Primordial black holes as dark matter: formation and astrophysical consequences

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P^3 (Particle Physics in Paris) seminar, May 26 2020

Supported by U.S. DOE Office of Science (HEP), and WPI, Japan

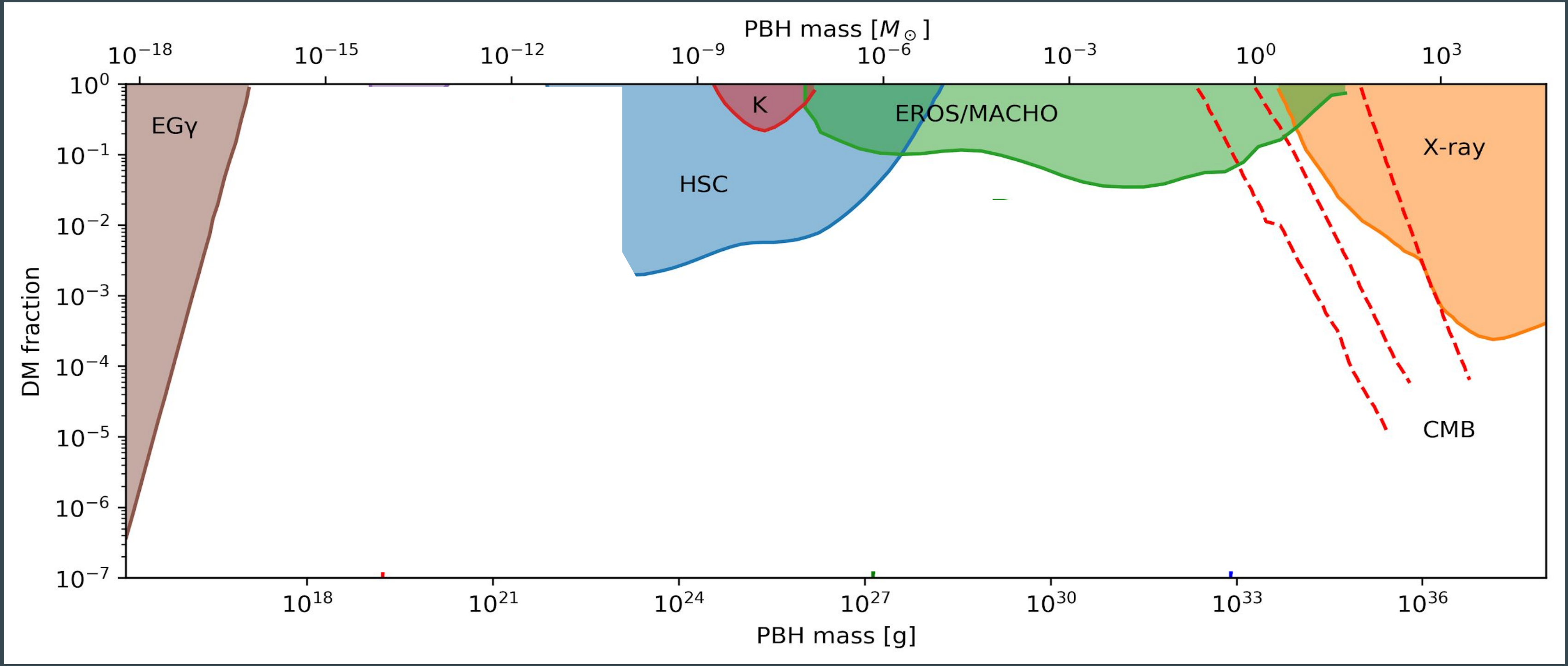
Primordial black holes

- Black holesan be produced in the early universe [Zeldovich, Novikov (1967); Hawking (1971), Carr]
- 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

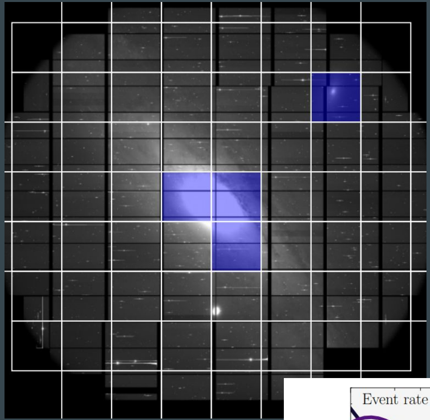
Formation scenarios

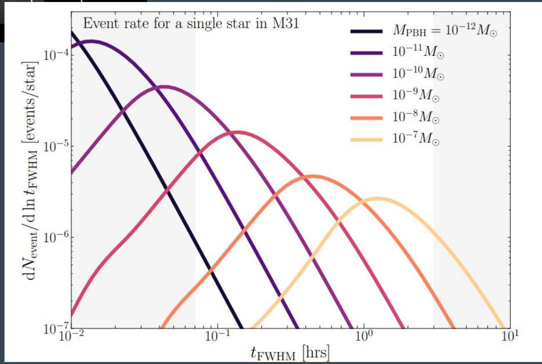
- Inflation [Carr; Garcia-Bellido, Linde et al. …] Spectrum of primordial density perturbations may have an extra power on some scale -> PBH
- Violent events, such as phase transitions, domain walls collapse.
- Matter-dominated phase is an opportunity [Zeldovich, Novikov; Khlopov, Polnarev, Zeldovich; Carr, Tenkanen; Georg, Melcher, Watson]
- Scalar field fragmentation: matter-dominated epoch with relatively few extremely massive particles per horizon ⇒ fluctuations are large [**Cotner**, AK; Fuller, AK, **Takhistov**; **Cotner**, AK, Takhistov, **Vitagliano**, Sasaki]
- Multiverse from inflation producing baby universes collapsing to PBH: extended mass function affords new ways to detect [Vilenkin et al., AK et al.]

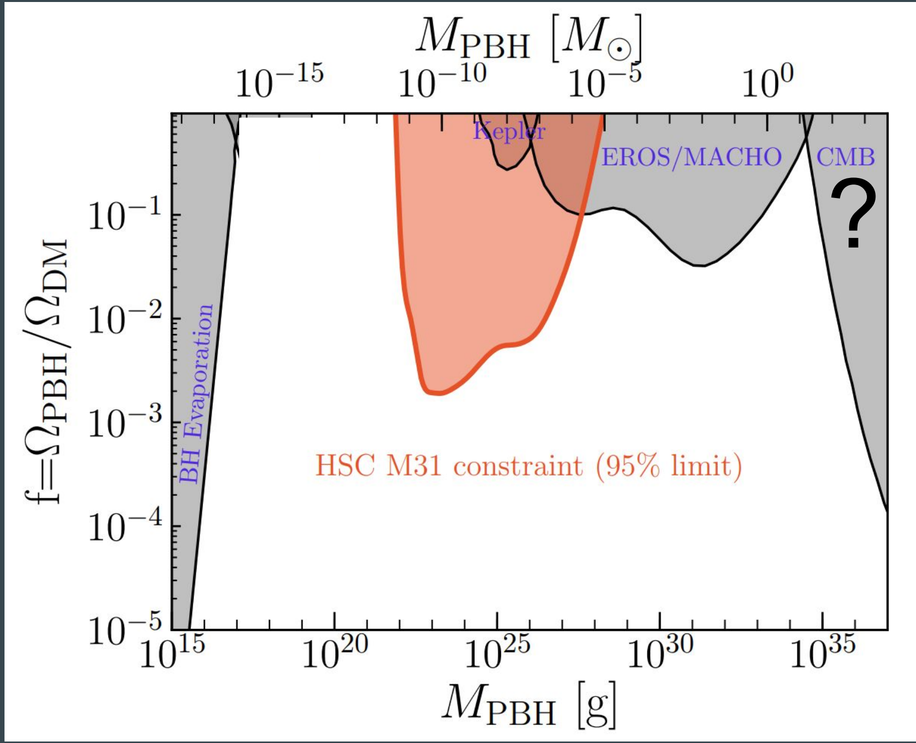
Experimental constraints



HSC search for PBH [Takada et al.]







A candidate microlensing event Subaru HSC obs. of M31

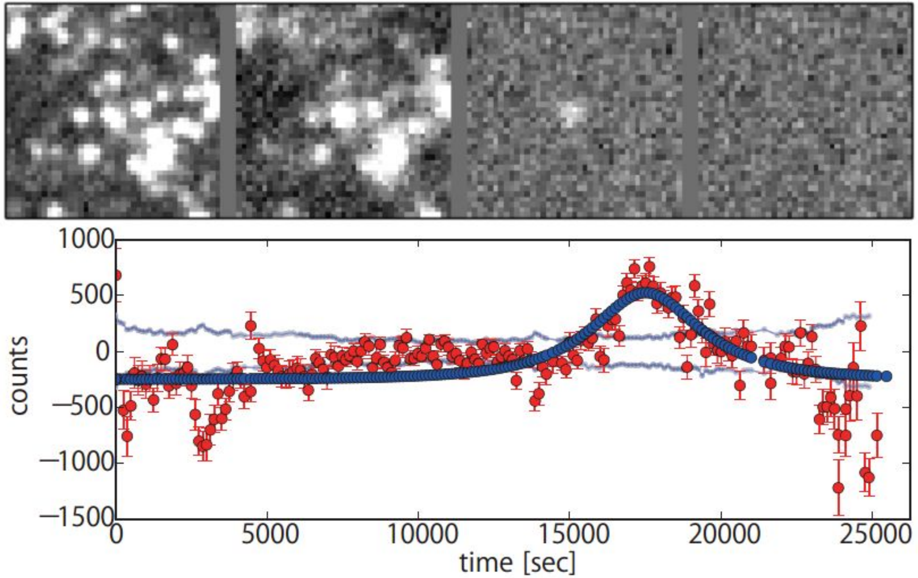


Figure 13. One remaining candidate that passed all the selection criteria of microlensing event. The images in the upper plot show the postage-stamped images around the candidate as in Fig. 7: the reference image, the target image, the difference image and the residual image after subtracting the best-fit 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 $\sim 10^{-7}\ M_{\odot}$
Need follow-up observations

[Niikura et al., Nature Astronomy arXiv:1701.02151]

Early Universe

Inflation

$p<0$

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

$p<0$

(dark energy dominated)

Scalar fields

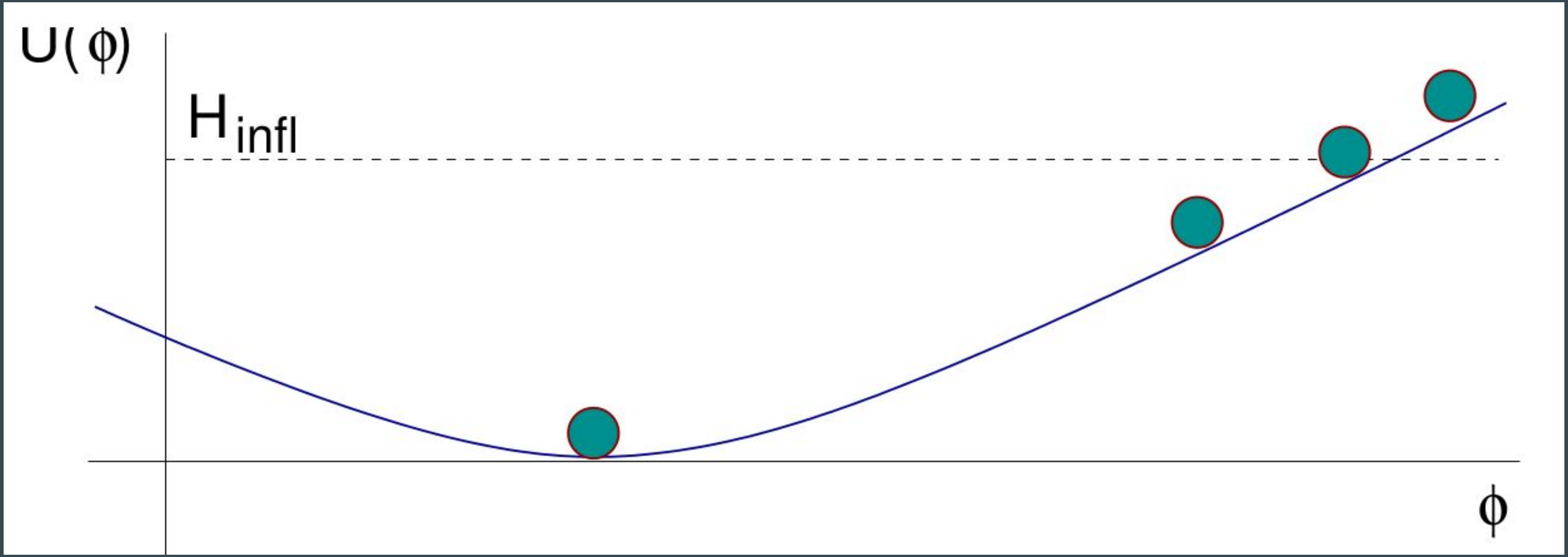
Simplest spin-zero object

Examples:

- Higgs field that gives an electron and other particles masses
- Supersymmetry - many scalar fields, including 100+ flat directions [Gherghetta et al., ‘95]

Scalar fields in de Sitter space during inflation

A scalar with a small mass develops a VEV
[Bunch, Davies; Affleck, Dine]



Scalar fields in de Sitter space during inflation

- If m=0, V=0, the field performs random walk:
- Massive, non-interacting field:
- Potential $V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4$

$$\langle\phi^2\rangle = \frac{H^3}{4\pi^2}t$$

$$\langle\phi^2\rangle = \frac{3H^4}{8\pi^2 m^2}$$

$$H\partial_t\langle\phi^2\rangle = \frac{H^4}{4\pi^2} - \frac{2m^2}{3}\langle\phi^2\rangle - 2\lambda\langle\phi^2\rangle^2$$

$$\langle\phi^2\rangle \rightarrow \frac{H^2}{\pi\sqrt{8\lambda}} \text{ for } m = 0$$

Scalar fields in de Sitter space during inflation

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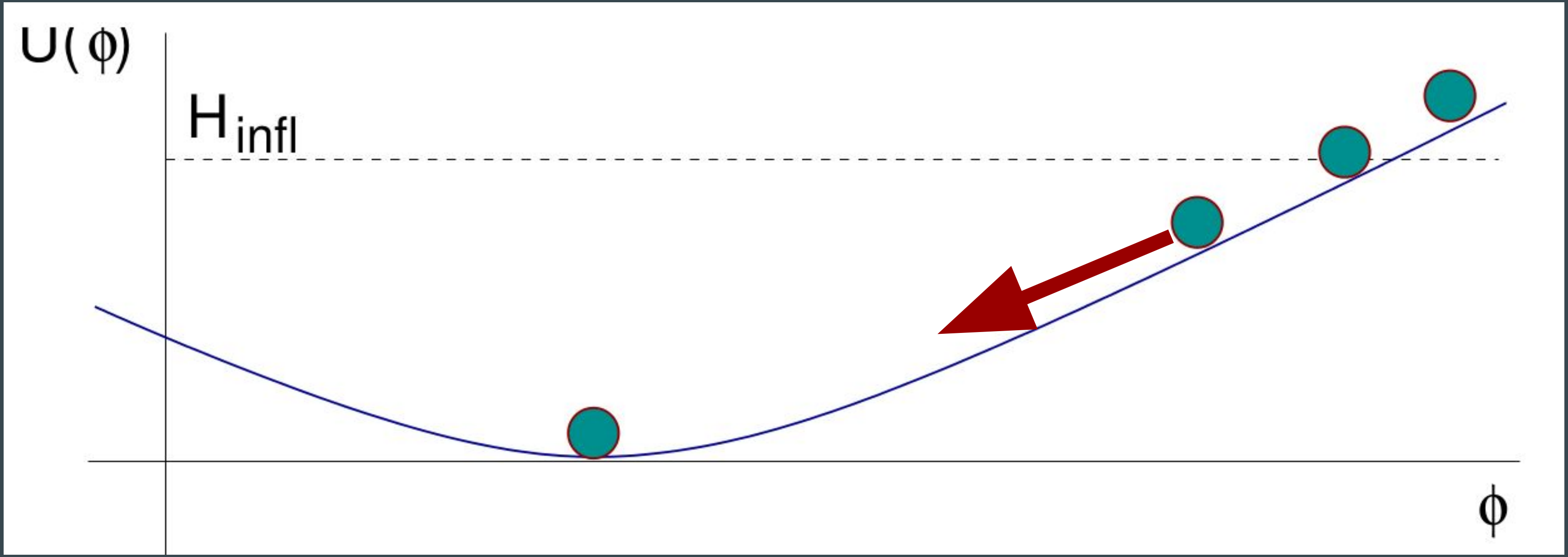
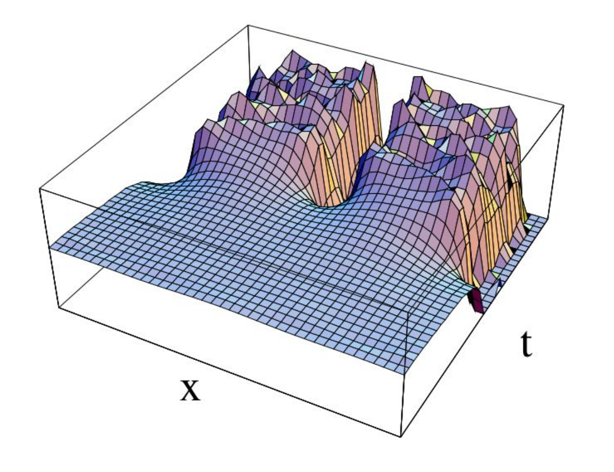
[Bunch, Davies; Affleck, Dine]



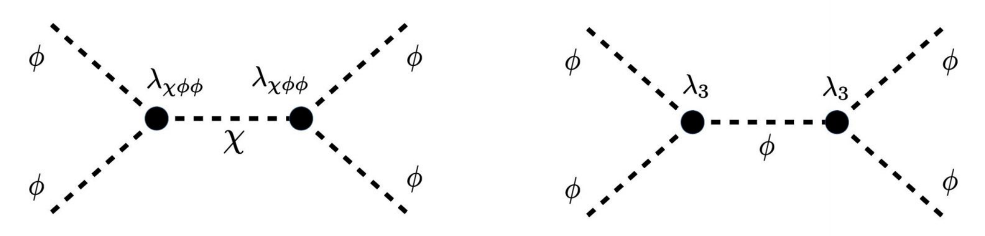
Scalar fields: an instability



Gravitational instability can occurs due to the attractive force of gravity.

Similar instability can occur due to scalar self-interaction which is **attractive**:

$$U(\phi) \supset \lambda_3 \phi^3$$ or $$\lambda_{\chi\phi\phi} \chi \phi^\dagger \phi$$



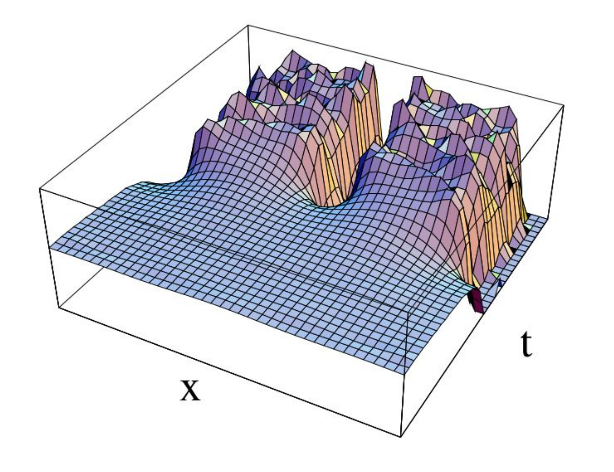
Scalar fields: an instability (Q-balls)

homogeneous solution $\varphi(x,t) = \varphi(t) \equiv R(t)e^{i\Omega(t)}$

$$\delta R, \delta\Omega \propto e^{S(t)-i\vec{k}\vec{x}}$$

$$\ddot{\delta\Omega} + 3H(\dot{\delta\Omega}) - \frac{1}{a^2(t)}\Delta(\delta\Omega) + \frac{2\dot{R}}{R}(\dot{\delta\Omega}) + \frac{2\dot{\Omega}}{R}(\dot{\delta R}) - \frac{2\dot{R}\dot{\Omega}}{R^2}\delta R = 0,$$

$$\ddot{\delta R} + 3H(\dot{\delta R}) - \frac{1}{a^2(t)}\Delta(\delta R) - 2R\dot{\Omega}(\dot{\delta\Omega}) + U''\delta R - \dot{\Omega}^2\delta R = 0.$$



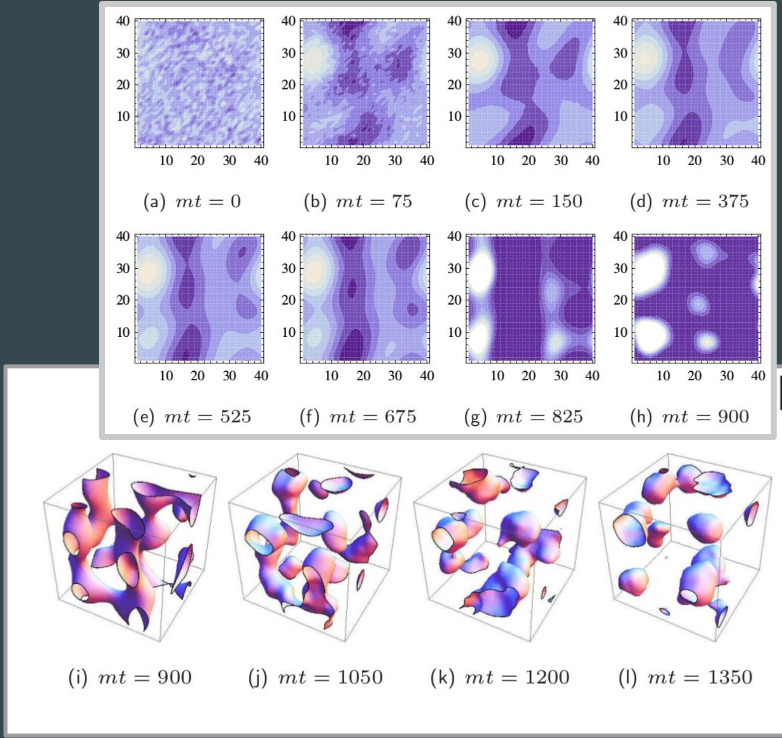
$(\dot{\Omega}^2 - U''(R)) > 0$ $\Rightarrow$ growing modes: $0<k<k_{max}$

$$k_{max}(t) = a(t)\sqrt{\dot{\Omega}^2 - U''(R)}$$

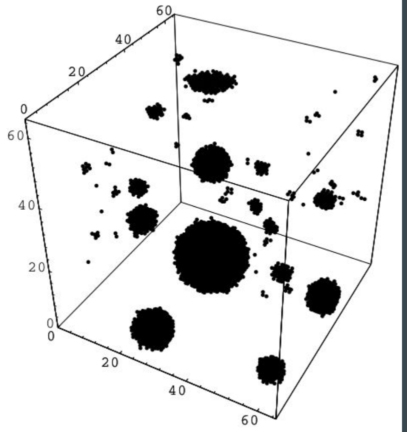
Also of interest: oscillons

AK, Shaposhnikov, hep-ph/9709492

Numerical simulations of scalar field fragmentation



[Multamaki].



[Kasuya, Kawasaki]

Q-balls: the min of energy for a fixed U(1) global number

Complex scalar field with a U(1) symmetry (e.g. B, L, B-L in SUSY)

U(1): $\phi \to e^{i\theta}\phi.$

Ground state with Q≠0 ?

vacuum: $\phi = 0$

conserved charge: $Q = \frac{1}{2i}\int \left(\phi^\dagger \overleftrightarrow{\partial_0}\, \phi\right) d^3x$

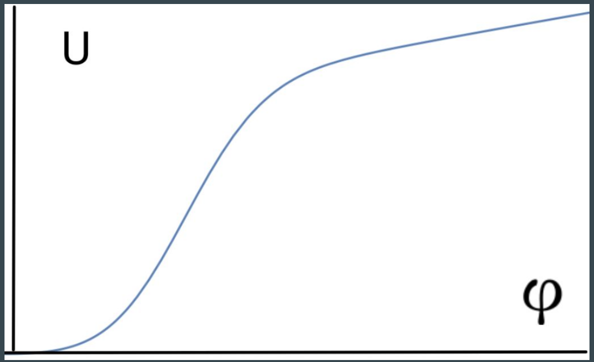
$Q \neq 0 \Rightarrow \phi \neq 0$ in some finite domain

$\Rightarrow$ Q-ball [Rosen; Friedberg, Lee, Sirlin; Coleman]

Q-balls exist if

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

Q-balls in a flat potential (as in SUSY)



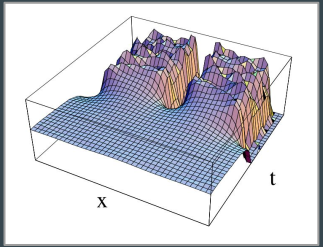
Q=global charge (e.g. baryon number) = number of particles

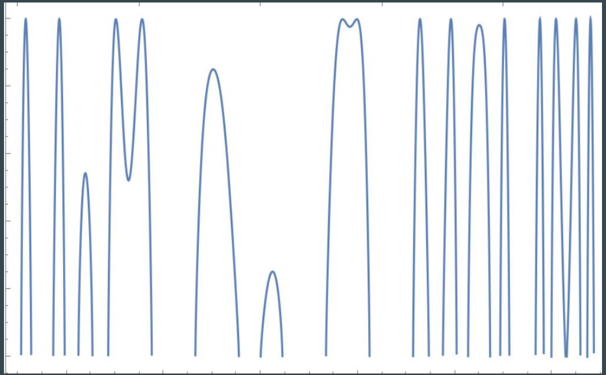
Mass $\propto Q^{3/4} \Rightarrow$

(Mass per particle) $\propto (Q^{3/4}/Q) = Q^{-1/4}$ **= decreases for large Q** $\Rightarrow$

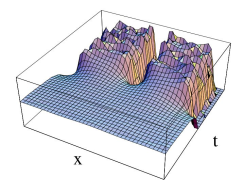
- min of energy
- stick together
- size fluctuations $\Rightarrow$

mass fluctuations





Early Universe



Inflation

origin of
primordial
perturbations

radiation dominated

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

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

structures don't grow

matter dominated

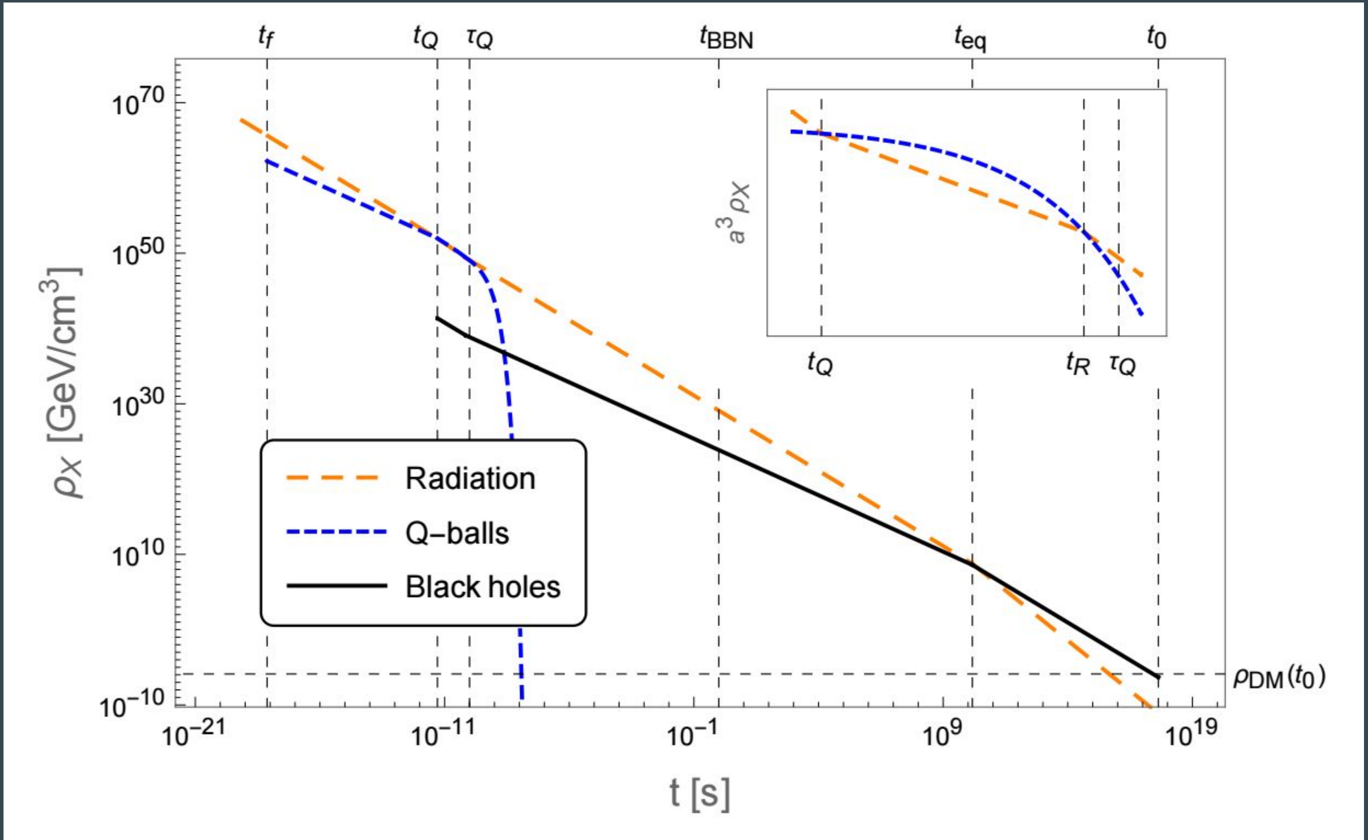
$p=0$

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

structures grow

modern era
(dark energy
dominated)

Scalar lump (Q-ball) formation can lead to PBHs

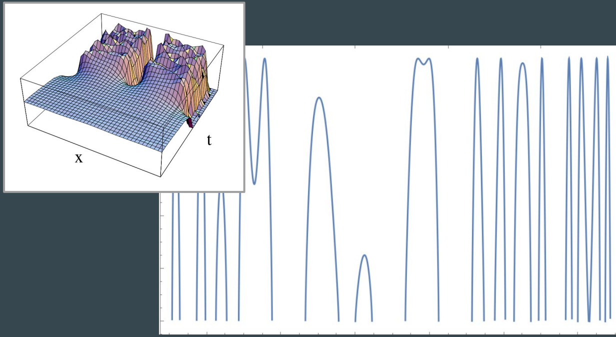


Intermittent matter dominated epoch in the middle of radiation dominated era

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

Few big lumps create large fluctuations

Matter-dominated phase has been considered before, but

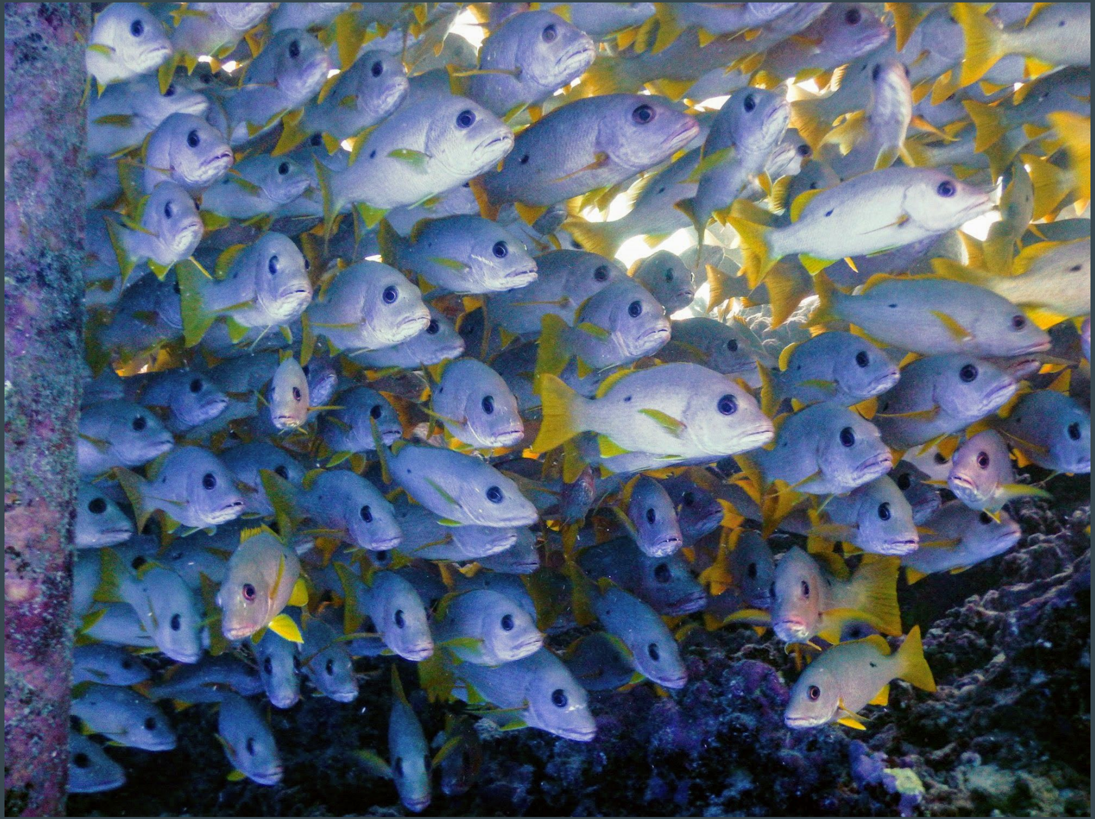


- usually, fluctuations are not big enough
- non-linear evolution cannot be reliably invoked: virialized systems do not make black holes
- in linear regime, PBH formation is suppressed in the absence of large fluctuations

Small number of large “particles” ⇒ large fluctuations, enough PBH for DM

Must account for suppression from non-spherical configurations, etc. -- still OK.

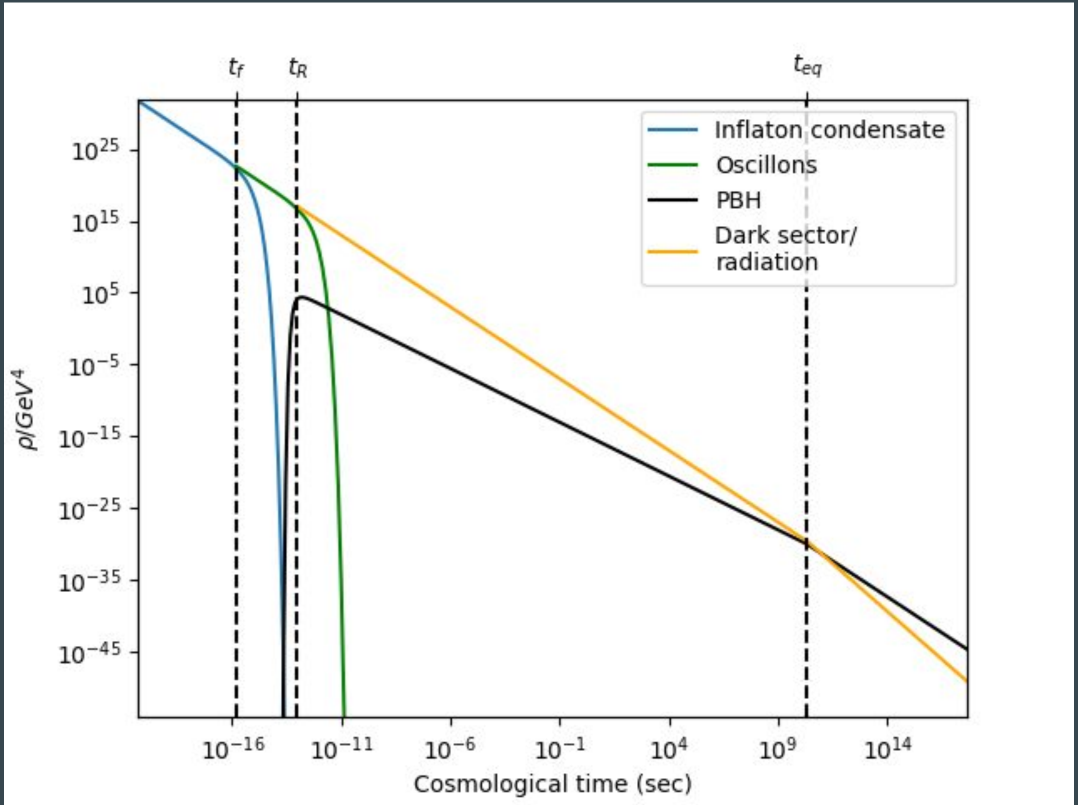
Many particles ⇒ only small Poisson fluctuations



FEW GIANT PARTICLES ⇒

LARGE *POISSON* FLUCTUATIONS

Scalar lump (oscillon) formation can lead to PBHs



Intermittent matter dominated epoch immediately after inflation

[Cotner, AK, Takhistov, Phys.Rev. D98 (2018), 083513]

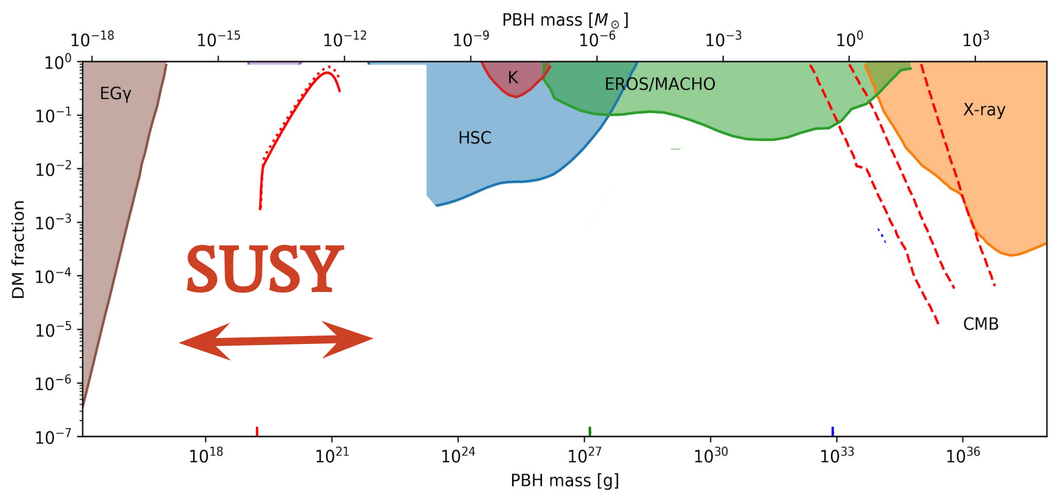
PBH from Supersymmetry: natural mass range

Flat directions lifted by SUSY breaking terms, which determine the scale of fragmentation.

$$10^{17}\mathrm{g} \lesssim M_{\mathrm{PBH}} \lesssim 10^{22}\mathrm{g}$$

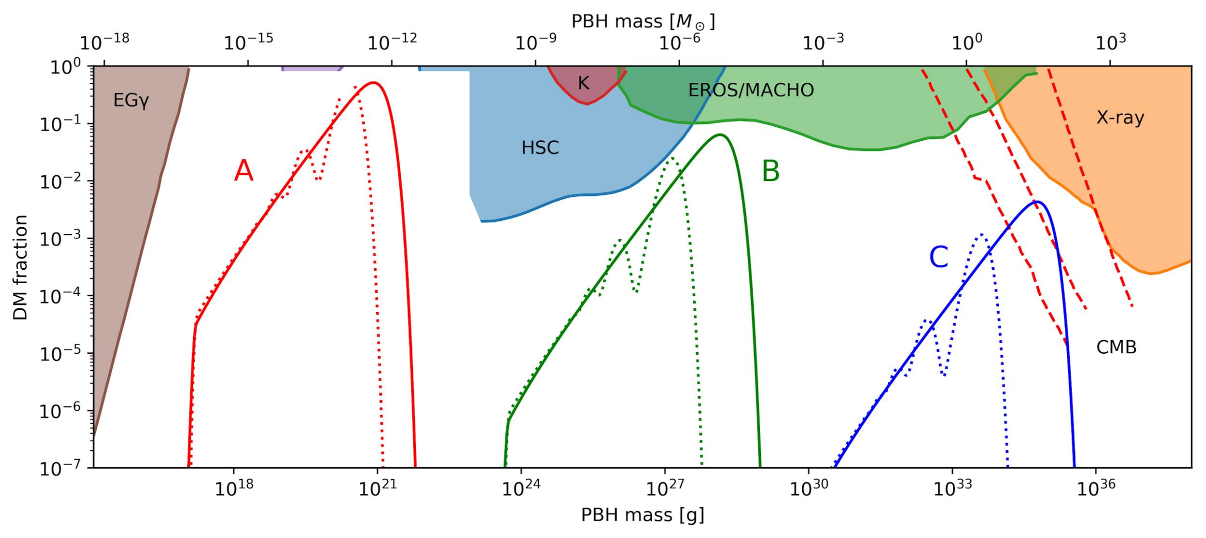
$$M_{\mathrm{hor}} \sim r_f^{-1}\left(\frac{M_{\mathrm{Planck}}^3}{M_{\mathrm{SUSY}}^2}\right) \sim 10^{23}\mathrm{g}\left(\frac{100\ \mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$

$$M_{\mathrm{PBH}} \sim r_f^{-1} \times 10^{22}\mathrm{g}\left(\frac{100\ \mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$



[Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103
Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019) 077]

Scalar lump formation ⇒ PBHs with different masses



Ω_{PBH}=1, (A)

0.2, (B)

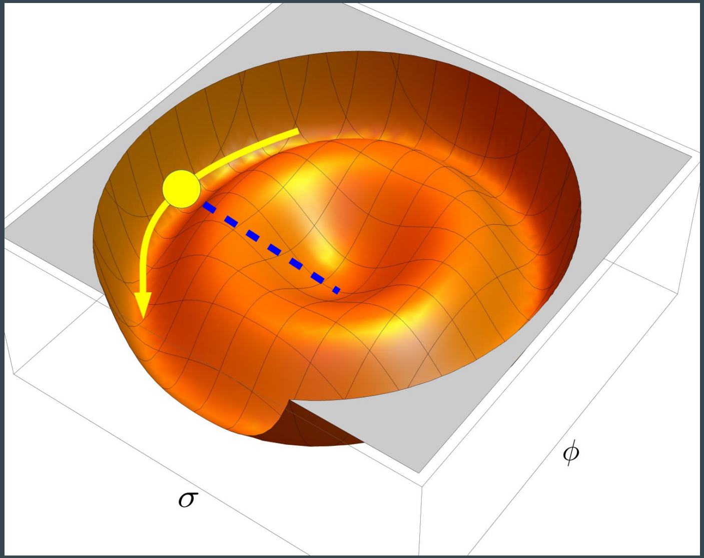
0.001 (C)

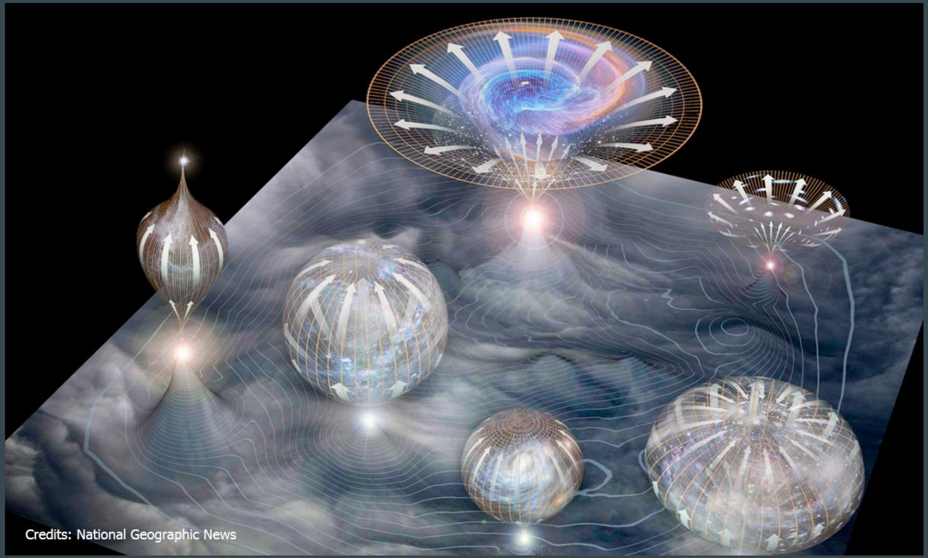
[Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103
Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019) 077]

Comparison with PBH from inflationary perturbations

	PBH Production Scenario	
	Inflationary Perturbations (*common mechanism*)	Field Fragmentation (*our mechanism*)
Source and type of large (CMB-scale) perturbations	inflaton fluctuations, curvature	inflaton fluctuations, curvature
Source and type of small (PBH-scale) perturbations	inflaton fluctuations, curvature	stochastic field fragmentation, isocurvature (fragment-lumps)
PBH source field	inflaton	inflaton or spectator field
Required potential condition	inflaton potential fine tuning	no new restrictions on inflaton potential, scalar field potential shallower than quadratic (attractive self-interactions)
PBH formation era ($t_{\rm PBH}$) and type	$t_{\rm BBN} \gtrsim t_{\rm PBH} \gtrsim t_{\rm reh}$, after reheating, radiation-dominated era	$t_{\rm BBN} \gtrsim t_{\rm PBH} \gtrsim t_{\rm inf}$, before or after reheating, temporary matter-dominated era
PBH size ($r_{\rm BH}$) vs. horizon ($r_{\rm H}$) at formation	$r_{\rm BH} \sim r_{\rm H} \sim H^{-1}$	$r_{\rm BH} \ll r_{\rm H} \sim H^{-1}$
PBH spin (a)	$a \sim 0$	$a \sim \mathcal{O}(1)$ possible

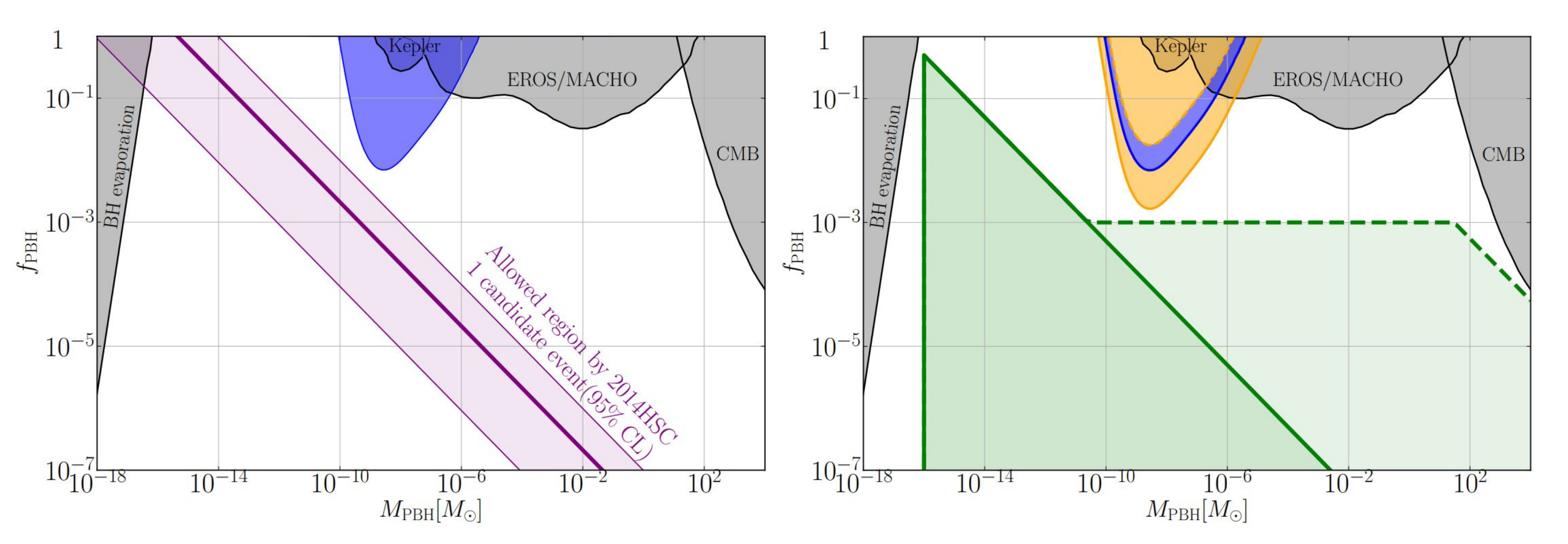
Another mechanism: inflationary multiverse





[Deng, Vilenkin arXiv:1710.02865;
AK, Sasaki, Sugiyama, Takada, Takhistov, Vitagliano, arXiv:2001.09160]

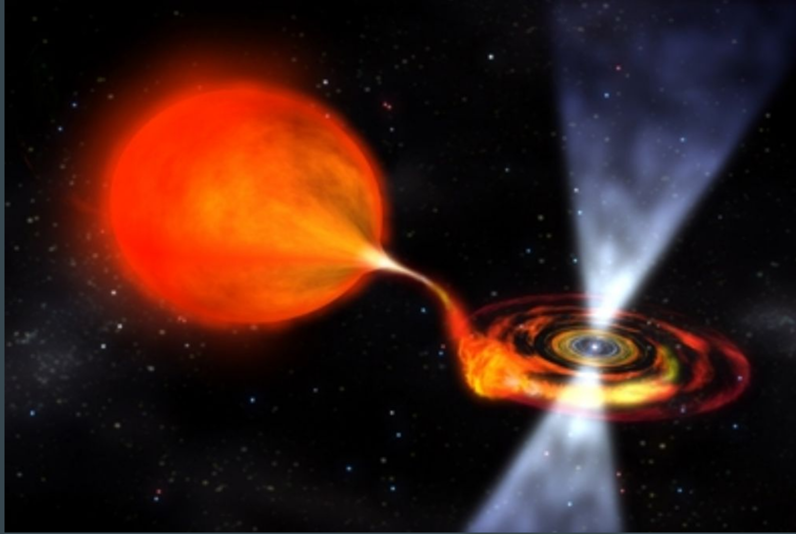
Tail of the mass the function $\propto M^{-1/2}$, accessible to HSC



[AK, Sasaki, Sugiyama, Takada, Takhistov, Vitaglian, arXiv:2001.09160]

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
- Missing pulsar problem…
  [e.g. Dexter, O'Leary, arXiv:1310.7022]
- What happens if NSs really are systematically destroyed by PBH?



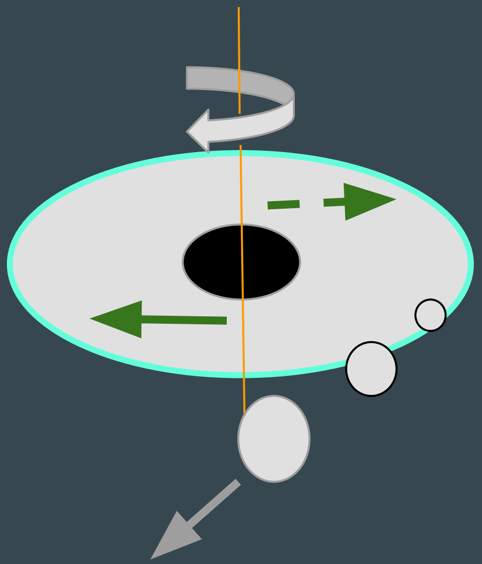
Fast-spinning millisecond pulsar. Image: NASA/Dana Berry

Neutron star destruction by black holes

⇒r-process nucleosynthesis, 511 keV, FRB

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

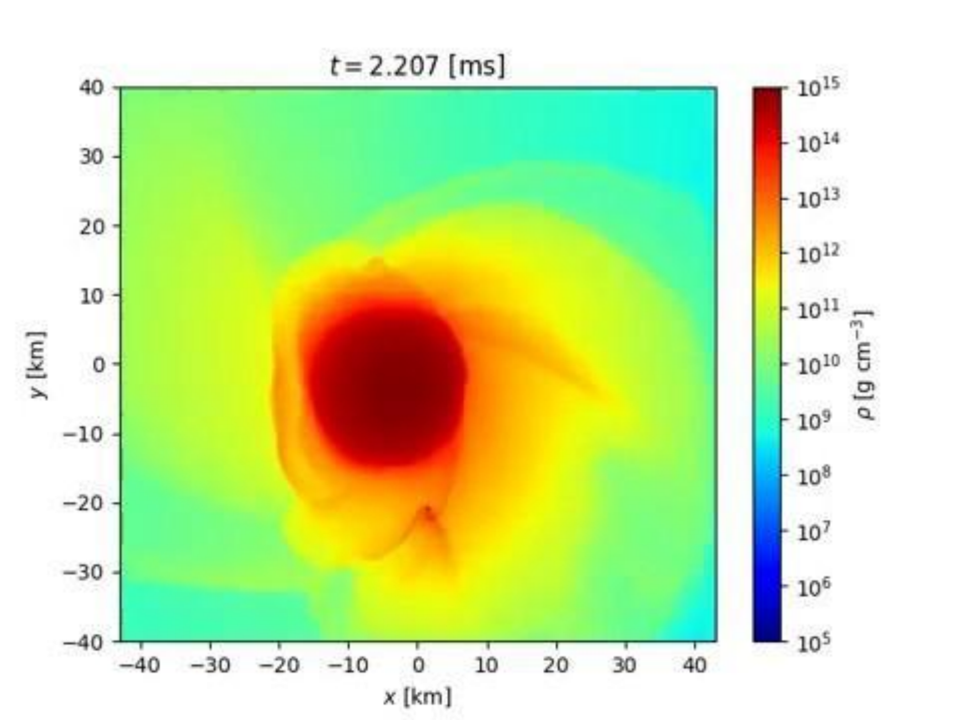
MSP spun up by an accreting PBH



- 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

Numerical simulations by David Radice (Princeton)



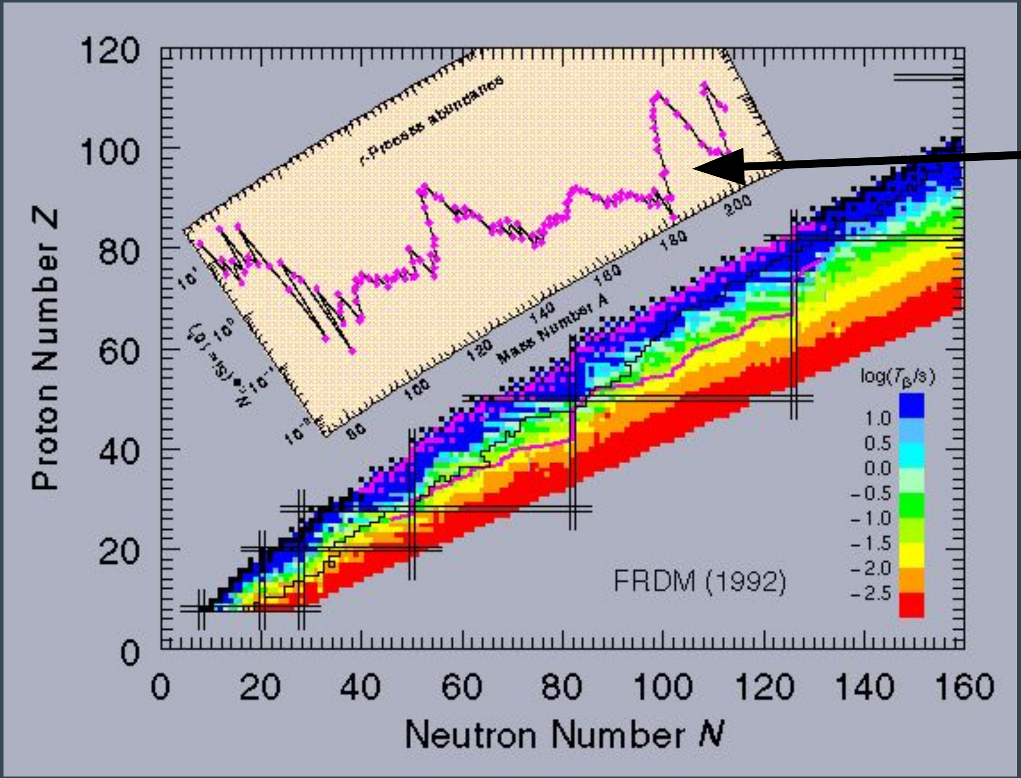
Preliminary results by
David Radice (Princeton U. and IAS)

Initial PBH mass for this simulation:

$M_{PBH} = 0.03\ M_\odot$

(preliminary results)

r-process nucleosynthesis: site unknown



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

Image: Los Alamos, Nuclear Data Group

r-process nucleosynthesis: site unknown

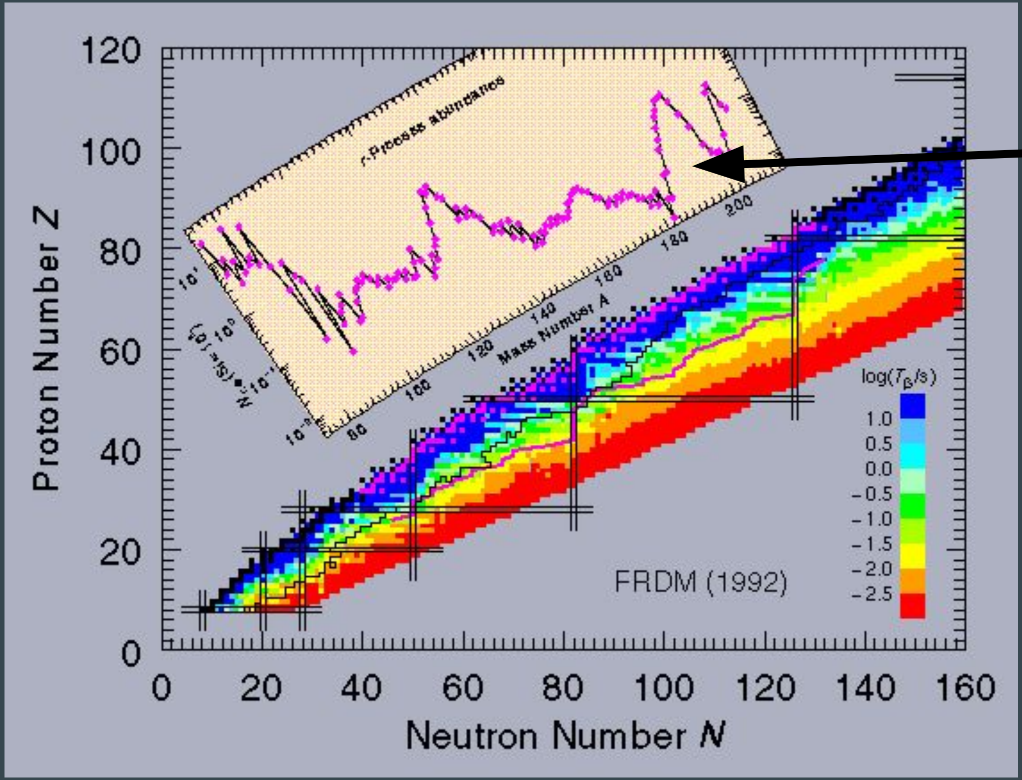
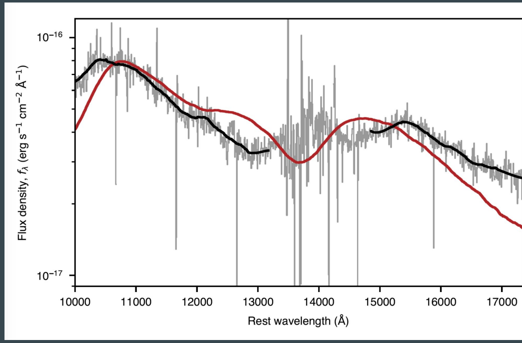


Image: Los Alamos, Nuclear Data Group

- **SN**? Problematic: neutrinos
- **NS mergers**? Can account for all r-process?



r-process material: observations

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

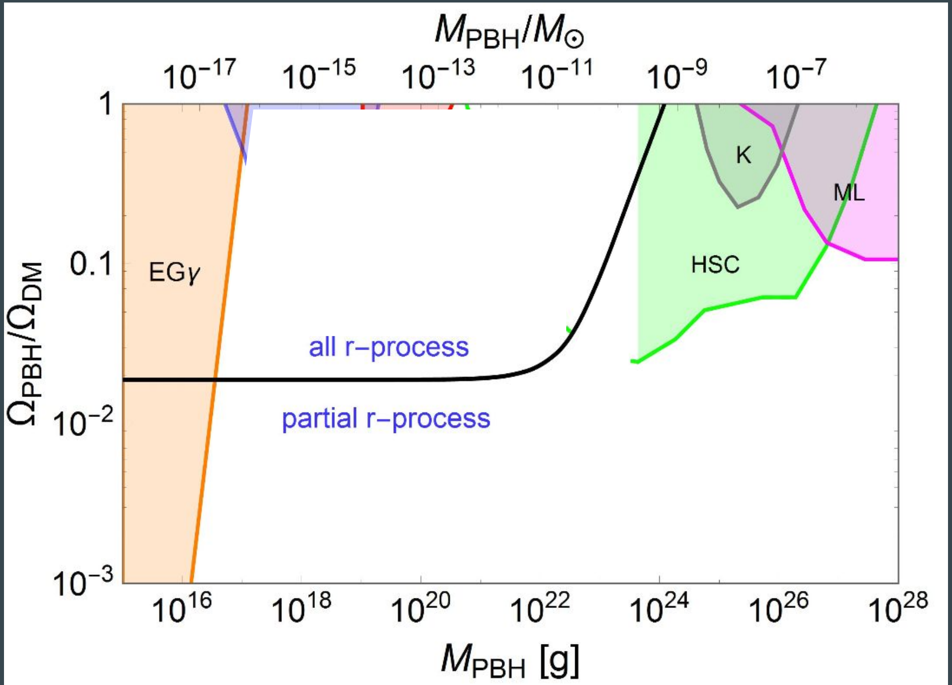
Ultra Faint Dwarfs (UFD): most of UFDs show no enhancement of r-process abundance.

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: **$M \sim 10^4\ M_\odot$** ✅
- 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. ✅

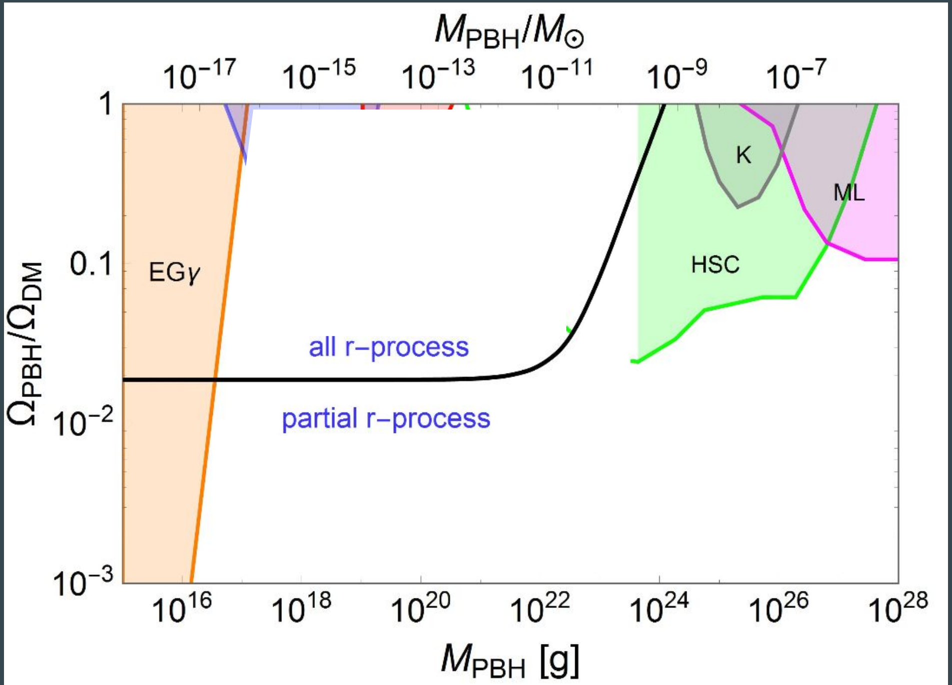


[Fuller, AK, Takhistov, PRL 119 (2017) 061101]

also, a *Viewpoint* PRL article by Hans-Thomas Janka

NS disruptions by PBHs

- Weak/different GW signal
- No significant neutrino emission
- Fast Radio Bursts
- Kilonova type event **without** a GW counterpart, but with a possible coincident FRB
- 511 keV line



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

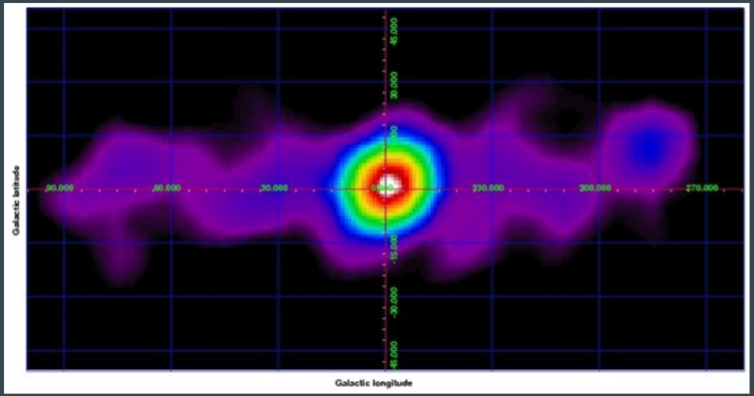
511-keV line in Galactic Center

Origin of positrons unknown. Need to produce 10^{50} positrons per year. Positrons must be produced with energies below 3 MeV to annihilate at rest. [Beacom,Yuksel '08]

Cold, neutron-rich material ejected in PBH-NS events is heated by β-decay and fission to T~0.1 MeV

→ **generate 10^{50} e^{+}/yr** for the rates needed to explain r-process nucleosynthesis.

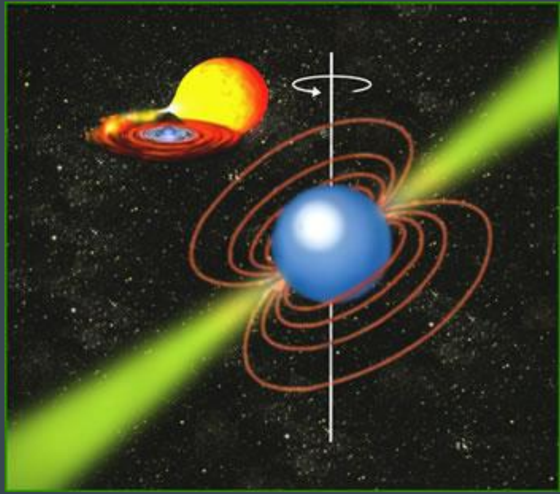
Positrons are non-relativistic.



ESA/Bouchet et al.

$$\Gamma(e^+e^- \to \gamma\gamma) \sim 10^{50}\mathrm{yr}^{-1}$$

Fast Radio Bursts (FRB)



Origin unknown. One repeater, others: non-repeaters. $\tau \sim$ ms.

PBH - NS events: final stages dynamical time scale $\tau \sim$ ms.

NS magnetic field energy available for release: $\sim 10^{41}$erg
Consistent with observed FRB fluence.

Massive rearrangement of magnetic fields at the end of the NS life, on the time scale ~ms produces an FRB.
(Of course, there are probably multiple sources of FRBs.)

GW detectors can discover small PBH…

PBH + NS

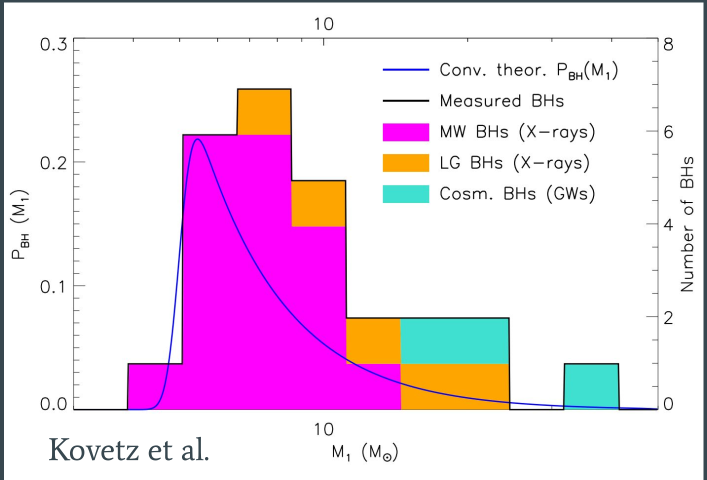
⇓

BH of 1-2 $M_\odot$

…if it detects mergers of

1-2 $M_\odot$ black holes

(not expected from evolution of stars)



[Takhistov, arXiv:1707.05849]

Conclusion

- Simple formation mechanism in the early universe:
  PBH from a scalar field fragmentation, PBH from vacuum bubbles
- PBH with masses 10^{-14} - 10^{-10} $M_{\odot}$, motivated by 1-100 TeV scale supersymmetry, can make up 100% (or less) of dark matter
- PBH is a generic dark matter candidate in SUSY
- If >10% of dark matter is PBH, they can contribute to r-process nucleosynthesis
- Signatures of PBH:
  - Kilonova without a GW counterpart, or with a weak/unusual GW signature
  - An unexpected population of 1-2 $M_{\odot}$ black holes (GW)
  - Galactic positrons, FRB, etc.
  - Microlensing (HSC) can detect the tail of DM mass function.