- **keV sterile neutrinos as dark matter**
- **SUSY Q-balls as dark matter**

Neutrino masses and sterile neutrinos

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:

$$M = \left(\begin{array}{cc} 0 & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{array} \right)$$

What is the *natural* scale of M?

Seesaw mechanism

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

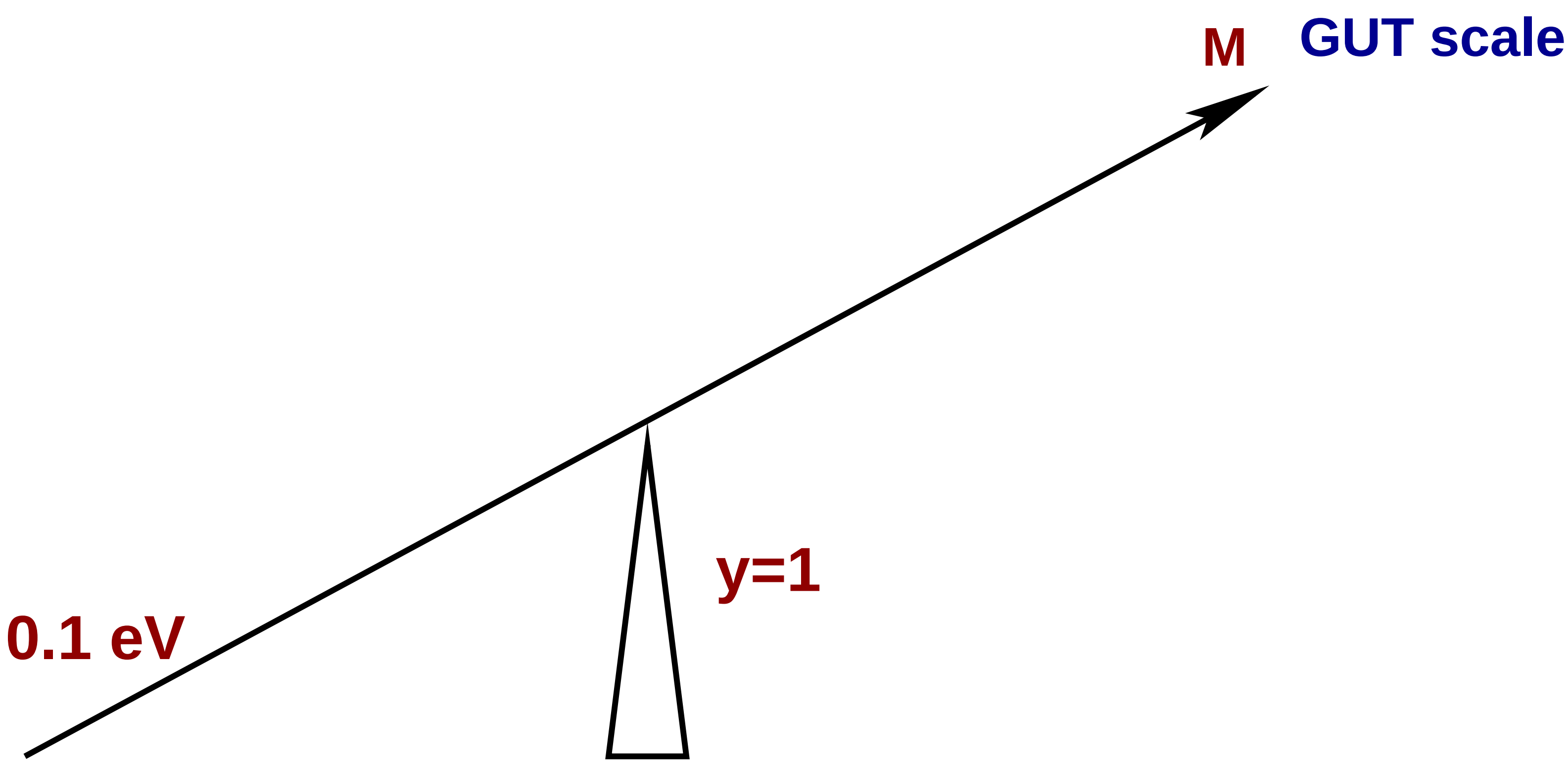
$$D_{ij} = y_{ij} \langle H \rangle$$

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

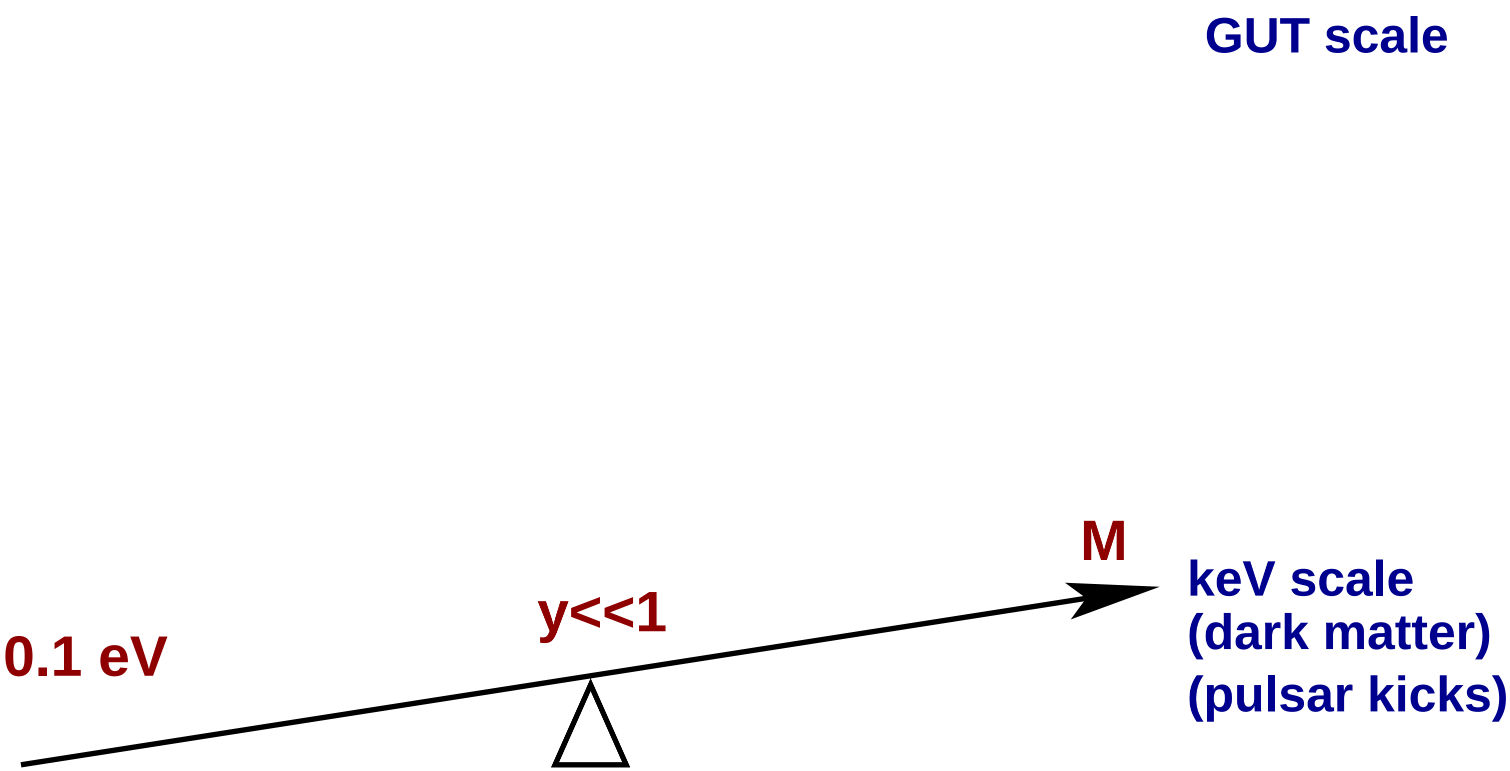
$$m_\nu \sim \frac{y^2 \langle H \rangle^2}{M}$$

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

Seesaw mechanism



Seesaw mechanism



Various approaches to small Majorana masses

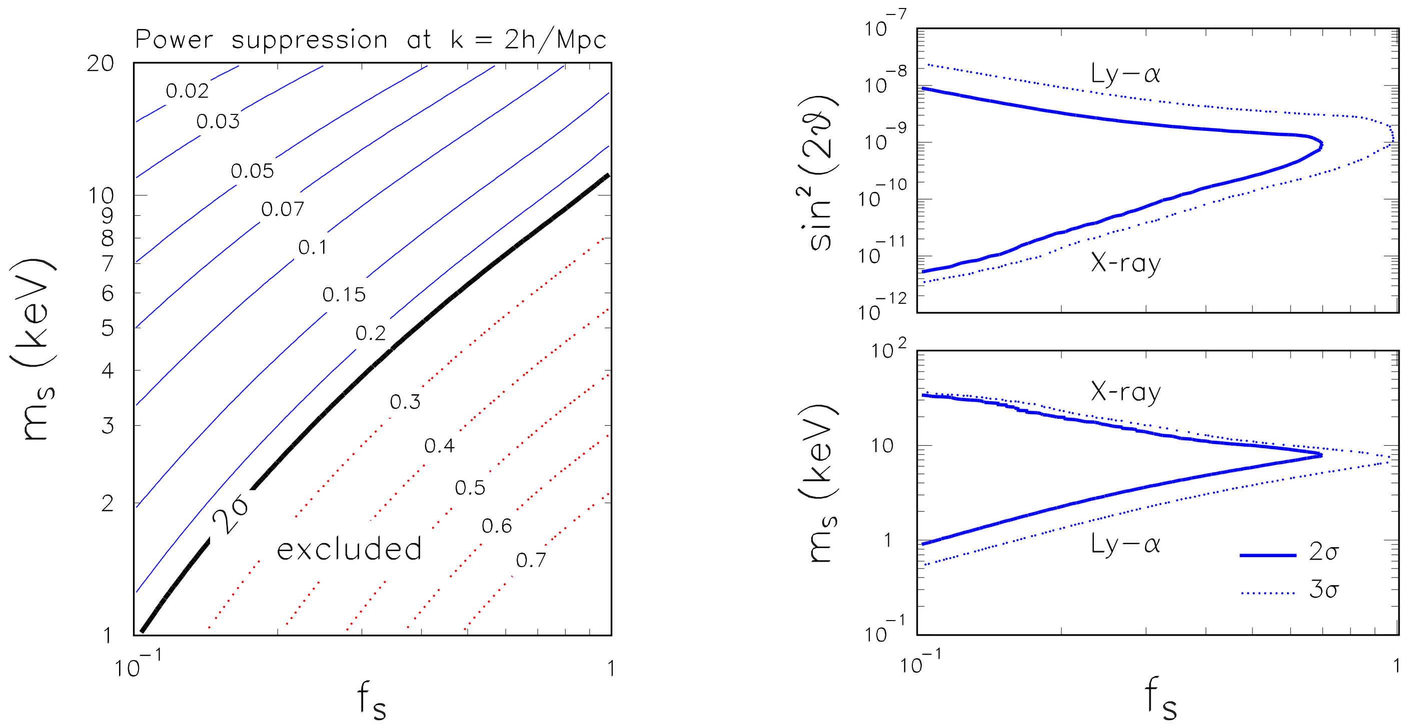
- Just write them down.
  - One sterile keV sterile neutrino, the dark matter candidate **[Dodelson, Widrow]**.
  - Three sterile neutrinos, one with a several keV mass (dark matter) and two degenerate with GeV masses and a keV splitting, νMSM **[Shaposhnikov et al.]**.
- Use **lepton number** conservation as the reason for a small mass **[de Gouvêa]**.
- Use **flavor symmetries**, new gauge symmetries **[Lindner et al.]**
- **Singlet Higgs** (discussed below) at the electroweak scale can generate the Majorana mass. Added bonuses:
  - production from $S \to NN$ at the electroweak scale generates *the right amount* of dark matter.
  - production from $S \to NN$ at the electroweak scale generates *colder* dark matter. A **"miracle"**: EW scale and mass at the keV scale (for stability) $\Rightarrow$ **correct DM abundance**. **[AK; AK, Petraki]**
- **Split seesaw** (discussed below) makes the scale separation natural. Dark matter cooled by various effects. $\Rightarrow$ **democracy of scales**

Sterile neutrinos as dark matter: production scenarios

Production **color coded** by **"warmness" vs "coldness"**:

- **Neutrino oscillations off resonance** [Dodelson, Widrow] No prerequisites; production determined by the mixing angle alone; no way to turn off this channel, except for low-reheat scenarios [Gelmini et al.]
- **MSW resonance in $\nu_a \to \nu_s$ oscillations** [Shi, Fuller] Pre-requisite: sizable lepton asymmetry of the universe. The latter may be generated by the decay of heavier sterile neutrinos [Laine, Shaposhnikov]
- **Higgs decays** [AK, Petraki] Assumes the Majorana mass is due to Higgs mechanism. **Sterile miracle: abundance a "natural" consequence of singlet at the electroweak scale**. Advantage: "natural" dark matter abundance
- **Split seesaw**: [AK, Takahashi, Yanagida]
  Two production mechanisms, **cold** and **even colder**.
  Advantage: "naturally" low mass scale

Lyman-α bounds on Dodelson-Widrow production



[Palazzo, Cumberbatch, Slosar, Silk]

100% of DM produced by oscillations not allowed: at least 30% must come from some other mechanism, for example, Higgs decays.

Challenges to CDM, hints of WDM?

- Too big to fail [Bolyan-Kolchin, Bullock, Kpalinghat,...]
- Cored profiles of dwarf spheroidals [Gilmore, Wyse; Strigari et al.]
- Minimal size of dSphs [Wyse et al.]
- overproduction of the satellite halos for galaxies of the size of Milky Way [Klypin; Moore]
- 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]
- 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.]

New scale or new Higgs physics?

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

To explain the pulsar kicks and dark matter, one needs $M \sim$ **keV**. Is this a new fundamental scale? Perhaps. Alternatively, it could arise from the Higgs mechanism:

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

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

Now $S \to NN$ decays can produce sterile neutrinos.

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 $T \sim m_S$ from decays $S \to NN$:

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

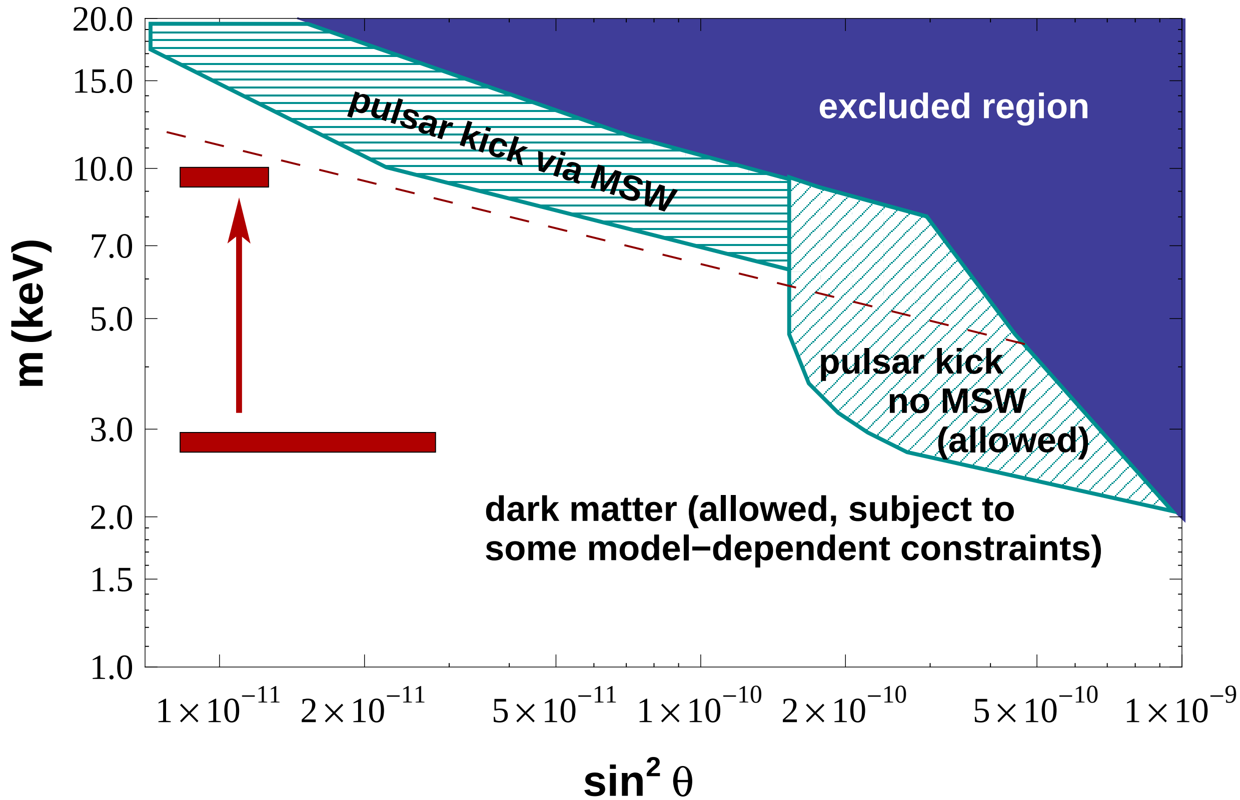
Here ξ is the dilution factor due to the change in effective numbers of degrees of freedom.

$\langle S \rangle \sim 10^2\,\mathrm{GeV}$ (EW scale)
$M_s \sim \mathrm{keV}$ (for stability) $\Rightarrow h \sim 10^{-8}$

$$\Rightarrow \Omega \approx 0.2$$

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

Cooling changes the clustering properties

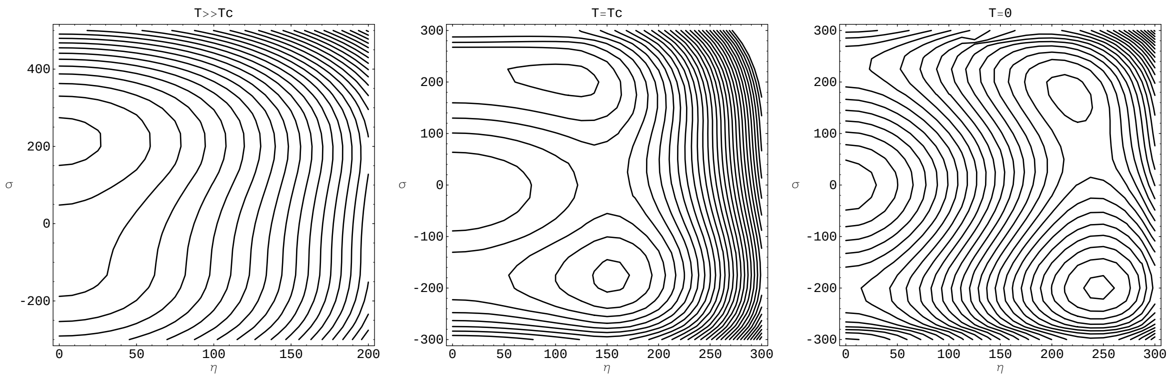


[AK, PRL **97**:241301 (2006); Petraki, AK, PRD 77, 065014 (2008); Petraki, PRD 77, 105004 (2008)]

Implications for the EW phase transition and the LHC

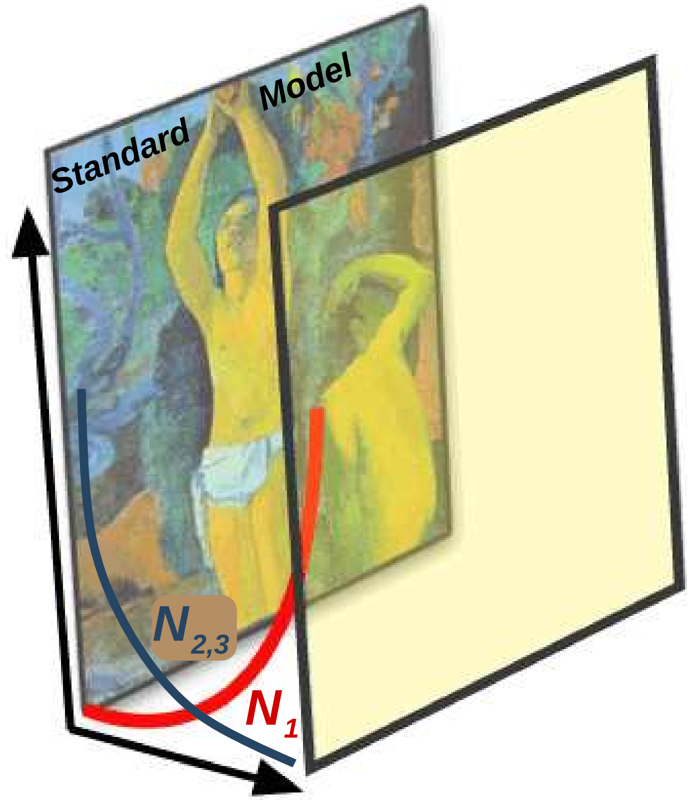
One may be able to discover the *singlet Higgs* at the LHC [Profumo, Ramsey-Musolf, G. Shaughnessy; Davoudiasl et al.; O'Connell et al.; Ramsey-Musolf, Wise]

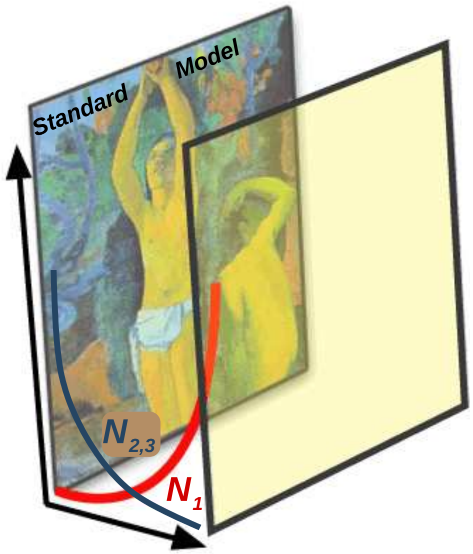
The presence of S in the Higgs sector changes the nature of the electroweak phase transition [AK, Petraki]



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

Split seesaw





Standard Model on $z = 0$ brane. A Dirac fermion with a bulk mass m:

$$S = \int d^4x\, dz\, M \left(i\bar{\Psi}\Gamma^A \partial_A \Psi + m\bar{\Psi}\Psi \right),$$

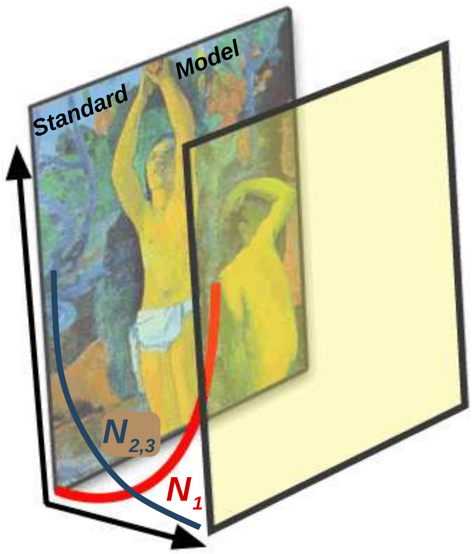
The zero mode: $(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0.$ behaves as $\sim \exp(\pm mz)$. The 4D fermion:

$$\Psi_R^{(0)}(z,x) = \sqrt{\frac{2m}{e^{2m\ell}-1}}\frac{1}{\sqrt{M}} e^{mz}\psi_R^{(4D)}(x).$$

Also, a $U(1)_{(B-L)}$ gauge boson in the bulk, $(B-L) = -2$ Higgs ϕ on the SM brane. The VEV $\langle\phi\rangle \sim 10^{15}$GeV gives right-handed neutrinos heavy Majorana masses.

[AK, Takahashi, Yanagida]

Split seesaw



Effective Yukawa coupling and the mass are suppressed:

$$M^{(R)}_{d=4} = M^{(R)}_{d=5}\left(\frac{2m_i}{M(e^{2m_i\ell}-1)}\right),$$

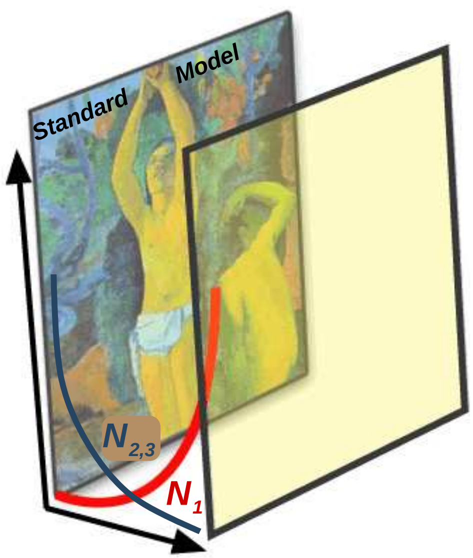
$$y_{d=4} = y_{d=5}\sqrt{\frac{2m_i}{M(e^{2m_i\ell}-1)}}$$

successful seesaw relation unchanged:

$$m_\nu \sim \frac{y^2_{d=4}\langle H\rangle^2}{M^{(R)}_{d=4}} = \frac{y^2_{d=5}\langle H\rangle^2}{M^{(R)}_{d=5}}$$

[AK, Takahashi, Yanagida]

Split seesaw: economical, natural extension of SM



- Democracy of scales: small difference in the bulk masses m_i results in exponentially large splitting between the sterile neutrino masses.
- An rather minimal model: SM augmented by three right-handed singlets can explain
  - observed **neutrino masses**
  - **baryon asymmetry** (via leptogenesis)
  - **dark matter**

  if, for example
  $M_1 = 5\,\mathrm{keV}$ or $M_1 = 17\,\mathrm{keV}$, and
  $M_{2,3} \sim 10^{15}\mathrm{GeV}$

[AK, Takahashi, Yanagida]

Dark matter production in Split Seesaw: two scenarios

The $\mathrm{U}(1)_{(B-L)}$ gauge boson couples to right-handed neutrinos. It becomes massive due to the Higgs VEV $\langle\phi\rangle \sim 10^{15}$GeV.

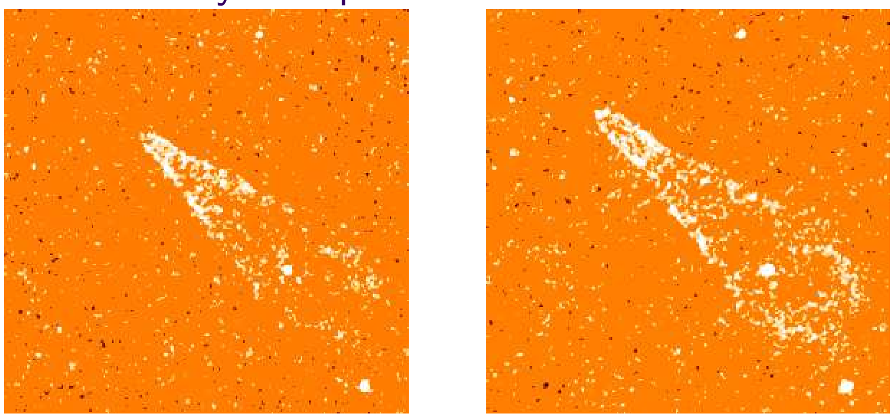
1. Reheat temperature $T_R \sim 5 \times 10^{13}\,\mathrm{GeV} \ll \times\langle\phi\rangle$, and sterile/righthanded neutrinos are out of equilibrium. Thermal abundance is never reached; correct DM abundance is controlled by T_R.
2. Reheat temperature $T_R > \langle\phi\rangle$, and sterile/right-handed neutrinos are in equilibrium before the first-order $\mathrm{U}(1)_{(B-L)}$ phase transition. After the transition, the temperature is below the $(B-L)$ gauge boson mass, and right-handed neutrinos are out of equilibrium. The entropy released in the first-order phase transition dilutes DM density and red-shifts the particle momenta.

The free-streaming length is further reduced by the entropy production from SM degrees of freedom. Both (1) and (2) produce acceptable DM abundance. DM from (2) is colder than from (1) by a factor ≈ 5, and colder than DW dark matter by factor ≈ 15.

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

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"...

Currently, hopes for SASI. (Can it be consistent with $\vec{\Omega} - \vec{v}$ correlation?)

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??

Neutron stars have large magnetic fields.

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.

Electroweak processes producing neutrinos (urca),

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

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

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

The asymmetry:

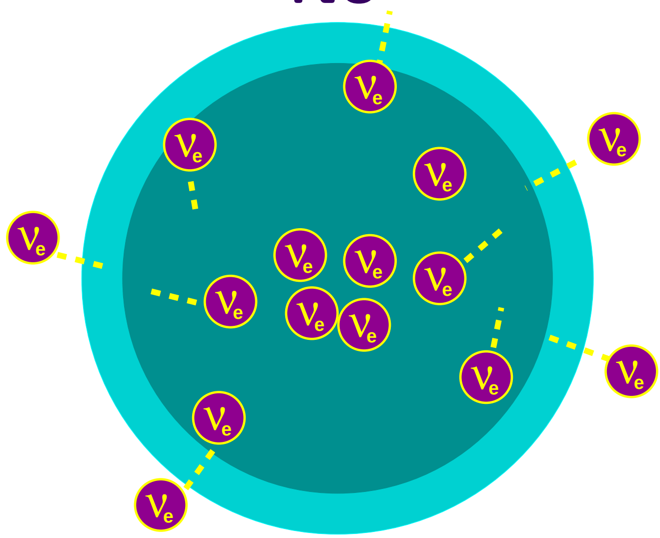
$$\tilde{\epsilon} = \frac{g_V^2 - g_A^2}{g_V^2 + 3g_A^2} k_0 \approx 0.4\, k_0,$$

where k_0 is the fraction of electrons in the lowest Landau level.
$k_0 \sim 0.3$ in a strong magnetic field.

$\Rightarrow \sim 10\%$ **anisotropy??**

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

No



Neutrinos are trapped at high density.

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

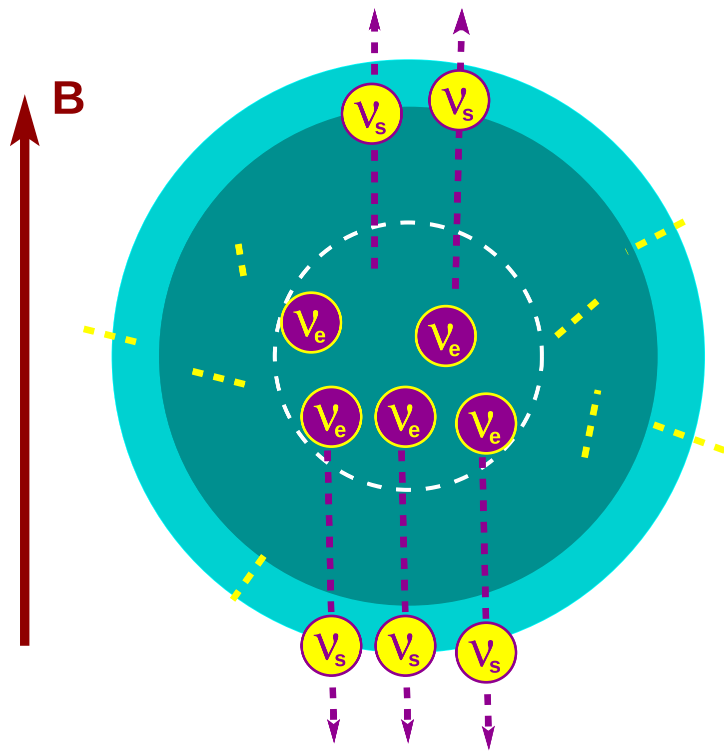
No

Rescattering washes out the asymmetry

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

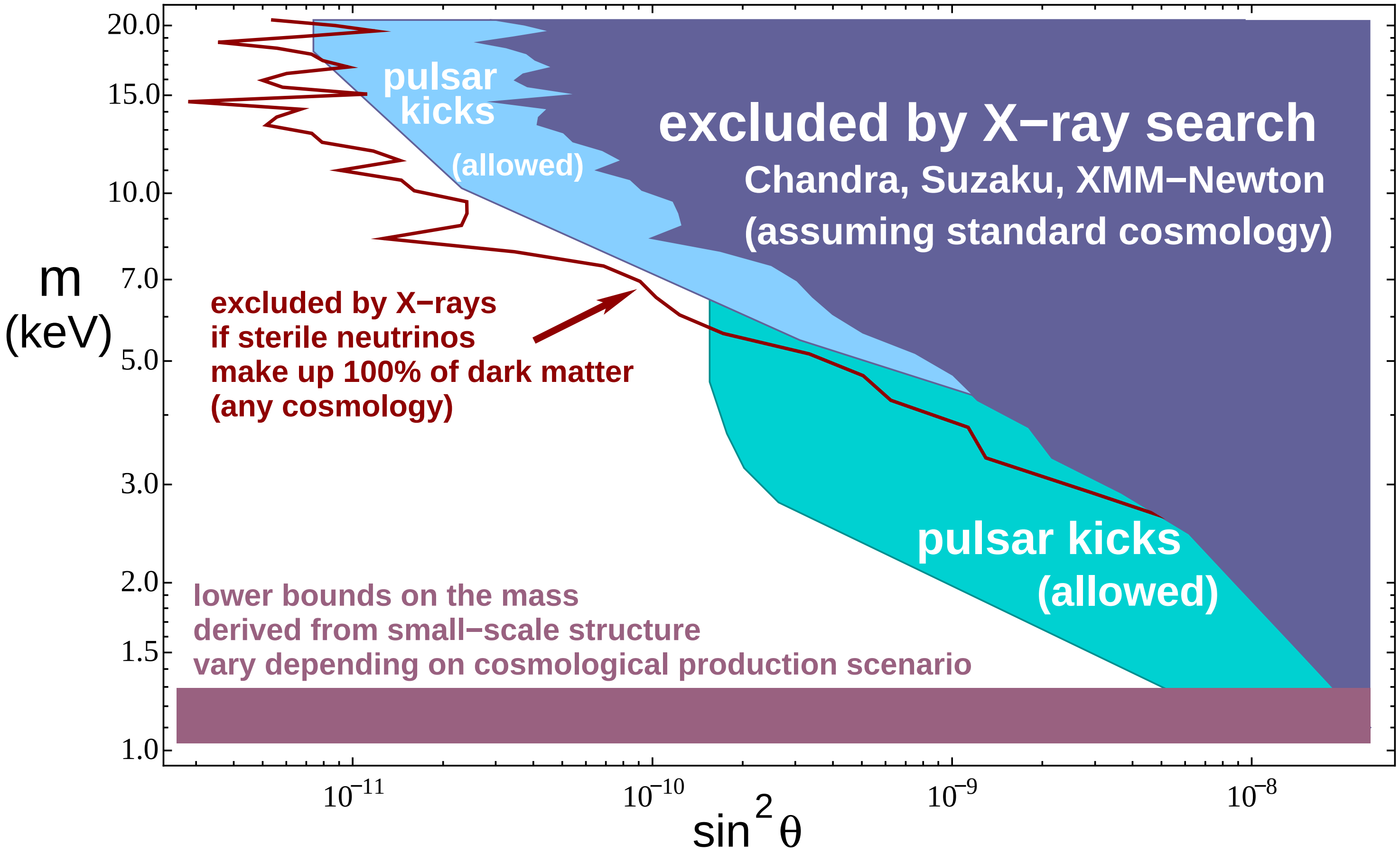
However, if a weaker-interacting sterile neutrino was produced in these processes, the asymmetry would, indeed, result in a pulsar kick!

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

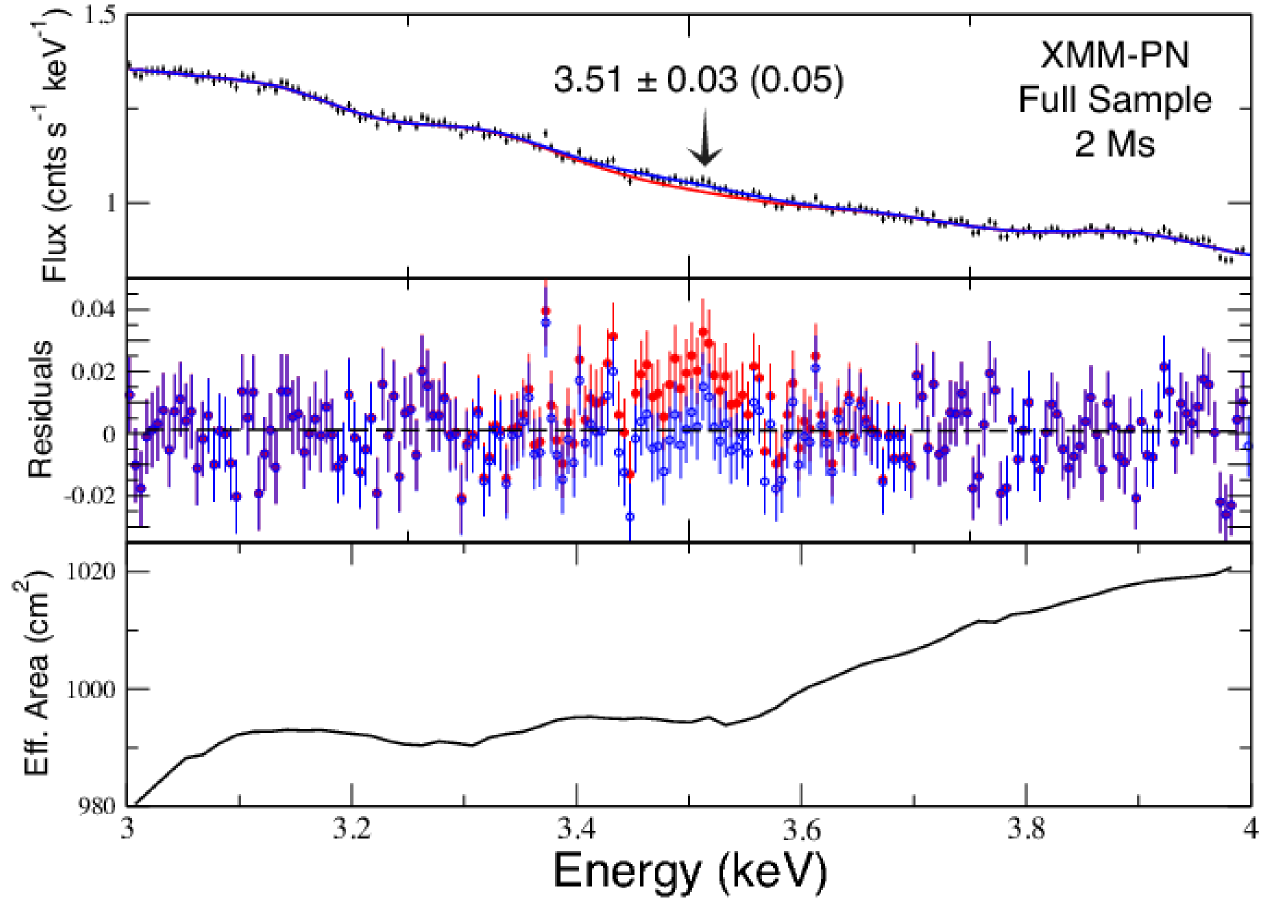


The mass and mixing required for the pulsar kick are consistent with dark matter.

Limits from X-ray searches



Unidentified line from Bulbul et al.; Boyarsky et al.



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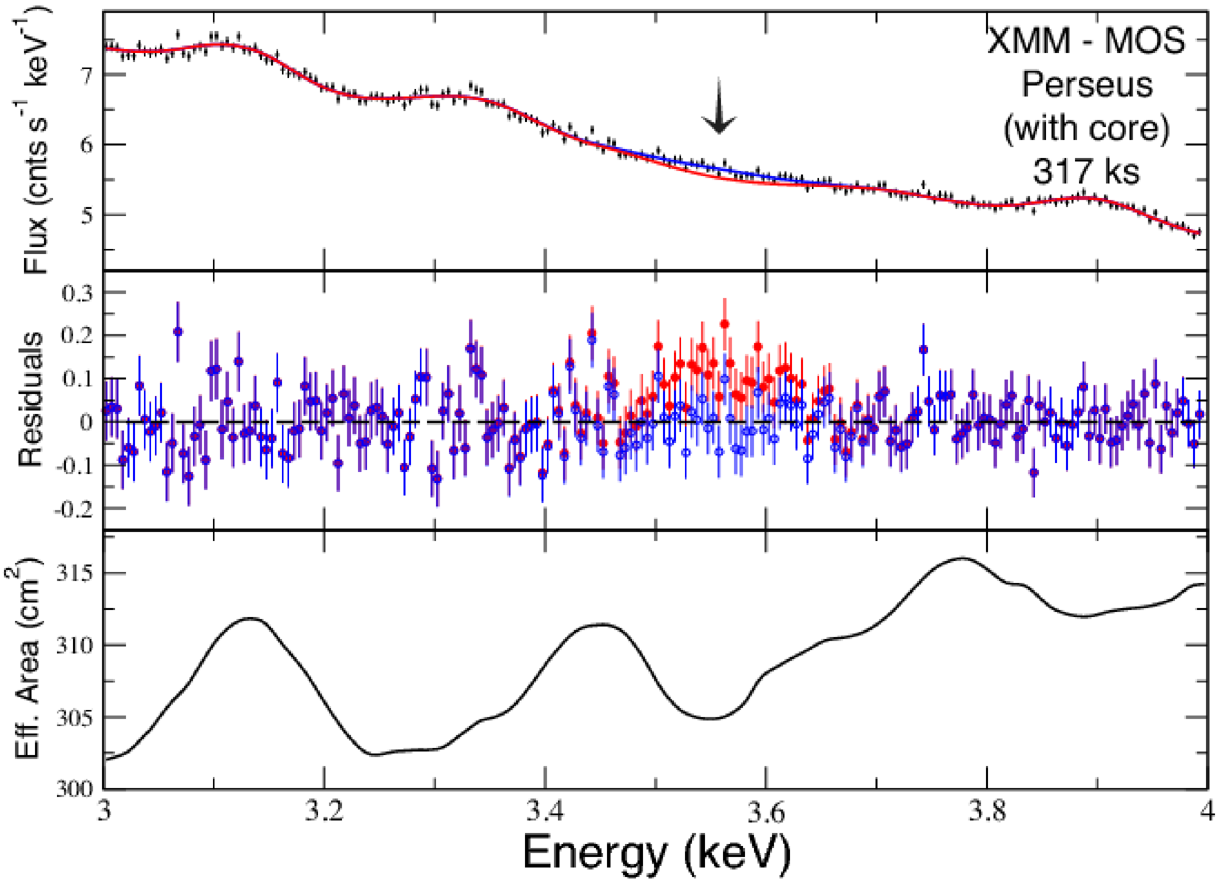
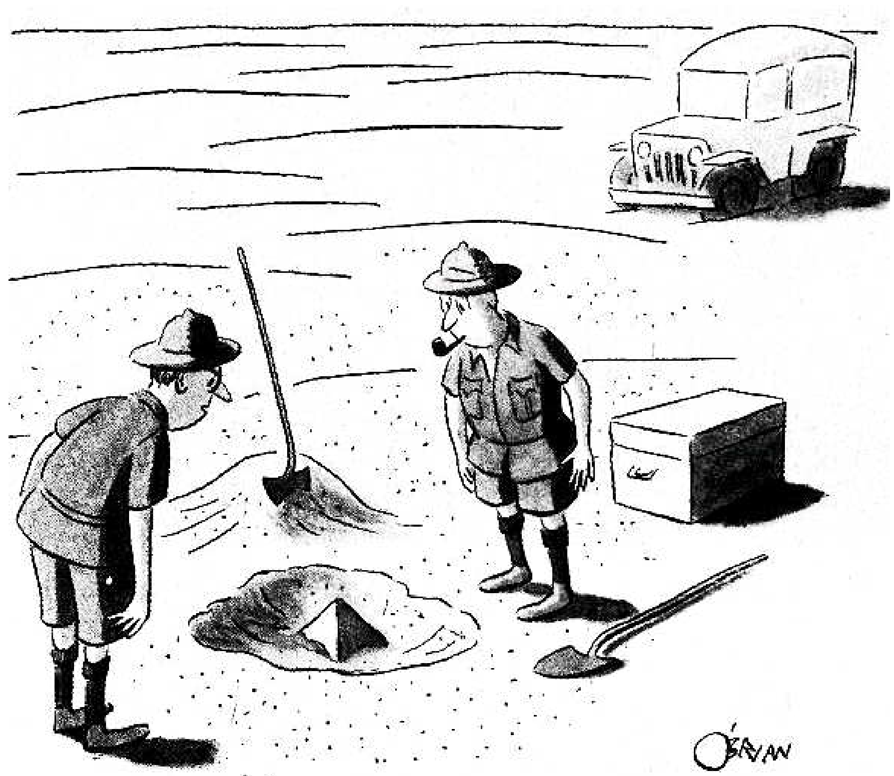


Conflicting follow-up...

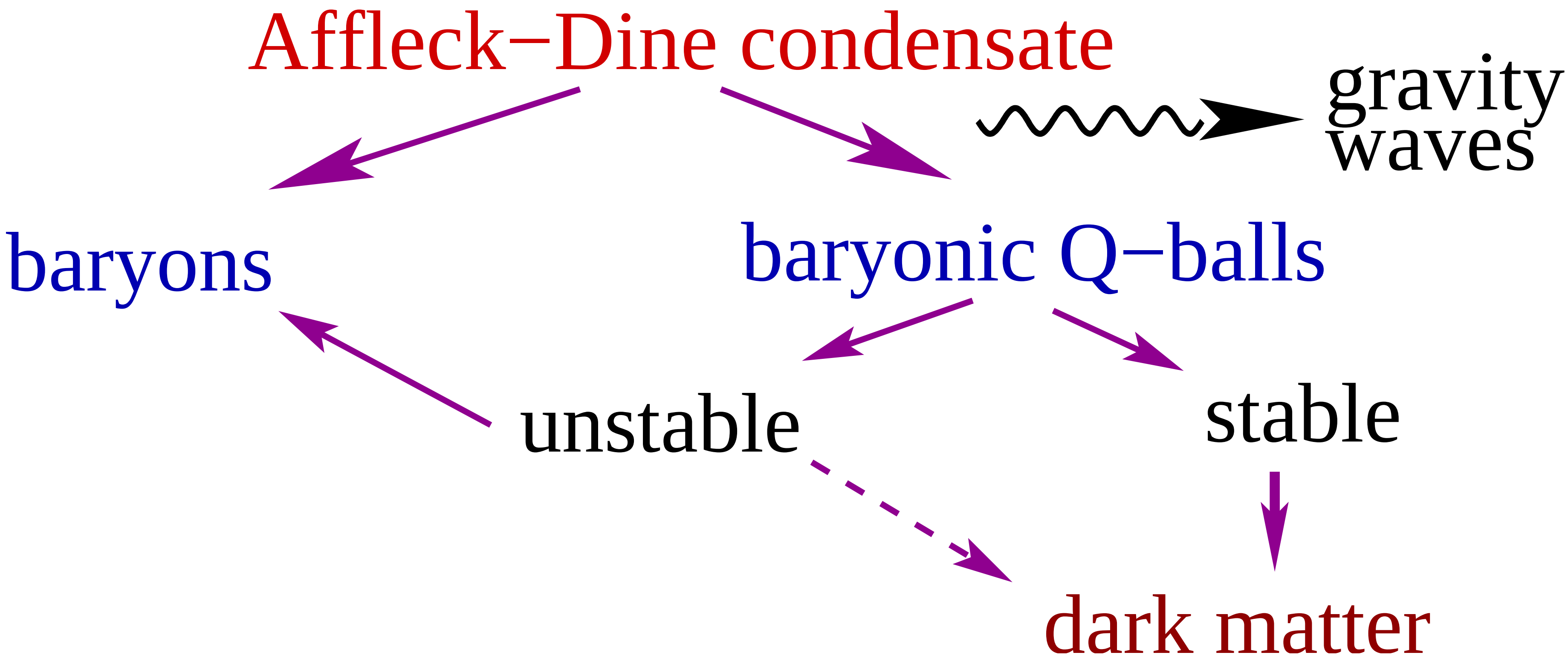
Urban et al., arXiv:1411.0050 Tamura et al., arXiv:1412.1869	confirm using Suzaku data of Perseus rule out using Suzaku data of Perseus
Malyshev et al. arXiv:1408.3531	exclusion at 4.6σ level based on stacked spectra of dwarf spheroiodals
Anderson et al., arXiv:1408.4115	exclusion at 11.8 σ (4.4 σ) using XMM-Newton (Chandra) spectra of outskirts of 89 (81) galaxies
Carlson et al. arXiv:1411.1758	signal has wrong morphology
Jeltema, Profumo arXiv:1408.1699	the line could be attrtibuted to potassium
Riemer-Sorensen arXiv:1405.7943	no line in Chandra data on Milky Way

Clues of the sterile neutrinos



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

Echoes of supersymmetry in the early universe



SUSY and Q-balls

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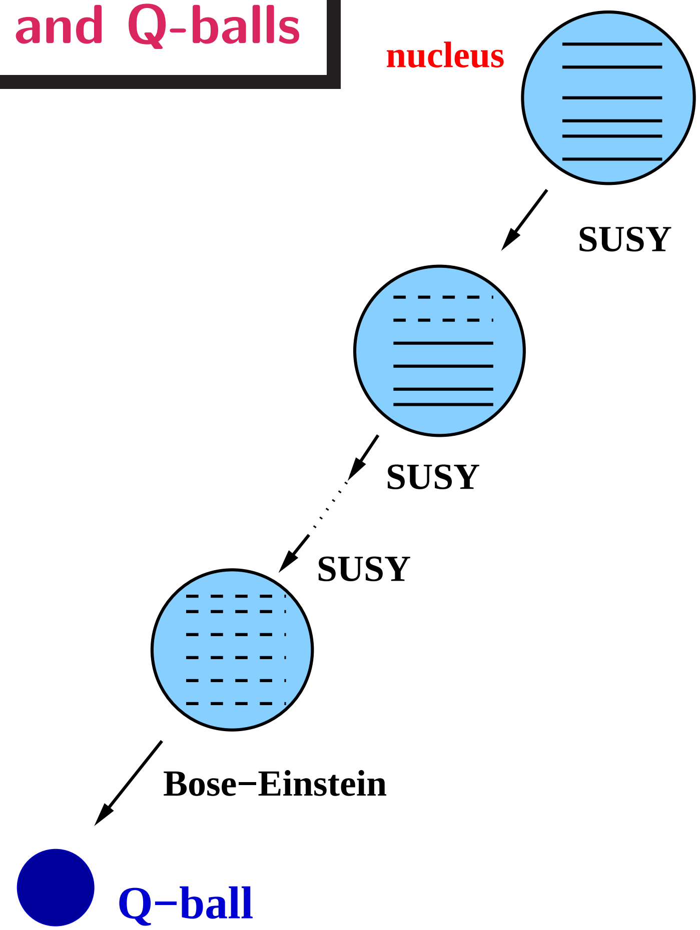

Q-balls

Let us consider a complex scalar field $\phi(x,t)$ in a potential that respects a U(1) symmetry: $\phi \to e^{i\theta}\phi$. Vacuum: $\phi = 0$

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$Q \neq 0 \Rightarrow \phi \neq 0$ in some finite domain $\Rightarrow$ Q-ball

Q-balls exist if

$$U(\phi)/\phi^2 = \text{min}, \quad \text{for } \phi = \phi_0 > 0$$

Finite ϕ_0: $M(Q) \propto Q$

Flat potential ($U(\phi) \sim \phi^p, p < 2$); $\phi_0 = \infty$:

$$M(Q) \propto Q^\alpha, \alpha < 1$$

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- the theory has scalar fields
- the scalar fields carry conserved global charge (baryon and lepton numbers)
- attractive scalar interactions (tri-linear terms, flat directions) force $(U(\phi)/\phi^2) = \min$ for non-vacuum values.

MSSM, gauge mediated SUSY breaking

Baryonic Q-balls (B-balls) are entirely stable if their mass per unit baryon charge is less than the proton mass.

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Such B-balls are entirely stable.

Inflation

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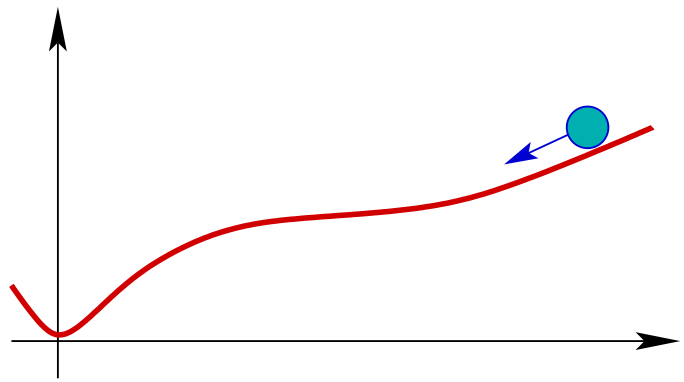
SUSY $\Rightarrow$ flat directions.

During inflation, scalar fields are displaced from their minima.



Affleck – Dine baryogenesis

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at the end of inflation
a scalar condensate
develops a large VEV
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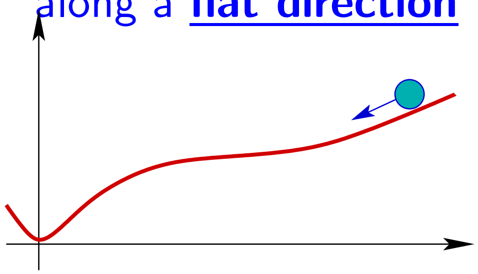

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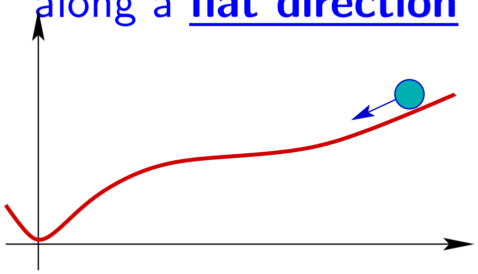

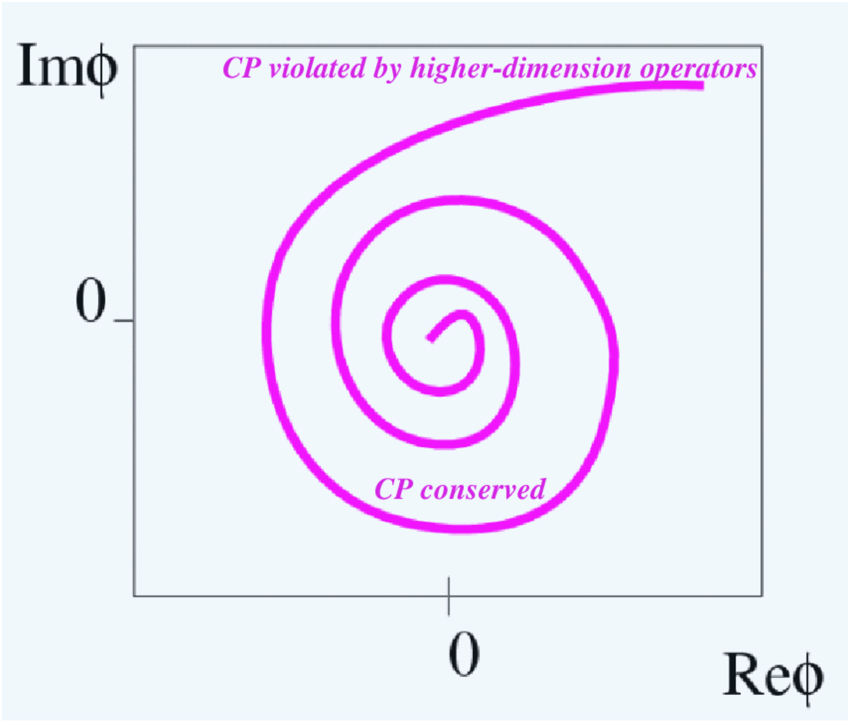

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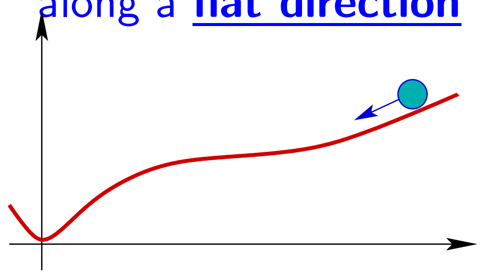
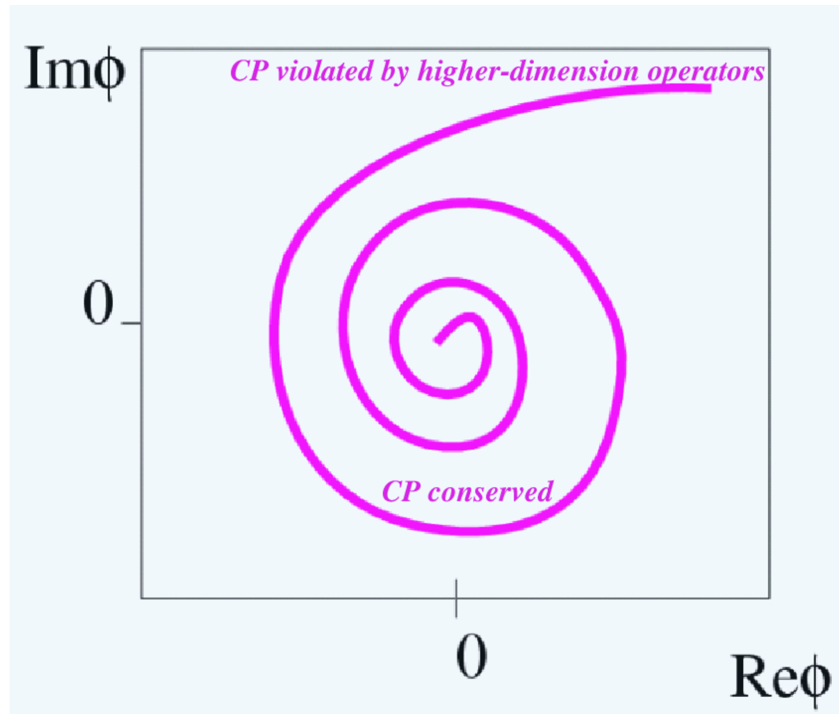
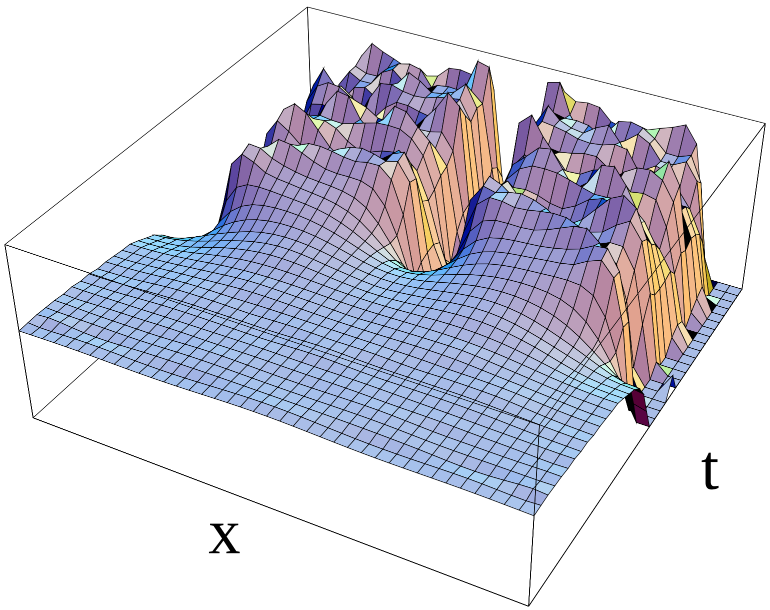


Baryon asymmetry: $\phi = |\phi| e^{i\omega t}$



Fragmentation of the Affleck-Dine condensate



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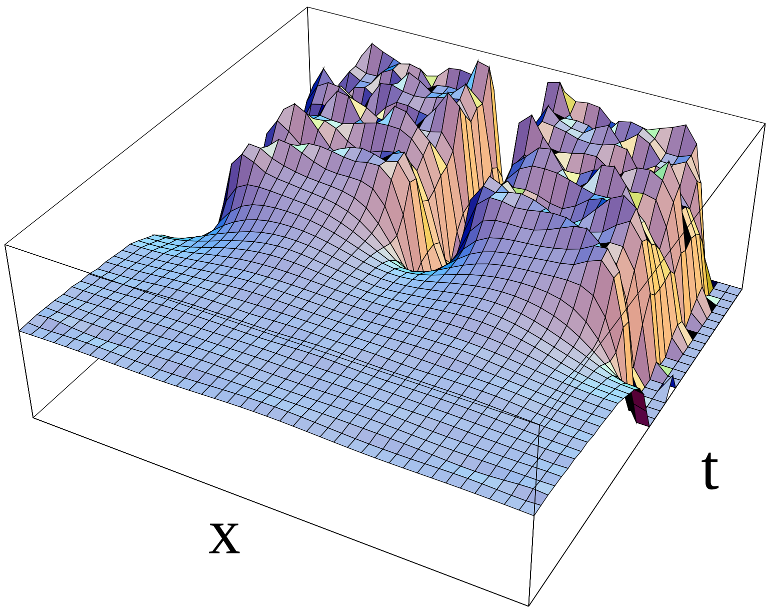

small inhomogeneities can grow

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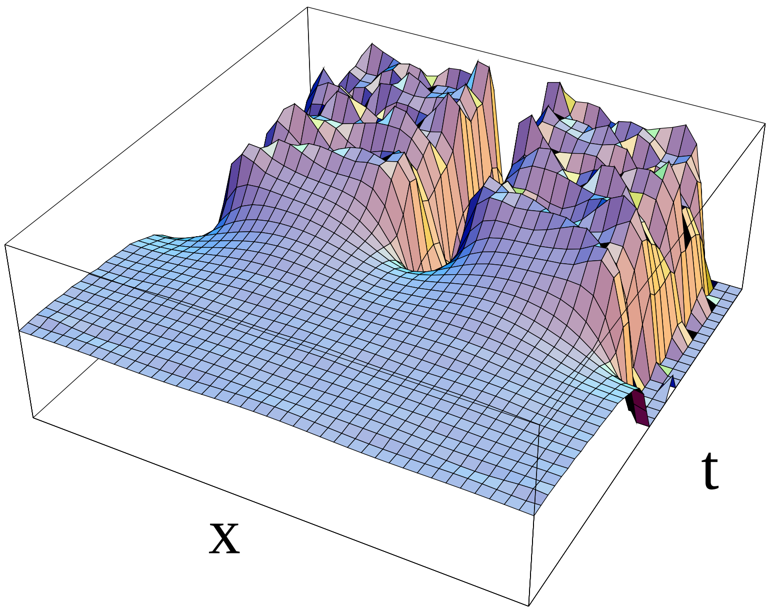

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$$0 < k < k_{\max} = \sqrt{\omega^2 - U''(\phi)}$$

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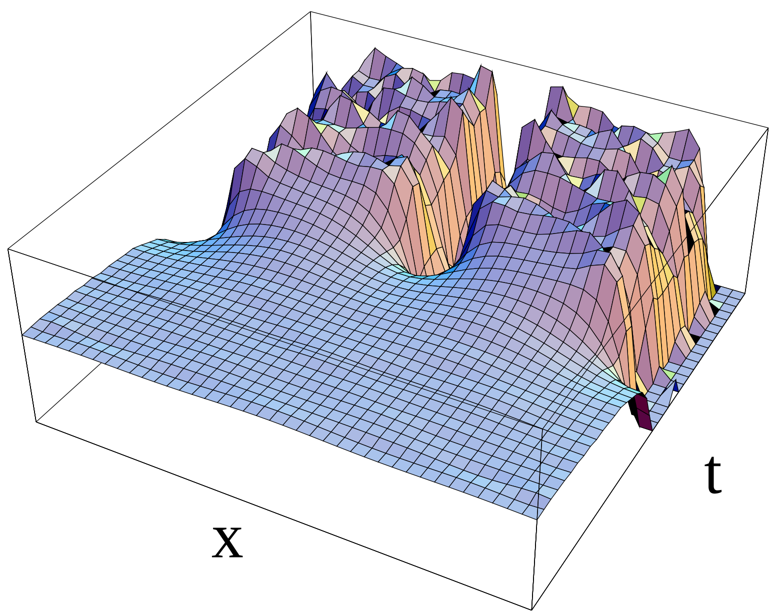

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$\Rightarrow$ **Lumps of baryon condensate**

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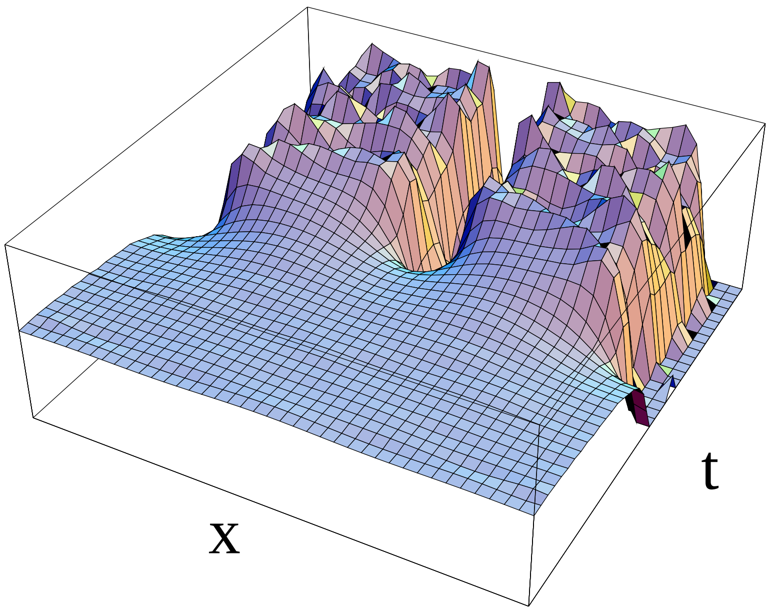

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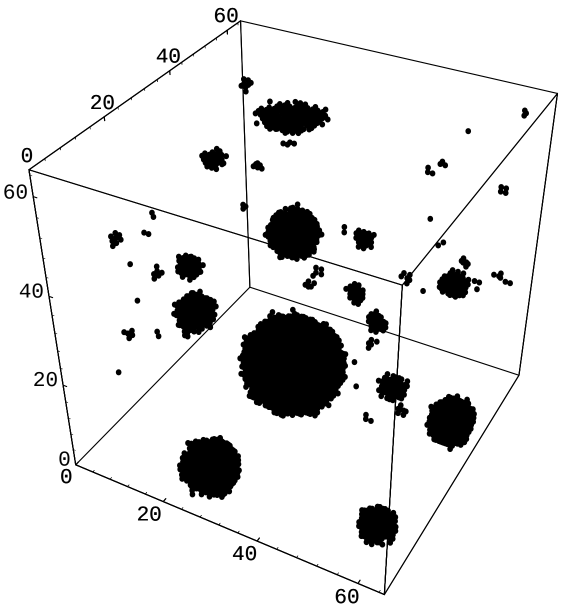
$$0 < k < k_{\max} = \sqrt{\omega^2 - U''(\phi)}$$

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

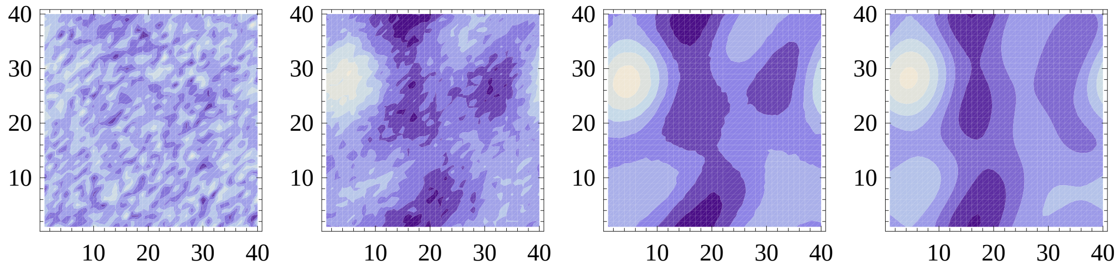
$\Rightarrow$ **Q-balls**

Numerical simulations of the fragmentation

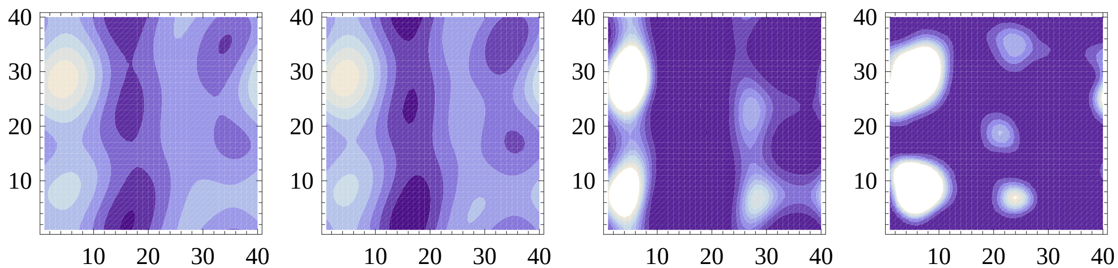


[Kasuya, Kawasaki]

Two-dimensional charge density plots [Multamaki].

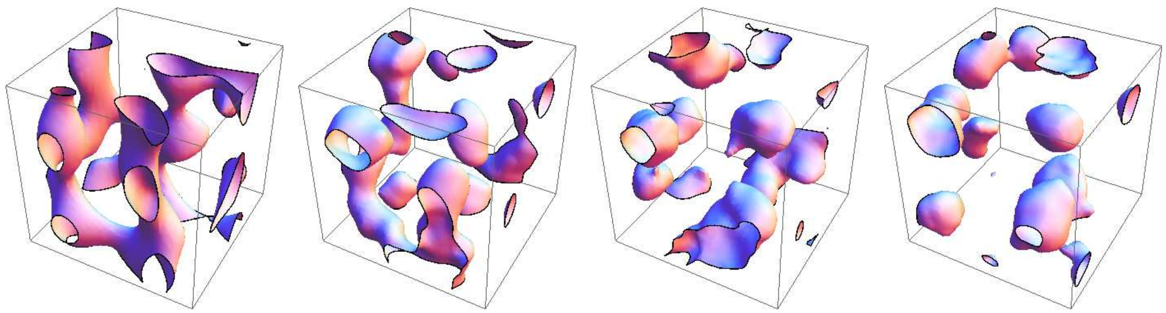


(a) $mt = 0$ (b) $mt = 75$ (c) $mt = 150$ (d) $mt = 375$



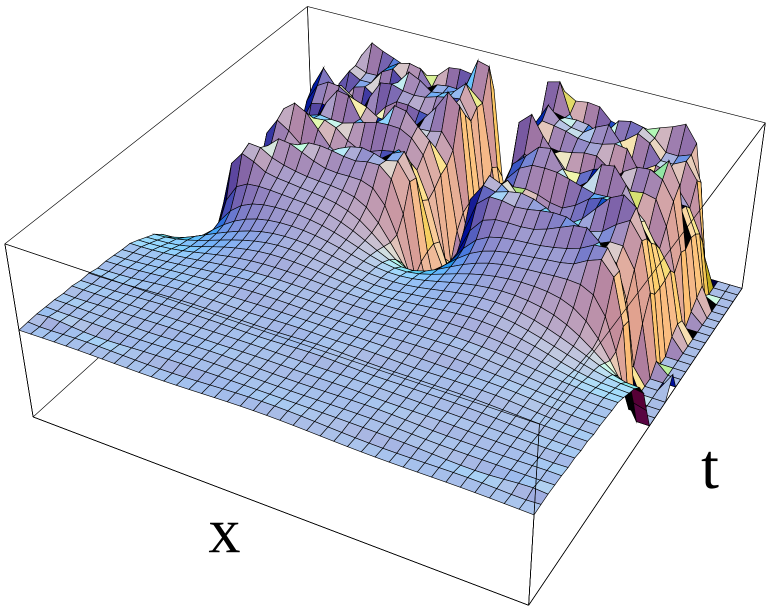
(e) $mt = 525$ (f) $mt = 675$ (g) $mt = 825$ (h) $mt = 900$

Three-dimensional charge density plots [Multamaki].



(i) $mt = 900$ (j) $mt = 1050$ (k) $mt = 1200$ (l) $mt = 1350$

Fragmentation of AD condensate can produce Q-balls



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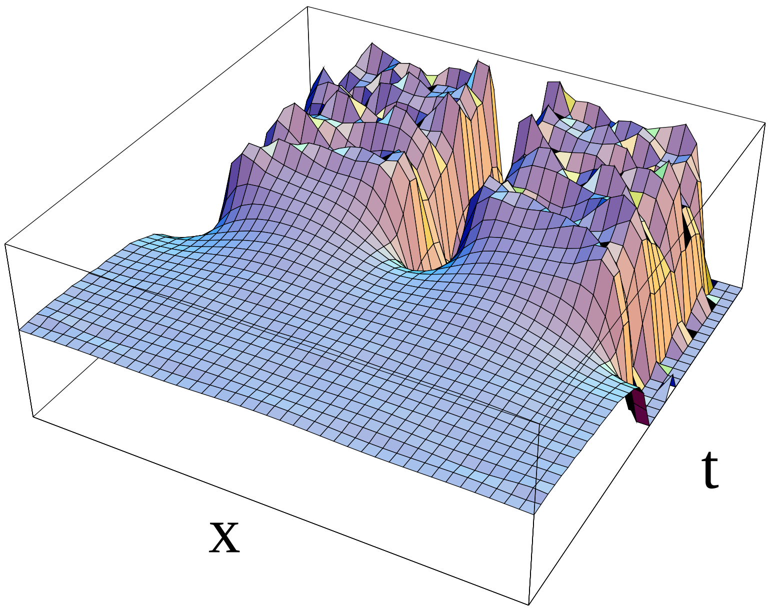

SUSY Q-balls may be stable or unstable

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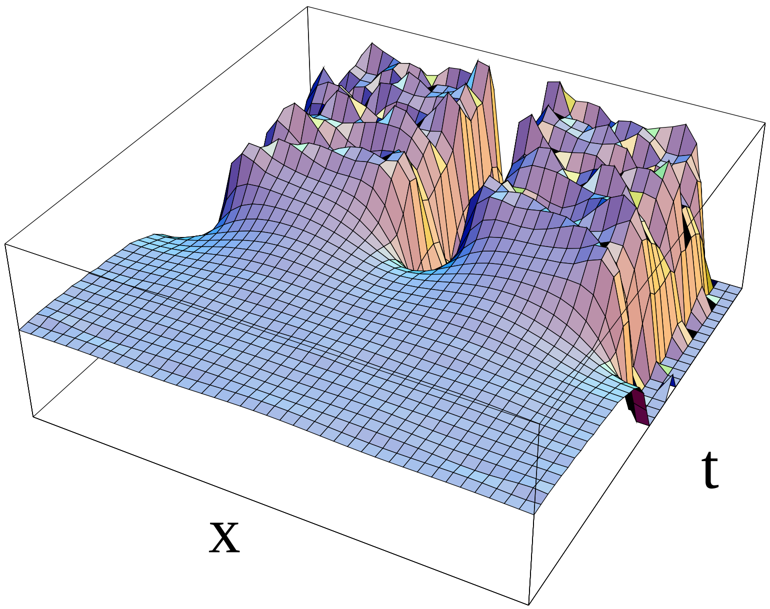

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if stable ⇒ **dark matter**

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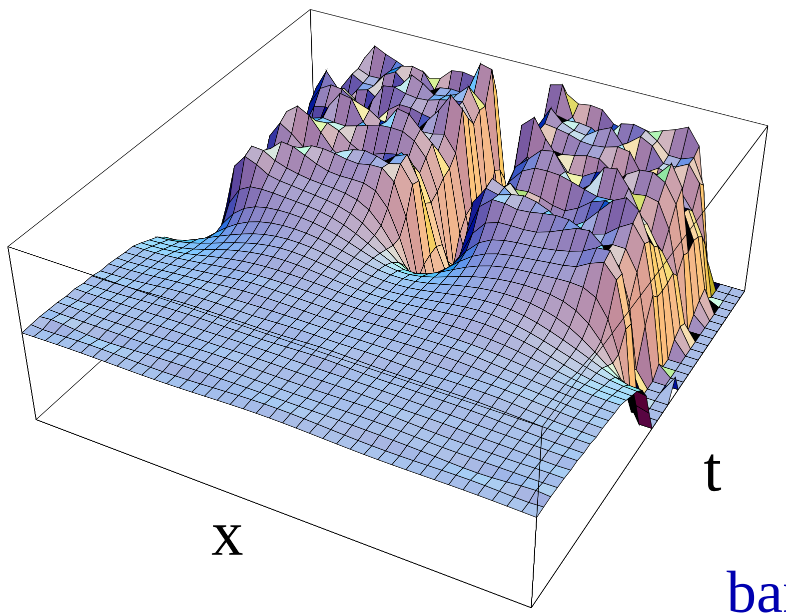

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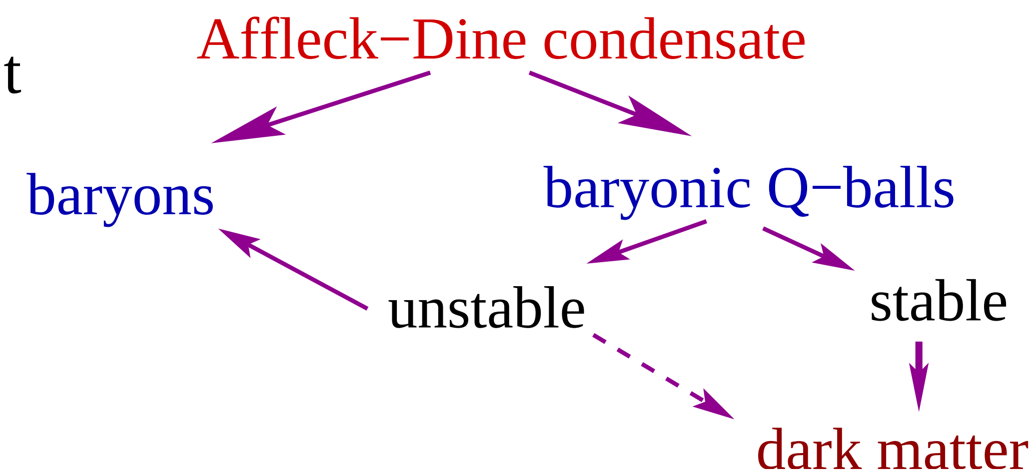
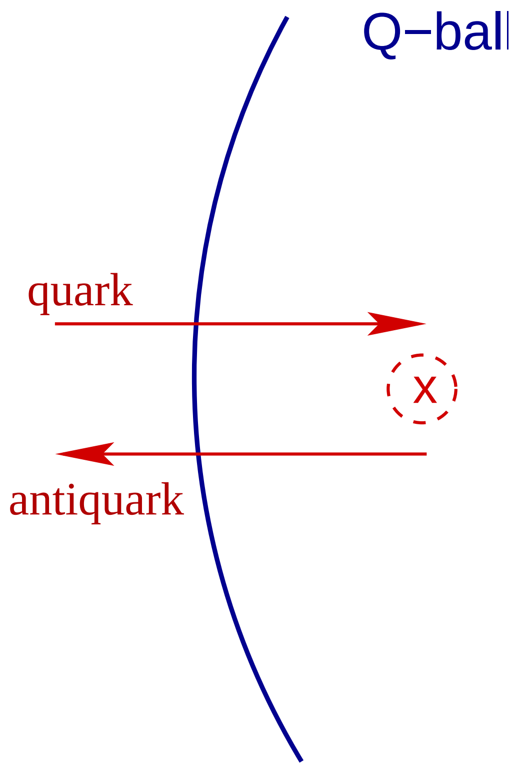


[AK, Shaposhnikov] Dark matter in the form of stable SUSY Q-balls?

Interactions of SUSY Q-balls with matter



There is a Majorana mass term for quarks inside coming from the quark-squark-gluino vertex. **Probability ~ 1 for a quark to reflect as an antiquark.** Very fast!

Stable Q-balls as dark matter

Q-balls can accommodate baryon number at lower energy than a nucleon $\Rightarrow$ **B-Balls catalyze proton decay** [AK,Kuzmin,Shaposhnikov,Tinyakov] Signal:

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

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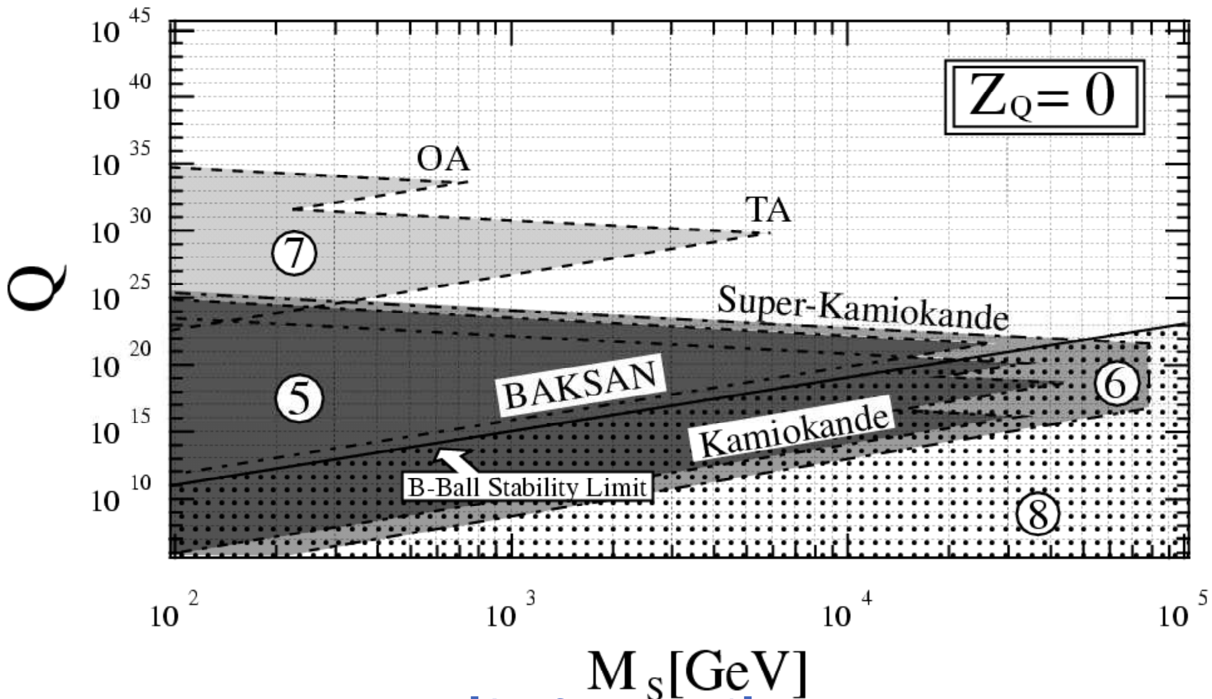
$\Rightarrow$ **experimental limits from Super-Kamiokande and other *large* detectors**

Present experimental limits



[Arafune *et al.*];

A "candidate event"

C.M.G. Lattes et al., Hadronic interactions of high energy cosmic-ray observed by emulsion chambers

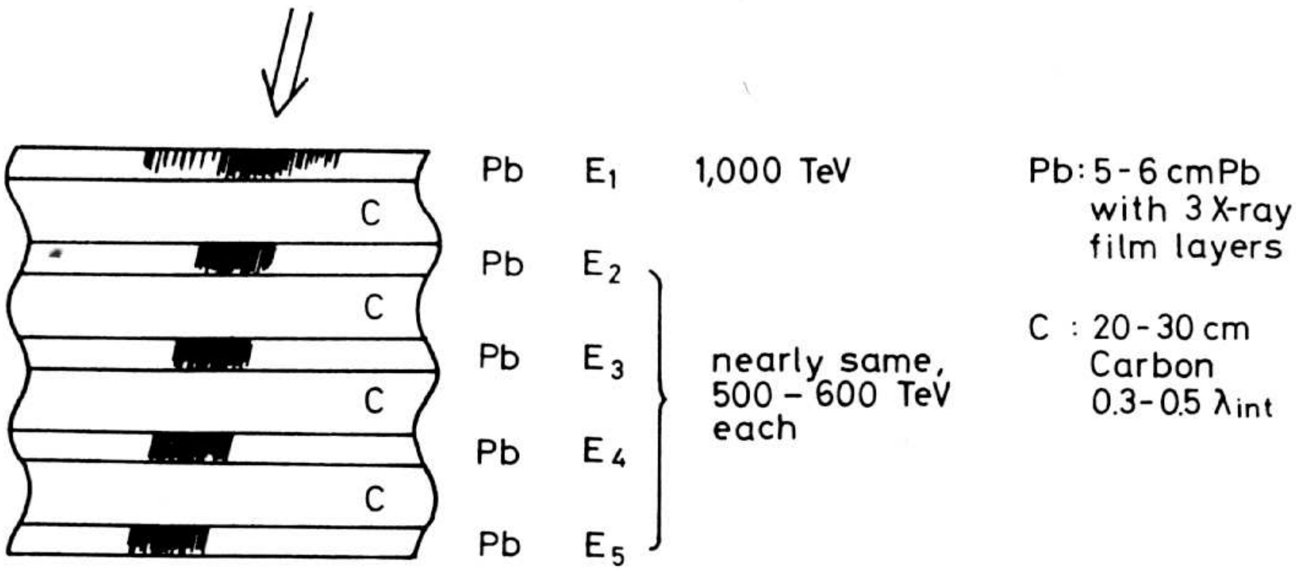
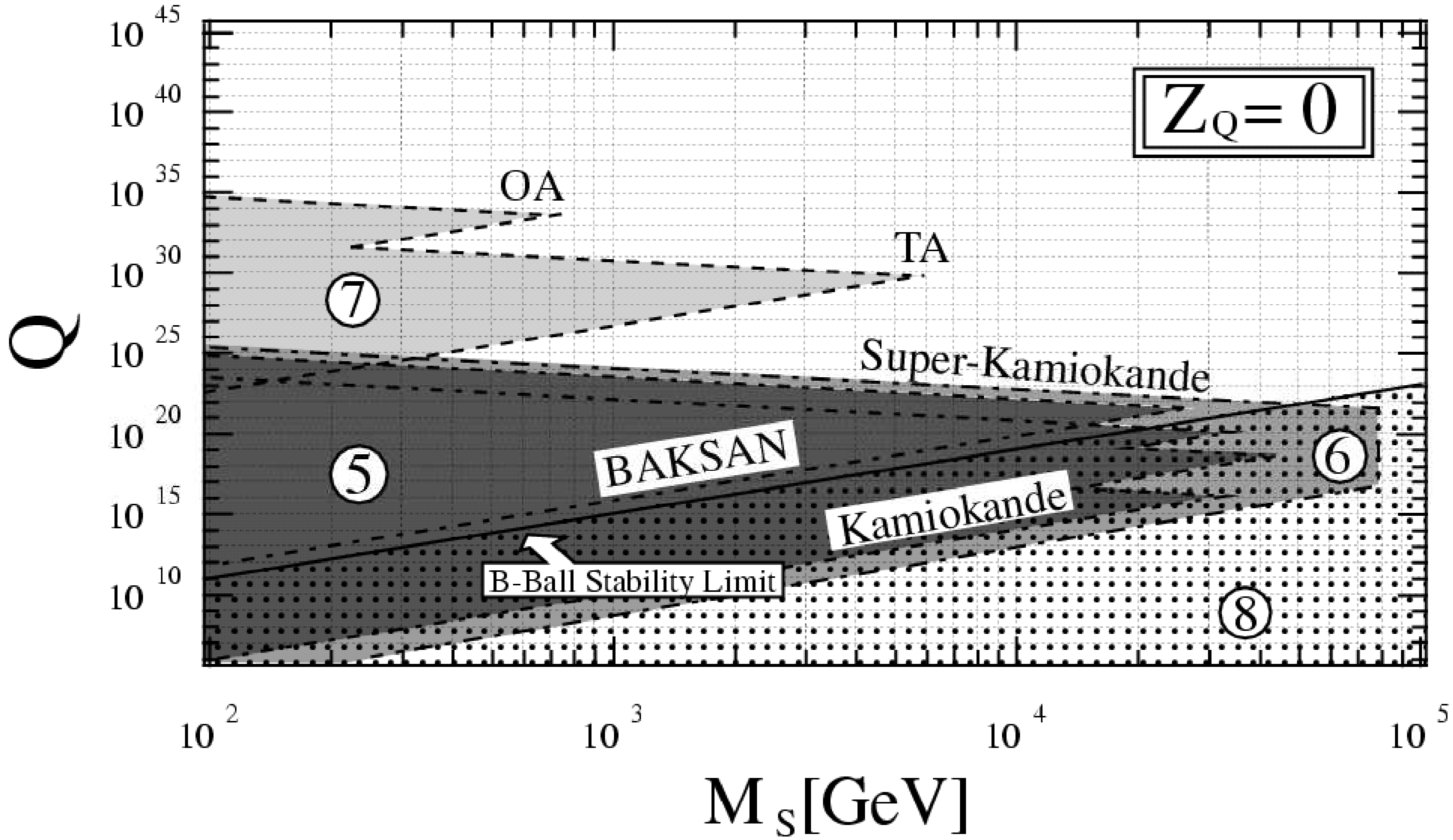


Fig. 47. Illustration of penetrating cores of Pamir experiment.

[Lattes, Fujimoto and Hasegawa, Phys.Rept. **65**, 151 (1980)]

$\Omega_{B-\mathrm{ball}} / \; \Omega_{\mathrm{matter}} \sim 6$



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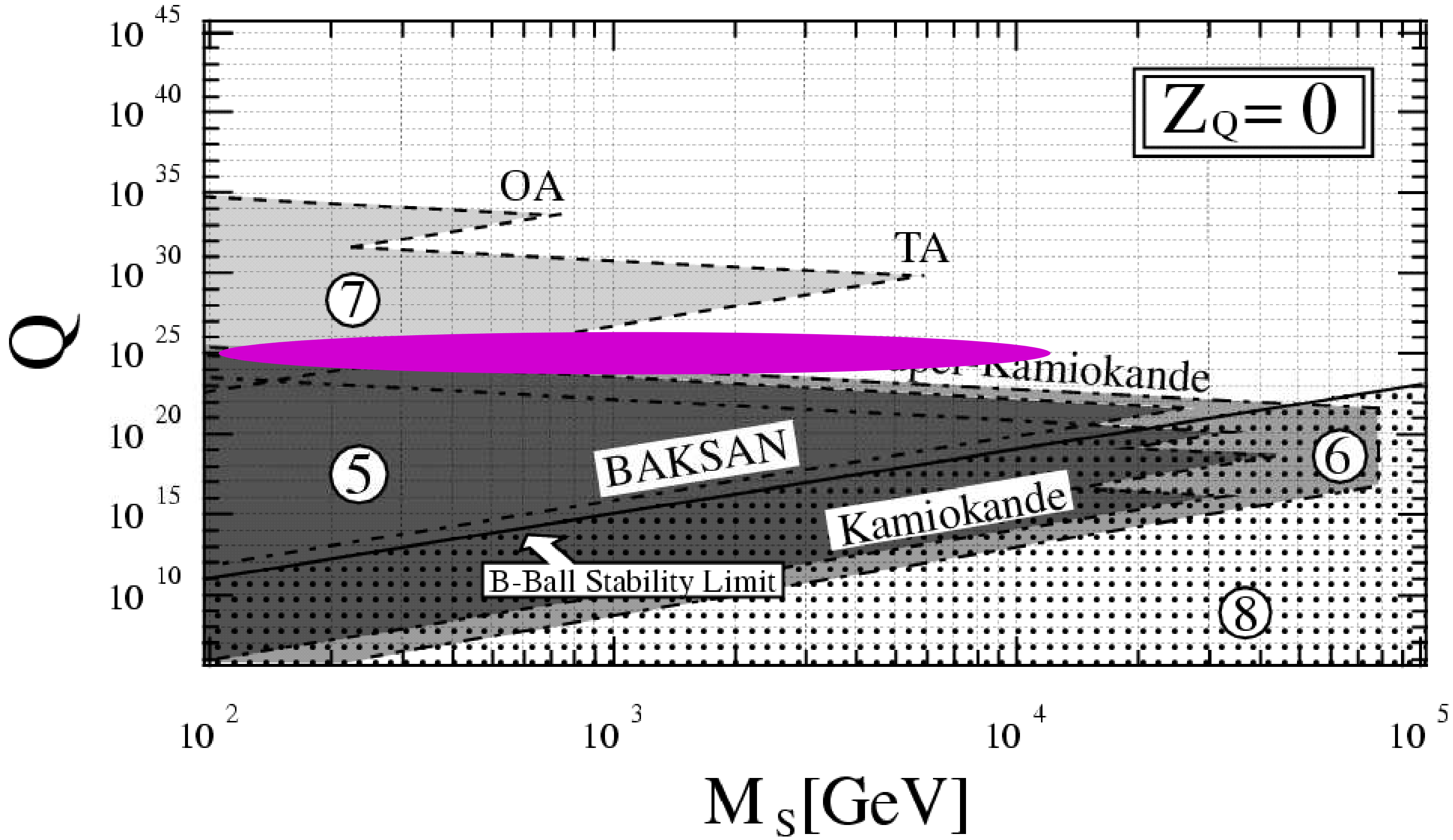

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Hence, *Q-balls are unstable*.

Decay of Q-balls results in *late non-thermal production of LSP.*

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**.

Astrophysical constraints

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- Q-balls pass through ordinary stars and planets

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Neutron stars: can they survive long enough?

Pulsars ages: oldest pulsars have $(\dot{P}/P) \sim (0.3-3)\times 10^{-10}\mathrm{yr}^{-1}$

Some pulsars are also known to be (at least) as old as **10 Gyr** based on the cooling ages of their white dwarf companions

Inside a neutron star Q-ball VEV grows fast and reaches values at which the flat direction is lifted by higher-dimension operators

Generally, the lifting terms can be written in the form

$$V^n(\phi)_{\text{lifting}} \approx \lambda_n M^4 \left(\frac{\phi}{M}\right)^{n-1+m} \left(\frac{\phi^*}{M}\right)^{n-1-m}$$

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- If $m = 0$, Q-balls change the way they grow after reaching a certain size Q_c.

Q-balls along "Flat" and "Curved" directions

	FD	CD
φ	$\frac{1}{\sqrt{2}}\Lambda Q^{1/4}$	$\varphi_{\max}$
ω	$\pi\sqrt{2}\Lambda Q^{-1/4}$	$\Lambda^2\varphi_{\max}^{-1} = \pi\sqrt{2}\Lambda {Q_c}^{-1/4} = \omega_c$
M	$4\pi\frac{\sqrt{2}}{3}\Lambda Q^{3/4}$	ωQ
R	$\frac{1}{\sqrt{2}\Lambda}Q^{1/4}$	$\left(\frac{3}{8\pi}\frac{1}{\Lambda^2\varphi_{\max}}Q\right)^{1/3} = (\frac{3}{2})^{1/3}(Q/Q_c)^{1/12}R_{FD}$

The change from FD to CD makes the Q-ball grow faster and neutron star is destroyed:

	FD Q-balls	CD Q-balls
t	**10^{10} years**	**1500 years**

Q-balls that go from FD to CD for $Q < 10^{57}$ are ruled out, unless the lifting terms can break the baryon number.

Detection: there is a caveat, electric charge

While the flat directions are gauge-invariant, a small number of scalar quanta can decay until kinematically forbidden.

This makes DM Q-balls electrically charged. Different signature: small ionization instead of massive pion production.

Difficult to detect in Super-K, HAWC, and other large detectors.

Conclusions

- keV sterile neutrinos can account for dark matter
- Different production scenarios $\Rightarrow$ different free-streaming properties. Not necessarily a warm dark matter with a detectable free-streaming lenth
- Generically, a two-component dark matter: DW + high-scale
- Controversy regarding the 3.5 keV line will be resolved by Astro-H and other future observations (Figueroa-Feliciano's talk)
- SUSY Q-balls are viable dark matter candidates: they form at the end of inflation under generic conditions.
- Search for SUSY Q-balls requies large detectors because the flux is small