faster:

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

H^+ catalyze the formation of molecular hydrogen!



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 precipitate the early star formation. Stars can reionize the universe by redshif $z_r = 17 \pm 5$ (WMAP)

Theoretical point of view

The following Lagrangian describes:

- the Standard Model physics
- dark matter
- baryon asymmetry

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

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

Leptogenesis

Consider the following lagrangian:

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

where H is the Higgs boson and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublets.
The lightest of sterile neutrinos, $\nu_{s,1}$ is the **keV** dark matter.
The other two sterile neutrinos, $\nu_{s,2}$ and $\nu_{s,3}$ are heavier.
This lagrangian offers a simple scenario for leptogenesis.

A viable scenario for leptogenesis:

- At least one of the $\boldsymbol{\nu_{s,a}}$, for example, $\boldsymbol{\nu_{s,3}}$ has a large enough Yukawa coupling to be in equilibrium at temperatures $T > 100$ GeV. This species is produced with zero asymmetry: $\boldsymbol{L_3 = 0}$.

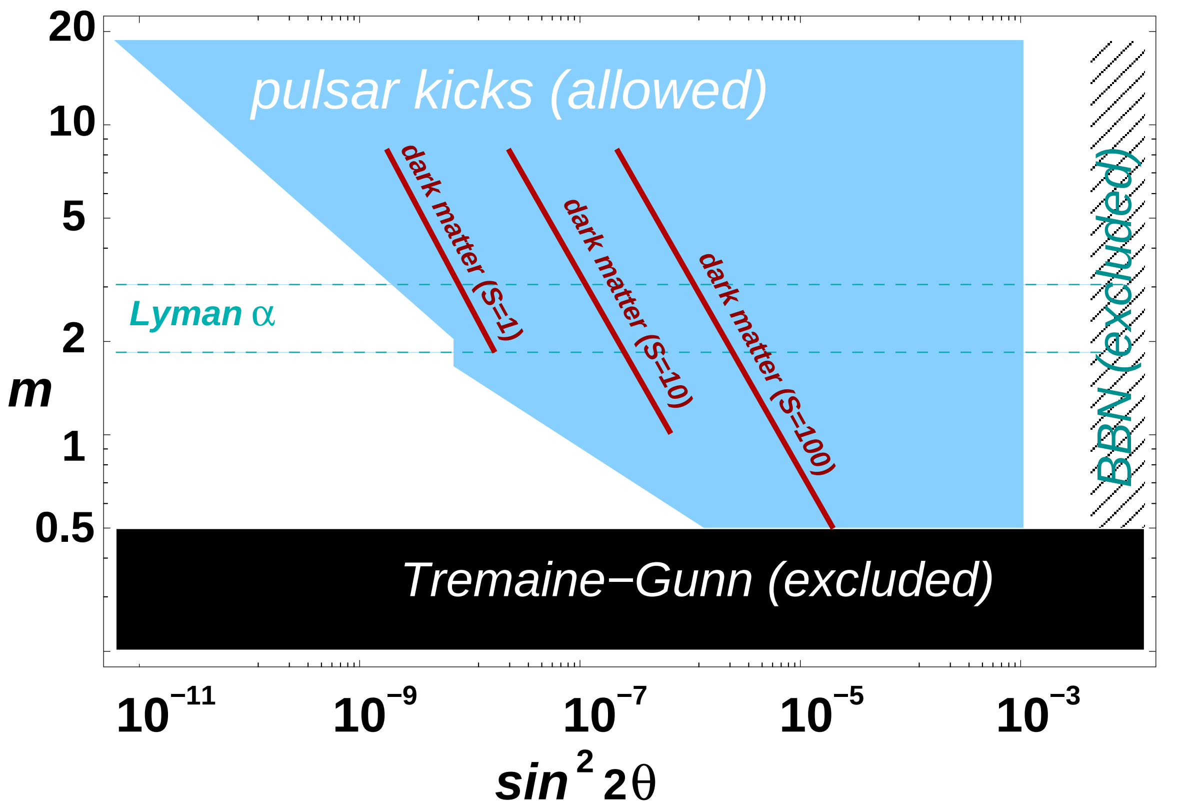
- CP violation is present in the mixing matrix of the singlets. Neutrino oscillations with CP violation produce a population of $\nu_{s,a}$ with

$$\boldsymbol{L_1 \neq 0,\ L_2 \neq 0,\ L_3 \neq 0,\ \text{but}\ \ L_{\rm tot} = L_1 + L_2 + L_3 = 0}$$

- The dark-matter neutrino, $\boldsymbol{\nu_{s,1}}$ is out of equilibrium at all times. Sphalerons convert $\boldsymbol{L_2 + L_3 \neq 0}$ into the baryon asymmetry.

[Akhmedov, Rubakov, Smirnov; Asaka, Shaposhnikov]

Heavy sterile neutrinos can dilute and cool down DM



Entropy increase by factor S, $1 < S < 100$. [Asaka, AK, Shaposhnikov]

Conclusion

- A sterile neutrino with keV mass and a small mixing is a viable dark matter candidate, free of CDM problems.

- 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**