Primordial black holes from scalar field dynamics

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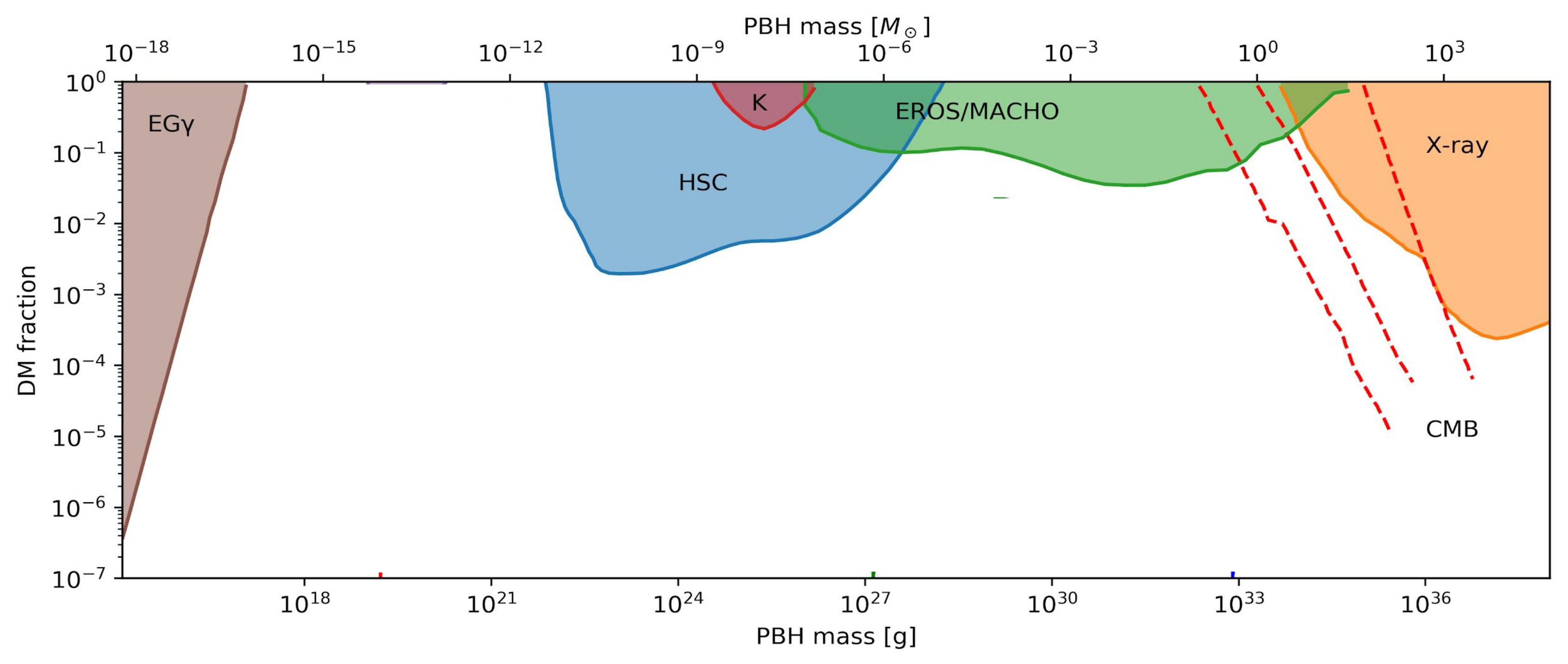
Primordial black holes

- 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

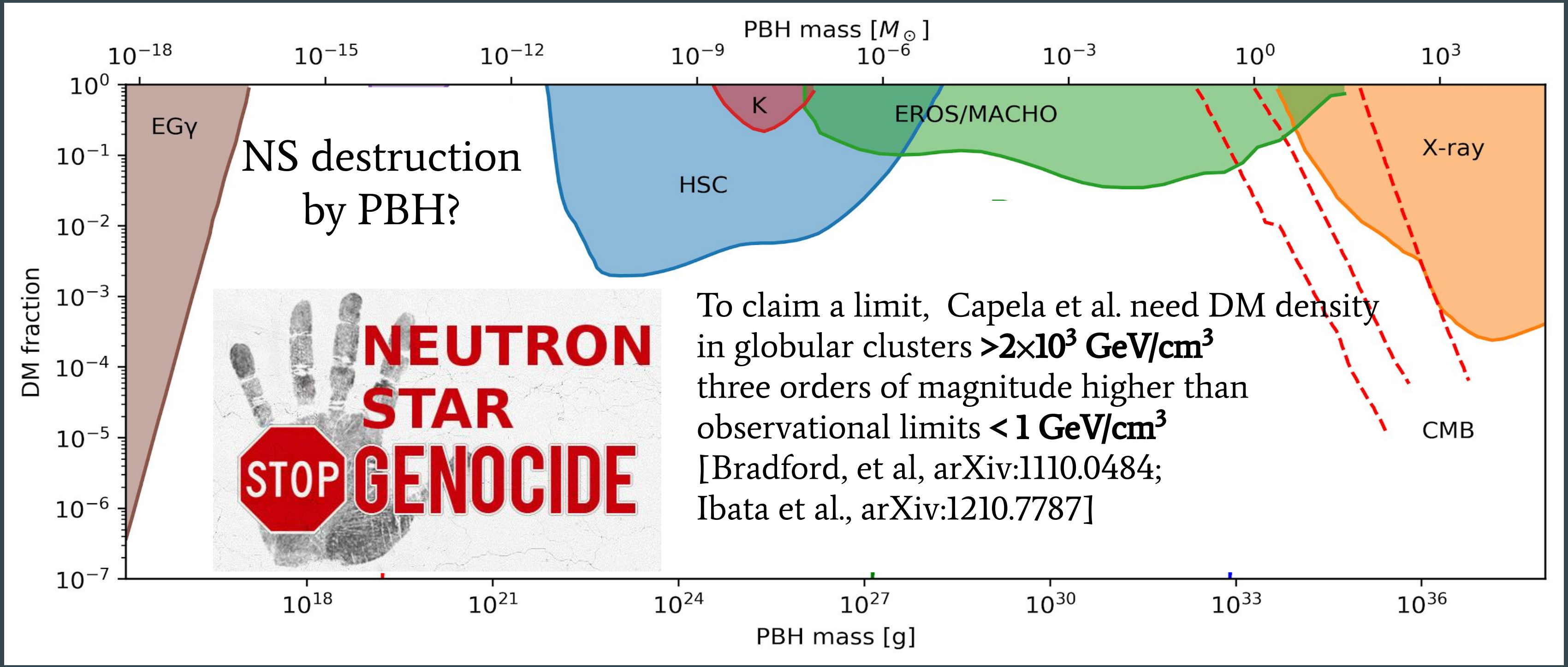
Formation

- Inflation [Carr; Garcia-Bellido, Linde et al.; Germani …] 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. Not easy, but possible to arrange [**talks by Carr, Germani, others**]
- Higgs dynamics
- Violent events, such as phase transitions, domain walls collapse.
- Scalar field fragmentation: matter-dominated epoch with relatively few extremely massive particles per horizon $\Rightarrow$ Poisson fluctuations are large [Cotner, AK, Phys. Rev. Lett. 119 (2017) 031103, arXiv:1612.02529; arXiv:1706.09003, arXiv:1801.03321]

Observational constraints



Observational constraints: neutron stars?



NS destruction by PBH?

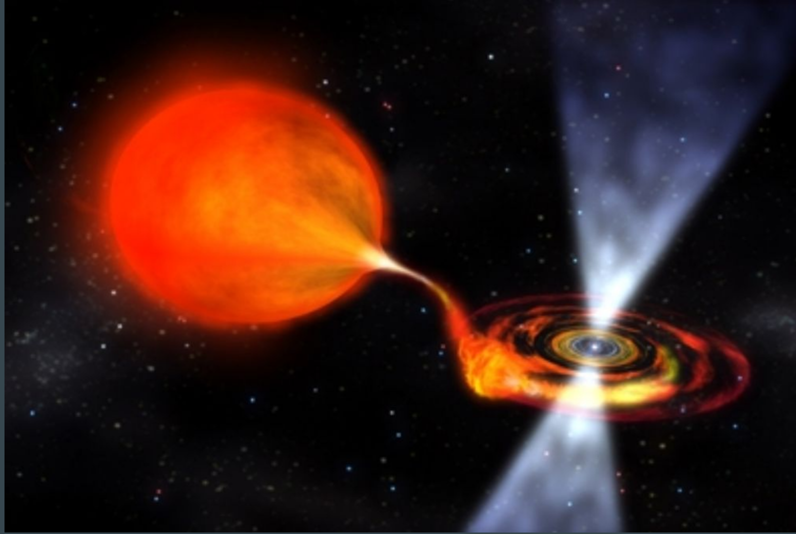
To claim a limit, Capela et al. need DM density in globular clusters **>2×10^3 GeV/cm^3** three orders of magnitude higher than observational limits **< 1 GeV/cm^3** [Bradford, et al, arXiv:1110.0484; Ibata et al., arXiv:1210.7787]

PBH can destroy neutron stars...

- DM density is high in the galactic center (no known NS, except for one young magnetar)
  ⇒ no constraint
- DM density is high in the dSph (no known NS)
  ⇒ no constraint
- “Missing pulsar problem”

Destruction of NS by PBH can contribute to r-process nucleosynthesis [talk by Takhistov]

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



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

MIcrolensing

Talk by Takada yesterday

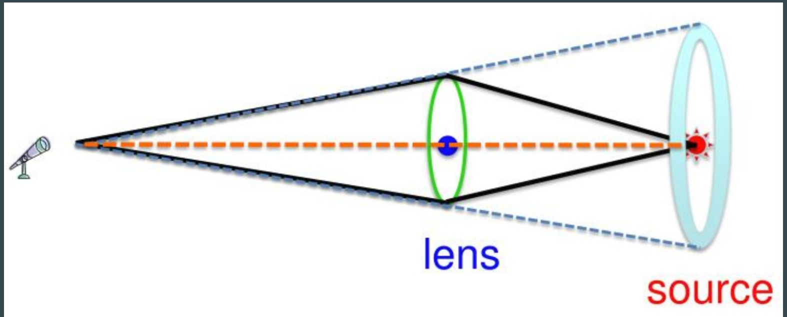
HSC is the flagship instrument:

- wide angle (M31 in FOV),
- high sensitivity: short exposures possible

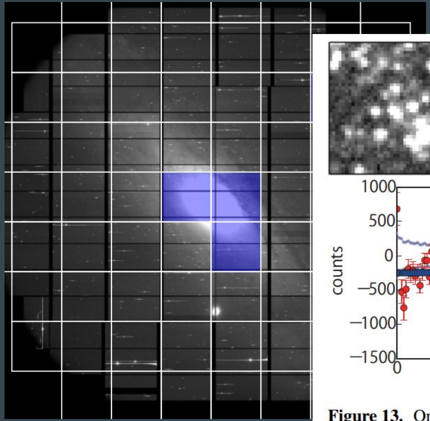
Limitations of microlensing:

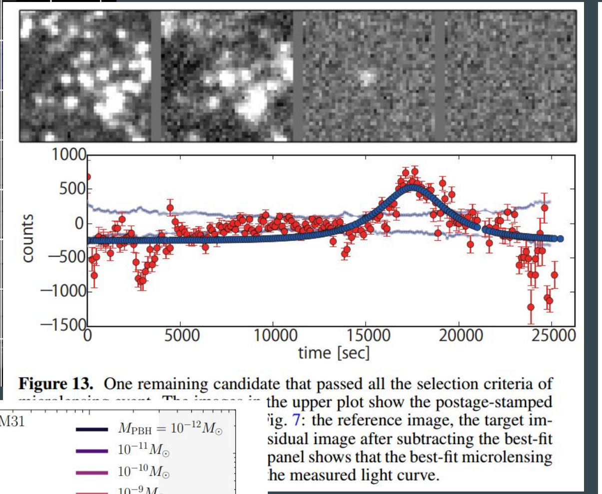
- finite size of the source
- wave effects

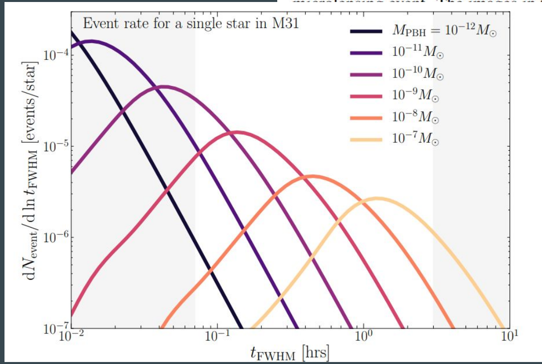
[Sugiyama, Kurita Takada, arXiv:1905.06066]

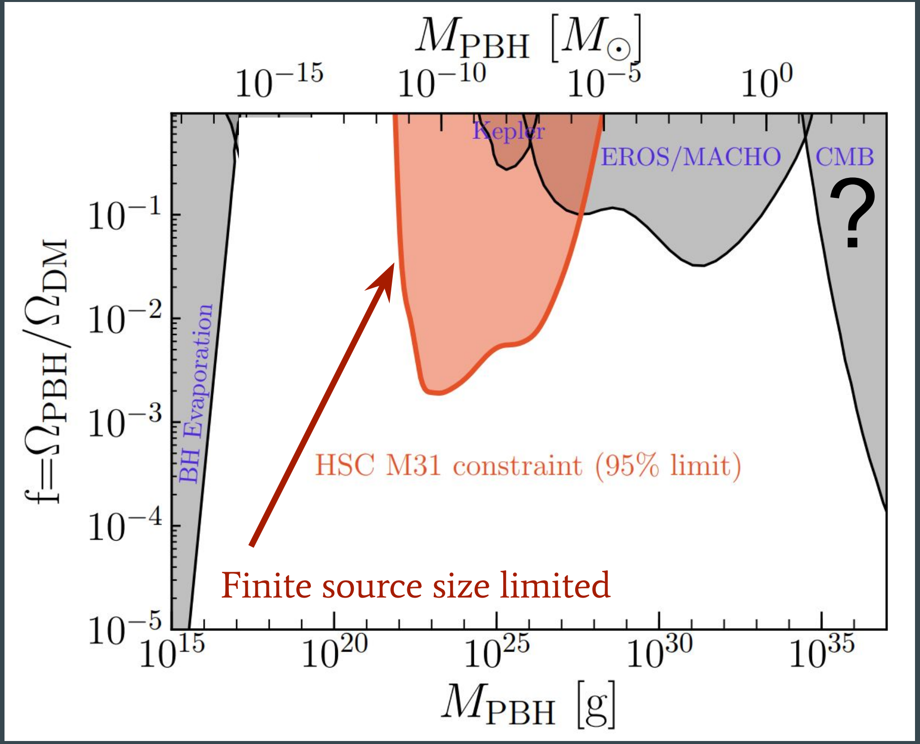


HSC search for PBH [Takada et al.]

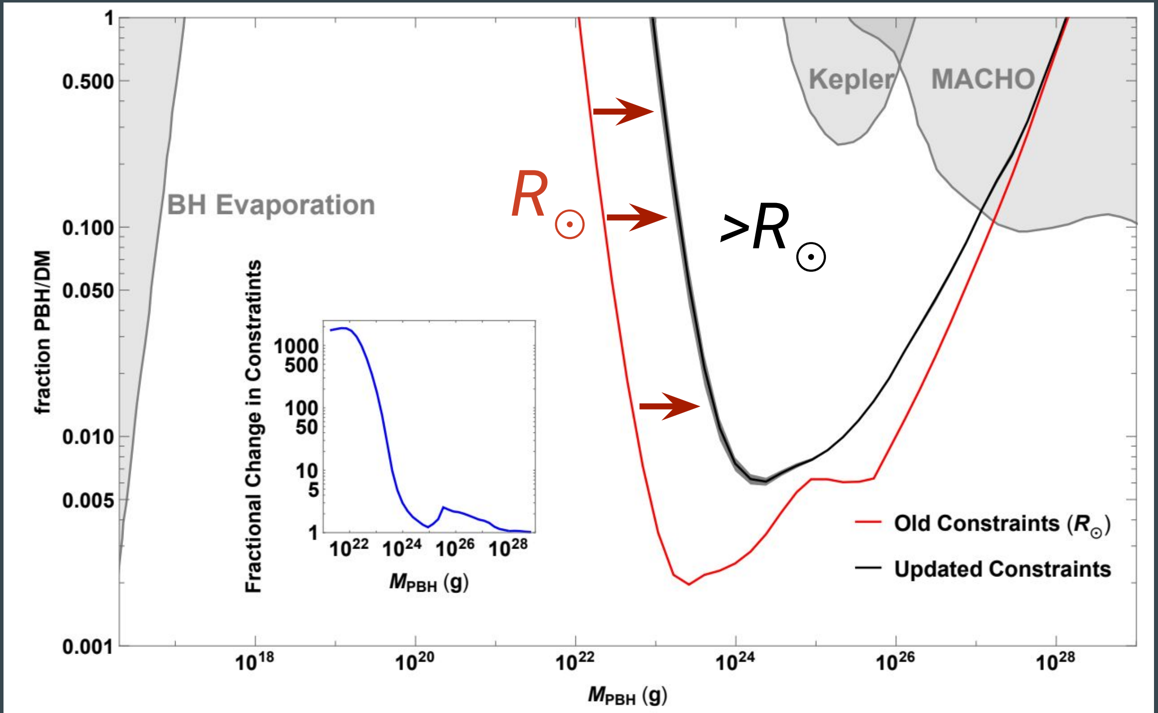








Finite size of stars limits magnification, relaxes constraints

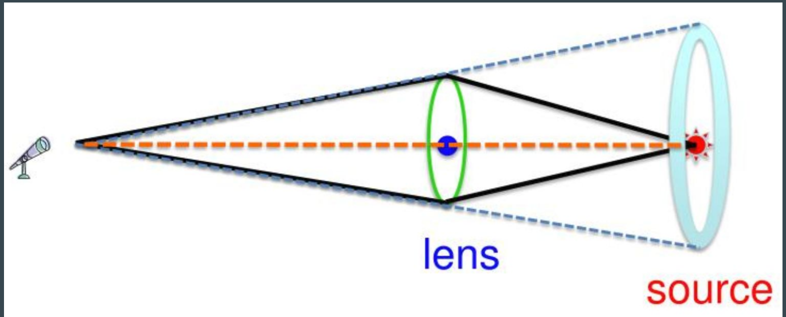


Stars in M31 bright enough for microlensing are typically > $R_\odot$ leading to modified limits [Smyth et al, 1910.01285]

Femtolensing

Source = GRB

Wavelength=small, can probe small PBH masses



Problems: finite-size effects, wave effects

No meaningful limit on PBH

[Katz et al., arXiv:1807.11495]

Survival of white dwarfs

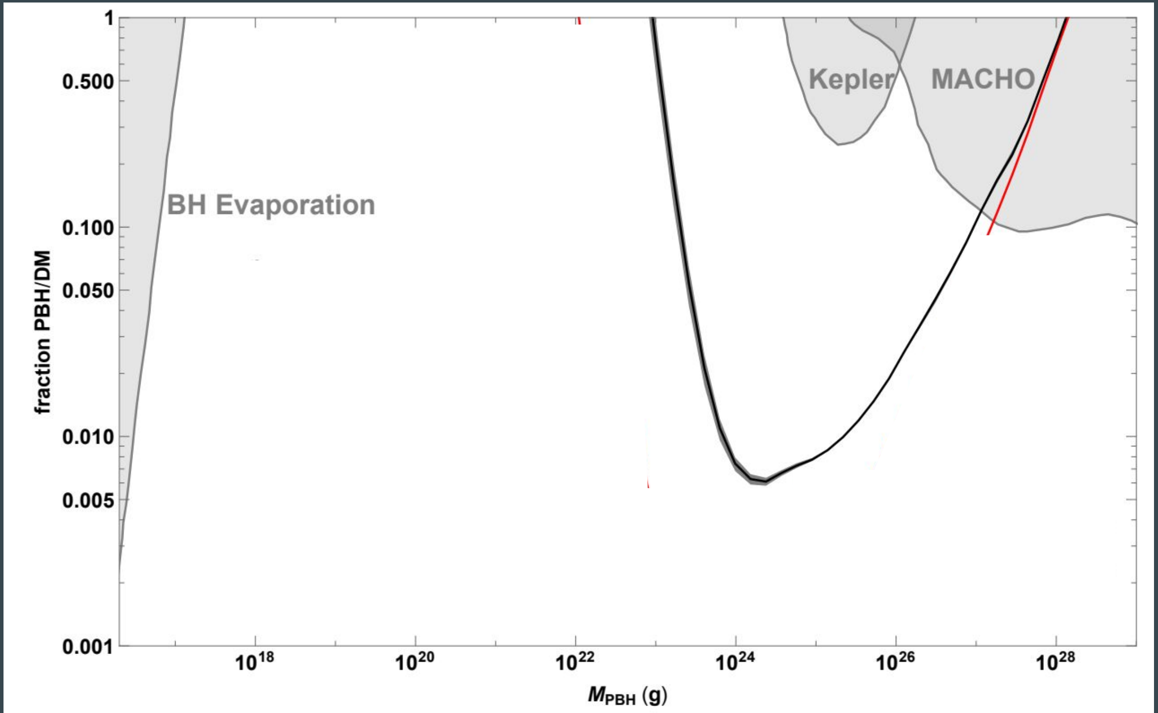
Can white dwarfs be ignited by a PBH going through it?

Possibly, but most likely -- not.

No meaningful limit on PBH

[Montero-Camacho et al., arXiv:1906.05950]

Constraints on PBH

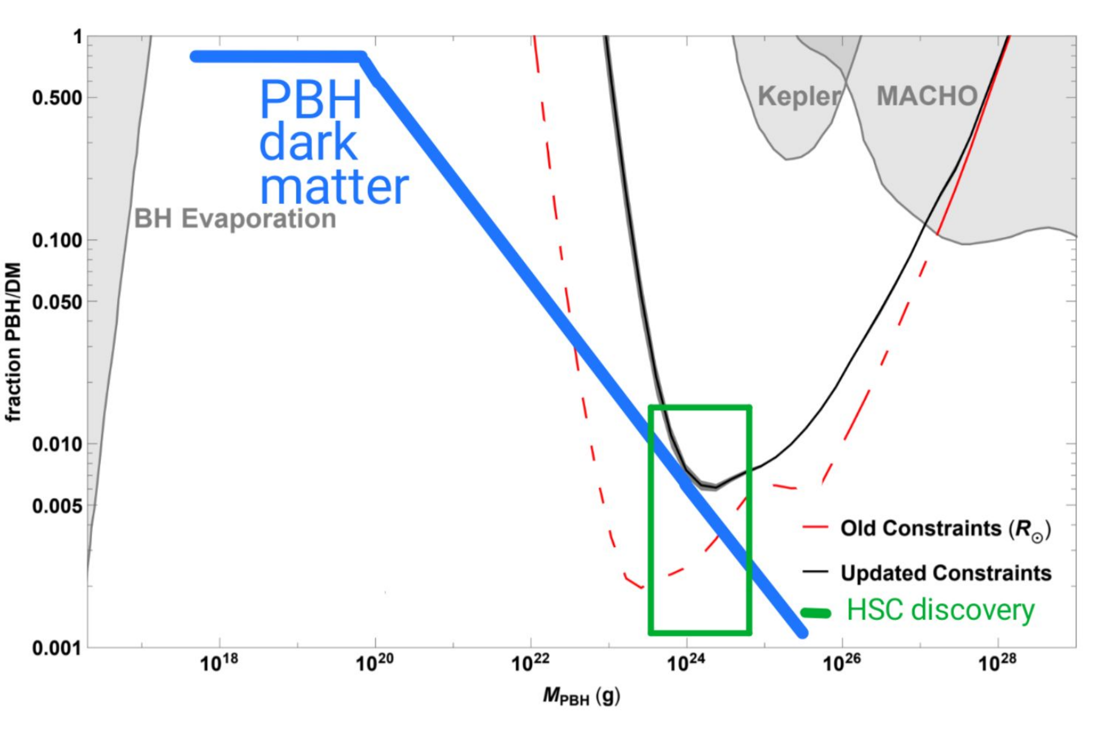


Observational constraints leave open a

five-orders-of-magnitude window.

Need new ideas for detection!

A class of models exist can be further probed by HSC



In class of models, the spectrum of PBH dark matter is extended, and the HSC can probe this signal using the high-mass tail.

[Sunao Sugiyama, AK, Takada, Takhistov, Vitagliano]

[**talk by Vitagliano**]

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]
- Can lead to PBH production in very generic cosmological scenarios [Cotner, AK, Sasaki, Takhistov]

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

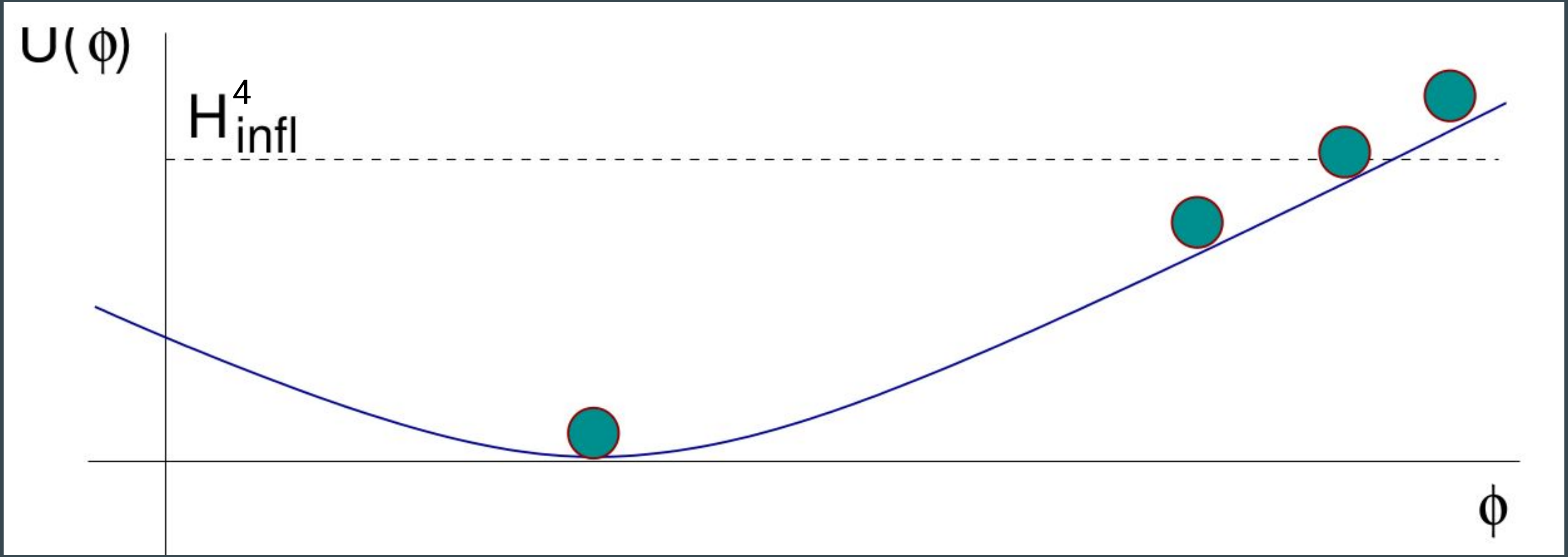
modern era

$p<0$

(dark energy dominated)

Scalar fields in de Sitter space during inflation

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



Scalar fields in de Sitter space during inflation

- If m=0, V=0, the field performs random walk:

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

- Massive, non-interacting field:

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

- Potential $V(\phi) = \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4} \phi^4$

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

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

[Starobinsky, Yokoyama, astro-ph/9407016]

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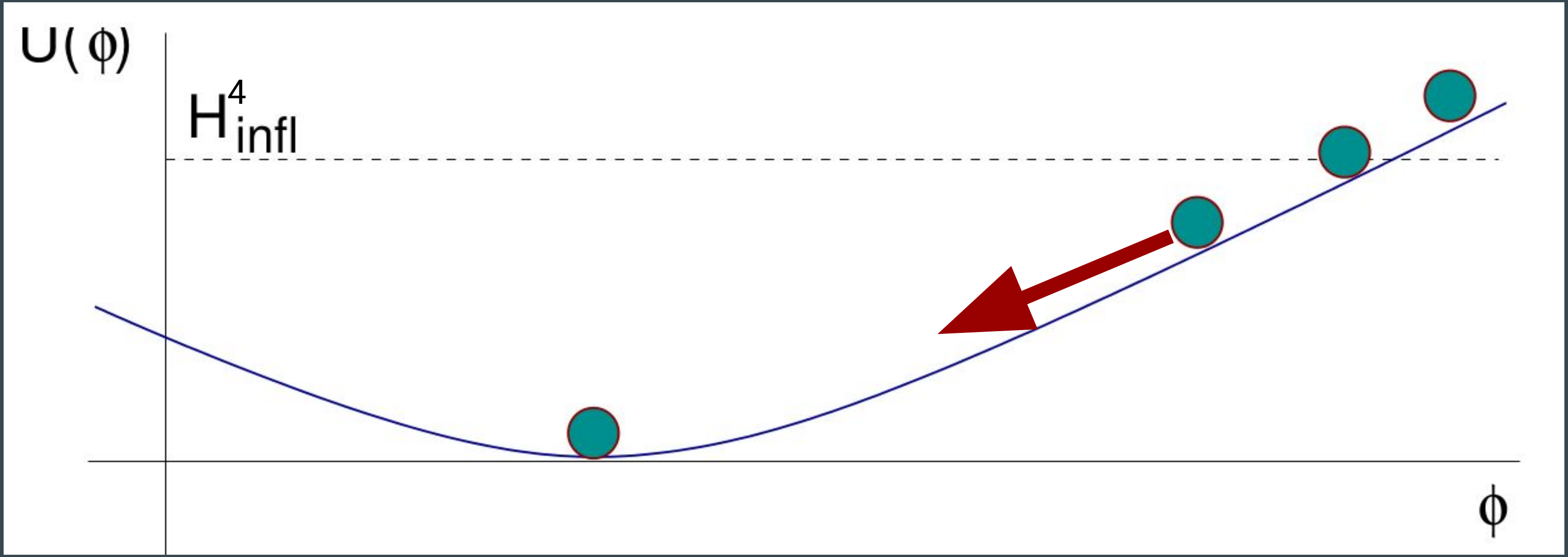
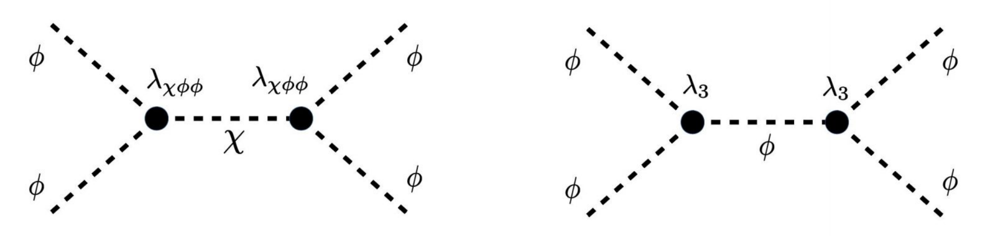


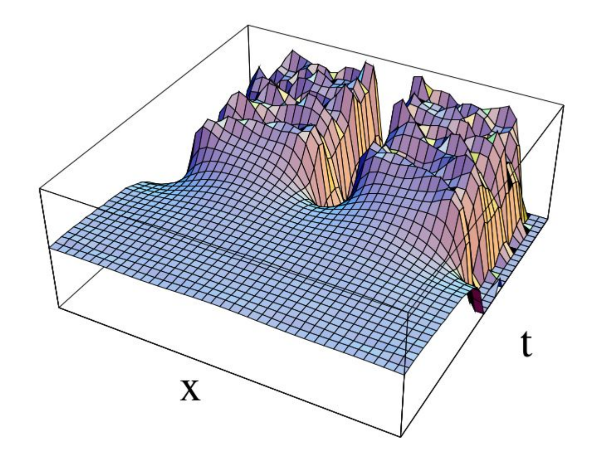
Scalar fields: an instability

Gravitational instability 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 $$\lambda_{\chi\phi\phi} \chi \phi^\dagger \phi$$



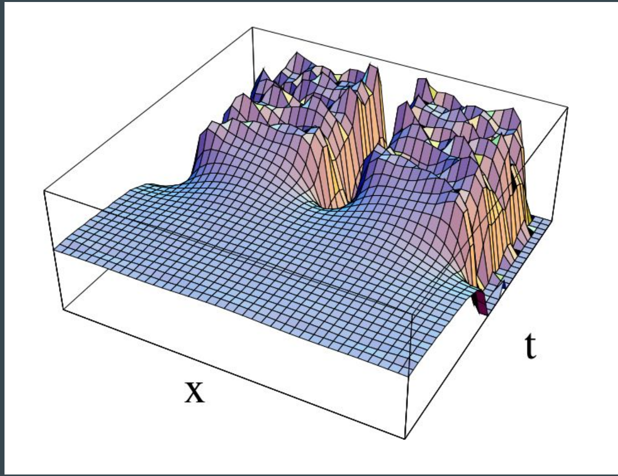


Scalar fields: an instability (Q-balls)

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

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

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



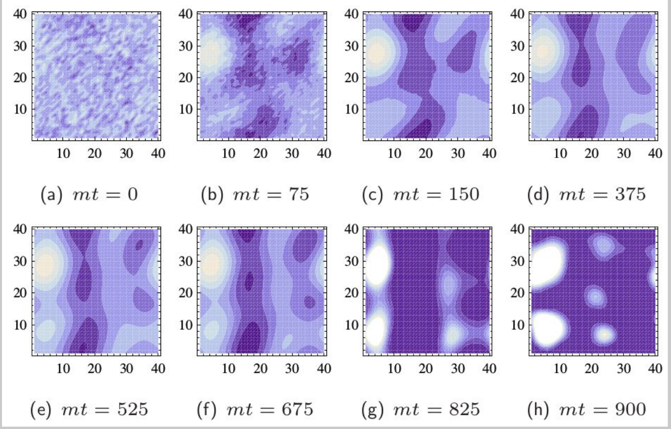
$(\dot{\Omega}^2 - U''(R)) > 0$ $\Rightarrow$ growing modes: $0<k<k_{max}$

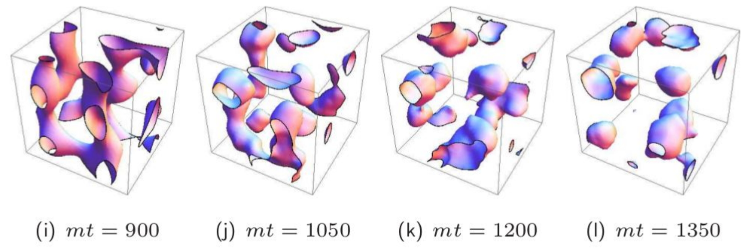
$$k_{max}(t) = a(t)\sqrt{\dot{\Omega}^2 - U''(R)}$$

Also: oscillons

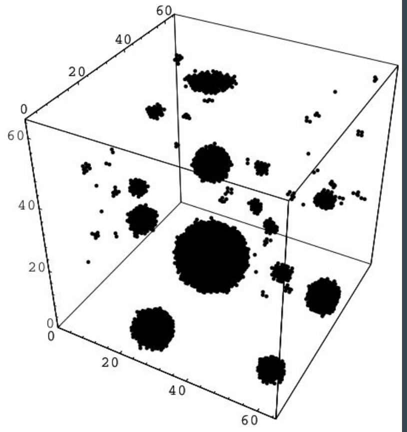
AK, Shaposhnikov, hep-ph/9709492

Numerical simulations of scalar field fragmentation



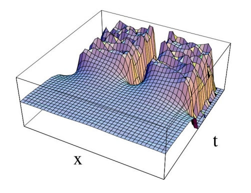


[Multamaki].



[Kasuya, Kawasaki]

Early Universe



Inflation

origin of primordial perturbations

radiation dominated

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

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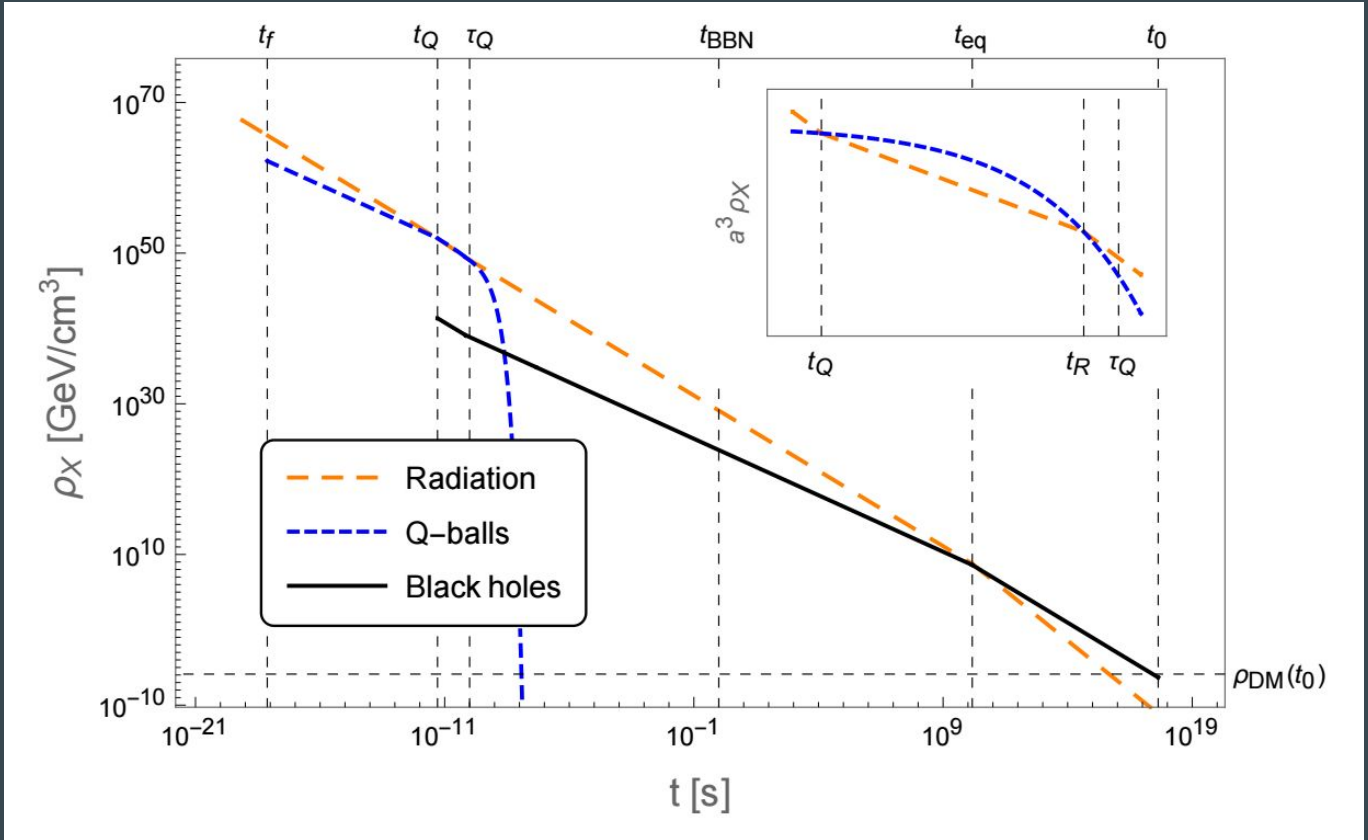
structures grow

modern era (dark energy dominated)

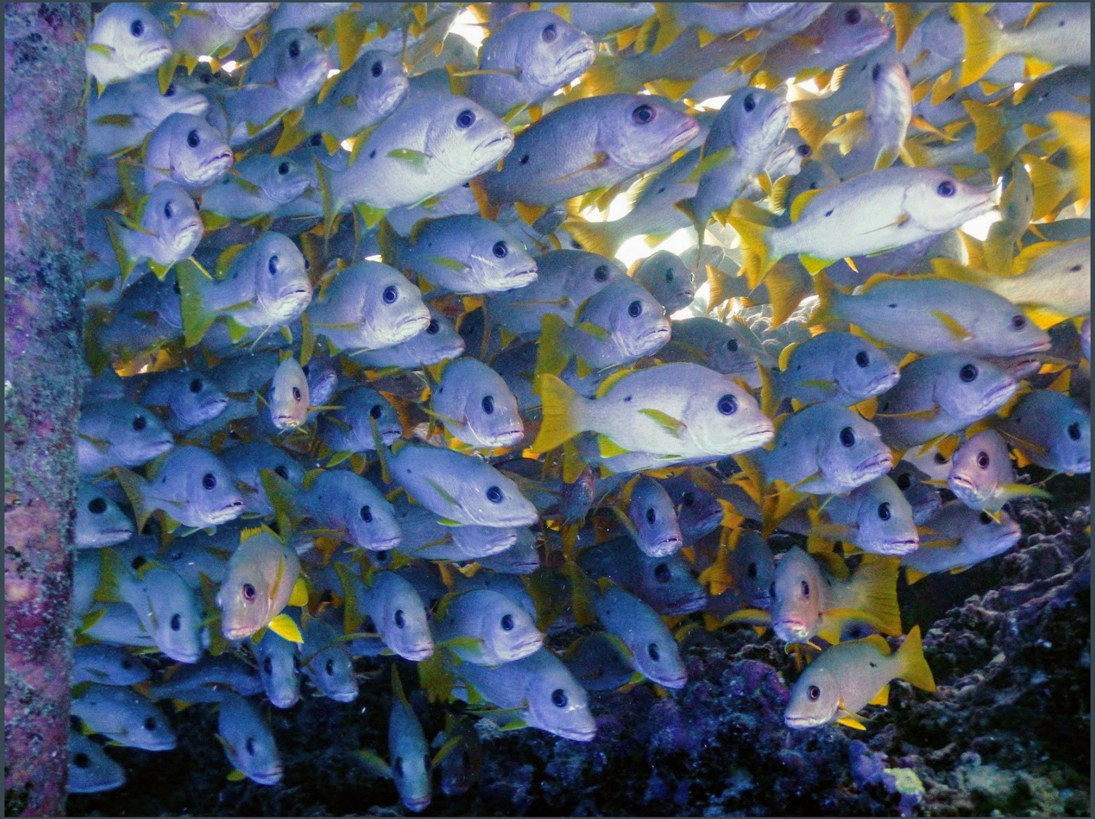
Scalar lump (Q-ball) formation can lead to PBHs



Intermittent matter dominated epoch in the middle of radiation dominated era

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

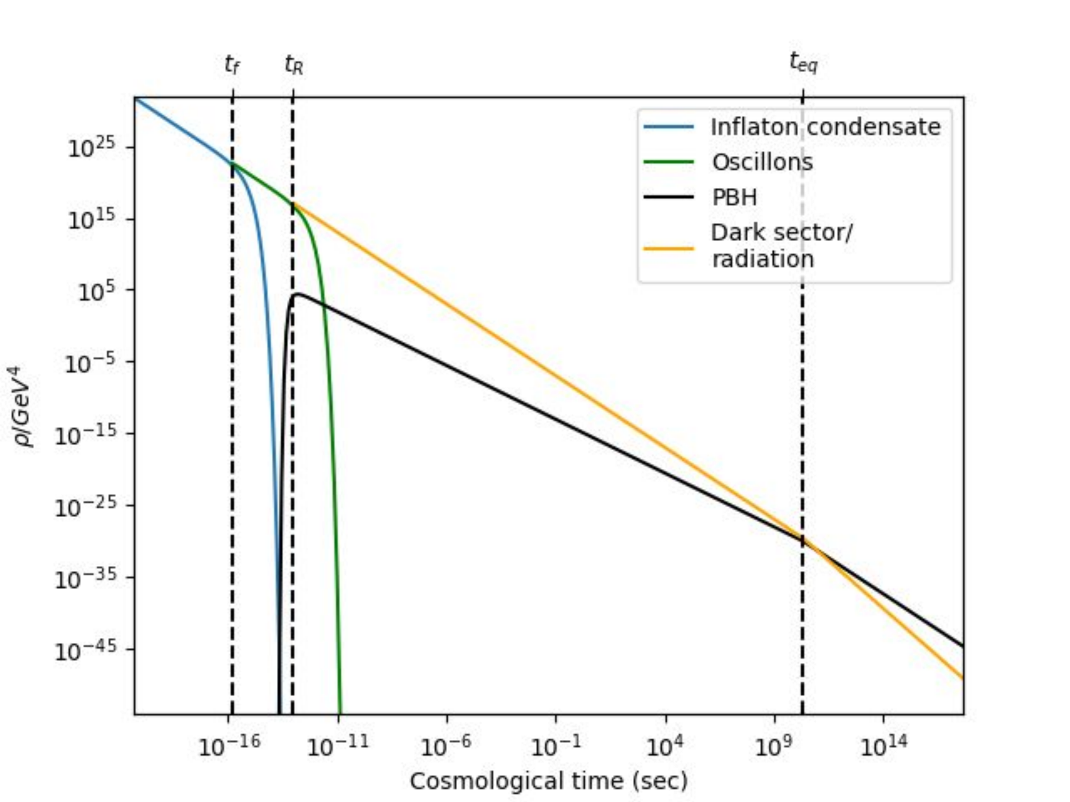
Many particles ⇒ only small Poisson fluctuations



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]

New results: talk by Kawasaki

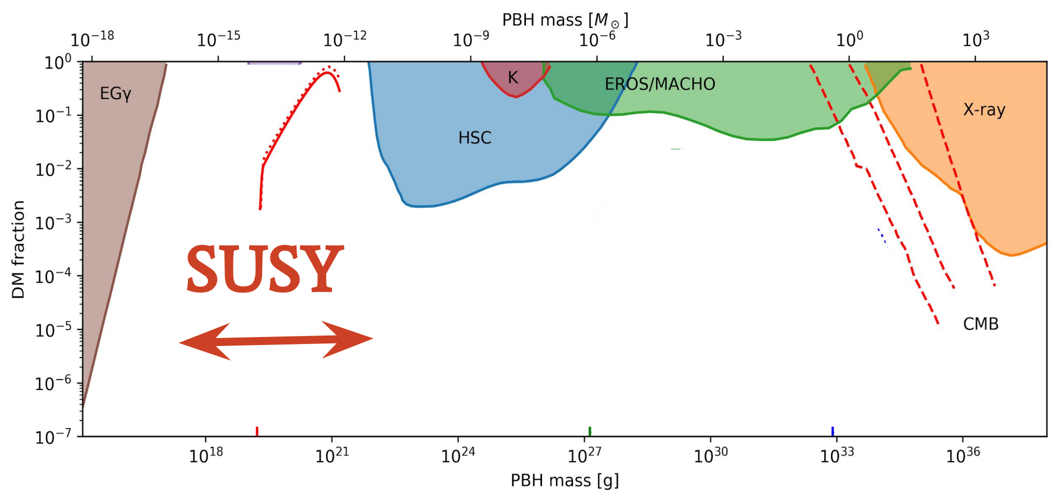
PBH from Supersymmetry: natural mass range

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

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

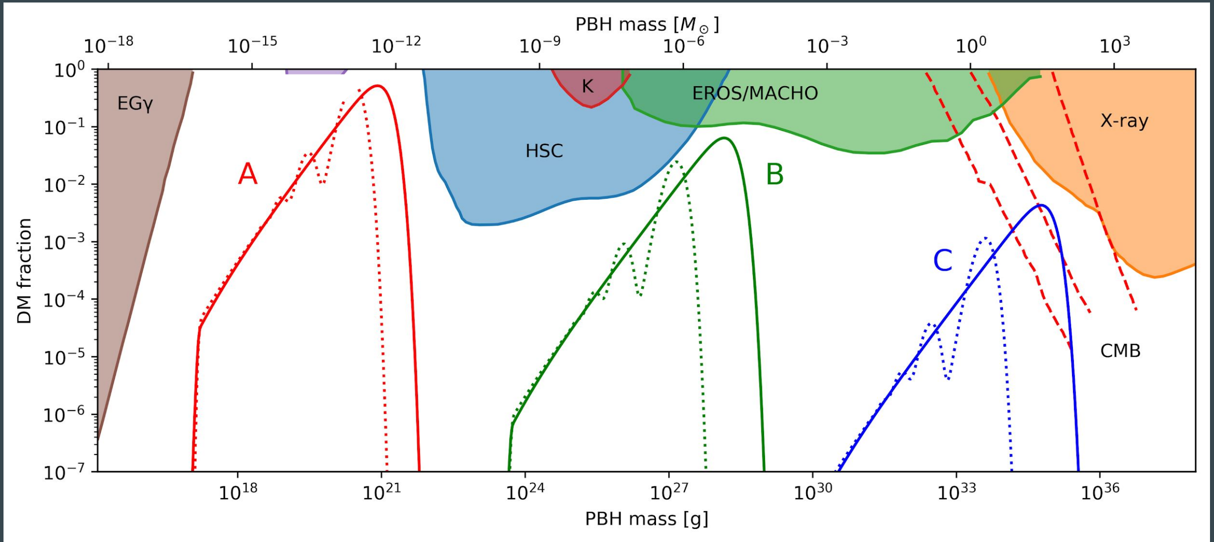
$$M_{\rm hor} \sim r_f^{-1}\left(\frac{M_{\rm Planck}^3}{M_{\rm SUSY}^2}\right) \sim 10^{23}\mathrm{g}\left(\frac{100\ \mathrm{TeV}}{M_{\rm SUSY}}\right)^2$$

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



[Cotner, AK, Sasaki, Takhistov, arXiv:1907.10613]

Scalar lumps leading to PBHs: Higgs? SUSY? Axion?



The smaller the scalar mass, the bigger the PBH mass

Mass function for Ω_{PBH}=1, 0.2, 0.001

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

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

[Cotner, AK, Sasaki, Takhistov 2019; arXiv:1907.10613]

Conclusion

- Simple formation mechanism in the early universe:
  PBH from a scalar field fragmentation
- 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