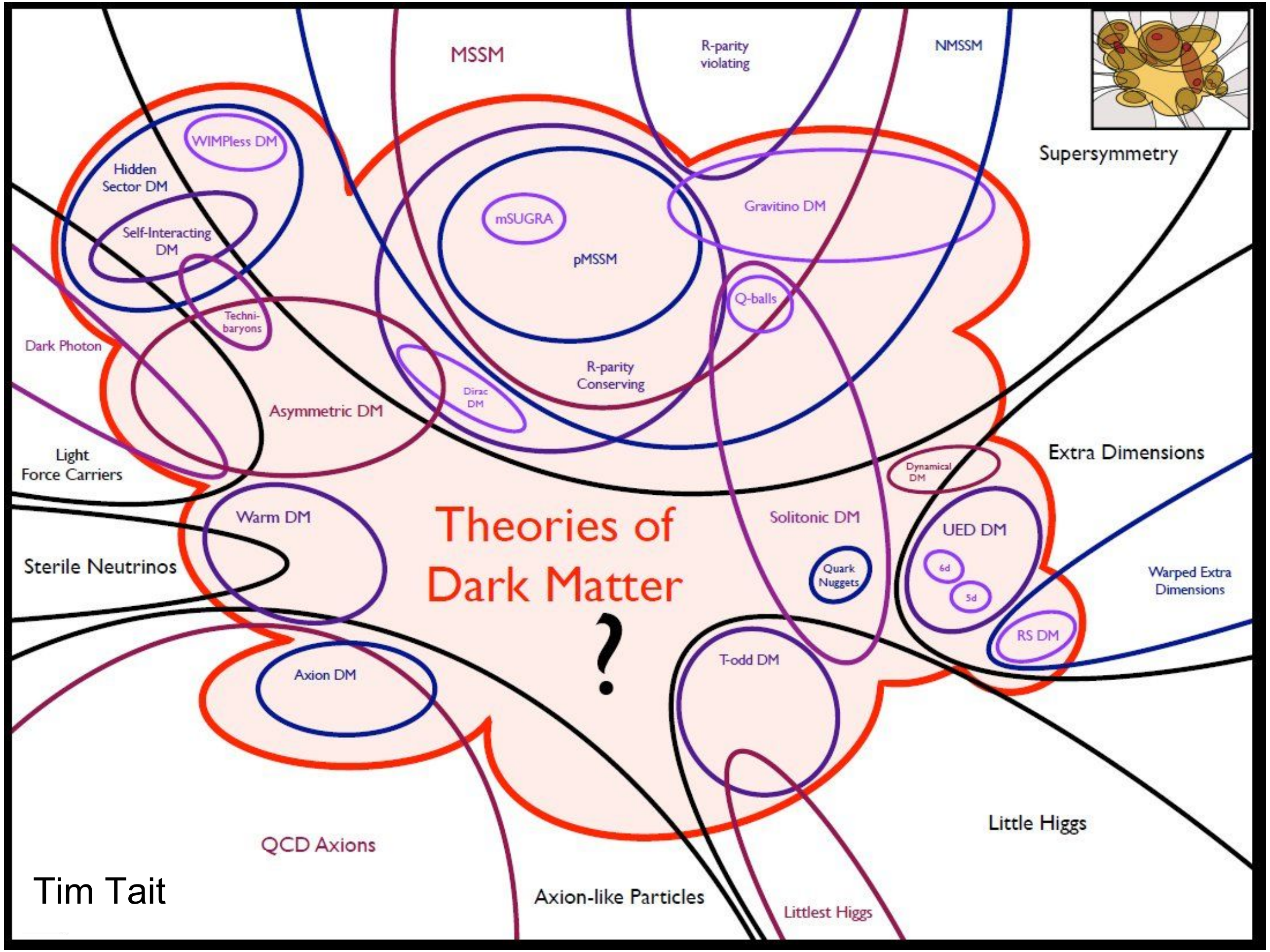
Primordial Black Hole Dark Matter

New Venues in Formation and Detection

Volodymyr Takhistov

University of California, Los Angeles
(UCLA)


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

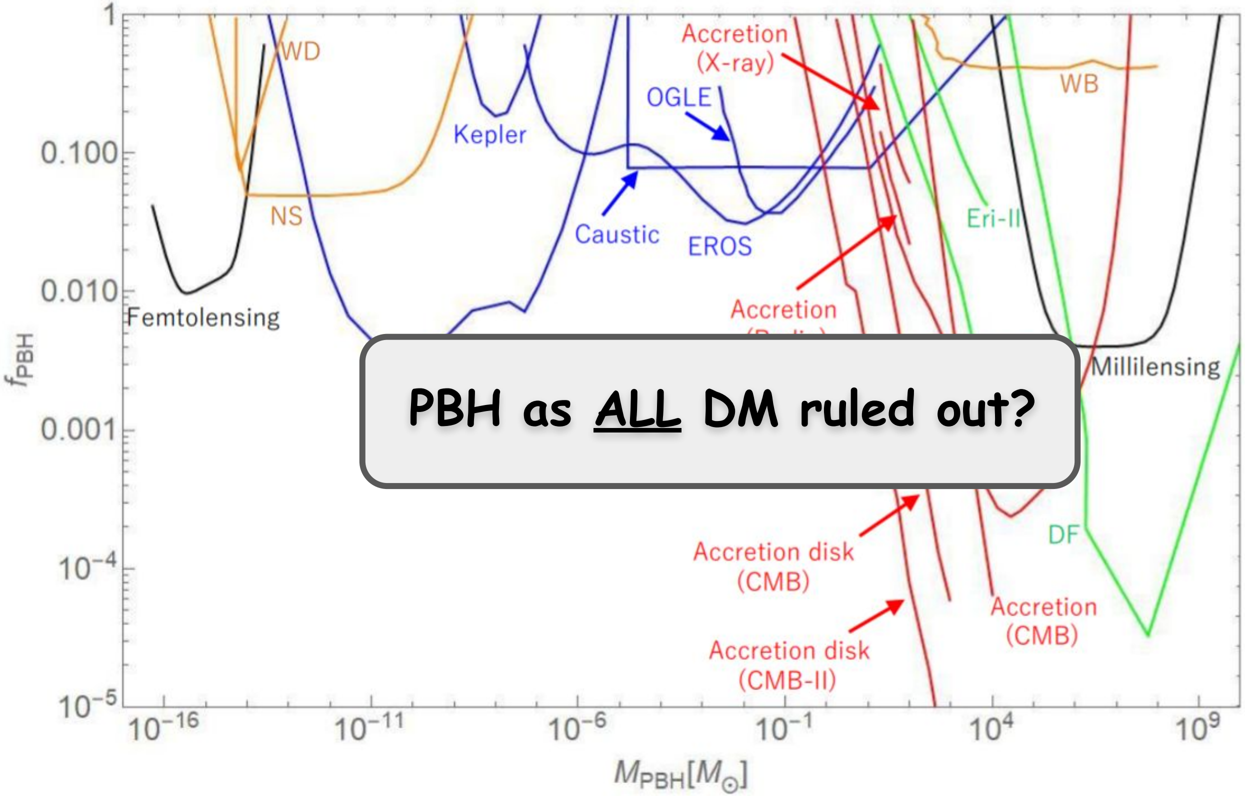
PBH DM

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

- Why get excited about PBH DM ?
  - no signs of particle DM
  - GW astronomy [Sasaki, Thorne+, 1997; Bird+, 2016; Garcia-Bellido+, 2015...]
  - already appear in standard cosmology (but unlikely)
  - generic in many BSM models
  - help solve astronomy puzzles (e.g. seed massive BHs)

[Kawasaki, Kusenko, Yanagida, 2012]

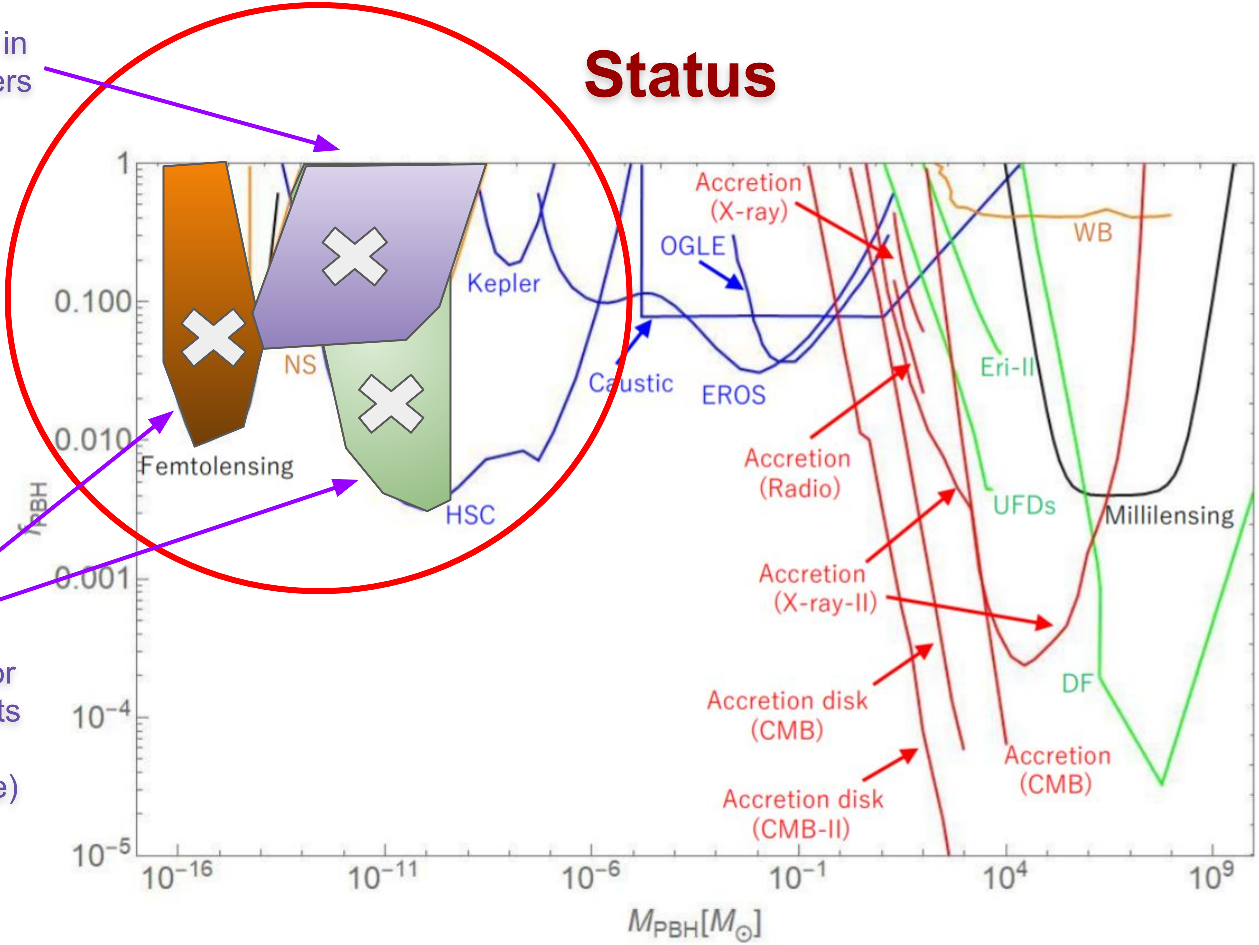
Status



[Sasaki+, 2017]

Status

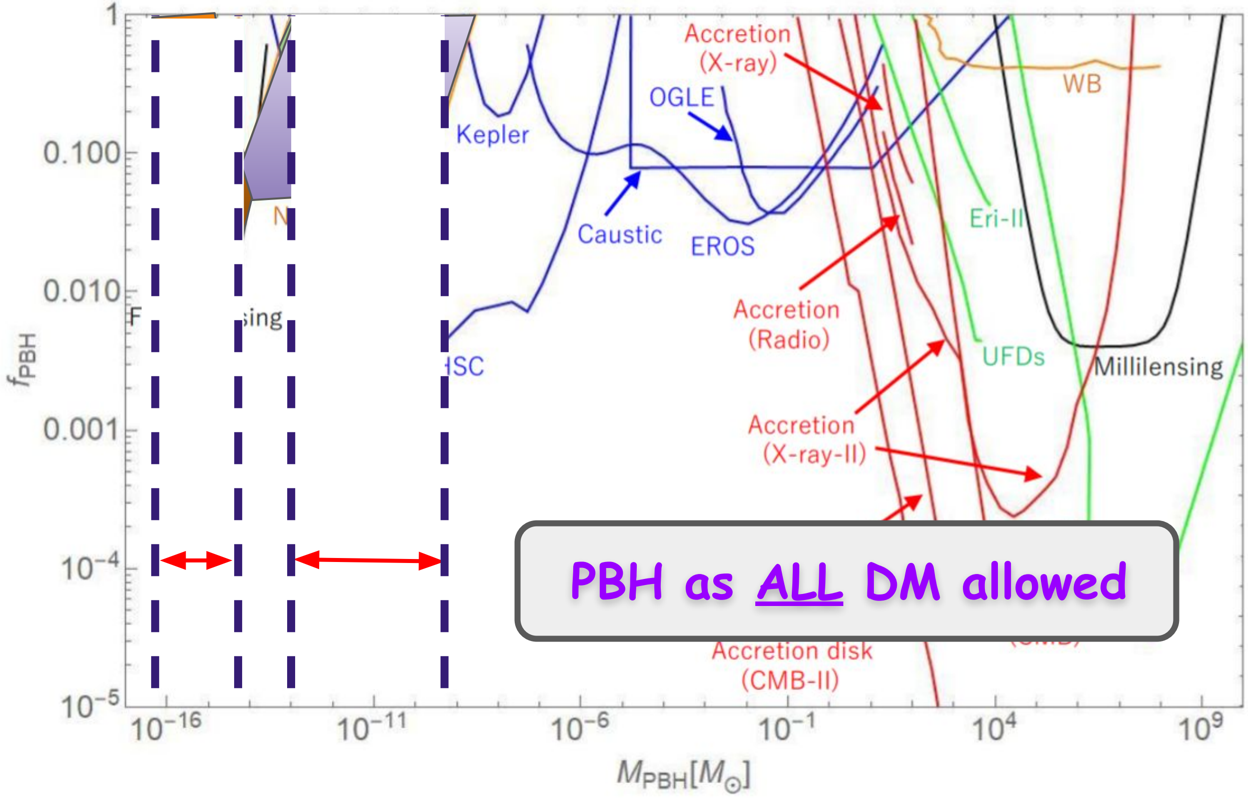
too much DM in globular clusters



didn't account for all lensing effects (wave optics / finite source size)

[Sasaki+, 2017]

Status



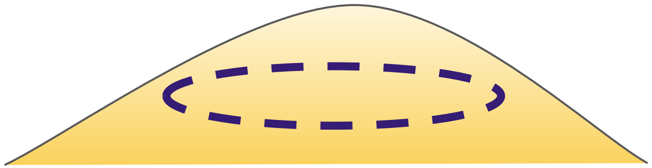
[Sasaki+, 2017]

How do PBHs form?

PBH formation: radiation-dominated era

- THE "standard scenario": large perturbations ($\delta \sim 1$) enter horizon $\rightarrow$ collapse

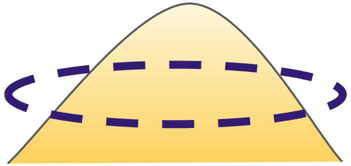
[Kawasaki, Sasaki,Yanagida ...]



PBH formation: radiation-dominated era

- THE "standard scenario": large perturbations ($\delta \sim 1$) enter horizon $\rightarrow$ collapse

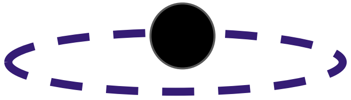
[Kawasaki, Sasaki,Yanagida ...]



PBH formation: radiation-dominated era

- THE "standard scenario": large perturbations ($\delta \sim 1$) enter horizon $\rightarrow$ collapse

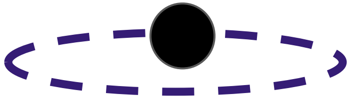
[Kawasaki, Sasaki,Yanagida ...]



PBH formation: radiation-dominated era

- THE "standard scenario": large perturbations ($\delta \sim 1$) enter horizon $\rightarrow$ collapse

[Kawasaki, Sasaki,Yanagida ...]



- Need to tune inflaton potential
- Sensitive to restrictions on scalar field behavior
    - Example: "string swampland conjectures" [Kawasaki, VT, 2018]

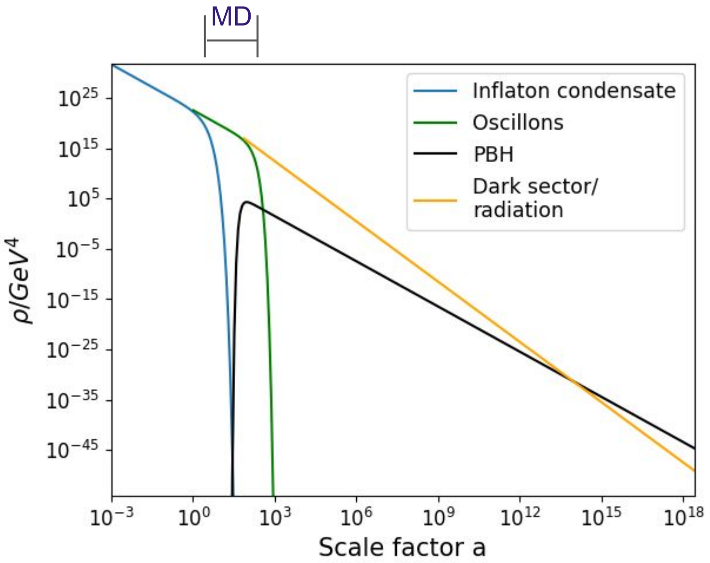
PBH formation: matter-dominated era

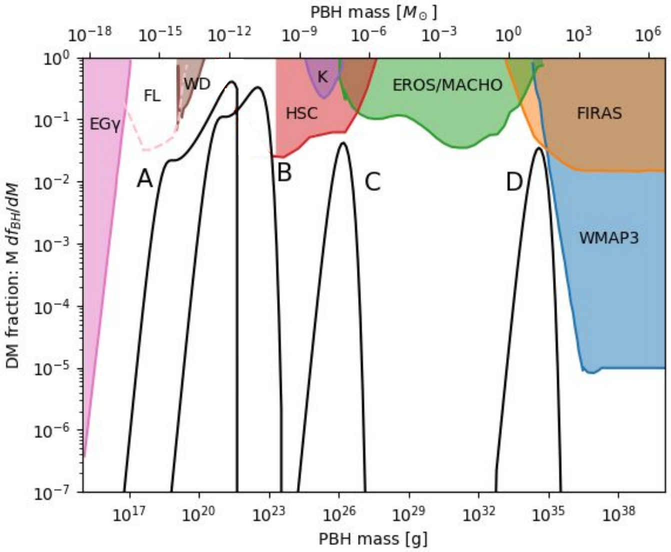
- In MD perturbations grow $\delta \sim a(t)$, even small ones can become large

- Simple general mechanism: **scalar field fragmentation**
  - A: spectator field (charged: Q-balls) [Cotner, Kusenko, PRL 2016]
  - B: inflating field (real: oscillons) [Cotner, Kusenko, VT, PRD 2018]

- Basic idea
  - after inflation oscillating field breaks apart
  - statistics govern lump distribution (big lumps → big fluctuations)
  - region densities grow with time → some collapse to BH

PBH formation: matter-dominated era





[Cotner, Kusenko, VT, PRD 2018]

* New analytic tools to streamline fragmentation computations to be released soon

[Cotner, Kusenko, VT, *prep.*]

How to test
open parameter space?

Compact stars as PBH laboratories

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

- Captured PBH settle and grow inside, destroying the star host

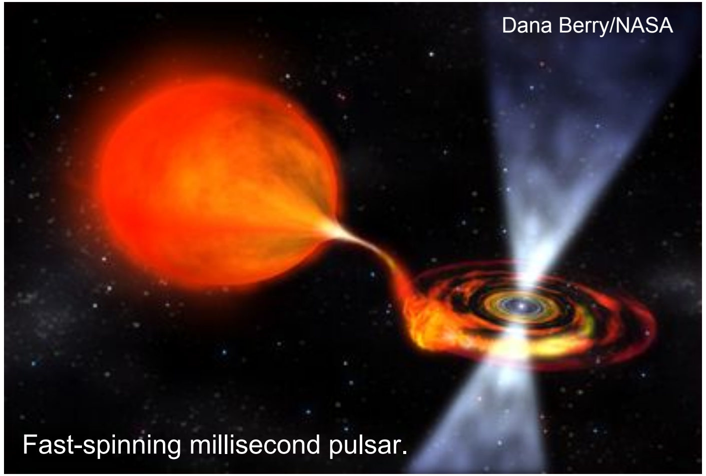
→ r-process nucleosynthesis, 511 keV, FRBs

[Fuller, Kusenko, VT, PRL 2017]

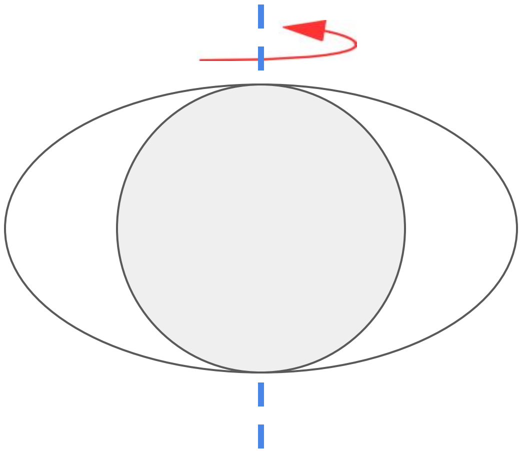
+ *Viewpoint Highlight* by H.-T. Janka

→ solar-mass BHs, GRBs, microquasars

[VT, PLB 2017; VT, 2017]



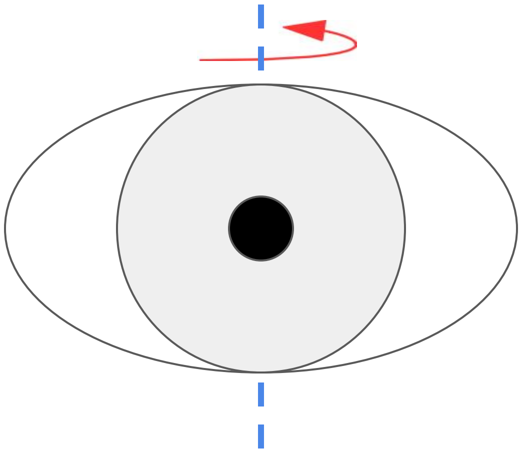
PBH inside MSP



- MSP near mass-shedding limit → stretched spheroid (analytic Roche lobe model)

[Fuller, Kusenko, VT, PRL 2017]

PBH inside MSP

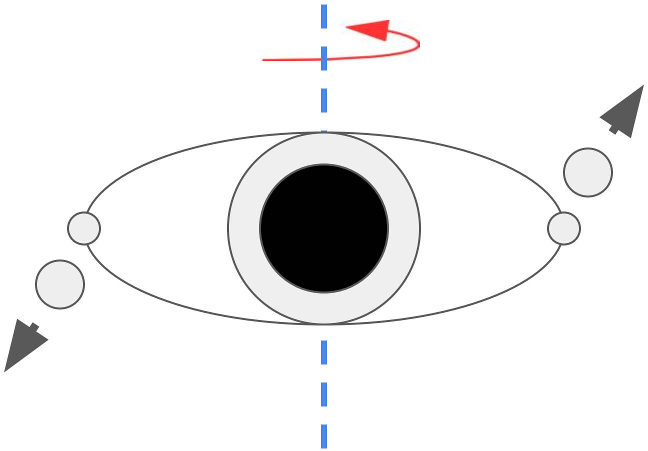


- MSP near mass-shedding limit → stretched spheroid (analytic Roche lobe model)
- Add PBH: star consumed from inside, contracts → angular momentum transferred out

* viscosity [Kouvaris, Tinyakov, 2015] & magnetic stresses ensure rigid rotation

[Fuller, Kusenko, VT, PRL 2017]

PBH inside MSP



- MSP near mass-shedding limit → stretched spheroid (analytic Roche lobe model)

- Add PBH: star consumed from inside, contracts → angular momentum transferred out

  * viscosity [Kouvaris, Tinyakov, 2015] & magnetic stresses ensure rigid rotation

- Matter exceeds escape velocity at equator → neutron-rich ejecta

[Fuller, Kusenko, VT, PRL 2017]

R-process: nucleosynthesis

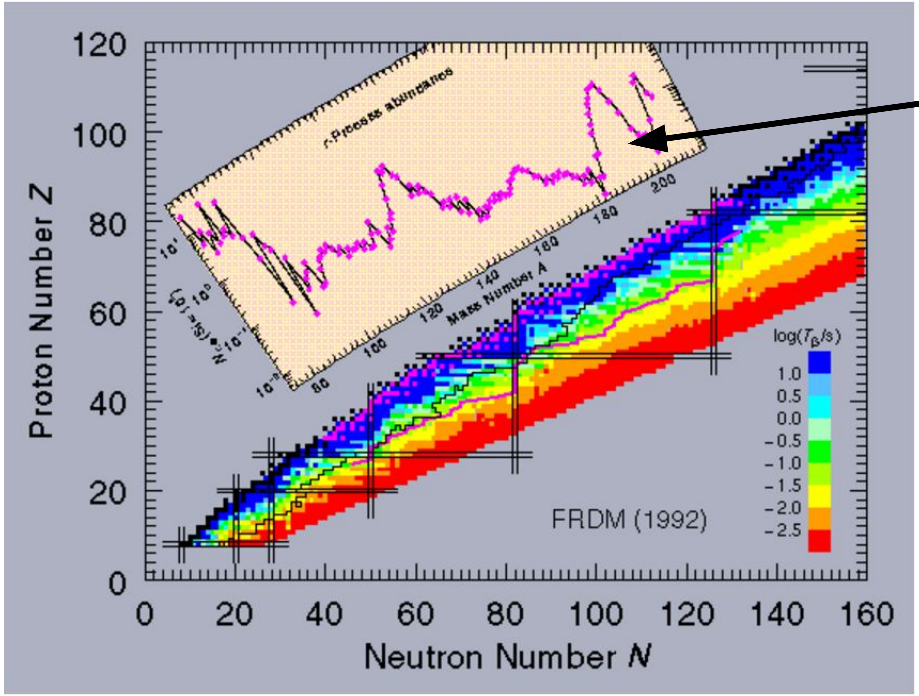


Image: Los Alamos, Nuclear Data Group

- Neutrons ***r***apidly captured before β-decay
- Dominant producer of heavy astro-elements
- Need neutron-rich setting, site unknown
  - SN? problem (neutrinos)
  - NS-NS? Make all? (evolution, kilonova)

R-process: observations

- Milky Way (total) $\sim 10^4 M_\odot$

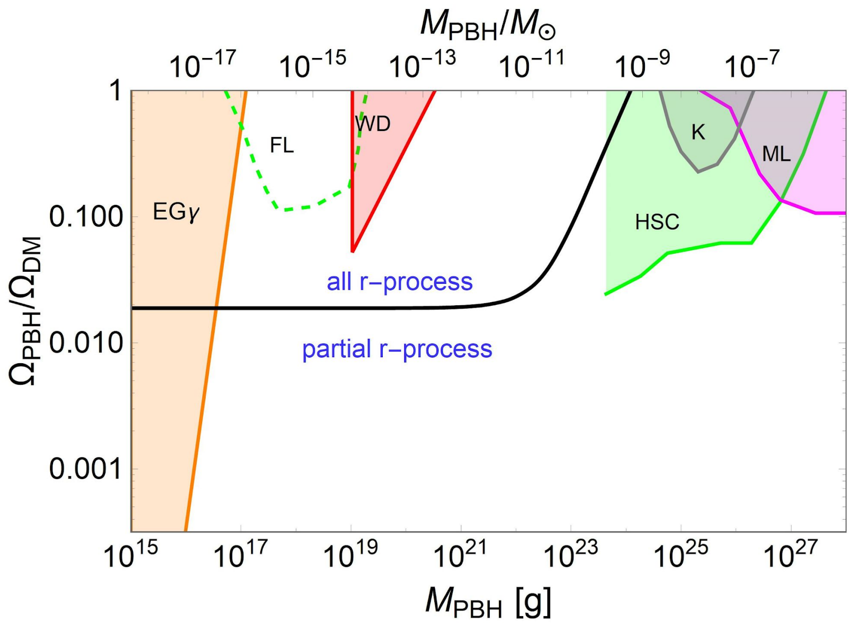
- Ultra-faint dwarfs (UFDs): 1 (Reticulum II) out of 10 shows large abundance

$\rightarrow$ consistent with "rare event" [Ji+, Nature 2016]

R-process: PBH-NS

- PBH-NS emits $\sim 0.1 M_\odot$
  (10x as NS-NS!)

- Consistent with abundances in Milky Way & UFDs ✔

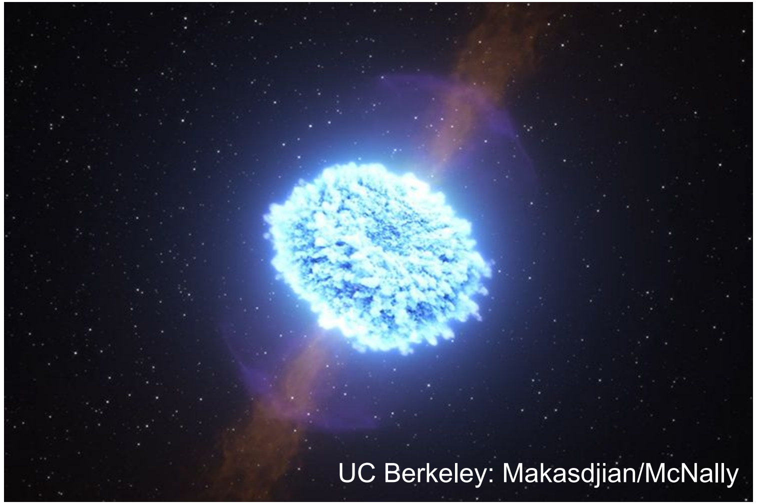


[Fuller, Kusenko, VT, PRL 2017]

PBH-NS laboratories: long kilonova

- Kilonova: afterglow from ejecta radioactive decays

- PBH-NS vs. mergers
  - more ejecta → longer kilonova
  - no merger GWs

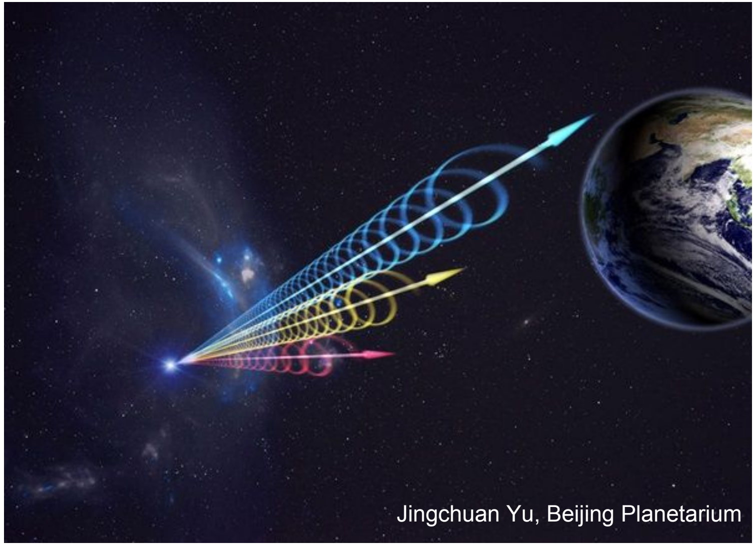


[Fuller, Kusenko, VT, PRL 2017]

PBH-NS laboratories: FRBs

- Fast Radio Bursts
  - origin unknown
  - ~100 found, 1 repeater

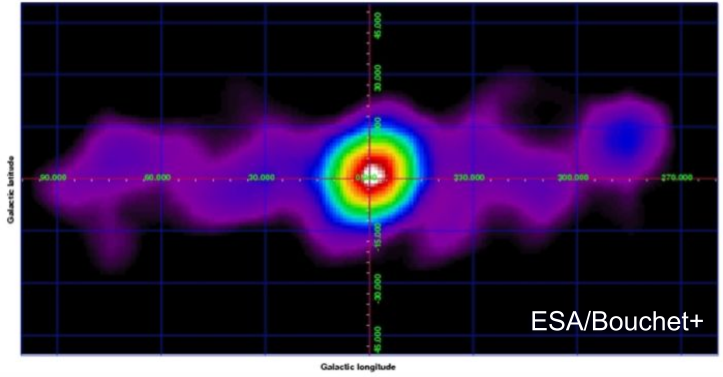
- Release of NS magnetic field energy on PBH-NS consumption timescales (ms)
  → non-repeating FRB



[Fuller, Kusenko, VT, PRL 2017]

PBH-NS laboratories: 511 keV

- Galactic Center 511 keV ***γ***-rays
  - consistent with e+ annihilation
  - e+ origin unknown
  - need e+ production rate 10^{50}/yr
  - need e+ energies < 3 MeV



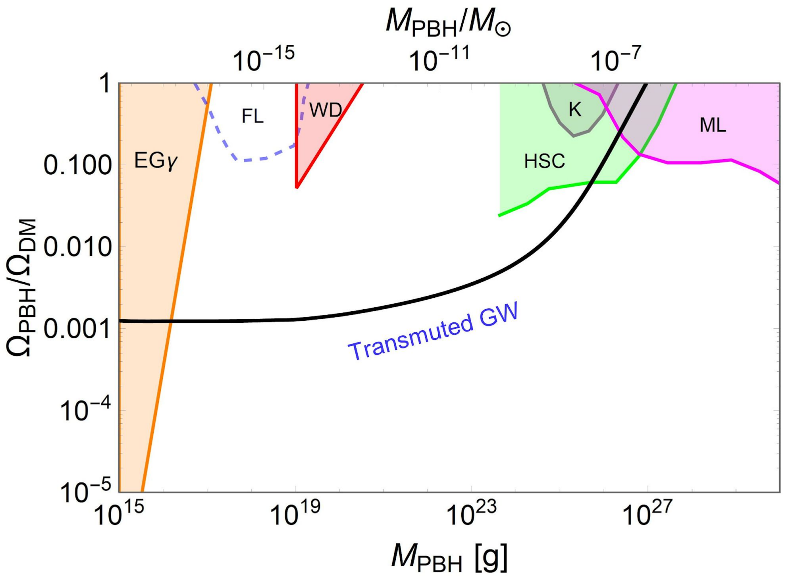
- Temperatures & production rates from PBH-NS ejecta consistent with GC signal

- 511 keV signal discovered in Reticulum II [Siegert+, 2016]
  → strengthens connection

[Fuller, Kusenko, VT, PRL 2017]

PBH-NS/WD laboratories: solar-mass BHs

- No astrophysical BHs $\lesssim 2M_\odot$
- PBH + NS/WD
  $\rightarrow$ "transmuted" solar-mass BHs
- New "transmuted" binary signals
  (e.g. double kilonova)
- Evade constraints on solar-mass PBHs

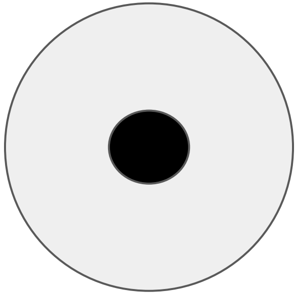


[VT, PLB 2017]

PBH-NS laboratories: GRBs

- “Standard” Gamma-ray Burst progenitor: BH + disk
  → disk accreted, binding energy released

- Can form from PBH-NS → GRB without GW

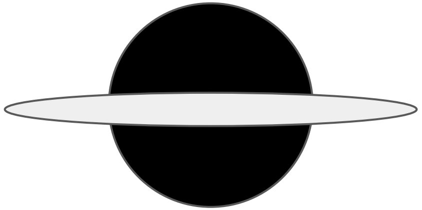


[VT, 2017]

PBH-NS laboratories: GRBs

- "Standard" Gamma-ray Burst progenitor: BH + disk
  → disk accreted, binding energy released

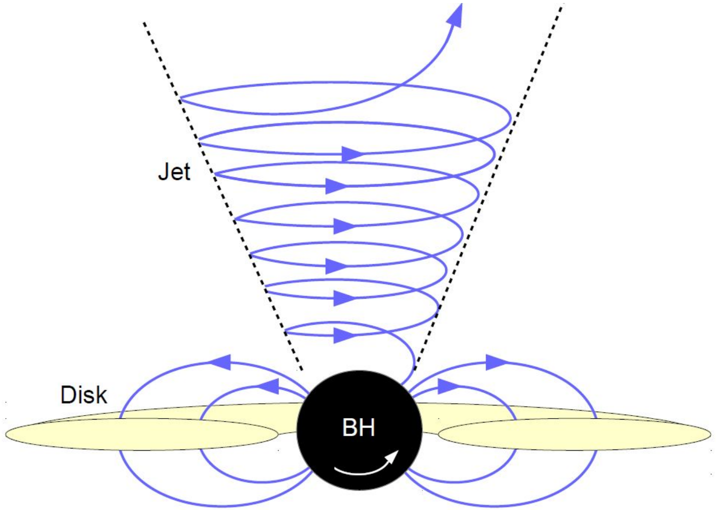
- Can form from PBH-NS → GRB without GW



[VT, 2017]

PBH-NS laboratories: GRBs

- GRB jet formation

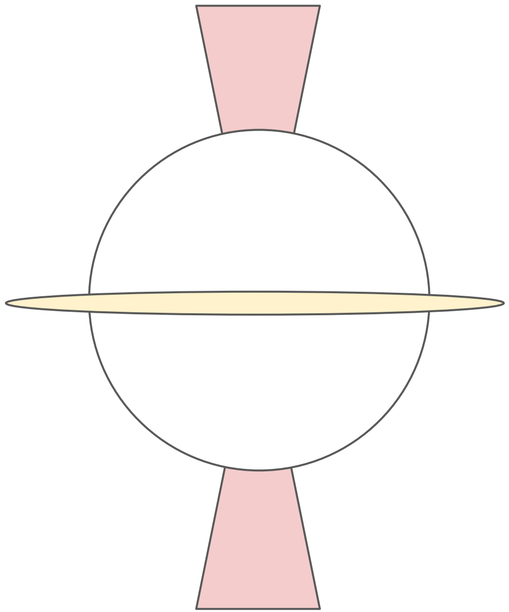


Blandford-Znajek
Mechanism

[VT, 2017]

PBH-WD laboratories: microquasars

- Accreting WD jets non-relativistic $L_{\text{jet}} \sim \dfrac{1}{R}$

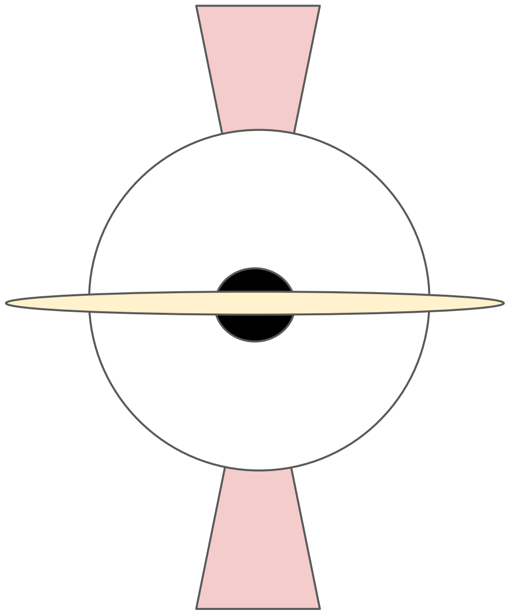


[VT, 2017]

PBH-WD laboratories: microquasars

- Accreting WD jets non-relativistic $L_{\text{jet}} \sim \dfrac{1}{R}$

- WD + PBH

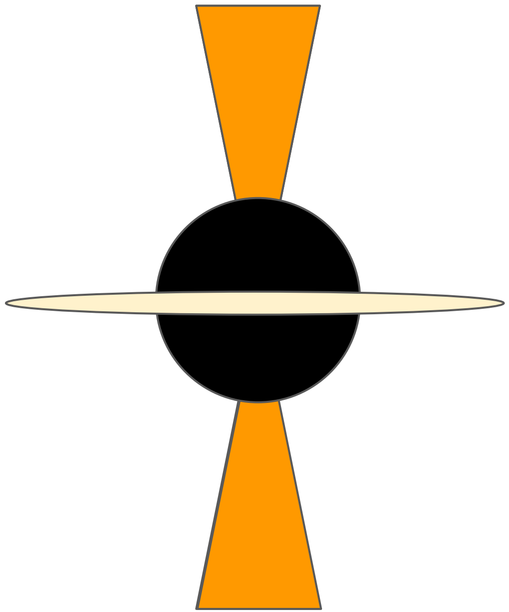


[VT, 2017]

PBH-WD laboratories: microquasars

- Accreting WD jets non-relativistic $L_{\text{jet}} \sim \dfrac{1}{R}$

- WD + PBH $\rightarrow$ solar-mass BH accretor
  - radius ⇩, luminosity ⇧



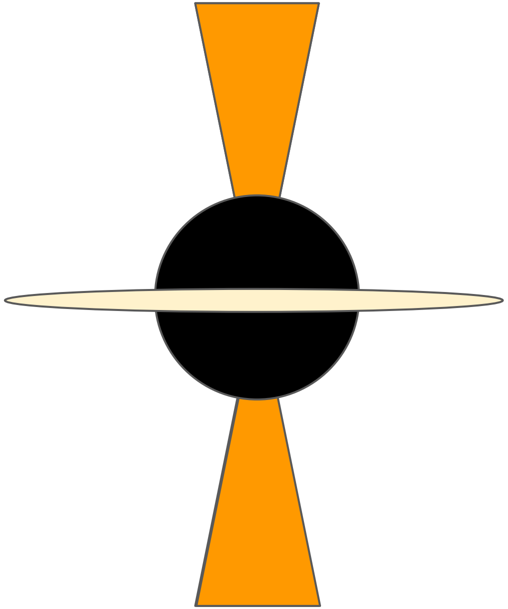
[VT, 2017]

PBH-WD laboratories: microquasars

- Accreting WD jets non-relativistic $L_{\text{jet}} \sim \dfrac{1}{R}$

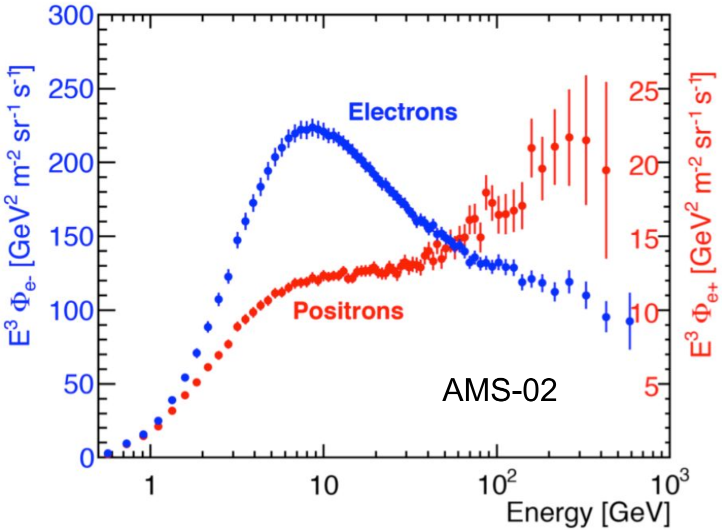
- WD + PBH $\rightarrow$ solar-mass BH accretor
  - radius ⇩, luminosity ⇧

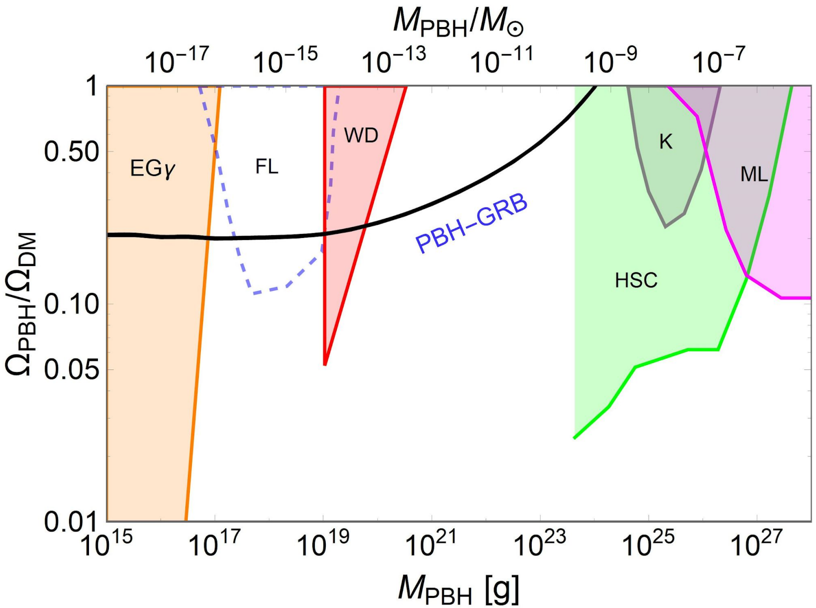
- Continuous relativistic jet microquasar



[VT, 2017]

PBH-NS/WD laboratories: jet positrons





- High-E positrons from PBH-GRB jets can contribute to excess
  → astro-DM connection

[VT, 2017]

Where do we stand?

- Renaissance era in PBH research
  $\rightarrow$ strong synergy with emerging field of multi-messenger astronomy

- Simple general formation mechanism: scalar field fragmentation

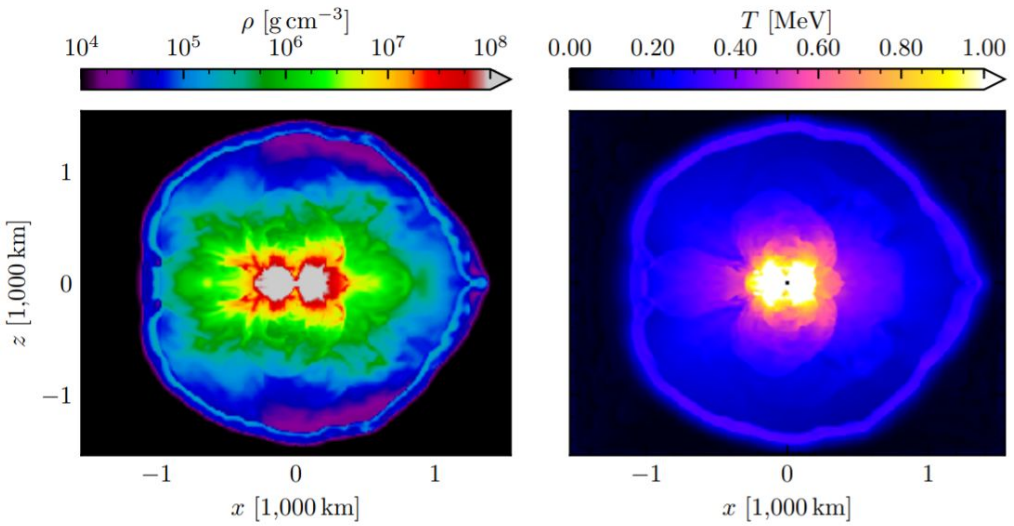
- Compact stars as PBH laboratories
  - probe open parameter space
  - many novel astrophysical signatures
  - possible solutions to astronomy puzzles

Another Excitement

Positrons and 511 keV emission as tracers of neutron star mergers

[Fuller, Kusenko, Radice, VT, 2018]

- After merger, expanding ejecta heated by nuclear processes to O(MeV)
  → thermal equilibrium population of e+e-



t = 10 ms

- Some positrons escape, annihilate → 511 keV signal

- A new multi-messenger signal component of **ALL** NS-NS/NS-BH mergers
  → **new tracer of merger history**

- Rates match observation of 511 keV signal from GC ✔

- 511 keV signal discovered in Reticulum II [Siegert+, 2016] → **confirms connection**

- **Doesn't rely on "new" hypothetical physics !!!**