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SUMMER SCHOOL ON PARTICLE PHYSICS

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Astroparticle Physics - Part 2

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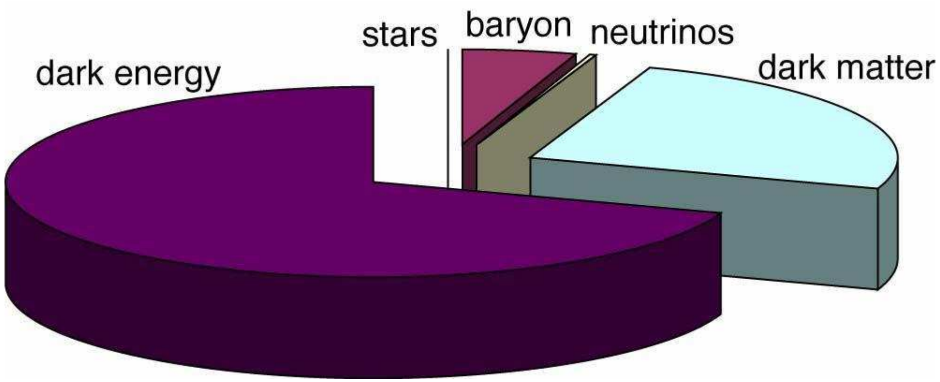
The universe

- 3% ordinary matter
- **27% dark matter**
- 70% dark energy (possibly, cosmological constant)



Dark matter: what is it?

Can make 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**

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 cosmology: dark matter

Sterile neutrinos are produced in primordial plasma through oscillations. The mixing angle is suppressed at high temperature:

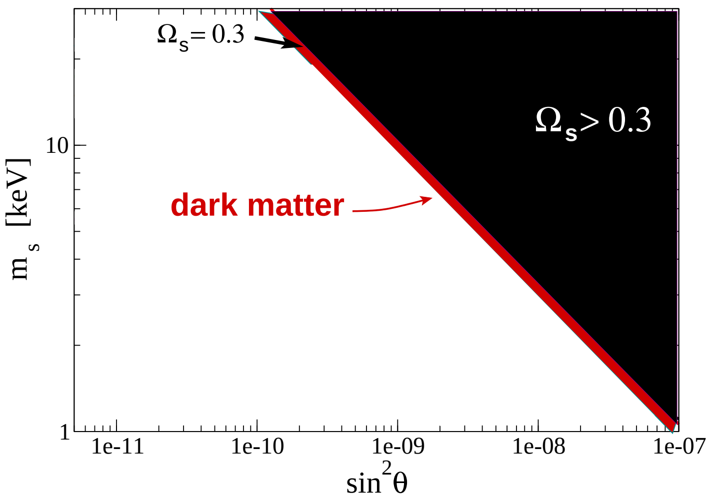
$$\sin^2 2\theta_m = \frac{(\Delta m^2/2p)^2 \sin^2 2\theta}{(\Delta m^2/2p)^2 \sin^2 2\theta + (\Delta m^2/2p \cos 2\theta - V(T))^2}, \quad (3)$$

For small angles,

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

Production of sterile neutrinos peaks at temperature

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

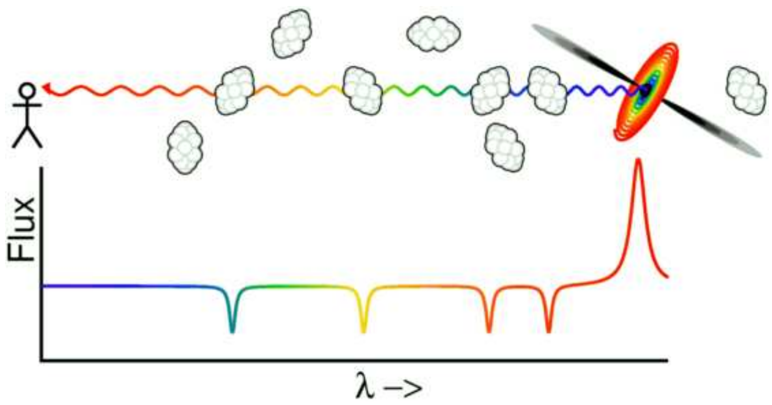


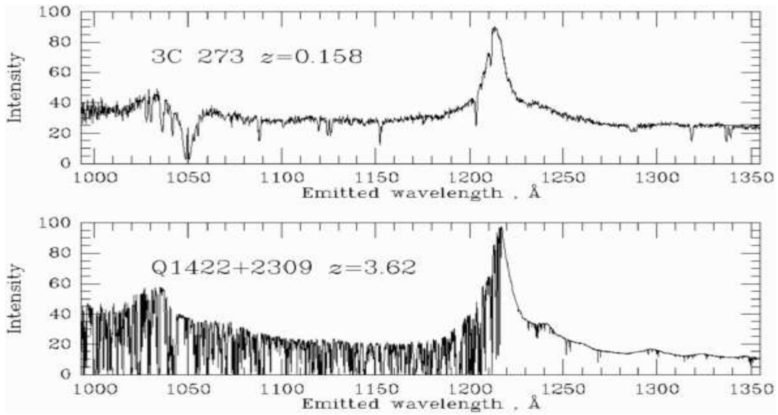
The resulting density of relic sterile neutrinos in conventional cosmology, in the absence of a large lepton asymmetry:

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

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

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





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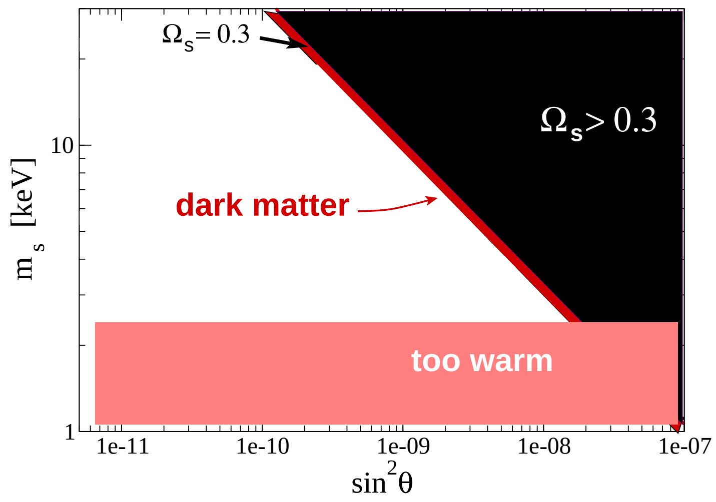
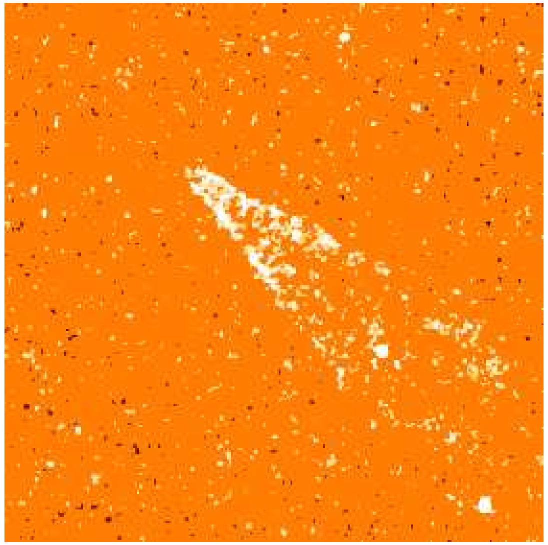
Lyman-α forest clouds show significant structure on small scales. Dark matter must be cold enough to preserve this structure.



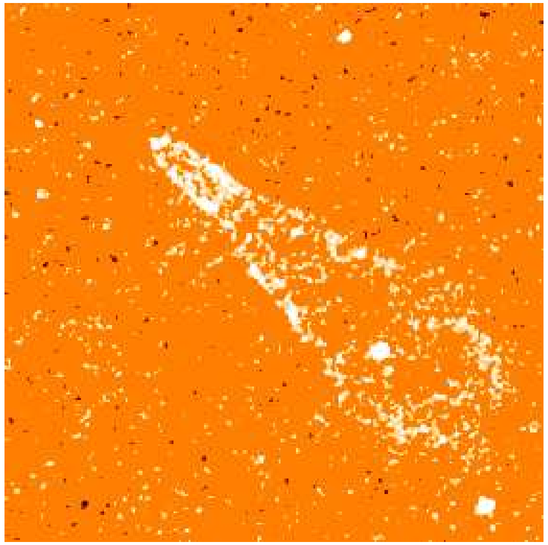
The pulsar velocities: a hint?

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

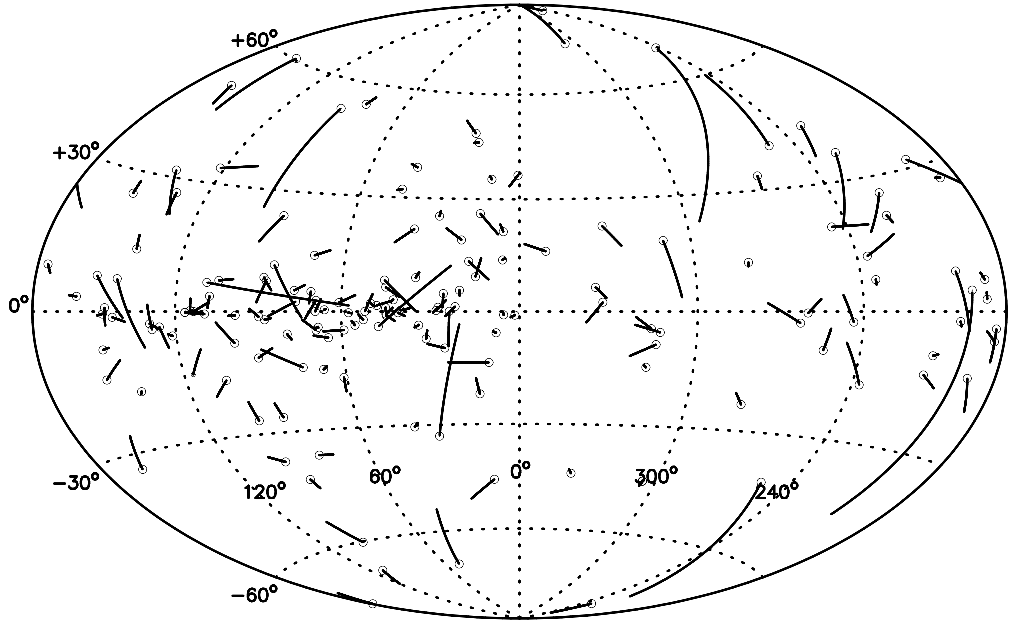


HST, December 1994



HST, December 2001

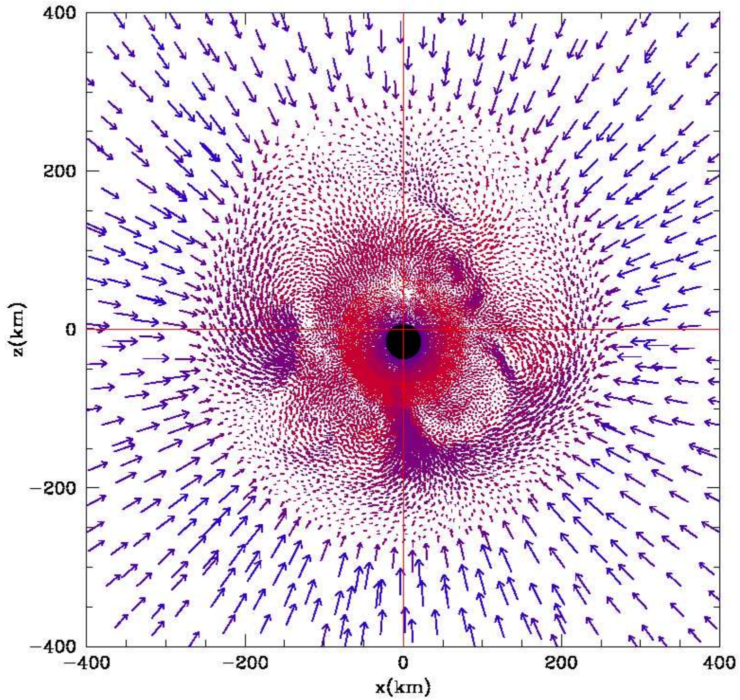
Map of pulsar velocities

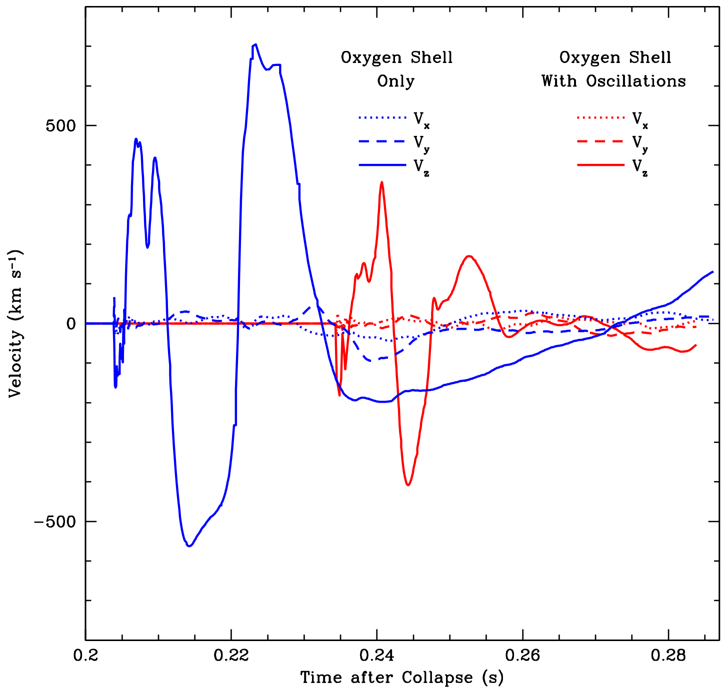


Proposed explanations:

- 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)

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*

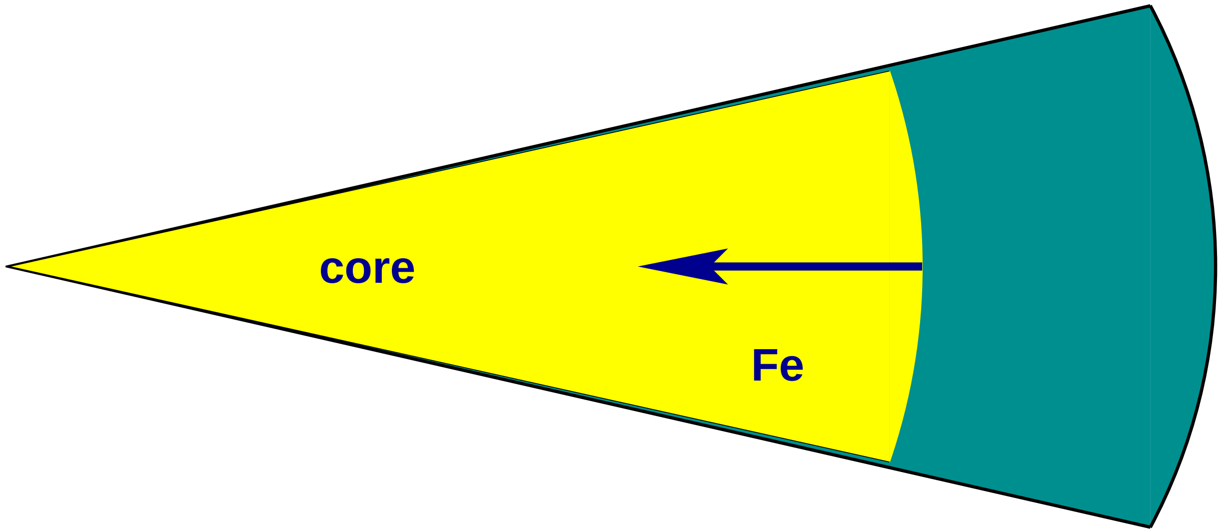
$\Rightarrow$ some neutron stars have surface magnetic fields as high as $10^{15} - 10^{16}$ **G**.

$\Rightarrow$ **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.

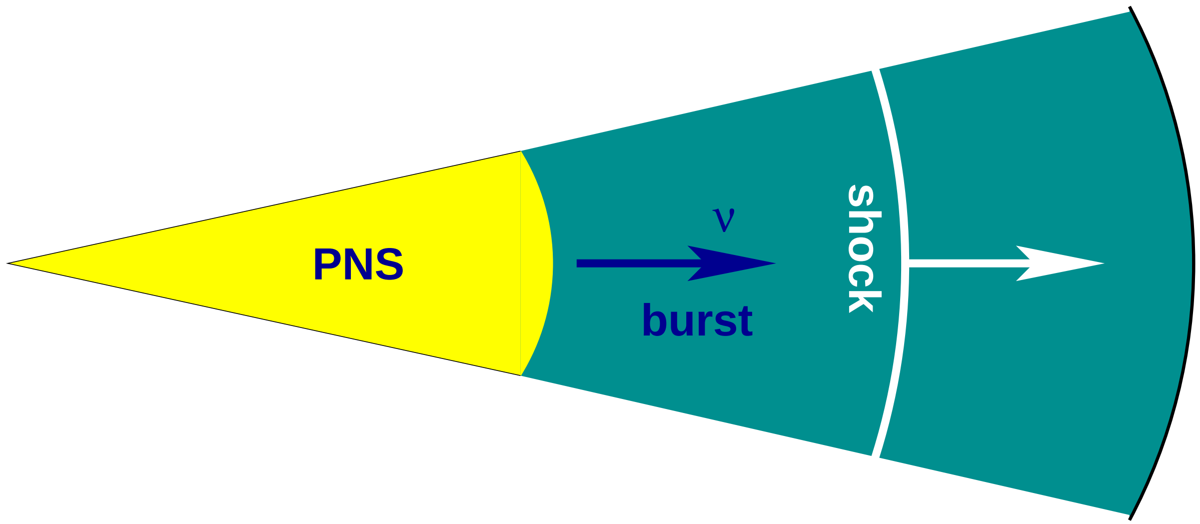
Core collapse supernova

Onset of the collapse: $t = 0$



Core collapse supernova

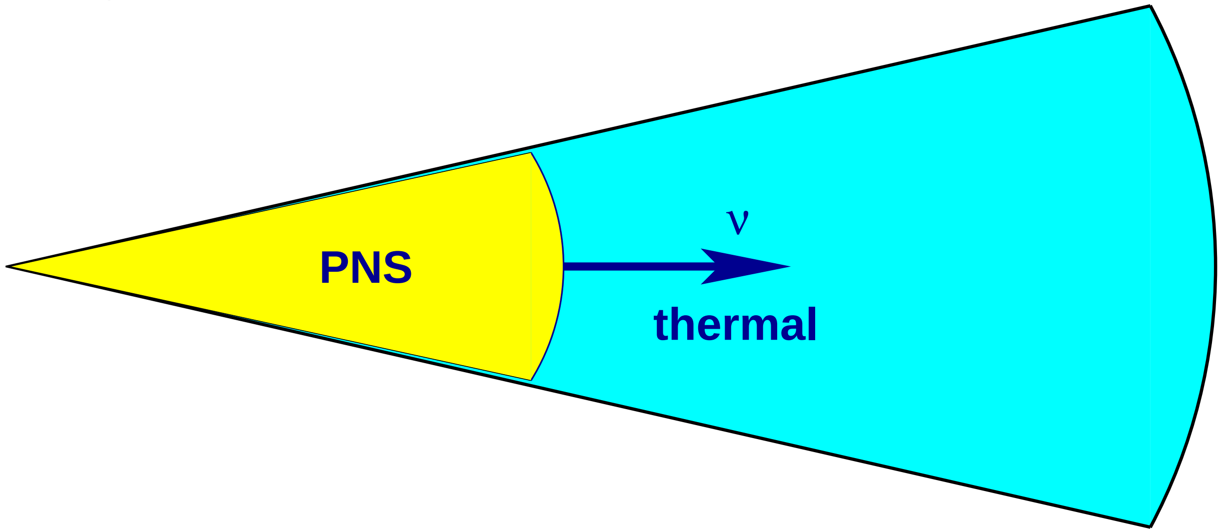
Shock formation and "neutronization burst": $t = 1 - 10$ ms



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.

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.

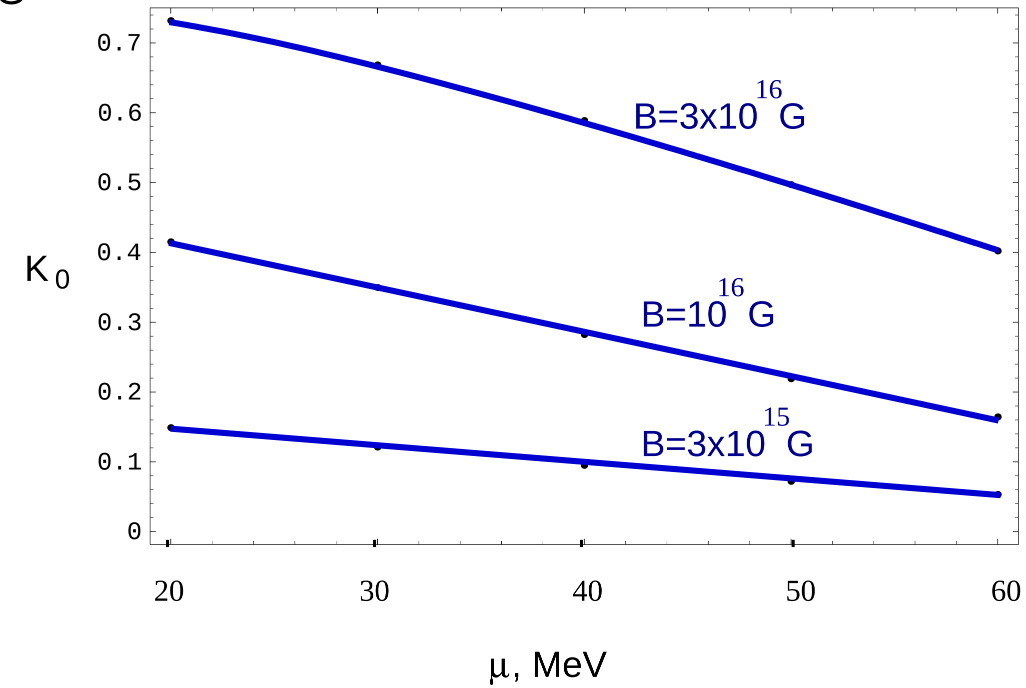
$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

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,

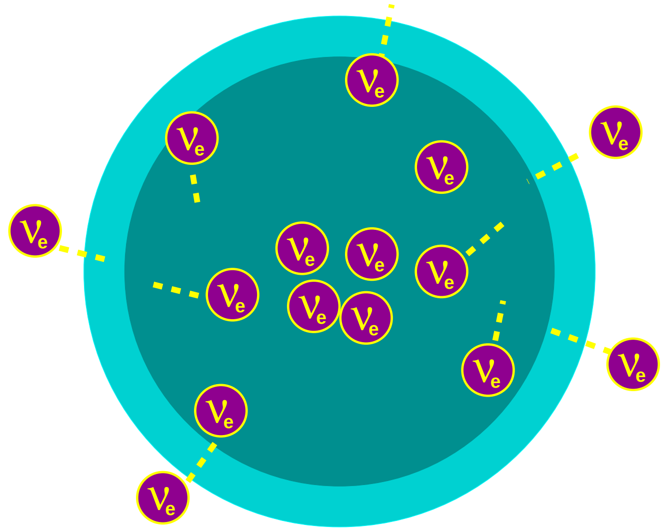


k_0 is the fraction of electrons in the lowest Landau level.

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?

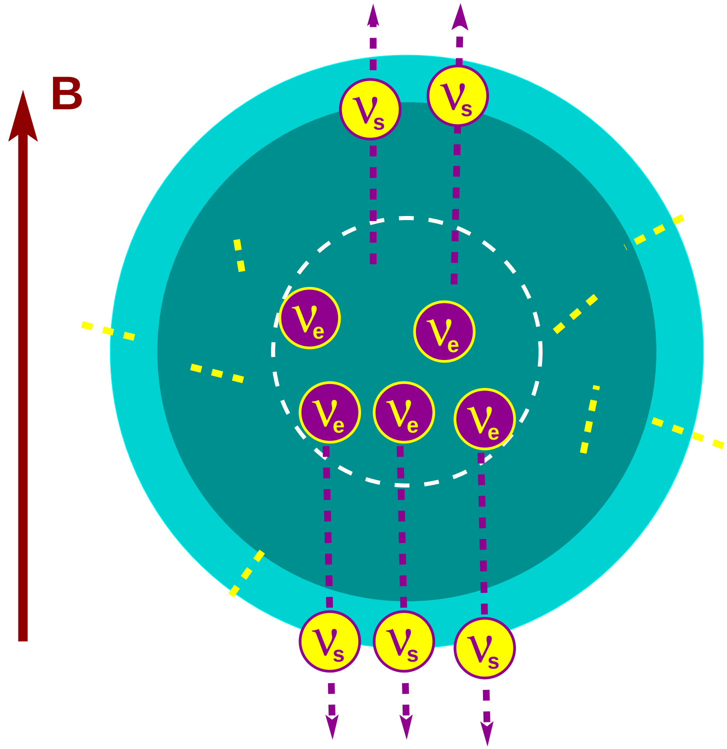
No

Rescattering washes out the asymmetry

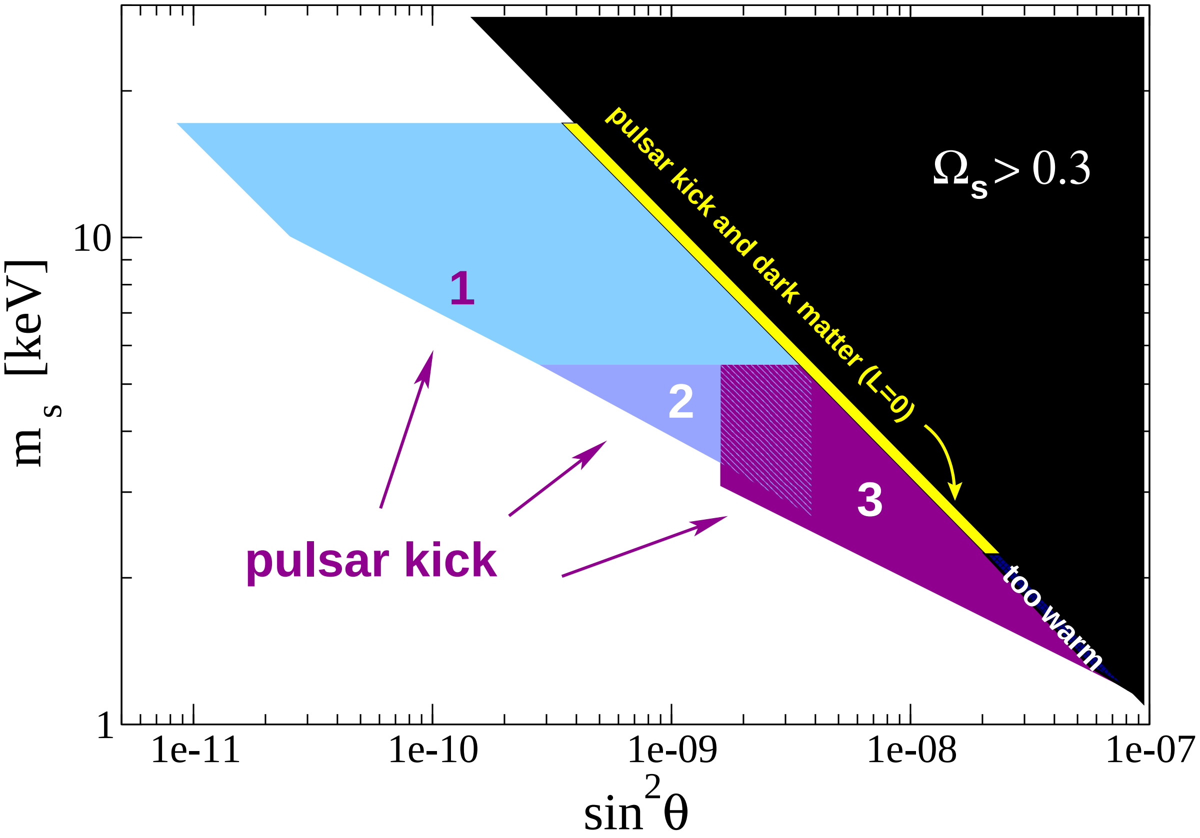
In approximate thermal equilibrium the asymmetries in scattering amplitudes do not lead to an anisotropic emission. Only the outer regions, near neutrinospheres, contribute (a negligible amount).

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

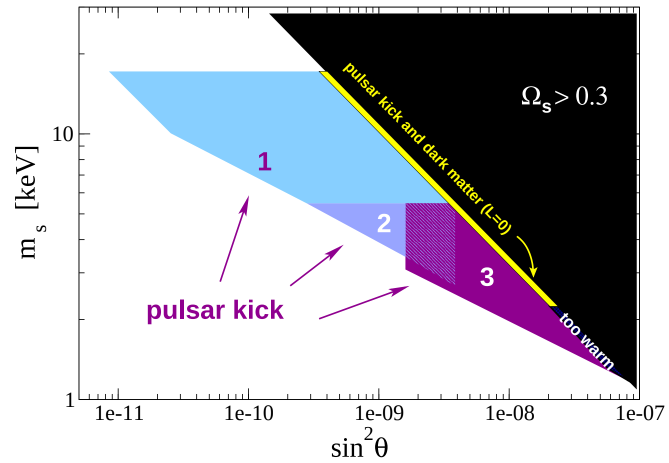
Sterile neutrinos leave the star without scattering. Hence, they give the pulsar a kick.



Resonance (Mikheev-Smirnov) & off-resonance oscillations



the pulsar kick regions overlap with the dark matter region



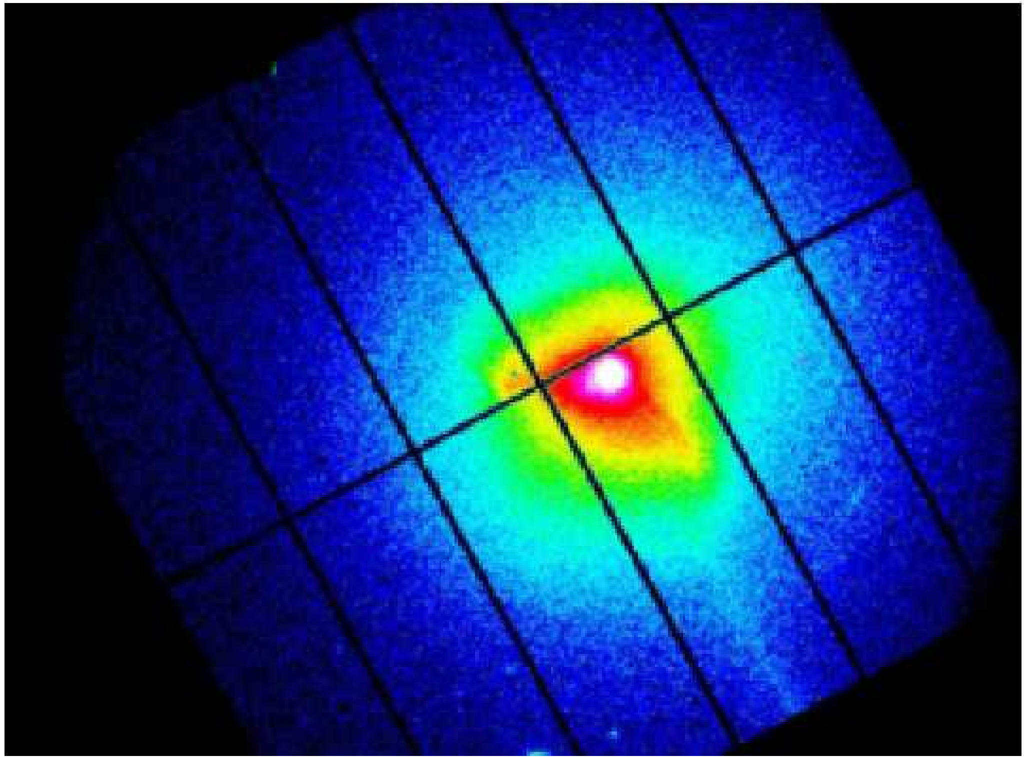
How "natural" is the mixing $\sin^2\theta \sim 10^{-8}$?

Models of neutrino masses commonly predict:

$$\sin^2\theta \sim \frac{m_1}{m_2}$$

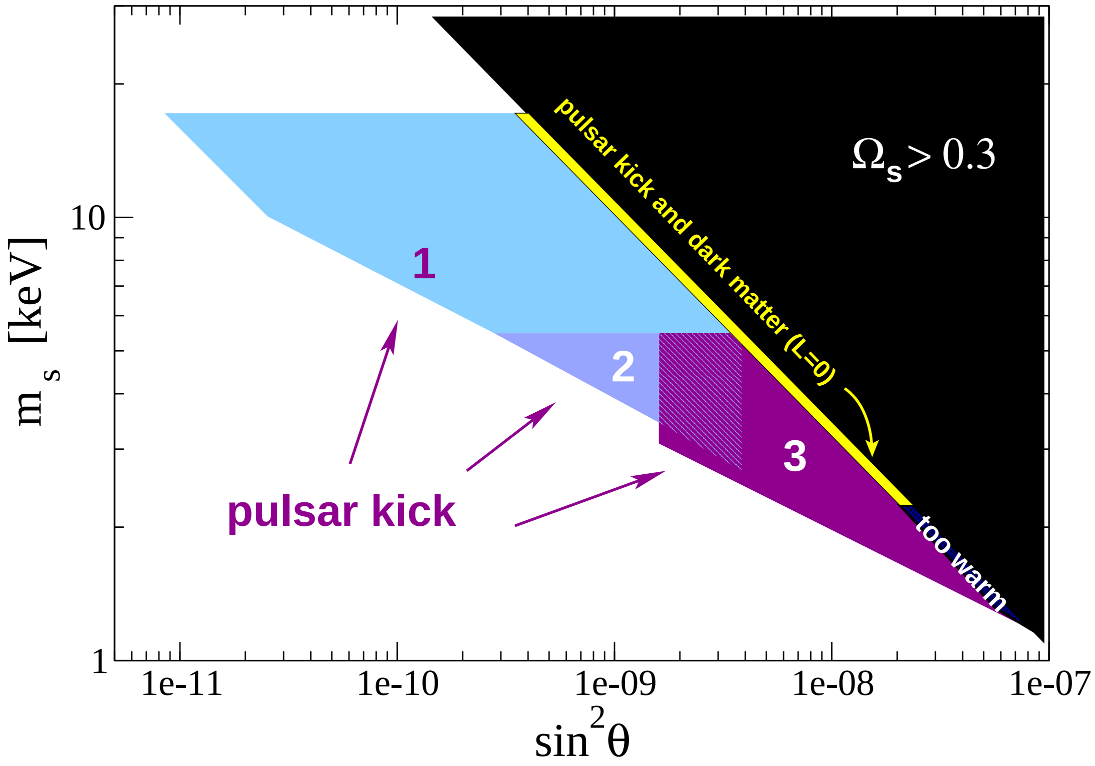
for a heavy neutrnio with a neutrino**10 keV**$=$ **10^4eV** mass and a light one with a 10^{-3}**eV** mass, this ratio is about right.

Chandra, XMM-Newton can see keV photons.



Virgo cluster image from XMM-Newton

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



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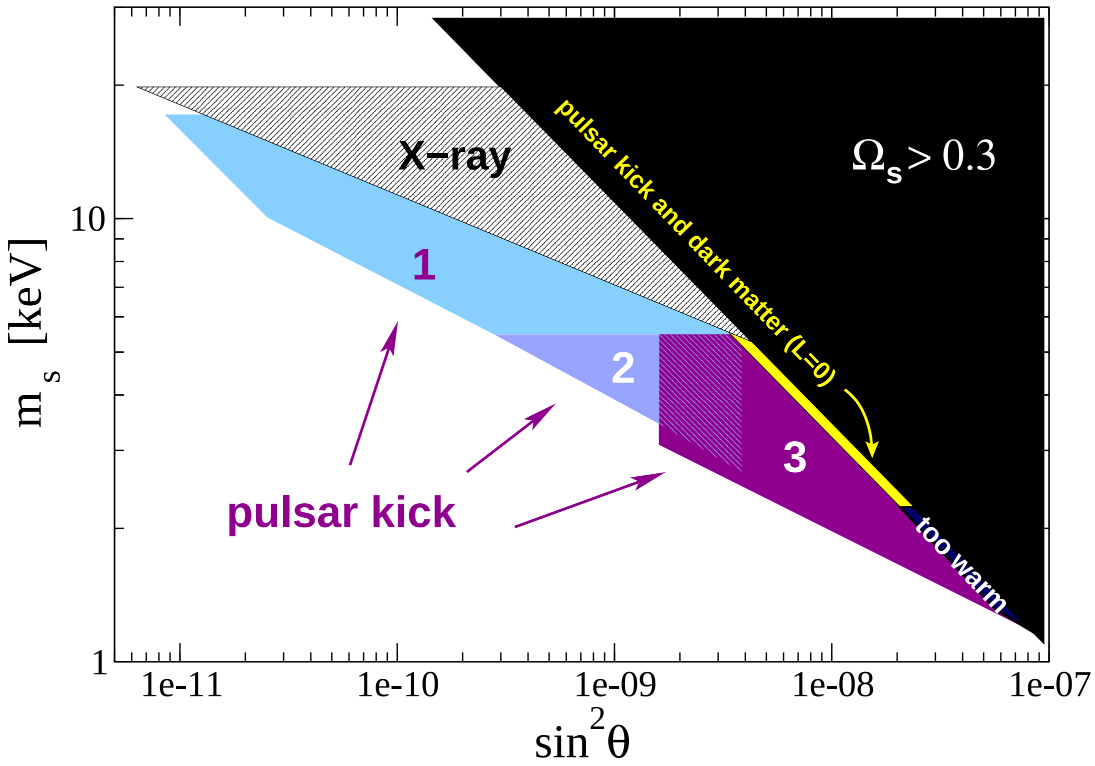

[Abazajian, Fuller, Tucker]

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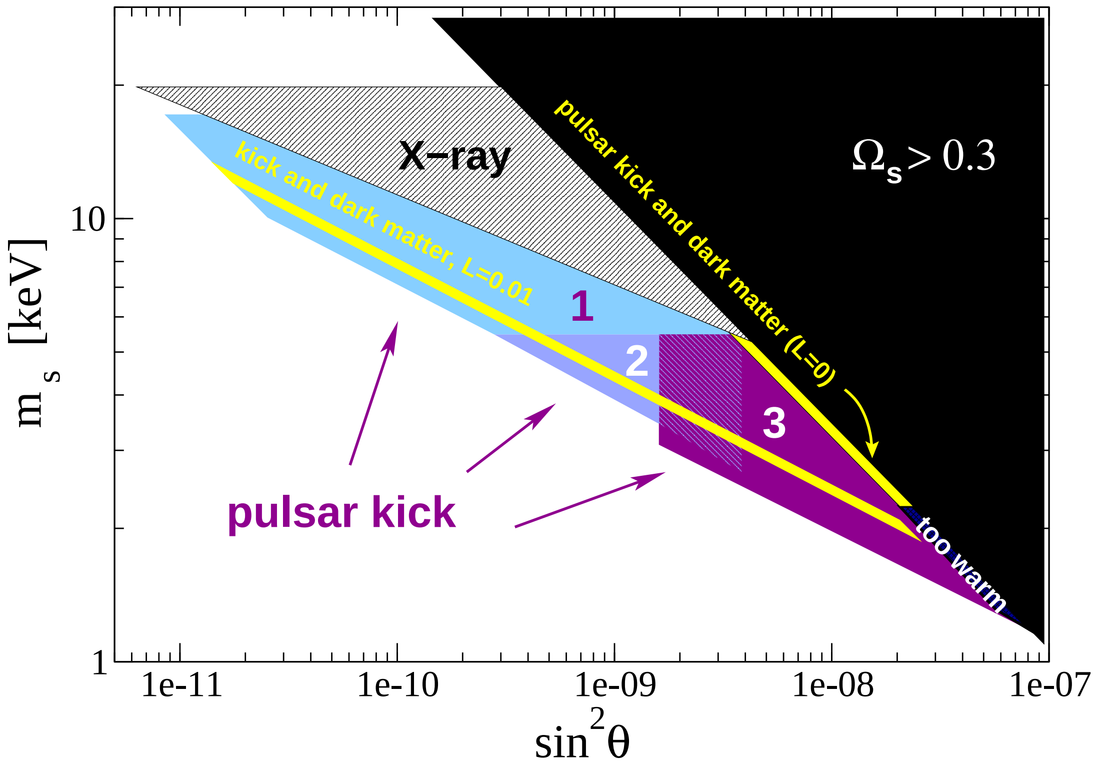
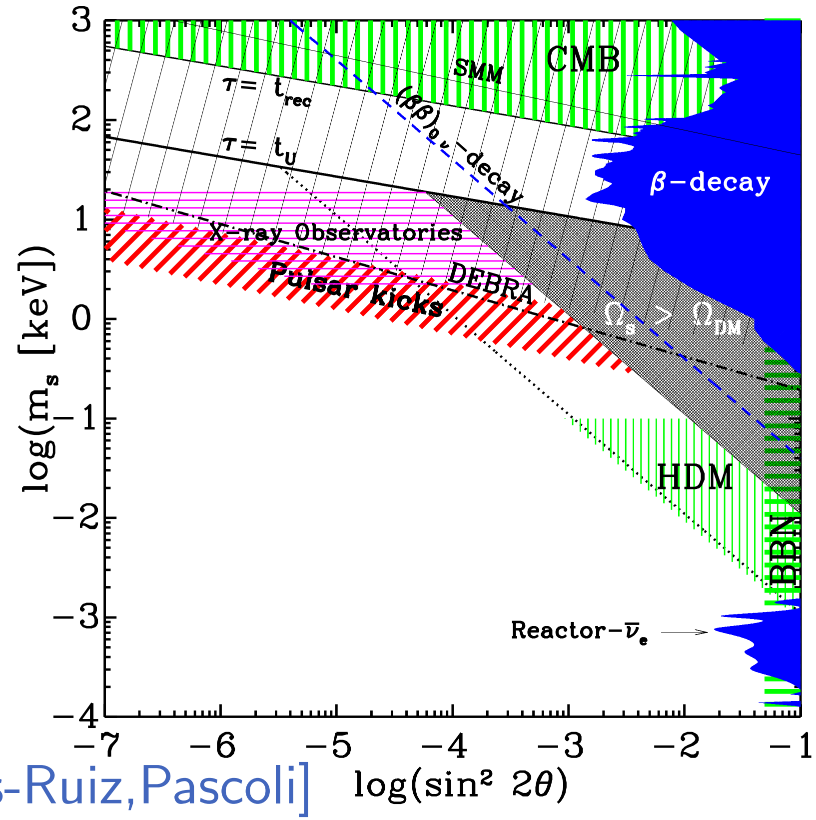


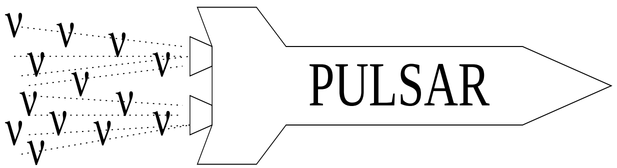
non-zero lepton asymmetry changes the dark matter range
[Abazajian, Fuller, Tucker]

Different cosmology, different limits



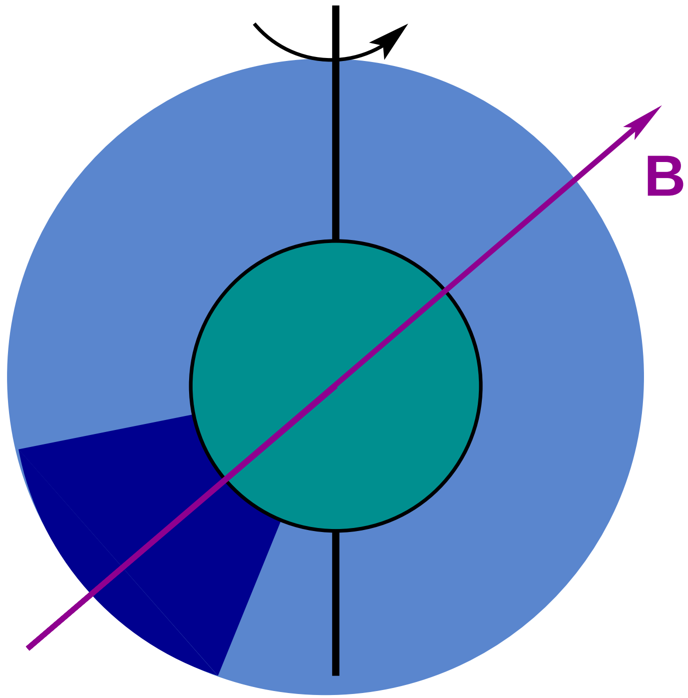
[Gelmini,Palomares-Ruiz,Pascoli]

Gravity waves

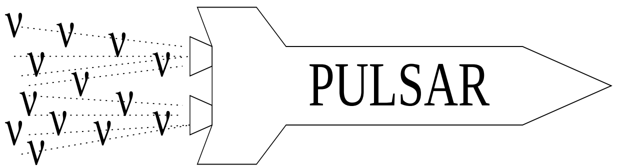


Artist's conception by Roulet [Summer School lectures in Trieste]

Rotating "beam" of neutrinos
is the source of GW



Gravity waves



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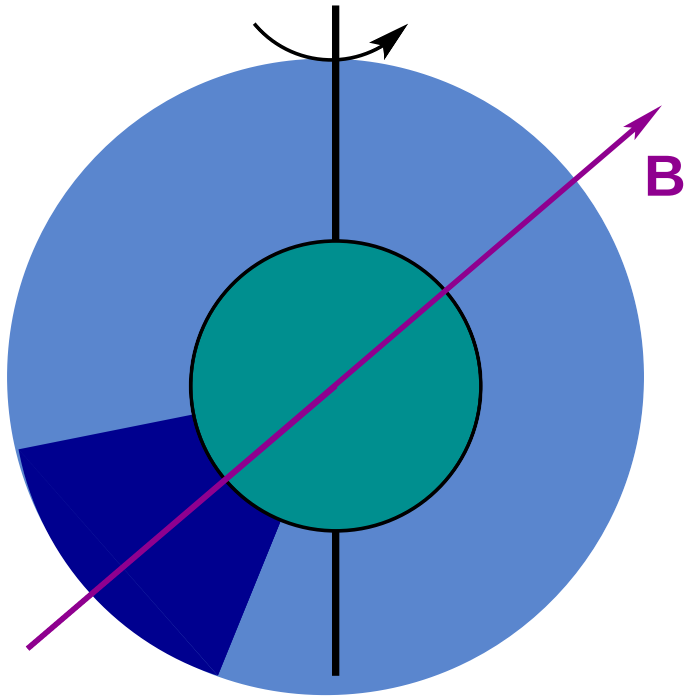
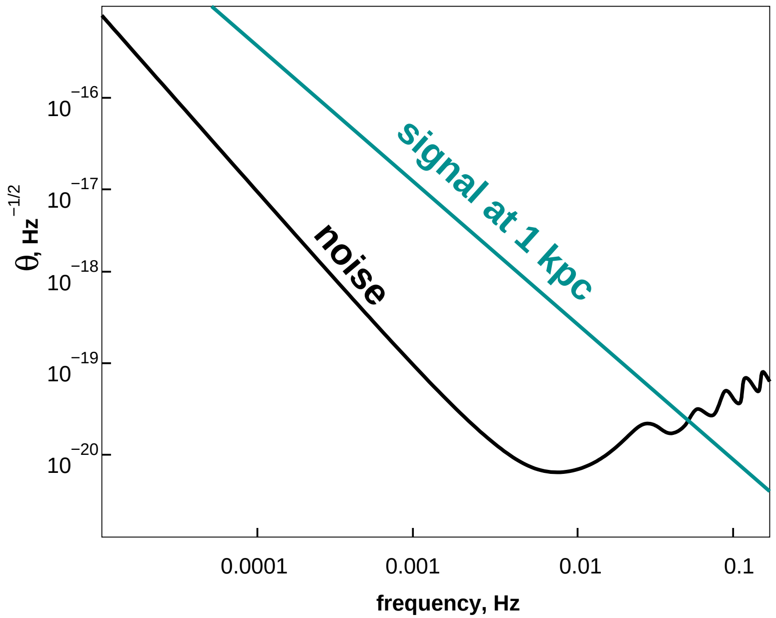
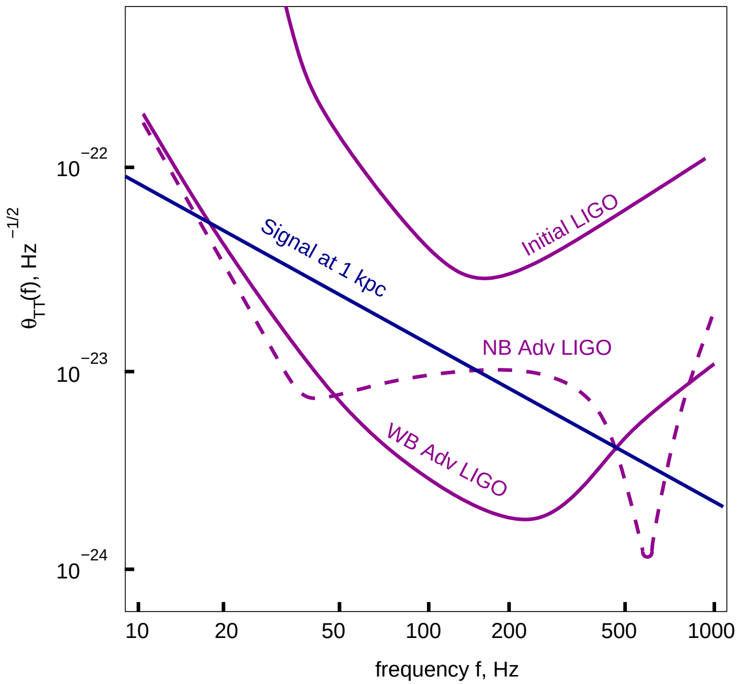


Predicted correlation: direction of $\vec{v}$ and $\vec{\Omega}$.

Gravity waves at LIGO and LISA

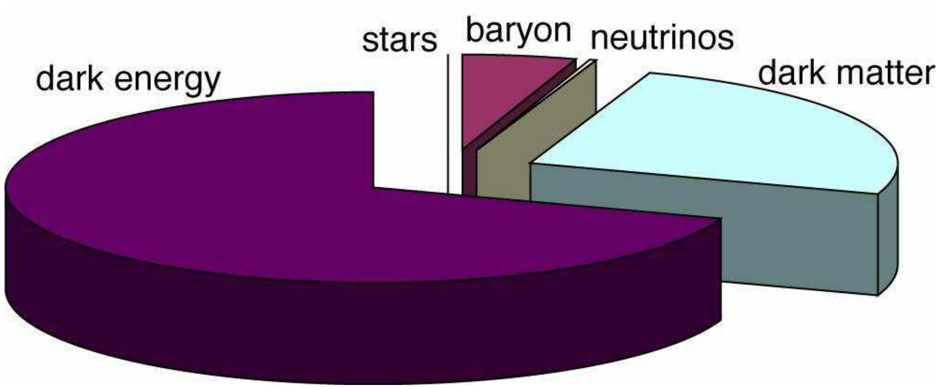




[Loveridge, PR D **69**, 024008 (2004)]

The universe

- **3% ordinary matter**
- 27% dark matter
- 70% dark energy (possibly, cosmological constant)



Baryon asymmetry

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

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

Conditions for baryogenesis

Baryogenesis requires [Sakharov '67]:

- $\mathbf{B}, \mathbf{C}, \mathbf{CP}$ violation
- universe out of thermal equilibrium

N.B. In 1967 the only argument in favor of B violation was... theoretical ambitions

All three conditions are satisfied in the Standard Model (to some extent)

Baryon and lepton numbers

The Standard Model lagrangian is invariant under four *global* U(1) symmetries, which correspond to the conservation of baryon and lepton numbers:

$$\text{quarks}: \quad q \quad \rightarrow \quad e^{i\alpha} q \tag{5}$$

$$\text{leptons}: \quad l_{e,\mu,\tau} \quad \rightarrow \quad e^{i\beta} l_{e,\mu,\tau} \tag{6}$$

However, not all of these symmetries survive quantization.

While the action is invariant under B, B+L, and B-L,

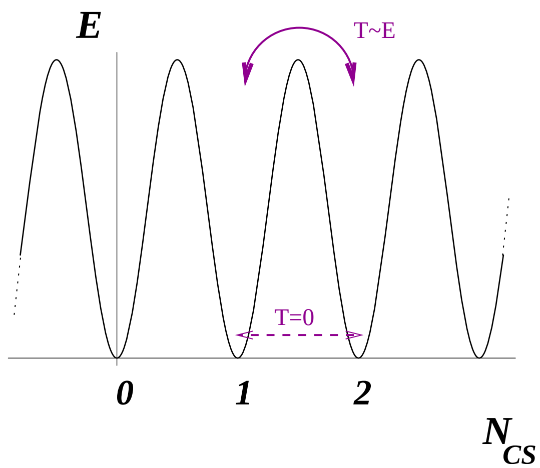
$$\int [dA_\mu][d\psi] \exp\left\{ -\int d^4x \mathcal{L} \right\} \tag{7}$$

the measure is not invariant under the global B+L: **anomaly**

$$\partial_\mu(\bar{\psi}\gamma^\mu\psi) = \frac{1}{32\pi^2} Tr(F_{\mu\nu}\tilde{F}^{\mu\nu}) \tag{8}$$

A change in baryon number can be caused by a change in the gauge field configurations!

Topological structure of gauge vacuum



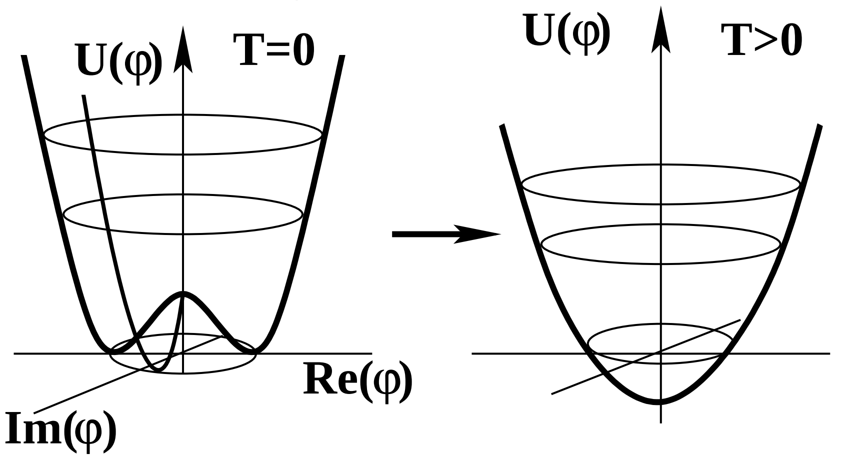
Vacua with different Chern-Simons (baryon) numbers are separated by a high barrier. At zero temperature,

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

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

Electroweak phase transition

Finite-temperature effects change the effective potential.



The Higgs mechanism turns on at some $T_c \sim 10^2$ GeV.

In the Standard Model

- $\mathbf{B}$ violation
- $\mathbf{B}, \mathbf{C}, \mathbf{CP}$ not conserved
- universe out of equilibrium at EW phase transition

ELECTROWEAK BARYOGENESIS!

[Kuzmin, Rubakov, Shaposhnikov '85]

Unfortunately, EW baryogenesis in the SM does not work.

- **Phase transition too weak**. B asymmetry is washed out if sphaleron transitions proceed after PT.

  Need $(v(T_c)/T_c) > 1 \Rightarrow m_H < 45\text{GeV}$, ruled out!

- **CP violation too small**

  CKM $\Rightarrow \eta \equiv \frac{n_B}{n_\gamma} \sim 10^{-20} \times (...)$ too small

EW baryogenesis in the MSSM is ruled out

Perhaps, the strongest evidence, in addition to the existence of dark matter, that the Standard Model is incomplete. Failure of the Standard Model to explain the correct baryon asymmetry is a precursor of future discoveries!

Cannot make baryons in SM $\Rightarrow$ need new physics

SUSY is an appealing candidate

- Electro-Weak MSSM,NMSSM

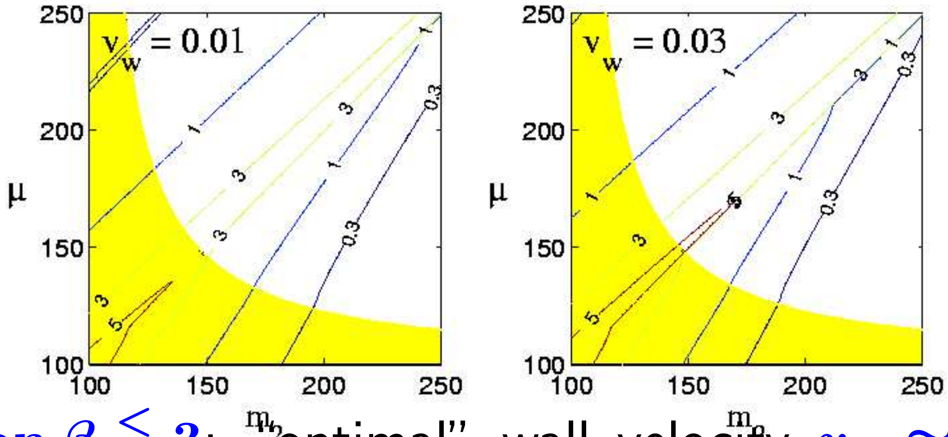
- **Affleck -Dine baryogenesis**

EW baryogenesis in the MSSM

Light right-handed stop, heavy left-handed stop
$\Longrightarrow$ stronger **first-order phase transition**

EW baryogenesis in the MSSM

Contours of baryon asymmetry in units 10^{-10} [Cline,Joyce,Kainulainen]. Shaded limits are excluded by LEP2 limits on chargino mass, $m_{\chi^\pm} > 104$ GeV.



Assumptions: $\tan\beta \lesssim 3$; "optimal" wall velocity $v_w \approx 0.02$; *very thin* wall, $l_w \approx 6/T$.

Cannot make baryons in SM ⇒ need new physics

SUSY is an appealing candidate

- **Electroweak, MSSM**
  Still viable but tightly constrained:
  - very light right-handed stop, heavy left-handed stop
  - light Higgs
  - must assume the "optimal" bubble wall velocity, $v_w \approx 0.02$, very thin wall, *etc.*

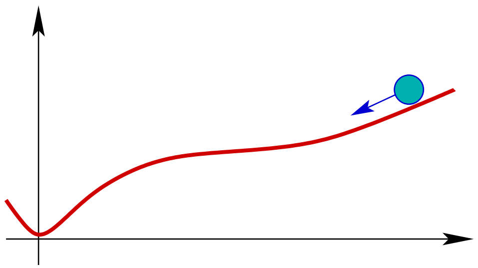
- **Affleck -Dine baryogenesis**

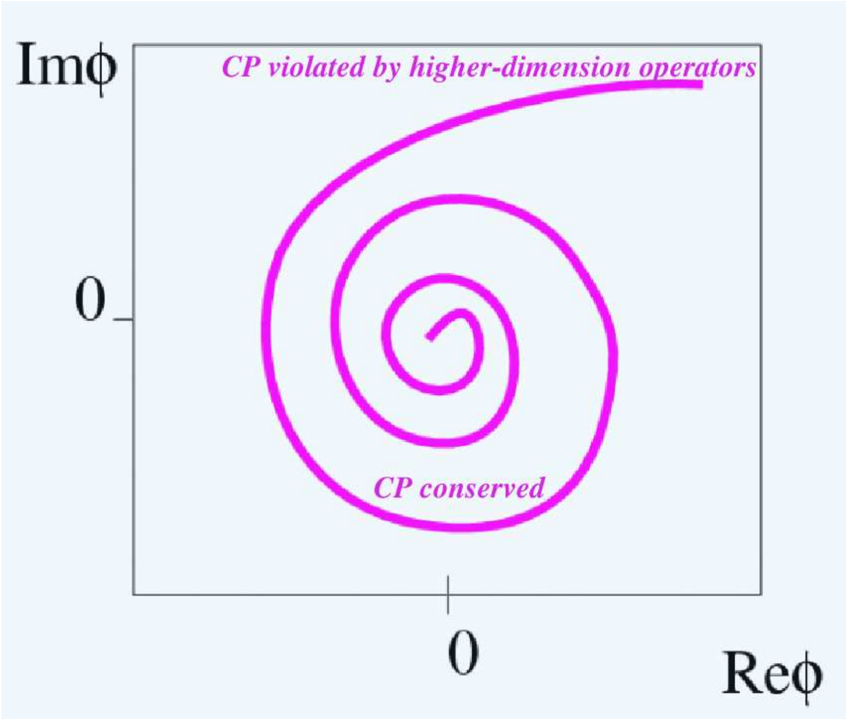
Affleck – Dine baryogenesis

- generic if there is **SUSY + inflation**
- easily reproduces baryon asymmetry of the universe, $\eta \sim 10^{-10}$
- verifiable predictions below a TeV scale
- may explain the ratio $\Omega_{\mathrm{dark}}/\Omega_{\mathrm{matter}}$

Affleck – Dine baryogenesis

at the end of inflation
a scalar condensate
develops a large VEV
along a **flat direction**





CP violation is due to time-dependent background.

Baryon asymmetry: $\phi = |\phi| e^{i\omega t}$

Affleck – Dine baryogenesis: an example

Suppose the flat direction is lifted by a higher dimension operator $W_n = \frac{1}{M^n}\Phi^{n+3}$. The expansion of the universe breaks SUSY and introduces mass terms $m^2 \sim \pm H^2$.

The scalar potential:

$$V = -H^2|\Phi|^2 + \frac{1}{M^{2n}}|\Phi|^{2n+4}$$

Assume the **inflation scale $E \sim 10^{15}$ GeV**

The Hubble constant during inflation is $H_I \approx E^2/M_p \approx 10^{12}$ **GeV**.

Reheat temperature $T_R \sim 10^9$ **GeV**

In this example, the final baryon asymmetry is

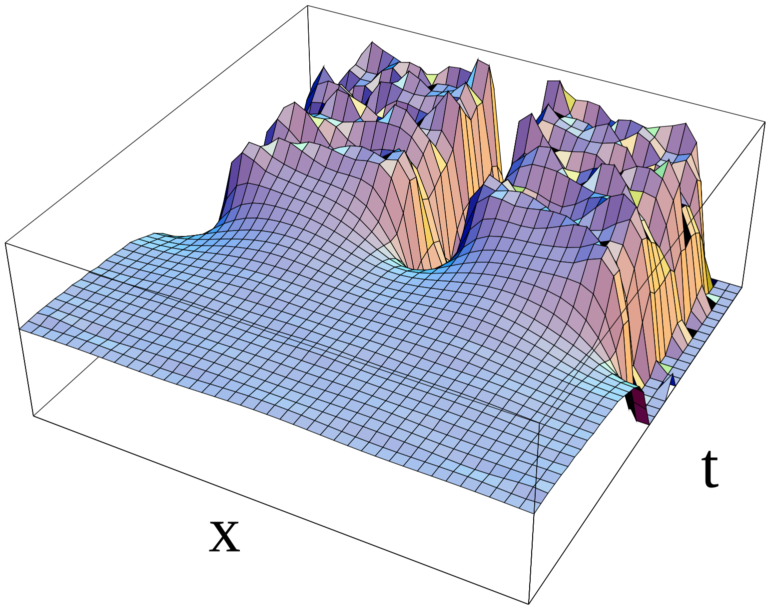
$$\frac{n_B}{n_\gamma} \sim \frac{n_B}{(\rho_I/T_R)} \sim \frac{n_B}{n_\Phi}\frac{T_R}{m_\Phi}\frac{\rho_\Phi}{\rho_I}$$

$$\sim 10^{-10}\left(\frac{T_R}{10^9\mathrm{GeV}}\right)\left(\frac{M_p}{m_{3/2}}\right)^{\frac{(n-1)}{(n+1)}}$$

Correct baryon asymmetry for $n = 1$. (For $n > 1$, too big.)

[This example is worked out in Dine, AK, Rev. Mod. Phys. **76**, 1 (2004)]

Fragmentation of the Affleck-Dine condensate



small inhomogeneities can grow

unstable modes:

$$0 < k < k_{\max} = \sqrt{\omega^2 - U''(\phi)}$$

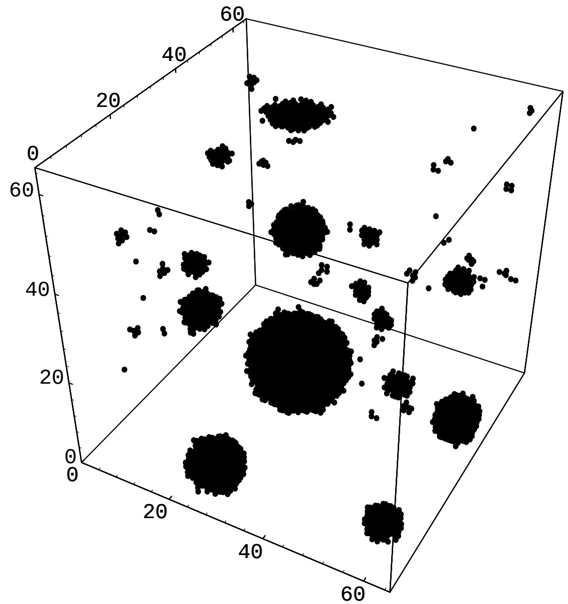
$\Rightarrow$ **Lumps of baryon condensate**

$\Rightarrow$ **Q-balls**

Fragmentation ≈ pattern formation

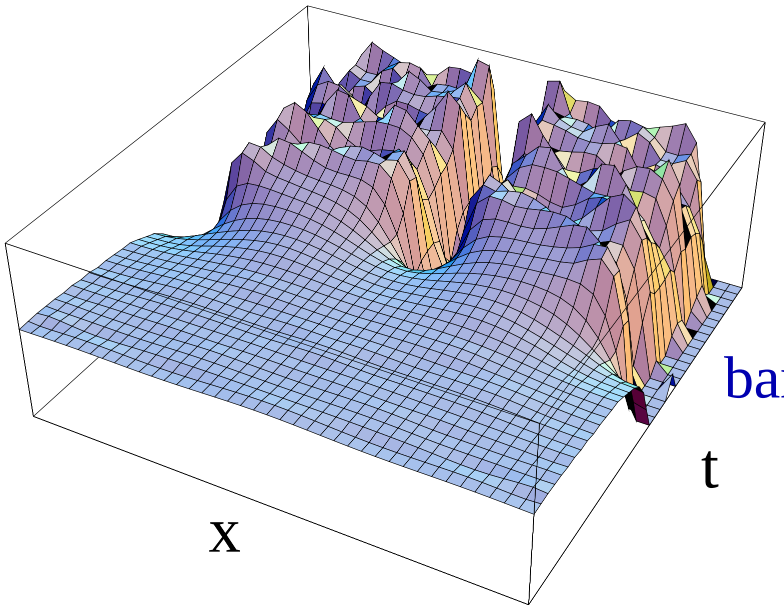
Familiar example:

Numerical simulations of the fragmentation



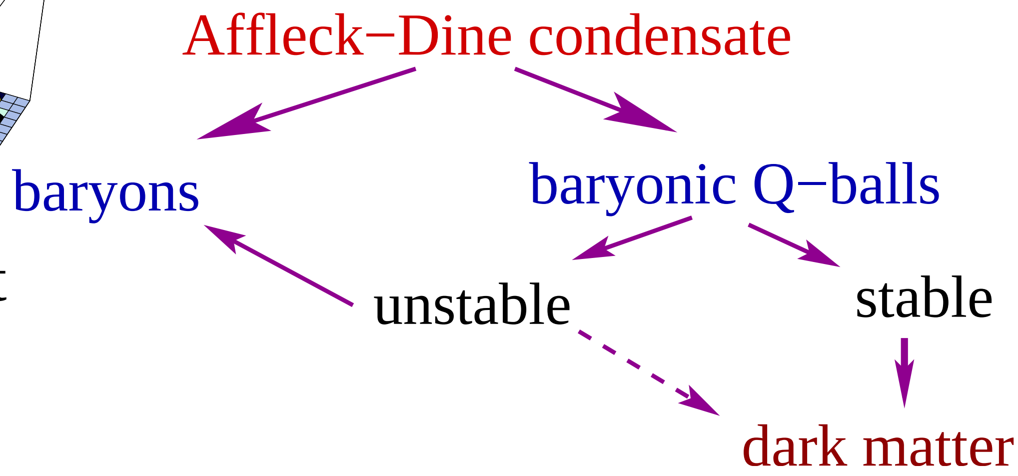
[Kasuya, Kawasaki]

Fragmentation of AD condensate can produce Q-balls



SUSY Q-balls may be stable or unstable

if stable ⇒ **dark matter**



Stable Q-balls as dark matter

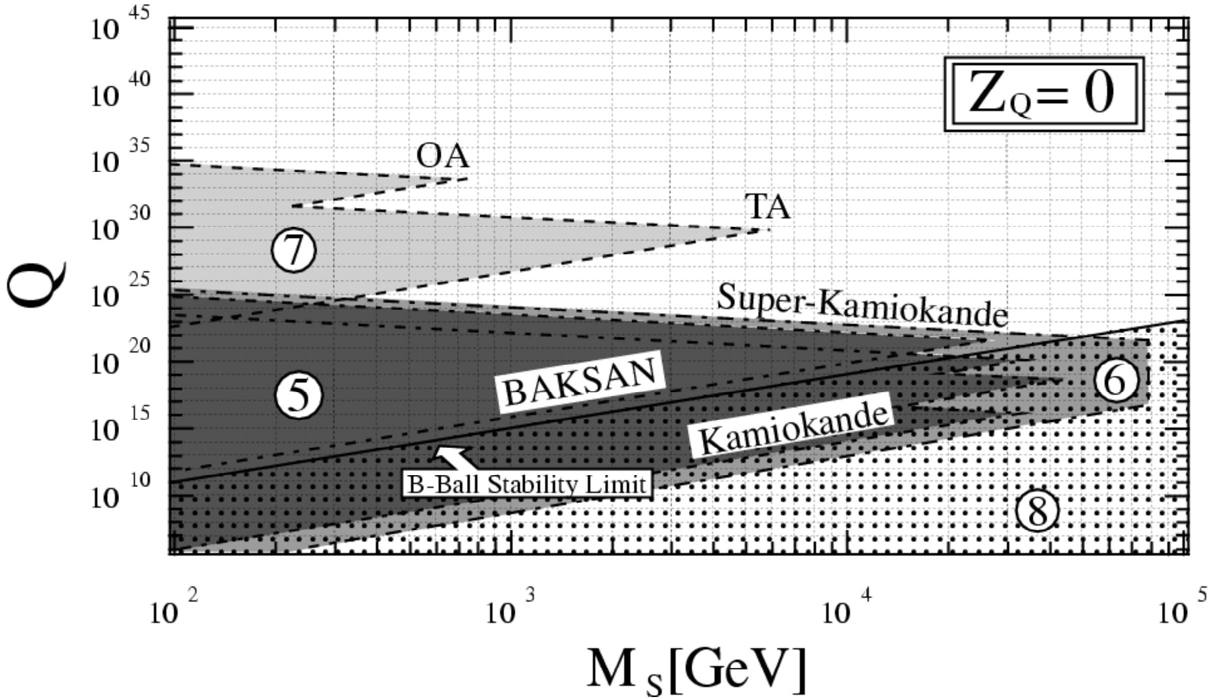
Q-balls can accommodate baryon number at lower energy than a nucleon
$\Rightarrow$ **B-Balls catalyze proton decay** Signal:

$$\frac{dE}{dl} \sim 100 \left(\frac{\rho}{1\,\mathrm{g/cm^3}} \right) \frac{\mathrm{GeV}}{\mathrm{cm}}$$

Heavy $\Rightarrow$ low flux

$\Rightarrow$ **experimental limits from Super-Kamiokande and other *large* detectors**

Present experimental limits



[Arafune *et al.*]

$$\Omega_{\rm B-ball}/\ \Omega_{\rm matter} \sim 10$$

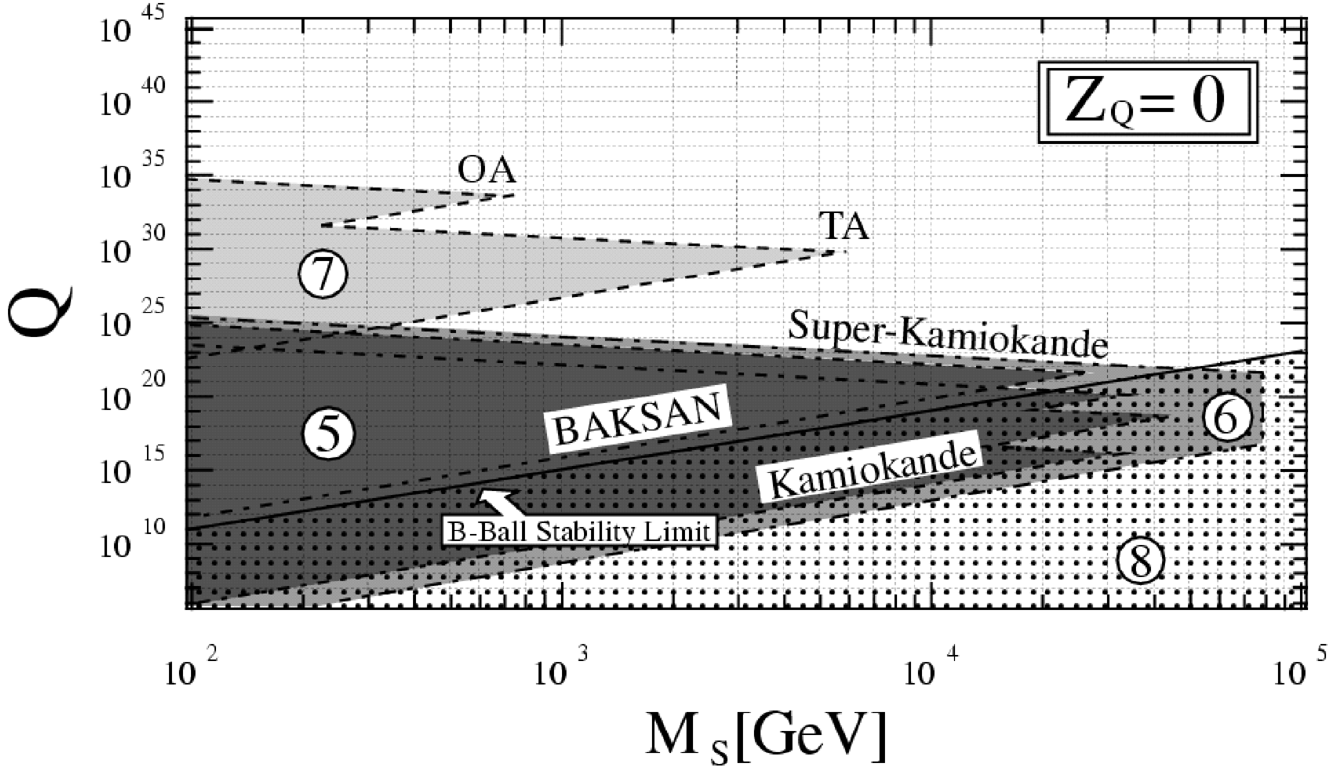
Ordinary and dark matter arise from the same process. Hence, one may be able to **explain why $\Omega_{\rm matter}$ and $\Omega_{\rm dark}$ are not very different**. [Fijii,Yanagida; Enqvist, McDonald; Laine, Shaposhnikov]

- expect $Q_{\rm B} \sim 10^{26\pm 2}$ (analytical calculations & numerical simulations)

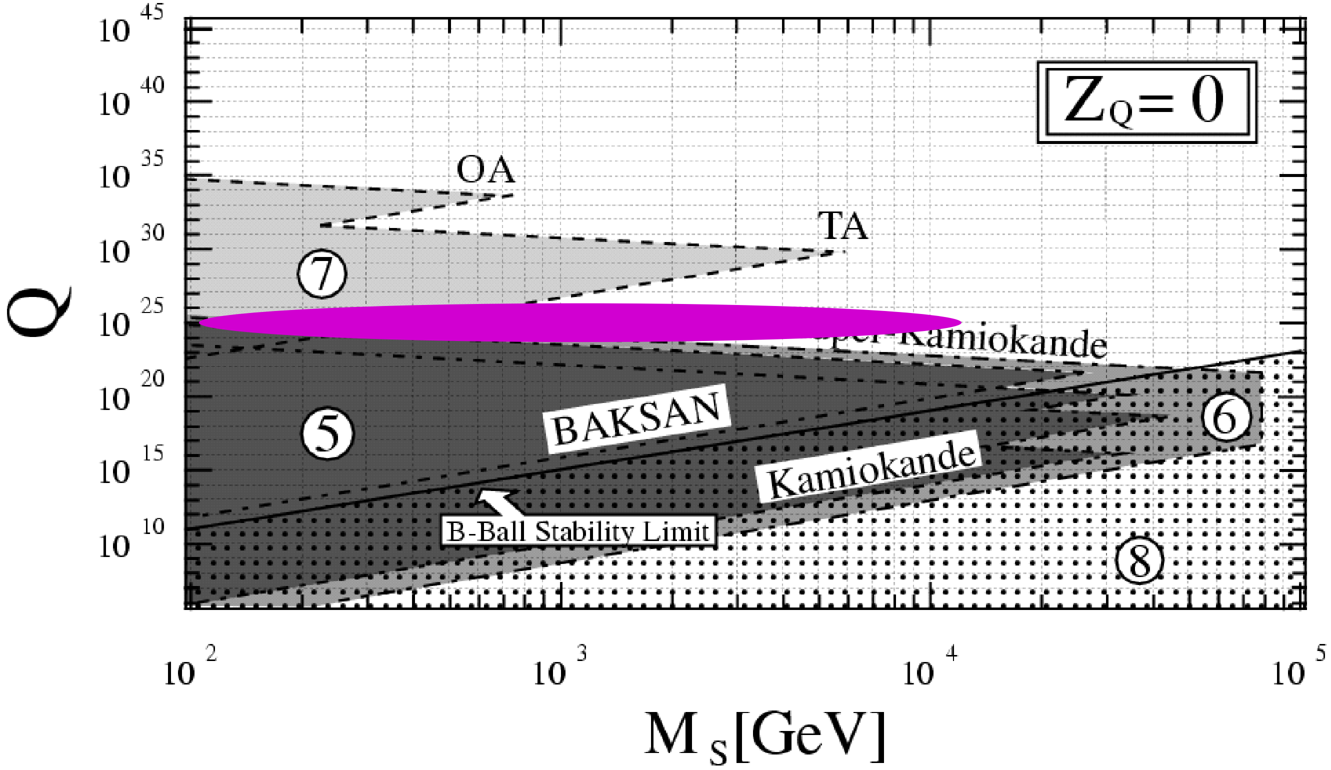
$\Omega_{\rm B-ball}/\Omega_{\rm matter} \sim 10$ implies

$$\eta_{\rm B} \sim 10^{-10} \left(\frac{M_{\rm SUSY}}{\rm TeV}\right) \left(\frac{Q_{\rm B}}{10^{26}}\right)^{-1/2}$$

$$\Omega_{B-ball}/\ \Omega_{matter} \sim 10$$



$$\Omega_{B-ball}/\ \Omega_{matter} \sim 10$$



Need something **bigger than Super-K**!

Leptogenesis

Electroweak sphalerons erase any primordial $(B + L)$

However, if high-scale physics produced some non-zero $(B - L)$, electroweak sphalerons could redistribute the asymmetry between B and L [Fukugita,Yanagida]

Example: decay of a heavy right-handed neutrino
(L is not conserved)

CP violation in the neutrino mass matrix?

[John Beacom's lectures]