Dark matter theory marches on

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Dark matter or something else? Modified gravity?

- The case for dark matter is strong.
- DM provides an explanation to several seemingly unrelated phenomena, from structure formation to gravitational lensing

Can modifications of gravity explain all these phenomena?

[talk by Erik Verlinde]

Suggestion: forget rotation curves.

The case for dark matter does not require the rotation curves.

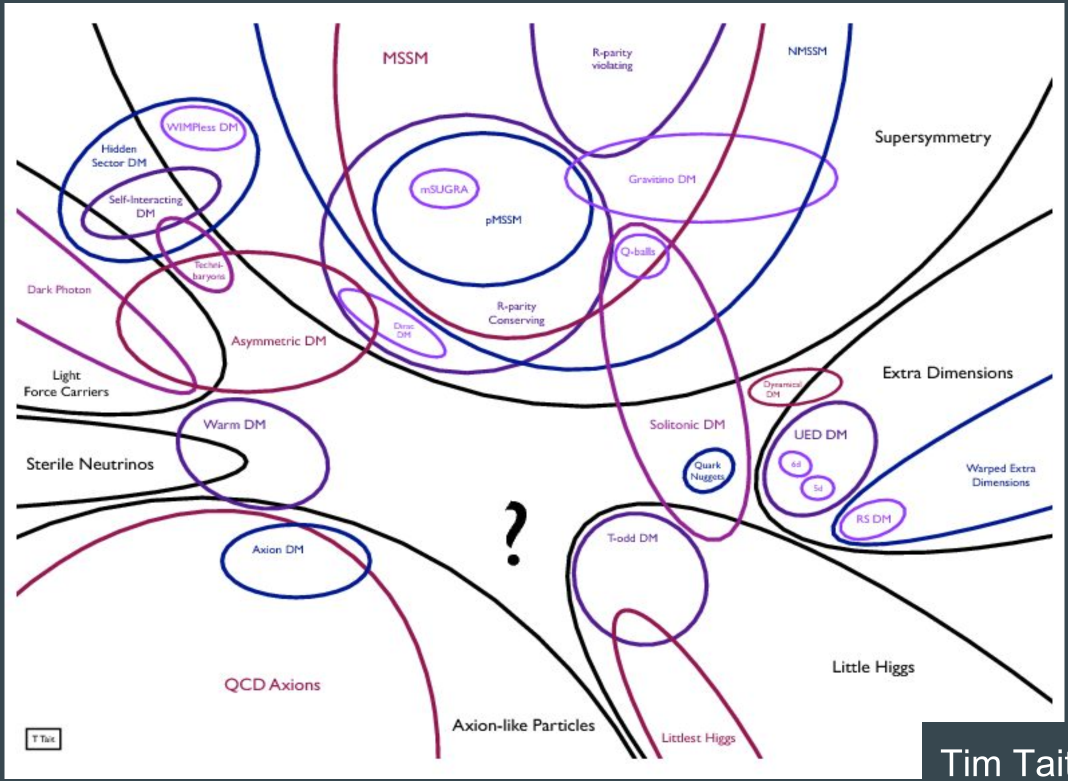
Dark matter

Most of the matter in the universe is not made of ordinary atoms

- Cosmic microwave background radiation
- Gravitational lensing
- Merging clusters
- X-ray emitting gas
- Rotation curves

All observations these observations can be explained if with a simple assumption of just one particle
(e.g., one right handed neutrino has a keV mass)

Dark matter : the landscape of possibilities



Tim Tait

WIMPs are popular:

- well motivated
- many detection techniques

non-WIMPs:

- equally well motivated, but
- often harder to search experimentally

One must search for many dark matter candidates

One looks for candidates that are well-motivated and compelling from the point of view of theory, which may show some observational hints, and for which an experiment is feasible

“non-WIMP dark matter” is like a “non-dog animal”

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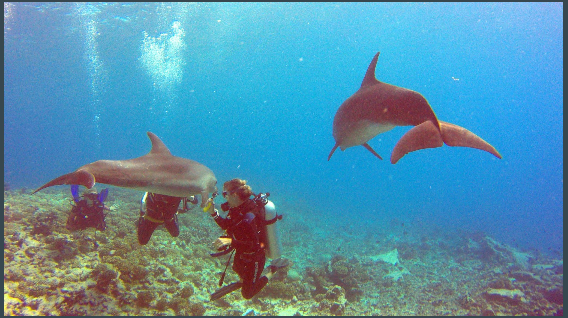


Sterile neutrinos as dark matter

Neutrino masses:

$$\mathcal{L}_{\nu_R} = \bar{\nu}^\alpha i \not{D} \nu^\alpha - \left(\lambda^\nu_{i\beta} \bar{L}^i \nu^\beta \tilde{\phi} + \text{h.c.} \right) - \frac{1}{2} M_{\alpha\beta} \bar{\nu}^\alpha \nu^\beta$$

$$m_\nu = \begin{pmatrix} 0 & \lambda_{i\beta}\langle\phi\rangle \\ \lambda^*_{\alpha j}\langle\phi\rangle & M_{\alpha\beta} \end{pmatrix}$$

$$\nu_s = \cos\theta\, \nu_R + \sin\theta\, \nu_L$$

Correct relic density for keV mass:

$$\Omega_{\nu_s} \approx 0.2 \, \frac{\sin^2 2\theta}{10^{-8}} \left[\frac{m_s}{3\ \text{keV}} \right]^{1.8}$$

[Dodelson, Widrow]

Sterile neutrinos as dark matter

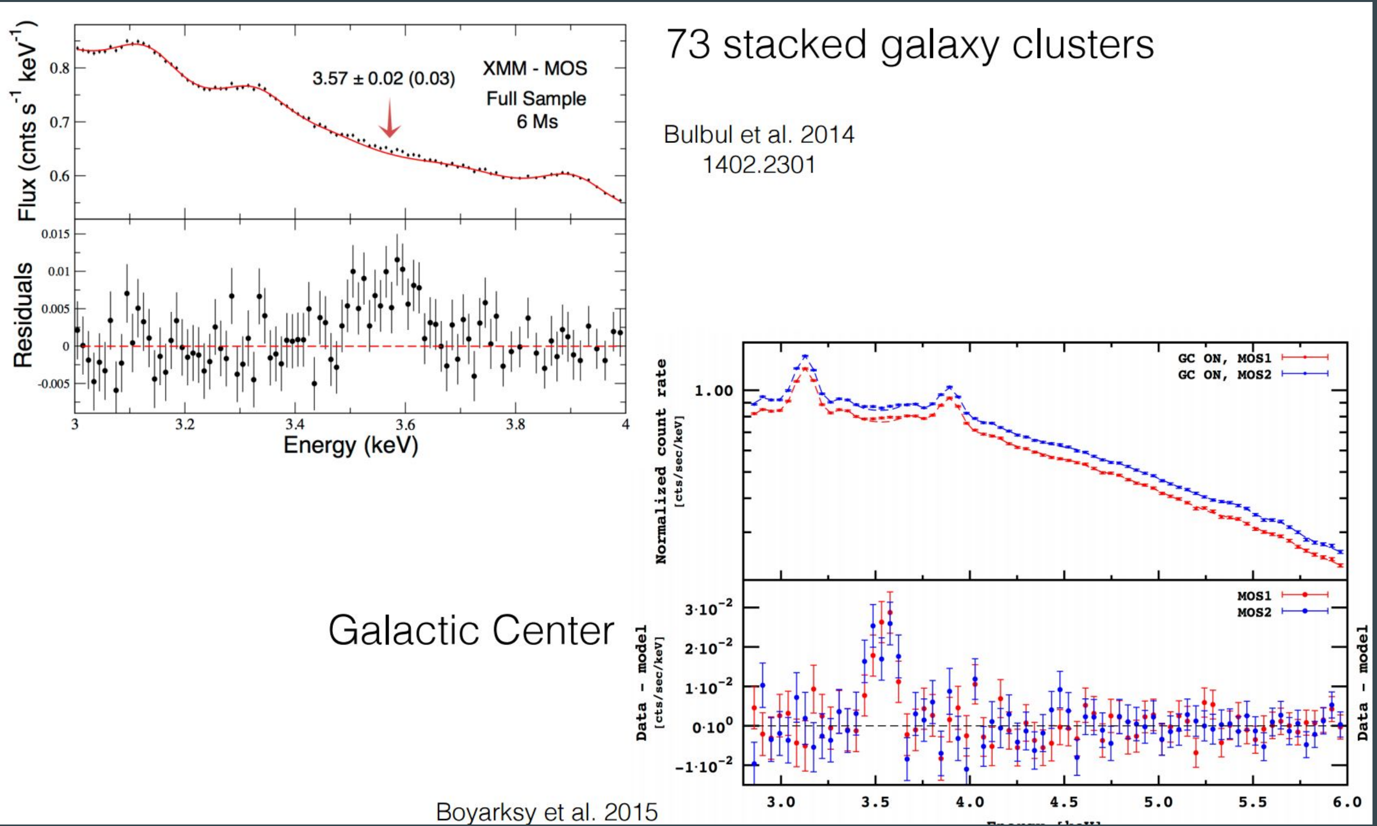
- neutrino masses are most easily explained if right-handed neutrinos exist. If one of them has mass in the keV mass range, it can be dark matter
- models exist, in which the abundance is “natural” (a non-WIMP miracle)
- depending on the production mechanism, can be warm or (practically) cold dark matter
- can explain the observed pulsar velocities
- can be discovered by a radiative decay line using X-ray telescopes:

$$\nu_s \rightarrow \nu_{e,\mu,\tau}\gamma, \quad E_\gamma = \frac{m_s}{2} \Rightarrow \text{narrow spectral line}$$

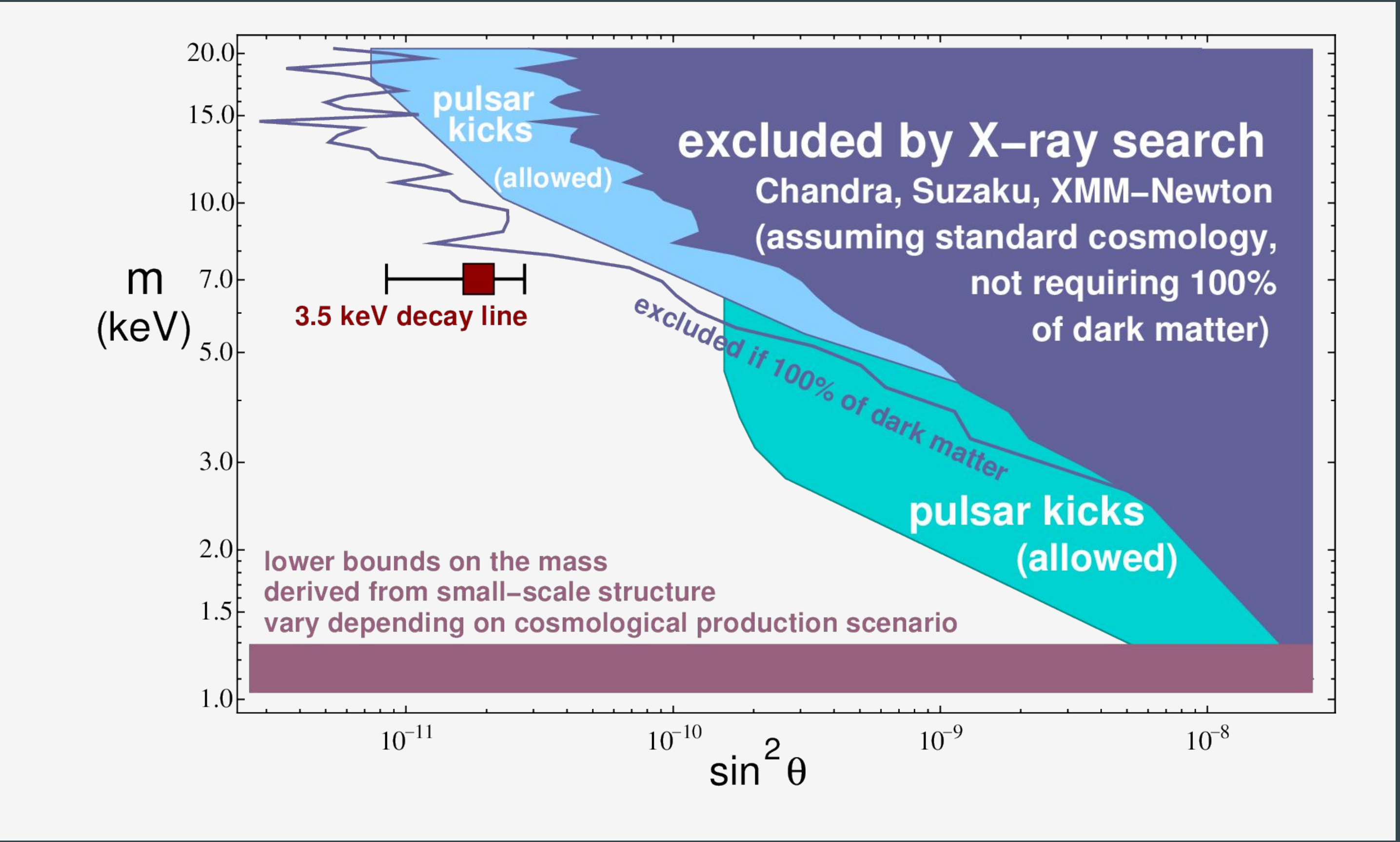
Similar signature from

- SIMPle Dark Matter [Boddy, Feng, Kaplinghat, Shadmi, Tait]
- “Exciting” dark matter [Weiner et al.]
- Supersymmetry/strings moduli dark matter [Murayama et al.; Loewenstein, AK, Yanagida]

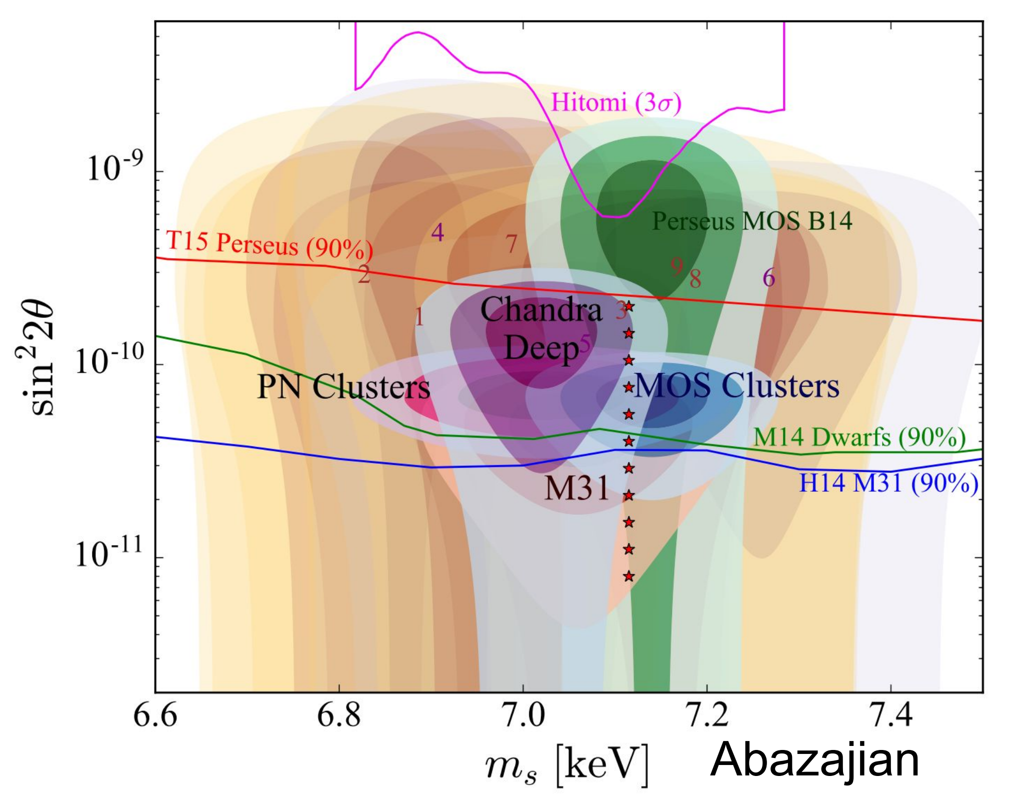
Unidentified 3.5 keV line: is it dark matter?

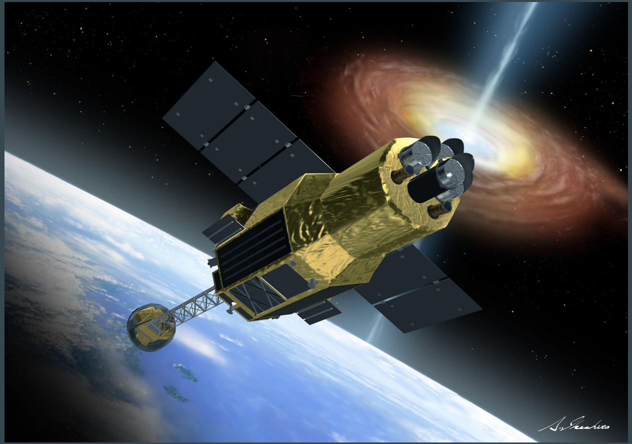


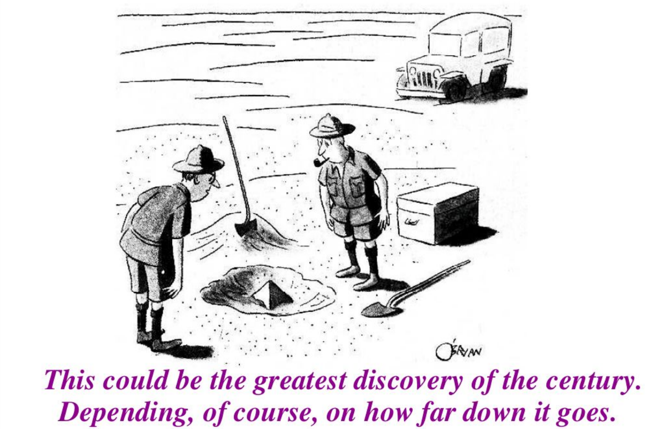
Dark-matter sterile neutrino

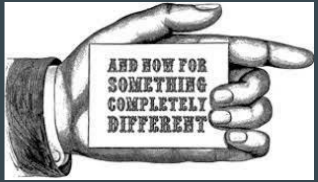


3.5 keV line: detected or not?









Primordial black holes, formed in Big Bang?

Can be produced in the early universe

Can account for dark matter. The only dark matter candidate that is not necessarily made of new particles. (Although new physics usually needed to produce PBHs)

Can seed supermassive black holes

Can probably contribute to the LIGO signal

Can account for all or part of r-process nucleosynthesis

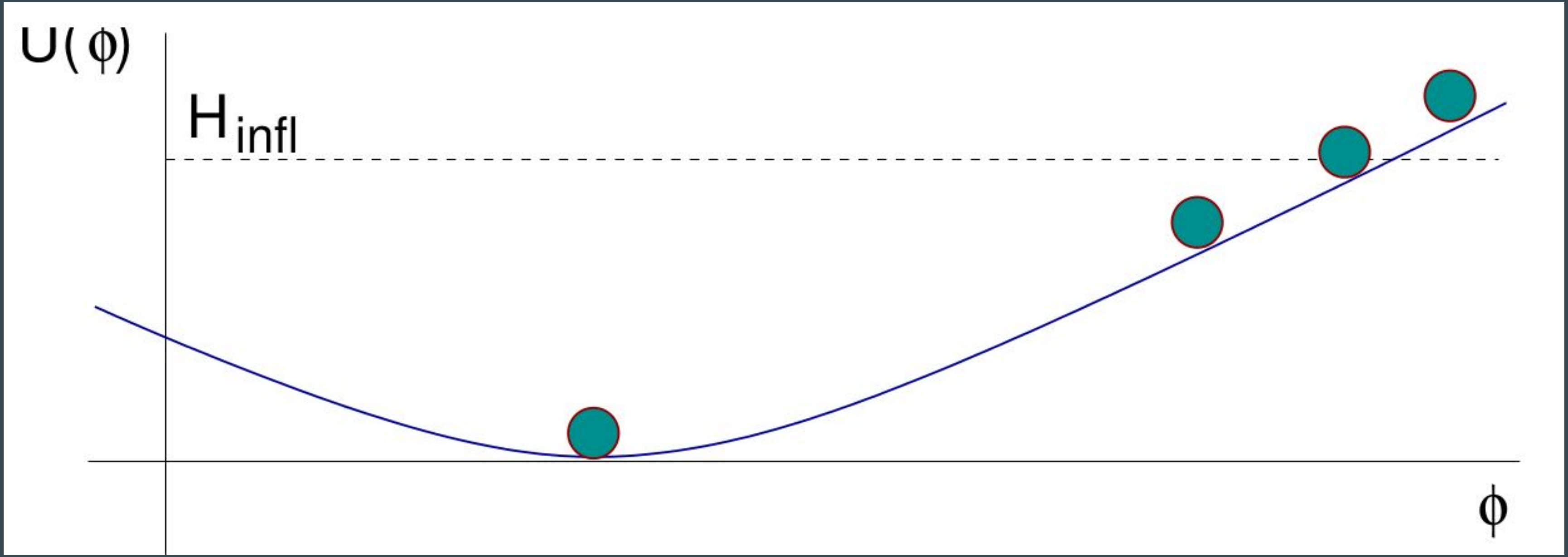
...and 511 keV line from the Galactic Center

Formation:

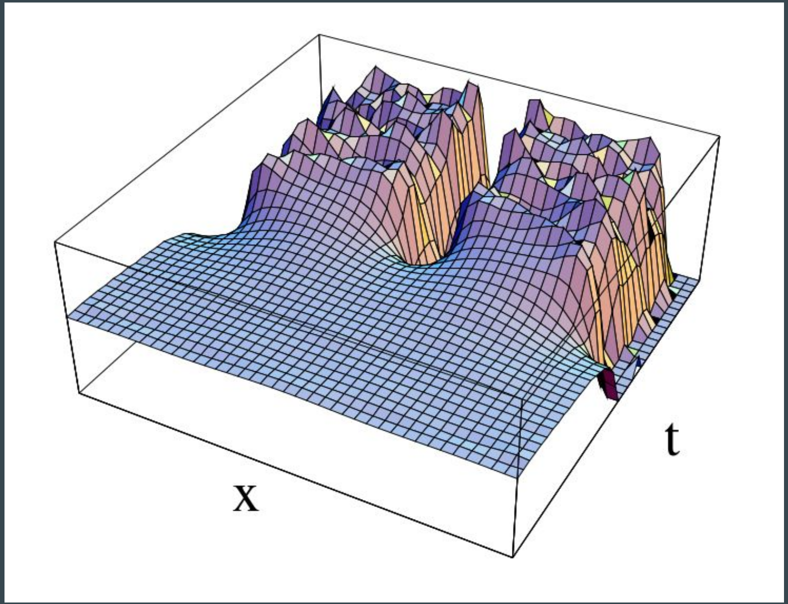
- Inflation [Garcia-Bellido, Linde et al.; ...] Spectrum of primordial density perturbations may not be scale invariant and may have an extra power on some scale: PBH are produced when the corresponding modes (re)enter horizon.
- Violent events, such as phase transitions
- Scalar field fragmentation: matter-dominated epoch with relatively few extremely massive particles per horizon ⇒ Poisson fluctuations
[Cotner, AK, Phys. Rev. Lett. 119 (2017) 031103]

Scalar fields in de Sitter space during inflation

A scalar with a small mass develops a VEV (for low- k modes, averaged over superhorizon scales).
[Bunch, Davies; Linde; Starobinsky; Vilenkin, Gibbons, Hawking; Lee, Weinberg; Starobinsky, Yokoyama]



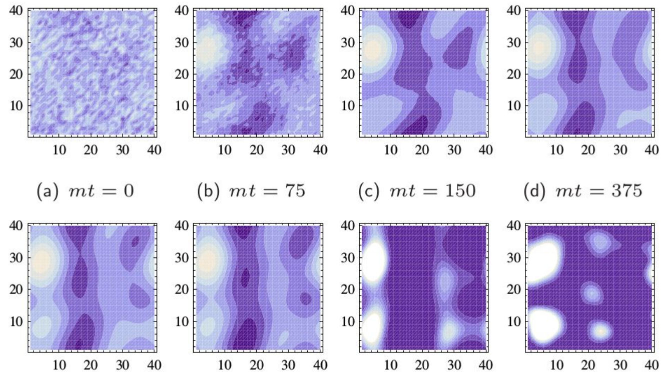
Scalar fields and Q-balls



- SUSY predicts many scalar fields: squarks and sleptons
- At the end of inflation, these fields form a coherent condensate
- Condensate unstable: breaks into Q-balls

AK 1997; AK, Shaposhnikov 1998;...

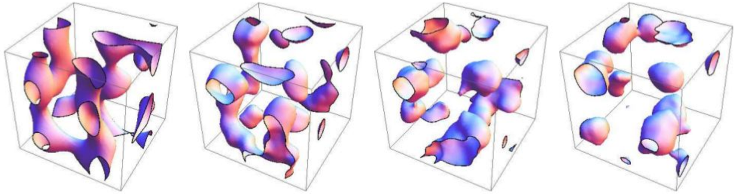
Numerical simulations of fragmentation



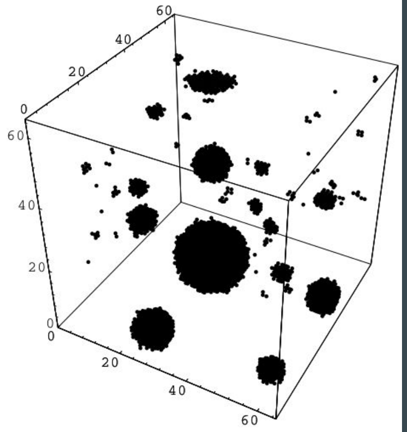
(a) $mt = 0$ (b) $mt = 75$ (c) $mt = 150$ (d) $mt = 375$

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

[Multamaki].

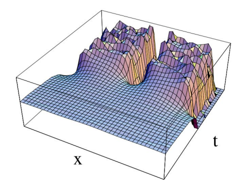


(i) $mt = 900$ (j) $mt = 1050$ (k) $mt = 1200$ (l) $mt = 1350$



[Kasuya, Kawasaki]

Early Universe



Inflation

origin of
primordial
perturbations

radiation dominated

$p=(1/3)\,\rho$

$\rho \propto a^{-4}$

structures don't grow

matter dominated

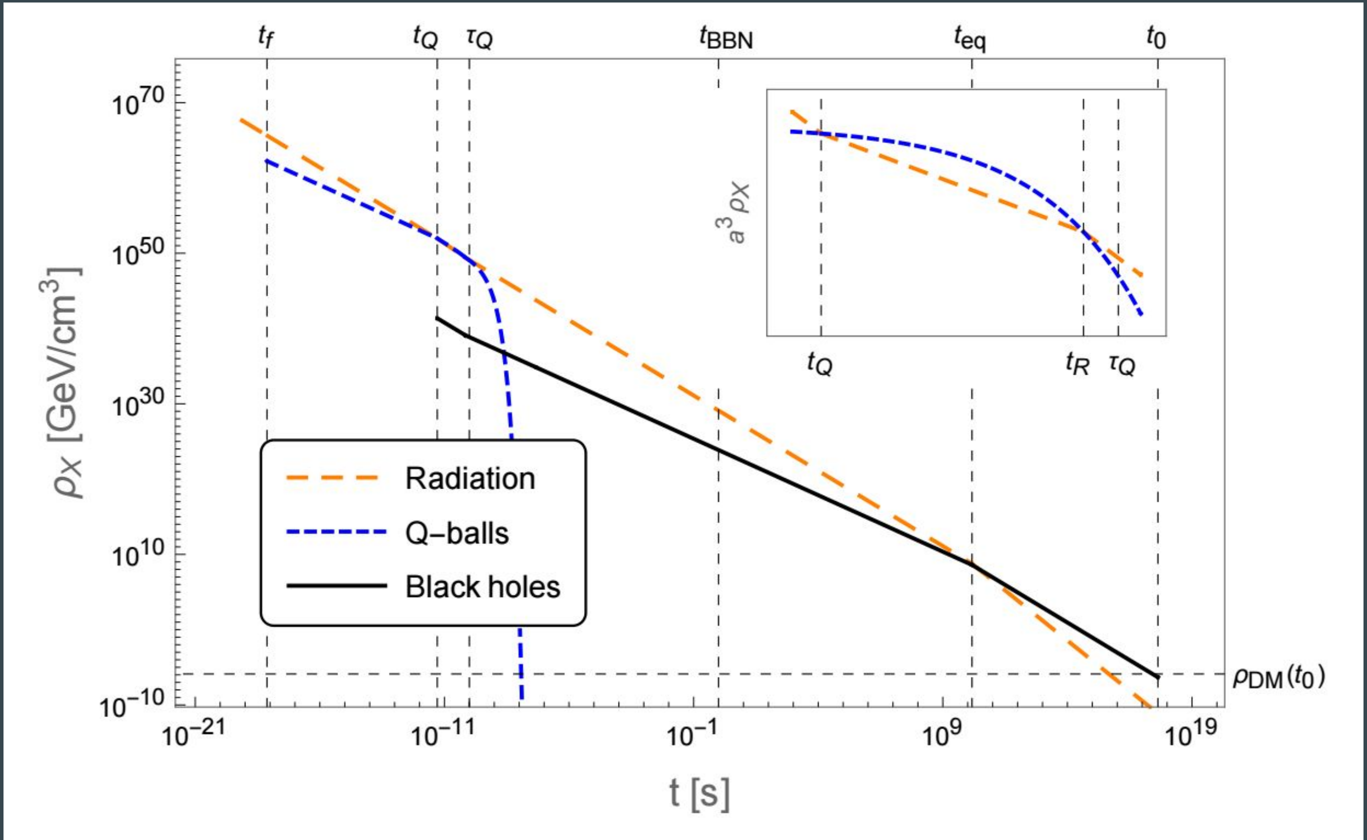
$p=0$

$\rho \propto a^{-3}$

structures grow

modern era
(dark energy
dominated)

SUSY Q-ball formation can lead to PBHs



Intermittent matter dominated epoch allows for growth of structure

[Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103]

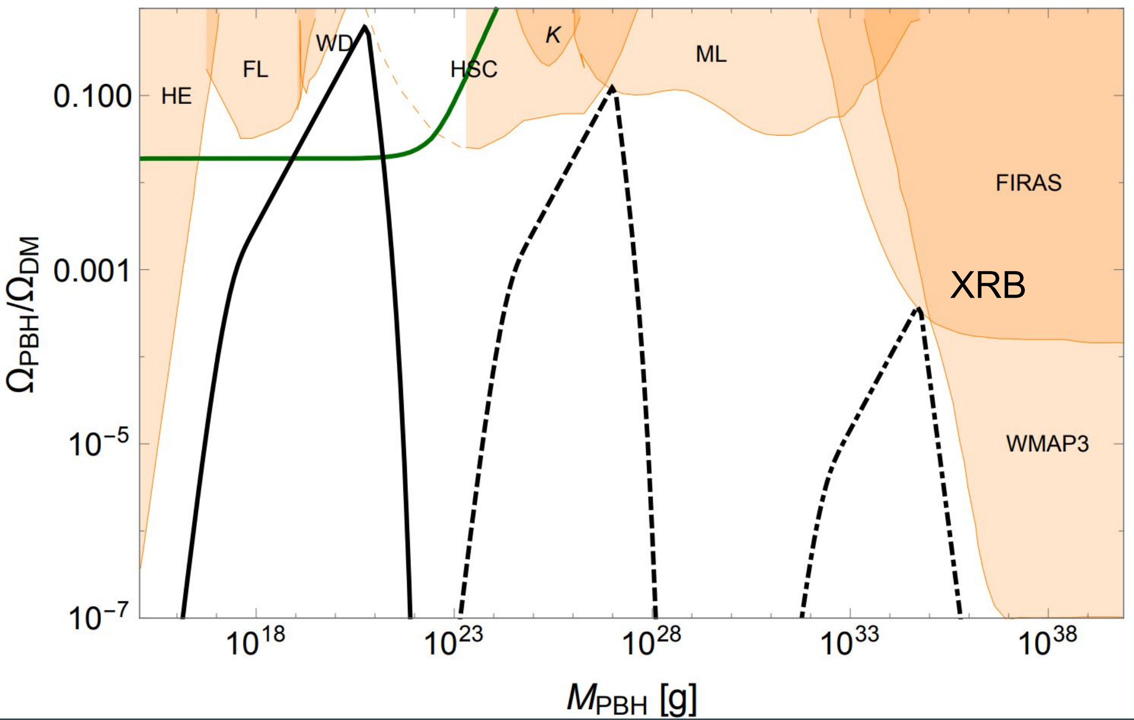
Matter-dominated universe

Volodymyr Takhistov

Matter with relatively few heavy particles creates large density fluctuations, leading to production of black holes.

Eric Cotner,
A UCLA graduate student

SUSY Q-ball formation can lead to PBHs



parameter space for

Ω_{PBH}=1, 0.2, 0.001

[Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103]

r-process above green line

A candidate microlensing event Subaru HSC obs. of M31

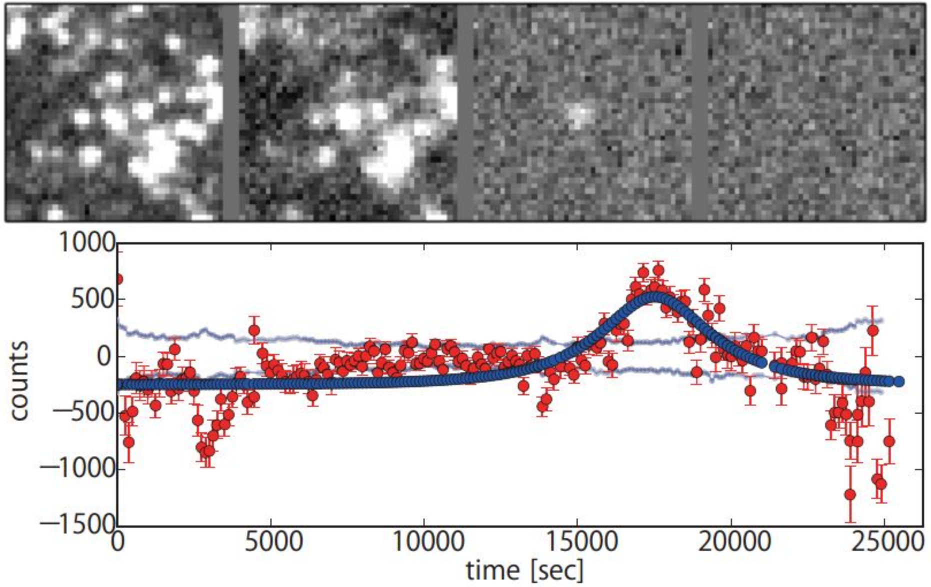


Figure 13. One remaining candidate that passed all the selection criteria of microlensing event. The images in the upper plot show the postage-stamped images around the candidate as in Fig. 7: the reference image, the target image, the difference image and the residual image after subtracting the best-fit PSF image, respectively. The lower panel shows that the best-fit microlensing model gives a fairly good fitting to the measured light curve.

Consistent with

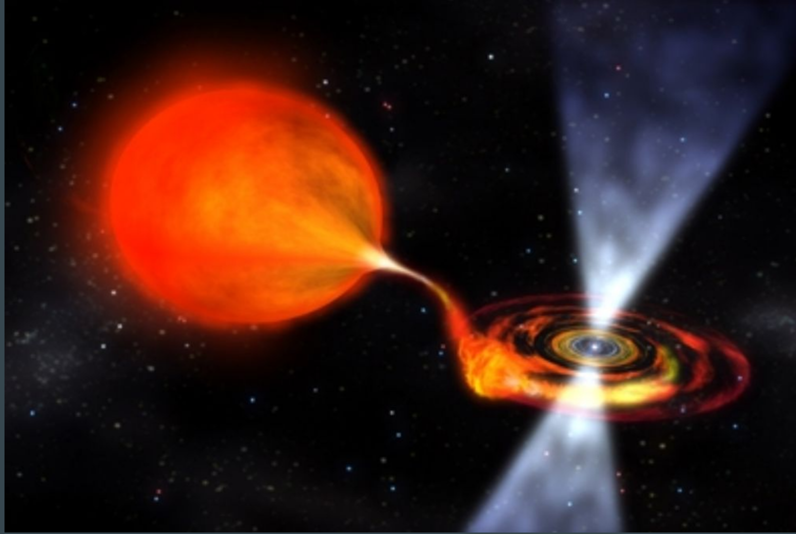
PBH mass ~10^{-7} $M_\odot$

Need follow-up observations

[Niikura et al., arXiv:1701.02151]

PBH and neutron stars

- Neutron stars can capture PBH, which consume and destroy them from the inside.
- Capture probability high enough in DM rich environments, e.g. Galactic Center
- Can set limits? No NSs in GC (except for one very young magnetar), no NSs in dwarf spheroidals, … A hint?!
- What happens if NSs really are systematically destroyed by PBH?



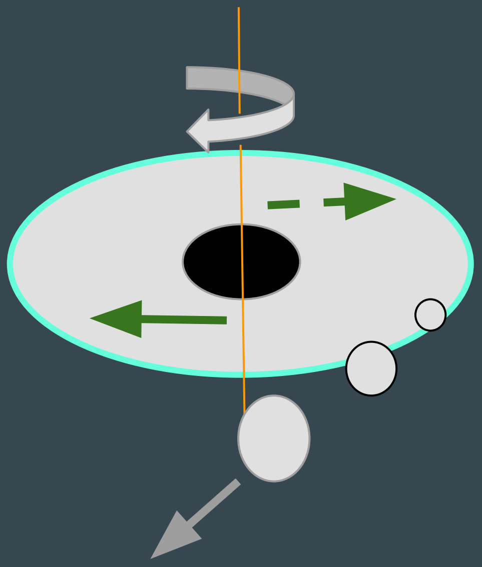
Fast-spinning millisecond pulsar. Image: NASA/Dana Berry

Neutron star destruction by black holes

⇒r-process nucleosynthesis, 511 keV, FRB

[Fuller, AK, Takhistov, Phys.Rev.Lett. 119 (2017) 061101]

MSP spun up by an accreting PBH



- MSP with a BH inside, spinning near mass shedding limit: elongated spheroid
- Rigid rotator: viscosity sufficient even without magnetic fields [Kouvaris, Tinyakov]; more so if magnetic field flux tubes are considered
- Accretion leads to a decrease in the radius, increase in the angular velocity (by angular momentum conservation)
- Equatorial regions gain speed in excess of escape velocity: ejection of cold neutron matter

[Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101] also, *Viewpoint* by H.-T. Janka

r-process material: observations

Milky Way (total): **$M \sim 10^4\ M_\odot$**

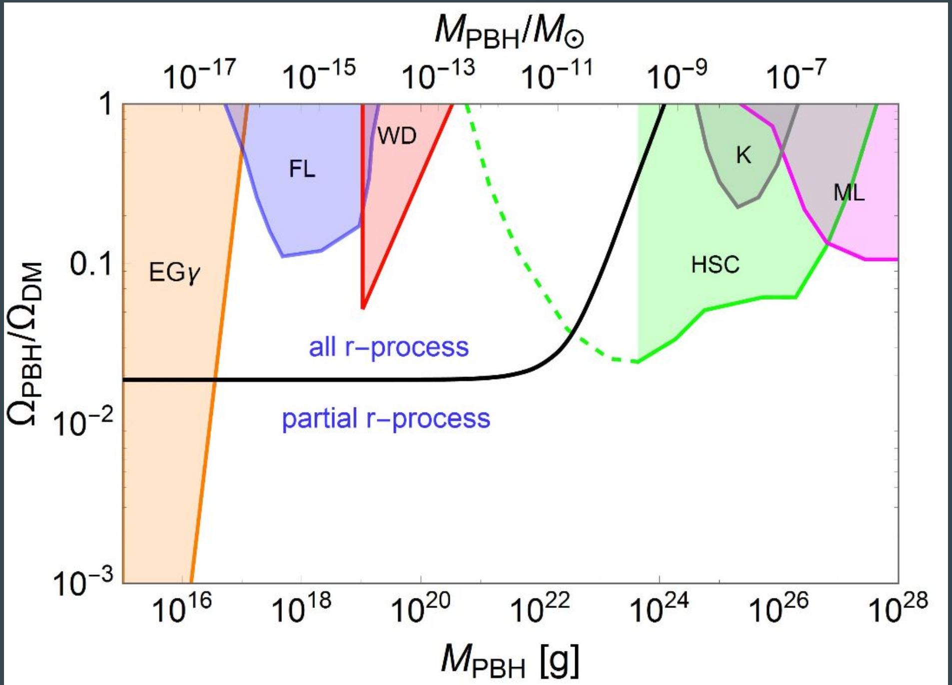
Ultra Faint Dwarfs (UFD): most of UFDs show no enhancement of r-process abundance.

However, **Reticulum II** shows an enhancement by factor **10^2-10^3**!

"Rare event" consistent with the UFD data: one in ten shows r-process material [Ji, Frebel et al. Nature, 2016]

NS disruptions by PBHs

- Centrifugal ejection of cold neutron-rich material (~0.1 $M_\odot$) MW: **M~10⁴ M$_\odot$** ✔
- UFD: a rare event, only one in ten UFDs could host it in 10 Gyr ✔
- Globular clusters: low/average DM density, but high density of millisecond pulsars. Rates OK. ✔



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r-process nucleosynthesis: site unknown

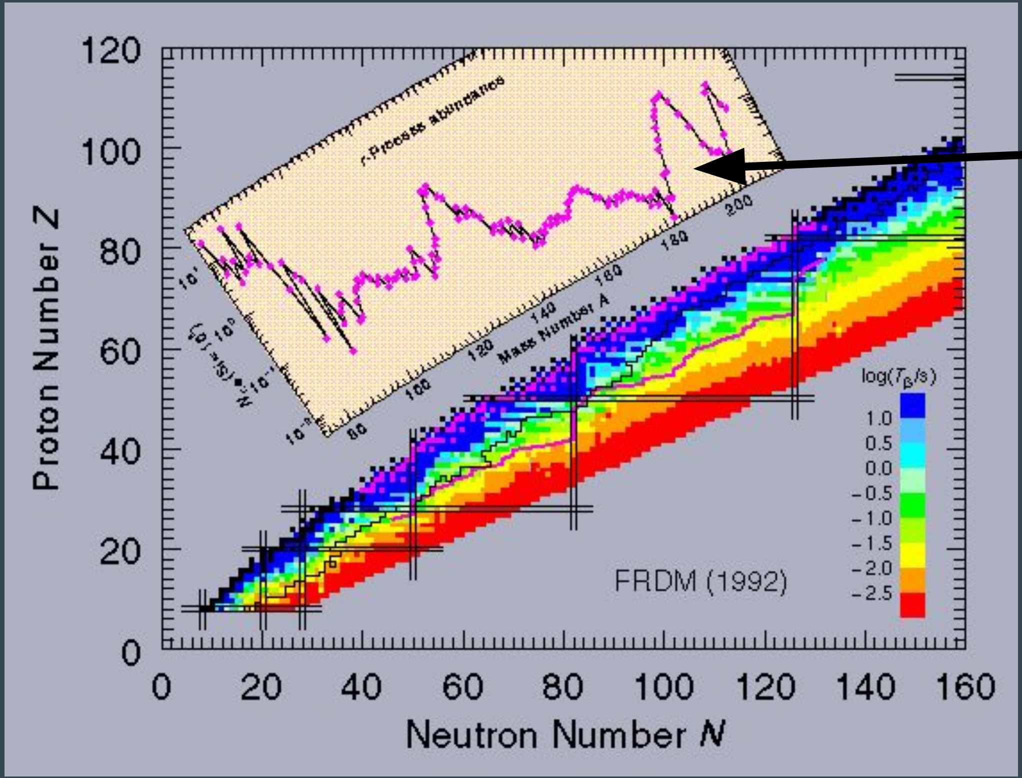

Image: Los Alamos, Nuclear Data Group

- s-process cannot produce peaks of heavy elements
- Observations well described by r-process
- Neutron rich environment needed
- Site? SNe? NS-NS collisions?..

Conclusion

Plethora of possibilities for DM is both a blessing and a curse

Hopefully, discoveries ahead!