Marvelous Manifestations of Primordial Black Holes

from Multiverse to Neutron Star Explosions

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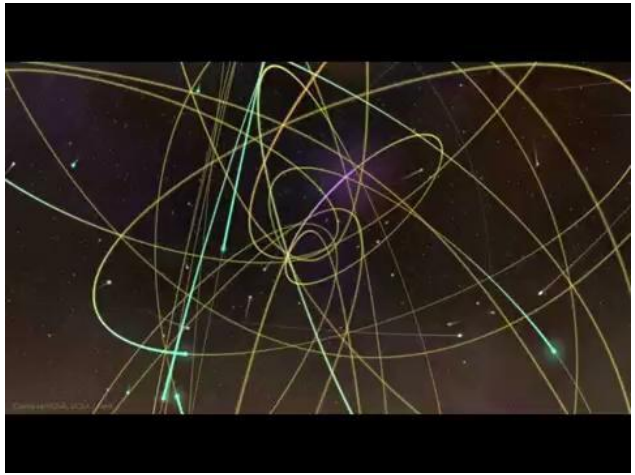
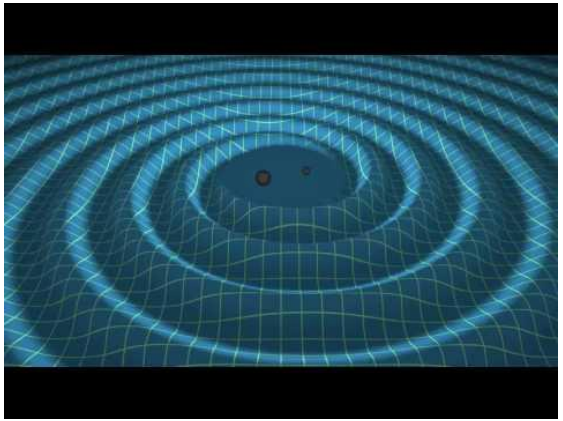
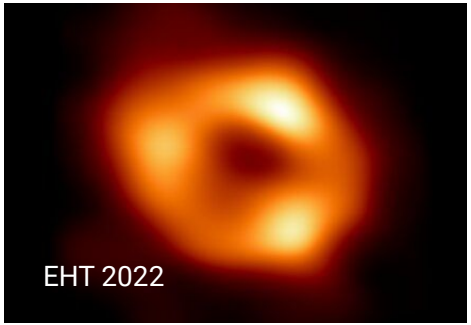
Black Holes Definitively Exist, Central in Astronomy



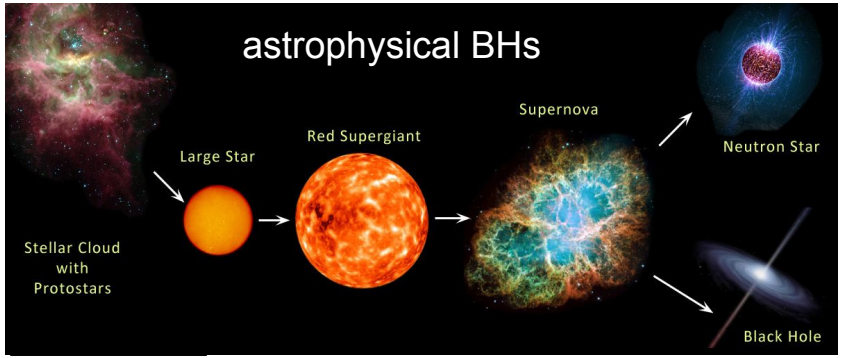
Sgr A*
Milky Way

BH binary merger

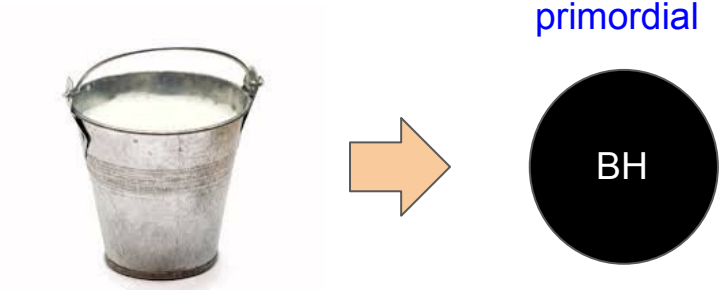




Primordial Black Holes (PBHs)



In early Universe, just roughly take scoop of ~ 50% overdensity to make BH

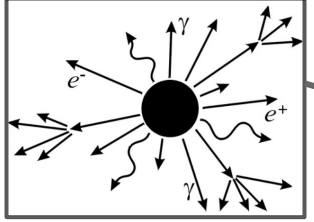


PBHs as dark matter

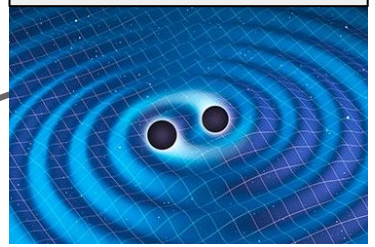
… a ***"Standard Model"*** candidate

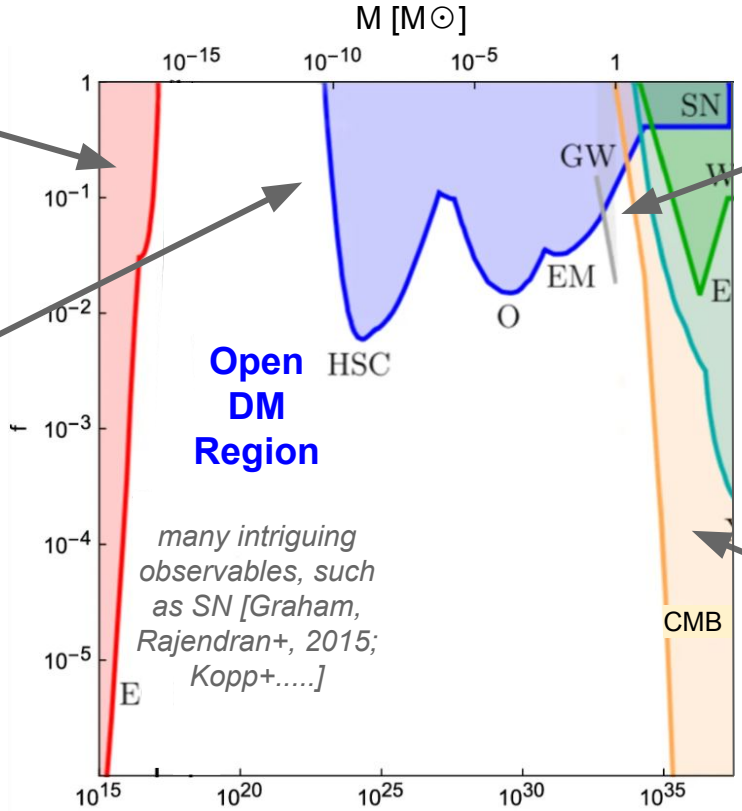
PBH DM Status

Hawking Evaporation

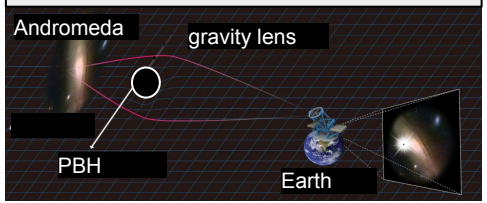


Gravitational Waves

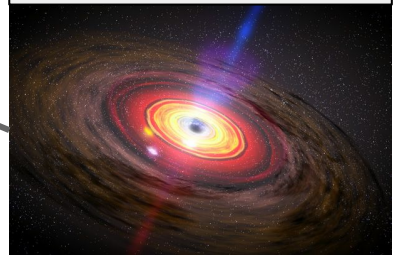




Microlensing



Accretion Emission



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

Formation and Possible Features

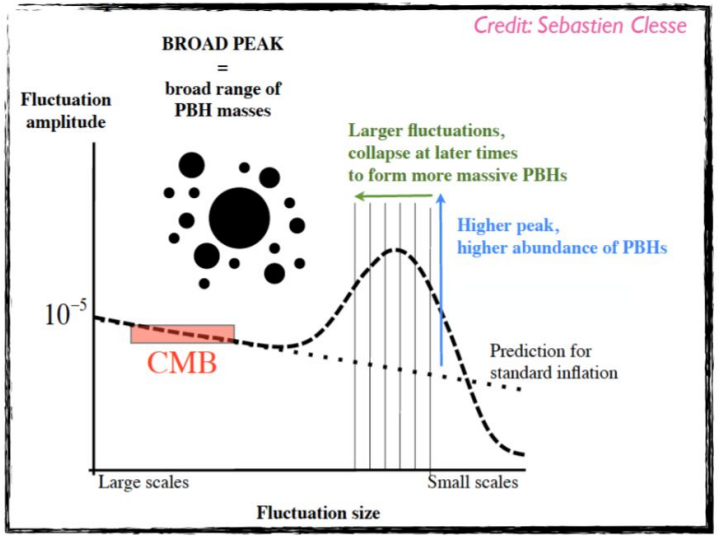
“Standard” PBH Formation

- Big perturbations ($\delta \sim 1$) enter horizon → collapse

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

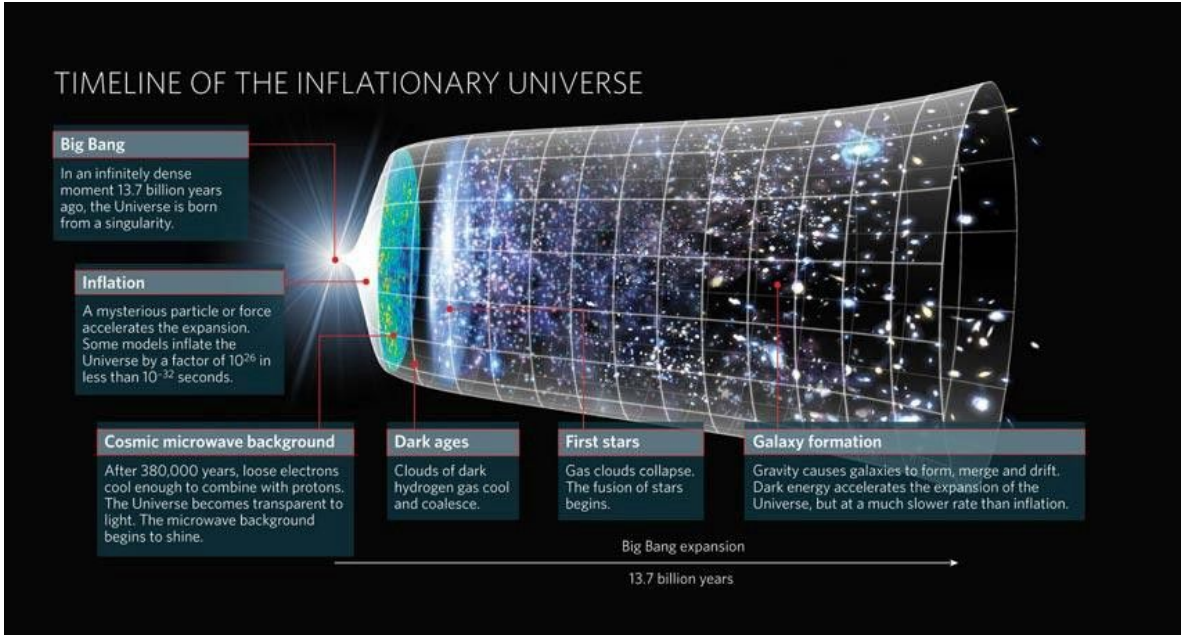
- Need to fine tune inflaton potential
  → sensitive to restrictions on field behavior
  - Example: “string swampland conjectures”

    [Kawasaki, **VT**, *PRD*, 1810.02547]

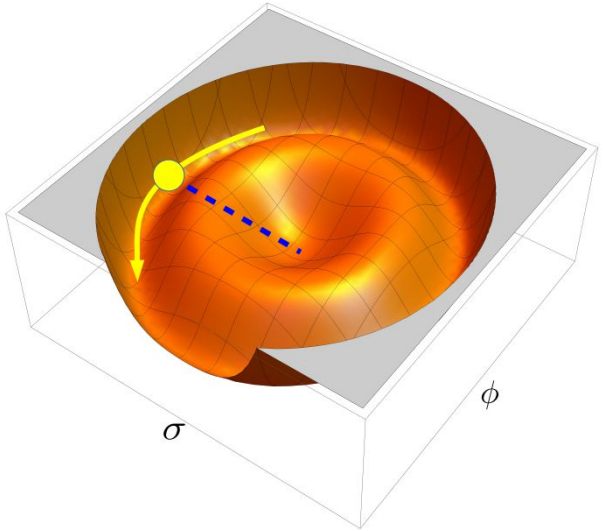


Scalar Fields Principal in Early Universe

- Scalars exist
  Happy 10th birthday Higgs Boson! *(July 2022)*
- Inflaton drives rapid early expansion, resolving Big Bang problems
- Scalars expected ubiquitous from fundamental theory



PBHs from Bubble Multiverse

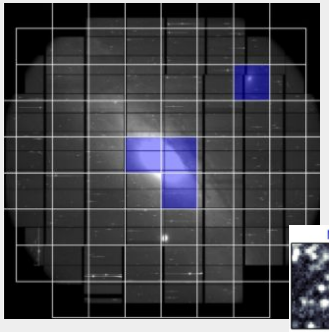


generic mechanism for PBHs broadly distributed in mass

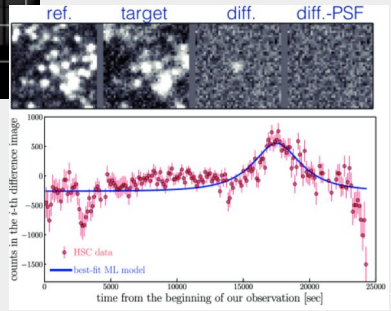
[Kusenko, Sasaki, Sugiyama, Takada, **VT**, Vitagliano, *Phys.Rev.Lett.*, 2001.09160]

[Deng, Vilenkin; Sasaki+, 1980s…]

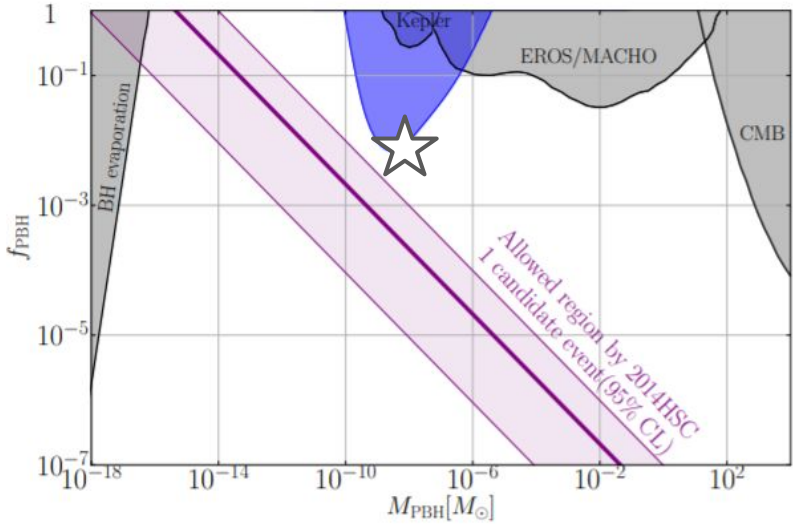
PBH DM from Bubble Multiverse: Detected by HSC ?!



Subaru (HSC)
Hyper-Suprime Cam
Andromeda
microlensing
event



[Niikura, Takada, Yasuda+, *Nature Astron.*, 2019]



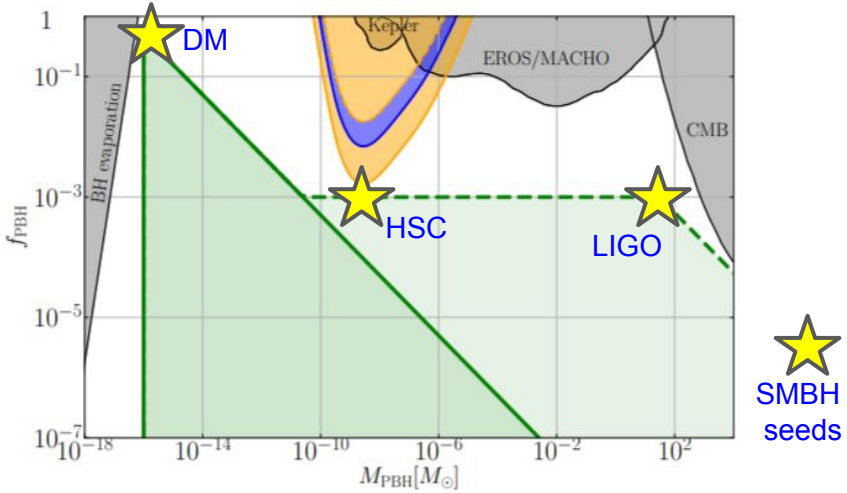
- **PBH DM from bubble multiverse consistent with detected HSC event !**

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

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

PBH DM from Bubble Multiverse: Detected by HSC ?!

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



- **Will be <u>definitively</u> tested with upcoming HSC data**

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

Yet Another Generic Mechanism: PBHs from Broken Inflaton

- In many models inflaton can break apart
- Sizable self-interactions: unstable oscillation modes
- A general potential potential $U(\phi) \sim |\phi|^n$ gives pressure-density relation

$$p = \left(\frac{n-2}{n+2}\right)\rho$$ [Enqvist, McDonald, 1997]

– for n < 2 (attractive interactions) → negative pressure (p < 0) → collapse

- Instabilities grow when overcome expansion rate

⇒ **inflaton fragments to oscillons** (massive, localized, long-lived solitonic lumps)

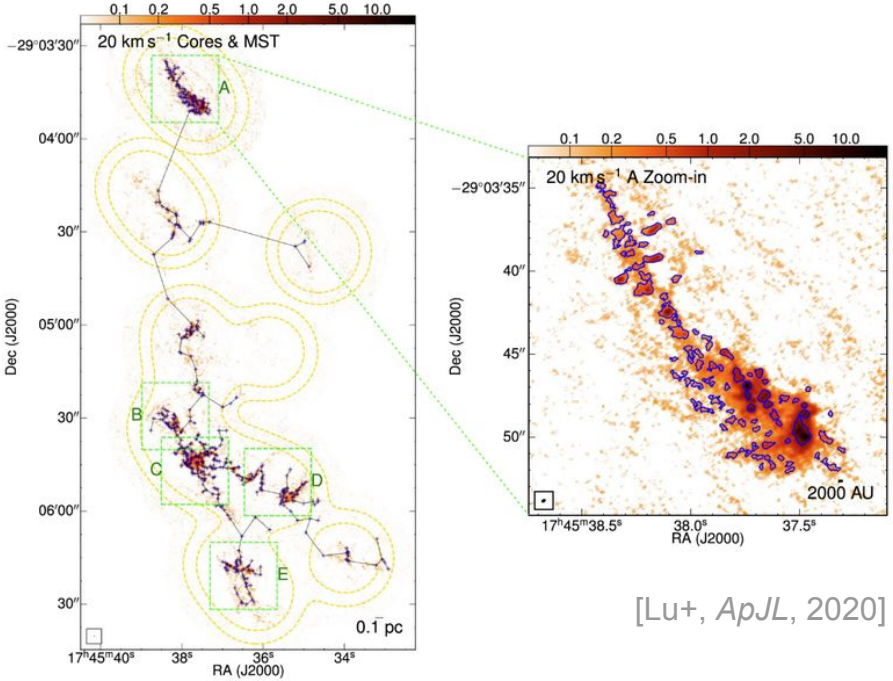
[Amin+, 2010, 2011..;Bogolyubsky, Mukhanov, 1976; Gleiser, 1993...] + many recent simulations

*** *fragmentation possibly very generic, if gravity is weakest force*

[Kusenko, **VT**, Yamada, Yamazaki, *PLB*, 1908.10930]

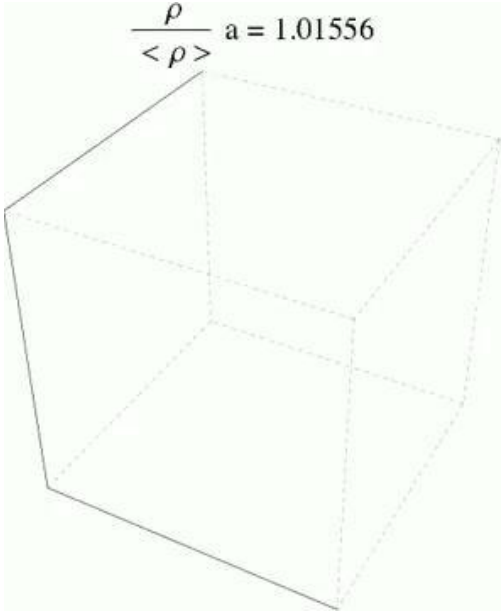
Analogy with Gravitational Jeans Instability

Jeans fragmentation
(massive molecular Galactic Center clouds)



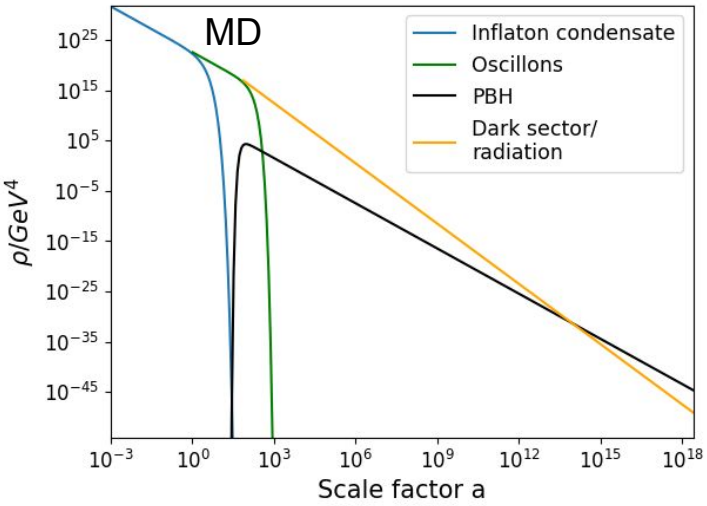
[Lu+, *ApJL*, 2020]

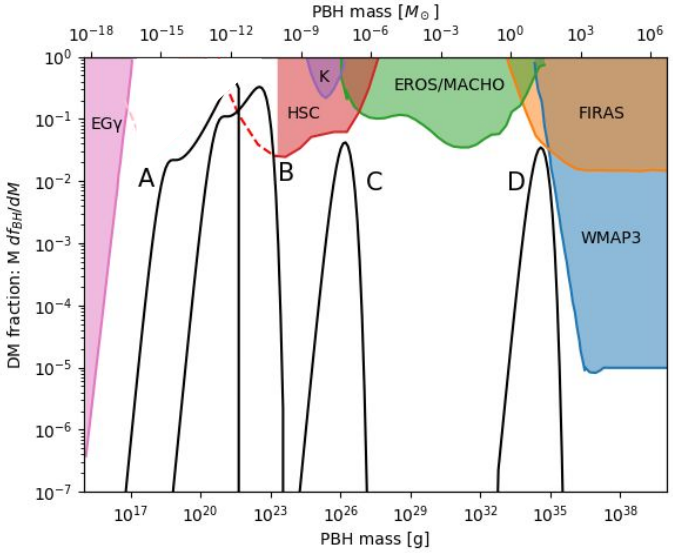
oscillon fragmentation
(string moduli)



[Antusch+, 2017]

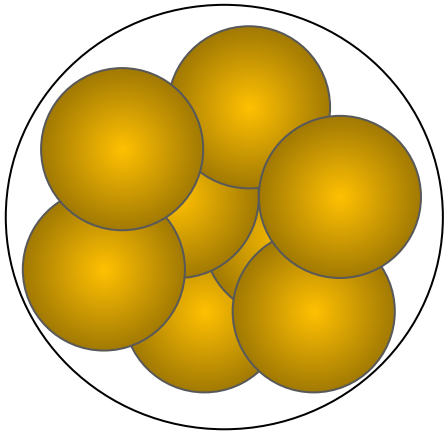
PBH Formation in Matter-Dominated Era





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

Aside: Fun with Sphere Packing



How dense can you pack identical spherical non-overlapping solitons to form black hole?

→ packing $\lesssim$ 74% volume

2022 Fields Medal for sphere packing:
8, 24 dimensions

Unusual Generic PBH Formation

	PBH Production Scenario	
	Inflationary Perturbations *(common mechanism)*	Field Fragmentation *(our mechanism)*
Source and type of large (CMB-scale) perturbations	inflaton fluctuations, curvature	inflaton fluctuations, curvature
Source and type of small (PBH-scale) perturbations	inflaton fluctuations, curvature	stochastic field fragmentation, isocurvature (fragment-lumps)
PBH source field	inflaton	inflaton or spectator field
Required potential condition	inflaton potential fine tuning	no new restrictions on inflaton potential, scalar field potential shallower than quadratic (attractive self-interactions)
PBH formation era ($t_{\rm PBH}$) and type	$t_{\rm BBN} \gtrsim t_{\rm PBH} \gtrsim t_{\rm reh}$, after reheating, radiation-dominated era	$t_{\rm BBN} \gtrsim t_{\rm PBH} \gtrsim t_{\rm inf}$, before or after reheating, temporary matter-dominated era
PBH size ($r_{\rm BH}$) vs. horizon ($r_{\rm H}$) at formation	$r_{\rm BH} \sim r_{\rm H} \sim H^{-1}$	$r_{\rm BH} \ll r_{\rm H} \sim H^{-1}$
PBH spin (a_s)	$a_s \sim 0$	$a_s \sim \mathcal{O}(1)$ possible

PBHs with sizable spin possible !

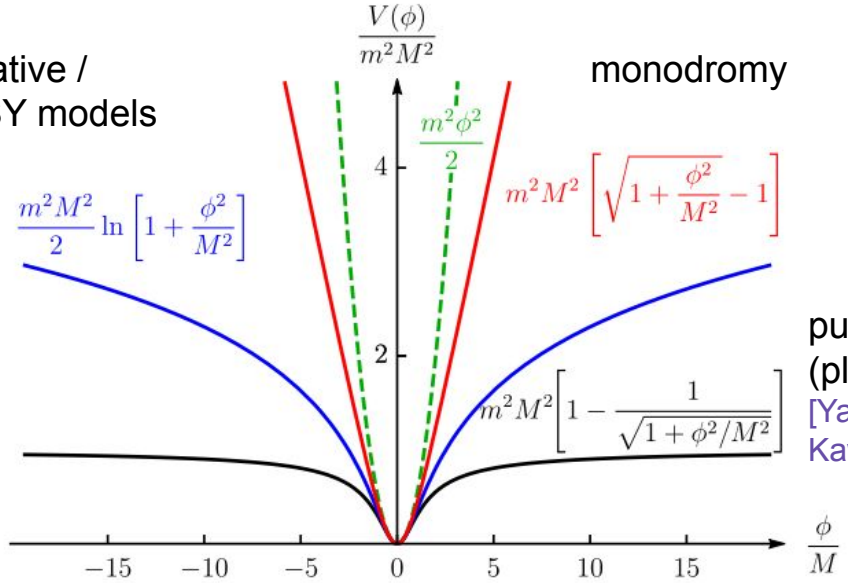
[Cotner, Kusenko, Sasaki, **VT**, *JCAP*, 1907.10613]

... and a novel source of GWs !

Fragmentation in Inflation Models

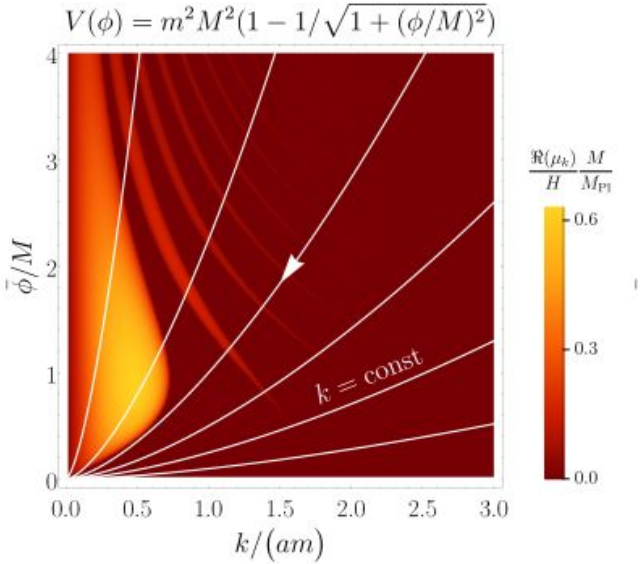
radiative / SUSY models

monodromy



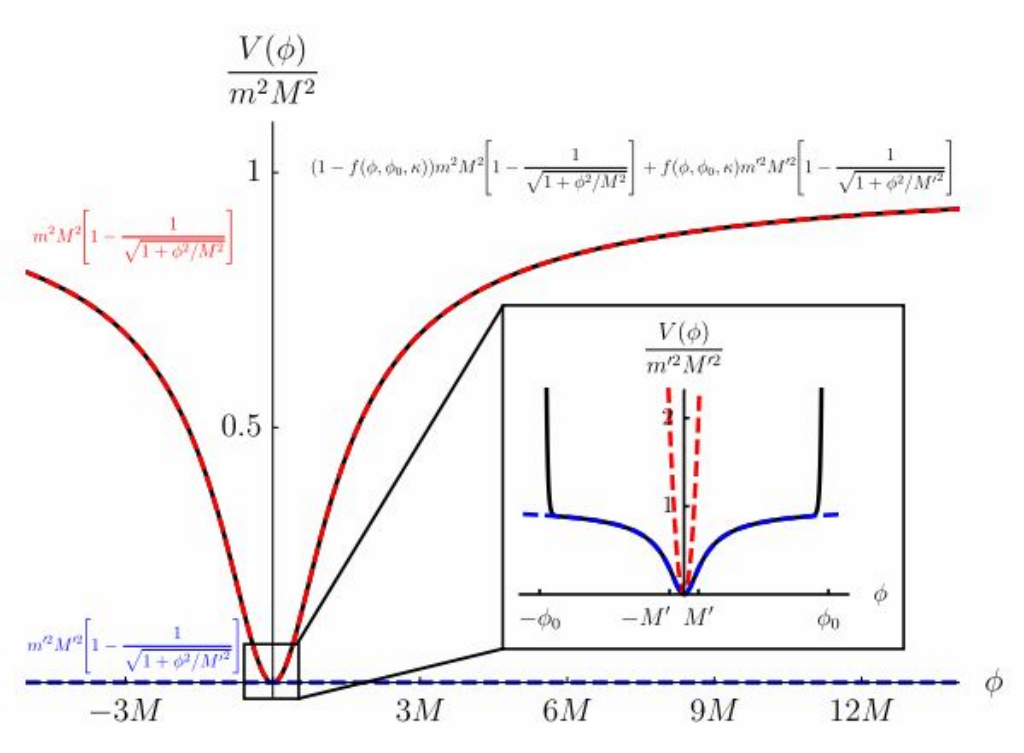
pure-natural (plateau) [Yamazaki+, 2017; Kawasaki…]

Floquet stability chart



[Lozanov, **VT**, 2204.07152]

Very Long-Lived Oscillons Possible



allowed by CMB

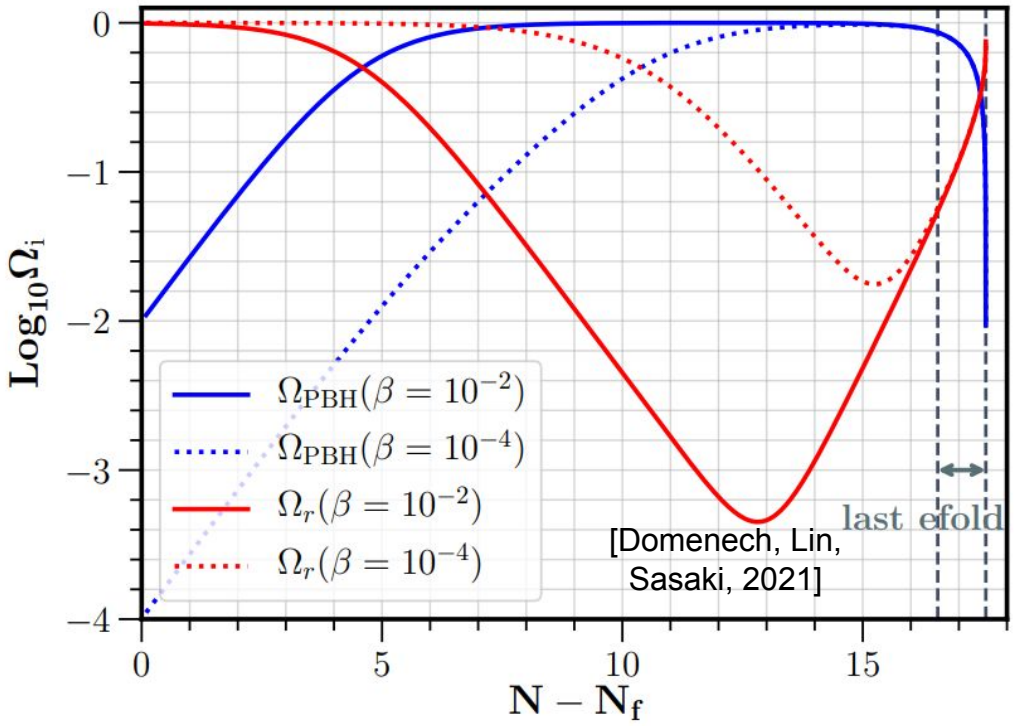
[Lozanov, **VT**, 2204.07152]

Induced GWs, Reminder on Early Evaporating PBHs

- Consider rapid Hawking evaporation of PBHs dominating the early Universe
- Leads to rapid transition of matter to radiation era

→ **strong induced GWs**

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



[Domenech, Lin, Sasaki, 2021; Kohri, Sasaki+, 2012…Inomata, Yanagida, Kawasaki…]
also [Domenech, **VT**, Sasaki, *PLB*, 2105.06816]

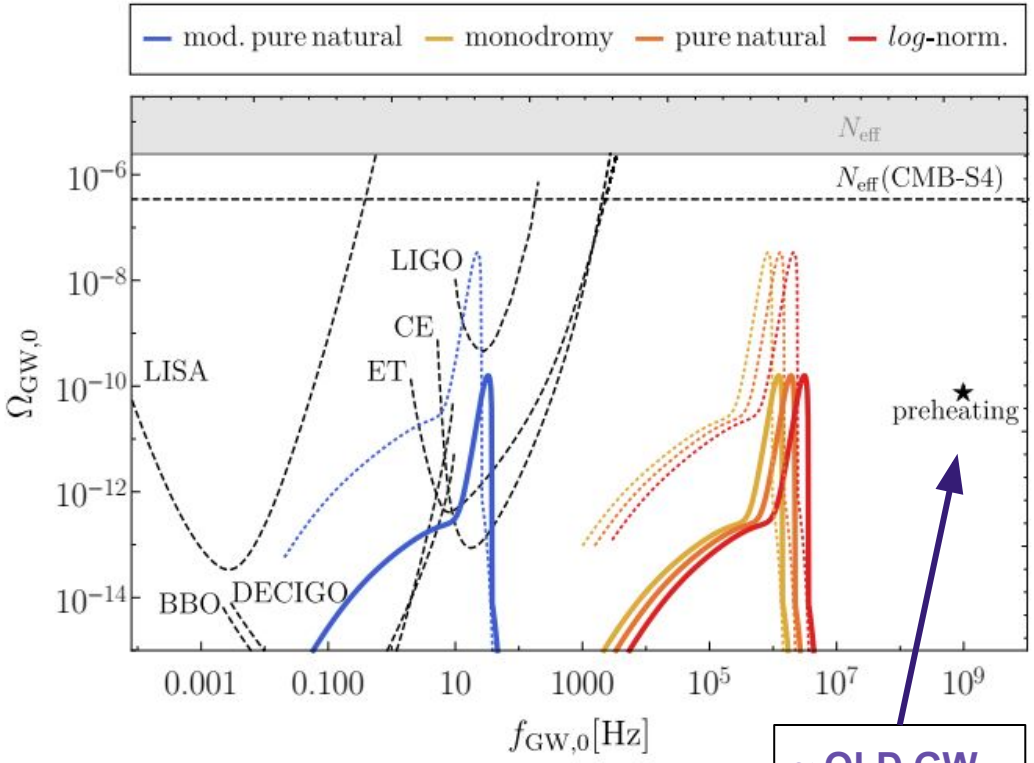
Oscillon-Induced GWs: A New Test of Early Universe

- Oscillons matter-dominate and subsequently rapidly decay

  → **strong induced GWs**

- **Unlike evaporating PBHs, directly test inflationary potential**

GW signal observable, possibly orders below in frequency than previously considered oscillon GWs from formation

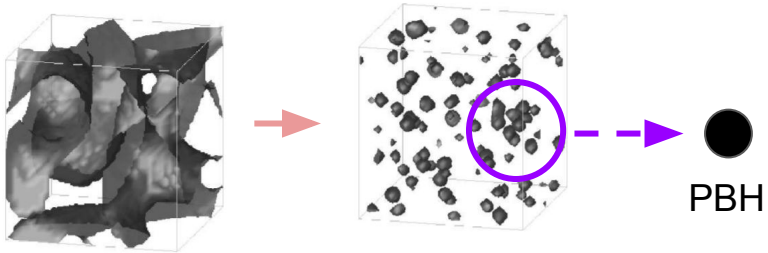


[Lozanov, **VT**, 2204.07152]

~ OLD GW RESULTS

Distinct PBH Features Possible

scalar fragmentation



PBHs peaked in mass + big spin possible

e.g. oscillons
[Cotner, Kusenko, **VT**, *PRD*, 1801.03321;
Cotner, Kusenko, Sasaki, **VT**, *JCAP*, 1907.10613]

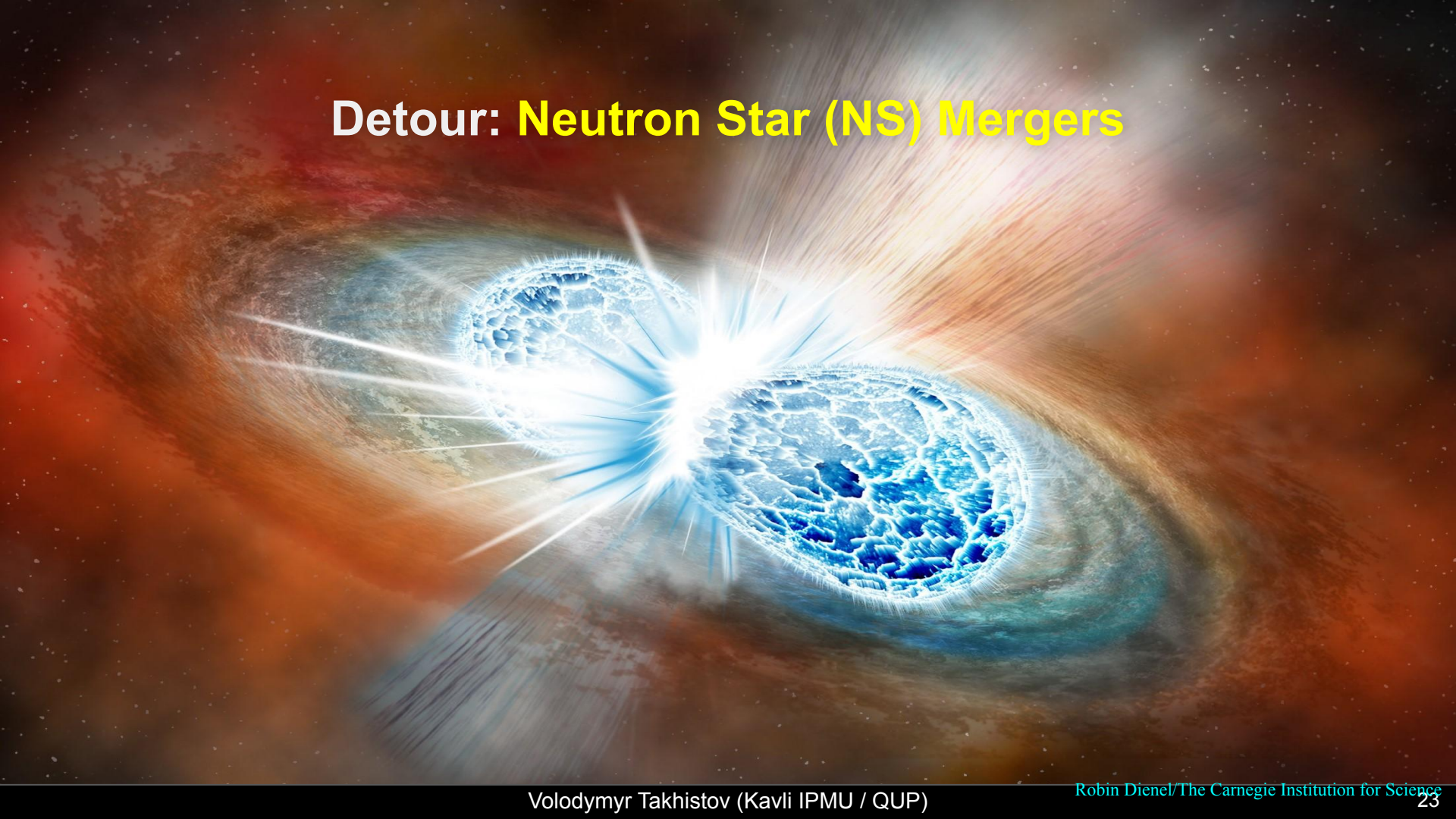
vacuum bubble "multiverse"

PBHs broadly distributed in mass

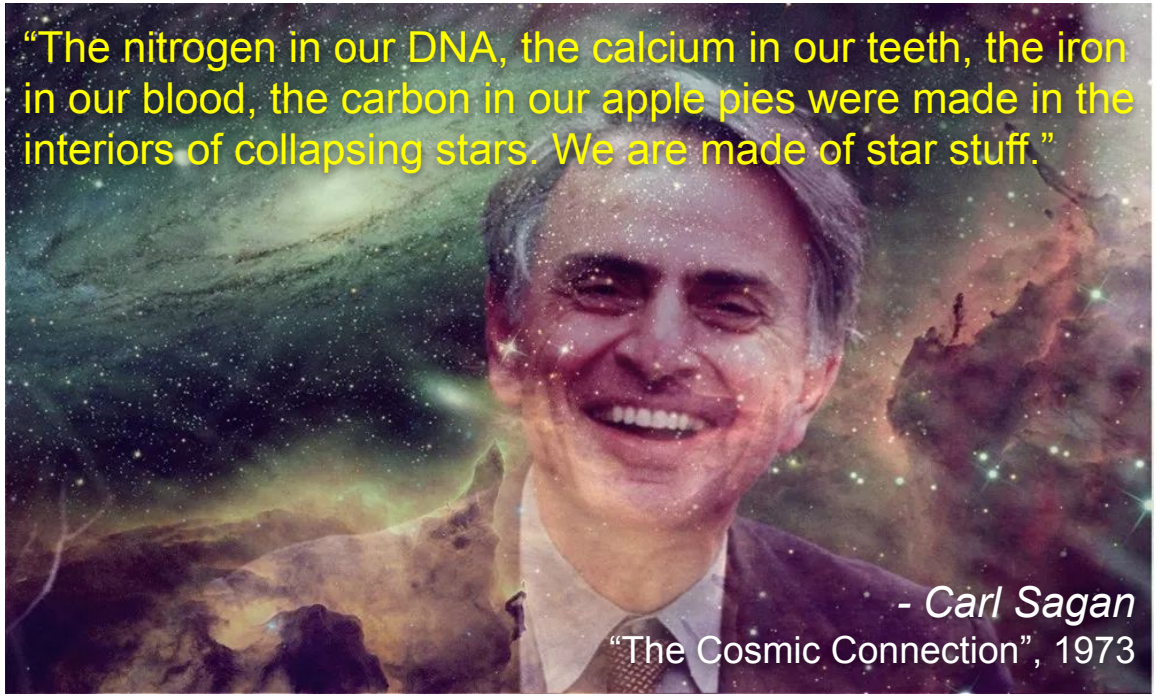
[Deng, Vilenkin, Sasaki...;
[Kusenko, Sasaki, Sugiyama, Takada, **VT**, Vitagliano, *Phys.Rev.Lett.*, 2001.09160]

Disrupting Astrophysics with PBHs

Detour: Neutron Star (NS) Mergers



Robin Dienel/The Carnegie Institution for Science



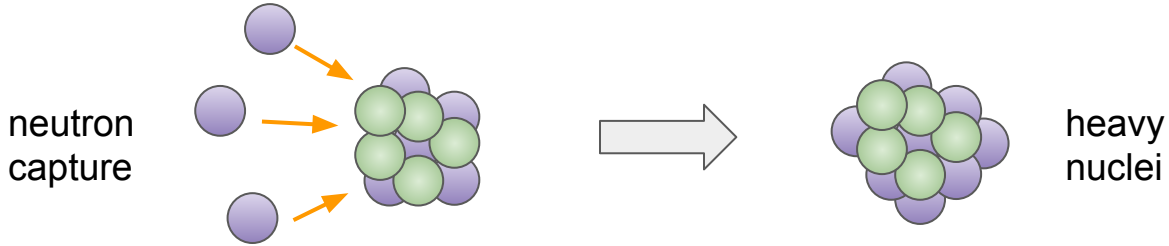
Where do heavy elements (gold) come from?

→ **major problem**

Heavy Element Production in Merger Material

- Ejected material is neutron rich → great site for r-process

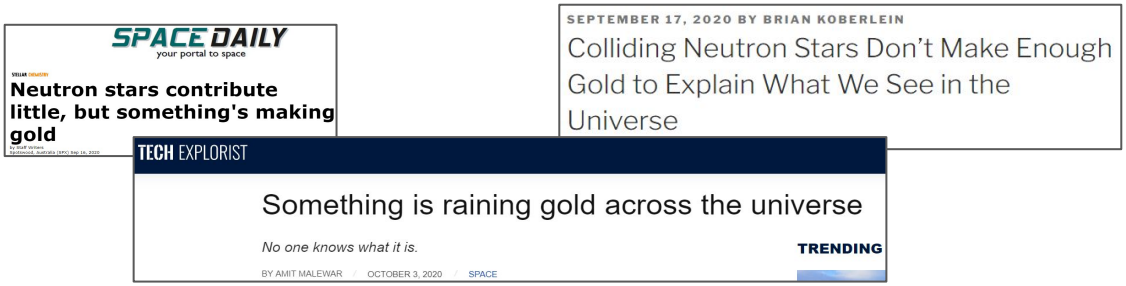
- **R-process nucleosynthesis**
  → main furnace of heavy elements in astronomy



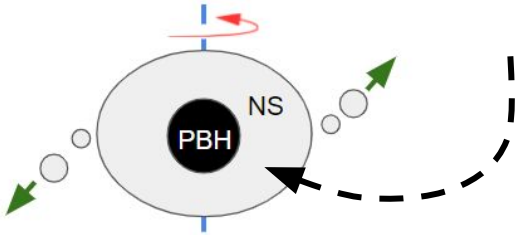
- Nuclear reactions in expanding ejecta produce heat + afterglow (kilonova)

Making Gold with Tiny PBHs

- **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



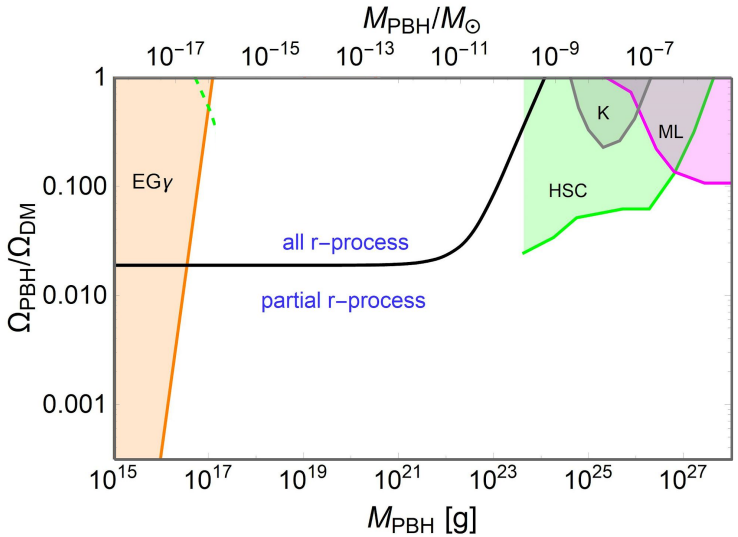
…need more simulations

[Fuller, Kusenko, **VT**, *Phys.Rev.Lett.*, 1704.01129] + Viewpoint Highlight by H.-T. Janka

PBH-NS: Nucleosynthesis

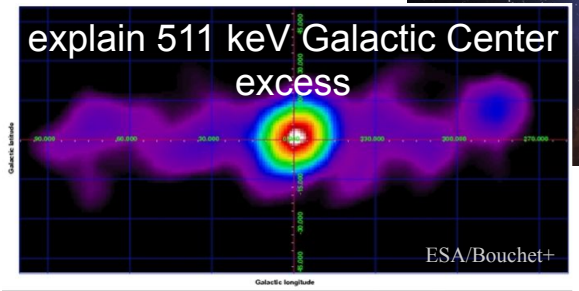
- Neutron-rich ejecta
  → heavy element production

- PBH-NS emission consistent with Milky Way & Ultra-faint Dwarf abundance



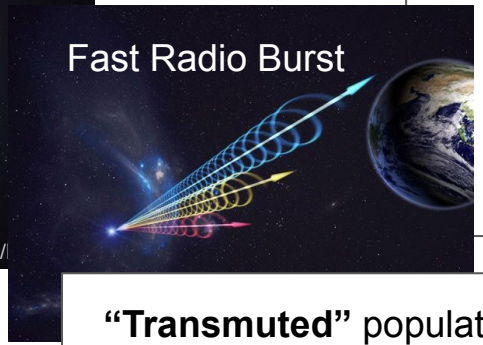
[Fuller, Kusenko, **VT**, *Phys.Rev.Lett.*, 1704.01129]

Neutron Stars (+ White Dwarfs) as PBH Laboratories

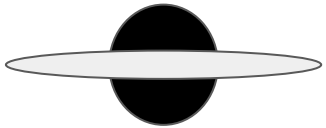


*** *can explain with regular NS-NS*

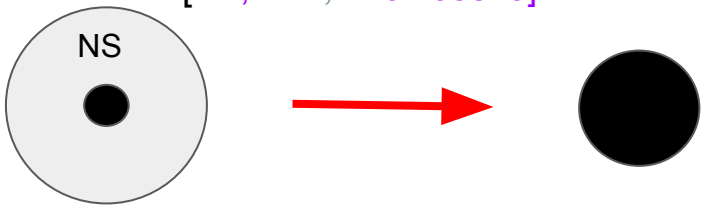
[Fuller, Kusenko, Radice, **VT**, *Phys.Rev.Lett.*, 1811.00133]



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



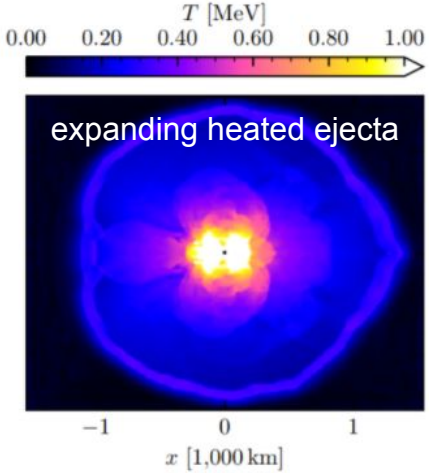
"Transmuted" population of solar-mass BHs
[**VT**, *PLB*, 1707.05849]

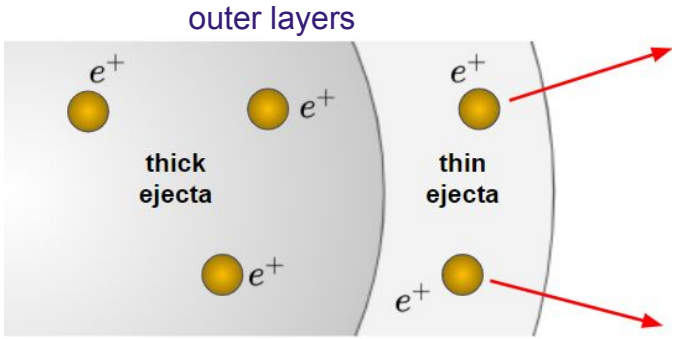


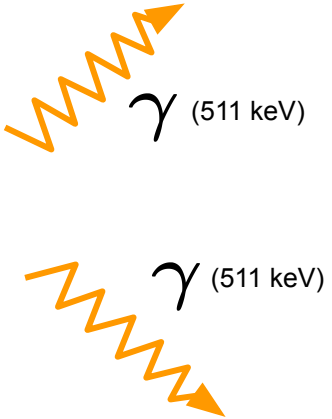
[Fuller, Kusenko, **VT**, *Phys.Rev.Lett.*, 1704.01129; **VT**, *PLB*, 1707.05849; **VT**, *PLB*, 1710.09458]

Briefly ~ Novel Generic Signal for NS Mergers

- Positrons produced in heated NS merger ejecta → some escape → annihilate to 511 keV





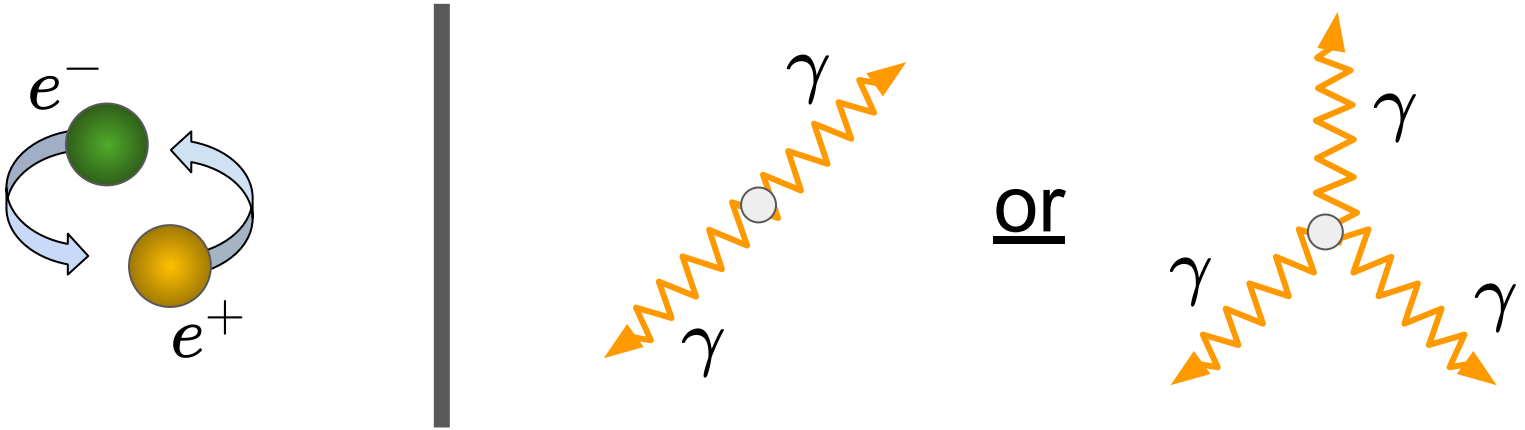


- **With LIGO observations can explain 511 keV signal in Galactic Center !**

[Fuller, Kusenko, Radice, **VT**, *Phys.Rev.Lett.*, 1811.00133]

511 keV radiation

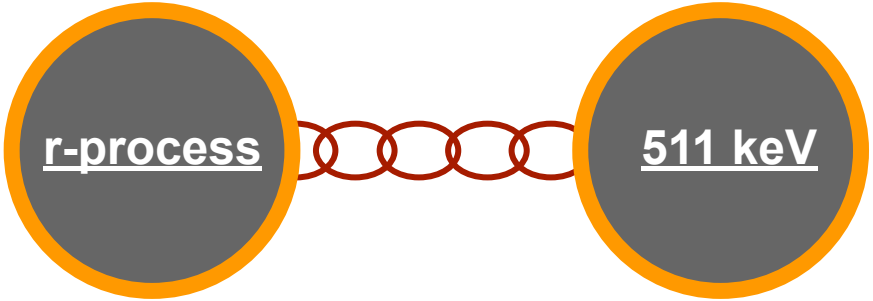
- Escaping ~MeV positrons annihilate via positronium bound state formation (as desired for Galactic Center excess) → **511 keV radiation** ✓



[Fuller, Kusenko, Radice, **VT**, *Phys.Rev.Lett.*, 1811.00133]

NS Signal Connection, Smoking Gun ?

- Proposal directly links r-process and 511 keV



- Observations of Reticulum II dwarf spheroidal hint at heavy elements + 511 keV ?

→ **smoking gun signal of mergers**

[Ji, Frebel+, *Nature*, 2016; Siegert+ 2016]
…Siegert+, 2021 → 511 keV might be reduced, but excess still possible

[Fuller, Kusenko, Radice, **VT**, *Phys.Rev.Lett.*, 1811.00133]

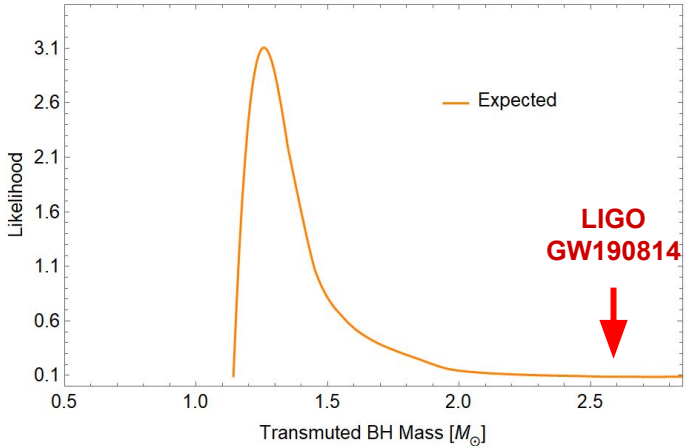
Origin of Solar-mass Black Holes

- Solar-mass (~1-2.5 M⊙) BHs unexpected in astrophysics → PBHs ? particle DM accumulation?

  [Reddy, Baryakhtar, Tsai, 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

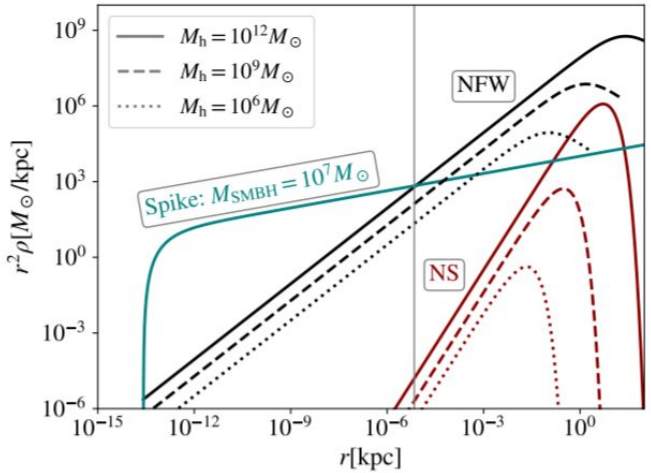


Large (> 1.5 M⊙) candidates unlikely to be from DM-NS interactions!

[**VT**, Fuller, Kusenko, *Phys.Rev.Lett.*, 2008.12780]

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

- PBH-PBH linked with LIGO BH-BH GW observations? [Bird+ *PRL* 2016, Sasaki+ *PRL 2016*….]
- **First BH-NS candidates observed by LIGO** [Abbott+, *ApJL*, 2021...] **....from PBHs?**
- Unlike PBH-PBH, PBH-NS can only form after star formation

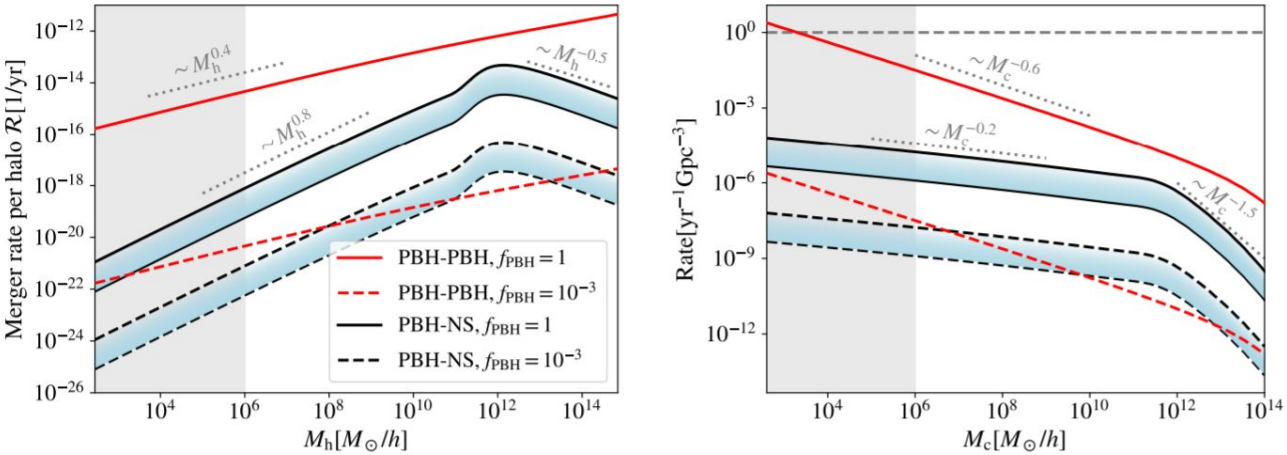


$$\mathcal{R}_{\mathrm{PBH-NS}} = 4\pi \int_0^{R_{\mathrm{vir}}} \mathrm{d}r r^2 \frac{\rho_{\mathrm{NS}}}{m_1} \frac{\rho_{\mathrm{PBH}}}{m_2} \langle \sigma v_{\mathrm{rel}} \rangle$$

2-body scattering with GW emission

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

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



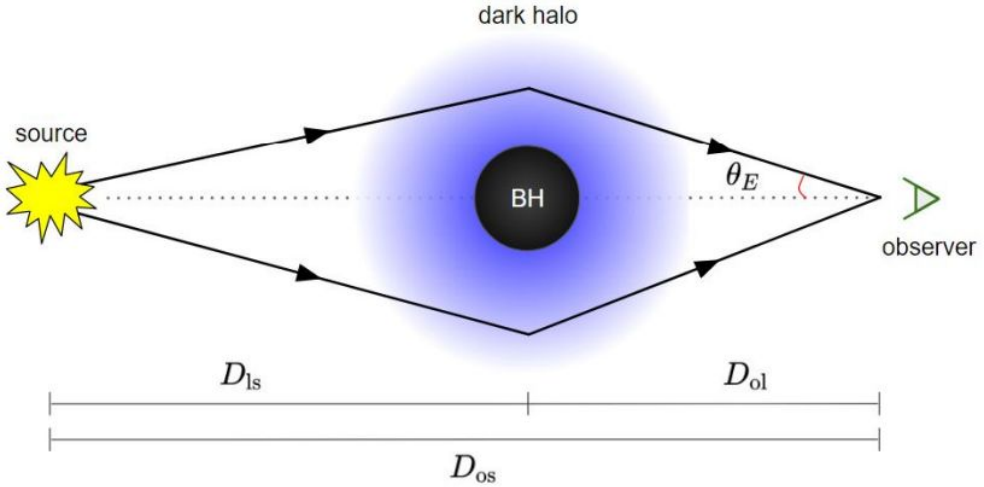
- **PBH-NS rates subdominant → observed NS-BH events are <u>astrophysical !</u>**
- *True, even if PBH-PBH are significant* → contributions from early Universe
- Do not expect significant multimessenger contributions / emissions from PBH-NS

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

** can try looking at particular galaxy*
[Tsai, Palmese, Profumo, Jeltma, 2020]

Cosmological Lensing, A Novel Test of Dressed PBHs

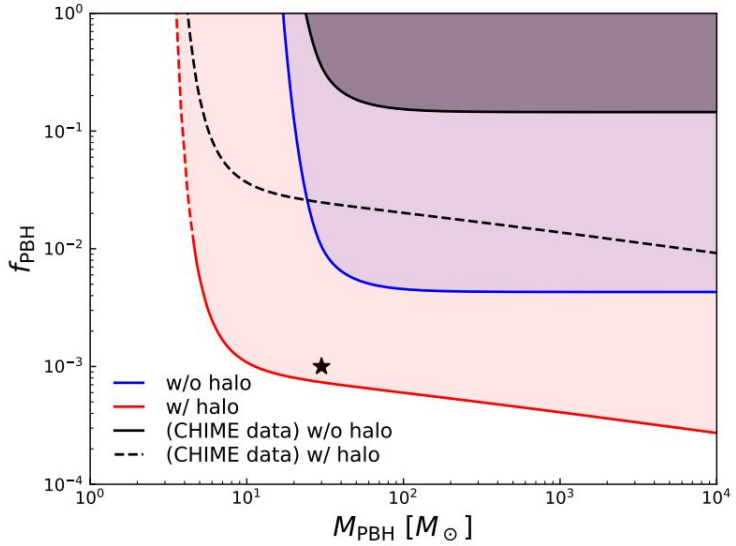
- Stellar-mass PBHs can only be subdominant DM
  → engulfed in massive halo dress of primary DM (e.g. axions, WIMPs) [Mack+, 2007; Ricotti+, 2008]
- While local lensing is inefficient, strong cosmological lensing (e.g. FRBs) **can directly test !**



[Oguri, **VT**, Kohri, 2208.05957]

Cosmological Lensing, A Novel Test of Dressed PBHs

- Already start exploring with CHIME FRB data, with ~10^5 FRBs will probe LIGO region



- **Method covers broad model range, applicable to other lensing: supernovae, caustics**

[Oguri, **VT**, Kohri, 2208.05957]

Are Intermediate-mass BHs Primordial ?

- GW190521 event ~ 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

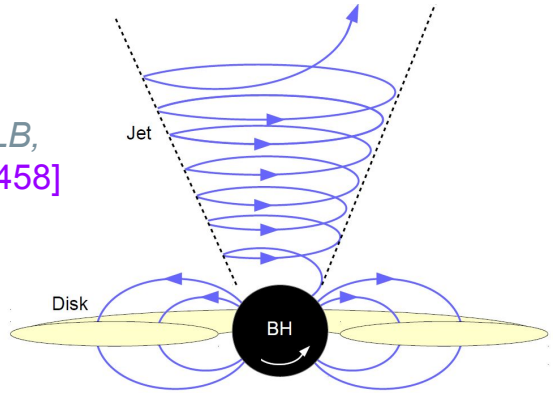
- Great testing site: dwarf galaxies (Leo T)

[Lu, **VT**+, *ApJ Lett.*, 2007.02213; **VT**+, *JCAP*, 2105.06099]

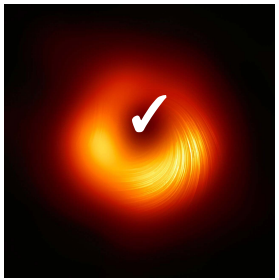
PBH Outflow Winds and Jets

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

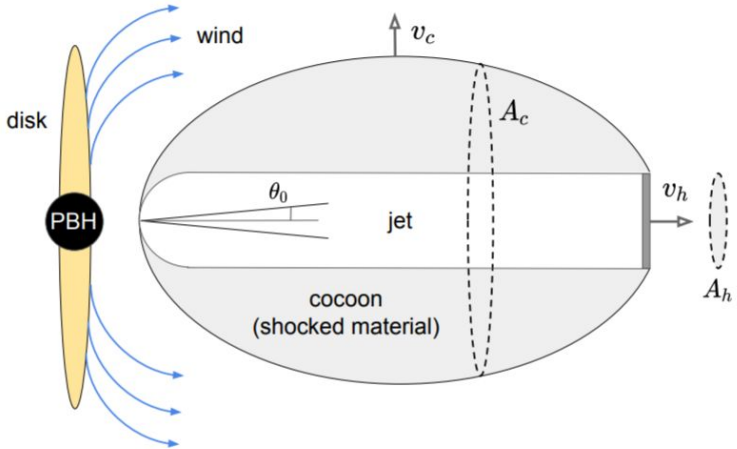
[**VT**, *PLB*, 1710.09458]



Blandford-Znajek Mechanism

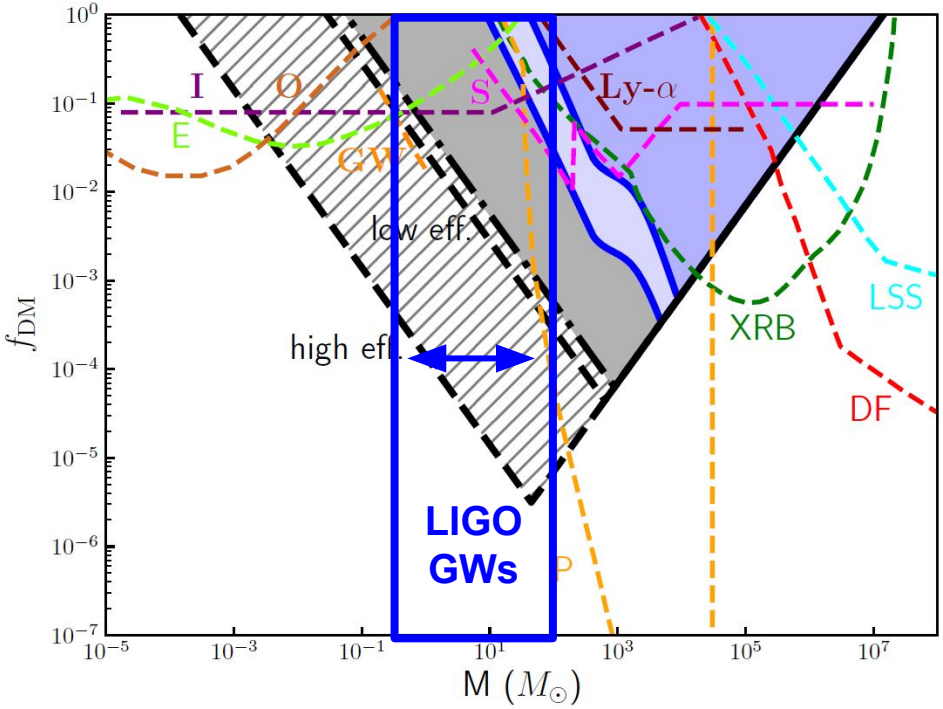


EHT M87
strong B-field + jet



[**VT+,** *MNRAS Lett.*, 2111.08699]

PBH Outflow Winds and Jets



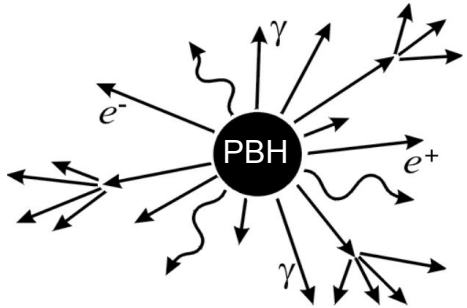
[**VT+,** *MNRAS Lett.*, 2111.08699]

** gas heating from evaporating PBHs*

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

Exploring Evaporating PBHs with GWs

- Evaporating PBHs with mass $\lesssim 10^9$ g unconstrained, ***how to explore scenarios ?***



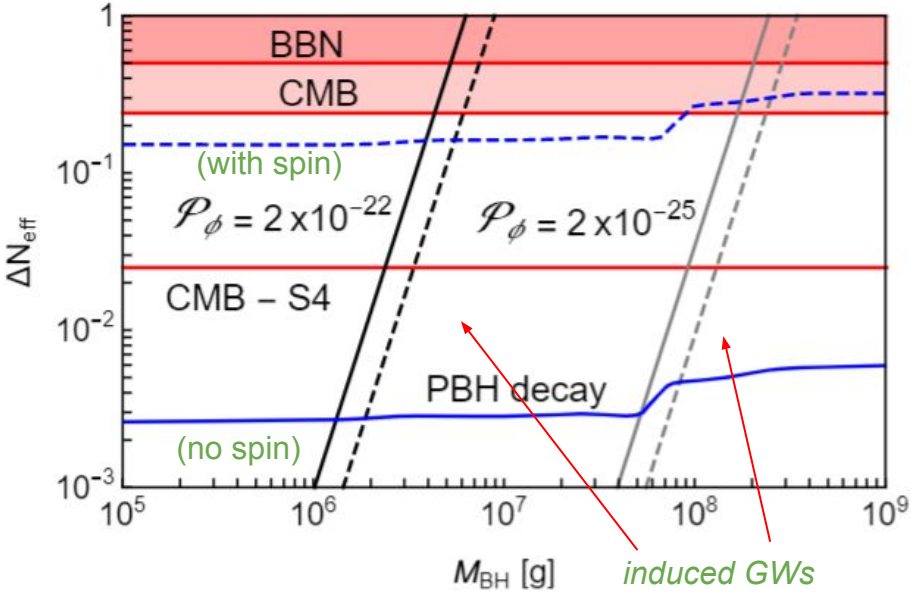
- Evaporating PBH emission products → "dark radiation" → change ΔN_{eff}
  - PBH *spin* distribution can significantly modify

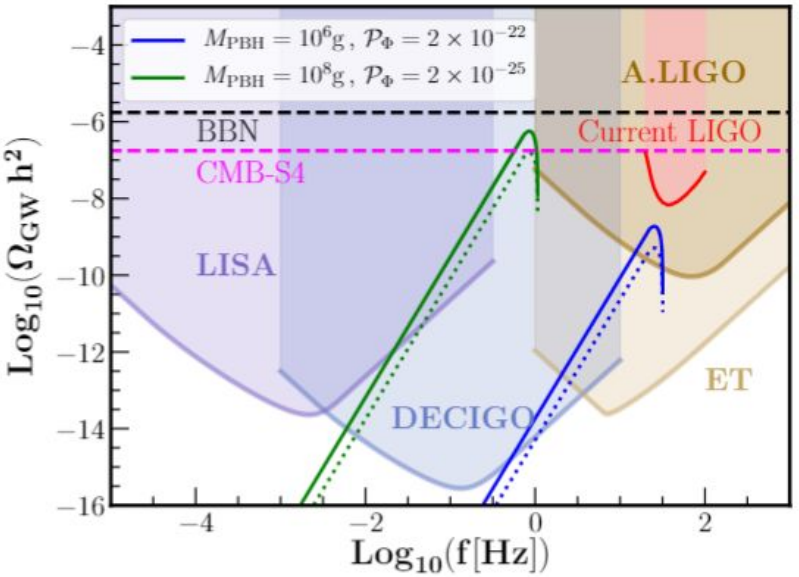
[Hooper+ 2020; Arbey, Auffinger+, 2021; Masina, 2021]

- Rapid evaporation of PBHs dominating Universe → induced GWs → 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

- PBHs ~ “Standard Model” dark matter
- Renaissance in the field, synergy with multimessenger astronomy breakthroughs
- Distinct PBH features possible, can generically appear in many models
- Connections with long-standing astronomy puzzles and numerous signatures

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

… Dark Matter ?