

Novel Manifestations of Primordial Black Holes

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Kavli Fellow

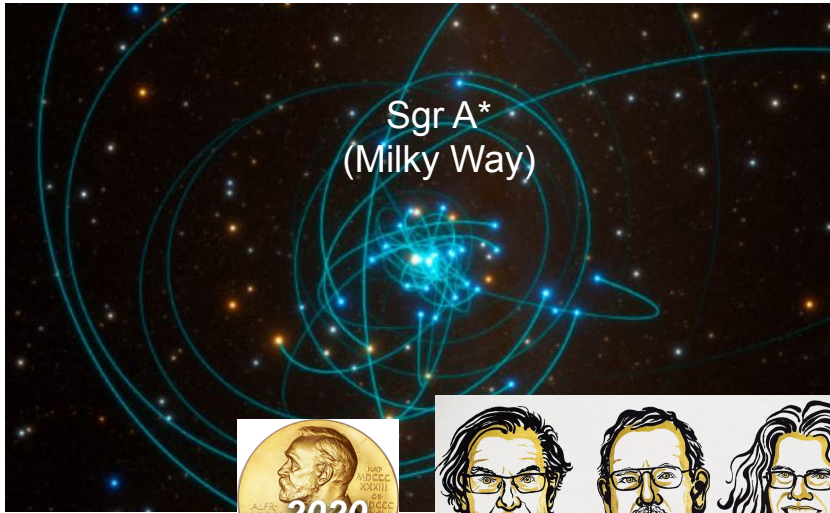
Kavli IPMU, University of Tokyo



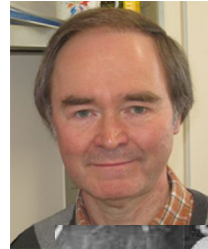
Black Holes

EXIST

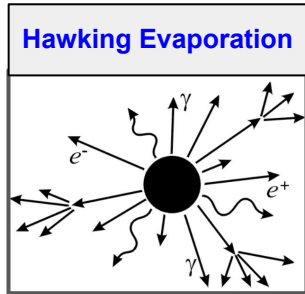
$$M_{\text{BH}} \sim 10^6 M_{\odot}$$



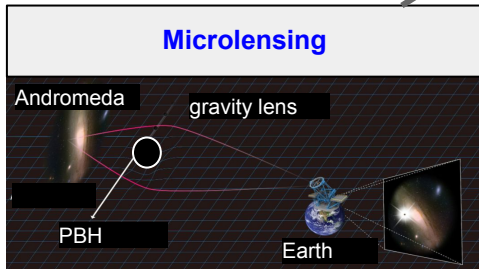
...might appear from early Universe (primordial), and contribute to dark matter



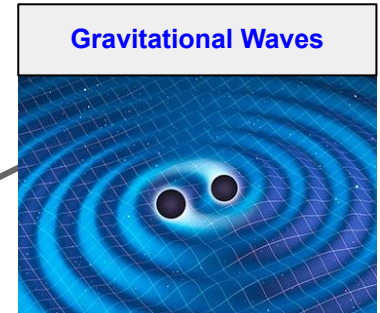
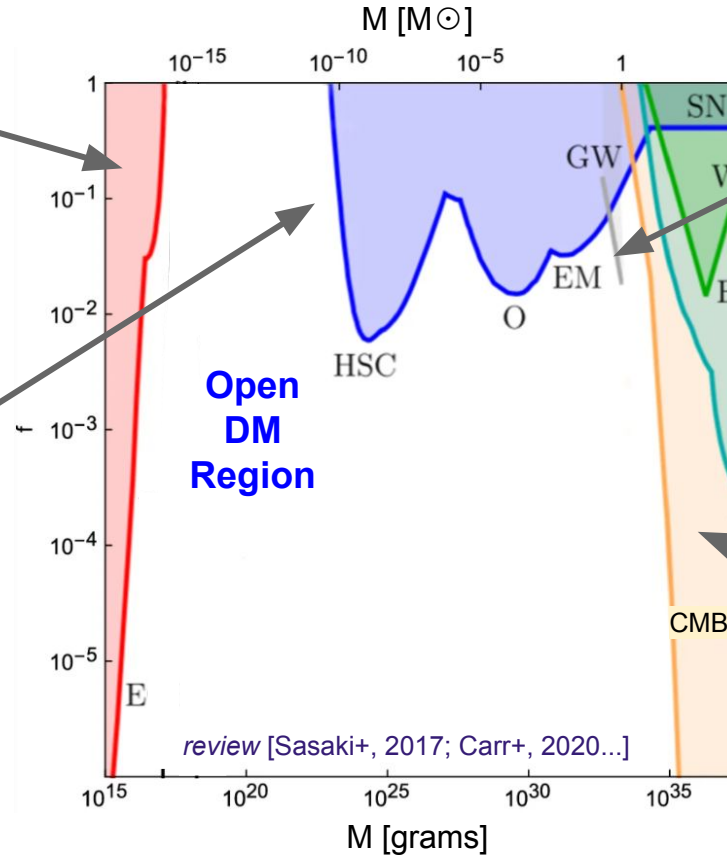
PBH Research Very Active



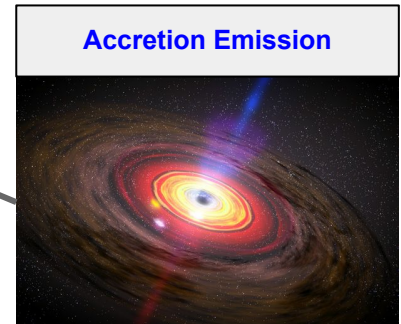
[Carr, Cirelli, Dasgupta, Dutta, Graham, Hooper, Kohri, Laha, Munoz, Profumo, Silk, Slatyer, Strigari...]



[Profumo, Sasaki, Takada...]



[Ali-Haimoud, Bird, Byrnes, Garcia-Bellido, Kamionkowski, Kovetz, Riotto, Sasaki, Silk...]



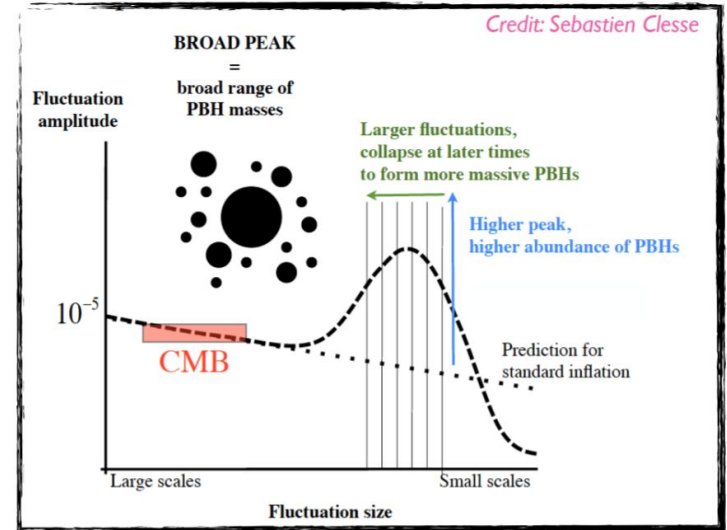
[Ali-Haimoud, Carr, Kamionkowski, Kohri, Mack, Ostriker, Ricotti...]

“Standard” PBH Formation

- Big perturbations enter horizon → collapse [Carr, Kamionkowski, Kawasaki, Sasaki, Silk, Yanagida...]

$$M_H \approx \frac{c^3 t}{G} = 10^{15} \text{ g} \left(\frac{t}{10^{-23} \text{ s}} \right)$$

- Need to fine tune inflaton potential
→ sensitive to restrictions on field behavior
- Example: “string swampland conjectures”
[Kawasaki, VT, PRD, 1810.02547]

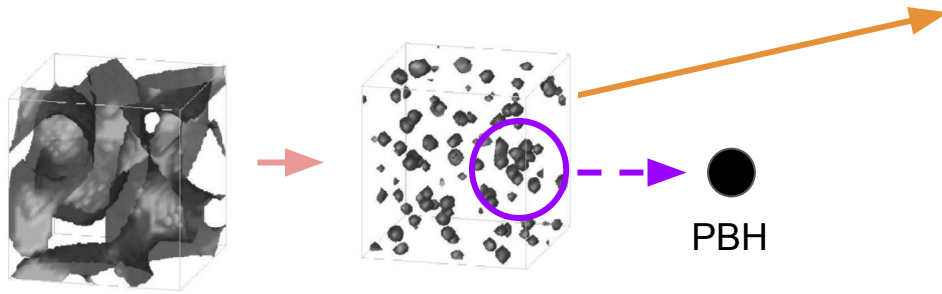


→ many formation mechanisms: e.g. domain walls & string loops [Deng, Ferrer, Garriga, Khlopov, Hawking, Vilenkin...]

Distinct PBH Features Possible

scalar fragmentation

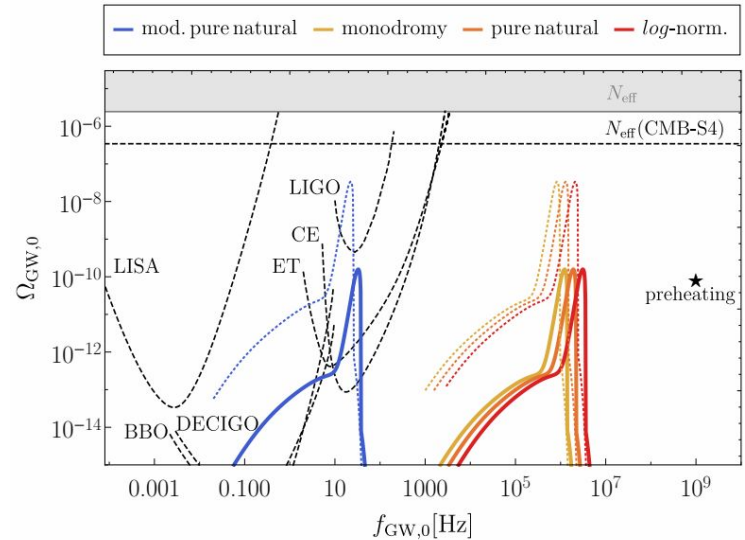
enhanced GWs from inflaton oscillon decays
→ novel probe of inflationary physics



PBHs peaked in mass
+ potential big spin

oscillons from inflaton

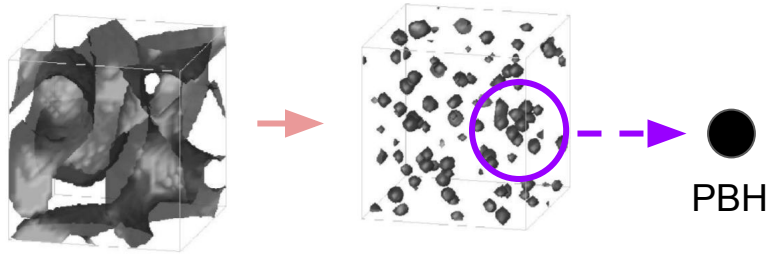
[Cotner, Kusenko, VT, *PRD*, 1801.03321;
Cotner, Kusenko, Sasaki, VT, *JCAP*, 1907.10613]



[Lozanov, VT, 2204.07152]

Distinct PBH Features Possible

scalar fragmentation

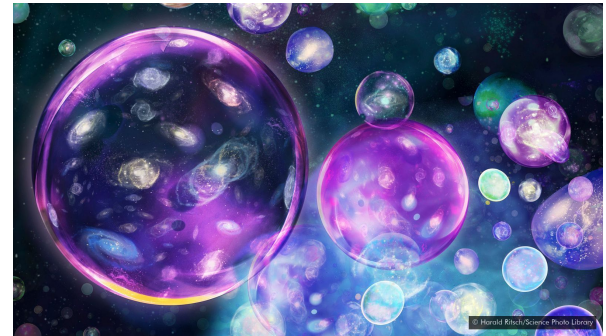


**PBHs peaked in mass
+ potential big spin**

oscillons from inflaton

[Cotner, Kusenko, **VT**, *PRD*, 1801.03321;
Cotner, Kusenko, Sasaki, **VT**, *JCAP*, 1907.10613]

vacuum bubble “multiverse”

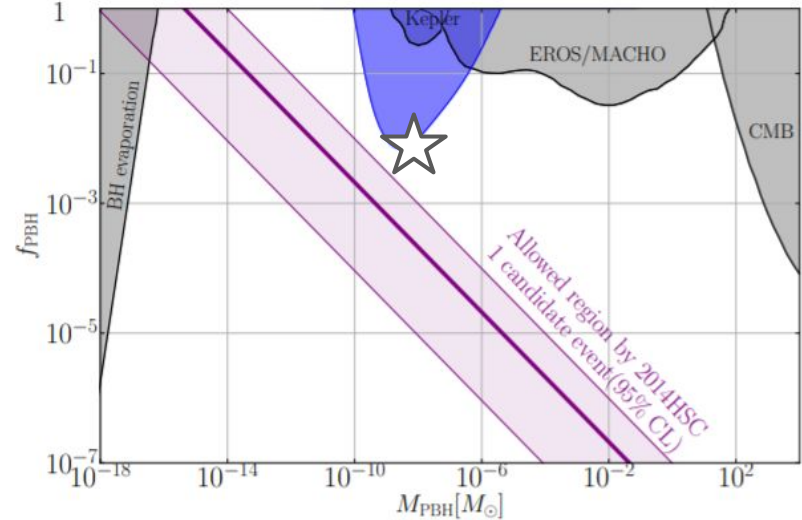
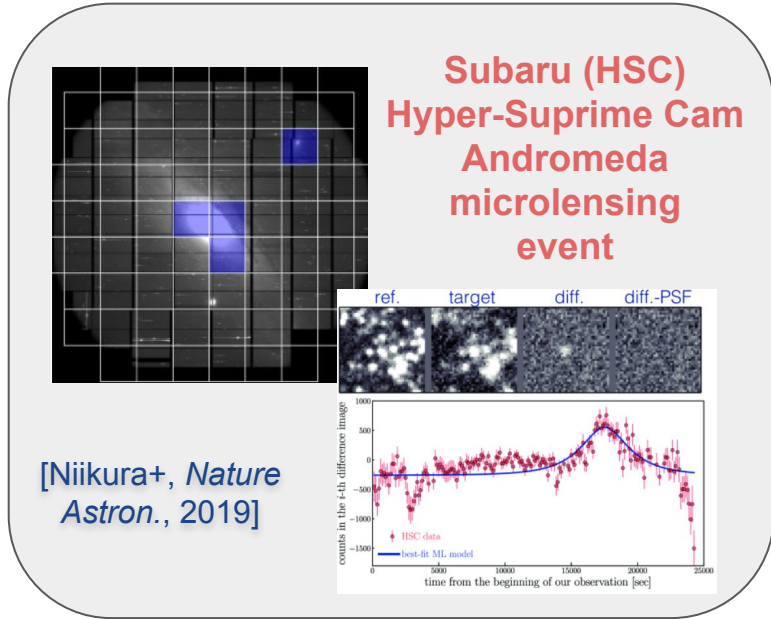


**PBHs broadly
distributed in mass**

[Deng, Sasaki, Vilenkin...;

[Kusenko, Sasaki, Sugiyama, Takada, **VT**,
Vitagliano, *PRL*, 2001.09160]

PBH DM from Bubble Multiverse: Detected by HSC ?!



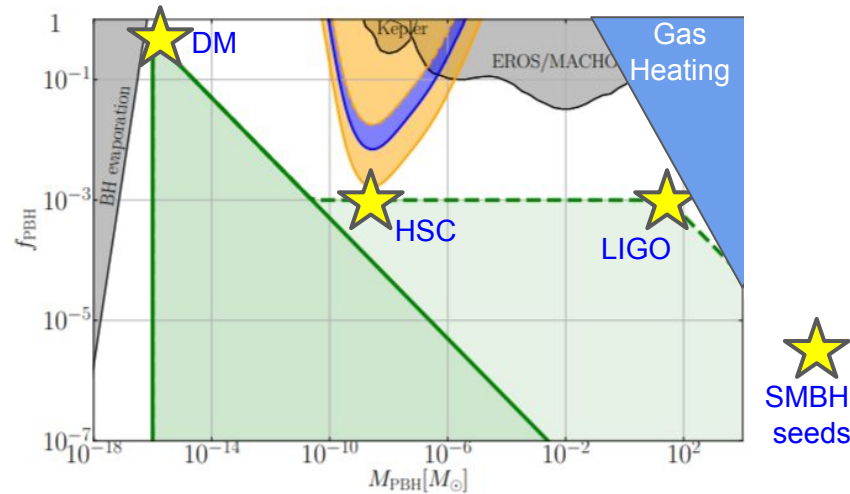
- **PBH DM from bubble multiverse consistent with detected HSC event !**

→ *tail of broad PBH distribution allows for indirect test of open DM window*

[Kusenko, Sasaki, Sugiyama, Takada, VT, Vitagliano, *PRL*, 2001.09160]

PBH DM from Bubble Multiverse: Detected by HSC ?!

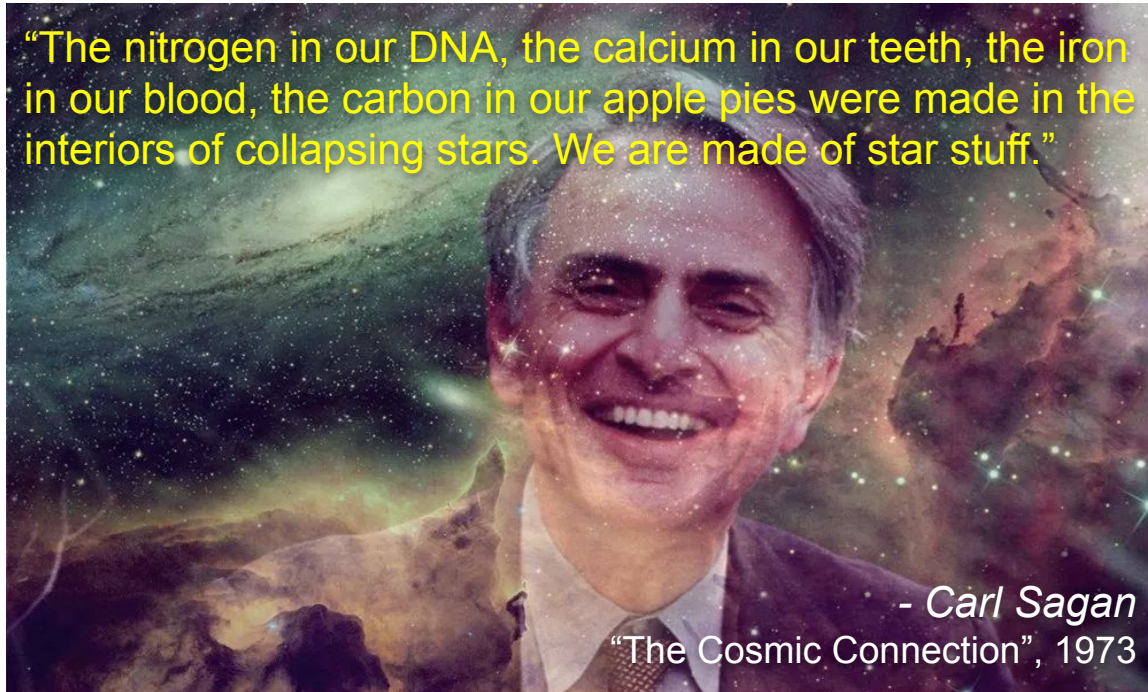
- Generalized model explains many observables simultaneously (DM, LIGO, SMBH seeds...)



*** indirectly test NANOGrav
GWs with HSC via PBHs
[Sugiyama, VT+, PLB,
2010.02189]

- Will be definitively tested with new HSC data !

[Kusenko, Sasaki, Sugiyama, Takada, VT, Vitagliano, PRL, 2001.09160]

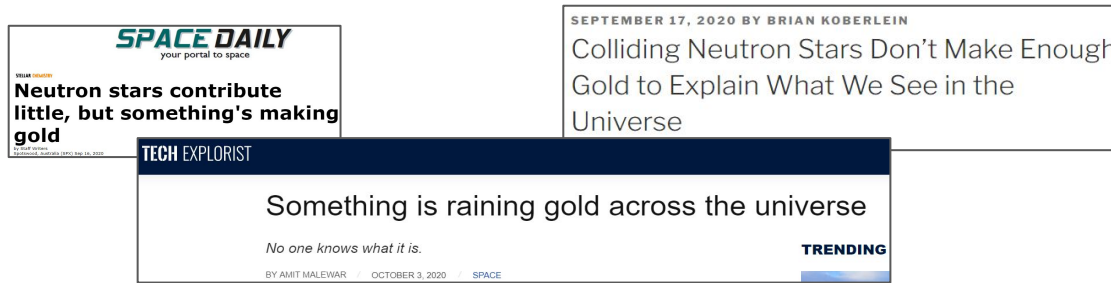


Where do heavy elements (gold) come from?
→ **major problem**

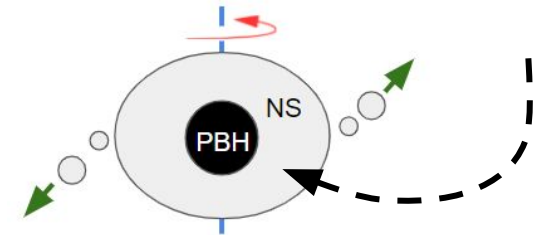
Making Gold with Tiny PBHs

- Origin of heavy elements (gold) long-standing problem

→ *neutron star mergers great, but might not be enough* e.g. [Kobayashi+, 2020]



- **Elegant solution: asteroid-mass PBHs making DM**
captured by neutron stars, small PBHs eat & explode them
→ “r-process nucleosynthesis” factories



[Fuller, Kusenko, VT, PRL, 1704.01129] + Viewpoint Highlight by H.-T. Janka

Neutron Stars (+ White Dwarfs) as PBH Laboratories

“orphan kilonova” without gravitational waves

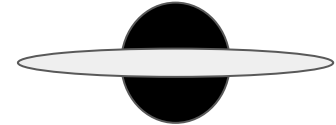


UC Berkeley: Makasdj

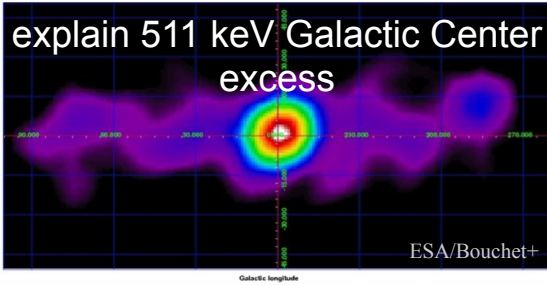
Fast Radio Burst



If **disk + BH** remains →
“orphan Gamma-ray Burst”
without gravitational waves
[VT, PLB, 1710.09458]



explain 511 keV Galactic Center excess

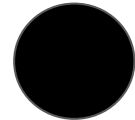
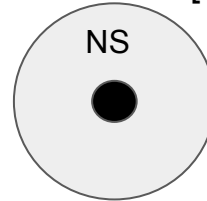


ESA/Bouchet+

*** can explain with regular NS-NS

[Fuller, Kusenko, Radice, VT,
PRL, 1811.00133]

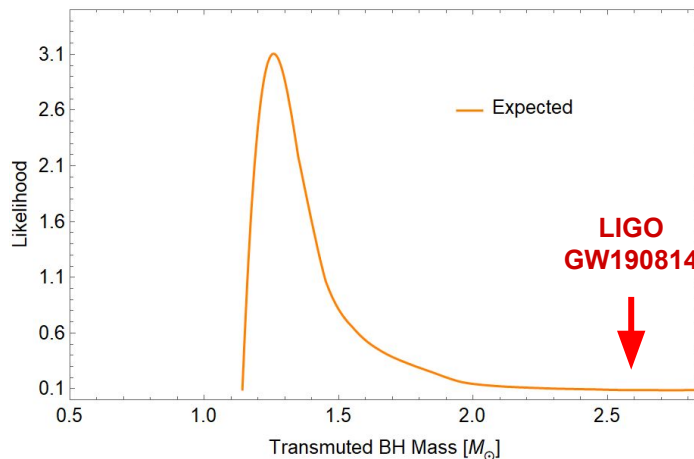
“Transmuted” population of solar-mass BHs
[VT, PLB, 1707.05849]



[Fuller, Kusenko, VT, PRL, 1704.01129; VT, PLB, 1707.05849; VT, PLB, 1710.09458]

Origin of Solar-mass Black Holes

- Solar-mass ($\sim 1\text{-}2.5 M_{\odot}$) BHs unexpected in astrophysics \rightarrow PBHs ? Transmuted?
- **LIGO detected candidate event** [Abbott+, *ApJL*, 2020...] ...**how to tell BH origin ?**
- **Solution:** *transmuted* BHs from PBHs (or particle) DM eating NSs follow NS mass distribution

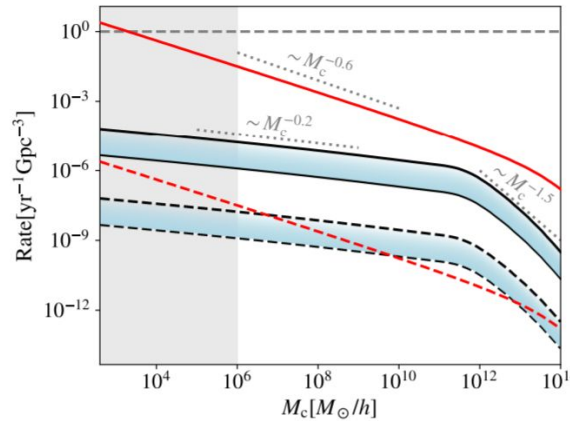
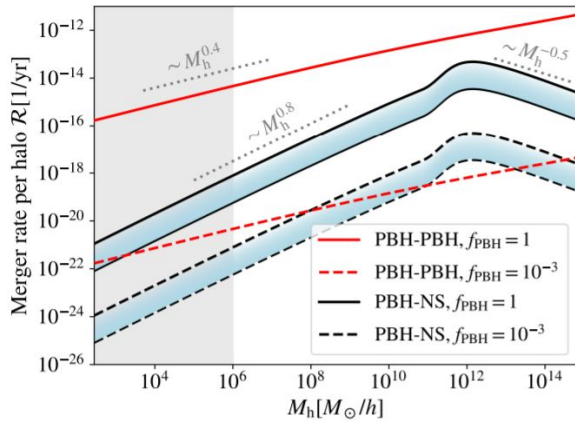


Large ($> 1.5 M_{\odot}$) candidates unlikely to be transmuted BHs!

[VT+, *PRL*, 2008.12780]

Identifying Black Hole - Neutron Star (BH-NS) Mergers

- PBH-PBH been linked with LIGO BH-BH GW events [Byrnes, Kamionkowski, Riotto, Sasaki ...]
- **First reported BH-NS candidates by LIGO** [Abbott+, *ApJL*, 2021...] *....from PBHs?*
- Unlike PBH-PBH, PBH-NS can only form after star formation



PBH-NS rates subdominant

→ **NS-BH are astrophysical**

*** even if PBH-PBH significant**

[Sasaki, VT, Vardanyan, Zhang, *ApJ*, 2110.09509]

Are Intermediate-mass BHs Primordial ?

- GW190521 event $\sim 150 M_{\odot}$ merger mass [Abbott+, *PRL*, 2020], first definitive IMBH detection
- **New general cosmology-independent observable:** interactions and **heating** of gas
- Gas heating mechanisms:
 - gravitational drag (dynamical friction)
 - accretion disk photons
 - accretion outflows / winds
- Great testing site: dwarf galaxies (Leo T)

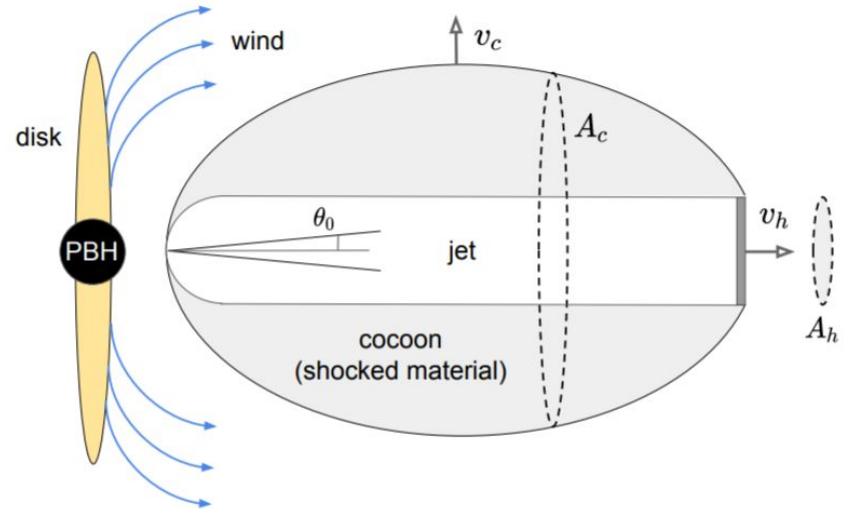
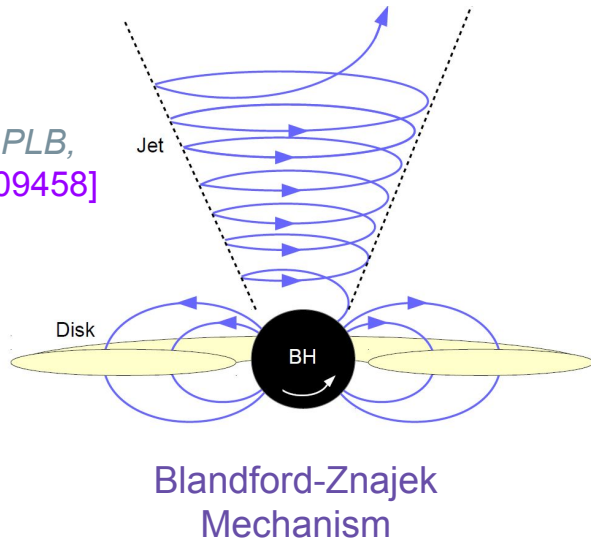


[Lu, VT+, *ApJL*, 2007.02213; VT, Lu+, *JCAP*, 2105.06099]

PBH Outflow Winds and Jets

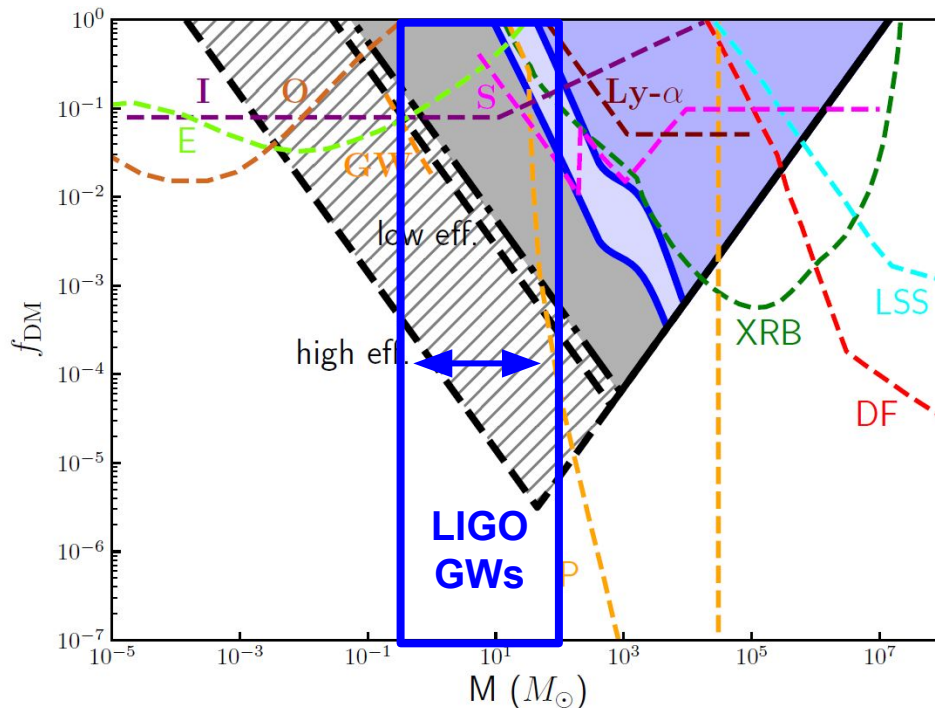
- Outflow winds and powerful jets (especially for spinning PBH) expected to deposit efficiently significant energy via shock heating $L \sim \epsilon \dot{M}$

[VT, PLB,
1710.09458]



[VT, Lu, Murase, Inoue, Gelmini, 2111.08699]

PBH Outflow Winds and Jets



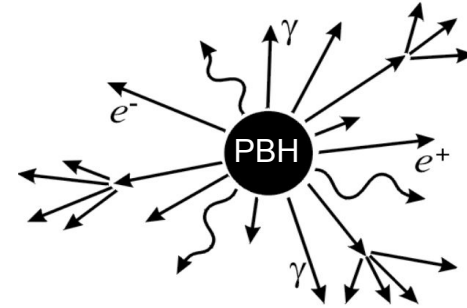
* gas heating from evaporating PBHs

[Laha, Lu, VT, PLB, 2009.11837]
(also [Kim, 2020])

[VT, Lu, Murase, Inoue, Gelmini, 2111.08699]

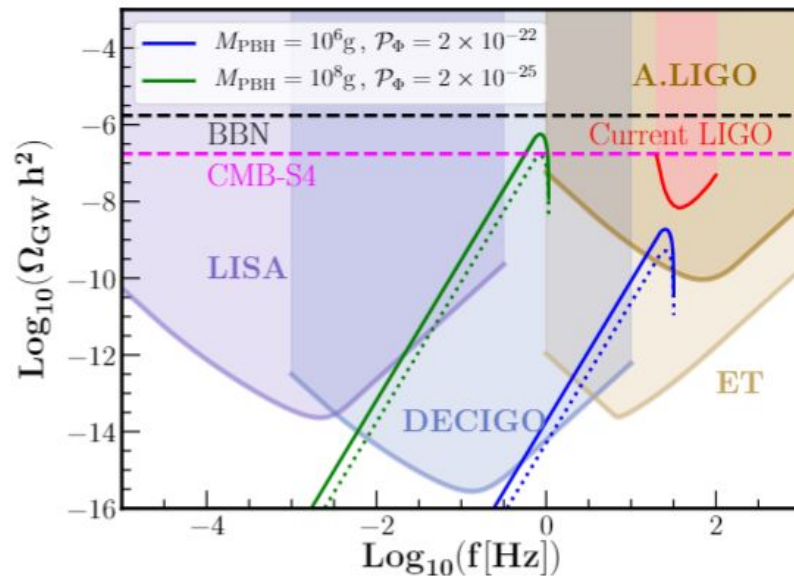
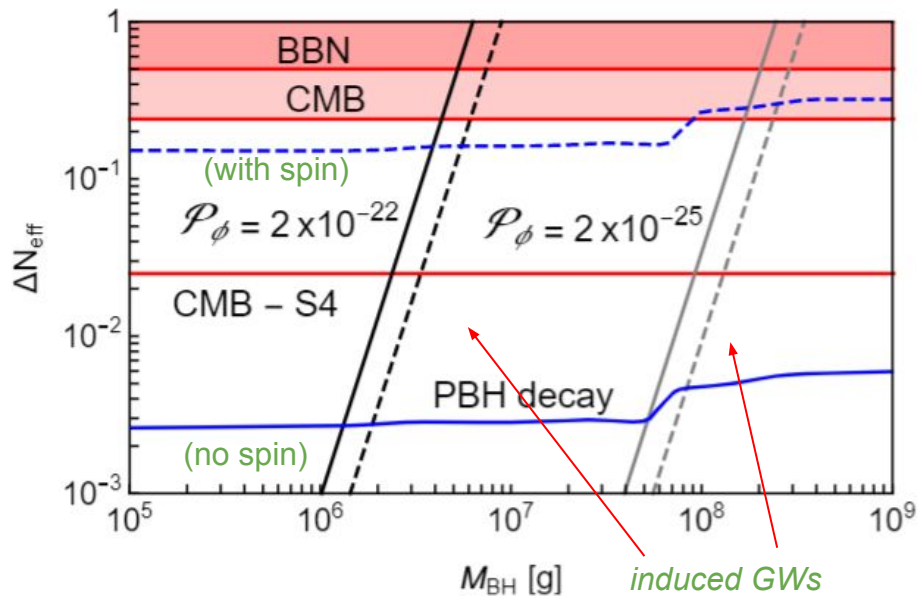
Exploring Evaporating PBHs with GWs

- Evaporating PBHs with mass $\lesssim 10^9$ g unconstrained, [how to explore scenarios ?](#)



- Evaporating PBH emission products \rightarrow “dark radiation” \rightarrow change ΔN_{eff}
 - PBH *spin* distribution can significantly modify [Hooper, Krnjaic, March-Russell, McDermott, 2020; Arbey, Auffinger+, 2021; Masina, 2021]
- Rapid evaporation of PBHs dominating Universe \rightarrow induced GWs \rightarrow change ΔN_{eff}
 - PBH *mass* distribution can significantly modify [Inomata, Kohri+, 2019; Papanikolaou, Vennin+, 2020; Domenech, Lin, Sasaki, 2020...]

Exploring Evaporating PBHs with GWs

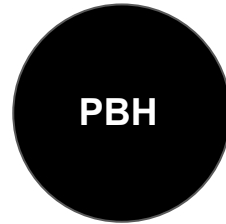


→ **Coincidence signals allow probing many scenarios over broad mass-range !**

[Domenech, VT, Sasaki, *PLB*, 2105.06816]

Summary

- Renaissance era in PBH research
- Strong synergy with observational (especially multi-messenger) astrophysics
- Many new ideas emerging for PBH production, signals, solutions to old puzzles



... Dark Matter ?