General relativistic simulations of binary black hole-neutron stars

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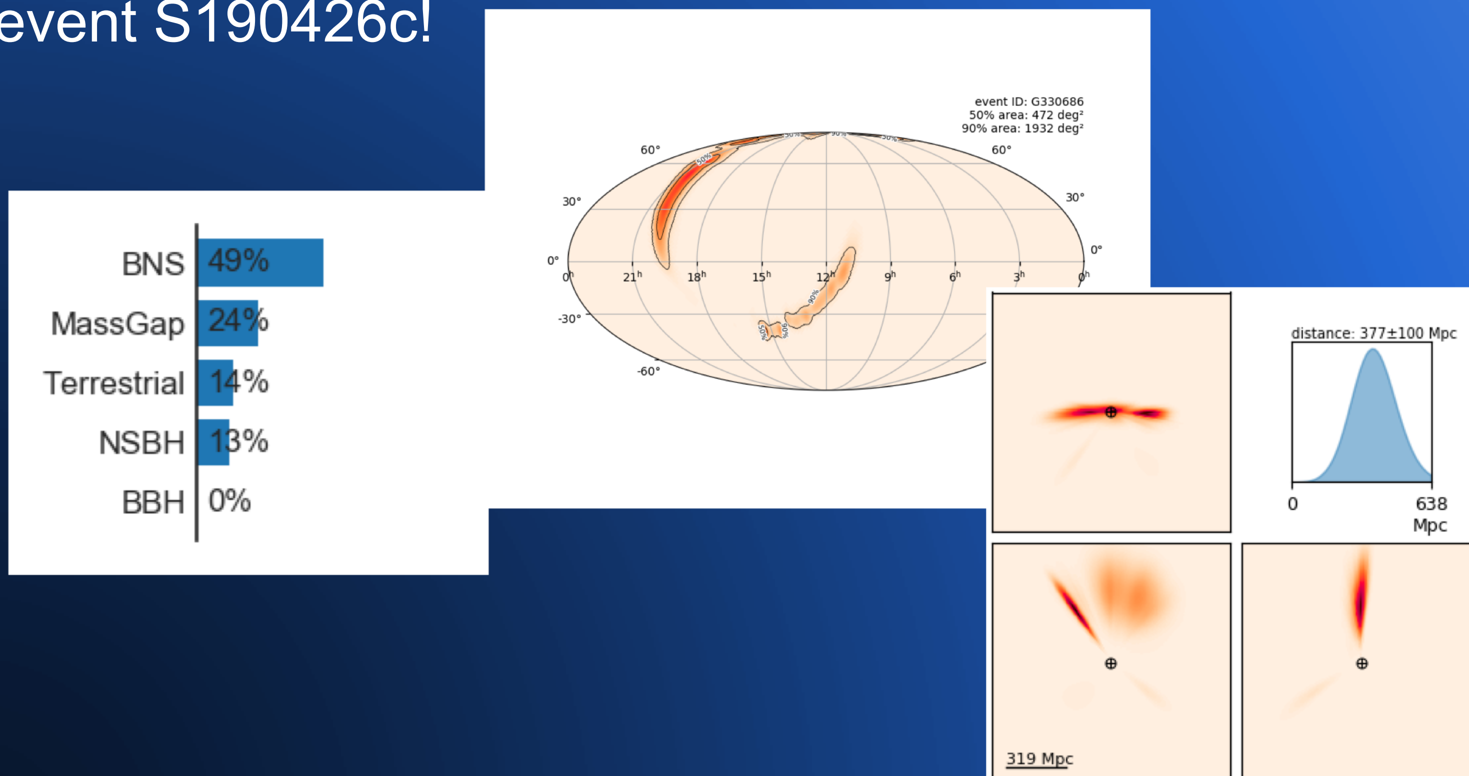
Have we detected a BHNS in GWs?

- O3 Superevent S190426c!



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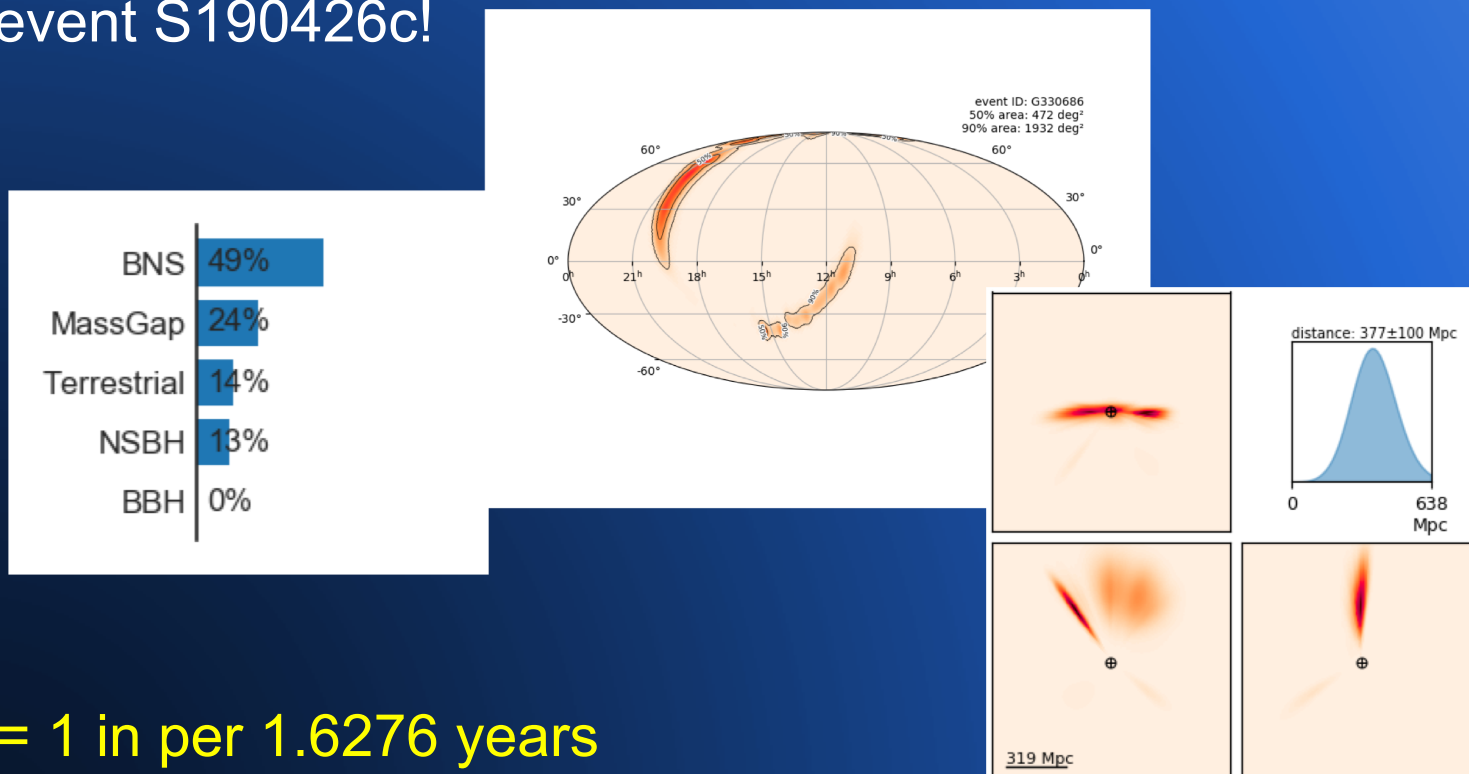

- But, FAR = 1 in per 1.6276 years

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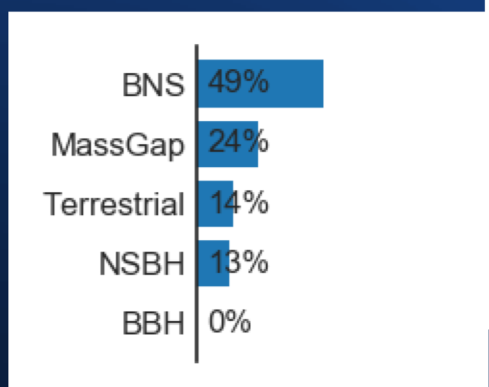
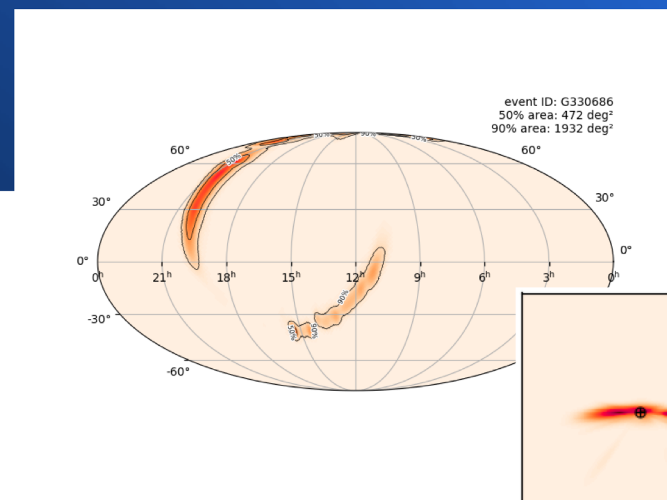
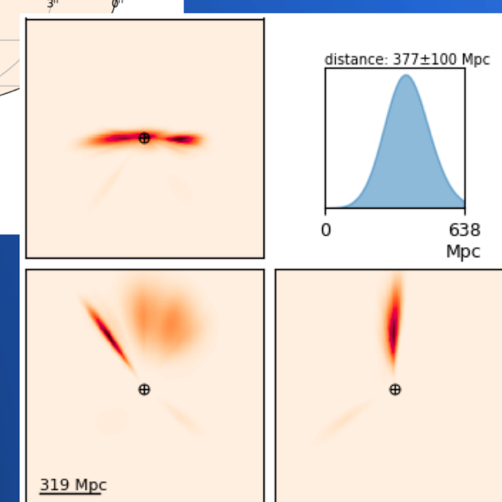






- But, FAR = 1 in per 1.6276 years

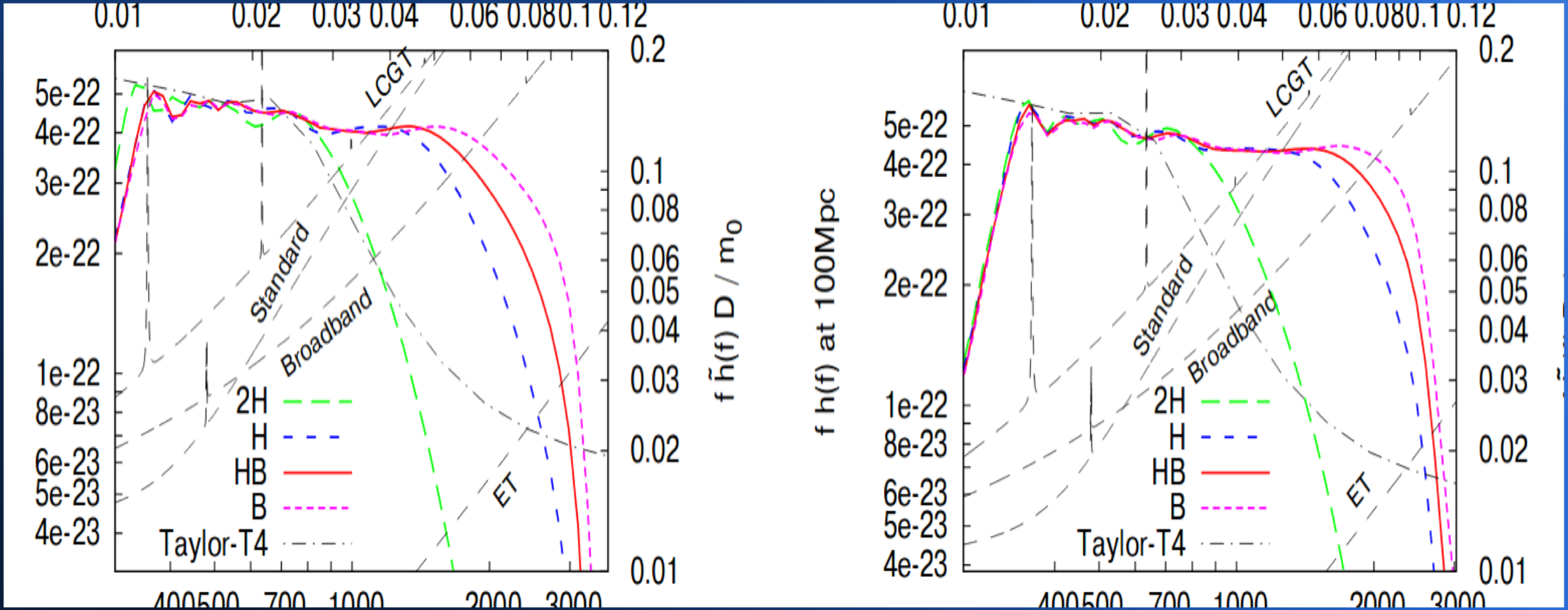
- It is a matter of time!

Motivation for simulating BH-NS mergers

- Their GWs are probes of BHs, gravitation and the nuclear EOS!
- Likely engines of short-hard Gamma Ray Bursts (SGRBs)!
- Likely engines of kilonovae/macronovae & sites for r-process elements
- Multi**$$#!3r detection → Cosmology, modified gravity (among other
- things)

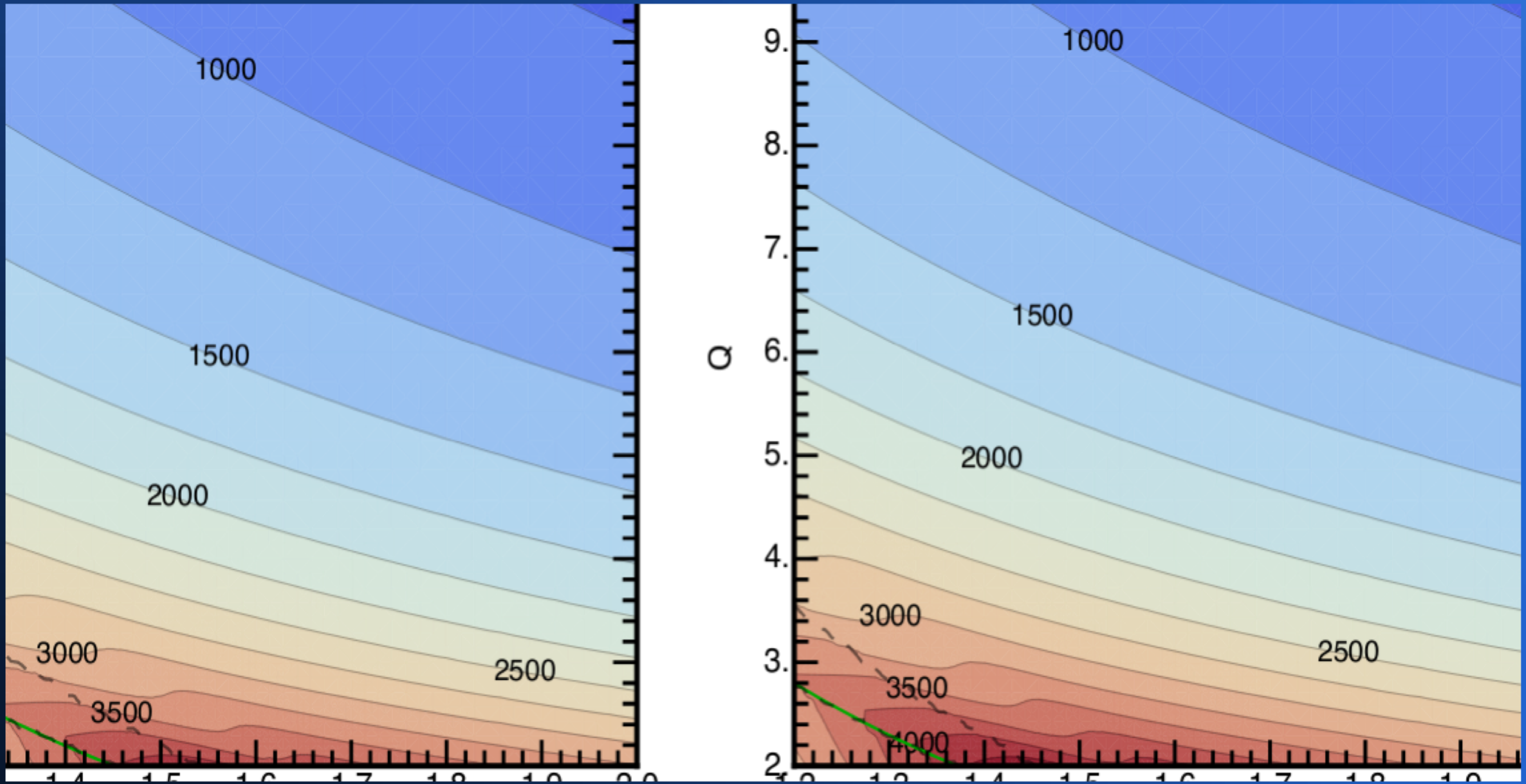
BHNS GWs → probes of EOS

- **The GW cut-off frequency** (Kyutokou et al. 2010, 2011, Kawaguchi et al. 2017)



BHNS GWs → probes of EOS

Pannarale, Berti et al. 2015, introduce a BHNS GW model → cut-off frequency



- Would likely need 3G GW detectors

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BH-NS electromagnetic counterparts

BH-NS mergers → BH+ejecta/matter

BH-NS mergers → BH+matter? Not trivial!

- Why is it difficult to create an accretion disk following merger of a quasicircular BH-NS?

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- Why is it difficult to create an accretion disk following merger of a quasicircular BH-NS?

- To have an appreciable disk, the NS must be tidally disrupted **outside** the (effective) innermost circular orbit (ISCO)

BH-NS mergers → BH+disk? Not trivial!

- Key parameters determining the interplay between ISCO and tidal disruption radius:
- $q=M_{BH}/M_{NS}$ and NS compaction, $C=GM_{NS}/R_{NS}c^2$ → tidal disruption radius

$$a_{tidal} = a_{g,NS} \Rightarrow r_{tidal} = 2\left(\frac{q}{10}\right)^{-2/3}\left(\frac{C}{0.2}\right)^{-1} r_{g,BH}, r_{g,BH} = \frac{GM_{BH}}{c^2}$$

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- BH spin → ISCO

$$r_{g,BH} \leqslant r_{ISCO} \leqslant 6r_{g,BH}$$

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- BH spin → ISCO $r_{g,BH} \leqslant r_{ISCO} \leqslant 6r_{g,BH}$

$$r_{ISCO} < 2r_{g,BH} for a = \frac{cJ}{GM^2} > 0.94!$$

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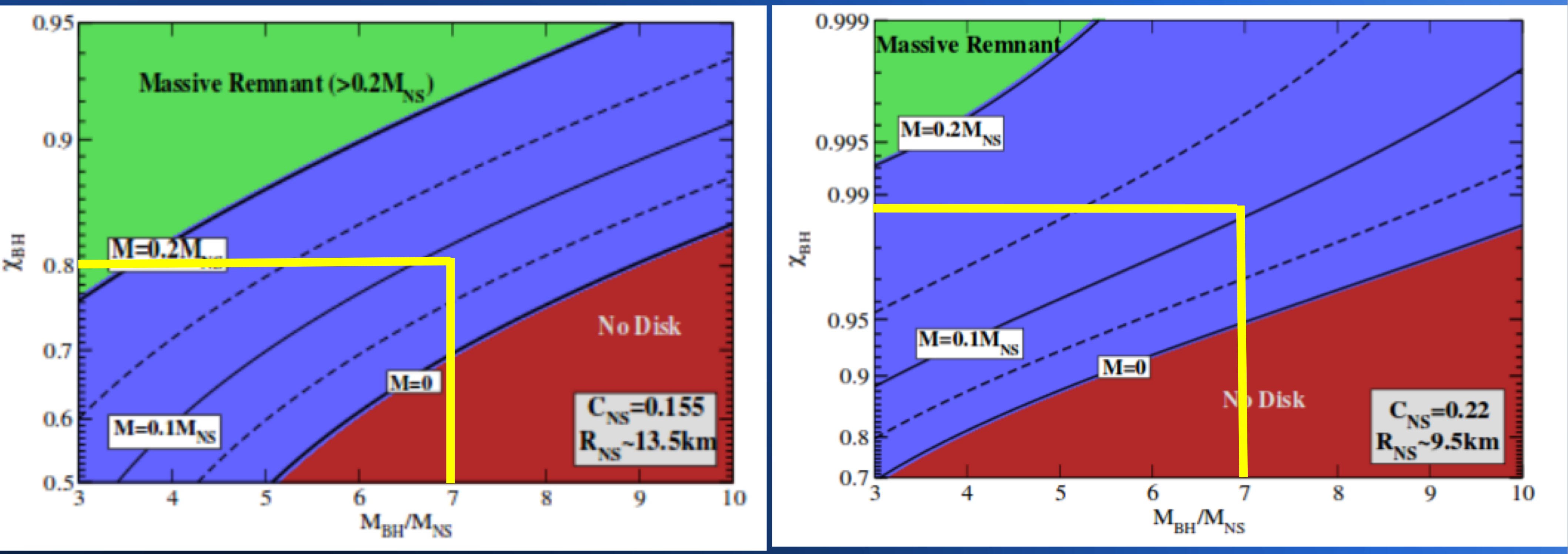
BH-NS mergers → BH+disk?

- Magnetic fields: dynamically unimportant → GR hydro simulations suffice

- Multiple BH-NS GR hydrodynamic simulations in full general relativity
- which are **quasicircular** with **irrotational** NS: Etienne et al. (2009),
- Etienne, **VP,** et al (2011), Duez et al. (2010), Foucart et al (2011), Kyotoku
- et al. (2011), Foucart et al (2012), Lovelace et al (2013), Deaton et al.
- (2013)

BH-NS mergers → BH+disk? Not trivial!

- Foucart (2012) compiled the results for the disk masses (**aligned BH spin**)



$$a = \frac{cJ}{GM^2} > 0.8$$

- Disk mass is 0.1Msun at "realistic" mass ratios for
- Strong constraint!

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BH-NS mergers → BH+disk? But, eccentricity?

- BH-NS binaries in globular clusters (GC) can form dynamically through single-signle and binary-single interactions and merge with high eccentricities.
- Moreover, >80% of GC pulsars have millisecond spin periods
- High eccentricity and prograde NS spin move the effective ISO inward closer to the BH
- NS spin makes the star less bound → increases tidal disruption radius

Eccentric BH-NS mergers → BH+disk?

- GR hydro simulations of dynamical capture BH-NS mergers: East, **VP**, Pretorius (2015):

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$$q = 4, a_{BH} = \frac{cJ_{BH}}{GM_{BH}^2} = 0, a_{NS} = \frac{cJ_{NS}}{GM_{NS}^2} = 0 - 0.4$$

- NS equation of state:

$$C_{NS} = \frac{GM_{NS}}{R_{NS}c^2} = 0.17, M_{NS} = 1.35M_{sol}$$

$$M_{d,circular} = 0!$$

Eccentric BH-NS mergers → BH+disk?

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- $M_{d,circular} = 0!$

  $M_{d,eccentric} = 0.01 - 0.18M_{NS}$

  $M_{u,eccentric} = 0.001 - 0.15M_{\odot}$

BH-NS mergers → jets?

BH-NS mergers with dipole B fields

VP, Milton Ruiz, Stu Shapiro (2015)

BH-NS mergers with dipole B fields

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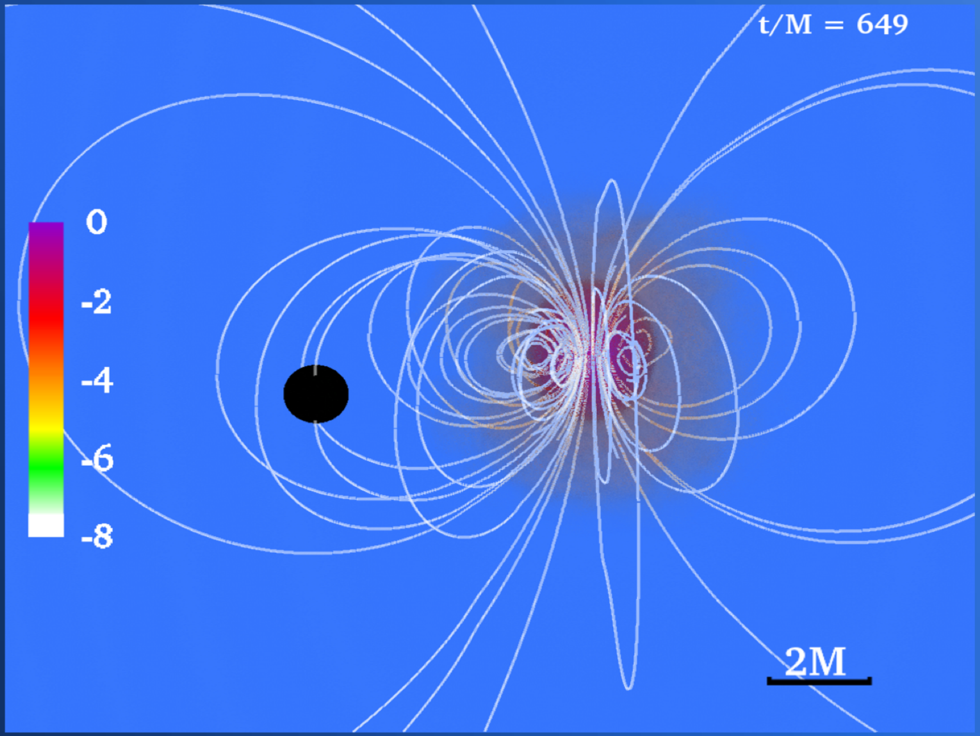
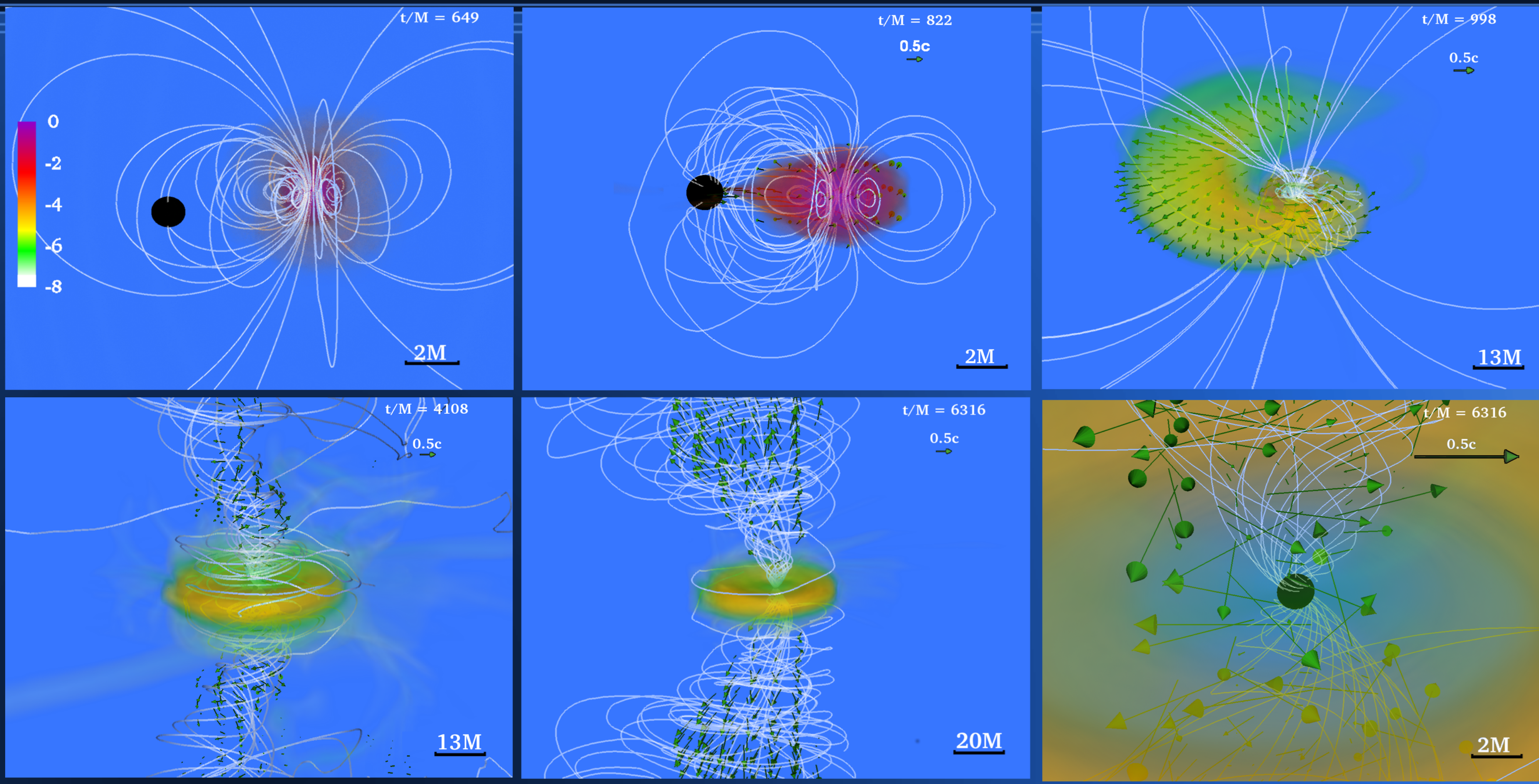
- BHNS sims at BH to NS mass ratio of 3:1

- BH spin 0.75

- Initial pulsar like B field → crucial component



An incipient jet emerges



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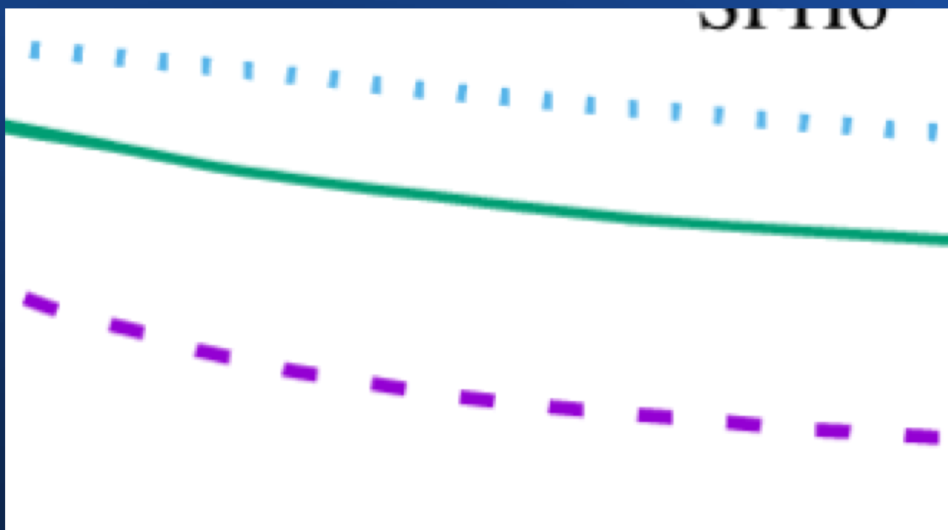
What about neutrino annihilation?

- Kyutokou et al. 2018 radiation-hydrodynamic sims BHNS q=4, spin=0.75



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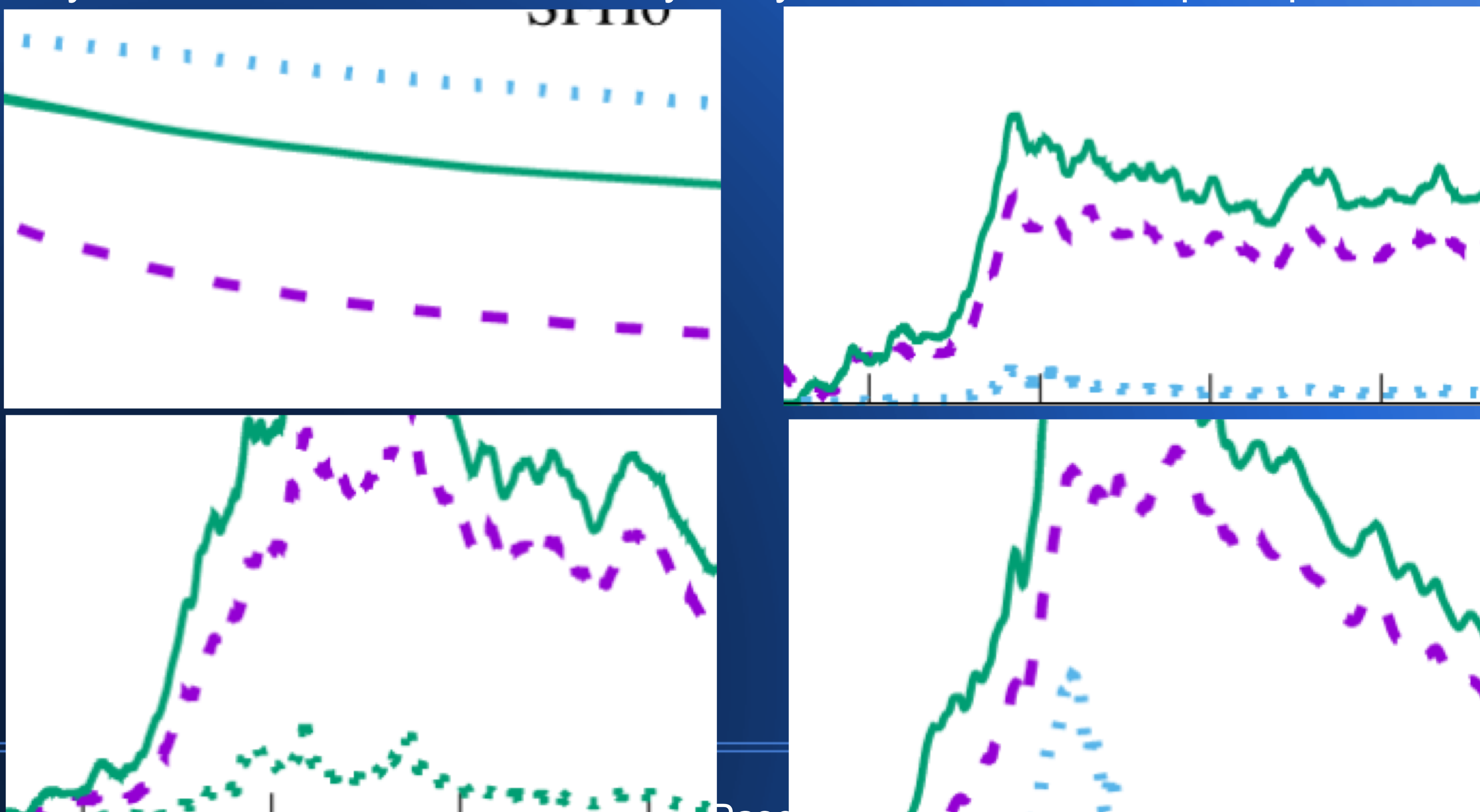


What about neutrino annihilation?

- **Stiff EOSs favor large masses outside the BH, but may disfavor**
- **sGRBs through the neutrino annihilation mechanism**

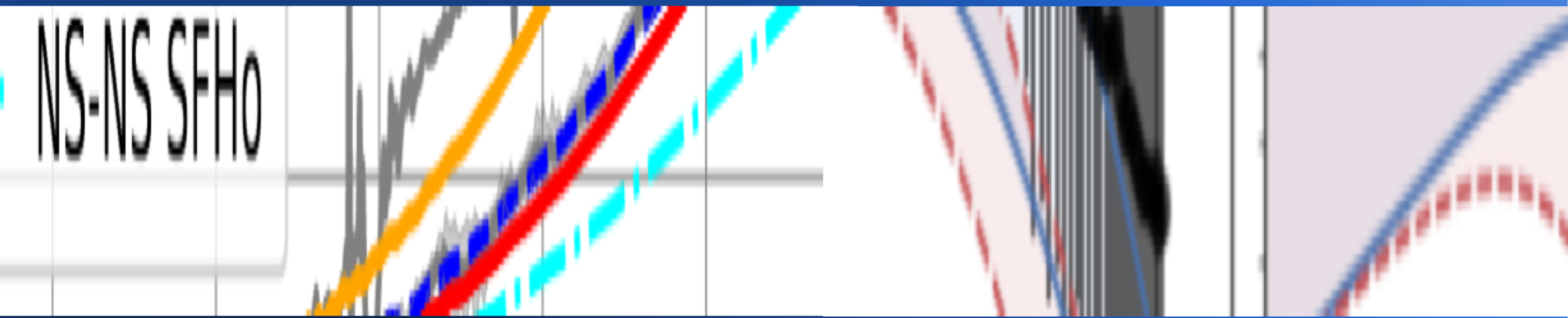
What about kilonovae/GW170817?

In contrast to binary neutron stars, to obtain large neutron rich ejecta/disk masses BHNSs require stiff EOSs!

Generally ejecta+disk masses 0.1Msun are possible for moderately high BH spins → kilonovae

What about kilonovae/GW170817?

- BHNS GWs are compatible with GW170817 (Hinderer et al. 2018)



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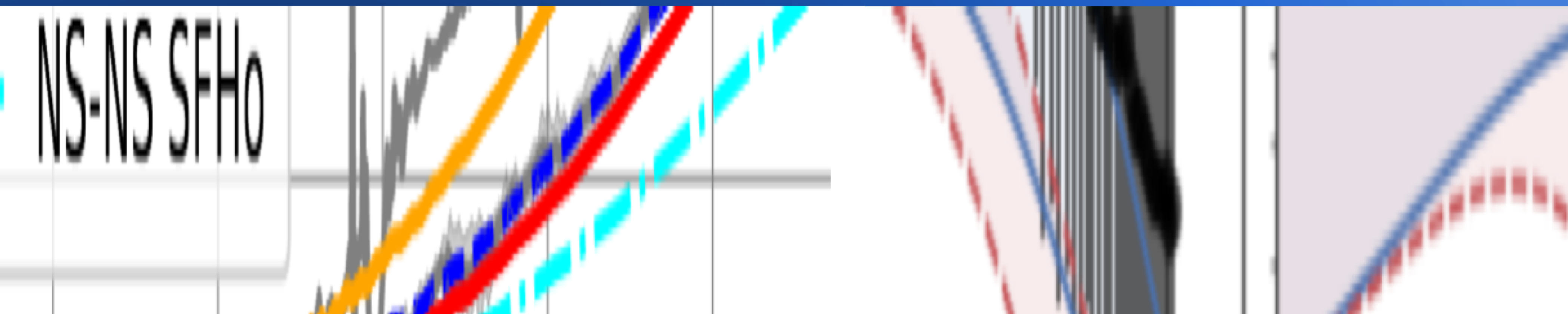
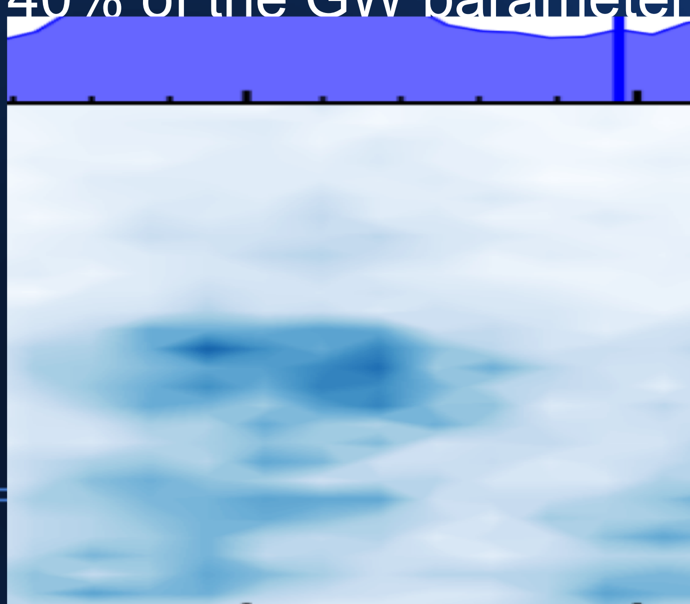


- About 40% of the GW parameters (C=M/R, Q, χ_{BH}) are compatible with EM



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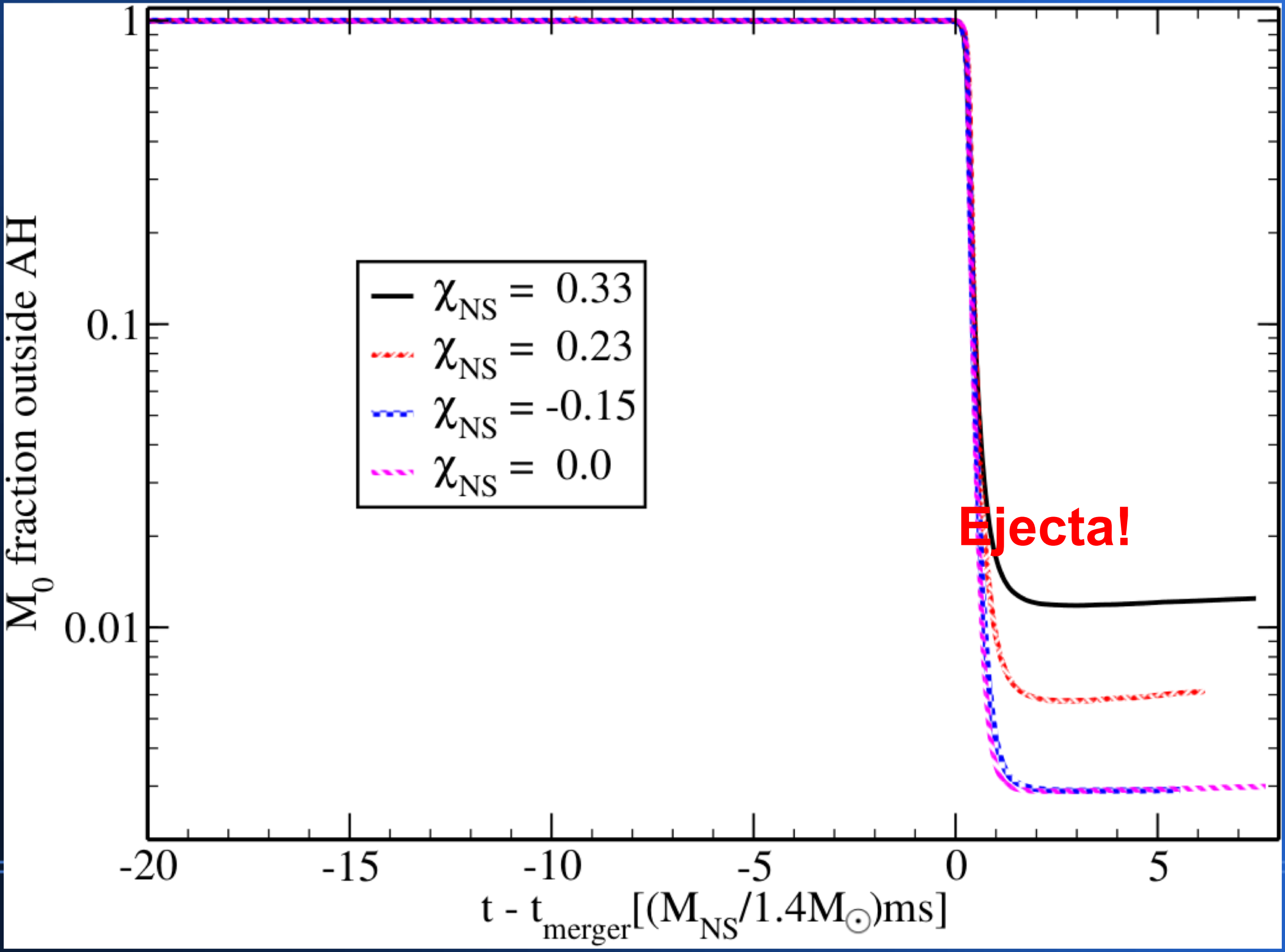
One complication: NS spin

- Ruiz, VP et al. (in prep.), BHNS with NS spin. q=5, BH spin = 0

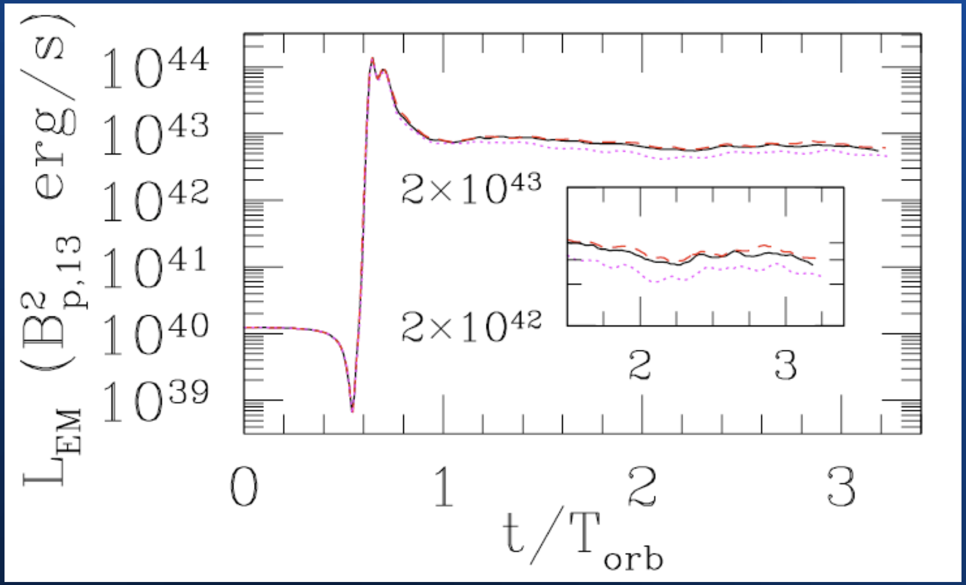


What about other EM signals?

- McWilliams, Janna Levin 2011 BH-NS unipolar inductor
- VP, Etienne, Shapiro (2013)
- GR Force-free simulations of BH-NS magnetospheric interactions

Energy extraction

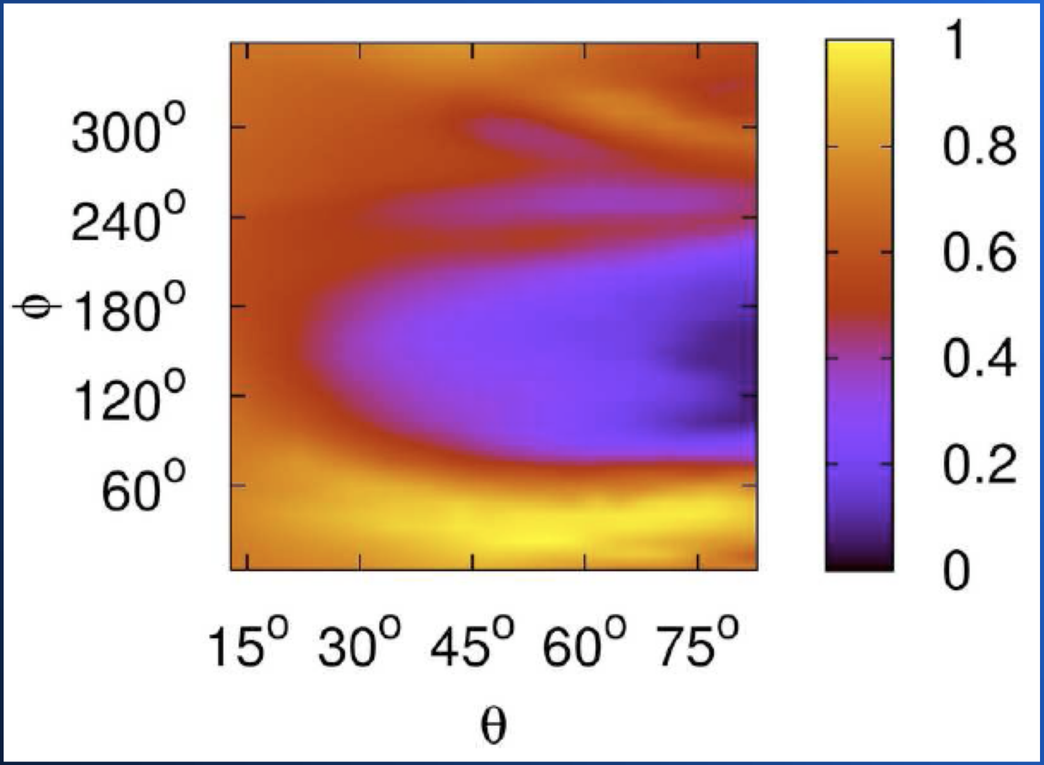
- Outgoing Poynting luminosity



$$L \approx 6 \times 10^{42} \left(\frac{B_{\mathrm{NS,p}}}{10^{13}\mathrm{G}} \right)^2 \left(\frac{M_{\mathrm{NS}}}{1.4 M_\odot} \right)^2 \frac{\mathrm{erg}}{\mathrm{s}}$$

- Energy can be extracted electromagnetically from binary BHNS!

Poynting flux angular distribution



- Beacon → “lighthouse effect”
- Characteristic quasiperiodic EM signature prior to merger?

Conclusions

- Computational gravity is a tool for
  - Discovering new phenomenology
  - Ruling out exotic physics/astrophysical models
  - Constraining/formulating new ideas to constrain unknown physics

- Computational gravity is crucial:
  - For GW and Multi**$$#!3r science
  - For understanding strong-field gravitation and relativistic
  - astrophysics

Probing the nuclear EOS with Joint GW+EM BHNS observations

VP (2016)

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- parameters (plus their uncertainties) can be run for parametrized nuclear
- EOSs to determine which EOSs result in a disk-less BH remnant.
- EOSs forming such a remnant are ruled out by the EM!

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- Such suite of simulations should have already started.

Probing the nuclear EOS with Joint GW+EM BHNS observations

- Foucart (2012) (disk mass predictions)

M_{NS} … M_{BH}

cal compaction for $M_{disk}=0$

$$C_{NS,crit}=\left(2+2.14\,q^{2/3}\frac{R_{ISCO}}{M_{BH}}\right)^{-1}$$

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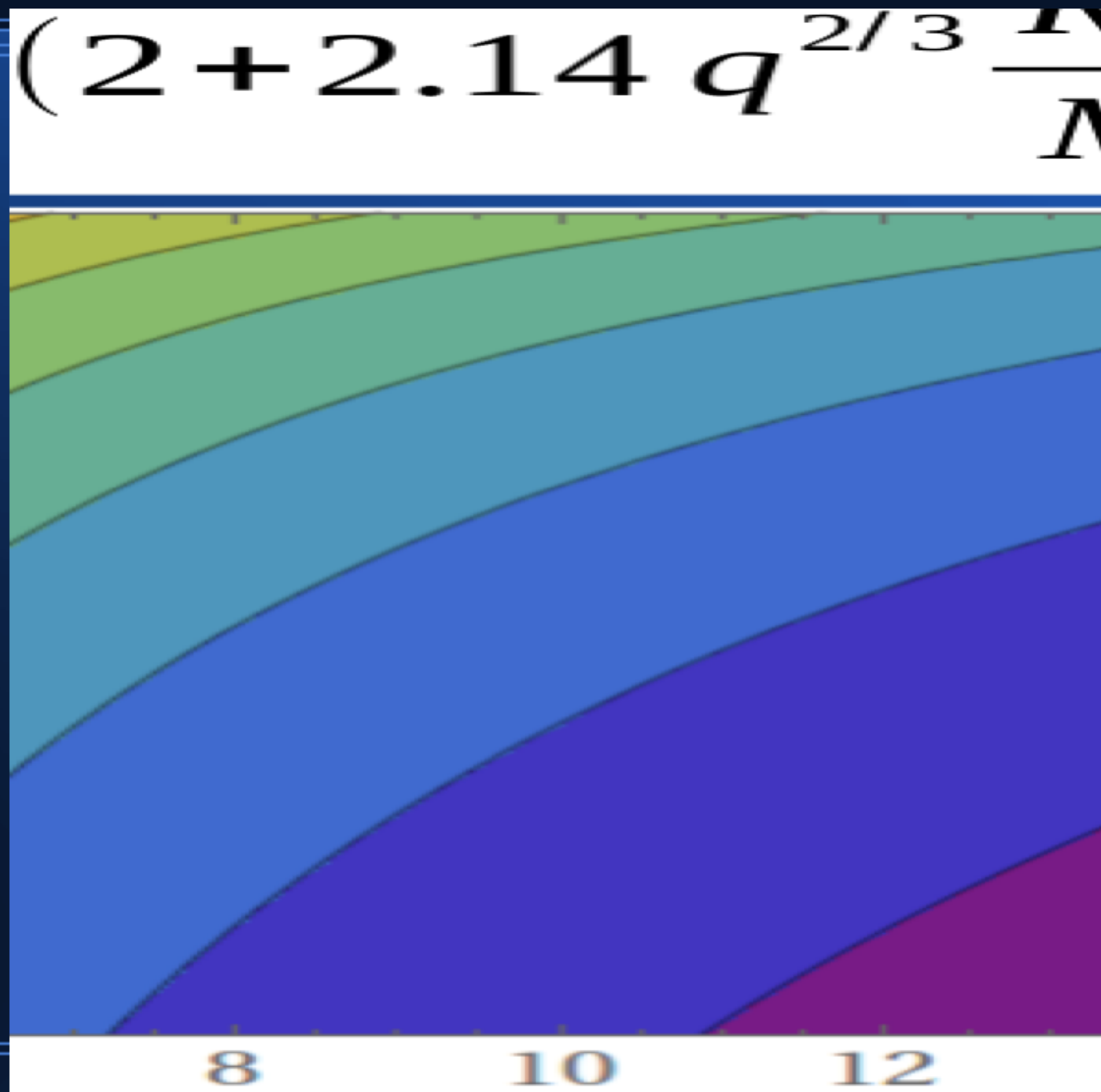

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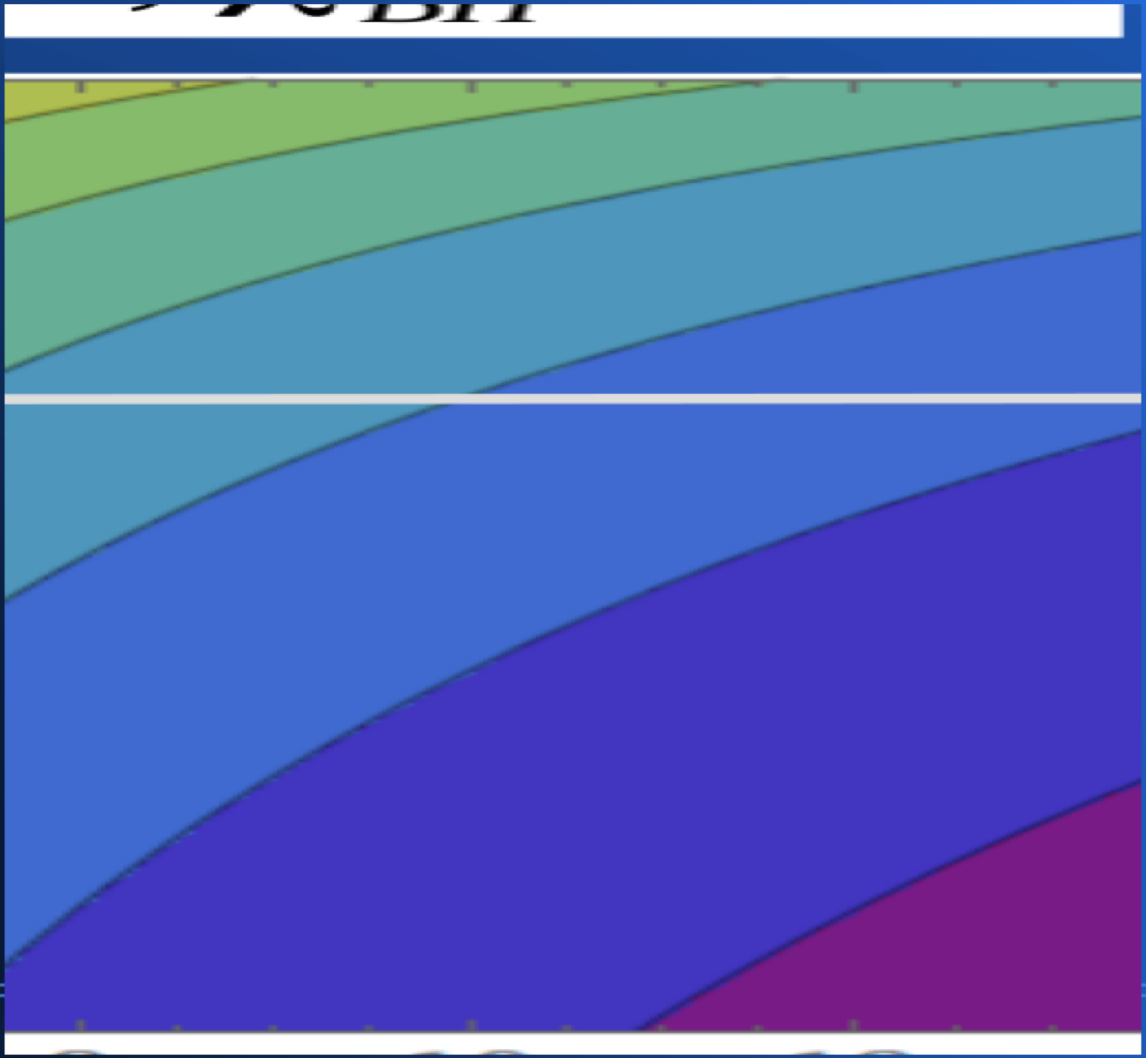

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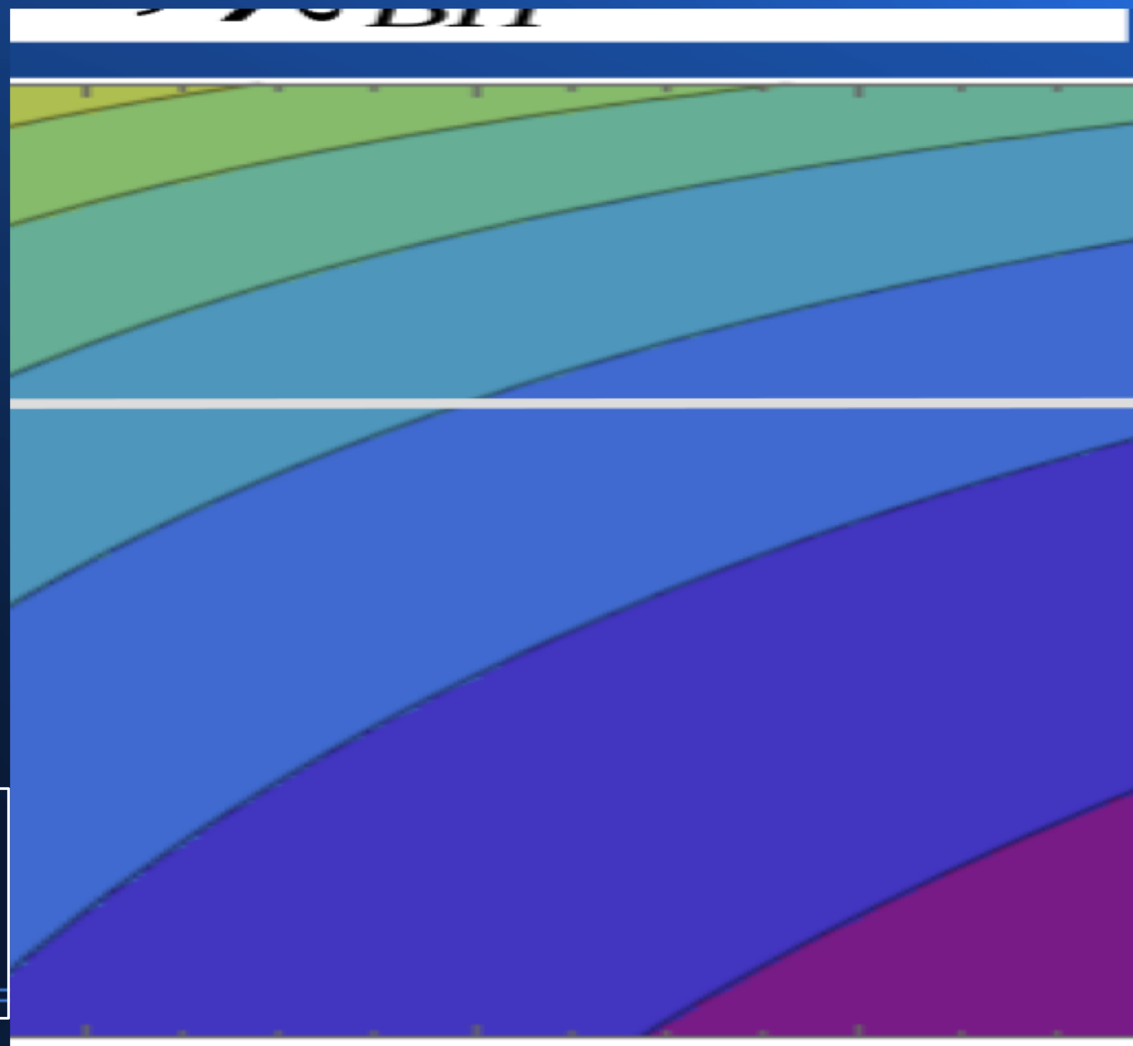

Similar idea with finite mass outside BH by Pannarale, Ohm 2014

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