Shining Light on Dark Matter with Black Holes

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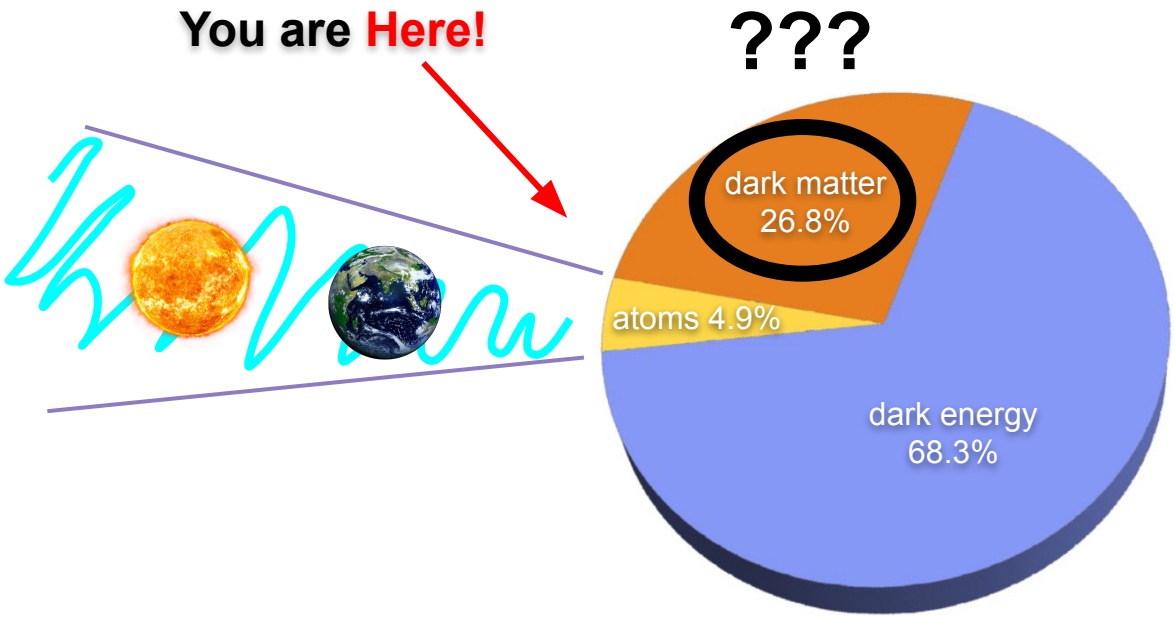
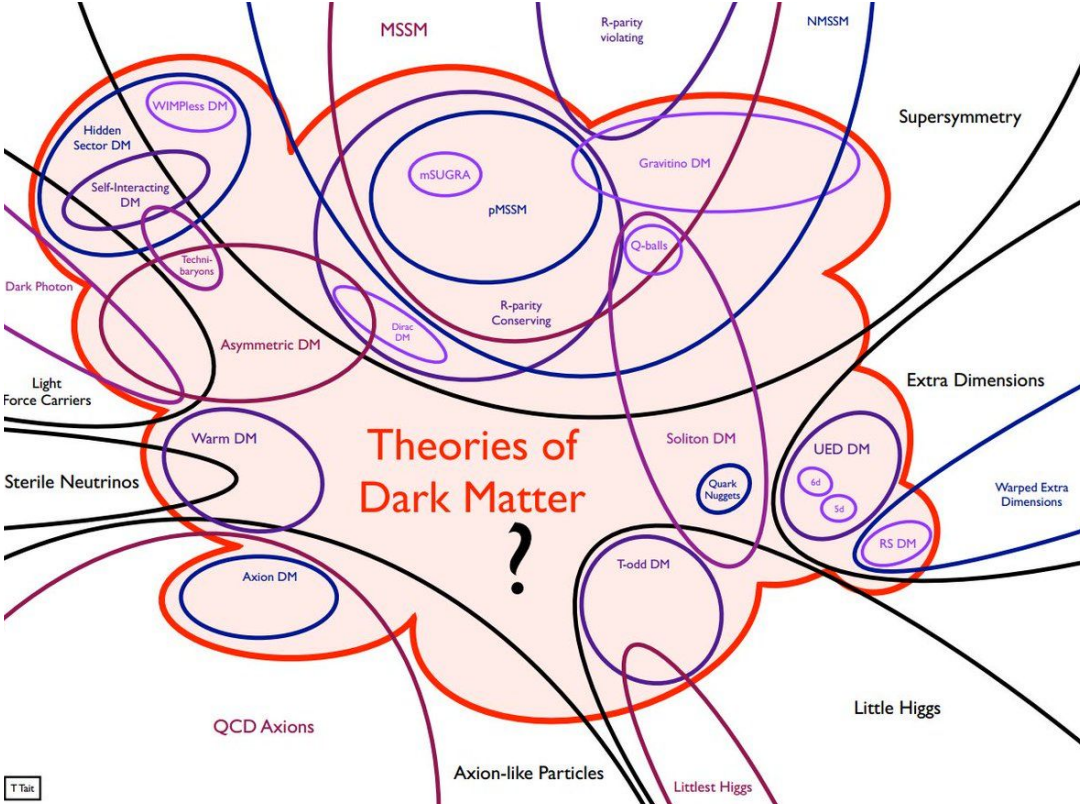
What is the Universe made of ?





Myriad of possibilities, no convincing signs thus far...

Transforming conventional DM science with a "Standard Model" candidate:

Primordial Black Holes (PBHs)

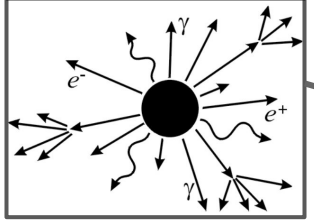
PBH DM

- **Black holes**
  - astrophysical → old stars
  - **primordial** → early Universe [Zeldovich, Novikov, Hawking, Carr...] ~ 50 years ago

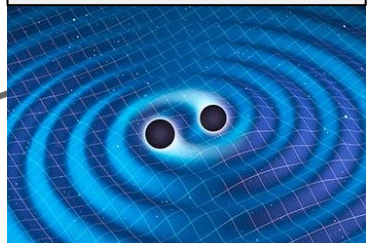
- **Why PBH DM ?**
  - alternative to particle DM
  - gravitational wave era
  - can appear in many models
  - help solve astronomy puzzles
  - *Black holes exist*

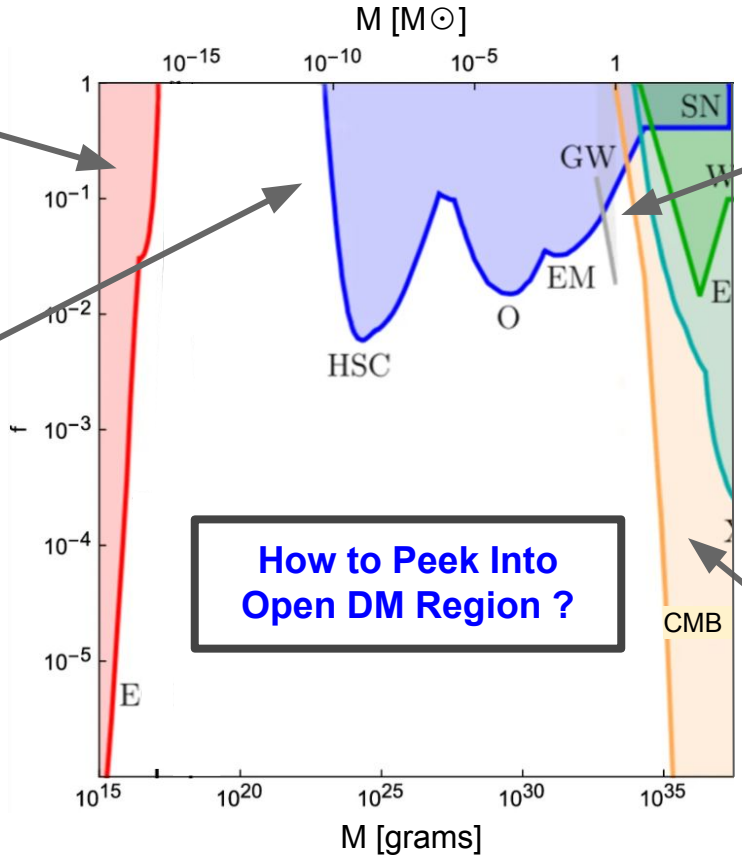
Status

Hawking Evaporation



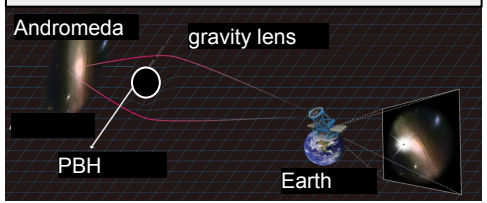
Gravitational Waves



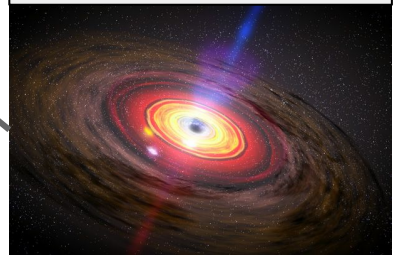


see [Reddy, Mack...]

Microlensing



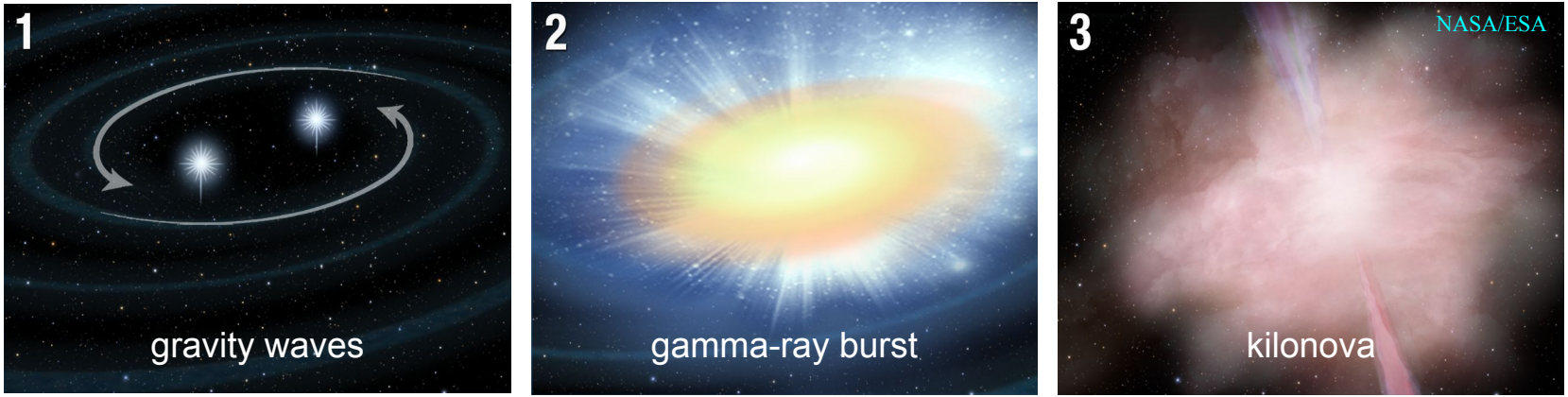
Accretion Emission



Aside: Neutron Star (NS) Mergers

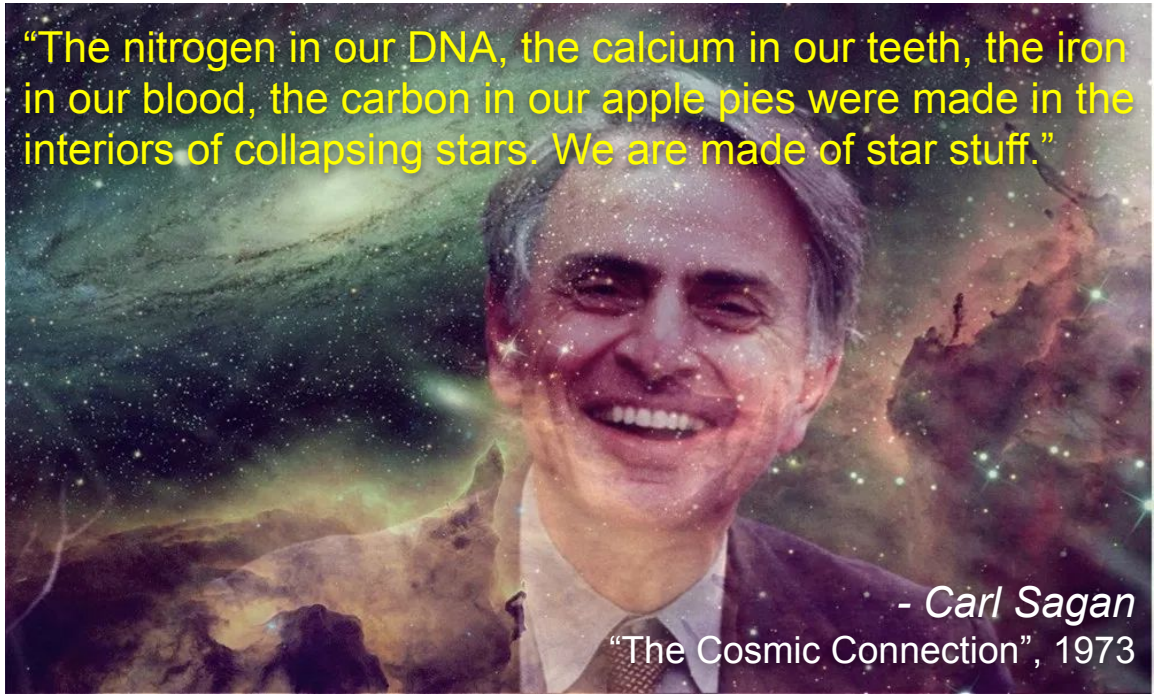
Robin Dienel/The Carnegie Institution for Science

Premier “Multi-messenger” Laboratories



- Definitive confirmation by historic 2017 NS-NS observation: LIGO, Fermi...

see [McLaughlin, Quataert, Kasen, Reddy, Surman...]



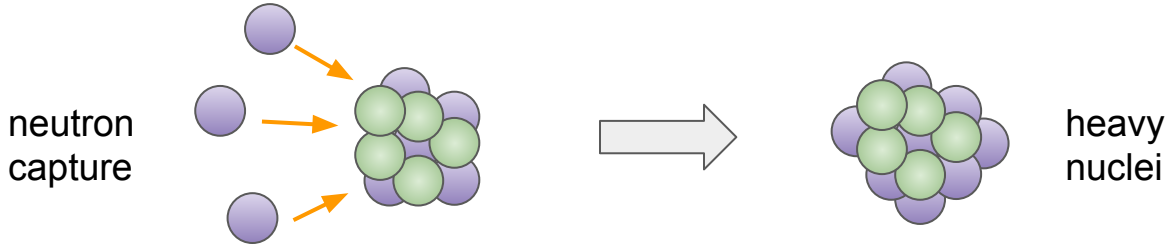
Where do heavy elements (gold) come from?

→ **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

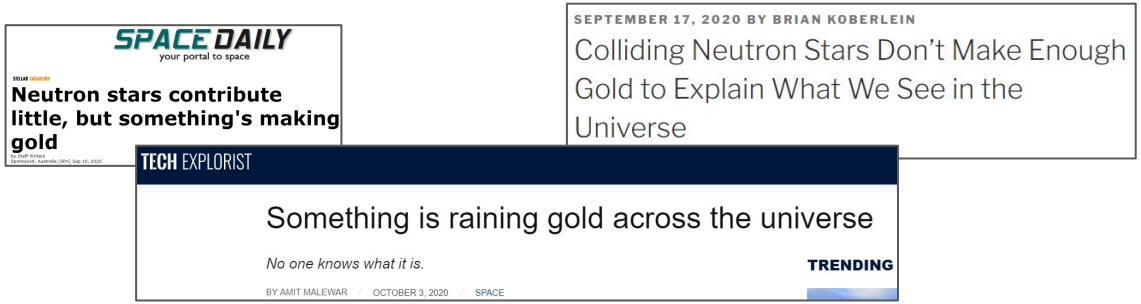


- Nuclear reactions in expanding ejecta produce heat + afterglow (kilonova)

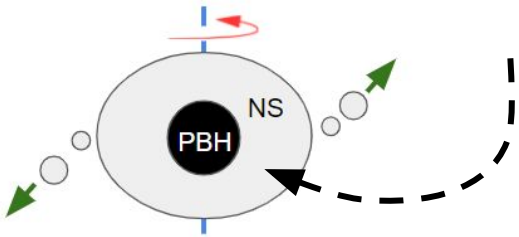
see [Balantekin, Fuller...]

Making Gold with Black Holes

- **Problem settled in 2017 ?** → *Mergers great, but might not be enough* e.g. [Kobayashi+, *2020*]

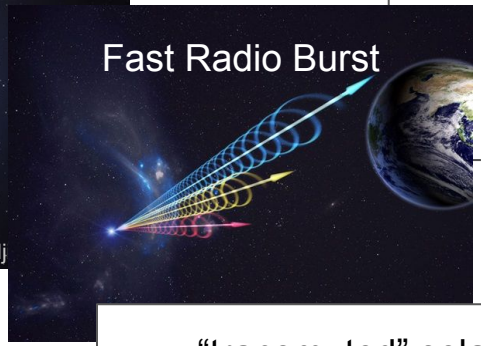


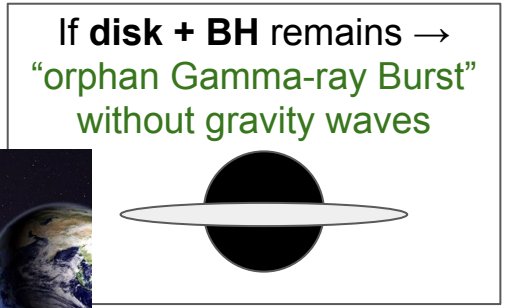
- **Help from the dark side: asteroid-mass PBHs making DM**
  captured by NSs, small PBHs consume and explode them
  → neutron rich ejecta, r-process factories

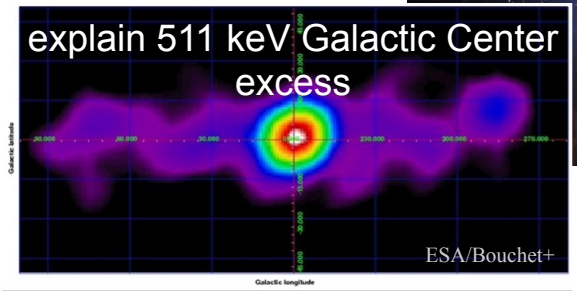


[Fuller, Kusenko, **VT**, ***Phys.Rev.Lett.***, 2017] **+ Viewpoint Highlight by H.-T. Janka**

Neutron Stars as PBH Laboratories

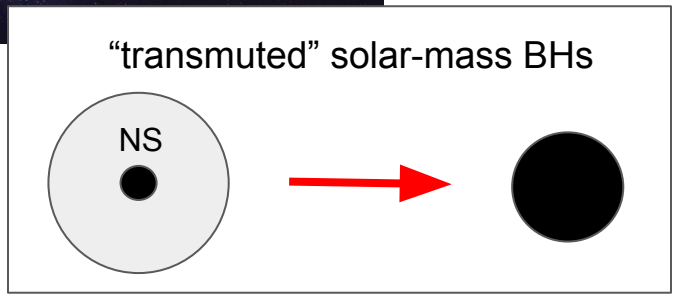






*** *can explain with regular NS-NS*

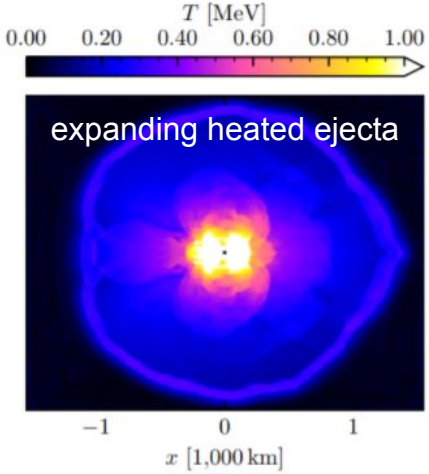
[Fuller, Kusenko, Radice, **VT**, ***Phys. Rev. Lett.***, 2019]

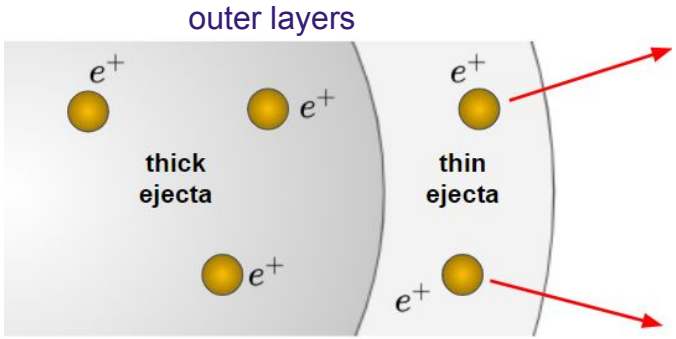


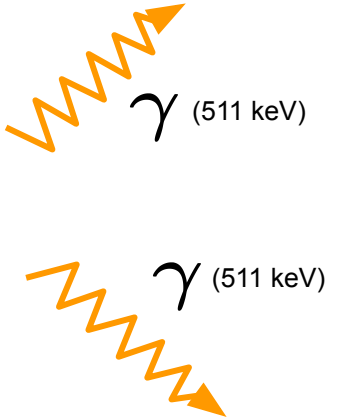
[Fuller, Kusenko, **VT**, ***Phys.Rev.Lett.***, 2017; **VT**, 2018; **VT**, 2019]

Novel Generic Signal for Mergers

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







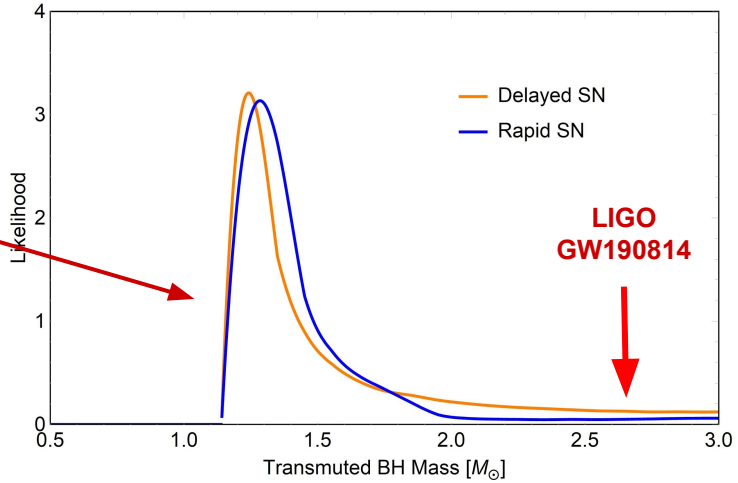
- **With LIGO observations can explain 511 keV signal in Galactic Center !**
  → ***link r-process and 511 keV emission*** *(smoking gun observed in dwarf galaxies !)*

[Fuller, Kusenko, Radice, **VT**, *Phys.Rev.Lett.*, 2019]

Origin of Solar-mass Black Holes

- Solar-mass (~1-2.5 M⊙) BHs unexpected in astrophysics → PBHs (or particle DM eating NS)
- **LIGO detected candidate event !** [Abbott+, *ApJL*, 2020...] **...how to tell BH origin ?**
- **Solution:** BHs from tiny PBH (or particle) DM eating NSs follow NS mass distribution

BH masses from DM eating NSs



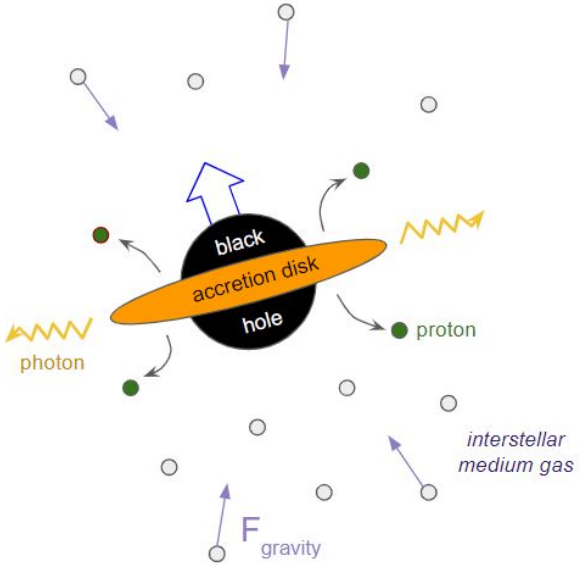
Large (> 1.5 M⊙) candidates unlikely to be transmuted BHs!

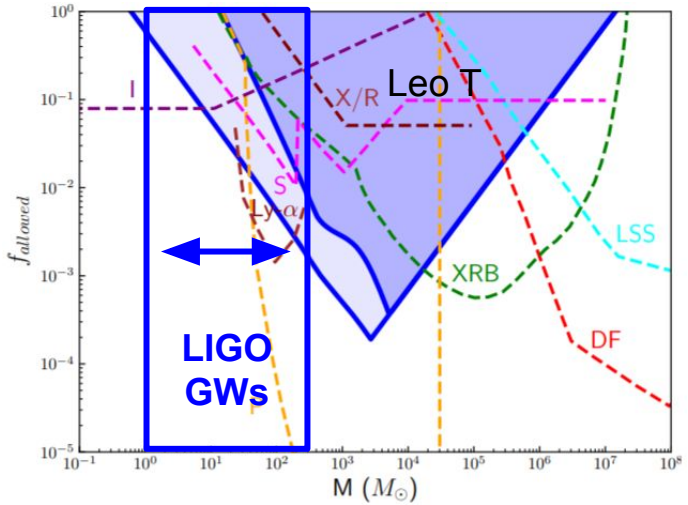
improved understanding of stellar evolution crucial...

[**VT**, Fuller, Kusenko, ***Phys.Rev.Lett.***, 2021]

Are Intermediate-mass Black Holes Primordial ?

- LIGO detected first intermediate-mass (~ 150 M⊙) BH [Abbott+, *PRL*, 2020]
- **New general PBH observable:** interactions and ***heating*** of surrounding gas





[Lu, **VT**+, *Astrophys.J.Lett.*, 2021]

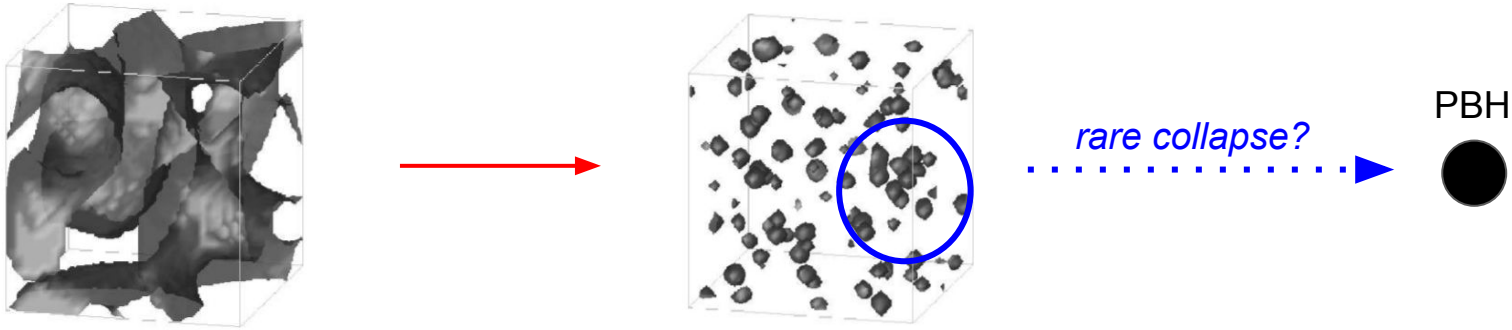
How did PBHs form ?

PBHs from Scalar Fragments

- Scalars very generic in BSM theories
- Post-inflation self-interacting scalars could fragment from instabilities (Q-balls/oscillons)

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

simulations [Multamaki, Vilja, 2002]



- PBHs from overdense region collapse (unrelated to inflation perturbations)

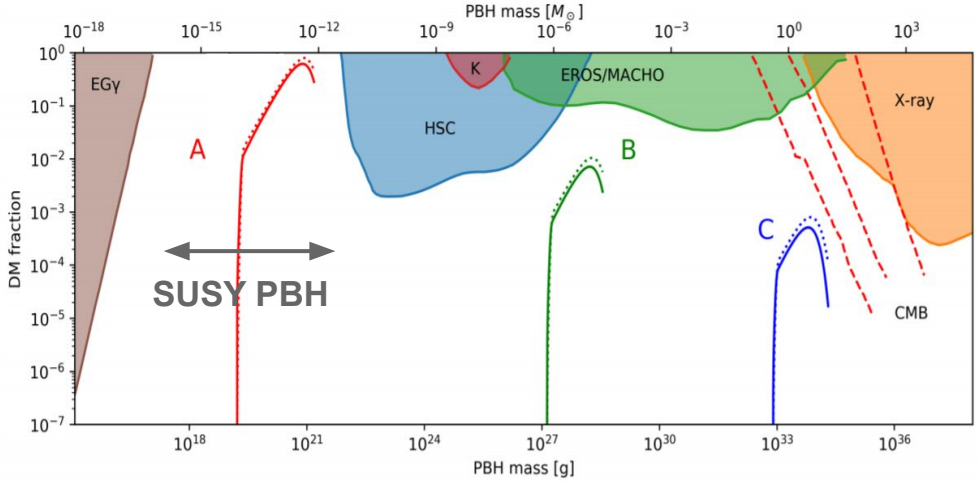
  [Cotner, Kusenko; Cotner, Kusenko, **VT**; Cotner, Kusenko, Sasaki, **VT**]

PBHs from Scalar Fragments

PBHs from low-scale SUSY

$$\rho_\phi \sim M_{\rm SUSY}^4$$

$$M_{\rm PBH} \sim 10^{20}\,{\rm g}\left(\frac{100\ {\rm TeV}}{M_{\rm SUSY}}\right)^2$$



- **Big (a ~ 1) BH spin possible** (hard to make in usual mechanisms)

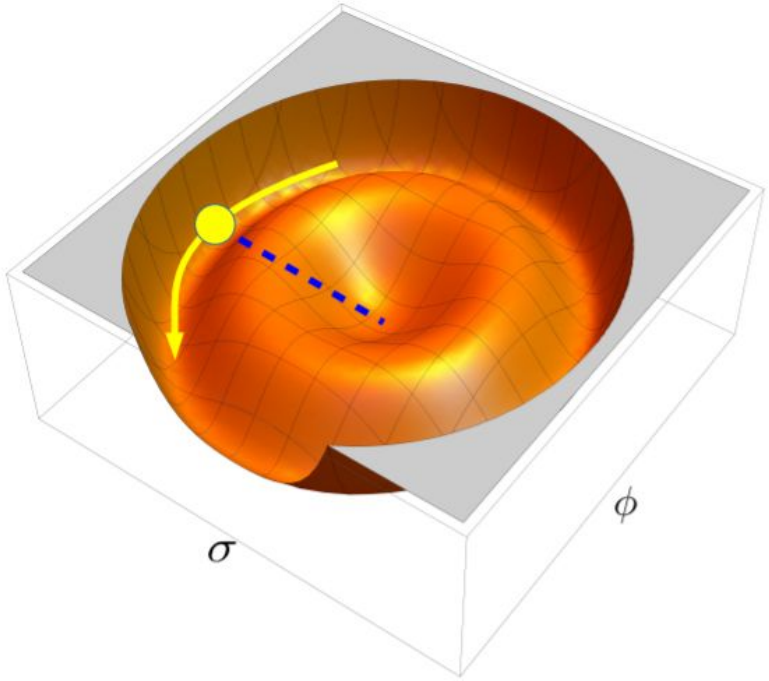
[Cotner, Kusenko; Cotner, Kusenko, **VT**; Cotner, Kusenko, Sasaki, **VT**]

PBHs from Bubble Multiverse

- Generic mechanism for making PBHs broadly distributed in mass

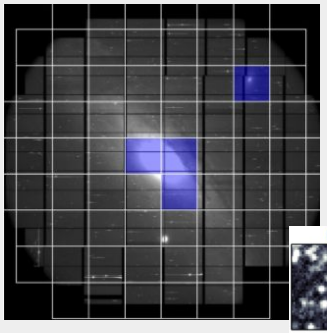
[Deng, Vilenkin....; Sasaki+, 1982...]

PBHs from Bubble Multiverse

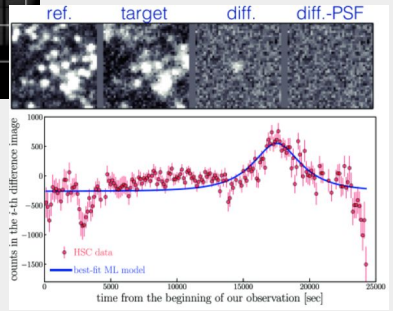


[Kusenko, Sasaki, Sugiyama, Takada, **VT**, Vitagliano, ***Phys.Rev.Lett.***, 2020]

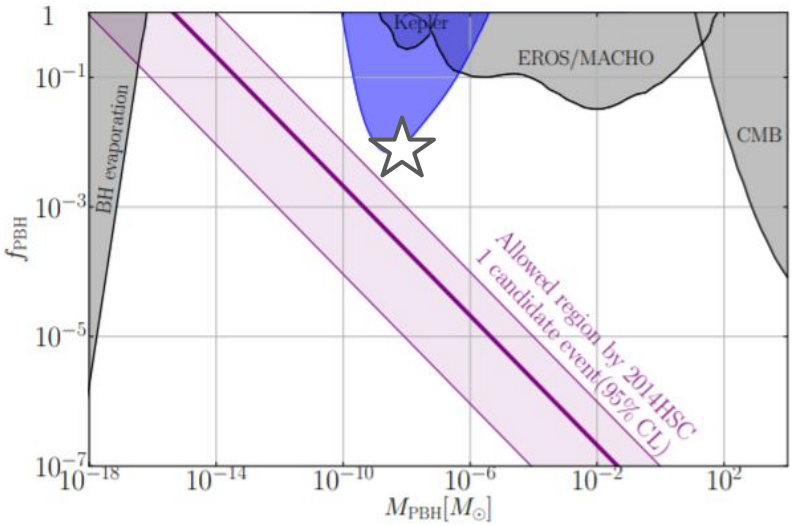
PBH DM from Bubble Multiverse: Detected by HSC ?!



Subaru (HSC)
Hyper-Suprime Cam
Andromeda
microlensing
event



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

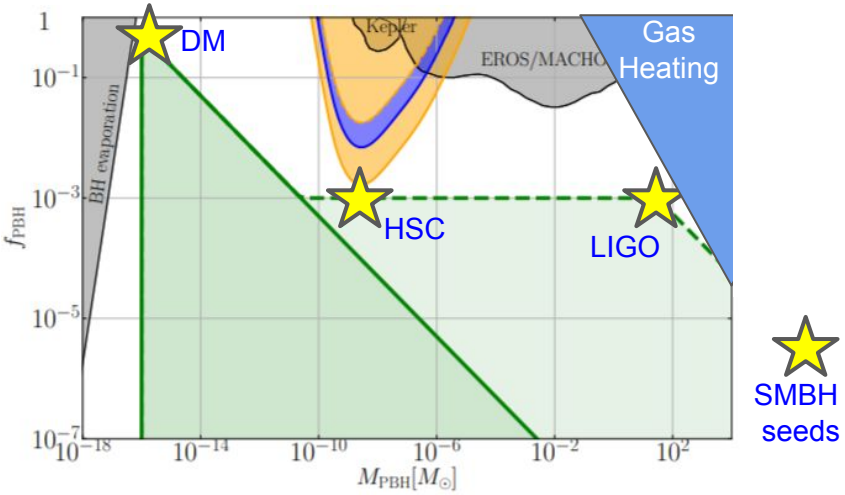


- **PBH DM from bubble multiverse consistent with detected HSC event !**

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

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 new HSC data !**

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

Summary

- Renaissance era in PBH research → synergy with multi-messenger astronomy
- PBH exciting “Standard Model” DM candidate, deep connections with major astronomy puzzles
- Aim for definitive statements about general role of PBHs with future studies !