Gaining Insight into PBH Dark Matter

with Compact Stars

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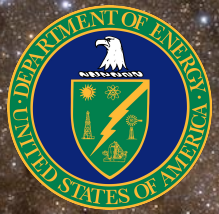
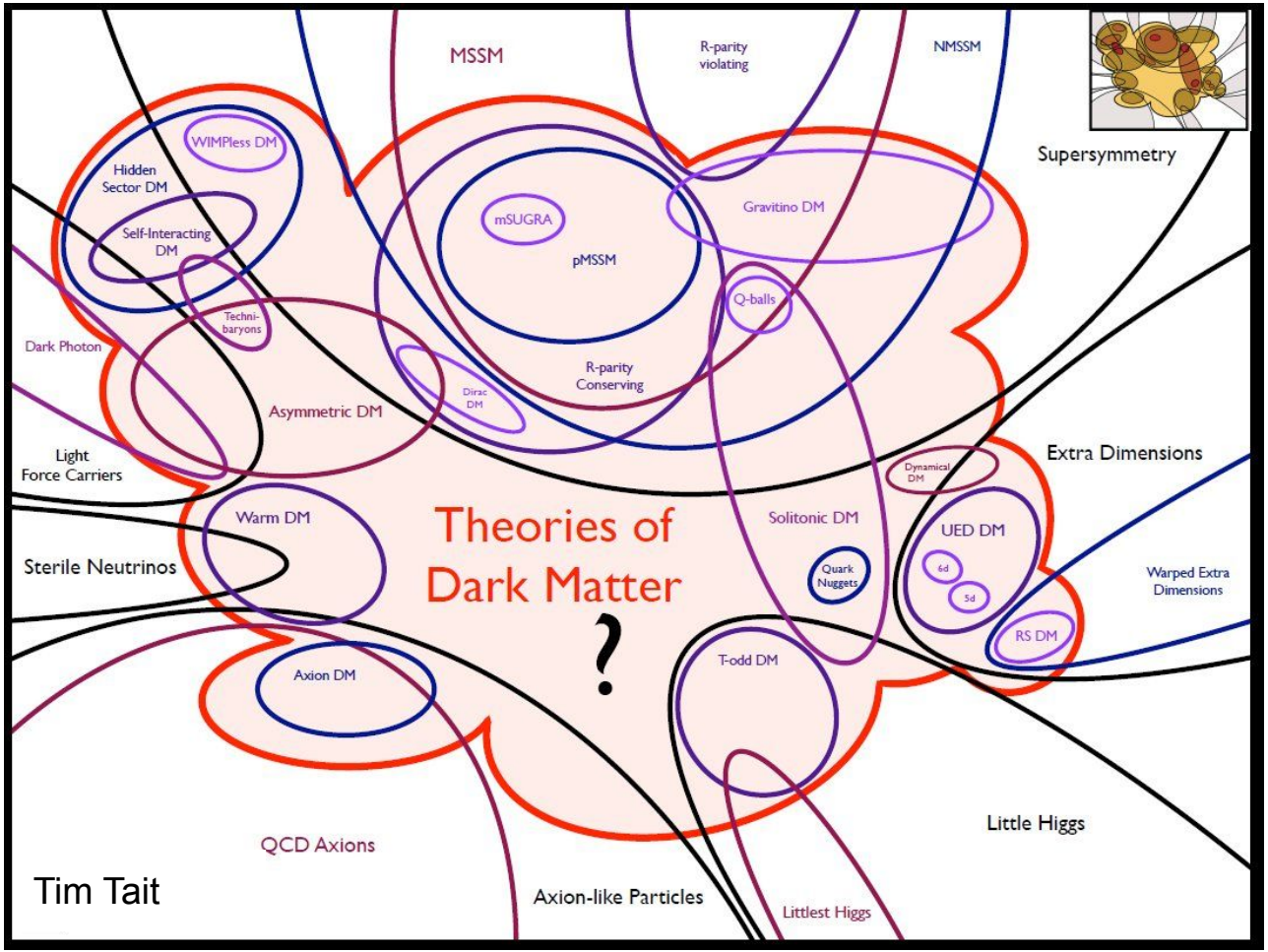



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Quark Nuggets
Warped Extra Dimensions
Sterile Neutrinos
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
Tim Tait

+ PBH!

PBH as DM

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

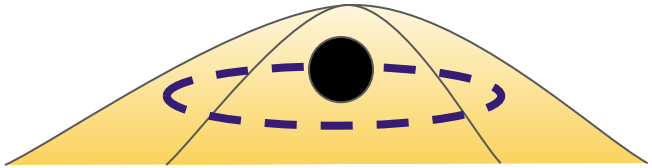
- Why get excited about PBH DM ?
  - no clear signs of particle DM
  - GW astronomy [Bird+ 2016; Sasaki, Thorne+ 1997...] [Riotto…]
  - generic in many BSM models [Fuller, Carr, Dolgov, Kawasaki, Kusenko, Gregory*..]
  - help solve astro puzzles (e.g. seed SMBH [Kusenko, Kawasaki...])
  - already might appear in standard cosmology (but unlikely)

Many expert talks...

PBH formation

- "Standard" scenario: large perturbations ($\delta \sim 1$) enter horizon → collapse

[Kawasaki, Sasaki ...]



- Need to fine tune inflaton potential

  → sensitive to restrictions on field behavior

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

PBH formation

- Attractive new general scenario: **scalar field fragmentation** → **A. Kusenko**

[Cotner, Kusenko, PRL, 2016]

+

[Cotner, Kusenko, VT, PRD, 2018]

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

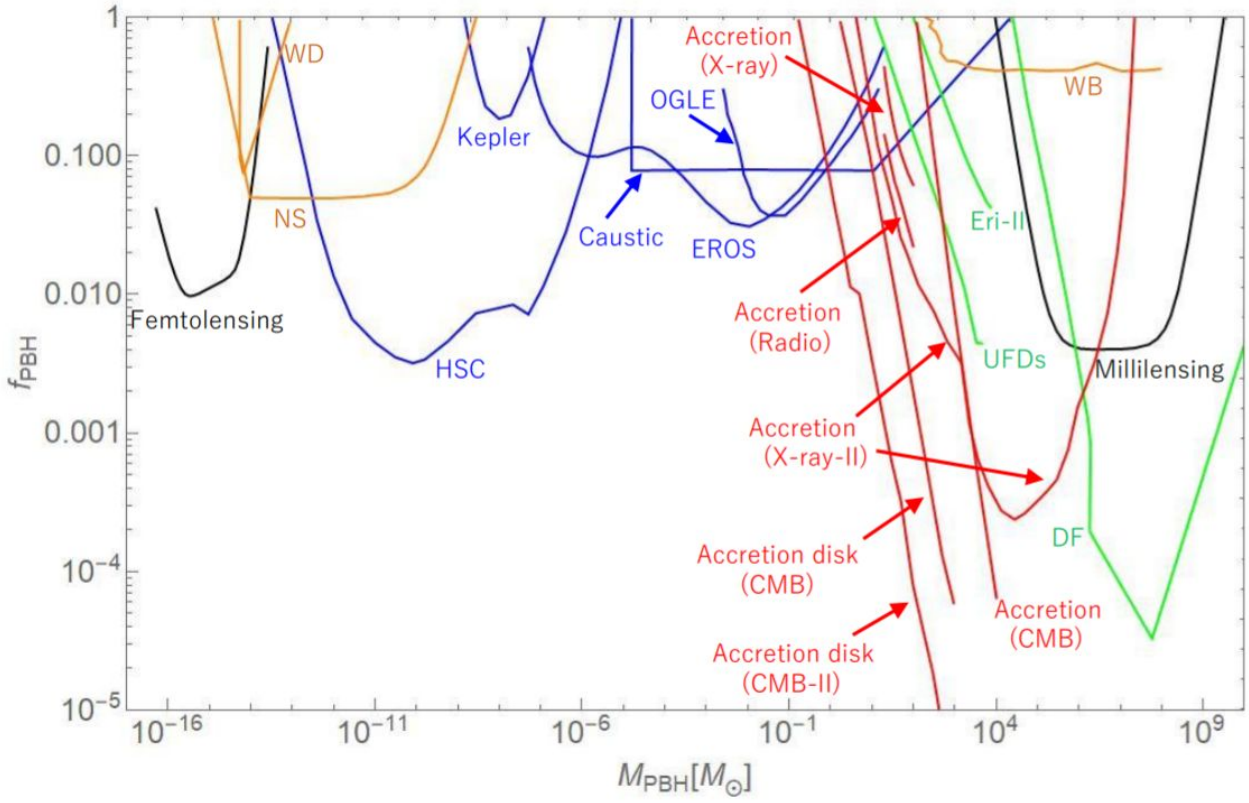
→ **many exciting things to explore further !**

… fragmentation could be very generic, in line with lore that gravity is weakest force

[Kusenko, VT, Yamada, Yamazaki, 2019]

Status of Affairs

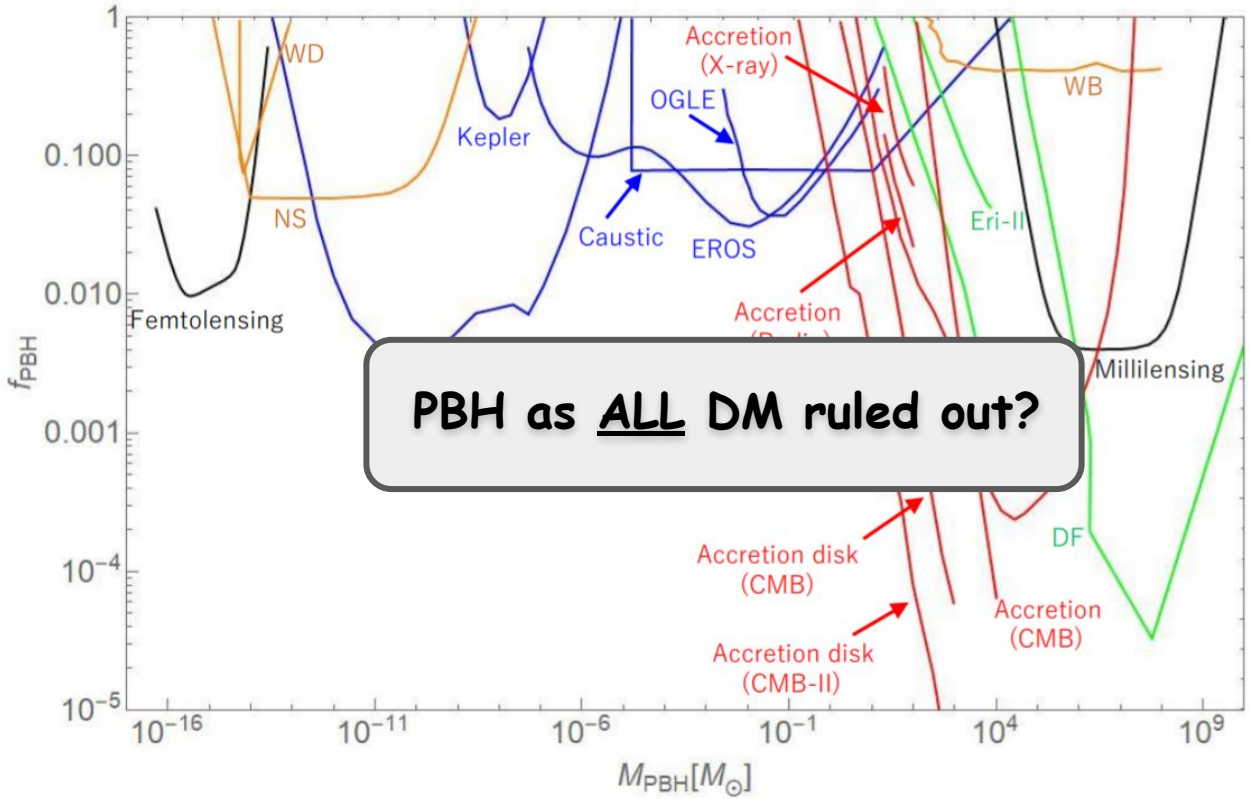
Status (2017)



[Sasaki+, 2017]

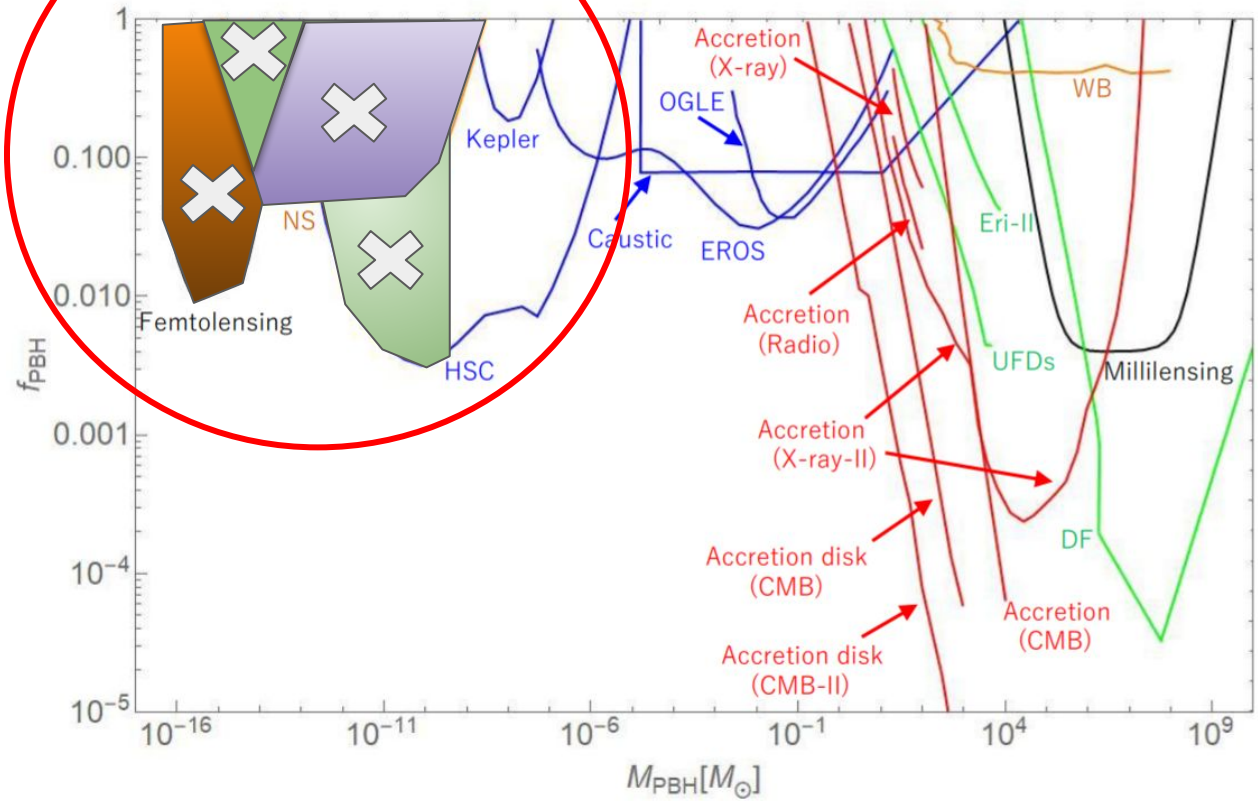
→ important to consider particle DM + PBH mix [Koushiappas]

Status (2017)



[Sasaki+, 2017]

Status (NOW)



[Sasaki+, 2017]

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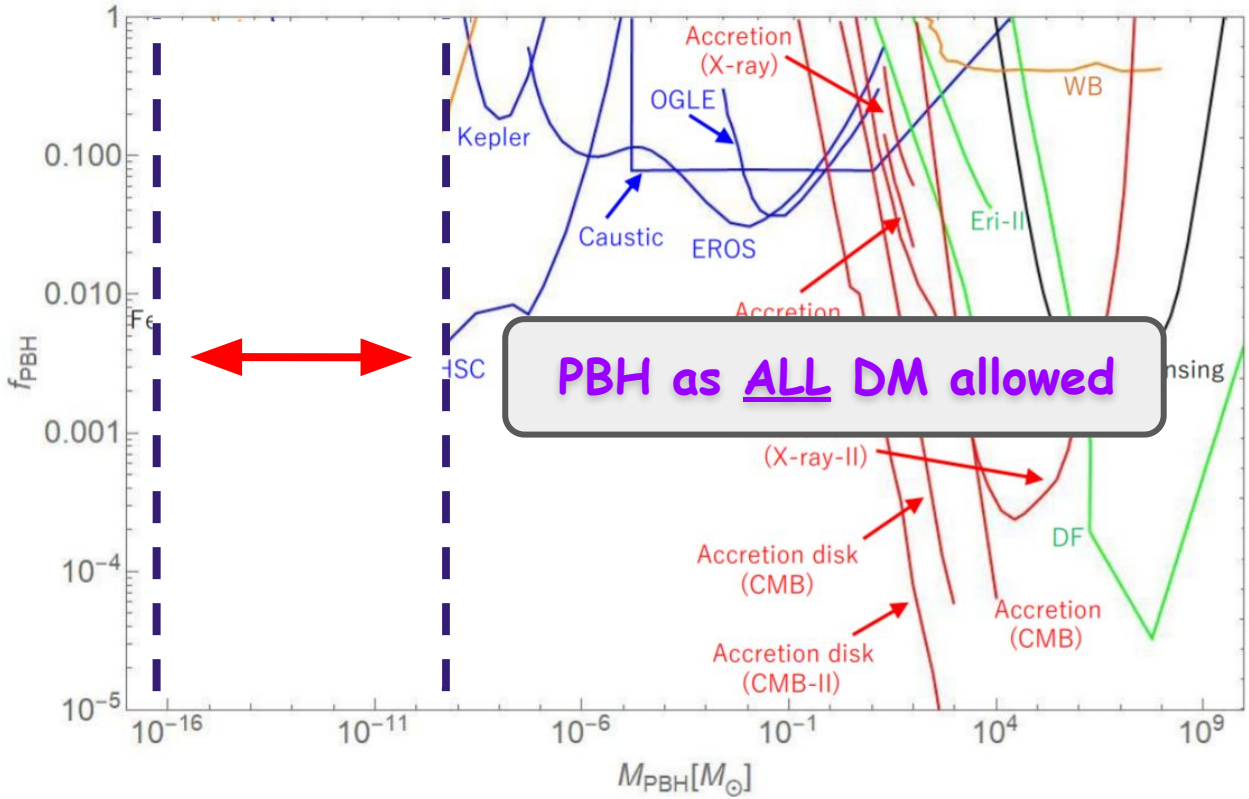
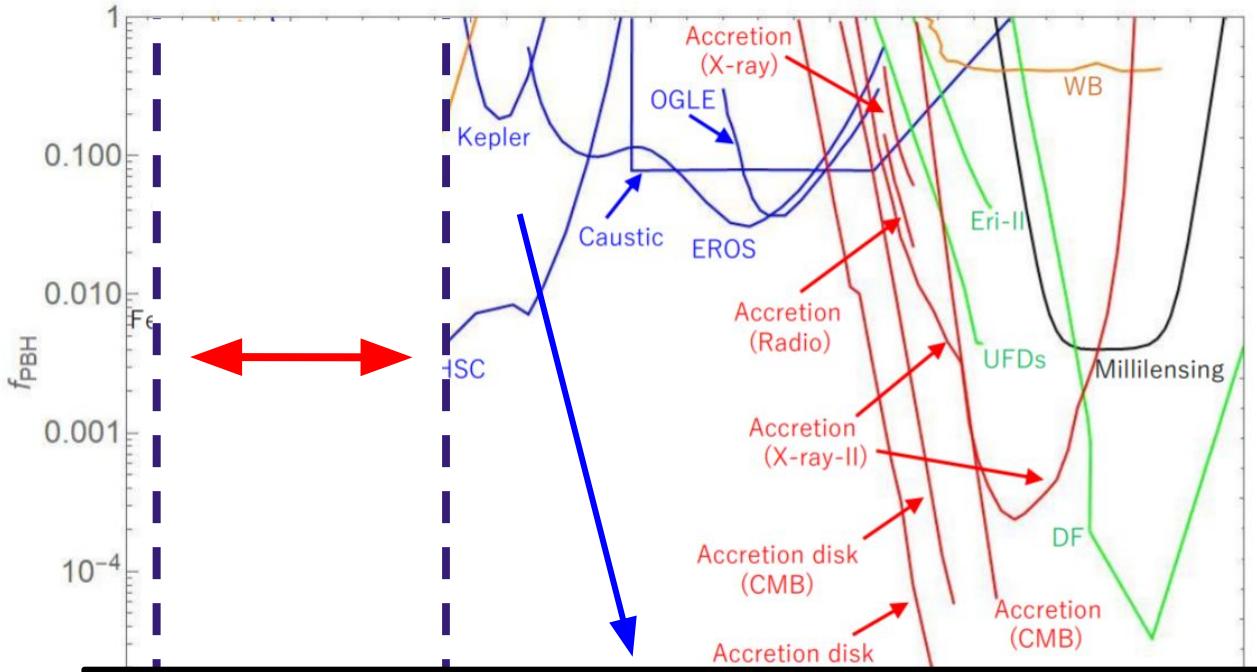


[Sasaki+, 2017]

Status (NOW)



[Sasaki+, 2017]

Important new results from HSC [Sugiyama, Takada...]
*can test interesting models [Vitagliano]

...can we gain some insight
into this interesting open region?

Compact stars as PBH laboratories

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

- Captured PBH settle and grow inside, destroy star
  → **new signals, potential open problem solutions**

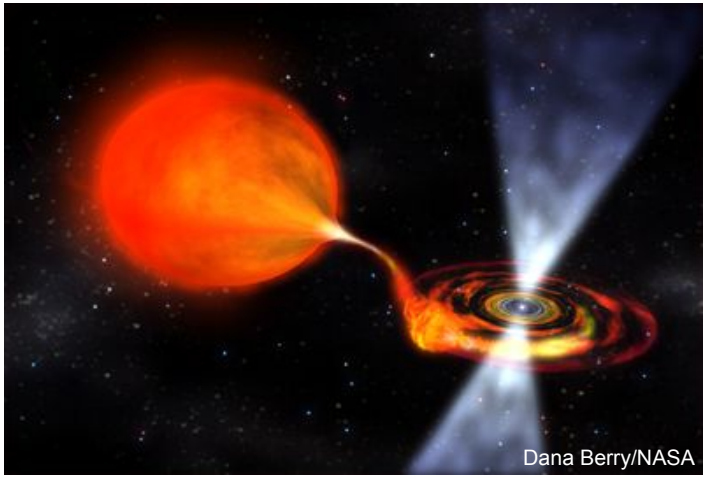
→ r-process nucleosynthesis, 511 keV, FRBs

[Fuller, Kusenko, VT, PRL, 2017]

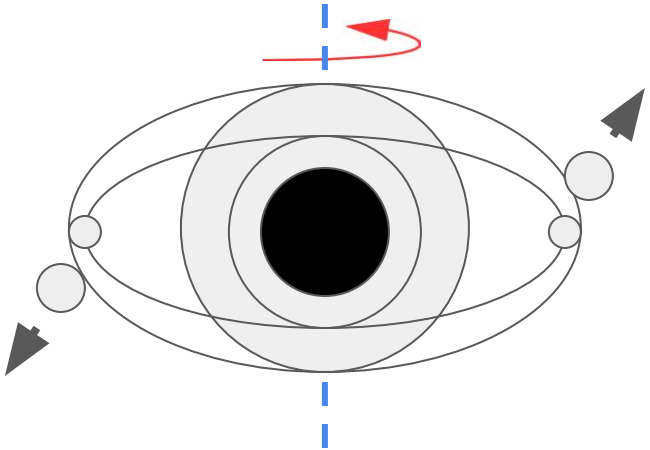
+ *Viewpoint Highlight* by H.-T. Janka

→ solar-mass BHs, GRBs, microquasars

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



PBH in millisecond pulsar

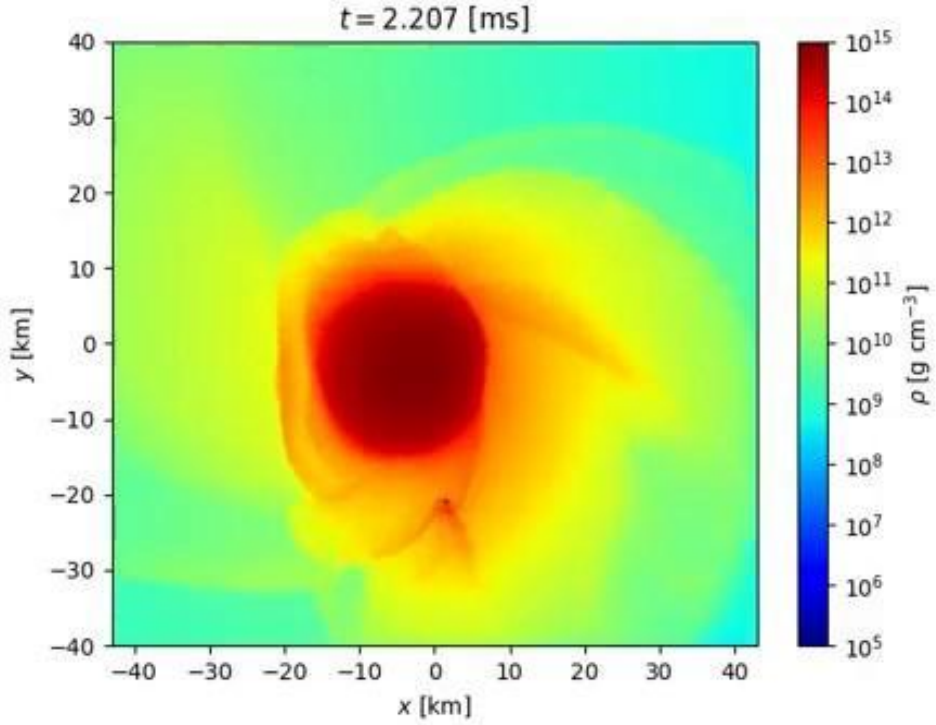


- MSP spins near mass-shedding limit
  → stretched spheroid (analytic Roche lobe model)
- **Add PBH:** star consumed → contracts → spins up
- Matter exceeds escape velocity at equator

→ neutron-rich material ejecta

[Fuller, Kusenko, VT, PRL, 2017]

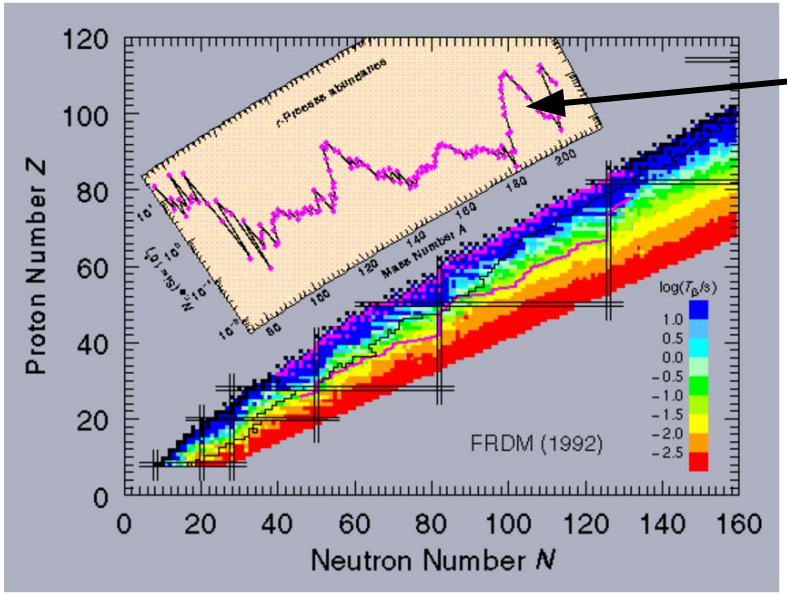
Neutron-rich material emission



preliminary simulations by David Radice (Penn State)

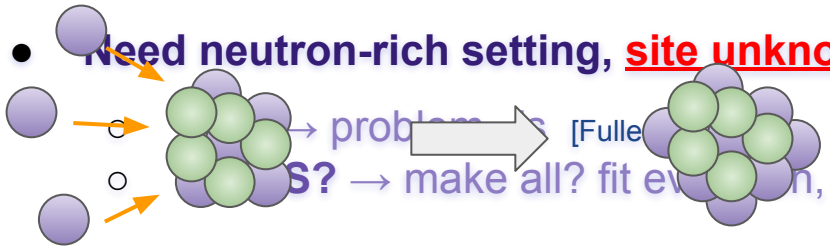
****** sensitive to input conditions, need more studies***

R-process nucleosynthesis: stellar gold factories



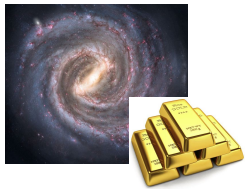
Los Alamos, Nuclear Data Group

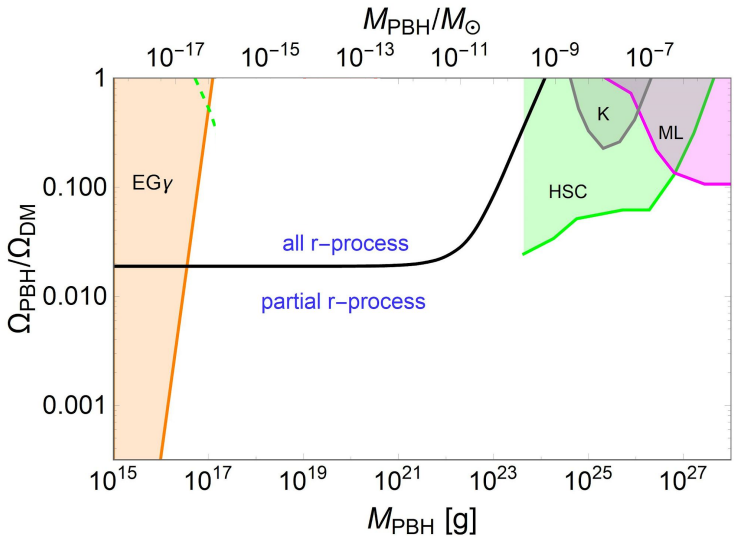
- Neutrons ***r***apidly captured before □-decay
- Main producer of heavy astro-elements
- **Need neutron-rich setting, site unknown**



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 !

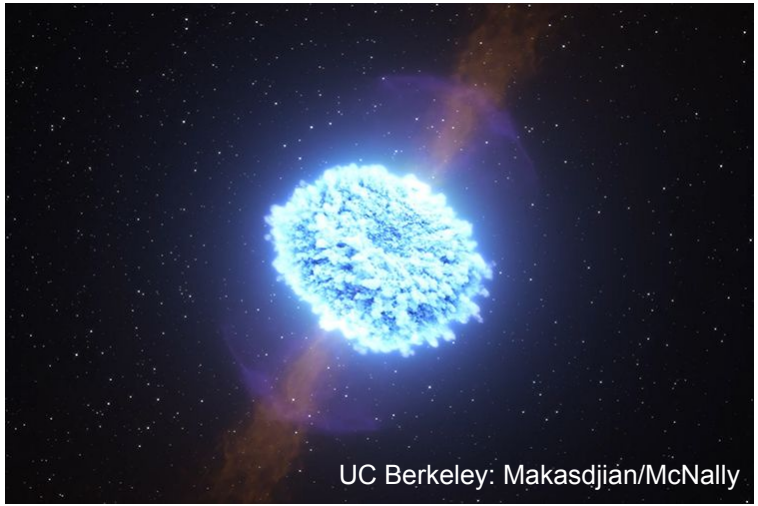
[Fuller, Kusenko, VT, PRL, 2017]

PBH-NS laboratory: orphan kilonovae

- **Kilonova:** afterglow from ejecta

- **PBH-NS vs. mergers**

  → ***"orphan kilonova"*** (w/o merger GWs)



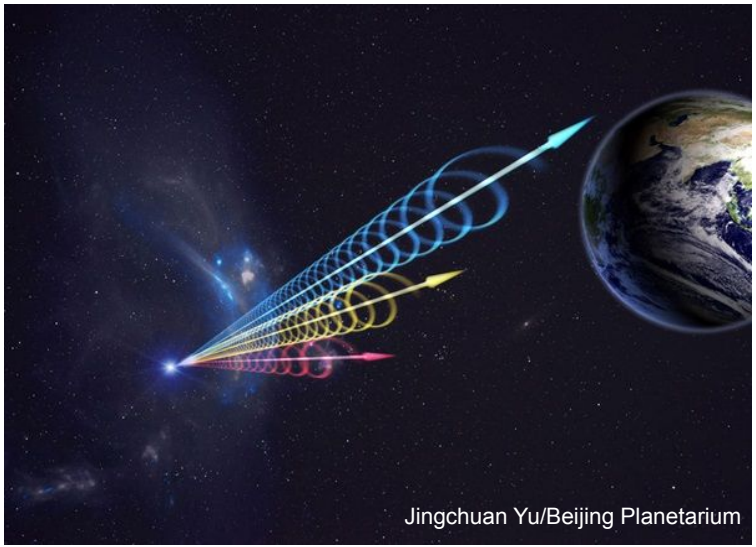
[Fuller, Kusenko, VT, PRL, 2017]

PBH-NS laboratory: fast radio bursts

- **Fast radio bursts:** brief radio pulse
  - origin unknown
  - >100 found, few repeaters [Amiri+, Nature 2019]

- Release % of NS magnetic field energy due to PBH-NS consumption as radio

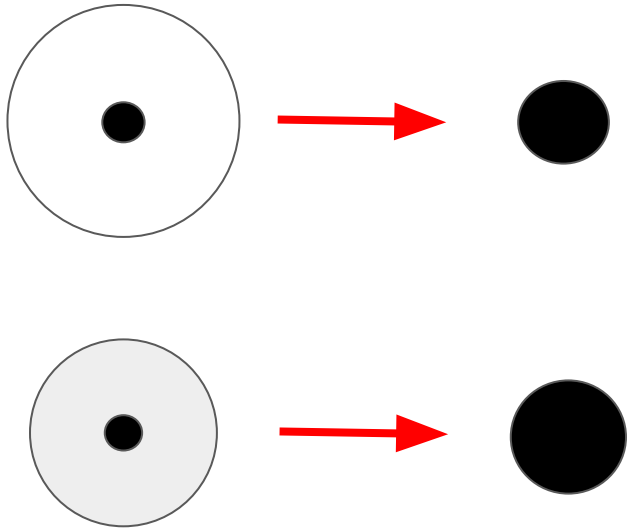
  → ***non-repeating FRB***



[Fuller, Kusenko, VT, PRL, 2017]

PBH-NS/WD laboratory: new solar-mass BHs

- No astro BHs $\lesssim 2\ M_\odot$
- **PBH + NS/WD: *new* ~0.5-2 $M_\odot$ BHs**
- Novel double binary signals possible (e.g. double kilonova)
- **Small population of solar-mass BHs made in late Universe, on top of asteroid-mass PBH DM**

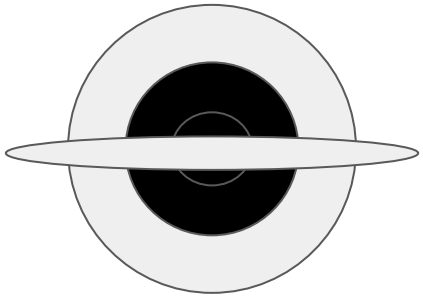


[VT, PLB, 2017]

PBH-NS laboratory: 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)



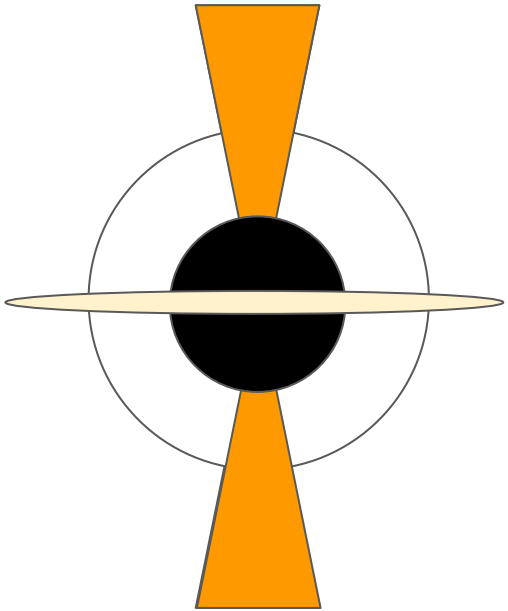
[VT, PLB, 2018]

PBH-WD laboratory: baby microquasars

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

- **WD + PBH** → solar-mass BH accretor
  - radius ⇩, luminosity ⇧

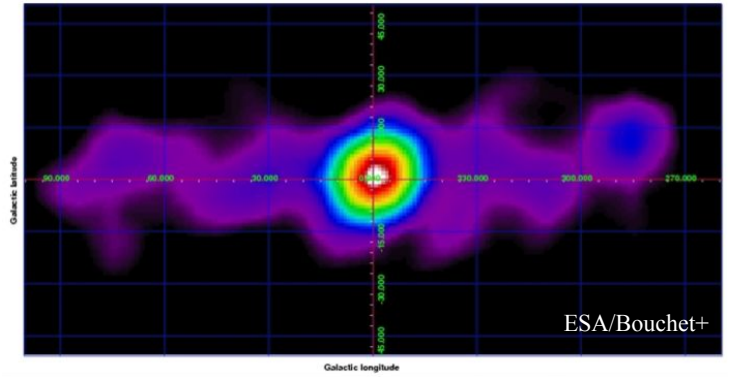
→ continuous jet ***"baby" microquasar***



[VT, PLB, 2018]

511 keV Galactic Center excess

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



→ can be explained by ejecta production from PBH-NS!

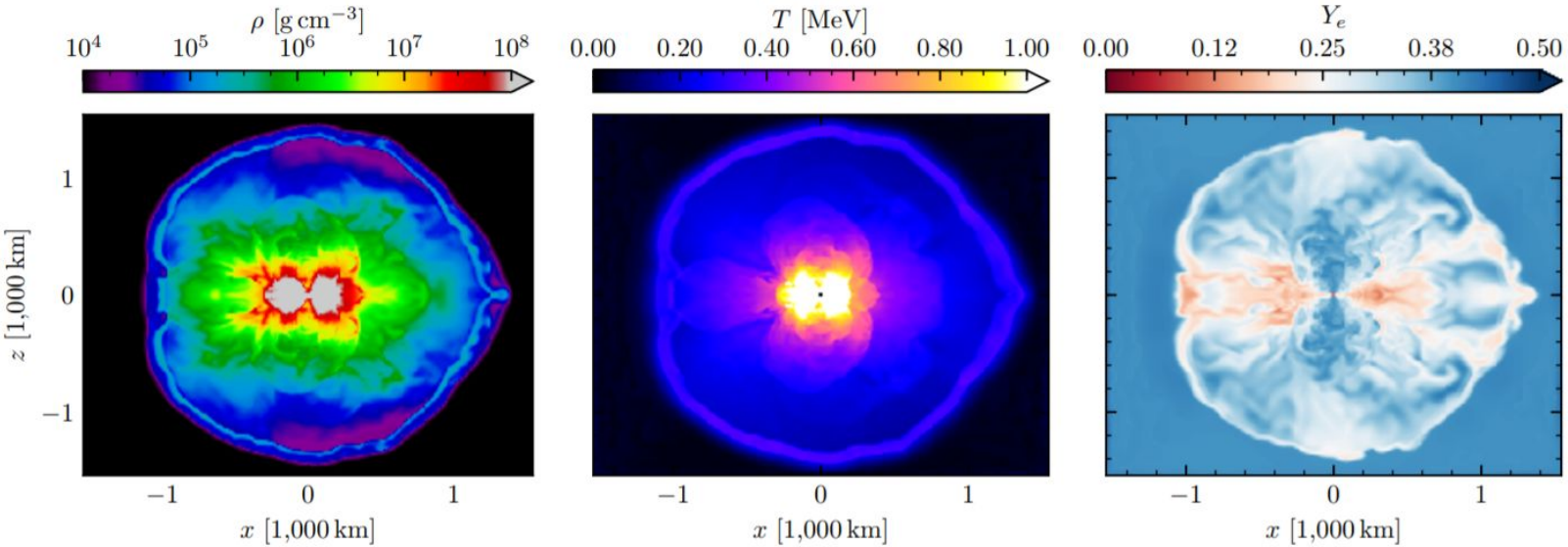
[Fuller, Kusenko, VT, PRL, 2017]

Novel generic signal of neutron star mergers

511 keV radiation

[Fuller, Kusenko, Radice, VT, PRL, 2019]

Start with NS-NS simulations

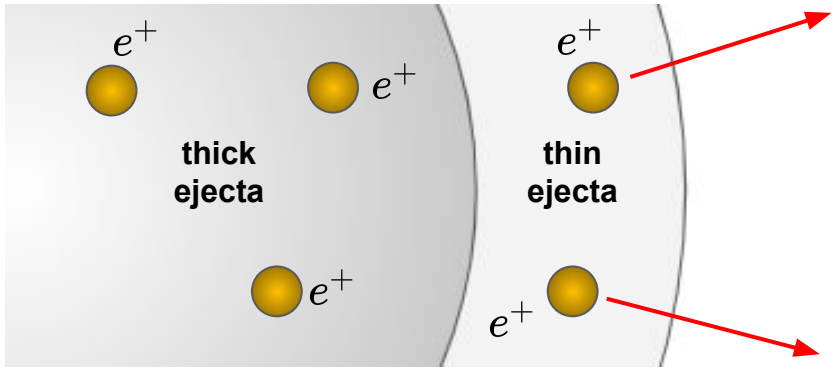


t = 10 ms

[Fuller, Kusenko, Radice, VT, PRL, 2019]

Positron production

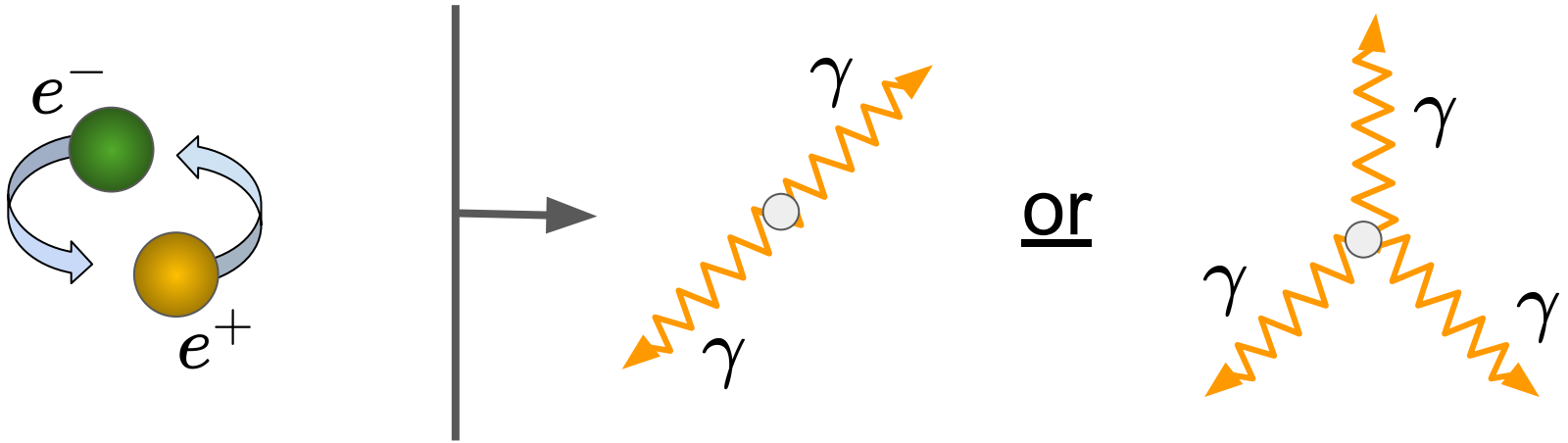
- Expanding ejecta heated to ~MeV → lots of thermal positrons produced
- Magnetic confinement in ejecta not perfect
  → some positrons escape from *"optically thin"* outer layers



[Fuller, Kusenko, Radice, VT, PRL, 2019]

511 keV radiation

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



[Fuller, Kusenko, Radice, VT, PRL, 2019]

Galactic Center emission

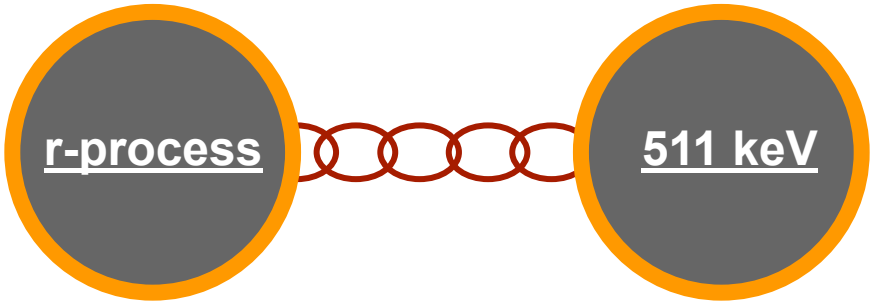
- **Take LIGO merger rates → 511 keV emission consistent with GC excess** ✓

- **NS binary kicks → expect some signal in Galactic disk, not only bulge** ✓
  - consistent with GC excess, difficulty for other proposals

[Fuller, Kusenko, Radice, VT, PRL, 2019]

A smoking gun signal !

- **Proposal directly links r-process and 511 keV**



- Observations of **Reticulum II** dwarf galaxy show heavy elements **AND** 511 keV

[Ji, Frebel+, *Nature*, 2016; Siegert+ 2016]

→ new smoking gun signal of merger emission !

[Fuller, Kusenko, Radice, VT, PRL, 2019]

Summary

- Renaissance era in PBH research → synergy with multi-messenger astronomy

- **Compact stars as PBH laboratories**
  - new observables to study DM
  - new venues to pursue open problems

Astroparticle physics naturally connects early Universe and observations