Compact Stars as Primordial Black Hole Laboratories

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Focus Week on Primordial Black Holes, Kavli IPMU

(11.15.2017)

U.S. DEPARTMENT OF ENERGY | Office of Science

PART I:

Forging Heavy Elements from PBHs

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

Prelude

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… actually, GWs from PBH already considered long before observation:

[Carr, 80; Bond,Carr, 84; Nakamura,Sasaki,Tanaka,Thorne, 97; Clesse,Garcia-Bellido, 15]

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- PBH appear in many BSM scenarios and strictly, don't require non-SM physics

  → **plausible that regardless of DM origin, some in PBH !**

Motivation: PBH formation

- PBH formation: density contrast $\frac{\delta\rho}{\rho} \sim \mathcal{O}(1)$ within horizon → collapse to BH

  ... *improbable without new physics*

see reviews
[Carr,Kuhnel,Sandstad,17; Khlopov,10]

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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

General Setup

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... what are the astrophysical consequences?

Compact Star Formation

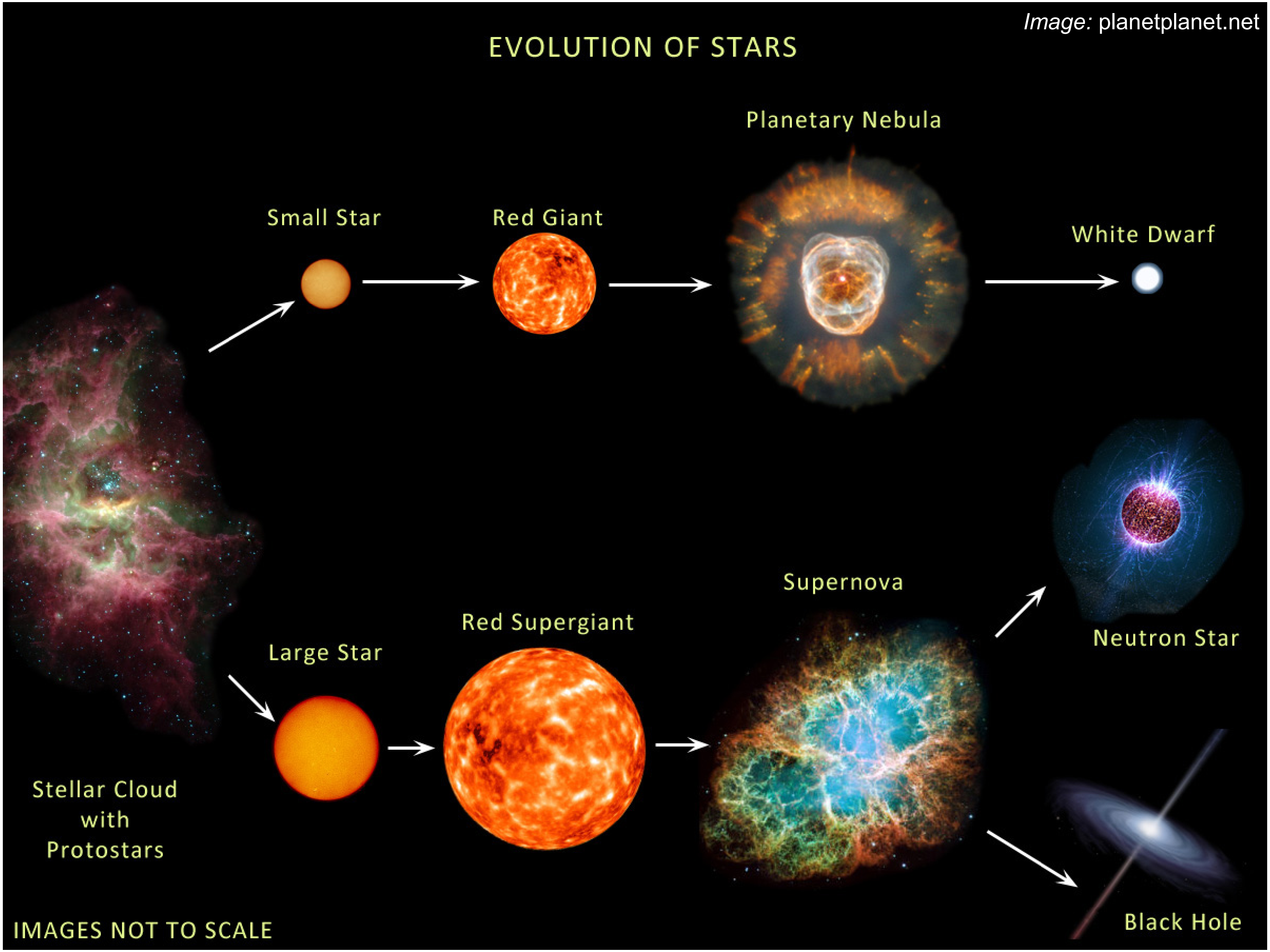

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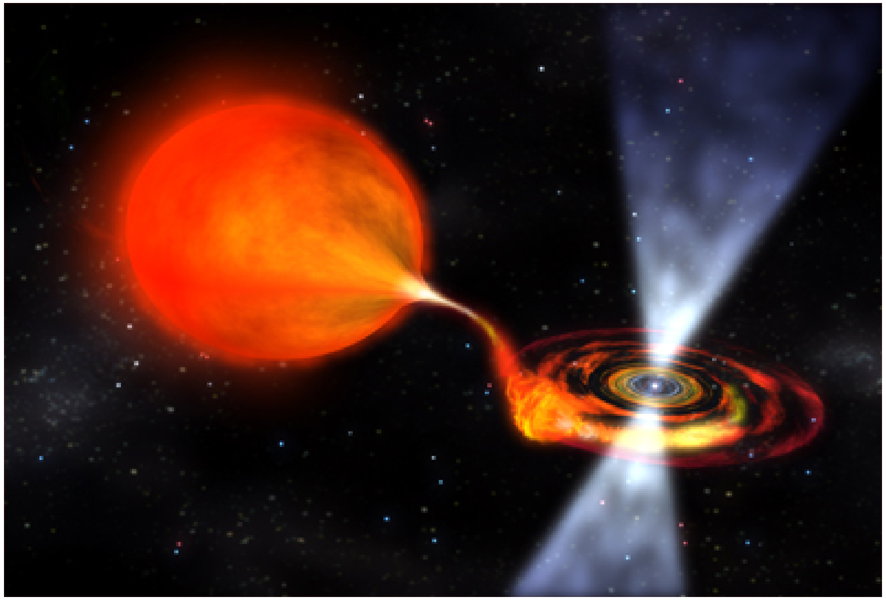
Image: NASA/Dana Berry



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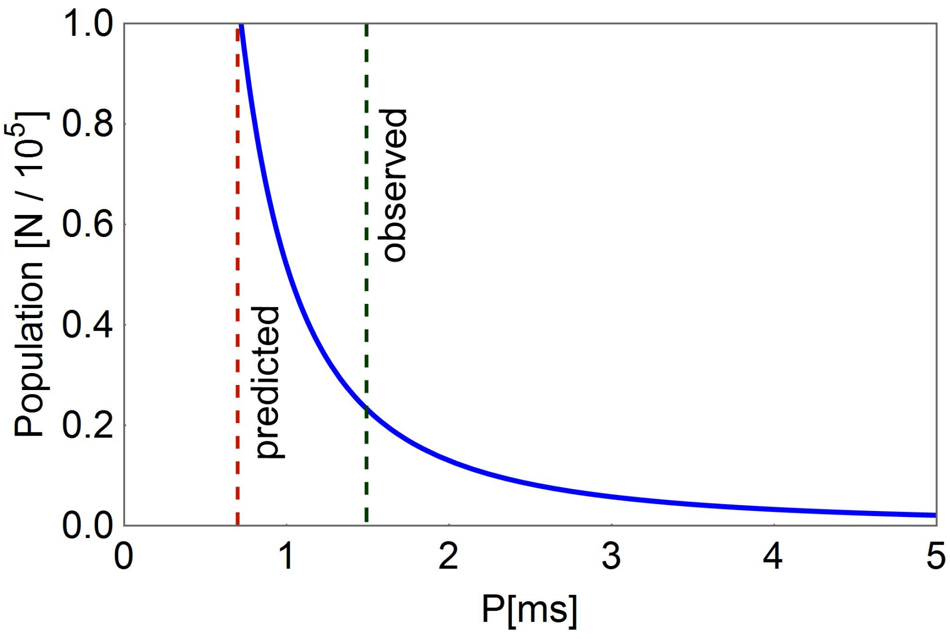
- Population vs. rotation period: [Cordes,Chernoff,97; Lorimer,13]



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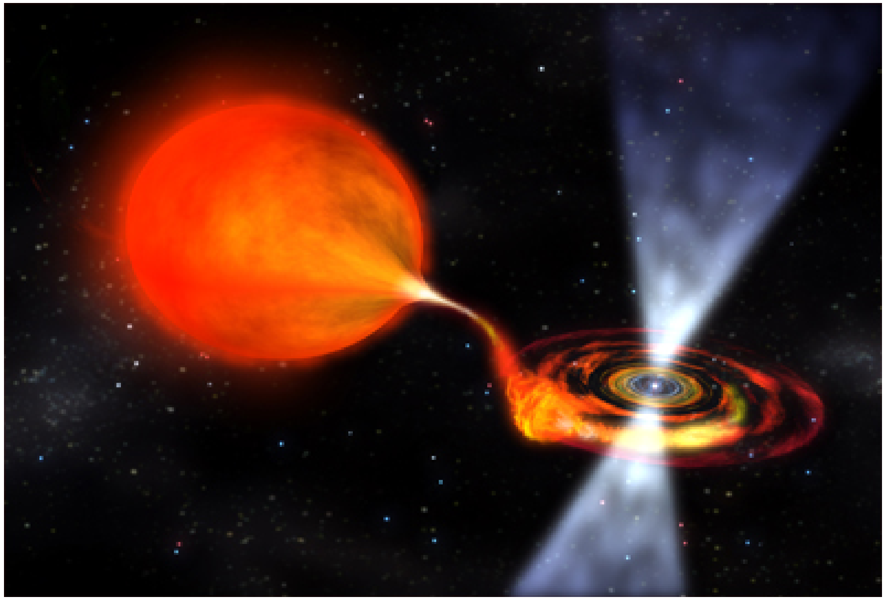

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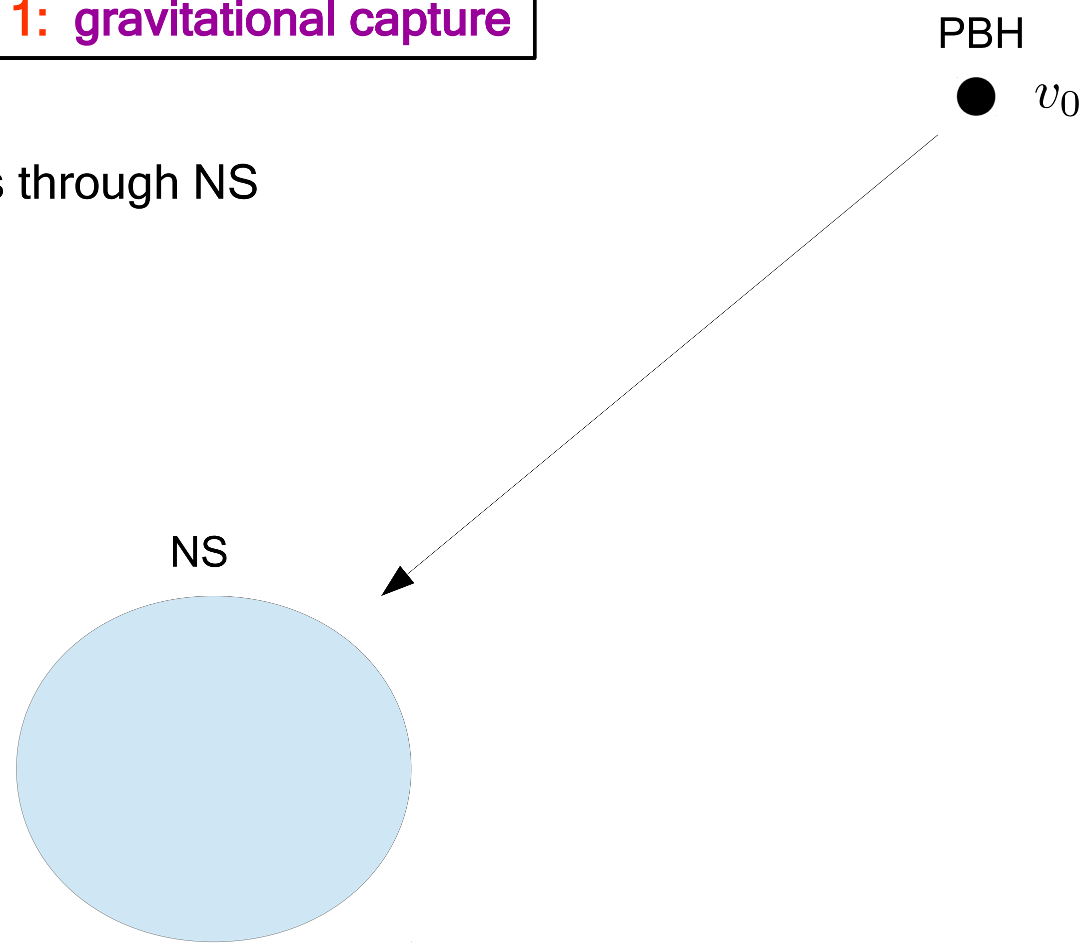

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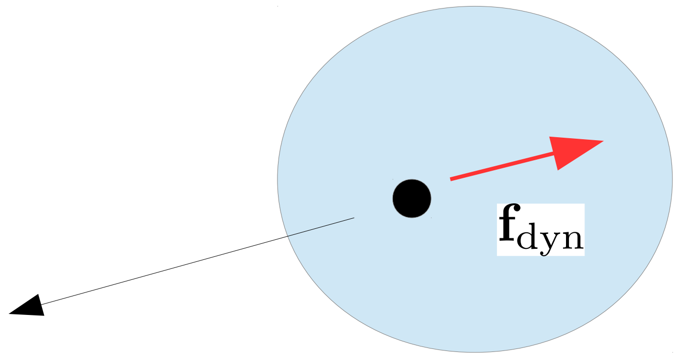

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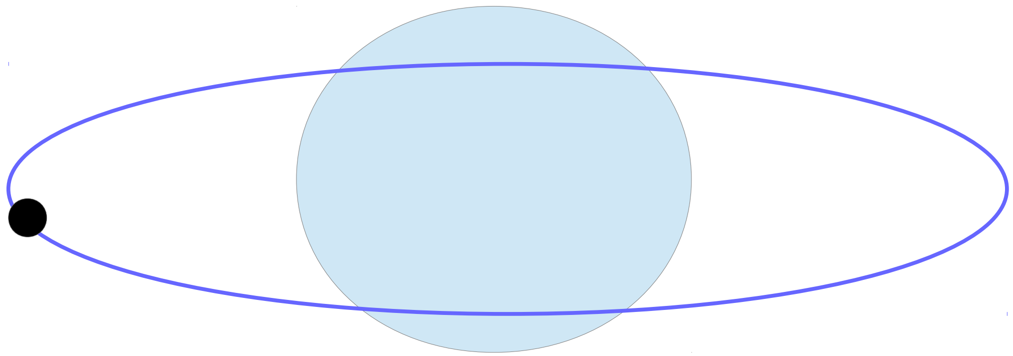
→ loses energy by dynamical friction $\mathrm{f}_{\mathrm{dyn}}$

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



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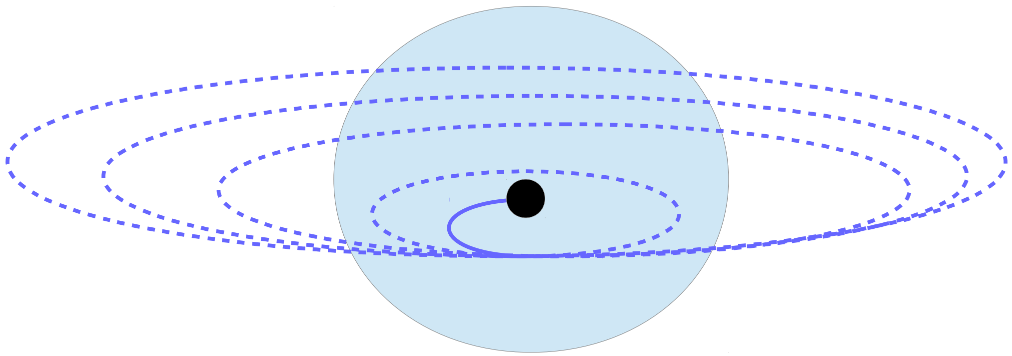
Stage 2: PBH in NS

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



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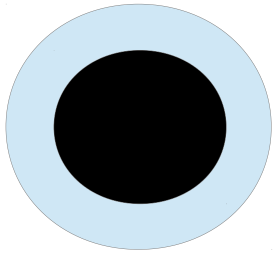
Stage 3: BH grows inside

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



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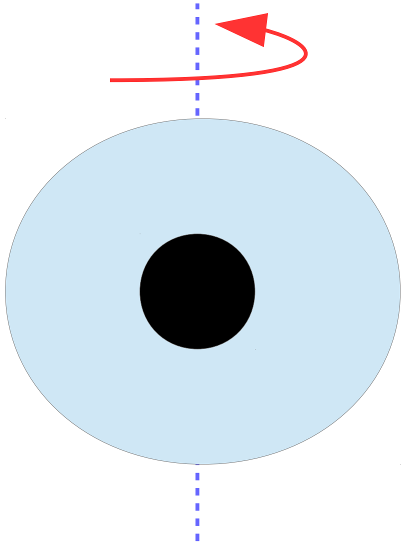
Bonus: consistent with recently discovered young GC magnetar [Mori+,13; Kennea+,13]

$\longrightarrow$ shows unusual activity … a hint of PBH consumption ??

Growing BH in Stars

- Previously, general studies considered BH growing inside a spherical star (Sun, NS)

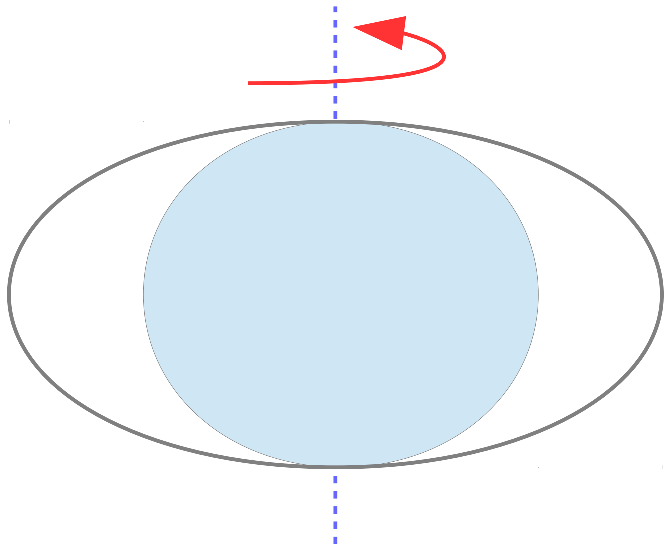
[Markovic,95;
Kouvaris,Tinyakov,13]



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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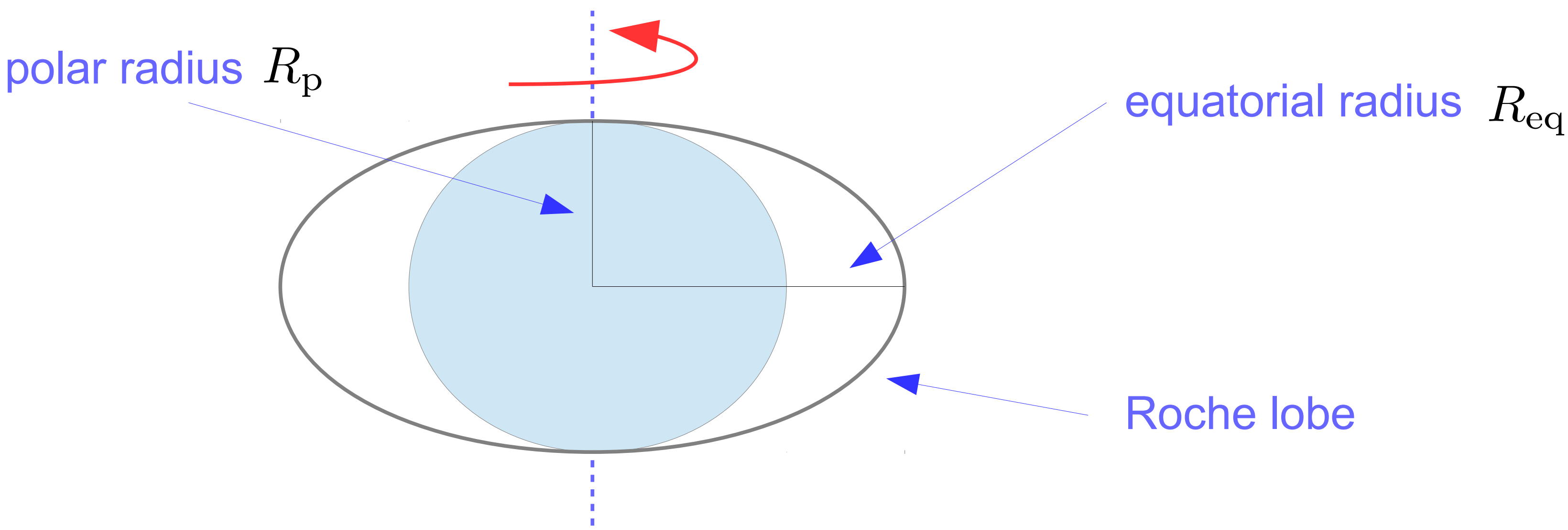

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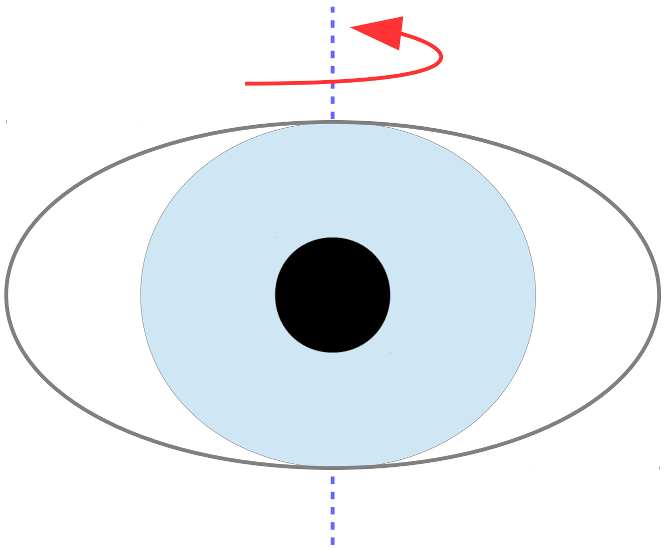

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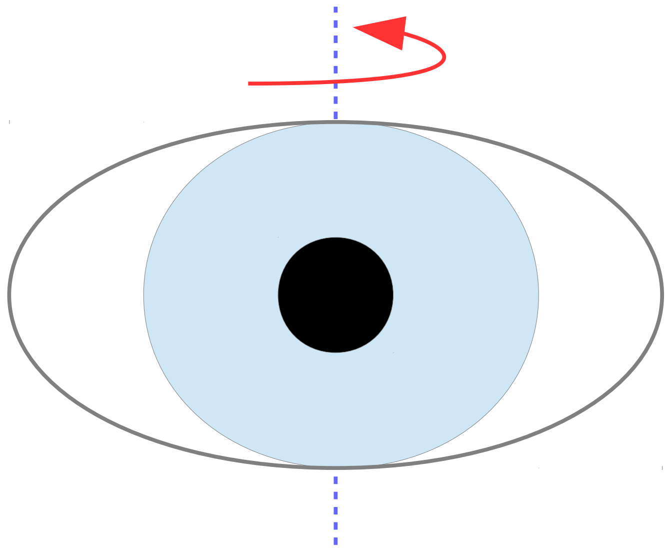

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→ analytically can show that matter exceeds escape velocity → **ejected mass !!**

Growing BH in NS: ejected mass

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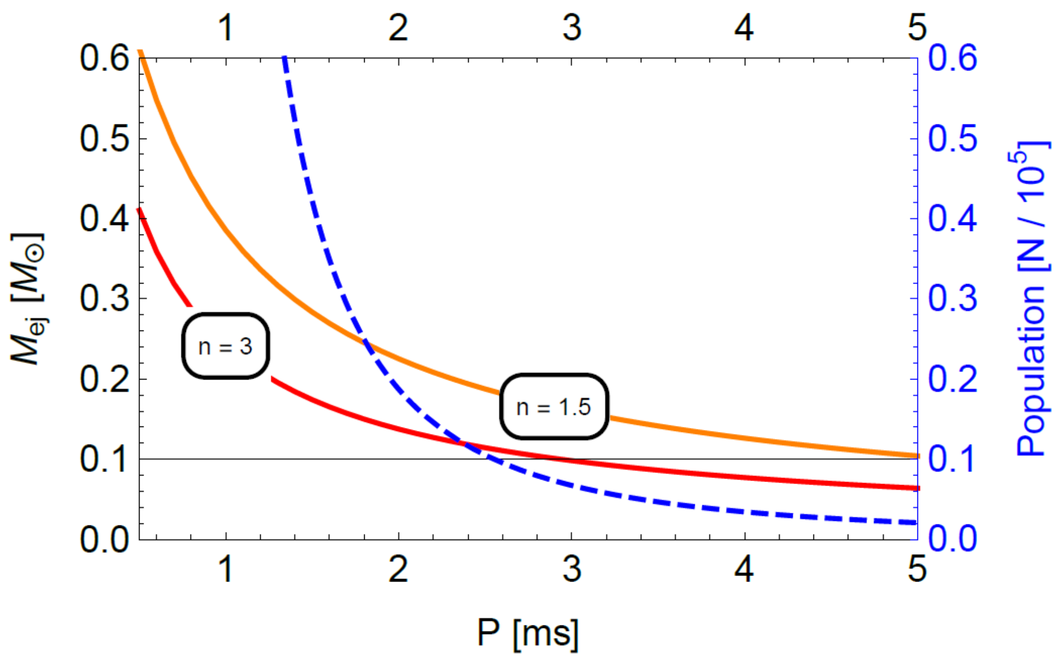
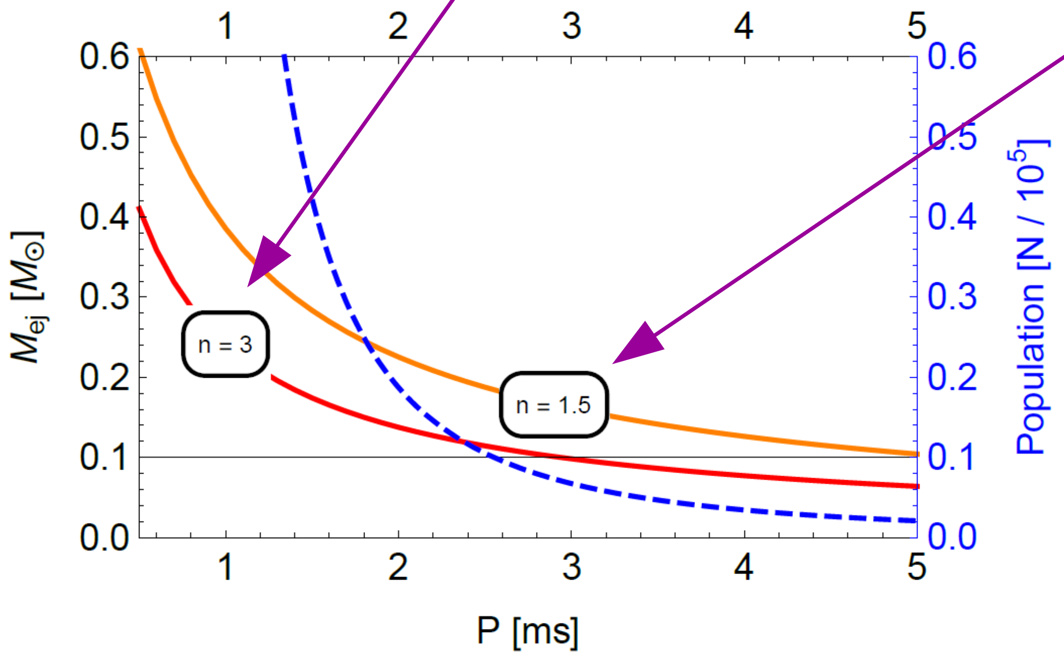


- Ejected mass:

cored NS profile (n = 3 polytrope)

less cored NS profile (n = 1.5 polytrope)



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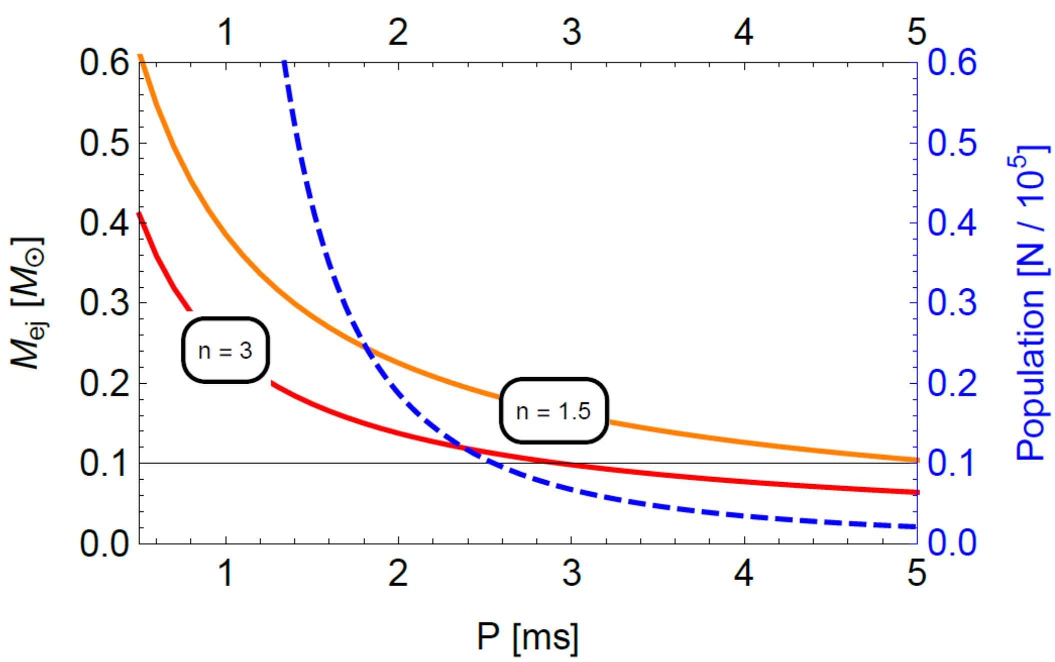

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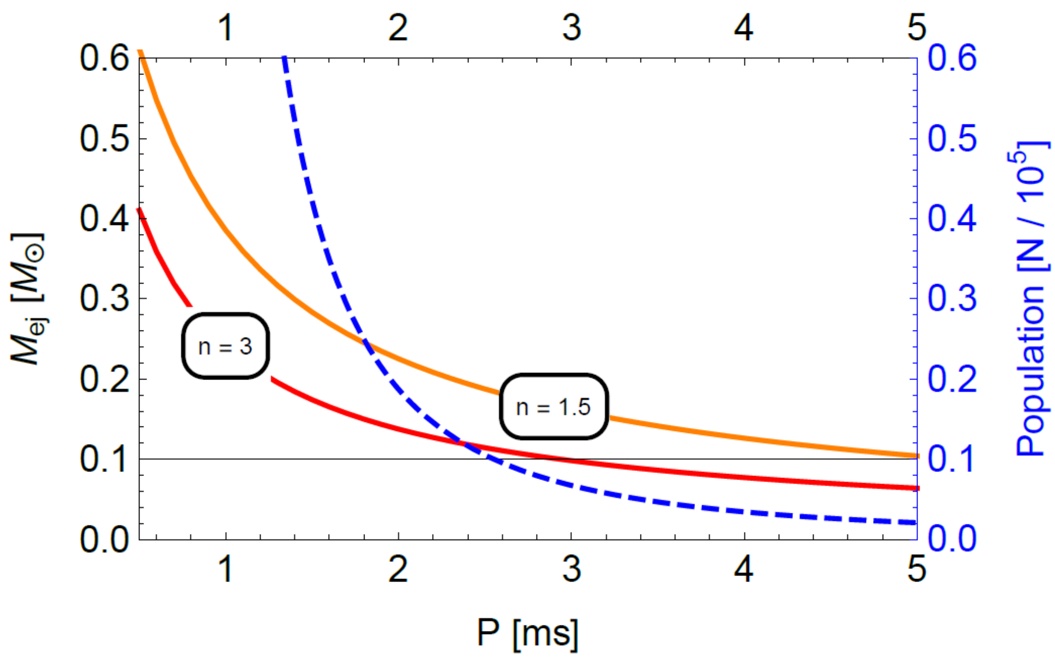

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- Ejecta neutron rich → **a site of r-process nuclesynthesis?**

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  - dominant mechanism for heavy element production

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

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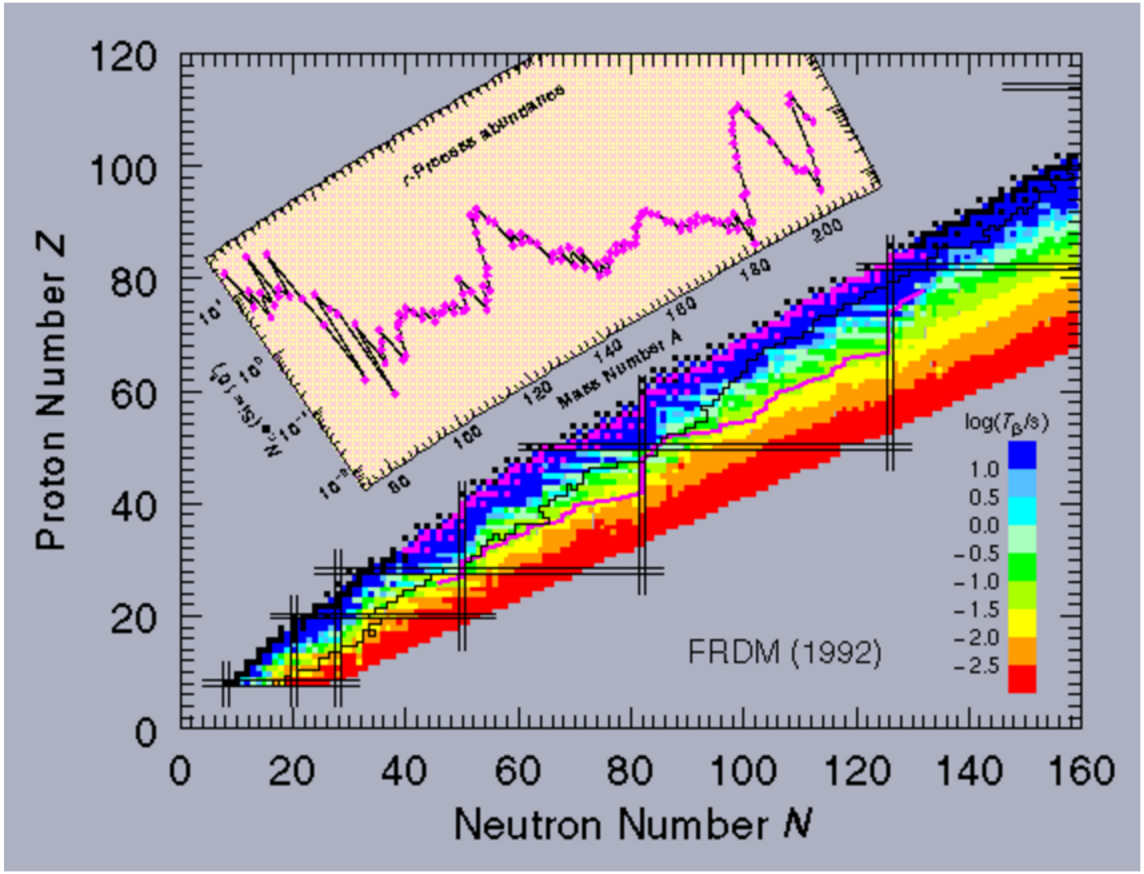

Image: Los Alamos, Nuclear Data Group

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PBH-NS r-process material O(10) larger than COM, several orders vs. SN !!

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can explain both simultaneously with PBH-NS

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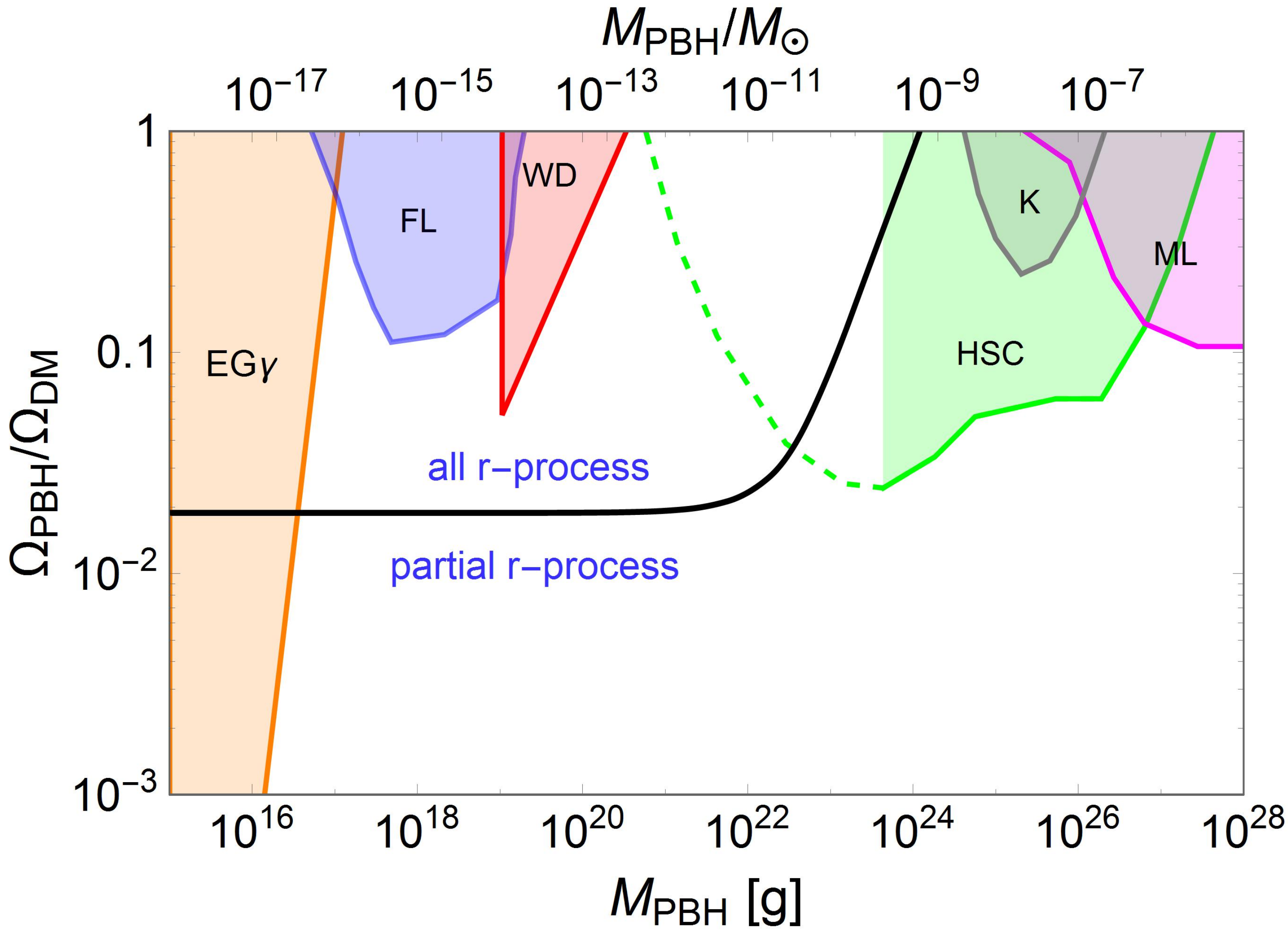

Other Signatures

Kilonova

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Fast Radio Bursts (FRB)

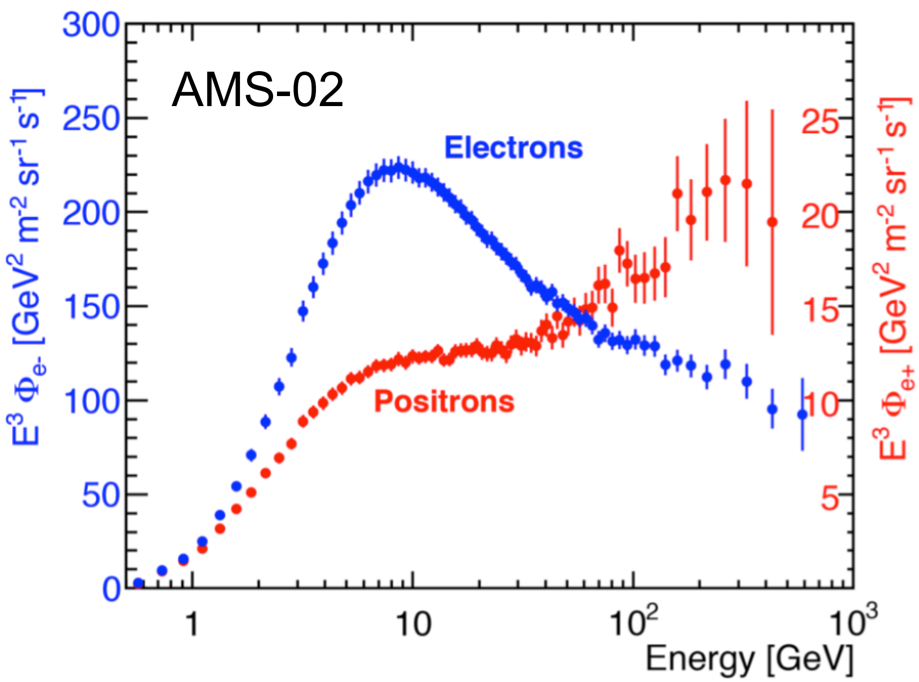
- Large energy release stored in magnetic flux tubes, if only (1-10)% of energy converted to radio waves → non-repeating FRB !

PART II:

Positrons from PBH GRBs (and Microquasars)

Based on: Takhistov [arXiv:1710.09458]

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



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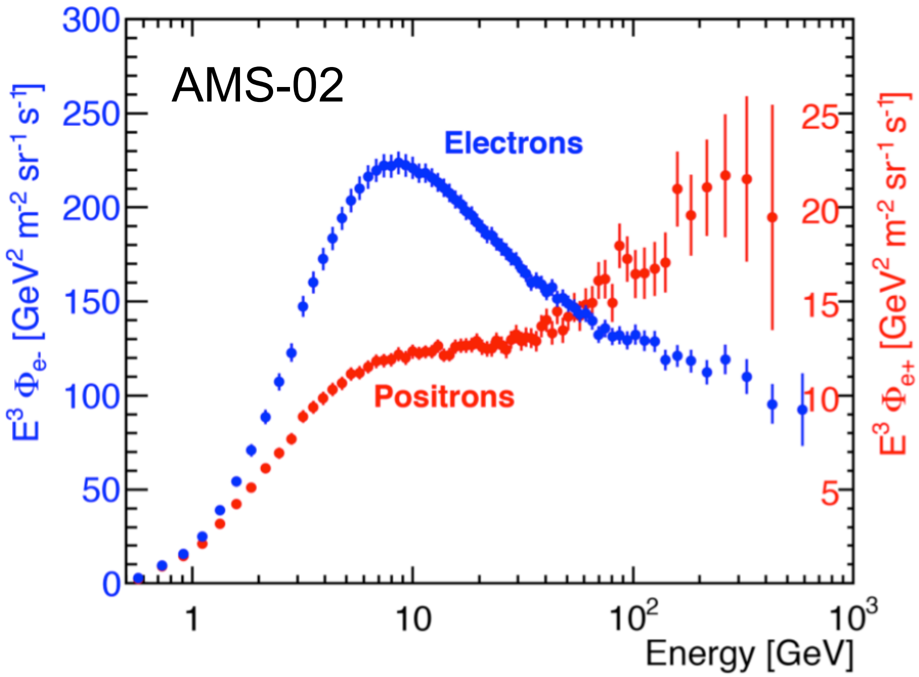

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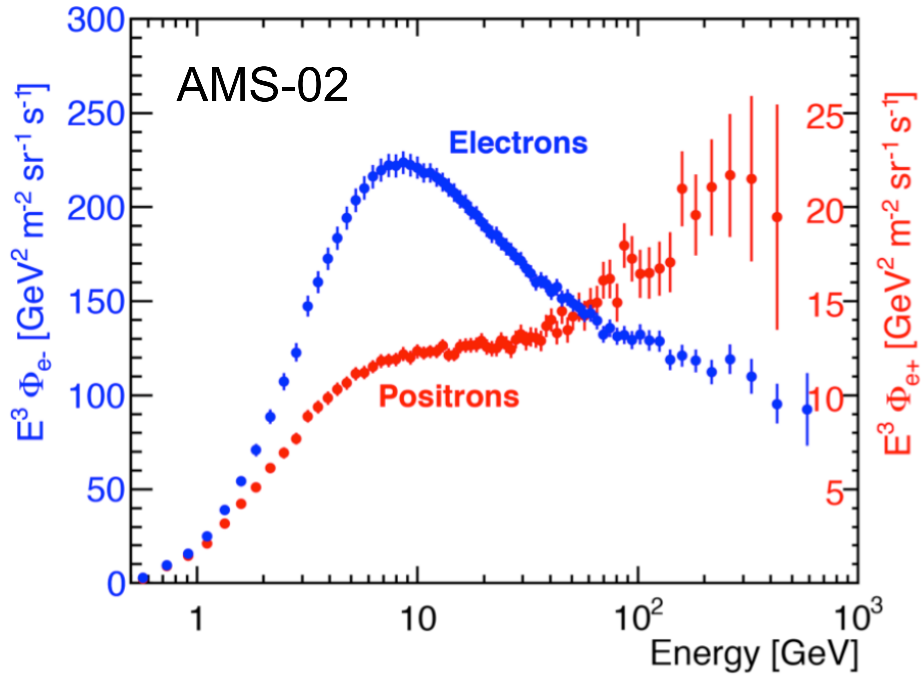

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PBHs can combine proposals of astro-sources with DM !

GRBs from PBHs

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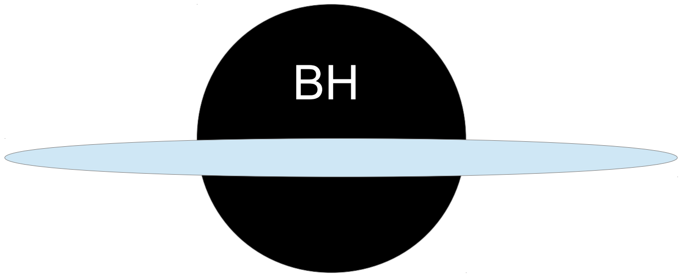

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$$M_d \simeq \mathcal{O}(10^{-1}) M_\odot$$

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

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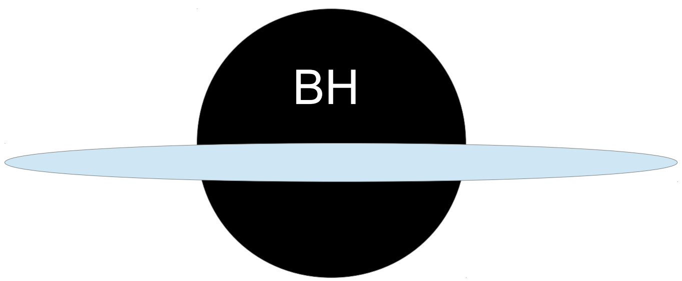

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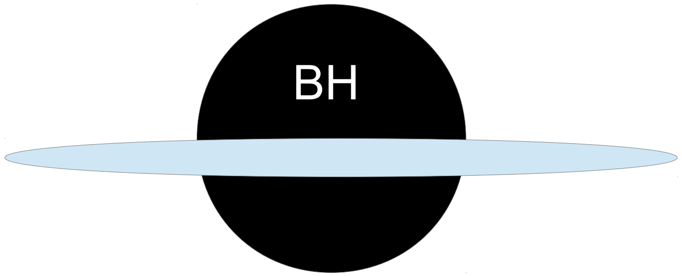

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BH + NS : assume BH captures most of NS angular momentum

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

GRBs from PBHs

PBH-star systems are sources of GRBs!

* without merger GWs

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Jet Launching

- Jet launching mechanisms:

  A) neutrino-antineutrino annihilation → hot disk

  B) MHD winds (Blandford-Payne) → magnetized disk [Blandford, Payne,82]

  C) Blandford-Znajek → magnetized spinning BH [Blandford,Znajek,77]

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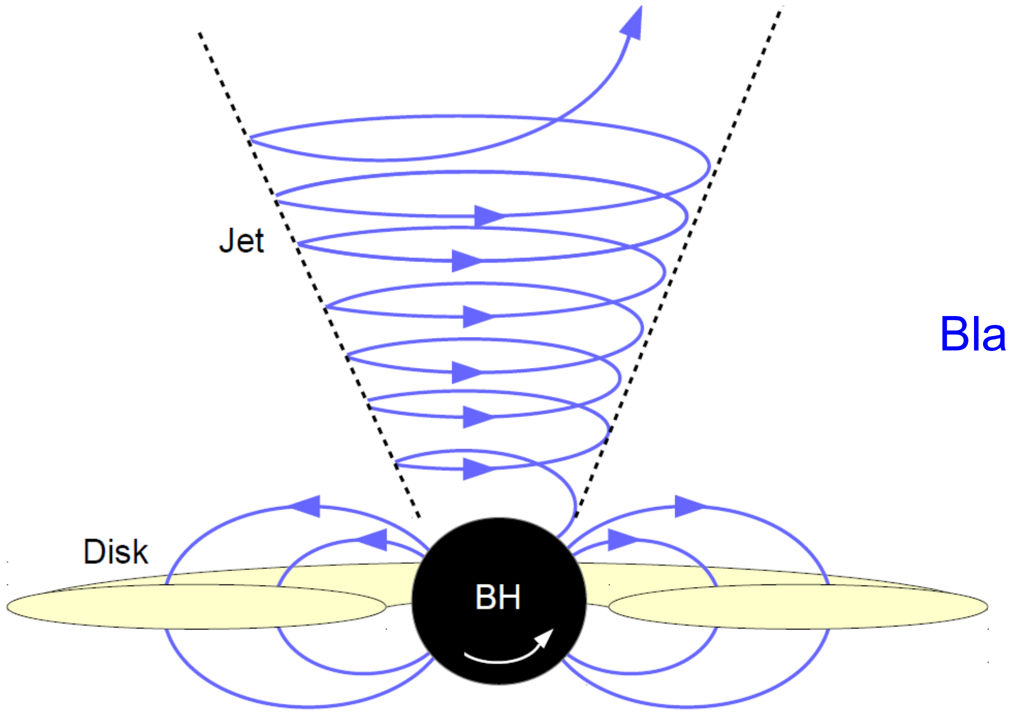

Blandford-Znajek

Jet Launching

- Jet launching mechanisms:

  A) neutrino-antineutrino annihilation → hot disk

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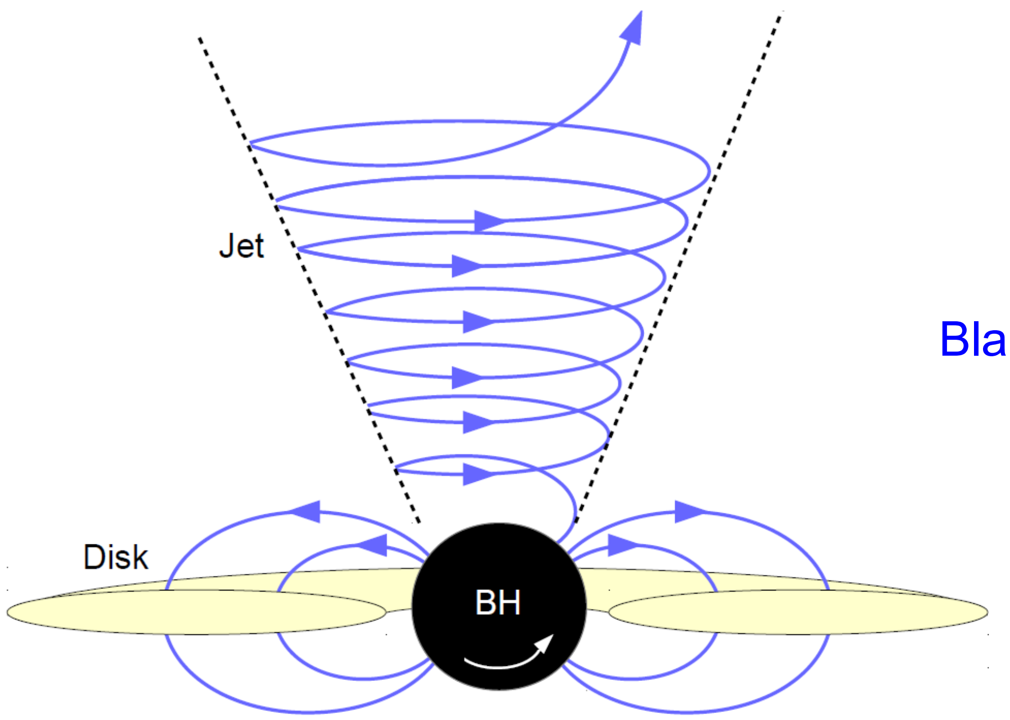
  C) Blandford-Znajek → magnetized spinning BH [Blandford,Znajek,77]

from PBHs:

✗

✓

✓



Blandford-Znajek

Accelerated Positrons

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

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

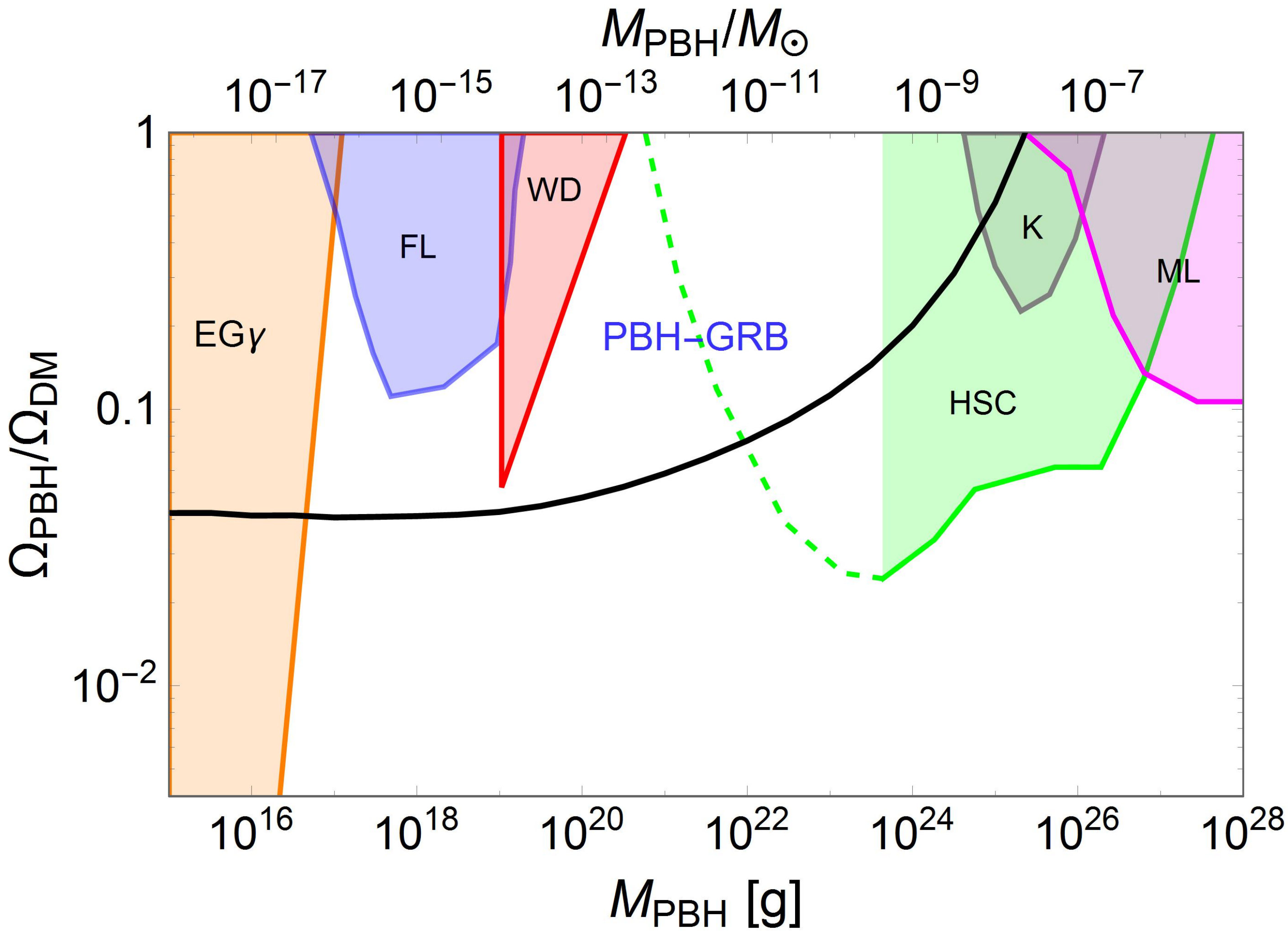
- Positrons diffuse, for 100 GeV diffusion time $t \sim 10^6 \mathrm{yrs}$

[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:

Transmuted GW Signals from PBHs

Based on: Takhistov [arXiv:1707.05849]

Tiny PBHs from the Past

If tiny PBHs consumed stars in the past,

how to see today?

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gravity waves from unusual solar-mass BHs

Solar-mass BHs: in astrophysics

- Smallest astrophysical black holes

observed: $\sim 5 - 10 M_{\odot}$ [Shaposhnikov,Titarchuk,09]

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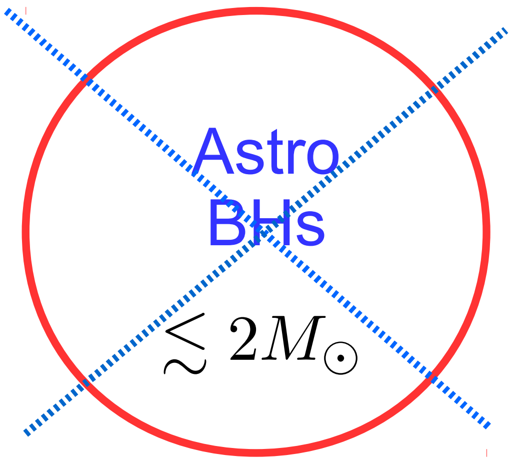

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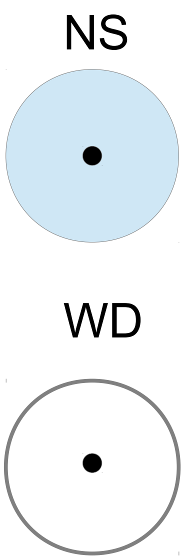
- PBH-star systems: solar mass BH factories



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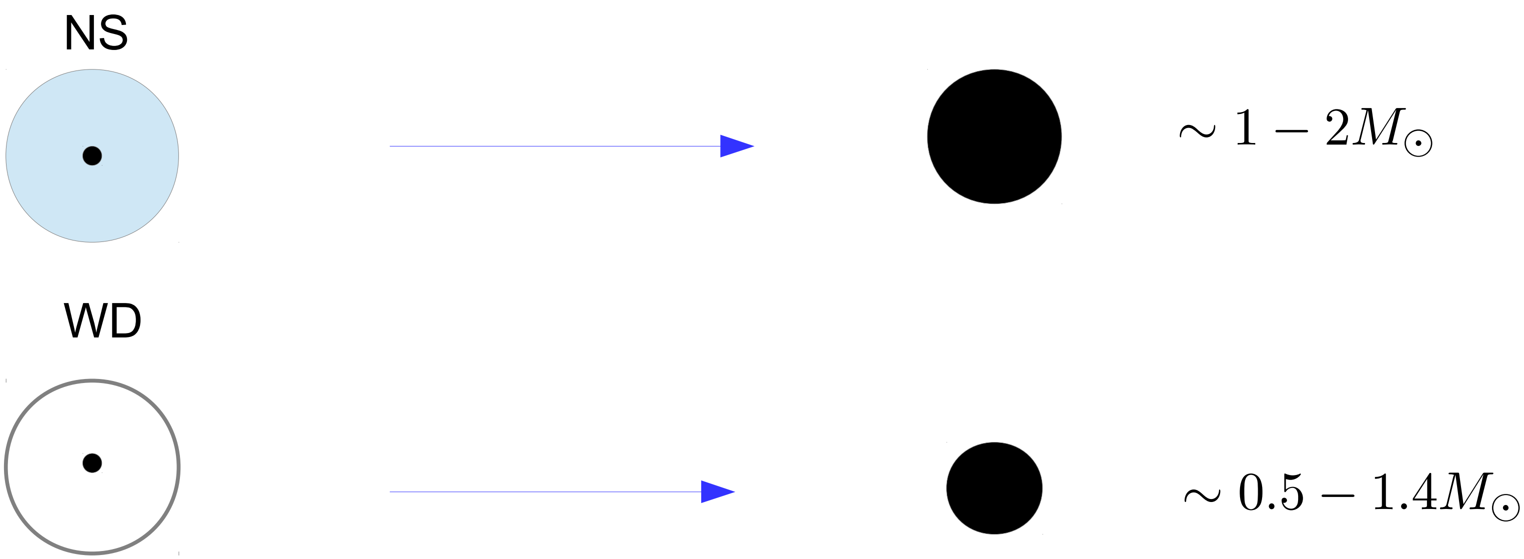

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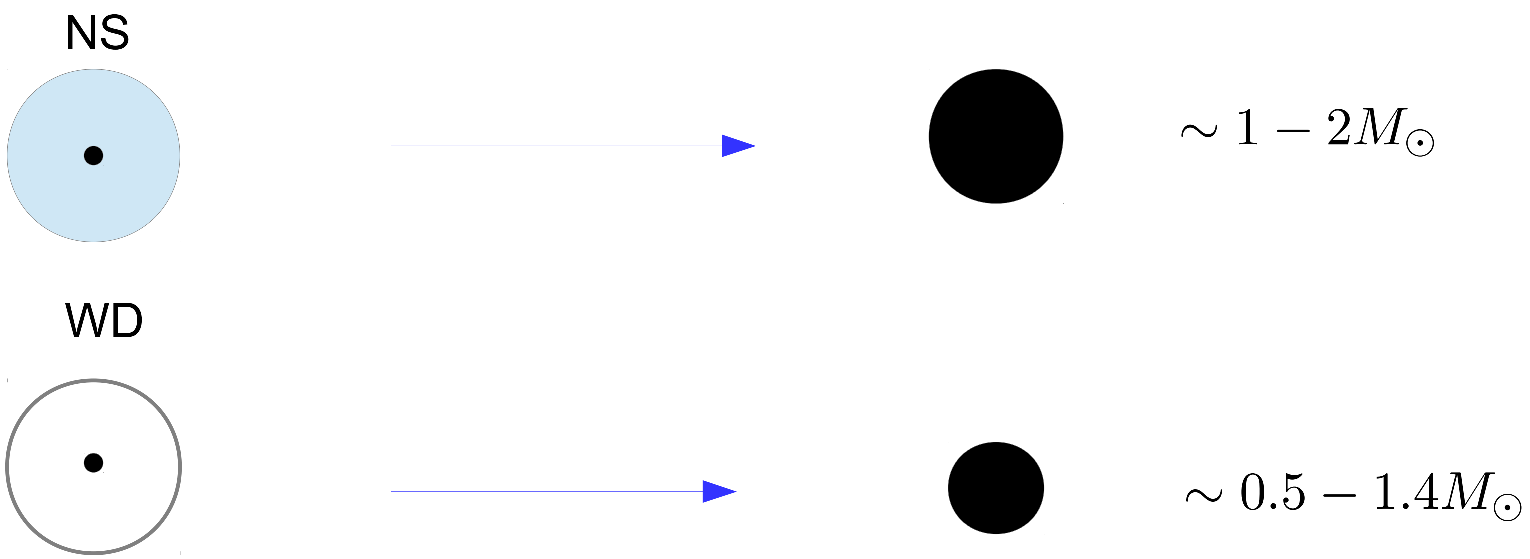
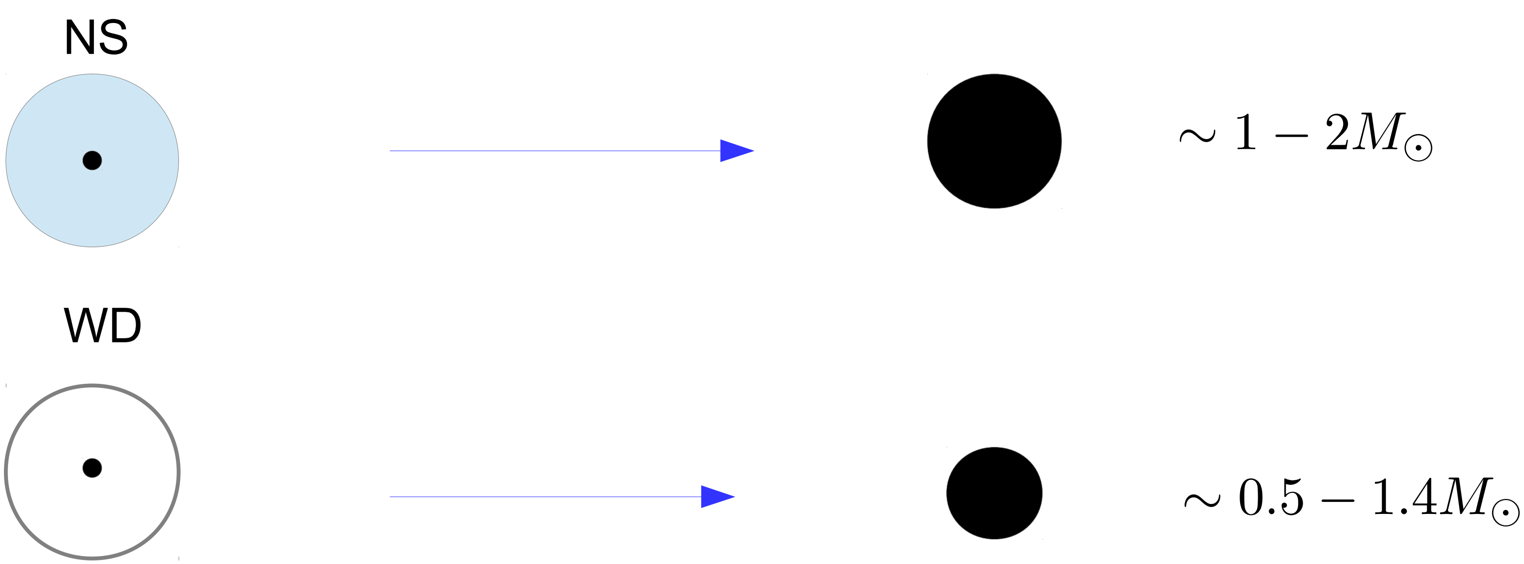


- Important: amount of ejected mass

Solar-mass BHs: from tiny PBHs

- PBH-star systems: solar mass BH factories

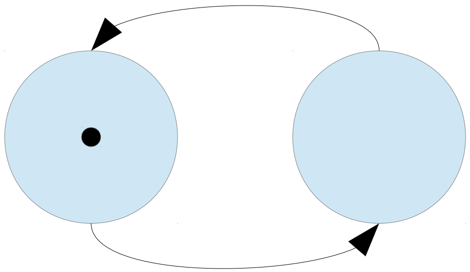


- Important: amount of ejected mass

How to detect? → new merger GW signals

Transmuted Binaries

NS-NS



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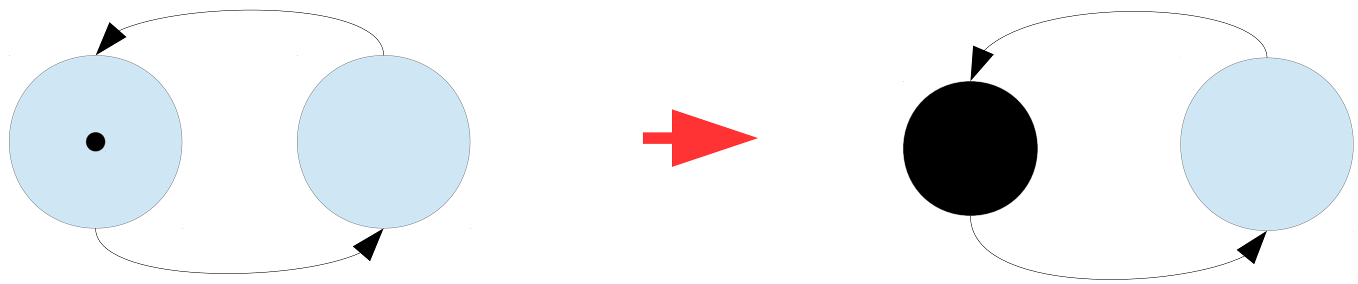

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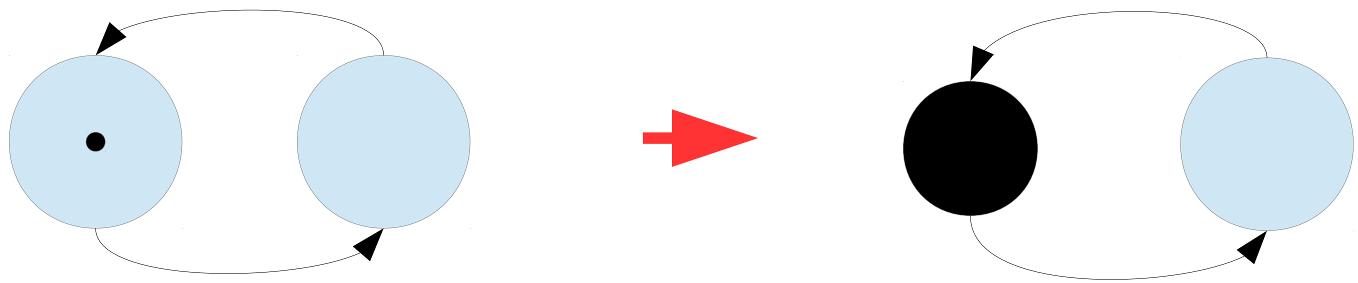
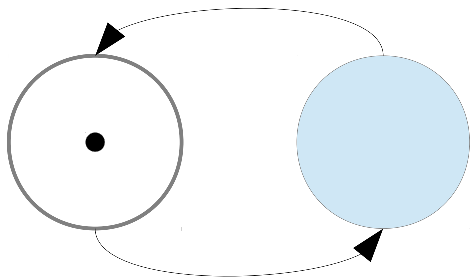
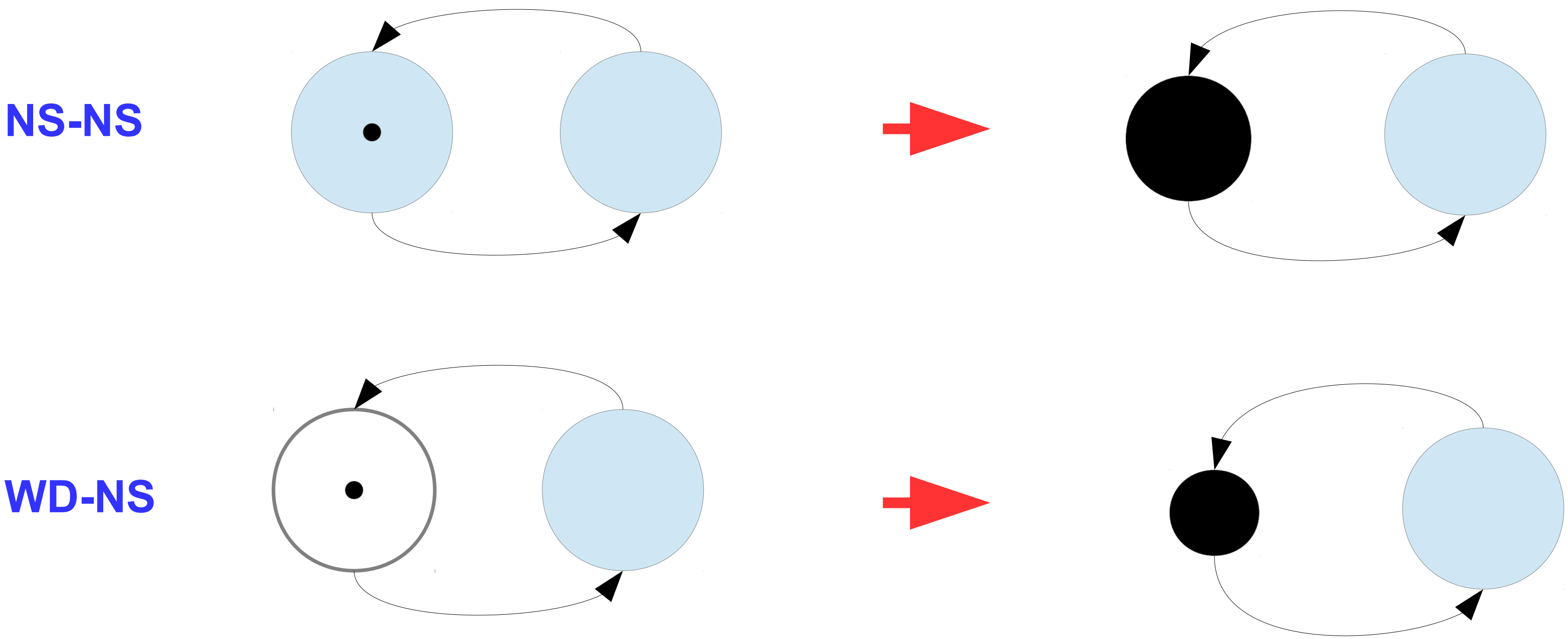


WD-NS



Transmuted Binaries

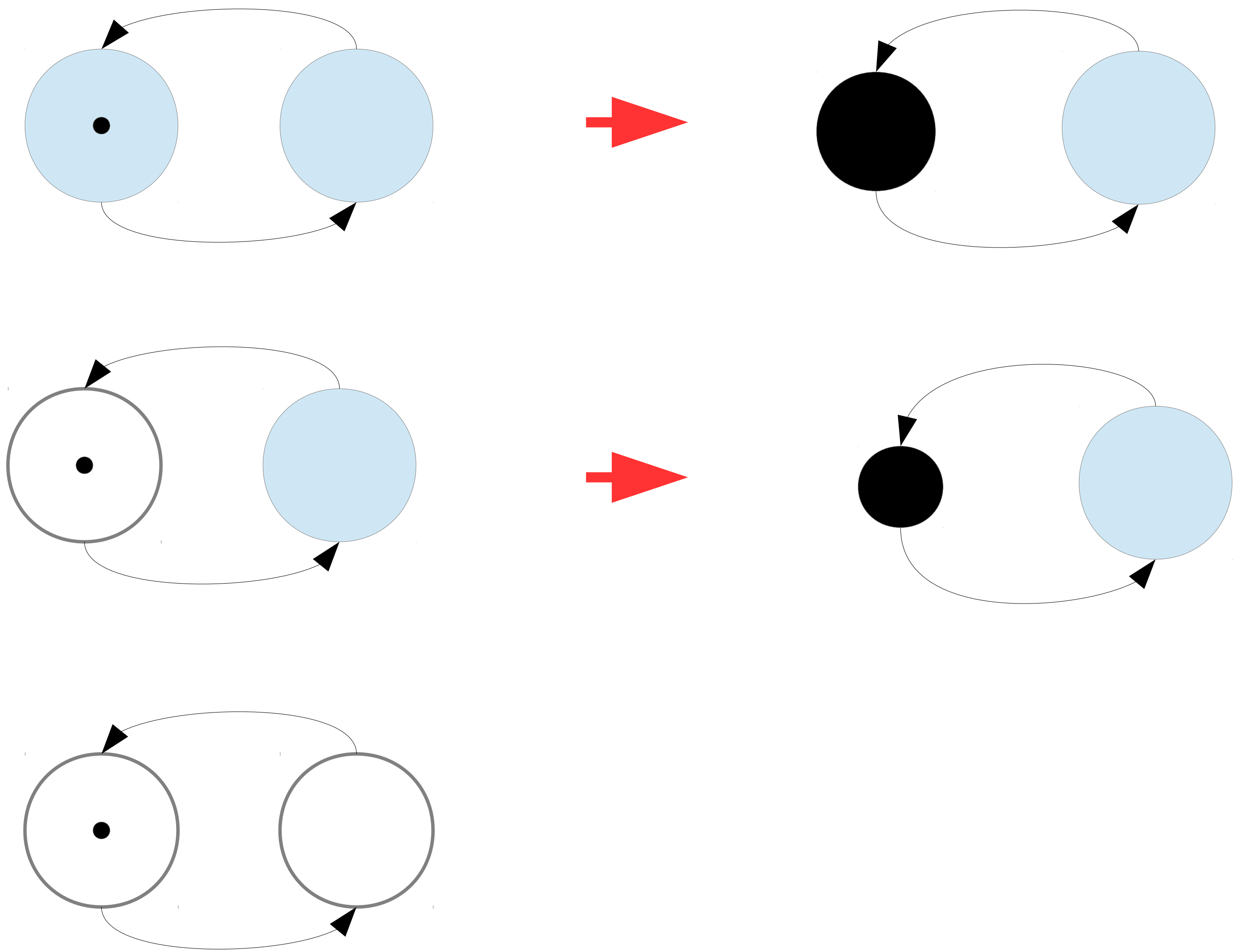


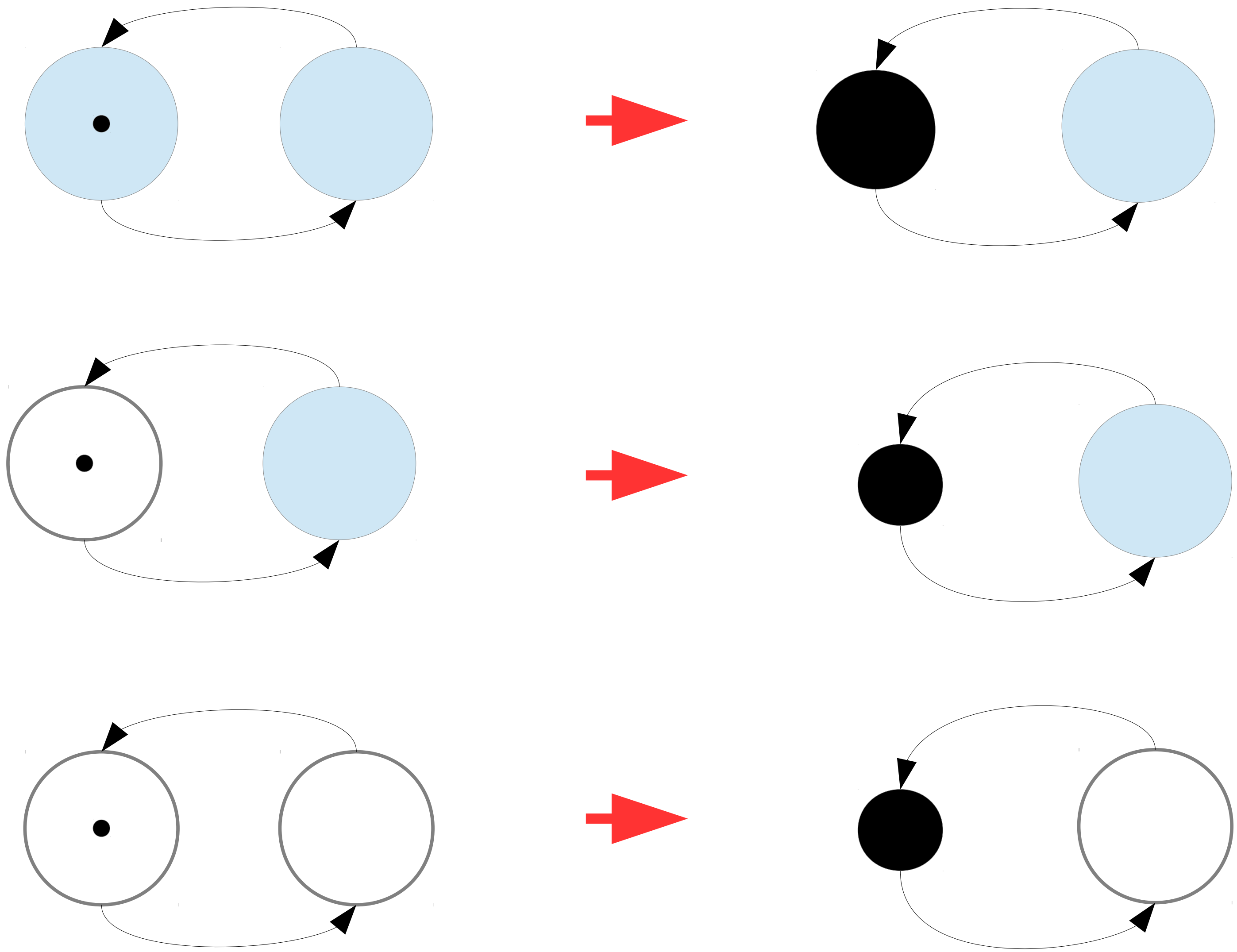
Transmuted Binaries

NS-NS

WD-NS

interacting WD-WD
(*cataclysmic variable*)





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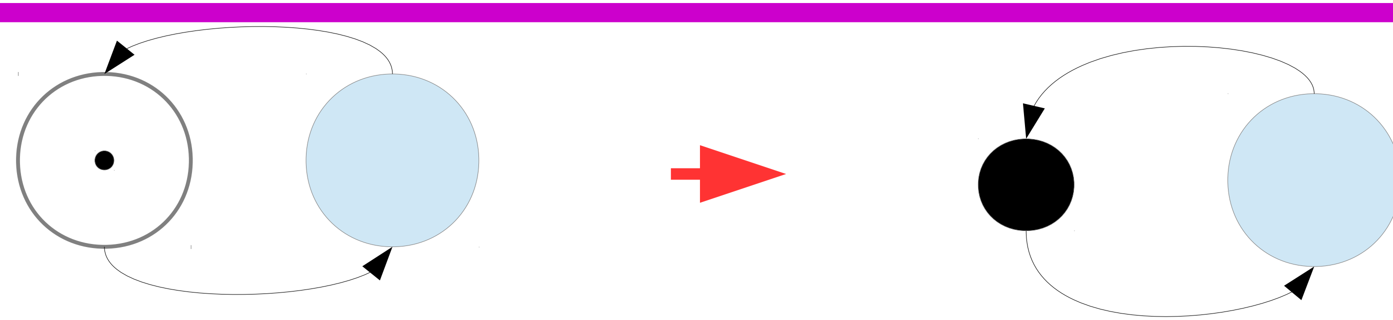

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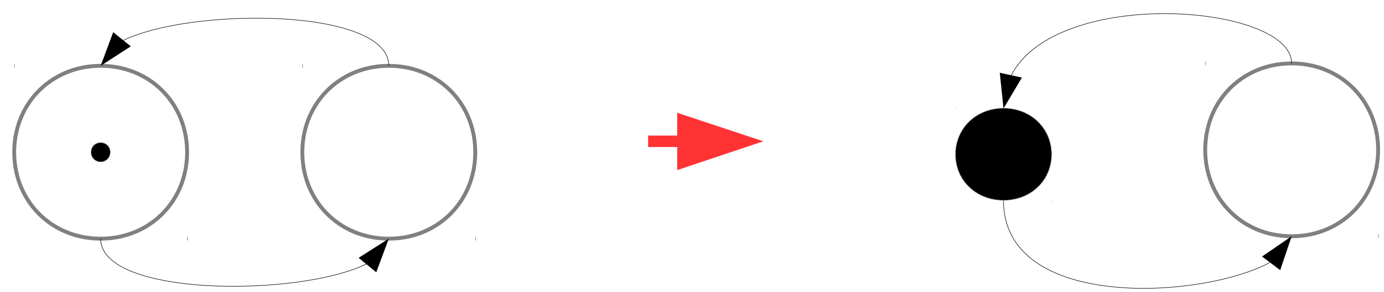


Compact Object Mergers

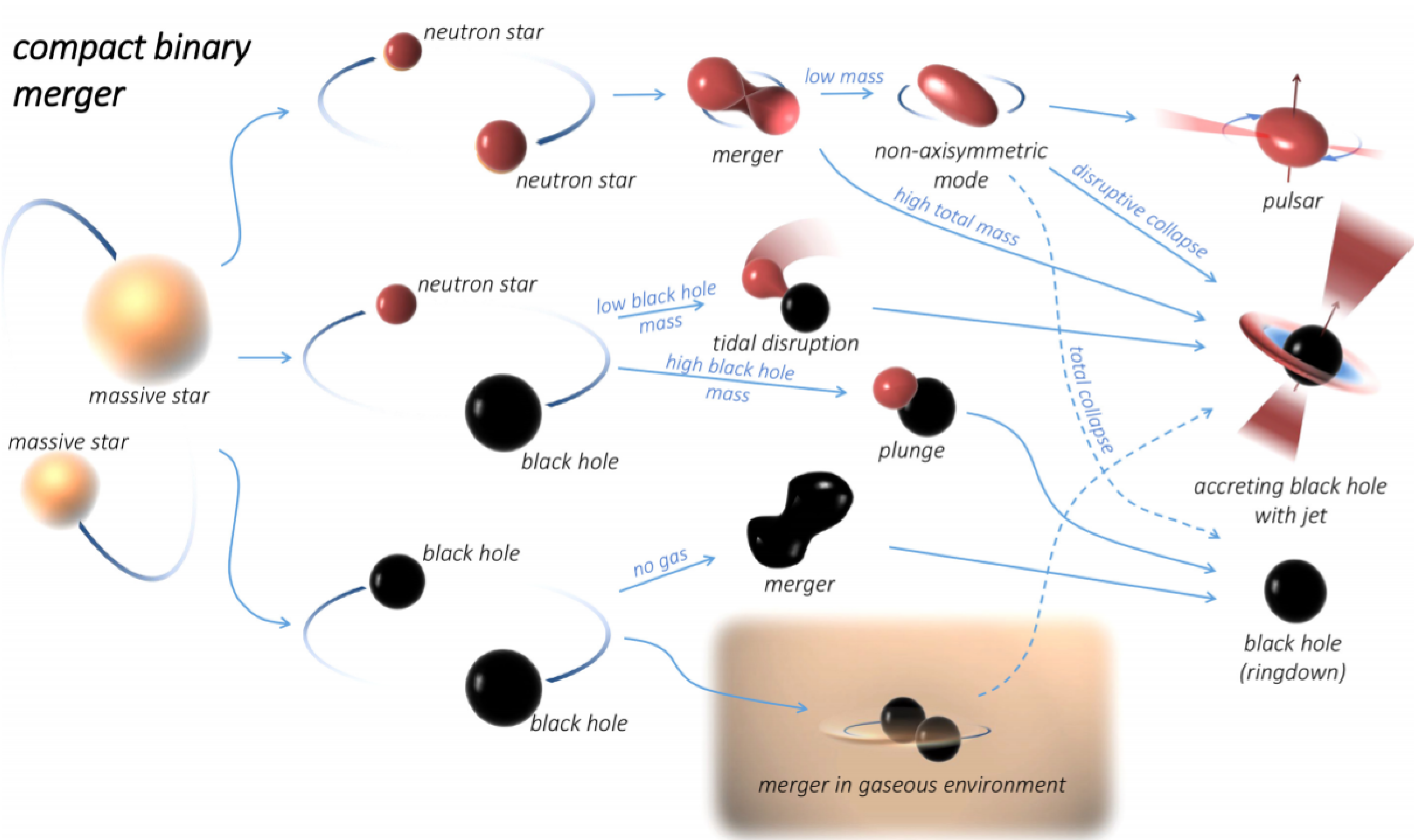


Image: Bartos,Kowalski,*"Multimessenger Astronomy"*

Binary GW Signals

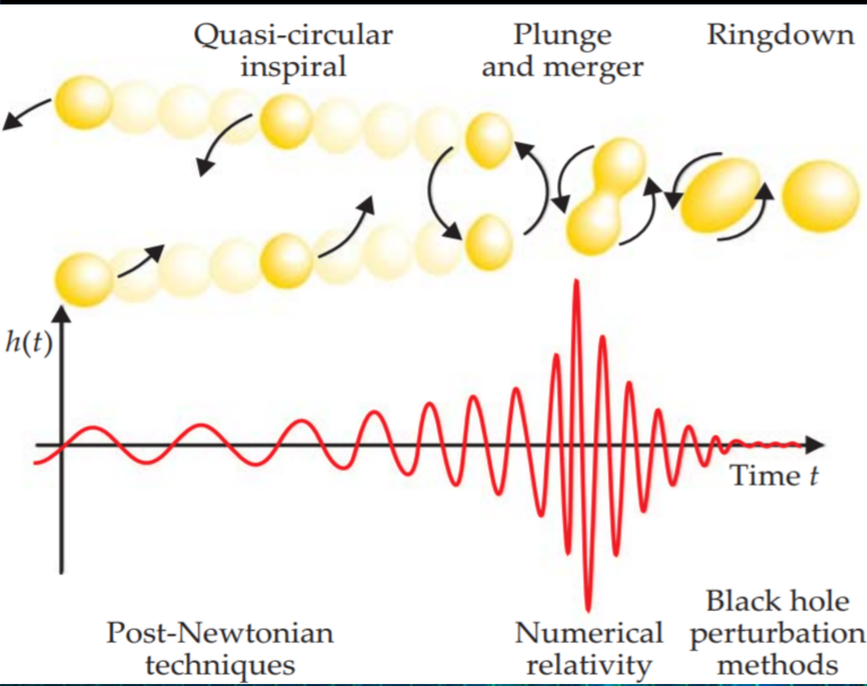
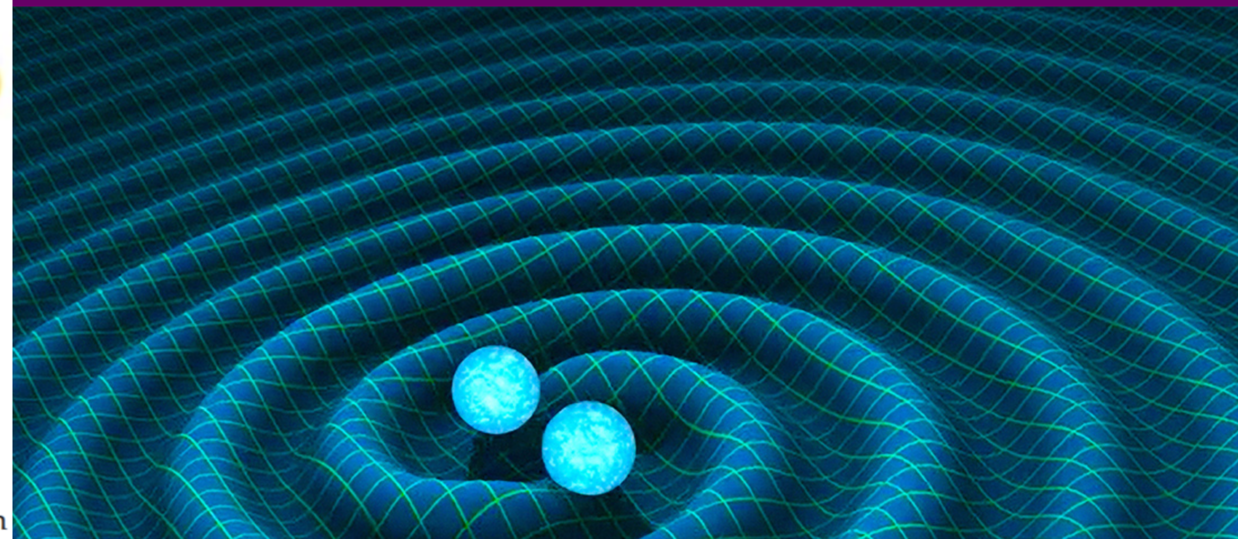
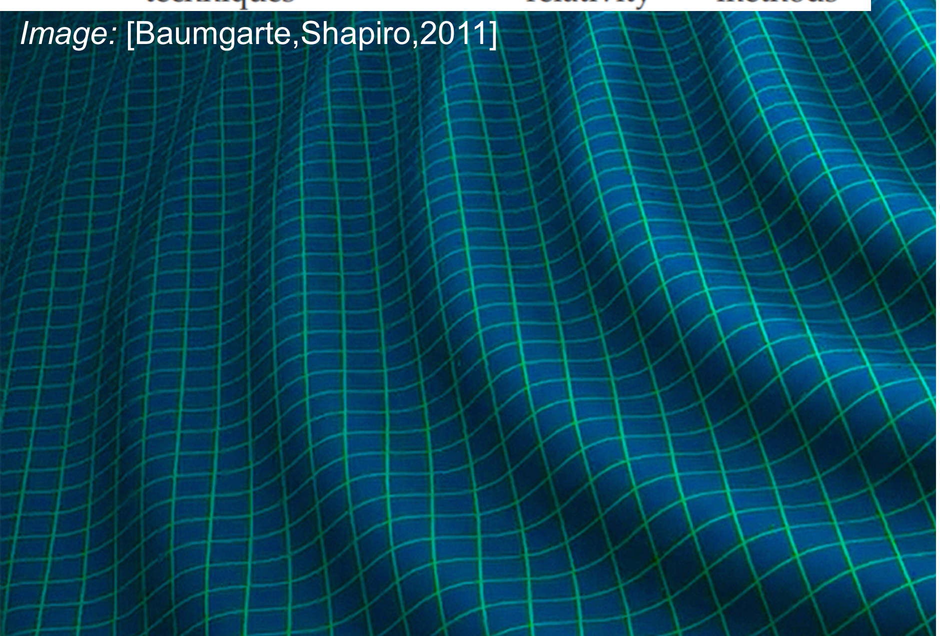
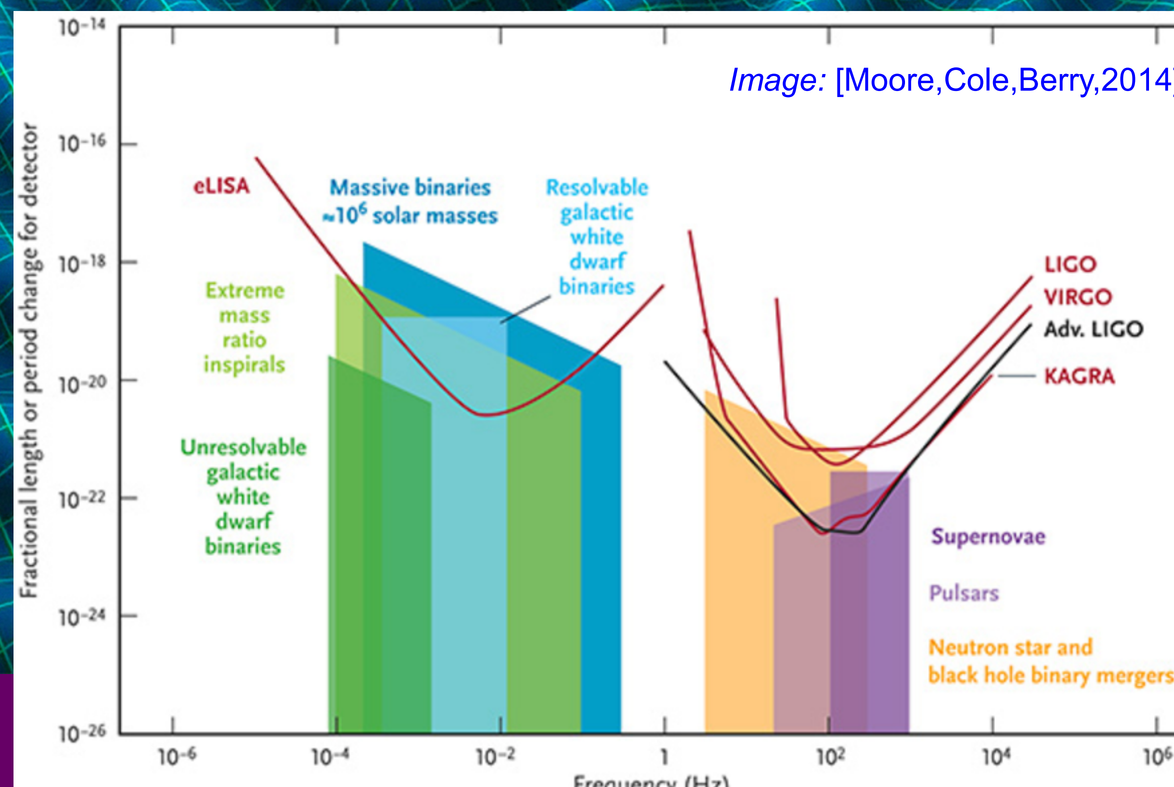


Image: [Baumgarte,Shapiro,2011]

Image: Kurt, Caltech-JPL







Transmuted GW Signals

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

  $\rightarrow$ depend on chirp mass $\mathcal{M}_c(M_1, M_2) \rightarrow$ same if no mass change

  $\rightarrow$ if ejected mass significant $\rightarrow$ see difference

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→ mostly happens at higher frequencies, distinguishing with aLIGO can be a challenge

GW Detection

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

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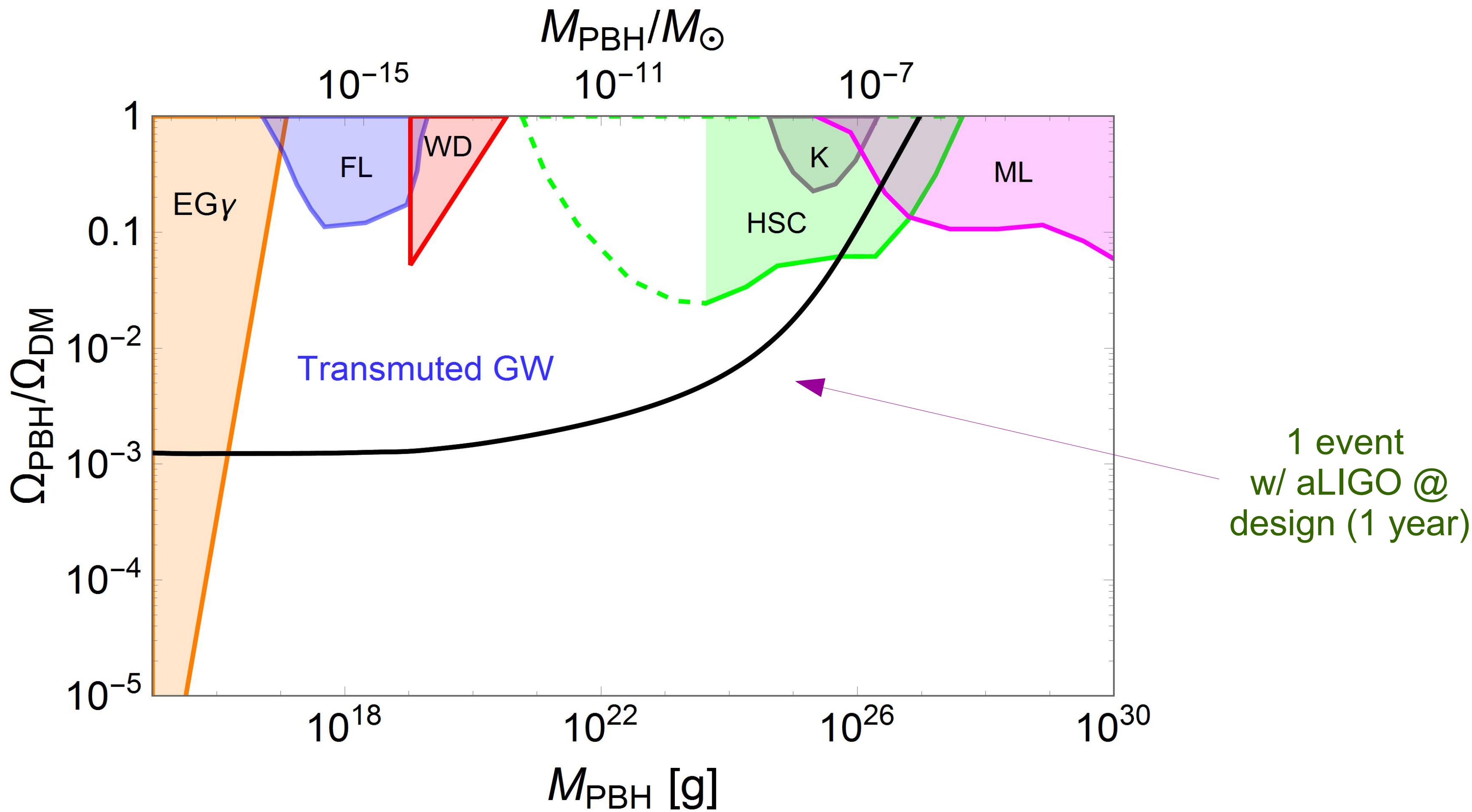

Detection

- Coincidence signals possible (e.g. double kilonova)

- Evade constraints from solar mass PBHs

solar BH mass important PBH probe !

Summary

- PBHs appear in many BSM scenarios, plausible at least some contribution to DM
- Recent interest in PBHs uncovered a lot of previously overlooked physics

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Compact Stars as PBH Laboratories

Possibility to Address Major Astronomy Puzzles !

- r-process nucleosynthesis abundance (MW, dSph)
- GC 511 keV line
- origin of fast radio bursts
- [partial] missing GC pulsars
- origin of sGRBs, accretion disk formation
- positron excess

Summary

- PBHs appear in many BSM scenarios, plausible at least some contribution to DM
- Recent interest in PBHs uncovered a lot of previously overlooked physics

Compact Stars as PBH Laboratories

New Predictions … New Lamp-posts

- Solar-mass BHs, without solar-PBH constraints
- New GW signals from NS, WD binaries
- New kilonova, without merger GWs
- SGRBs without merger GWs
- Binaries: double kilonova, sGRBs ...
- New solar micro-quasars
- Discrete events → differentiate with WIMP capture

Thank You for Attention!