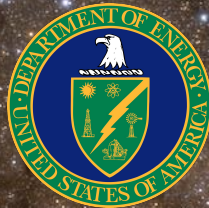


Primordial Black Hole Dark Matter

and ways to find it

Volodymyr Takhistov

University of California, Los Angeles
(UCLA)

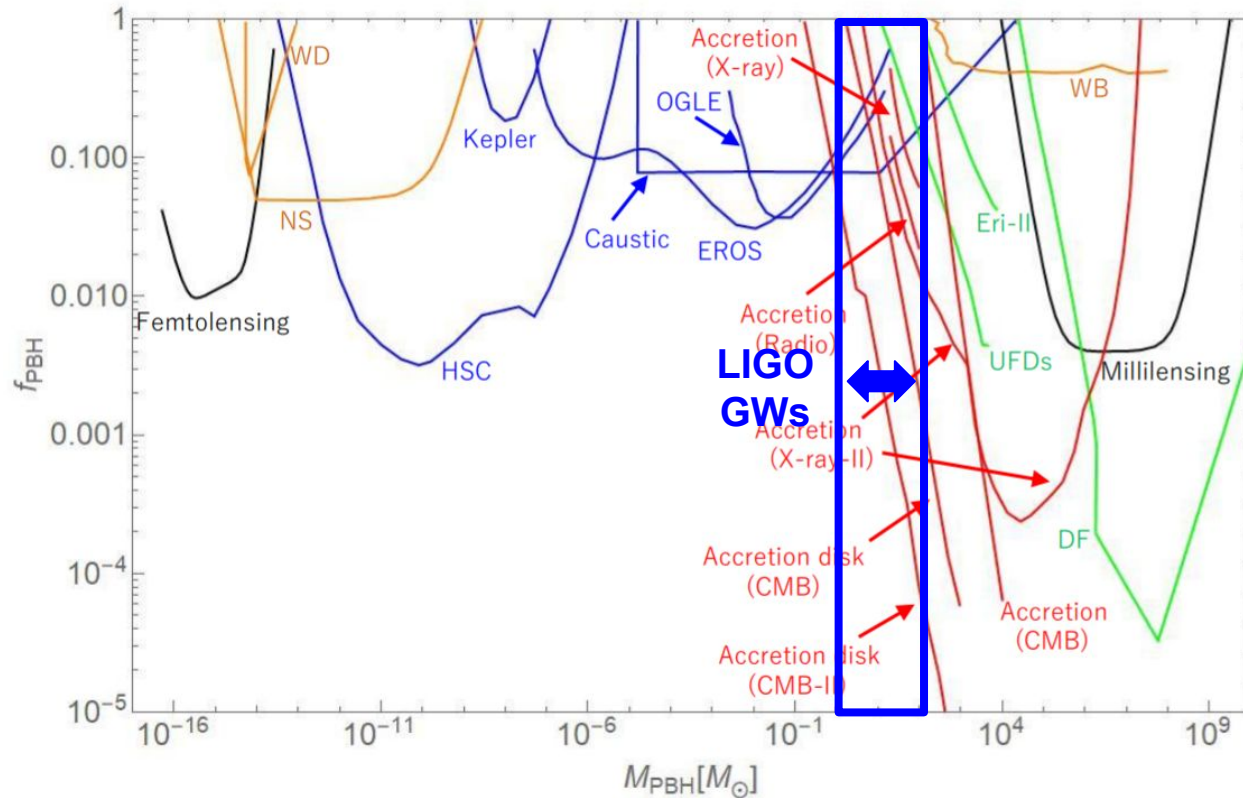


PBH Dark Matter

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

- Why PBH DM ?
 - no clear signs of particle DM
 - GW astronomy [Bird+ 2016; Sasaki, Thorne+ 1997...]
 - generic in many BSM models
 - help solve astro puzzles
 - already possible in standard cosmology (unlikely)

PBH Status (2017)

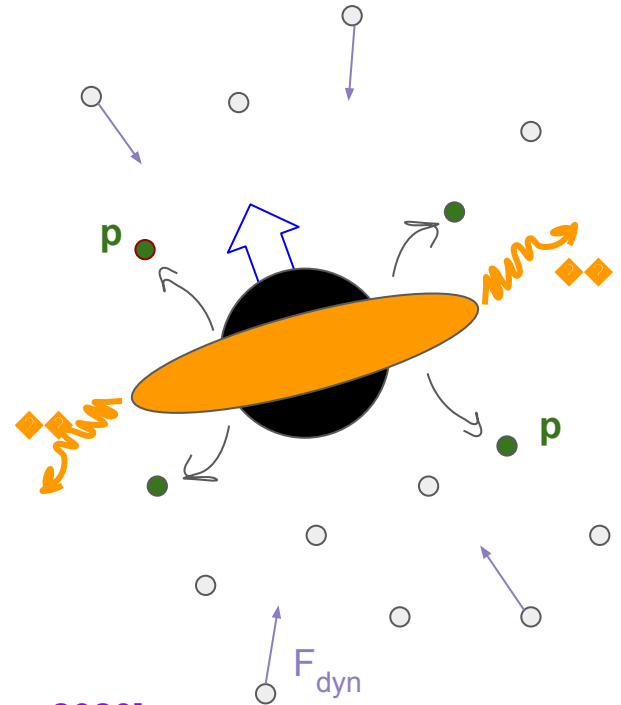


[Sasaki+, 2017]

A New Robust Constraint for LIGO PBHs

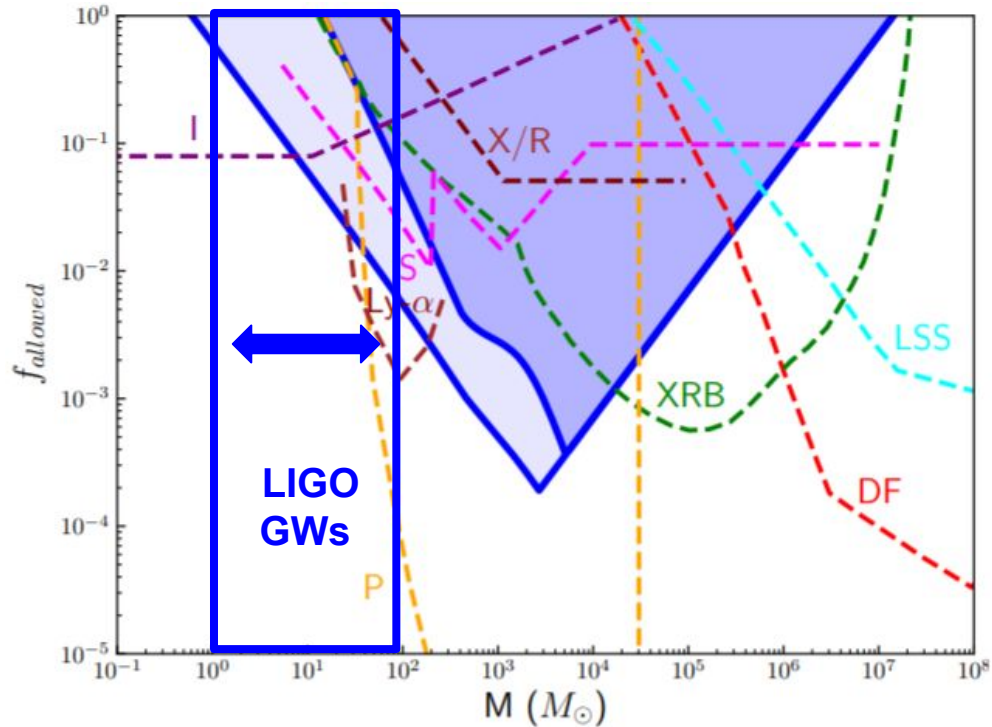
PBH Gas Heating

- PBH traversing interstellar medium interacts with gas → gas heated
- Main PBH gas heating mechanisms:
 - dynamical friction (“gravity drag”)
 - accretion disk photon emission
 - accretion mass (baryon) outflows / winds
- Great testing site: dwarf DM-rich galaxies (Leo T)
- Constrain PBHs if cooling can’t balance heating
→ robust, independent of cosmology



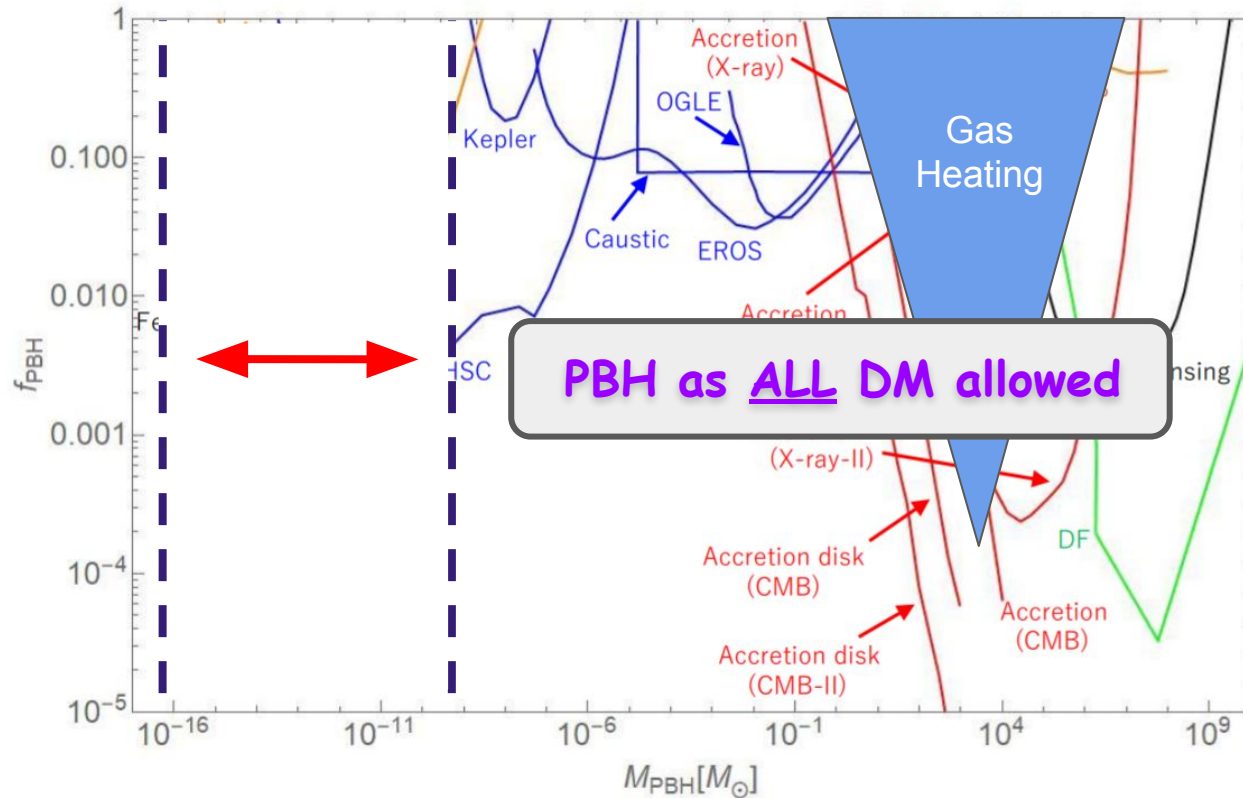
[Lu, VT, Gelmini, Hayashi, Inoue, Kusenko, 2020]

PBH Gas Heating



[Lu, VT, Gelmini, Hayashi, Inoue, Kusenko, 2020]

PBH Status (2020)

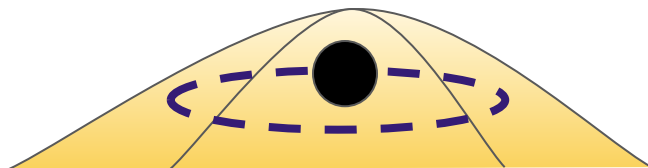


[Sasaki+, 2017]

How to Form PBHs ?

“Standard” PBH Formation

- Big perturbations ($\delta \sim 1$) enter horizon (radiation era) \rightarrow collapse



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

New General Alternative: Scalar Fragmentation

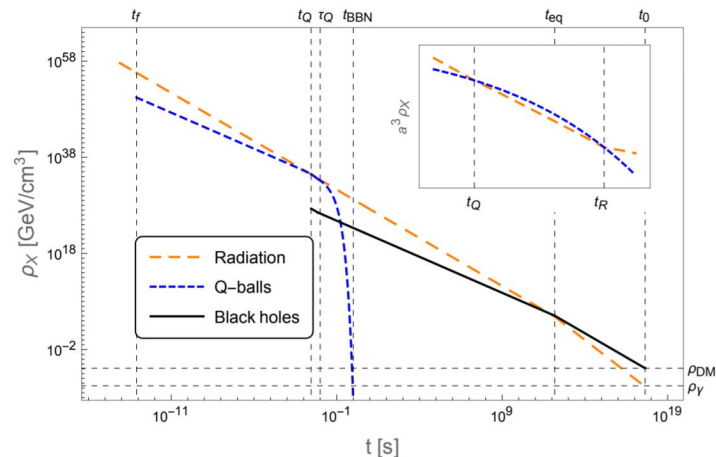
- Scalars exist and very generic in BSM & top-down theories
 - SUSY models expect $O(100)$ scalars with flat potential, often $U(1)$ charged [Gerghetta+, 1995]
- Post-inflation scalars with attractive self-interactions could break apart due to instabilities
 - complex \rightarrow Q-balls [Coleman, 1985]
 - real \rightarrow oscillons
 - spectator field or the inflaton



*** fragmentation possibly very generic, if gravity is weakest force
[Kusenko, VT, Yamada, Yamazaki, *PLB*, 2019]

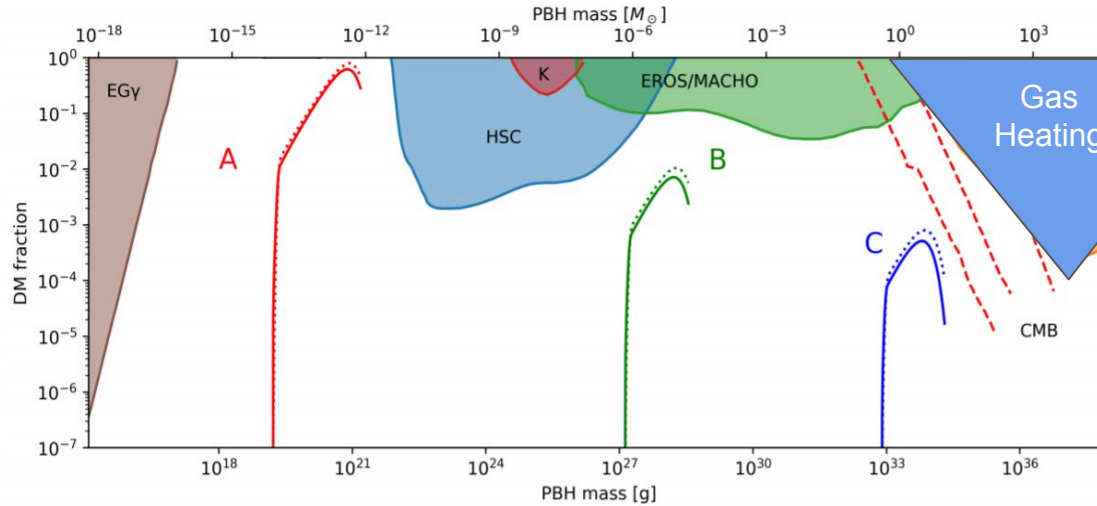
New General Alternative: Scalar Fragmentation

- Fragments are big (% horizon) and stable
- Fragmentation is random
→ large density fluctuations, unrelated to inflation
- Some rare regions can collapse → PBH



[Cotner, Kusenko, *PRL*, 2016; Cotner, Kusenko, *VT*, *PRD*, 2018;
Cotner, Kusenko, Sasaki, *VT*, *JCAP*, 2019]

New General Alternative: Scalar Fragmentation



Big (a ~ 1) BH spin possible → hard to make in usual mechanisms !

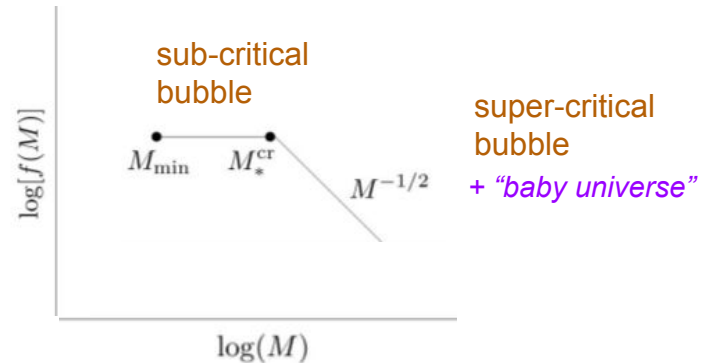
[Cotner, Kusenko, Sasaki, VT, JCAP, 2019]

Another General Scenario With Scalars...

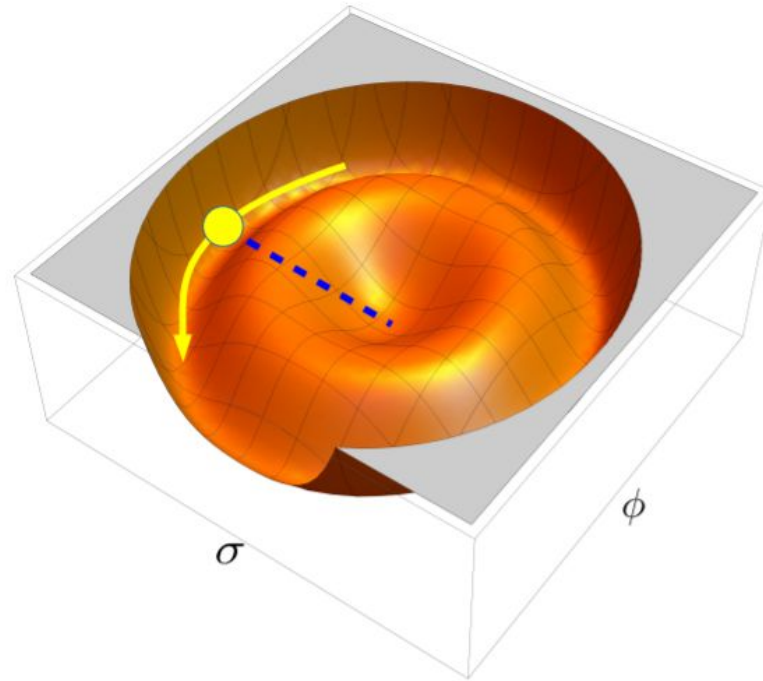
PBHs from Bubble Multiverse

- Multi(scalar)-field inflation motivated from top-down theories
→ inflaton potential has complicated shape and many minima
- During inflation inflaton can tunnel to near-by minimum → vacuum bubbles
- Bubbles broadly distributed in size → some will contain “baby universe” inside
- Bubbles expand and after inflation collapse
→ PBHs with extended mass-spectrum

*** *many previous studies* [Sasaki, Deng, Vilenkin, Zheng, Yamada...]

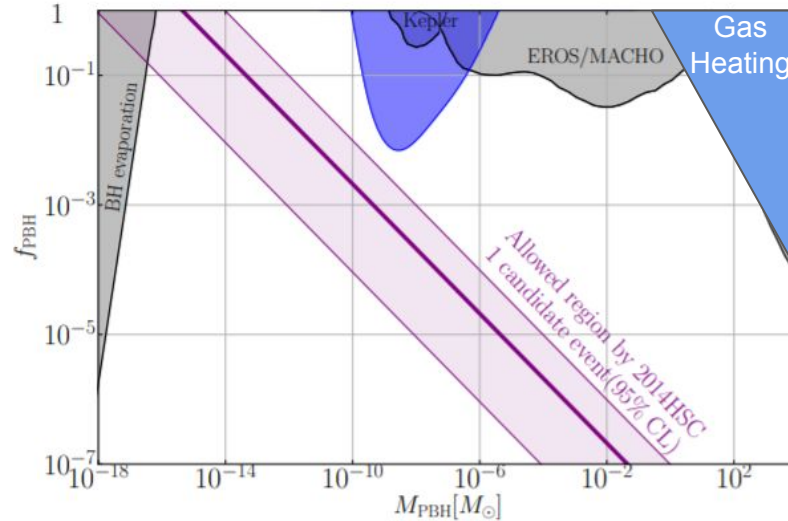


PBHs from Bubble Multiverse: A Fresh Look



[Kusenko, Sasaki, Sugiyama, Takada, VT, Vitagliano, 2020]

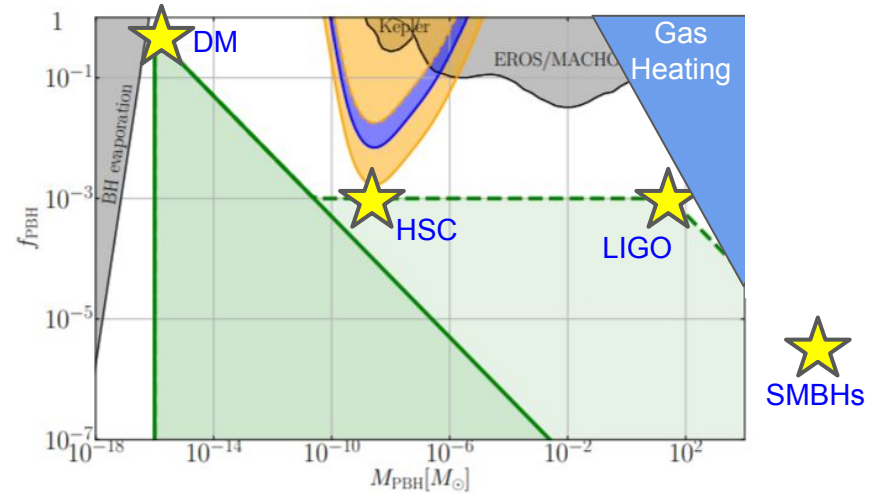
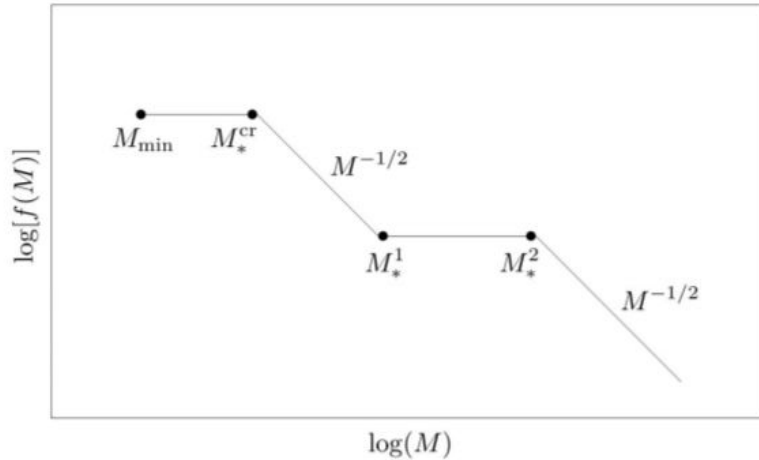
PBH DM from Bubble Multiverse: Detected by HSC ?!!



- Extended tail from vacuum bubble PBH allows to indirectly test open DM region
→ **PBH DM compatible with HSC candidate event !**

[Kusenko, Sasaki, Sugiyama, Takada, VT, Vitagliano, 2020]

PBH DM from Bubble Multiverse: One Model for Everything



- **One generalized model explains all major features simultaneously**
→ dark matter, HSC event, LIGO events, seeds of supermassive BHs

upcoming HSC observations will definitively test bubble multiverse PBH DM !

[Kusenko, Sasaki, Sugiyama, Takada, VT, Vitagliano, 2020]

... A Peak Inside the Open DM Window ?

Compact Stars as PBH Laboratories

- Small PBHs can be captured by compact stars (NS/WD) in DM-rich environments
[Capela, Pshirkov, Tinyakov, Kouvaris]

- Captured PBH grows inside & destroys star
→ exciting observables !

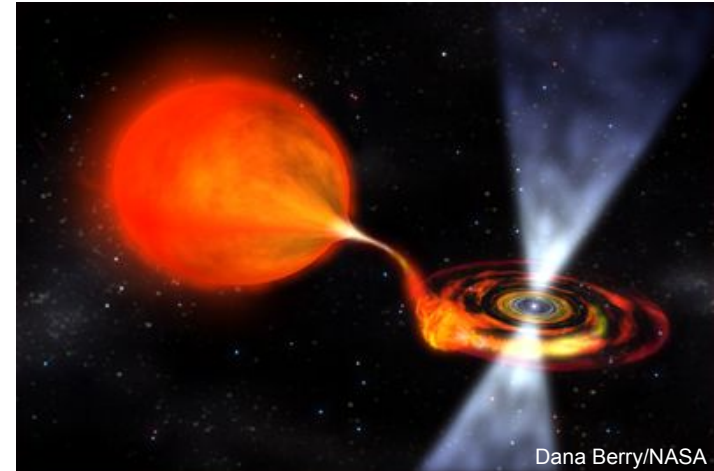
→ r-process nucleosynthesis, 511 keV, FRBs

[Fuller, Kusenko, VT, *PRL*, 2017]

& Viewpoint Highlight by H.-T. Janka

+ solar-mass BHs, new GRBs & microquasars

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



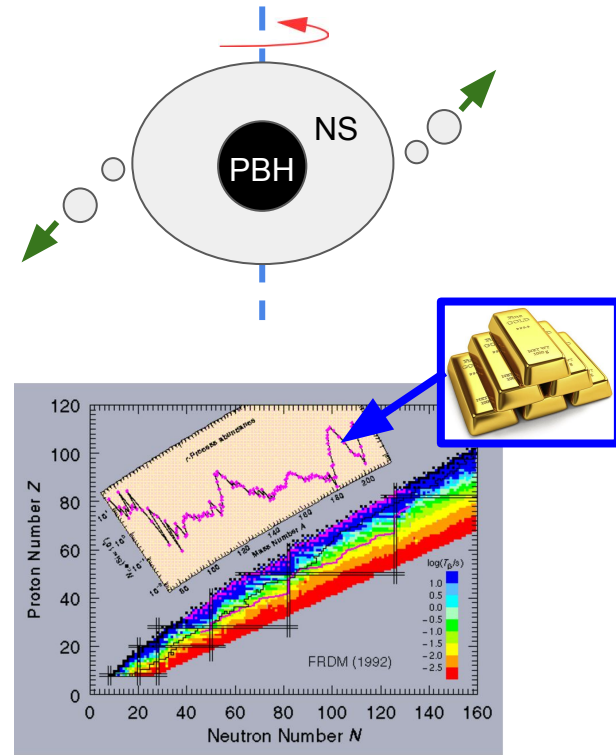
Dana Berry/NASA

PBHs in Millisecond Pulsars

- MSPs spin near mass-shedding limit
- **MSP + PBH:** star consumed, contracts, spins up
→ neutron-rich ejecta possible

*** *need more simulation studies*

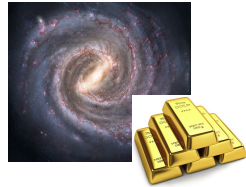
- Great site for **r-process nucleosynthesis**
(*stellar heavy element factory*)



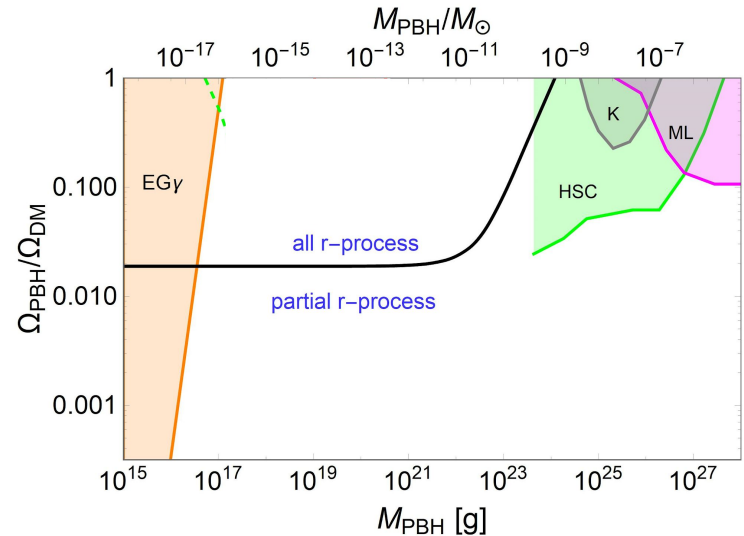
[Fuller, Kusenko, VT, PRL, 2017]

Making Gold with Black Holes

- Heavy element abundance
 - Milky Way - contains $10^4 M_{\odot}$
 - UFDs - 1 in 10 (Reticulum II) shows EXCESS [Ji+, Nature 2016]



→ can explain with PBH-NS !

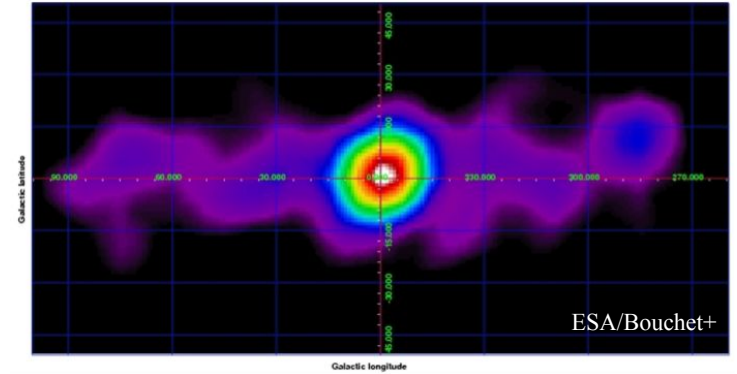


[Fuller, Kusenko, VT, *PRL*, 2017]

Explaining 511 keV in Galactic Center

- Observations (SPI/INTEGRAL) show Galactic Center shines in 511 keV γ -rays
 - consistent w/ e^+ annihilation [Beacom, Yuksel, 2006]

→ can explain with PBH-NS !

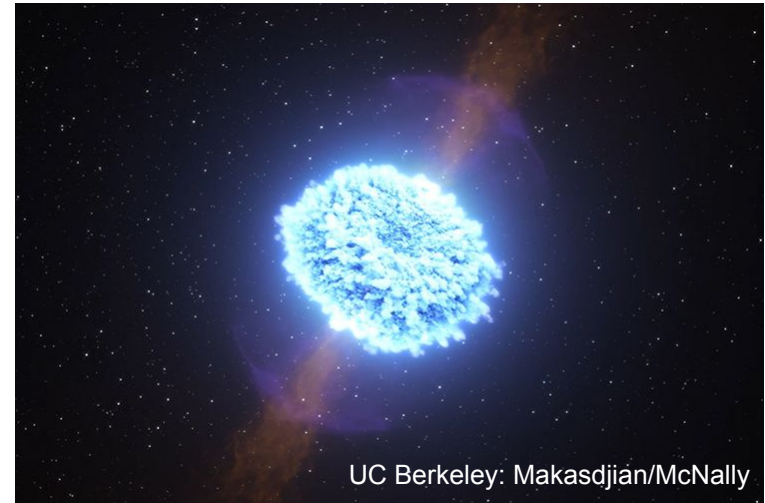


*** *also explained with standard NS-NS mergers* [Fuller, Kusenko, Radice, VT, PRL, 2019]

[Fuller, Kusenko, VT, PRL, 2017]

PBH-NS Lab Exotics: Orphan Kilonovae

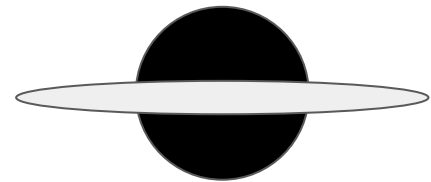
- **Kilonova:** afterglow from ejecta
- PBH-NS vs. mergers
→ “orphan kilonova” (w/o merger GWs)



[Fuller, Kusenko, VT, *PRL*, 2017]

PBH-NS Lab Exotics: Orphan GRBs

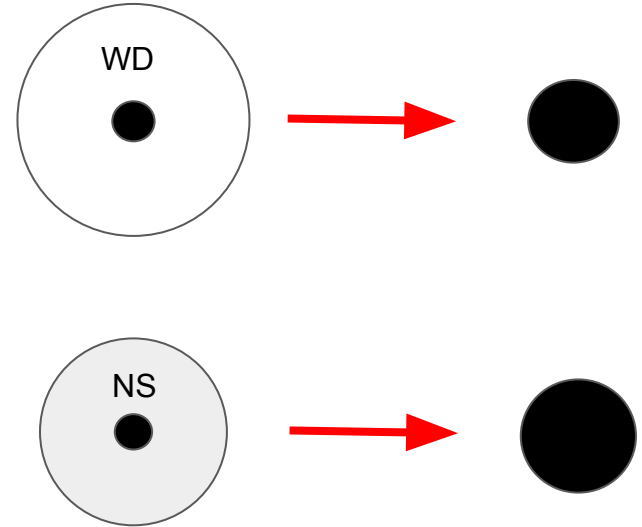
- “Standard” short gamma-ray burst progenitor: BH + disk
→ disk accreted, binding energy released
- If disk forms, could be from PBH-NS
→ “orphan GRB” (w/o merger GWs)



[VT, PLB, 2018]

PBH-NS/WD Lab Exotics: Late Solar-mass BHs

- No astro BHs $\lesssim 2.5 M_{\odot}$
- PBH + NS/WD \rightarrow new $\sim 0.5\text{-}2.5 M_{\odot}$ BHs
- New BH population
 \rightarrow small PBHs as DM + sub-population of $\sim M_{\odot}$ BHs made in late Universe



[VT, PLB, 2018]

Summary

- Renaissance era in PBH research → synergy with multi-messenger astronomy
- Many new ideas for PBH formation and detection
 - PBHs from scalar fragmentation → peaked spectrum, big spin possible
 - PBHs from vacuum bubbles → broad spectrum, can explain many observables
 - compact stars as PBH laboratories → novel signatures
- Aim for definitive statements about general role of PBHs with future studies !