Dark matter, the view from space

- Identification of dark matter will be a great discovery with important ramifications for fundamental physics
- Earth vs Space
  - complementarity
  - symbiosis
  - competition
- Dark matter from SUSY
- Dark matter from the neutrino sector
  - theoretical motivation
  - production in the early universe
  - independent astrophysical hints

Dark matter

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The only data at variance with the Standard Model

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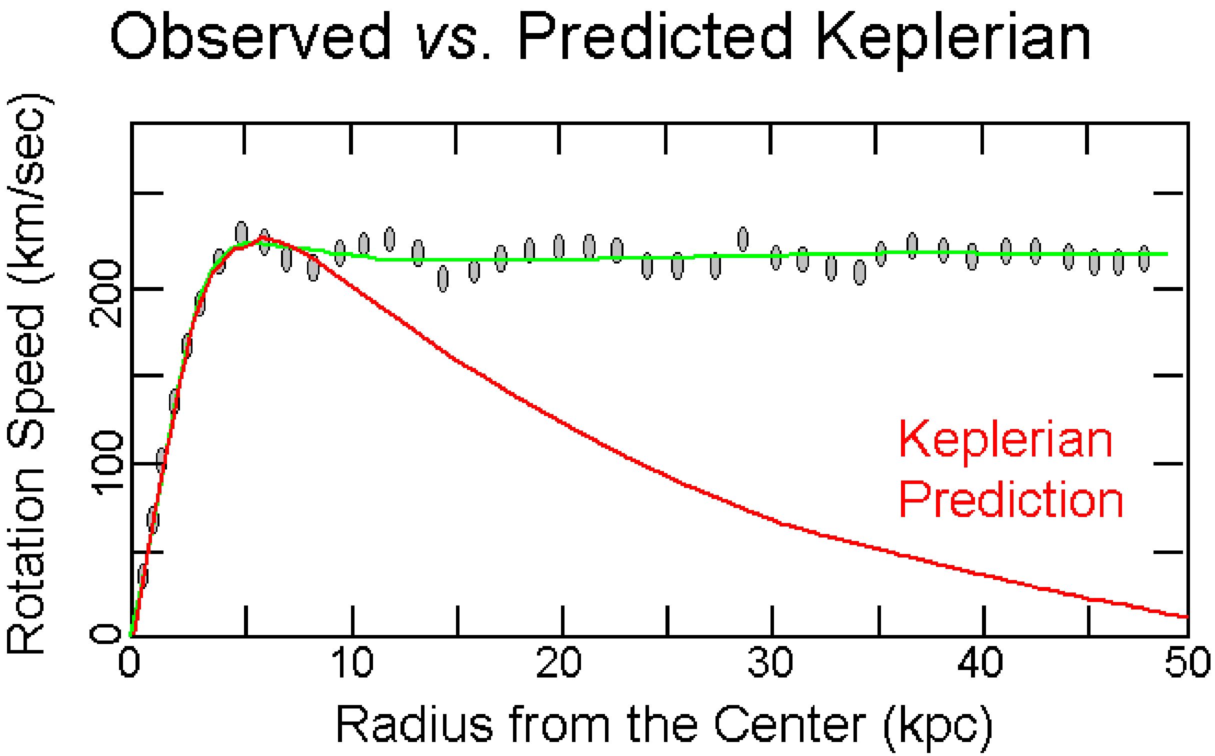
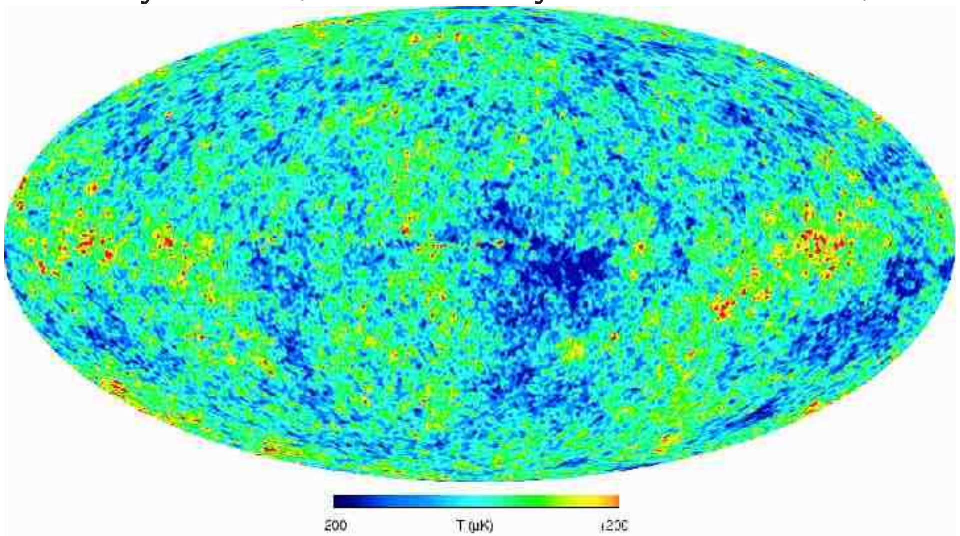
- neat: 1E0657-56 shows separation of ordinary matter (gas) from dark matter

Galactic rotation curves

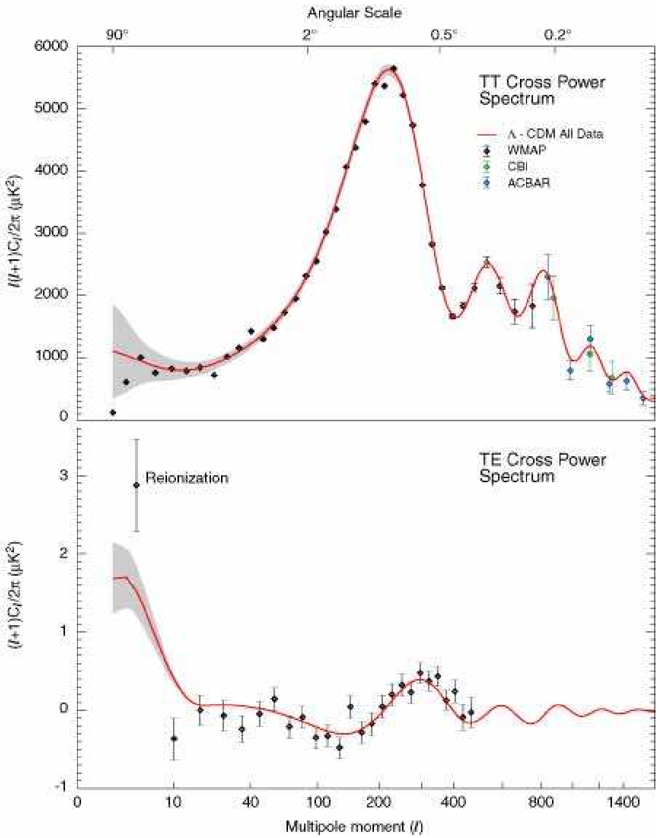


Cosmic microwave background radiation (CMBR)

At *decoupling*, the atoms formed and the universe became transparent to radiation. Radiation emitted at that time has been red-shifted into the microwave range. Fluctuations have been measured first by COBE, and later by BOOMERANG, MAXIMA, ..., WMAP:



Power spectrum measured by WMAP



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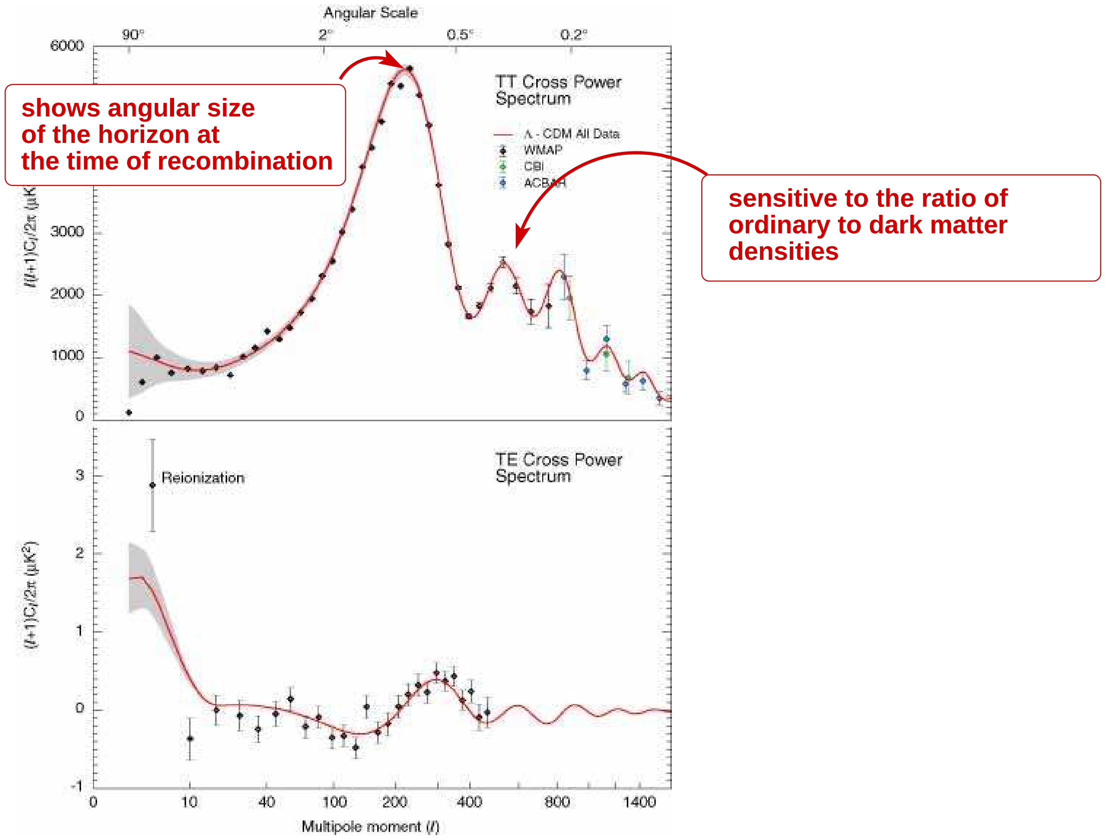
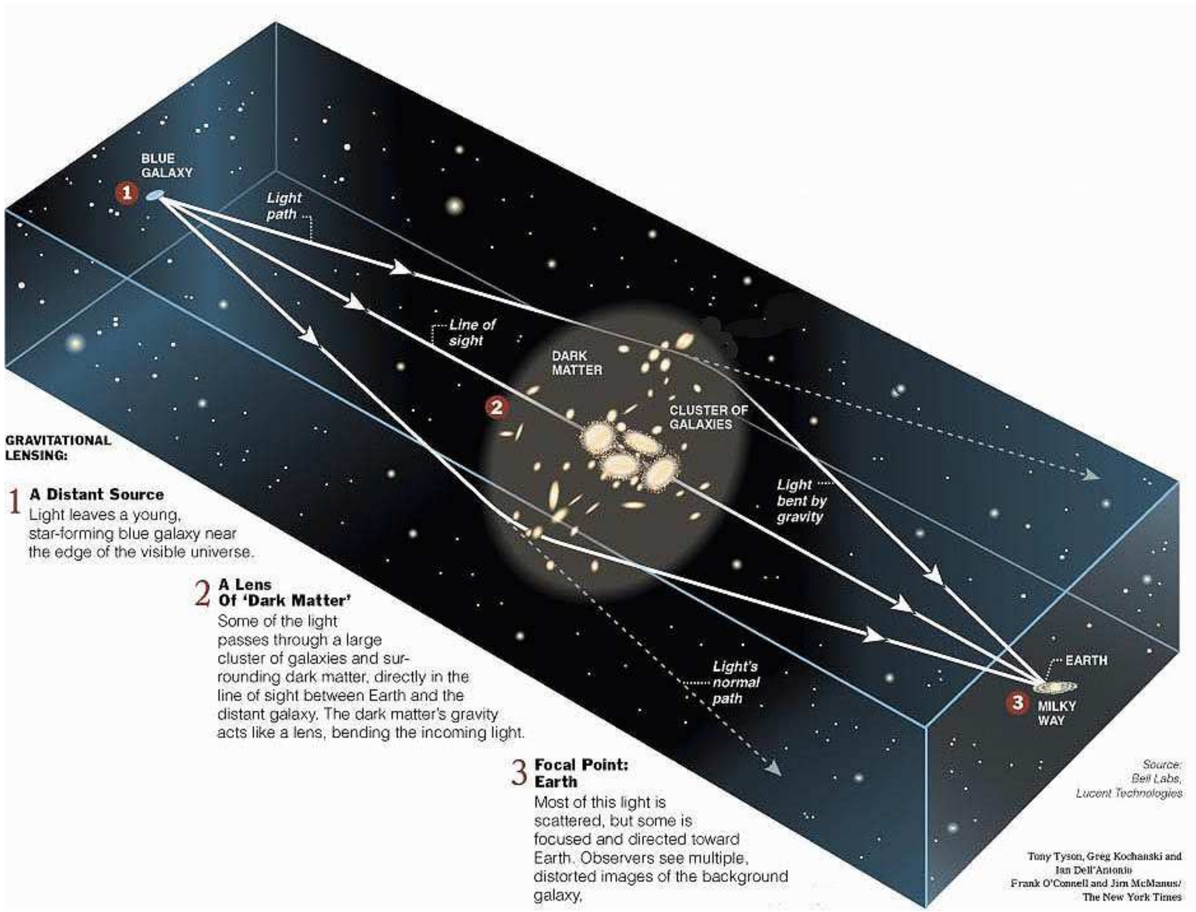
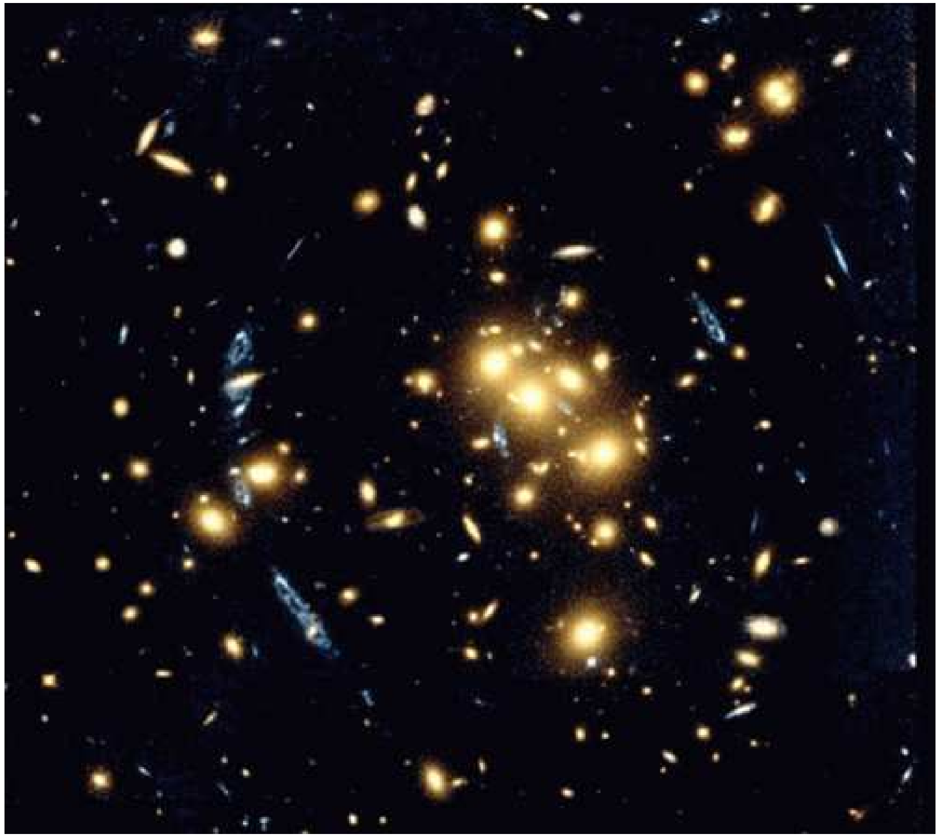
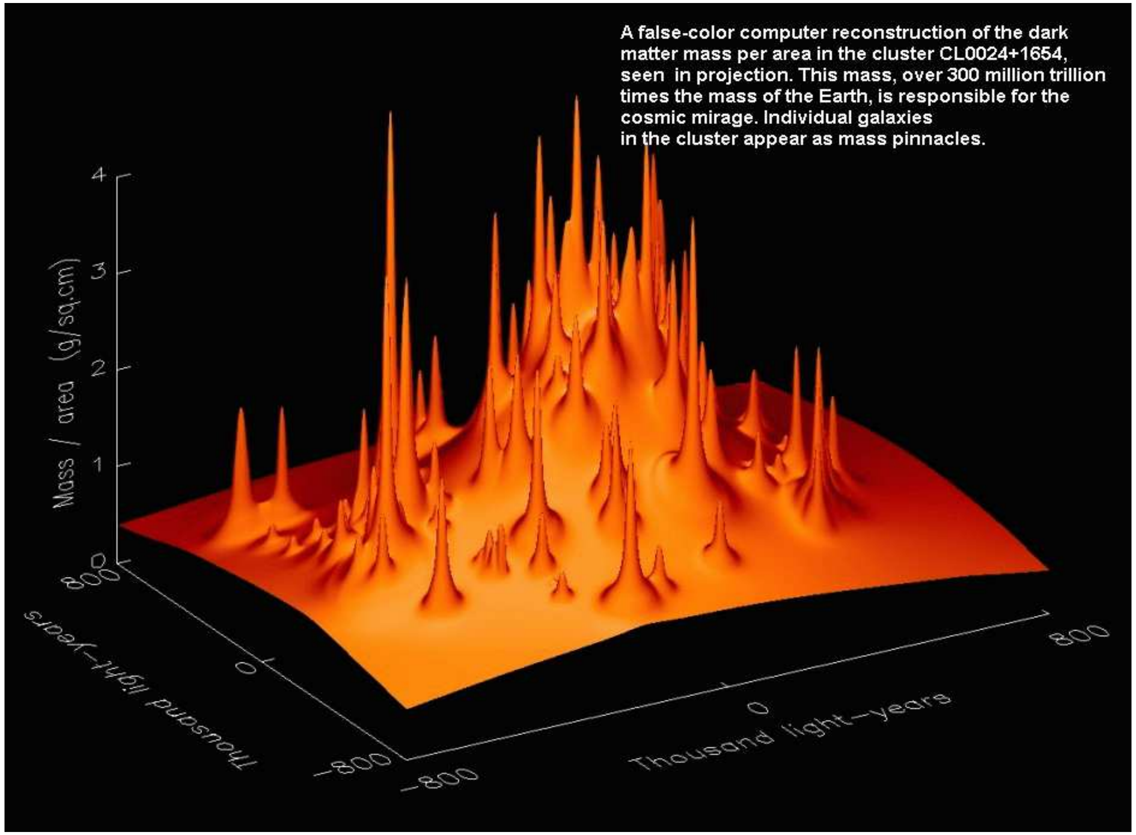


Gravitational lensing: seeing the invisible

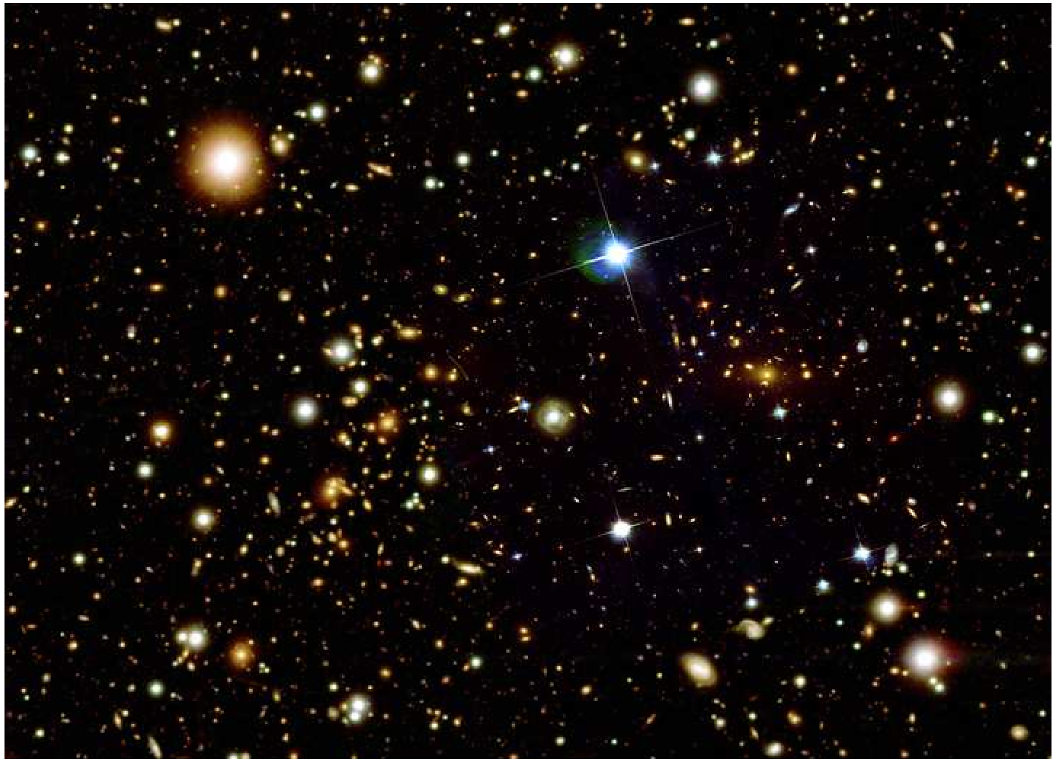




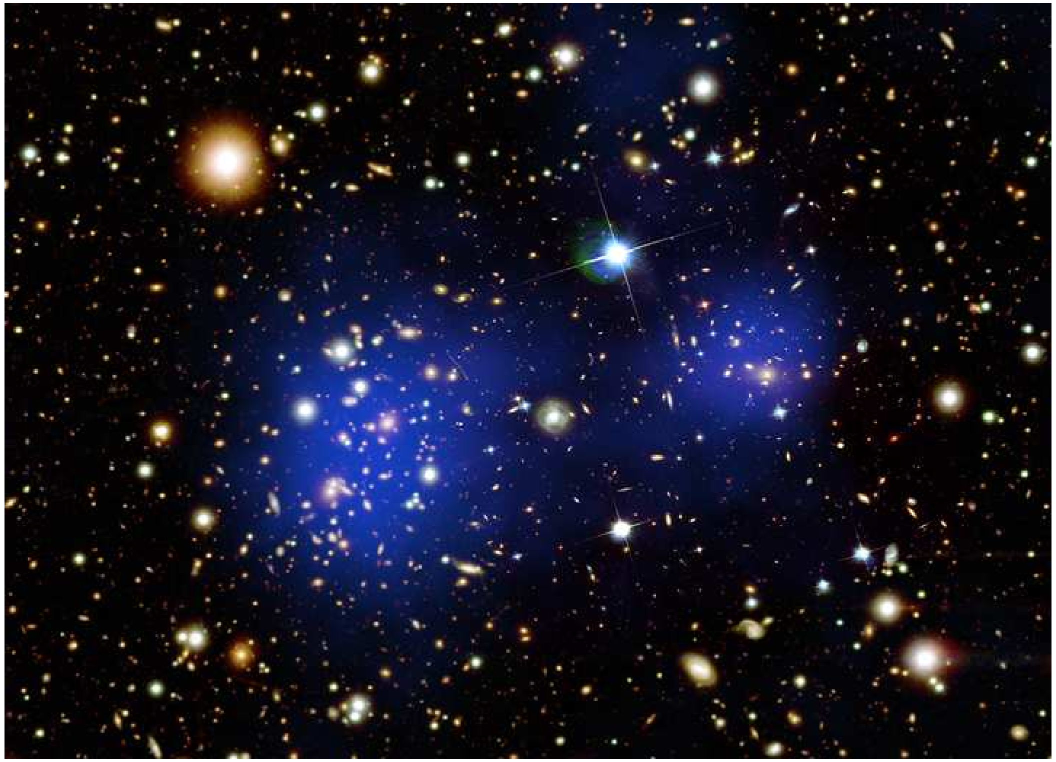


Foreground cluster CL0024+1654 produces multiple images of a blue background galaxy in the HST image (left). Mass reconstruction (right).

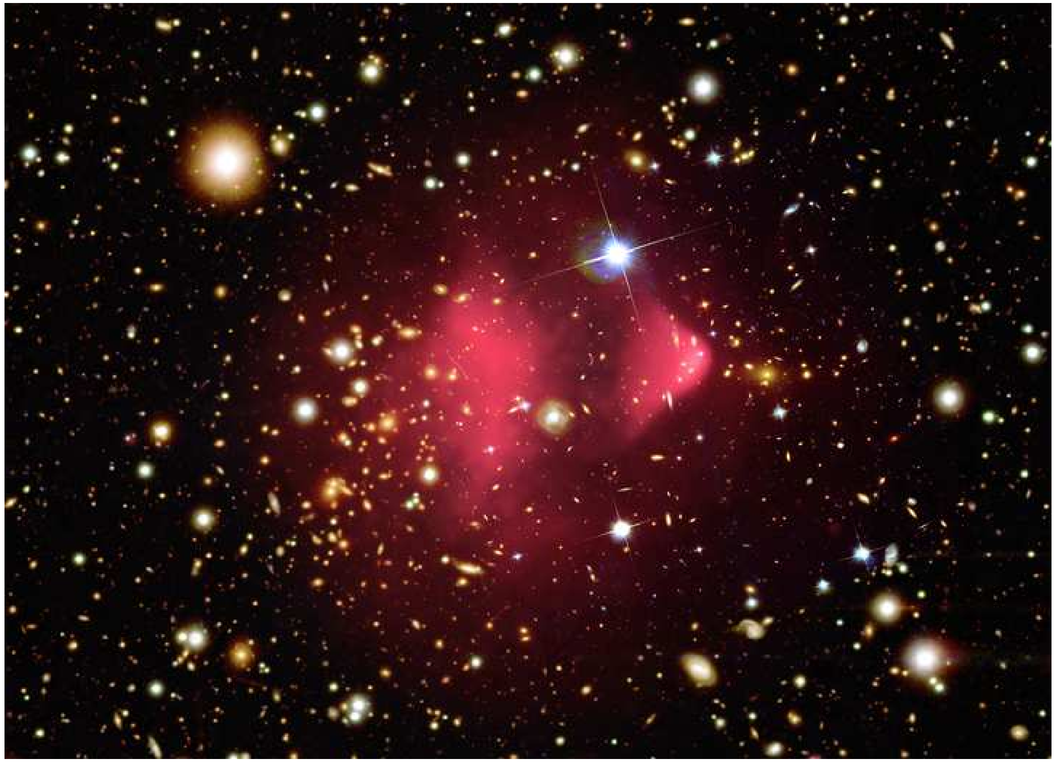
Merging clusters: optical image of 1E 0657-56



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



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



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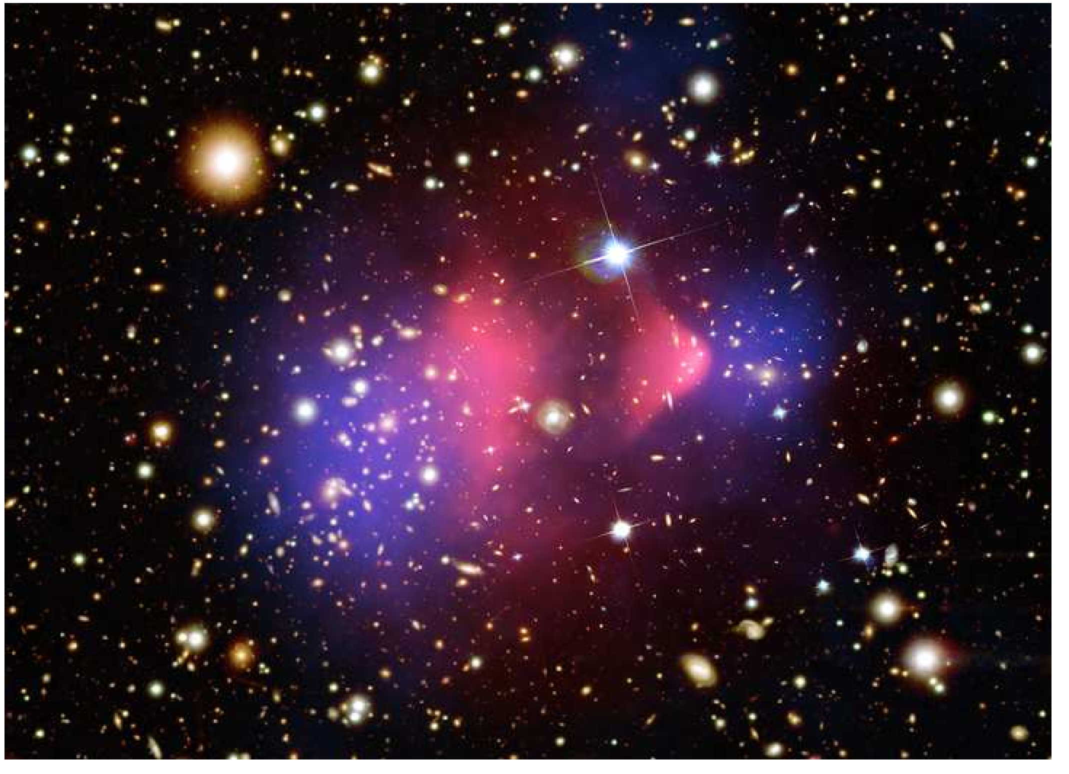
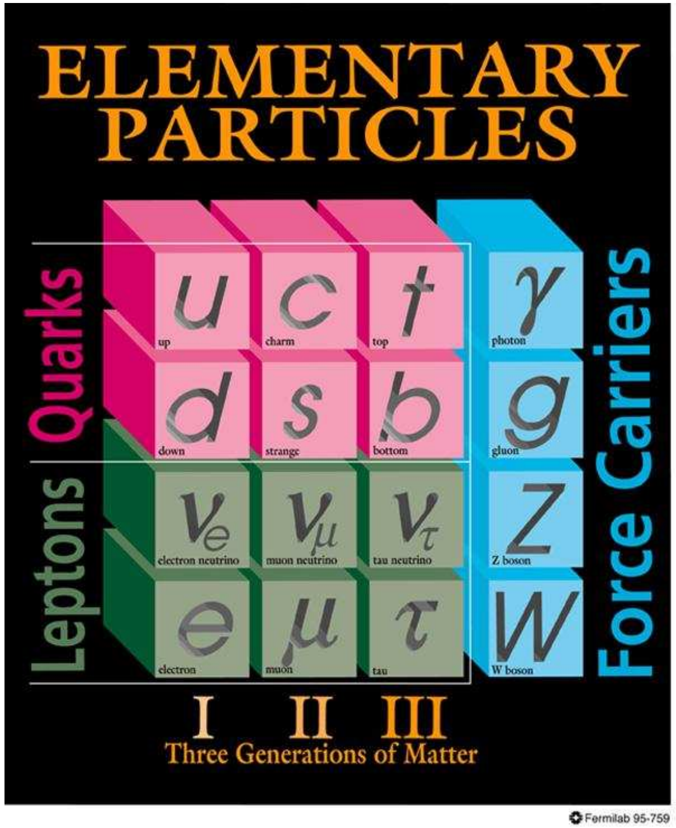


Gass, dark matter separated.

None of the known particles can be dark matter



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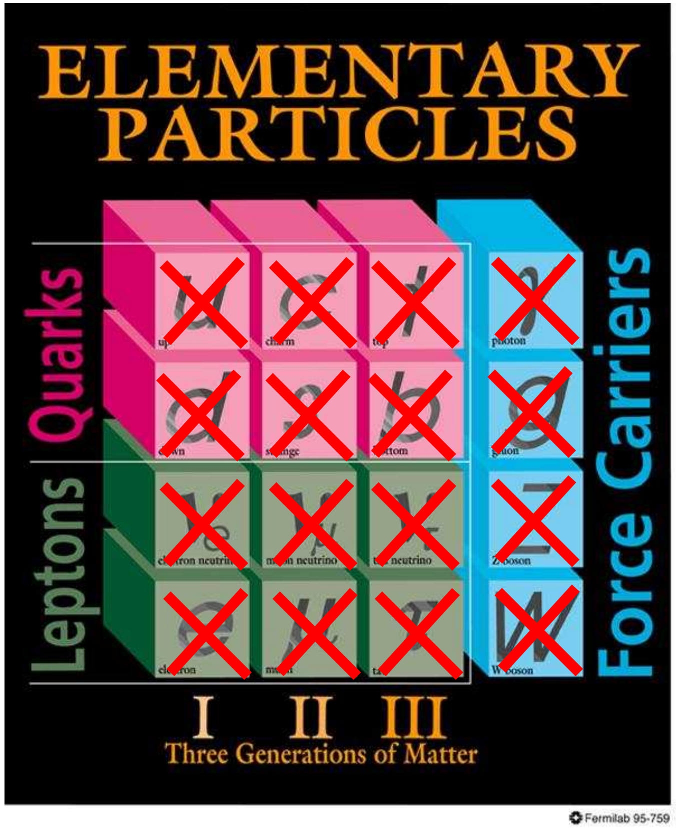
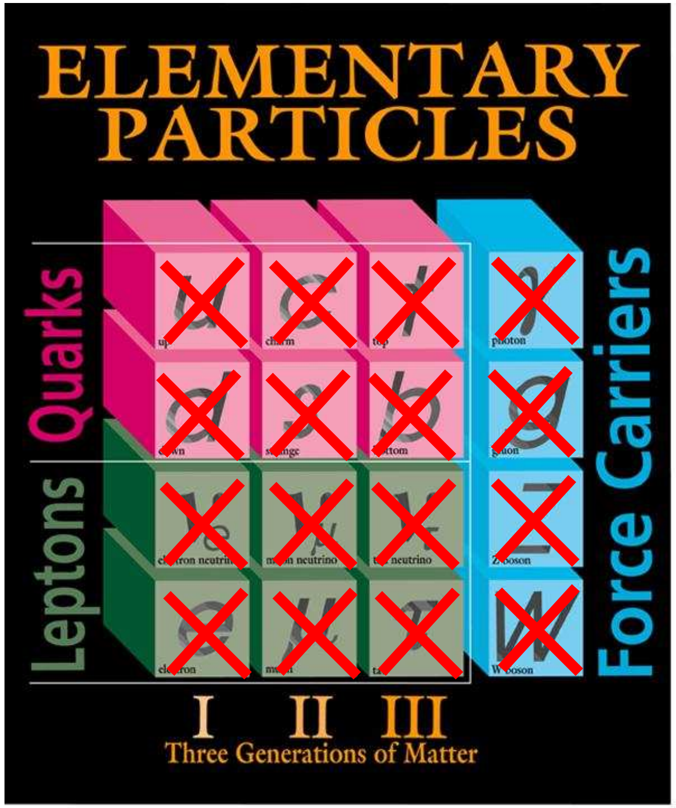


Dark matter ⇒ new physics (at least one new particle)



Fermilab 95-759

The dark side: what is dark matter?

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- ...observational clues

One has to guess the answer before one can make a discovery!

Space–Ground complementarity

	Ground	**Space**
WIMP	Direct detection	Indirect detection
Sterile neutrino	?	X-ray observations
Axion	relic axions solar axions man-made axions	?

Dark matter: beautiful theoretical ideas

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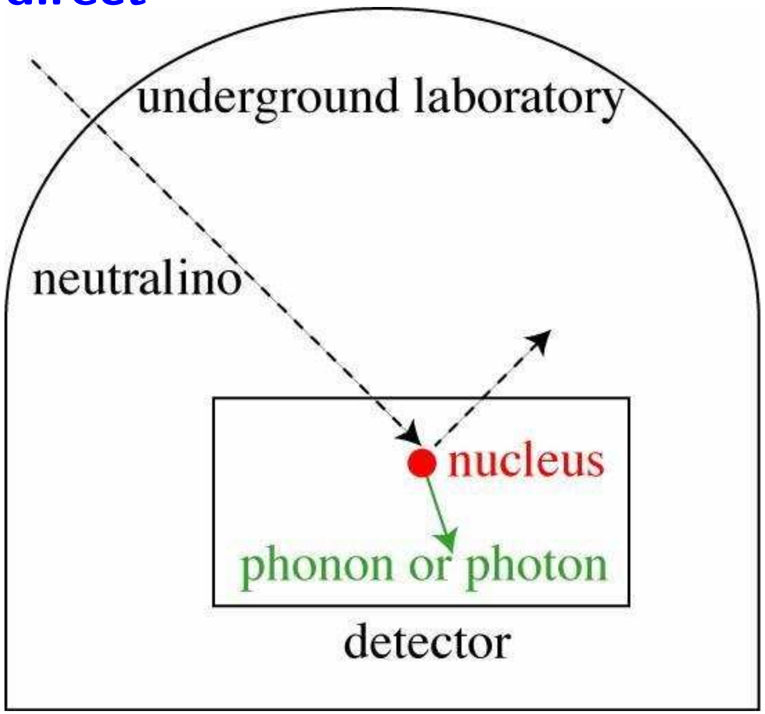
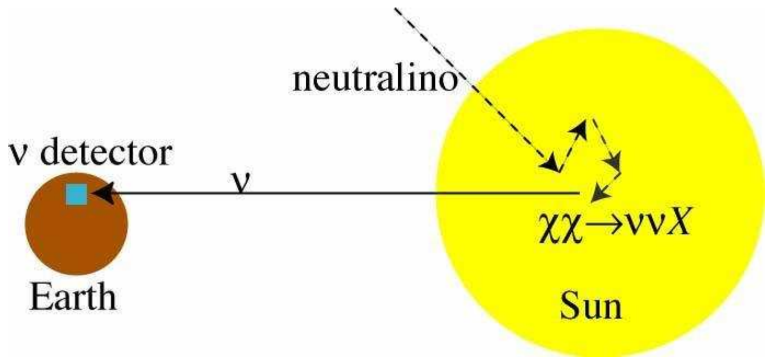
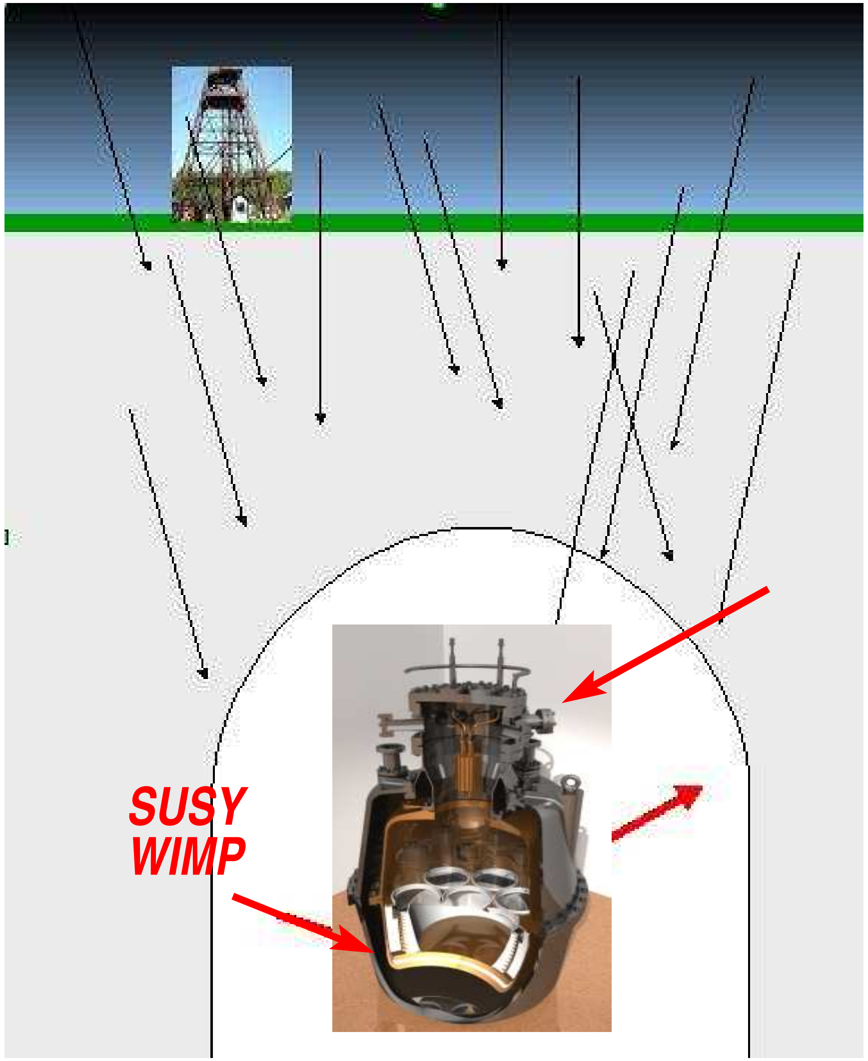
No experimental evidence of SUSY so far.

SUSY LSP dark matter: detection

direct **indirect**



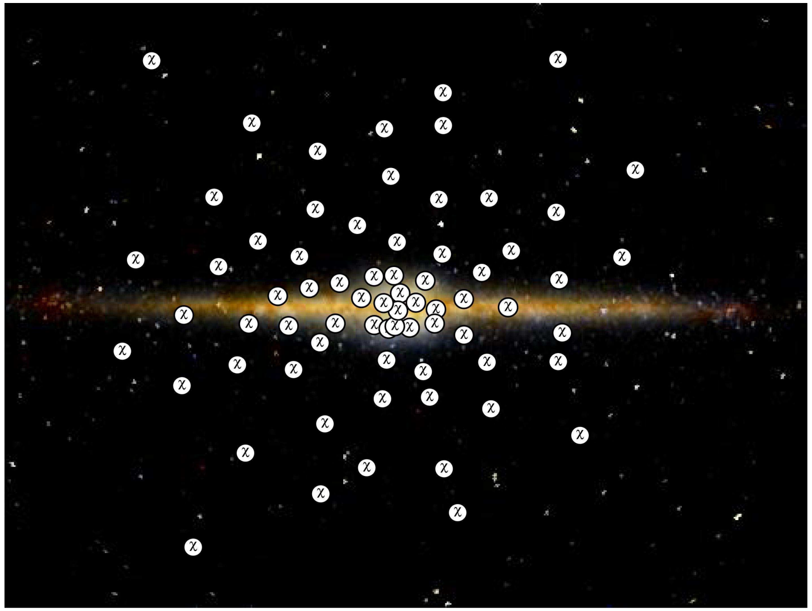




Direct detection

Weakly interacting particles (WIMP) can penetrate through rock; they can be detected in underground detectors, 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 **(GLAST talk by Dermer)**.

Neutrino masses and dark matter

neutrino mass $\Rightarrow$ right-handed states exist!

The discovery of the neutrino mass is the discovery of new particles (at some scale).

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The discovery of the neutrino mass is the discovery of new particles (at some scale).

Discovery requires space instruments!

[talks by Abazajian, Loewenstein]

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:

$$M = \left(\begin{array}{cc} \tilde{m}_{3\times 3} & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{array}\right)$$

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What is the scale of M?

Astrophysical implications of "small" M: dark matter

Light sterile neutrino with mass $\sim M$.

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side benefit: explanation of the pulsar kicks, supernova asymmetries

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- oscillations on resonance, if the lepton asymmetry is non-negligible [Fuller, Shi; Laine, Shaposhnikov]
- **production mechanisms which do not involve oscillations**
  - inflaton decays directly into sterile neutrinos [Shaposhnikov, Tkachev]
  - Higgs physics: both mass and production [AK, Petraki]

Dark matter free streaming (cold or warm?)

Free streaming depends on the production mechanism.

$$\lambda_{FS} \approx 1\,\mathrm{Mpc} \left(\frac{\mathrm{keV}}{m_s}\right) \left(\frac{\langle p_s \rangle}{3.15\,T}\right)_{T\approx 1\,\mathrm{keV}}$$

The ratio

$$\left(\frac{\langle p_s \rangle}{3.15\,T}\right)_{T\approx 1\,\mathrm{keV}} = \begin{cases} 0.9 & \text{for production off} - \text{resonance} \\ 0.6 & \text{for MSW resonance (depends on L)} \\ 0.2 & \text{for production at T} > 100\ \text{GeV} \end{cases}$$

Neutrino masses: new scale or new Higgs physics?

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

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$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i \partial_\mu \gamma^\mu \right) N_a - y_{\alpha a} H \, \bar{L}_\alpha N_a - h_a \, S \, \bar{N}_a^c N_a + V(H, S)$$

$$M = h \langle S \rangle$$

Now $S \longrightarrow NN$ decays can produce sterile neutrinos [AK, Petraki, Shaposhnikov, Tkachev]

For small h, the sterile neutrinos are out of equilibrium in the early universe, but S is in equilibrium. There is a new mechanism to produce sterile dark matter at $\boldsymbol{T \sim m_S}$ from decays $\boldsymbol{S \longrightarrow NN}$:

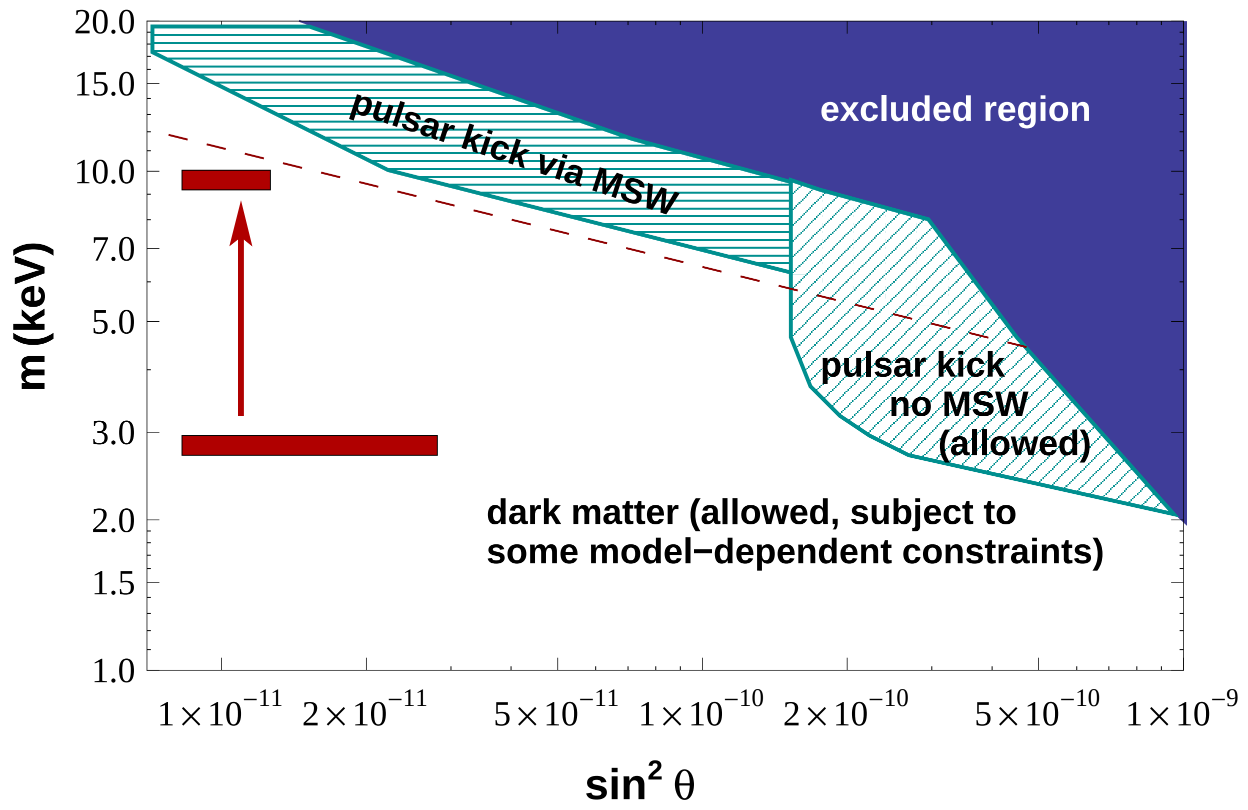
$$\boldsymbol{\Omega_s = 0.2 \left(\frac{33}{\xi}\right) \left(\frac{h}{1.4 \times 10^{-8}}\right)^3 \left(\frac{\langle S \rangle}{\tilde{m}_S}\right)}$$

Here ζ is the dilution factor due to the change in effective numbers of degrees of freedom.

$$\boldsymbol{\langle S \rangle = \frac{M_s}{h} \sim \frac{\text{few keV}}{1.4 \times 10^{-8}} \sim 10^2\,\text{GeV}}$$

The sterile neutrino momenta are red-shifted by factor $\boldsymbol{\zeta^{1/3} > 3.2}$. [AK, Petraki]

Cooling changes the Lyman-α bounds



[AK, PRL **97**:241301 (2006); Petraki, AK, PRD 77, 065014 (2008); Petraki, PRD 77:105004 (2008)]

Implications for the EW phase transition and the LHC

One may be able to discover the *singlet Higgs* at the LHC [Profumo, Ramsey-Musolf, G. Shaughnessy; Davoudiasl et al.; O'Connell et al.; Ramsey-Musolf, Wise]

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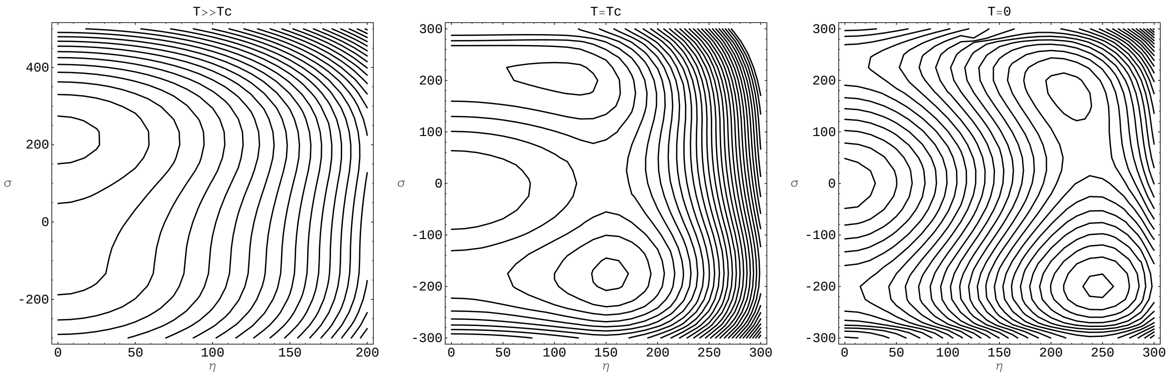
The presence of S in the Higgs sector changes the nature of the electroweak phase transition [AK, Petraki]



First-order transition, CP in the Higgs sector $\Longrightarrow$ **electroweak baryogenesis**

Astrophysical clues: supernova

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- 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]

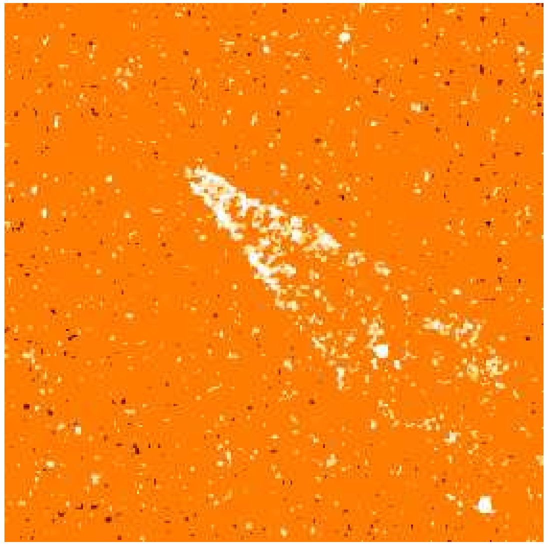
The pulsar velocities.

The pulsar velocities.

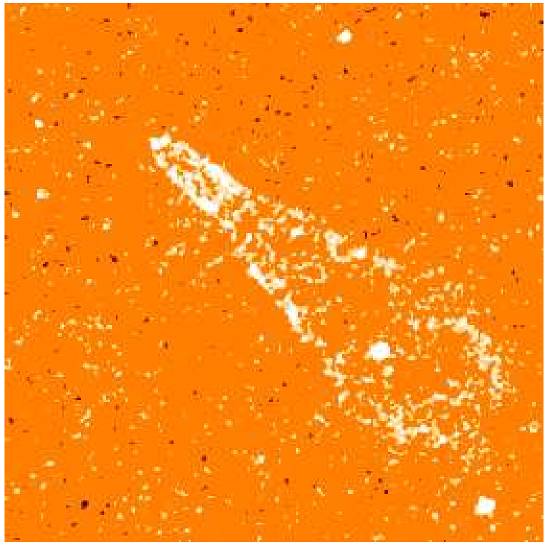
Pulsars have large velocities, $\langle v \rangle \approx 250 - 450$ km/s.
[Cordes *et al.*; Hansen, Phinney; Kulkarni *et al.*; Lyne *et al.*]

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

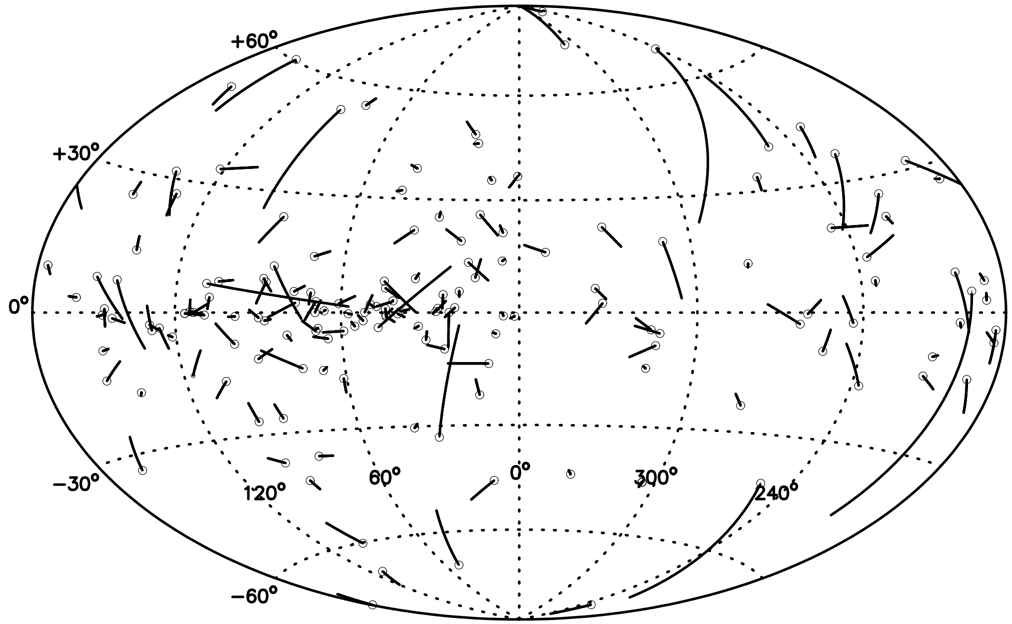


HST, December 1994



HST, December 2001

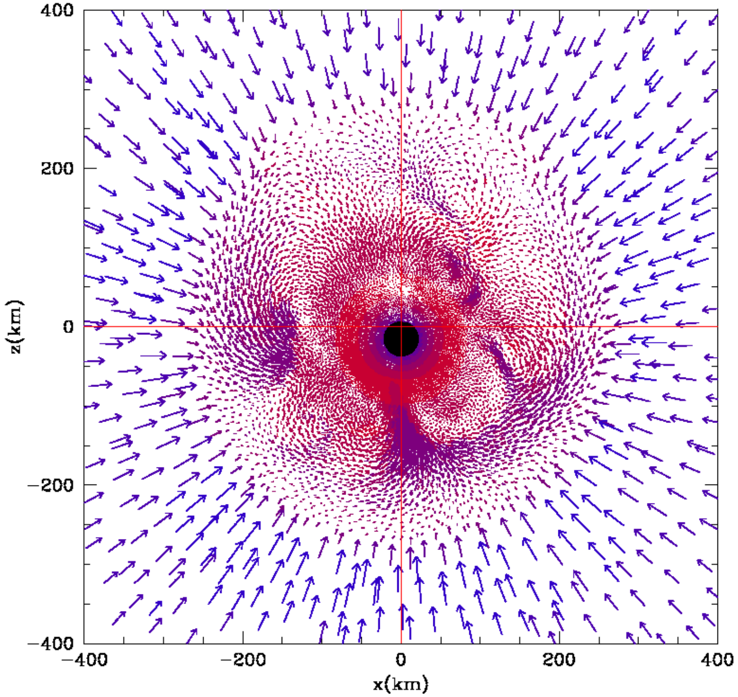
Map of pulsar velocities

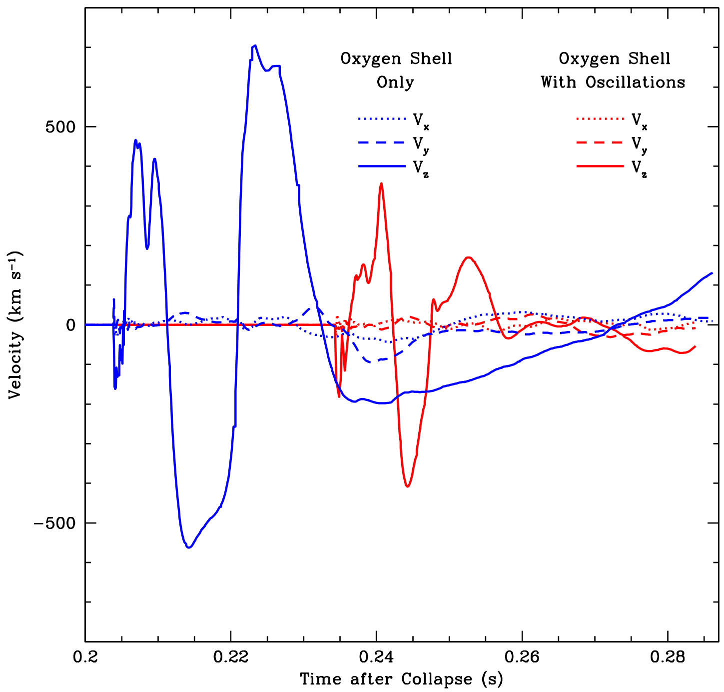


Proposed explanations:

- 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)
- 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]

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:

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

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99% of this energy is emitted in neutrinos

Pulsar kicks from neutrino emission?

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

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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: $t = 0$

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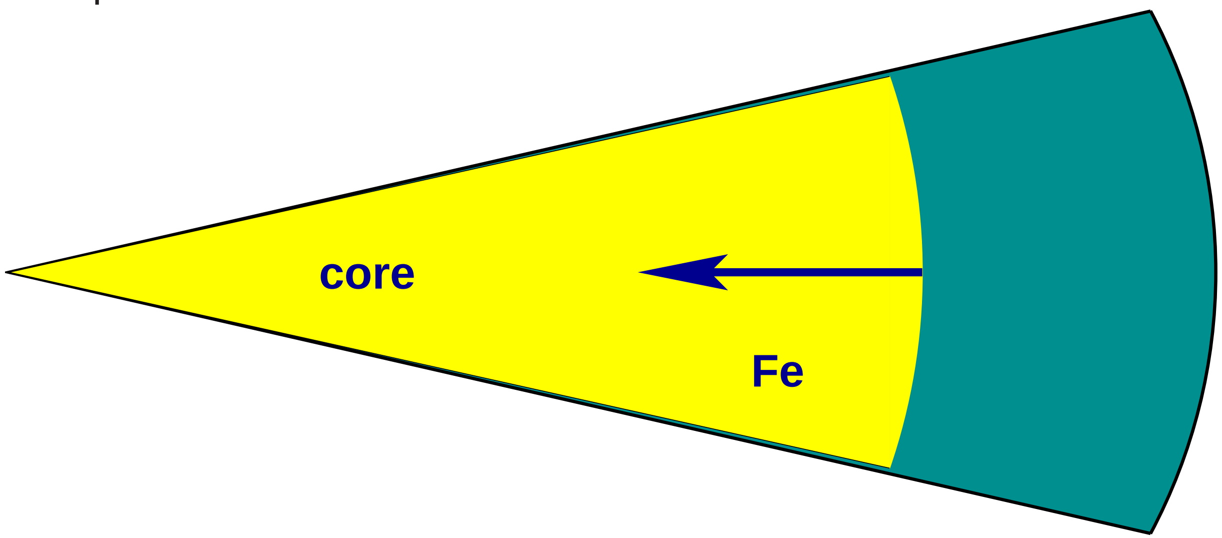
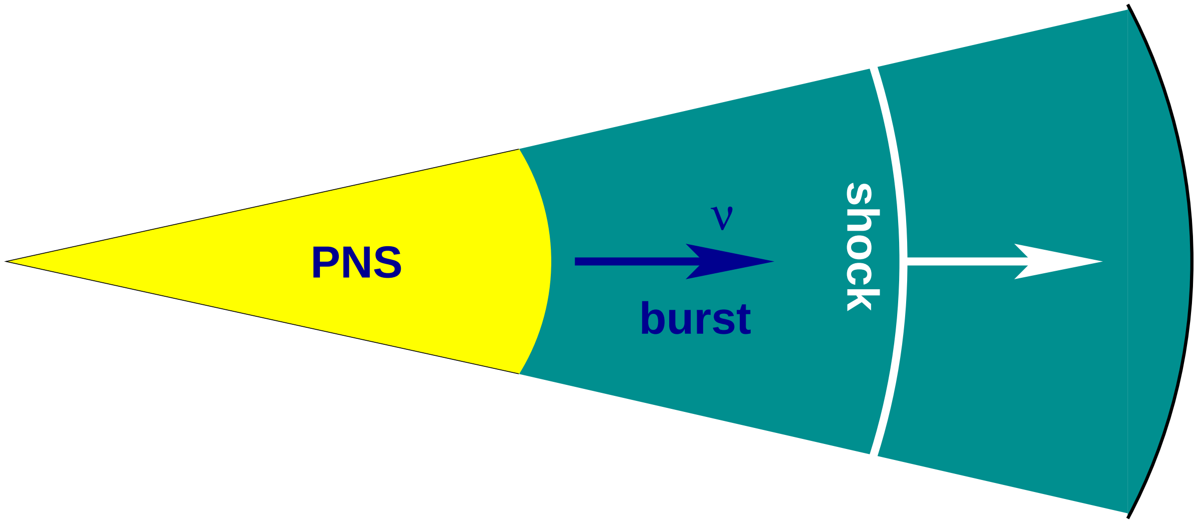


Core collapse supernova

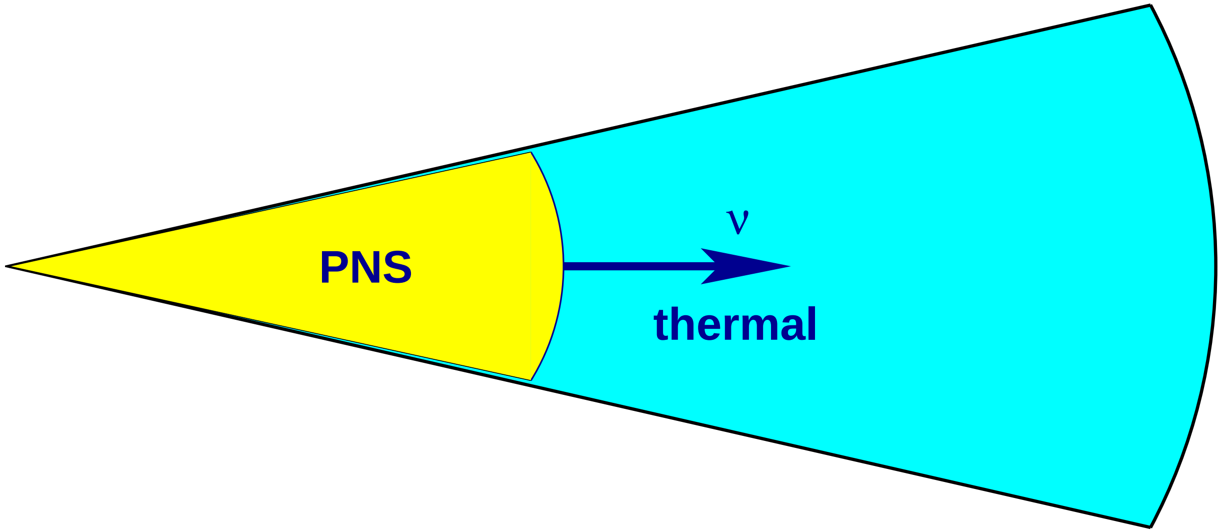
Shock formation and "neutronization burst": $t = 1 - 10$ **ms**



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),

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

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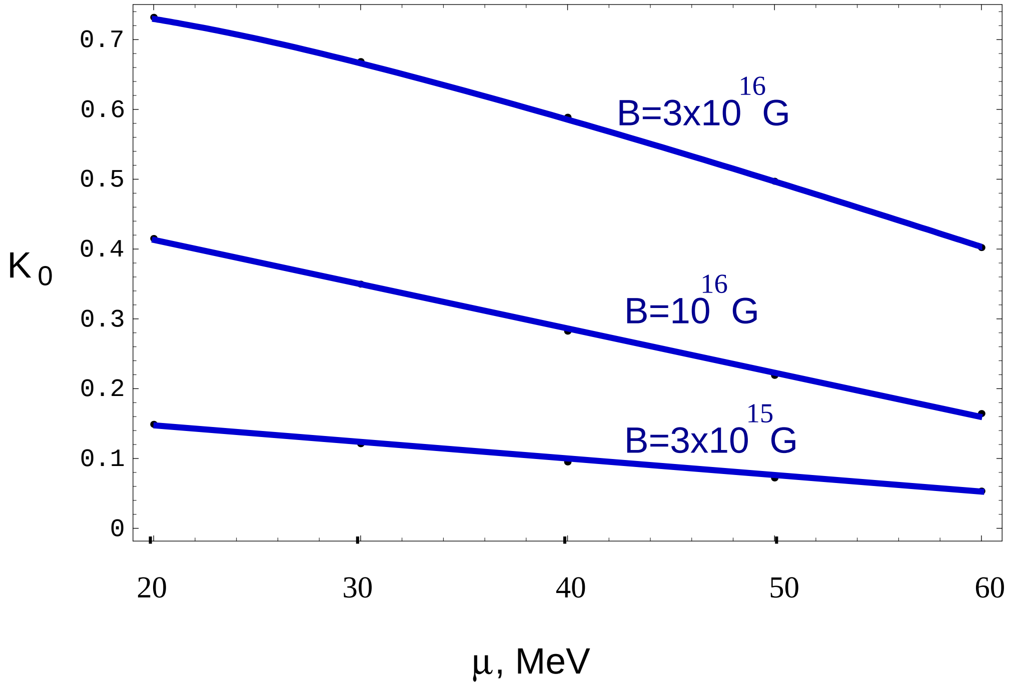
$$\sigma(\uparrow \; e^-, \uparrow \; \nu) \neq \sigma(\uparrow \; e^-, \downarrow \nu)$$

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]

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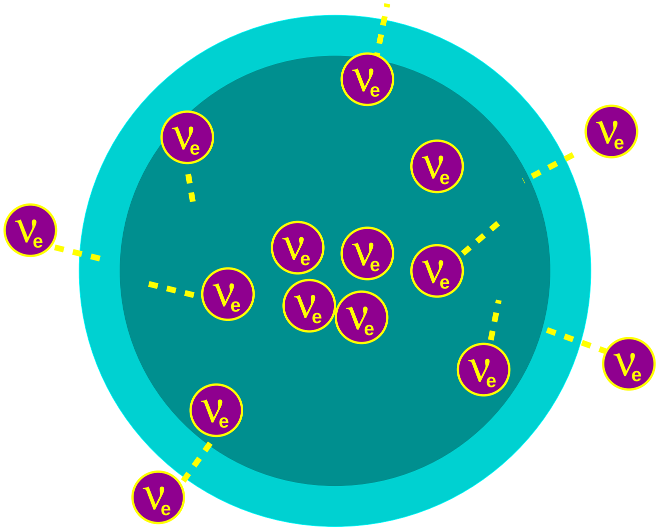

Neutrinos are trapped at high density.

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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].

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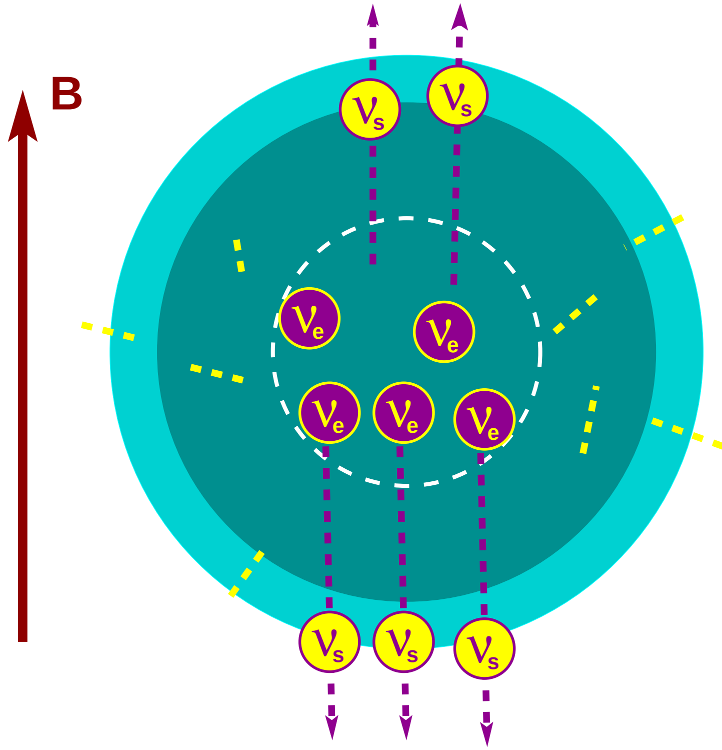
However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

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


B
ν_s
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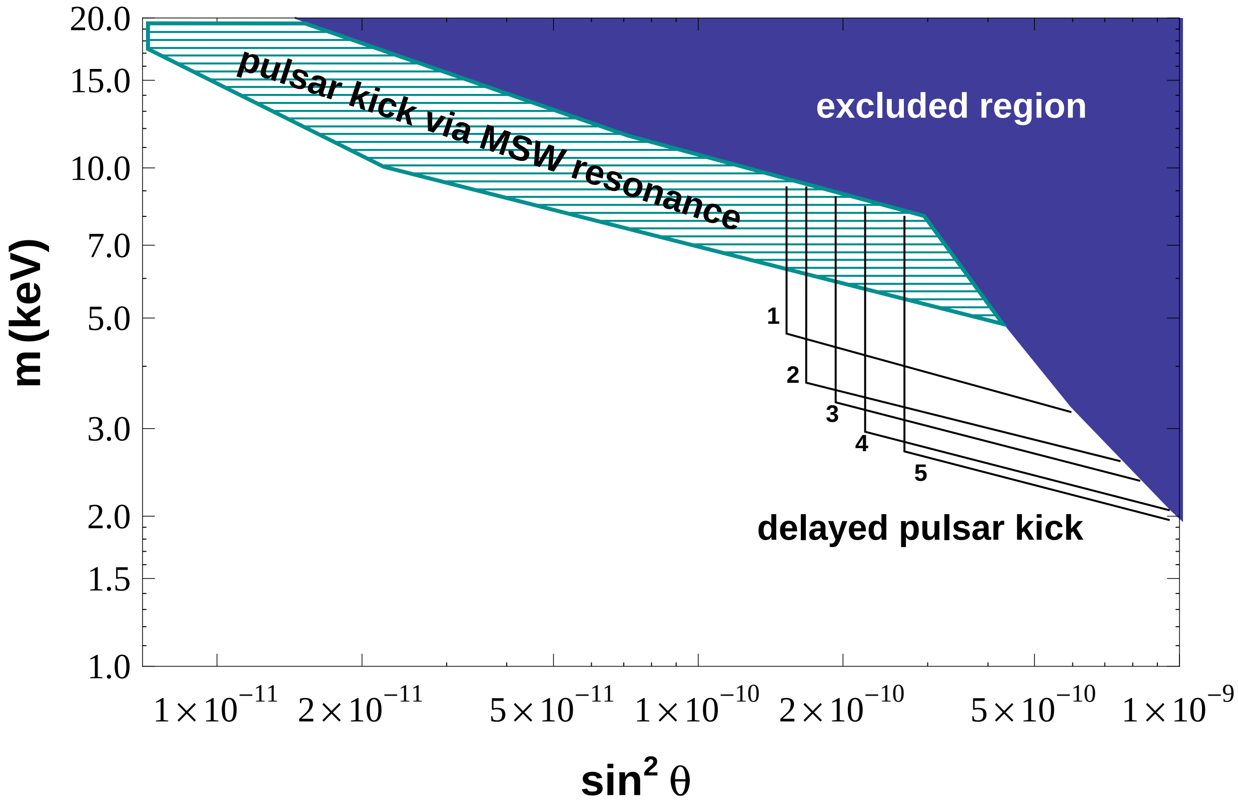
Allowed range of masses and mixing angles



[A.K., Segrè; Fuller, A.K.,Mocioiu,Pascoli; Barkovich, D'Ollivo, Montemayor; AK et al.]

Other predictions of the pulsar kick mechanism

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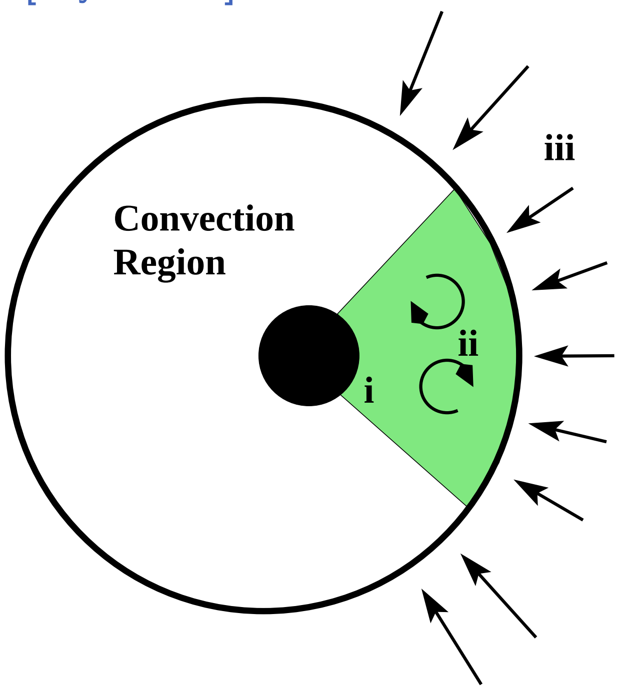
- Stronger supernova shock [Fryer, AK]



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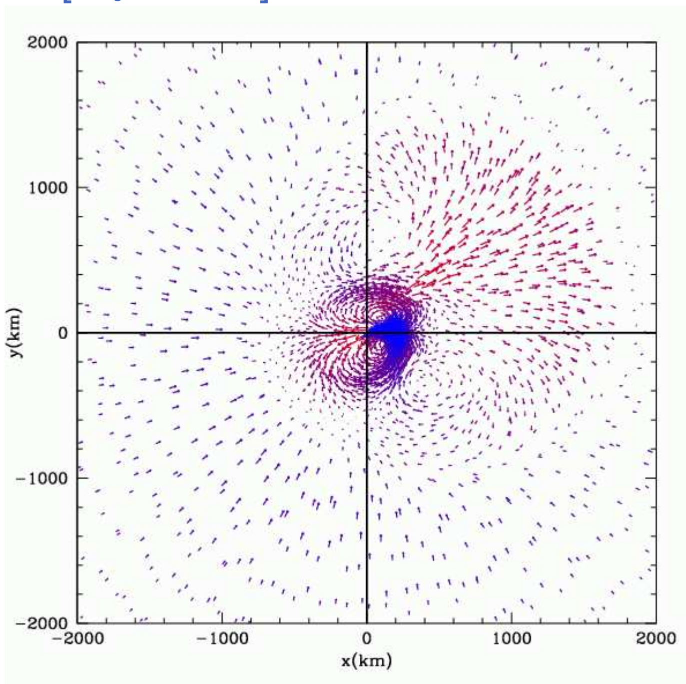

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- Stronger supernova shock [Fryer, AK; Fuller, Hidaka]
- **No $B - v$ correlation** expected because
  - the magnetic field *inside* a hot neutron star during the *first ten seconds* is very different from the surface magnetic field of a cold pulsar
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Other predictions of the pulsar kick mechanism

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- **No $B - v$ correlation** expected because
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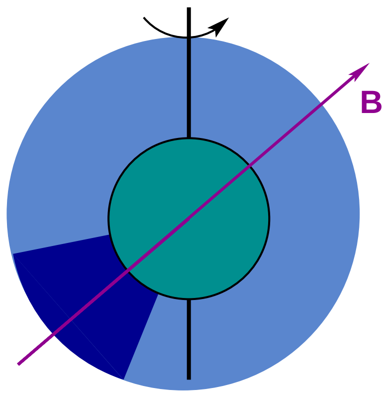
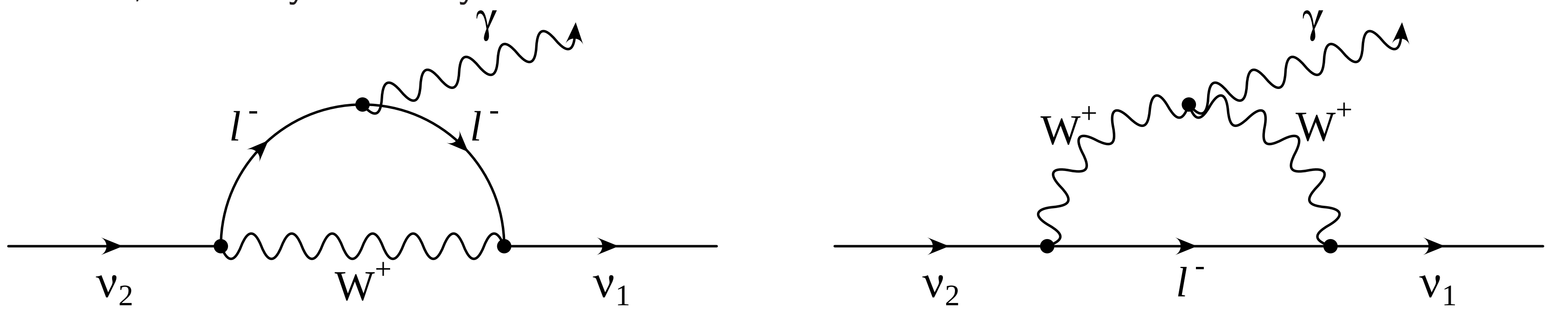
  - rotation washes out the x, y components
- **Directional $\vec{\Omega} - \vec{v}$ correlation** was predicted, because
  - the direction of rotation remains unchanged
  - only the z-component survives

  This correlation has been confirmed by recent data.



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. Concentrations of dark matter emit X-rays. [Abazajian, Fuller, Tucker; Dolgov, Hansen; Shaposhnikov et al.]

[talks by Abazajian, Loewenstein]

Star formation and reionization

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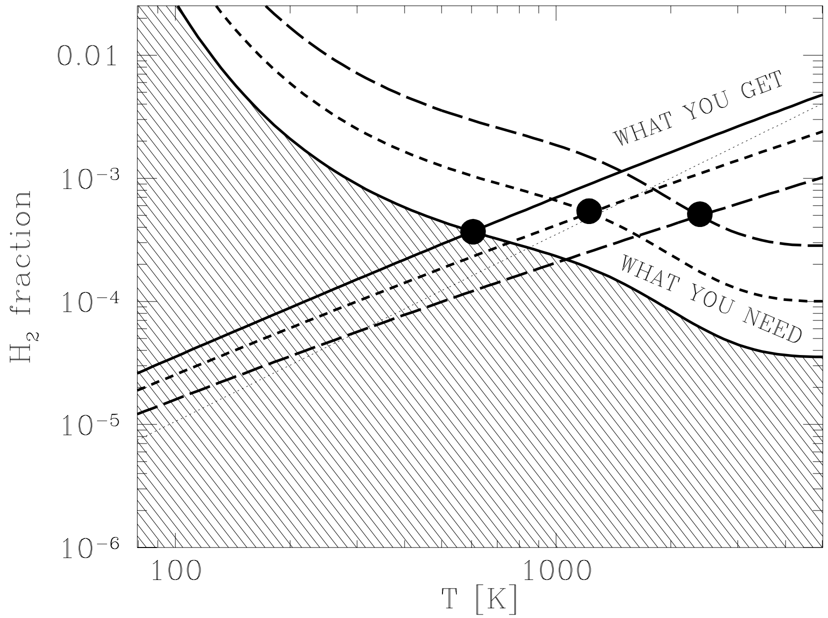
Molecular hydrogen is necessary for star formation



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

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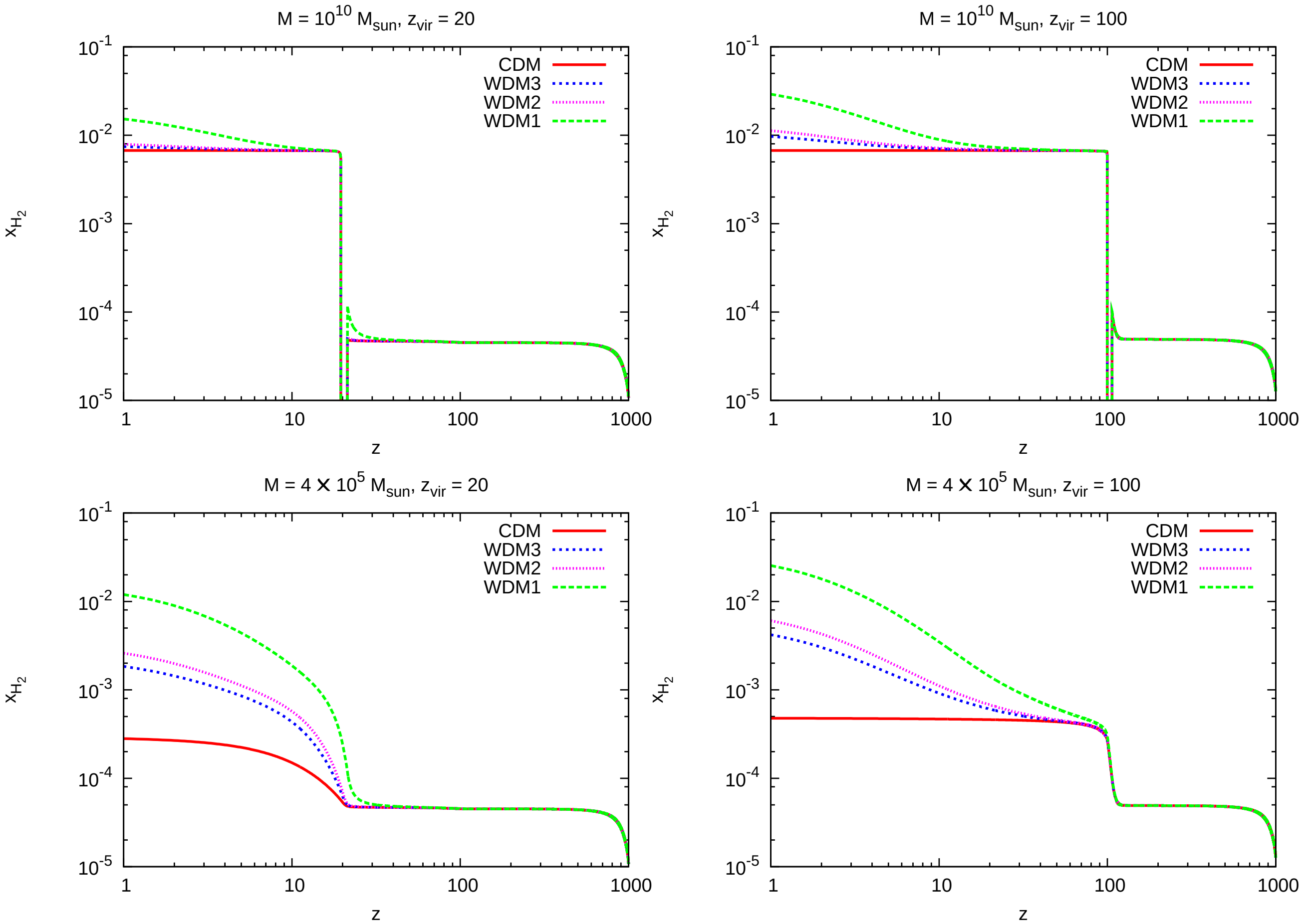
H^+ produced by X-rays from $\nu_2 \longrightarrow \nu_1\gamma$ catalyze the formation of molecular hydrogen

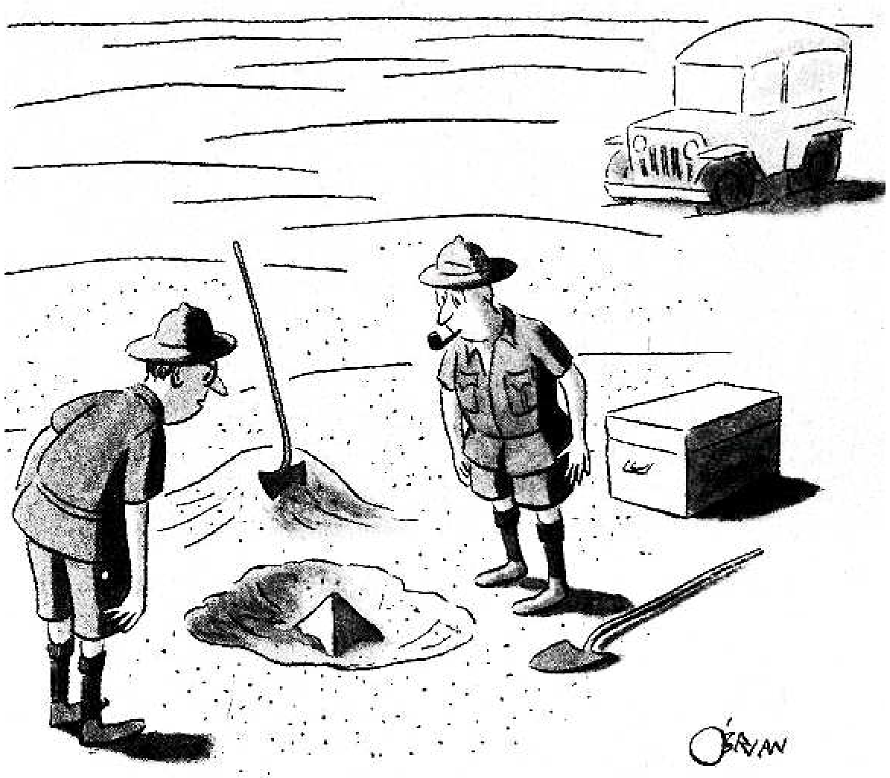
[Biermann, AK, PRL **96**, 091301 (2006)]

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



[Biermann, AK; Stasielak, Biermann, AK]

Clues of sterile neutrinos



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

Summary

- Space instruments can detect forms of dark matter unaccessible to ground-based detectors.
- Example: relic sterile neutrinos can only be discovered by space-based instruments
- Complementarity, symbiosis, competition
- talks by Abazajian, Loewenstein