U.S. DEPARTMENT OF ENERGY | Office of Science

Compact Stars as Primordial Black Hole Laboratories

Volodymyr Takhistov (UCLA)

PACIFIC-2018

(2.13.2018)

Why care about PBHs ???

Motivation: PBH DM

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- PBHs appear in many BSM scenarios and strictly, don't require new physics

  → **"suggestive" that regardless of DM origin, some in PBHs**

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- Thus, PBHs can span vast mass range (with mass spectrum):

$$10^{15}\ \mathrm{g} \lesssim M_{\rm BH} \lesssim 10^{55}\ \mathrm{g}$$

Hawking evaporation $\left(10^{-18}\ M_\odot\right)$ $\left(10^{22}\ M_\odot\right)$ curvature restriction

Sketch of Setup

- If PBHs form DM

  → many in DM-rich environments (e.g. Galactic Center)

- GC contains highest SN/star-formation rate

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- Thus, NS-PBH interactions $(\sim \rho_{\mathrm{DM}} \times \rho_{\mathrm{NS}})$ should be rather generic

What can we learn from astrophysics of PBH-compact star interactions ???

Three Stories of PBHs and Compact Stars

- **How PBHs can make gold** (r-process nucleosynthesis)
- **PBH-induced fireballs and torches** (GRBs and microquasars)
- **Imprints of tiny PBHs from the past** (transmuted GW signals)

PART I:

How PBHs Make Gold

Based on: Fuller, Kusenko, Takhistov [arXiv:1704.01129, PRL (2017)]

Nucleosynthesis

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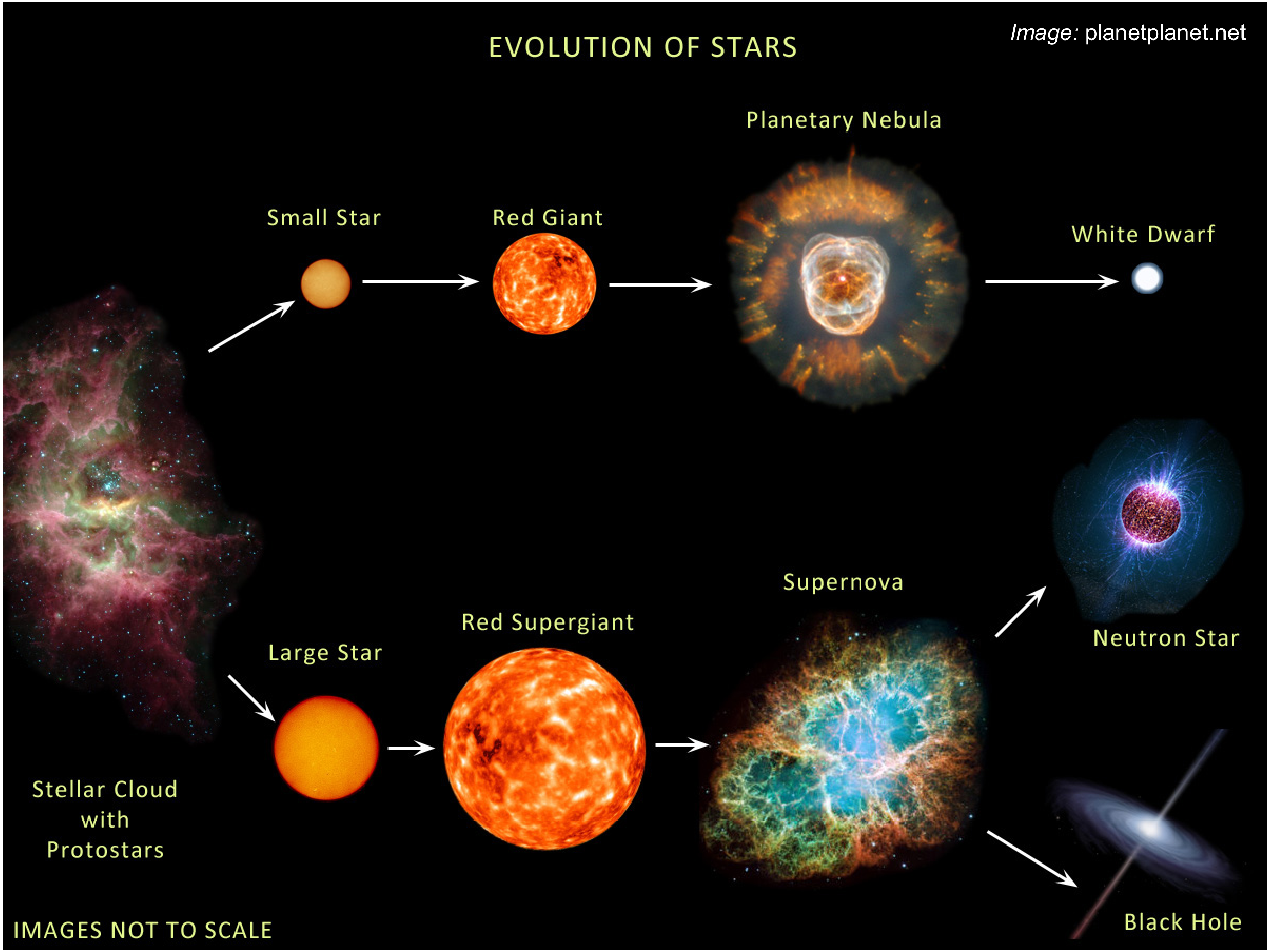
could be primordial black holes

Compact Star Formation

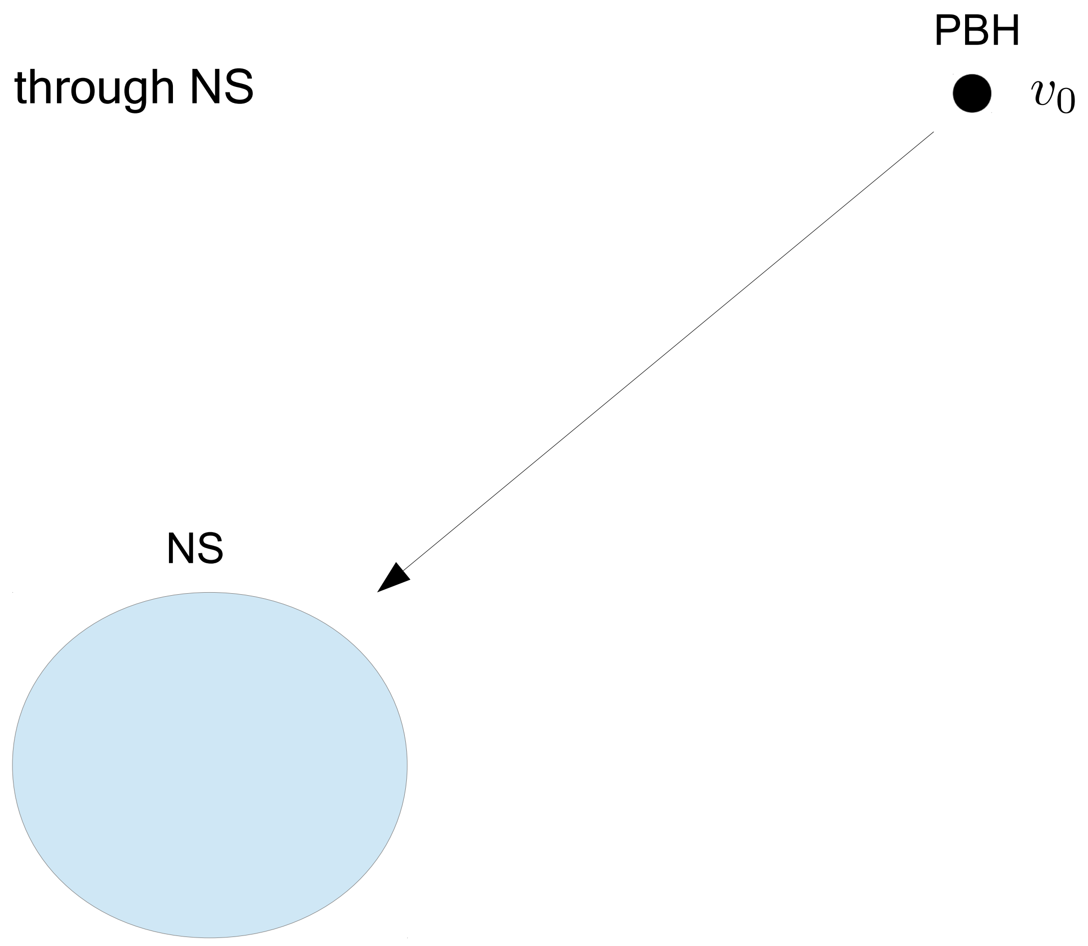


NS-PBH Capture

[Capela,Pshirkov,Tinyakov,13-14]

Stage 1: gravitational capture

$\rightarrow$ PBH approaches and passes through NS



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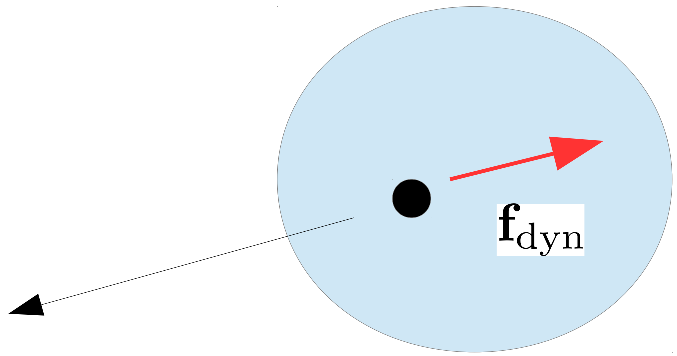

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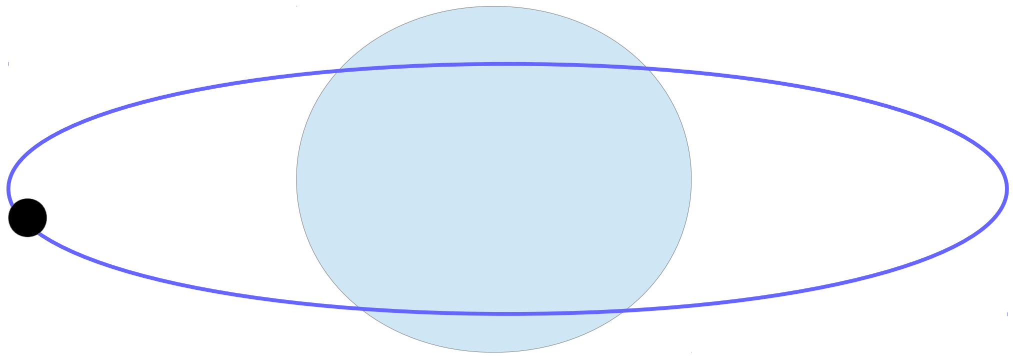
→ if $E_{\mathrm{loss}} > \mathrm{KE}_{\mathrm{PBH}}$ → **captured !**

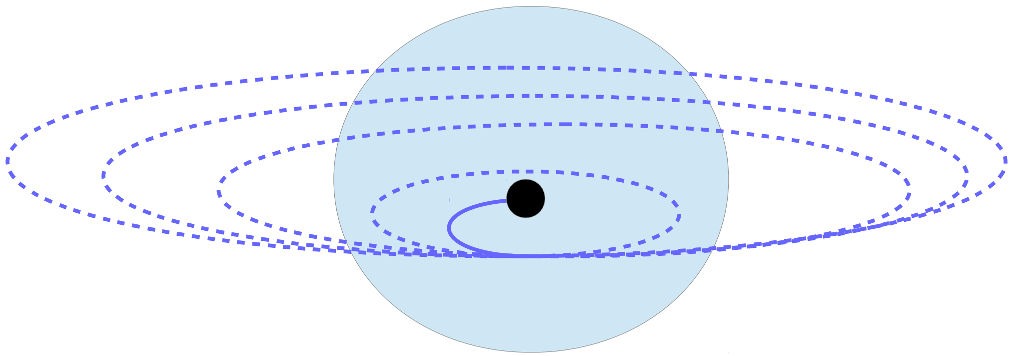


NS-PBH Capture

[Capela,Pshirkov,Tinyakov,13-14]

Stage 2: PBH in NS

→ captured PBH continues passing through NS, until it settles inside



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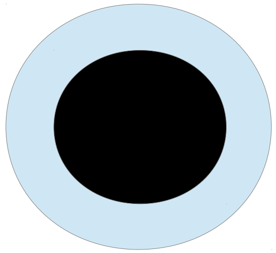
Stage 3: PBH grows

→ PBH inside NS grows via Bondi accretion, consuming the host star



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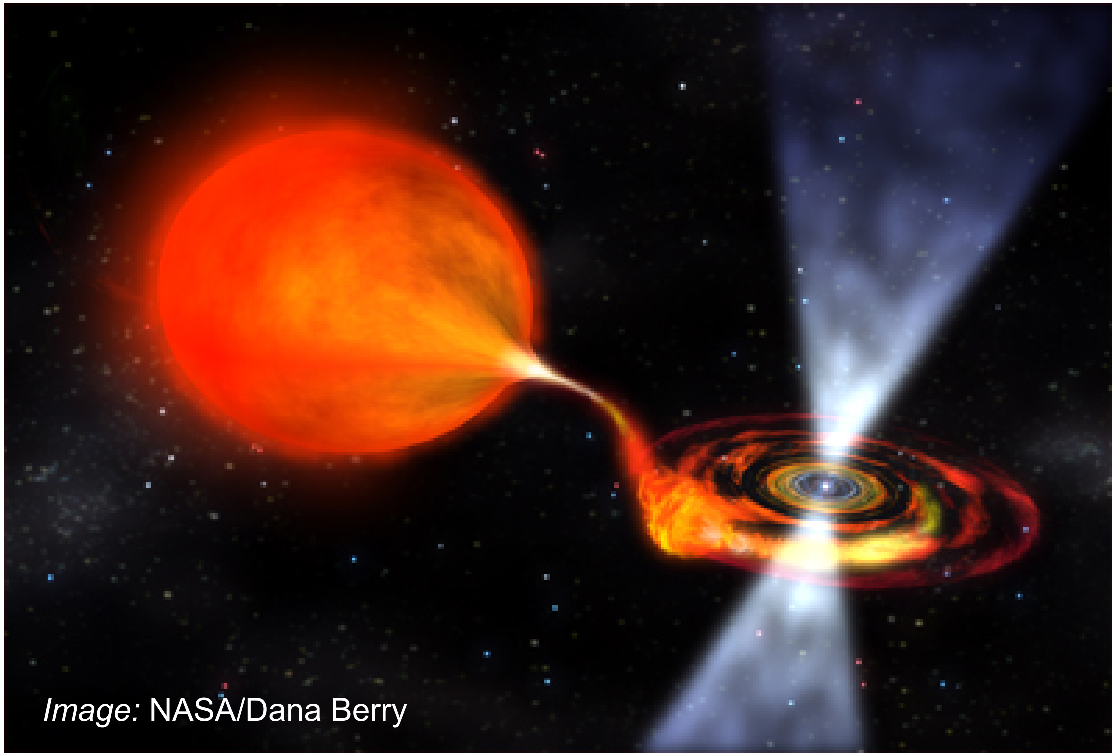
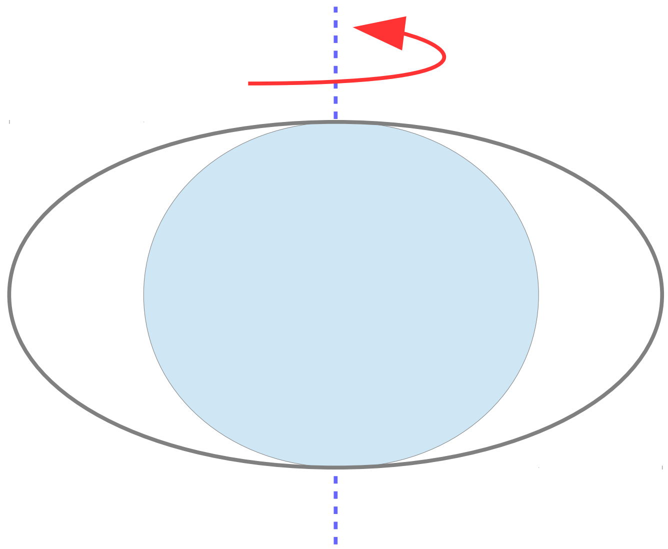
- MSPs are "recycled pulsars" → binary pulsar accretes matter from companion, spun-up



Growing BH in NS: angular momentum transfer

- MSP spinning near mass shedding limit → elongated spheroid (Roche lobe model)

[Shapiro,Teukolsky,83]



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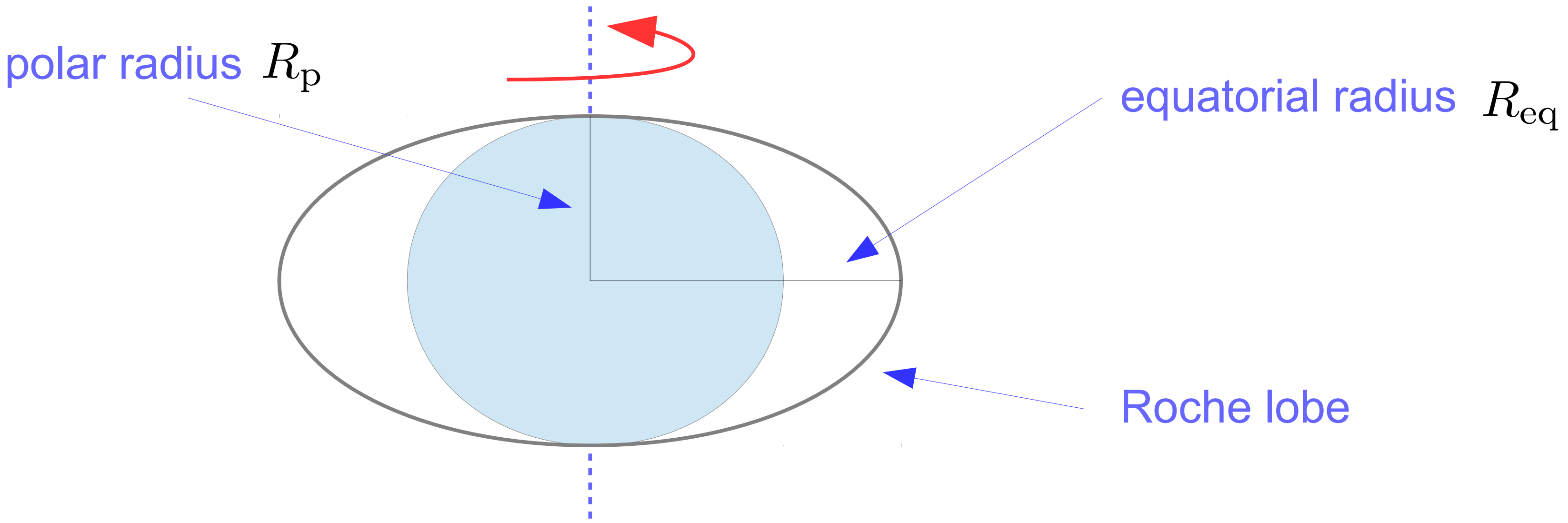

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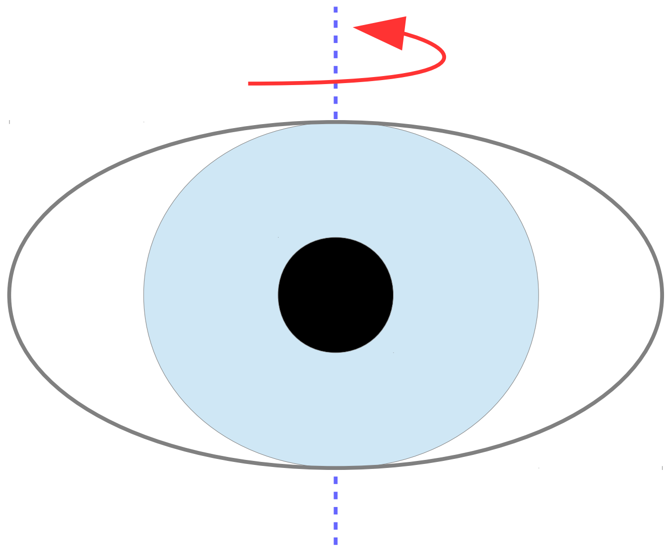

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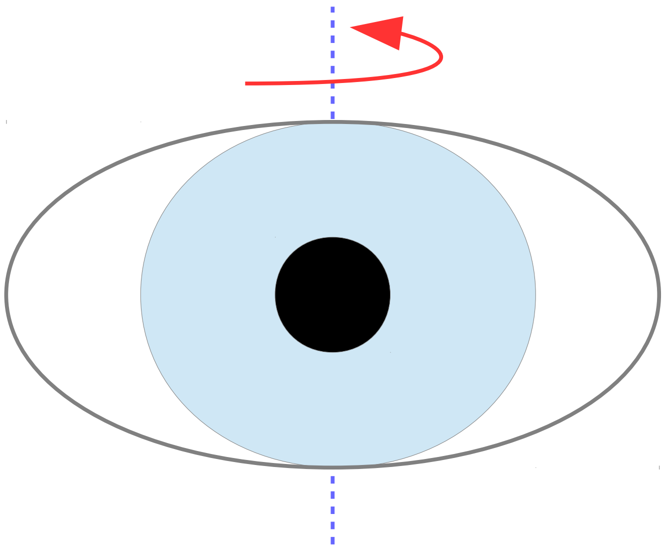

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→ analytically showed that matter exceeds escape velocity → **ejected mass !!**

Growing BH in NS: ejected mass

10 x more than from NS-NS !!!

Ejected mass:

- Population averaged: $\langle M_{\rm ej}\rangle \sim \mathcal{O}(0.2) M_\odot$

- Neutron rich $\rightarrow$ **a site of r-process nuclesynthesis**

R-process

[long list (Meyer,Schramm, *others*)]

- (R)apid-process nucleosynthesis:

  - dominant mechanism for heavy element production

  - neutrons capture on seed nuclei faster than β-decay → build up heavy elements

  - very sensitive to environment

- Leading production sites: SN, compact object mergers (COM)

  … each has problems

R-process: abundance from PBH-NS

- R-process material in Galaxy: $\sim 10^4 M_\odot$

- Recent UFD observations show consistency with 1 rare r-process event [Ji+,16]

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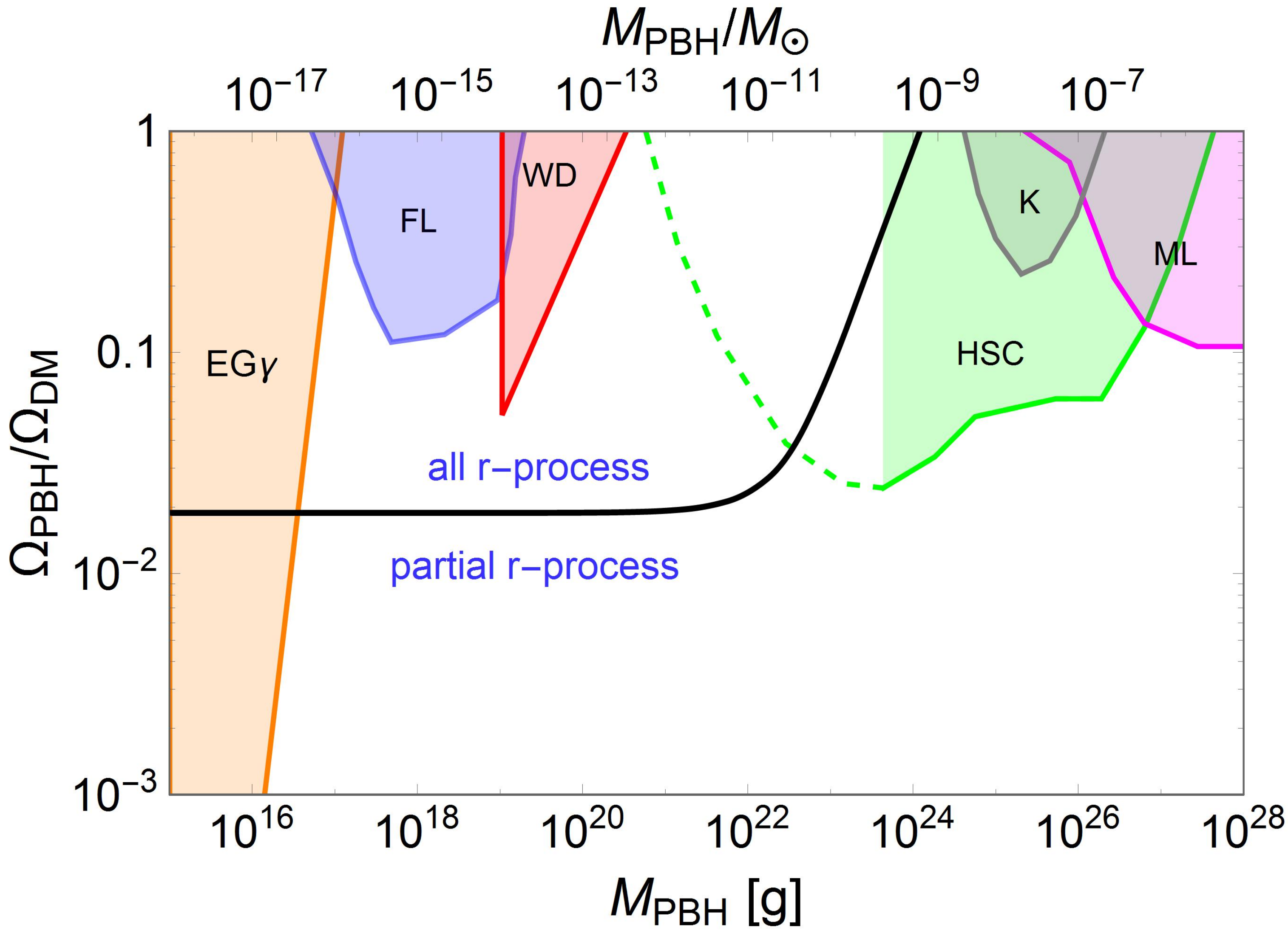
can explain simultaneously with PBH-NS

R-process: abundance from PBH-NS



Other Signatures

Can also obtain:

- Kilonova
- 511 keV GC line
- FRB

.. without accompanying strong GW or neutrino signals

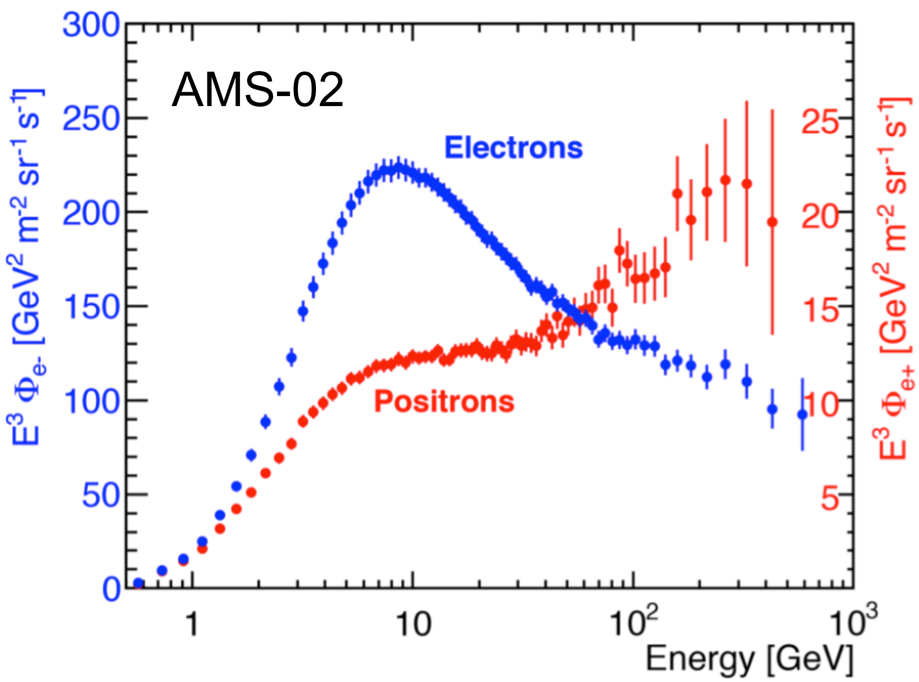
PART II:

Positrons from PBH Fireballs (and Torches)

Based on: Takhistov [arXiv:1710.09458]

Positron Excess

- Experiments see positron excess above 30 GeV (AMS-02, Pamela, Fermi)



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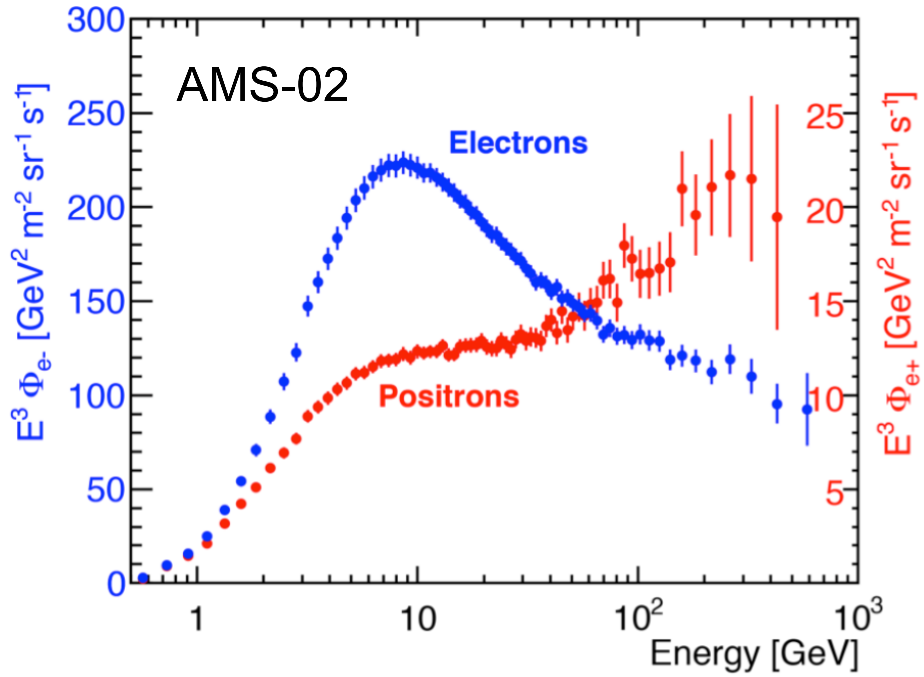

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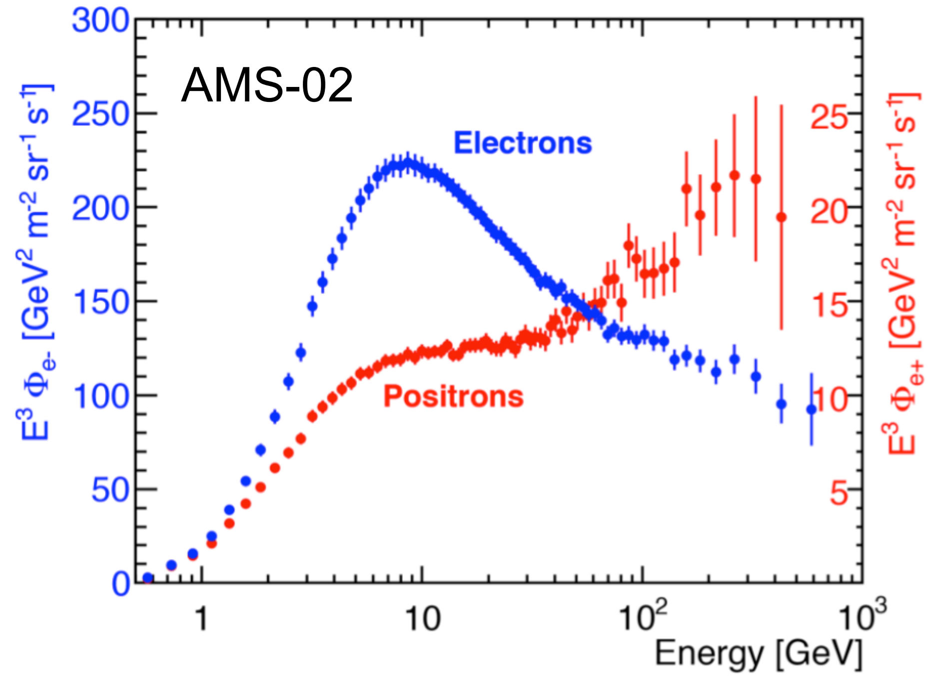

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PBHs can link astro-sources with DM !

Gamma-ray Bursts from PBHs

- Short GRBs: irregular EM emissions $t \sim 0 - 2\mathrm{s}$, $E \sim 10^{48} - 10^{50}\mathrm{erg}$

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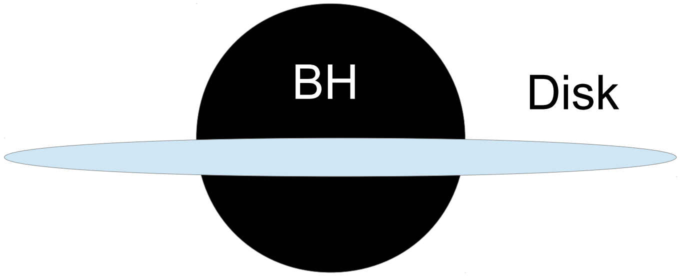

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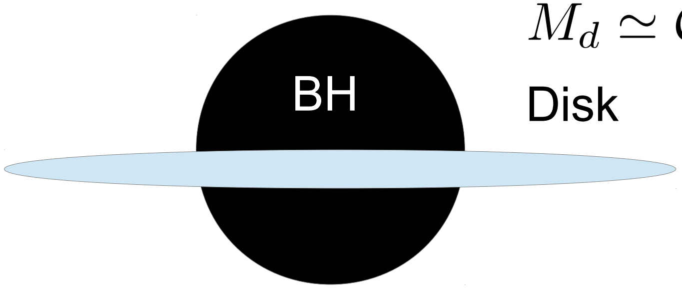

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Disk

up to 42% disk binding energy release

$$E_\mathrm{b} = 0.42 M_d = 10^{53}(M_d/M_\odot)\mathrm{erg}$$

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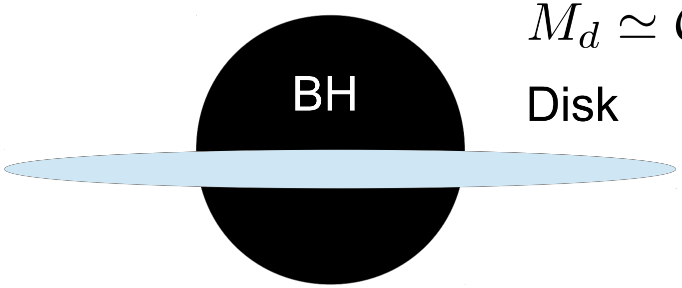

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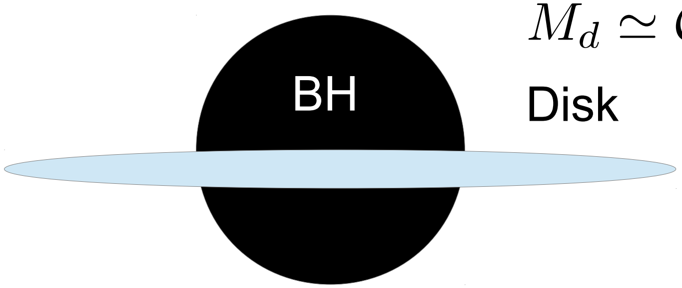

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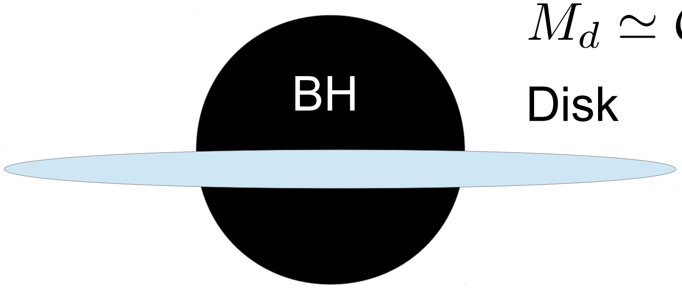

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$\rightarrow$ analytically show **formation of accretion disk generic!**

Gamma-ray Bursts from PBHs

PBH-star systems as sources of sGRBs!!

* without merger GWs

Jet Launching

- Jet launching mechanisms:

  A) neutrino-antineutrino annihilation $\rightarrow$ hot disk

  B) MHD winds (Blandford-Payne) $\rightarrow$ magnetized disk [Blandford, Payne,82]

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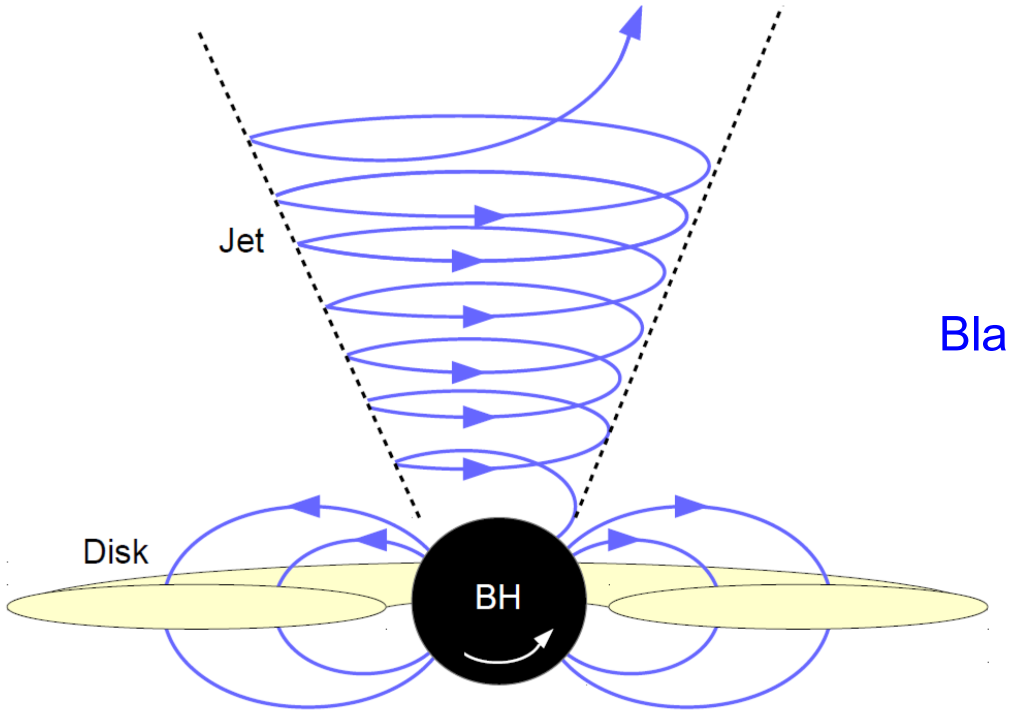

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from PBHs:

✗ (?)

✓

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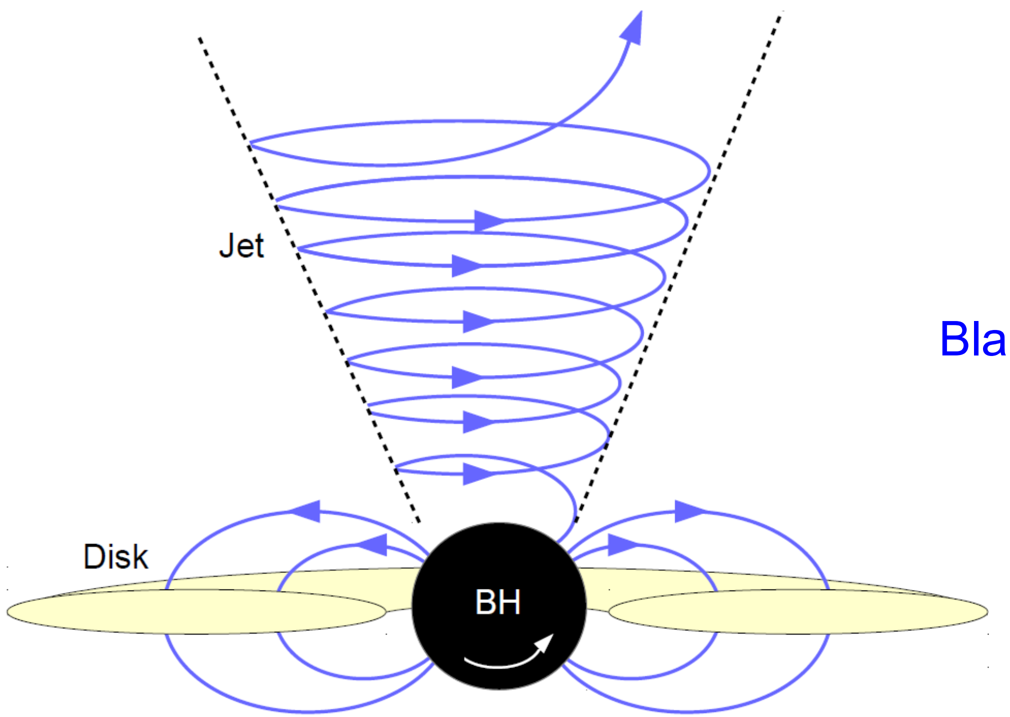


Blandford-Znajek

Accelerated Positrons

[Ioka,08;
Bertone,Kusenko+,04]

- Jet relativistic $\longrightarrow$ result in GeV-TeV accelerated positrons

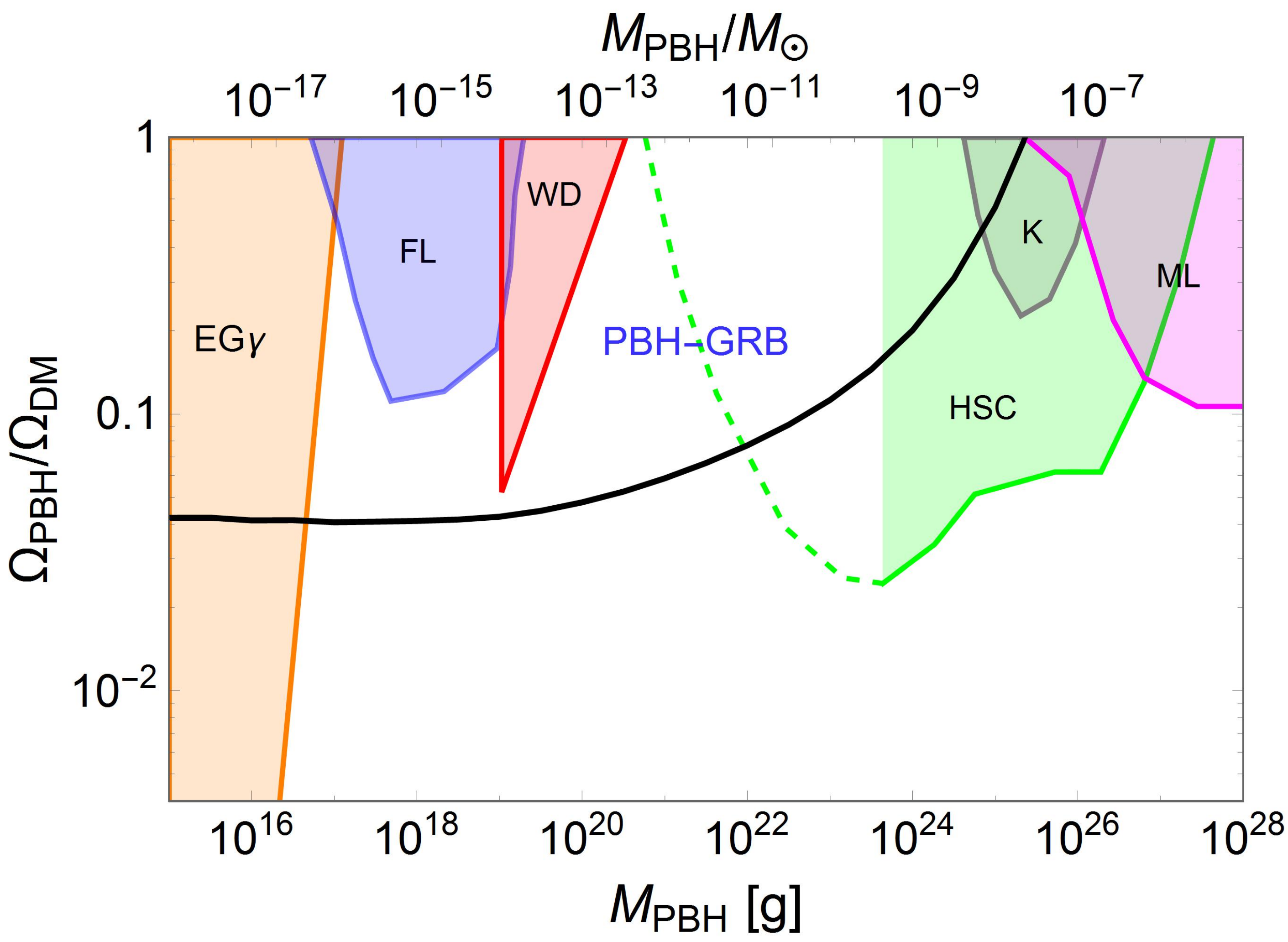
- Positrons diffuse, for 100 GeV diffusion time $t \sim 10^6 \mathrm{yrs}$

[Strong,Moskalenko,Reimer,04]

- GRBs can account for excess if occurred during diffusion time [Ioka,08]

(alternatively, a continuous micro-quasar jet shinning for the duration)

Positron Excess from PBHs



PART III:

Imprints of Tiny PBHs from the Past

Based on: Takhistov [arXiv:1707.05849]

Tiny PBHs from the Past

If tiny PBHs consumed stars in the past,

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signals from unusual solar-mass BHs

Solar-mass BHs: in astrophysics

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~~Astro BHs~~ $\cancel{\lesssim 2M_\odot}$

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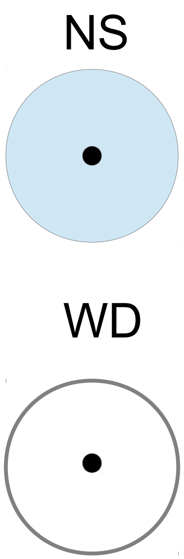

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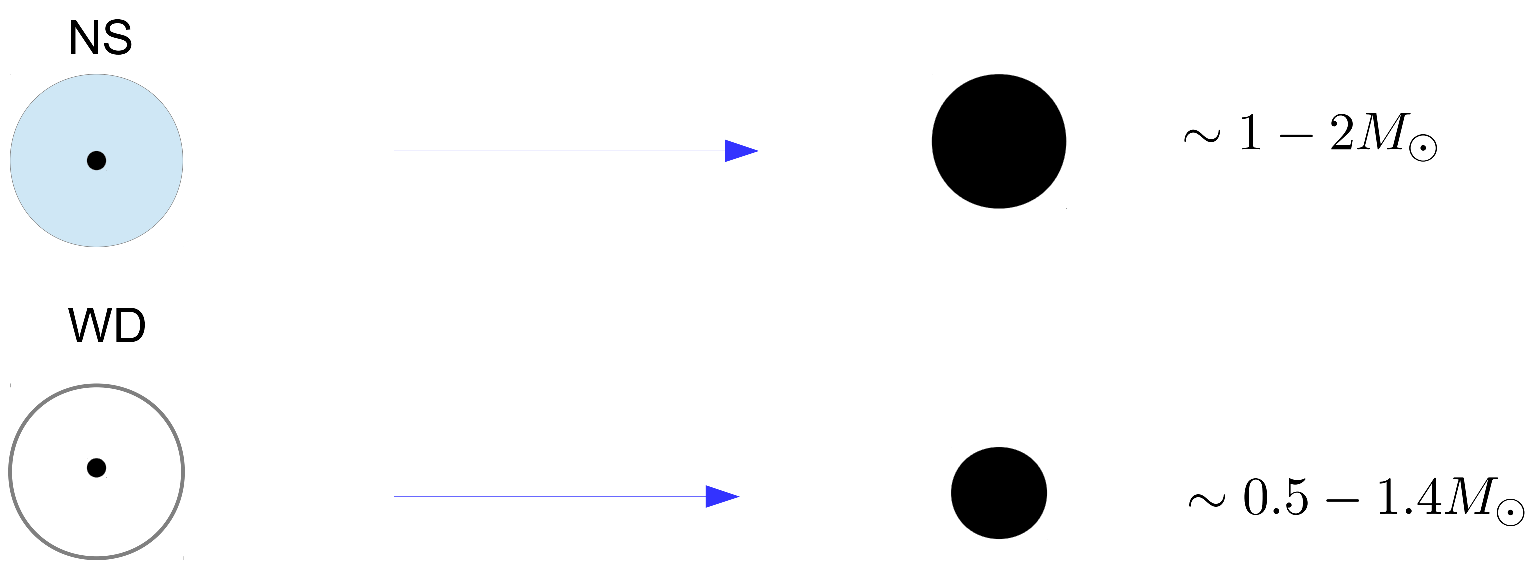

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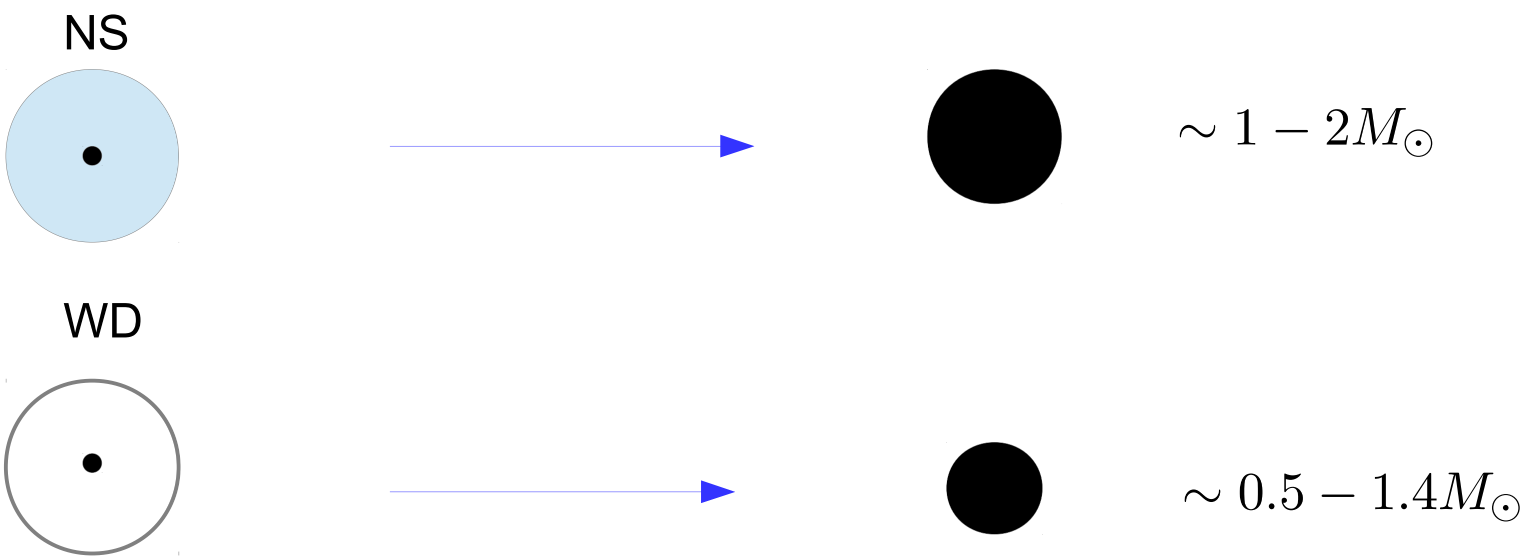

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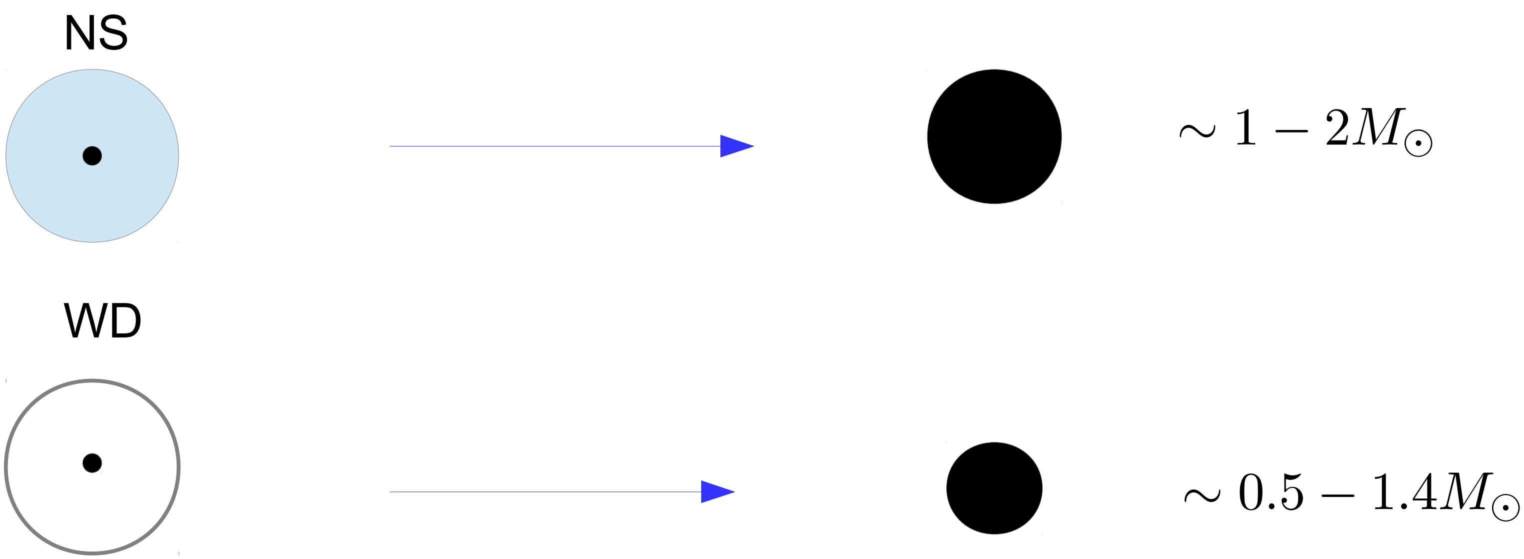

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How to detect? $\rightarrow$ new merger GW signals

Transmuted Binaries

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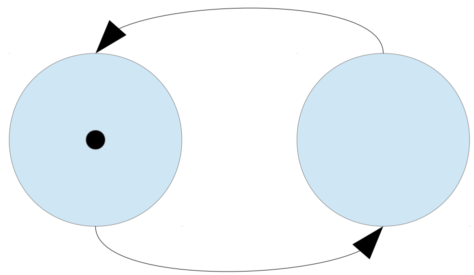

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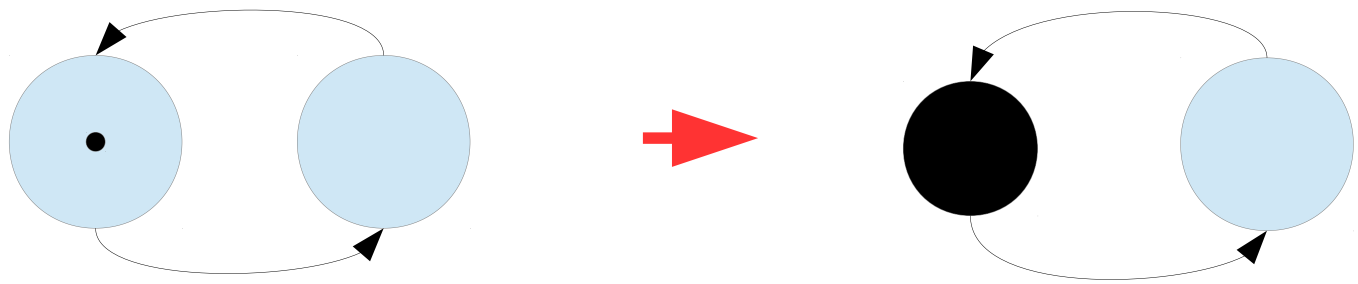

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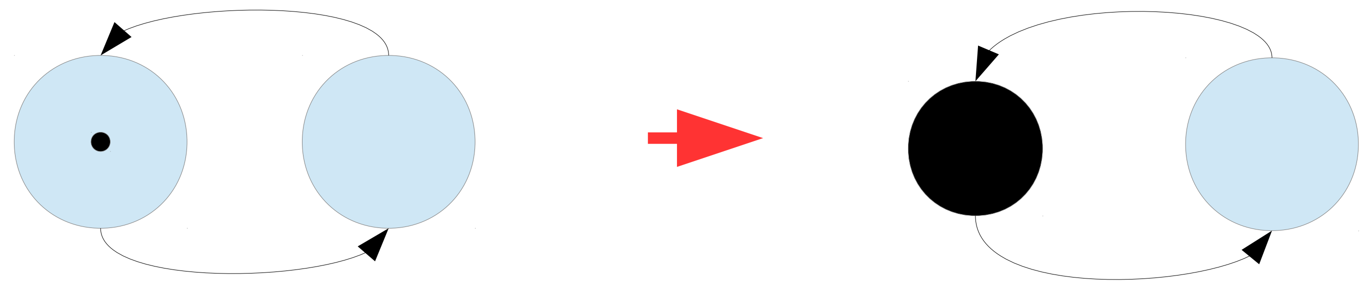
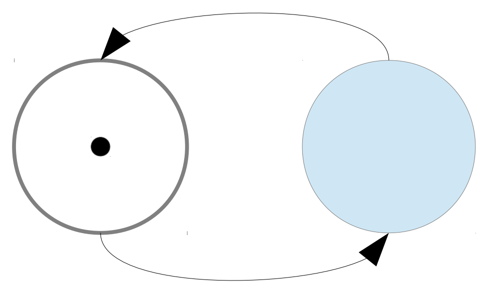


WD-NS



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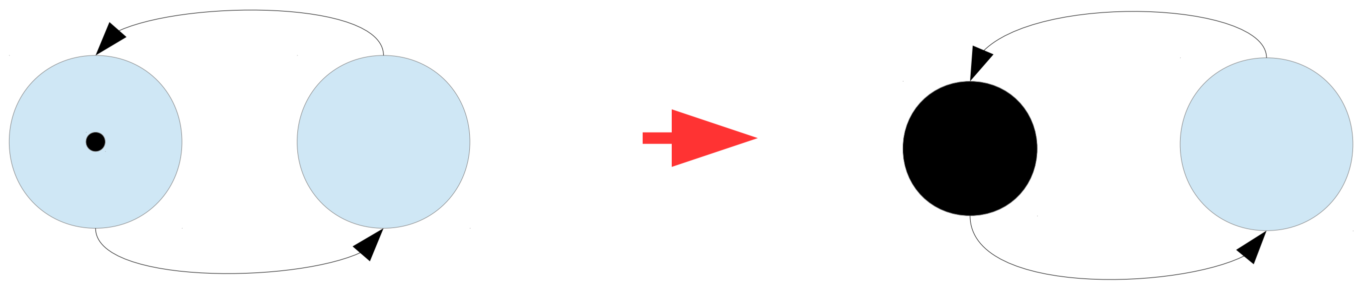

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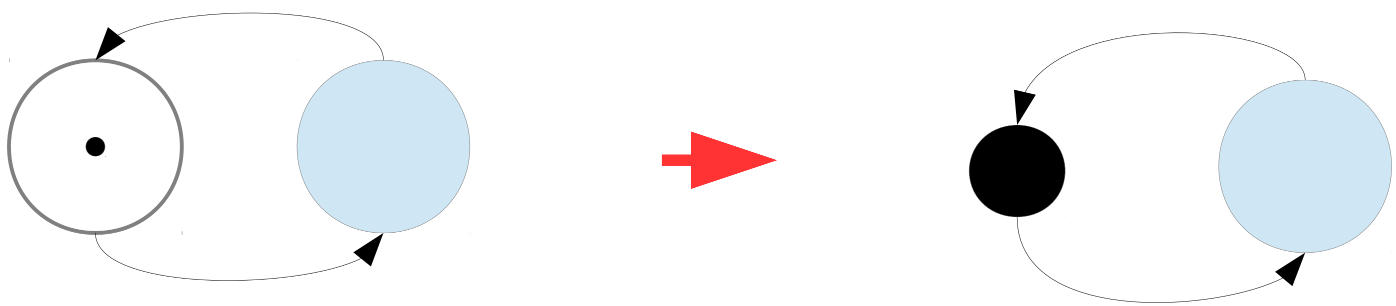

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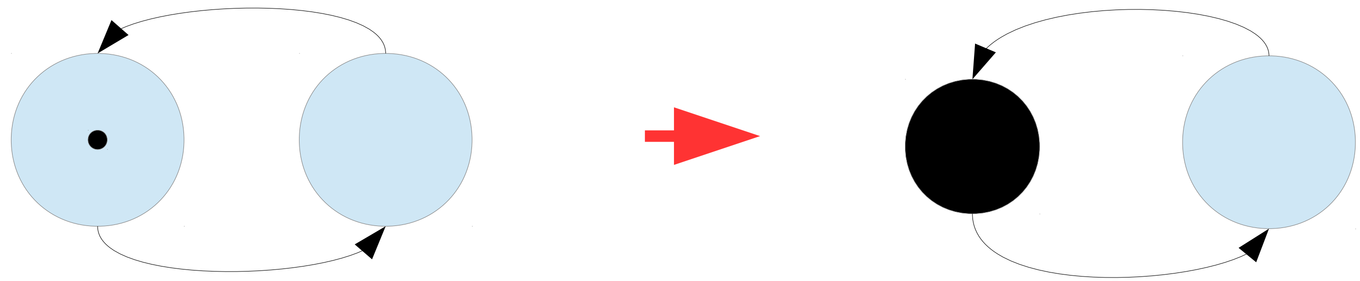
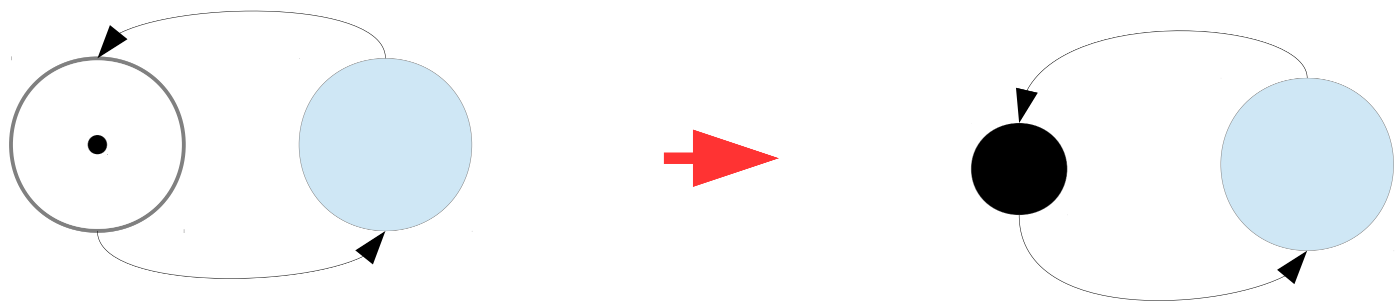
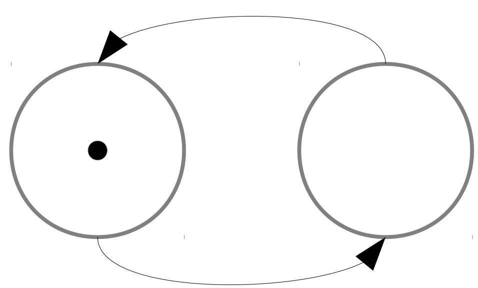


WD-NS



interacting WD-WD
(*cataclysmic variable*)

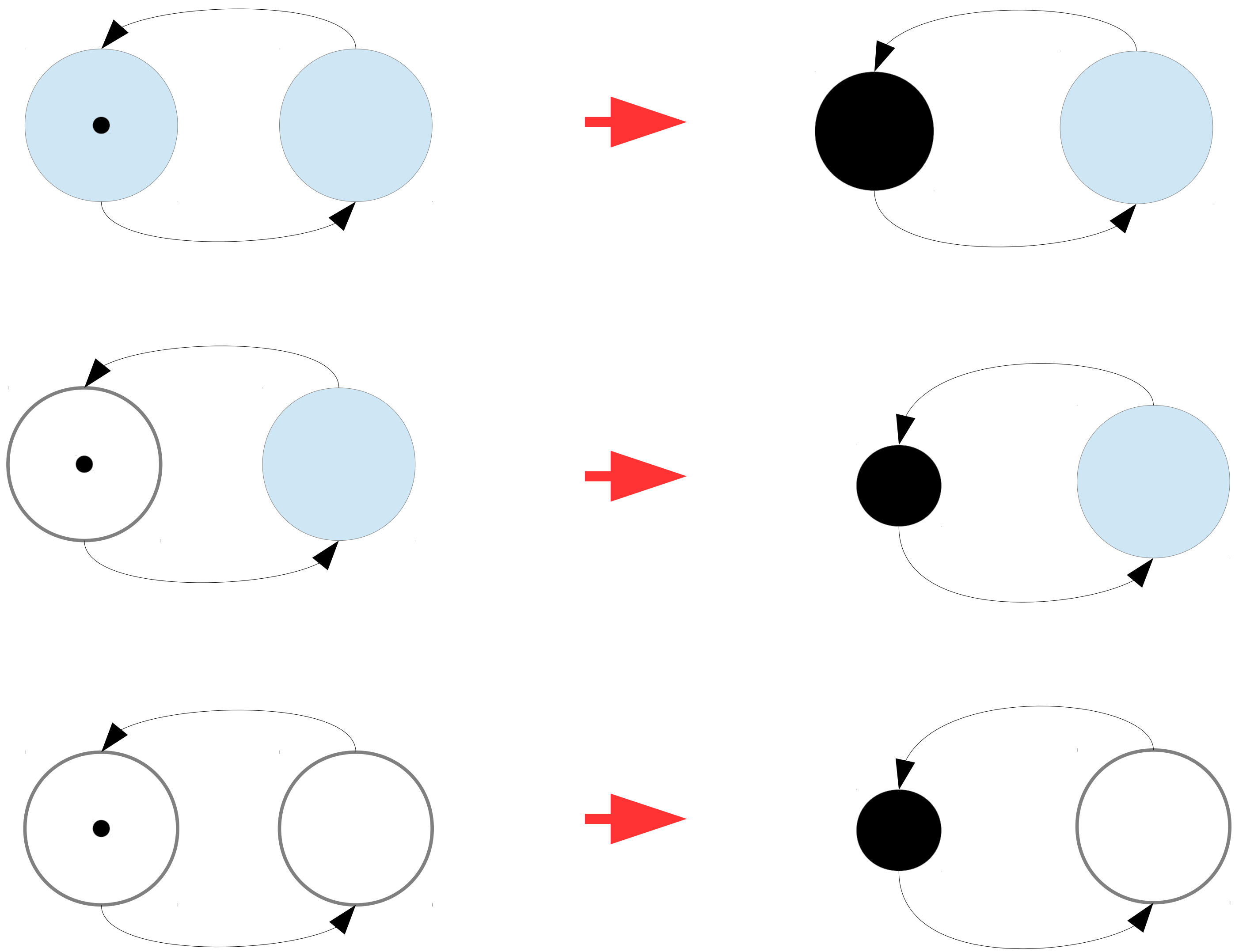


Transmuted Binaries

NS-NS

WD-NS

interacting WD-WD
(*cataclysmic variable*)

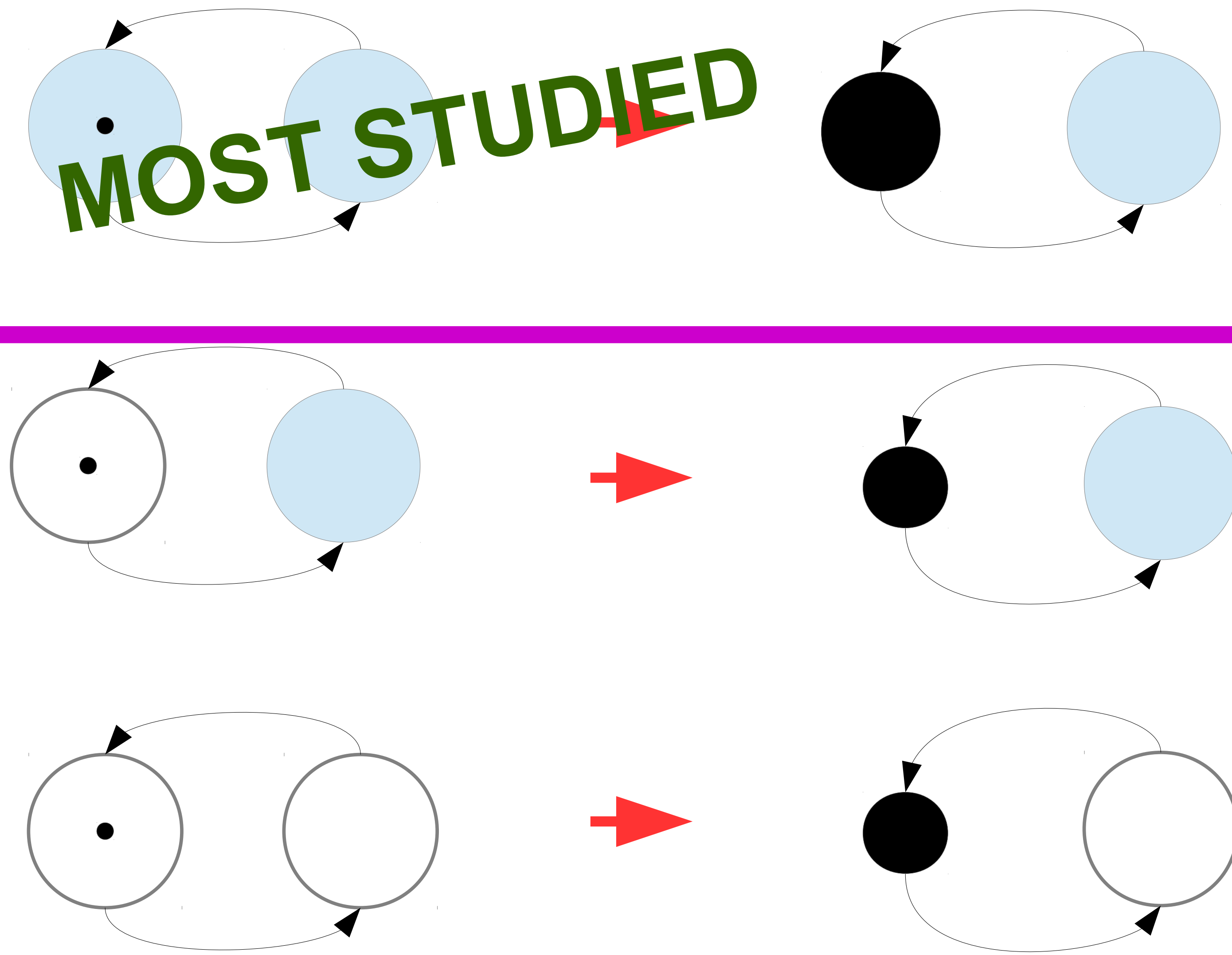


Transmuted Binaries

NS-NS

WD-NS

interacting WD-WD
(*cataclysmic variable*)



Compact Object Mergers

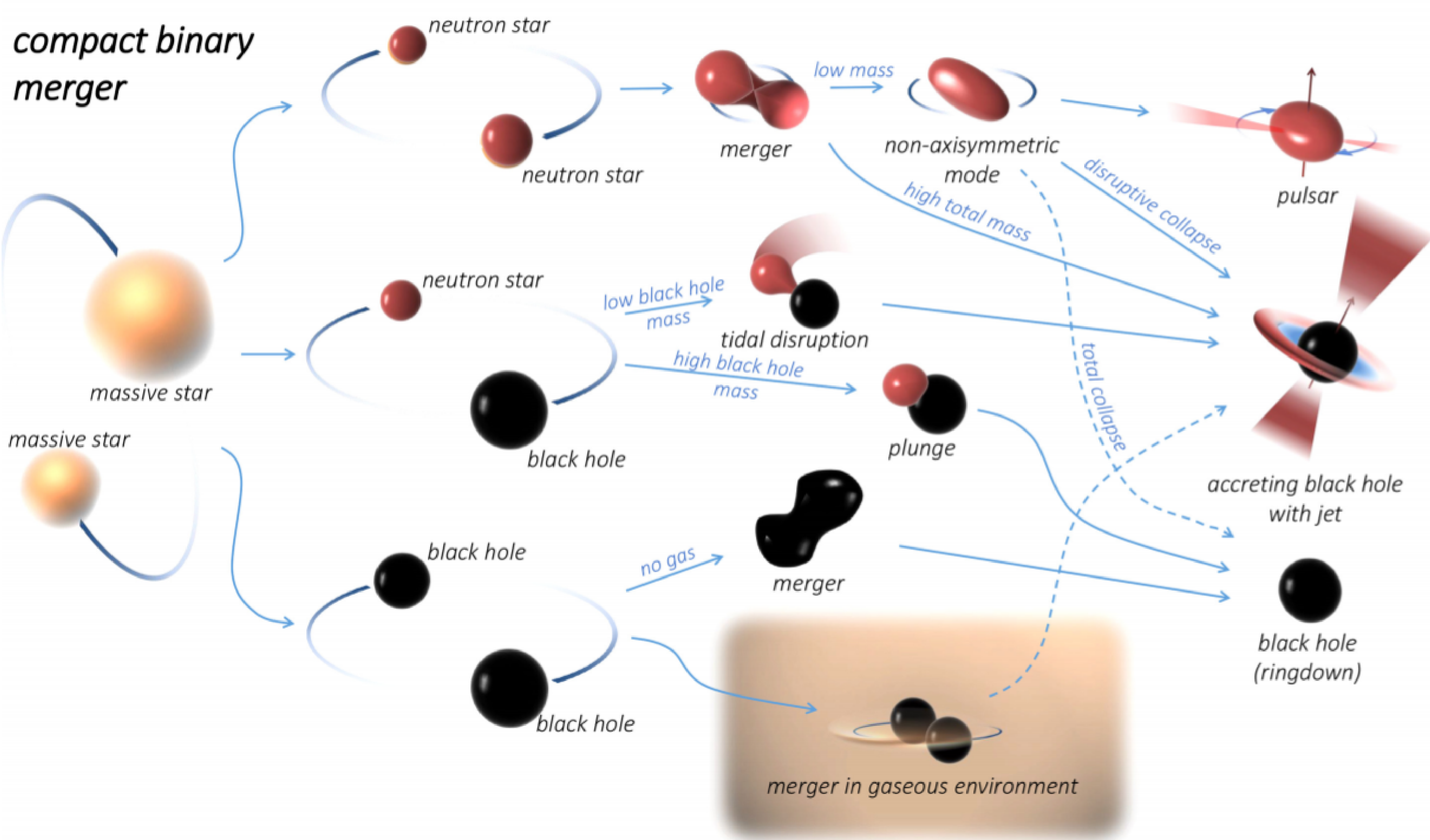


Image: Bartos,Kowalski,*“Multimessenger Astronomy”*

Transmuted GW Signals

- General features (e.g. merger time, GW luminosity)

  $\longrightarrow$ depend on chirp mass $\mathcal{M}_c(M_1, M_2) \longrightarrow$ will change with non-zero ejecta

- Distinguishing signatures

  $\longrightarrow$ merger / ringdown

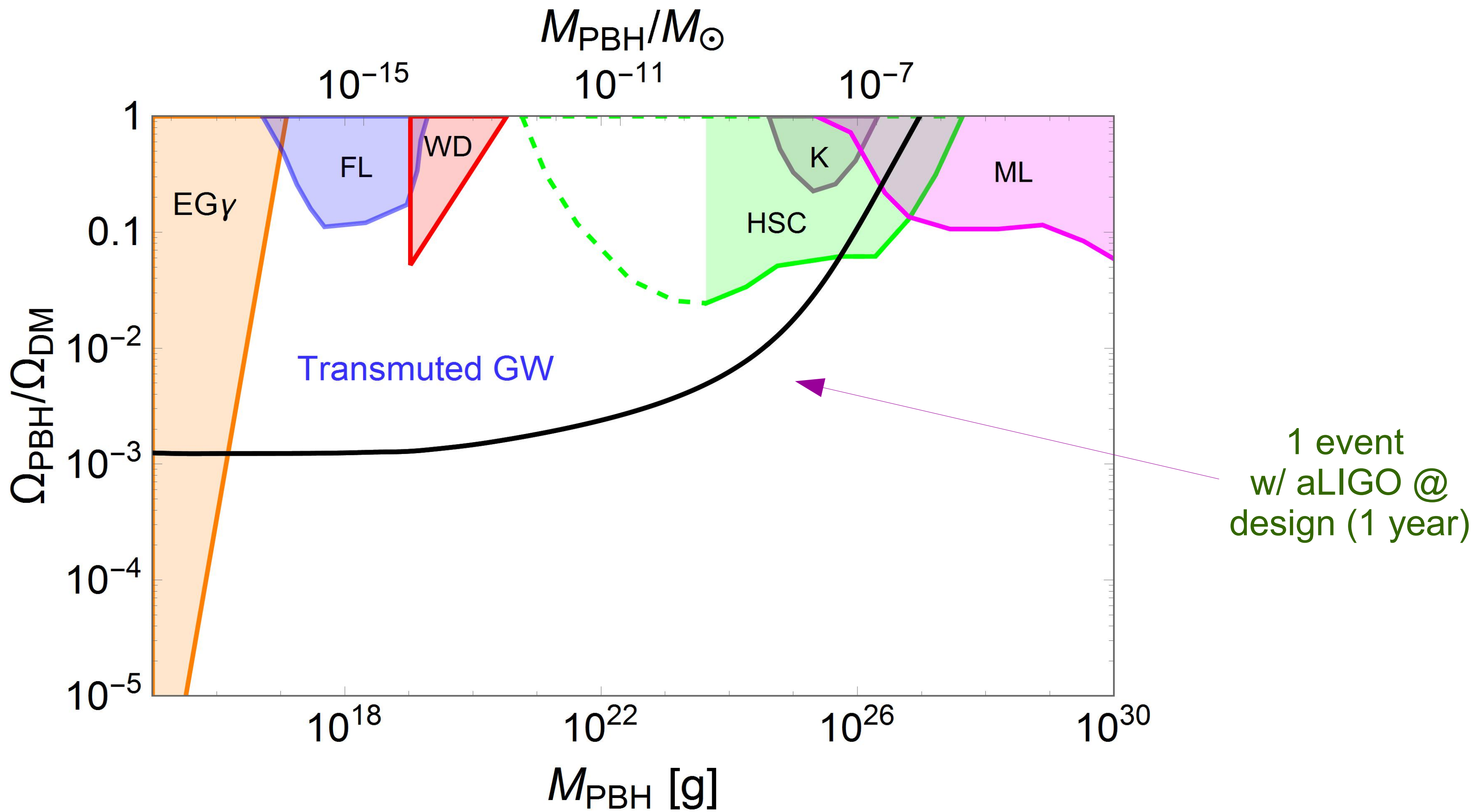
  $\longrightarrow$ coincidence signals (double kilonova)

GW Detection

- Transmuted NS signals $\rightarrow$ detectable by LIGO
- Transmuted WD signals $\rightarrow$ detectable by LISA

GW Detection

- Transmuted NS signals → detectable by LIGO
- Transmuted WD signals → detectable by LISA



Constraints

- Evade constraints from solar mass PBHs

solar BH mass important PBH probe !

Summary

- PBHs appear in many BSM scenarios, suggestive at least some of DM
- Recently uncovered a lot of related overlooked physics

Compact Stars as PBH Laboratories

Can Aid with Major Astronomy Puzzles !

- nucleosynthesis abundance
- GC 511 keV line
- fast radio bursts
- missing GC pulsars
- GRBs
- positron excess

Summary

- PBHs appear in many BSM scenarios, suggestive at least some of DM
- Recently uncovered a lot of related overlooked physics

Compact Stars as PBH Laboratories

New Signals … New Lamp-posts

- Solar-mass BHs, w/o constraints
- New GW signals from binaries
- New kilonova, w/o GWs
- sGRBs w/o GWs
- Double signals (kilonovas, sGRBs...)
- New solar micro-quasars
- Discrete events → differentiate with WIMP capture

Thank You for Attention!