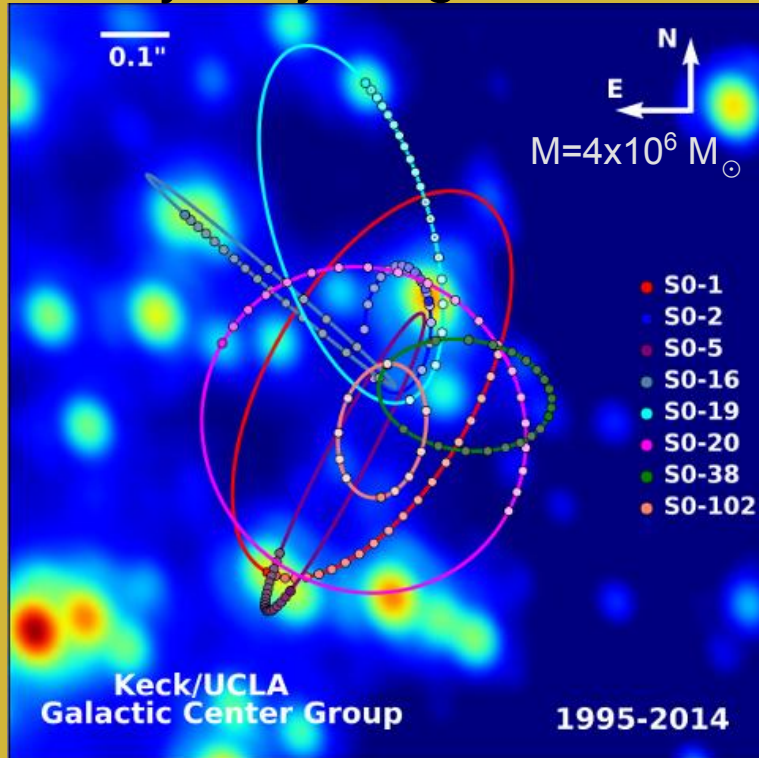


Particle physics models that predict dark matter in the form of **primordial black holes**

Alexander Kusenko
(UCLA and Kavli IPMU)
Naples, June 20, 2023

Nobel Prize 2020: Black holes' existence confirmed

Milky Way, Sagittarius A*



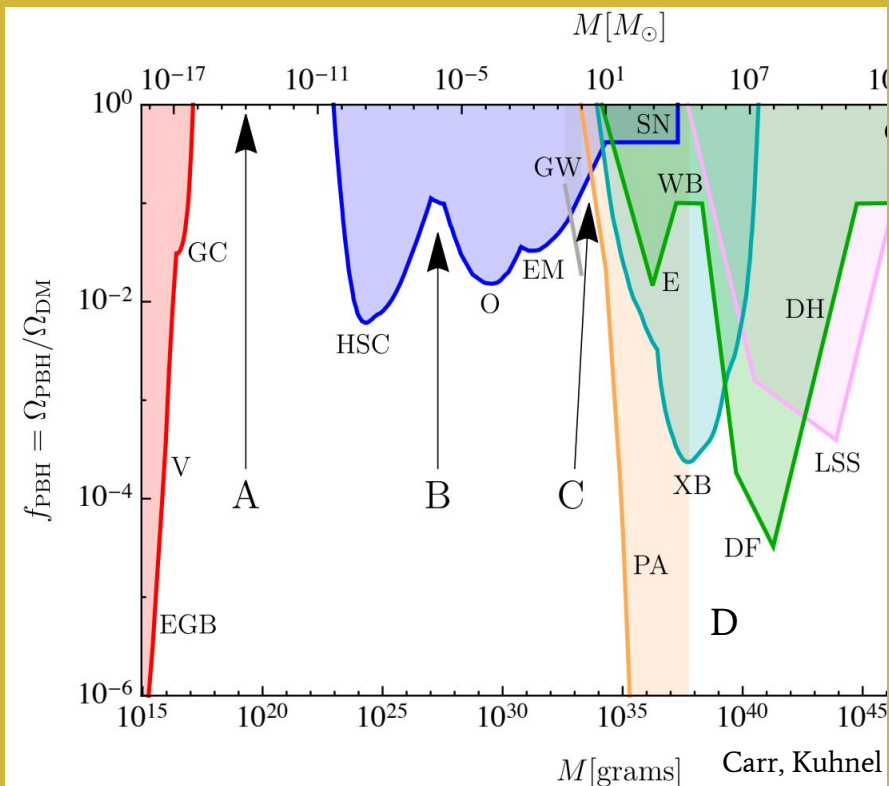
R. Penrose
R. Genzel
A. Ghez



Observations: BHs exist!

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

Experimental constraints



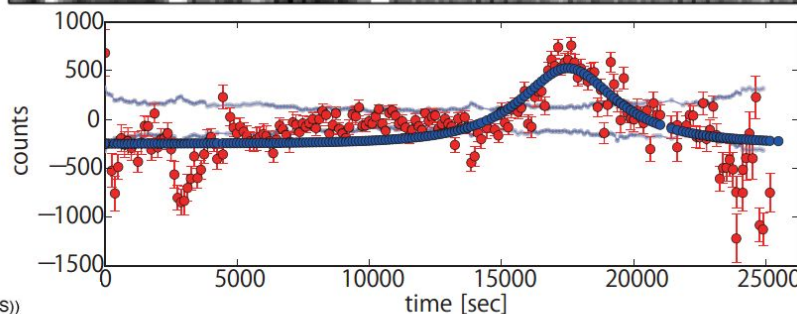
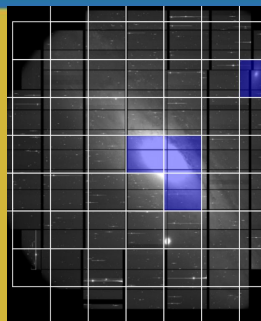
A - Dark matter

B - candidate events from HSC, OGLE
[1701.02151, 1901.07120]

C - interesting for GW, as well as transmuted NS
-> BH population [1707.05849; 2008.12780]

D - seeds of supermassive black holes
[astro-ph/0204486,
arXiv:1202.3848, 2008.11184]

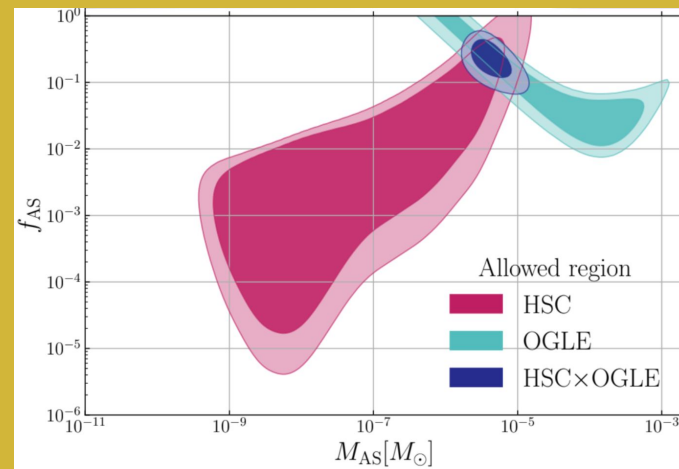
First candidate events



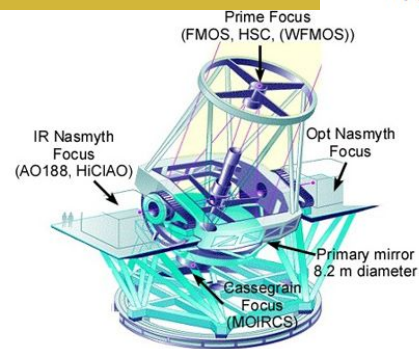
3. One remaining candidate that passed all the selection criteria of sing event. The images in the upper plot show the postage-stamped around the candidate as in Fig. 7: the reference image, the target image, and the residual image after subtracting the best-fit microlensing model, respectively. The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

[Takada et al., IPMU]

**First candidate events
from HSC and OGLE**
[Niikura et al., Nature Astron.]



Sugiyama



How to make PBHs

Need a $\sim 30\%$ or higher overdensity early enough in the history of the universe.

- **Primordial fluctuations enhanced on small scales (inflation model)**
- Yukawa interactions, “long-range” forces, radiative cooling \Rightarrow PBH
- Supersymmetry: Q-balls as building blocks of PBH
- Supersymmetry: Q-balls with long-range scalar forces
- Multiverse \Rightarrow PBHs



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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, \Rightarrow instability similar to
stronger than gravity 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]

Strong long-range force: instability and structure formation

$$\delta(x, t) = \delta\rho/\rho$$

energy density perturbations (radiation)

$$\Delta(x, t) = \Delta n_\psi / n_\psi$$

density perturbations of a kinetically decoupled particle

$$\ddot{\delta}_k + \frac{1}{t}\dot{\delta}_k - \frac{3}{8t^2}(\Omega_r\delta_k + \Omega_m\Delta_k) = 0$$

\Rightarrow

$$\Delta_k(a) \approx \Delta_{k,\text{in}} \left(\frac{t}{t_{\text{in}}} \right)^{p/2}, \quad p = \sqrt{\frac{3}{2}(1 + \beta^2)\Omega_\psi}$$

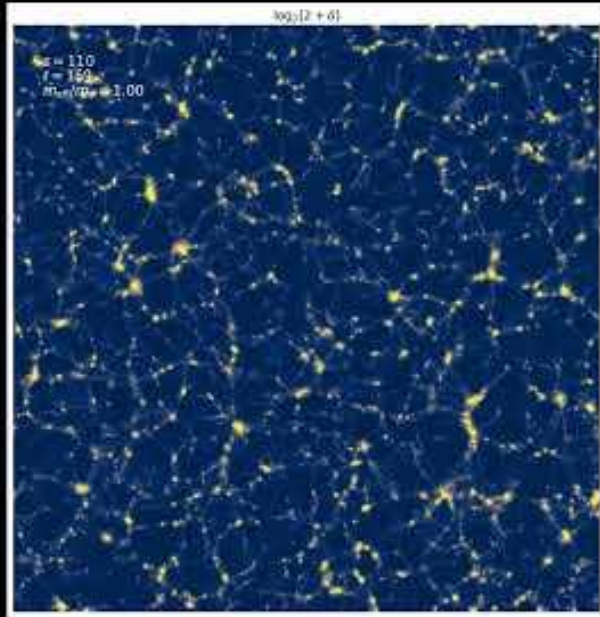
$$\ddot{\Delta}_k + \frac{1}{t}\dot{\Delta}_k - \frac{3}{8t^2}[\Omega_r\delta_k + \Omega_m(1 + \beta^2)\Delta_k] = 0$$

$$\beta \equiv y(M_P/m_\psi) \gg 1$$

$p = \text{huge} \Rightarrow$

[Flores, AK, 2008.12456, PRL] **fast growth, even in the radiation-dominated era!**

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



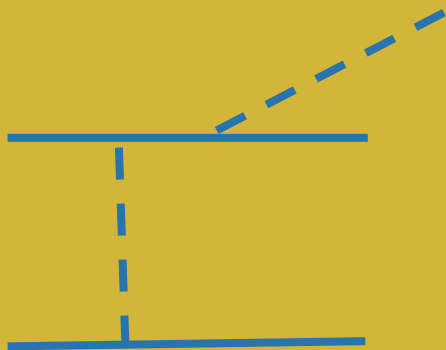
N-body simulation of the structure growth from Yukawa interactions

Domenech, Inman, Sasaki,
AK [2304.13053]

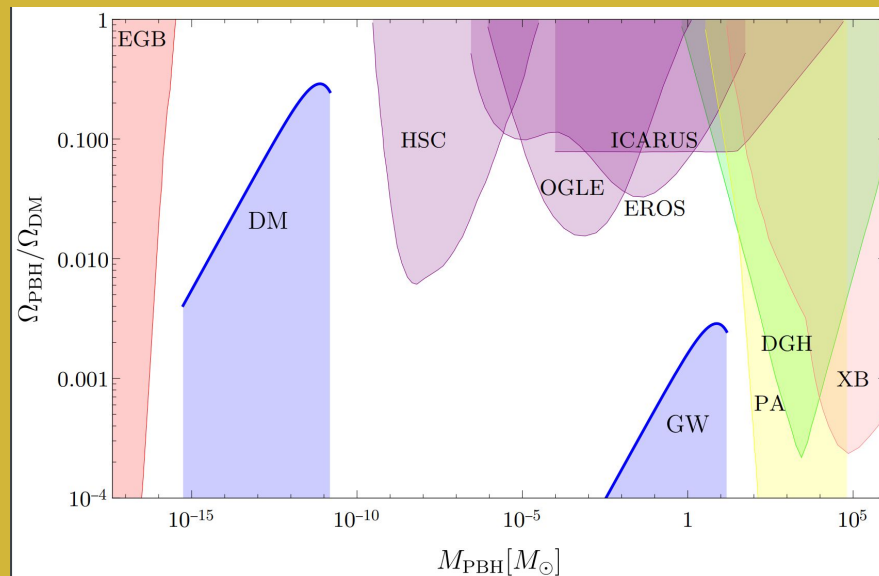
Rapid growth of structures... plus radiative cooling!

Same Yukawa fields allow particles moving with acceleration emit scalar waves

\Rightarrow radiative cooling and collapse to black holes



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



PBH DM abundance natural for $m_\psi \sim 1\text{-}100\text{ GeV}$

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

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

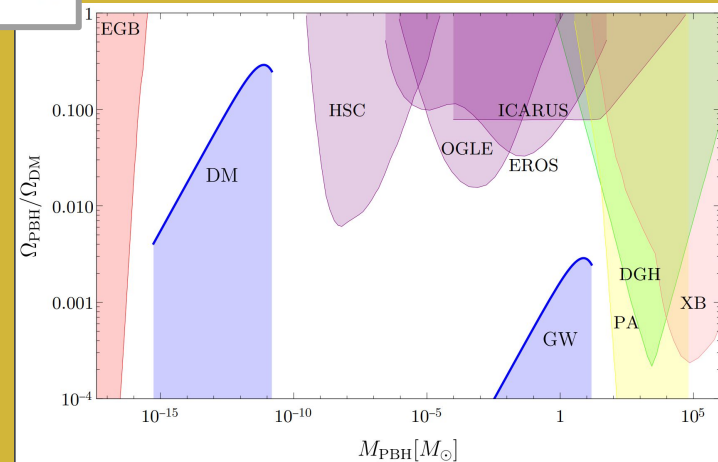
Similar to asymmetric dark matter

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

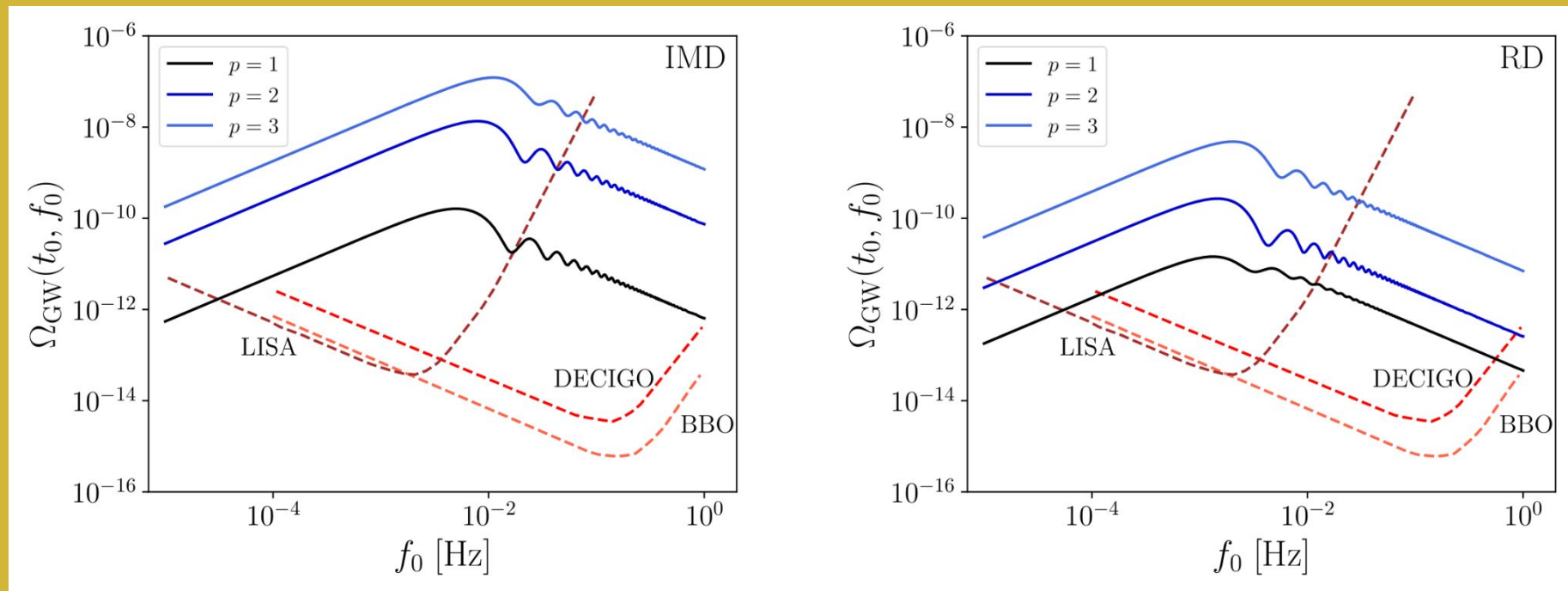
[Flores, AK, 2008.12456, PRL 126 (2021) 041101]

Natural explanation for the ratio

(dark matter density) / (ordinary matter density)
for $\sim 1\text{-}100\text{ GeV}$ masses



Gravitational waves from early halo formation



[Flores, AK, Sasaki, Phys. Rev. Lett, in press, 2209.04970]

Other possible consequences of early halo formation

Structure formation in RD era!

Many possible consequences

Inhomogeneous heating
by collapsing halos



Electroweak baryogenesis, even if the phase
transition is second order!
[Flores, AK, Pearce, White, 2208.09789]

Inhomogeneous heating
by collapsing halos

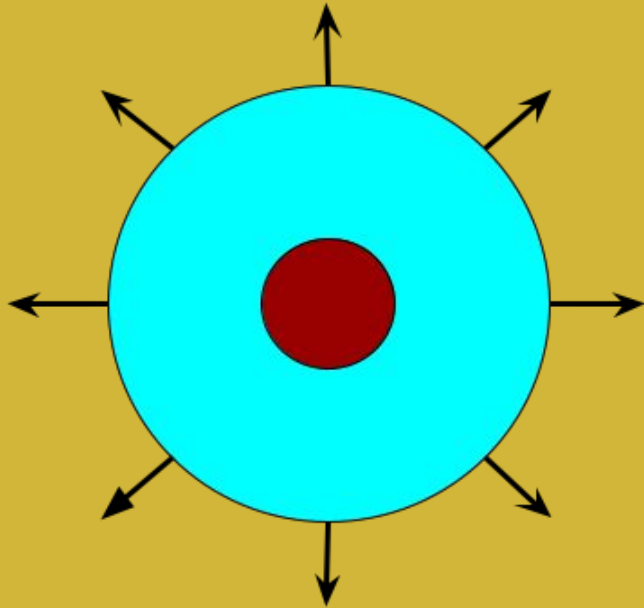


Magnetogenesis
[Durrer, AK, 2209.13313]

Side note: inhomogeneous cold electroweak baryogenesis

Halos of fermions form \rightarrow annihilate \rightarrow heat SM plasma

inhomogeneously \rightarrow departure from thermal equilibrium $t \sim t_{\text{fireball exp}}$



Baryogenesis

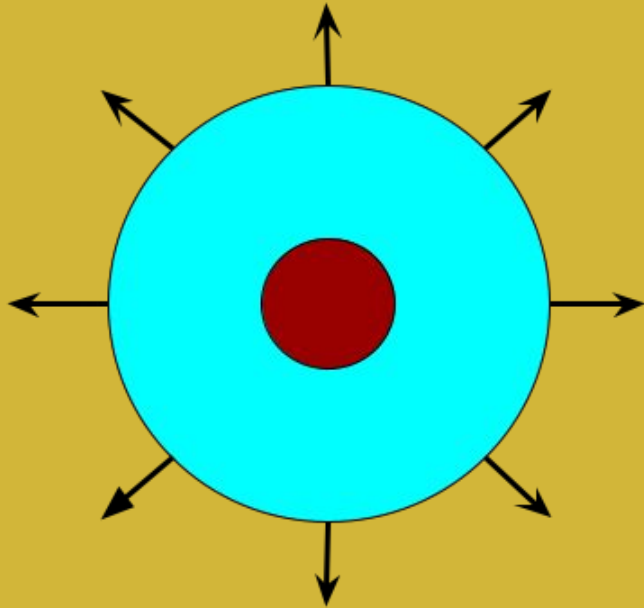
- without a first-order PT
- at low temperature
($10 \text{ MeV} < T < 100 \text{ GeV}$)

SM transition OK;
still need a source of CPV
[Flores et al. 2208.09789]

Side note: WIMP reheating and blast freezing!

Halos of fermions form \rightarrow annihilate \rightarrow heat SM plasma

inhomogeneously \rightarrow departure from thermal equilibrium $t \sim t_{\text{fireball exp}}$



- **WIMP rethermalize, then freeze out faster: $t_{\text{fireball exp}} \ll H^{-1}$**
- **WIMP dark matter OK for cross sections believed to be ruled out $\langle \sigma n v \rangle \sim 1/t_{\text{fireball exp}} \gg H$**

[Flores et al. 2306.04056]

How to make PBHs

Need a $\sim 30\%$ or higher overdensity early enough in the history of the universe.

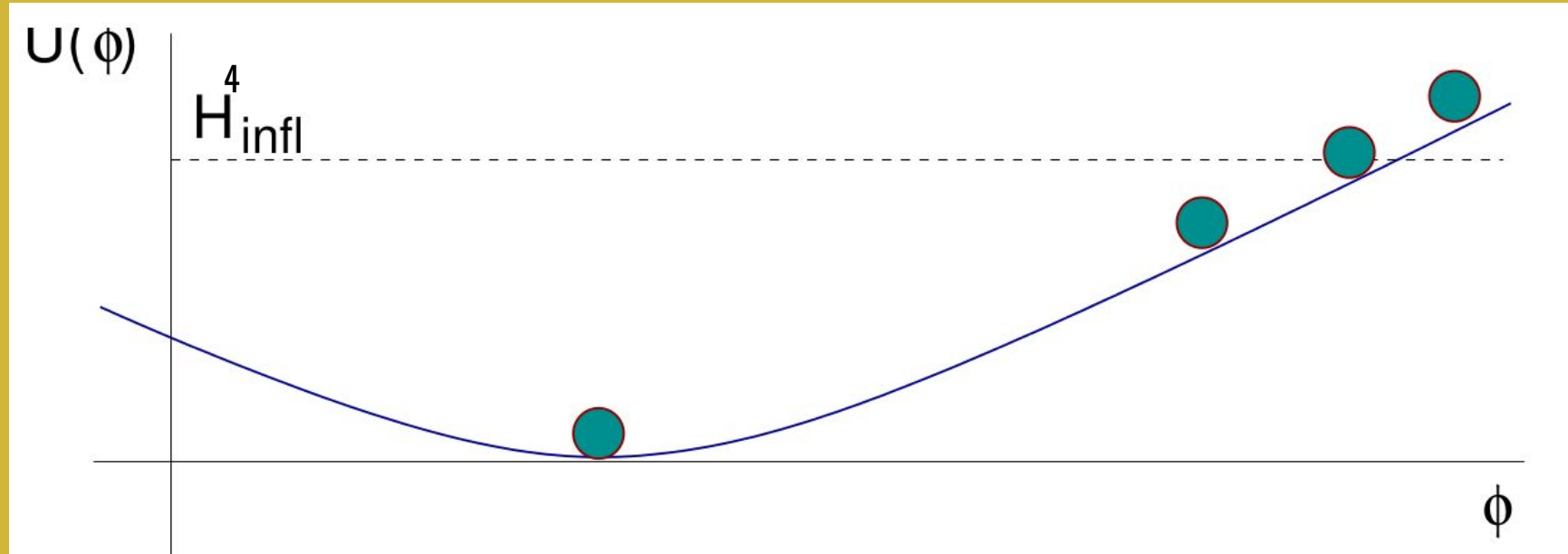
- Primordial fluctuations enhanced on small scales (modify inflation)
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Scalar fields in de Sitter space (used by Affleck-Dine)

A scalar with a small mass develops a VEV

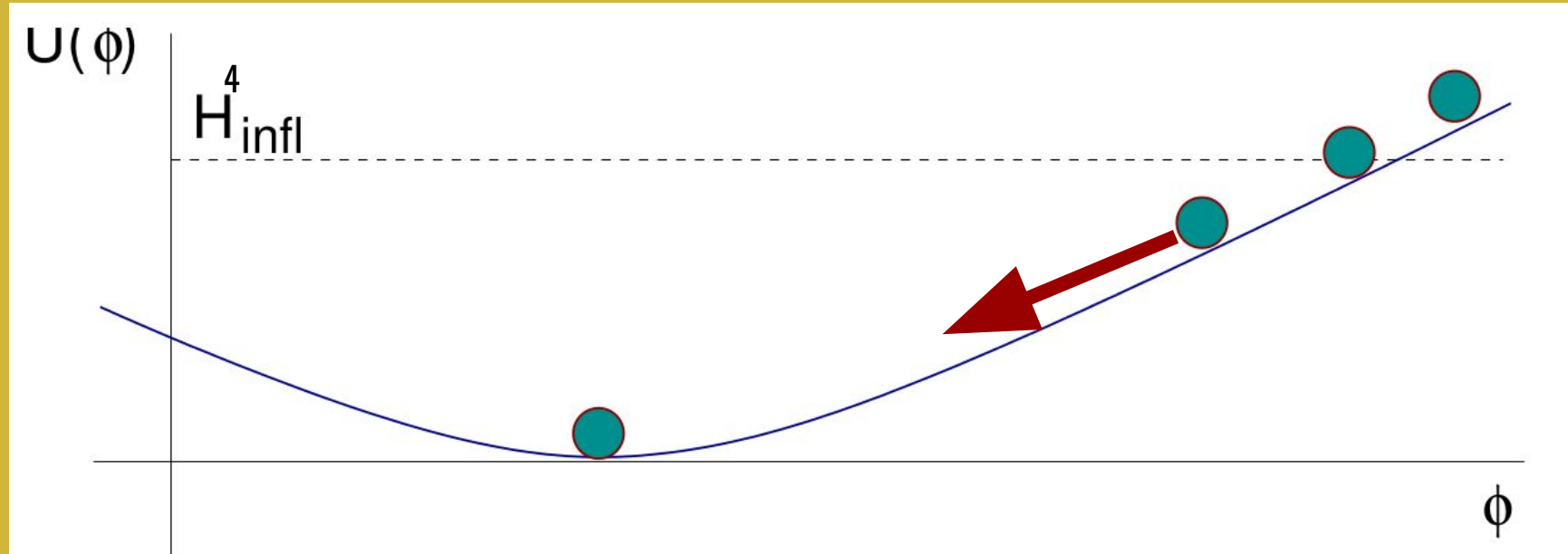
[Chernikov, Tagirov; Starobinsky, Zeldovich; Bunch, Davies; Linde; Affleck, Dine; Starobinsky, Yokoyama]



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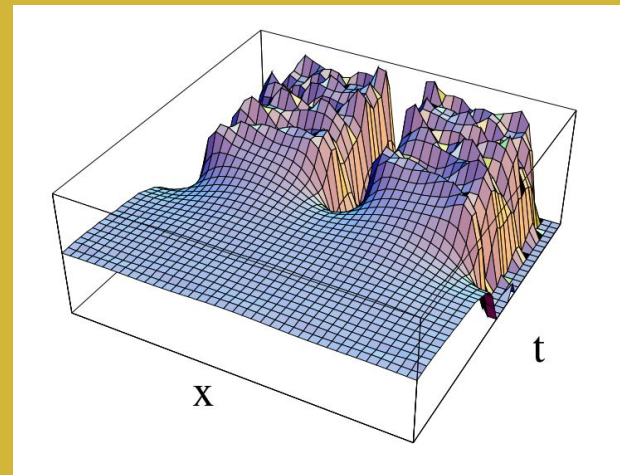
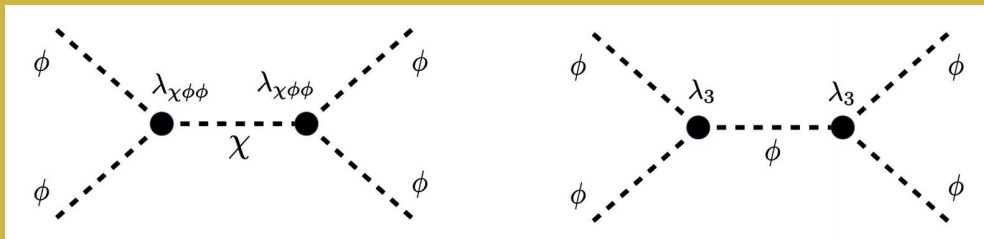


Scalar fields: an instability (Q-balls)

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

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

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



[AK, Shaposhnikov, hep-ph/9709492]

Scalar fields: an instability (Q-balls)

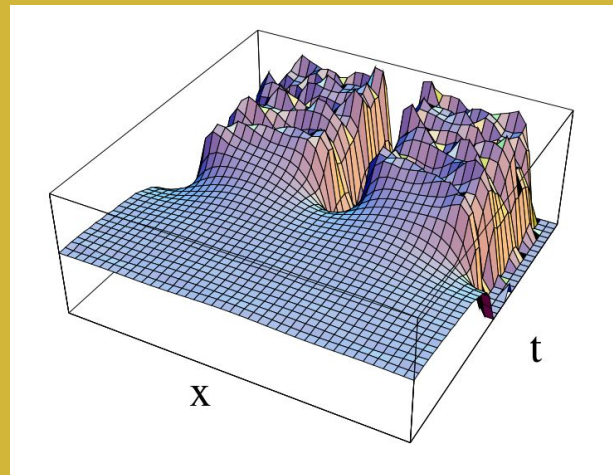
homogeneous solution $\varphi(x, t) = \varphi(t) \equiv R(t)e^{i\Omega(t)}$

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

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

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

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

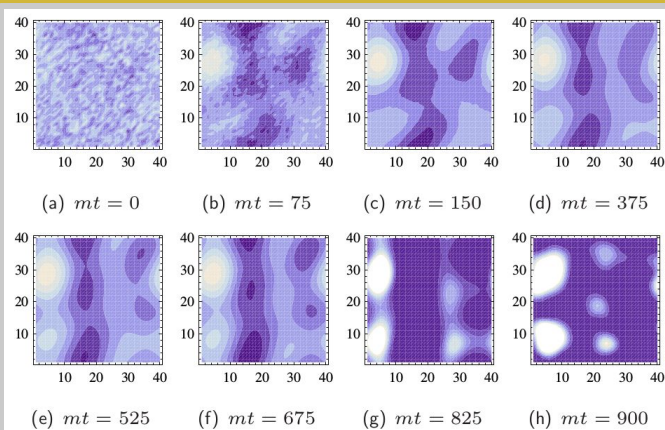


$$k_{\max}(t) = a(t)\sqrt{\dot{\Omega}^2 - U''(R)}$$

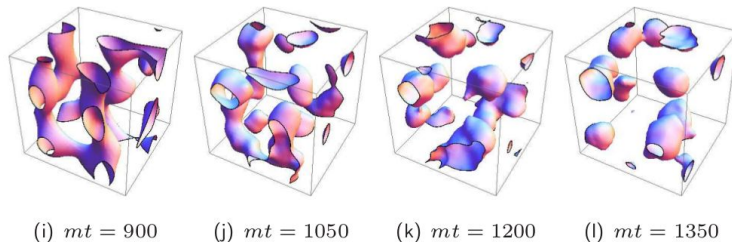
Also of interest: oscillons

AK, Shaposhnikov, hep-ph/9709492

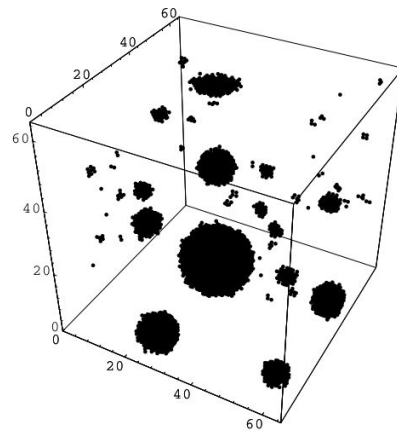
Numerical simulations of scalar field fragmentation



[Multamaki].

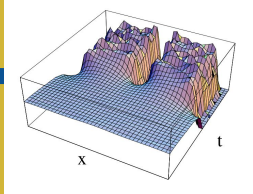


SUSY Q-balls



[Kasuya, Kawasaki]

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



Inflation

origin of
primordial
perturbations

radiation dominated

$$p = \frac{1}{3} \rho$$

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

structures don't grow

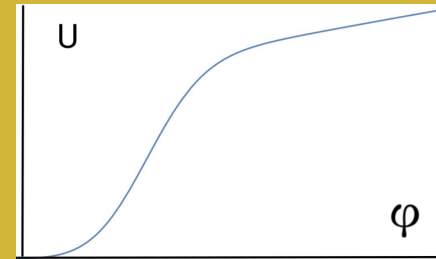
matter dominated

$$p = 0$$

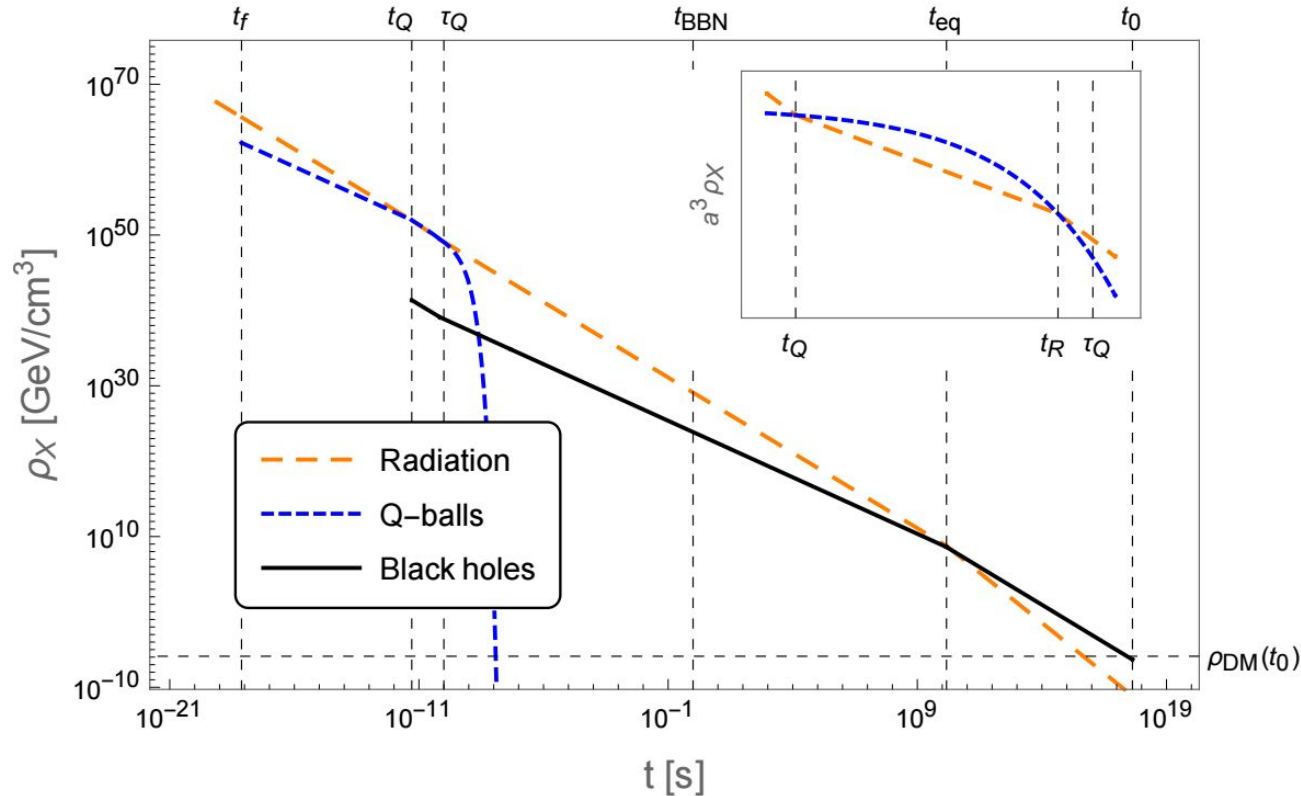
$$\rho \propto a^{-3}$$

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.

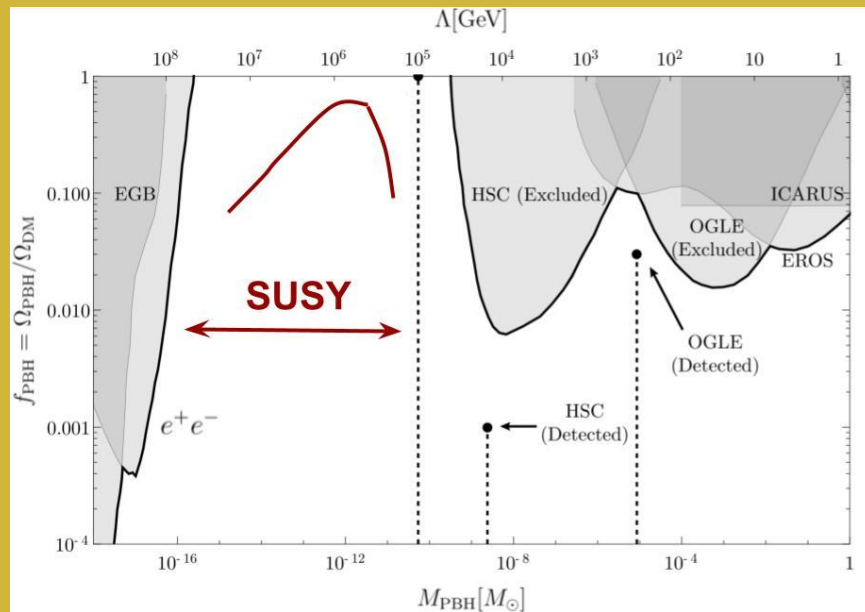
$$M_{\text{hor}} \sim r_f^{-1} \left(\frac{M_{\text{Planck}}^3}{M_{\text{SUSY}}^2} \right) \sim 10^{23} \text{g} \left(\frac{100 \text{ TeV}}{M_{\text{SUSY}}} \right)^2$$

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

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

Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019) 077

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



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- **Supersymmetry: Q-balls with long-range scalar forces**
- Multiverse => PBHs



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

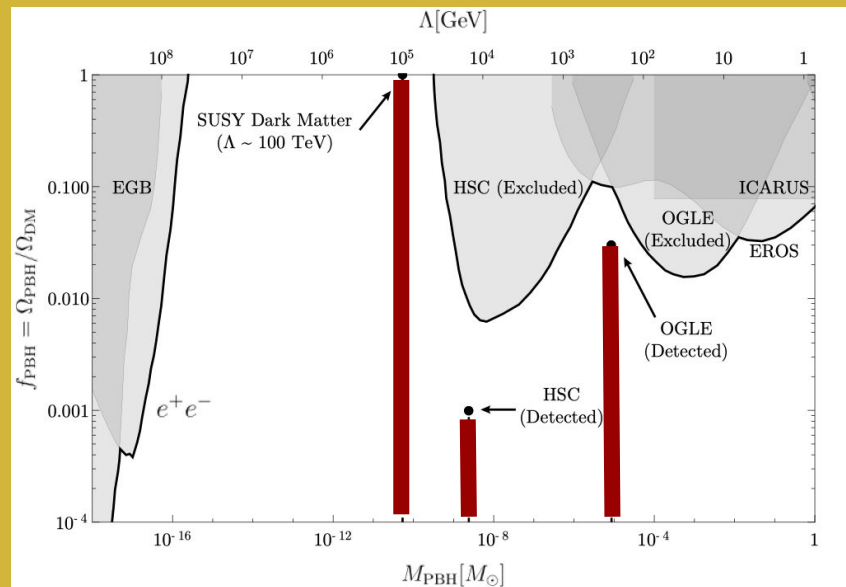
$$V(\varphi, \chi) = U(\varphi) + \frac{1}{2}m_\chi^2\chi^2 - y\chi\varphi^\dagger\varphi + \frac{\lambda}{4}\chi^4$$

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

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

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

Flores, AK, 2108.08416



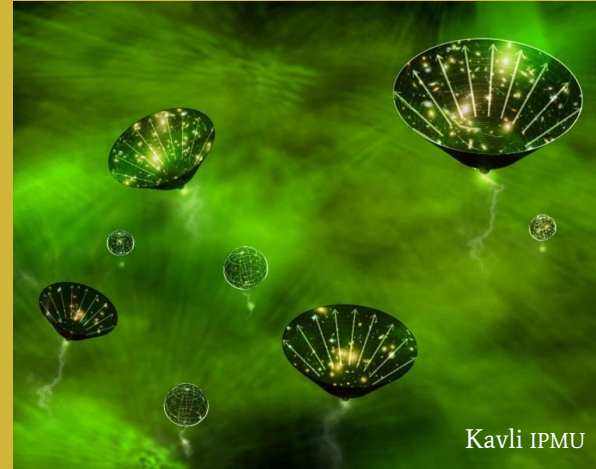
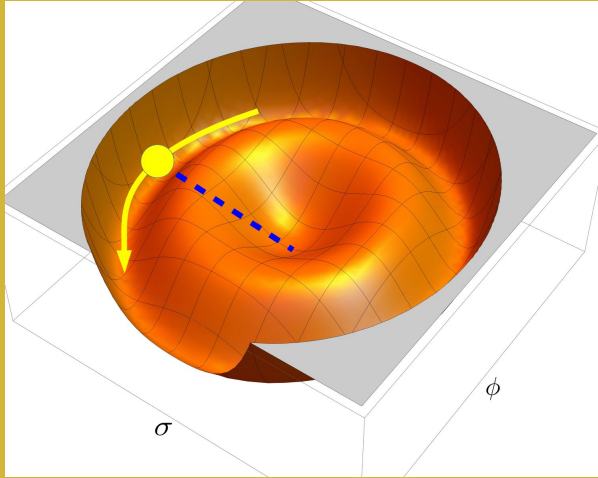
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And yet another mechanism: inflationary multiverse

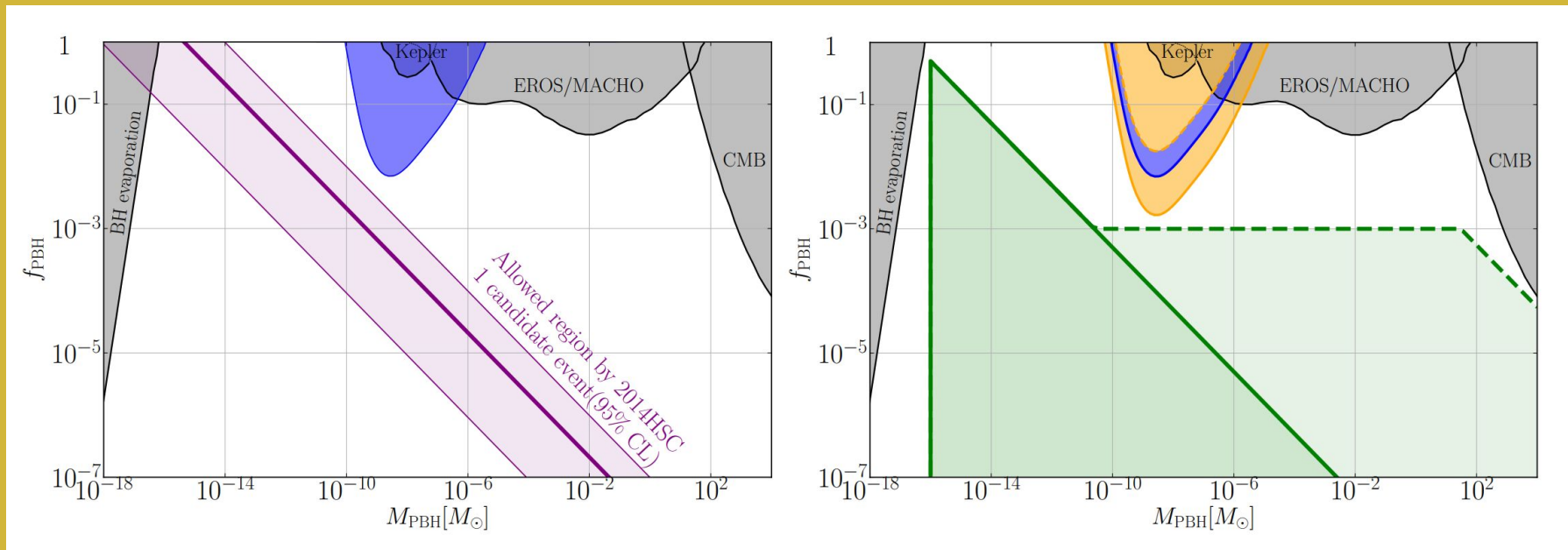


Tunneling events lead to nucleation of baby universes, which appear to outside observer as black holes.

Deng, Vilenkin JCAP 12 (2017) 044

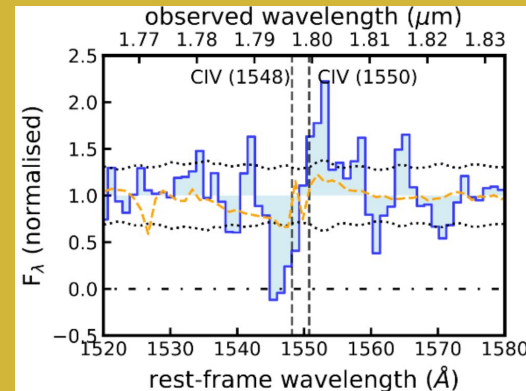
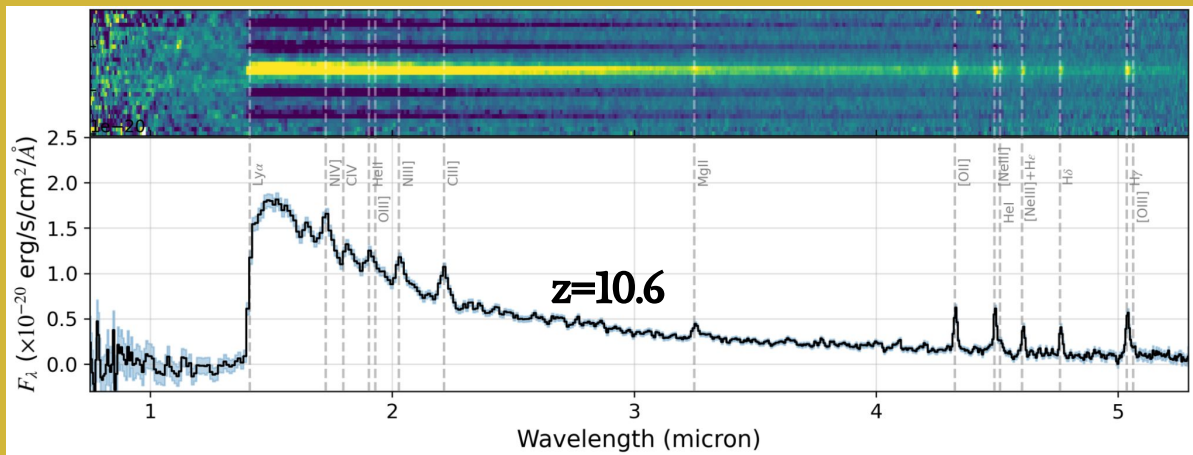
AK, Sasaki, Sugiyama, Takada, Takhistov, Vitagliano, Phys Rev Lett 125 (2020) 181304

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]

Supermassive black holes at high redshift – a mystery



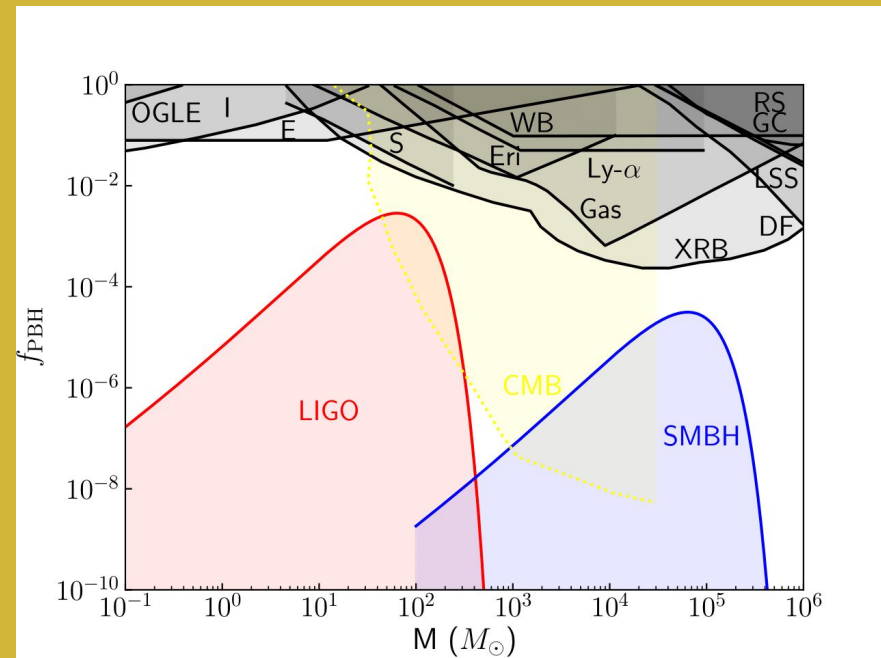
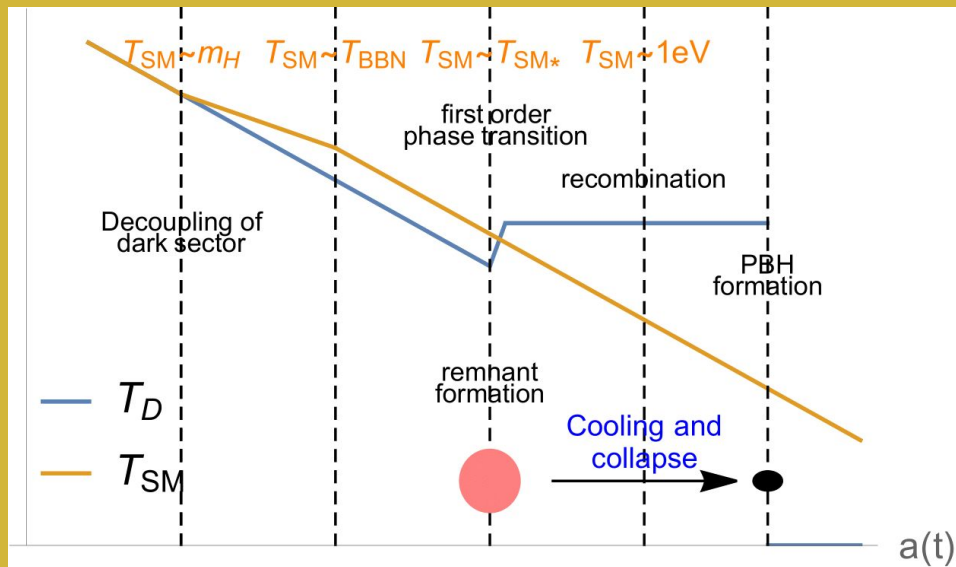
Bunker et al., 2302.07256;

Maiolino et al. (in prep.)

- A JWST observation suggests that a galaxy GN-z11 at $z=10.60$ has a supermassive black hole – **only 430 Myr after the Big Bang!**
- Other SMBHs: **quasars** exist at very early times, such as J0313–1806 at redshift $z = 7.642$

**Too early to make
SMBHs from stars!
⇒ PBH seeds?**

Late forming PBH can evade CMB constraints



[Lu, Kawana, AK, Phys.Rev.D 107 (2023) 10, 103037; 2210.16462]

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

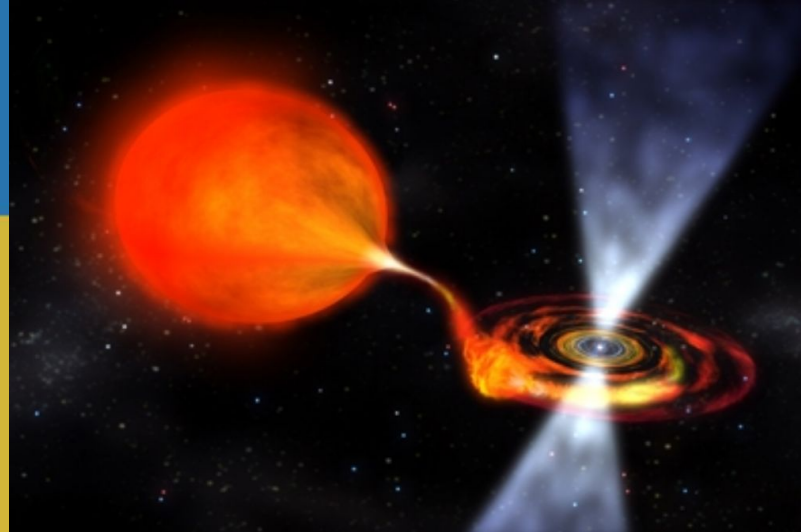
PBH and neutron stars

- 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]
- What happens if NSs really are systematically destroyed by PBH?

Neutron star destruction by black holes

⇒ r-process nucleosynthesis, 511 keV, FRB

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

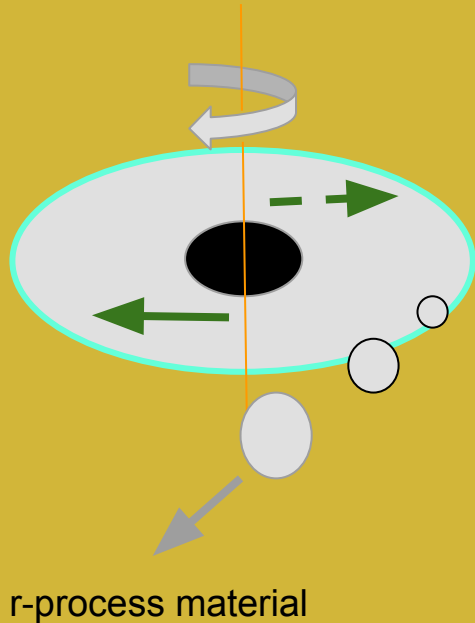


Fast-spinning millisecond pulsar.

Image: NASA/Dana Berry



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

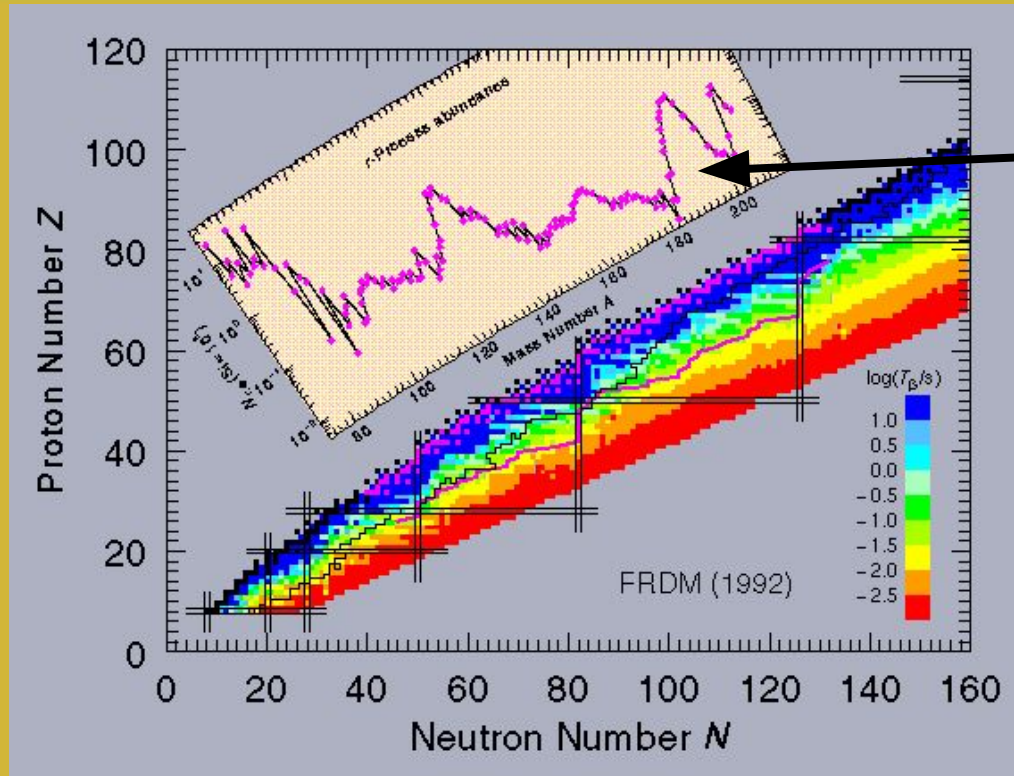
[Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101] also, *Viewpoint* by H.-T. Janka

Primordial black holes, neutron stars, and the origin of gold

- Light elements are formed in the Big Bang
- Heavy elements, up to Fe, are made in stars
- What about Au, Pt, U...? PBH can play a role

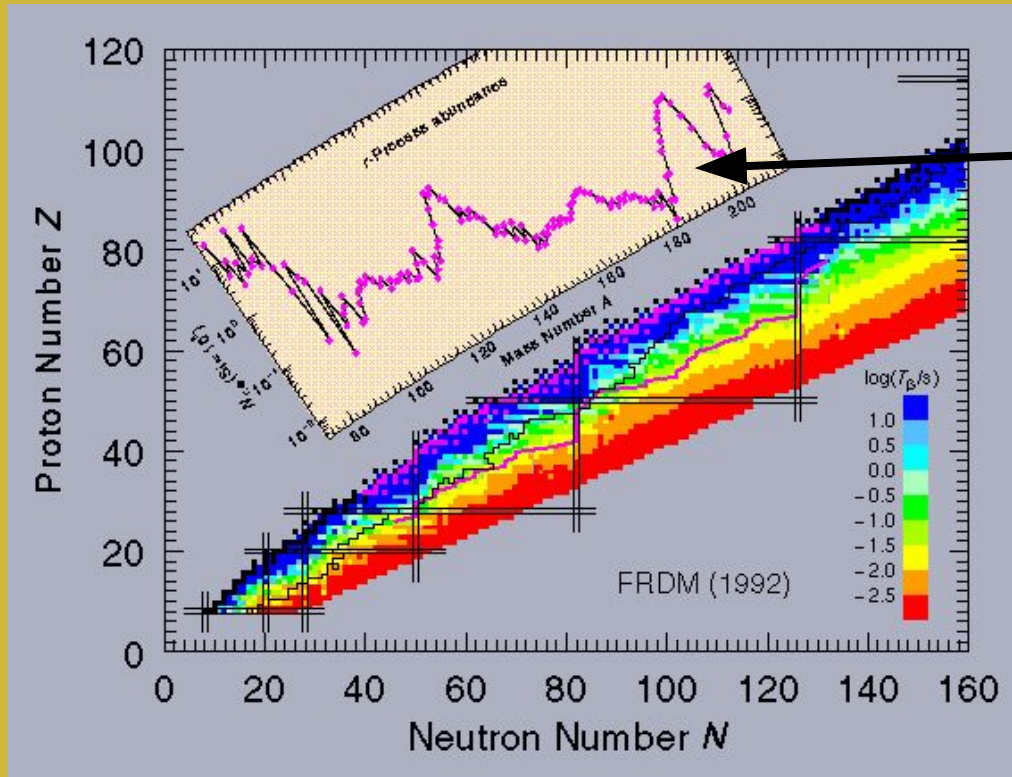


r-process nucleosynthesis: site unknown



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

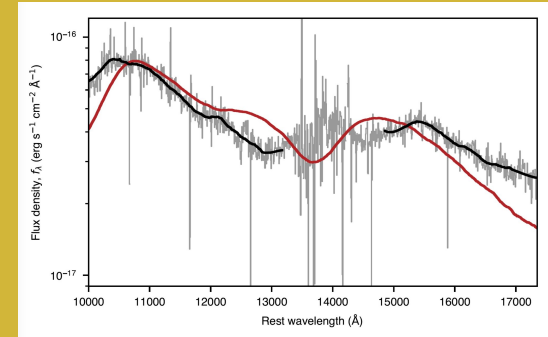
r-process nucleosynthesis: site unknown



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



Image: Los Alamos, Nuclear Data Group



NS-NS might not be not enough...

THE ASTROPHYSICAL JOURNAL, 900:179 (33pp), 2020 September 10

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.

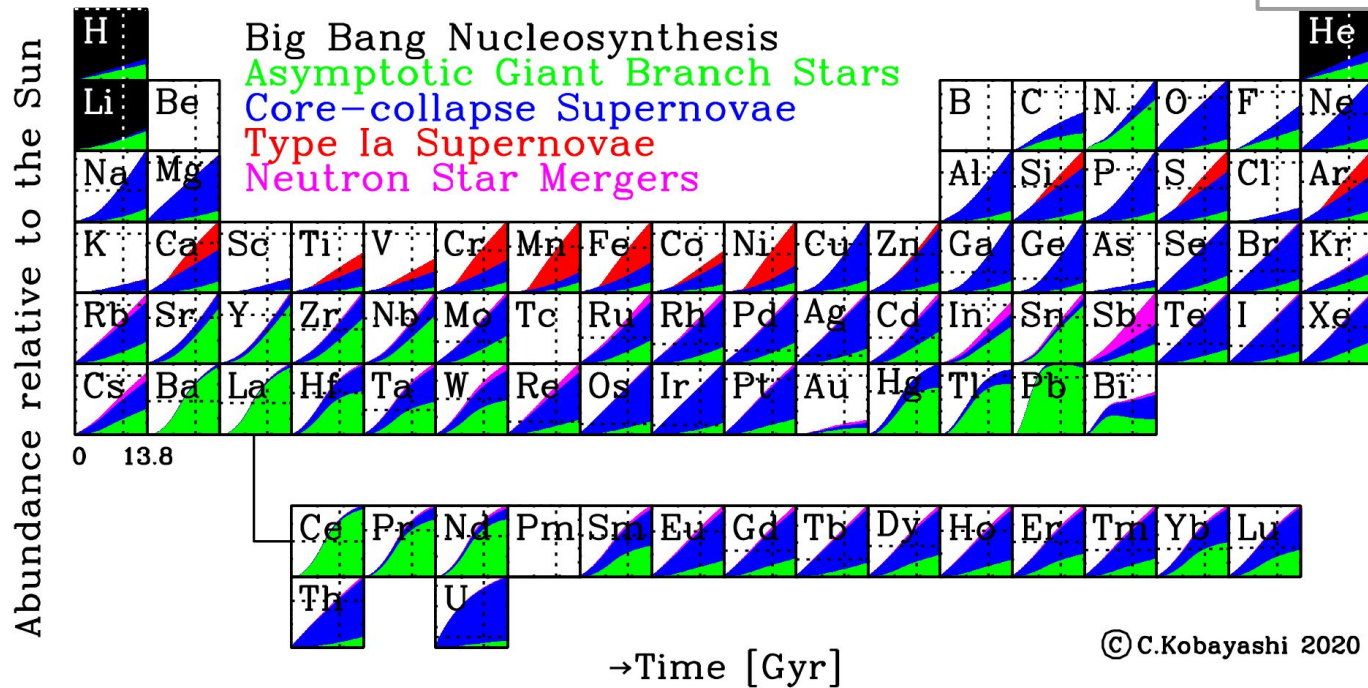


Figure 39. The time evolution (in Gyr) of the origin of elements in the periodic table: Big Bang nucleosynthesis (black), AGB stars (green), core-collapse supernovae including SNe II, HNe, ECSNe, and MRSNe (blue), SNe Ia (red), and NSMs (magenta). The amounts returned via stellar mass loss are also included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

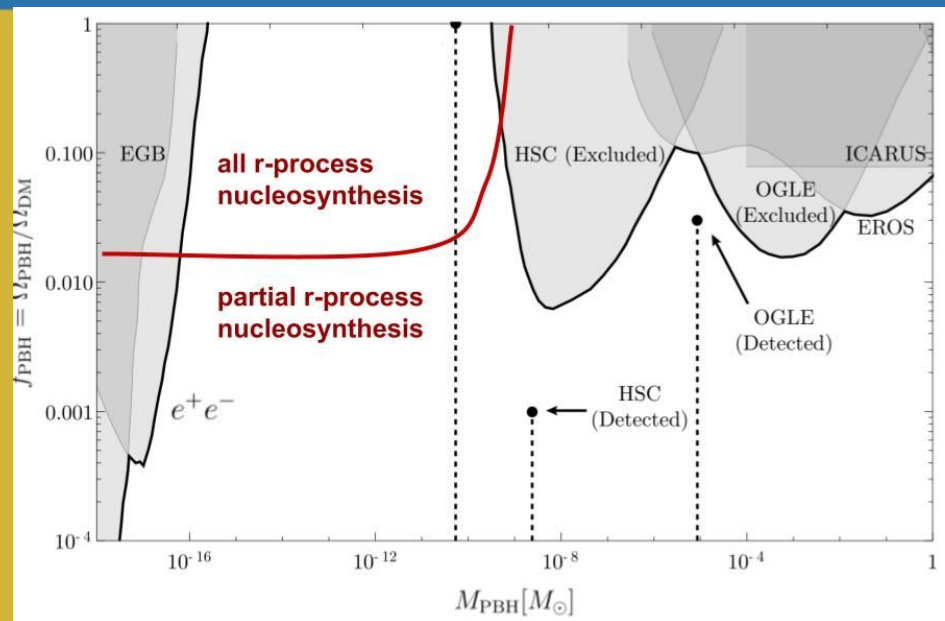
"Rare event" consistent with the UFD data:

one in ten shows r-process material

[Ji, Frebel et al. Nature, 2016]

NS disruptions by PBHs

- Centrifugal ejection of cold neutron-rich material ($\sim 0.1 M_{\odot}$)
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. ✓

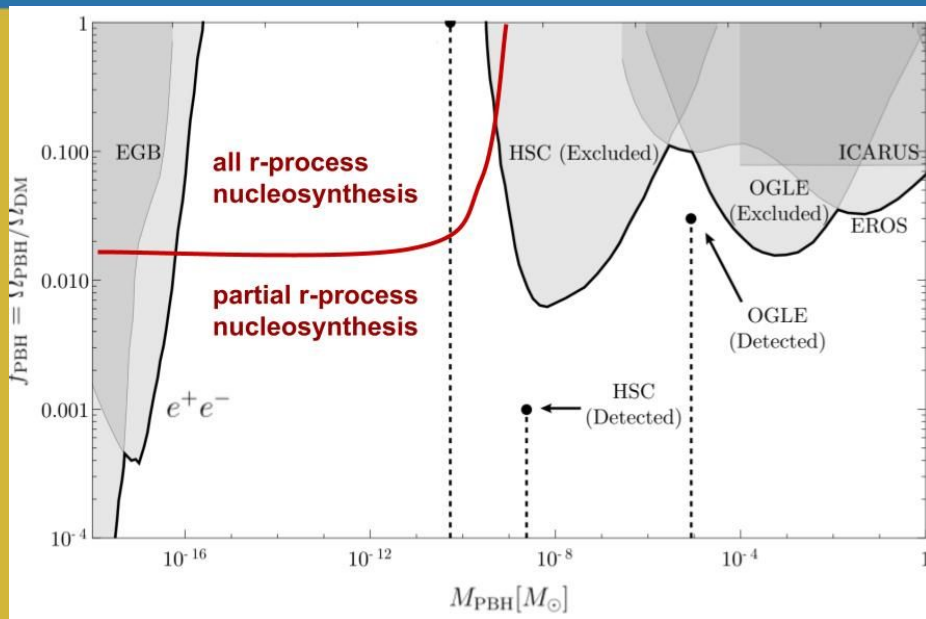


[Fuller, AK, Takhistov, PRL 119 (2017) 061101]

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



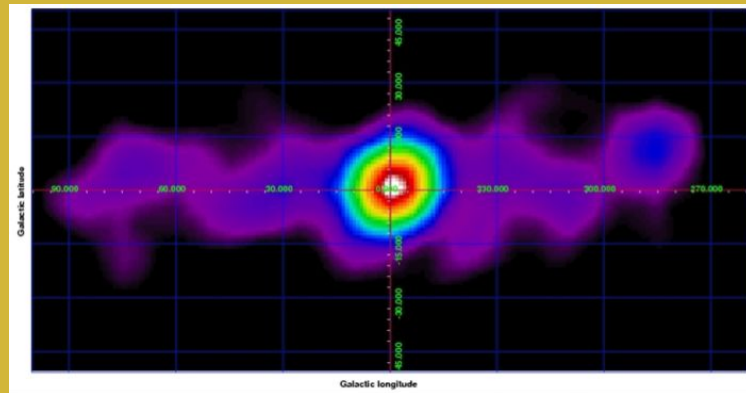
[Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101]

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 $T \sim 0.1$ MeV

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



ESA/Bouchet et al.

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

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

Fast Radio Bursts (FRB)

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

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

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

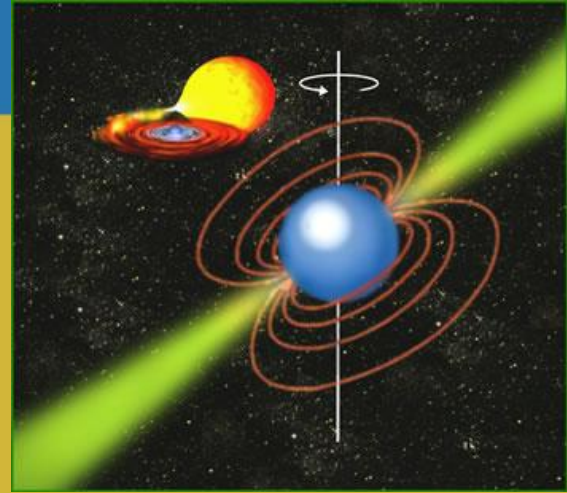
Massive rearrangement of magnetic fields at the end of the NS life, on the time scale $\sim \text{ms}$ produces an FRB.

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 from NS->BH process

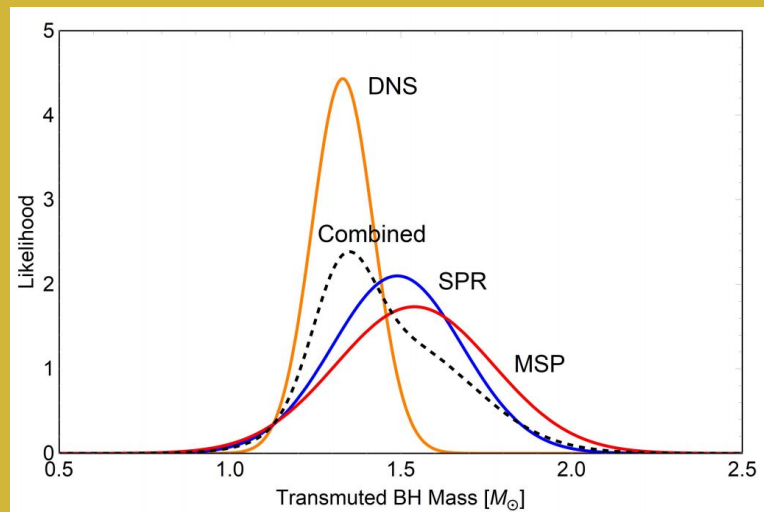
PBH + NS



BH of $1-2 M_{\odot}$

[Takhistov et al., 1704.01129, 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
- Microlensing (HSC) can detect the tail of DM mass function.
- PBH can contribute to r-process nucleosynthesis
- Signatures of PBH:
 - Kilonova without a GW counterpart, or with a weak/unusual GW signature
 - GW from early halo formation
 - An unexpected population of 1-2 M_{\odot} black holes (GW)
 - Galactic positrons, FRB, etc.
- Yukawa forces \Rightarrow primordial structures \Rightarrow PBH, baryogenesis, other consequences!