Primordial Black Hole Dark Matter

New Venues in Formation & Detection

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PBH as DM

- Black holes
  - astrophysical → old stars
  - primordial → early Universe [Zeldovich, Novikov, 1967; Hawking, 1971; Carr, Hawking, 1974]

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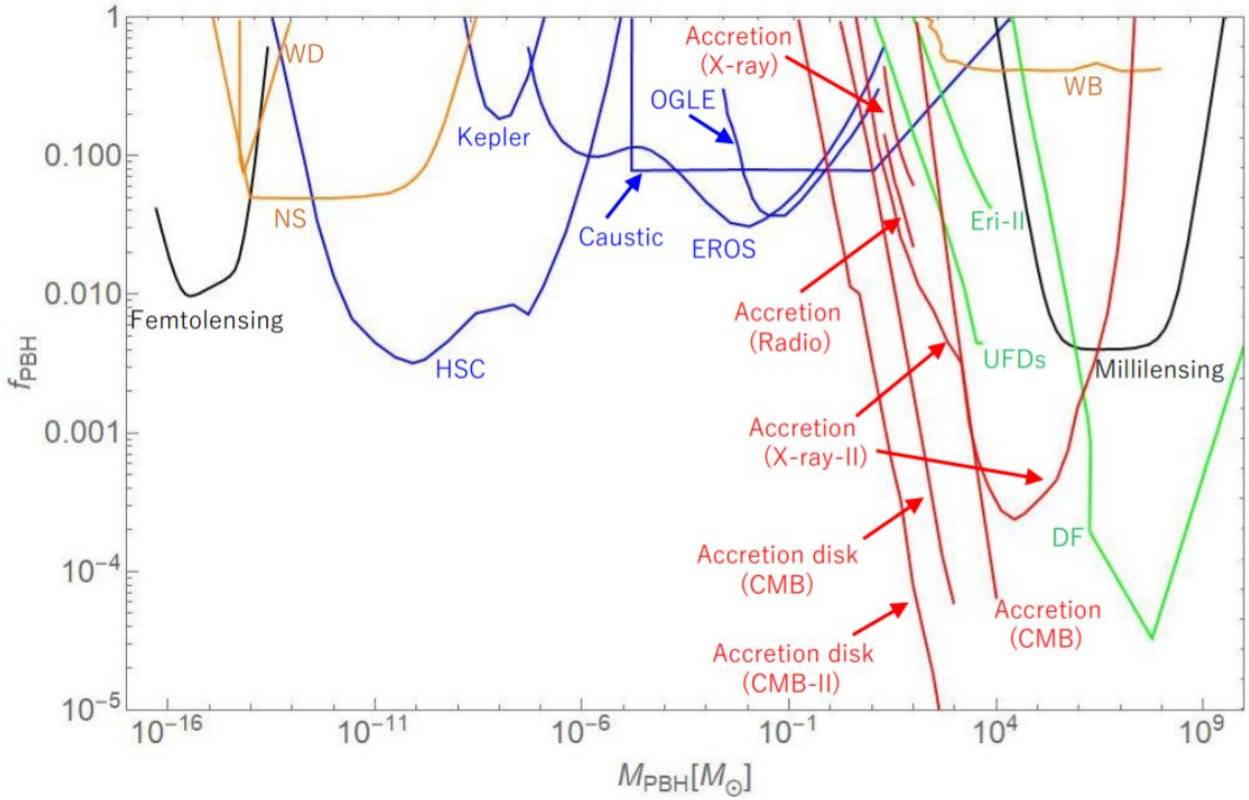
- Why get excited about PBH DM ?
  - no clear signs of particle DM
  - GW astronomy [Bird+ 2016, ...]
  - generic in many BSM models
  - help solve astro puzzles
  - already appear in standard cosmology (but unlikely)

Status (2017)



[Sasaki+, 2017]

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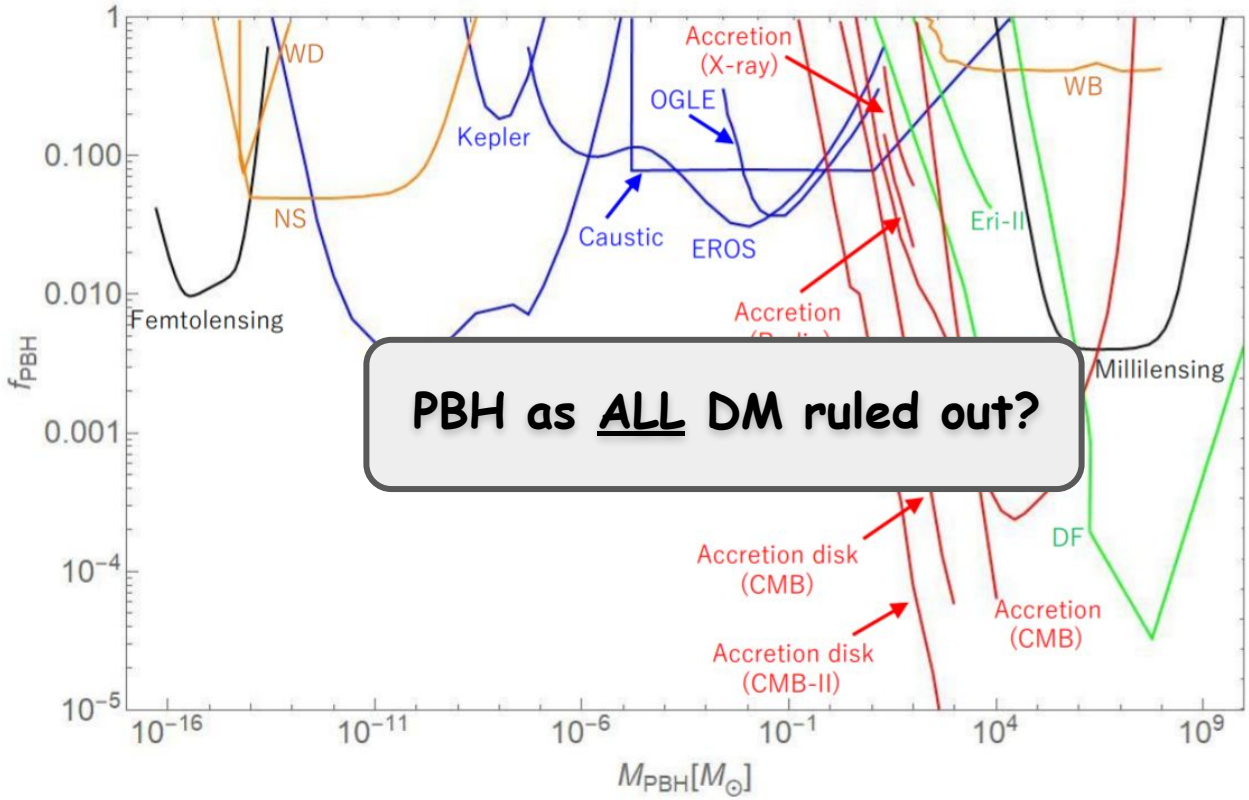
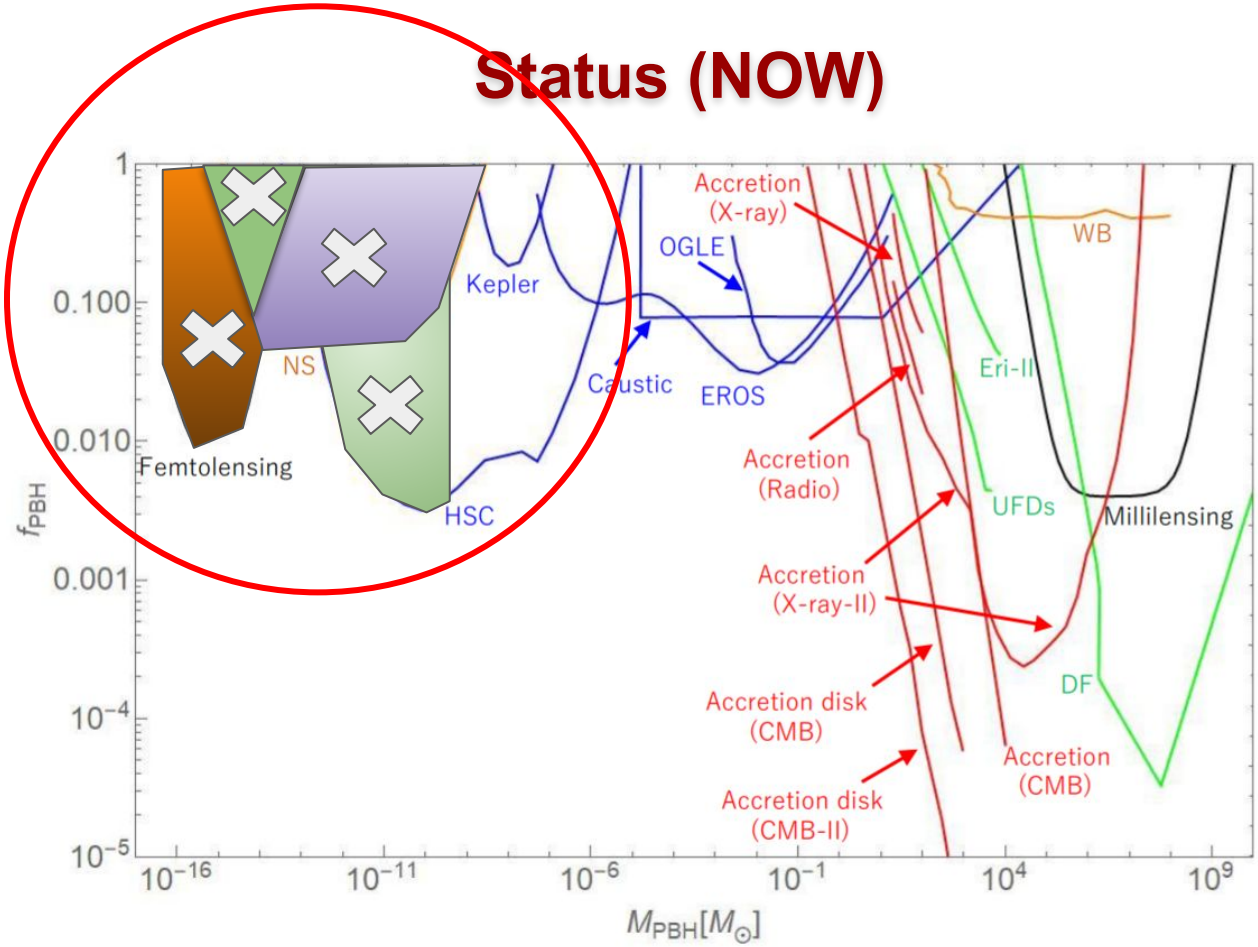


PBH as <u>ALL</u> DM ruled out?

[Sasaki+, 2017]

Status (NOW)



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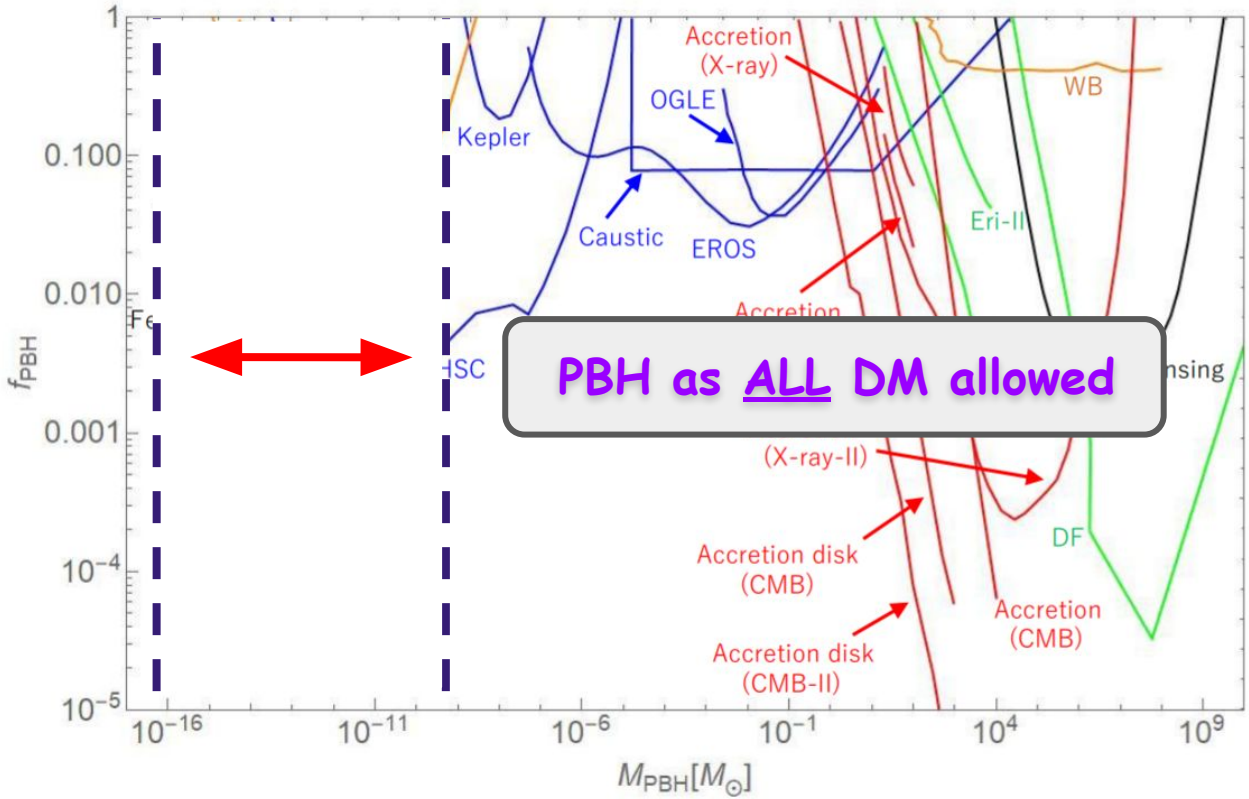


PBH as ALL DM allowed

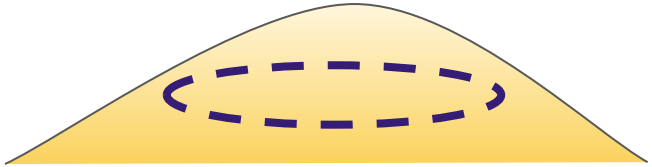
[Sasaki+, 2017]

How do PBHs form?

PBH formation: radiation-dominated era

- THE “standard scenario”: large perturbations ($\delta \sim 1$) enter horizon $\rightarrow$ collapse

[Kawasaki, Sasaki,Yanagida ...]



PBH formation: radiation-dominated era

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[Kawasaki, Sasaki,Yanagida ...]

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[Kawasaki, Sasaki,Yanagida ...]

- Need to fine tune inflaton potential

  $\rightarrow$ sensitive to restrictions on field behavior

  - Example: "string swampland conjectures" [Kawasaki, VT, PRD, 2018]

New generic PBH production mechanism:

scalar field fragmentation

[Cotner, Kusenko, PRL, 2016] - complex field
[Cotner, Kusenko, VT, PRD, 2018] - real field
[Cotner, Kusenko, Sasaki, VT, 2019] - general framework

Scalars in early Universe

- Scalars exist (Higgs) & generic in BSM theories (e.g. moduli)

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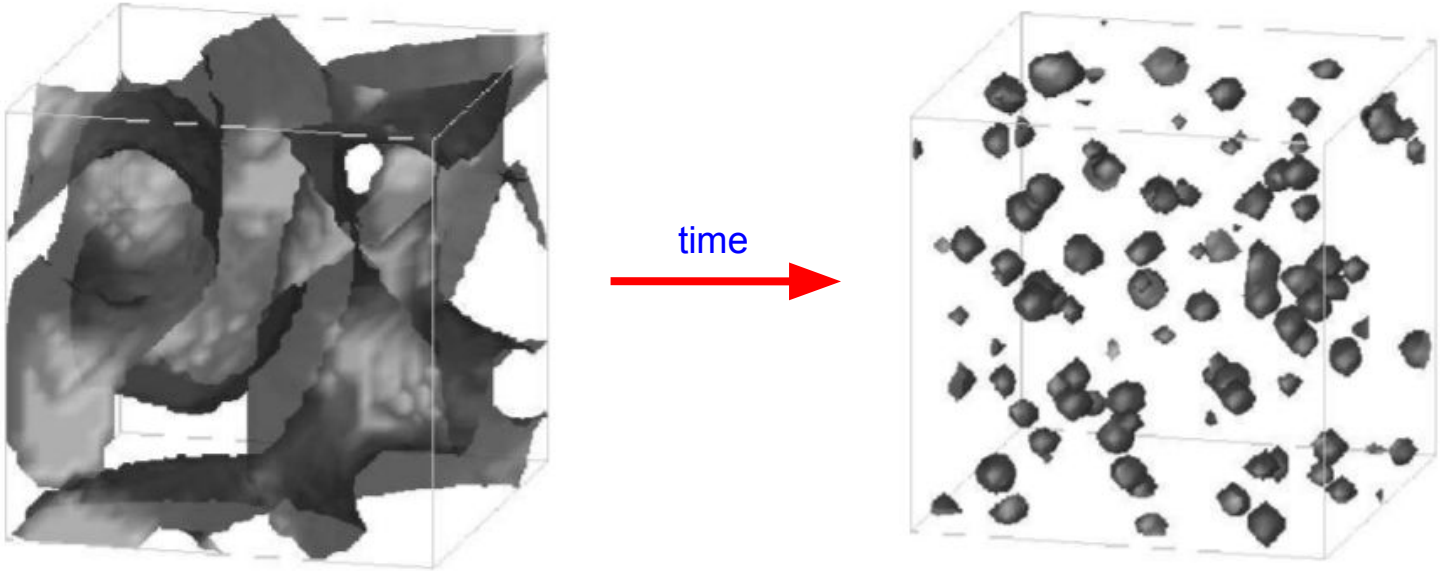
- SUSY predicts many scalars, typically U(1) charged

- Take charged scalar with self-interactions after inflation:
  $\rightarrow$ field can break into piece from instabilities (Q-balls) [Coleman, 1985]

- Lumps are big (% of Horizon) and stable (conserved charge)

Simulations



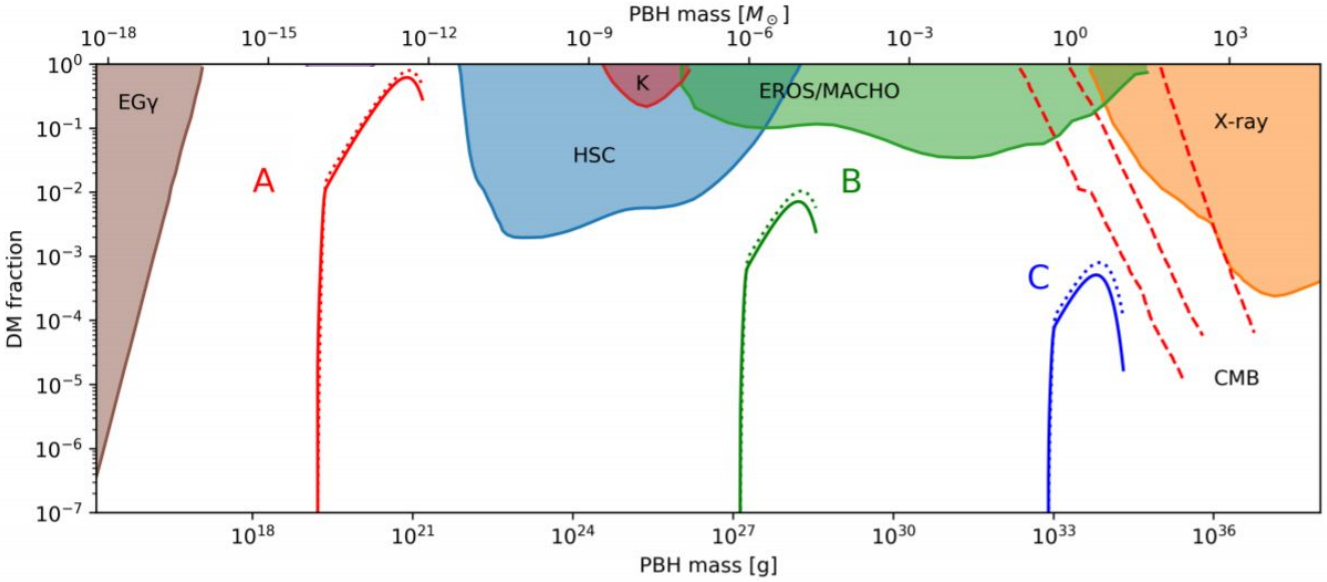
[Multamaki, Vilja, 2002]

PBH formation idea

- Fragmentation is random & pieces are big: **large density fluctuations**
  → density fluctuations independent from inflation

- Some rare regions can collapse to BHs

Resulting PBHs



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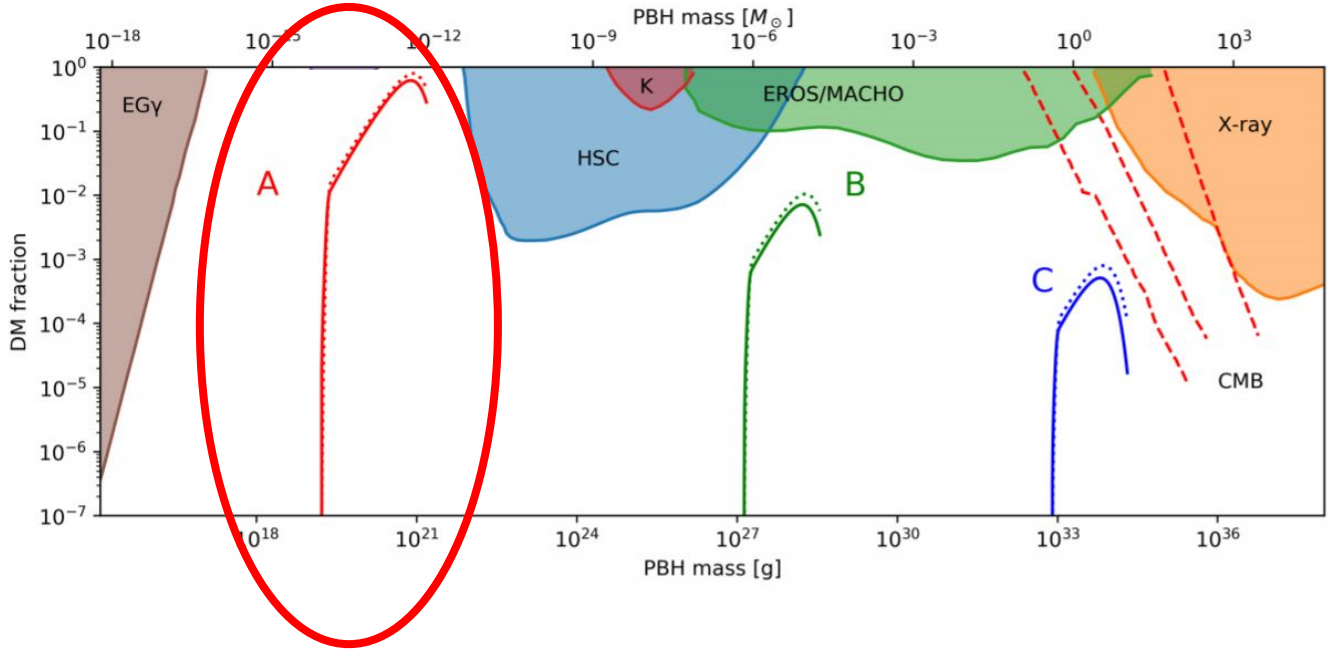


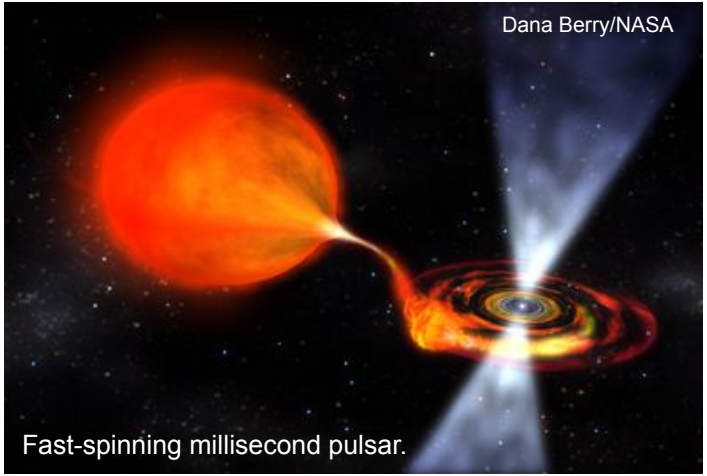
PBH from low-scale SUSY → “PBH miracle”

Novel ideas for signals in open parameter space?

Compact stars as PBH laboratories

- PBHs can be effectively captured by NS or WD in DM-rich environments (e.g. Galactic Center)

- Captured PBH settle and grow inside, destroy star
  → new signals, can help solve open problems



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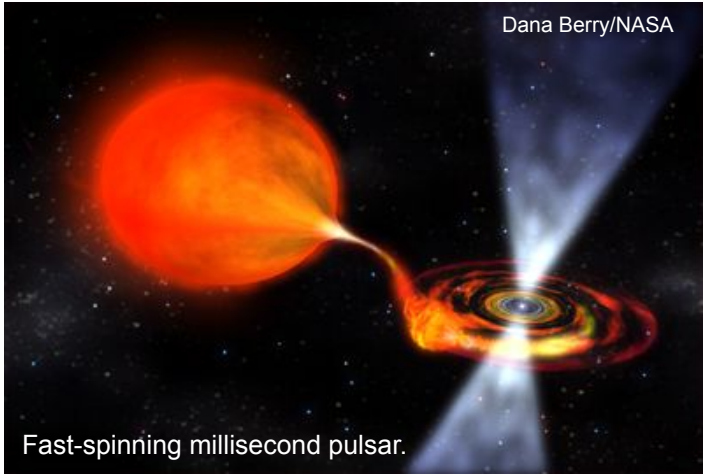
→ r-process nucleosynthesis, 511 keV, FRBs

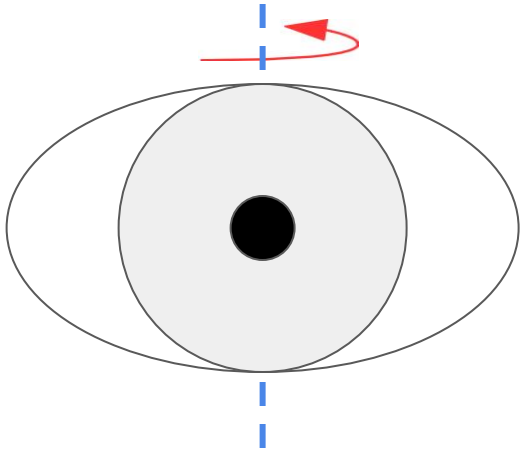
[Fuller, Kusenko, VT, PRL, 2017]
+ *Viewpoint Highlight* by H.-T. Janka

→ solar-mass BHs, GRBs, microquasars

[VT, PLB, 2017; VT, PLB, 2018]



PBH inside millisecond pulsar



- Star consumed → contracts → spins up
- **Neutron rich matter ejected**

[Fuller, Kusenko, VT, PRL, 2017]

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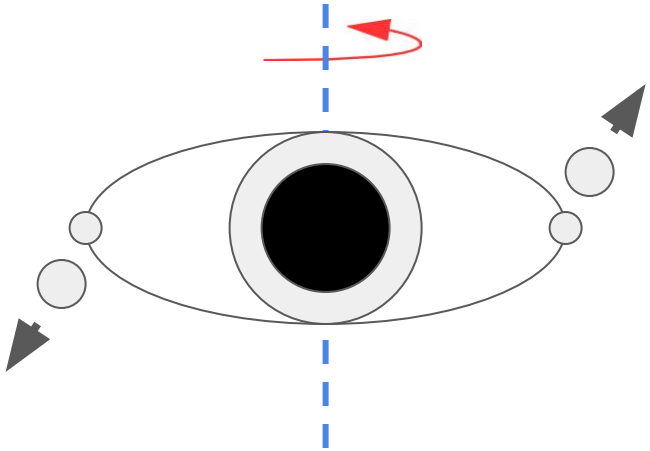

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PBH-NS: r-process nucleosynthesis

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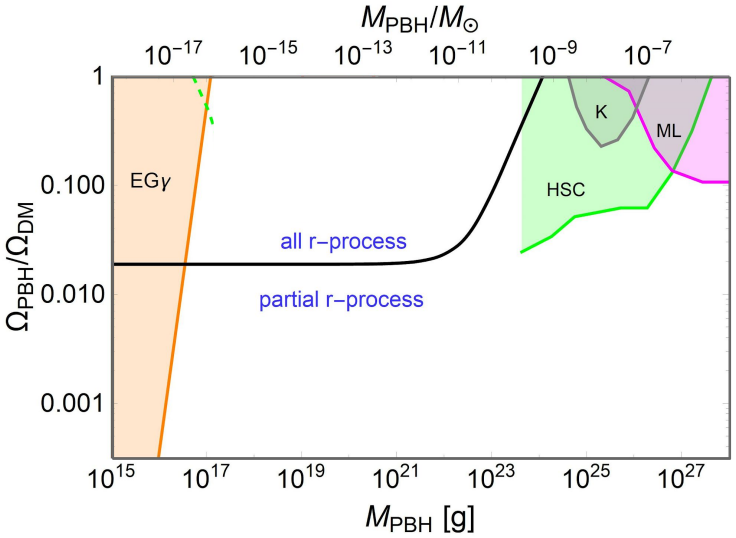
- **PBH-NS consistent with abundance in Milky Way & UFDs**

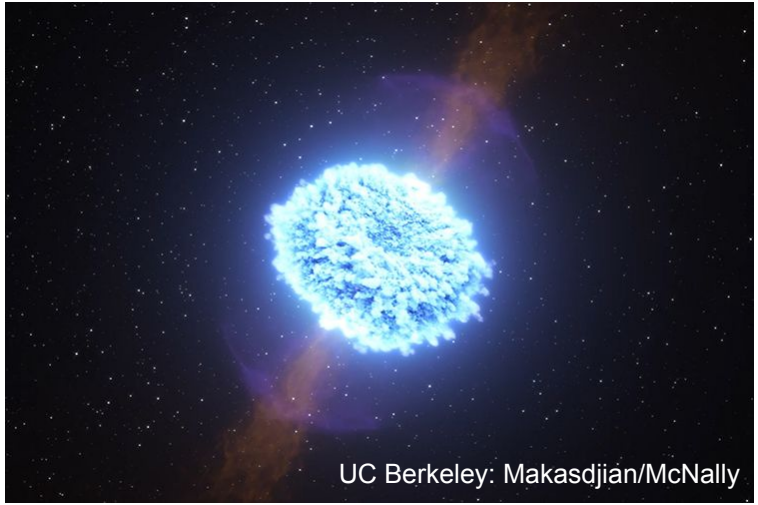


[Fuller, Kusenko, VT, PRL, 2017]

PBH-NS laboratories: long kilonova

- Kilonova: afterglow from ejecta

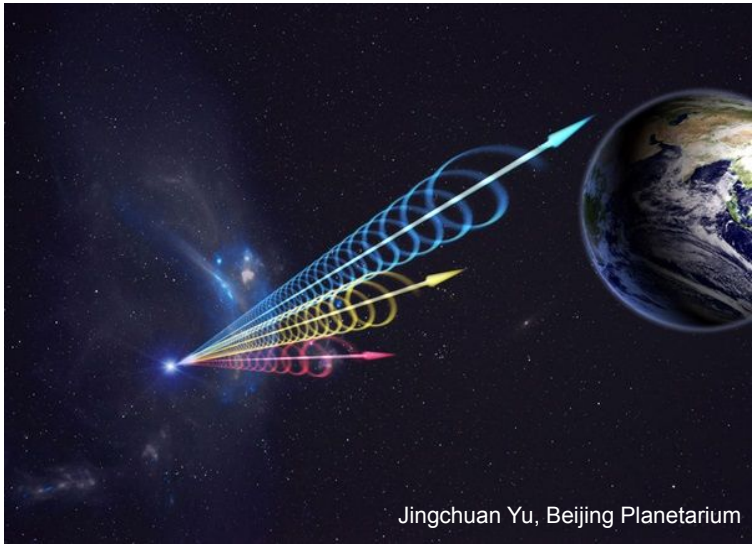
- PBH-NS vs. mergers
  → **kilonova w/o merger GWs**



[Fuller, Kusenko, VT, PRL, 2017]

PBH-NS laboratories: FRBs

- Release of NS B-field energy as radio
  → **non-repeating FRB**

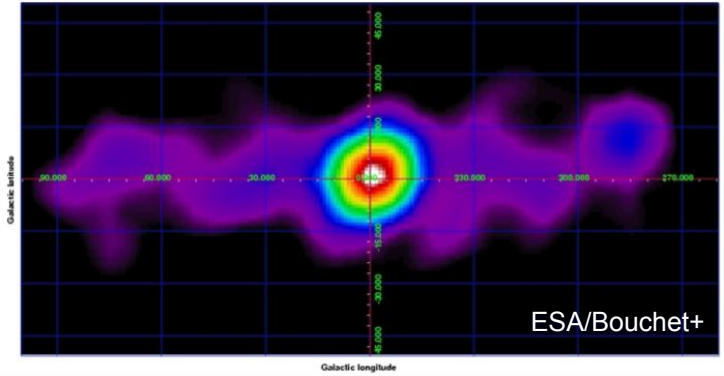


[Fuller, Kusenko, VT, PRL, 2017]

PBH-NS laboratories: 511 keV

- Galactic Center 511 keV γ-rays
  - Likely e+ annihilation

- **Consistent w/ PBH-NS production**



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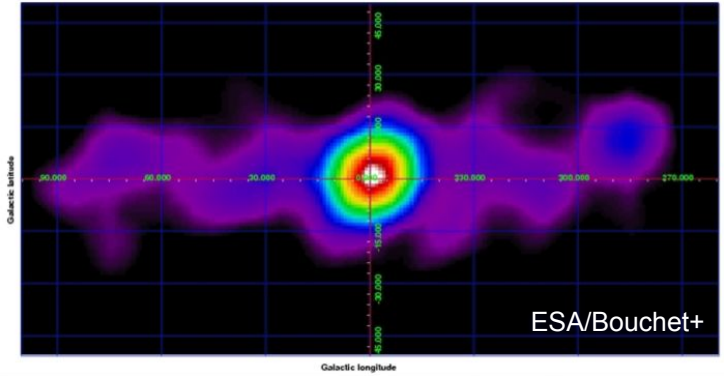


**** can be explained from regular NS mergers** [Fuller, Kusenko, Radice, VT, PRL, 2019]

[Fuller, Kusenko, VT, PRL, 2017]

PBH-NS/WD laboratories: solar-mass BHs

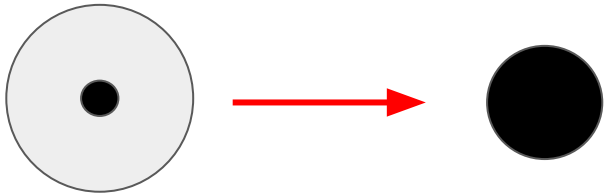
- No astro BHs $\lesssim 2M_\odot$

[VT, PLB, 2017]

PBH-NS/WD laboratories: solar-mass BHs

- No astro BHs $\lesssim 2M_\odot$

- PBH + NS/WD
  $\rightarrow$ **new solar-mass BHs**



[VT, PLB, 2017]

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- "Standard" GRB progenitor: BH + disk
  → disk accreted, binding energy released

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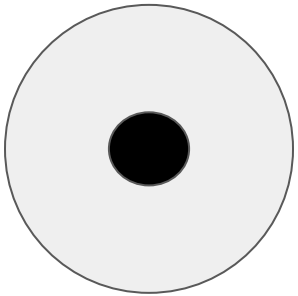
- Could be from PBH-NS → **GRB without GW**



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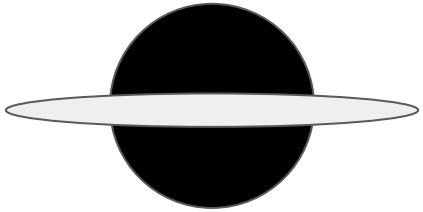
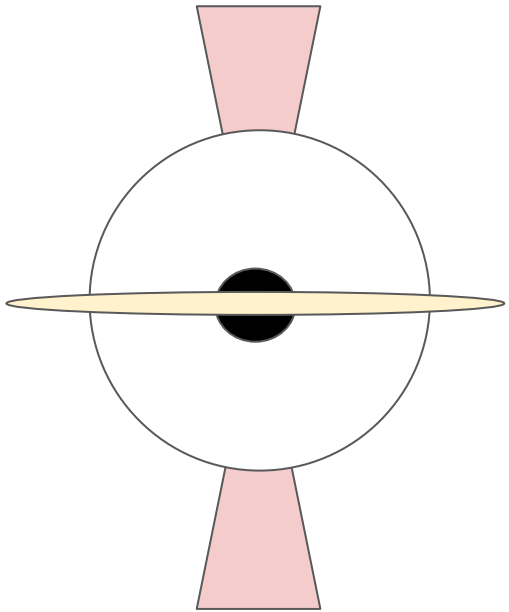


[VT, PLB, 2018]

PBH-WD laboratories: microquasars

- WDs have non-relativistic jets $L_{\rm jet} \sim \frac{1}{R}$



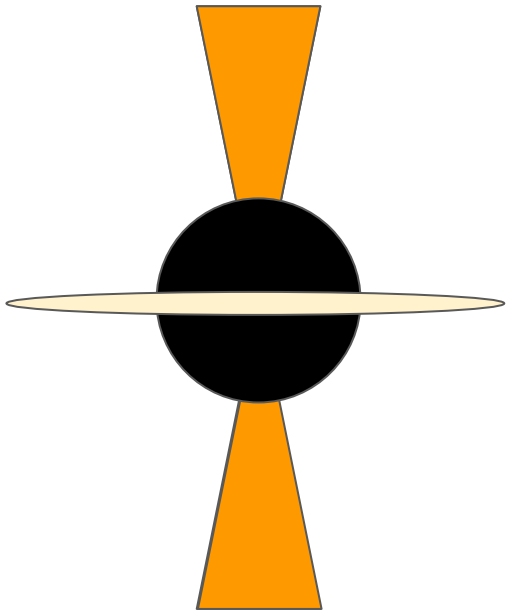
[VT, PLB, 2018]

PBH-WD laboratories: microquasars

- WDs have non-relativistic jets $L_{\rm jet} \sim \frac{1}{R}$

- WD + PBH $\rightarrow$ solar-mass BH accretor
  - radius ⇩, luminosity ⇧

- Continuous relativistic jet **solar microquasar**



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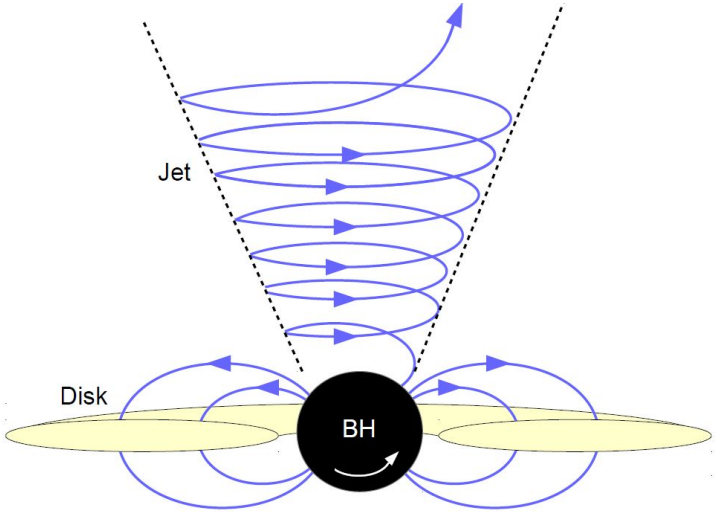
PBH-NS laboratories: GRB jets

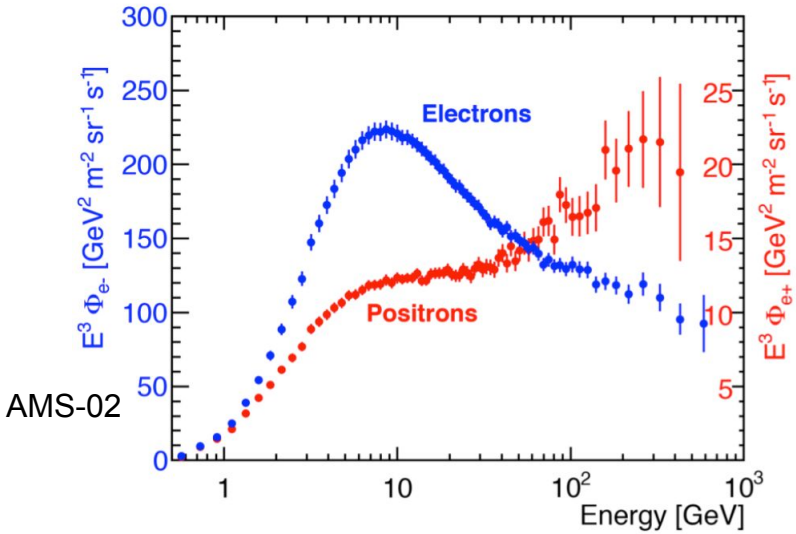
- GRB jet



Blandford-Znajek Mechanism

[VT, PLB, 2018]

PBH-NS/WD laboratories: jet positrons



- e+ from jets can contribute to excess → **astro-DM connection**

[VT, PLB, 2018]

Summary

- Renaissance era in PBH research
  → strong synergy with emerging field of multi-messenger astronomy

- **Simple general formation mechanism: scalar field fragmentation**
  → avoids usual issues of fine-tuning

- **Compact stars as PBH laboratories: new signals, help solve astro puzzles**