

# Black Holes

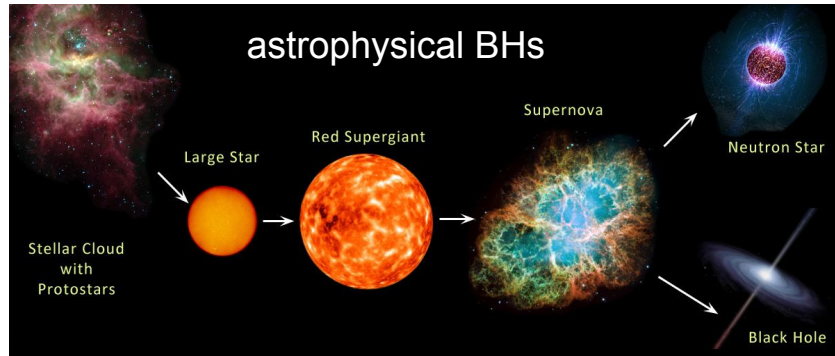
## as New Dark Matter Factories

Volodymyr Takhistov

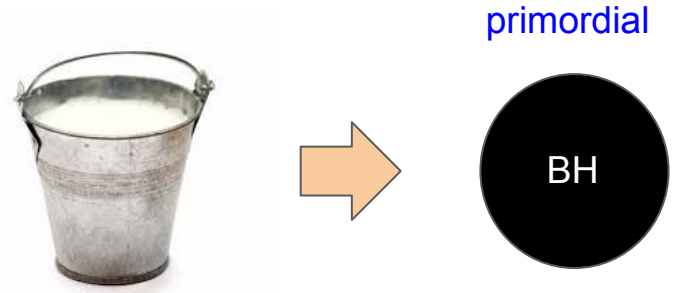
QUP & Theory Center, KEK & SOKENDAI & Kavli IPMU, U. Tokyo



# Primordial Black Holes (PBHs)



In early Universe, just roughly take scoop of  $\sim 50\%$  overdensity to make BH

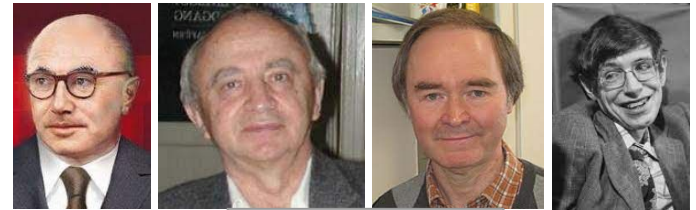


## PBHs as Dark Matter (DM)

→ importantly, BHs definitively **exist**

*many great reviews*

[Sasaki+, 2018; Green, Kavanagh, 2020; Carr, Kuhnel, 2020, 2022; Carr, Kohri, Sendouda, Yokoyama, 2020; Escrivá, Kuhnel, Tada, 2022 ...]

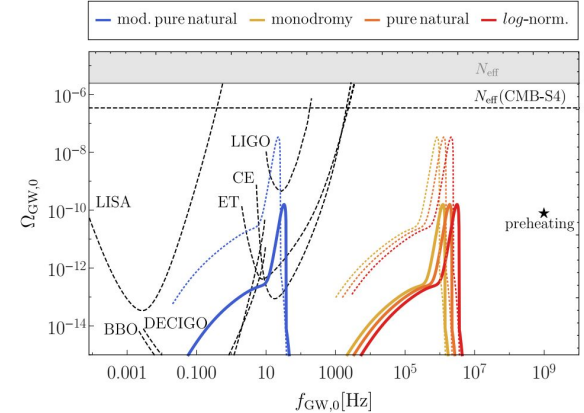
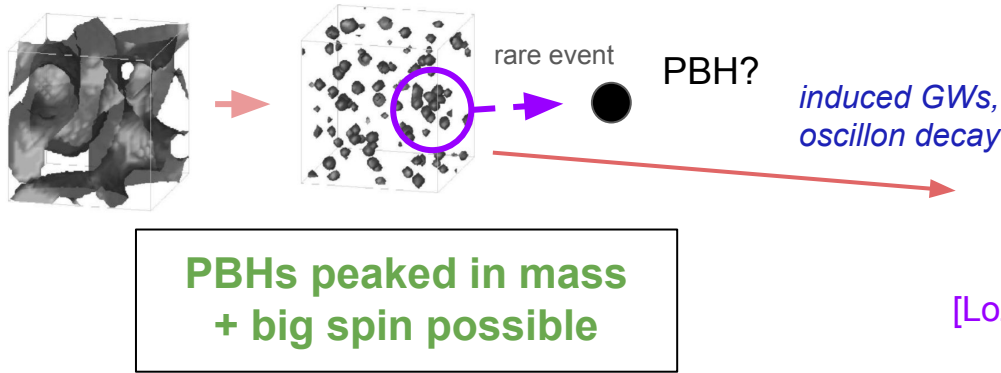


~ 50 years ago

# Myriad Formation Scenarios, Distinct Features Possible

- *Conventional picture*: big perturbations ( $\delta \sim 1$ ) enter horizon  $\rightarrow$  collapse
- Distinct PBH features possible in different scenarios *novel early Universe probes distinct from CMB*

Ex.) *scalar fragmentation to (inflaton) oscillons*



[Lozanov, VT, *Phys.Rev.Lett*, (2023) 2204.07152]

[Cotner, Kusenko, VT, *PRD*, (2018) 1801.03321;  
Cotner, Kusenko, Sasaki, VT, *JCAP*, (2019) 1907.10613]

*numerical/simulation progress [Amin, Lim, Serpico, ...], but need more*

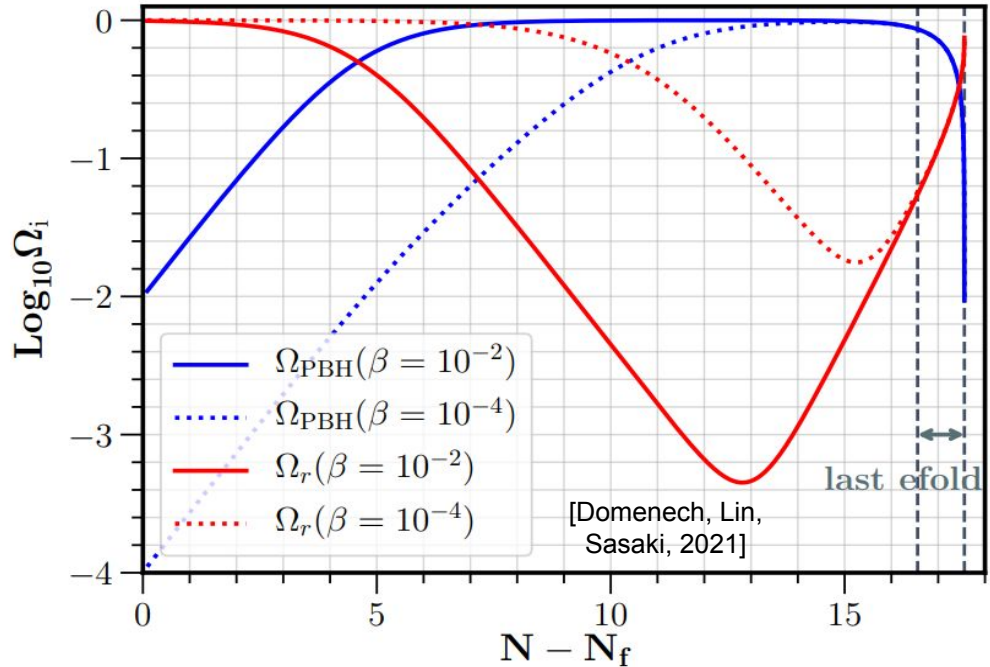
\*\*\* *new induced GWs from solitons isocurvature*  
[Lozanov, Sasaki, VT, (2023), 2304.06709;  
Lozanov, Sasaki, VT, (2023), *PLB*, 2309.14193;  
Lozanov, Pi, Sasaki, VT, Wang, (2023), 2310.03594]

# Aside: Induced GWs from Early Evaporating PBHs

- Consider rapid Hawking evaporation of PBHs dominating early Universe
- Rapid transition of matter to radiation era from decays

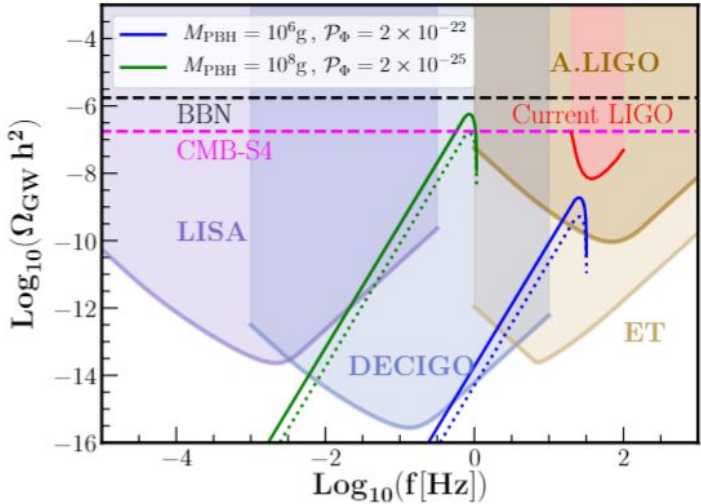
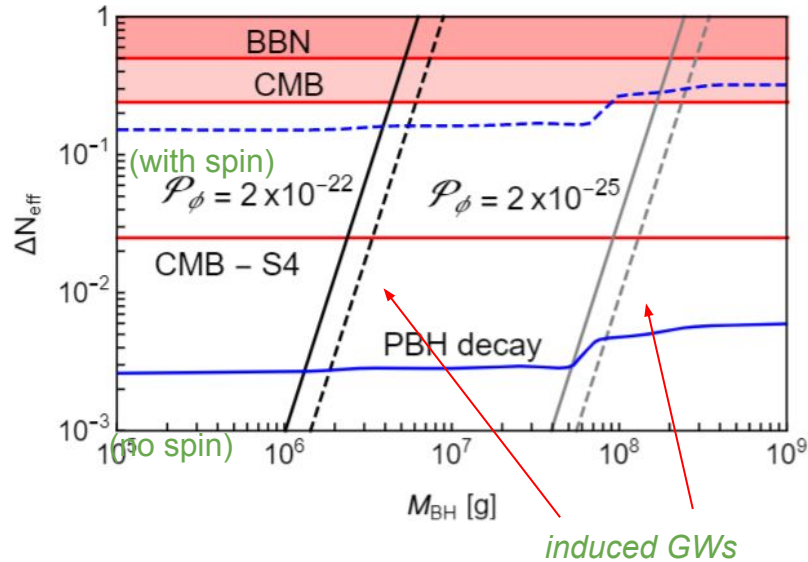
→ strong induced GWs

$$\Omega_{\text{GW}} \propto f(\Phi'_{\text{grav}} \Phi'_{\text{grav}})$$



[Sasaki, Domenech, Kohri, Inomata, Terada, Yanagida, Kawasaki...]

# Probing Spin, Mass Distributions of Evaporating PBHs with GWs



- Evaporating PBHs also emit gravitons → GWs  $\Delta N_{\text{eff}}$  [Hooper+, 2020; Arbey, 2021; Masina, 2021]
- coincidence with induced GWs can probe many scenarios over broad mass/spin range

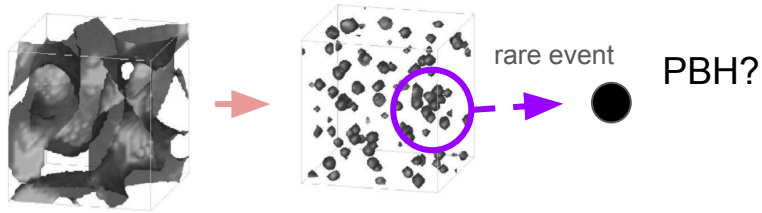
\* spin modifies emission and induced GWs [Domenech, VT, Sasaki, Phys.Lett.B, (2021), 2105.06816]  
 (further studies [Cheek, Heurtier, Perez-Gonzalez, Turner, 2022])

# Myriad Formation Scenarios, Distinct Features Possible

- *Conventional picture*: big perturbations ( $\delta \sim 1$ ) enter horizon  $\rightarrow$  collapse
- Distinct PBH features possible in different scenarios

Ex.)

*scalar fragmentation to (inflaton) oscillons*

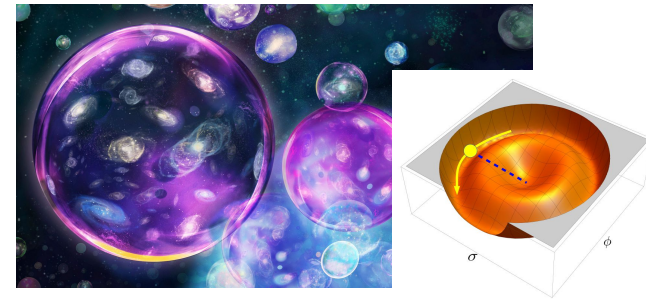


**PBHs peaked in mass  
+ big spin possible**

[Cotner, Kusenko, **VT**, *PRD*, (2018) 1801.03321;  
Cotner, Kusenko, Sasaki, **VT**, *JCAP*, (2019) 1907.10613]

*numerical/simulation progress [Amin, Lim, Serpico, ...], but need more*

*vacuum bubble “multiverse”*

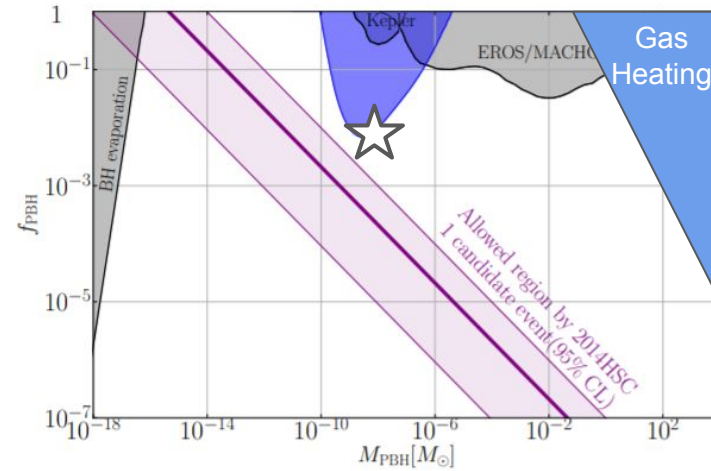
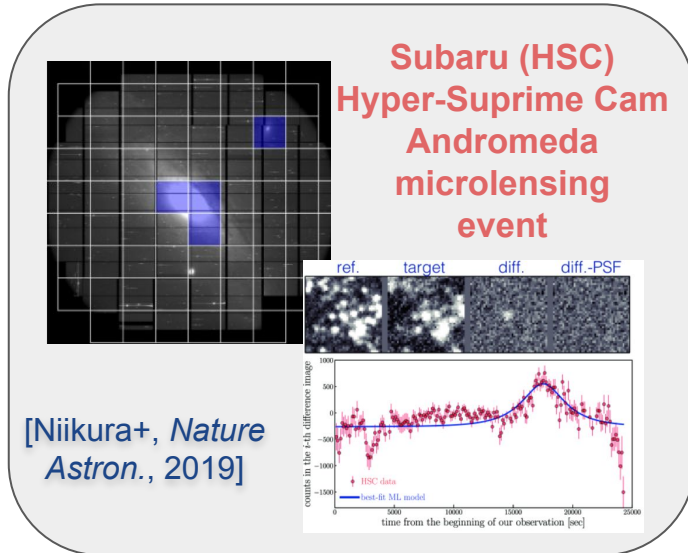


**PBHs broadly  
distributed in mass**

see also [Deng, Vilenkin, Sasaki...]

[Kusenko, Sasaki, Sugiyama, Takada, **VT**,  
Vitagliano, *Phys.Rev.Lett.*, (2020) 2001.09160]

# PBH DM from Bubble Multiverse: Detected by HSC ?!



- **PBH DM from bubble multiverse consistent with detected HSC event**
- Can probe open parameter space with extended tail

[Kusenko, Sasaki, Sugiyama, Takada, VT, Vitagliano, *Phys.Rev.Lett.*, (2020) 2001.09160]

# PBH DM can Help Probe New Fundamental Force Regimes

- QCD strong force tested in limited regimes, in Standard Model (SM) confines  $\lesssim \text{GeV}$
- Dynamics readily modified in BSM theories, **high-T transitions** (1st order) natural from scalars

[Ipek, Tait, PRL, 2018]

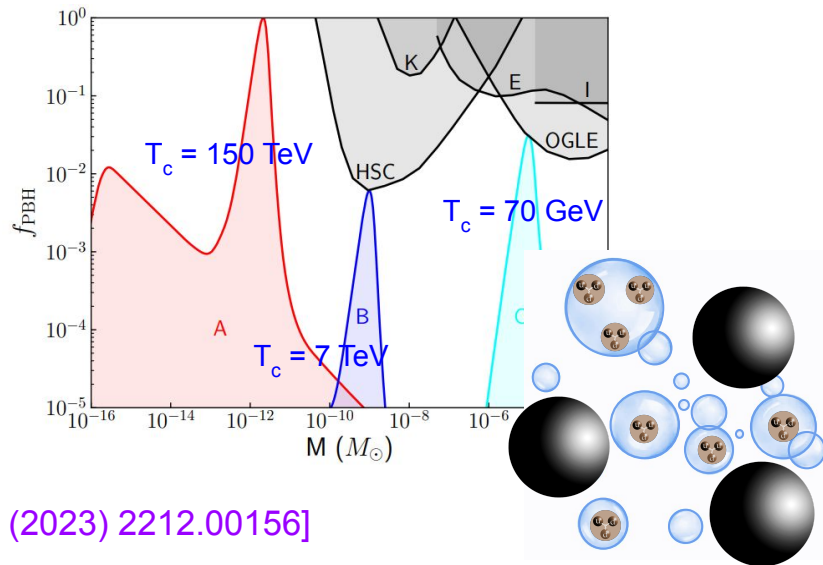
$$\mathcal{L} \supset -\frac{1}{4} \left( \frac{1}{g_{s0}^2} + \frac{S}{M} \right) G_{\mu\nu}^a G_a^{\mu\nu} + \dots \quad \Lambda(\langle S \rangle) = \Lambda_0 \text{Exp} \left[ \frac{24\pi^2}{2N_f - 33} \frac{\langle S \rangle}{M} \right]$$

- **How to test? PBHs, enhanced collapse**

$$M_H \sim 5 \times 10^{-10} M_\odot \left( \frac{T}{10 \text{ TeV}} \right)^{-2}$$

- can be **ALL DM**, unlike SM QCD PBHs
- explain observational hints? (microlensing...)

\*\*\* PBHs from high-T QCD cross-over also possible  
[Escriva, Subils, 2023; Escriva, Tada, Yoo, 2023]

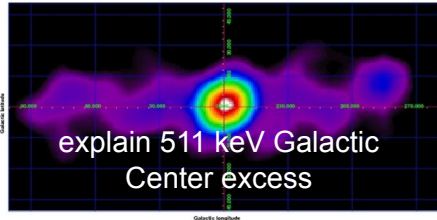


[Lu, VT, Fuller, Phys.Rev.Lett, (2023) 2212.00156]

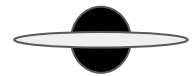


# PBH DM in Intriguing “Windows”: Asteroid-mass BHs

- PBH can be all DM in asteroid-mass window  $\sim 10^{17}$ - $10^{22}$  g - remains poorly constrained recent reviews [Gorton, Green, 2024; Tinyakov, 2024], multitude of proposals for future
- **Compact stars as PBH laboratories** - possible link to major puzzles and unusual signatures (active field, many insights [Tinyakov+, 2014; Bramante, Graham, Kouvaris, Kaiser, Bertone....])



If disk + BH → “orphan Gamma-ray Burst”  
 [VT, Phys.Lett.B., (2019), 1710.09458]



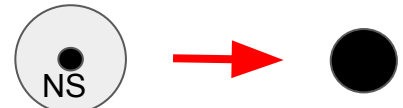
\*\*\* can explain with just NS-NS mergers

[Fuller, Kusenko, Radice, VT, Phys.Rev.Lett., (2018), 1811.00133]



Heavy element abundance (e.g. gold)

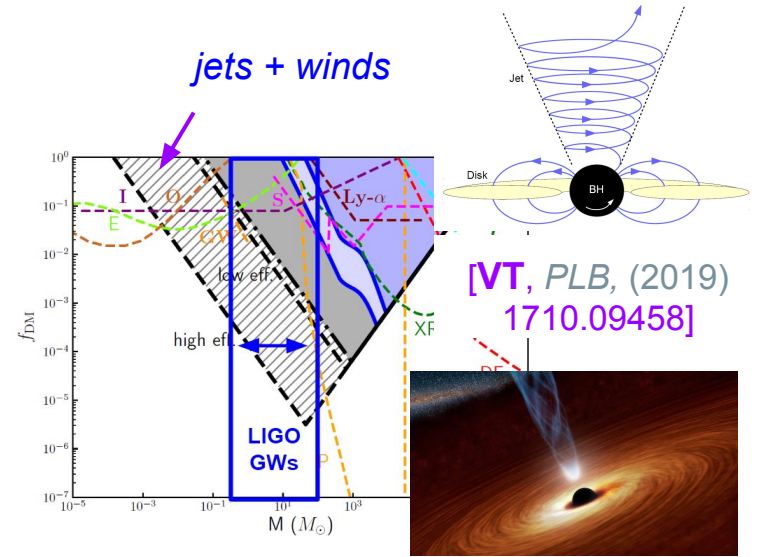
“Transmuted” solar-mass BHs  
 [VT, Phys.Lett.B., (2018), 1707.05849]



[Fuller, Kusenko, VT, Phys.Rev.Lett., (2017), 1704.01129; VT, Phys.Lett.B., (2018), 1710.09458; VT, Phys.Lett.B (2018), 1707.05849; VT+ Phys.Rev.Lett., (2021), 2008.12780]

# PBH DM in Intriguing “Windows”: Heating LIGO BHs

- PBH mergers linked with LIGO GW observations? [Bird, Byrnes, Cholis, Muñoz, Ali-Haïmoud, Kamionkowski, Kovetz, Raccanelli, Riess, Sasaki, Clesse, Garcia-Bellido, Sasaki, Suyama, Hütsi, Raidal, Vaskonen, Veermäe + many]
- Important to look for additional independent tests
- Broad cosmology-independent probe: gas heating
- Gas heating mechanisms:
  - gravitational drag (dynamical friction)
  - accretion disk photons
  - accretion outflows / winds
  - relativistic jets (especially for spinning PBHs)
- Great testing site: dwarf galaxies (Leo T)

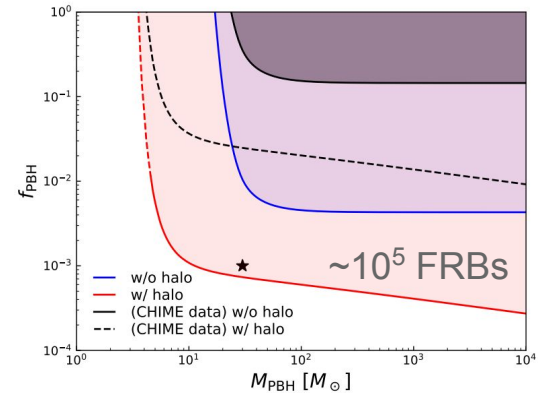
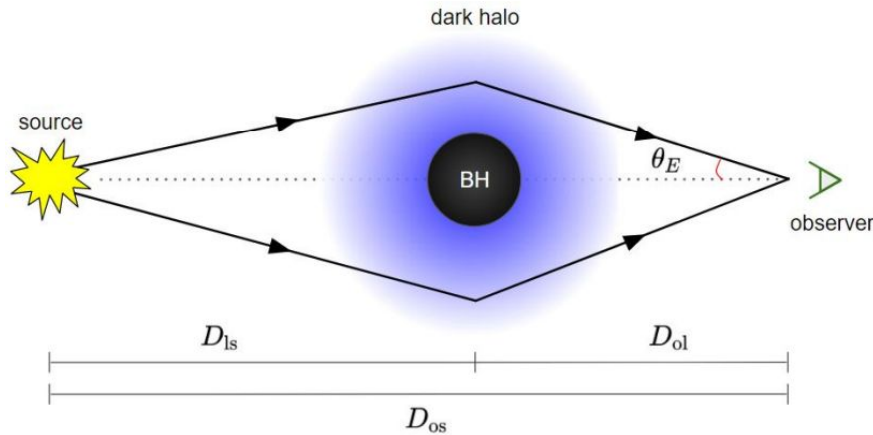


\* *first analysis of sub-solar BH accretion disks and emission*

[Lu, VT+, *ApJ Lett.*, (2020) 2007.02213; VT+, *JCAP*, (2021) 2105.06099; VT+ *MNRAS Lett.*, (2022) 2111.08699]

# If PBH DM & Particles Mixed, General Test? Dressed PBHs

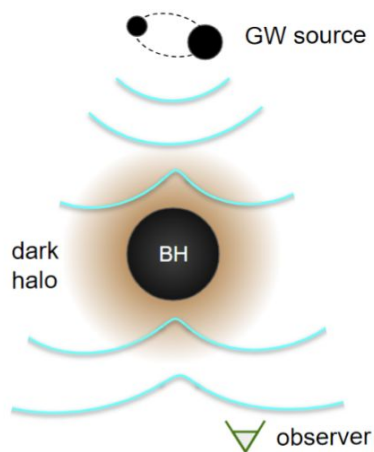
- Stellar-mass PBHs relevant for LIGO can only comprise subdominant DM  
→ engulfed in massive halos of other DM (e.g. axions/WIMPs.) [Mack+, 2007; Ricotti+, 2008, Silk+]
- Strong cosmological lensing (e.g. FRBs) can test population of dressed PBHs
- Already start exploring regions with survey data, method applicable to other lenses



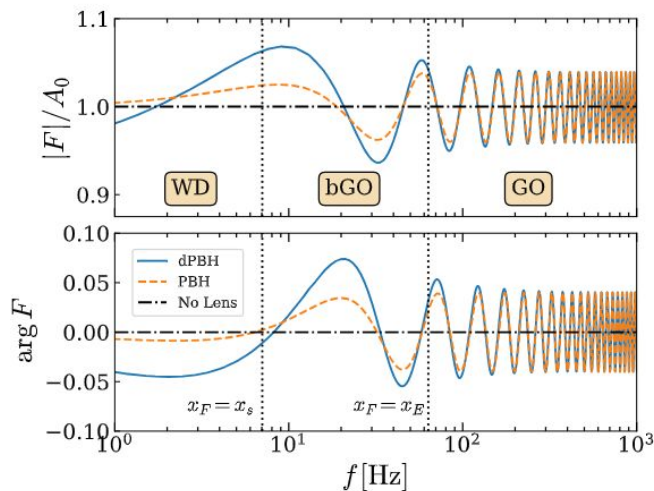
[Oguri, VT, Kohri, *Phys.Lett.B.*, (2023), 2208.05957]

# Direct Individual Probe of Mixed PBH DM? Diffractive GW Lensing

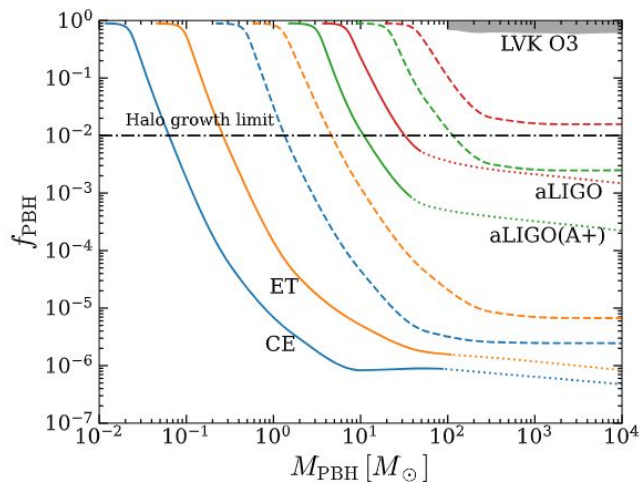
- **Diffractive GW lensing** by PBHs allows distinguishing *individual* DM halos  
 → *general “direct test” of primordial BH origin and scenarios with particle DM*
- Can break degeneracy of PBH vs halo-dressed PBH on even-by-event basis



GWs “scan” objects  
over wide frequency range



[Choi, Jung, Lu, VT, (2023) 2311.17829]



(other estimates w/o degeneracy or diffraction  
[Urutia, Vaskonen, Vermae, 2023])

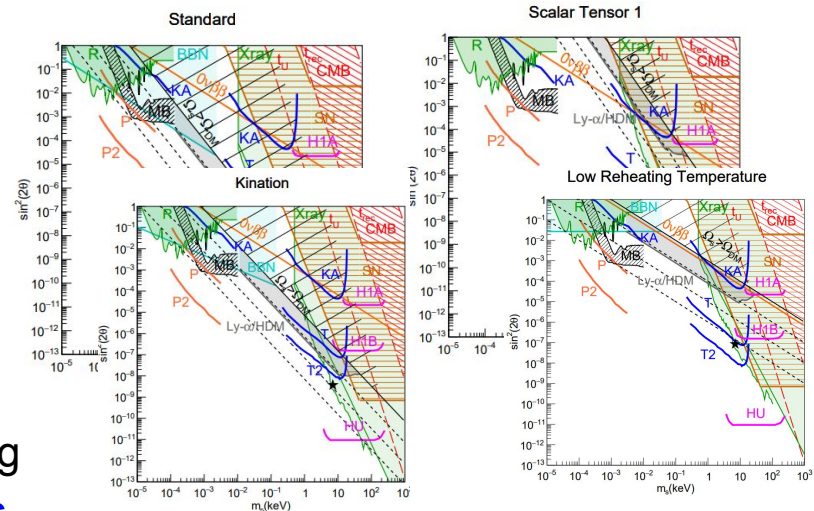
# PBHs as Unique DM factories: Sterile Neutrinos

- Besides comprising DM, PBH can serve as unique DM factories → unusual DM production via Hawking emission (e.g. [Krnjaic, Hooper, Munoz, Turner, Yuber-Perez, Cheek, Heurtier, McDermott])
- Sterile neutrinos** well motivated (e.g.  $\nu$ -mass, anomalies, leptogenesis),  $\sin(\theta)$  active- $\nu$  mixing
- Rich cosmology, at O(keV) typical warm DM candidate e.g. [Boyarsky+, Fuller, Abazajian...]

Ex.) Hubble tension and decaying sterile  
 [Gelmini, Kusenko, VT, JCAP, (2019) 1906.10136]

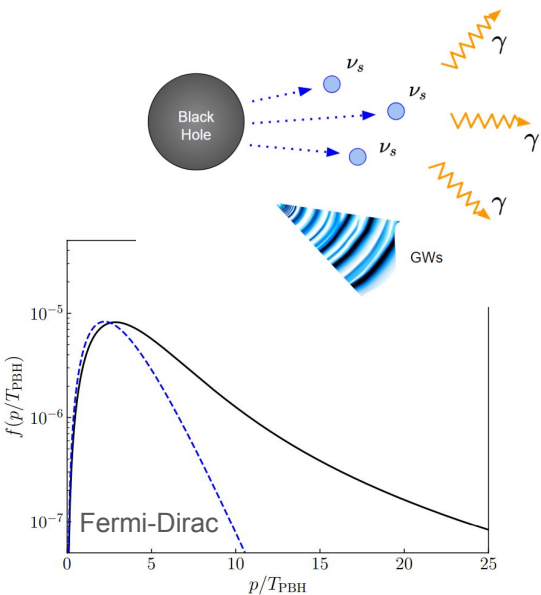
Sterile- $\nu$  as probes of early Universe  
 [Gelmini, Lu, VT, PLB (2019) 1909.04168;  
 Gelmini, Lu, VT, JCAP (2019) 1909.13328;  
 Gelmini, Lu, VT, JCAP (2020) 1911.03398;

- Conventional sterile- $\nu$  DM mechanisms (e.g. [Dodelson, Widrow, 1993]) sensitively rely on  $\nu$ -mixing → **very different story for PBH neutrino genesis**

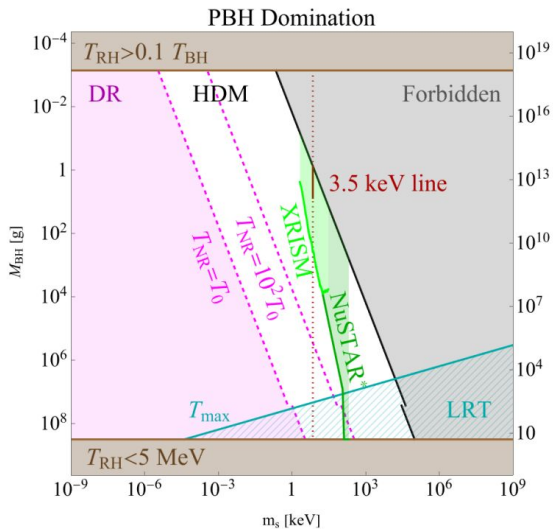


# PBH Neutrino genesis: Sterile- $\nu$ DM Independent of Coupling

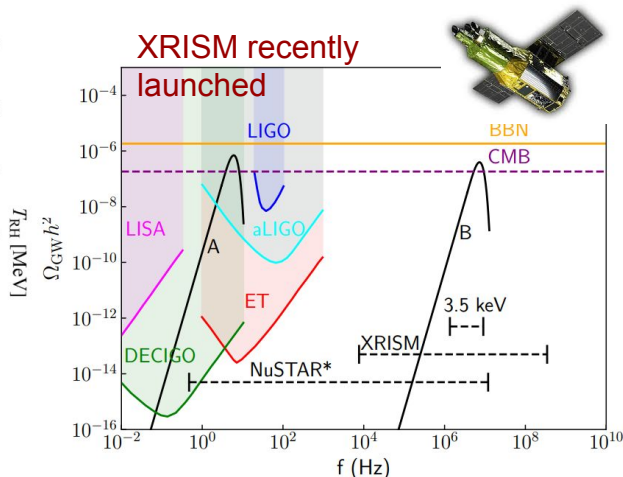
- Unlike conventional mechanisms, PBHs can make sterile- $\nu$  DM with **arbitrary small mixing**
- **Distinct spectrum**, in some cases can be effectively low-reheating scenario



*very distinct hotter spectrum*



[Chen, Gelmini, Lu, VT, (2023), *PLB*, 2309.12258;  
Chen, Gelmini, Lu, VT, (2023), 2312.12136]



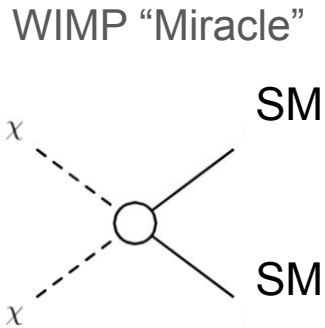
*unique GW + X-ray signatures*

\*\* PBH axion emission gives new diffuse axion background [Eby, VT, (2024), 2402.00100]

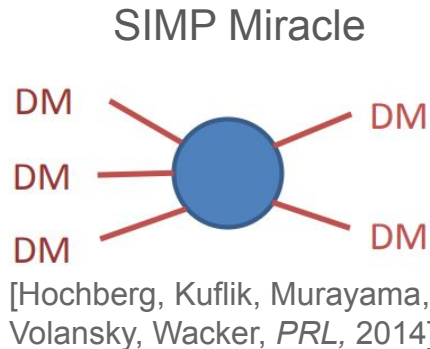
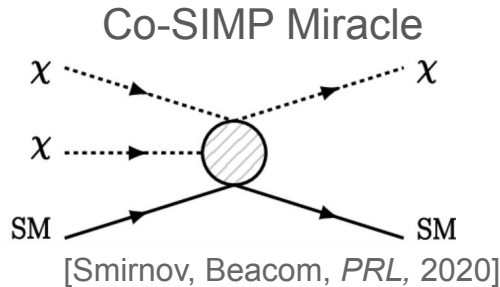
# Conceptually New DM from Old PBHs

conventional particle DM relies on interactions

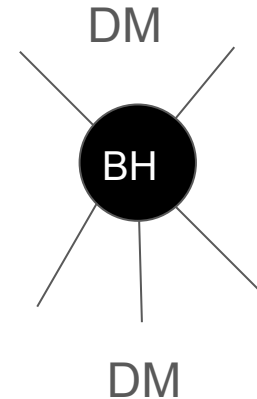
Ex.)



abundance set by annihilation



new general idea:  
**Regurgitated DM**



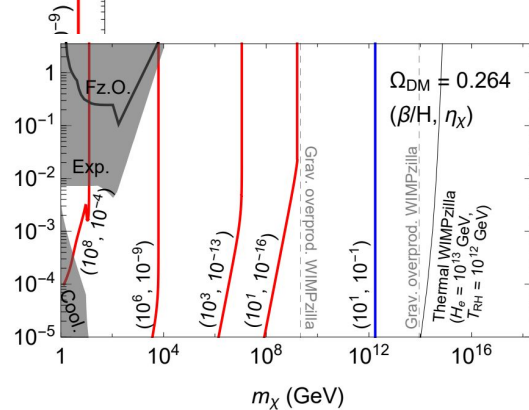
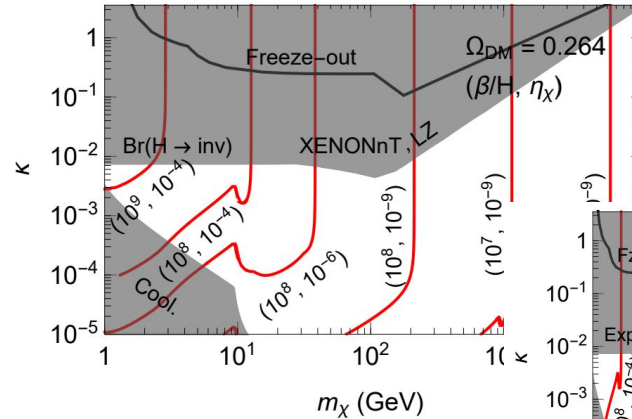
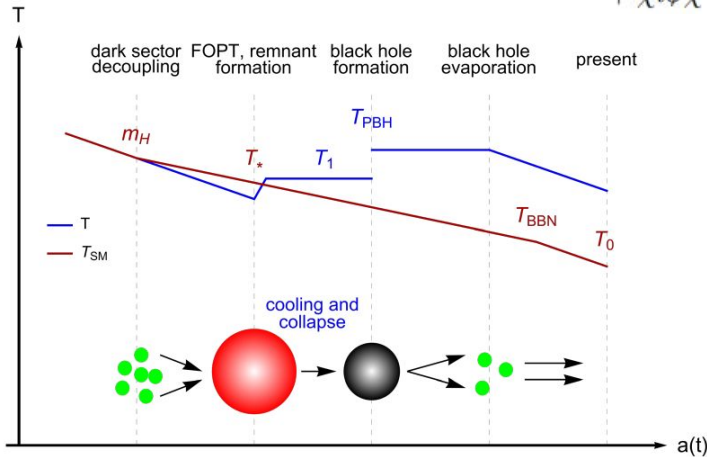
BH "scrambles", re-emits DM with new properties, doesn't rely on interactions

[Kim, Lu, Marfatia, *VT*, (2023), 2309.05703]

# Regurgitated DM

- Concrete realization within minimal model, dark sector with scalar/fermion, Yukawa force and Higgs portal

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{\mu^2}{2} \phi^2 - \frac{\kappa}{2} \phi^2 (\mathcal{H}^\dagger \mathcal{H}) - V(\phi) + \bar{\chi} i \not{\partial} \chi - y_\chi \phi \bar{\chi} \chi,$$



- Can make DM ~1-10<sup>16</sup> GeV, opening parameter space**

- Other realizations also possible

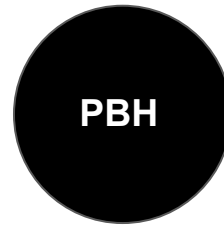
[Kim, Lu, Marfatia, VT, (2023), 2309.05703]



# Conclusions

- PBHs ~ “Standard Model” DM candidate - BHs exist, very different from particle DM
- Distinct realizations and intriguing features possible, connections to puzzles and novel signals
- PBHs can relate to DM in more than one way, including as novel DM factories distinct from conventional particle DM production mechanisms

*Bright Future for Exploration and Discoveries*



*... Dark Matter ?*