Primordial black holes: new formation scenarios and astrophysical manifestations

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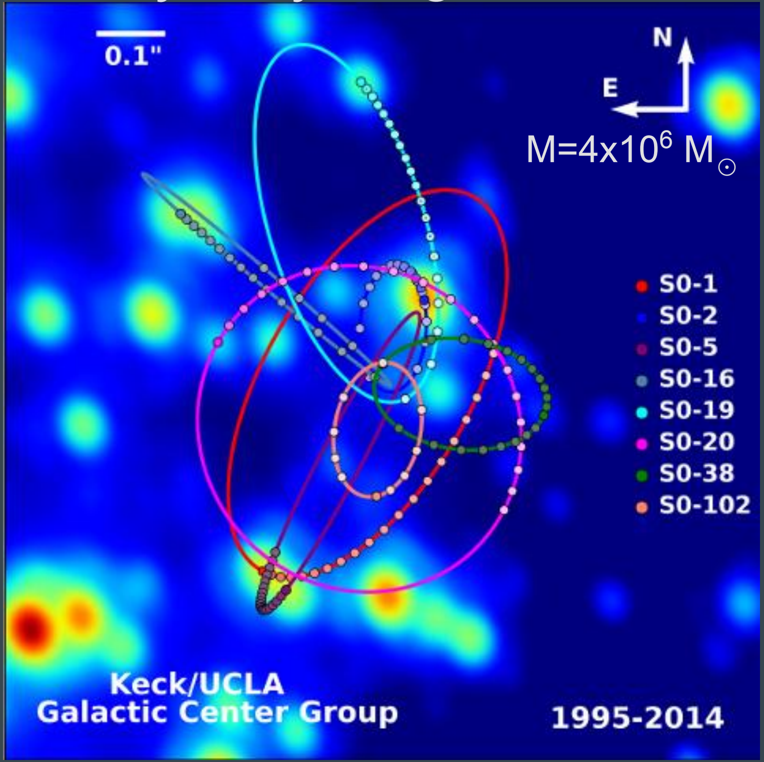
Nobel Prize 2020: Black holes' existence confirmed

Milky Way, Sagittarius A*

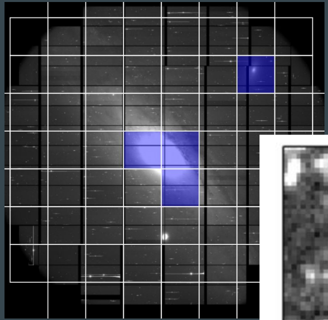


R. Penrose
R. Genzel
A. Ghez

Observations: BHs exist!

⇒ **PBH is a plausible**
dark matter candidate:
the only candidate
known to exist in nature

First candidate events [Takada et al., Kavli IPMU]



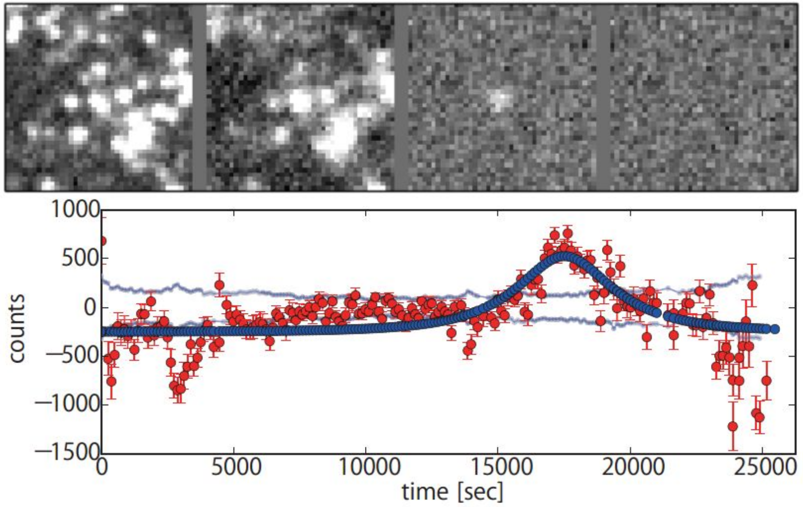
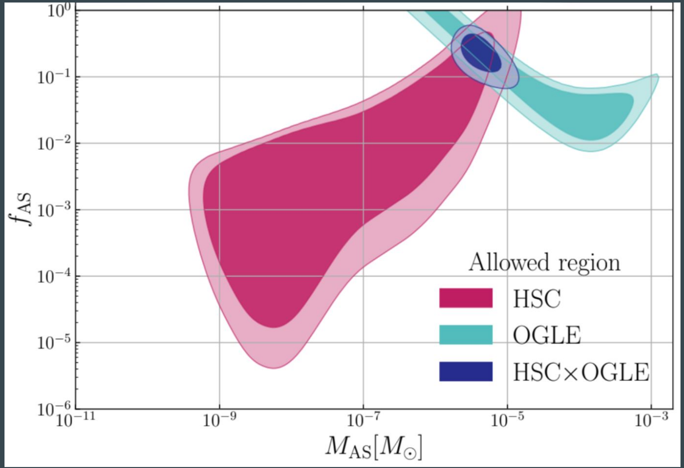


Figure 13. One remaining candidate that passed all the selection criteria of microlensing event. The images in the upper plot show the postage-stamped images around the candidate as in Fig. 7: the reference image, the target image, the difference image and the residual image after subtracting the best-fit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

First candidate events from HSC and OGLE

[Niikura et al.. Nature Astron., arXiv:1701.02151, 1901.07120]



Primordial black holes

Review: talks by Kohri, Takada, Sasaki

This talk:

- New formation mechanisms and their connections to BSM physics and astrophysical observations
  - Yukawa interactions: very simple, generic
  - Supersymmetry: PBH is a natural DM candidate
  - ...

How to make PBHs

Need a ~30% or higher overdensity early enough in the history of the universe.

- Primordial fluctuations enhanced on small scales (modify inflation)

- **Other large fluctuations**
  eMD with a few "large" particles, inflation - as usual

- **Early growth of (isocurvature) perturbations due to non-gravitational forces, such as Yukawa force**

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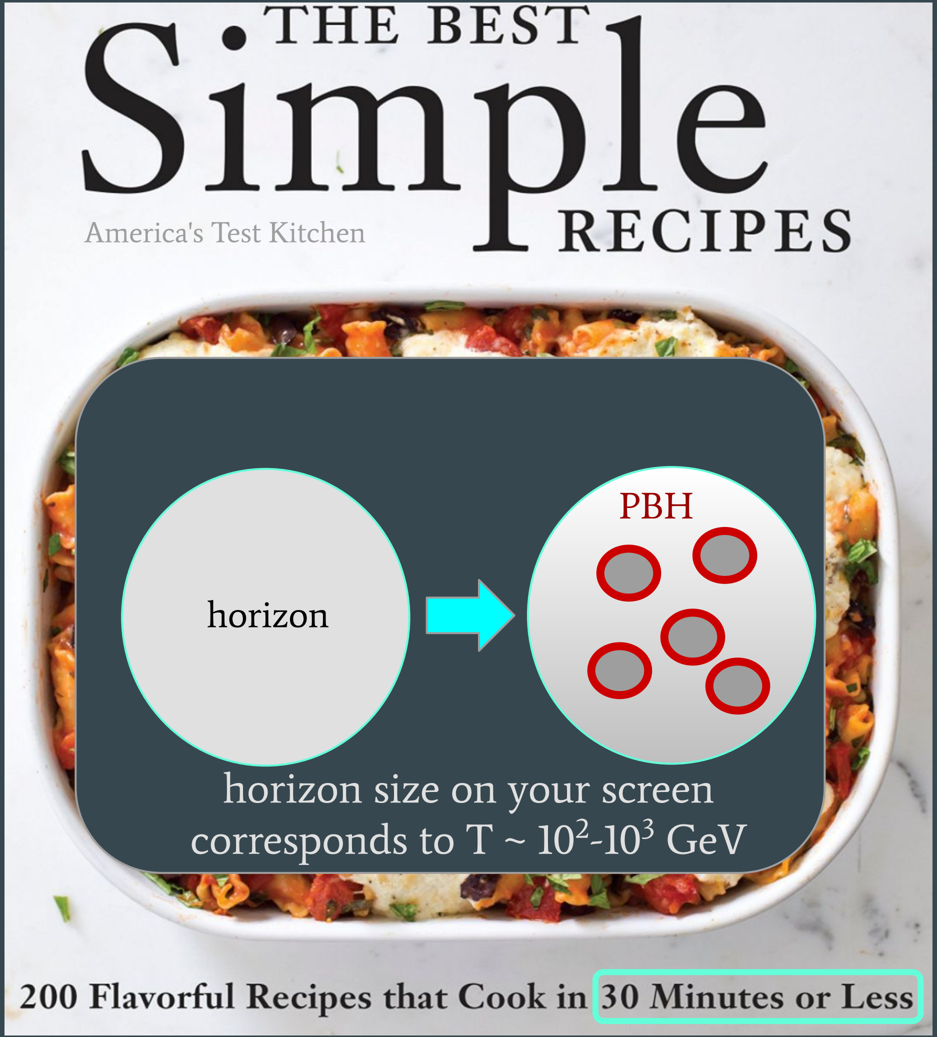
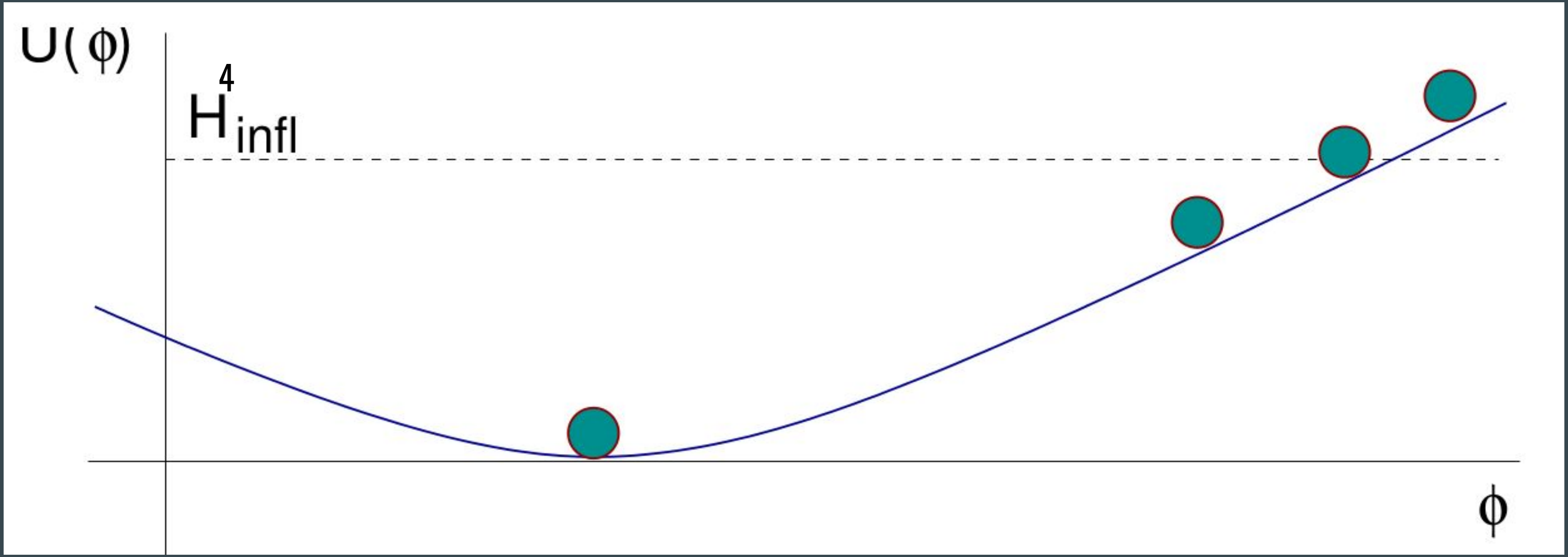


Scalar fields in de Sitter space (used by Affleck-Dine)

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



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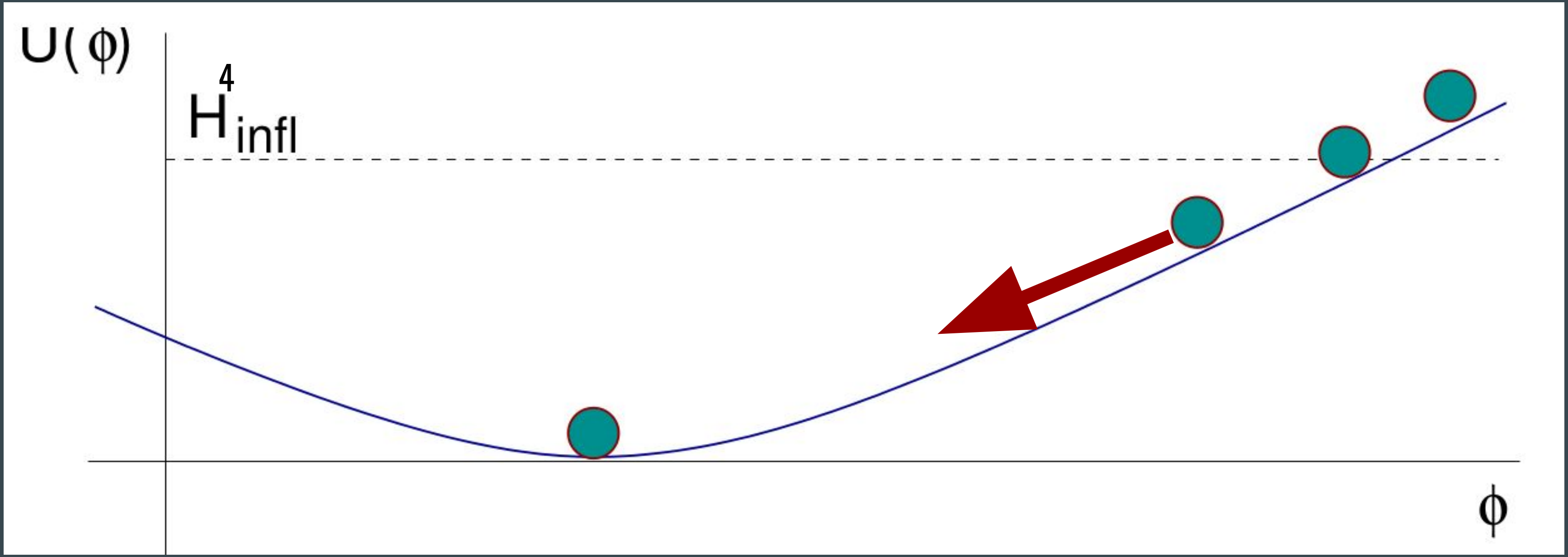
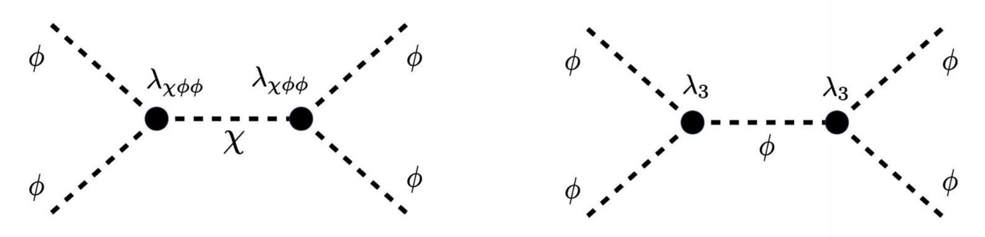


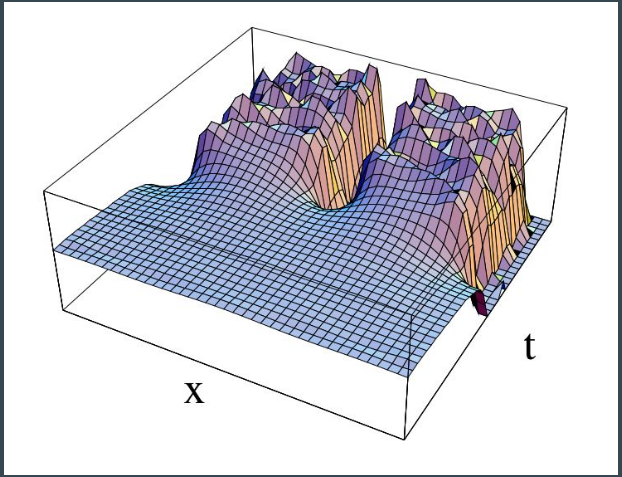
Scalar fields: an instability (Q-balls)

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





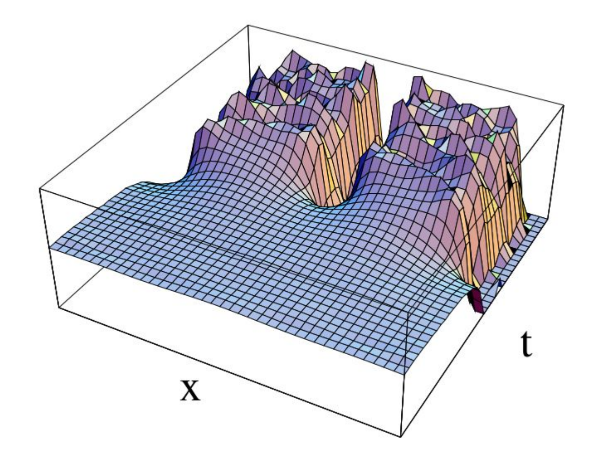
[AK, Shaposhnikov, hep-ph/9709492]

Scalar fields: an instability (Q-balls)

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

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

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



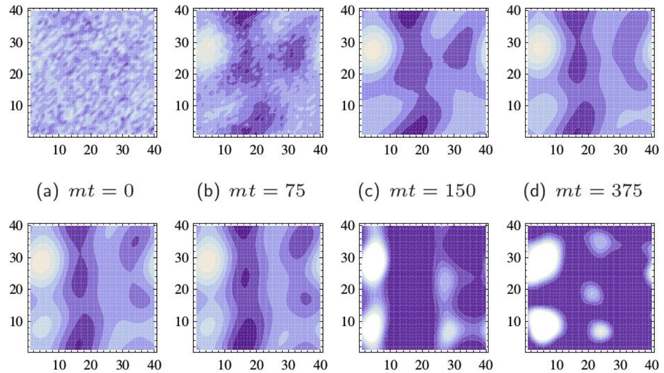
$(\dot{\Omega}^2 - U''(R)) > 0$ $\Rightarrow$ growing modes: $0<k<k_{max}$

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

Also of interest: oscillons

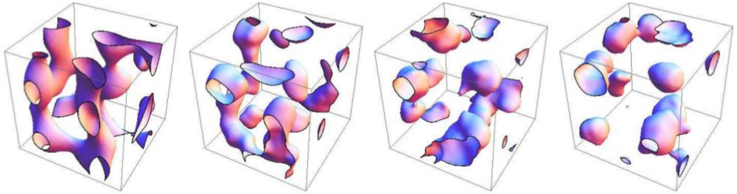
AK, Shaposhnikov, hep-ph/9709492

Numerical simulations of scalar field fragmentation



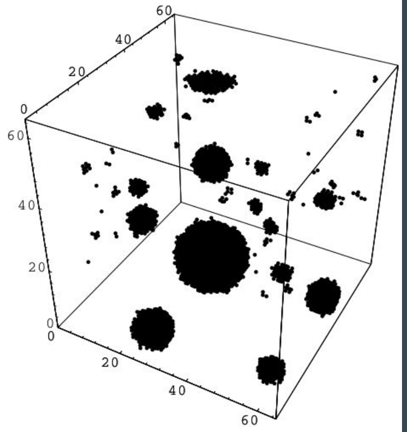
(a) $mt = 0$ (b) $mt = 75$ (c) $mt = 150$ (d) $mt = 375$

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



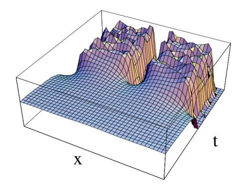
(i) $mt = 900$ (j) $mt = 1050$ (k) $mt = 1200$ (l) $mt = 1350$

[Multamaki].



[Kasuya, Kawasaki]

Affleck - Dine baryogenesis (SUSY): scalars are flat directions



Inflation

origin of
primordial
perturbations

radiation dominated

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

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

structures don't grow

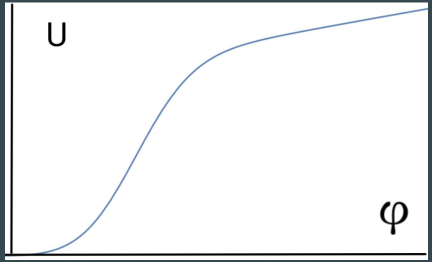
matter dominated

$p=0$

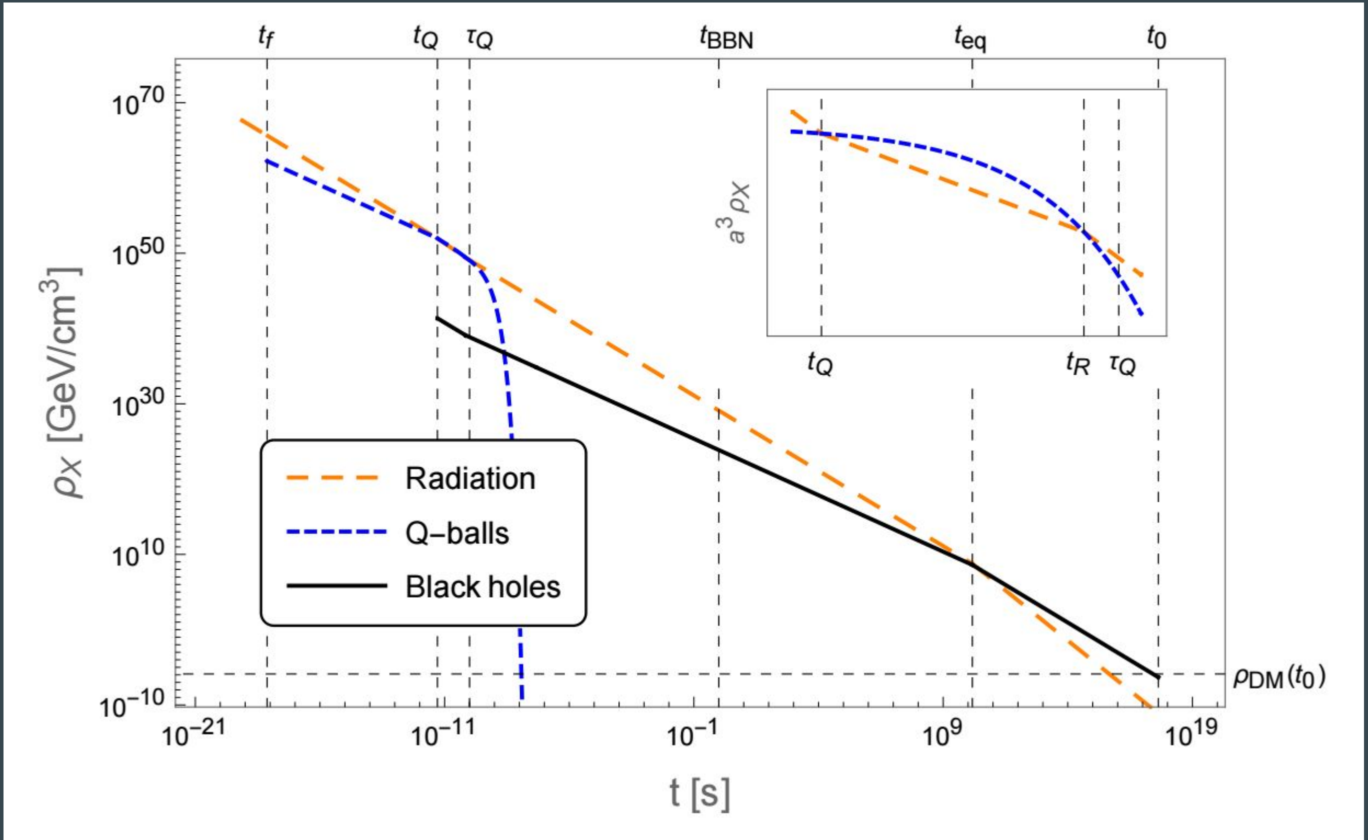
$\rho \propto a^{-3}$

structures grow

modern era
(dark energy
dominated)



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



Early matter dominated epoch in the middle of radiation dominated era

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

Affleck-Dine process and scalar fragmentation in SUSY

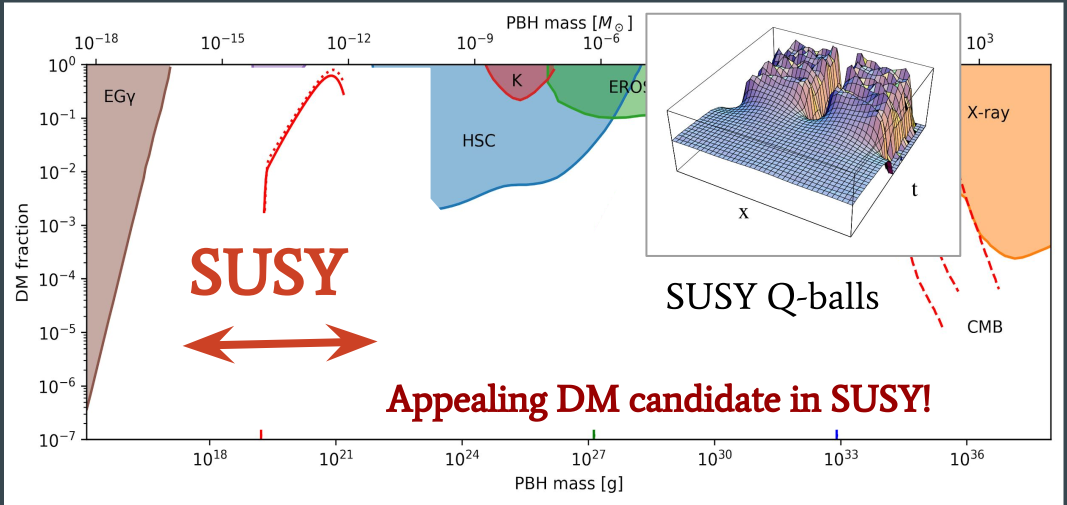
[Cotner, AK, Sasaki, Takhistov et al.,1612.02529, 1706.09003, 1801.03321, 1907.10613]

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

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

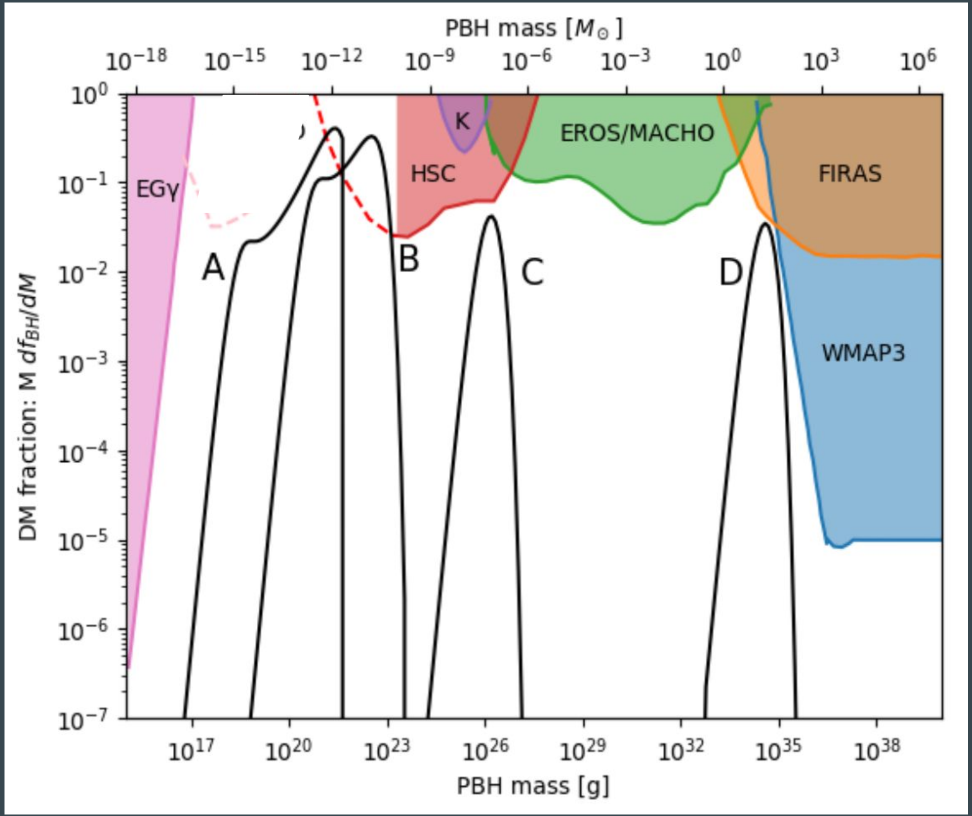
$$M_{\mathrm{hor}} \sim r_f^{-1}\left(\frac{M_{\mathrm{Planck}}^3}{M_{\mathrm{SUSY}}^2}\right) \sim 10^{23}\mathrm{g}\left(\frac{100\ \mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$

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

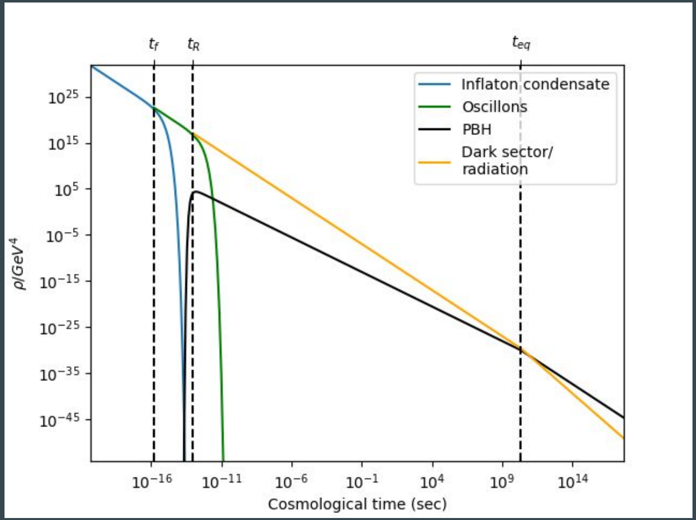


Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103
Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019) 077

Other scalar lumps, **oscillons** can similarly lead to PBHs



Intermittent matter dominated epoch immediately after inflation [Cotner, AK, Takhistov, Phys.Rev. D98 (2018), 083513]



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PBH formation mechanism: Yukawa "fifth force"

Yukawa interactions:

$$V(r) = \frac{y^2}{r} e^{-m_\chi r}$$

$$y\chi\bar{\psi}\psi$$

a heavy fermion interacting with a light scalar

A light scalar field $\Rightarrow$ long-range attractive force, stronger than gravity $\Rightarrow$ instability similar to gravitational instability, only stronger

$\Rightarrow$ **halos form** even in radiation dominated universe

[Amendola et al., 1711.09915; Savastano et al., 1906.05300; Domenech, Sasaki, 2104.05271]

Same Yukawa coupling provides a source of **radiative cooling** by emission of gravitational radiation $\Rightarrow$ **halos collapse to black holes**

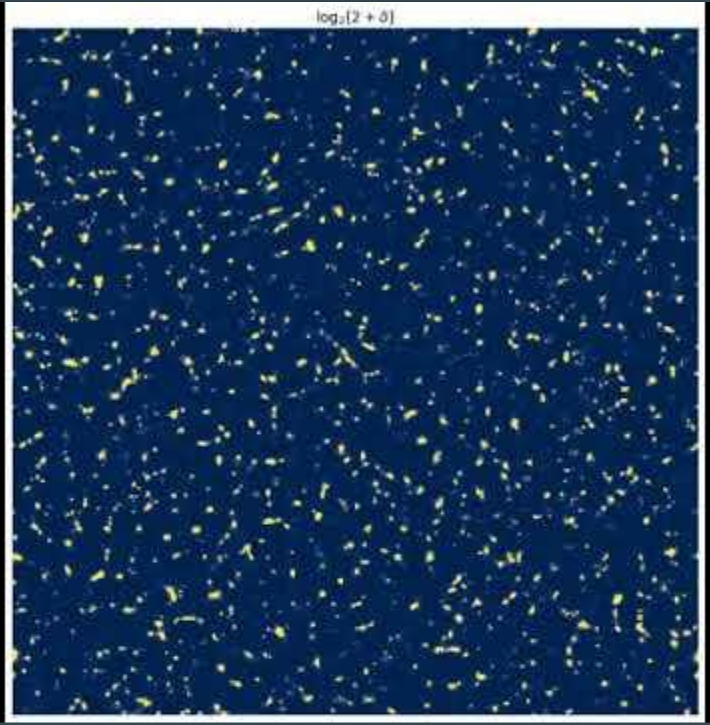
[Flores, AK, 2008.12456, PRL 126 (2021) 041101; 2008.12456]

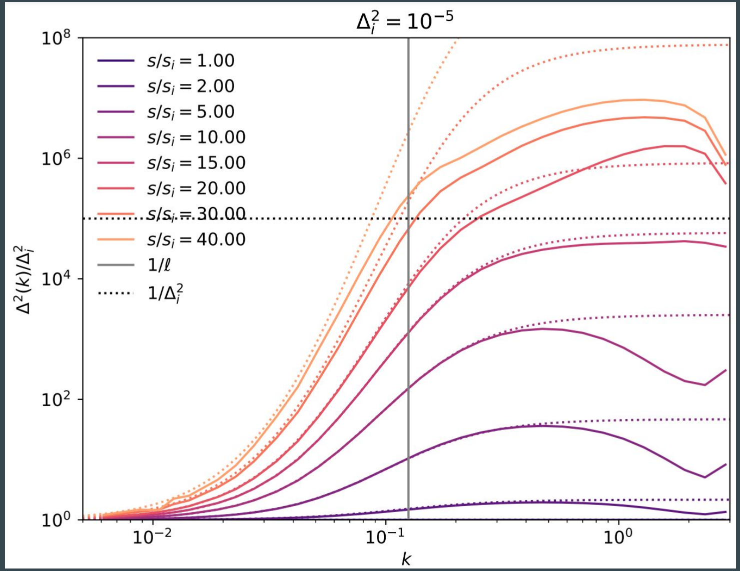
Growth of structures due to Yukawa force: N-body simulations

Inman, PRELIMINARY

Domenech, Inman, Sasaki, AK

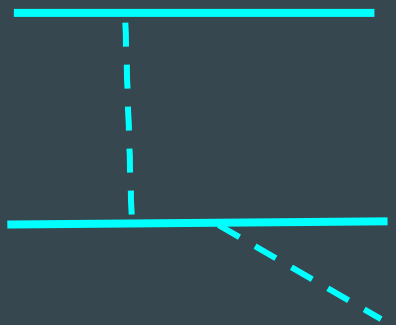
work in progress



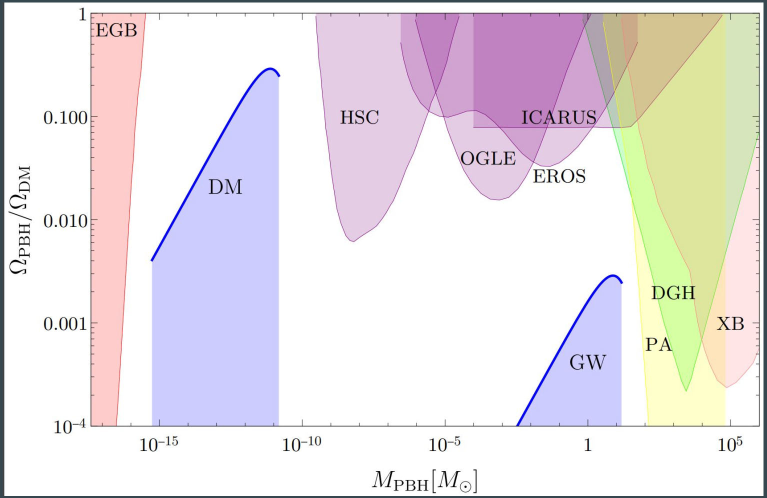


Rapid growth of structures… plus radiative cooling!

Same Yukawa fields allow particles moving with acceleration emit scalar waves



⇒ radiative cooling and collapse to black holes



Flores, AK, Phys.Rev.Lett. 126 (2021) 4, 041101; 2008.12456

PBH DM abundance natural for m_ψ~1-100 GeV

Asymmetric dark matter models: Asymmetry in the dark sector = baryon asymmetry

In our case, all these particles end up in black holes:

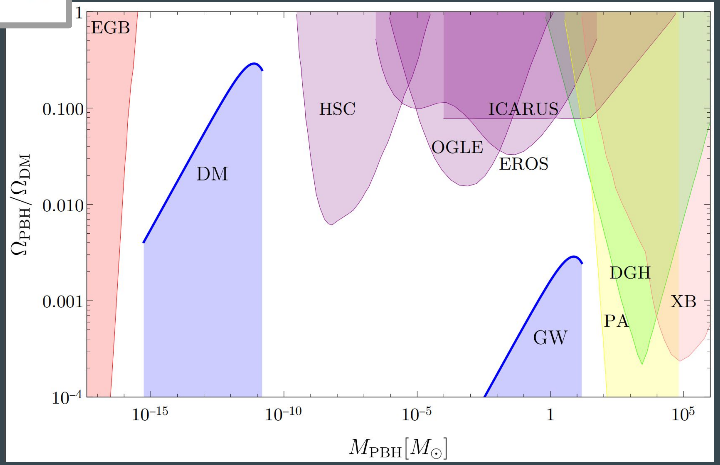
$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = 0.2\frac{m_\psi}{m_p}\frac{\eta_\psi}{\eta_{\rm B}} = \left(\frac{m_\psi}{5\,\rm GeV}\right)\left(\frac{\eta_\psi}{10^{-10}}\right)$$

[Flores, AK, 2008.12456, PRL 126 (2021) 041101]

Natural explanation for why

(dark matter density) ~ (ordinary matter density)

for ~1-100 GeV masses



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Yet another way to get PBHs from SUSY: long-range forces

A SUSY flat direction φ can couple to another SUSY scalar, χ, which can mediate long-range forces between SUSY Q-balls, leading to Yukawa long-range potential

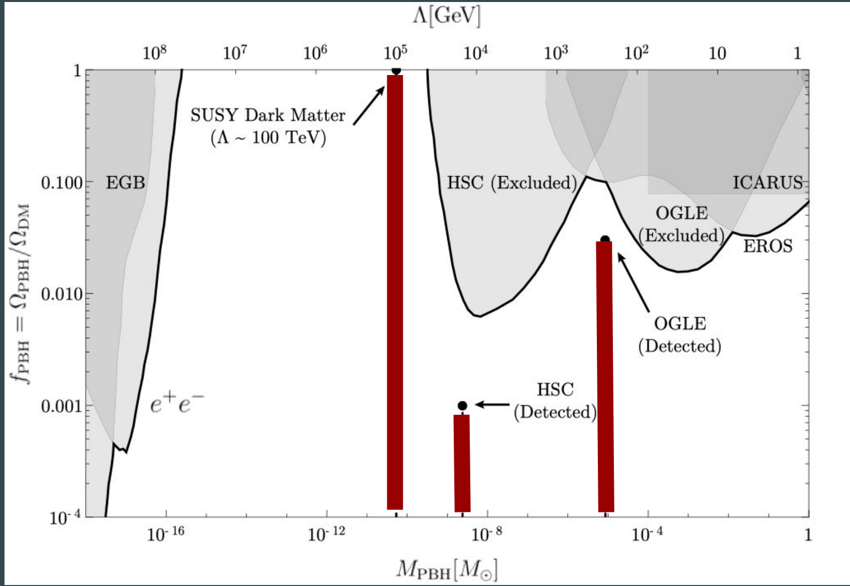
$$V(\varphi,\chi) = U(\varphi) + \frac{1}{2}m_\chi^2\chi^2 - y\chi\varphi^\dagger\varphi + \frac{\lambda}{4}\chi^4$$

$$f_{\rm PBH} = \frac{\Omega_{\rm DM}}{\Omega_{\rm DM}} \simeq \left(\frac{e^{-1/2\varepsilon}}{2\times10^{-13}}\right)\left(\frac{\Lambda}{10^5\ {\rm GeV}}\right)^2\left(\frac{10^6\ {\rm GeV}}{T_f}\right)$$

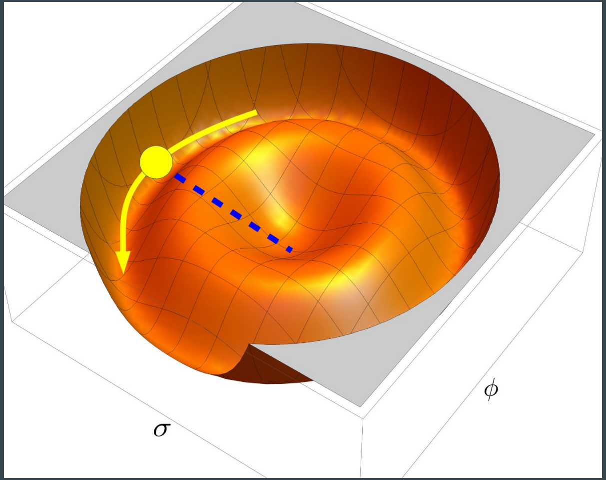
$$M_{\rm PBH} \simeq 10^{23}\ {\rm g}\left(\frac{100\ {\rm TeV}}{\Lambda}\right)^2$$

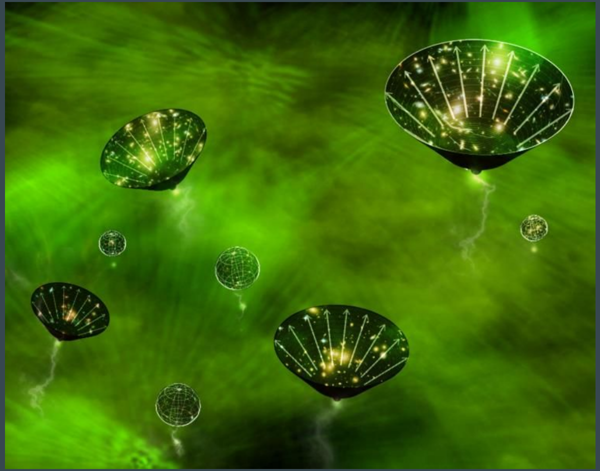
Long-range forces work as in the case of Yukawa interaction but **individual Q-balls** grow until they reach the mass/size of a BH

Flores, AK, 2108.08416



And yet another mechanism: inflationary multiverse



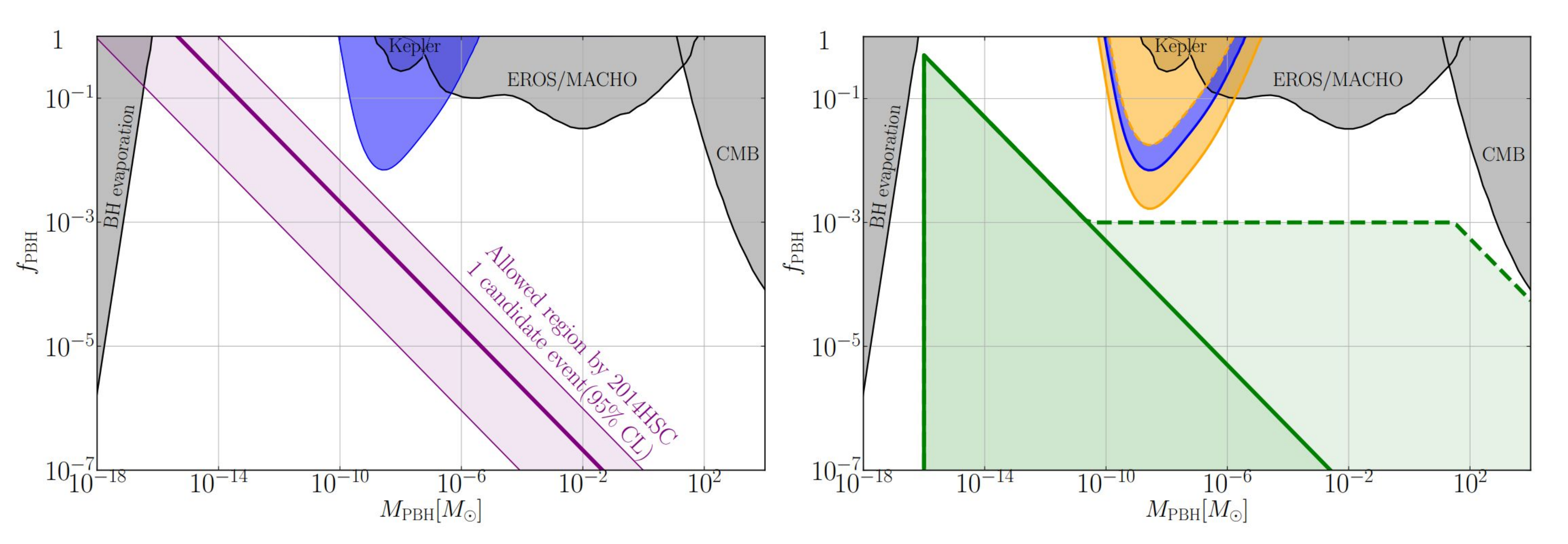


Tunneling events lead to nucleation of baby universes, which appear to outside observer as black holes.

Deng, Vilenkin arXiv:1710.02865

AK, Sasaki, Sugiyama, Takada, Takhistov, Vitagliano, 2001.09160, PRL 125 (2020) 181304

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



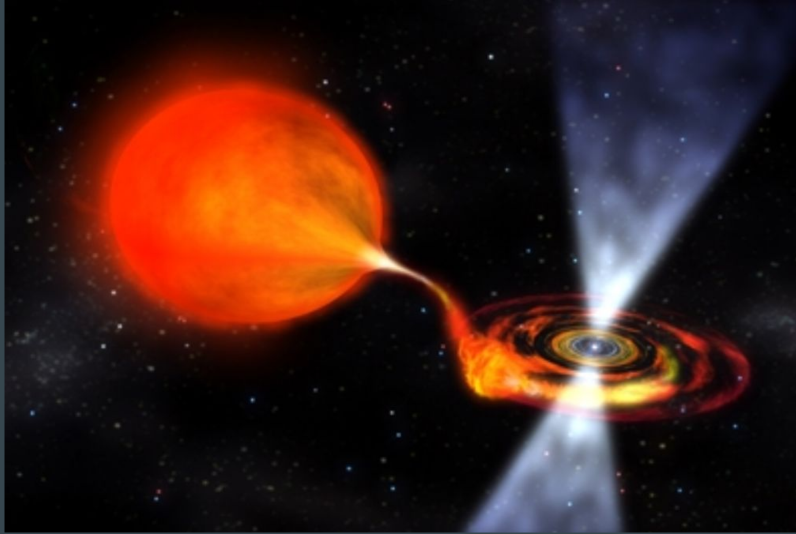
[AK, Sasaki, Sugiyama, Takada, Takhistov, Vitagliano, Phys.Rev.Lett. 125 (2020) 181304
arXiv:2001.09160]

PBH masses, spins, and a *new window on the early universe*

Formation mechanism	Mass range	PBH spin
Inflationary perturbations [review: 2007.10722]	DM, LIGO, supermassive	small
Yukawa "fifth force" [2008.12456]	DM, LIGO, supermassive	small
Long-range forces between SUSY Q-balls [2108.08416]	DM (mass range: 10^{-16}-10^{-6} $M_\odot$)	small
Supersymmetry flat directions, Q-balls [1612.02529, 1706.09003, 1907.10613]	DM (mass range: 10^{-16}-10^{-6} $M_\odot$)	large
Light scalar field Q-balls (not SUSY) [1612.02529, 1706.09003, 1907.10613]	DM, LIGO, supermassive	large
Oscillons [1801.03321]	DM, LIGO, supermassive	large
Multiverse bubbles [1512.01819, 1710.02865, 2001.09160]	DM, LIGO, supermassive	small

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?



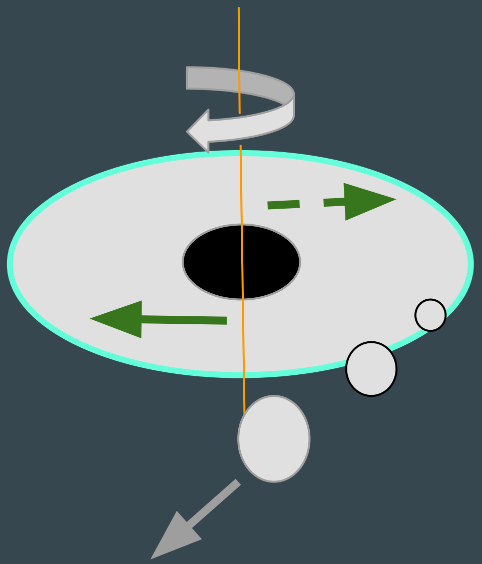
Fast-spinning millisecond pulsar. Image: NASA/Dana Berry

Neutron star destruction by black holes

$\Rightarrow$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 nucleosynthesis: site unknown

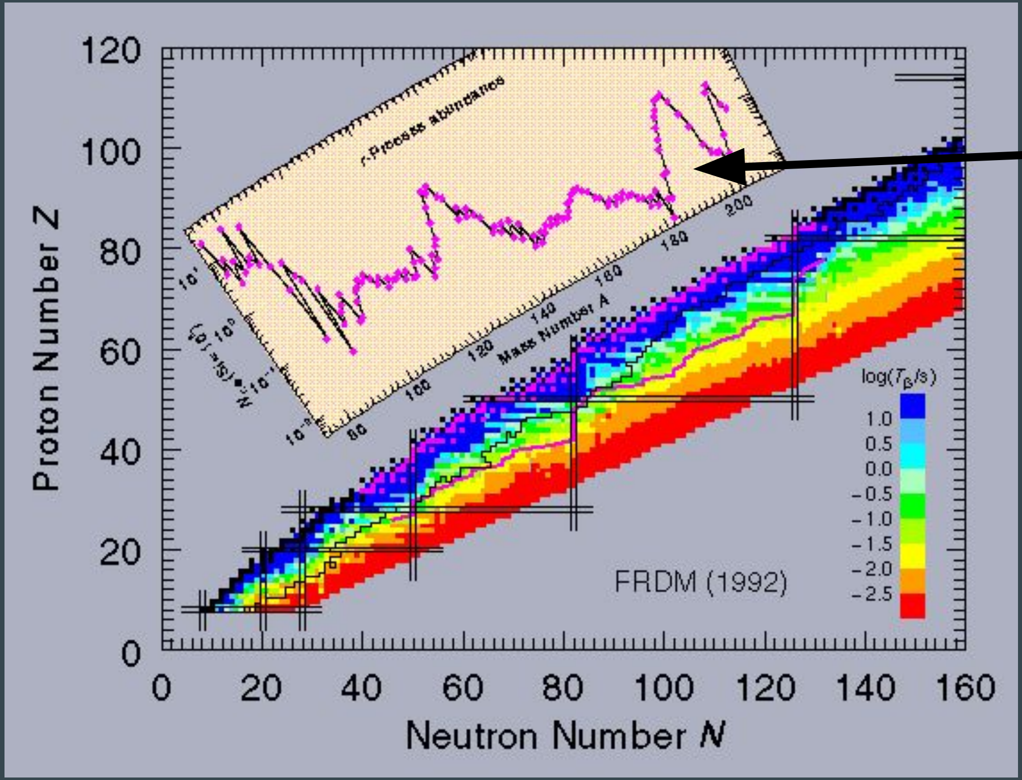


Image: Los Alamos, Nuclear Data Group

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

r-process nucleosynthesis: site unknown

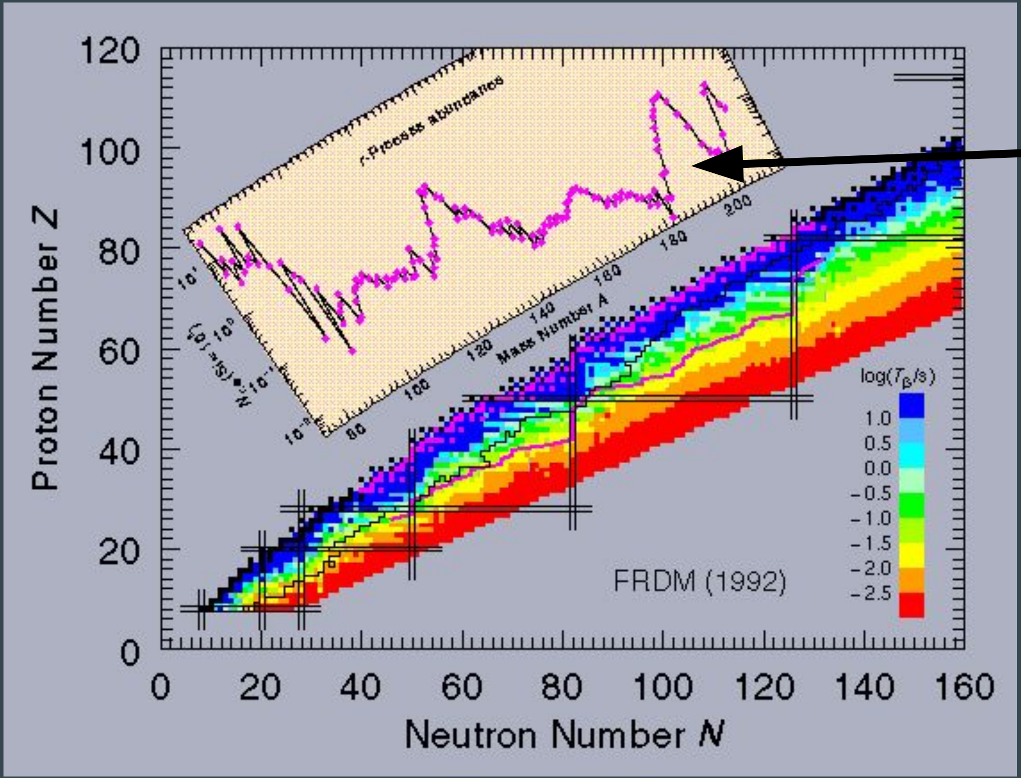
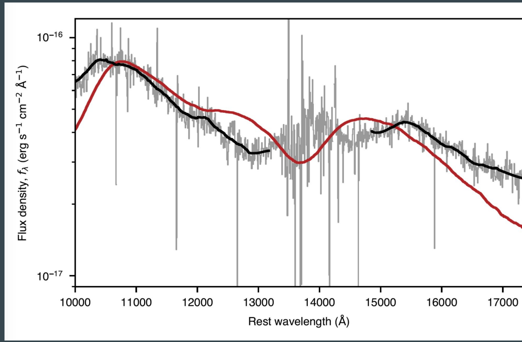


Image: Los Alamos, Nuclear Data Group

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



NS-NS might not be not enough...

SCIENTISTS DAZED AND CONFUSED BY EXTRAORDINARY AMOUNT OF GOLD IN THE UNIVERSE

There's too much gold in the universe. No one knows where it came from.

By Rafi Letzter - Staff Writer 12 days ago

Something is showering gold across the universe. But no one knows what it is.

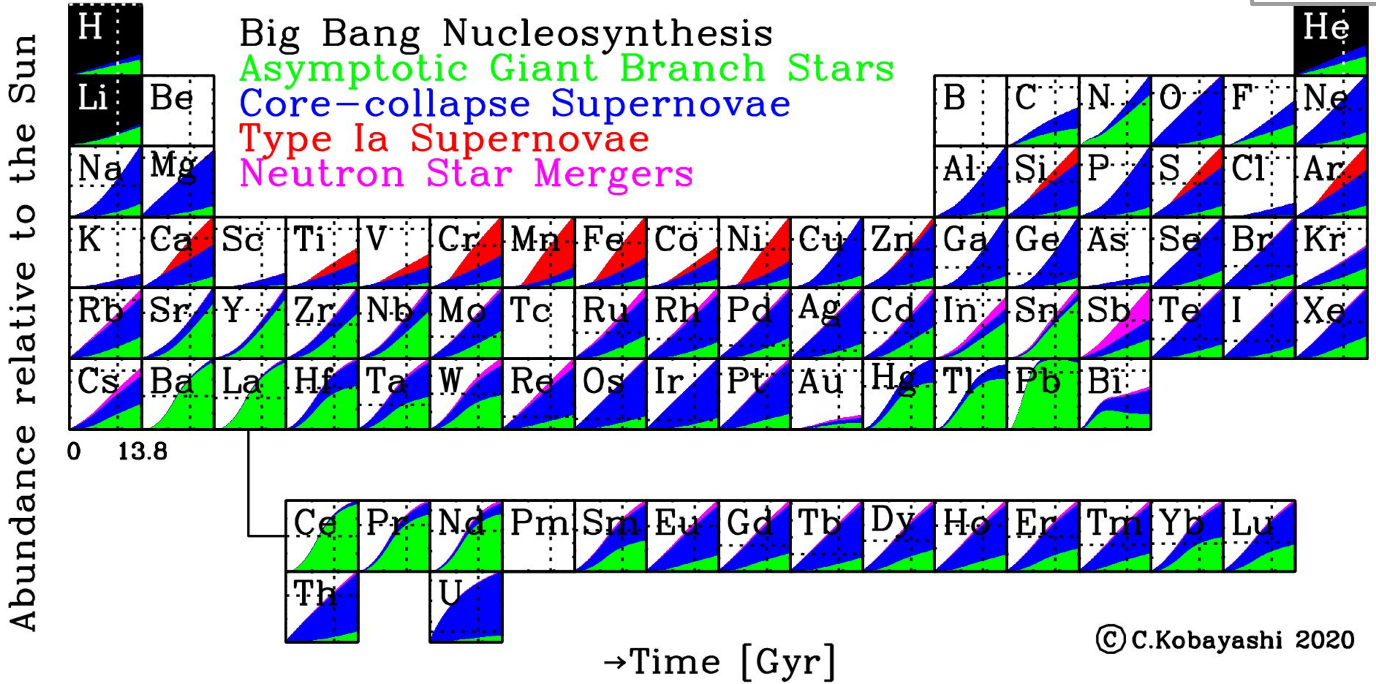


Figure 39. The time evolution (in Gyr) of the origin of elements in the periodic table: Big Bang nucleosynthesis (black), AGB stars (green), core-collapse supernovae including SNe II, HNe, ECSNe, and MRSNe (blue), SNe Ia (red), and NSMs (magenta). The amounts returned via stellar mass loss are also included for AGB stars and core-collapse supernovae depending on the progenitor mass. The dotted lines indicate the observed solar values.

[Kobayashi et al., ApJ 900:179, 2020]

r-process material: observations

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

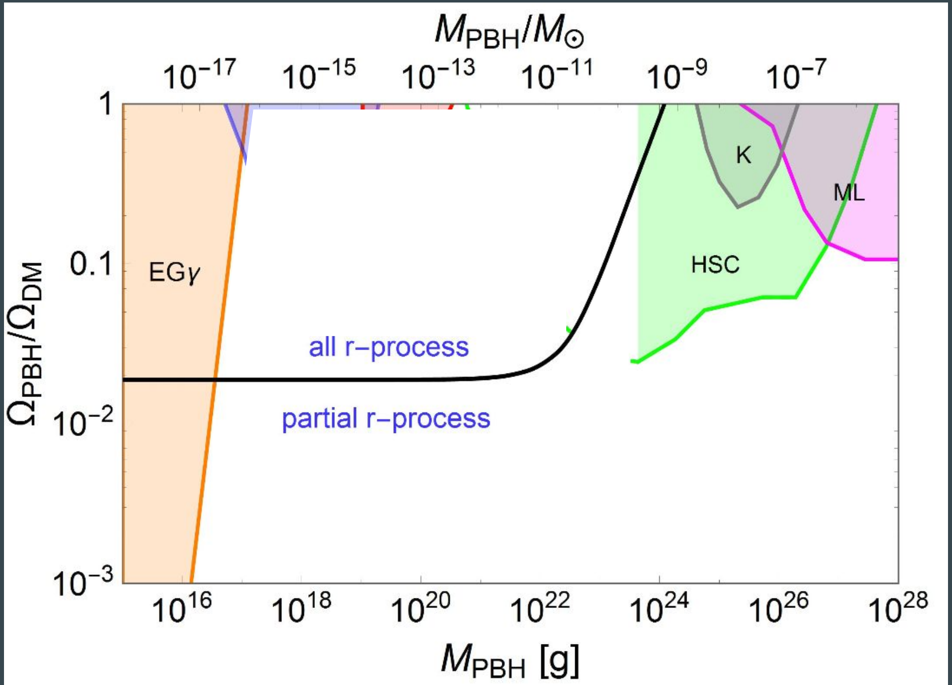
Ultra Faint Dwarfs (UFD): most of UFDs show no enhancement of r-process abundance.

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~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. ✔

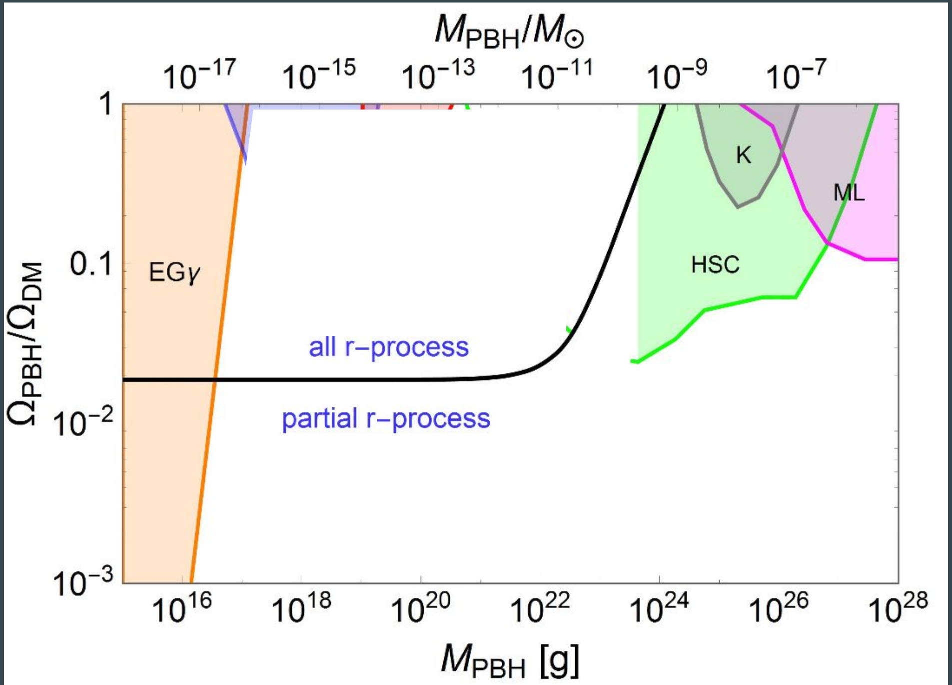


[Fuller, AK, Takhistov, PRL 119 (2017) 061101]

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 event **without** a GW counterpart, but with a possible coincident FRB (LSST, ZTF,...)
- 511 keV line



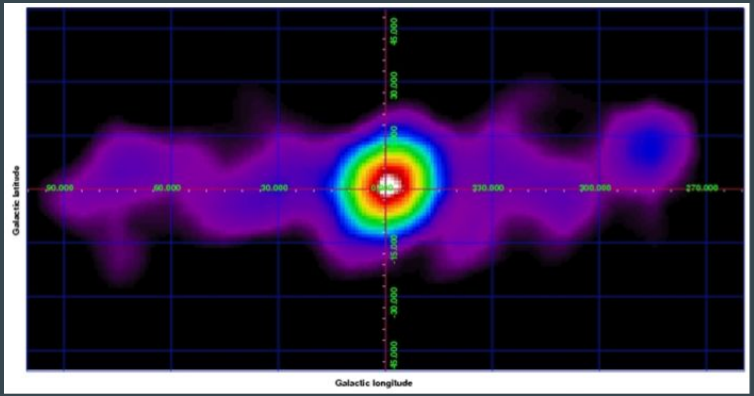
Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101]

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.

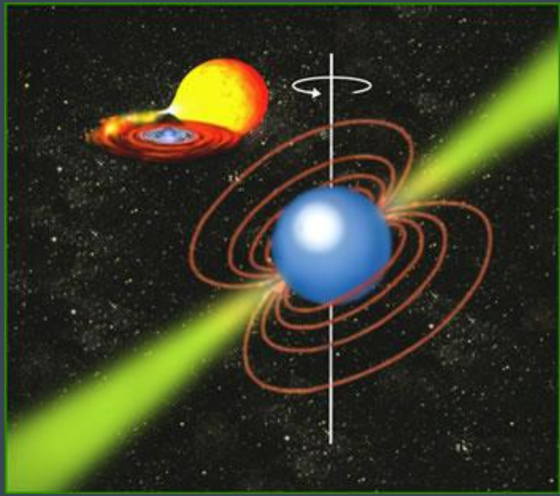


ESA/Bouchet et al.

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

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

Fast Radio Bursts (FRB)



Origin unknown. One repeater, others: non-repeaters. τ~ ms.

PBH - NS events: final stages dynamical time scale τ~ ms.

NS magnetic field energy available for release: $\sim 10^{41}$erg

Massive rearrangement of magnetic fields at the end of the NS life, on the time scale ~ms produces an FRB.

Consistent with observed FRB fluence.

Fuller, AK, Takhistov, Phys.Rev.Lett. 119 (2017) 6, 061101; 1704.01129

Abramowicz, Bejger, Wielgus, Astrophys. J. 868, 17 (2018); 1704.05931

Kainulainen, Nurmi, Schiappacasse, Yanagida, arXiv:2108.08717

GW detectors can discover small PBH...

PBH + NS

⇓

BH of 1-2 $M_\odot$

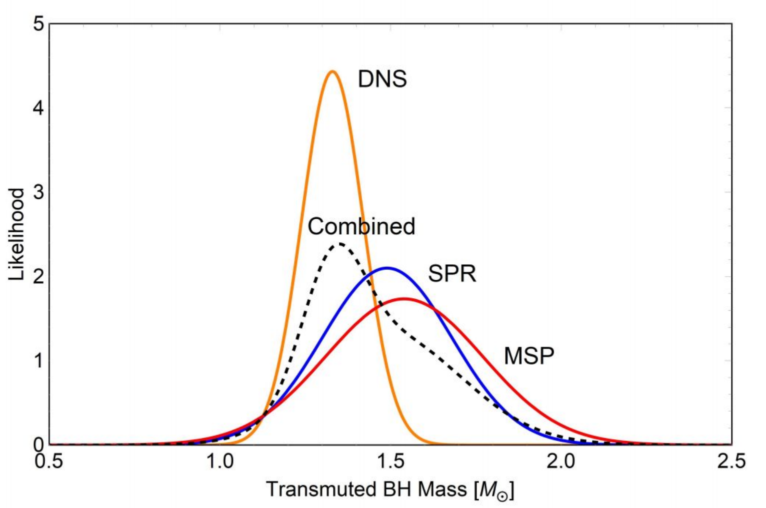
Talk by George Fuller

[Takhistov et al., arXiv:1707.05849; 2008.12780]

...if it detects mergers of

1-2 $M_\odot$ black holes

(not expected from evolution of stars)



Conclusion

- Simple, generic formation scenarios in the early universe:
  PBH from scalar forces, PBH from a scalar field fragmentation,
  PBH from vacuum bubbles...
- PBH with masses 10^{-16} - 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**
- PBH from ~ 1-100 GeV scale particles can naturally explain DM abundance
- 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.
- GW signatures and spins are model dependent

Formation mechanism	**Mass range**	**PBH spin**
Inflationary perturbations [review: 2007.10722]	DM, LIGO, supermassive	small
Yukawa “fifth force” [2008.12456]	DM, LIGO, supermassive	small
Long-range forces between SUSY Q-balls [2108.08416]	DM (mass range: 10^{-16}-10^{-6} $M_\odot$)	small
Supersymmetry flat directions, Q-balls [1612.02529, 1706.09003, 1907.10613]	DM (mass range: 10^{-16}-10^{-6} $M_\odot$)	large
Light scalar field Q-balls (not SUSY) [1612.02529, 1706.09003, 1907.10613]	DM, LIGO, supermassive	large
Oscillons [1801.03321]	DM, LIGO, supermassive	large
Multiverse bubbles [1512.01819, 1710.02865, 2001.09160]	DM, LIGO, supermassive	small