

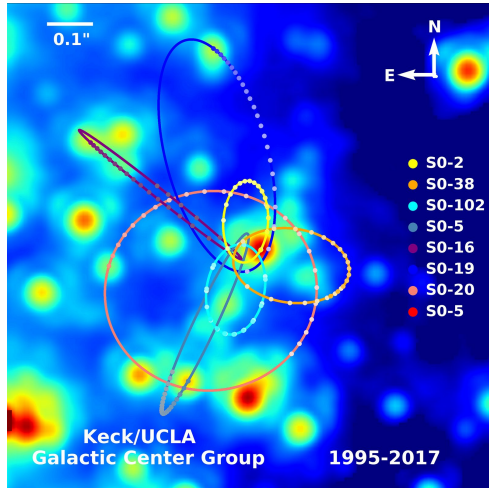
Primordial Black Holes as Dark Matter

Volodymyr Takhistov

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

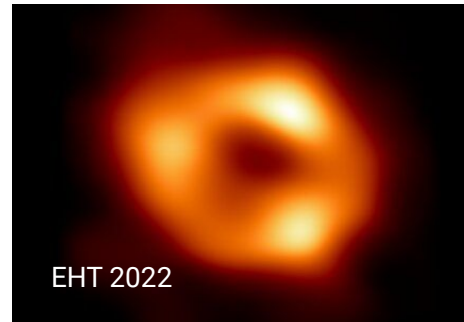


Black Holes **Definitively Exist**, Central in Astronomy

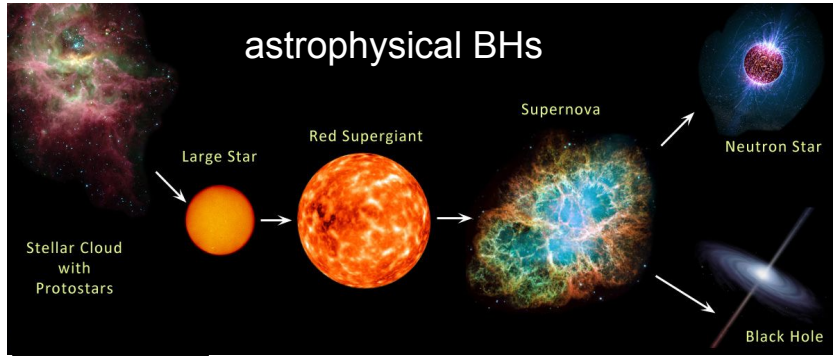


Sgr A*
Milky Way

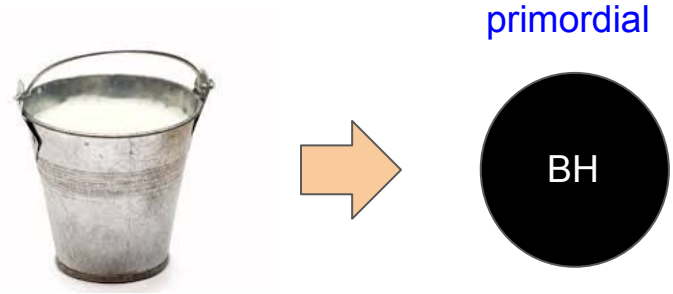
BH binary merger



Primordial Black Holes (PBHs)



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



PBHs as dark matter

... a ***“Standard Model”*** candidate, but benefits from beyond SM physics



PBHs conceptually distinct from particle dark matter

Very active rapidly developing field, hard to cover everything in half-hour...selective topics

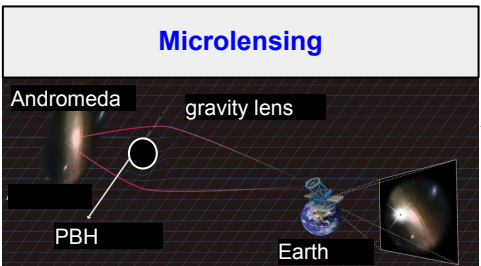
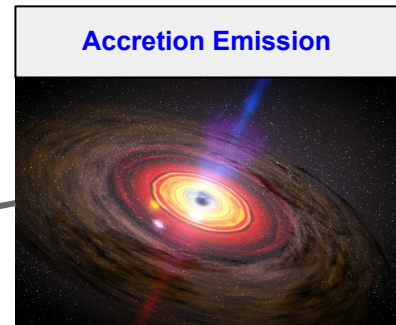
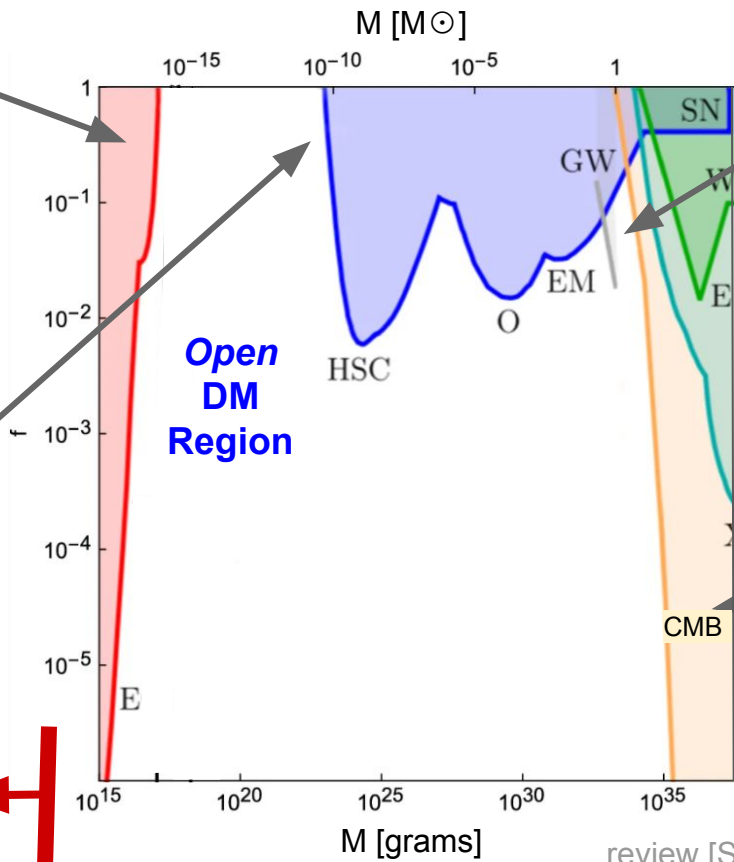
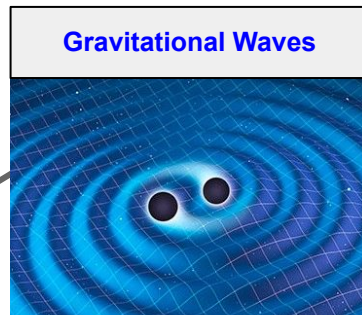
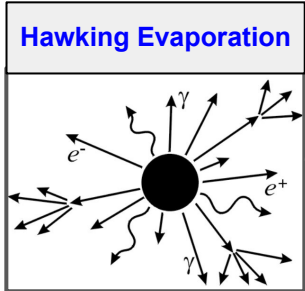
iNSPIRE search
“primordial black hole”

~1500 papers !



Many great contributions are from UCLA Dark Matter 2023 participants

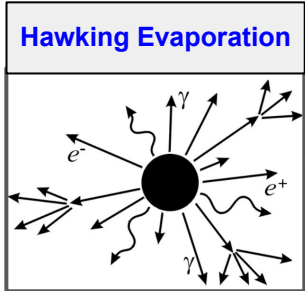
PBH DM Status



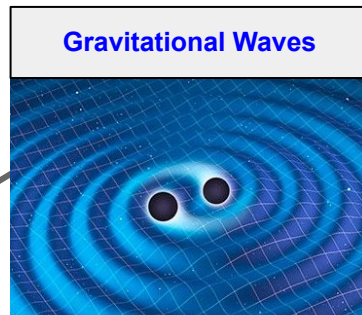
Particle DM from PBHs, Extremal BHs, PBH Baryogenesis...

review [Sasaki+, 2017; Carr+, 2020, Green+, 2020...]

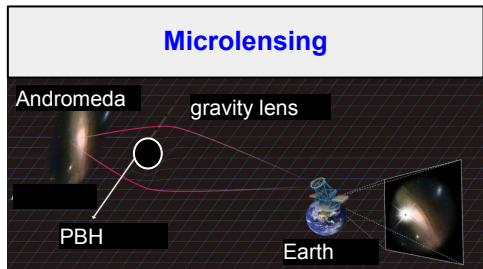
PBH DM Status



[Slatyer, Profumo, Cirelli, Dutta, Carr, Ballesteros, Auffinger, Graham, Kohri, Laha, Munoz...]



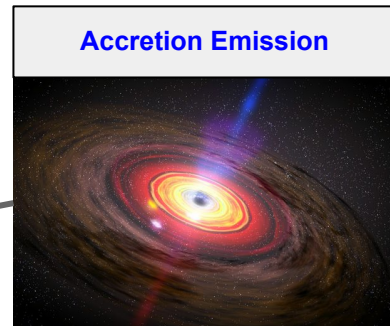
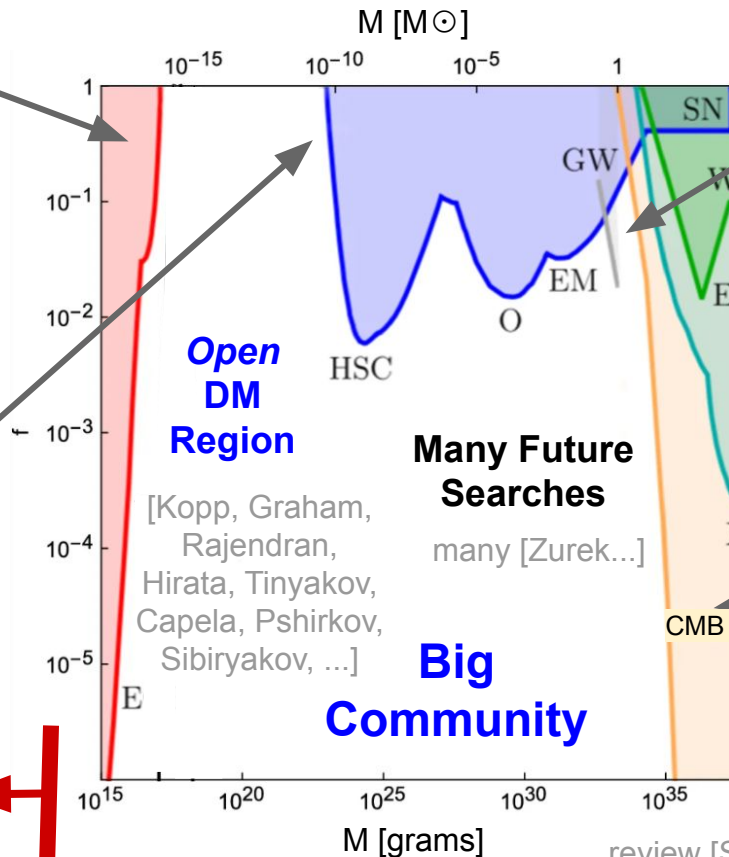
[Riotto, Kovetz, Bird, Kamionkowski, Garcia-Bellido, Sasaki, Byrnes, Boehm, Kobakhidze, Hutsi, Vaskonen, Picker...]



[Takada, Sasaki, Profumo...]

Particle DM from PBHs, Extremal BHs, PBH Baryogenesis...

[Silk, Dolgov, Hooper, Krnjaic, Gondolo, Turner, Sasaki...]

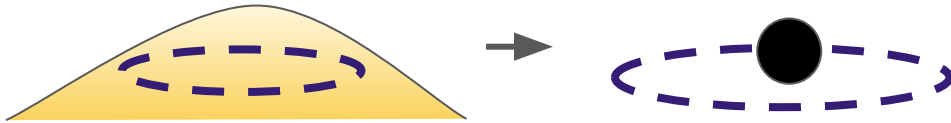


[Carr, Ricotti, Ostriker, Mack, Ali-Haimoud, Kamionkowski, Kohri...]

review [Sasaki+, 2017; Carr+, 2020, Green+, 2020...]

“Standard” PBH Formation

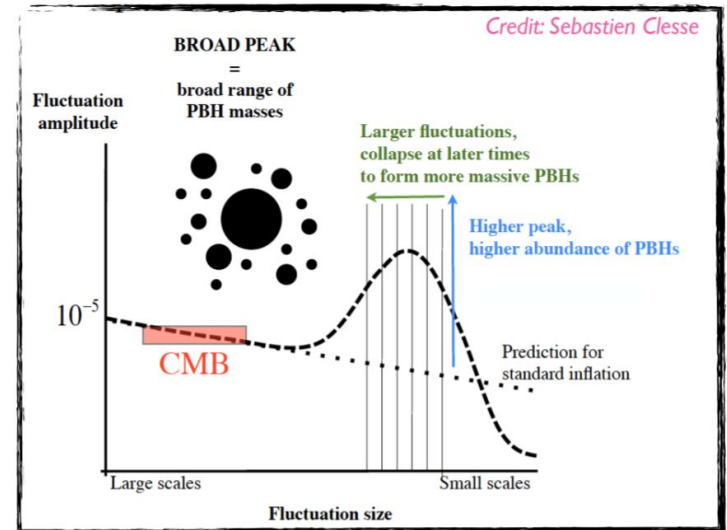
- Big perturbations ($\delta \sim 1$) enter horizon \rightarrow collapse [Carr, Kawasaki, Sasaki, Riotto...]



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

- Need to tune inflaton potential
 \rightarrow sensitive to restrictions on field behavior
- Example: “string swampland conjectures”
[Kawasaki, VT, PRD, (2018) 1810.02547]

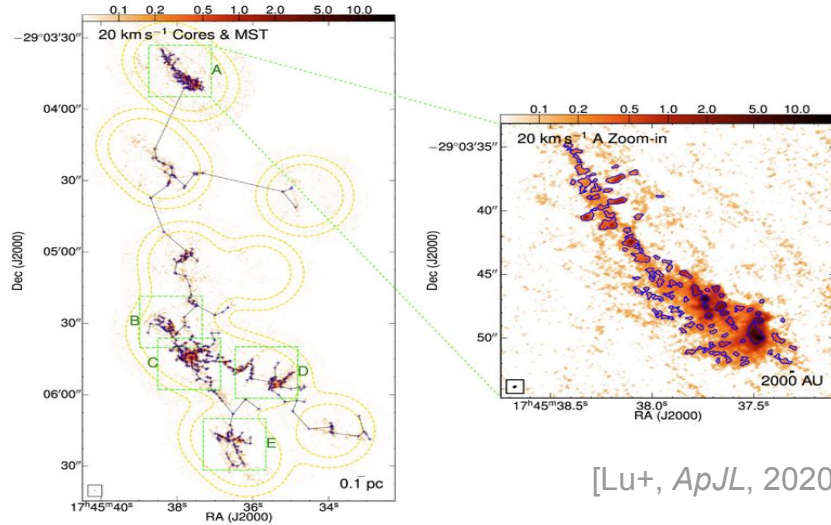
Very many PBH formation scenarios...



Distinct PBH Features Possible, Some Examples

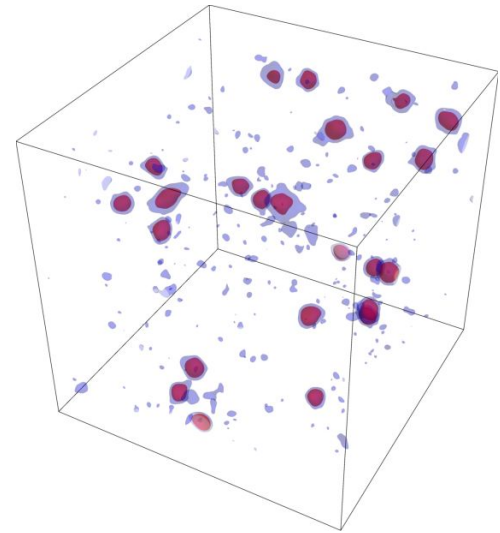
In early Universe, attractively self-interacting scalar fields can fragment into solitonic “lumps”

Jeans fragmentation analogy
(massive molecular Galactic Center clouds)



[Lu+, *ApJL*, 2020]

oscillon fragmentation
(string moduli fields)

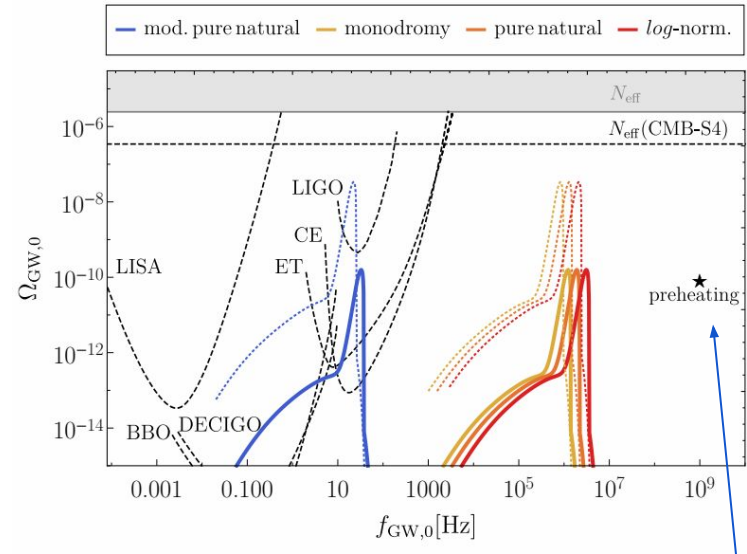
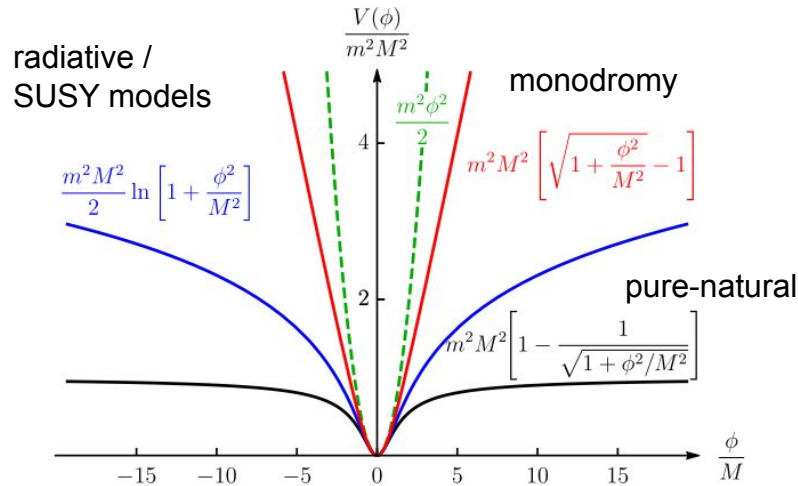


[Antusch+, 2017]

Distinct PBH Features Possible, Some Examples

In many theories inflaton can break to oscillons \rightarrow decays result in dramatically enhanced GWs

\rightarrow new route to probe inflationary physics independent of CMB!

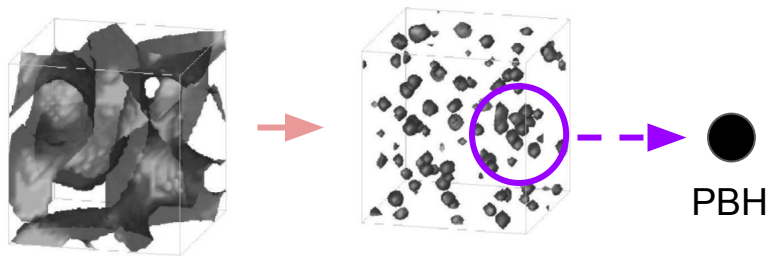


[Lozanov, VT, *Phys.Rev.Lett.* (accepted), (2022) 2204.07152]

\sim Old GW results

Distinct PBH Features Possible, Some Examples

scalar fragmentation



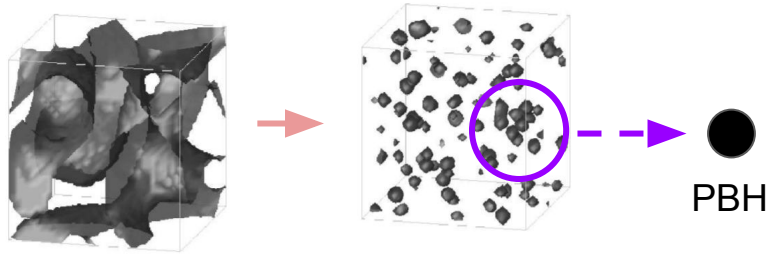
**PBHs peaked in mass
+ big spin possible**

inflaton oscillons

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

Distinct PBH Features Possible, Some Examples

scalar fragmentation

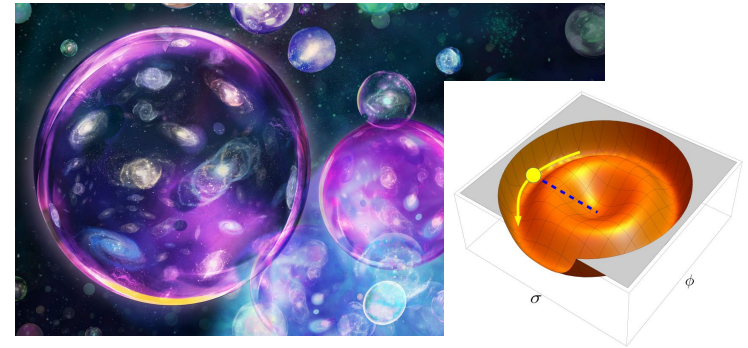


**PBHs peaked in mass
+ big spin possible**

inflaton oscillons

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

vacuum bubble “multiverse”

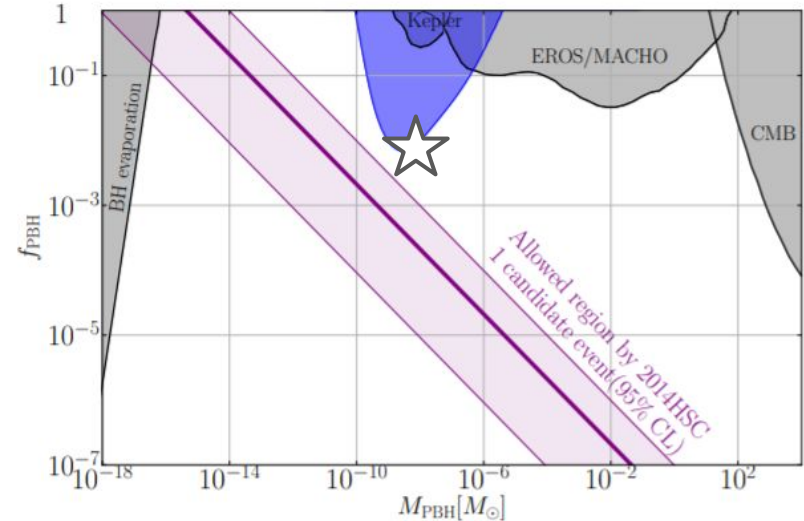
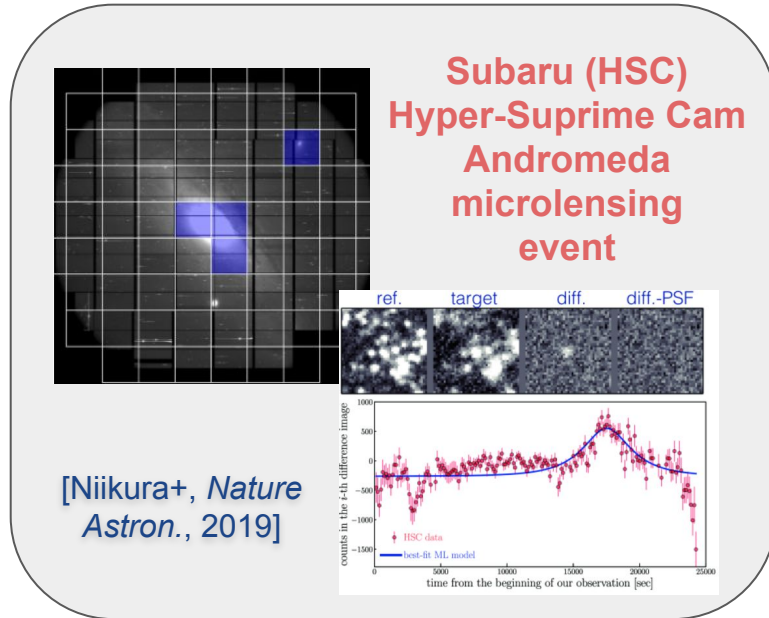


**PBHs broadly
distributed in mass**

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

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

Distinct PBH Features Possible, Some Examples

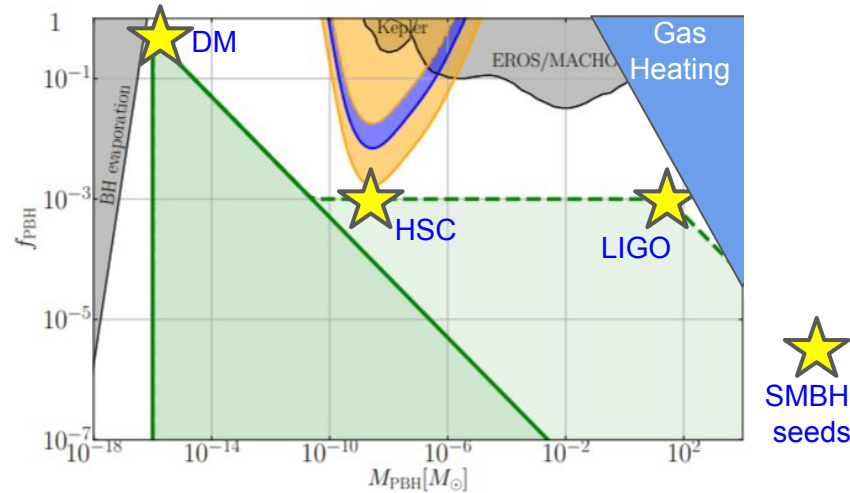


- **PBH DM from bubble multiverse consistent with detected HSC event**

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

Distinct PBH Features Possible, Some Examples

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



- Will be definitively tested with new HSC data !

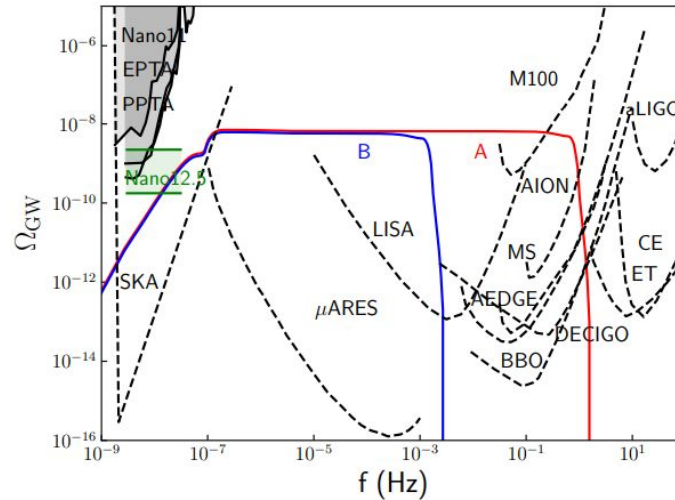
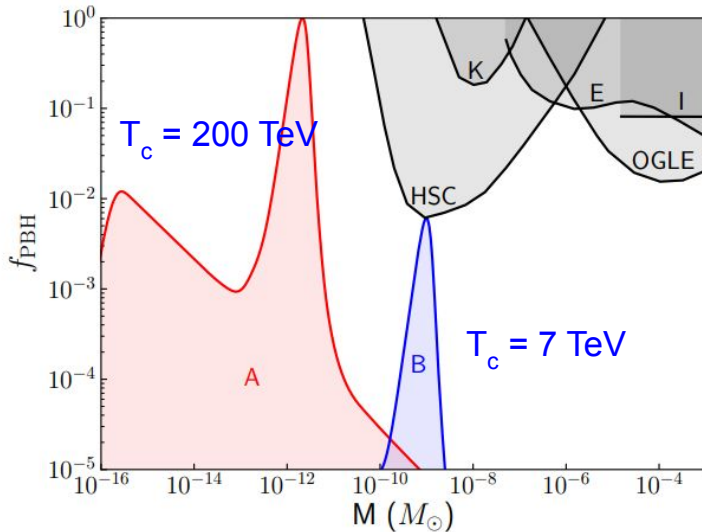
[Kusenko, Sasaki, Sugiyama, Takada, VT, Vitagliano, *Phys.Rev.Lett.*, (2020) 2001.09160]

Distinct PBH Features Possible, Some Examples

Strong force could be very different in early Universe, with high-T QCD phase transition

[Ipek, Tait, 2018]

PBHs from high-T QCD transition **CAN** be all of DM & associated GWs explain NANOGrav excess
 → very different from ~solar-mass PBHs associated with SM QCD transition, *cannot* be all DM

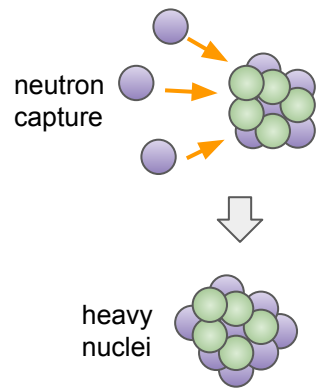


PBHs excellent proxies for exploring fundamental physics in unique ways

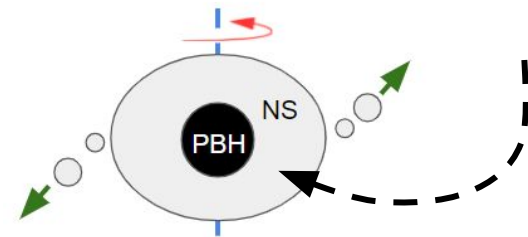
[Lu, VT, Fuller, (2022) 2212.00156]

Making Gold with Tiny DM PBHs

- Can asteroid-mass PBH DM in open window help solve major puzzles?
- Origin of heavy elements (gold) major 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, *Phys.Rev.Lett.*, (2017) 1704.01129] + Viewpoint Highlight by H.-T. Janka

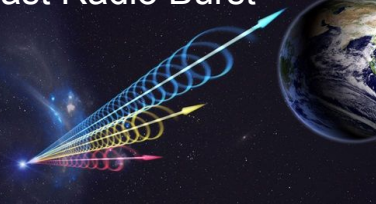
Neutron Stars (+ White Dwarfs) as PBH Laboratories

“orphan kilonova” without gravitational waves

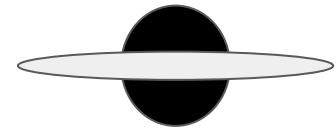


UC Berkeley: Makasdjian/

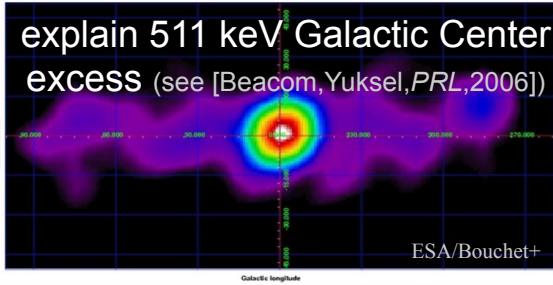
Fast Radio Burst



If disk + BH remains →
“orphan Gamma-ray Burst”
without gravitational waves
[VT, PLB, (2017) 1710.09458]



explain 511 keV Galactic Center
excess (see [Beacom, Yuksel, PRL, 2006])

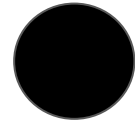
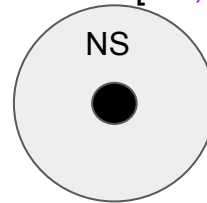


ESA/Bouchet+

*** can explain with regular NS-NS

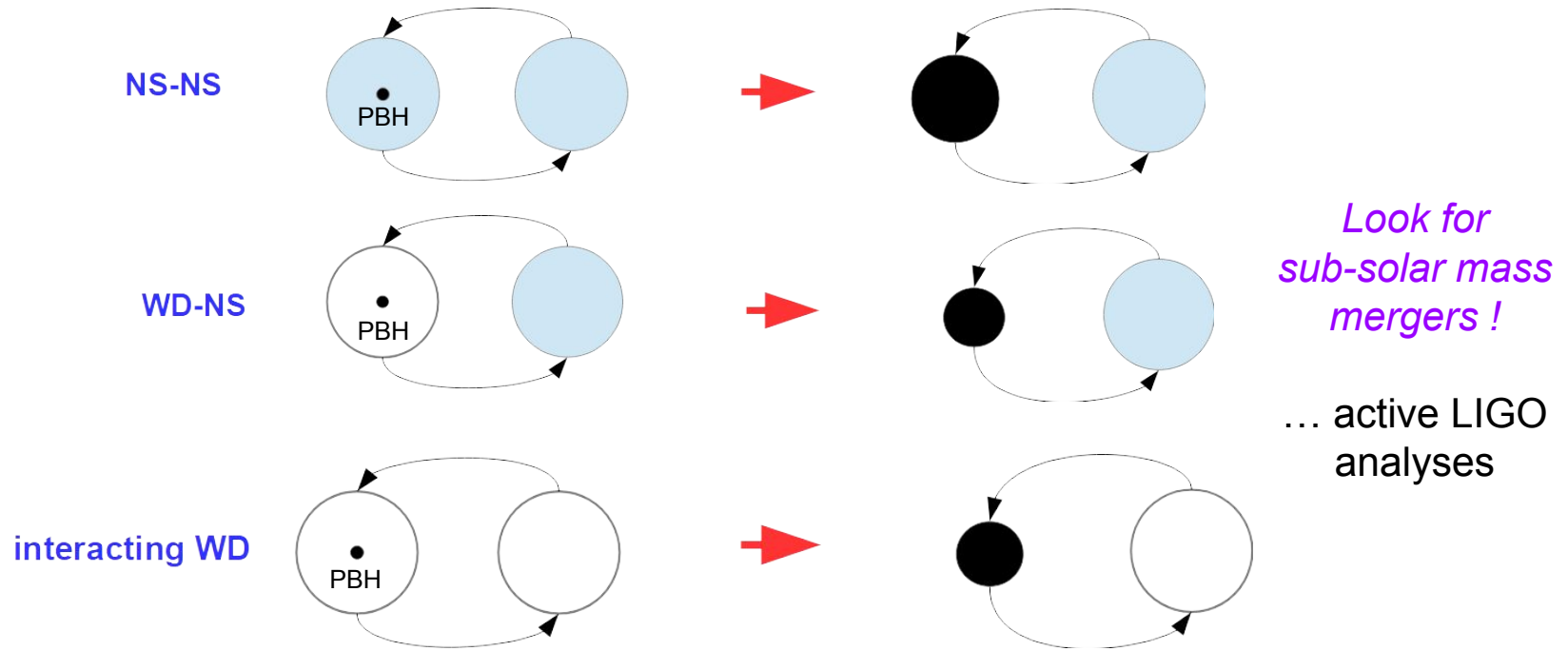
[Fuller, Kusenko, Radice, VT,
Phys.Rev.Lett., (2018) 1811.00133]

“Transmuted” population of solar-mass BHs
[VT, PLB, (2017) 1707.05849]



[Fuller, Kusenko, VT, Phys.Rev.Lett., (2017) 1704.01129; VT, PLB, (2017) 1707.05849; VT, PLB, (2017) 1710.09458]

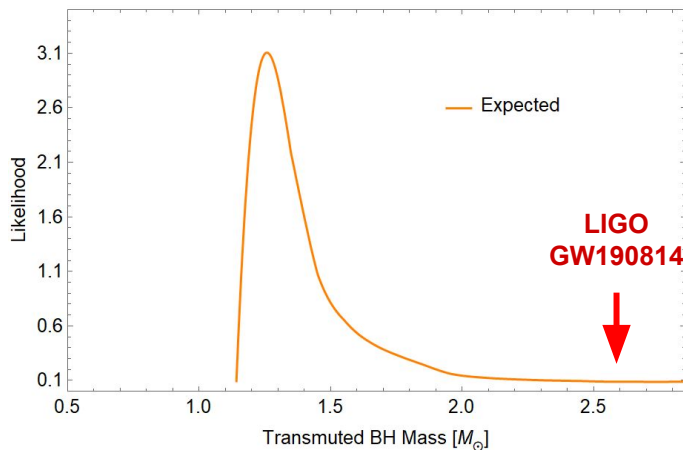
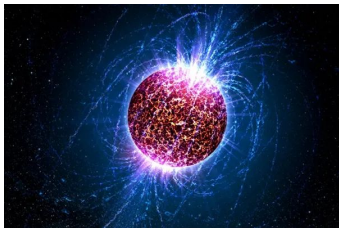
Transmuted Solar-Mass BH Mergers



[VT, PLB, (2017) 1707.05849]

Origin of Solar-mass Black Holes

- Solar-mass ($\sim 1\text{-}2.5 M_{\odot}$) BHs unexpected in astrophysics
→ PBHs ? particle DM accumulation? [Reddy, Baryakhtar, Capela, Tinyakov, Yu, Kouvaris...]
- **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

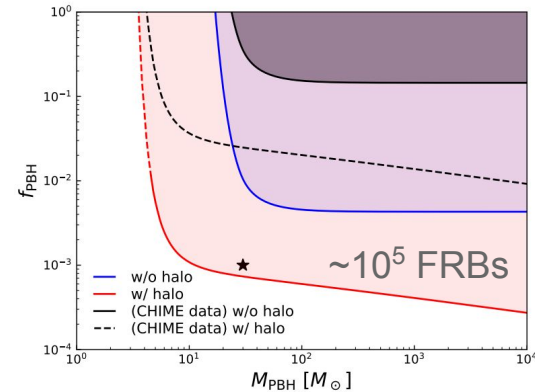
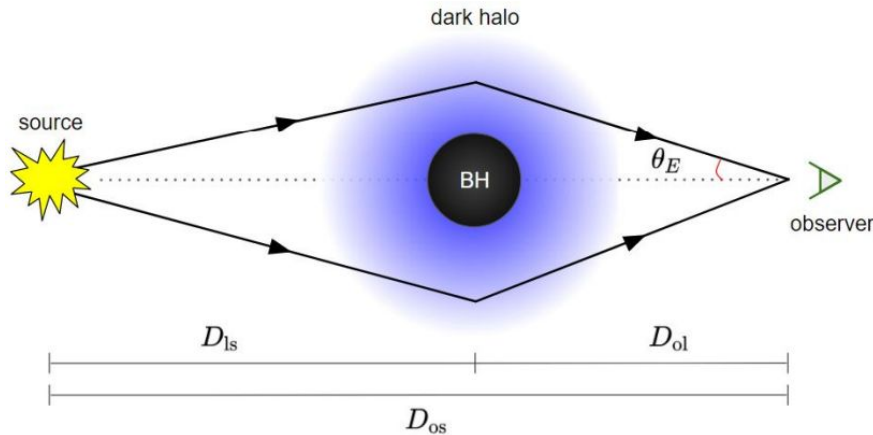


Large ($> 1.5 M_{\odot}$) candidates unlikely to be from DM-NS interactions!

[VT+, *Phys.Rev.Lett.*, (2020) 2008.12780] (follow up: [Dasgupta+, 2020])

Cosmological Lensing, A Novel Test of Dressed PBHs

- Stellar-mass PBHs relevant for LIGO can only comprise subdominant DM
→ engulfed in massive halo dress of primary DM (e.g. axions) [Mack+, 2007; Ricotti+, 2008]
* *PBHs incompatible with annihilating WIMPs* [Lacki, Beacom, *ApJL*, 2010; ...]
- Strong cosmological lensing (e.g. FRBs) **can directly test !**
- **Already start exploring regions with CHIME FRB data, method applicable to other lenses**



[Oguri, VT, Kohri, (2022) 2208.05957]

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)

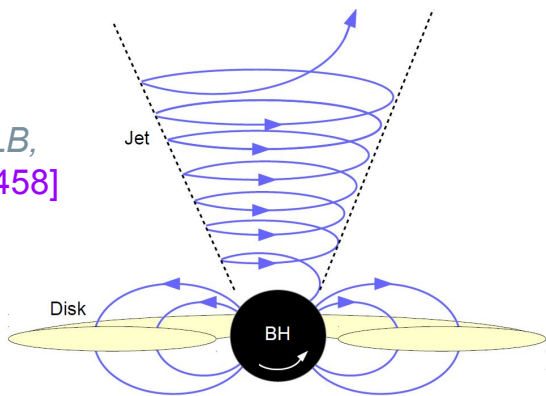


[Lu, VT, Gelmini, Hayashi, Inoue, Kusenko, *ApJ Lett.*, (2020) 2007.02213;
VT, Lu, Gelmini, Hayashi, Inoue, Kusenko, *JCAP*, (2021) 2105.06099]

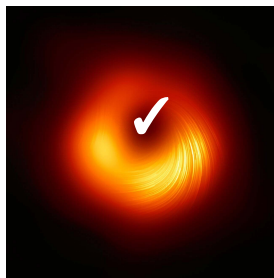
PBH Outflow Winds and Jets

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

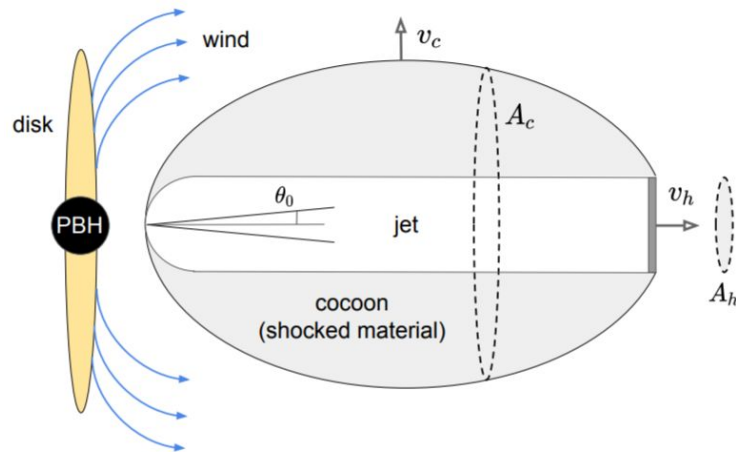
[VT, PLB,
1710.09458]



Blandford-Znajek
Mechanism

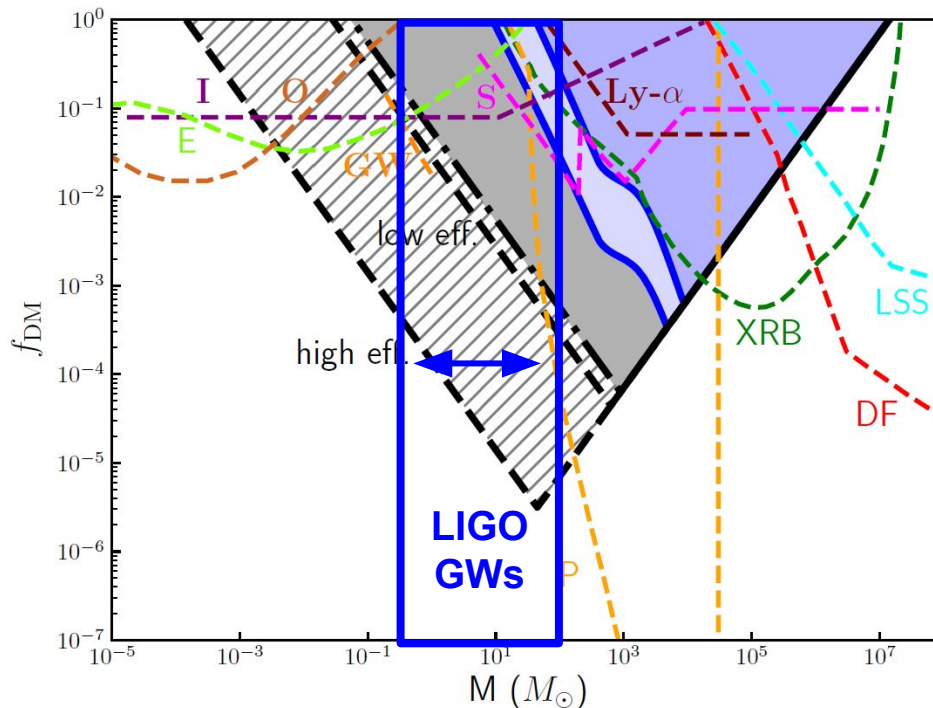


EHT M87
strong B-field + jet



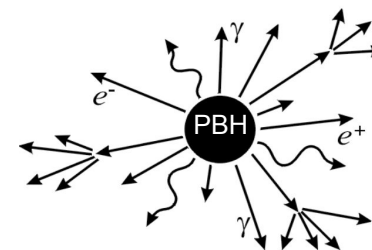
[VT, Lu, Murase, Inoue, Gelmini, *MNRAS Lett.*, (2021) 2111.08699]

PBH Outflow Winds and Jets



* gas heating from evaporating PBHs

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



[VT, Lu, Murase, Inoue, Gelmini, MNRAS Lett., (2021) 2111.08699]

What's Next ?

... broad brush questions on some key aspects

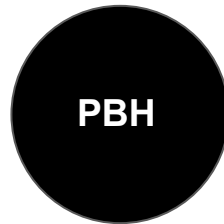
- What are exact PBH predictions from different formation scenarios, can we classify them?
- What different PBH features and connections to major puzzles are possible?
- What are regimes of validity, limitations of existing constraints?
- What are signatures from mixed DM scenarios with PBHs, if PBHs are subdominant DM ?
- What are most promising approaches to explore open PBH DM parameter window(s)?
- What are best observables for distinguishing PBHs with e.g. astrophysical BHs ?
- Lots of upcoming astrophysical data and already hints exist, especially in GWs...

When can we say we found PBHs?

Summary

- PBHs ~ “Standard Model” dark matter, distinct from particle candidates
- Renaissance in the field, special synergy with multi-messenger astro breakthroughs
- Can generically appear in many models, with distinct features
- Connections with long-standing puzzles and numerous signatures

Could be already lurking in data ! → essential to confront new observations



... Dark Matter ?