

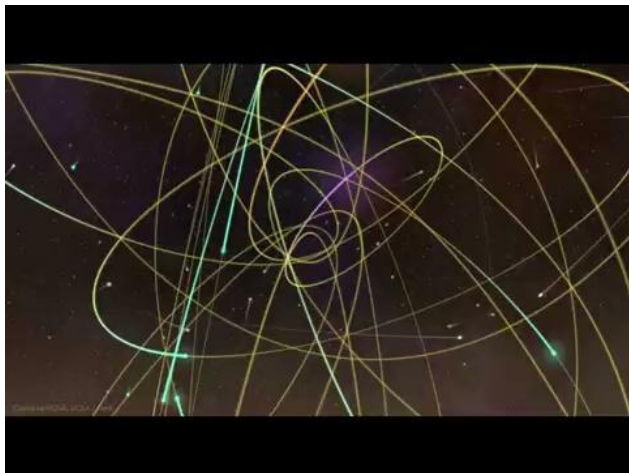
Primordial Black Holes: New Signatures and New Dark Matter

Volodymyr Takhistov

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

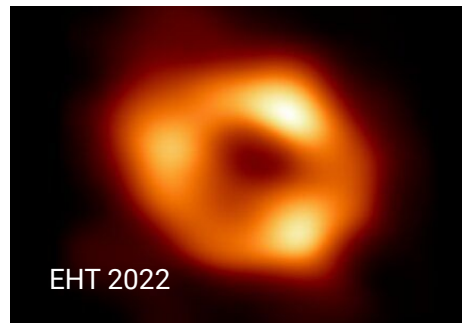
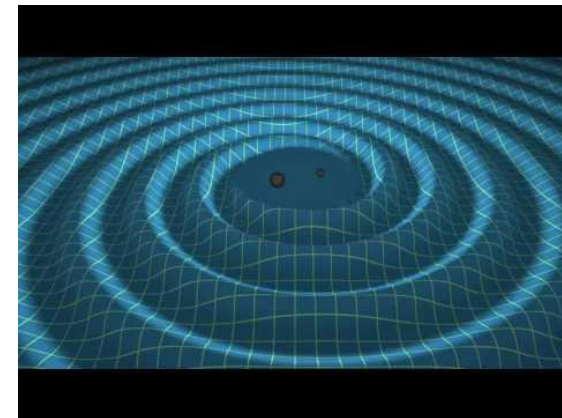


Black Holes **Definitively Exist, Central in Astronomy**



Sgr A*
Milky Way

BH binary merger



EHT 2022

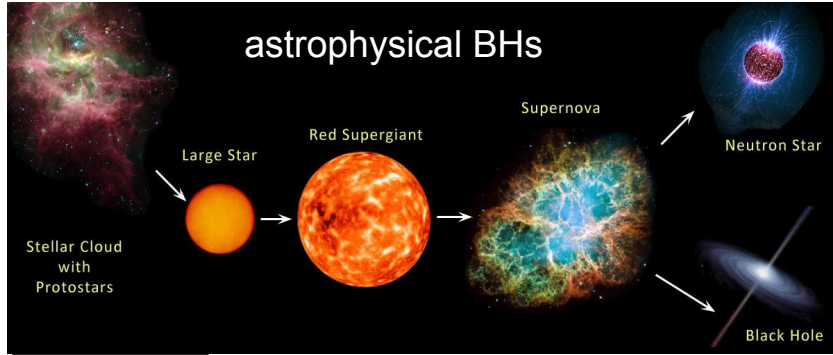


colloquium by J. Silk

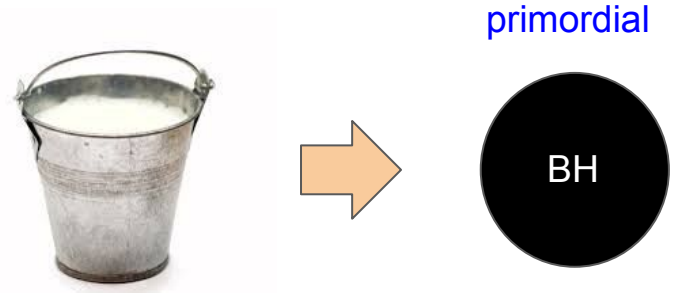
... are observations hinting at non-particle DM ?

Ancient Black Holes

Primordial Black Holes (PBHs)



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

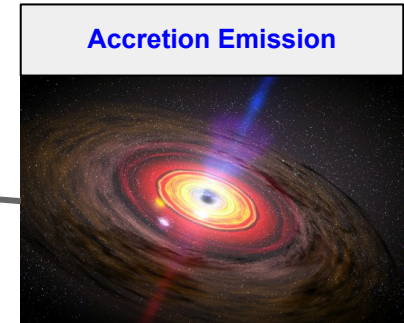
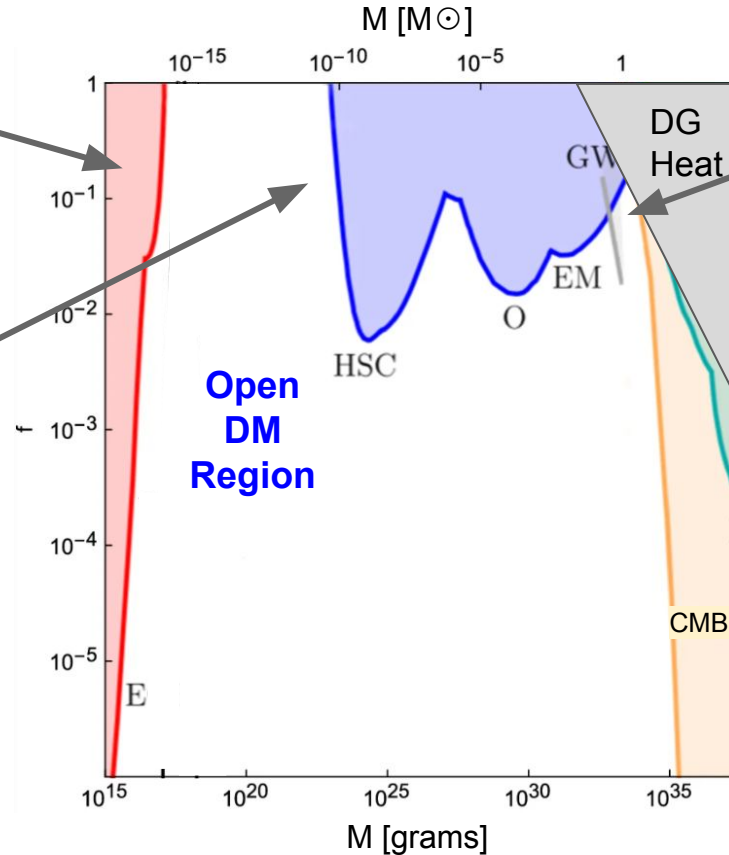
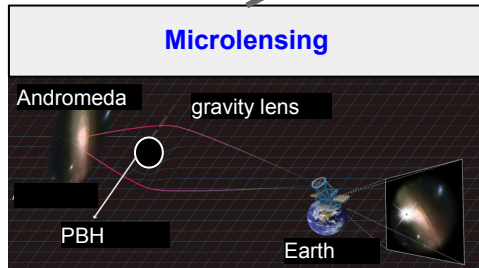
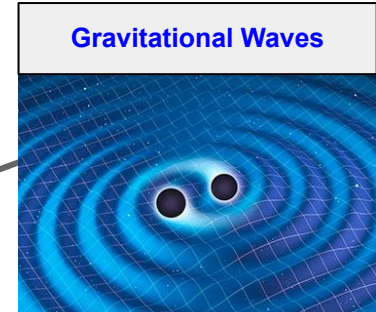
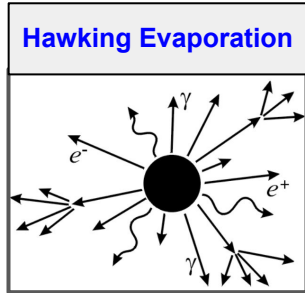


PBHs as dark matter

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



Status

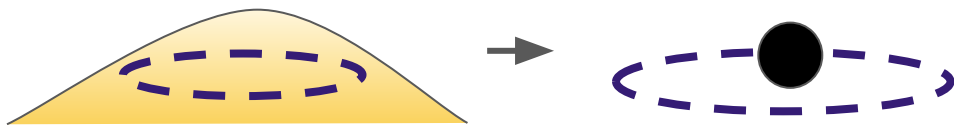


reviews [Sasaki, Green, Carr, Yokoyama, Kohri, Kuhnel, others]

Formation and Possible Features

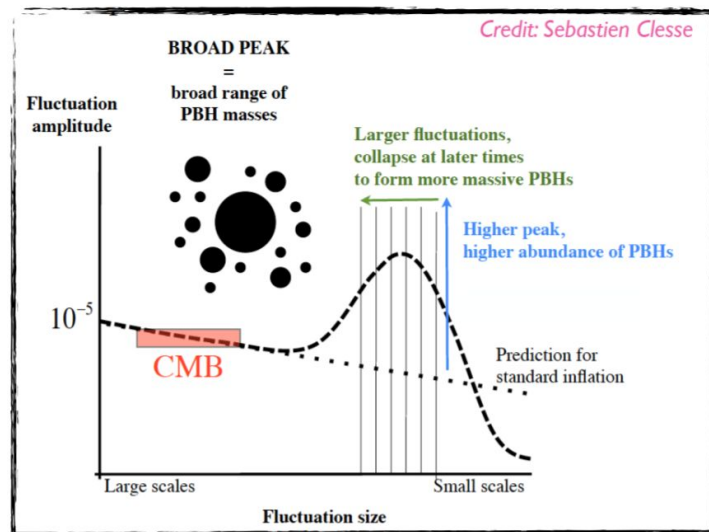
“Standard” PBH Formation

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

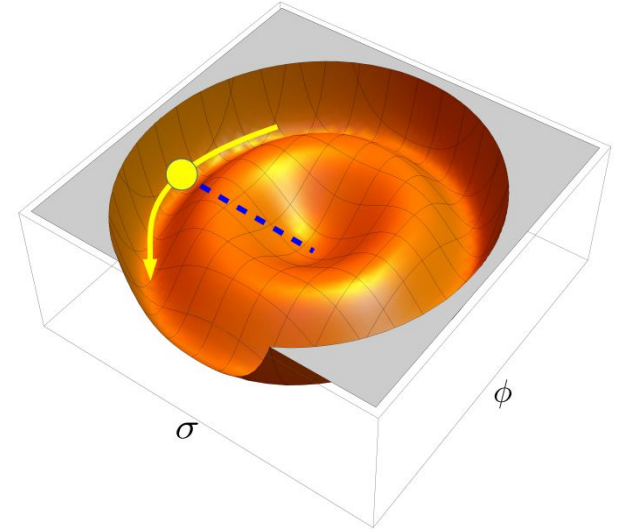
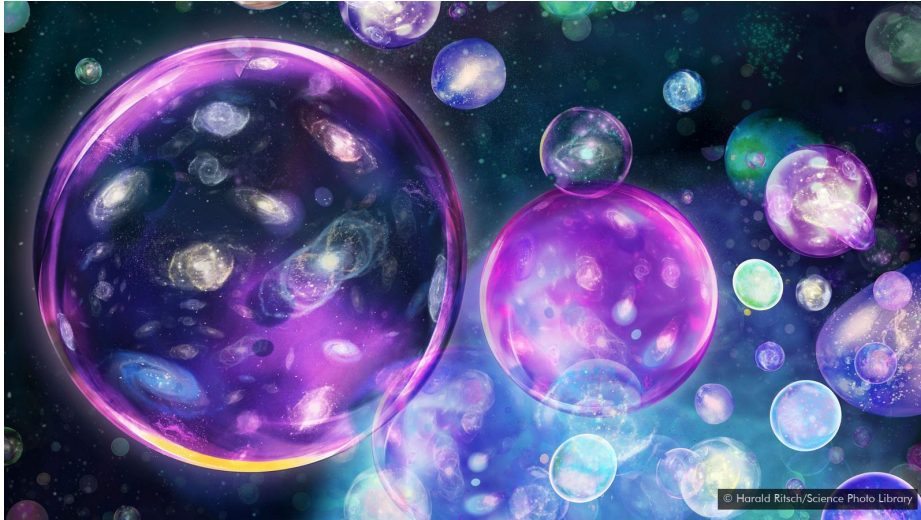


$$M_H \approx \frac{c^3 t}{G} = 10^{15} \text{ g} \left(\frac{t}{10^{-23} \text{ s}} \right)$$

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



PBHs from Bubble Multiverse

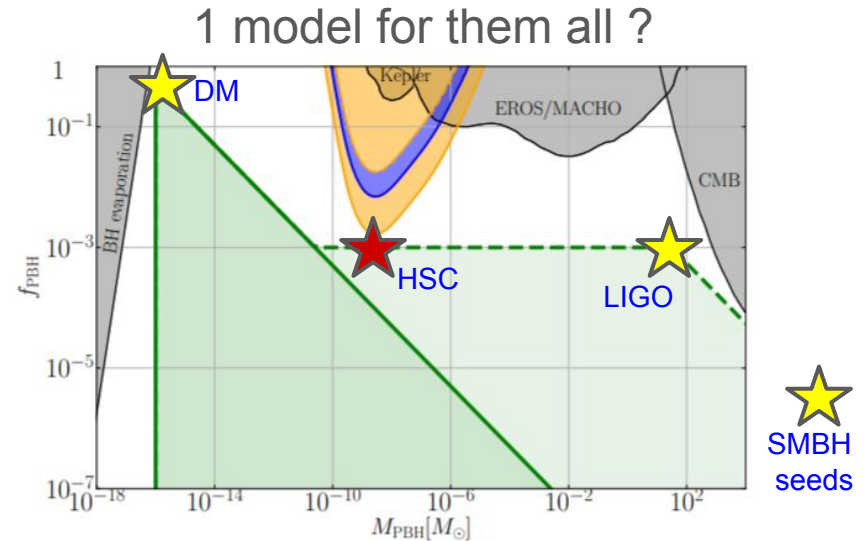
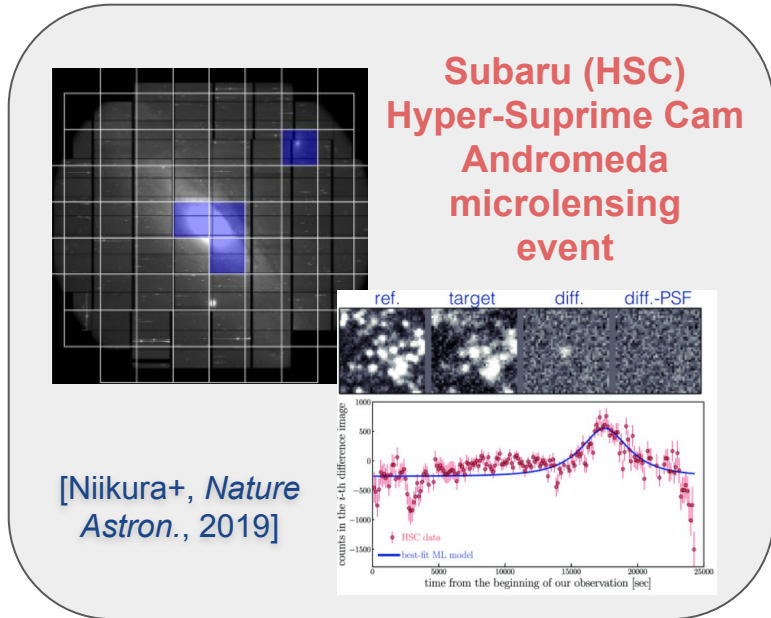


generic mechanism for PBHs broadly distributed in mass

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

[Sasaki+, 1980s; Deng, Vilenkin...]

PBH DM from Bubble Multiverse: Detected by HSC ?!



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

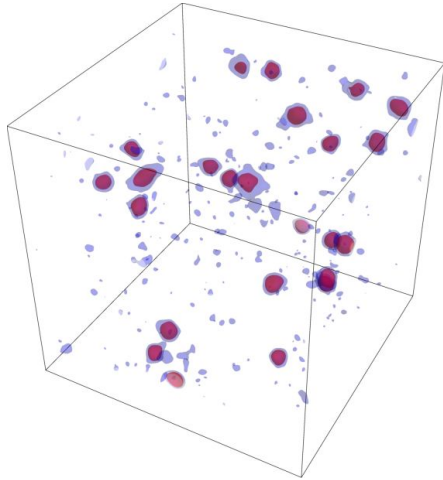
→ *tail of PBH distribution allows for indirect test of open DM window*

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

Distinct PBH Features Possible

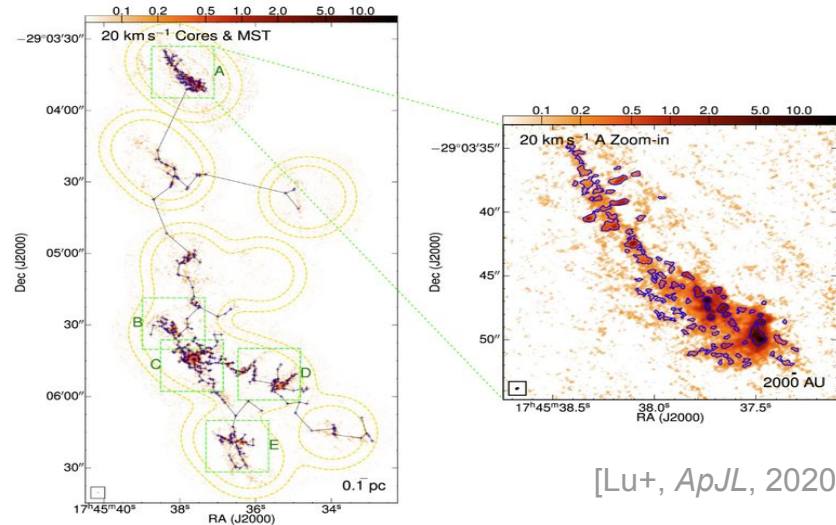
In early Universe, attractively self-interacting scalar fields can experience unstable oscillations
→ can break apart into solitonic “lumps”

oscillon fragmentation
(string moduli scalar fields)



[Antusch+, 2017]

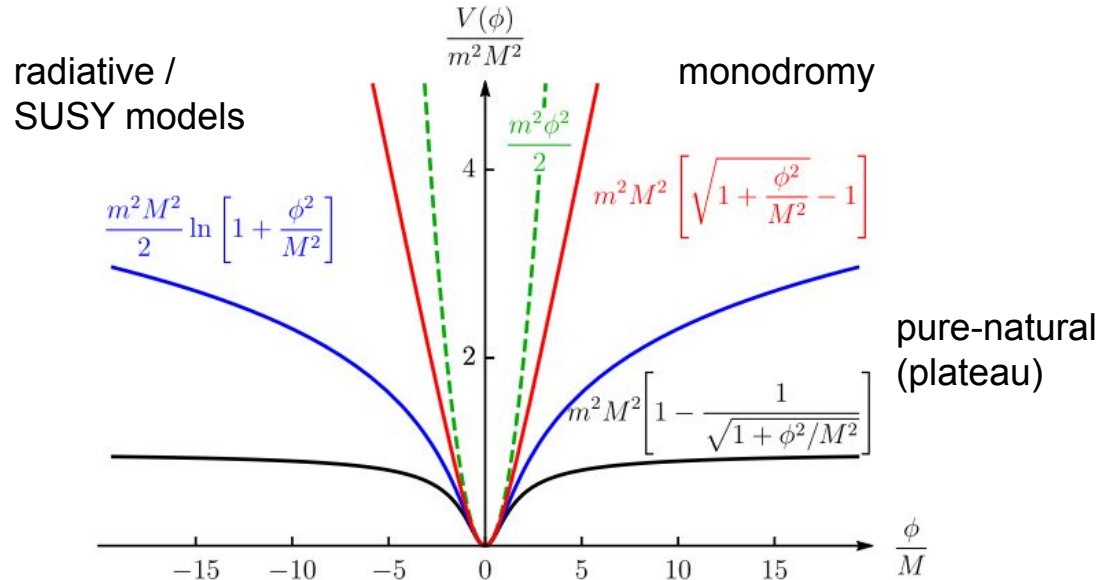
Jeans fragmentation analogy
(massive molecular Galactic Center clouds)



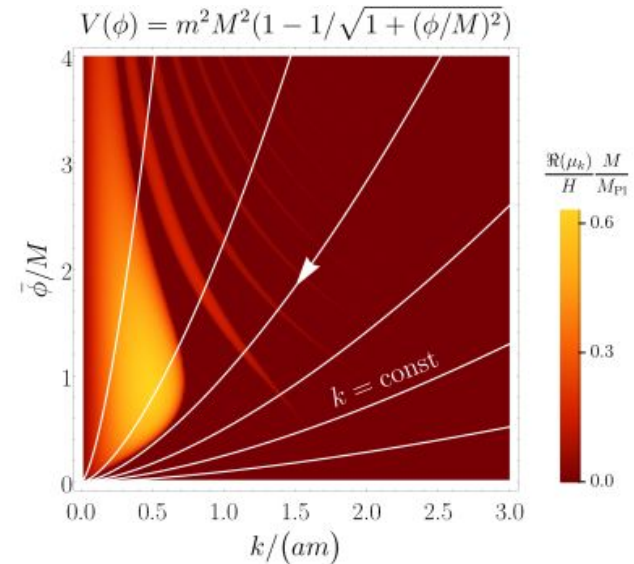
[Lu+, *ApJL*, 2020]

Fragmentation in Inflation Models

In many theories inflaton scalar that drives rapid early Universe expansion can break into oscillons



Floquet stability chart



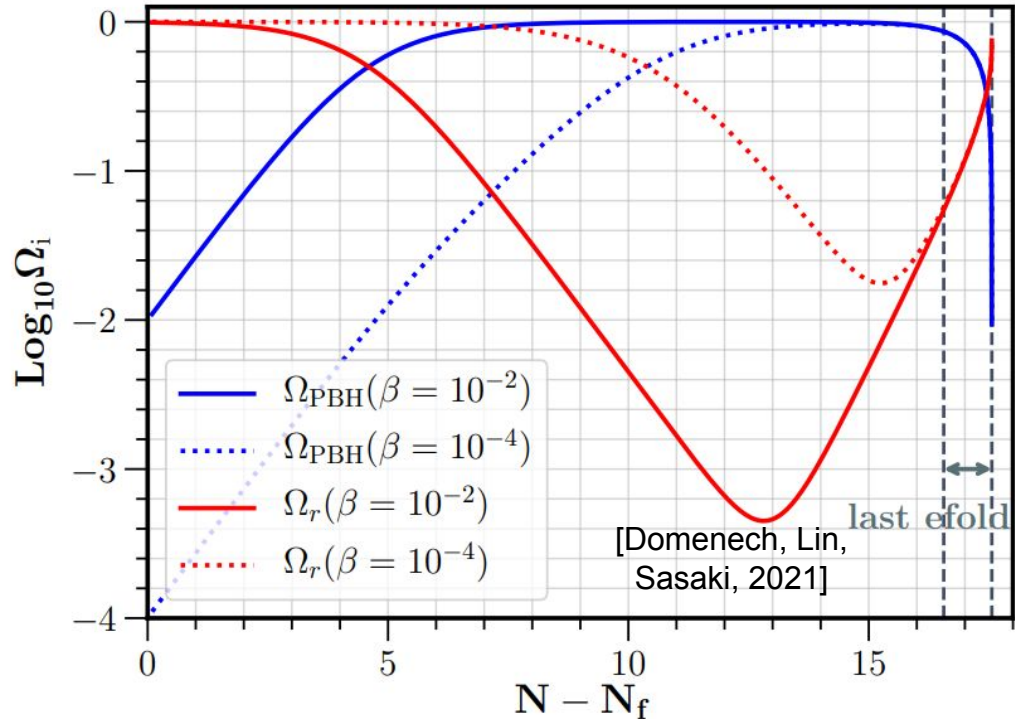
[Lozanov, VT, *Phys.Rev.Lett.*, (2023) 2204.07152]

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

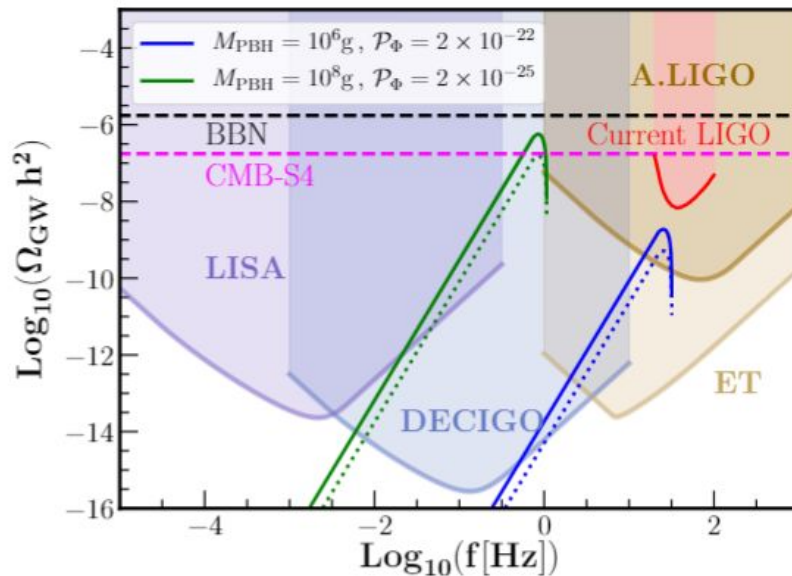
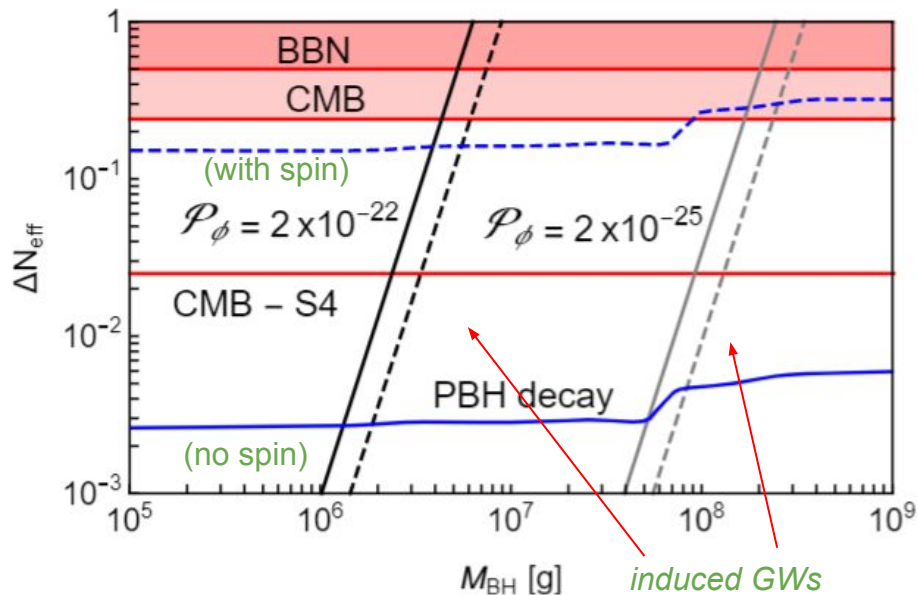
→ strong induced GWs

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



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

Probing Spin and Mass Distributions of Evaporating PBHs



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

[Domenech, VT, Sasaki, *Phys.Lett.B*, (2021), 2105.06816] (see also Turner, Perez-Gonzales+ 2022)

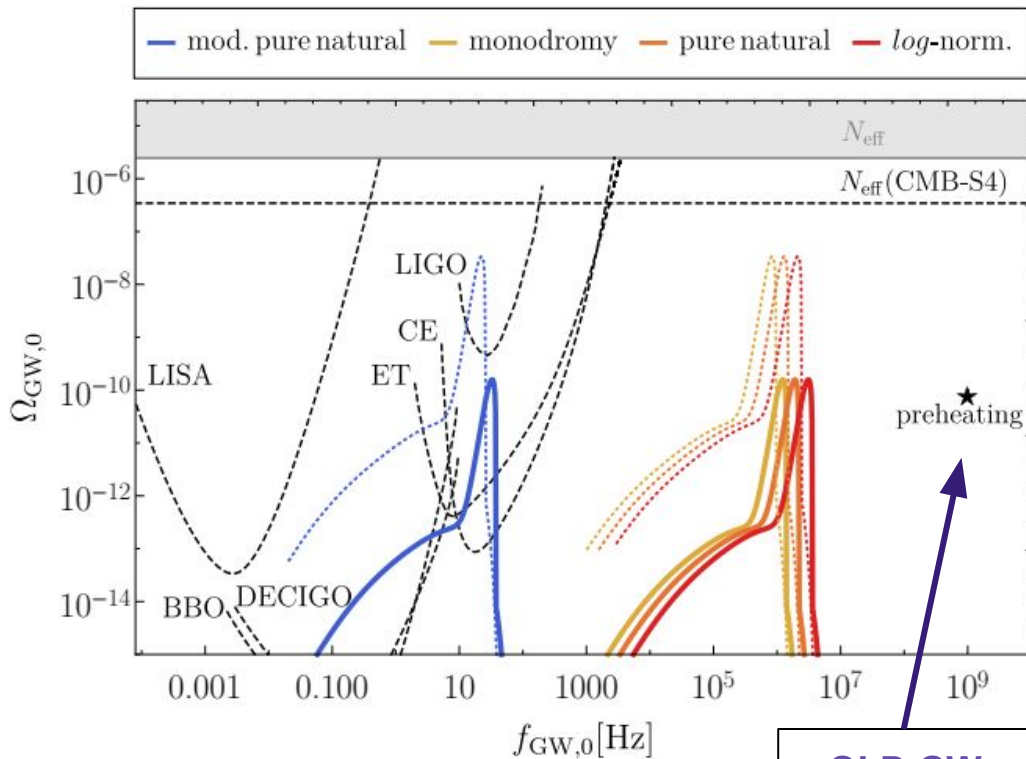
Oscillon-Induced GWs: A New Test of Early Universe

- 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

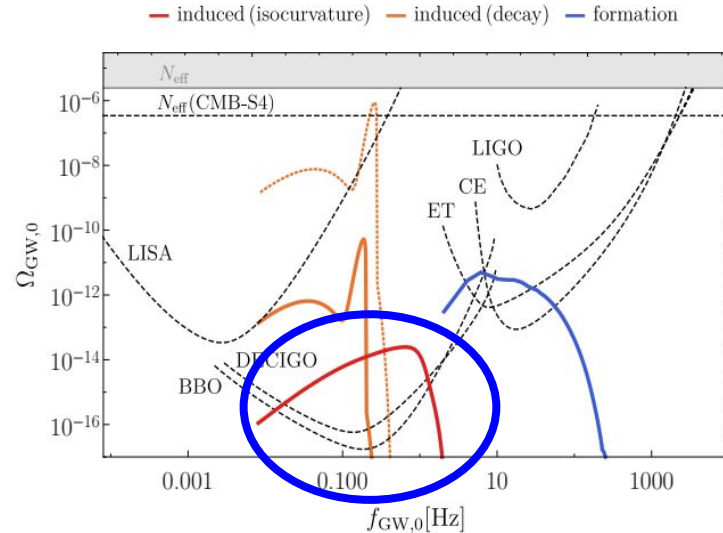
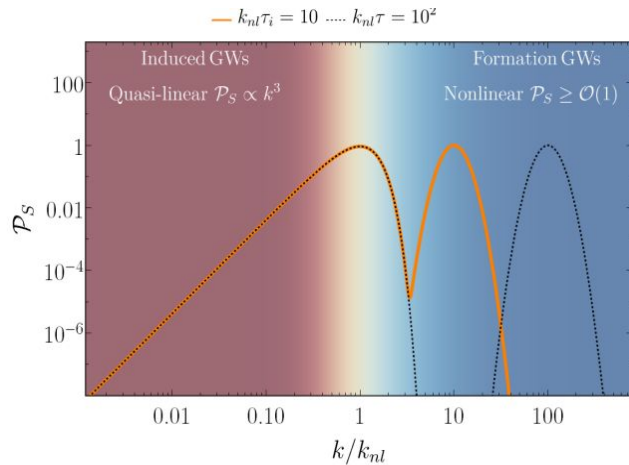


[Lozanov, VT, *Phys.Rev.Lett.*, (2023) 2204.07152]

~ OLD GW RESULTS

Universal Gravitational Waves from Cosmological Solitons

- Solitons/defects often appear in early Universe theories
→ monopoles, Q-balls, oscillons, strings, domain walls...
- Second order (induced) GWs are sourced by conversion of isocurvature perturbations associated with soliton formation to curvature perturbations → **universal GWs signatures**
- Novel predictions of many cosmological theories !



Example:

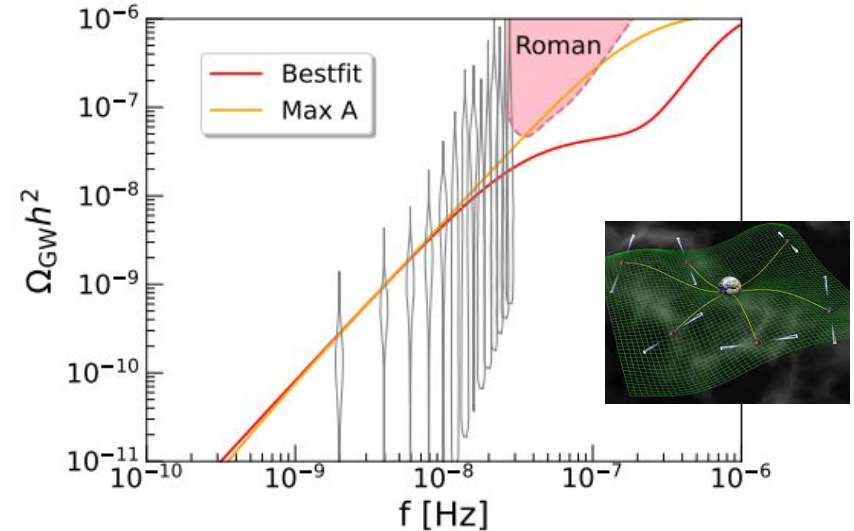
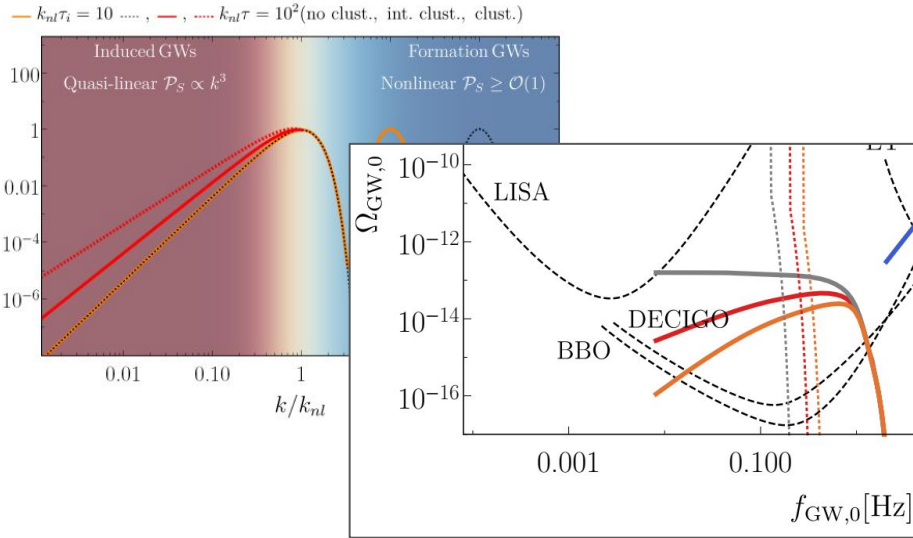
Axion-like oscillons

[Lozanov, Sasaki, VT, (2023), 2304.06709]

Universal Gravitational Waves from Cosmological Solitons

provide test for soliton clustering
(gravity, Yukawa force...)

well fit NANOGrav data for axion-like oscillons
(w/o PBH overproduction)

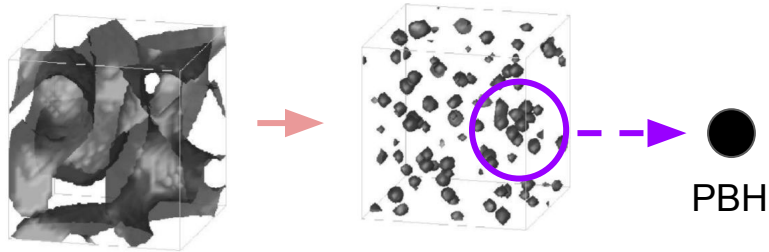


[Lozanov, Sasaki, VT, (2023), 2309.14193]

[Lozanov, Pi, Sasaki, VT, Wang, (2023), 2310.03594]

Distinct PBH Features Possible, Some Examples

scalar fragmentation



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

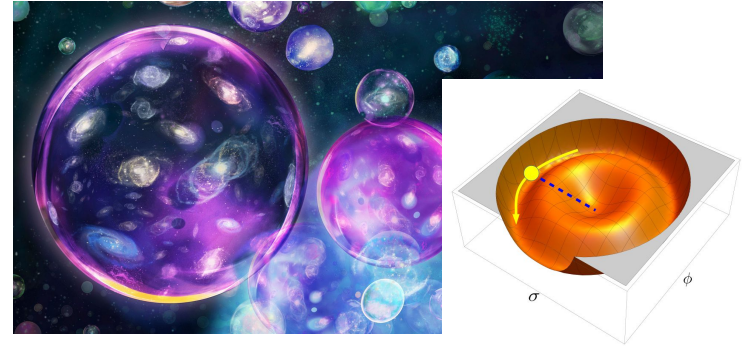
inflaton oscillons

[Cotner, Kusenko, **VT**, *PRD*, (2018) 1801.03321;

Cotner, Kusenko, Sasaki, **VT**, *JCAP*, (2019) 1907.10613]

also Q-balls [Cotner, Kusenko, *PRL* (2017)] + forces [Flores..]

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]

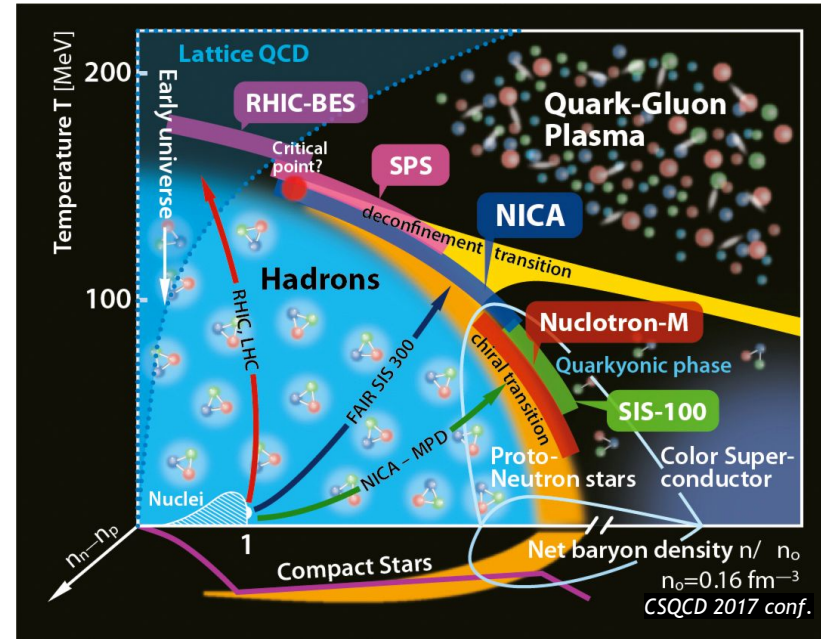
PBHs as Unique Probes of Fundamental Strong Force

- QCD strong force tested only in limited regimes
- In Standard Model QCD confines \lesssim GeV scale
- Many BSM theories predict novel QCD dynamics
 → scalars naturally lead to new high-T transitions
 [Ipek, Tait, PRL, 2018]

$$\mathcal{L} \supset -\frac{1}{4} \left(\frac{1}{g_{s0}^2} + \frac{S}{M} \right) G_{\mu\nu}^a G_a^{\mu\nu} + \dots$$

$$\Lambda(\langle S \rangle) = \Lambda_0 \text{Exp} \left[\frac{24\pi^2}{2N_f - 33} \frac{\langle S \rangle}{M} \right]$$

- Extreme early Universe conditions set unique laboratory to test unexplored QCD regimes



Black Holes as Unique Probes of Fundamental Strong Force

High-temperature phase transition modify equation of state (pressure vs. density relation) of Universe

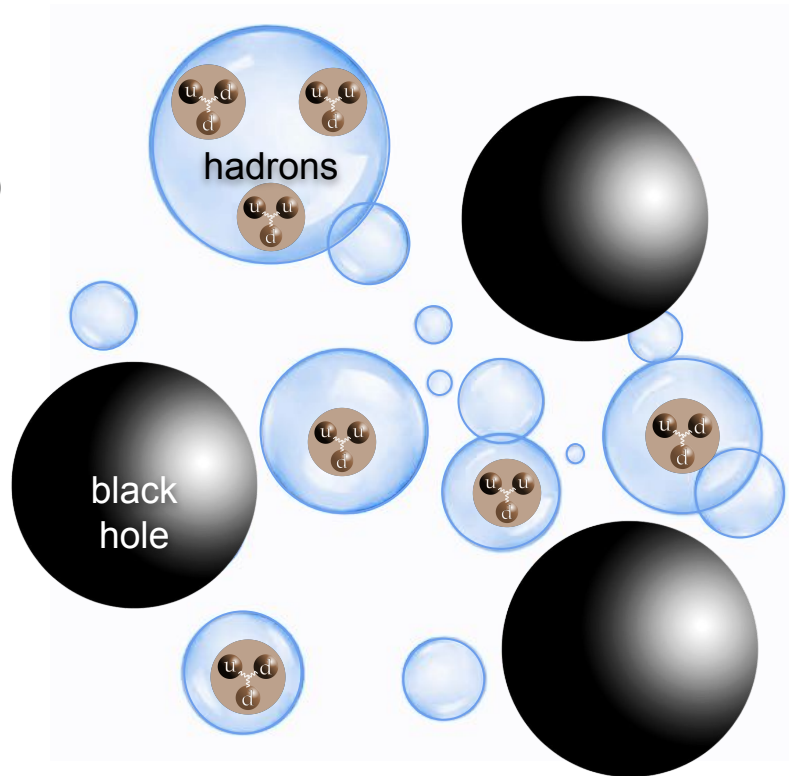
→ *phase transition enhances collapse of cosmological perturbations*

Primordial Black Holes

$$M_H \simeq 4.8 \times 10^{-10} M_\odot \left(\frac{T}{10 \text{ TeV}} \right)^{-2} \left(\frac{g_*}{106.75} \right)^{-1/2}$$

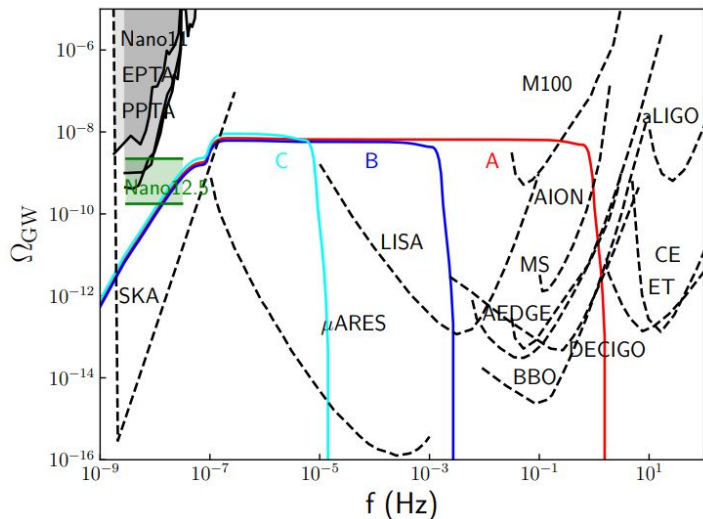
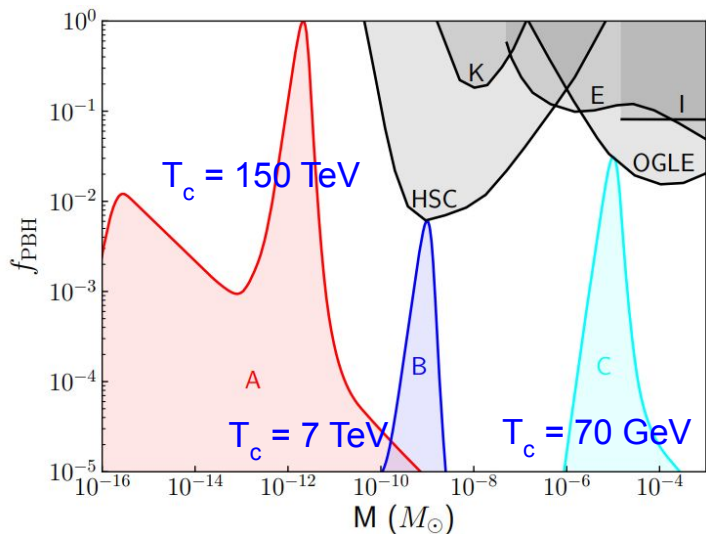
~ black hole mass

~ phase transition temperature



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

PBHs as Unique Probes of Fundamental Strong Force



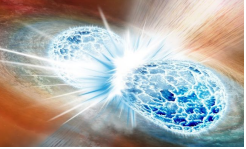
PBHs excellent for exploring fundamental physics in unique ways

PBHs of High-T QCD transition can be ALL DM & contribute to NANOGrav GWs

- very different from \sim solar-mass PBHs associated with SM QCD transition, *cannot* be all DM
- new insights into fundamental strong force from black holes and astrophysical surveys

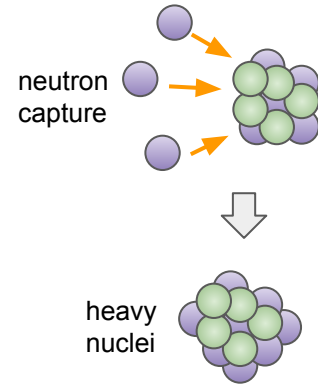
[Lu, VT, Fuller, *Phys.Rev.Lett*, (2023) 2212.00156]

Disrupting Astrophysics with PBHs



Making Gold with Tiny DM PBHs

- Can asteroid-mass PBH DM in open window help solve puzzles?
- Origin of heavy elements (gold) major long-standing problem
→ *neutron star mergers great, but might not be enough* e.g. [Kobayashi+, 2020]



SPACE DAILY
your portal to space

Neutron stars contribute little, but something's making gold

SEPTEMBER 17, 2020 BY BRIAN KOBERLEIN

SEPTEMBER 17, 2020 BY BRIAN KOBERLEIN

Colliding Neutron Stars Don't Make Enough Gold to Explain What We See in the Universe

TECH EXPLORIST

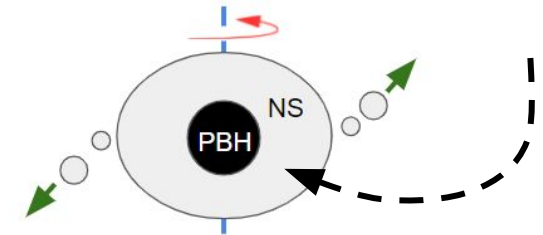
Something is raining gold across the universe

No one knows what it is.

BY AMIT MALEWAR / OCTOBER 3, 2020 / SPACE

TRENDING

- **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

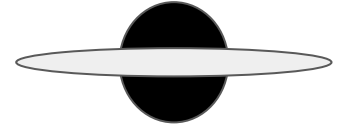


UC Berkeley: Makasdj

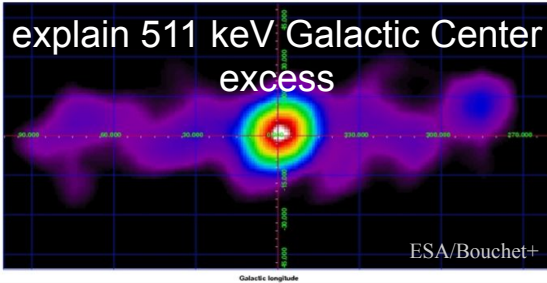
Fast Radio Burst



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



explain 511 keV Galactic Center
excess

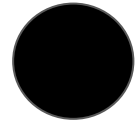
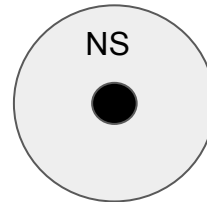


ESA/Bouchet+

*** can explain with just NS-NS mergers

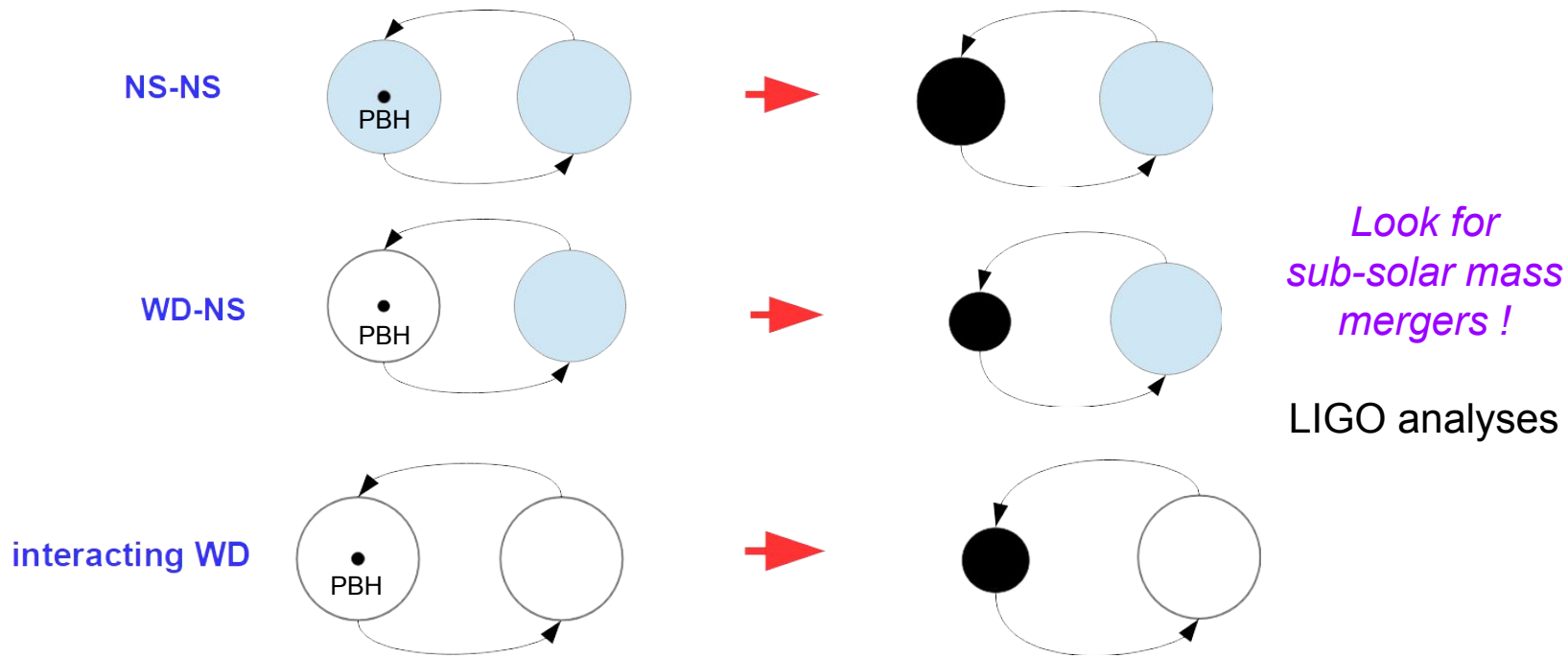
[Fuller, Kusenko, Radice, Takhistov,
Phys.Rev.Lett., (2018) 1811.00133]

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



[Fuller, Kusenko, VT, *Phys.Rev.Lett.*, (2017) 1704.01129; VT, *Phys.Lett.B.*, (2018) 1707.05849 + (2019), 1710.09458]

Transmuted (Sub)Solar-Mass BH Mergers



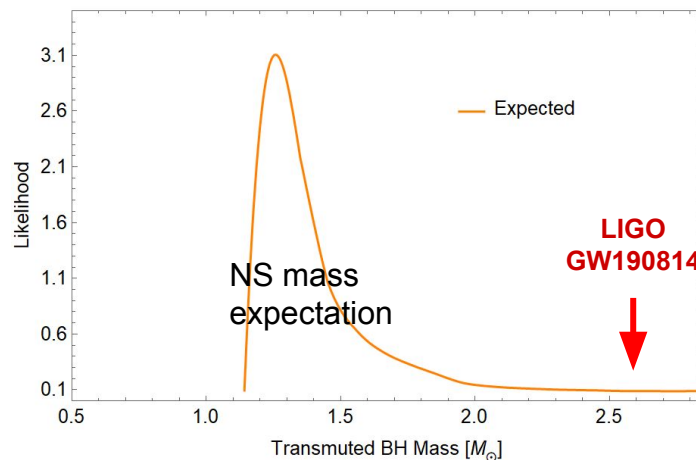
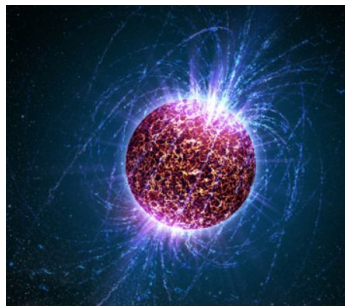
*Look for
sub-solar mass
mergers !*

LIGO analyses

[VT, *Phys.Lett.B*, (2017) 1707.05849]

Origin of Solar-mass Black Holes

- Solar-mass ($\sim 1-2.5 M_{\odot}$) BHs unexpected in astrophysics \rightarrow PBHs ? particle DM eating NS ?
- **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



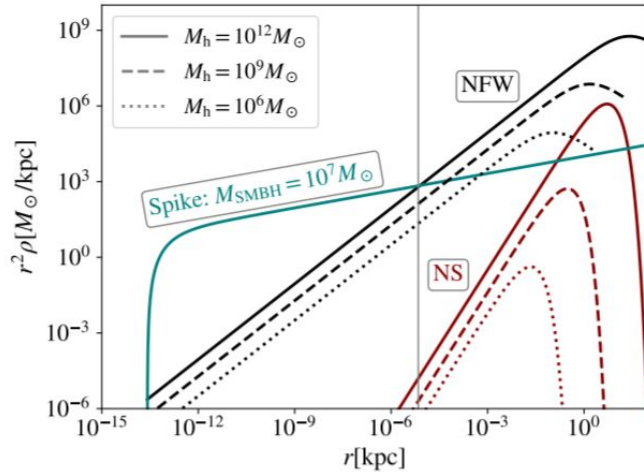
Large ($> 1.5 M_{\odot}$) candidates unlikely to be from DM eating NS!

[VT, Fuller, Kusenko, *Phys.Rev.Lett.*, (2020), 2008.12780]

* for redshift effects, see Dasgupta+ 2020

Identifying BH - 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

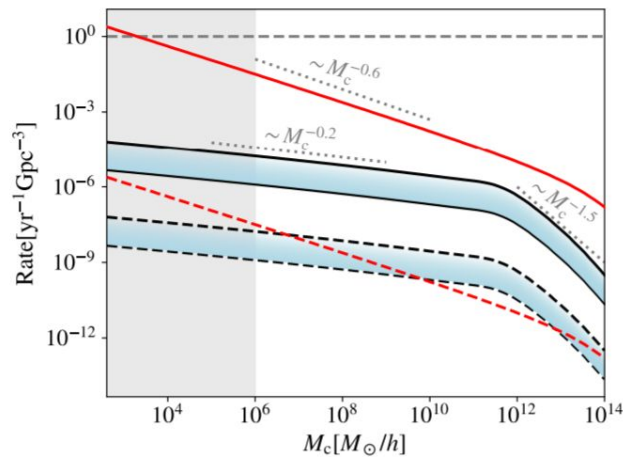
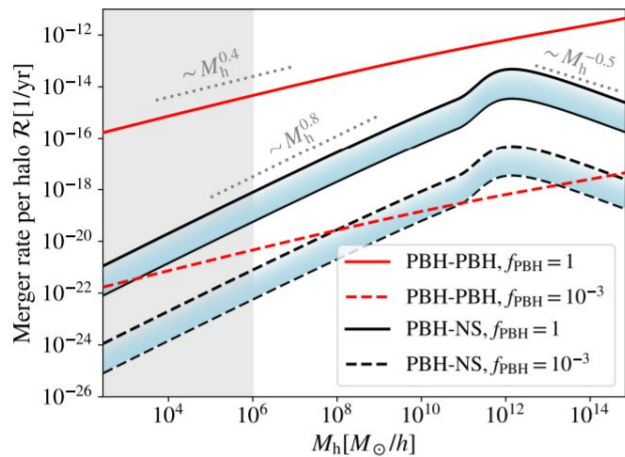


$$\mathcal{R}_{\text{PBH-NS}} = 4\pi \int_0^{R_{\text{vir}}} dr r^2 \frac{\rho_{\text{NS}}}{m_1} \frac{\rho_{\text{PBH}}}{m_2} \langle \sigma v_{\text{rel}} \rangle$$

2-body scattering with GW emission

[Sasaki, VT, Vardanyan, Zhang, *ApJ* (2021), 2110.09509]

Identifying BH - Neutron Star (BH-NS) Mergers



- PBH-NS rates subdominant → **observed NS-BH events expected to be astrophysical**
- *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*, (2021), 2110.09509]

Are Intermediate-mass BHs Primordial ?

- GW190521 event $\sim 150 M_{\odot}$ merger mass [Abbott+, *PRL*, 2020], first definitive IMBH detection
- **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)

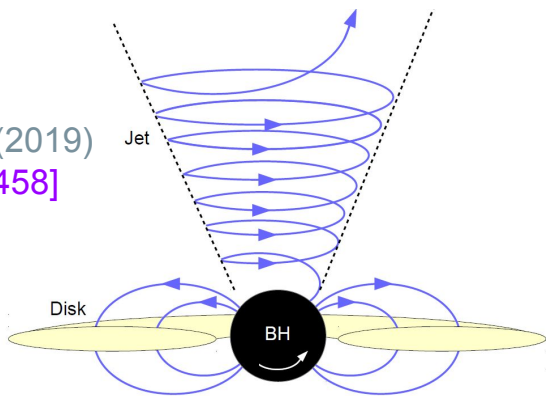


[Lu, VT, Gelmini, Hayashi, Inoue, Kusenko, *ApJ Lett.*, (2020) 2007.02213;
VT, Lu, Gelmini, Hayashi, Inoue, Kusenko, *JCAP*, (2021) 2105.06099]

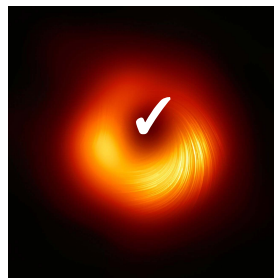
PBH Outflow Winds and Jets

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

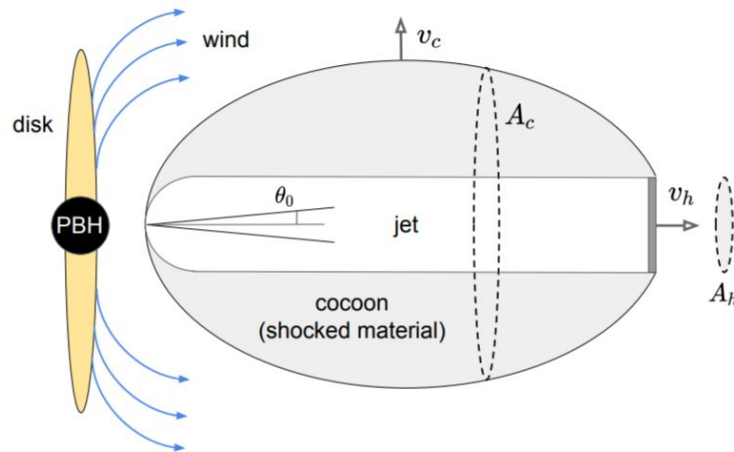
[VT, PLB, (2019)
1710.09458]



Blandford-Znajek
Mechanism

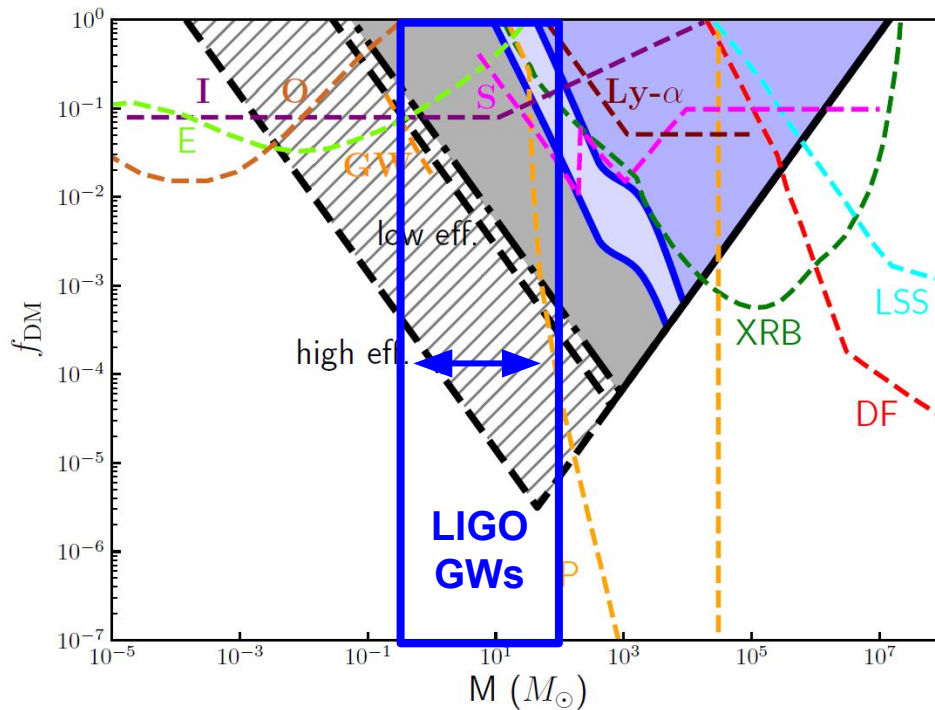


EHT M87
strong B-field + jet



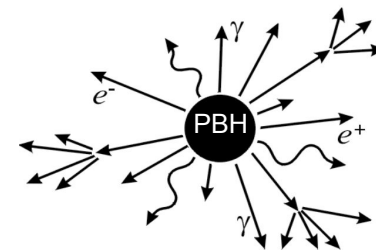
[VT, Lu, Murase, Inoue, Gelmini, *MNRAS Lett.*, (2021) 2111.08699]

PBH Outflow Winds and Jets



* gas heating from evaporating PBHs

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

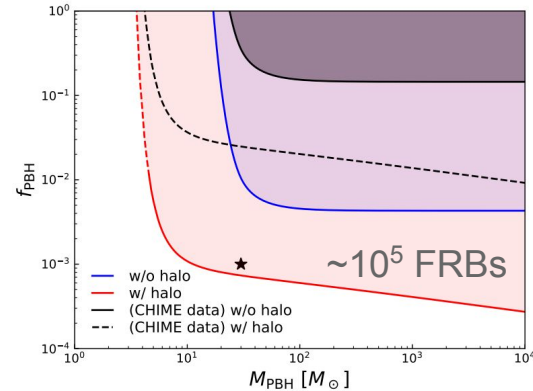
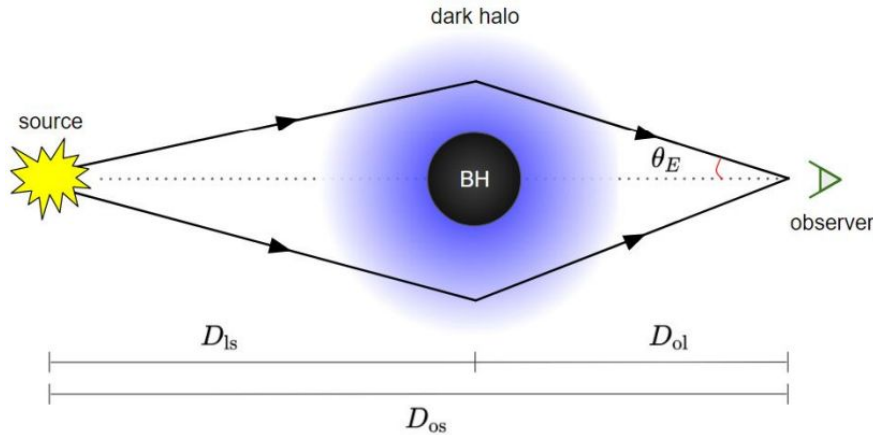


[VT, Lu, Murase, Inoue, Gelmini, MNRAS Lett., (2021) 2111.08699]

If PBHs not all DM, is there general test?

Lensing 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+]
* PBHs with annihilating WIMPs strongly constrained [Lacki, Beacom, ApJL, 2010; ...]
- Strong cosmological lensing (e.g. FRBs) **can test population of dressed PBHs**
- Already start exploring regions with CHIME FRB data, method applicable to other lenses

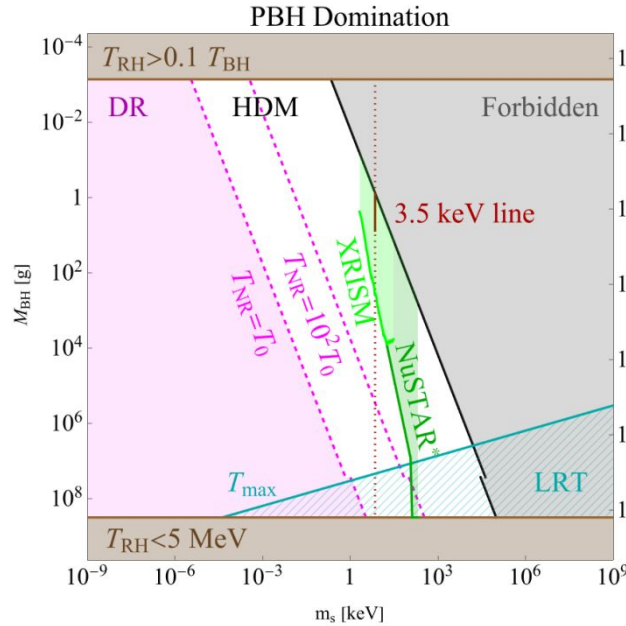
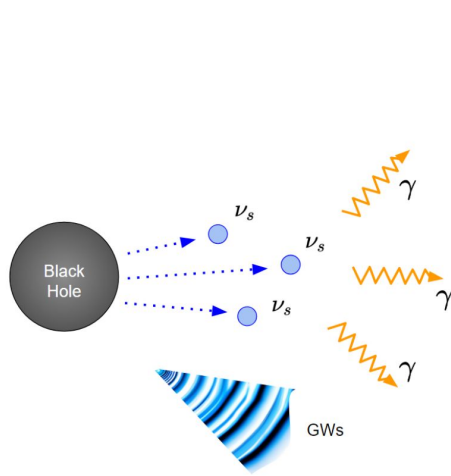


[Oguri, VT, Kohri, *Phys.Lett.B.*, (2023) 2208.05957]

New Dark Matter from PBHs

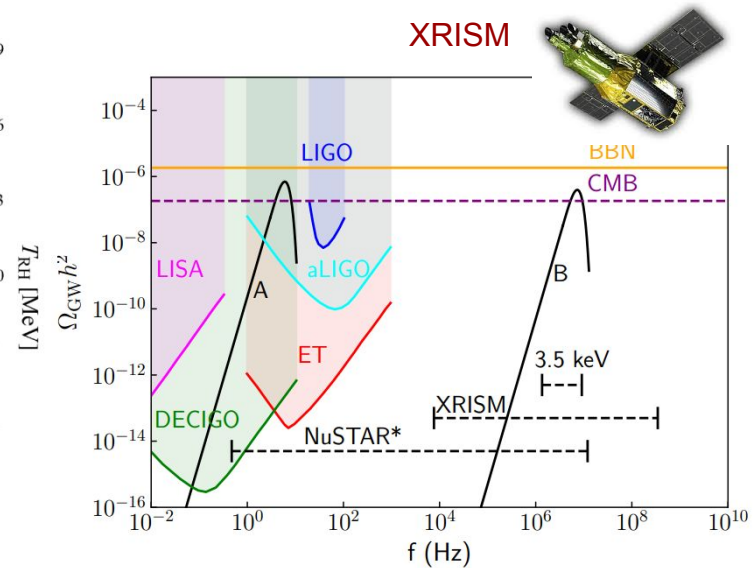
PBH Neutrino genesis: Novel Sterile-neutrino DM Production

- Sterile neutrino DM mechanisms typically rely on sizable couplings, mixing with SM ν 's
- Evaporating PBHs can produce sterile neutrino DM with *arbitrary small* mixing



many other PBH DM mechanisms..

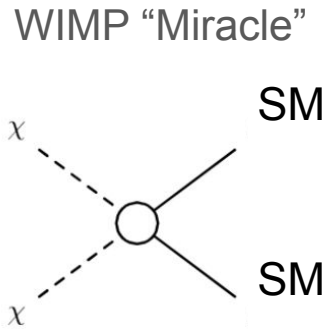
[Chen, Gelmini, Lu, VT, (2023), 2309.12258]



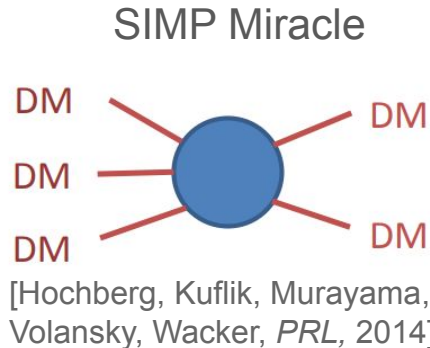
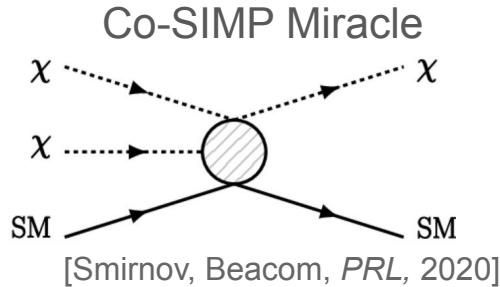
unique GW + X-ray signatures

New DM from PBHs

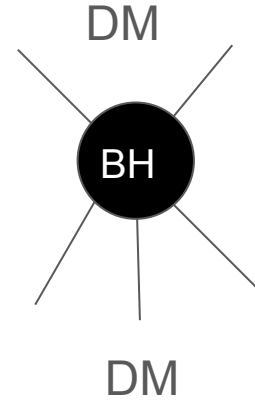
conventional particle DM relies on interactions



abundance set by annihilation



conceptually new general idea:
Regurgitated DM

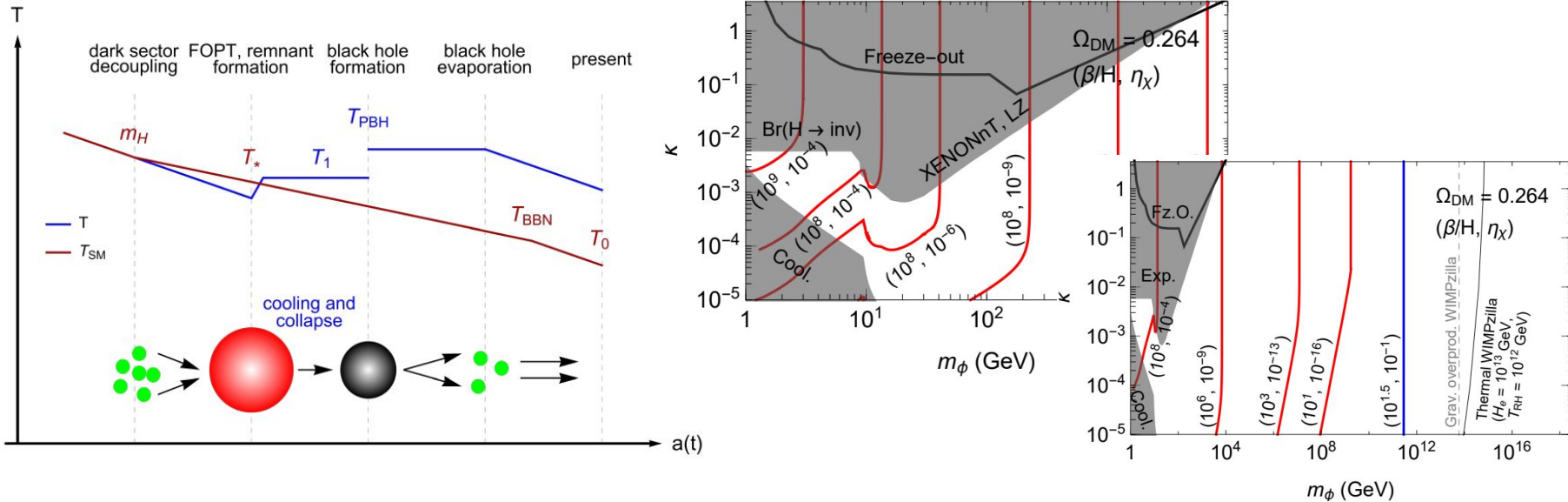


BH "scrambles", re-emits DM with new properties, doesn't rely on interactions

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

Regurgitated DM

- Concrete realization within minimal model of dark sector with scalar/fermion and Yukawa force

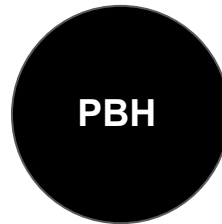


- Can make fermion/scalar DM $\sim 1-10^{16}$ GeV, opening parameter space**

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

Summary

- PBHs ~ “Standard Model” dark matter, very different from particle dark matter
- Appear in many theories, intriguing features, connections to puzzles and other fields
- **Manifestations could be already lurking in data**
- **Delve Deep Search Wide** → *especially applicable to rich physics of PBHs*



... *Dark Matter ?*