MONASH University

OzGrav

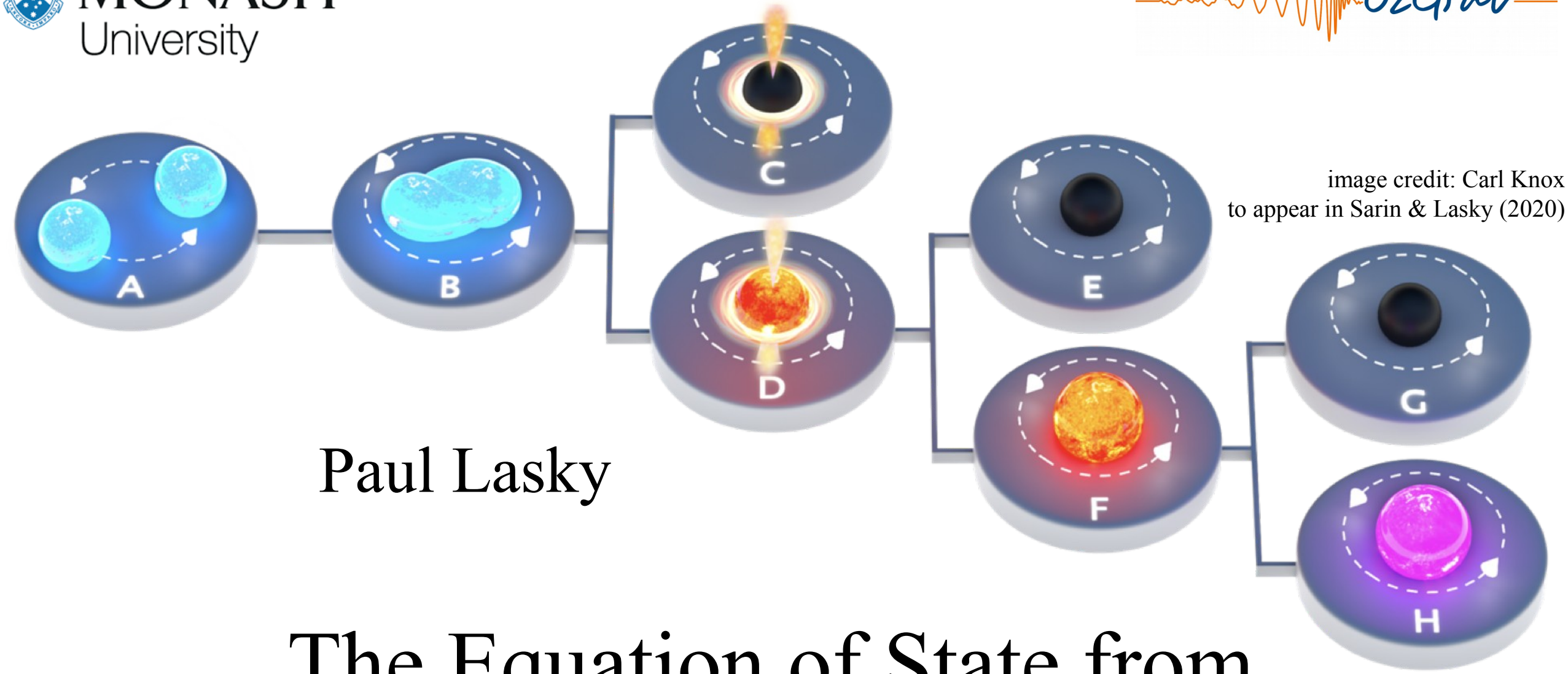
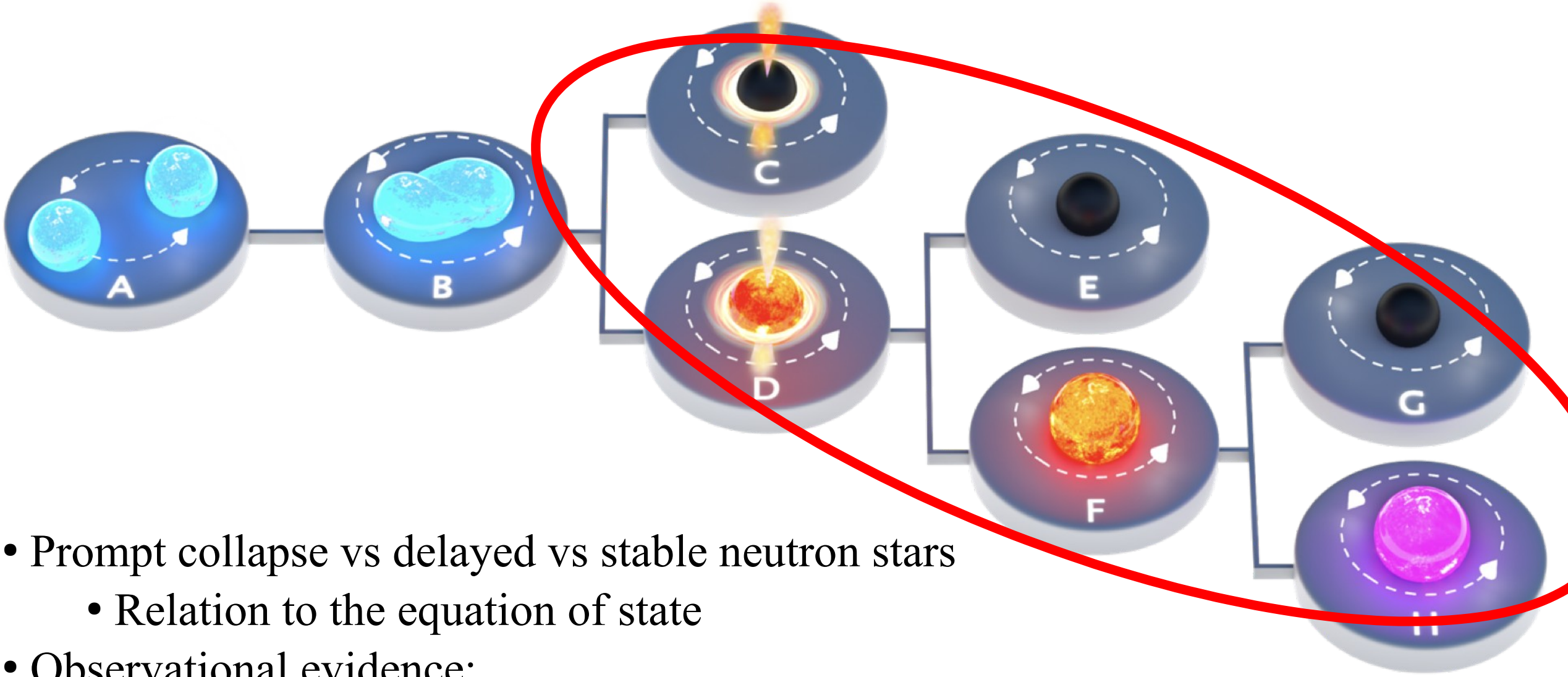


image credit: Carl Knox
to appear in Sarin & Lasky (2020)

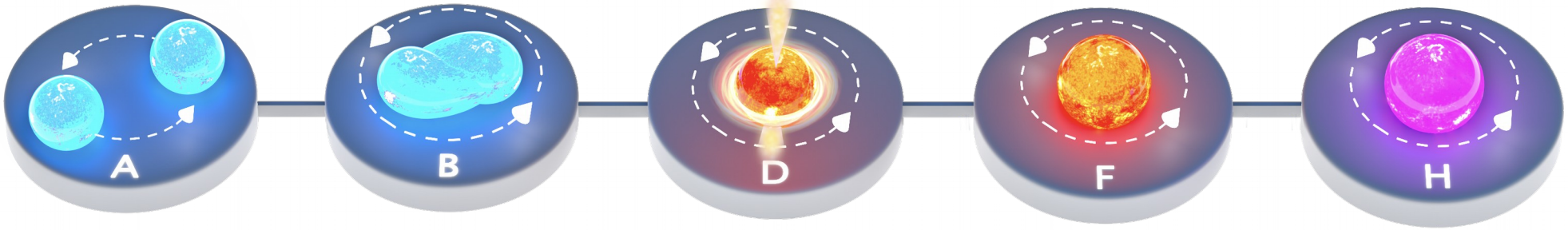
Paul Lasky

The Equation of State from Neutron Star Post-Merger Remnants



- Prompt collapse vs delayed vs stable neutron stars
  - Relation to the equation of state
- Observational evidence:
  - Short gamma-ray bursts
  - Gravitational waves – current and future observatories

Stable Neutron Star: $M < M_{\mathrm{TOV}}$



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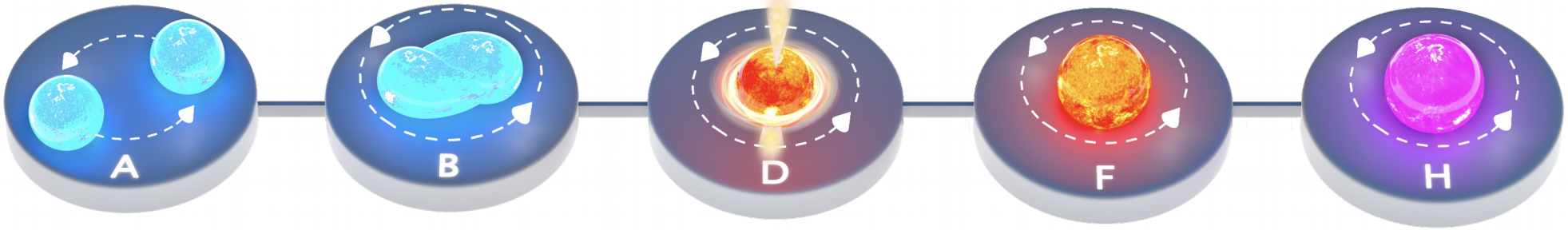
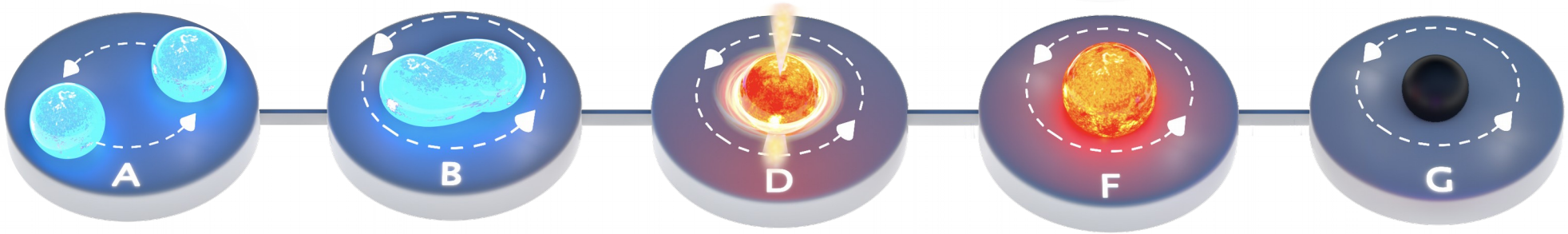


Supramassive Neutron Star: $1.0 \leq M/M_{\rm TOV} \lesssim 1.2$ Collapse: ~10 – 10,000 s

(Ravi & PL 2014)



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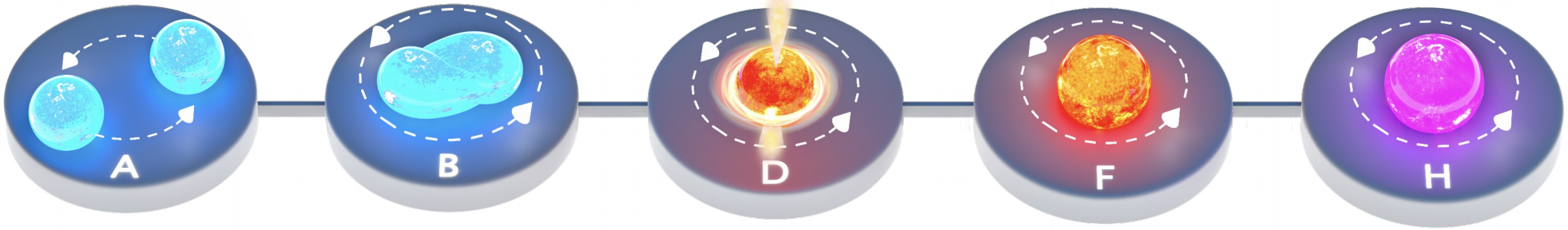

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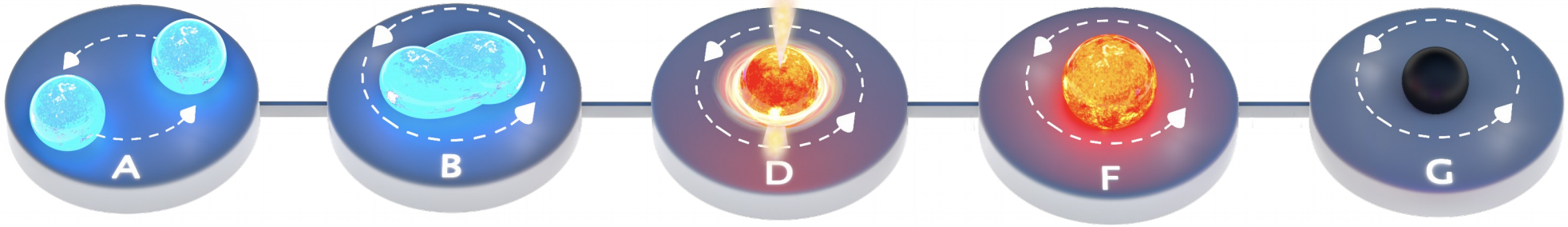
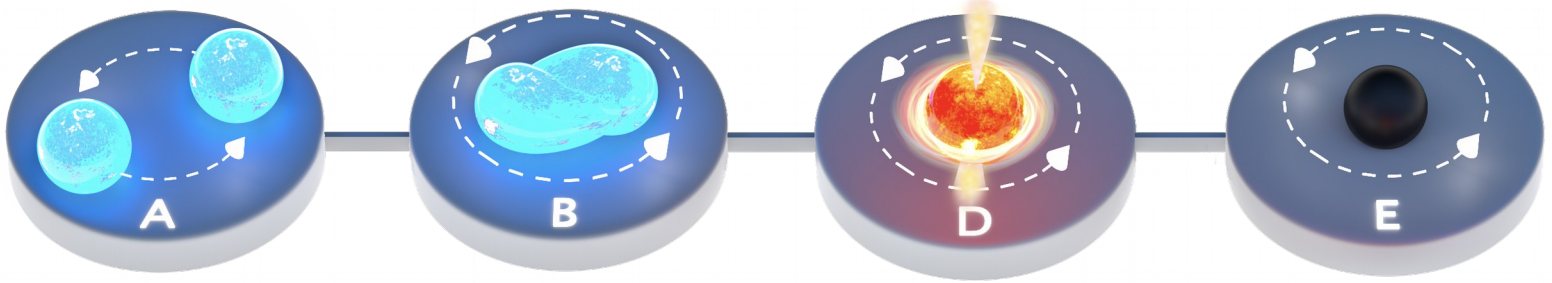


Hypermassive Neutron Star: $1.2 \lesssim M/M_{\rm TOV} \lesssim 1.5$ Collapse: ~1 – 100 ms (??)



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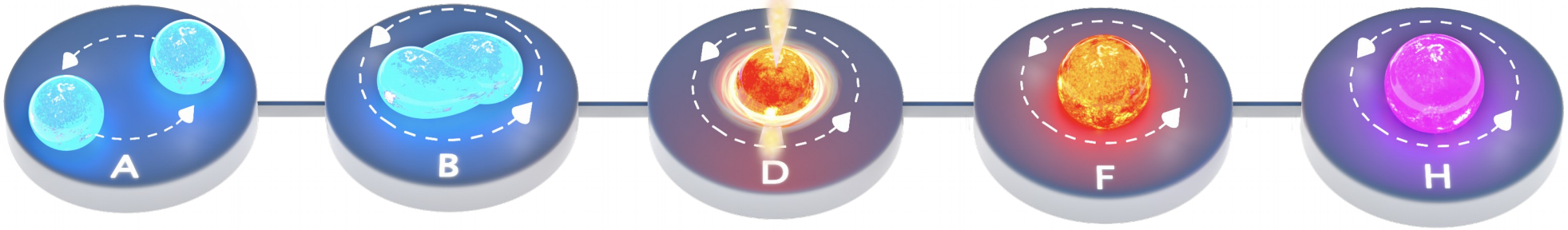

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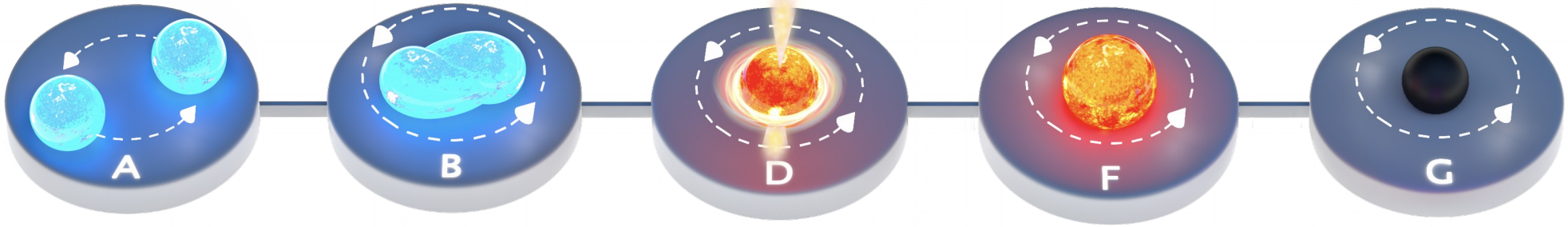

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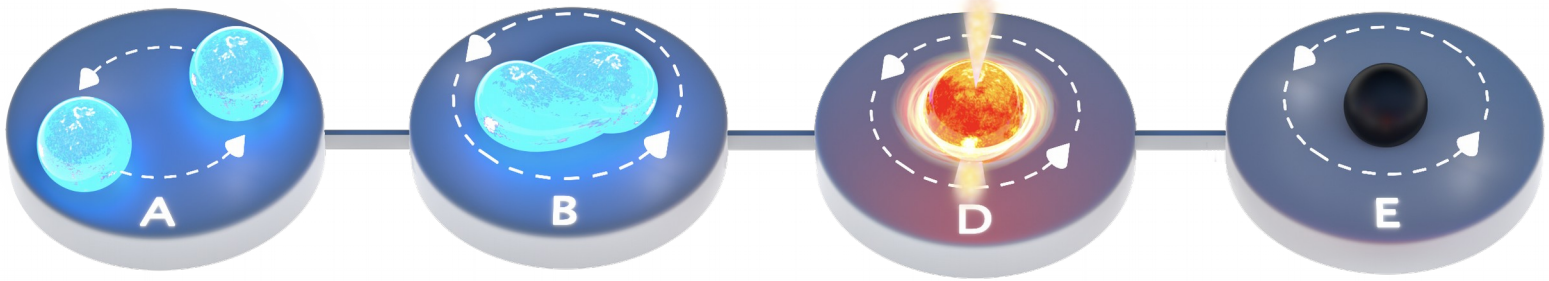
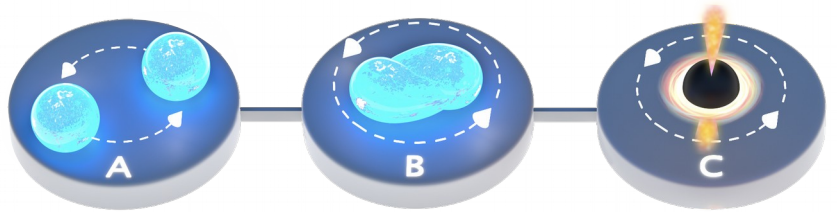
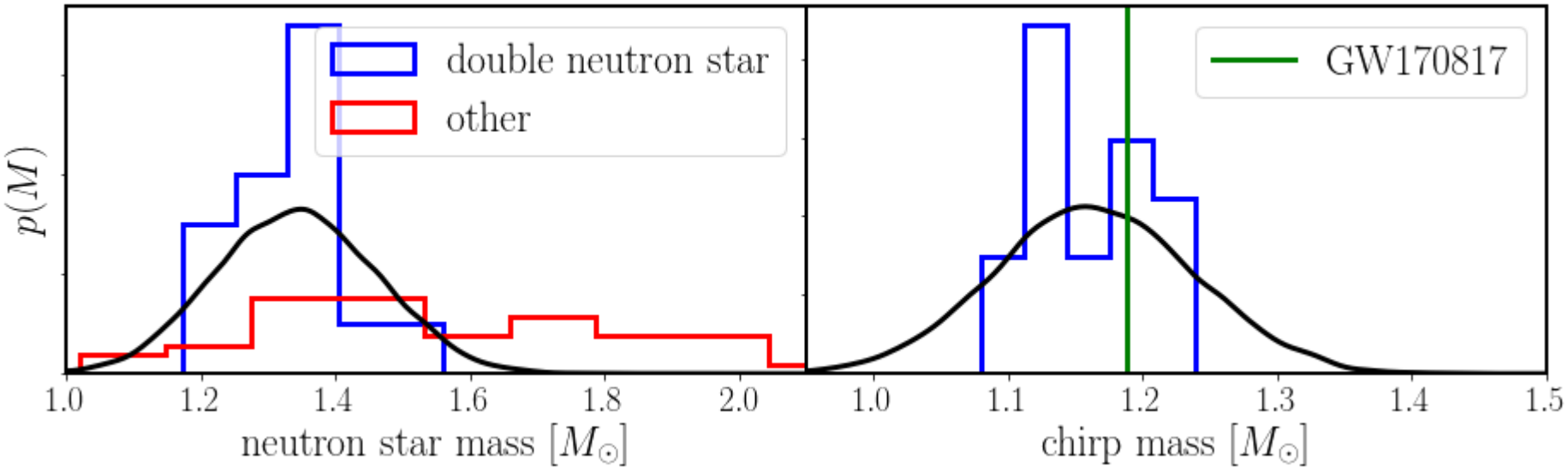


Prompt collapse: $M \gtrsim 1.5 M_{\rm TOV}$



How massive are merger remnants?



Mass distributions:
Kiziltan+2013,
Alsing+2018
Farrow+2019

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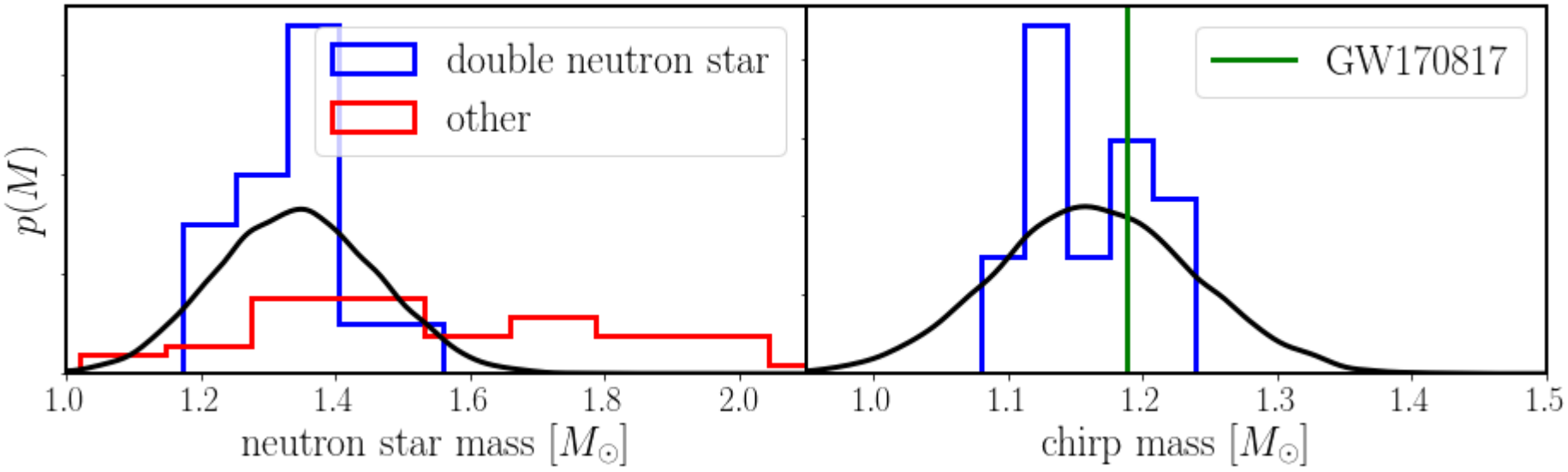

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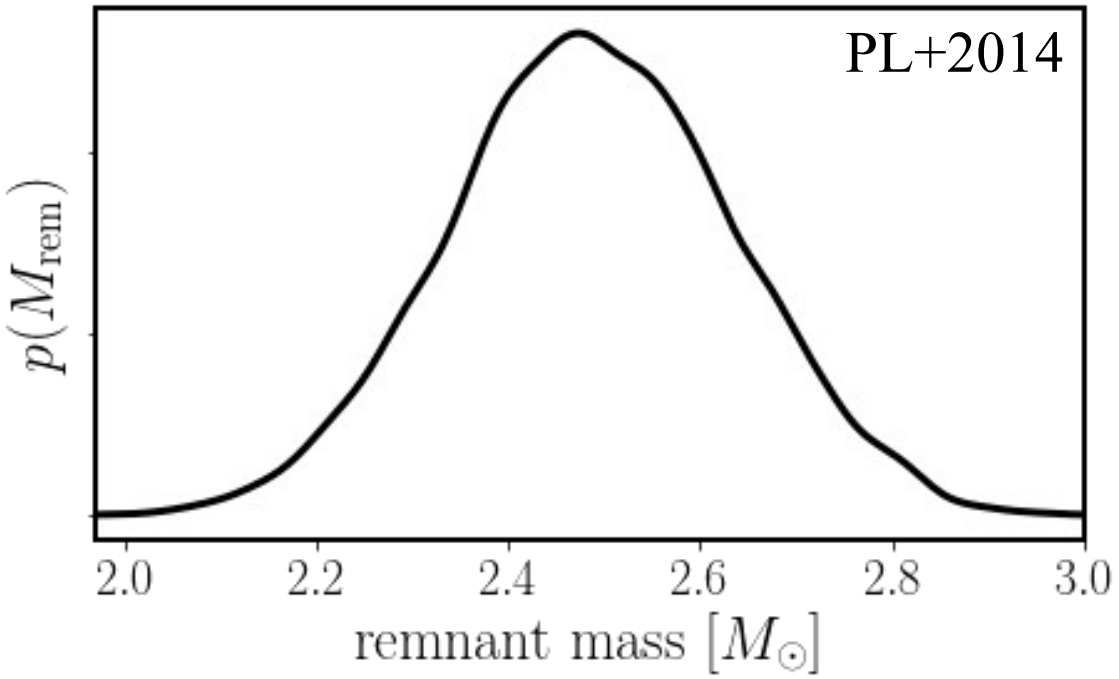

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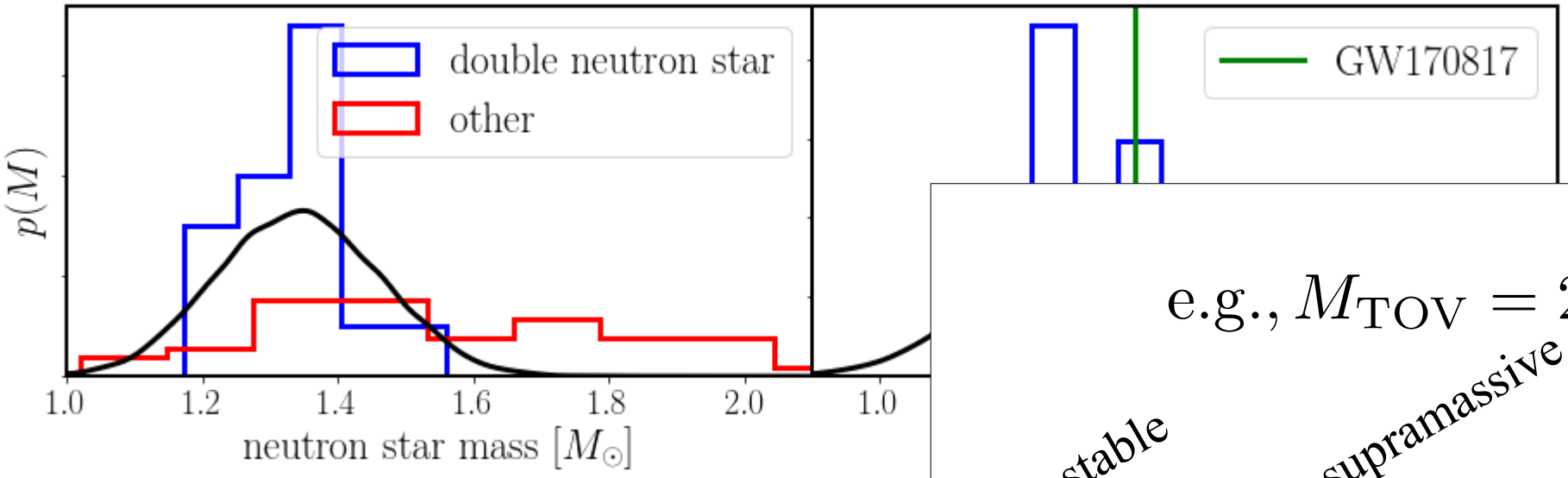

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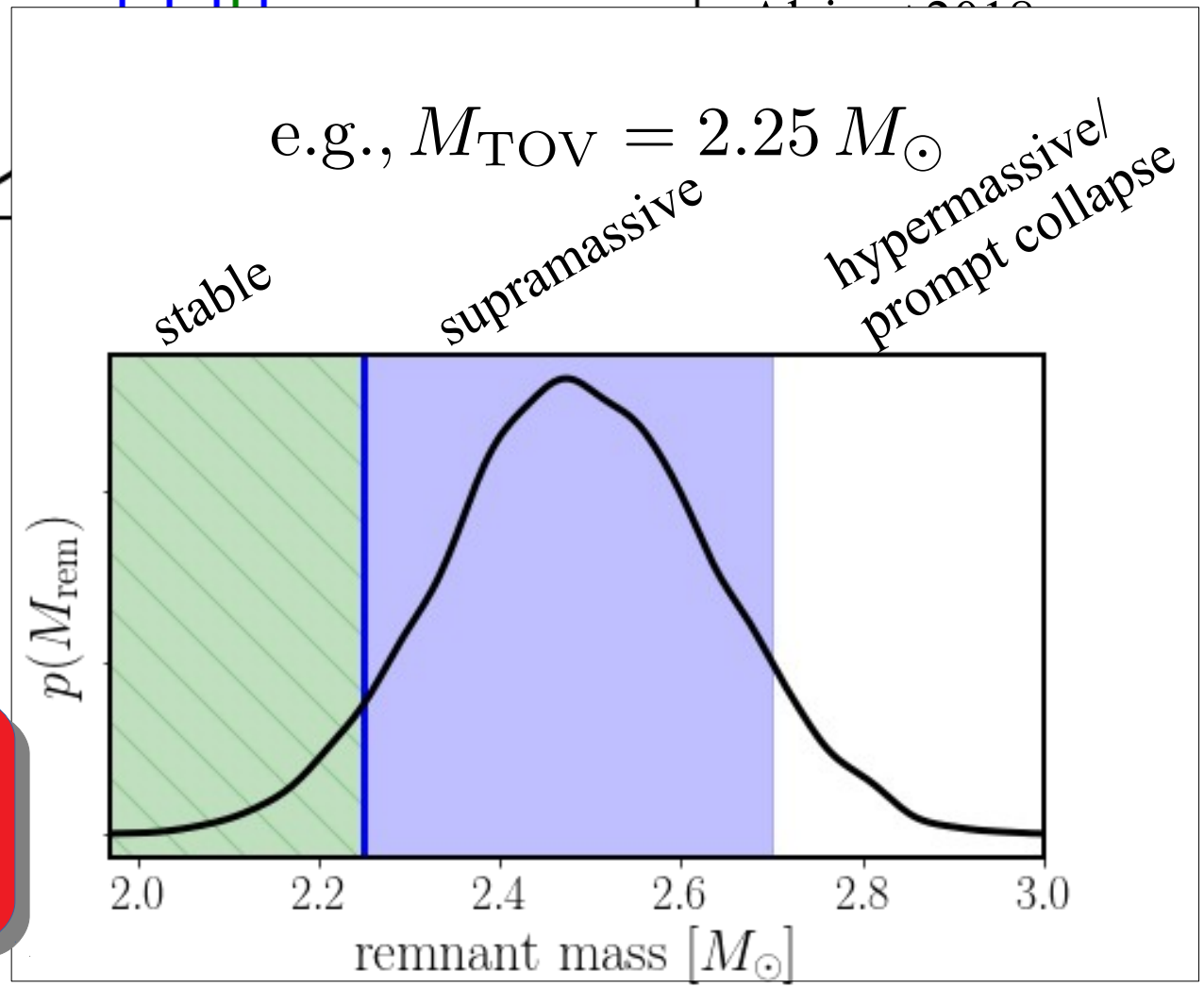
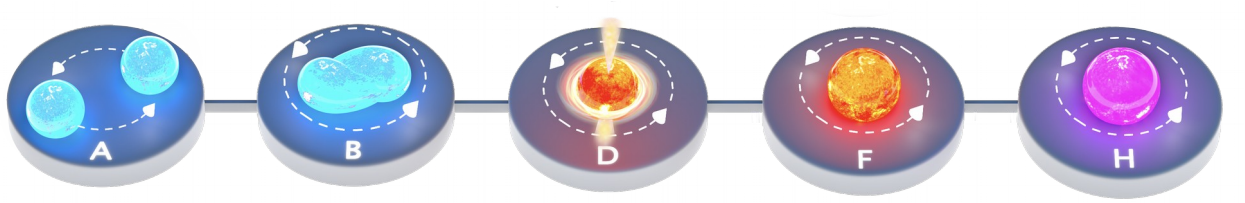
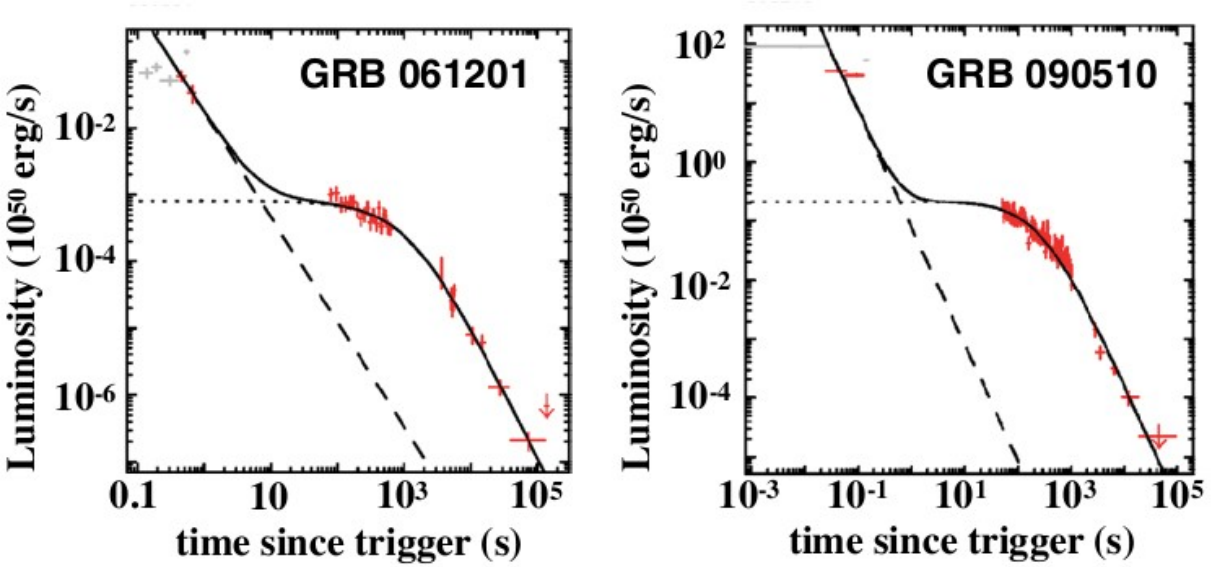
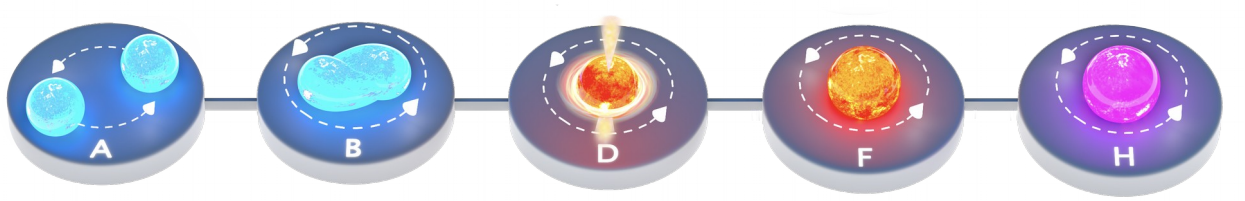


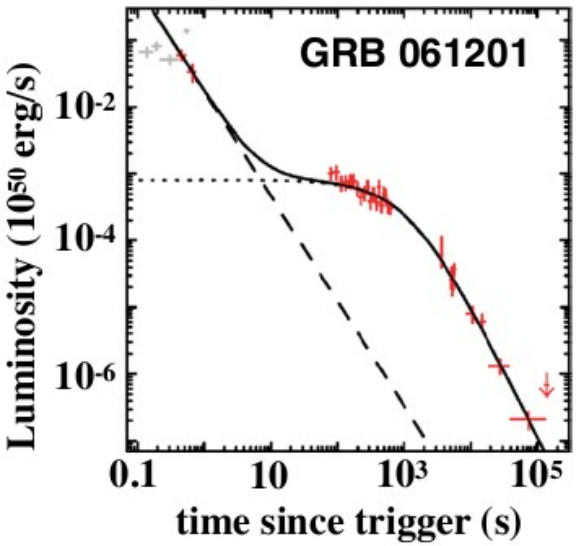
Even if $M_{\rm TOV} \approx 2\,M_\odot$, a large fraction of remnants will be stable/supramassive, and almost all the rest will be hypermassive

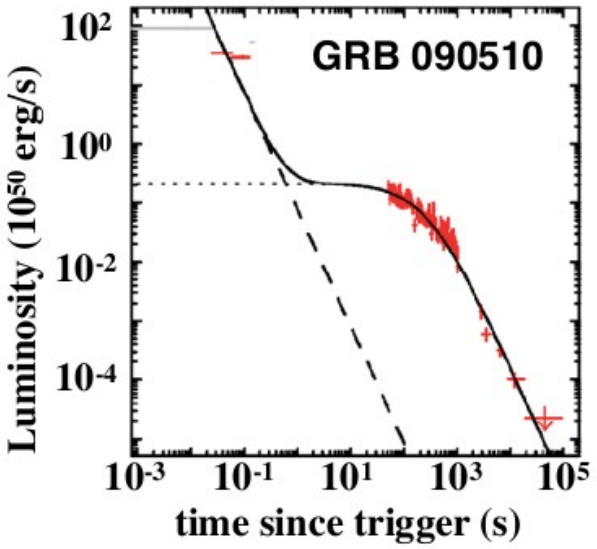


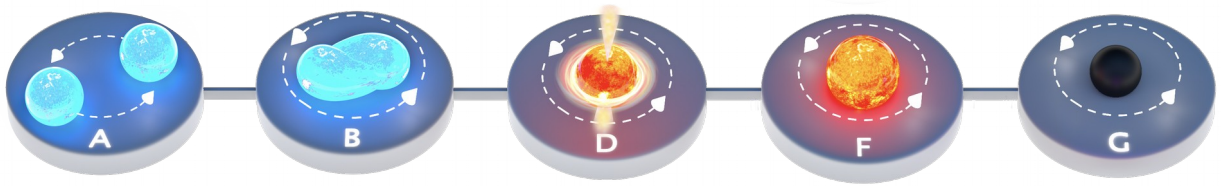


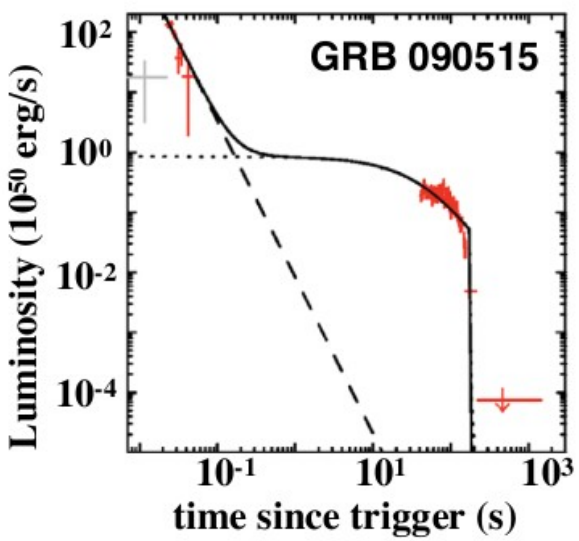
Rowlinson+2013

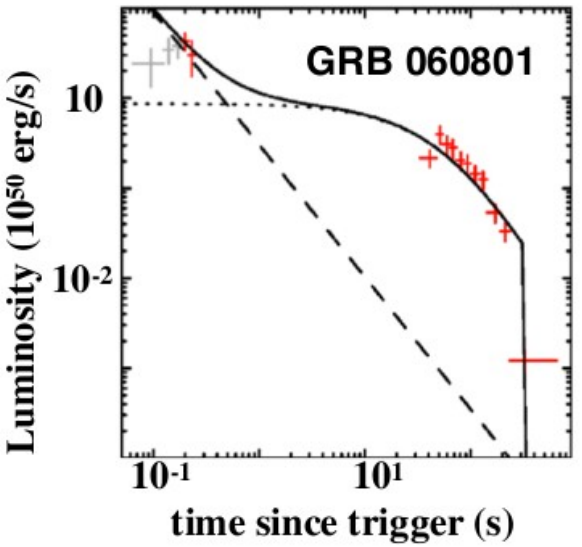




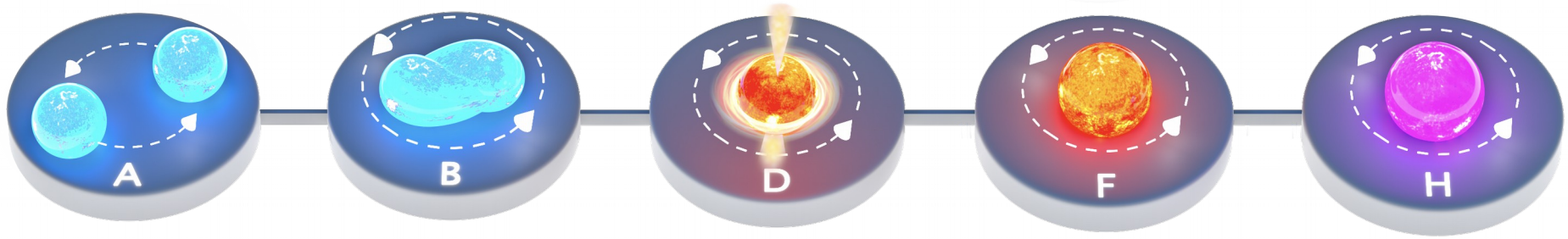


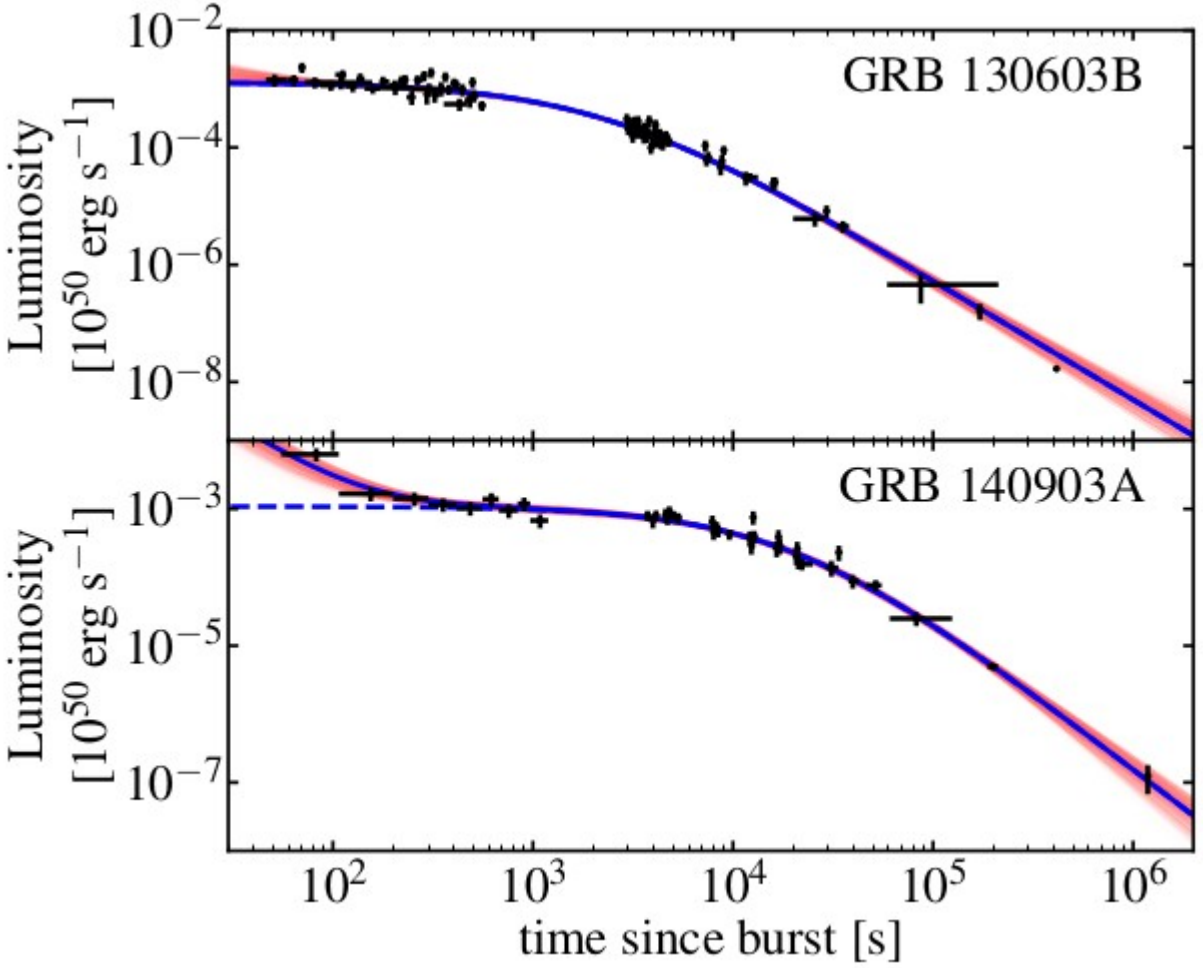




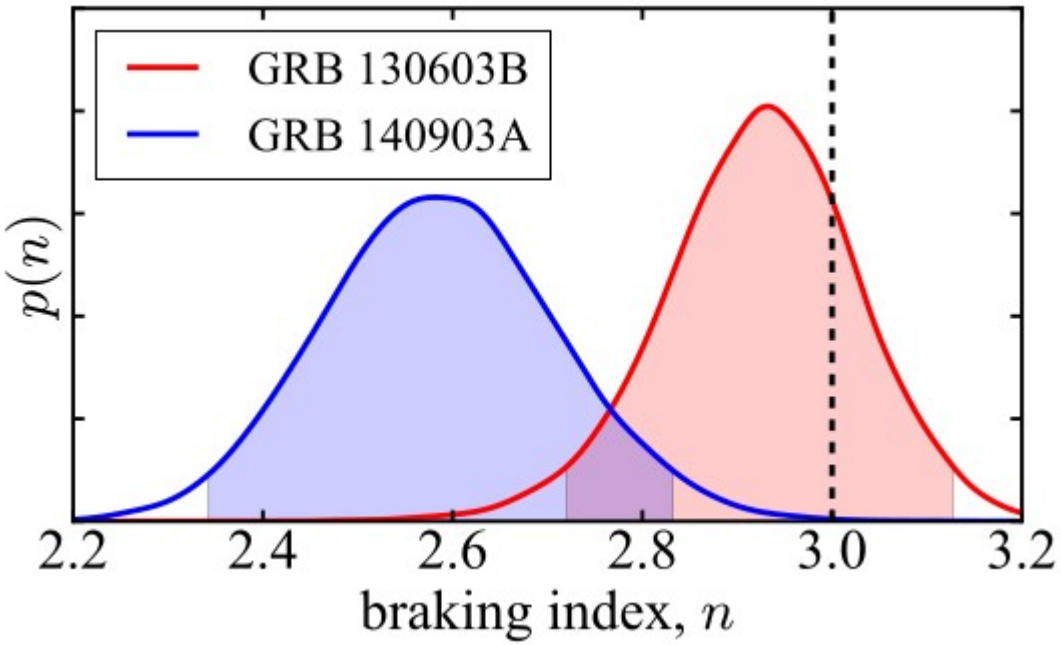


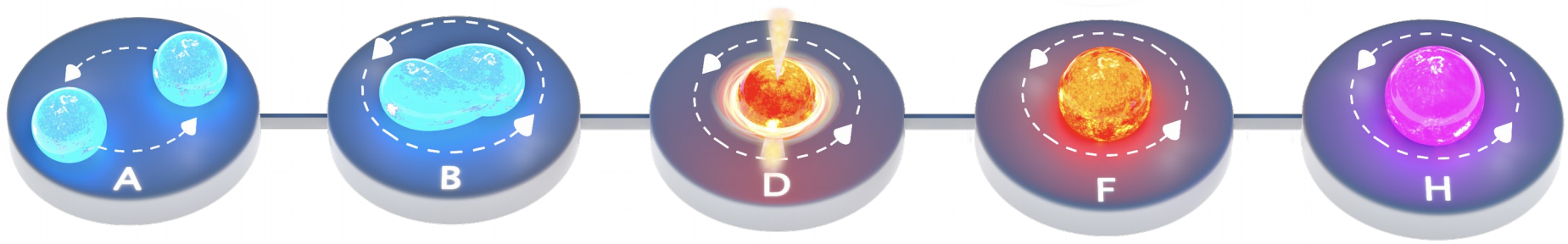
Rowlinson+2013



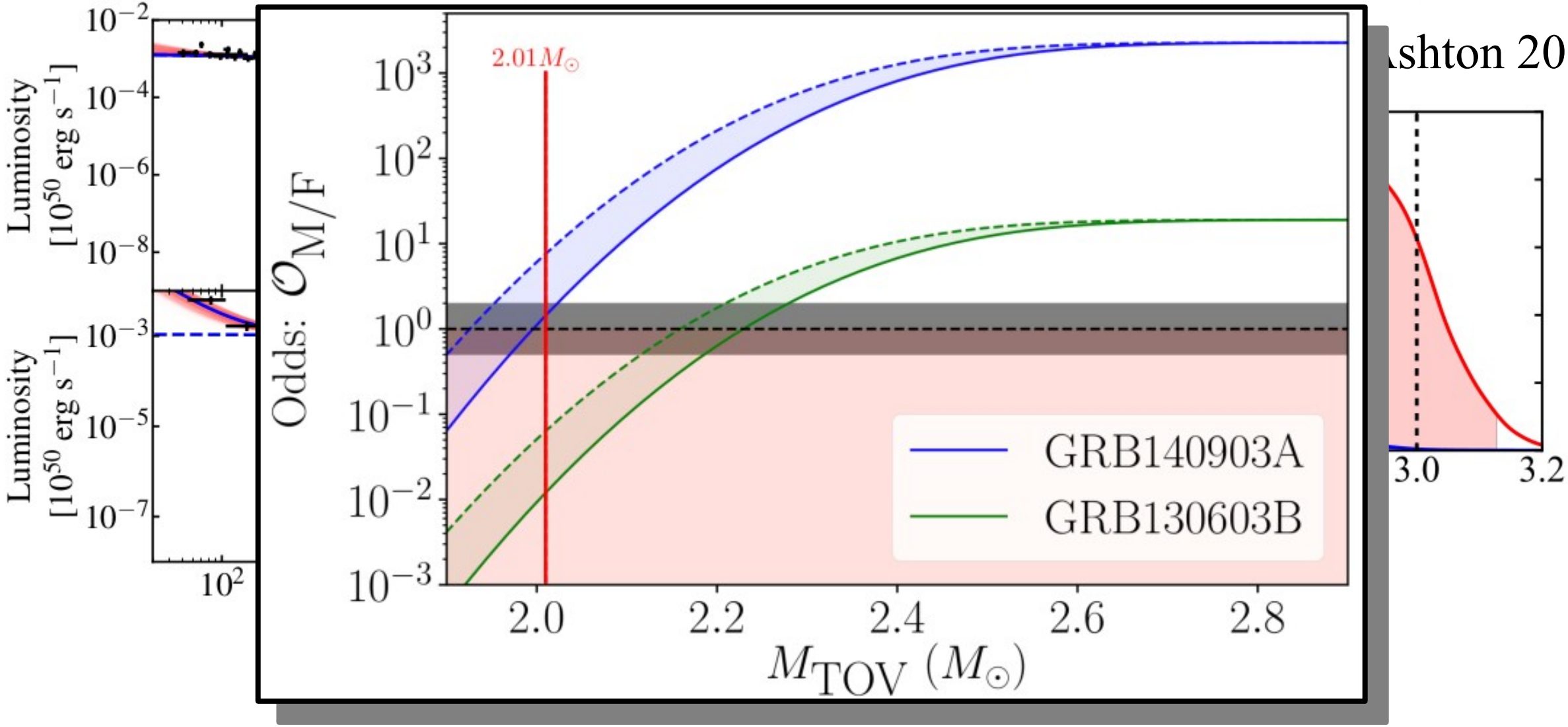


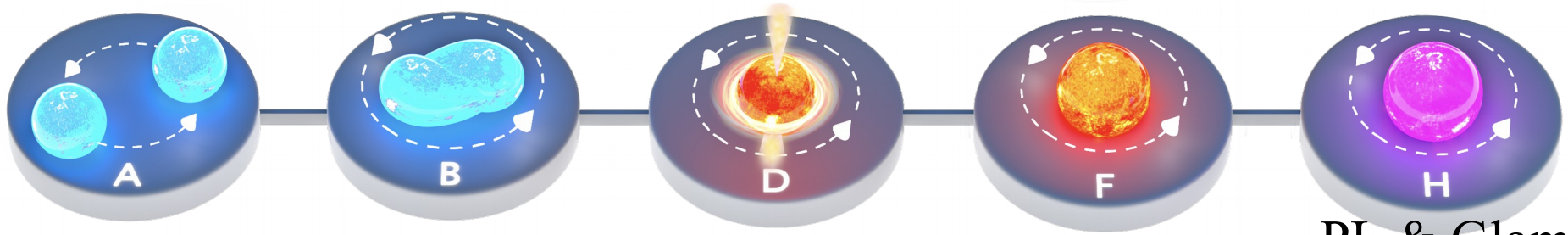
PL+2017, Sarin, PL, Ashton 2019



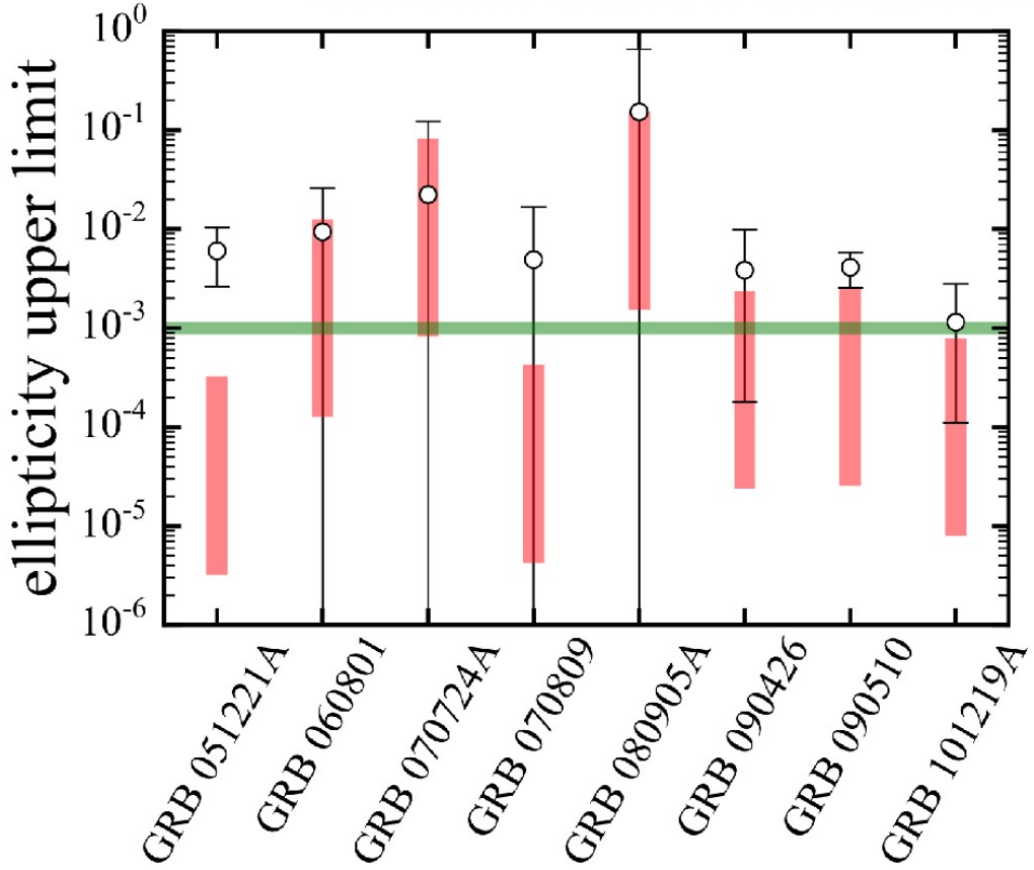

A
B
D
F
H

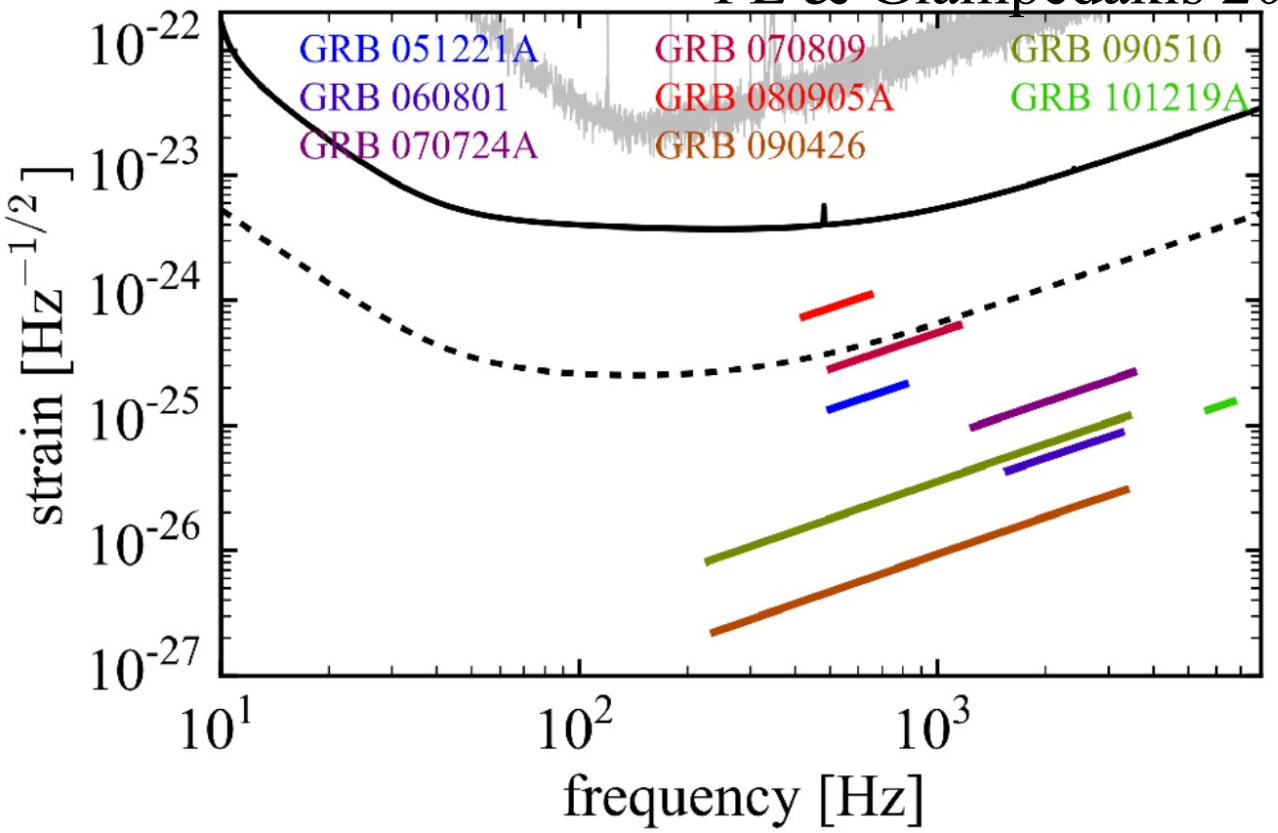
shton 2019


Luminosity [10^{50} erg s^{-1}]
10^{-2}
10^{-4}
10^{-6}
10^{-8}
Luminosity [10^{50} erg s^{-1}]
10^{-3}
10^{-5}
10^{-7}
10^{2}
Odds: $\mathcal{O}_{\rm M/F}$
$2.01M_\odot$
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
2.0
2.2
2.4
2.6
2.8
$M_{\rm TOV}$ $(M_\odot)$
GRB140903A
GRB130603B
3.0
3.2



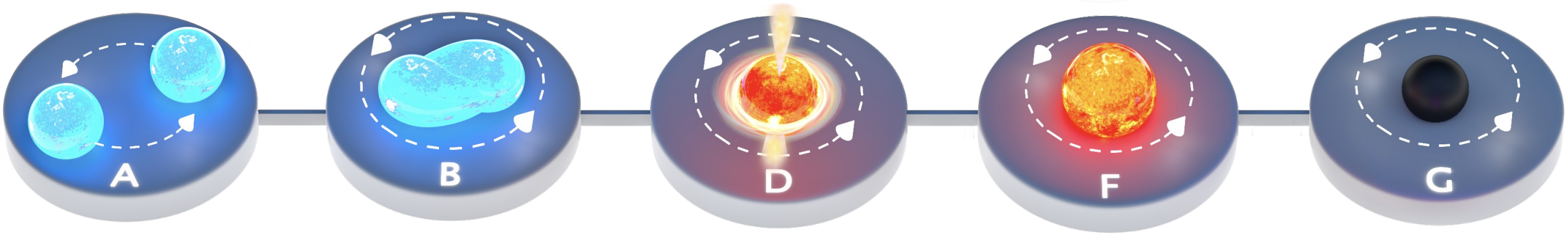
PL & Glampedakis 2016





GW detection? Not likely. (Sarin, PL+2018)

Horizon distance: aLIGO ~ 2 Mpc. Einstein telescope ~ 45 Mpc.


A
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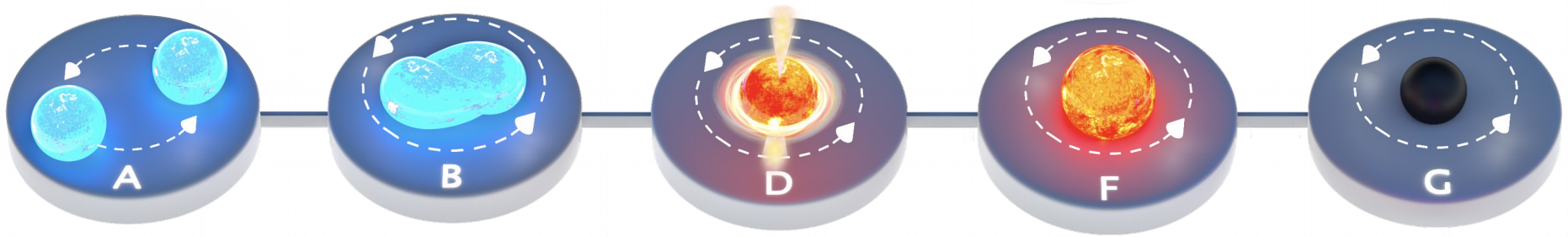
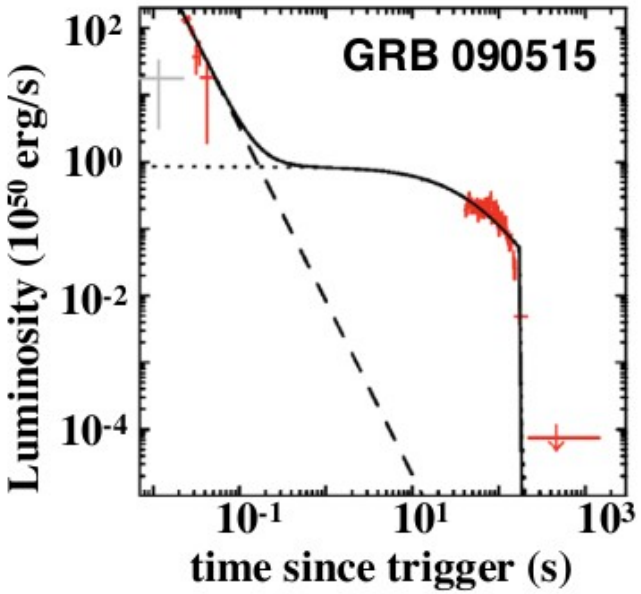
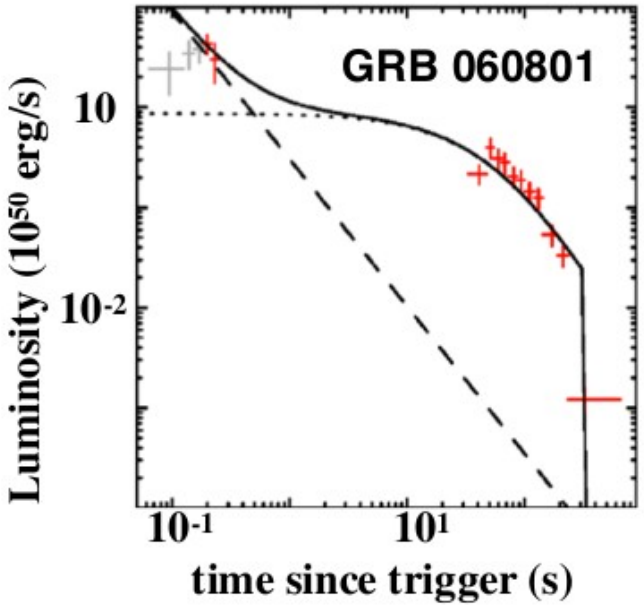
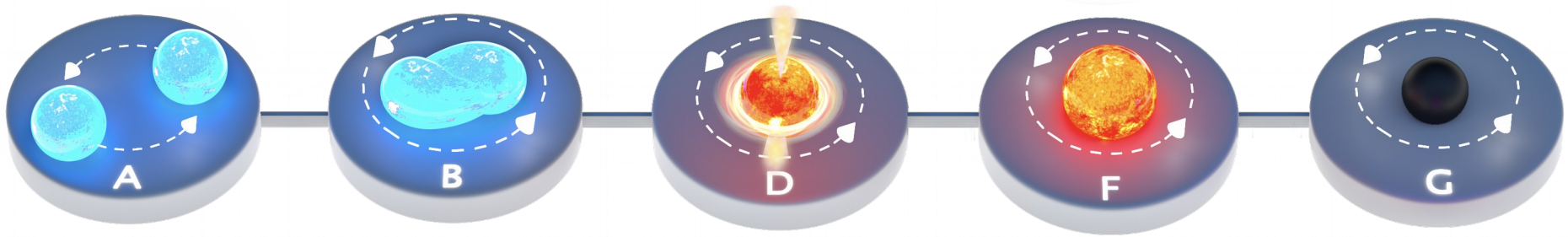
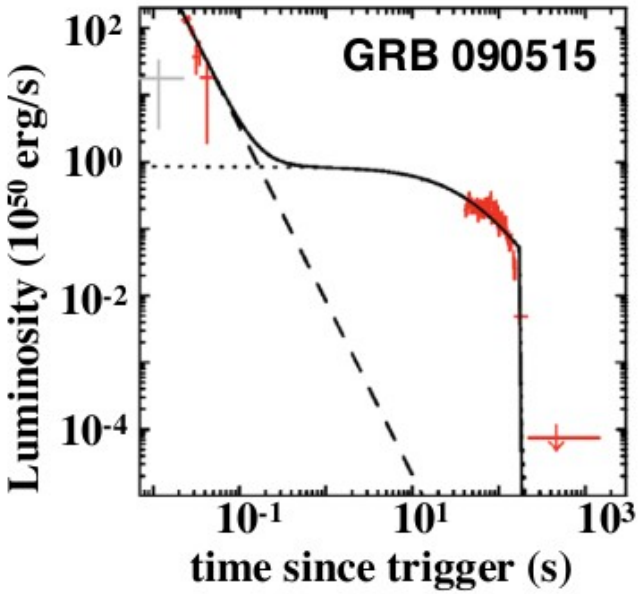


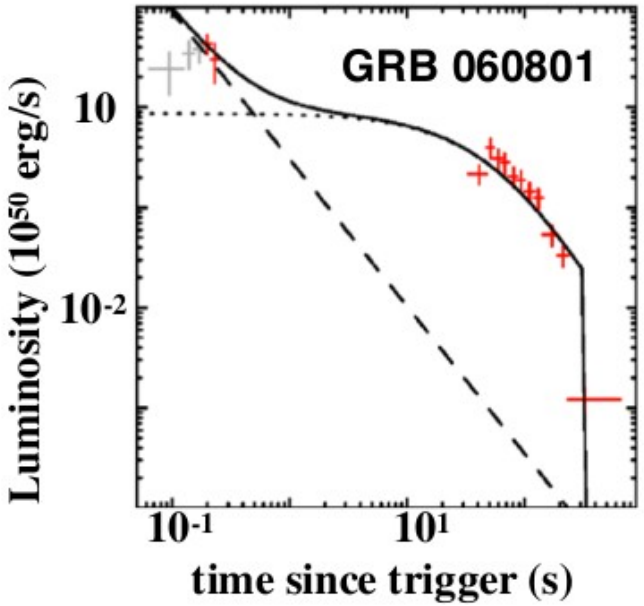




Rowlinson+2013







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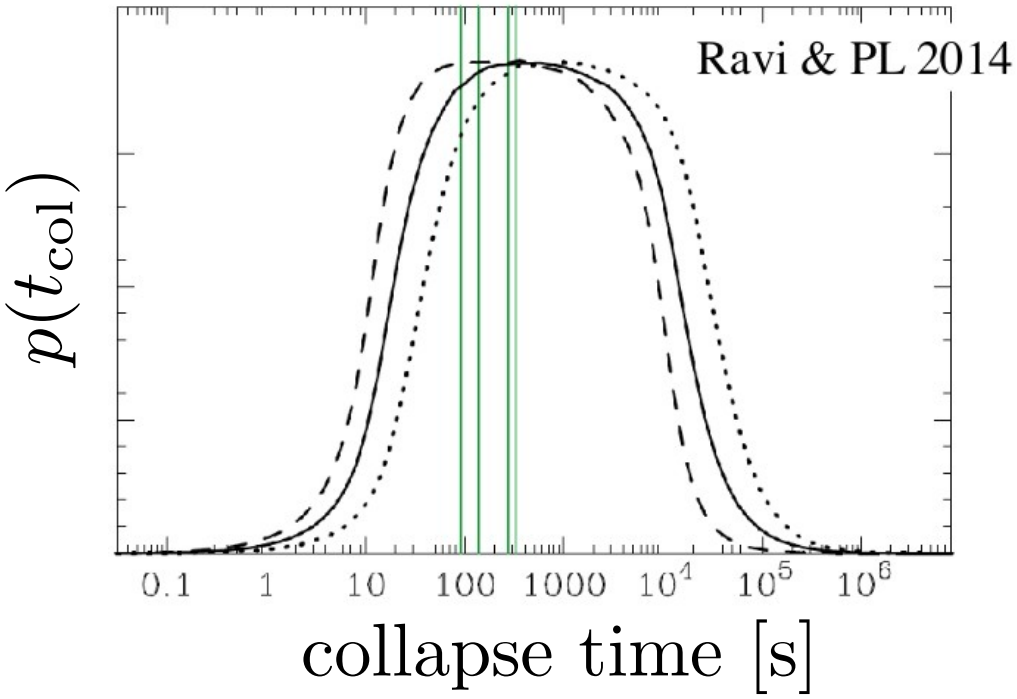
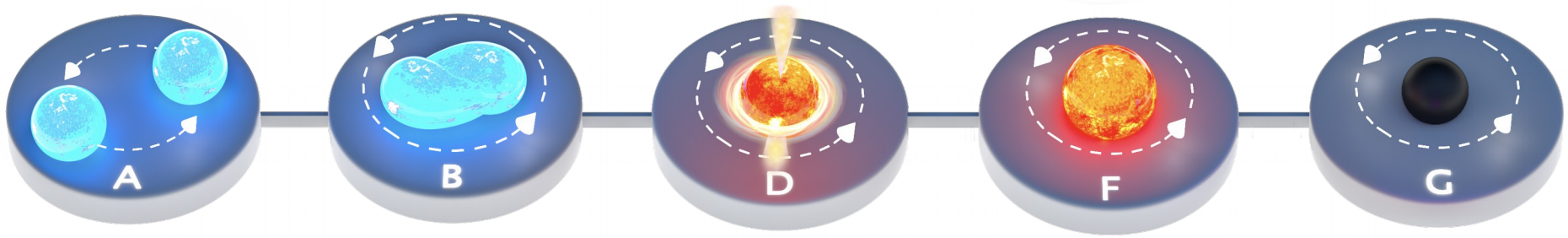


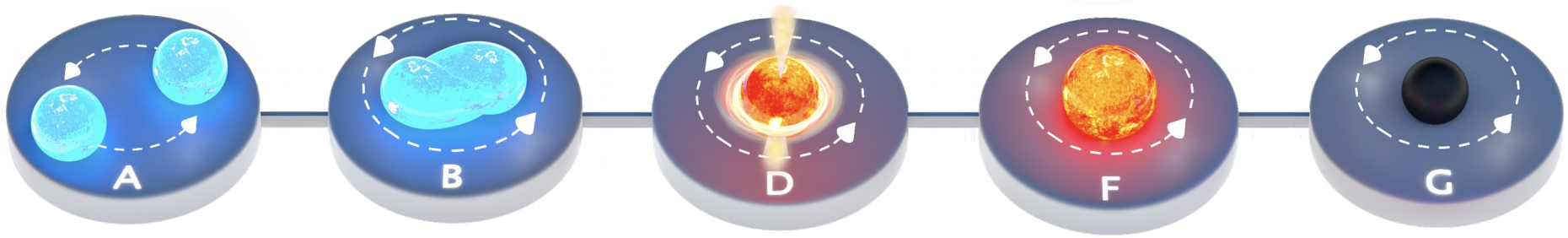
- Collapse times smaller than expected
  - Fan+2013, Ravi & PL 2014
- Equation of state or gravitational-wave emission?
  - PL+2014, Gao+2016, Li+2016, ...



Gravitational waves or deconfined quarks?

What causes the premature collapse of neutron stars born in short gamma-ray bursts?

Sarin, PL & Ashton 2020



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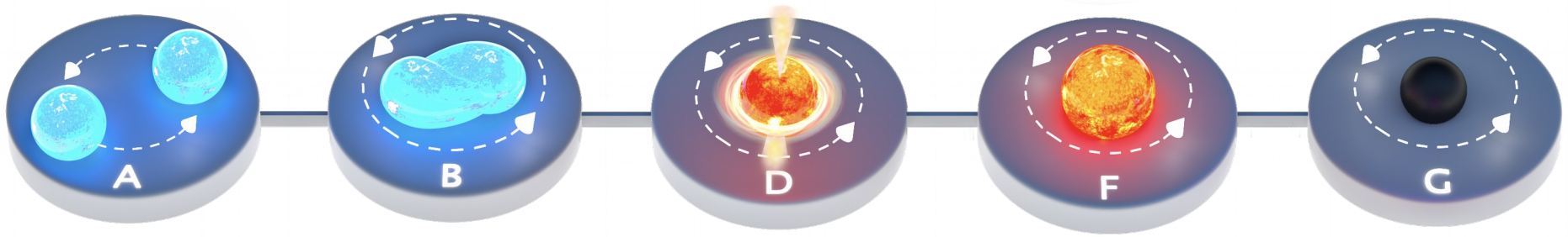

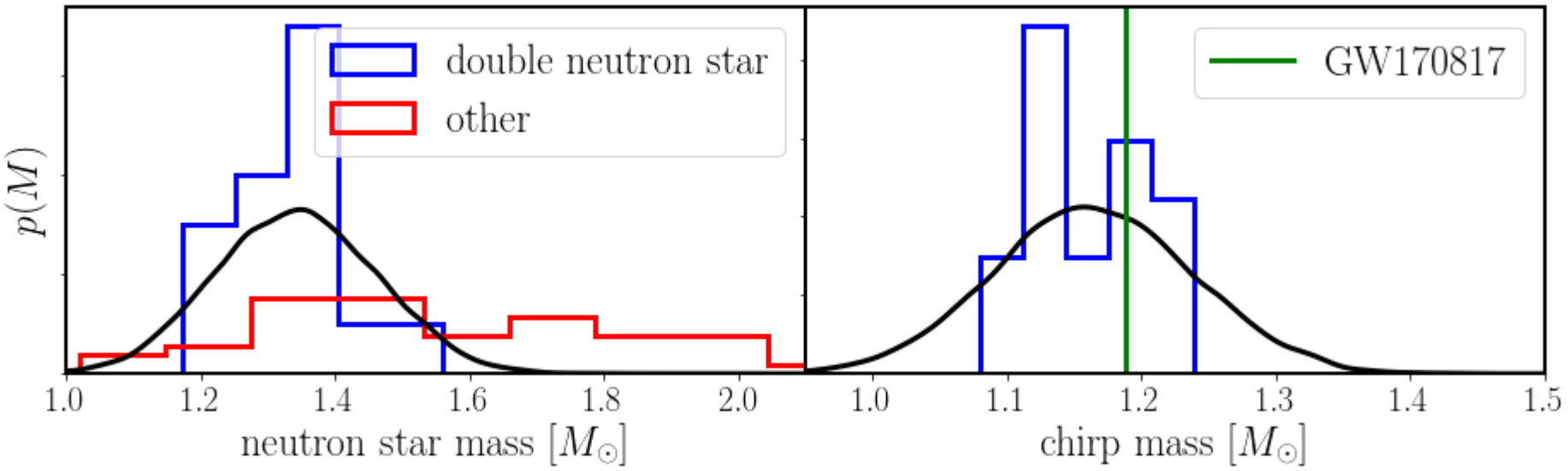

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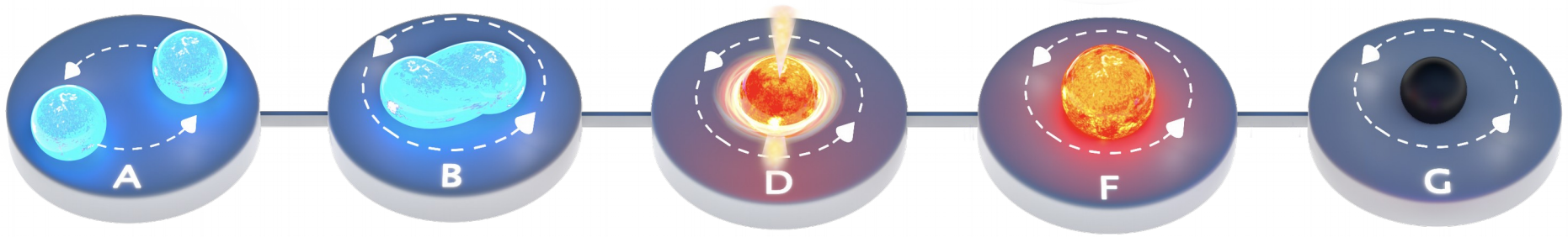

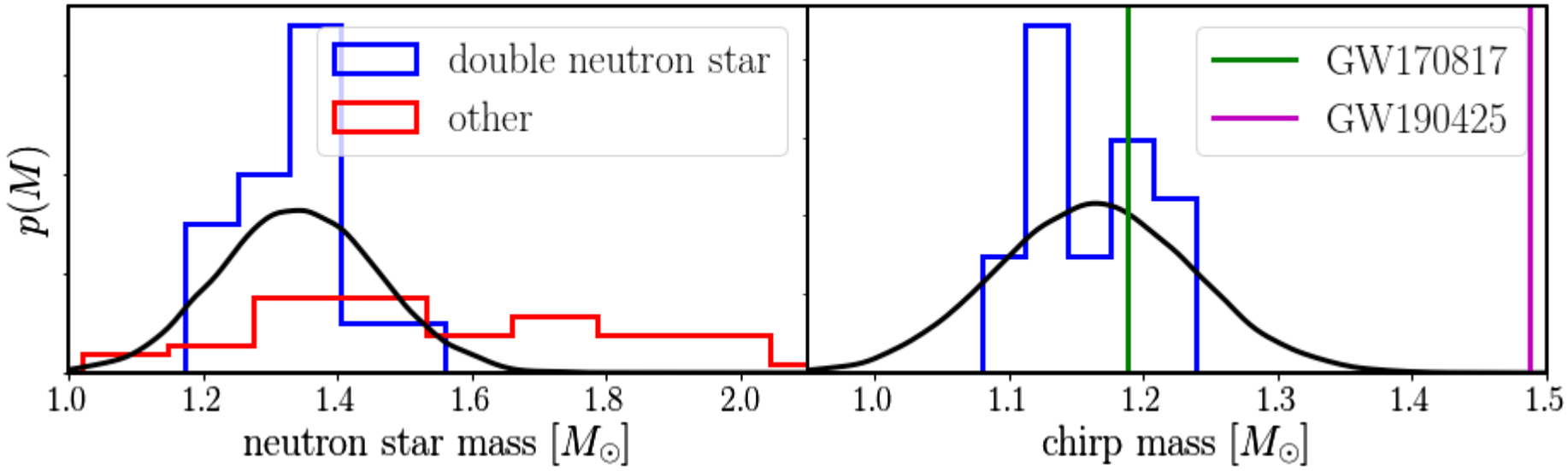

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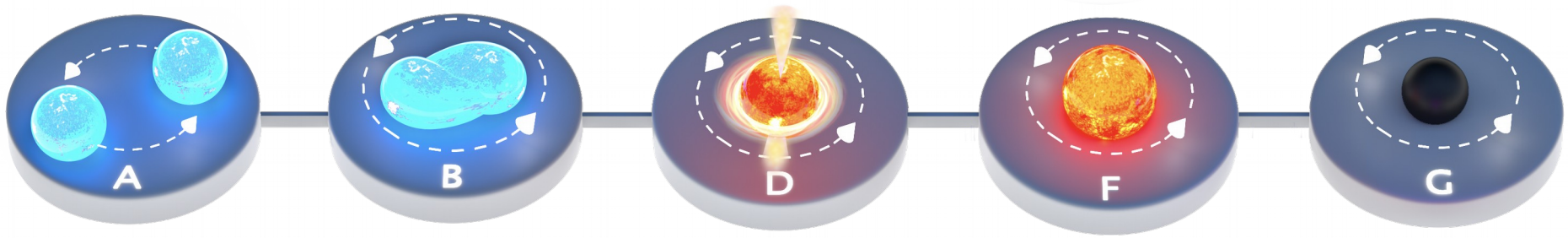
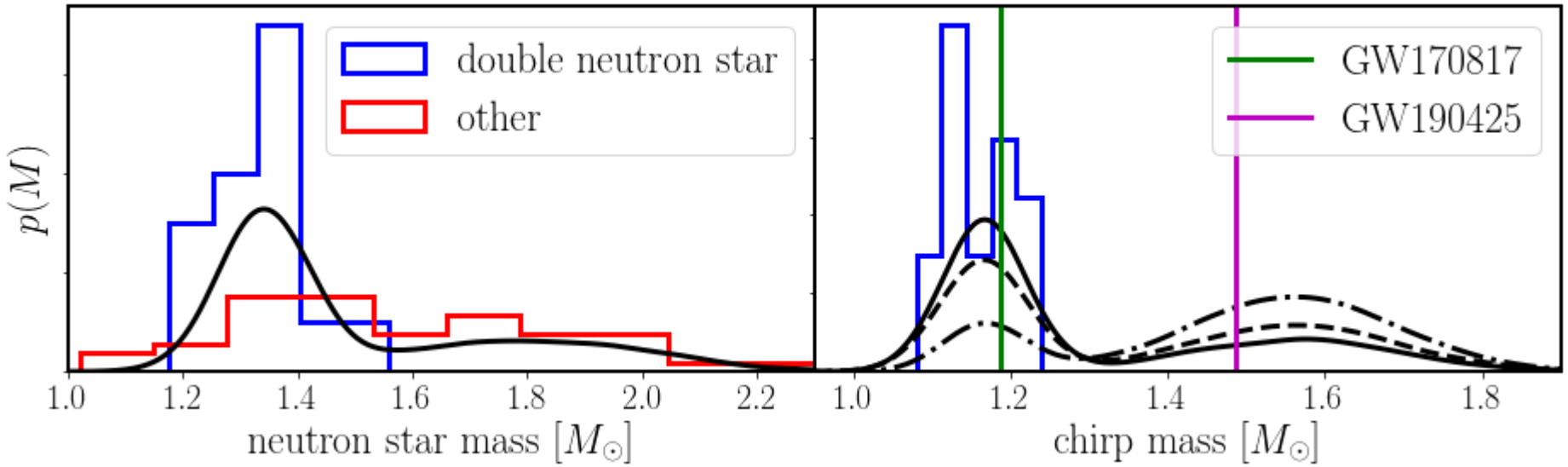
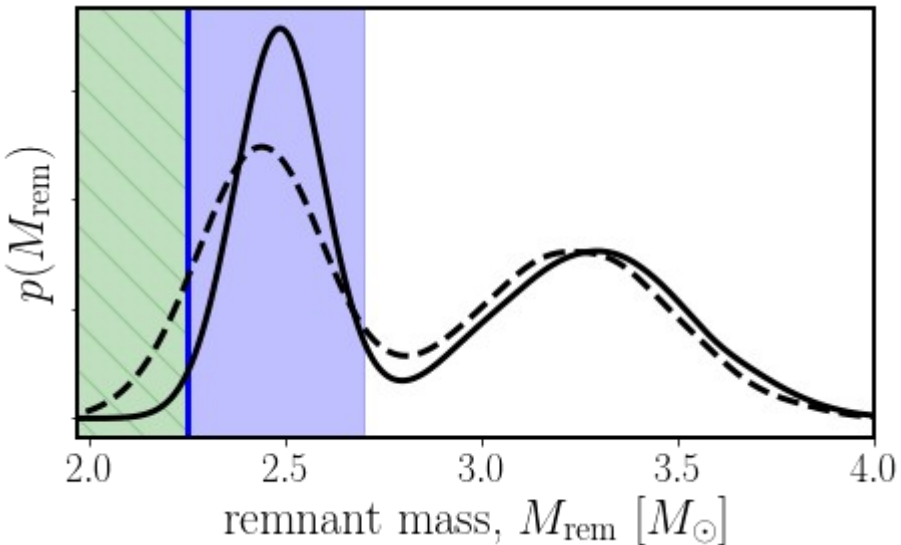
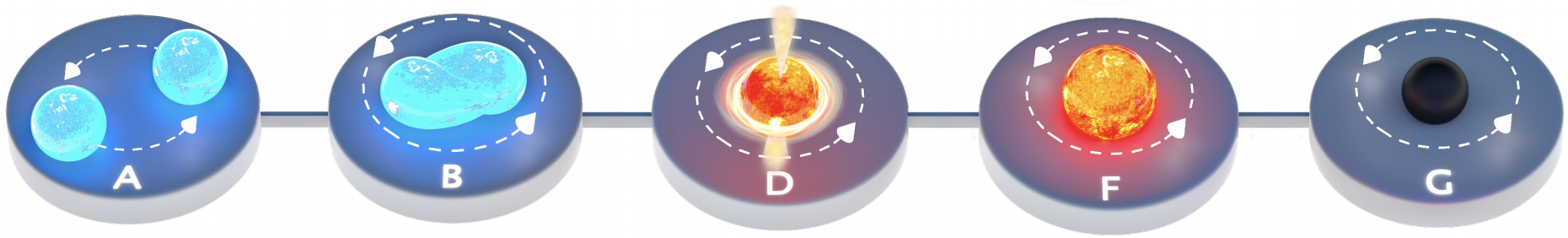




Sarin, PL & Ashton 2020





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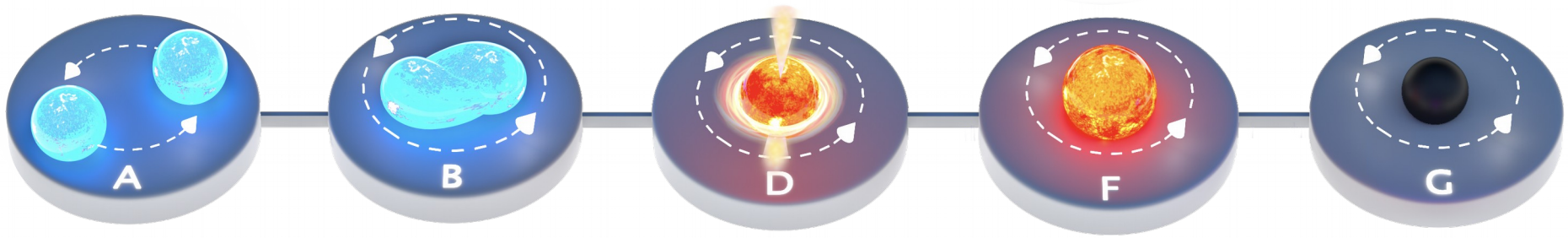

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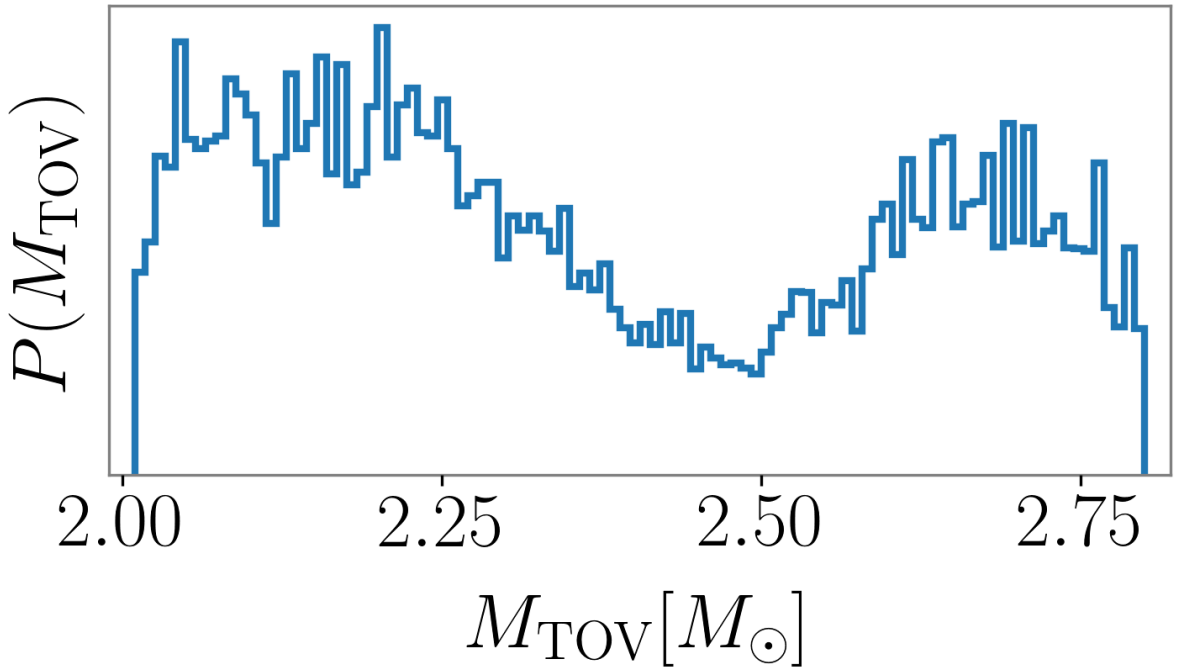
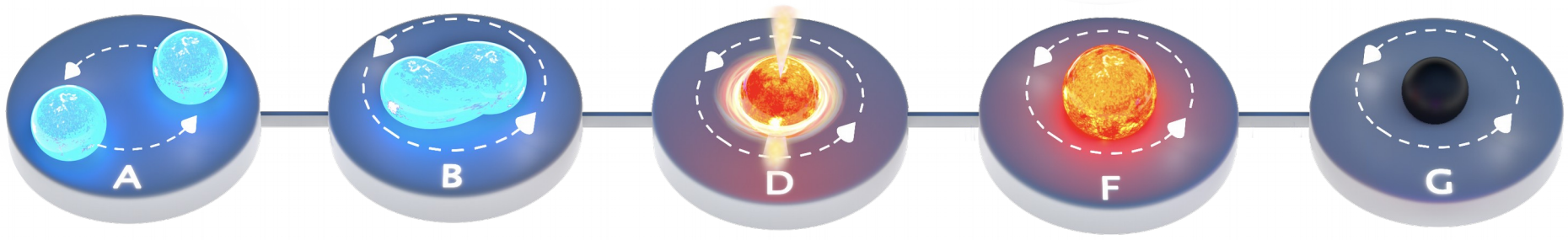


- Weak constraints – largely because unknown progenitor mass distribution.
- If assume GW190425 *not* a neutron star merger: $M_{\rm TOV} = 2.26^{+0.31}_{-0.17}\,M_\odot$
- More gravitational-wave observations → better constraints!

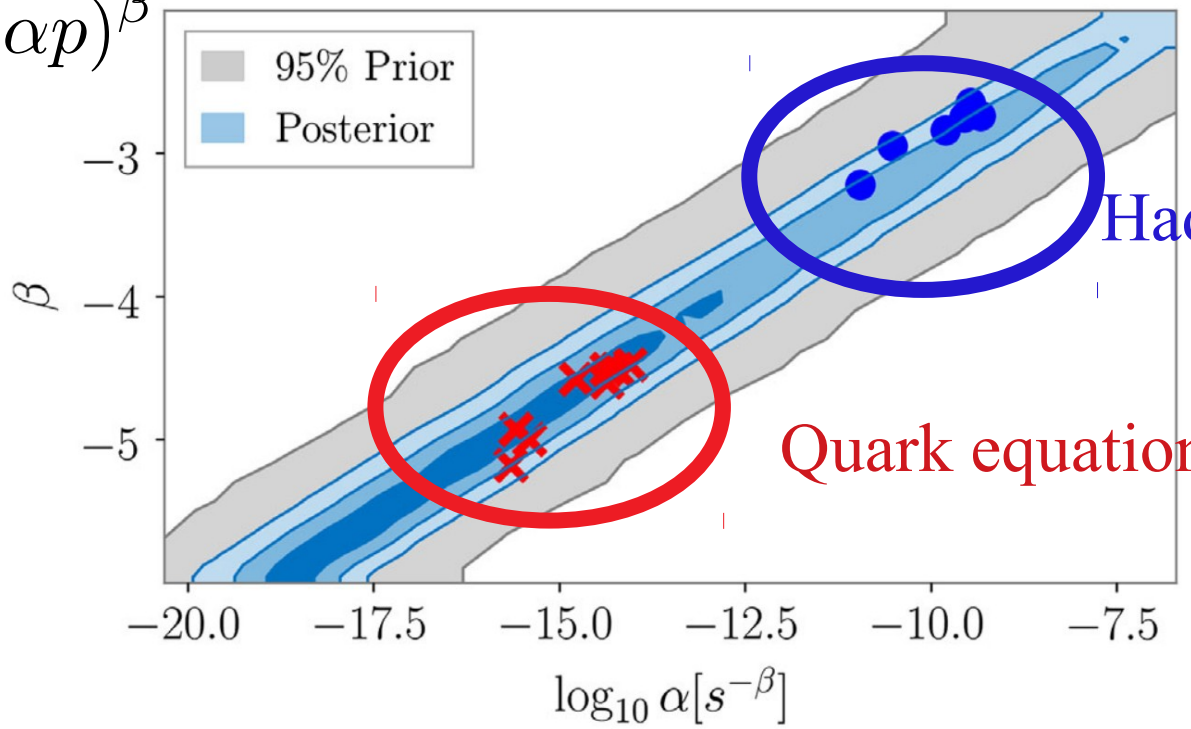


Gravitational waves or deconfined quarks?

What causes the premature collapse of neutron stars born in short gamma-ray bursts?

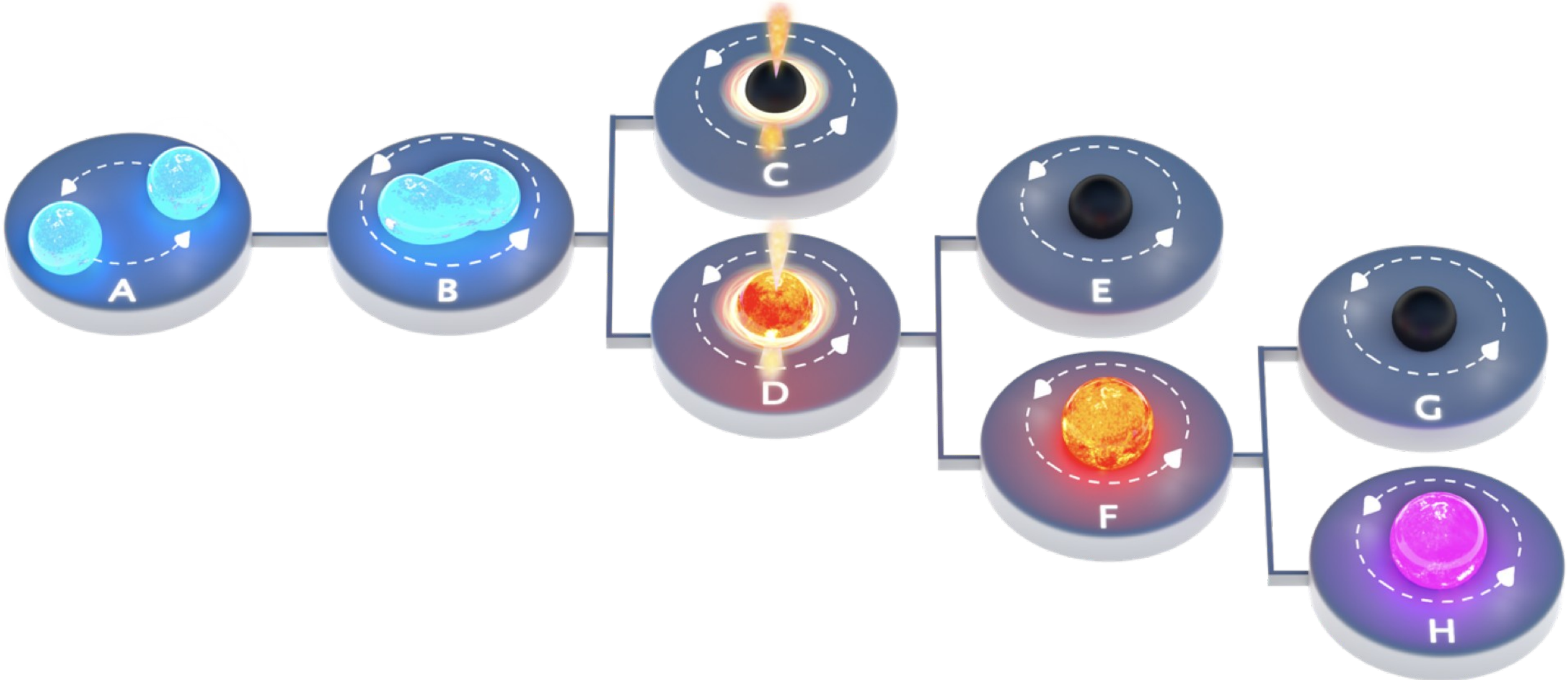
$$M_{\max} = M_{\mathrm{TOV}} \left(1 + \alpha p\right)^{\beta}$$

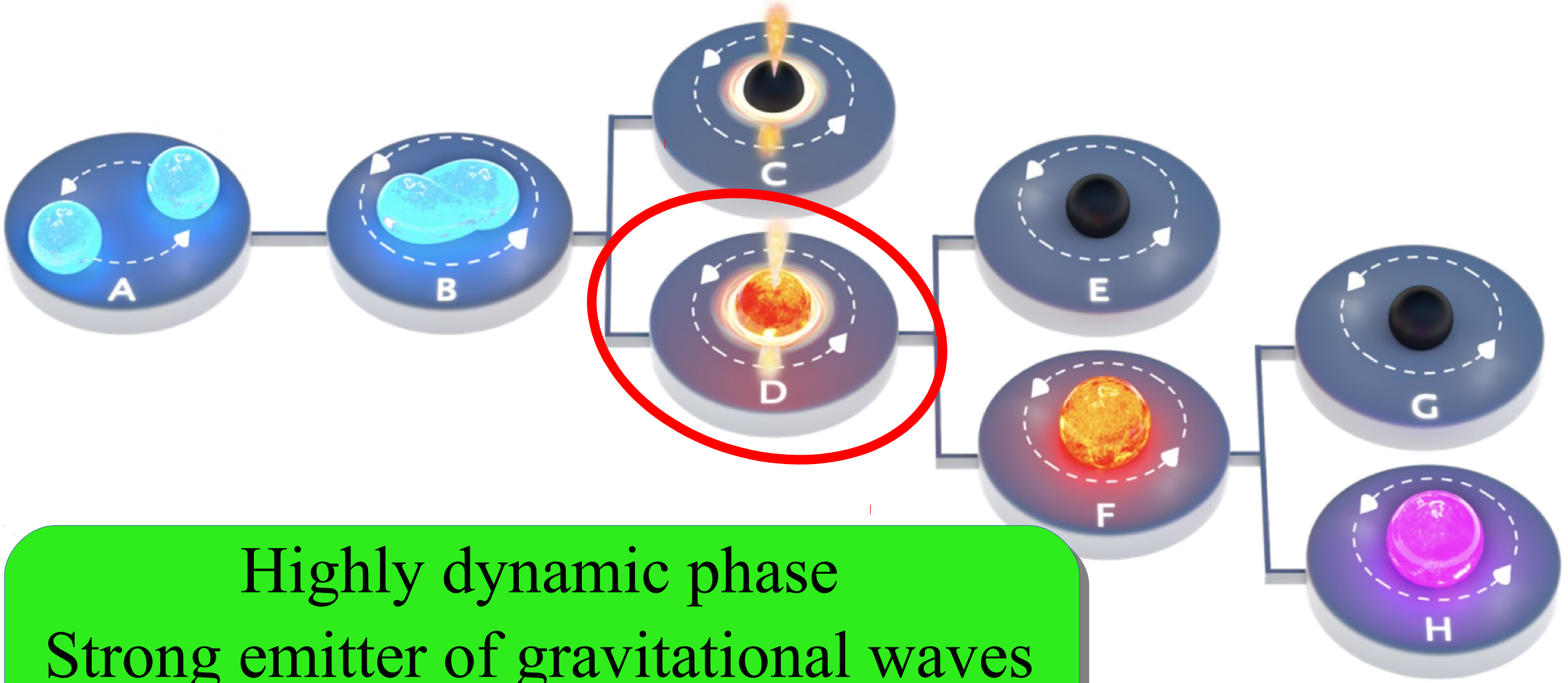
Sarin, PL & Ashton 2020



Hadronic equations of state

Quark equations of state

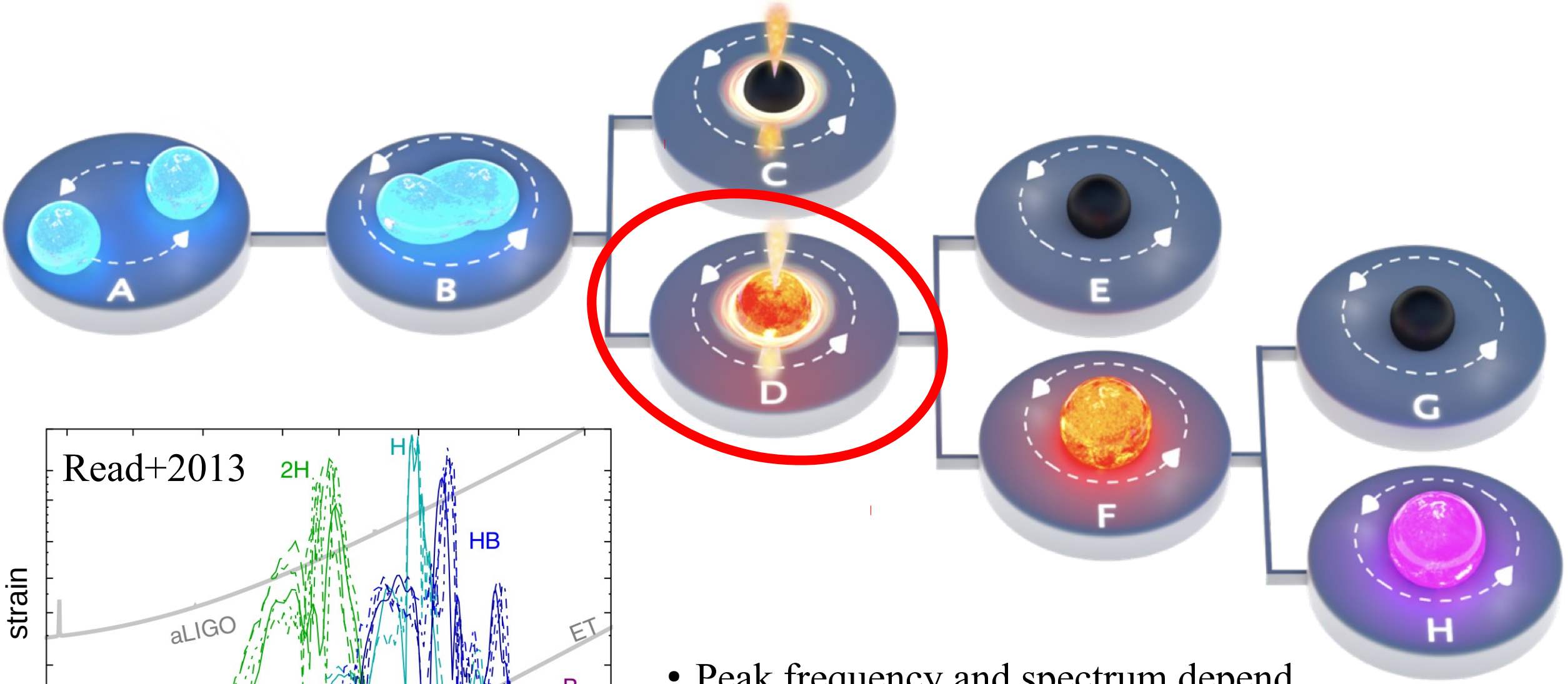

A
B
C
D
E
F
G
H



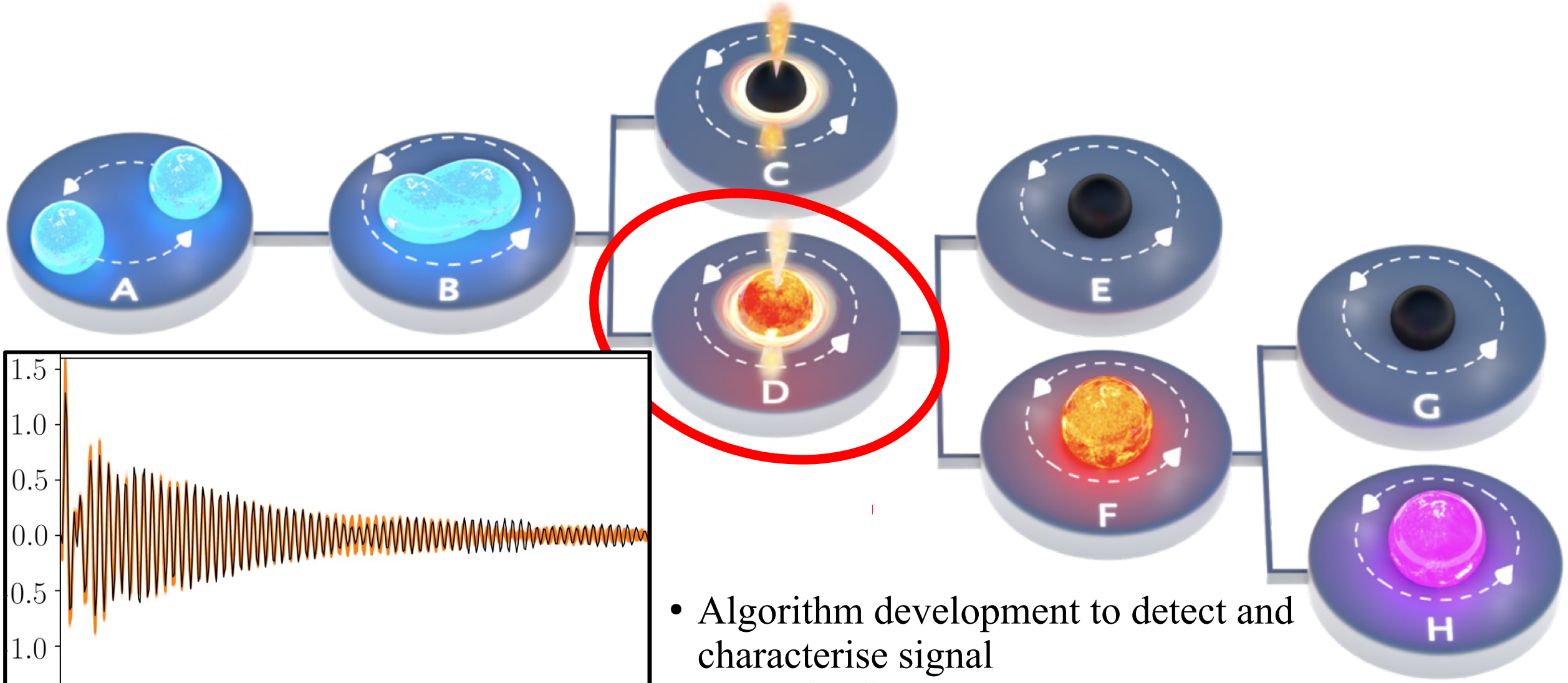
Highly dynamic phase

Strong emitter of gravitational waves

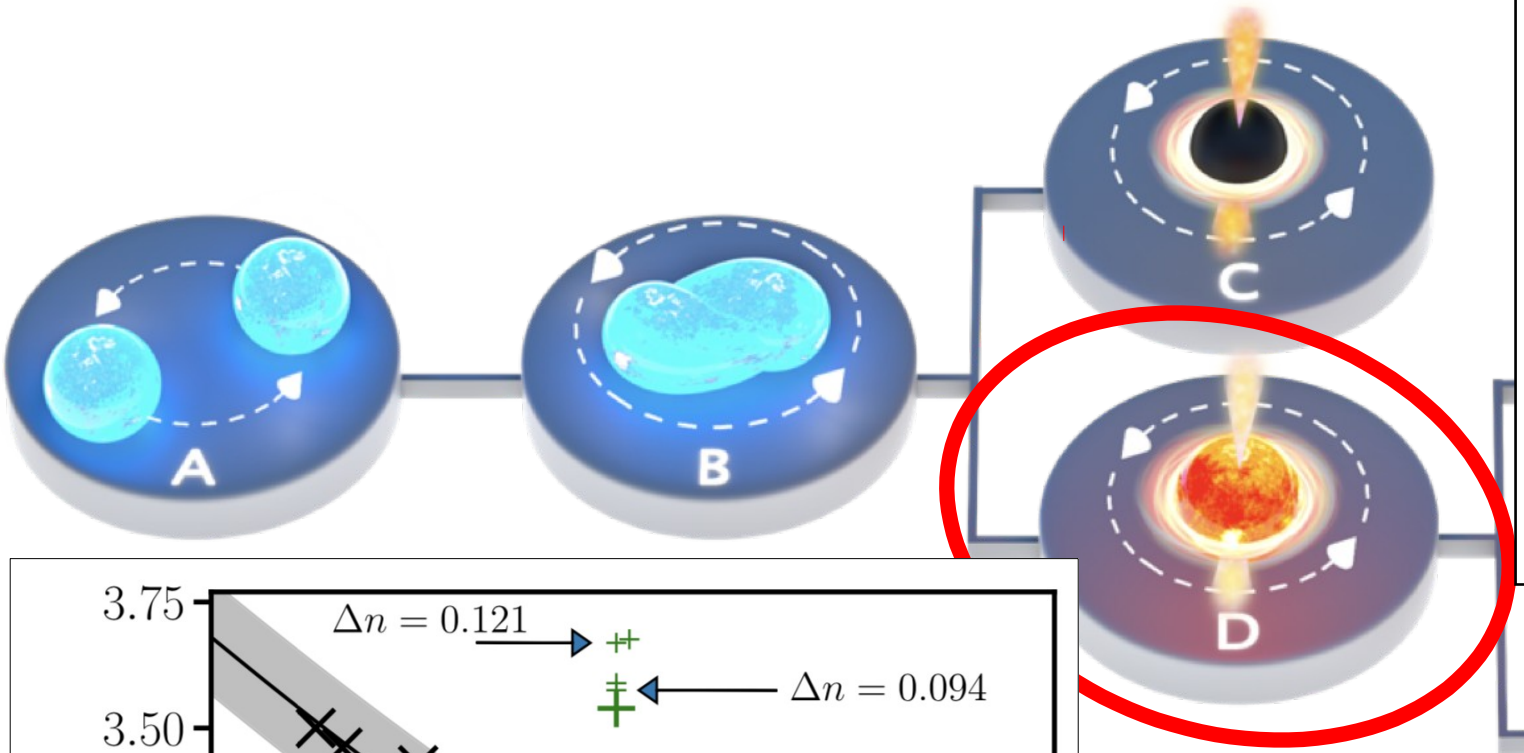
Measure the HOT equation of state here

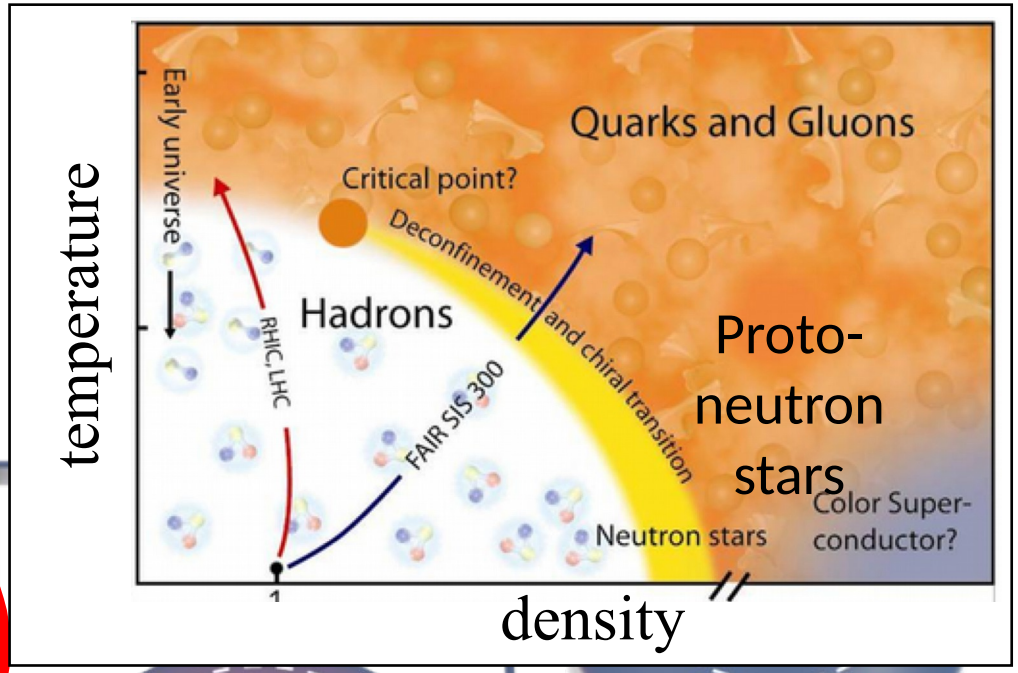


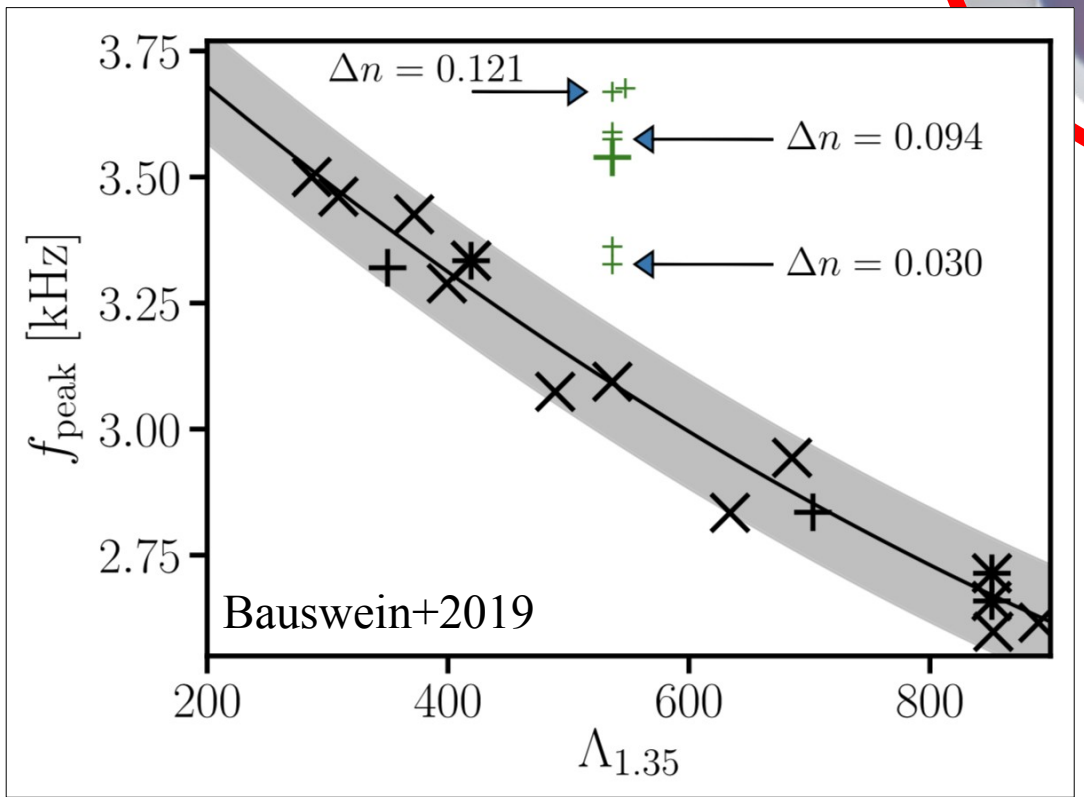
- Peak frequency and spectrum depend sensitively on the equation of state!

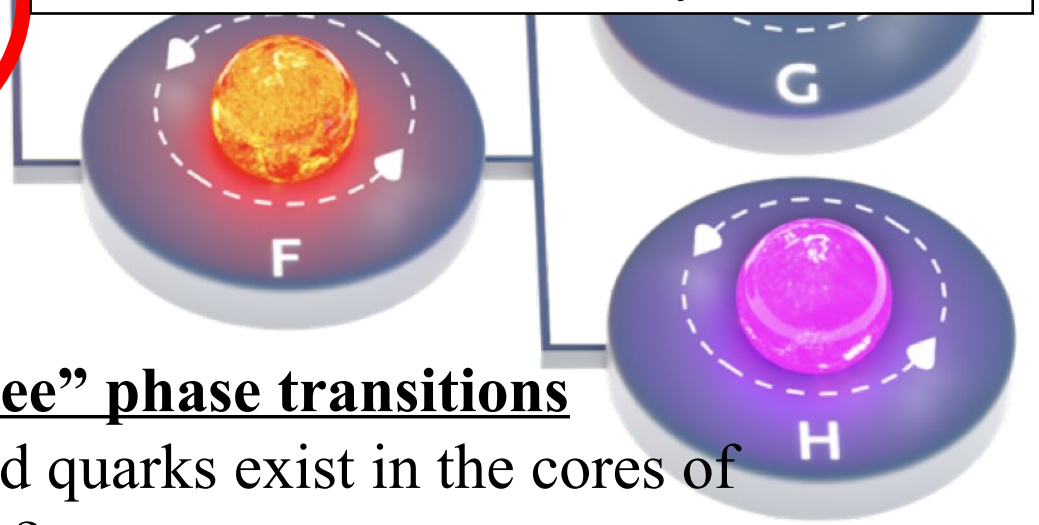


- Algorithm development to detect and characterise signal
  - e.g., chatziioannou+2017; Easter, PL+ 2018; Easter, Ghonge, PL+2020



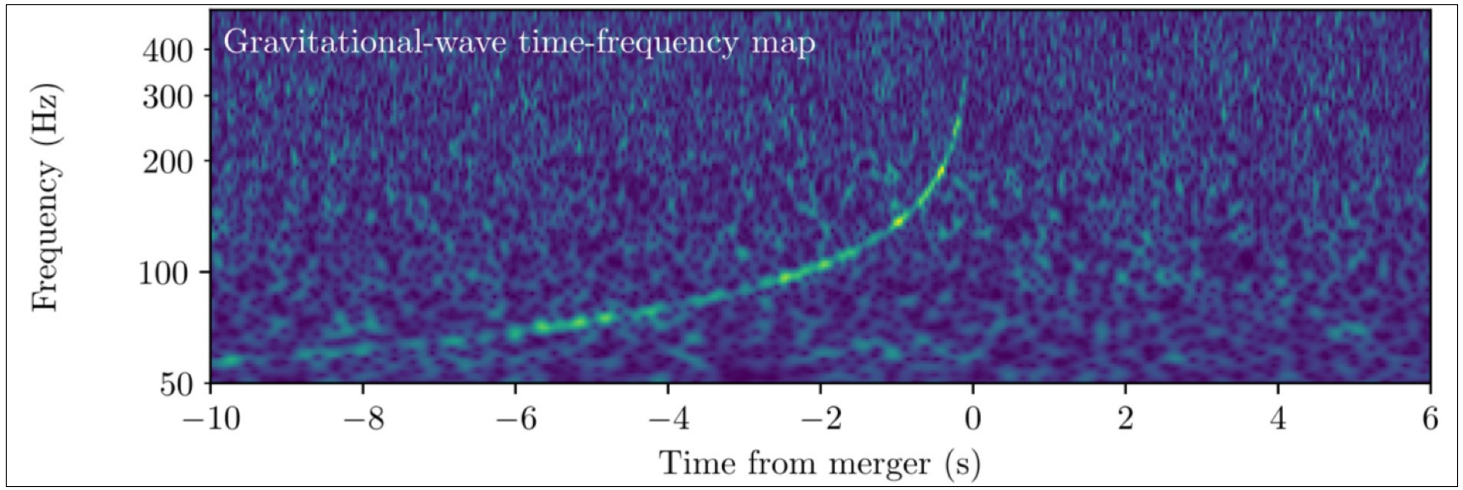






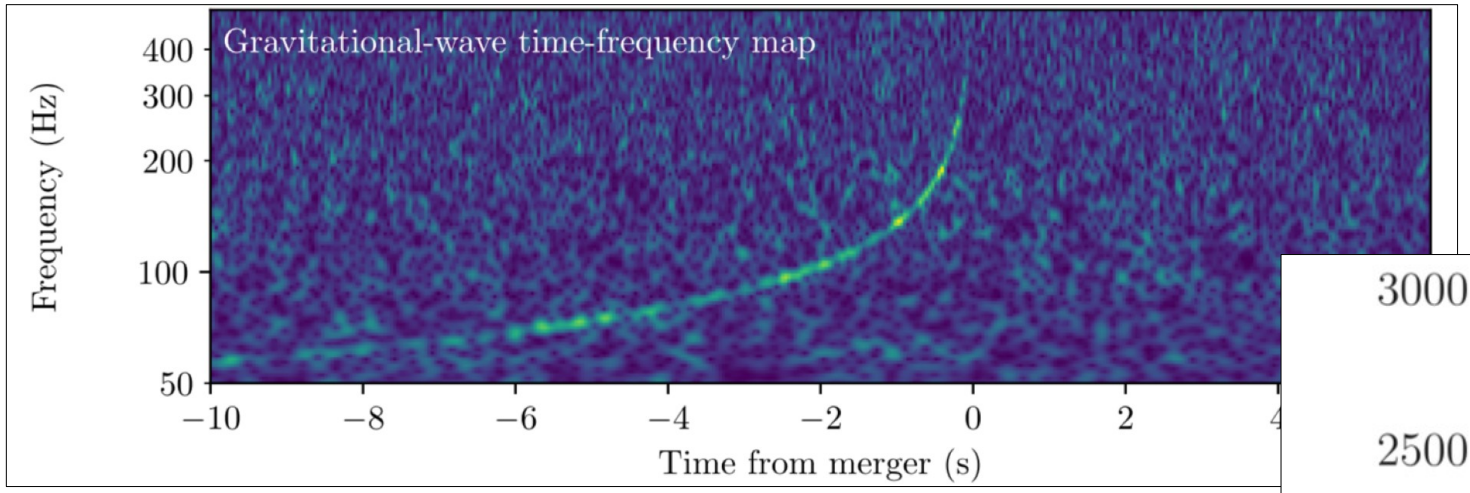
Potential to "see" phase transitions

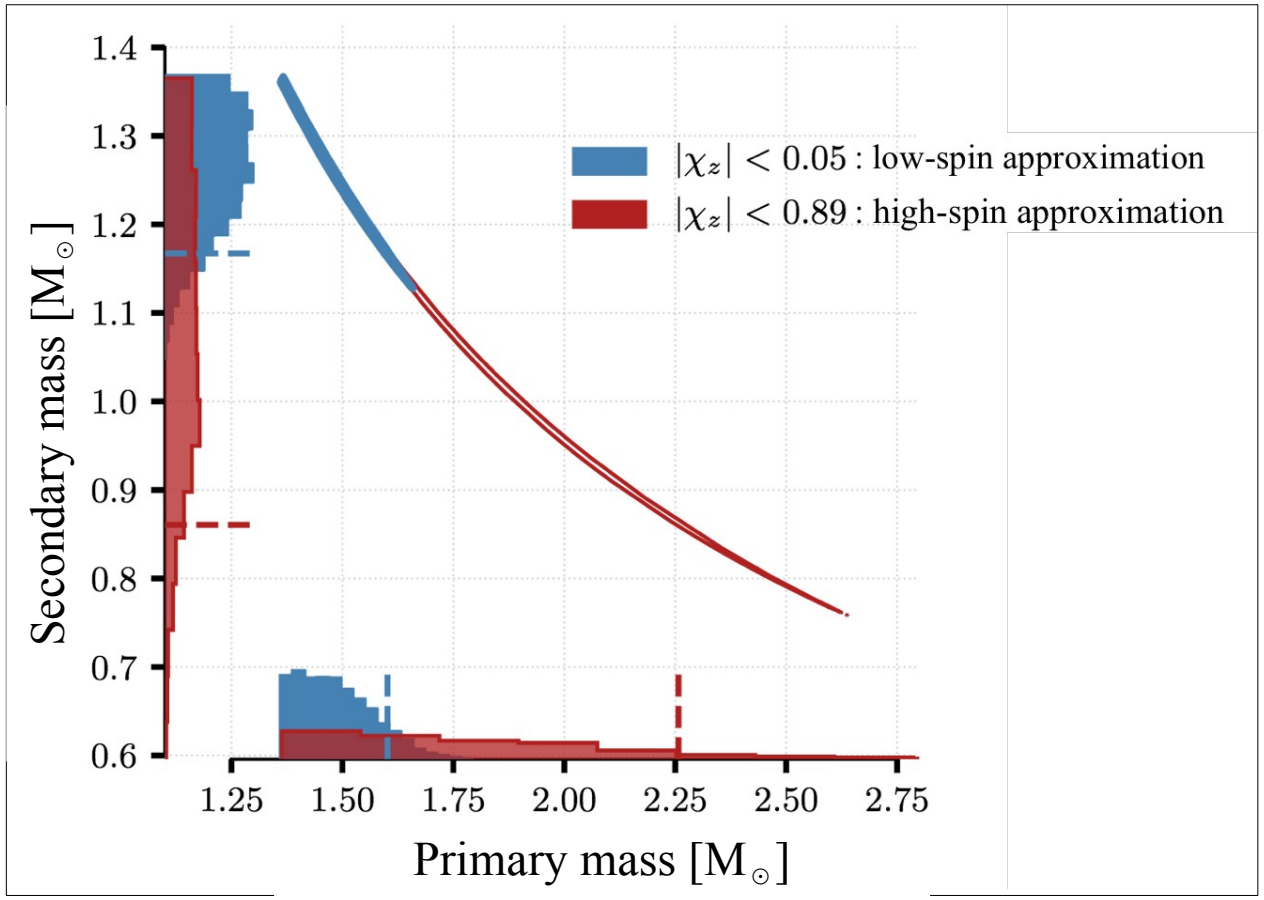
- Do deconfied quarks exist in the cores of neutron stars?
- Hyperons, ….
- See Bauswein+2019

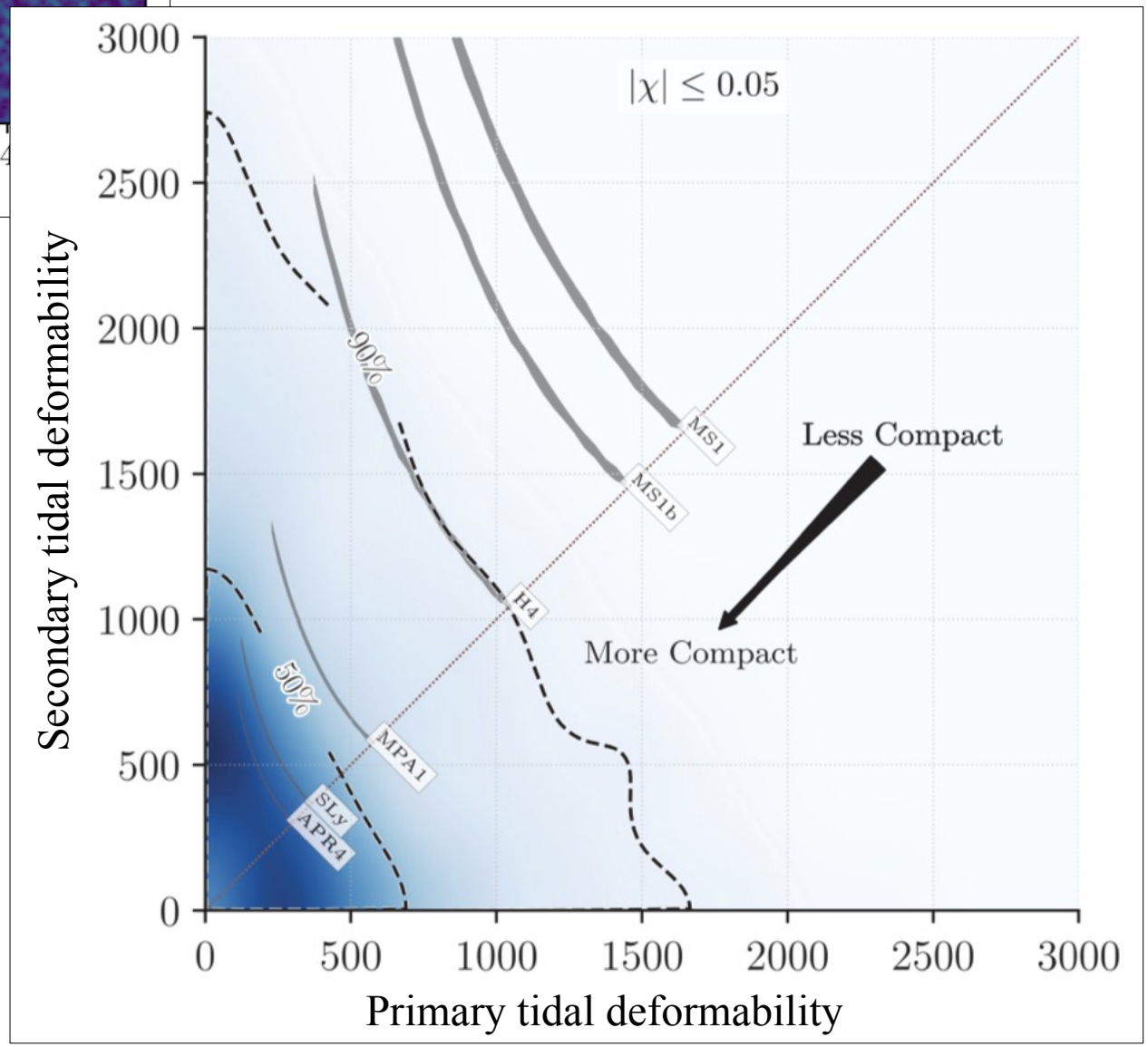

Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)

GW170817

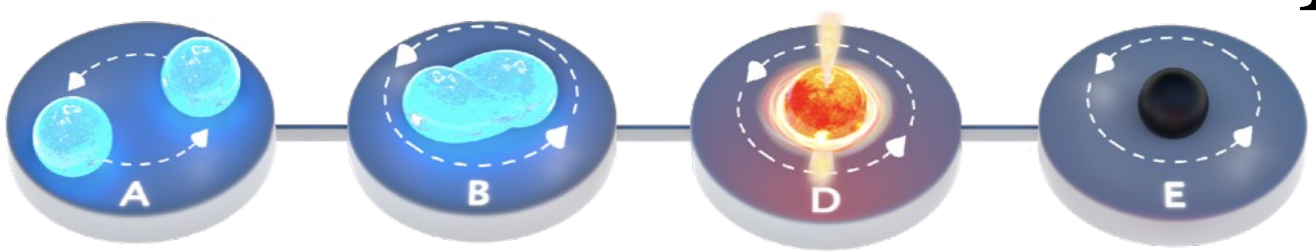
GW170817


Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
Time from merger (s)

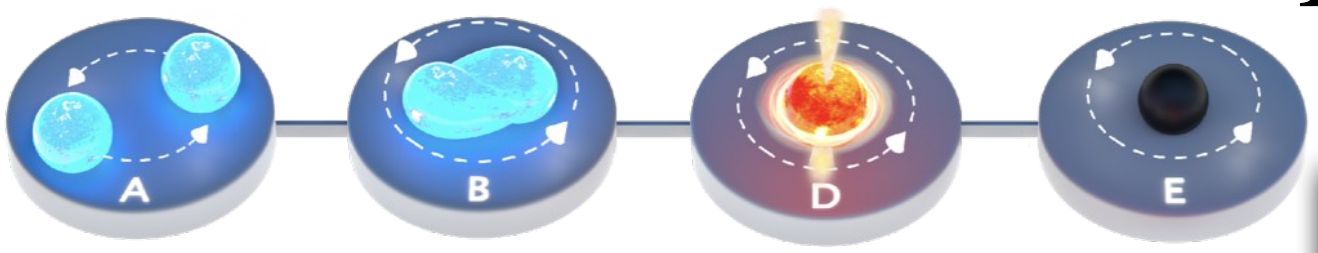

$|\chi_z| < 0.05$: low-spin approximation
$|\chi_z| < 0.89$: high-spin approximation
Secondary mass [$M_\odot$]
Primary mass [$M_\odot$]
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
1.25
1.50
1.75
2.00
2.25
2.50
2.75


$|\chi| \leq 0.05$
90%
50%
MS1
MS1b
H4
MPA1
SLy
APR4
Less Compact
More Compact
Secondary tidal deformability
Primary tidal deformability
3000
2500
2000
1500
1000
500
0

GW170817: post merger

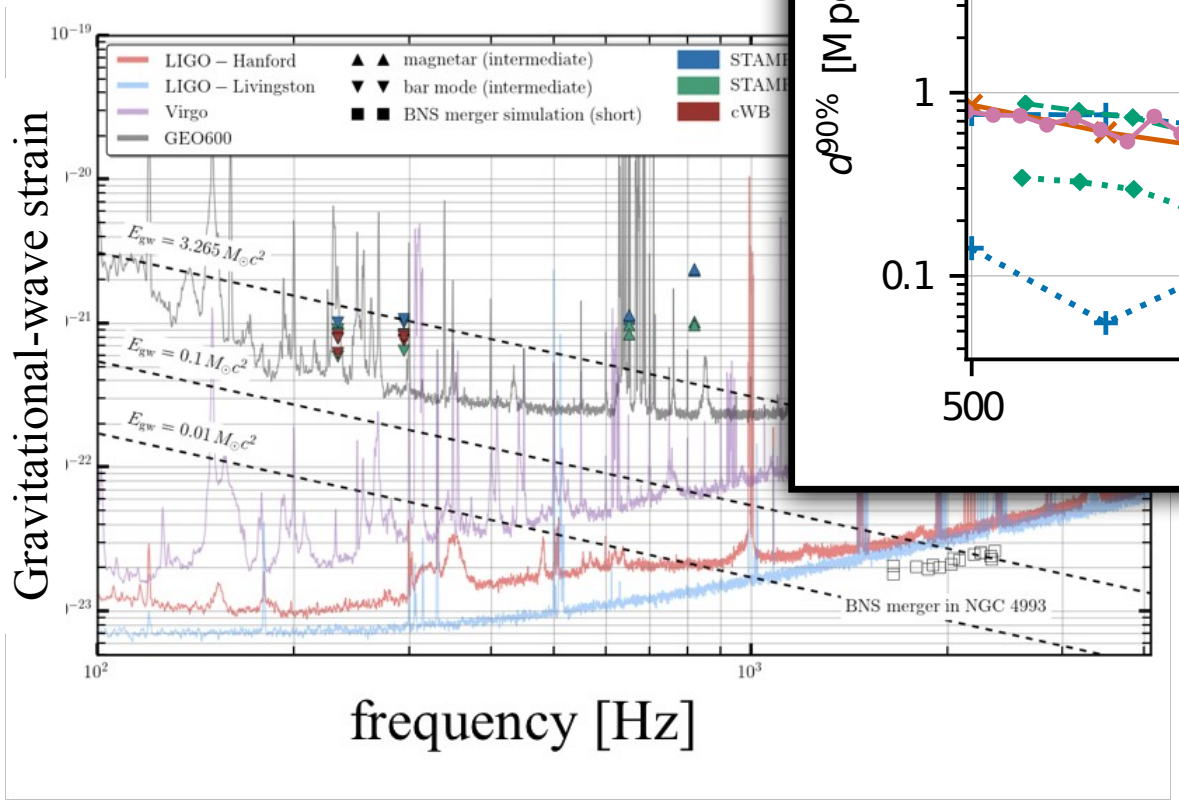


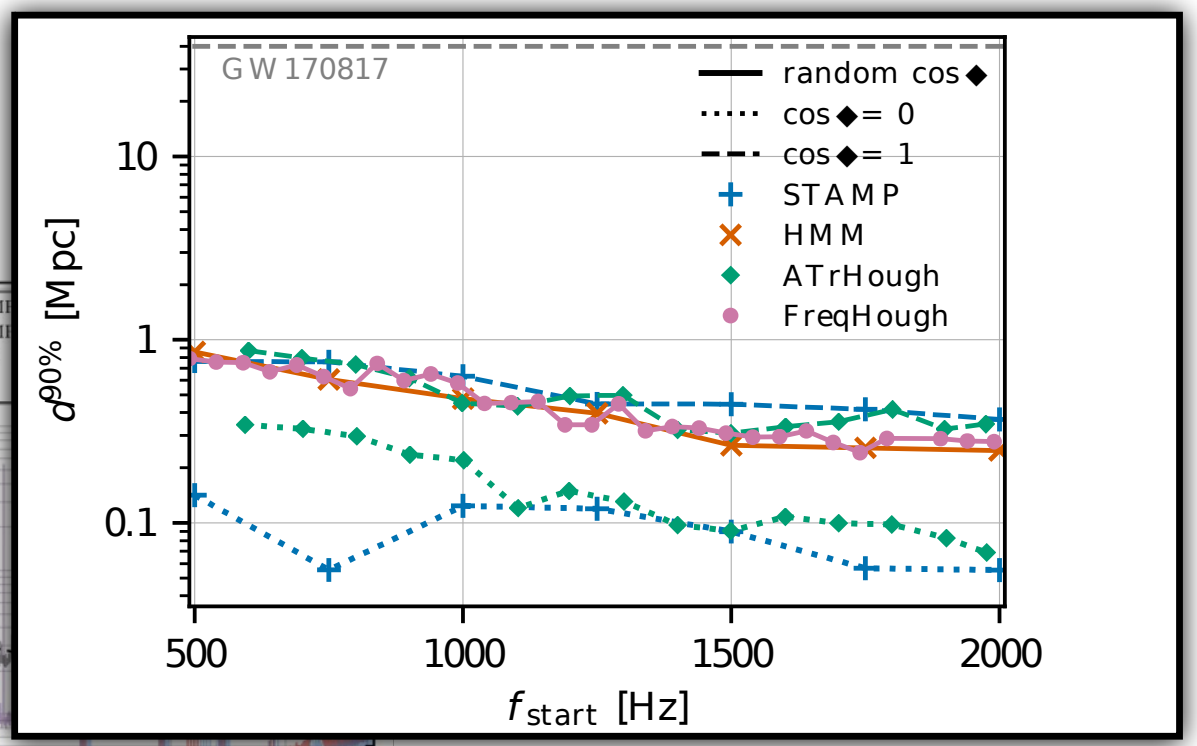
GW170817: post merger



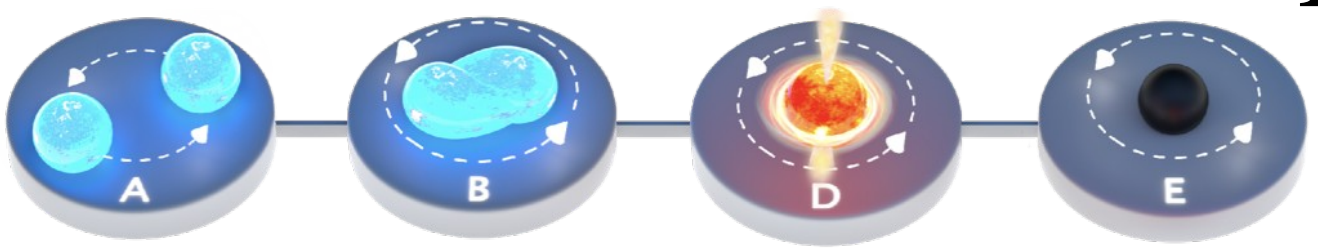
Abbott+2017, 2019

- No gravitational waves
  (not surprising)

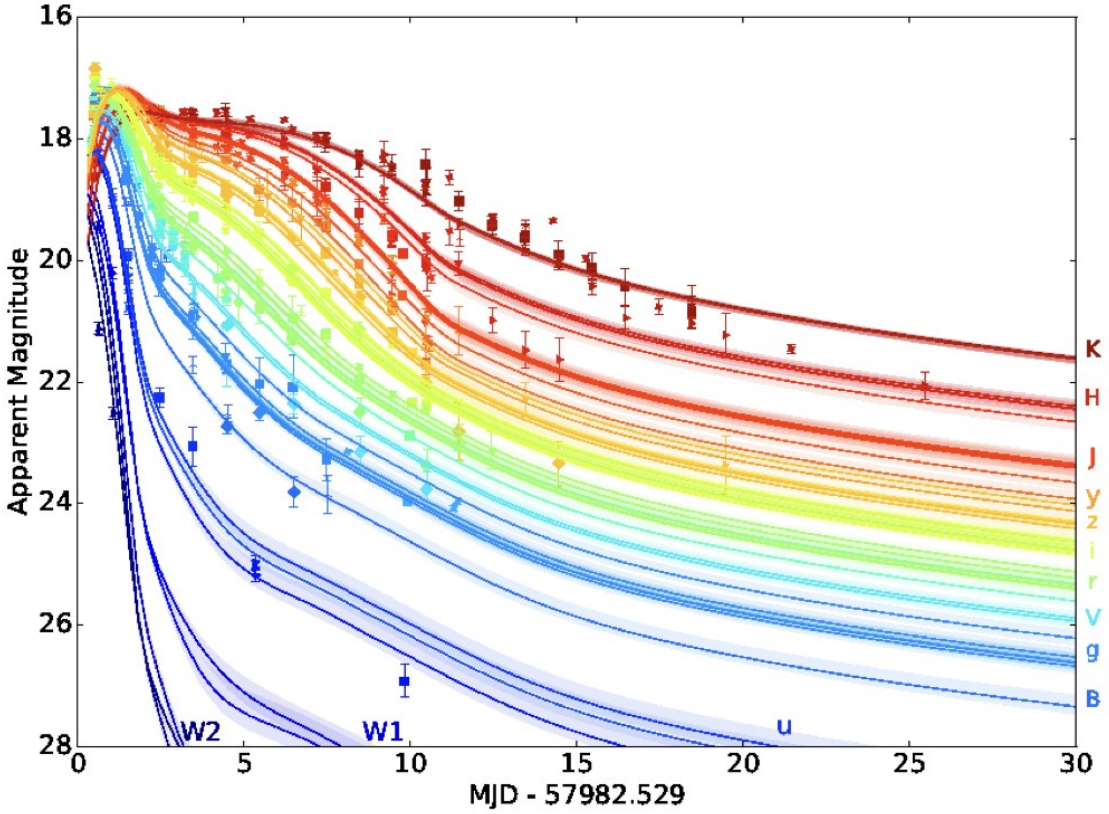




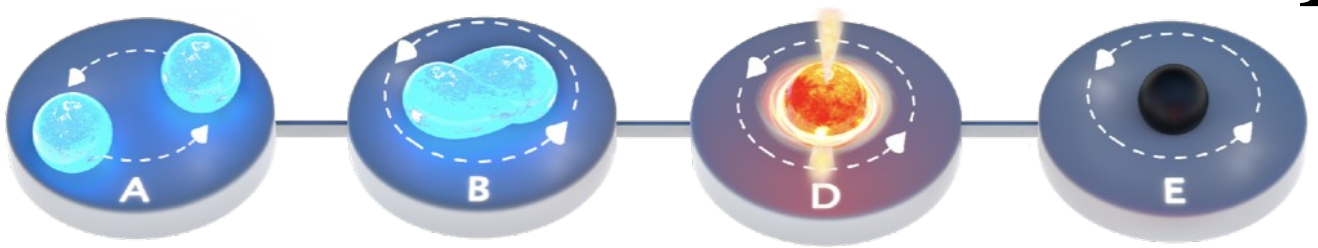
GW170817: post merger



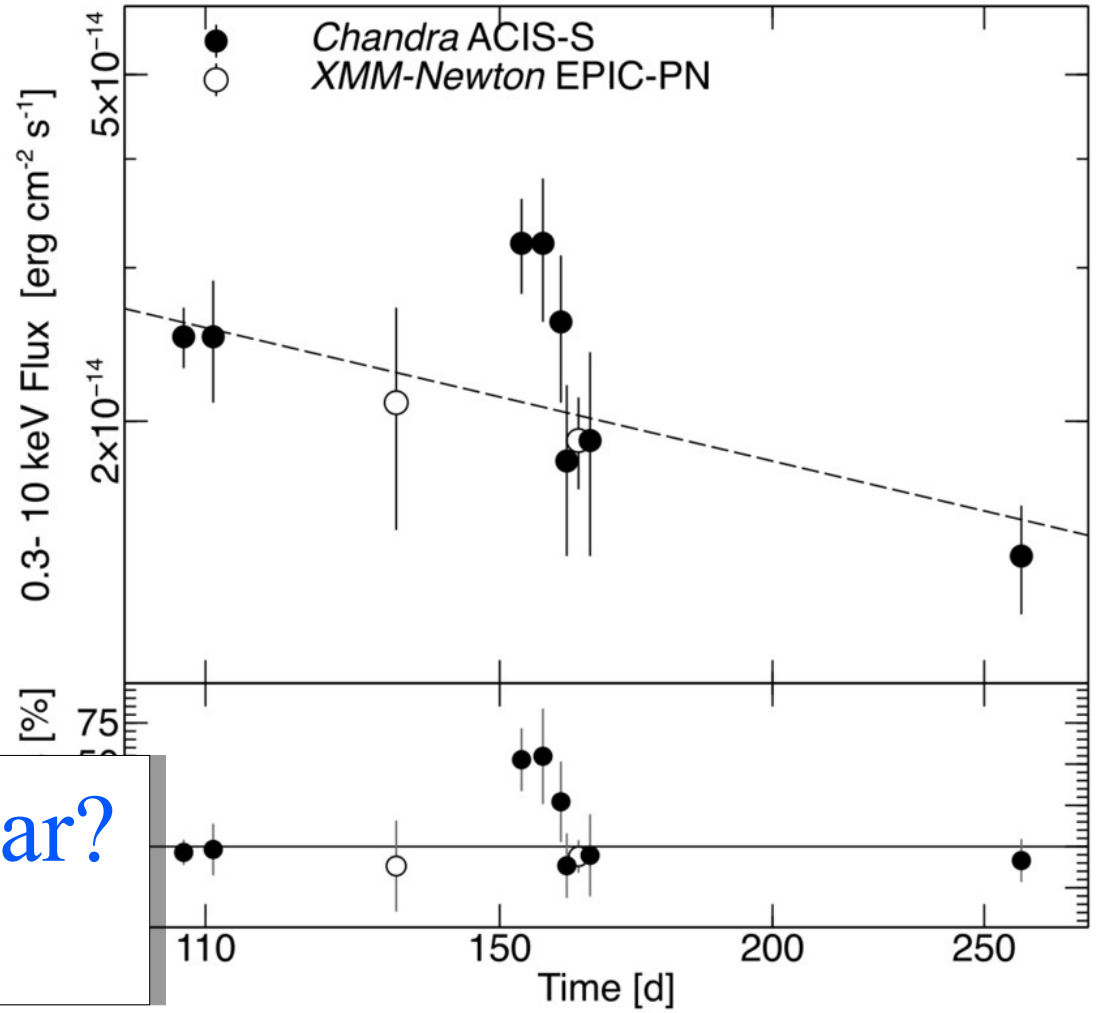
- No gravitational waves
  (not surprising)
- Colour of kilonova
- kilonova light-curve fitting
  (some groups fit with long-lived remnant, others without)



GW170817: post merger

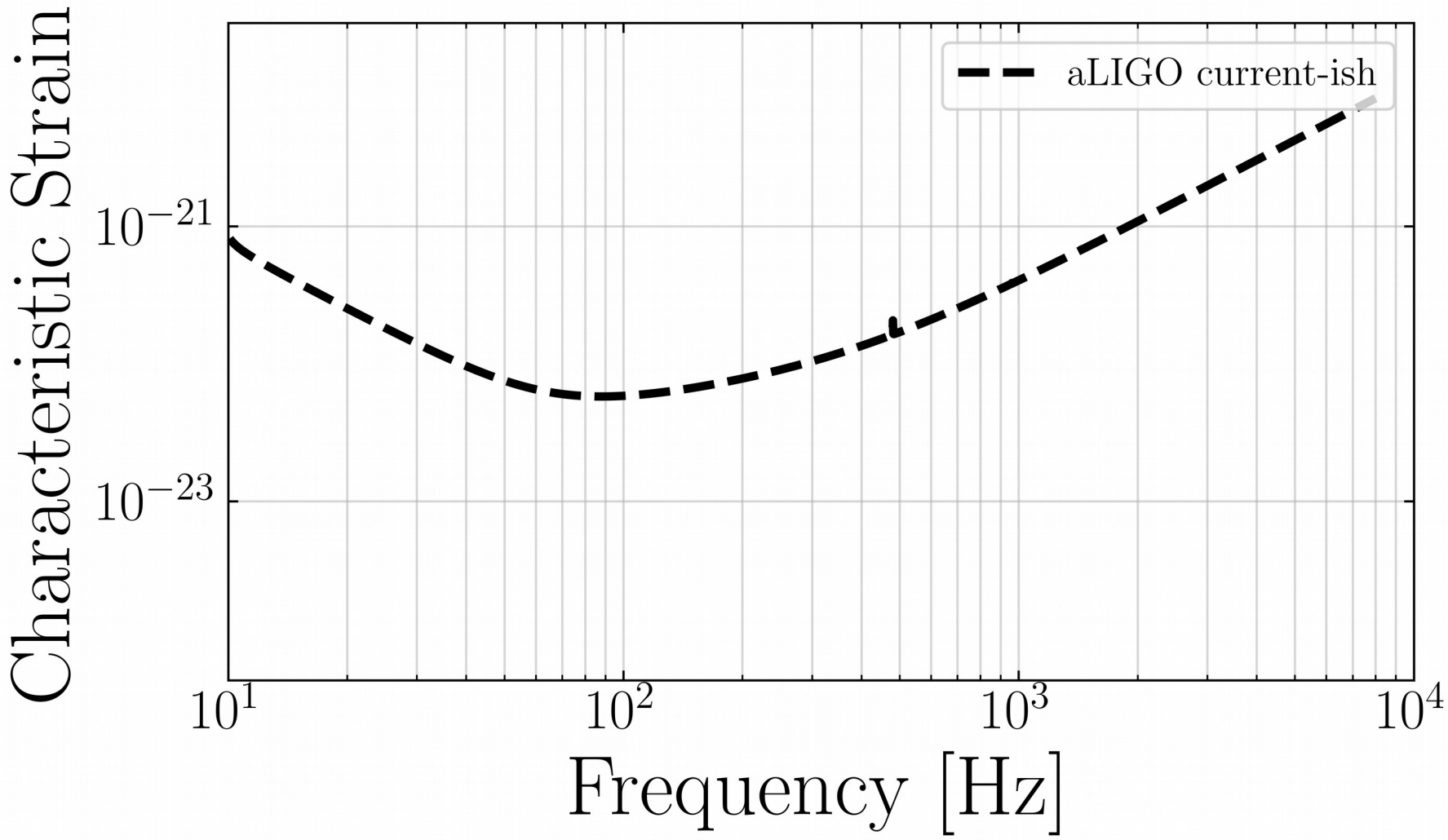


- No gravitational waves
  (not surprising)
- Colour of kilonova
- kilonova light-curve fitting
  (some groups fit with long-lived remnant, others without)
- X-ray bump at 160 days

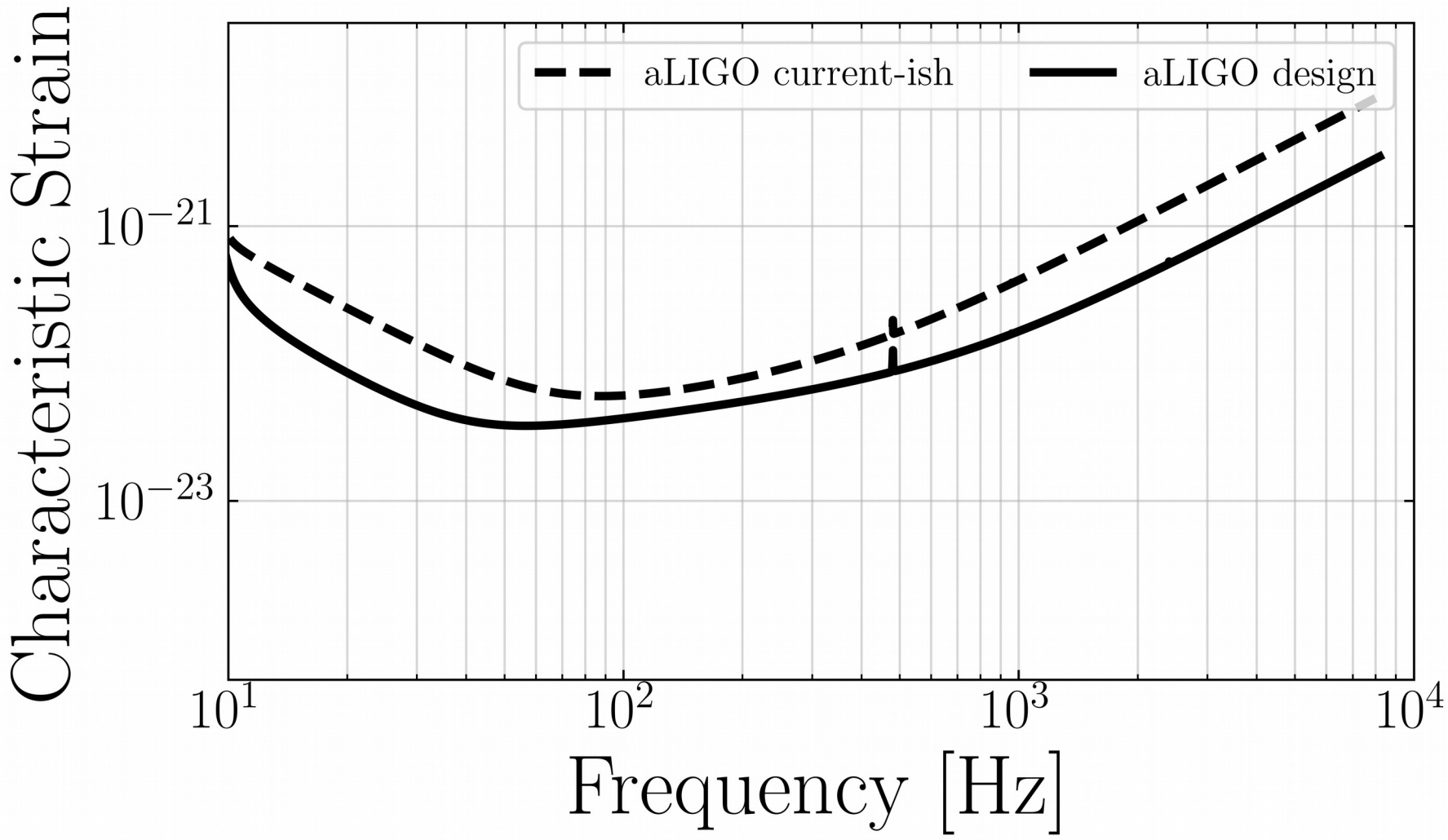


Short-lived, long-lived neutron star?
we don't really know

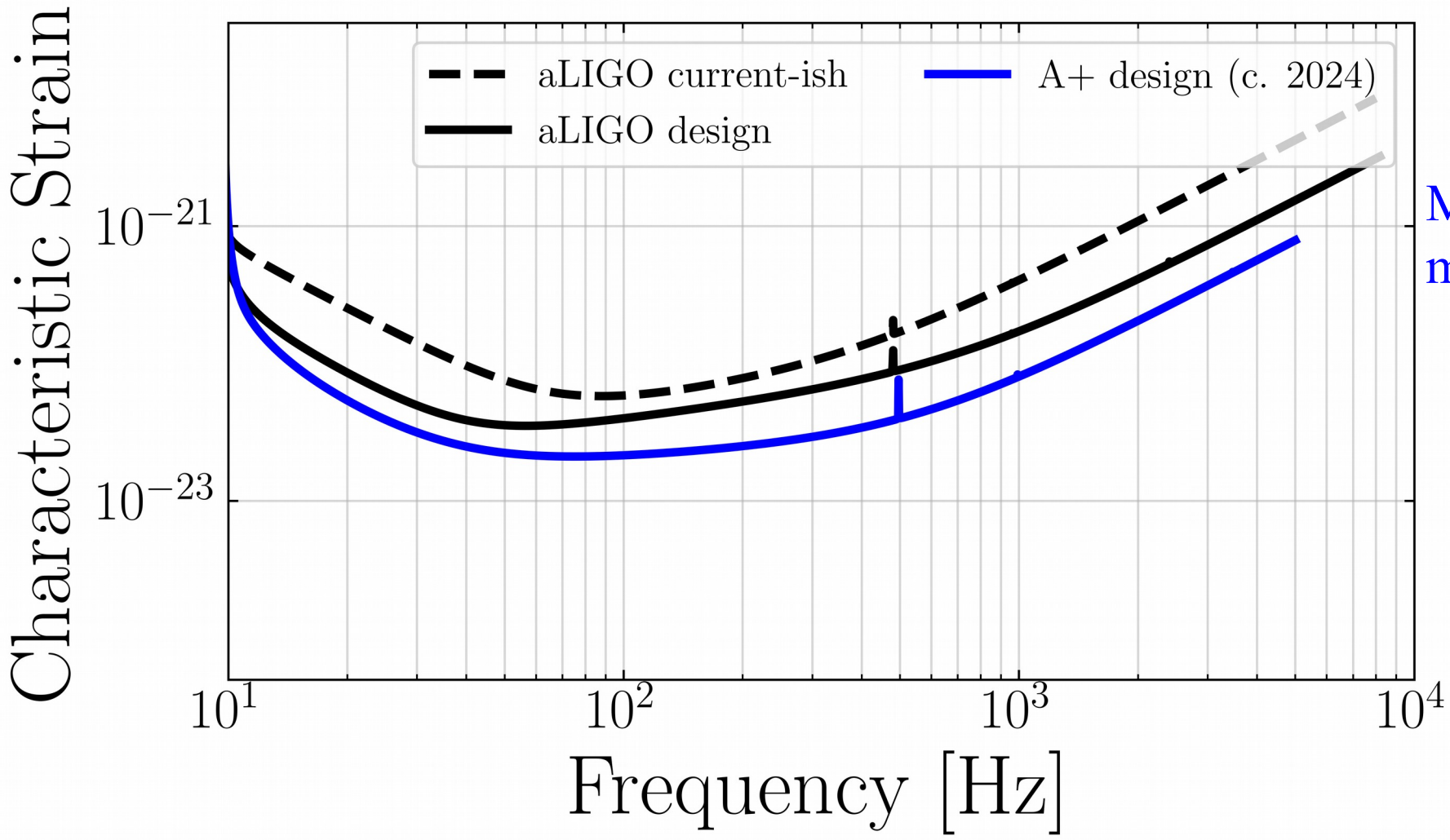
What's next in gravitational-wave astronomy?



What's next in gravitational-wave astronomy?

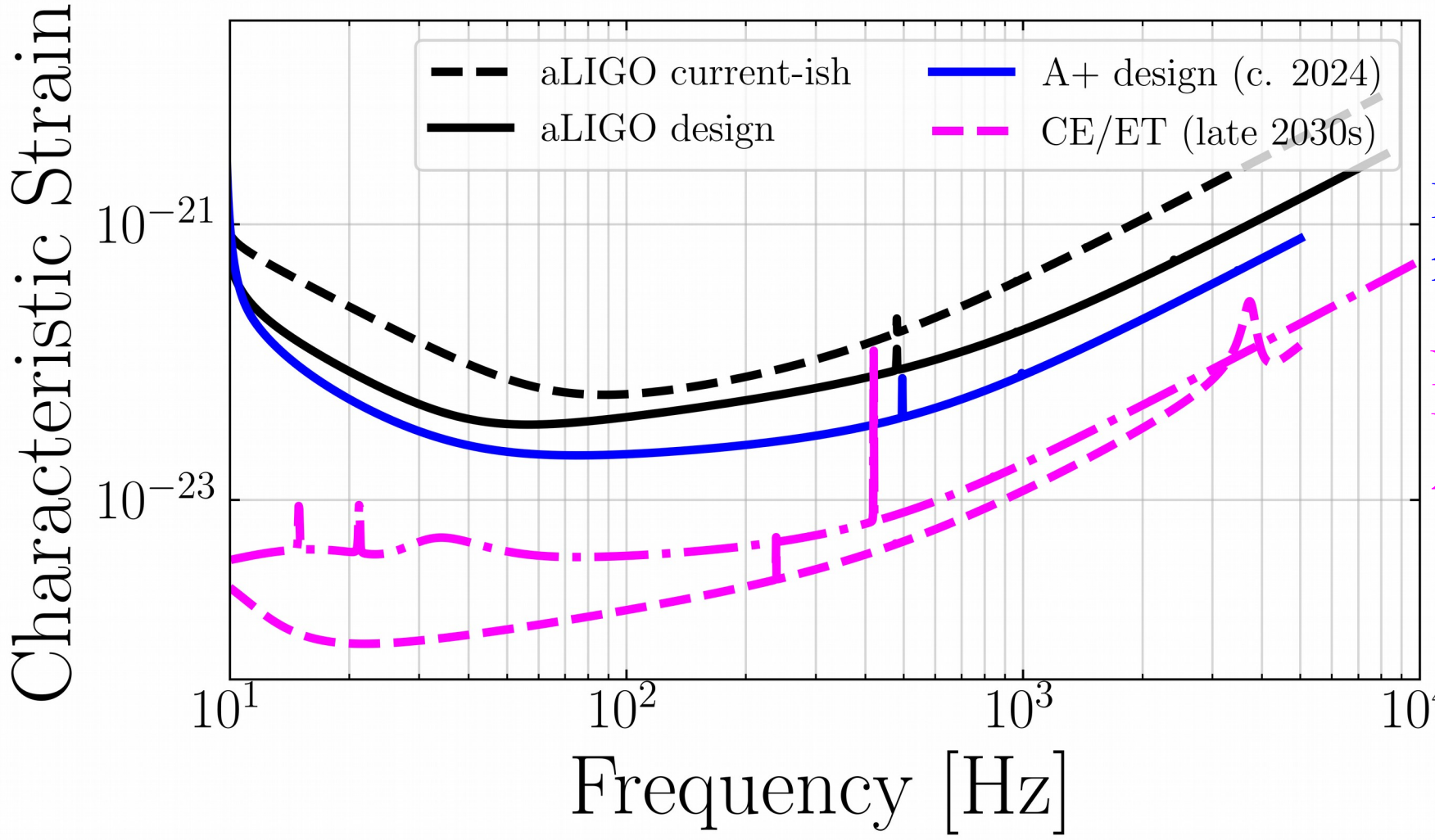


What's next in gravitational-wave astronomy?



Mostly funded,
minimal technology risk

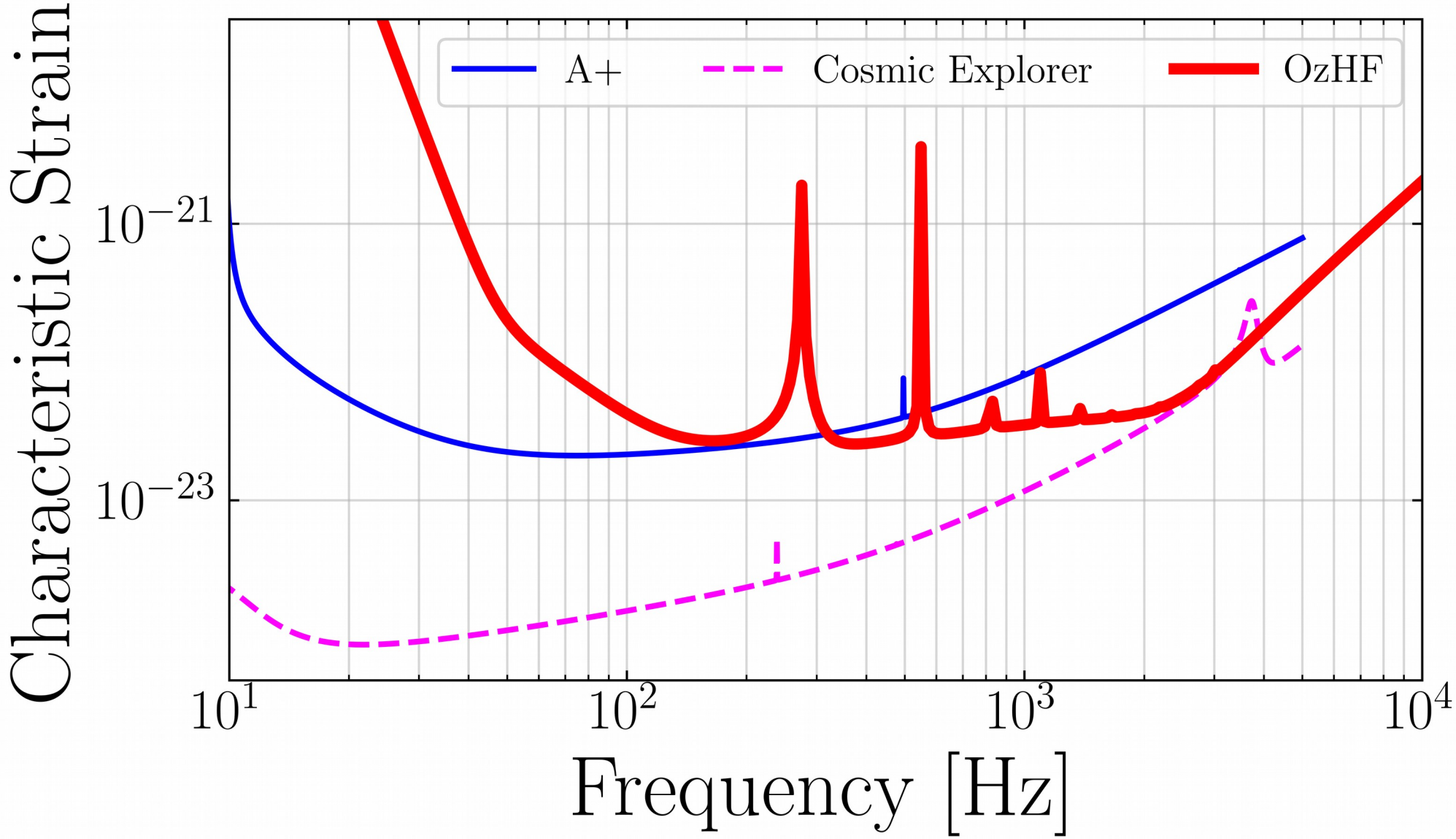
What's next in gravitational-wave astronomy?



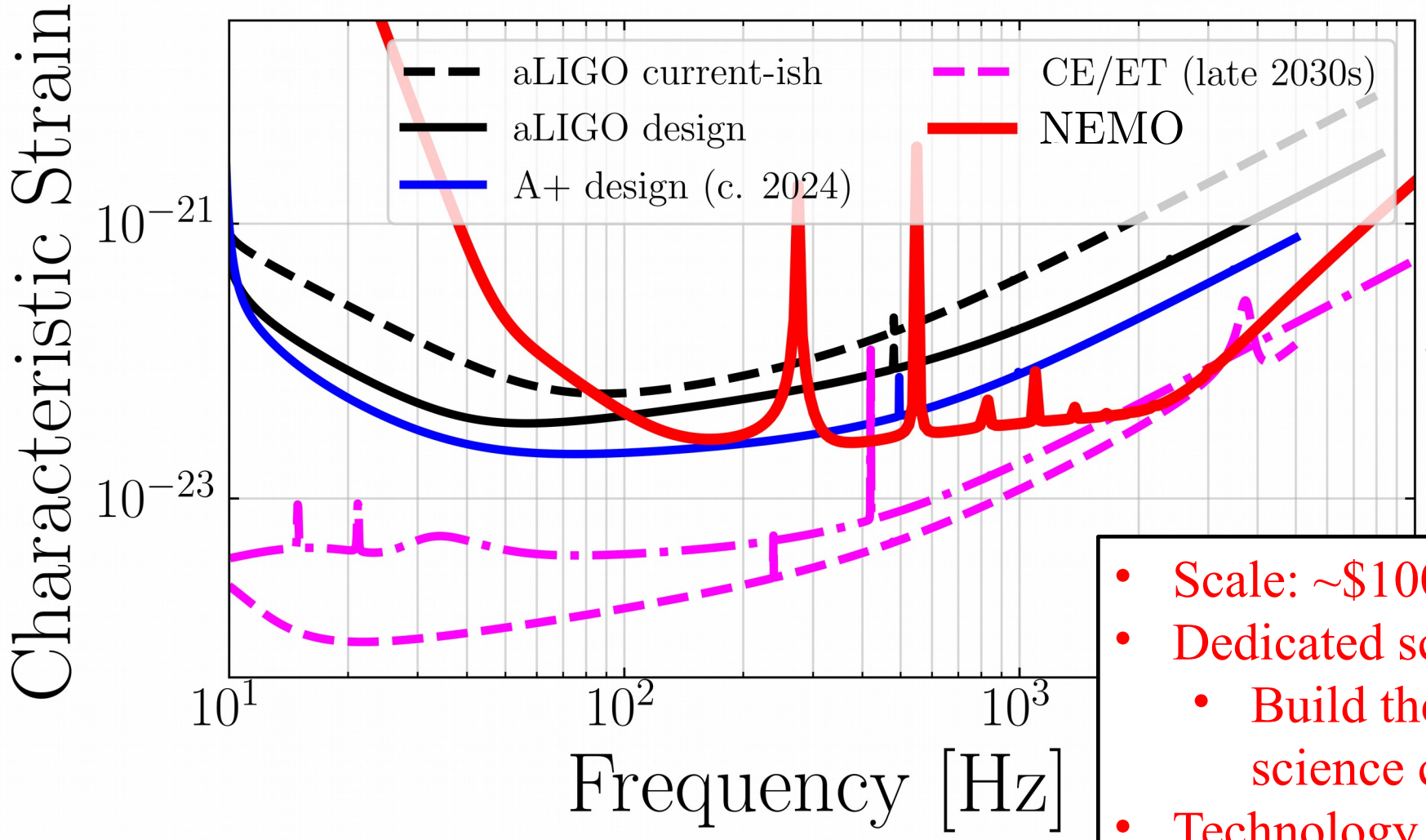
Mostly funded,
minimal technology risk

Not funded,
Unchartered territory in
terms of technology

NEMO: A matter machine



Introducing NEMO

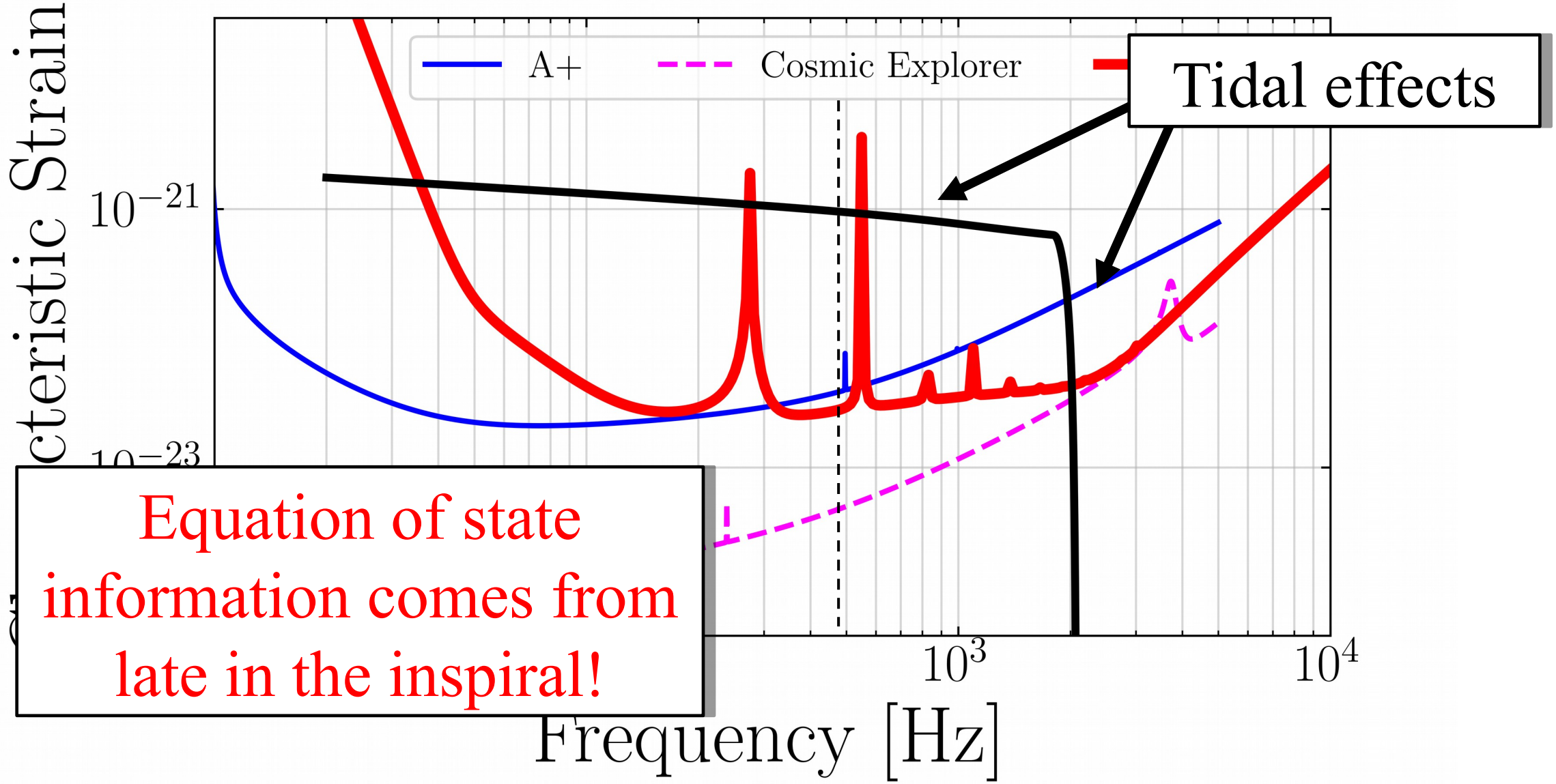


Mostly funded, minimal technology risk

Not funded, Unchartered territory in terms of technology

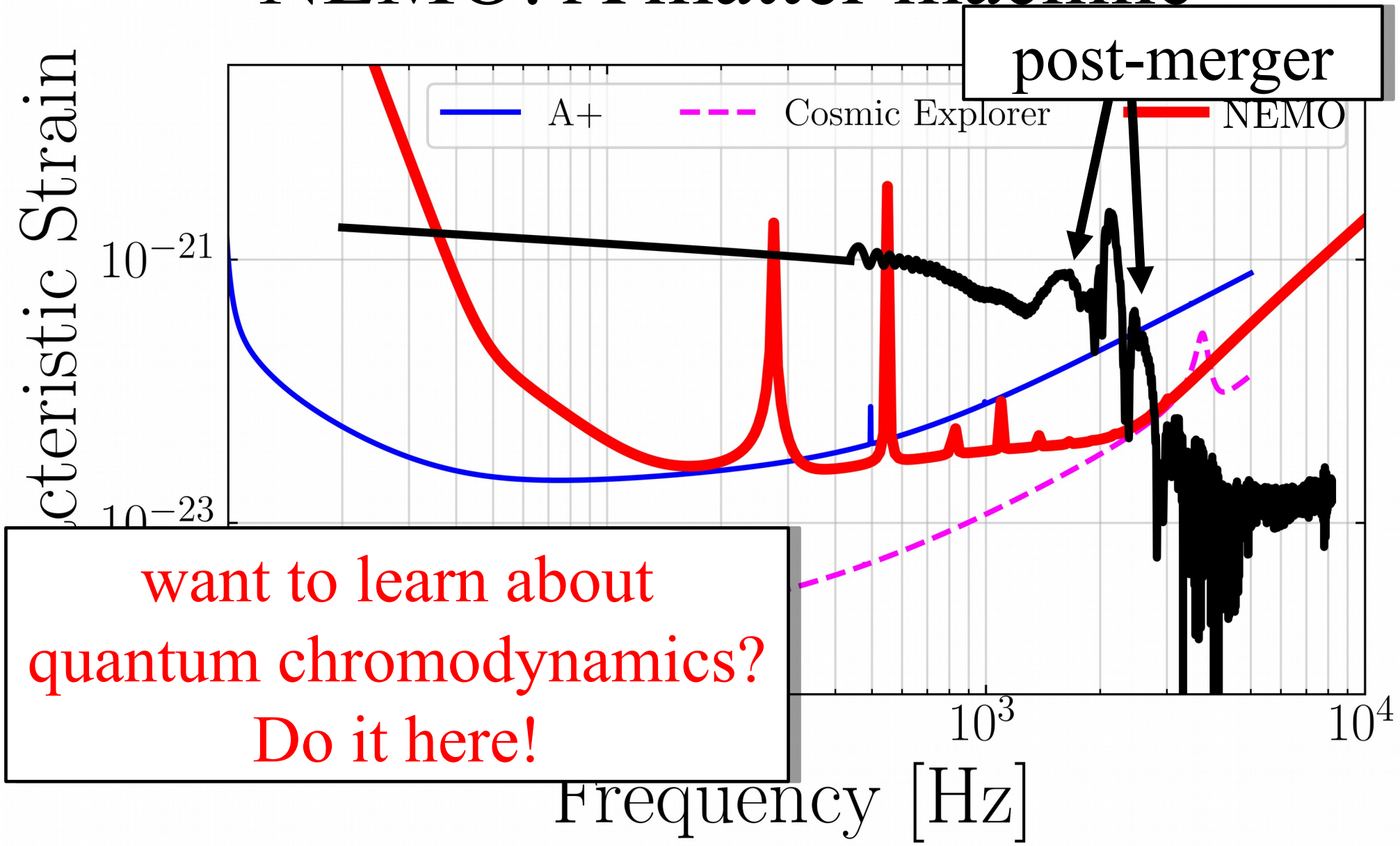
- Scale: ~$100 M (cf ~$1B for CE)
- Dedicated science goals:
  - Build the detector around the science case: **neutron stars**
- Technology development for full 3G detectors

NEMO: A matter machine



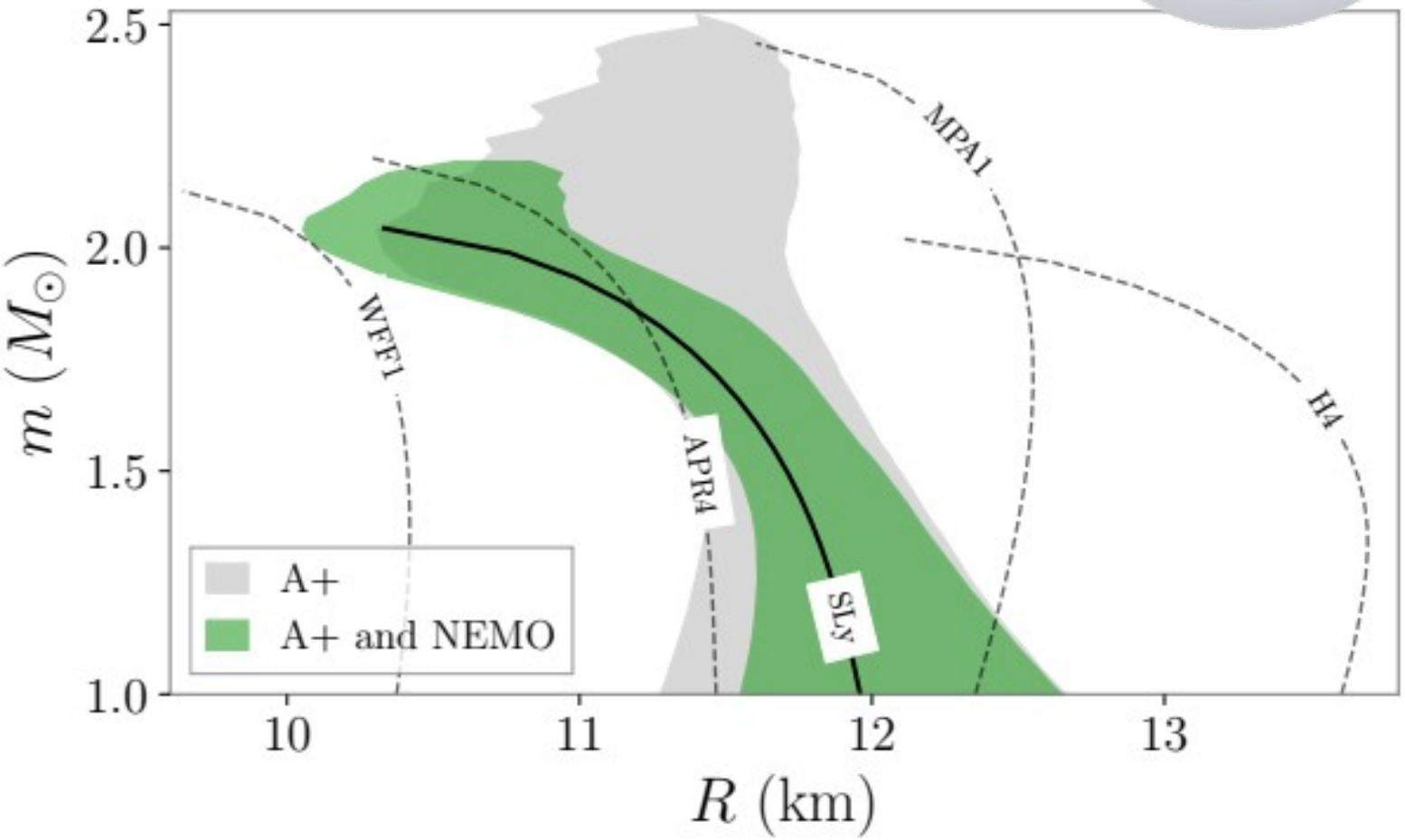
Equation of state information comes from late in the inspiral!

NEMO: A matter machine

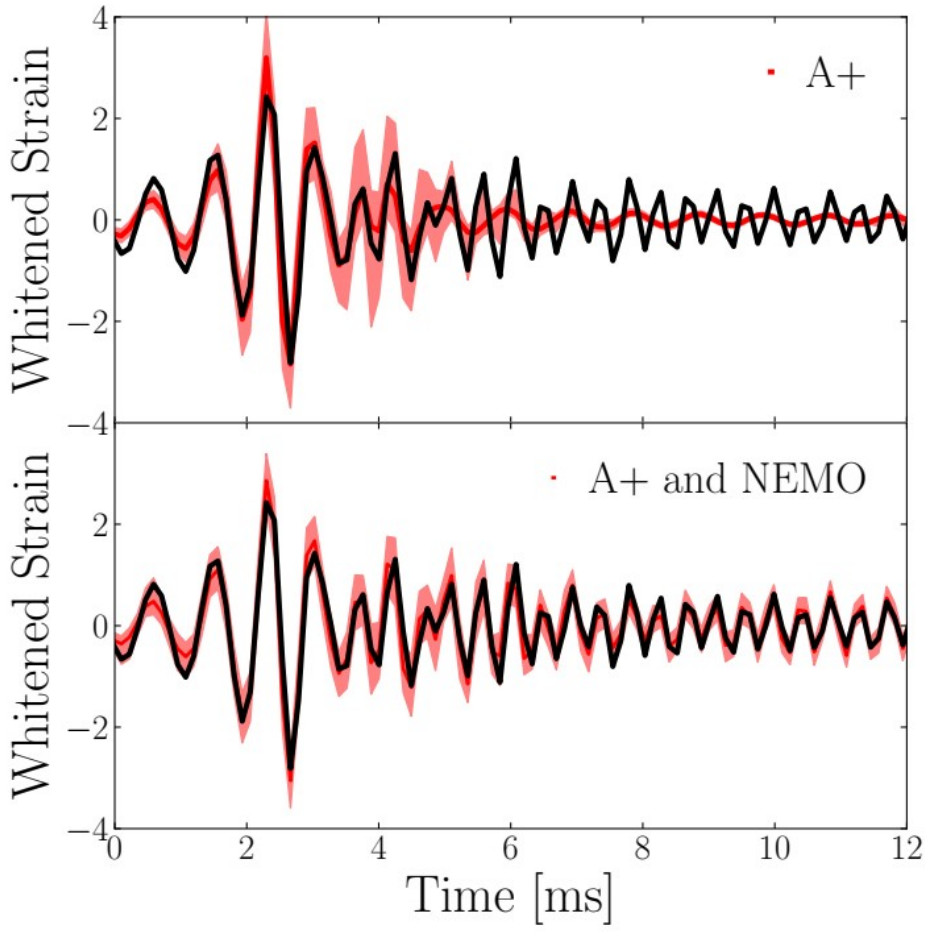


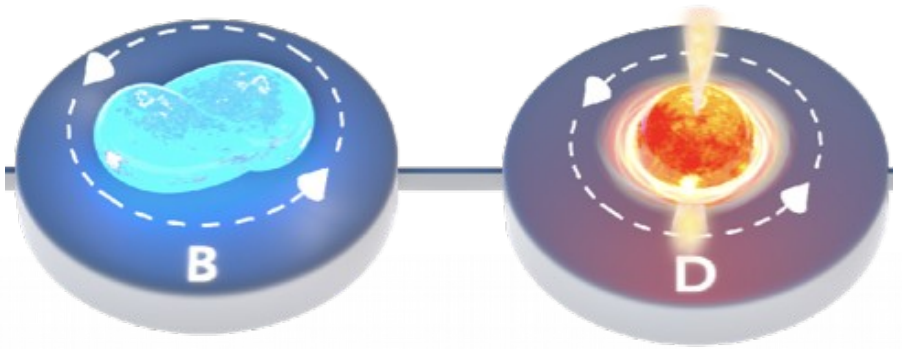
want to learn about
quantum chromodynamics?
Do it here!

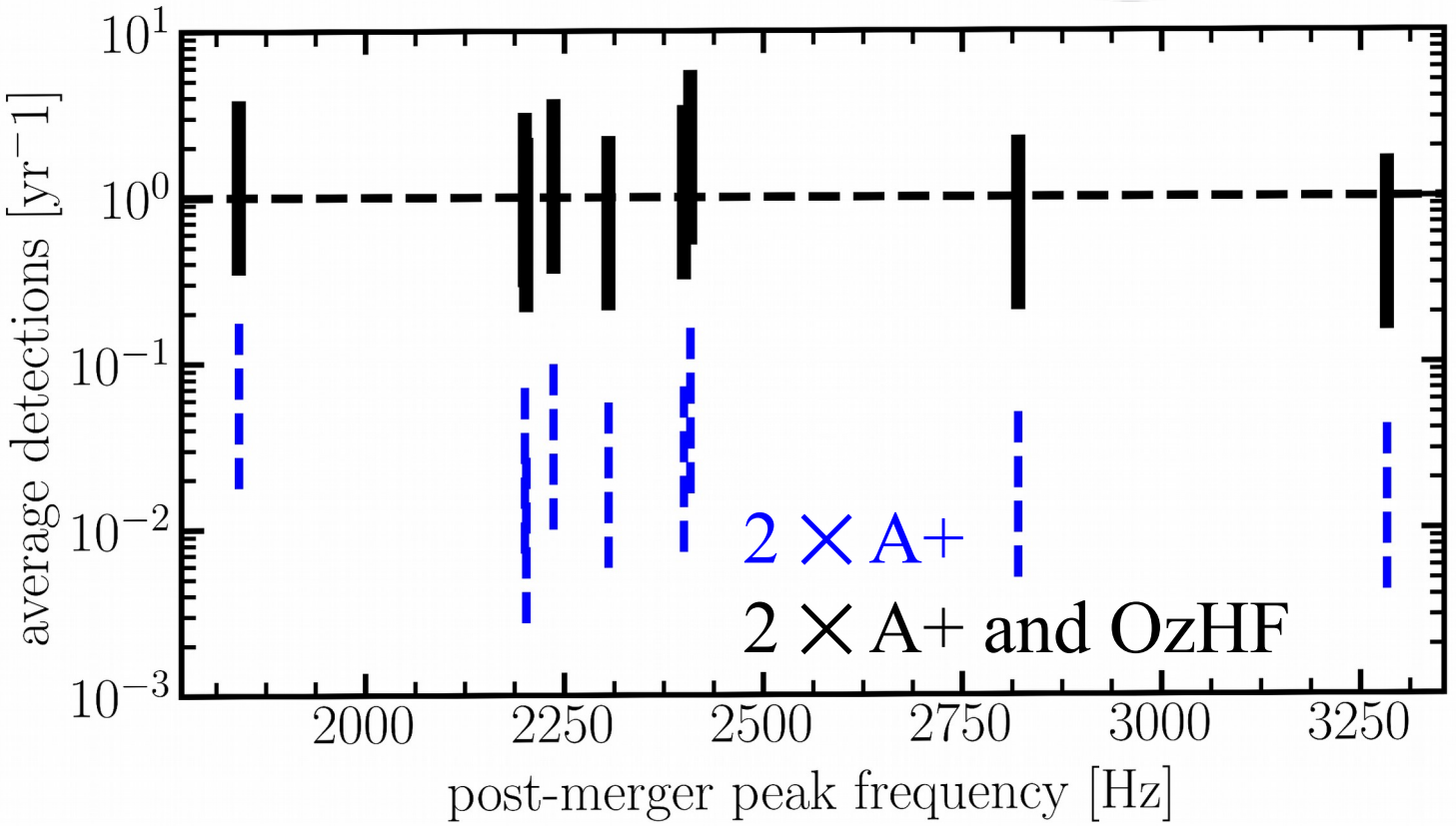
OzHF: A matter machine



NEMO: A matter machine

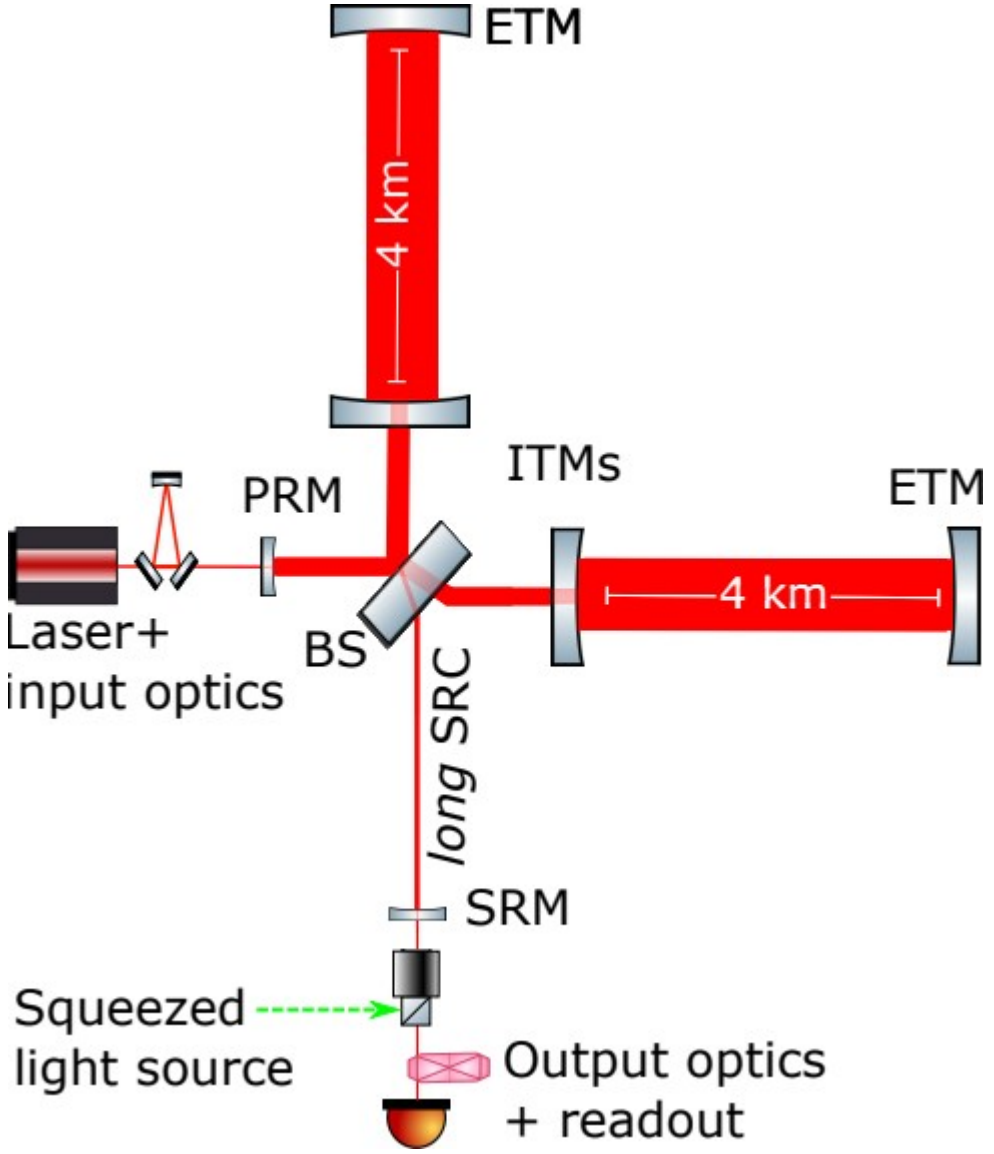




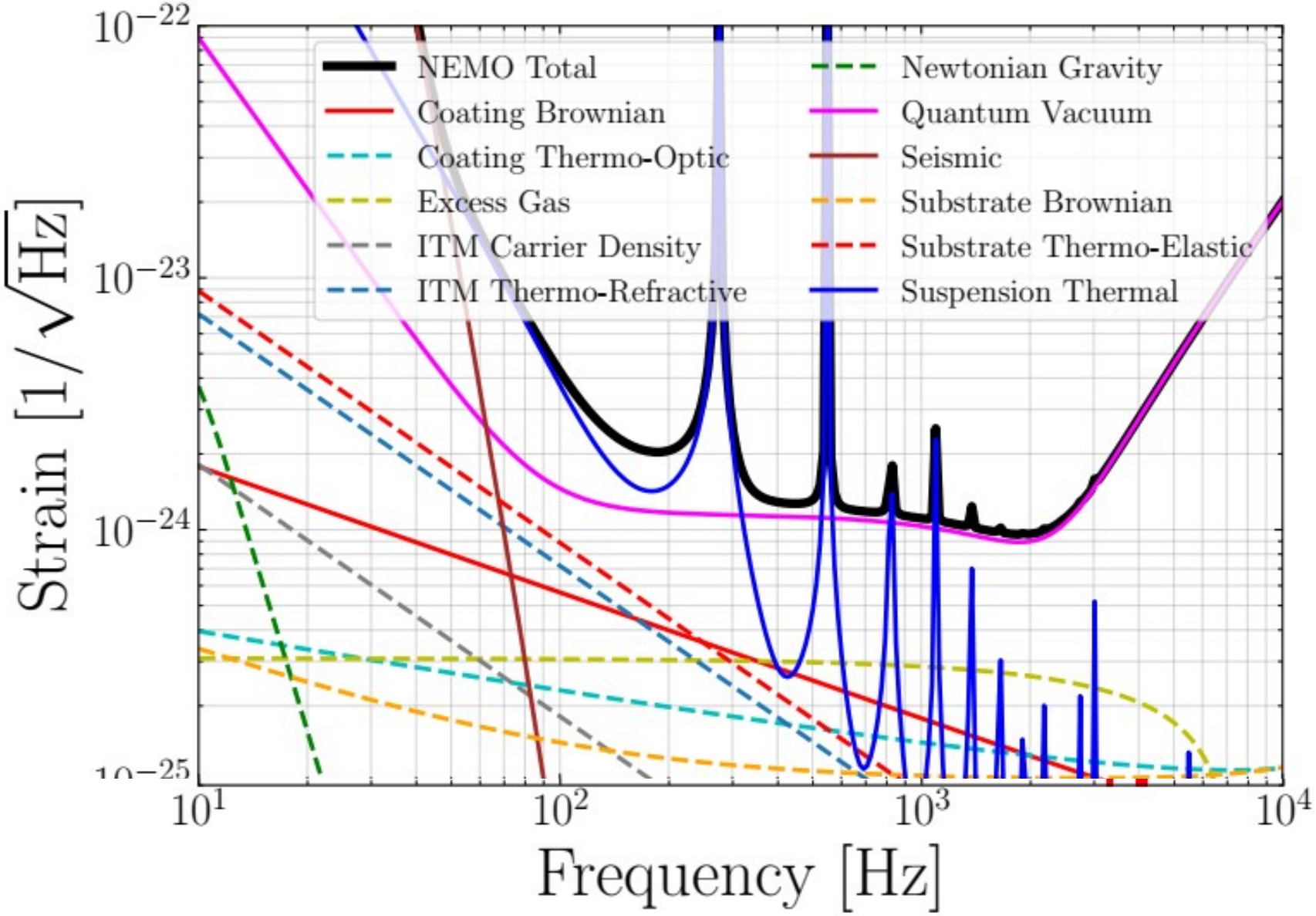


NEMO: preliminary design

- 4km arms
- 74 kg Silicon test masses
- Cooling: 123K
- 2 micron wavelength
- 500 W input power
- 4.5 MW in arms
- 7 dB Squeezing
- Suspension: steel
- **Neglect low frequency isolation**



NEMO: preliminary design



NEMO: Neutron Star Extreme Matter Observatory

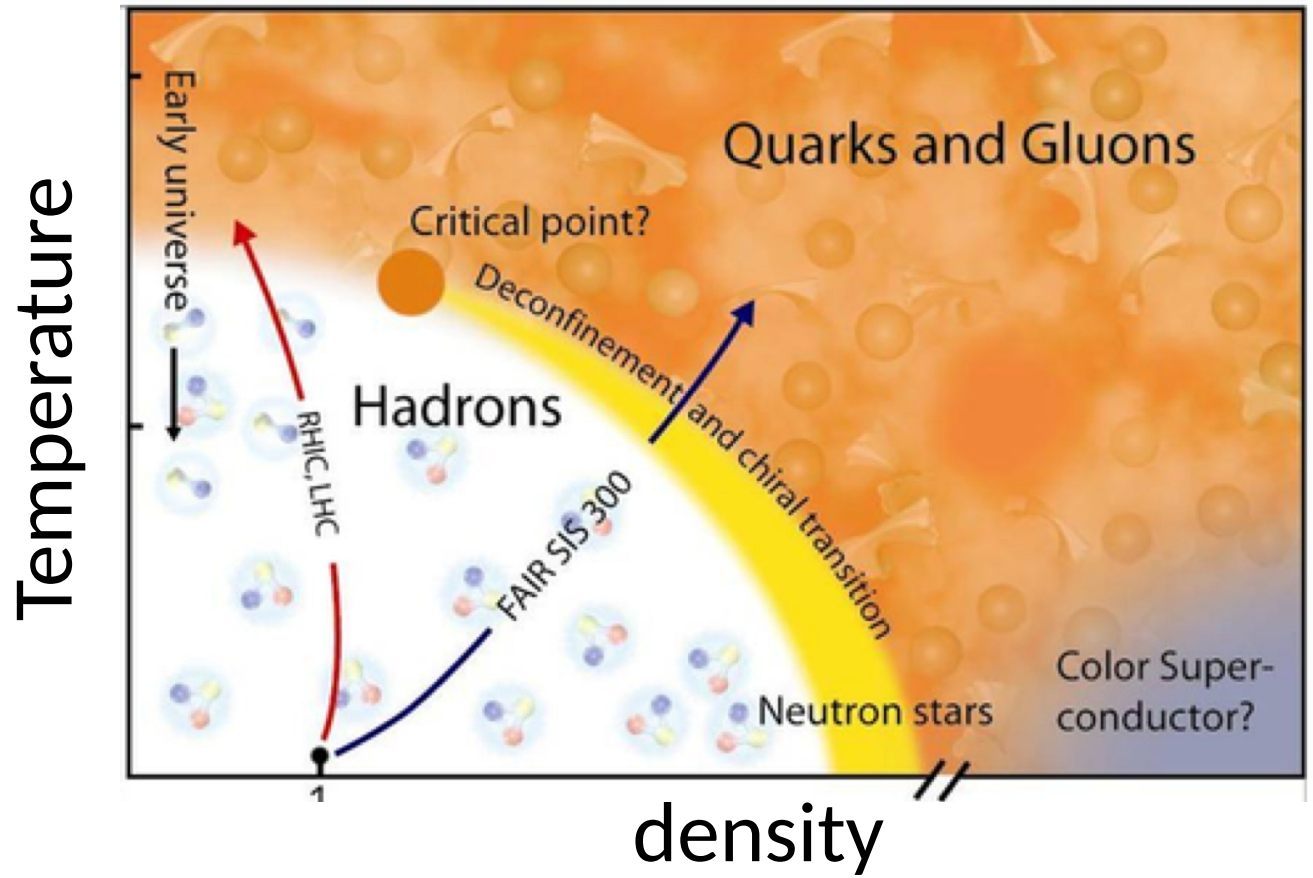
(arXiv:2007.03128)

Science Case

- Binary Black Holes ✘
- **Binary Neutron Stars** ✔
- Neutron Star – Black Holes ?
- Supernovae ?
- Isolated Neutron Stars ?
- Cosmology ✔
- Exotica ?

Project Scale

- ~$100M
- Scalable Infrastructure
- Location?



MONASH University

OzGrav

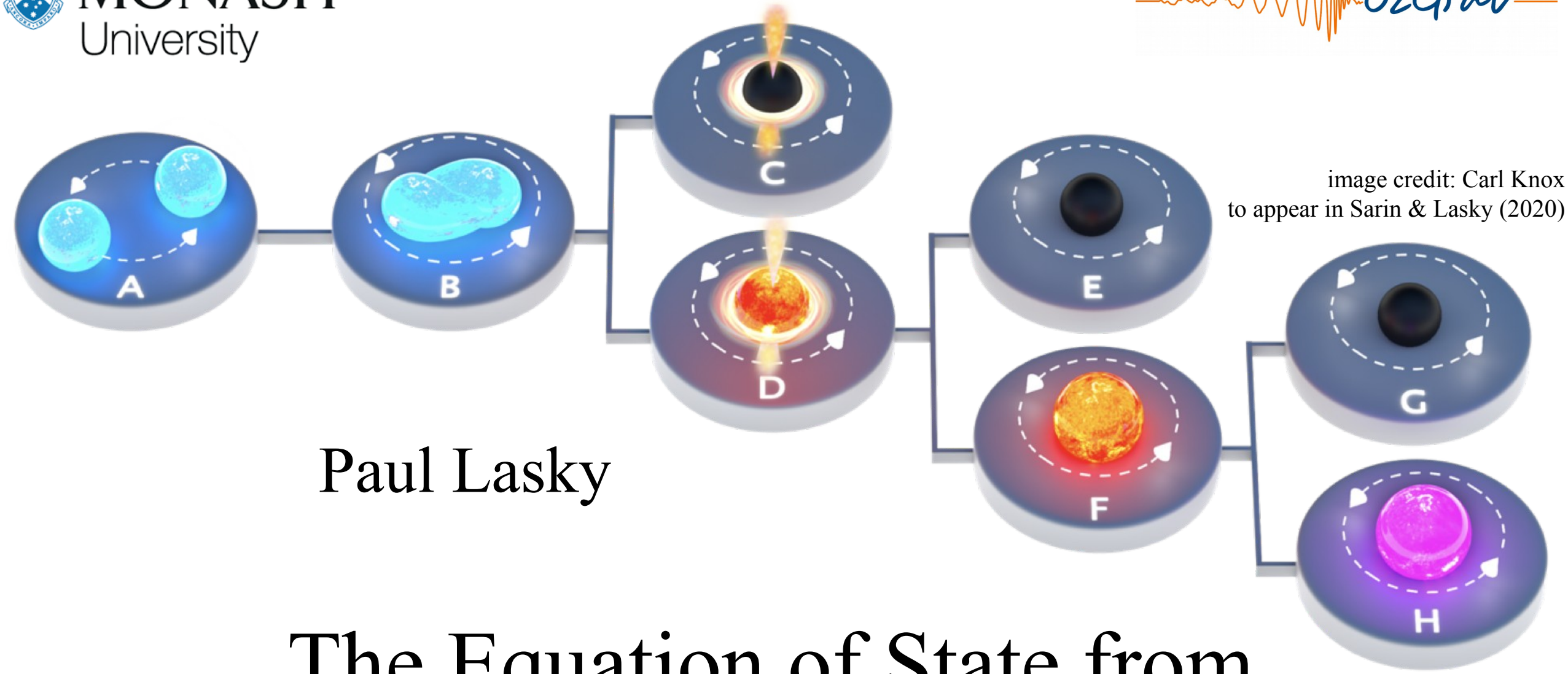


image credit: Carl Knox
to appear in Sarin & Lasky (2020)

Paul Lasky

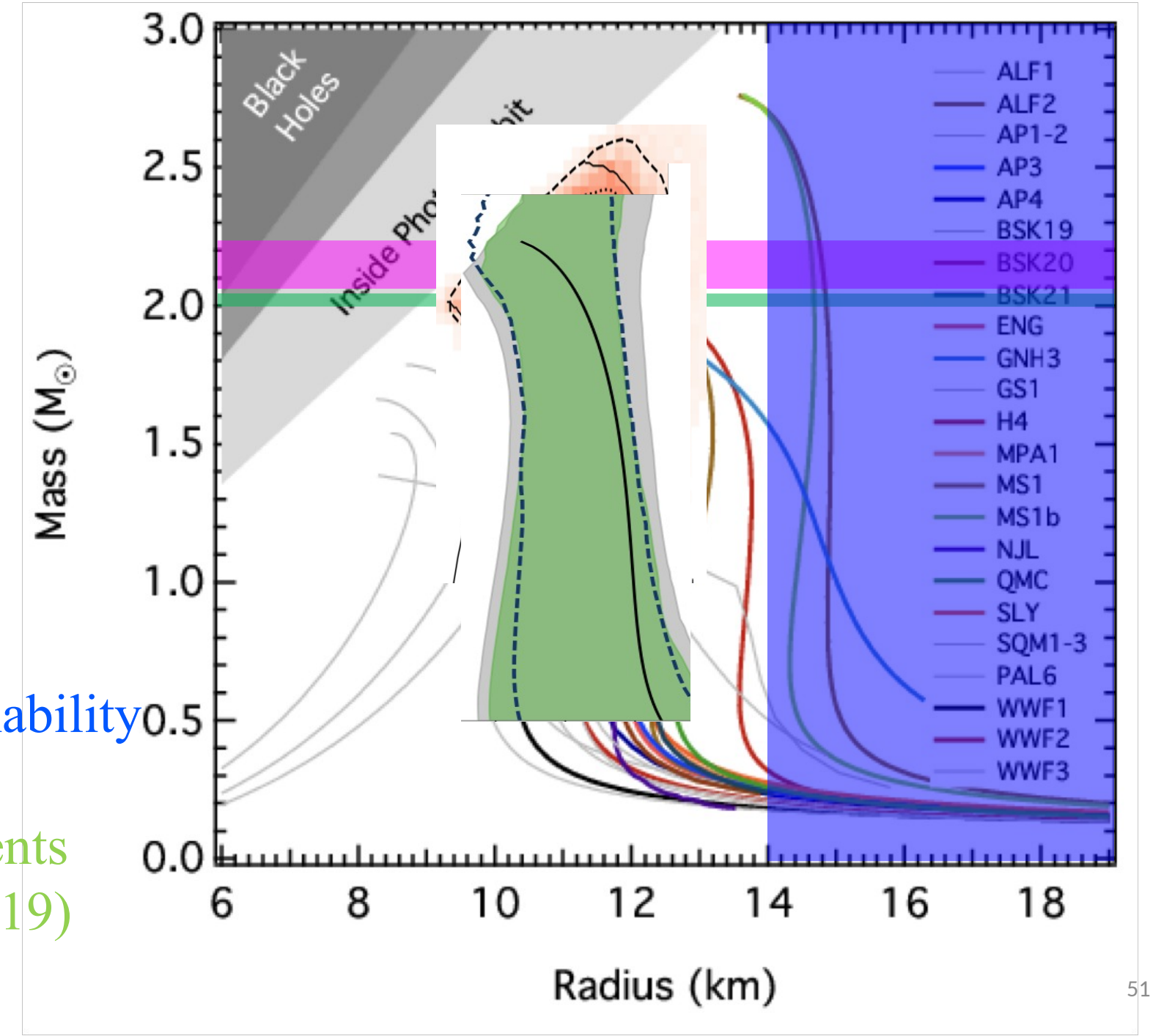
The Equation of State from Neutron Star Post-Merger Remnants

Pulsar observations:

- J0348+0432 (Antoniadis+2013)
- J0740+6620 (Cromartie+2020)
- J0030+0451 (Raaijmakers+2020; NICER)

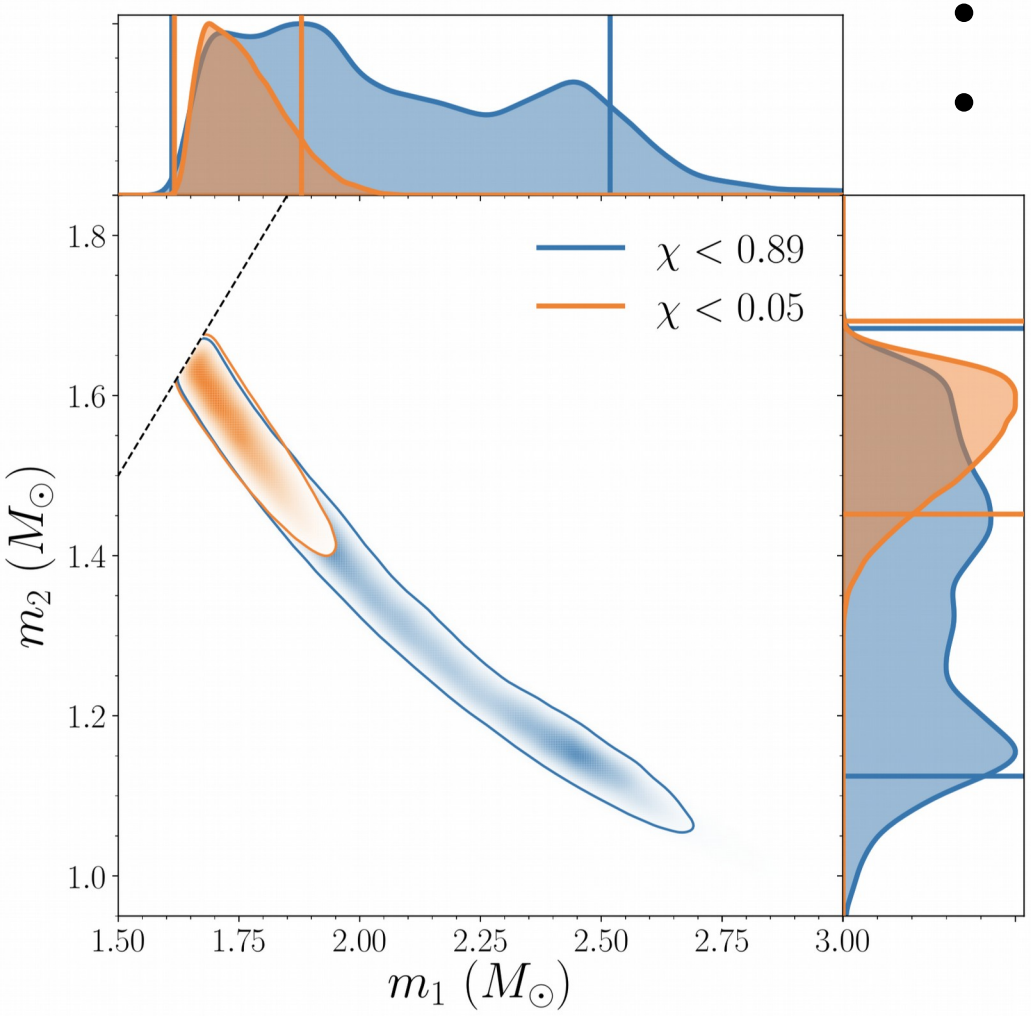
GW170817 tidal deformability

First 40 LIGO/Virgo events (Hernandez Vivanco+2019)

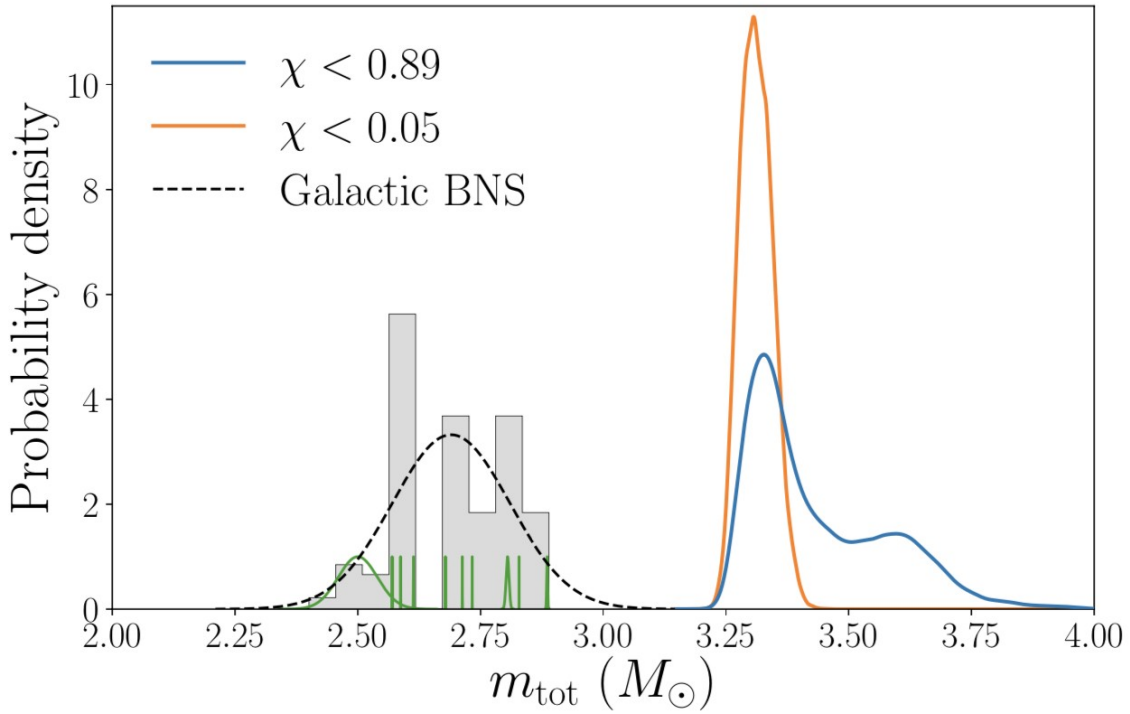


GW190425: The ANZAC day event

Abbott+2020



- weird event for lot's of reasons
- no substantial new information about the equation of state ($d_L \sim 160$ Mpc)



GW190814: a 2.6 solar mass neutron star or black hole?

Abbott+2020