Dark matter and black holes

Alexander Kusenko
(UCLA and Kavli IPMU)

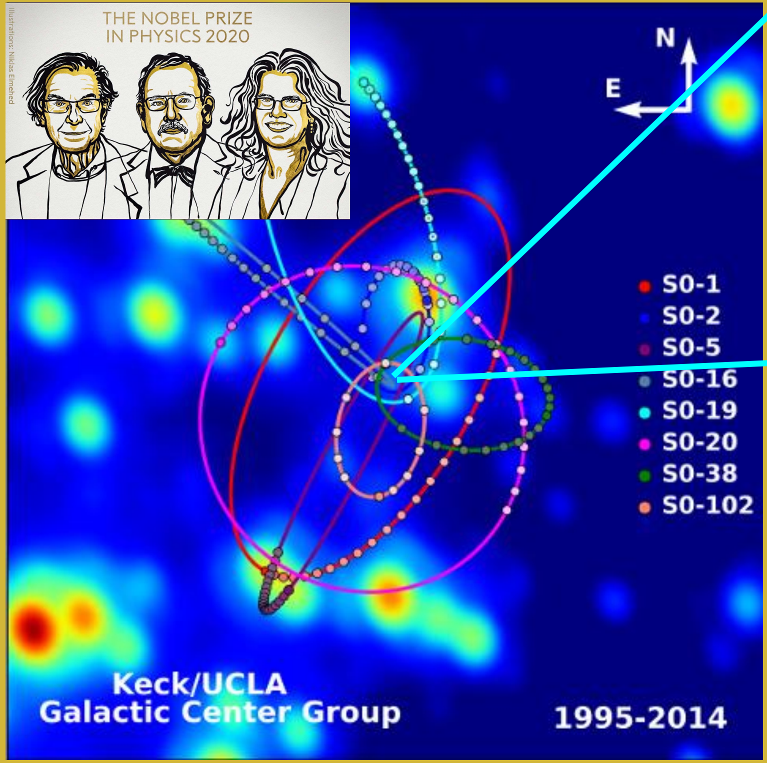
Supported by U.S. DOE Office of Science (HEP) and WPI, Japan

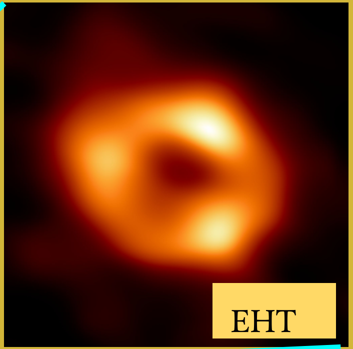
Happy birthday to Director of the Universe!

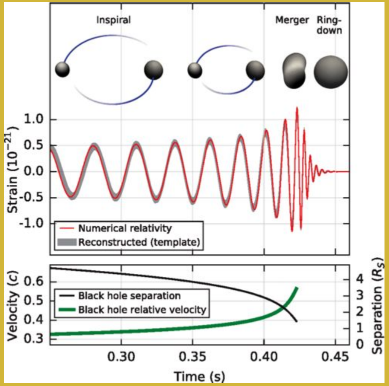
From brilliant physics – to leading P5,
His mind endeavors, so science may thrive.
His ideas are bold, his talents diverse –
Hitoshi, Director of the Universe!

Credits: AK+AI

Black holes: multimessenger observations

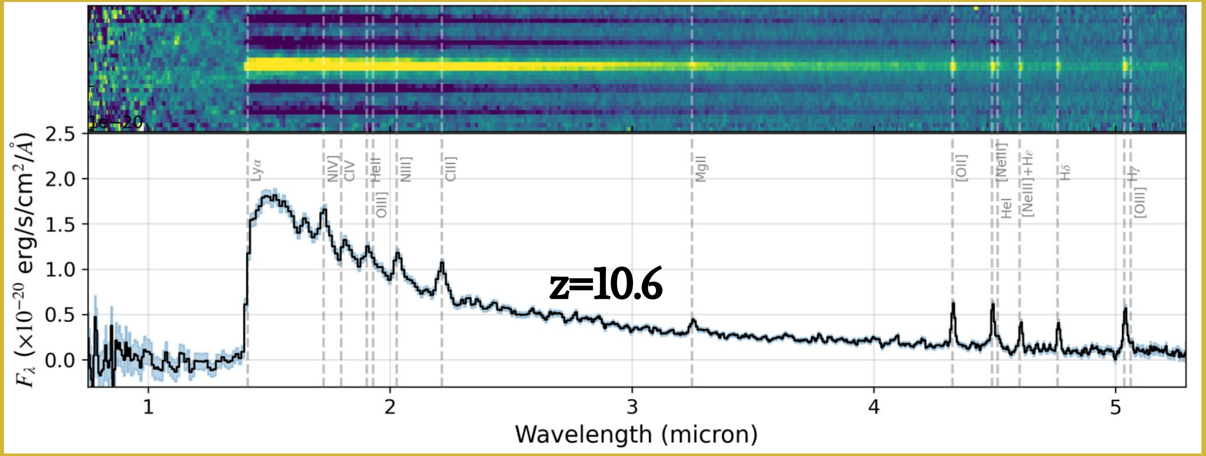


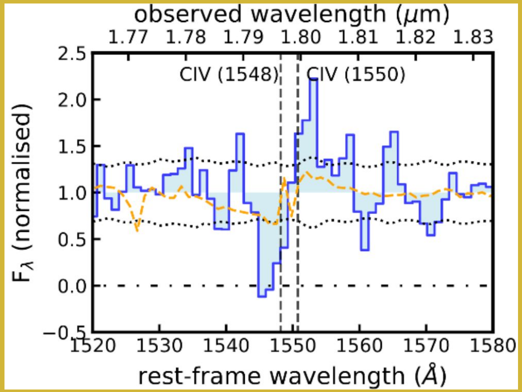




Abbott et al., Phys. Rev. Lett. 116, 061102

SMBH mystery dark matter can (miraculously) solve





Bunker et al., 2302.07256;

- 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!

Direct collapse: a large cloud of gas collapses into a SMBH

The gas must remain hot to keep the Jeans mass high and prevent fragmentation.

This requires a low fraction of H_2, the main cooling agent.

Astrophysical sources of radiation are not successful at facilitating direct collapse (shielding, heating, etc.)

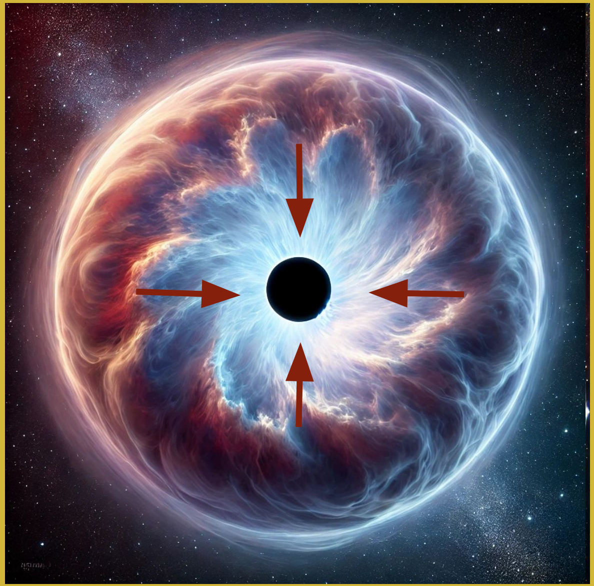


Image credits: AK+AI

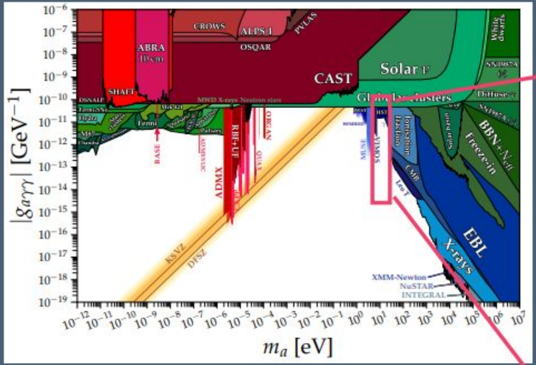
Direct collapse: need to reduce H_2, the cooling agent!

- Photodissociation & photodetachment require a LW radiation background.
- DM decay can produce the necessary radiation (ALP OK, but not QCD axions)
- Decaying particles can be
  - all of the DM (with a low decay rate), or
  - a fraction of DM (particle X, with higher decay rate)
- Two body decay, monochromatic (relevant for ALPs) or
- Three body decay
- Majorons? (Yanagida+Lu, work in progress)


$$\mathrm{H} + e^- \rightarrow \mathrm{H}^- + \gamma,$$
$$\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + e^-.$$

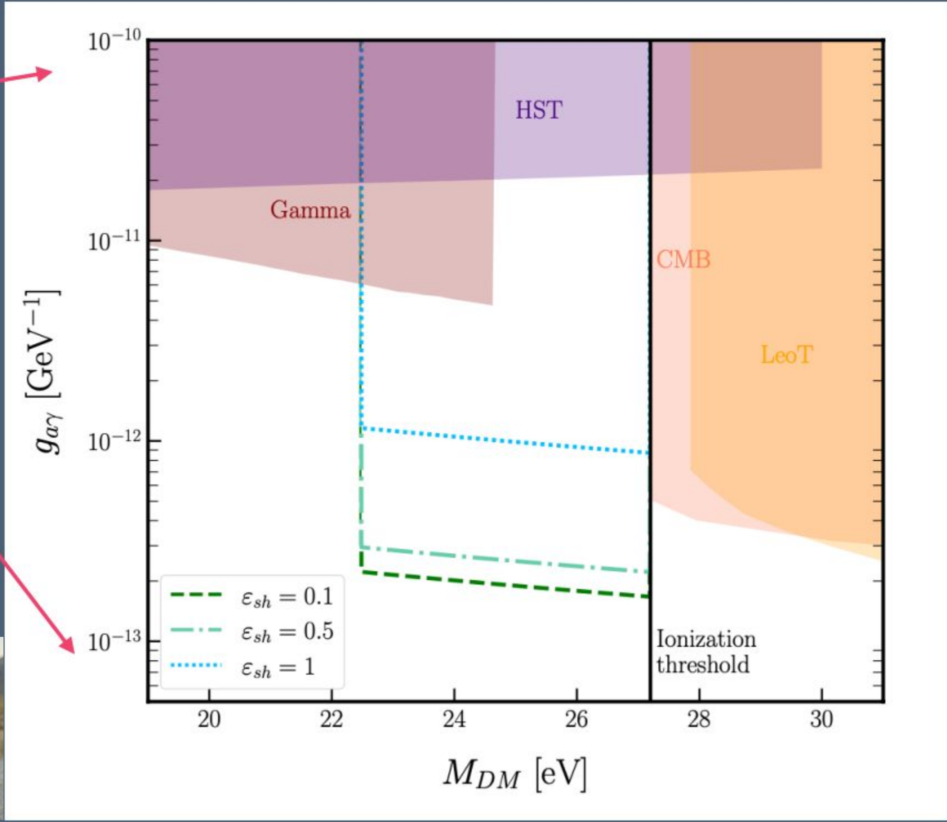
Lu, Picker, AK, Phys. Rev. Lett.
133 (2024) 9, 091001 [2404.03909]

(1) Slowly decaying DM or (2) small admixture of fast decaying DM

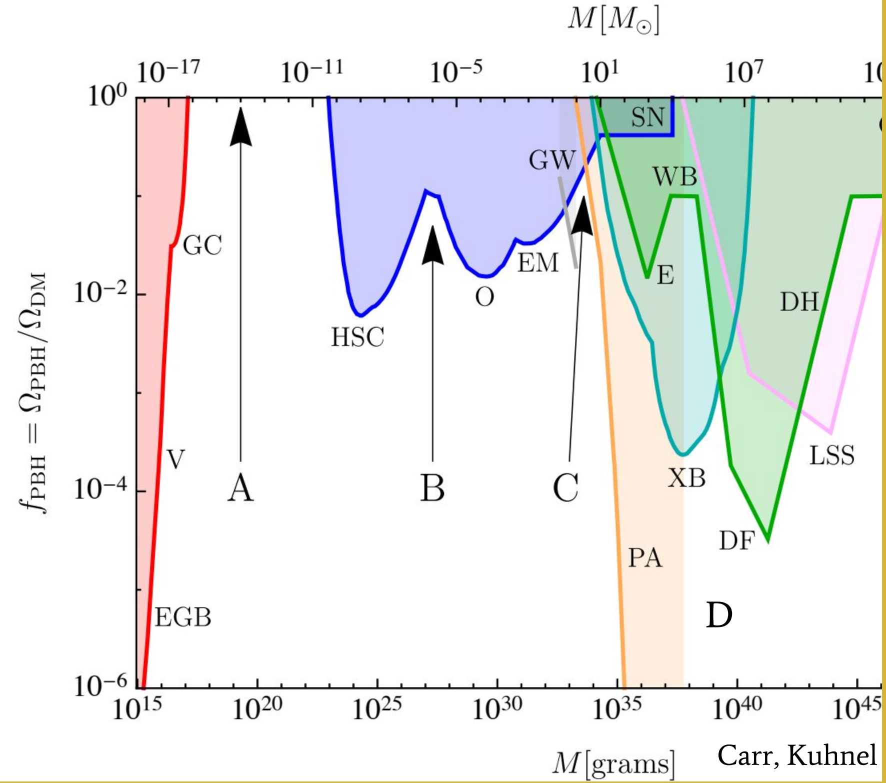


[Credit: Ciaran O'Hare]

Lu, Picker, AK, Phys. Rev. Lett. 133 (2024) 9, 091001 [2404.03909]



Primordial black holes as dark matter



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, 2312.15062]

Primordial black holes as dark matter (Sutten's Law)

Sutton's Law as taught in US medical schools:
When diagnosing, one should first consider the most obvious possible causes.

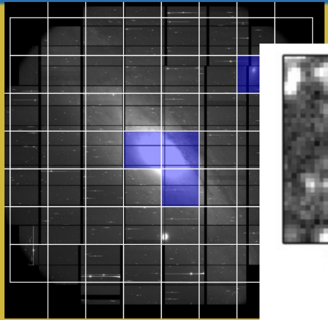
Black holes exist and can be produced in the early universe (via multiple scenarios): could they be dark matter?

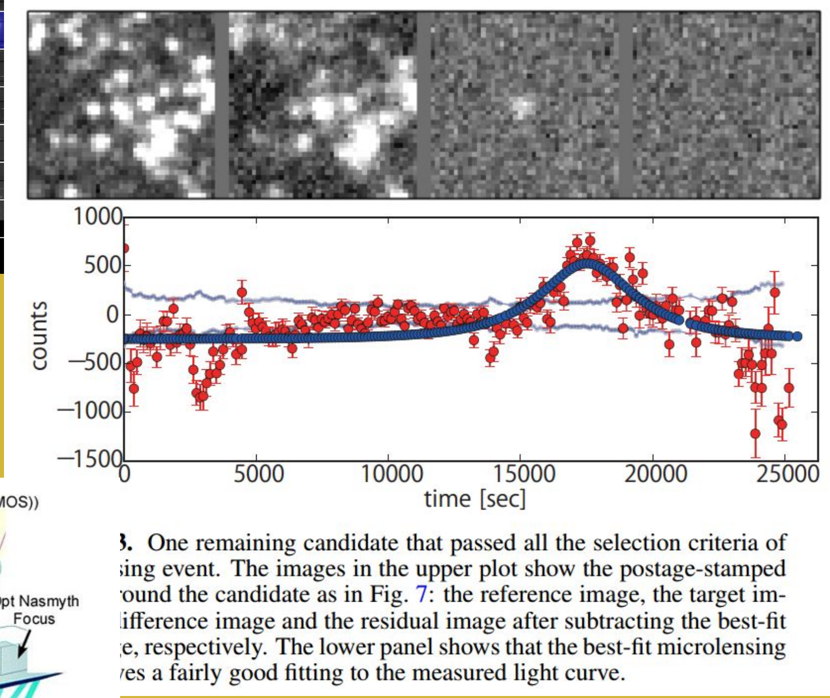
(image: Eastern State Penitentiary)

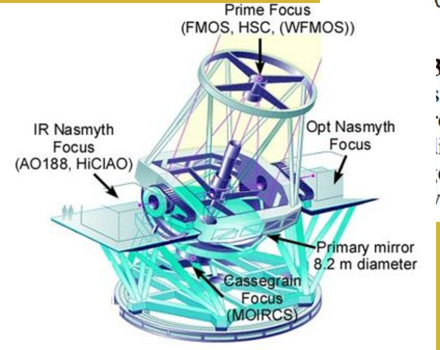
Mitch Ohnstad (reporter):
-Why do you rob banks?

Willie Sutton:
-Because that's where the money is.

HSC search for PBH: Takada, Sugiyama,... – inspired by Hitoshi

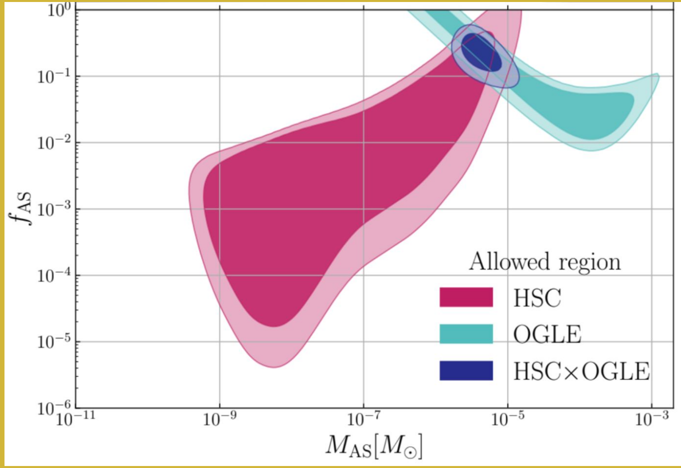






First candidate events from HSC and OGLE

[Niikura et al.. Nature Astron.]



[Takada et al., Kavli IPMU]

Sugiyama

How to make PBHs

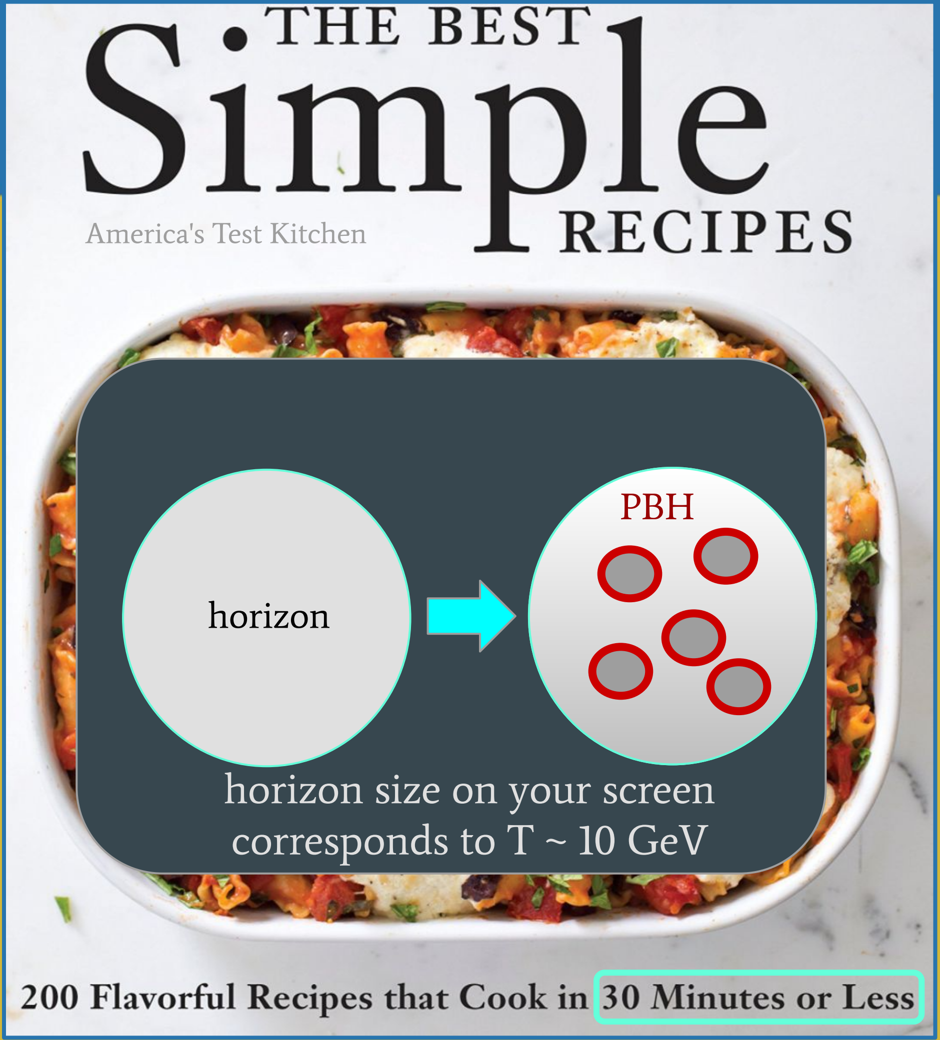
Need a ~30% or higher overdensity early enough in the history of the universe.

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

How to make PBHs

Need a ~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 => PBH**
- Supersymmetry: Q-balls as building blocks of PBH
- Supersymmetry: Q-balls with long-range scalar forces
- Multiverse => PBHs



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]

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

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

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

$\Rightarrow$

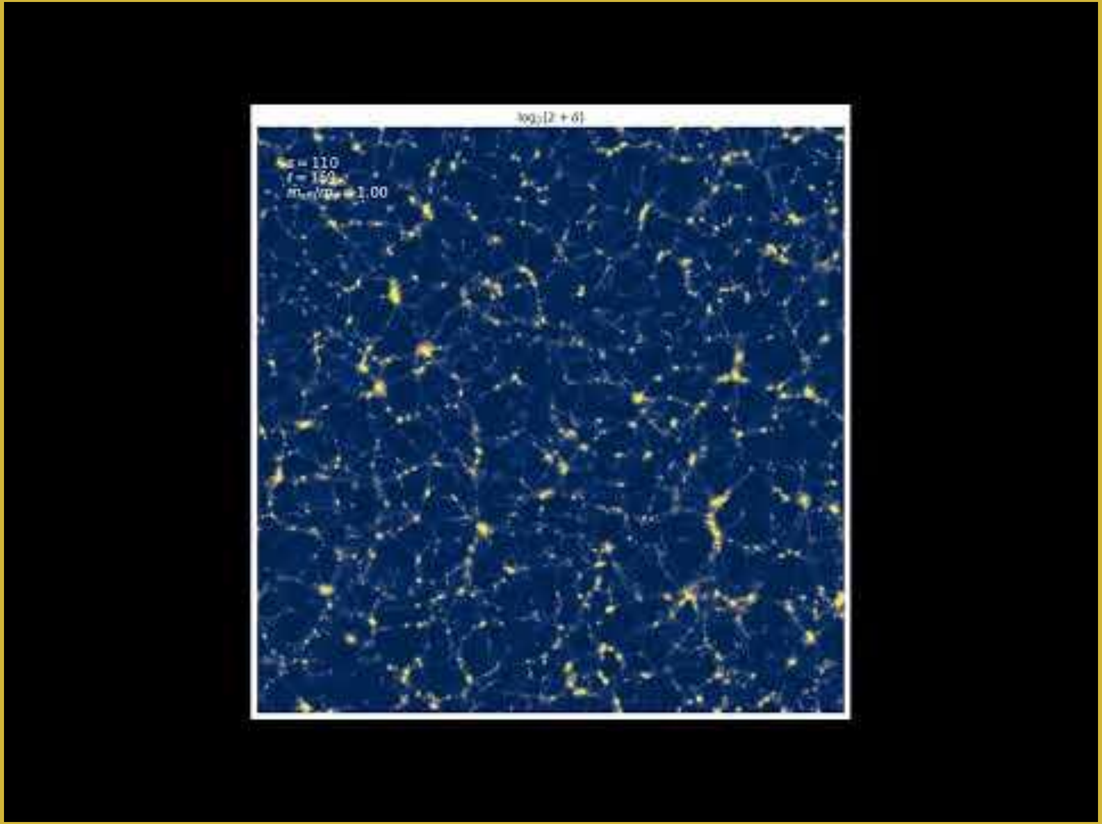
$$\Delta_k(a) \approx \Delta_{k,\mathrm{in}} \left(\frac{t}{t_{\mathrm{in}}}\right)^{p/2}, \quad p = \sqrt{\frac{3}{2}(1+\beta^2)\Omega_\psi}$$

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

p = huge $\Rightarrow$

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

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

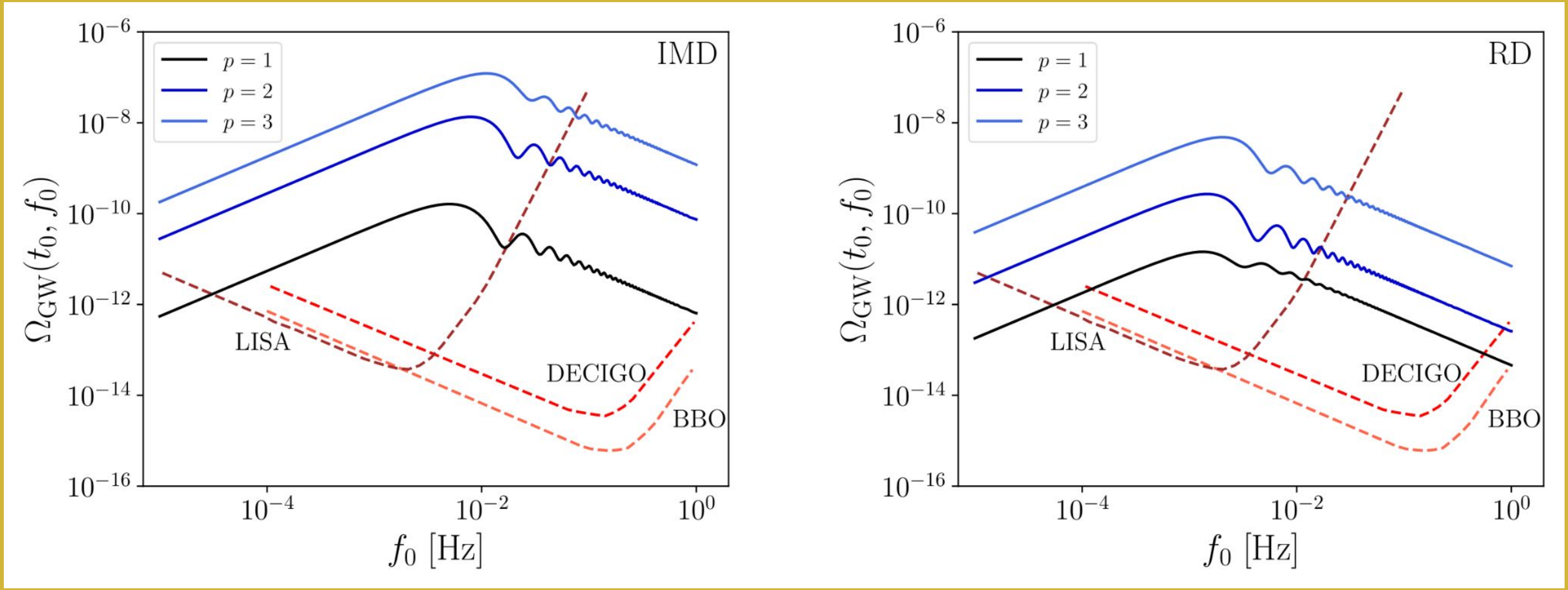


N-body simulation of the structure growth from Yukawa interactions

Inman

Domenech, Inman, Sasaki, AK [2304.13053]

Gravitational waves from early halo formation



[Flores, AK, Sasaki, Phys.Rev.Lett. 131 (2023) 1, 1; 2209.04970]

Possible consequences of early halo formation

Structure formation in RD era!

Many possible consequences

Inhomogeneous heating
by collapsing halos

$\Rightarrow$ PBH dark matter

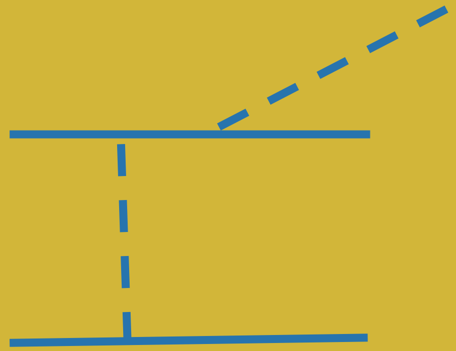
$\Rightarrow$ Electroweak baryogenesis, even if the phase transition is second order!
[Flores et al., Phys.Rev.D 108 (2023) 9, 9]

$\Rightarrow$ Defrosting and Blast Freezing Dark Matter
[Flores et al., Phys.Rev.D 108 (2023) 10, 10]

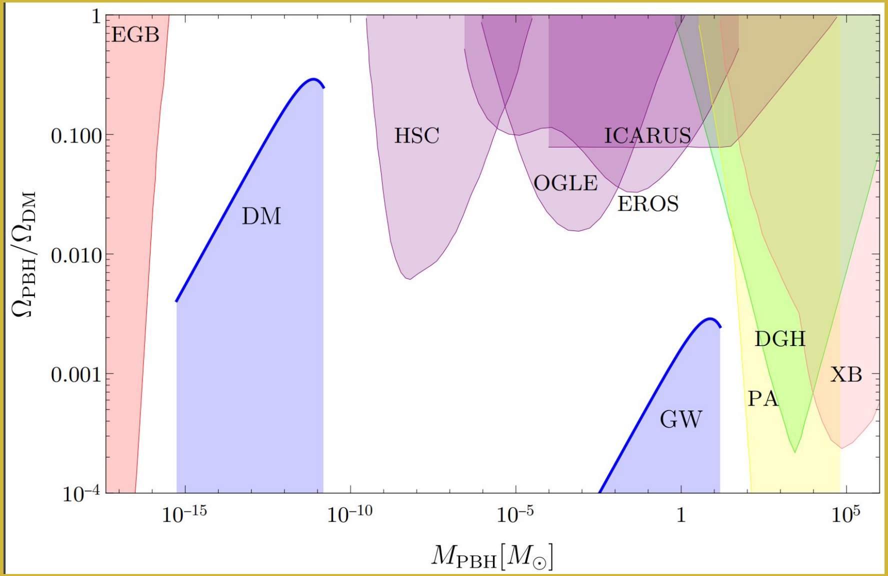
$\Rightarrow$ Magnetogenesis
[Durrer, AK, JCAP 11 (2023) 002; 2209.13313]

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:

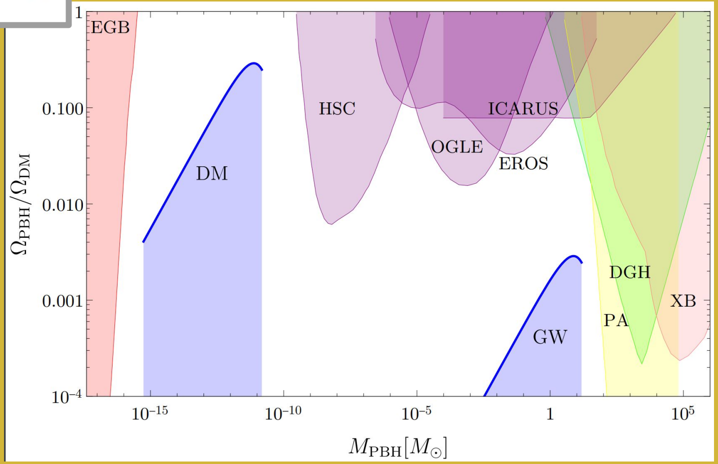
$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = 0.2 \frac{m_\psi}{m_p} \frac{\eta_\psi}{\eta_{\rm B}} = \left(\frac{m_\psi}{5\,{\rm GeV}}\right)\left(\frac{\eta_\psi}{10^{-10}}\right)$$

Similar to asymmetric dark matter [For reviews, see Zurek 1308.0338; Petraki, Volkas 1305.4939]

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

Natural explanation for the ratio

(dark matter density) / (ordinary matter density) for ~1-100 GeV masses



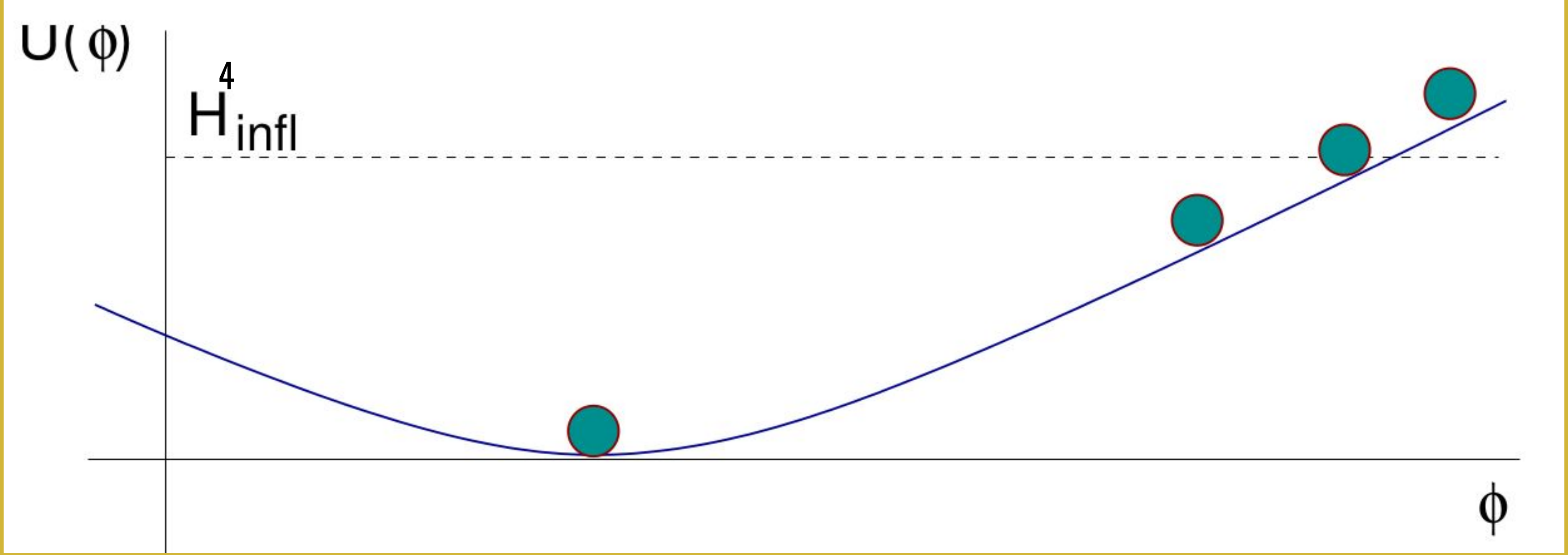
How to make PBHs

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

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

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]



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:

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

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

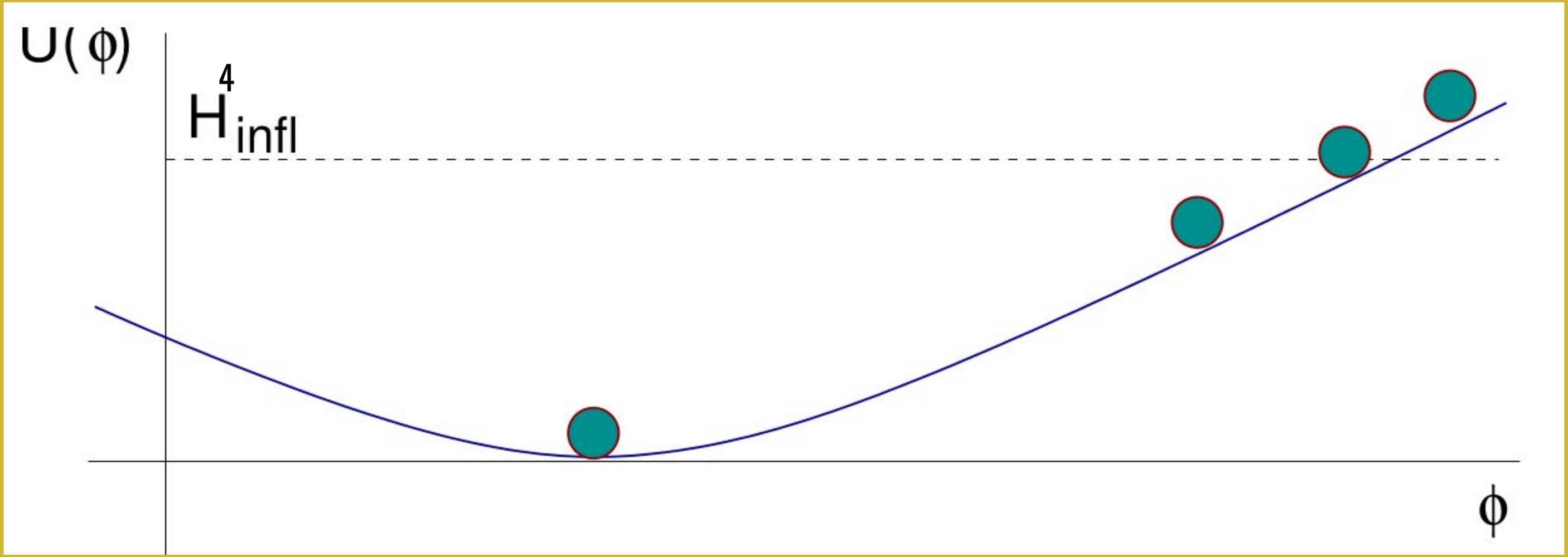
- Potential $V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4$

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

Starobinsky, Yokoyama, Phys.Rev.D 50 (1994) 6357

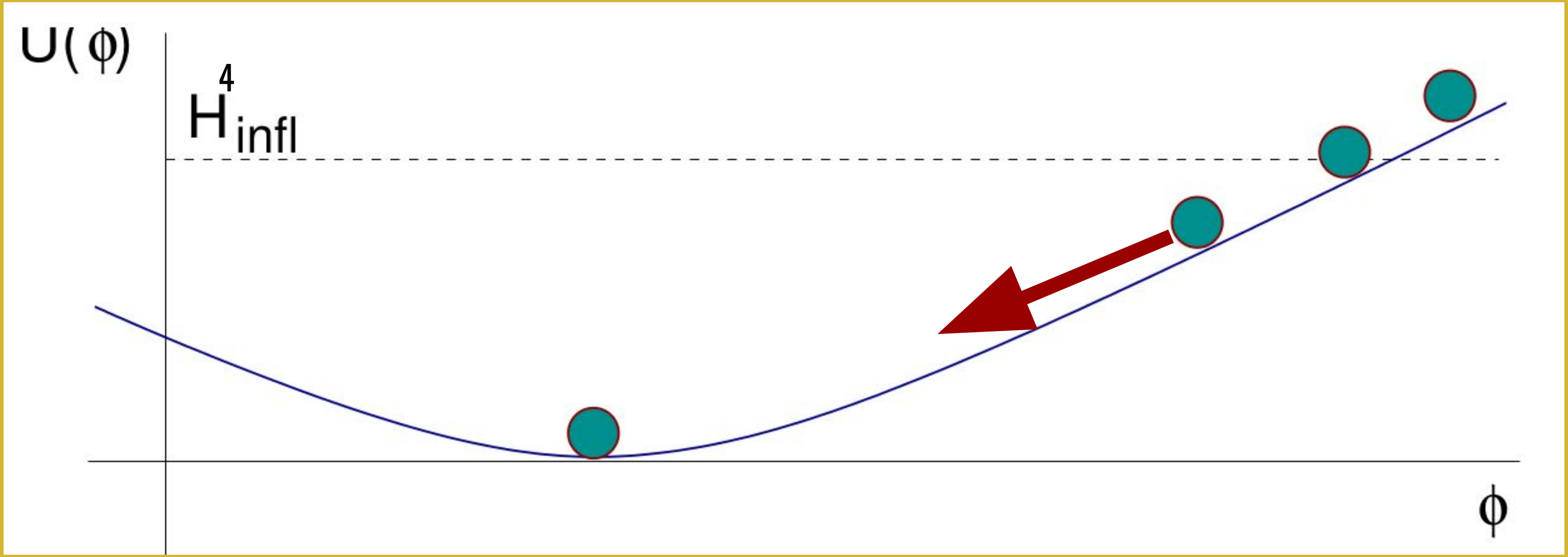
Scalar fields in de Sitter space (used by Affleck-Dine)

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



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]

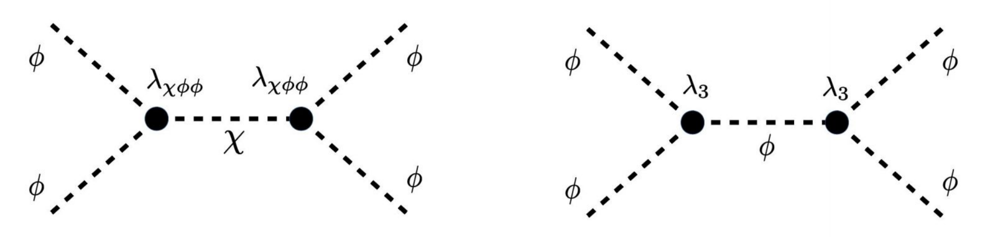


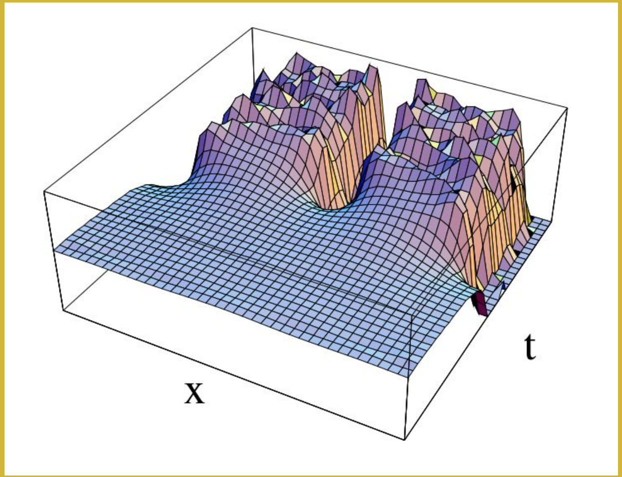
Scalar fields: an instability (Q-balls)

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

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

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





[AK, Shaposhnikov, hep-ph/9709492]

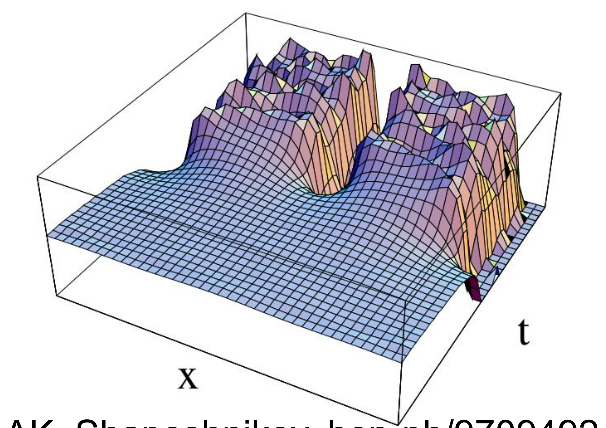
Scalar fields: an instability (Q-balls)

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

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

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

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



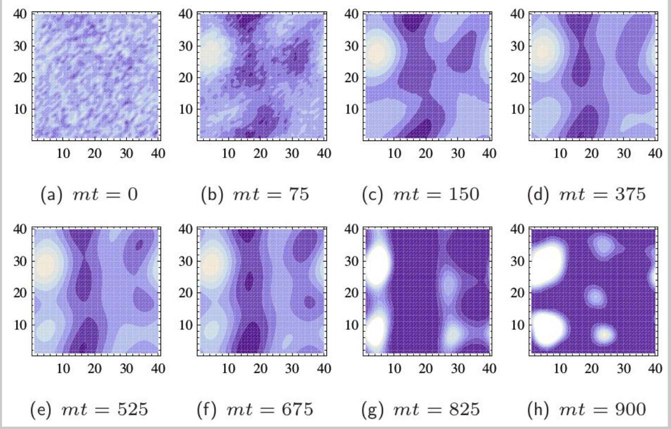
AK, Shaposhnikov, hep-ph/9709492

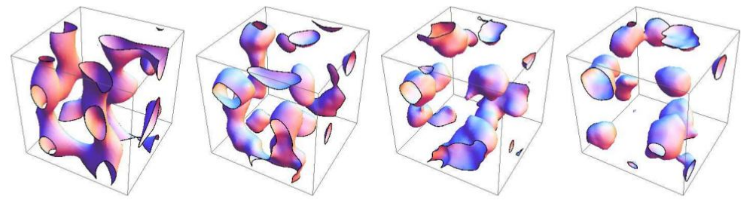
$(\dot{\Omega}^2 - U''(R)) > 0$ ⇒ growing modes: $0<k<k_{max}$

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

Also of interest: oscillons [Cotner, AK, Takhistov, 1801.03321]

Numerical simulations of scalar field fragmentation

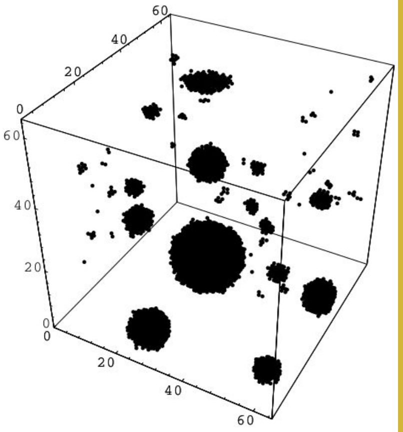




(i) $mt = 900$ (j) $mt = 1050$ (k) $mt = 1200$ (l) $mt = 1350$

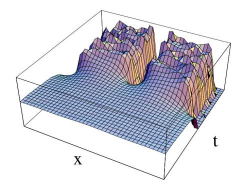
[Multamaki].

SUSY Q-balls



[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

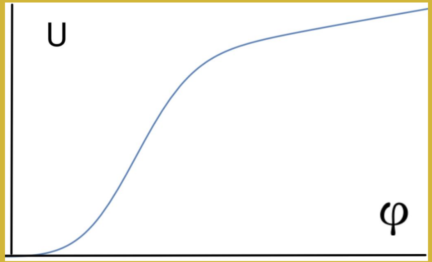
matter dominated

$p=0$

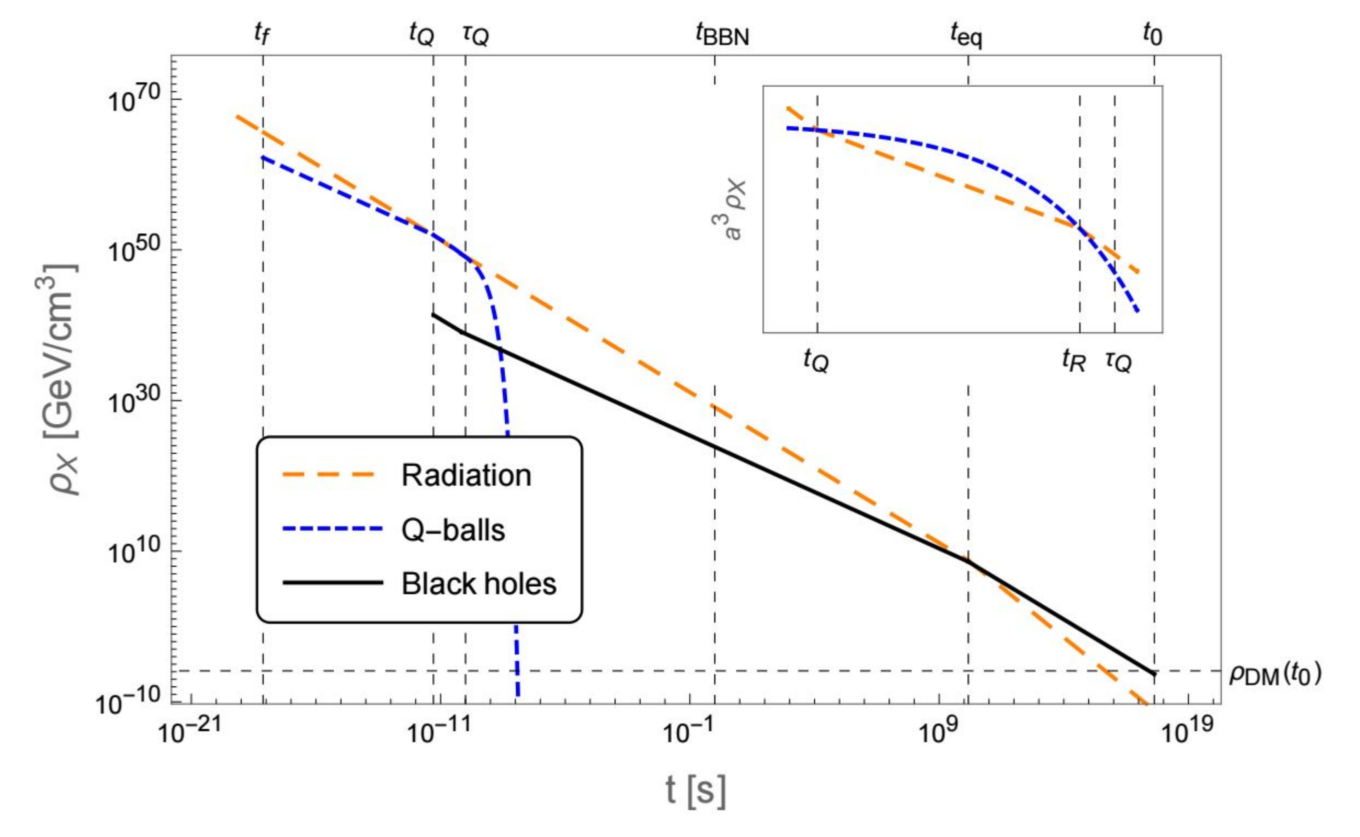
$\rho \propto a^{-3}$

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

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

Affleck-Dine process and scalar fragmentation in SUSY

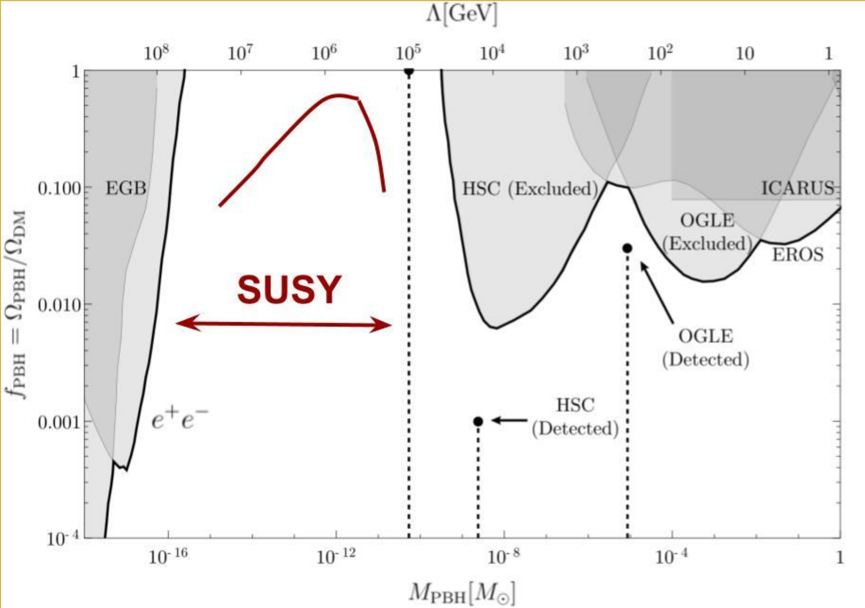
[Cotner, AK, Sasaki, Takhistov et al.,1612.02529, 1706.09003, 1801.03321, 1907.10613]

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

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

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

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



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

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

PBH and neutron stars

Image: AK + AI

- 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]

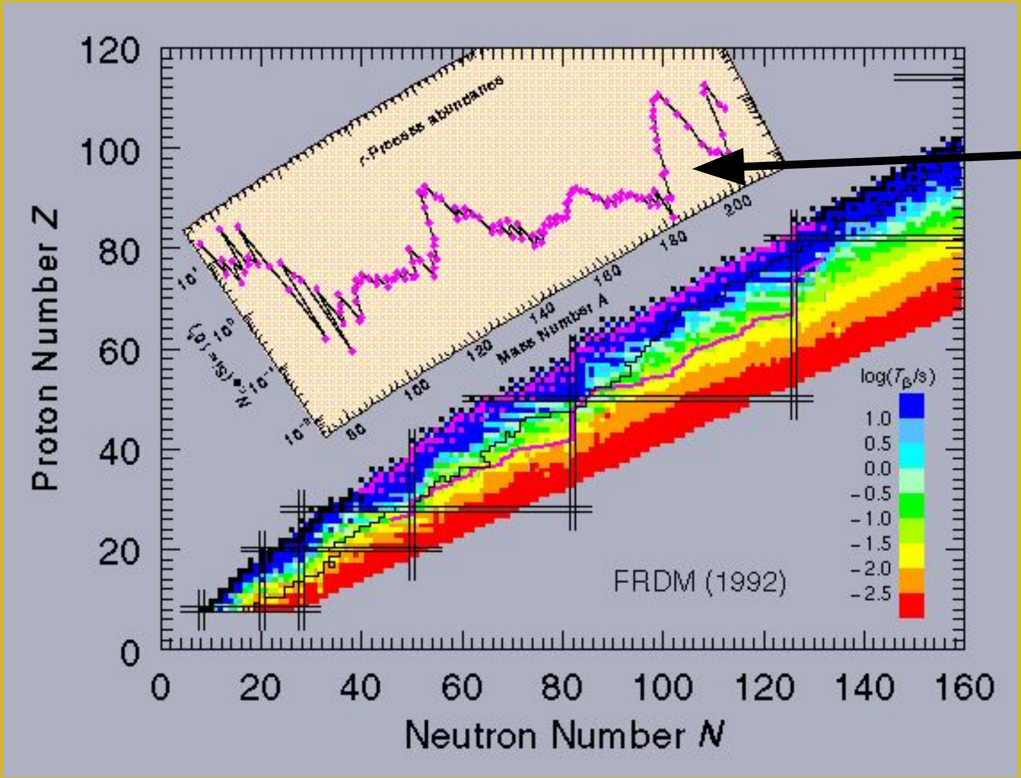
MSP spun up by an accreting PBH

r-process material

- 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



- 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

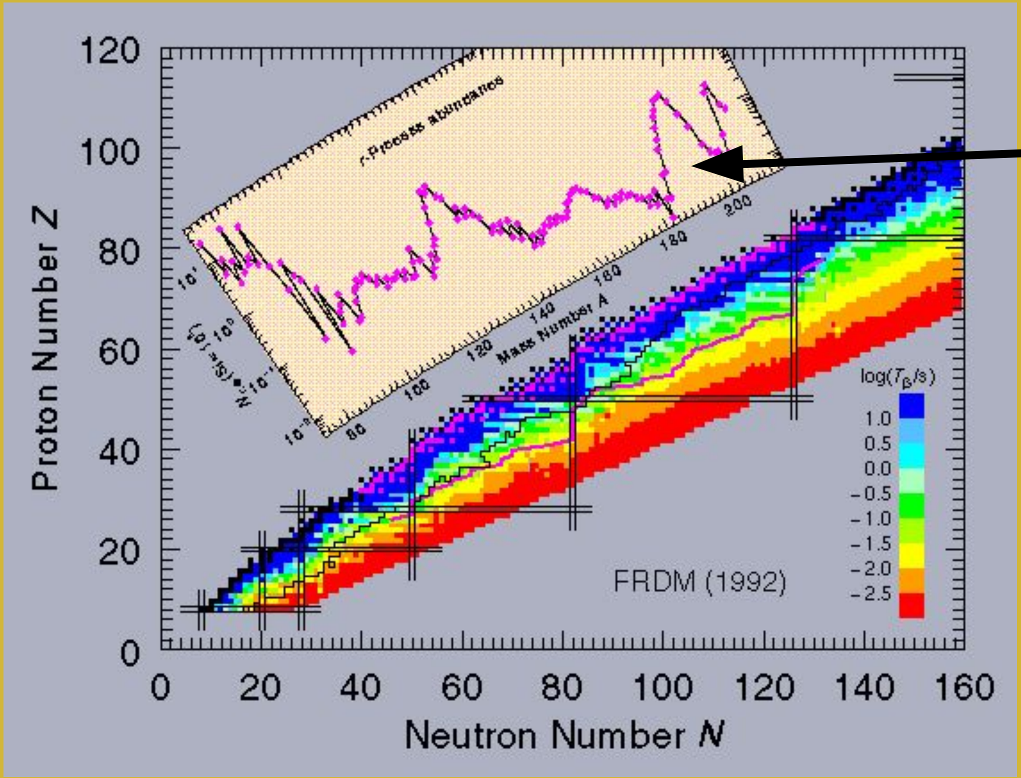
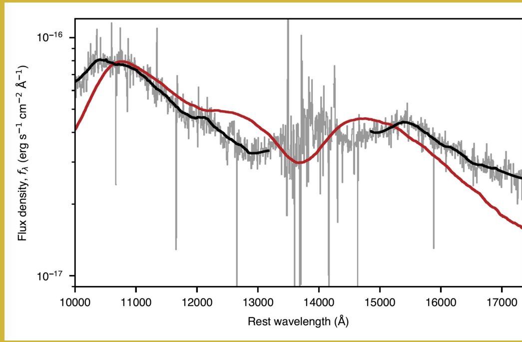


Image: Los Alamos, Nuclear Data Group

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



NS-NS may 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.

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

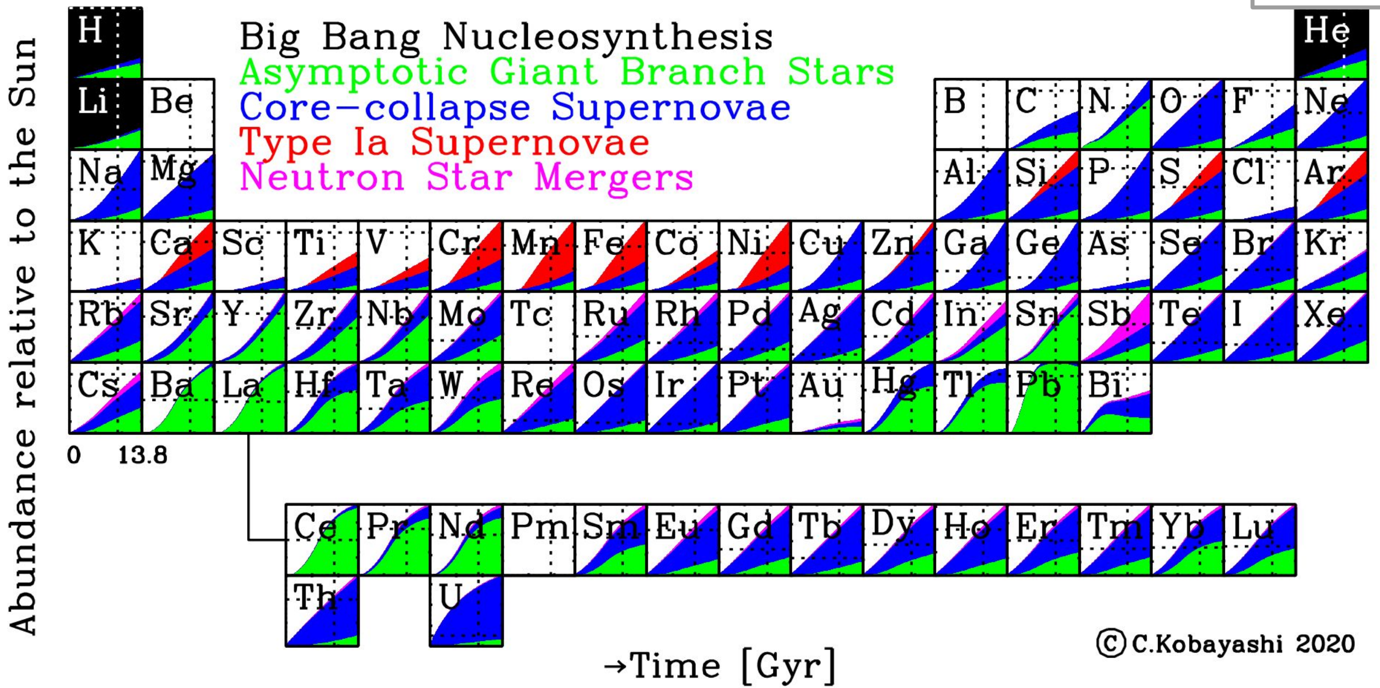


Figure 39. The time evolution (in Gyr) of the origin of elements in the periodic table: Big Bang nucleosynthesis (black), AGB stars (green), core-collapse supernovae including SNe II, HNe, ECSNe, and MRSNe (blue), SNe Ia (red), and NSMs (magenta). The amounts returned via stellar mass loss are also included 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): **$M \sim 10^4\ M_\odot$**

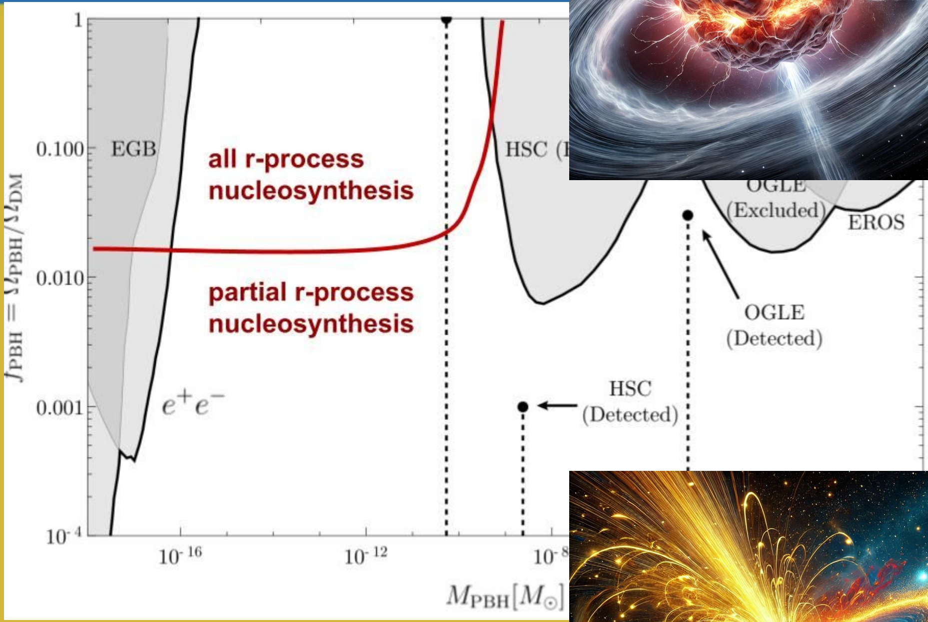
Ultra Faint Dwarfs (UFD): most of UFDs show no enhancement of r-process abundance.

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: **$M \sim 10^4\ M_\odot$** ✔
- 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

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

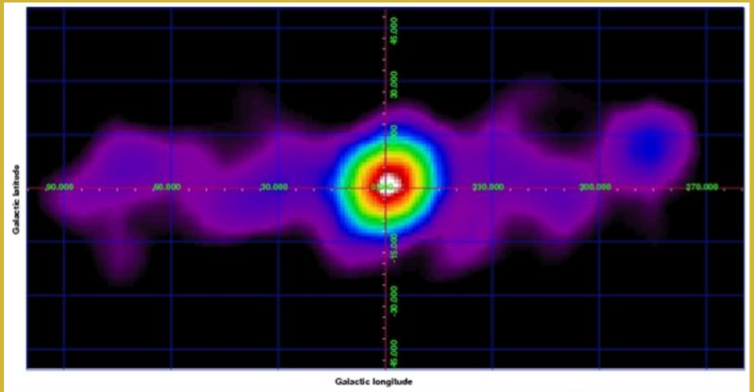
Image credit: AK + AI

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.

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

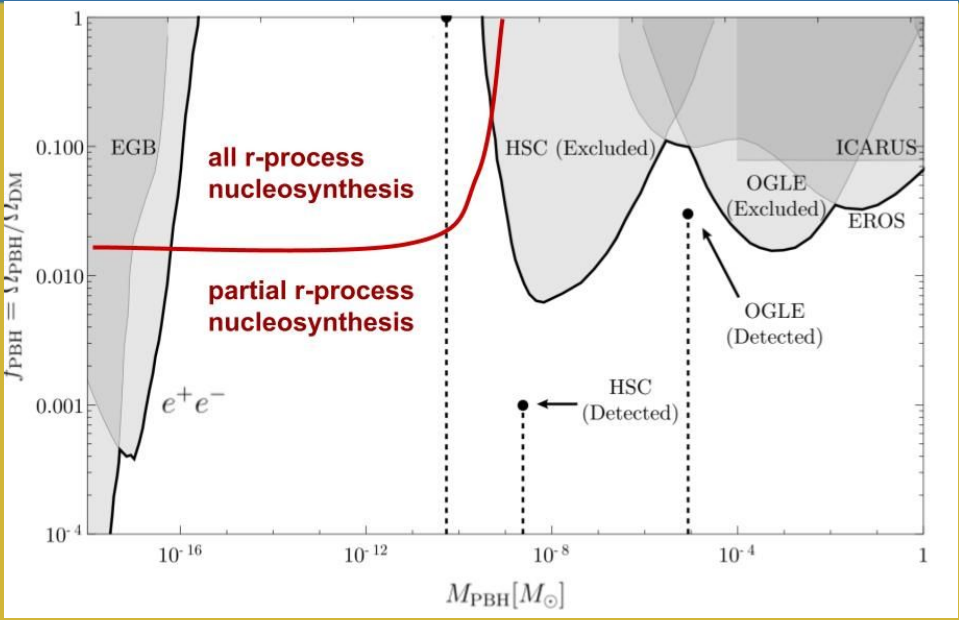
Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101

Smoking gun signature:

- Kilonova event without a GW counterpart, but with a possible coincident FRB (Vera Rubin Observatory, ZTF,...)
- Weak/different GW signal
- No significant neutrino emission
- Fast Radio Burst
- 511 keV line

⇒ neutron star was disrupted by something other than NS-compact star merger

⇒ **PBH dark matter (or another exotic scenario)**



[Fuller, AK, Takhistov, PRL 119 (2017) 061101]
also, a *Viewpoint* PRL article by Hans-Thomas Janka

GW detectors can discover small PBH from NS->BH process

PBH + NS

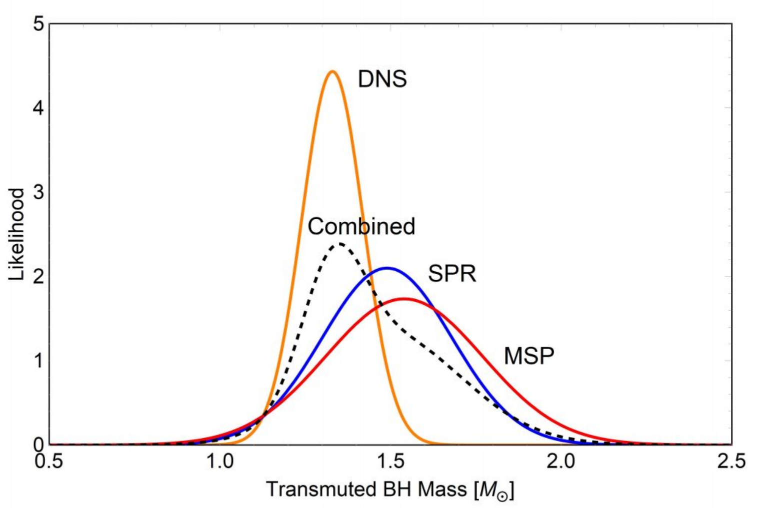
⇓

BH of 1-2 $M_\odot$

...if it detects mergers of

1-2 $M_\odot$ black holes

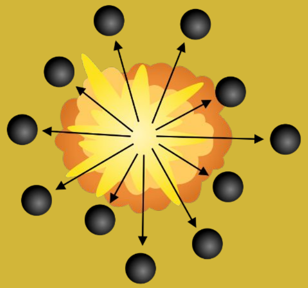
(not expected from evolution of stars)



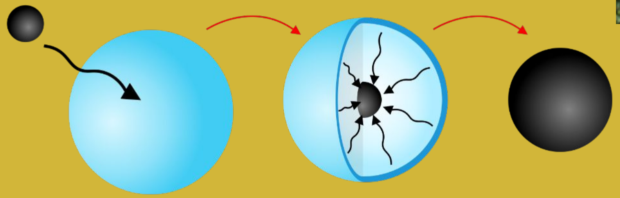
Fuller et al., PRL 119 (2017) 6, 061101 [1704.01129]
Takhistov et al., 1707.05849, 2008.12780

G objects: remnants of NS to BH conversions?

1. Primordial black holes produced in Big Bang make up part or all of dark matter.



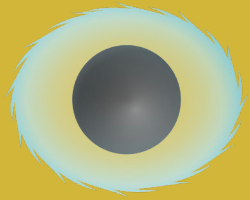
2. A microscopic black hole falls into a neutron star, eats it from the inside, and creates a 1-2 solar mass black hole



Flores, AK, Ghez, Naoz, 2308.08623

3. A 1-2 solar mass black hole, surrounded by a gaseous atmosphere, is observed in the vicinity of the supermassive black hole at the galactic center as a G-object. The small black hole's gravity holds the gas together and protects the G-object from being torn apart by the gravitational pull of the supermassive black hole.

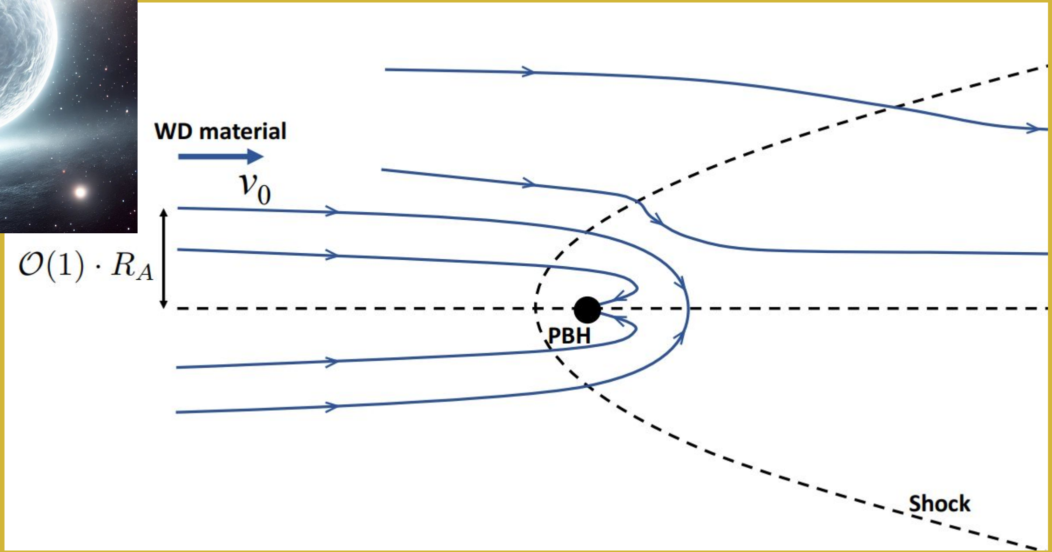
Supermassive black hole



Small black hole surrounded by gas

White dwarfs ignited by a PBH ⇒Type Ia supernova

Murayama, Leung, Nomoto, AK, work in progress



Montero-Camacho et al., 1906.05950

Happy birthday to Director of the Universe!

From brilliant physics – to leading P5,
His mind endeavors, so science may thrive.
His ideas are bold, his talents diverse –
Hitoshi, Director of the Universe!

Credits: AK+AI