# Primordial black holes as dark matter

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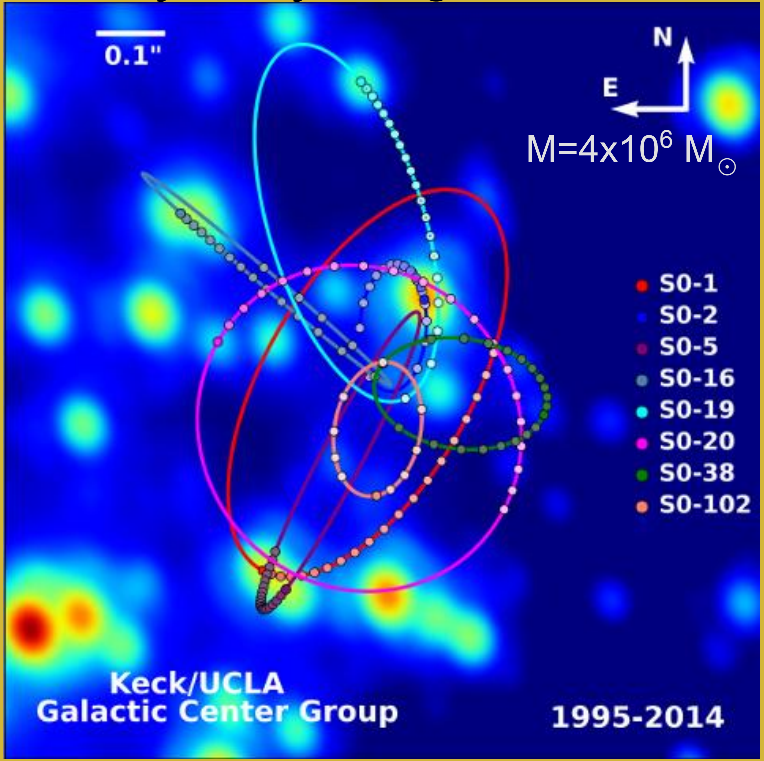
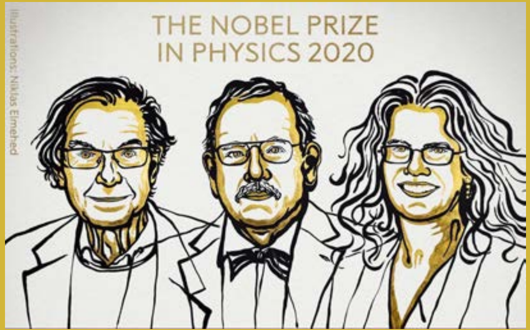
Supported by U.S. DOE Office of Science (HEP) and WPI, Japan

# Nobel Prize 2020: Black holes' existence confirmed

Milky Way, Sagittarius A*



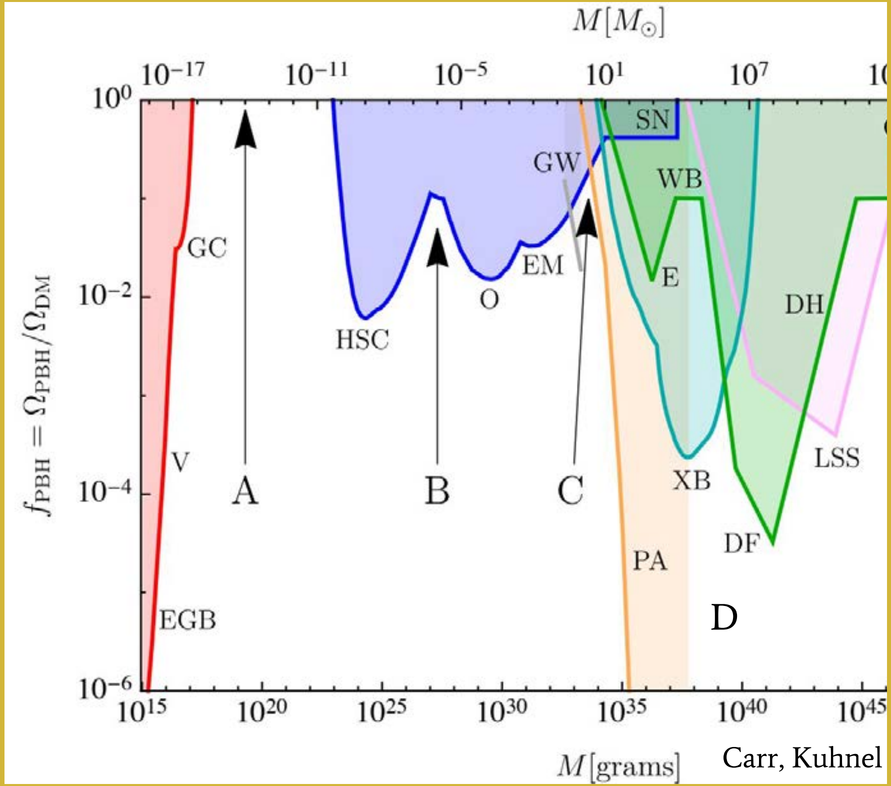

**R. Penrose**
**R. Genzel**
**A. Ghez**




Observations: BHs exist!

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

# Experimental constraints



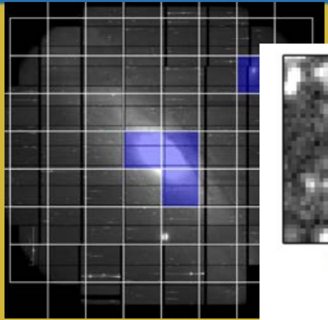

**A - Dark matter**

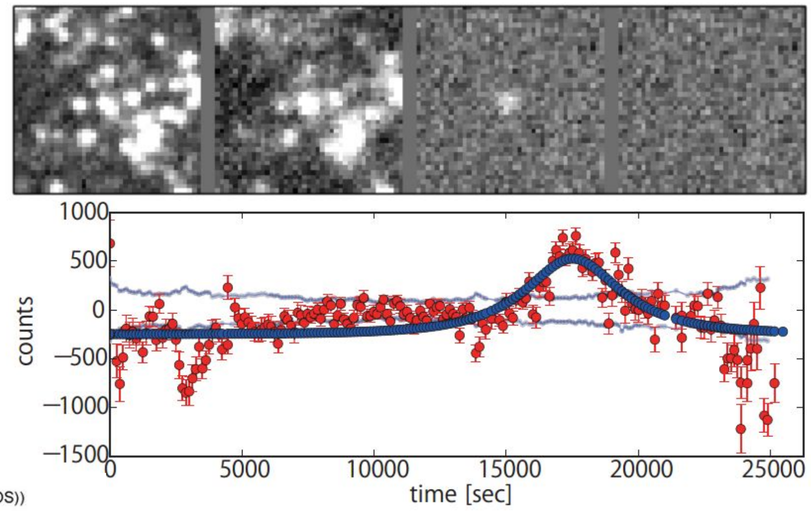
B - candidate events from HSC, OGLE [1701.02151, 1901.07120]

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

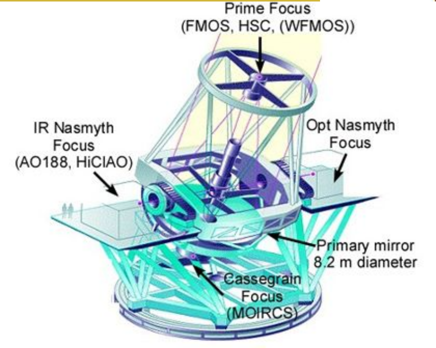
D - seeds of supermassive black holes [astro-ph/0204486, arXiv:1202.3848, 2008.11184, 2312.15062]

# First candidate events





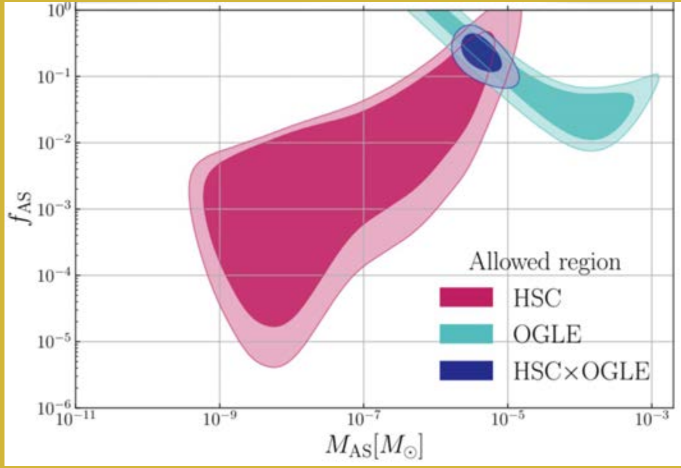

3. One remaining candidate that passed all the selection criteria of
sing event. The images in the upper plot show the postage-stamped
round the candidate as in Fig. 7: the reference image, the target im-
ifference image and the residual image after subtracting the best-fit
e, respectively. The lower panel shows that the best-fit microlensing
es 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 ~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

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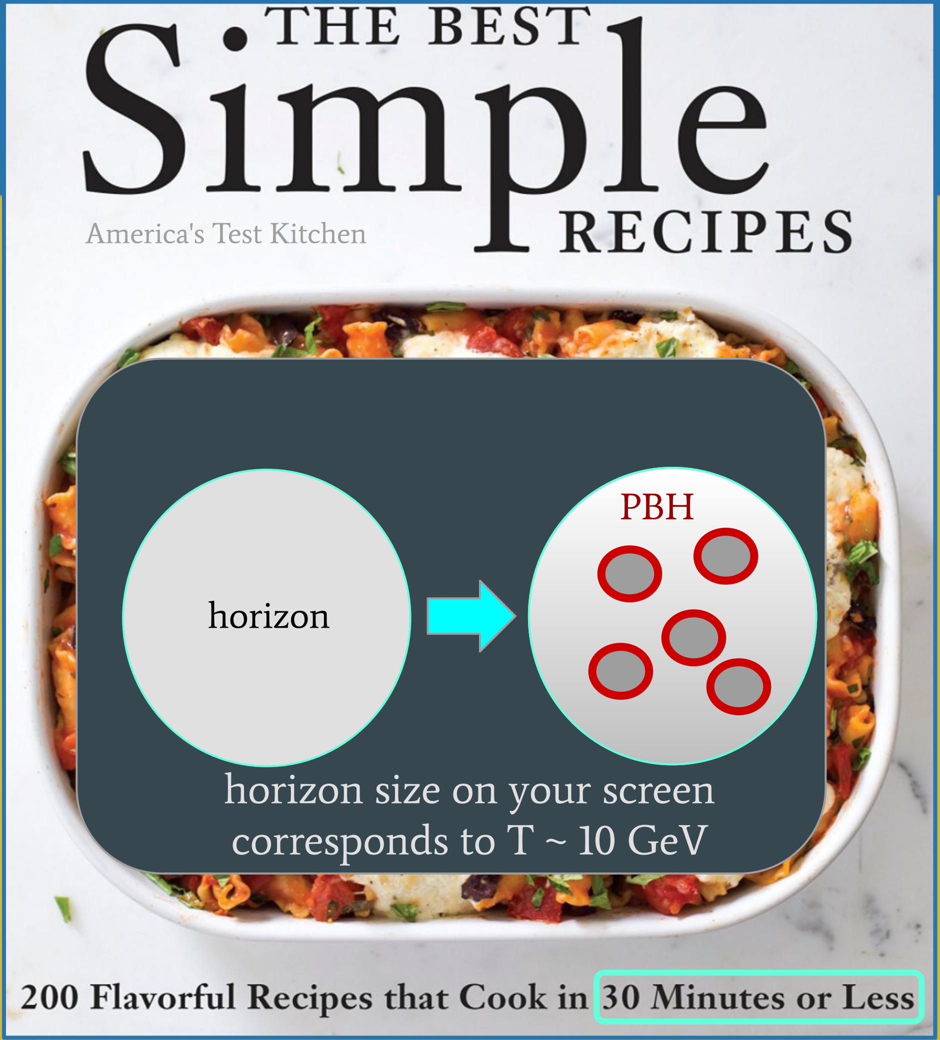


# PBH formation mechanism: Yukawa "fifth force"

**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]

# 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

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

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

$\Rightarrow$

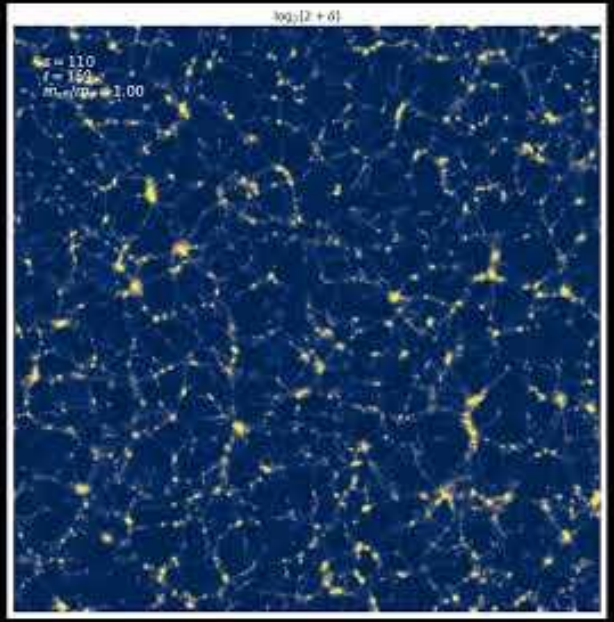
$$\Delta_k(a) \approx \Delta_{k,\mathrm{in}}\left(\frac{t}{t_{\mathrm{in}}}\right)^{p/2}, \quad p = \sqrt{\frac{3}{2}(1+\beta^2)\Omega_\psi}$$

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

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

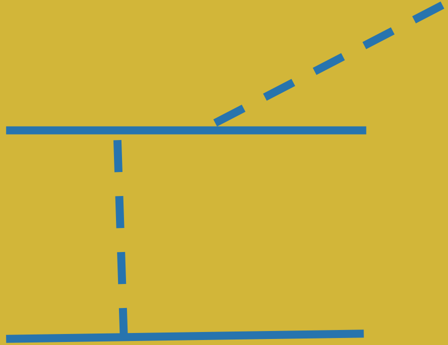


N-body simulation of the structure growth from Yukawa interactions

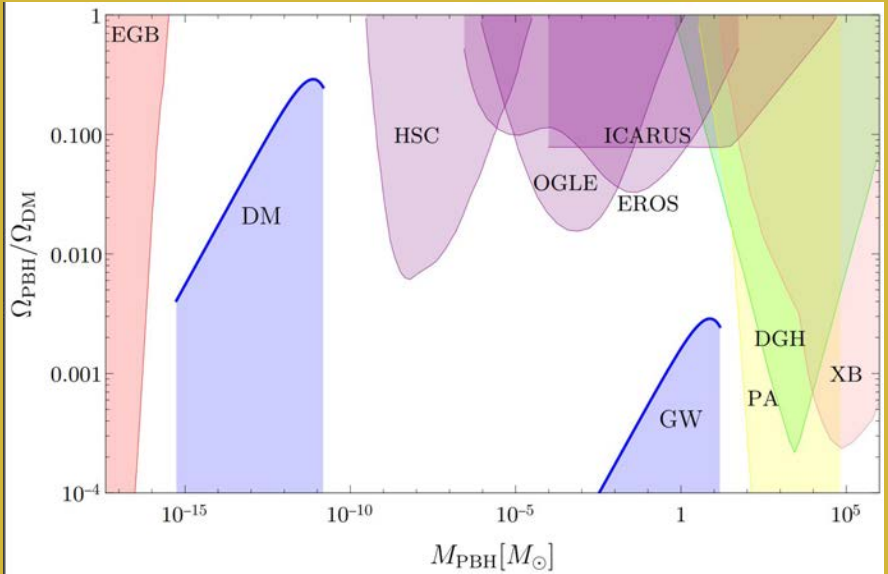
Domenech, Inman, Sasaki, AK [2304.13053]

# 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 $m_\psi$~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:

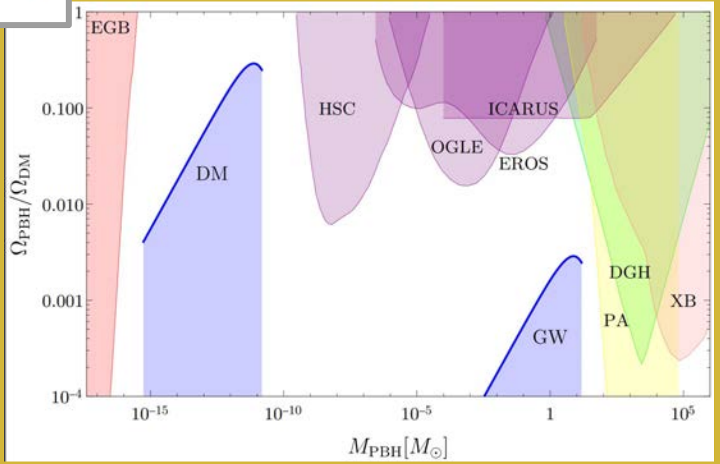
**Similar to asymmetric dark matter**

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

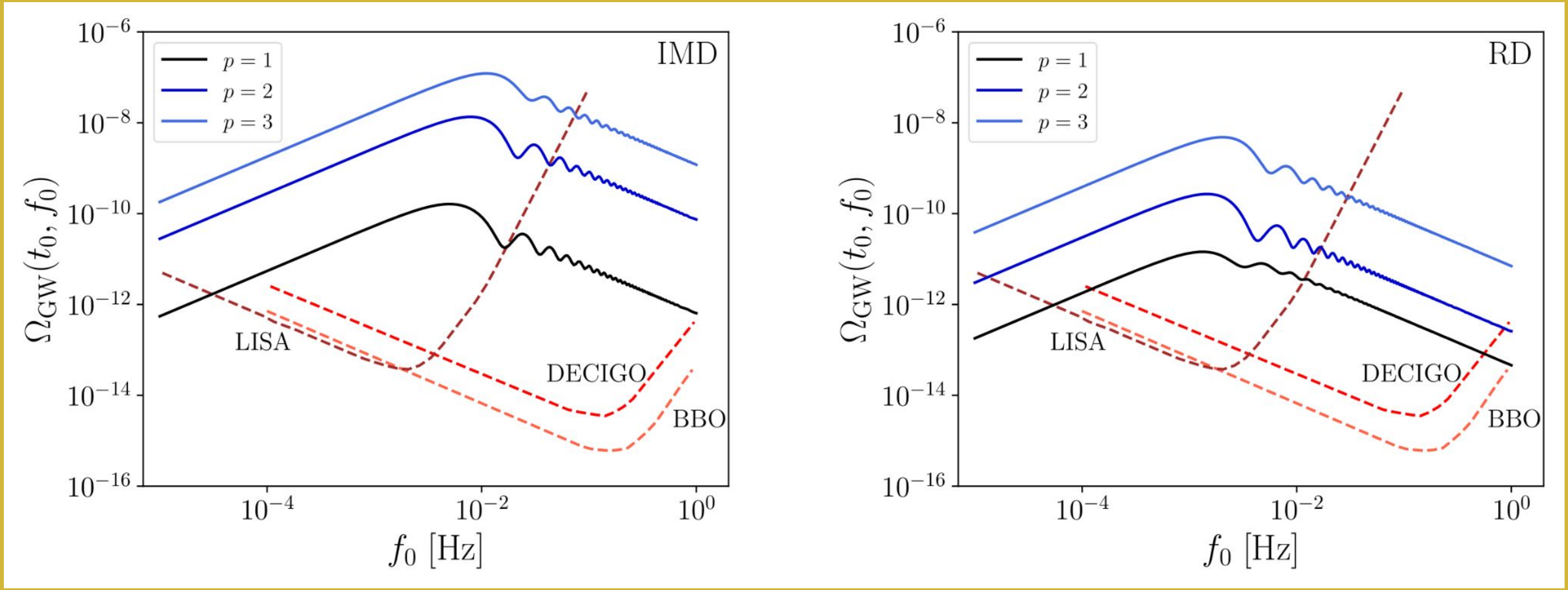
[Flores, AK, 2008.12456, PRL 126 (2021) 041101]

Natural explanation for the ratio

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



# Gravitational waves from early halo formation




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

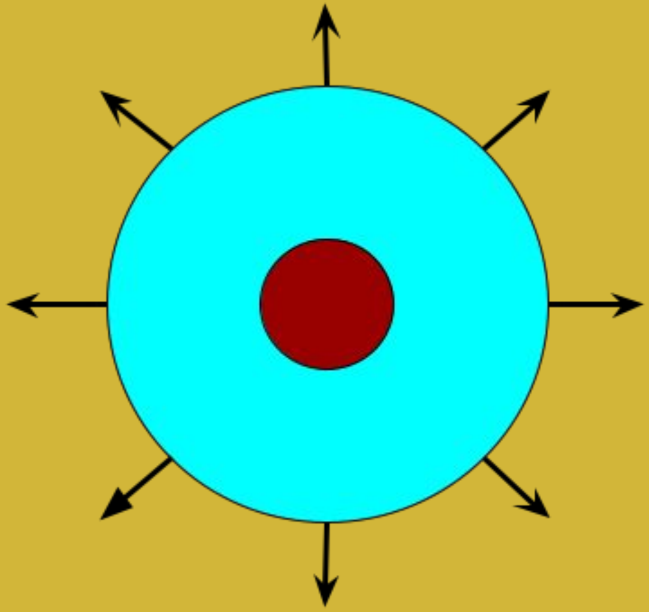
# Other possible consequences of early halo formation

## Structure formation in RD era! Many possible consequences

| | | |
|---|---|---|
| Inhomogeneous heating by collapsing halos | $\Rightarrow$ | Electroweak baryogenesis, even if the phase transition is second order! [Flores, AK, Pearce, White, 2208.09789] |
| Inhomogeneous heating by collapsing halos | $\Rightarrow$ | Magnetogenesis [Durrer, AK, 2209.13313] |

# Side note: inhomogeneous cold electroweak baryogenesis

Halos of fermions form -> annihilate -> heat SM plasma inhomogeneously -> departure from thermal equilibrium $t \sim t_{\text{fireball exp}}$



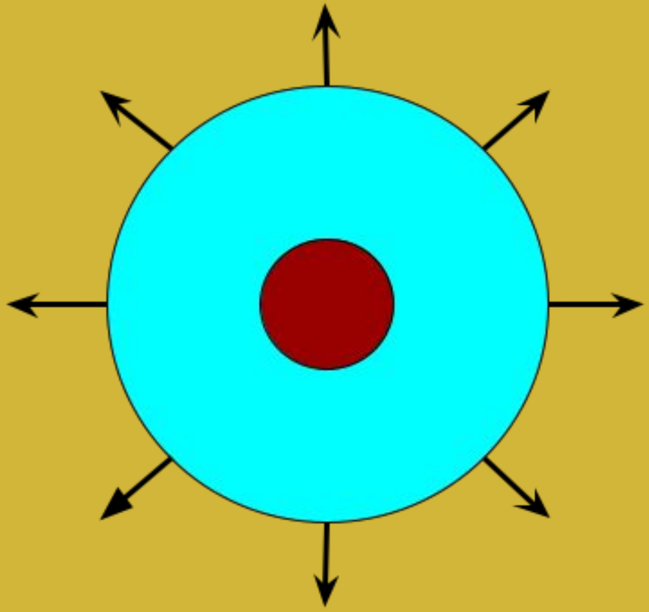
**Baryogenesis**

- **without a first-order PT**
- **at low temperature (10 MeV < T < 100 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 -> annihilate -> heat SM plasma inhomogeneously -> 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]

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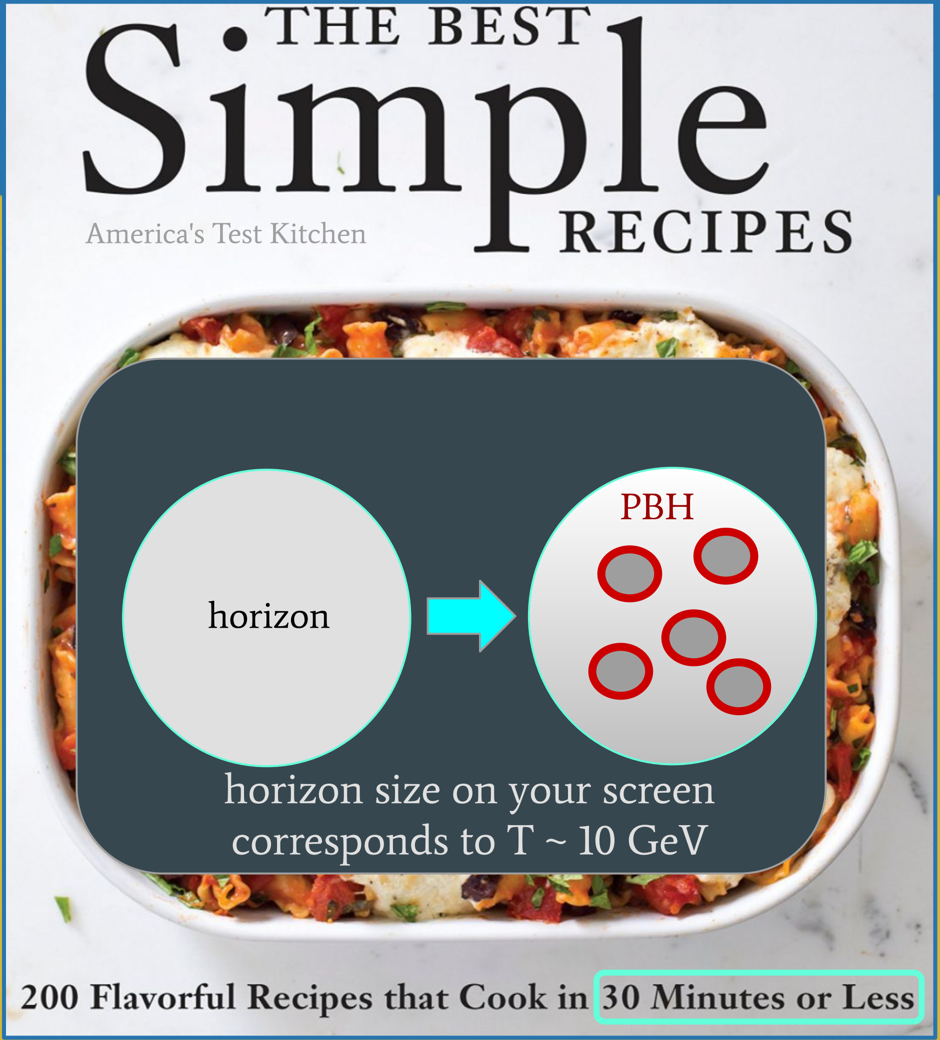
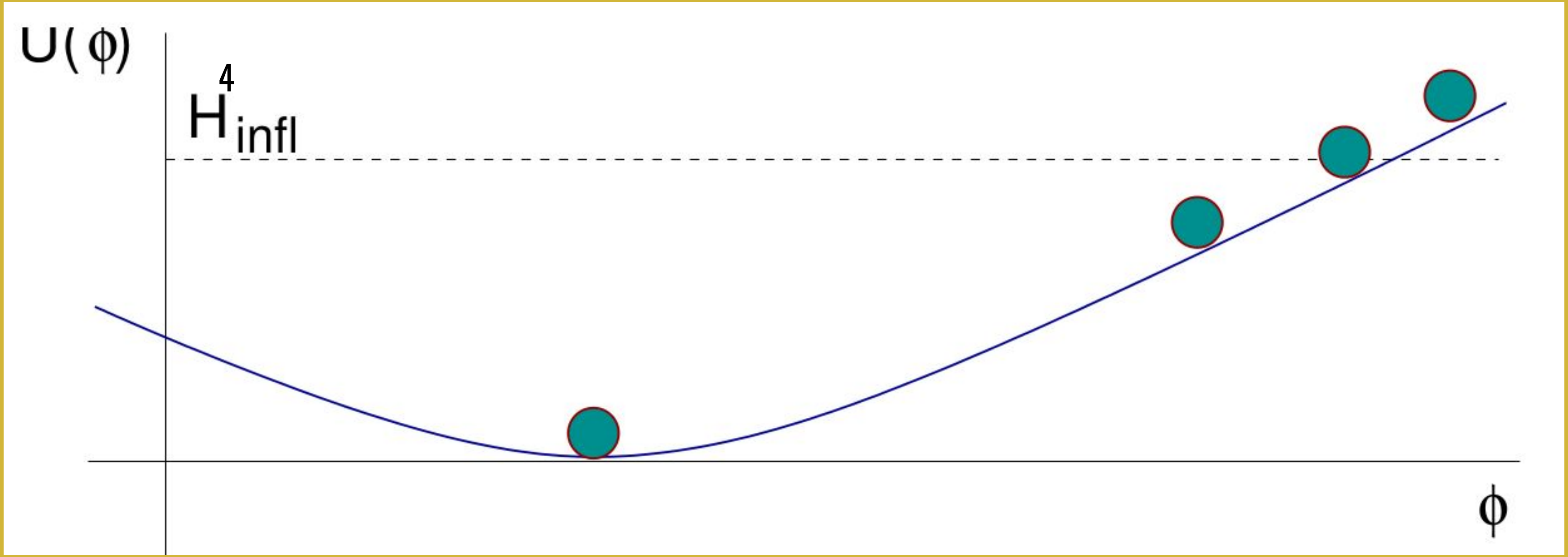


# Scalar fields in de Sitter space (used by Affleck-Dine)

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



# Scalar fields in de Sitter space during inflation

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

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

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

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

- 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

# Supersymmetry breaking in expanding universe

Flat directions: $\mathbf{V(\varphi) = 0}$ guaranteed by SUSY

Nonzero energy density $\Rightarrow$ SUSY breaking

During inflation, the energy density $\Lambda$ alters the flat direction potential by terms of the order $\boldsymbol{\delta V \sim c\,(\Lambda^4/M_{Pl}^2) \sim c\,H^2\varphi^2}$

If $\mathbf{c < 0}$, the min of $\mathbf{V(\varphi)}$ is shifted.

Two effects: (1) the min of V is at a large $\varphi$, ***not*** $\varphi=0$

(2) $\varphi$ is ***not*** at the minimum of $V(\varphi)$

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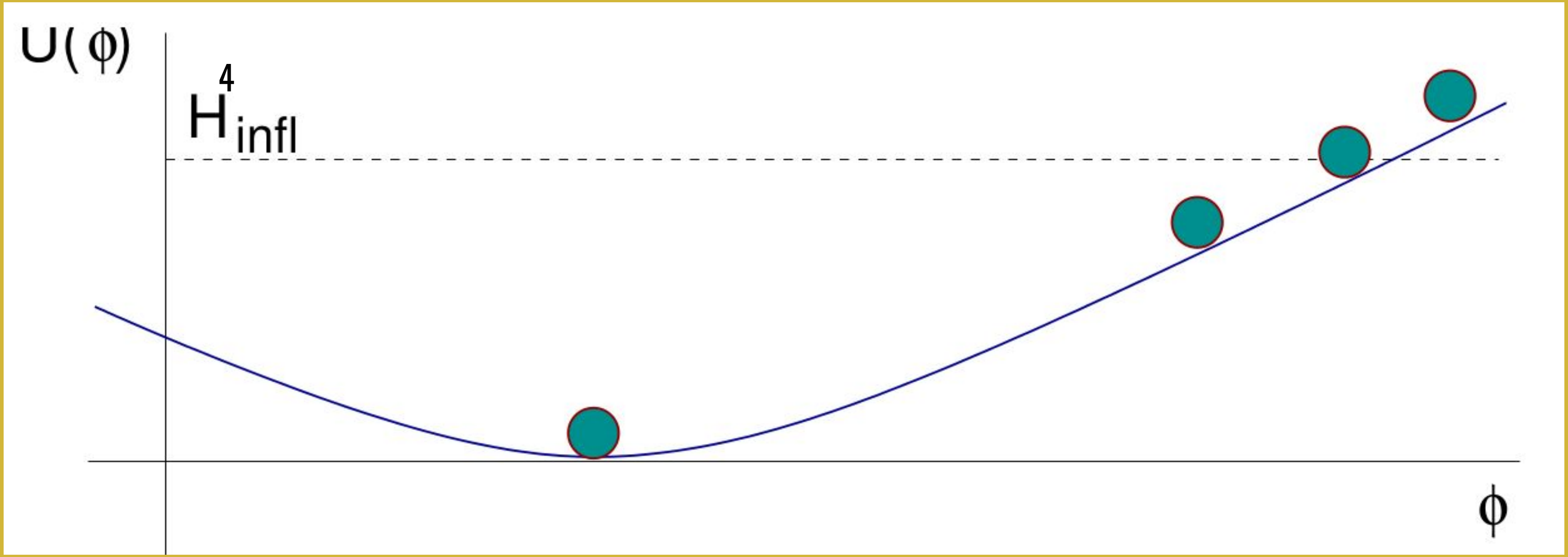

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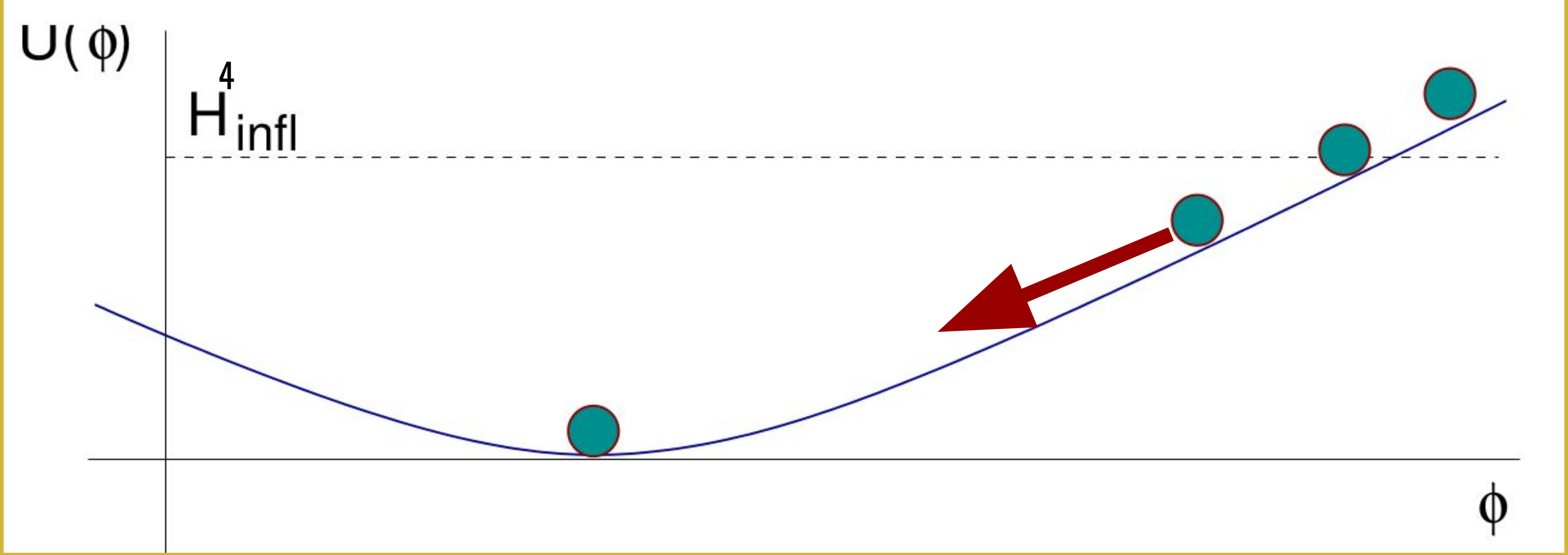
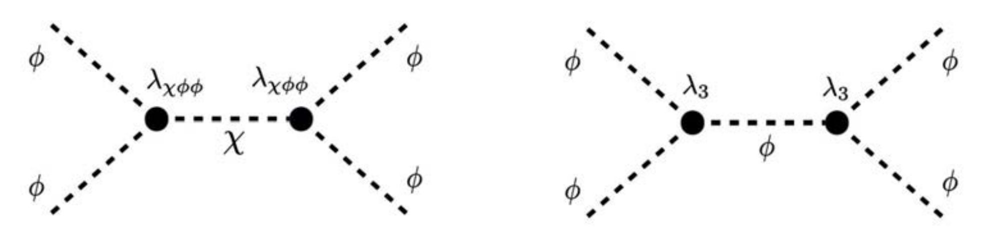


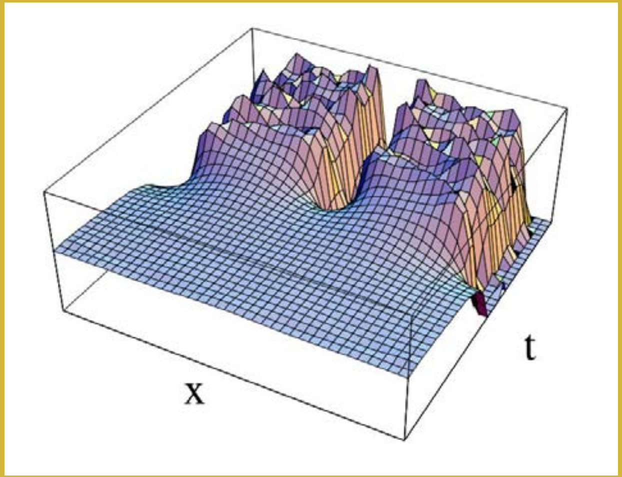
# Scalar fields: an instability (Q-balls)

**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]

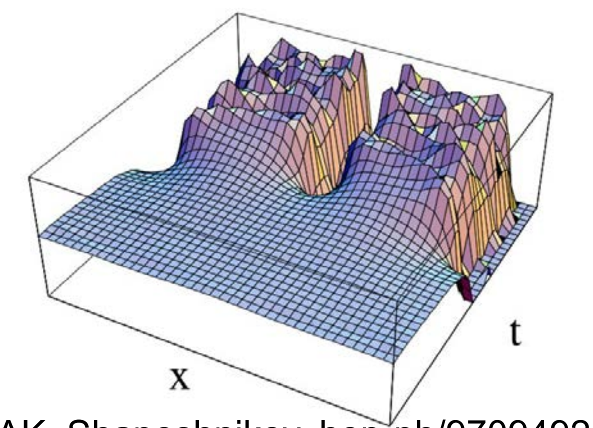
# Scalar fields: an instability (Q-balls)

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

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

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

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



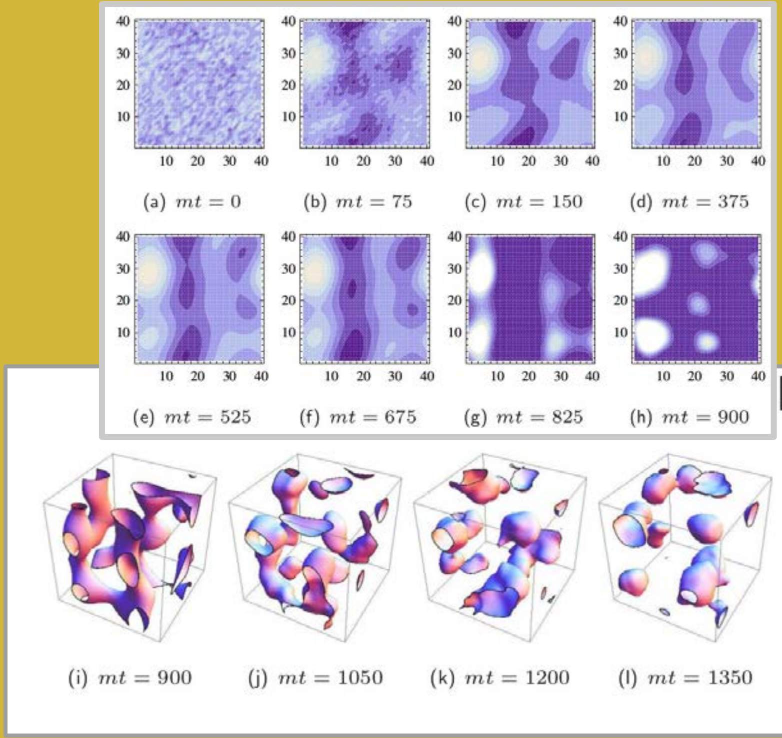

AK, Shaposhnikov, hep-ph/9709492

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

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

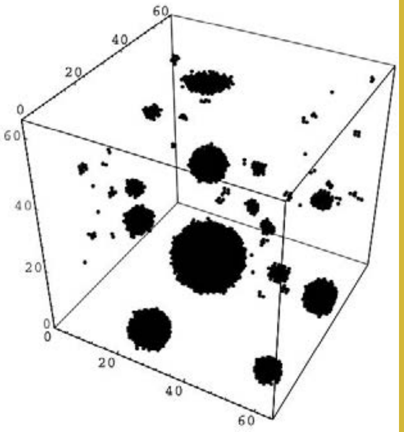
**Also of interest: oscillons [Cotner, AK, Takhistov, 1801.03321]**

# Numerical simulations of scalar field fragmentation



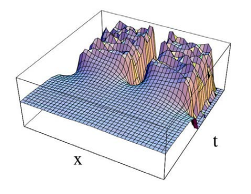

[Multamaki].

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

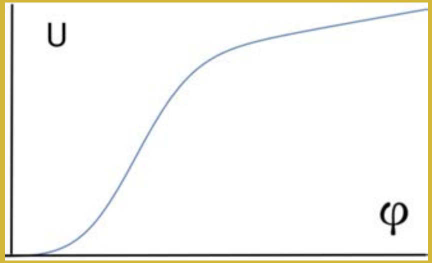
matter dominated

$p=0$

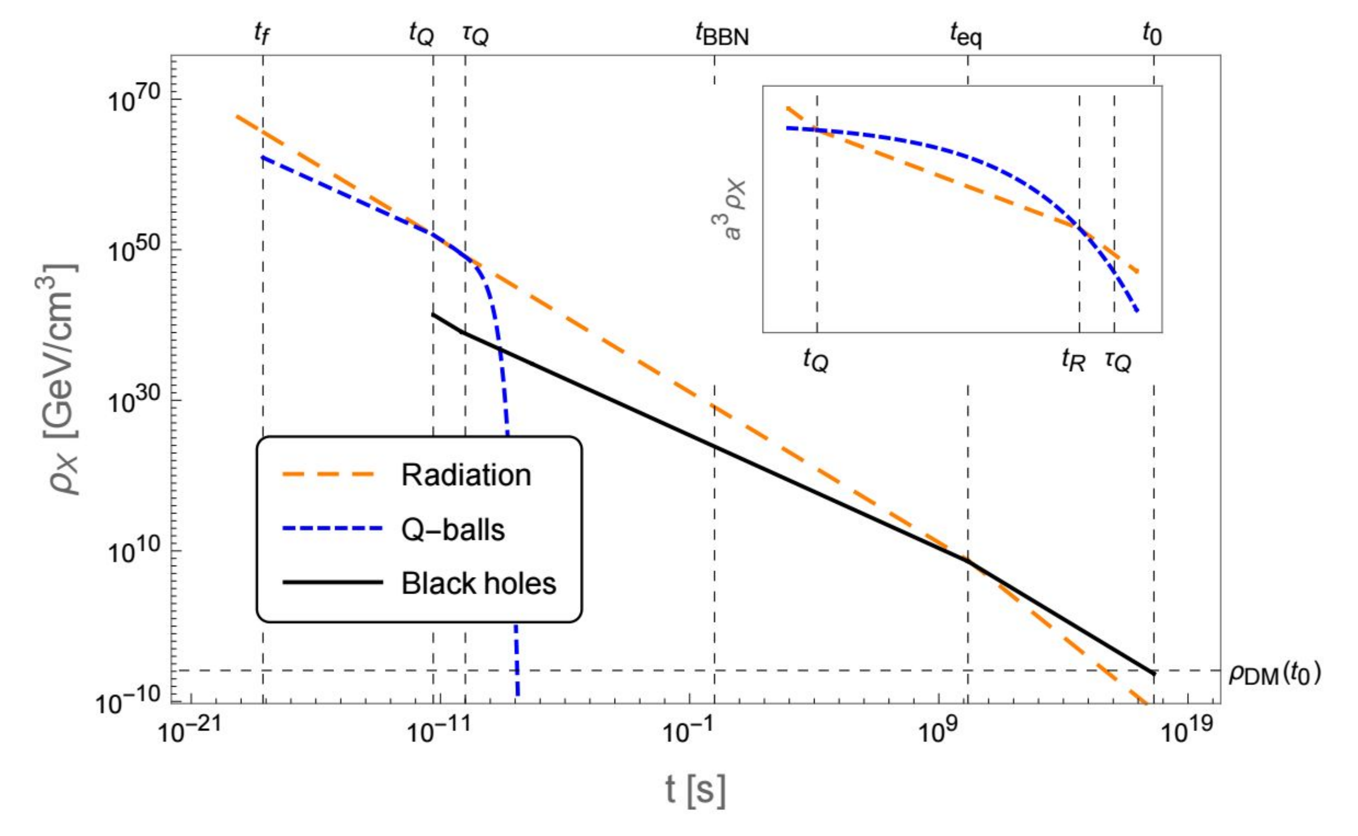
$\rho \propto a^{-3}$

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

# Size of “particles” affects Poisson fluctuations

many small particles ⇒
small (poisson) fluctuations

few GIANT PARTICLES⇒
LARGE POISSON FLUCTUATIONS

# Affleck-Dine process and scalar fragmentation in SUSY

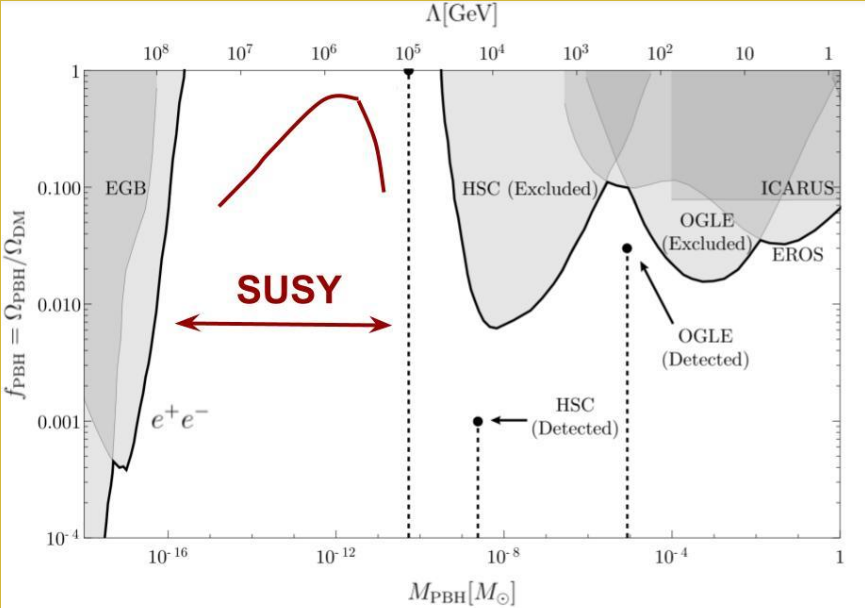
[Cotner, AK, Sasaki, Takhistov et al.,1612.02529, 1706.09003, 1801.03321, 1907.10613]

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

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

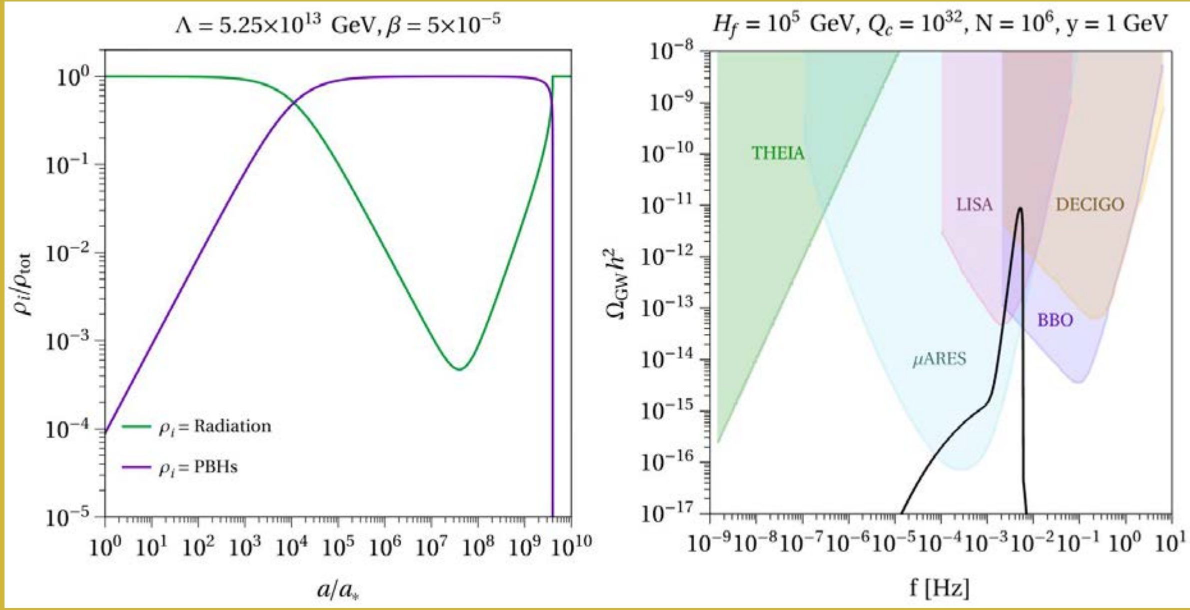
$$M_{\mathrm{hor}} \sim r_f^{-1}\left(\frac{M_{\mathrm{Planck}}^3}{M_{\mathrm{SUSY}}^2}\right) \sim 10^{23}\mathrm{g}\left(\frac{100\ \mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$

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



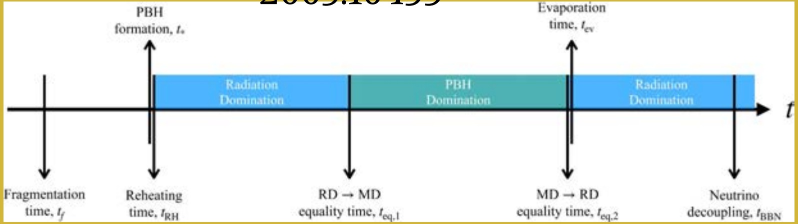

Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103
Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019) 077

# Gravitational waves





Inomata et al.,1904.12879, 2003.10455




Flores, AK, Pearce, Perez-Gonzalez, White, 2308.15522

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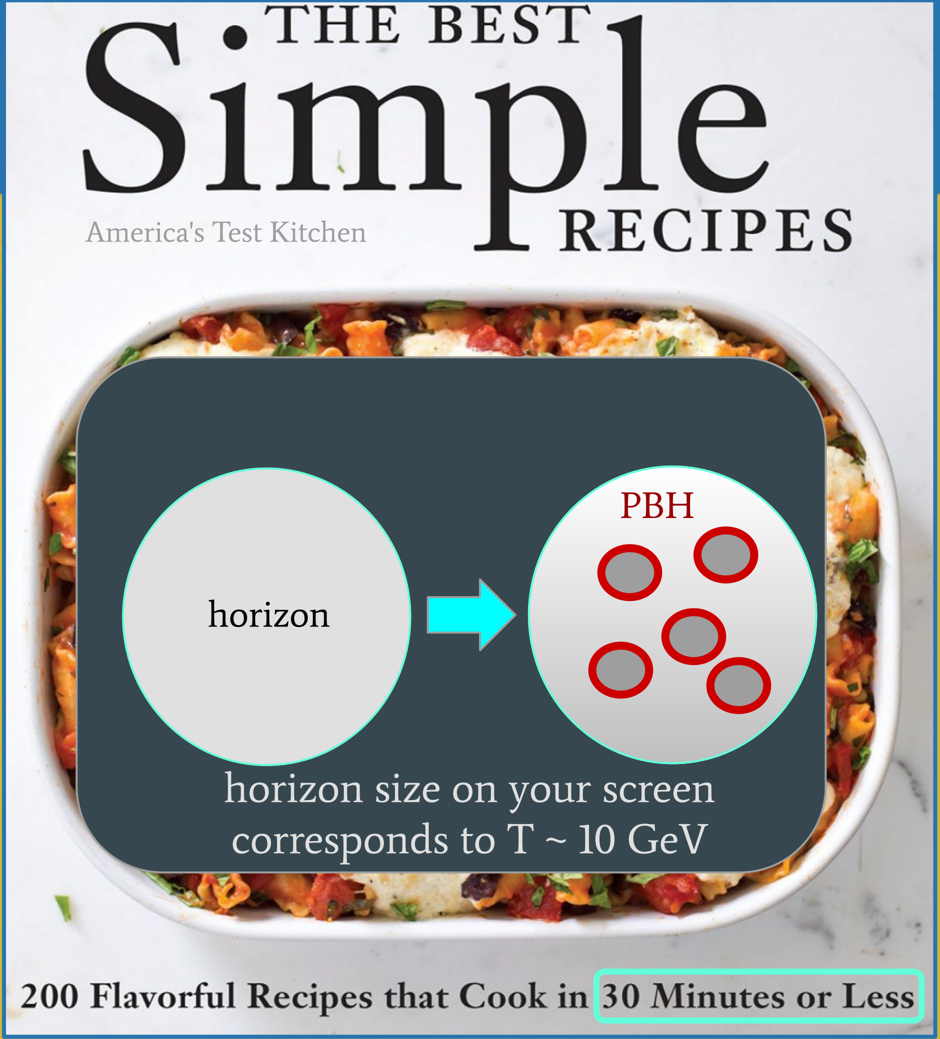


# Yet another way to get PBHs from SUSY: long-range forces

A SUSY flat direction $\varphi$ can couple to another SUSY scalar, $\chi$, which can mediate long-range forces between SUSY Q-balls, leading to Yukawa long-range potential

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

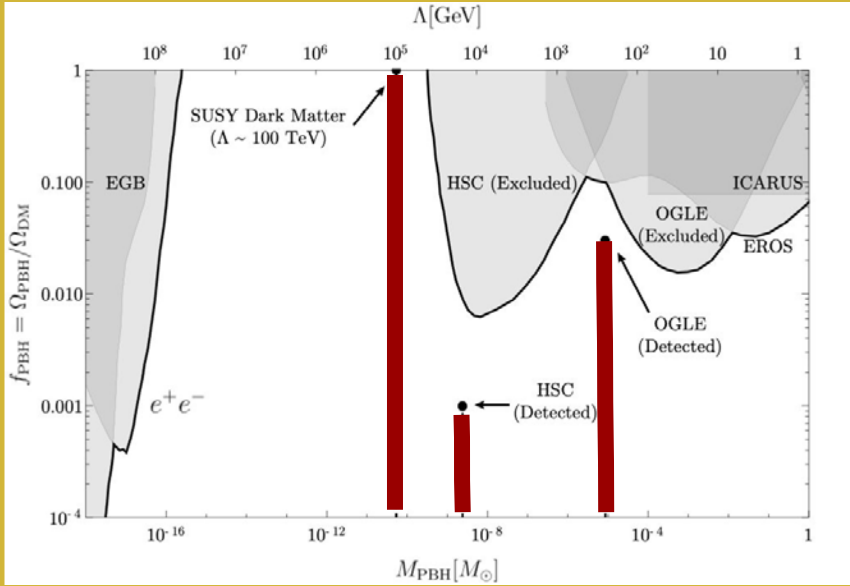
Long-range forces work as in the case of Yukawa interaction but **individual Q-balls** grow until they reach the mass/size of a BH

$$f_{\rm PBH} = \frac{\Omega_{\rm DM}}{\Omega_{\rm DM}}$$

$$\simeq \left(\frac{e^{-1/2\varepsilon}}{2\times 10^{-13}}\right)\left(\frac{\Lambda}{10^5\ \rm GeV}\right)^2\left(\frac{10^6\ \rm GeV}{T_f}\right)$$

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

Flores, AK, 2108.08416



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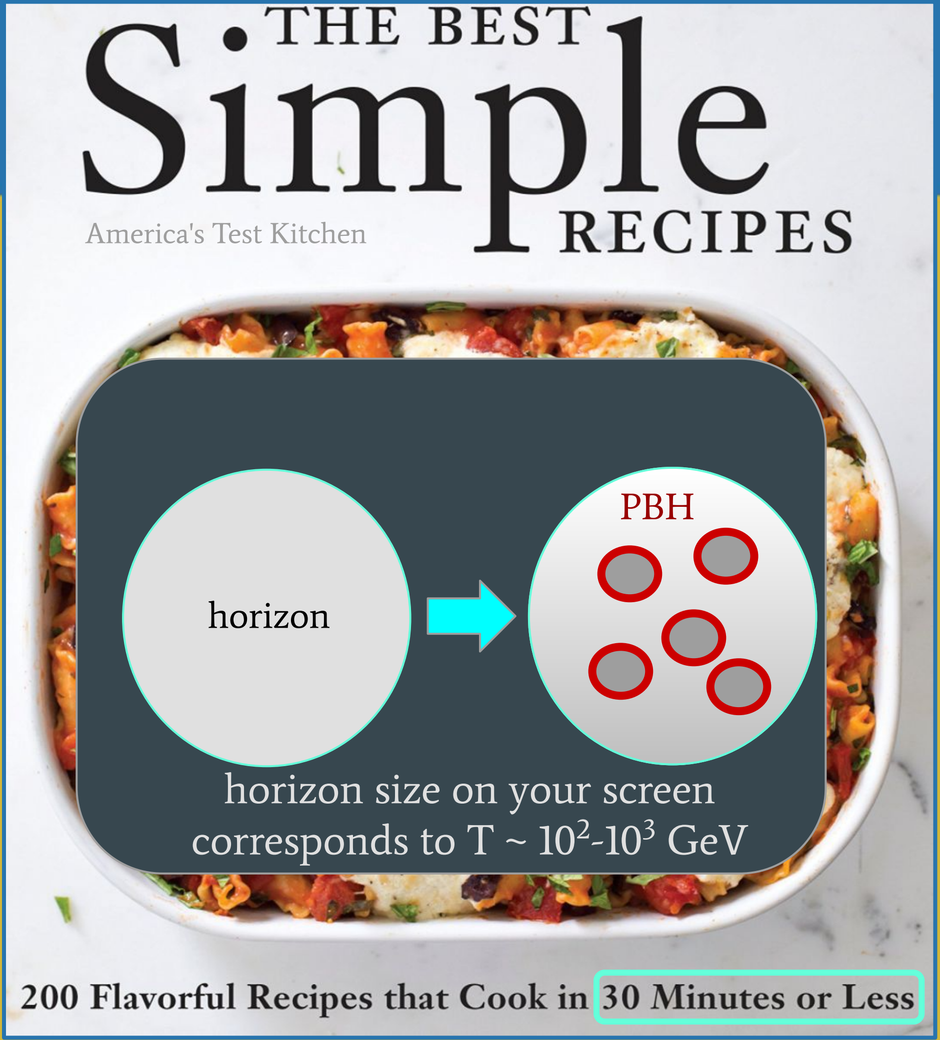
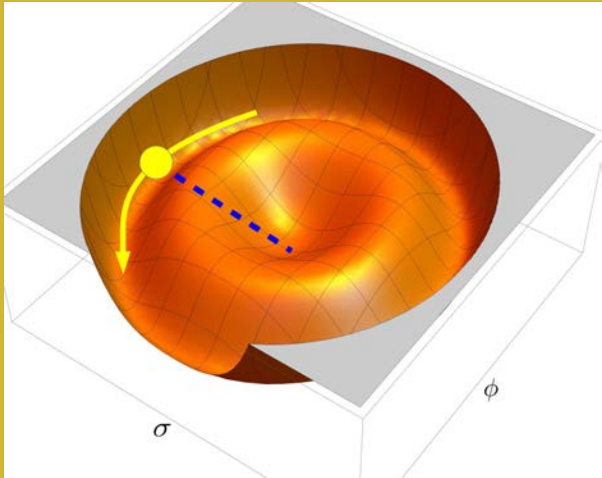
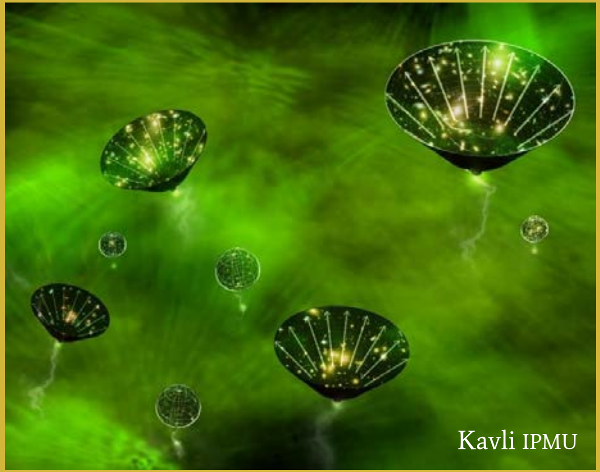


# And yet another mechanism: inflationary multiverse



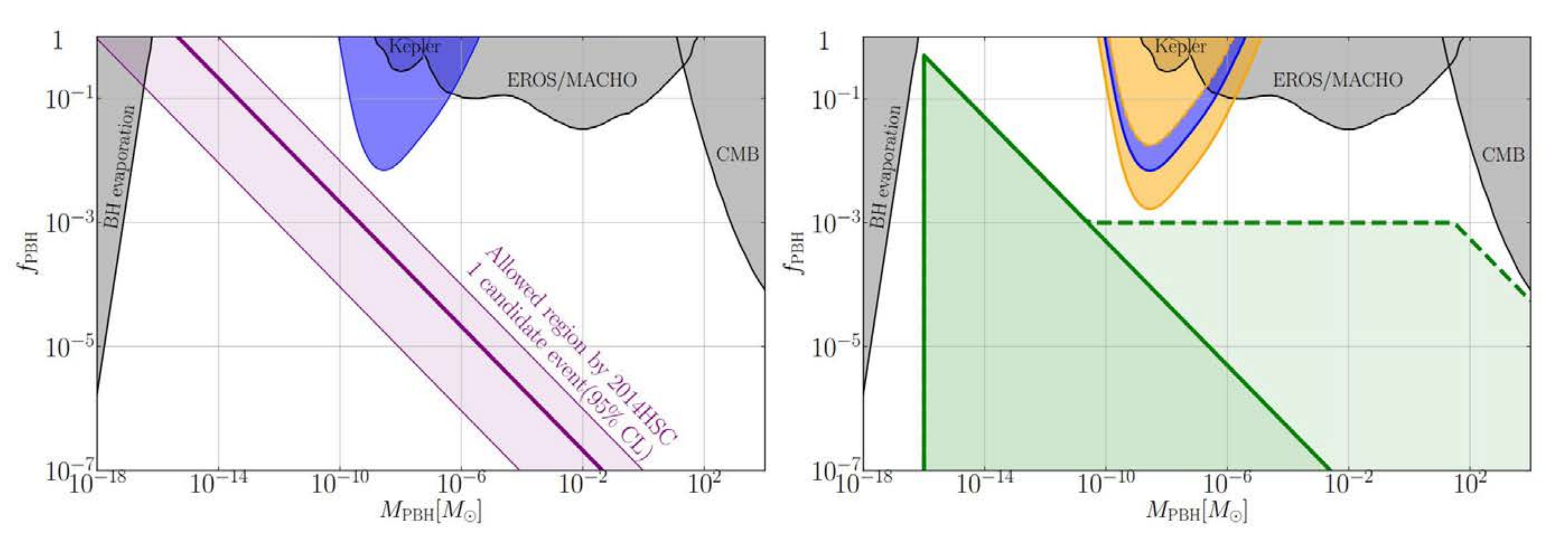




Tunneling events lead to nucleation of baby universes, which appear to outside observer as black holes.

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

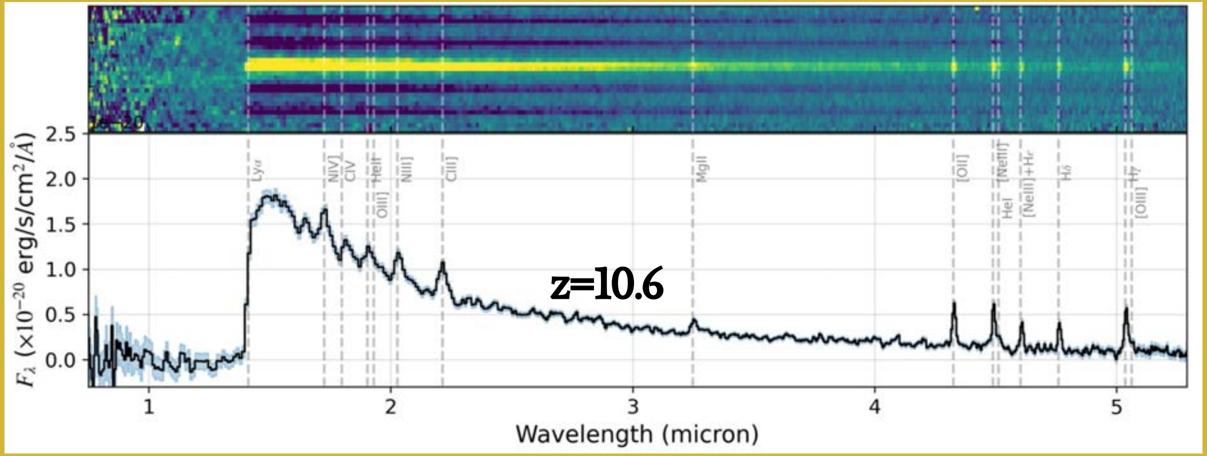


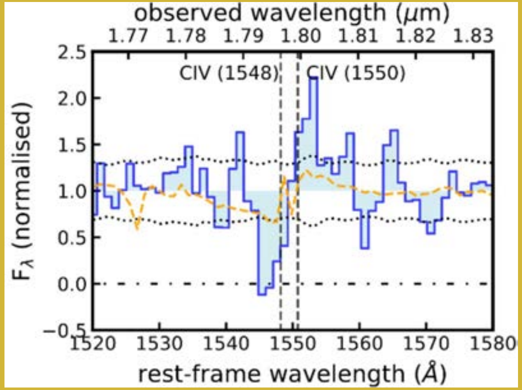

[AK, Sasaki, Sugiyama, Takada, Takhistov, Vitagliano, Phys.Rev.Lett. 125 (2020) 181304 arXiv:2001.09160]

# 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 |

# 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!**
$\Rightarrow$ **PBH seeds?**

# Primordial black holes seed SMBH or enable direct collapse

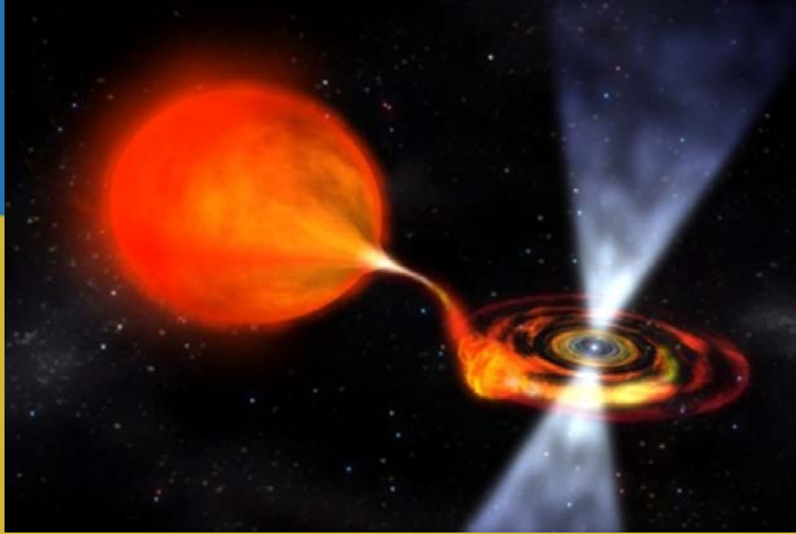
Models can produce PBH with masses as large as $10^5 M_\odot$

Kawasaki, AK, Yanagida, 1202.3848
Kohri, Nakama, Suyama, 1405.5999
Kawasaki, Murai, 1907.02273

Also, evaporation of small PBH can heat gas enough to enable direct collapse [Picker]

Also, particle decays can facilitate DC [Lu]

# PBH and neutron stars



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

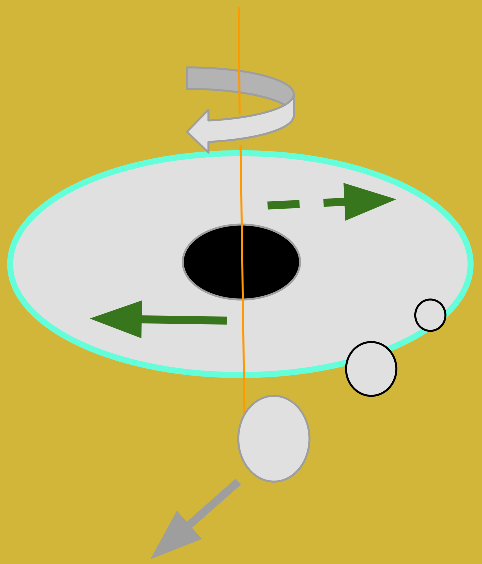
- Neutron stars can capture PBH, which consume and destroy them from the inside.
- Capture probability high enough in DM rich environments, e.g. Galactic Center
- Missing pulsar problem… [e.g. Dexter, O'Leary]
- What happens if NSs really are systematically destroyed by PBH?

## 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

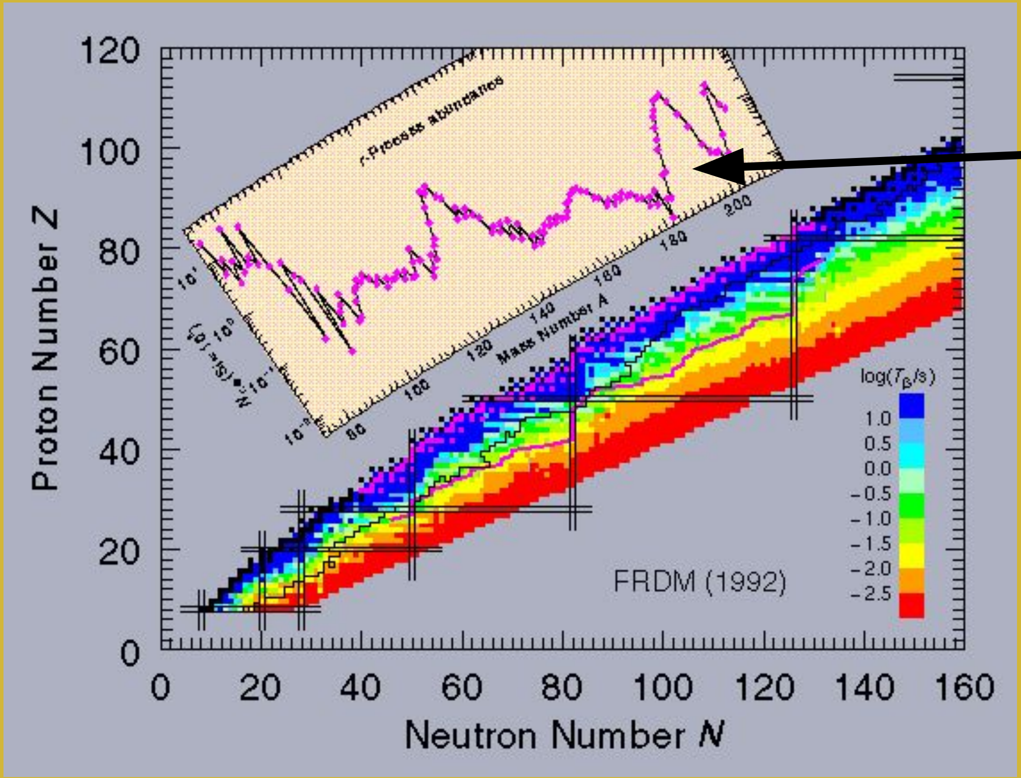
[Fuller, AK, Takhistov, Phys. Rev. Lett. 119 (2017) 061101] also, *Viewpoint* by H.-T. Janka

# 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?..

Image: Los Alamos, Nuclear Data Group

# r-process nucleosynthesis: site unknown

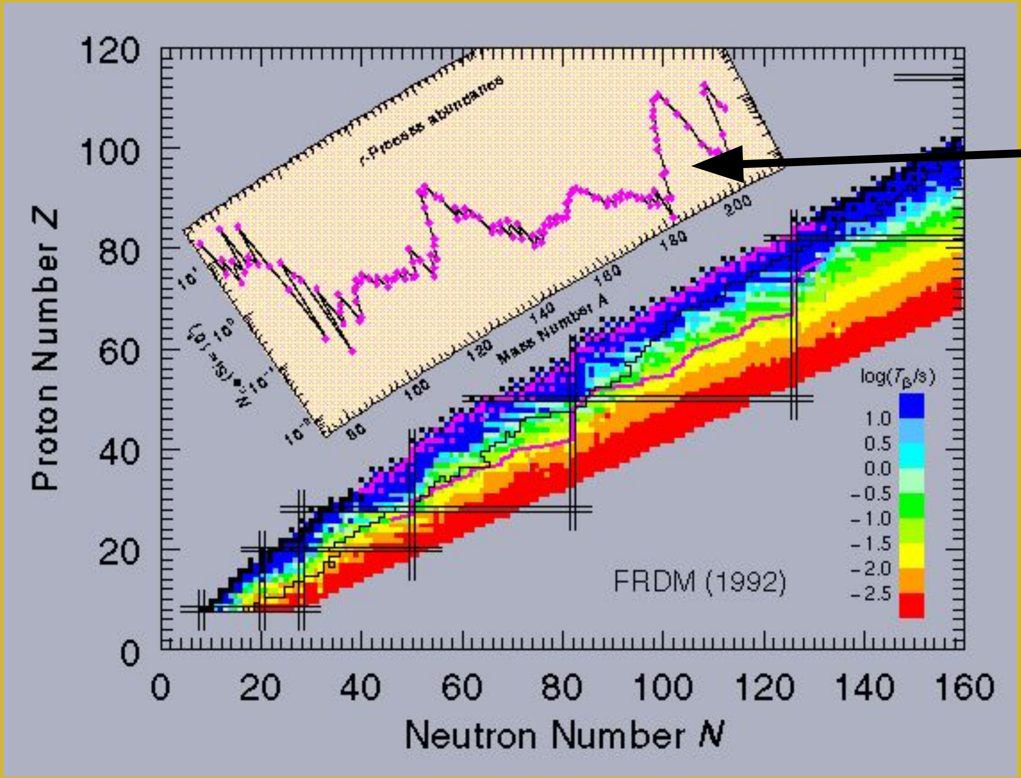
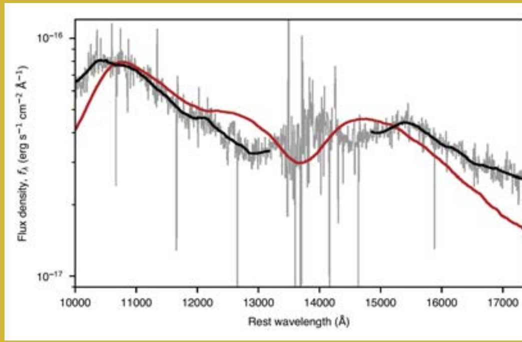



Image: Los Alamos, Nuclear Data Group

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



# NS-NS 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.

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

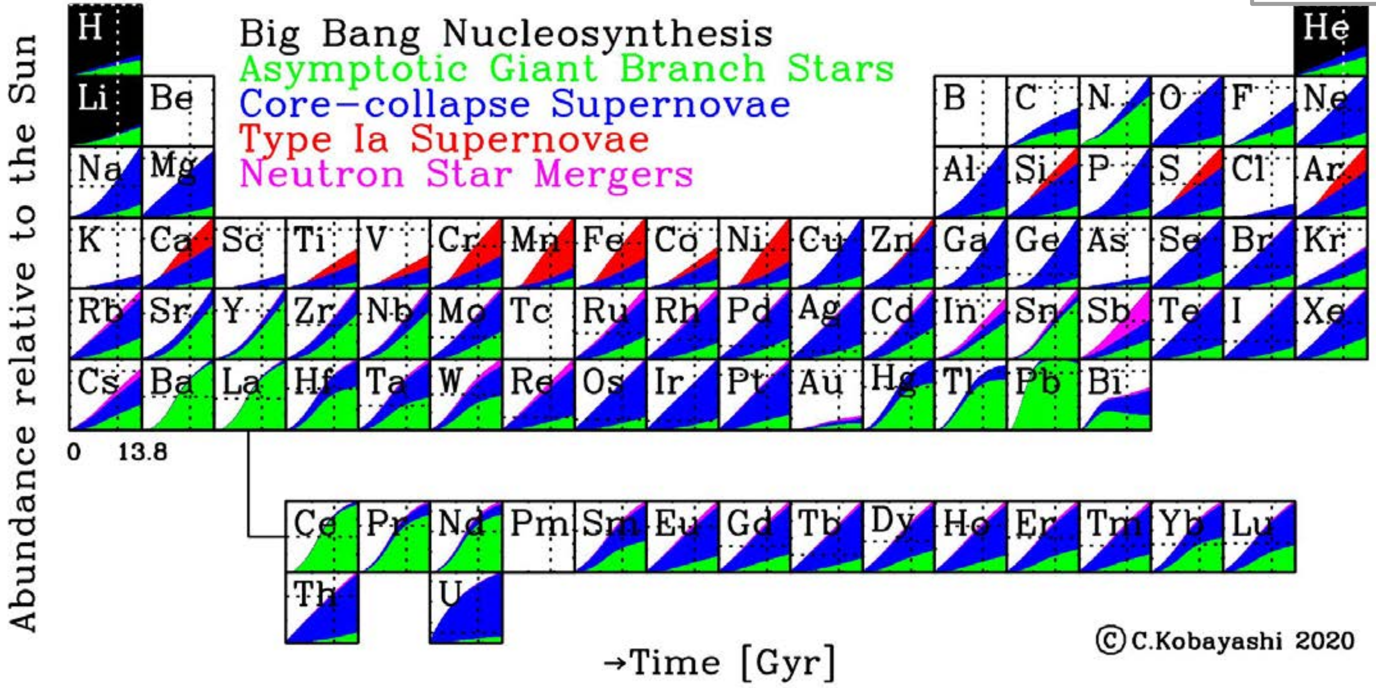



**Figure 39.** The time evolution (in Gyr) of the origin of elements in the periodic table: Big Bang nucleosynthesis (black), AGB stars (green), core-collapse supernovae including SNe II, HNe, ECSNe, and MRSNe (blue), SNe Ia (red), and NSMs (magenta). The amounts returned via stellar mass loss are also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

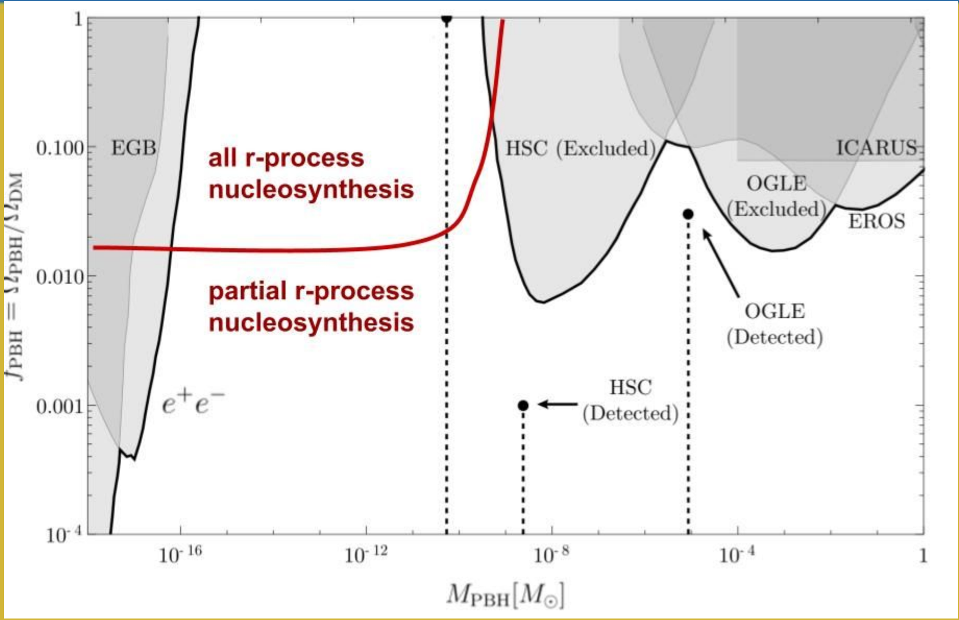
Ultra Faint Dwarfs (UFD): most of UFDs show no enhancement of r-process abundance.

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~10⁴ M☉** ✔
- 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. ✔

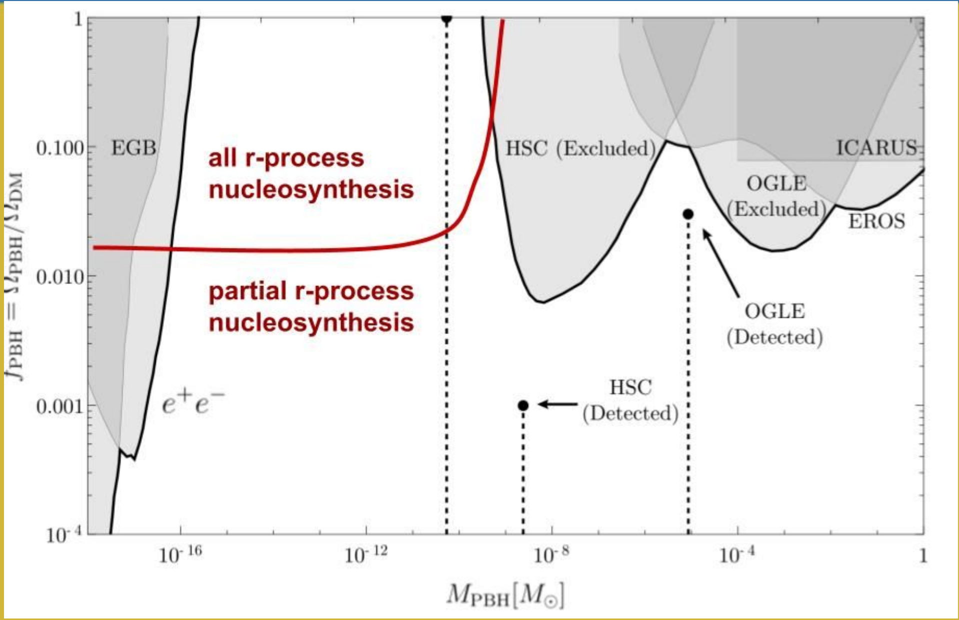



[Fuller, AK, Takhistov, PRL 119 (2017) 061101]

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, PRL 119 (2017) 061101]

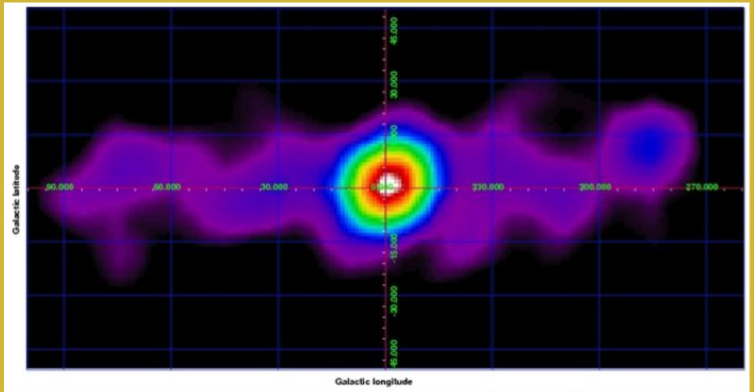
also, a *Viewpoint* PRL article by Hans-Thomas Janka

# 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.

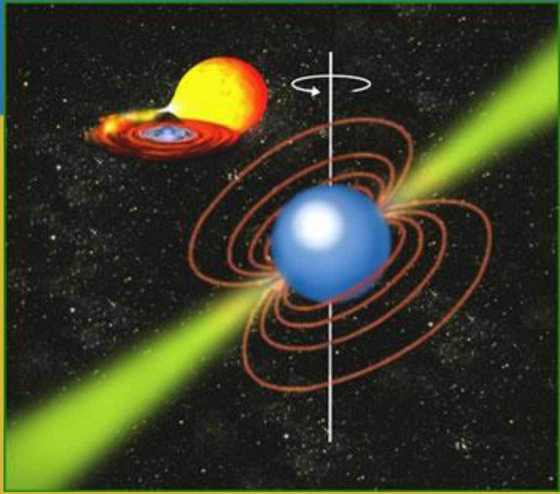



ESA/Bouchet et al.

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

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

# Fast Radio Bursts (FRB)



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

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

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

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 from NS->BH process

**PBH + NS**

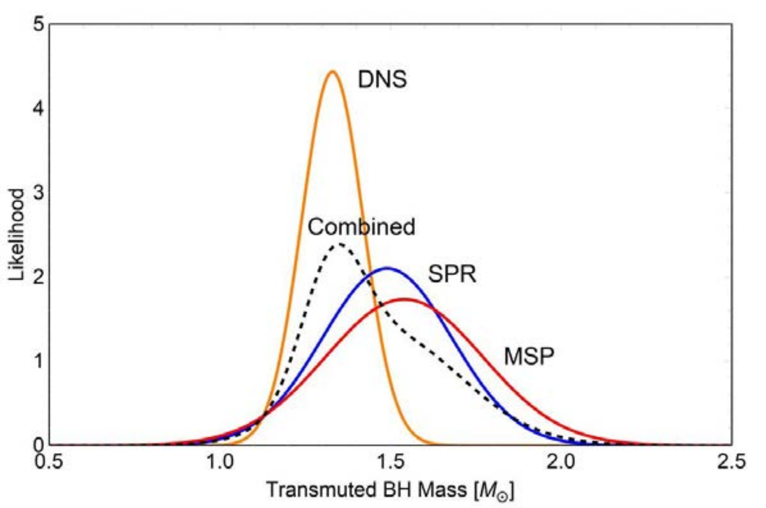
**⇓**

**BH of 1-2 $M_\odot$**

...if it detects mergers of

**1-2 $M_\odot$ black holes**

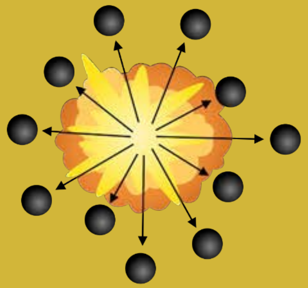
(not expected from evolution of stars)



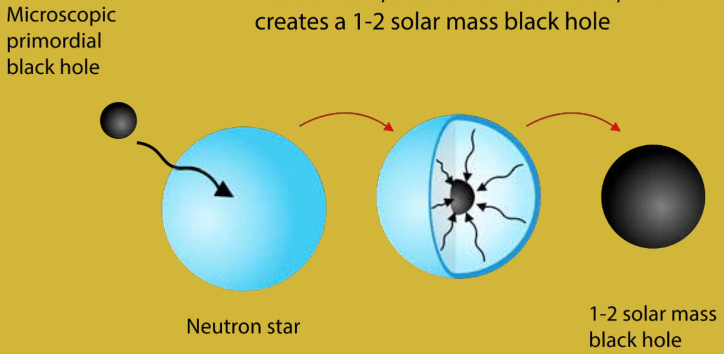

Fuller et al., PRL 119 (2017) 6, 061101 [1704.01129]
Takhistov et al., 1707.05849, 2008.12780

# G objects

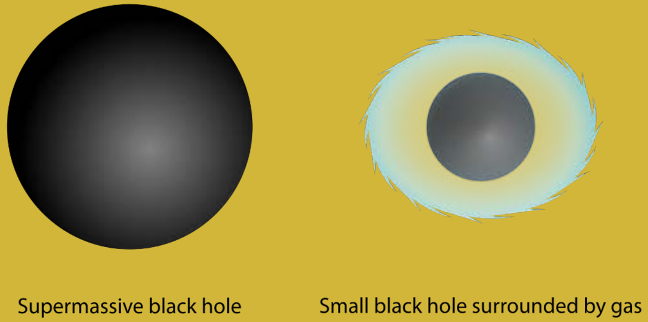
**1.** Primordial black holes produced in Big Bang make up part or all of dark matter.



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




**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.




Flores, AK, Ghez, Naoz, 2308.08623

# 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, others) 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 ⇒ primordial structures ⇒ PBH, baryogenesis, other consequences!