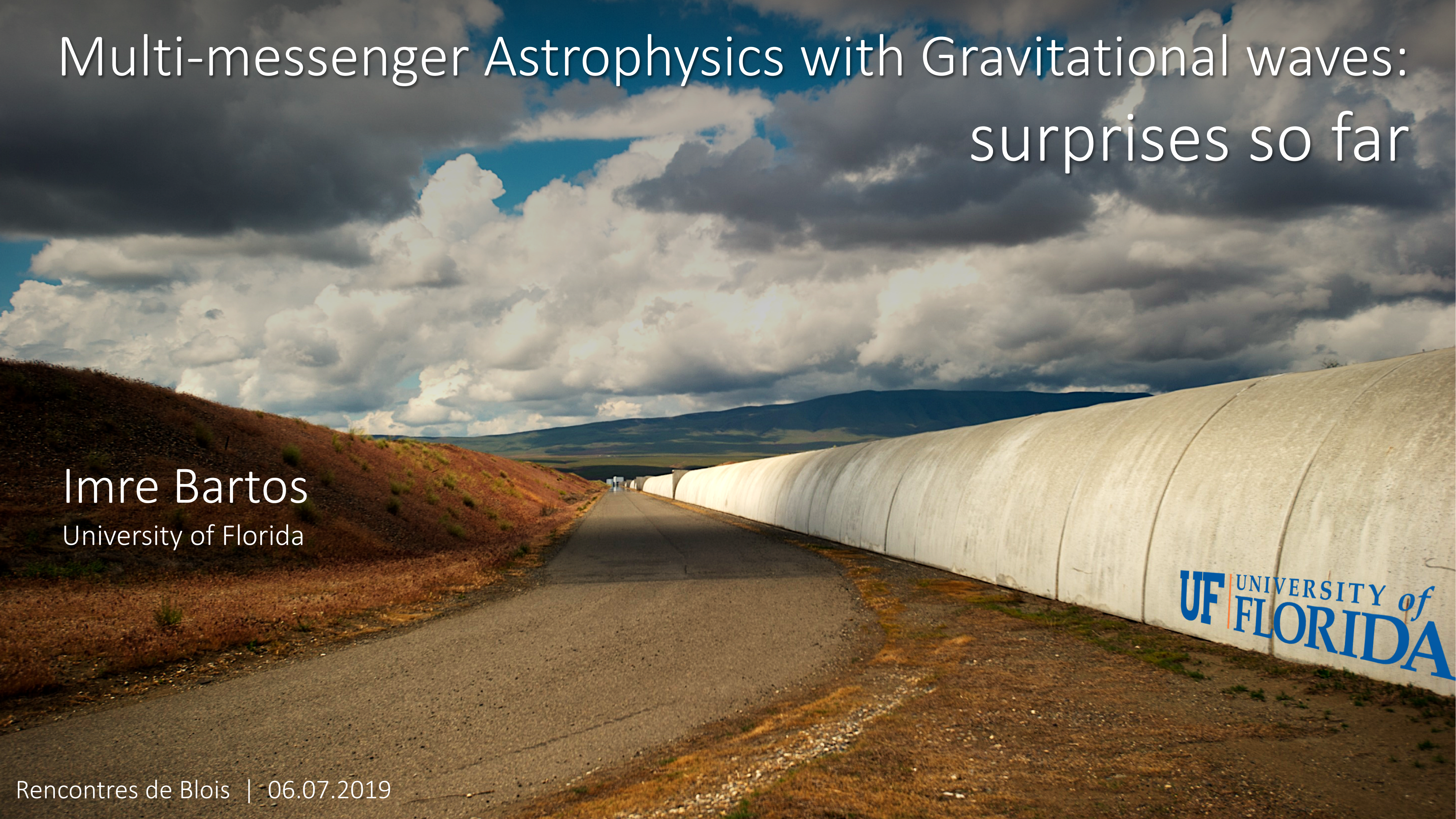
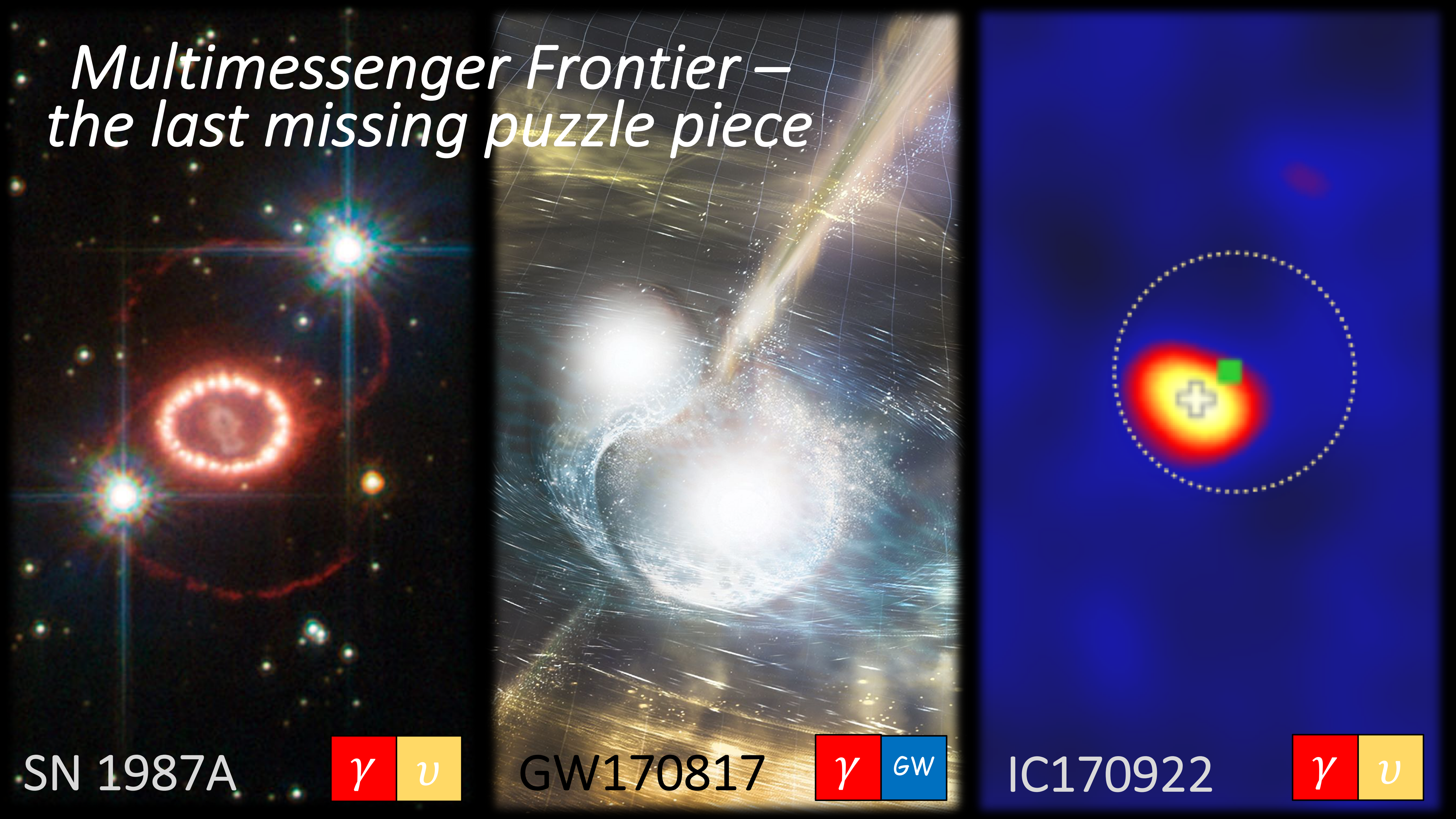


Multi-messenger Astrophysics with Gravitational waves: surprises so far

Imre Bartos
University of Florida

Rencontres de Blois | 06.07.2019


Multimessenger Frontier –
the last missing puzzle piece
SN 1987A
γ
υ
GW170817
γ
GW
IC170922
γ
υ

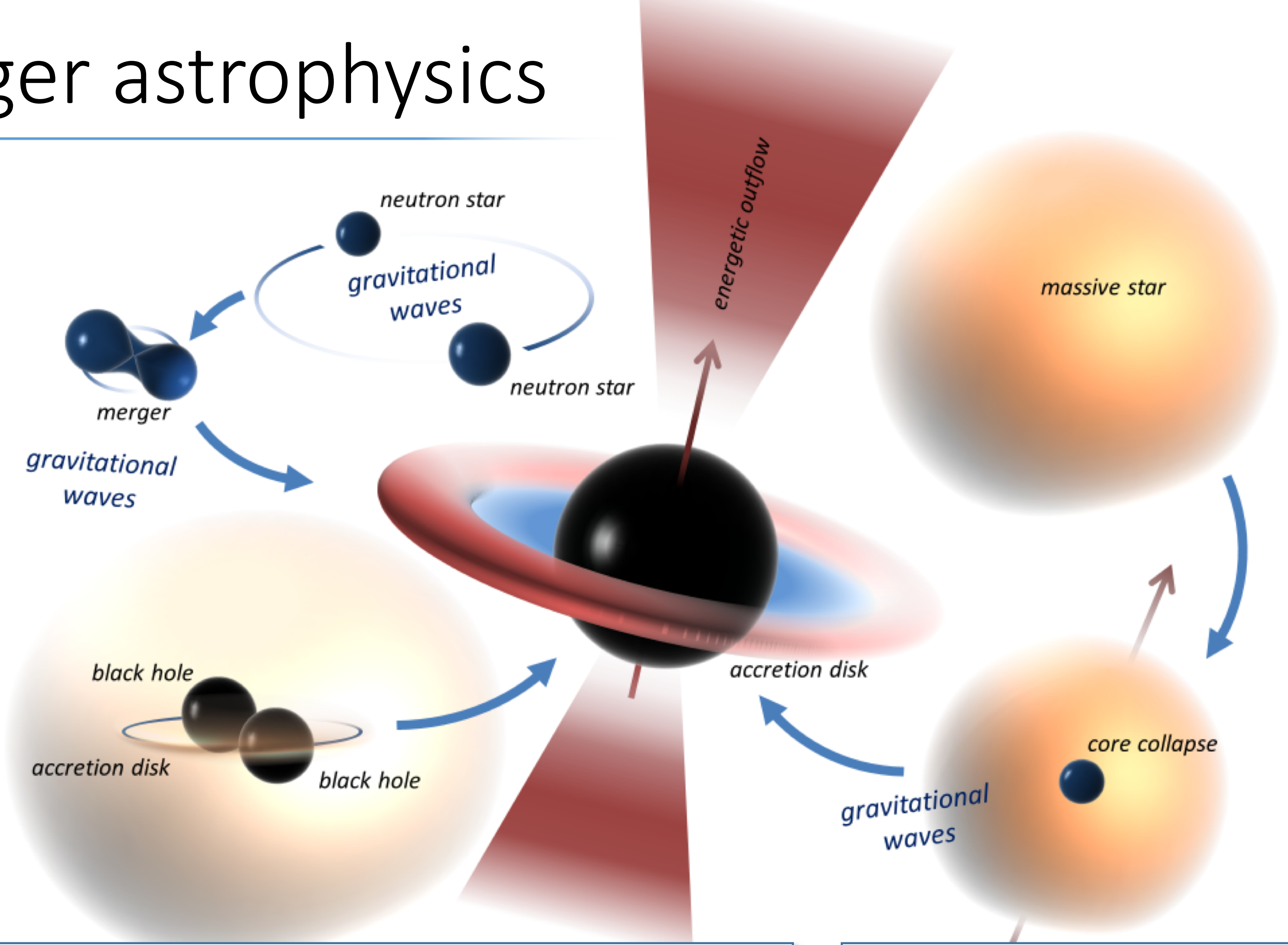
Multimessenger astrophysics

<u>Gravitational waves:</u>
- Compact object formation / evolution

<u>EM radiation:</u>
- Particle acceleration
- Environment

<u>Neutrinos:</u>
- Stellar core / structure
  Particle acceleration

<u>Cosmic rays:</u>
- Particle acceleration
- Environment

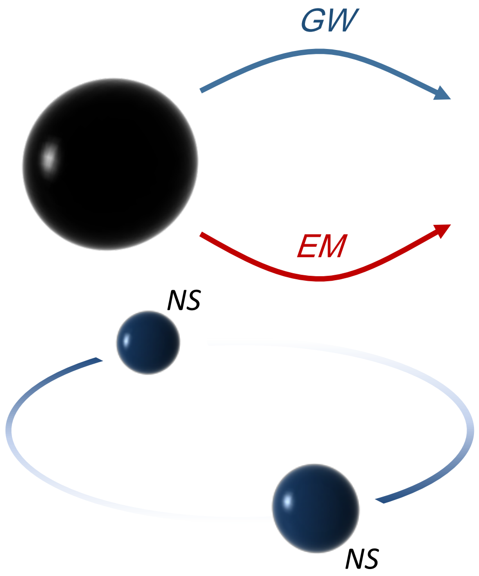


<u>Powerful transients:</u>
1. compact binary merger
2. stellar core collapse

<u>Goals:</u>
1. Learn more
2. Detect more

Science targets

Fundamental physics

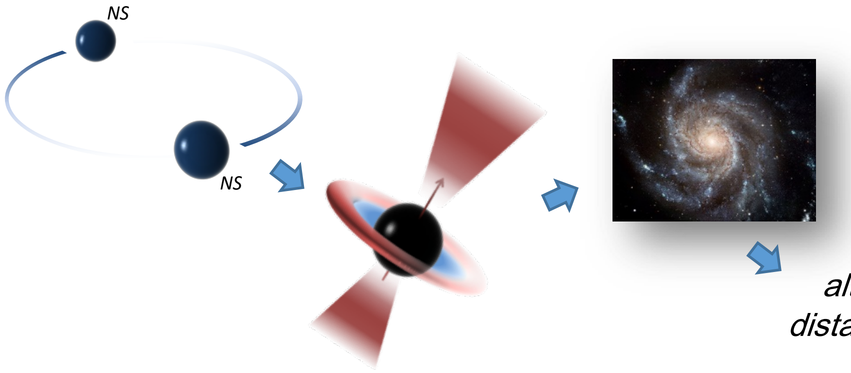


speed of gravity

tests of general relativity

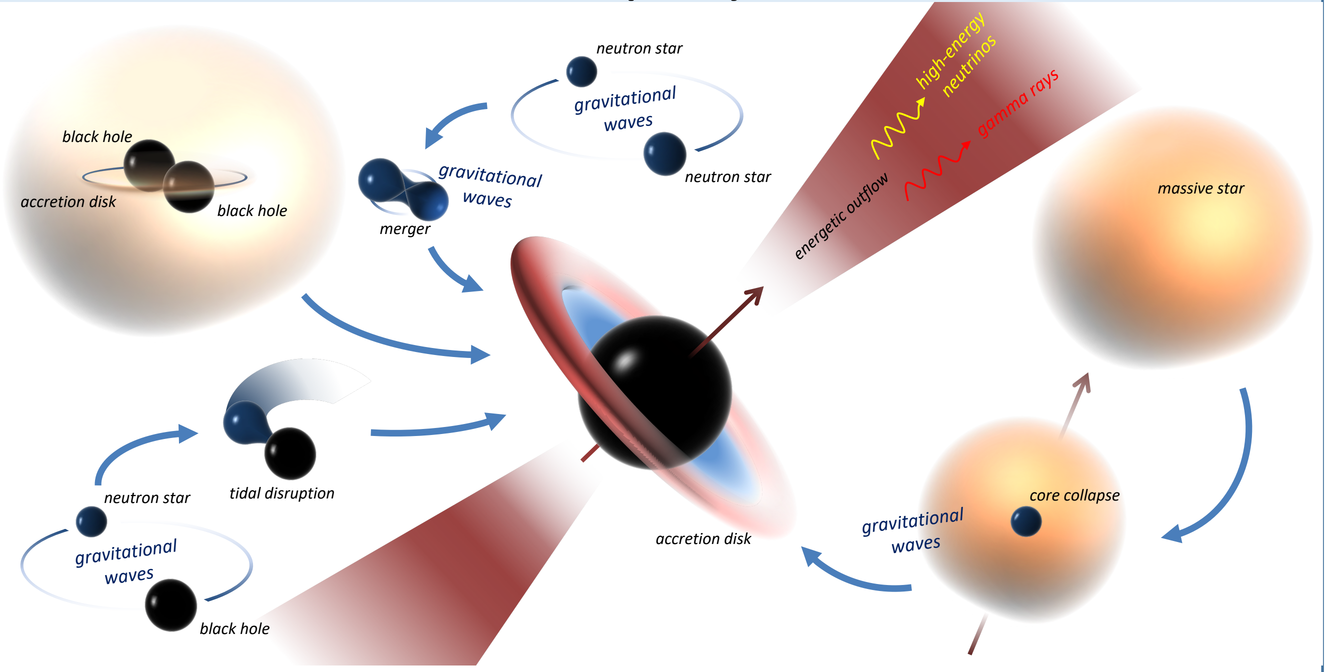
equation of state
of supranuclear matter

Cosmology



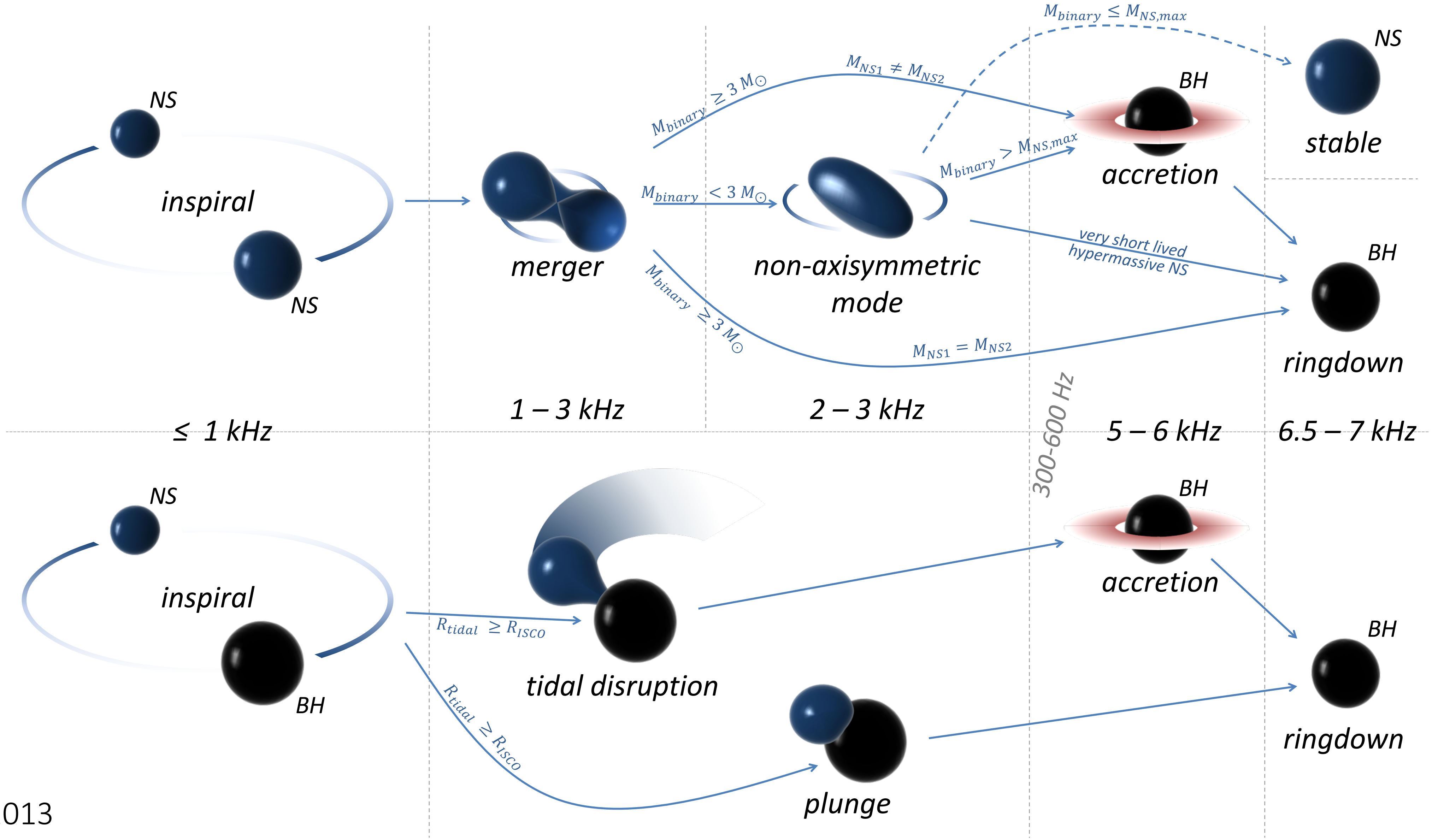
alternative
distance ladder

Astrophysics



- *Cosmic particle acceleration*
- *Black hole accretion*
- *Stellar core collapse*
- *Compact binary formation channels*
- *Intermediate mass black holes*
- *Origin of heavy elements*
- *Environment in galactic nuclei*
- *Relativistic outflows*
- *…*

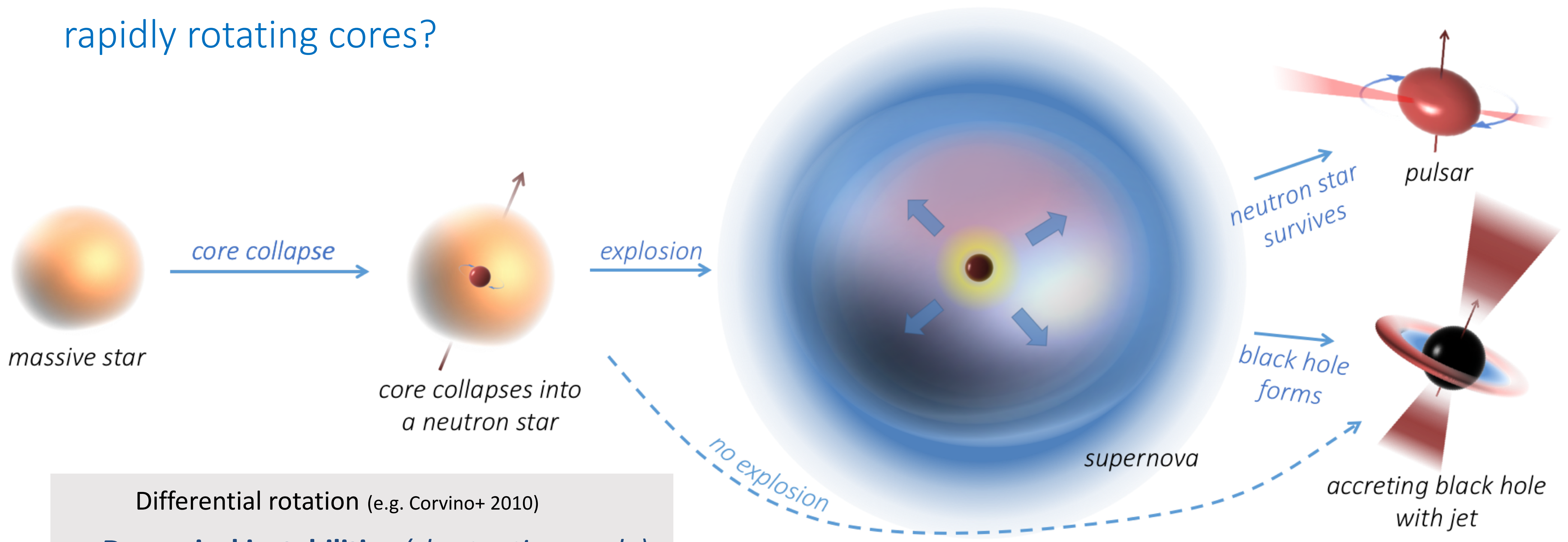
Compact binary mergers



Bartos+ 2013

Stellar core collapse

Gravitational waves from rapidly rotating cores?

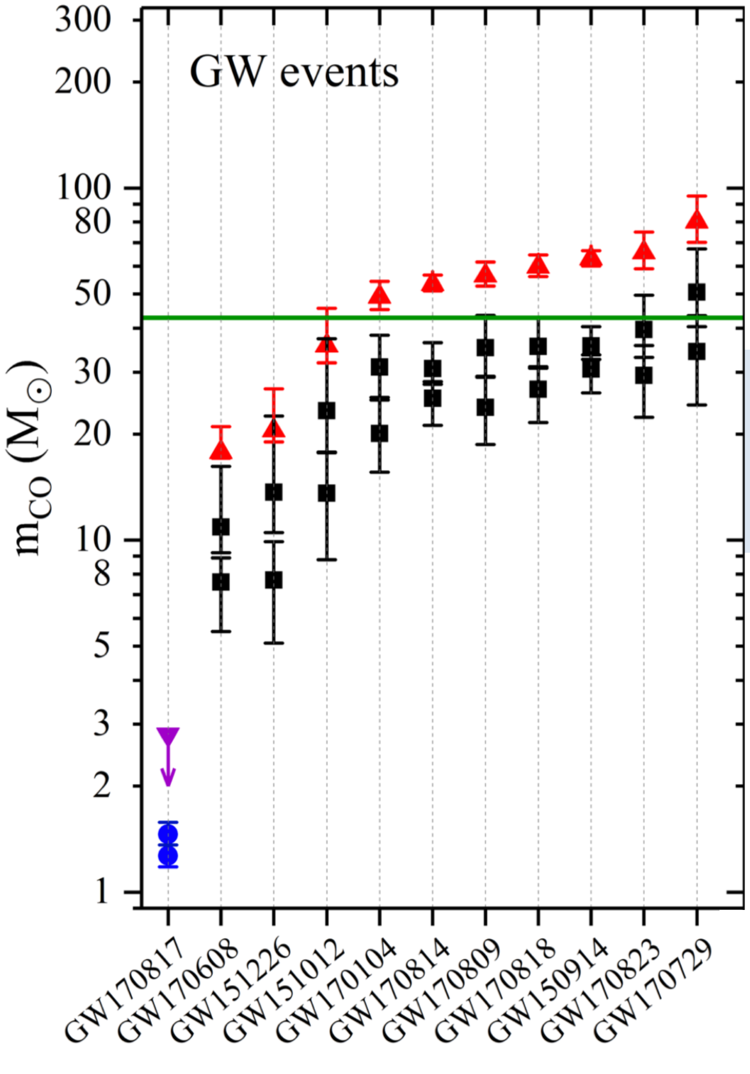


Differential rotation (e.g. Corvino+ 2010)

- **Dynamical instabilities** *(shorter time scale)*
- **Secular instabilities** *(longer time scale)*
- **Magnetic distortion**

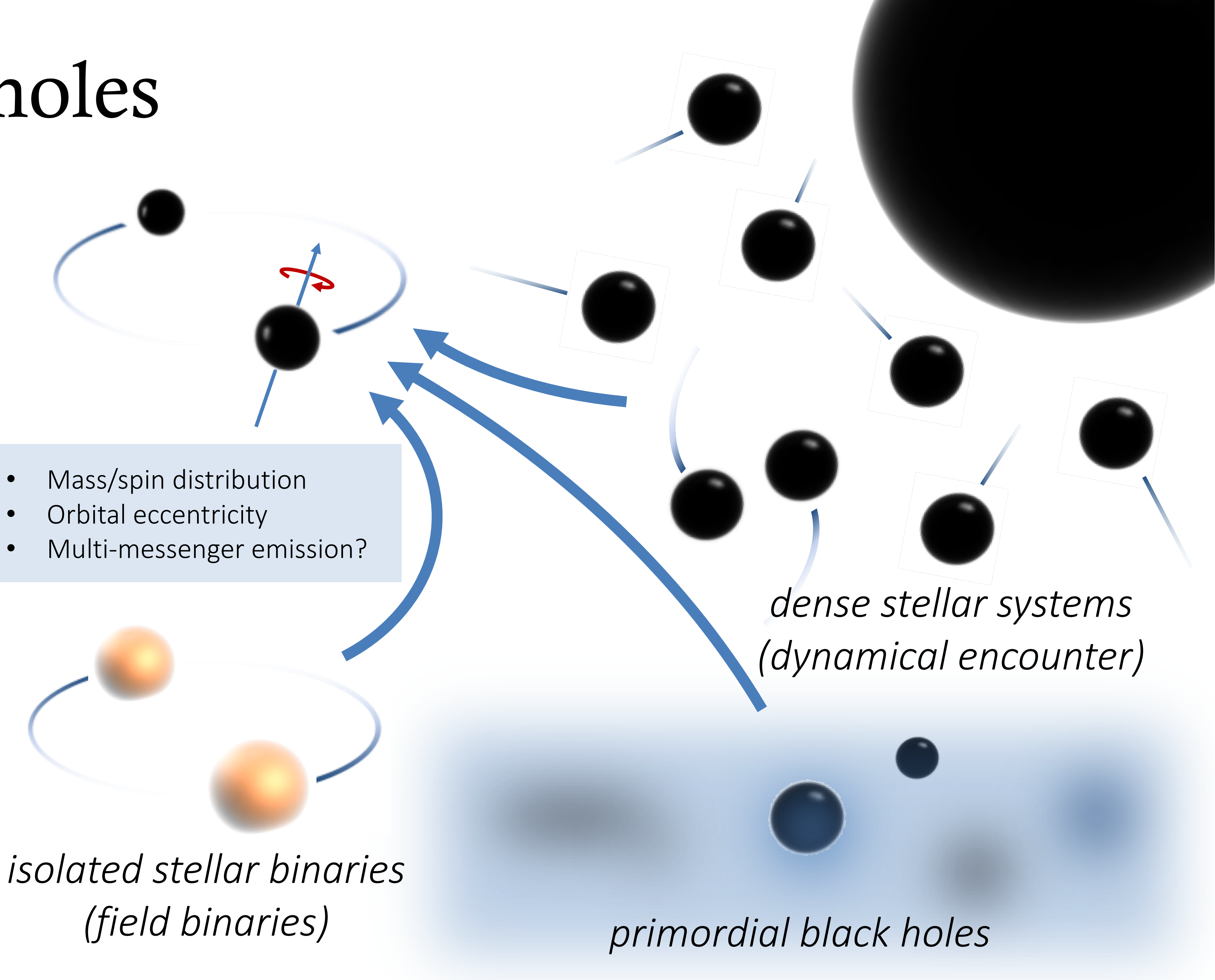
Fallback accretion? *(Piro & Thrane, 2012)*

Binary black holes

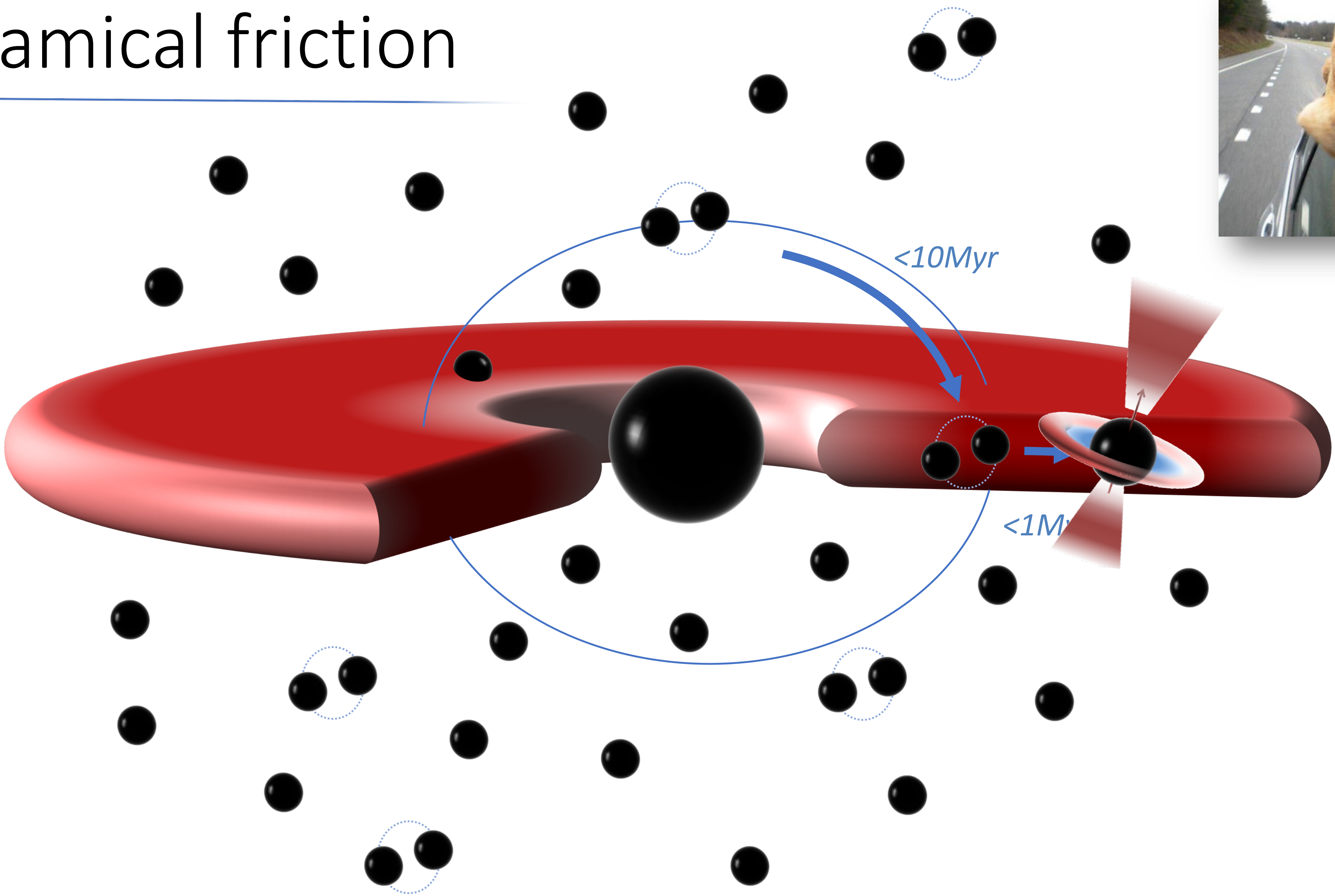


LIGO+Virgo 2018

- Mass/spin distribution
- Orbital eccentricity
- Multi-messenger emission?

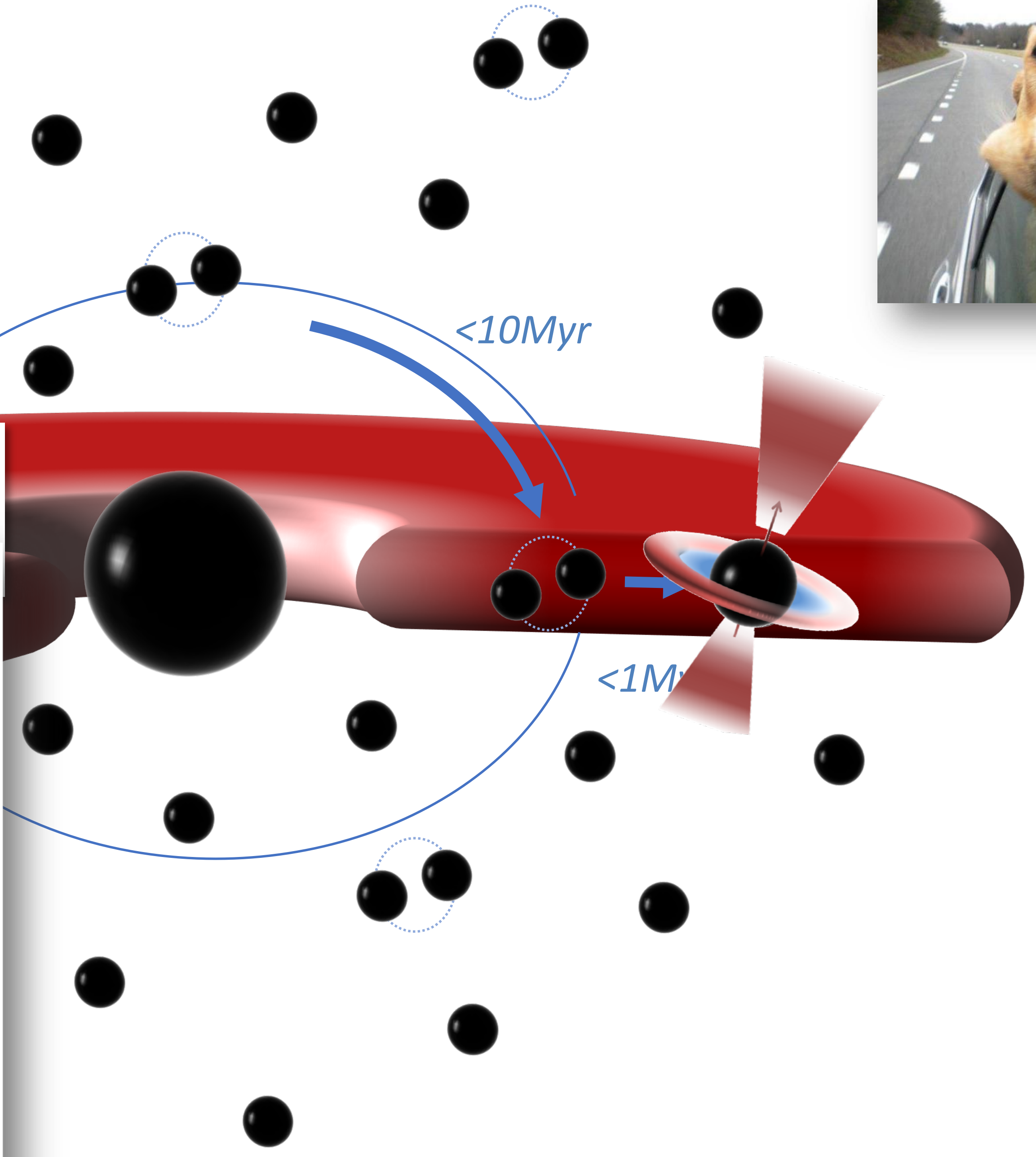


Dynamical friction

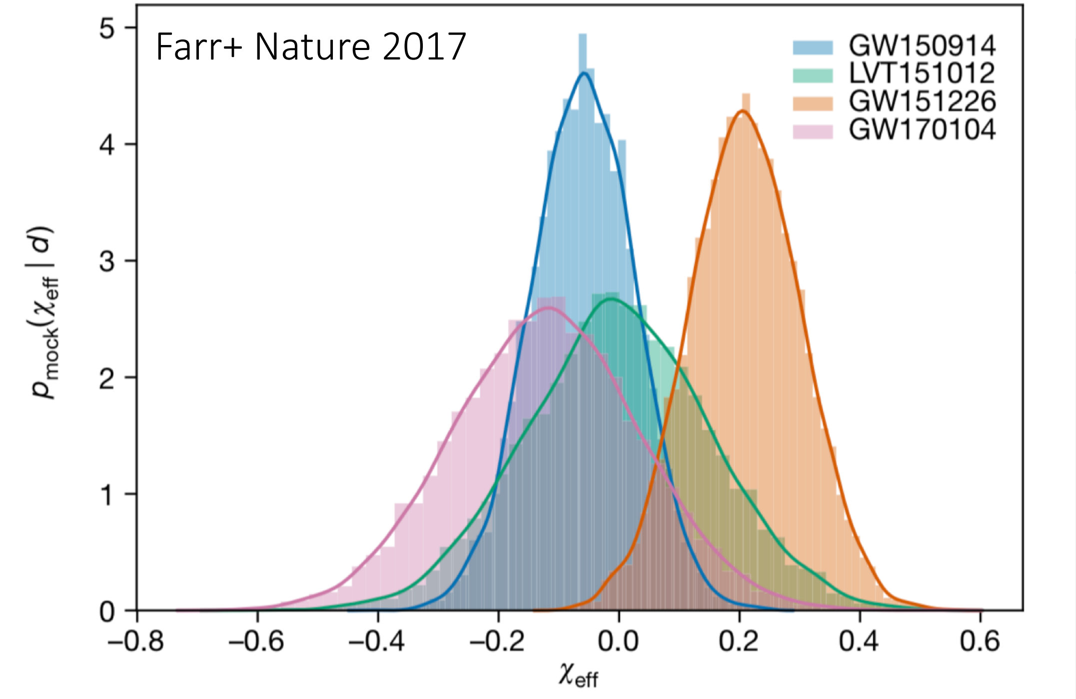


Bartos+ ApJ 2017

Dynamical friction

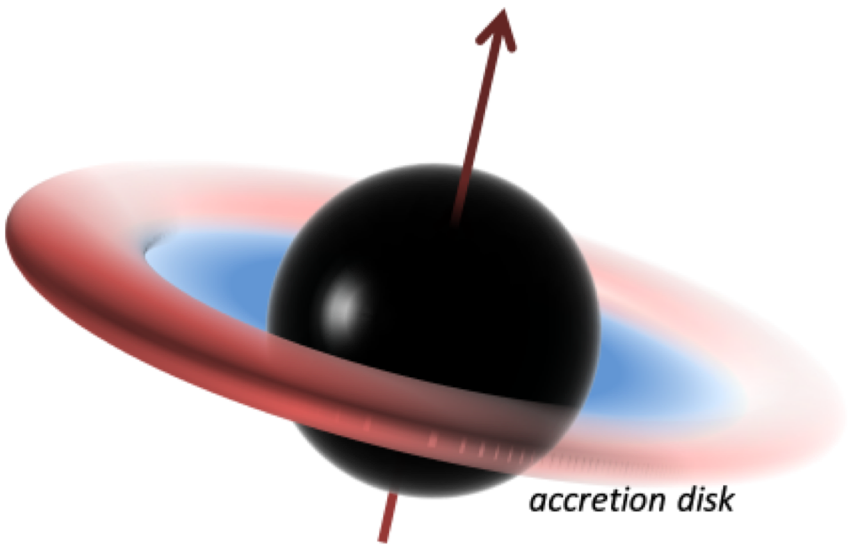


Black hole spin distribution consistent with "chance-encounter" origin.



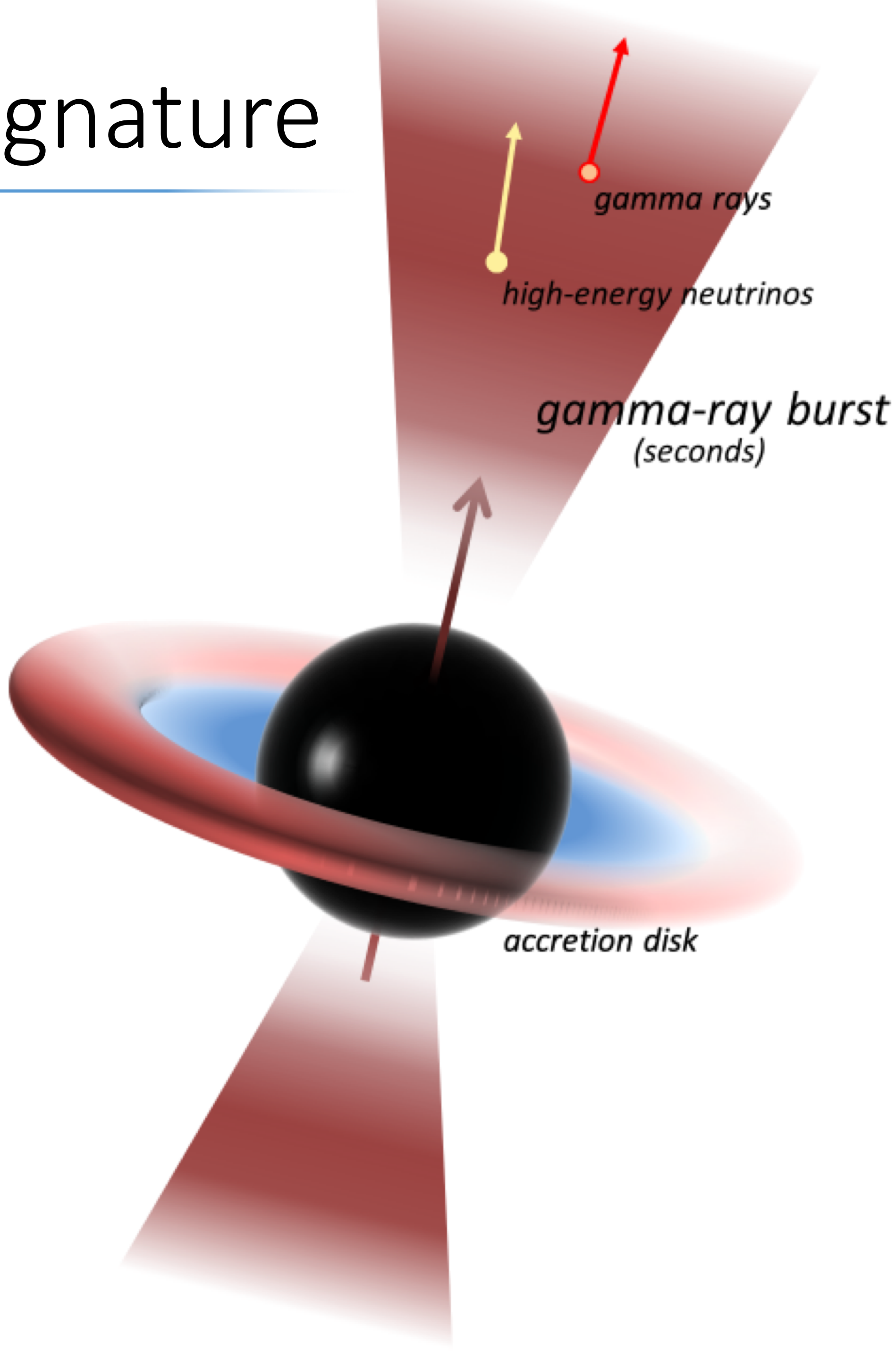
Bartos+ ApJ 2017

Electromagnetic signature

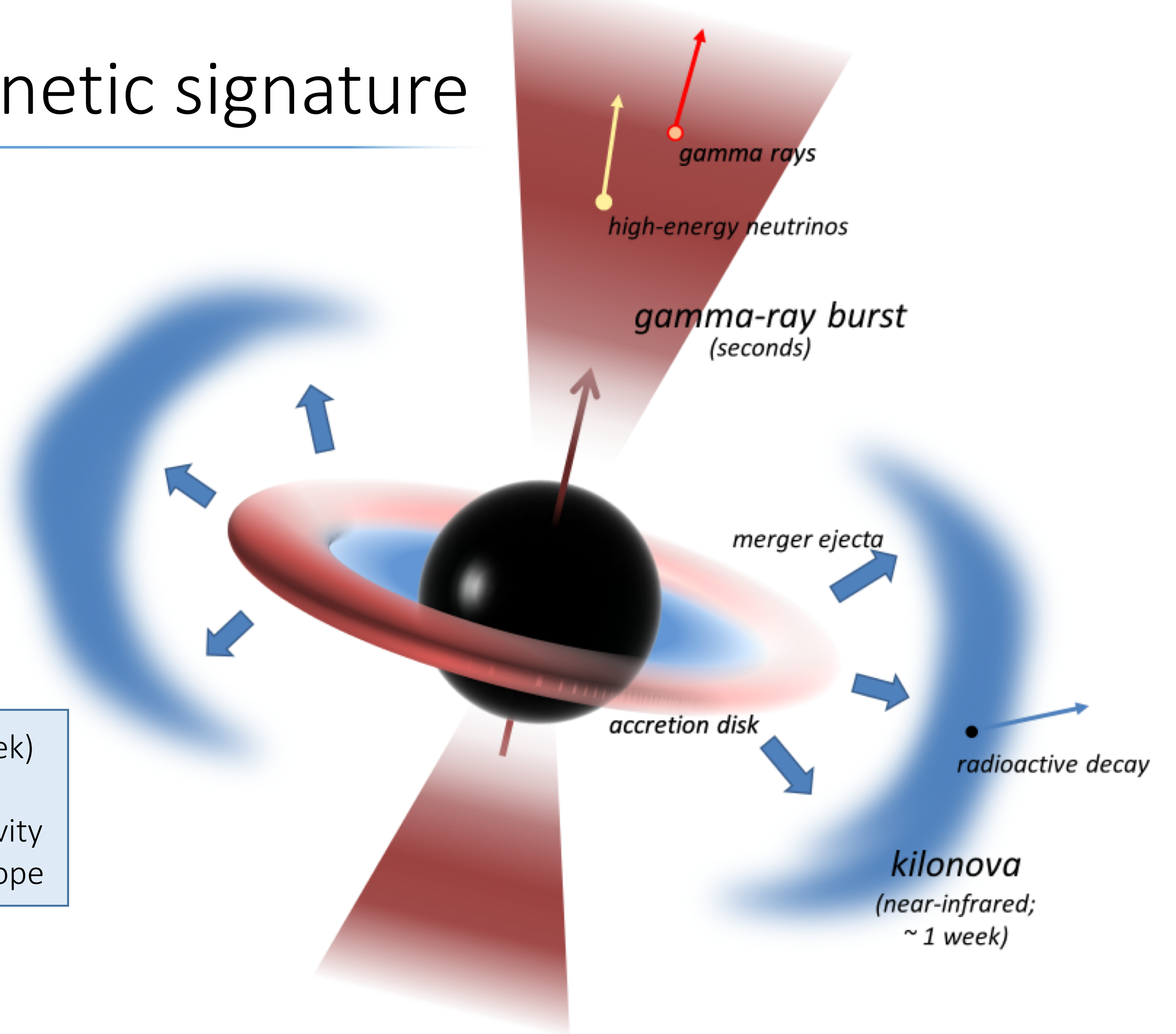


Electromagnetic signature

- Beamed
- Good gamma-ray FoV
- Limited localization (difficult to follow-up)



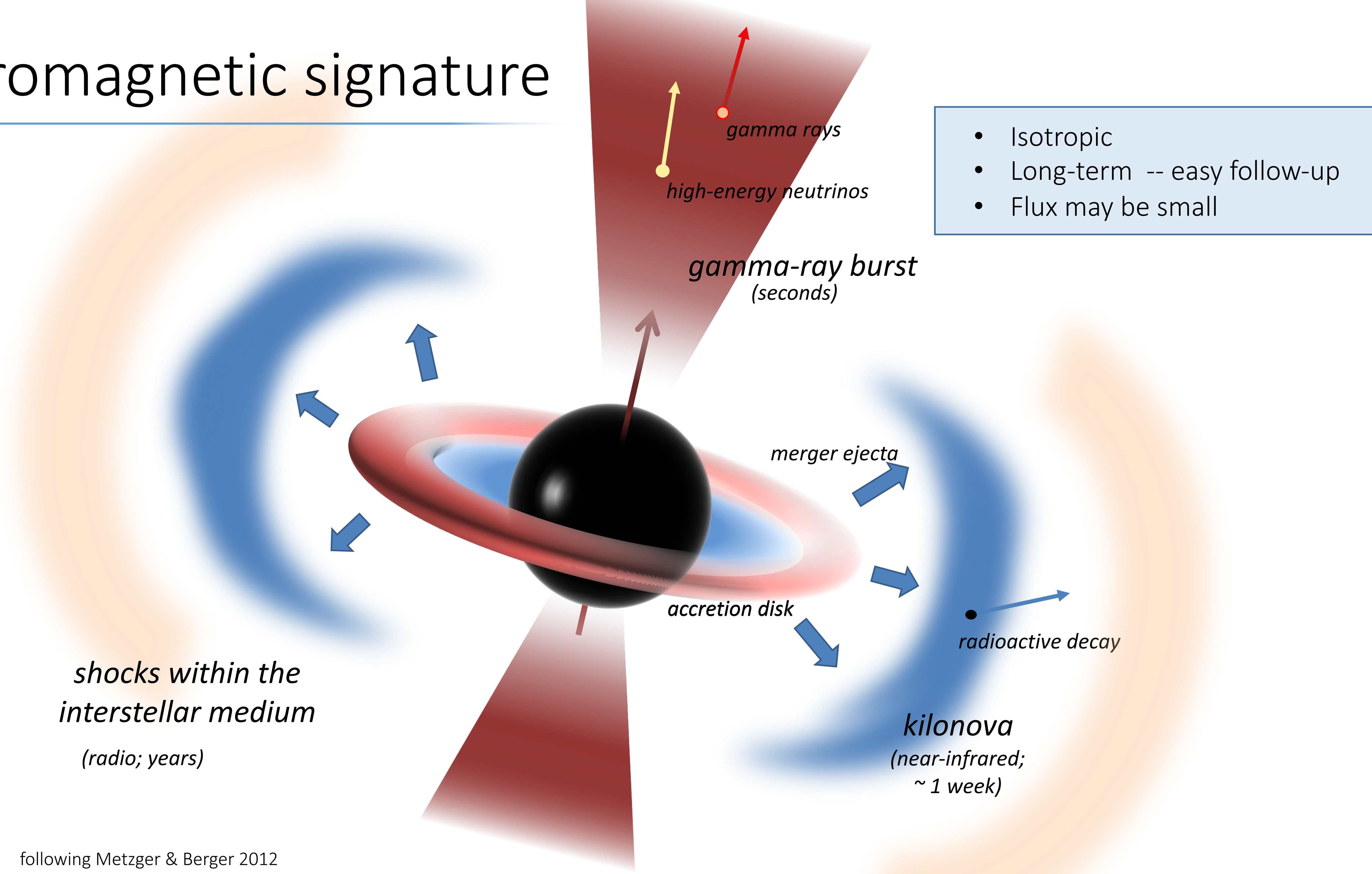
Electromagnetic signature



- Good time frame (~week)
- ~Isotropic
- Limited IR FoV / sensitivity
  → not for every telescope

Electromagnetic signature

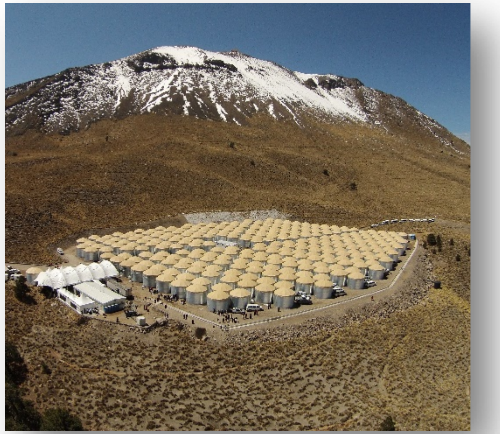
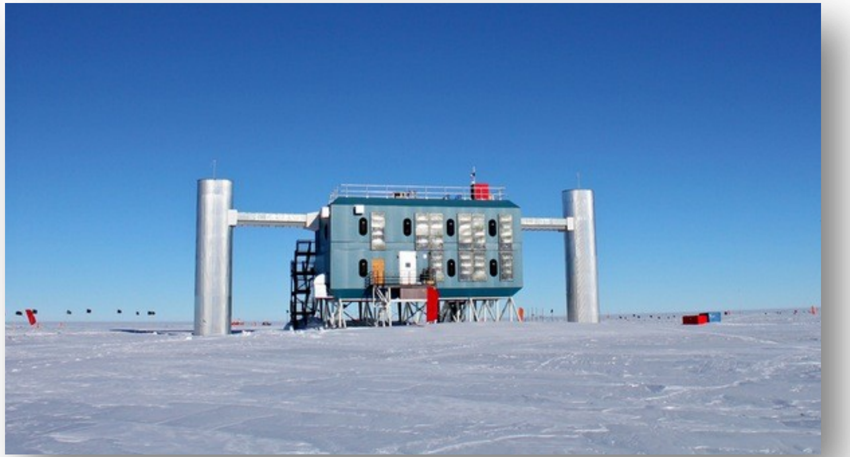
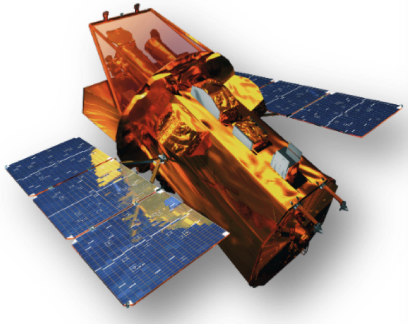
- Isotropic
- Long-term -- easy follow-up
- Flux may be small

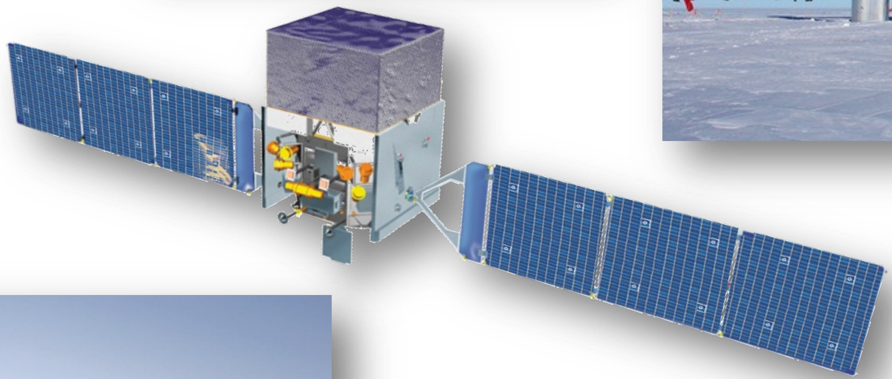
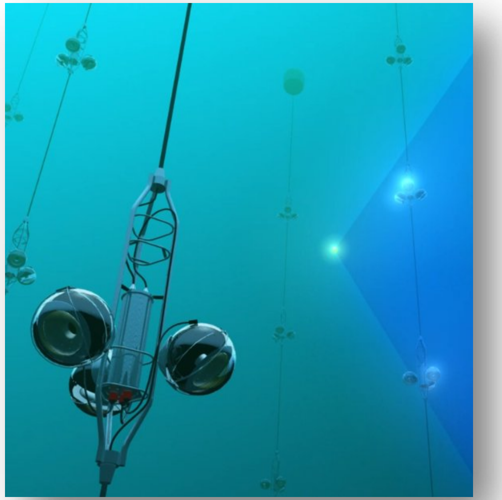


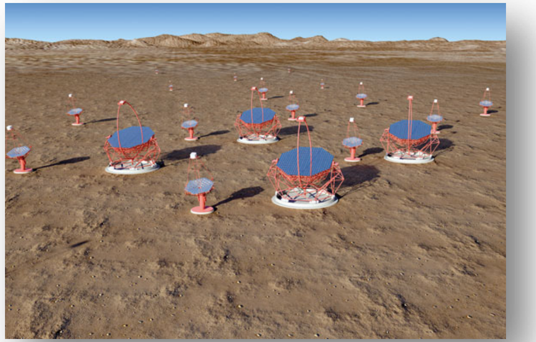
following Metzger & Berger 2012

friends 80+



Earth | Space

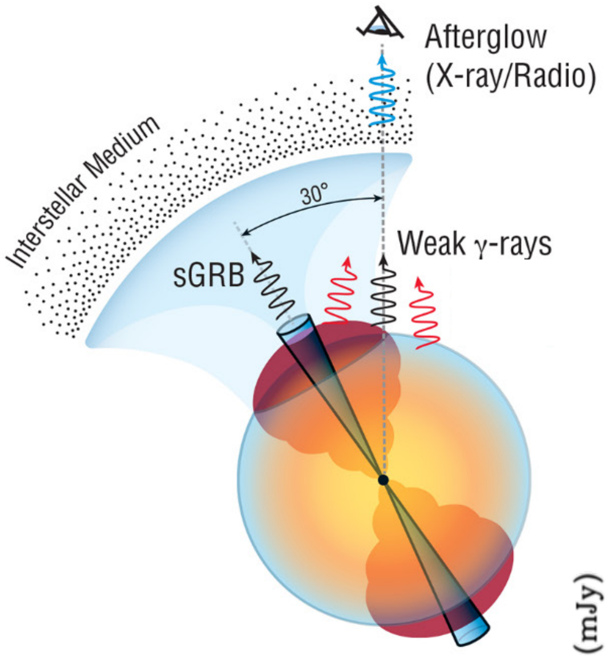
- *Annually improving detectors*
- *More detectors → better localization*

	LIGO		Virgo		KAGRA	
	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc
Early	40 – 80	415 – 775	20 – 65	220 – 615	8 – 25	80 – 250
Mid	80 – 120	775 – 1110	65 – 85	615 – 790	25 – 40	250 – 405
Late	120 – 170	1110 – 1490	65 – 115	610 – 1030	40 – 140	405 – 1270
Design	190	1640	125	1130	140	1270

Abbott+ Living Reviews in Relativity, (2017)

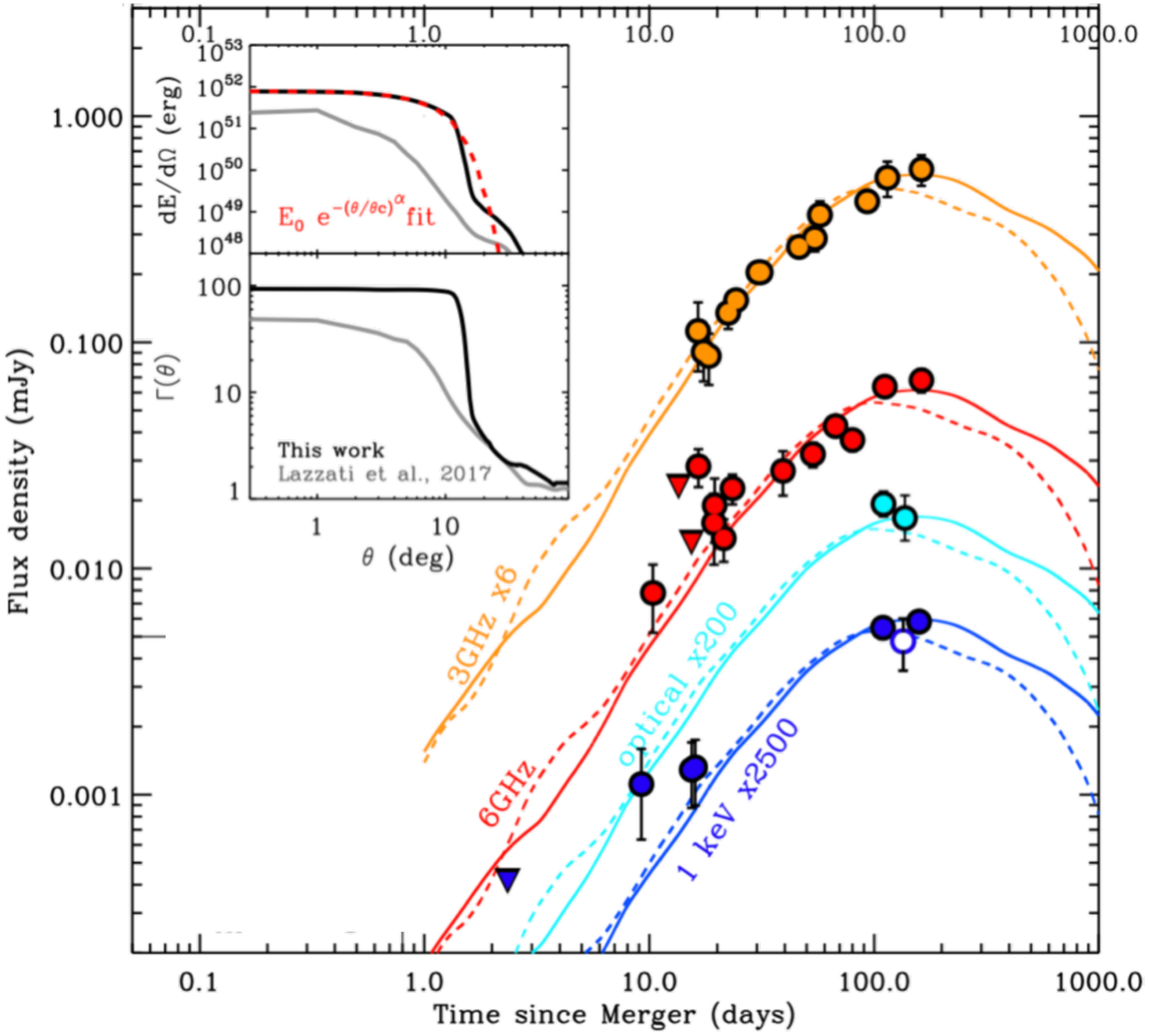
Image credit: LIGO

GW170817
an off-axis GRB



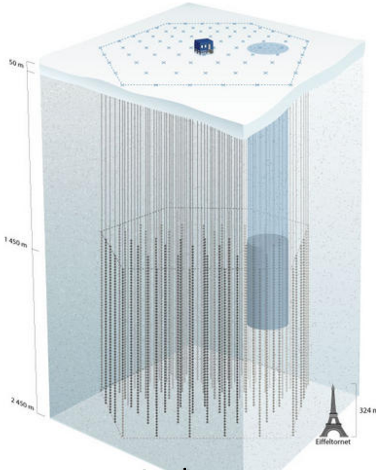
Kasliwal+ 2017

- First GW+high-energy discovery
  - Already very informative
- Afterglow observations point to <u>structured jet</u>.
  (Margutti, Ghirlanda, Lazzati, Mooley, …)
  - ~30% of GWs from BNS will have GRB counterpart.
  - Significant fraction (10%) of GRBs should be nearby.
    (Gupte & Bartos 2018)
- How does TeV emission look like at large viewing angles?
  - Fermi-LAT did not detect this event.
  - Can help differentiate between emission mechanisms.
  - This will be central to whether CTA will see LIGO/Virgo sources.

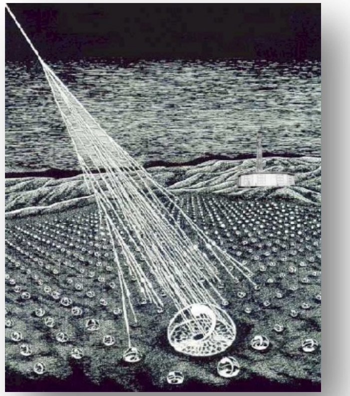


Margutti+ 2018

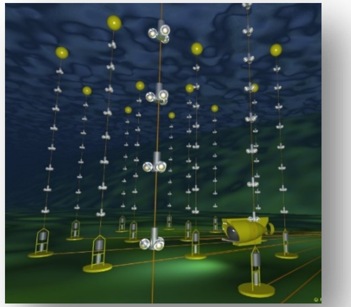
Ultra-high energy emission from neutron star mergers?



IceCube



Pierre Auger

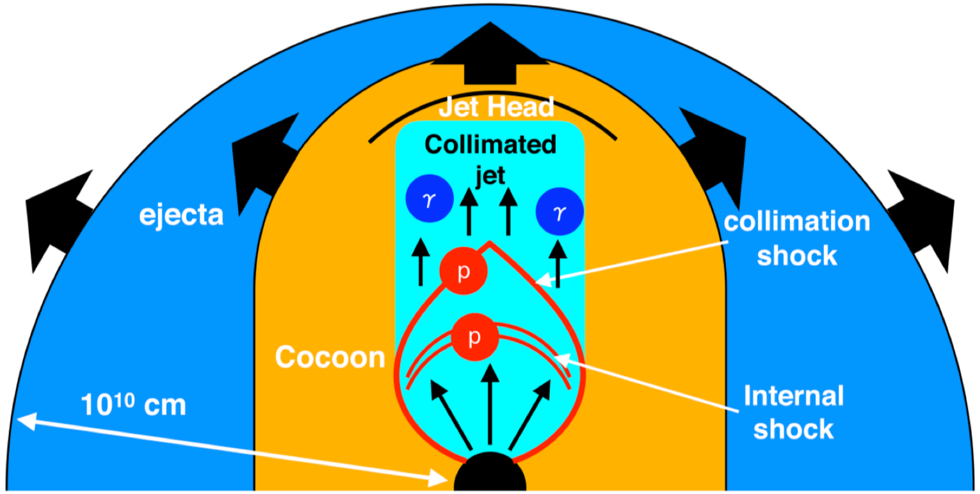


ANTARES

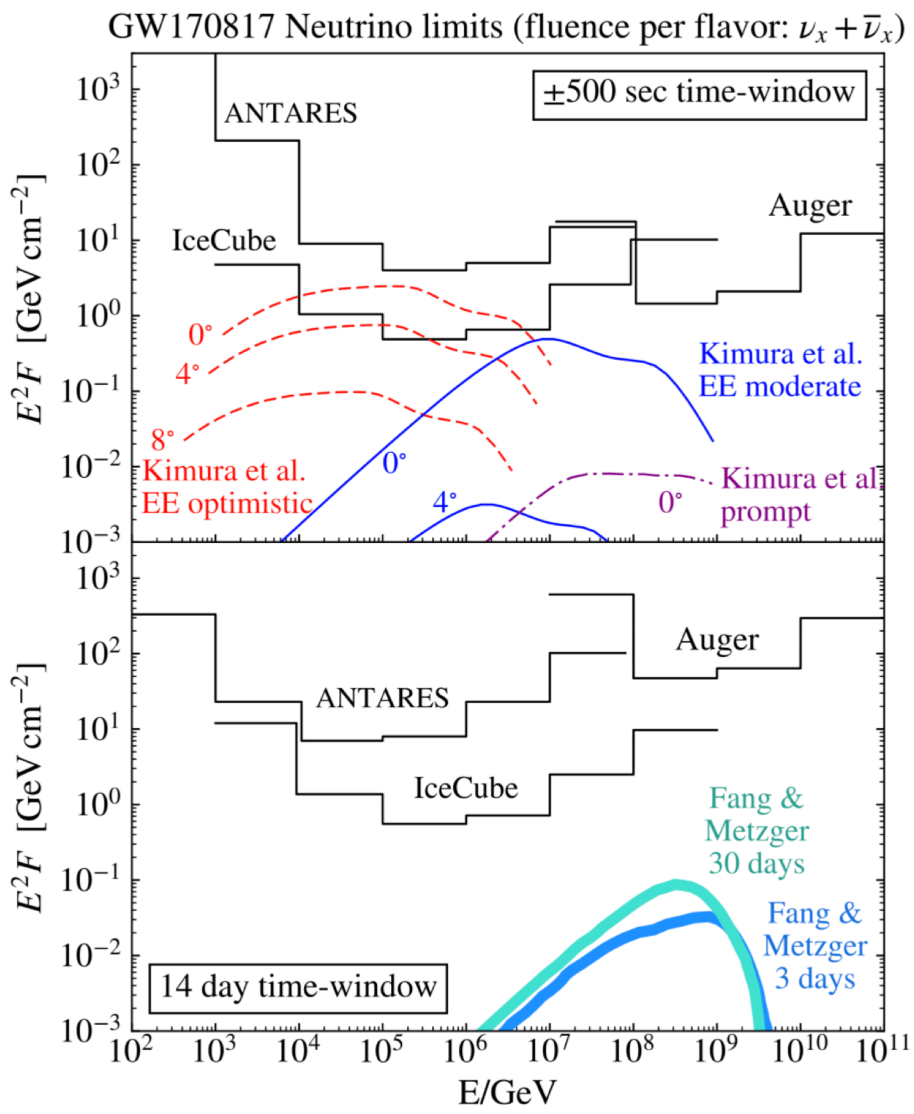
- High-energy neutrinos:
  - Probe PeV+ particle acceleration
  - All-sky detectors --- rapidly provide precise location
  - ν's can escape environments γ-rays cannot

- High-energy (TeV-PeV) neutrinos could have been detected for on-axis GW170817.

- Relativistic outflow will interact with slower ejecta
  → alter neutrino emission
  → can probe jet structure.

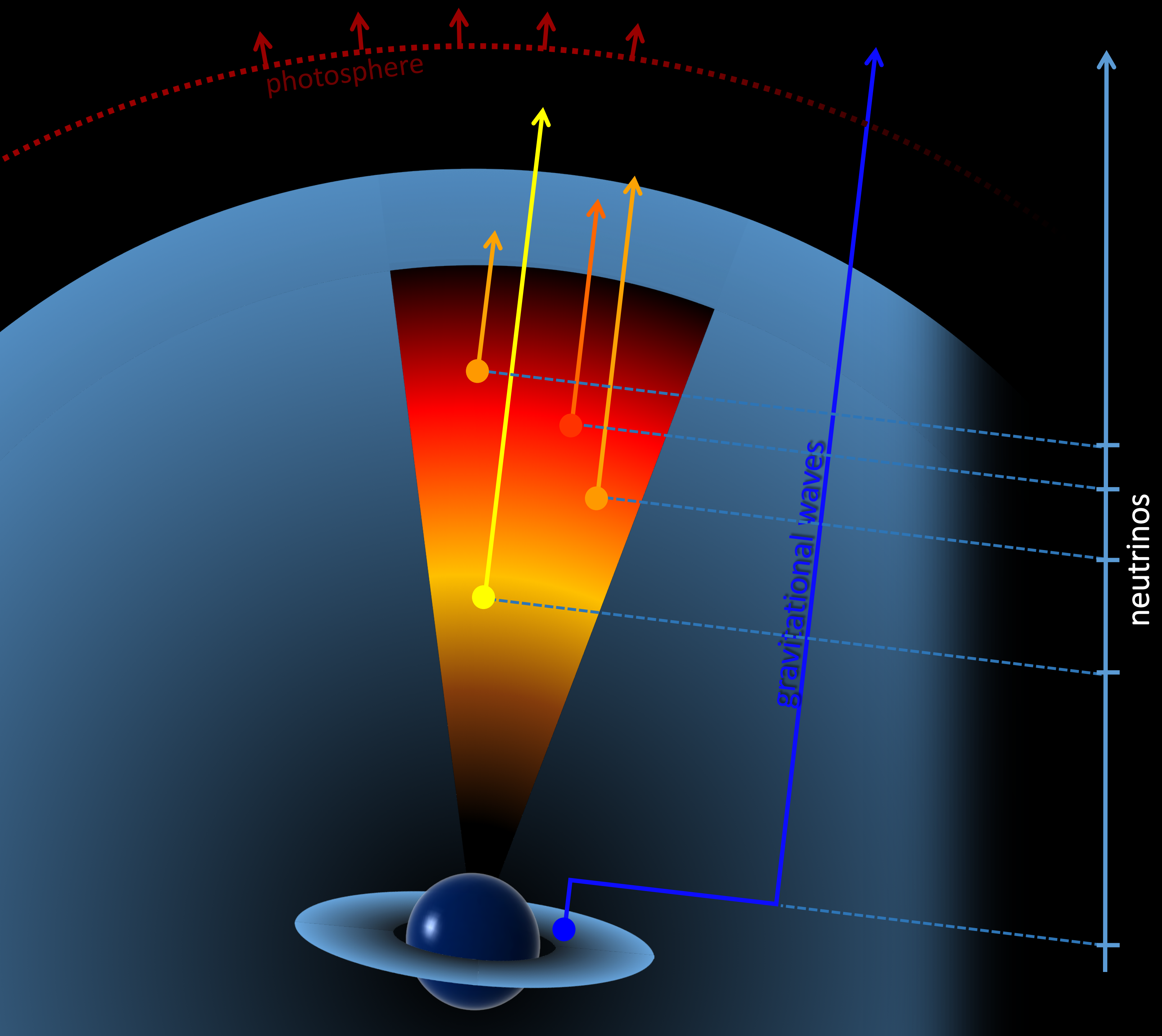


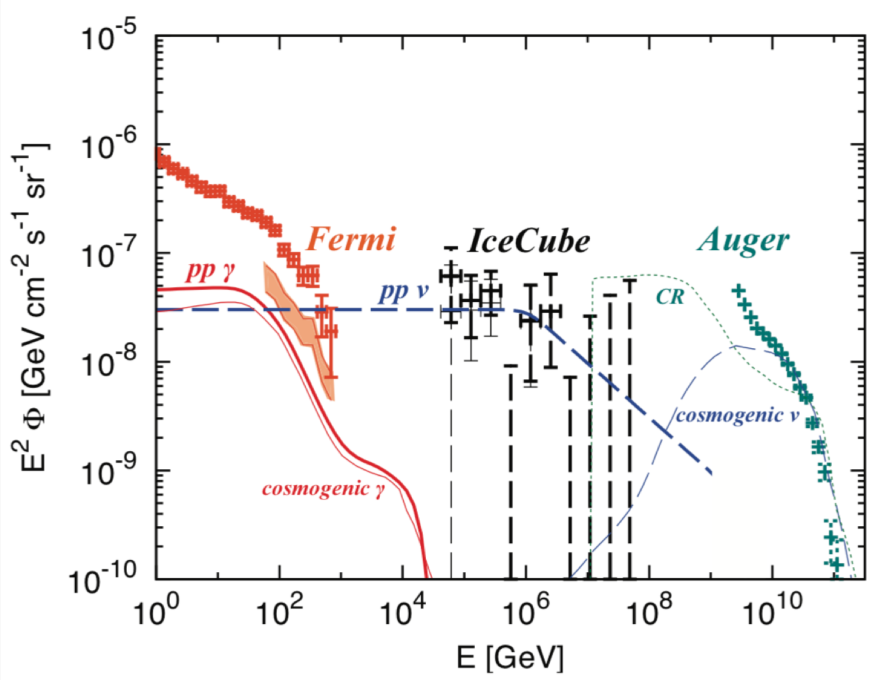
Kimura, Murase, Bartos, Ioka, Heng, Meszaros 2018



ANTARES, IceCube, Pierre Auger, LIGO, Virgo 2017

Hidden cosmic accelerators?



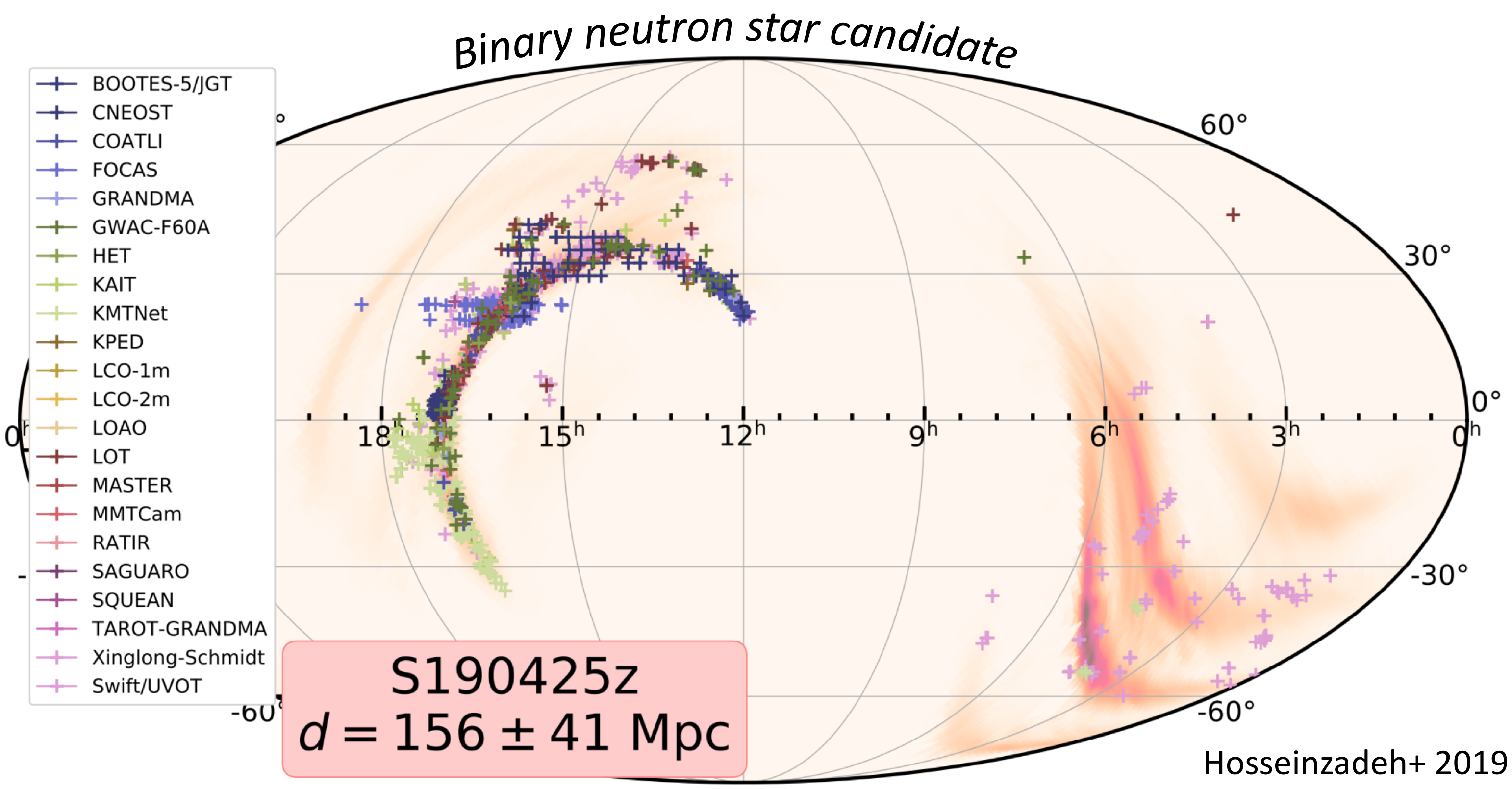


Murase & Waxman 2016

Razzaque+ 2003
Bartos+ 2012
Murase+ 2013, 2015

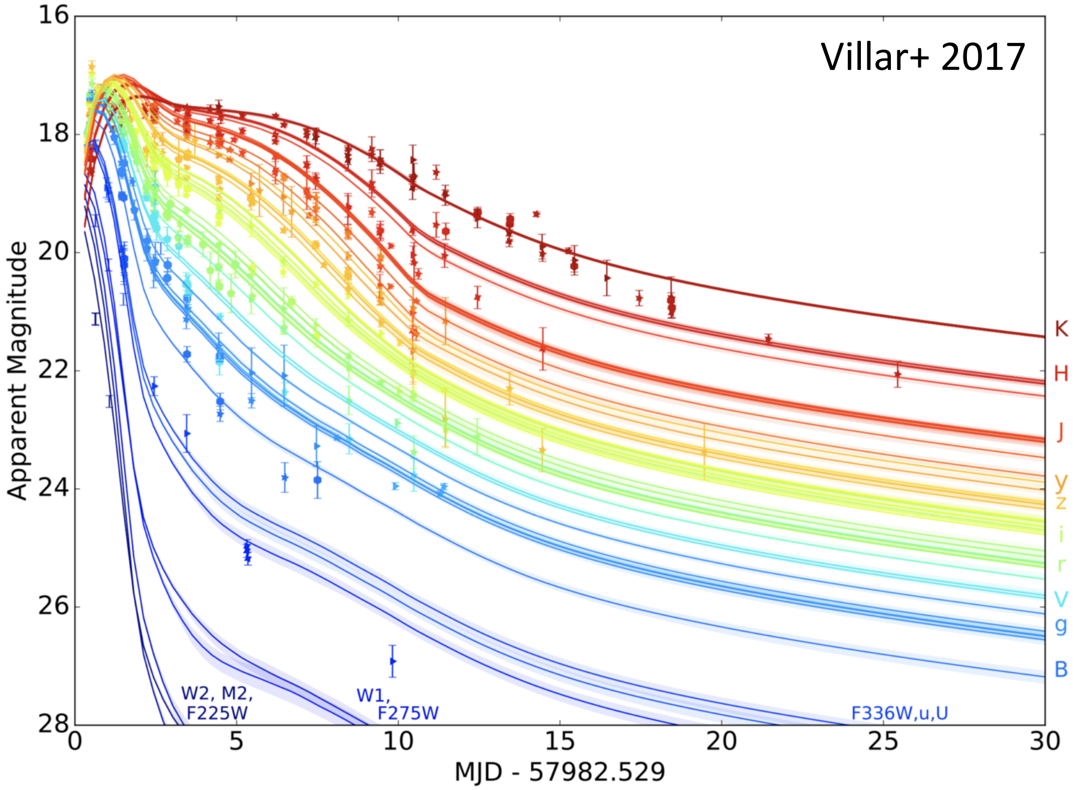
EM follow-up is difficult

- First NS-NS candidate during O3 already detected (along with many new BH-BH mergers).
- Poor localization – Hanford was off.
- No GRB / high-energy neutrino counterpart.
- Dozens of observatories, 100s of observations (>230 GCN circulars).
- Extensive observation campaign only covered ~50% of volume.
- Many false positives.
- Galaxy targeted searches --- < 1% covered.

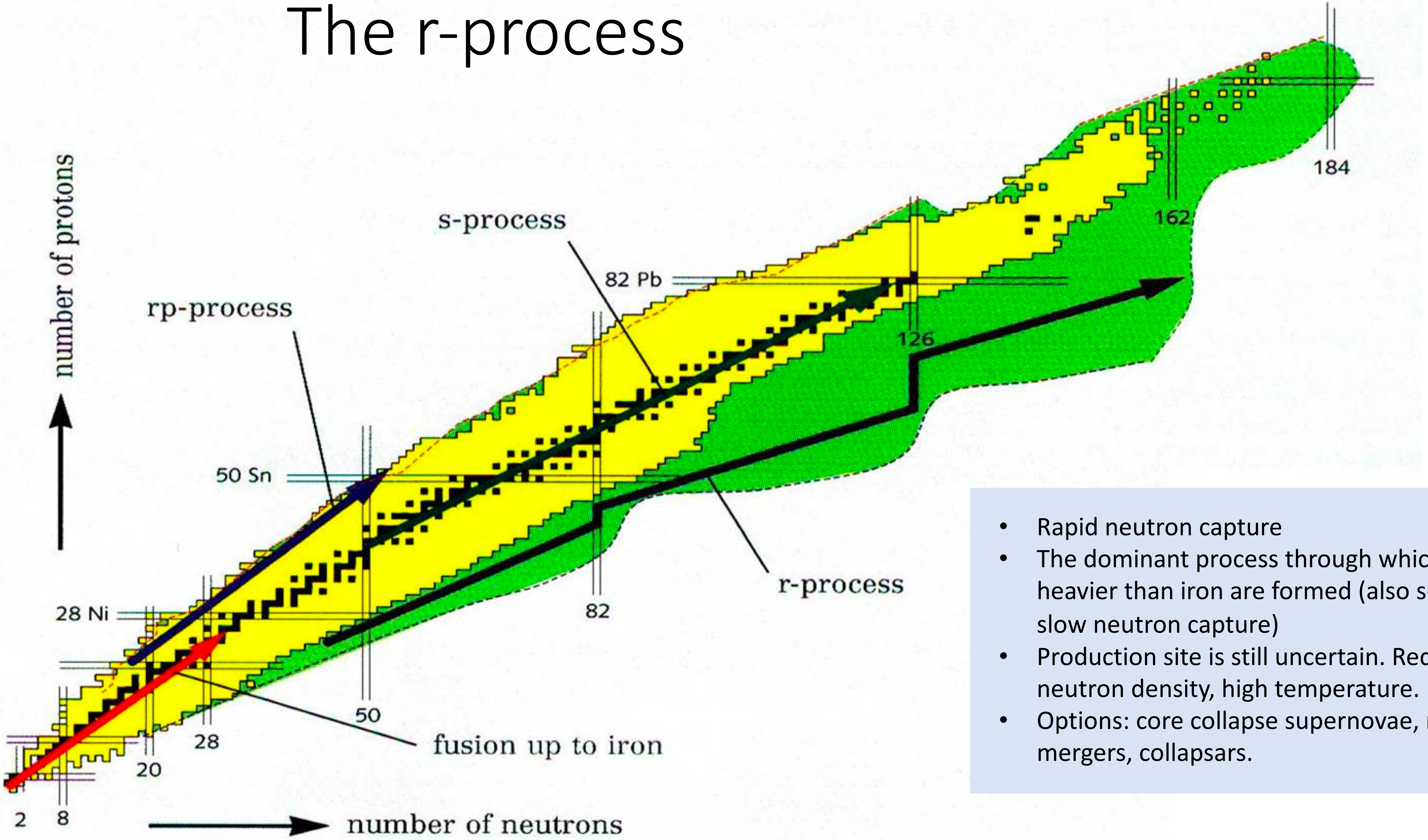


Hosseinzadeh+ 2019


nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
ANATOMY OF A
KILONOVA
Aftermath of the merger between two neutron stars
PAGES 36, 64, 67, 71, 75, 80 & 85
HEALTH
LESSONS FROM SILICON VALLEY
Former funder seeks tech disruption for biomedicine
PAGE 23
MOLECULAR ECOLOGY
EVOLUTION IN ACTION
Tracing mutations in 60,000 generations of bacteria
PAGES 42 & 45
GENOMICS
CHROMOSOME COMPLEXITY
Two mechanisms that guide 3D structure of the genome
PAGES 38 & 51
NATURE.COM/NATURE
2 November 2017 £10
Vol. 551, No. 7678

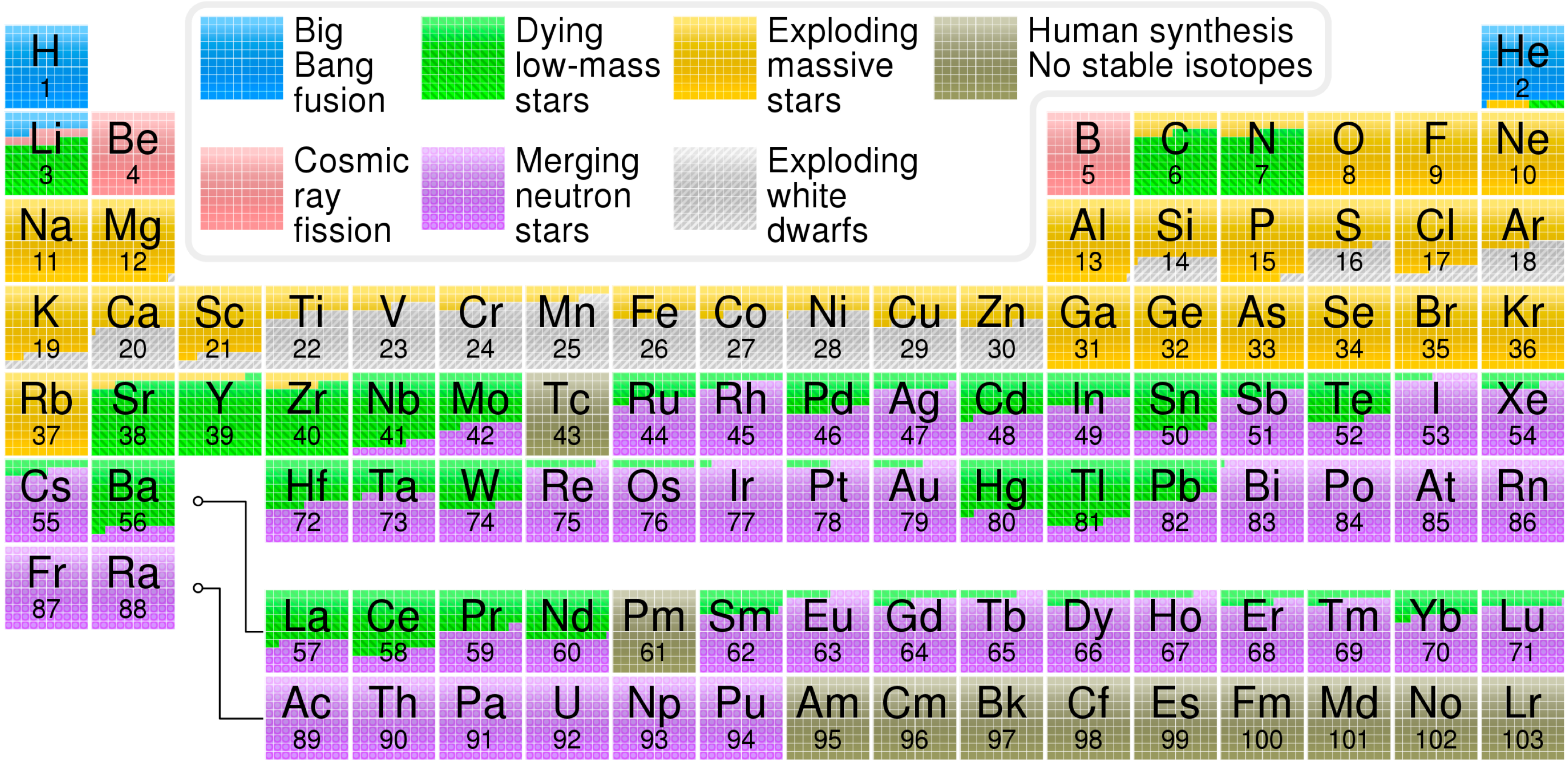

Villar+ 2017
Apparent Magnitude
MJD - 57982.529
16
18
20
22
24
26
28
0
5
10
15
20
25
30
K
H
J
y
z
i
r
V
g
B
W2, M2,
F225W
W1,
F275W
F336W,u,U

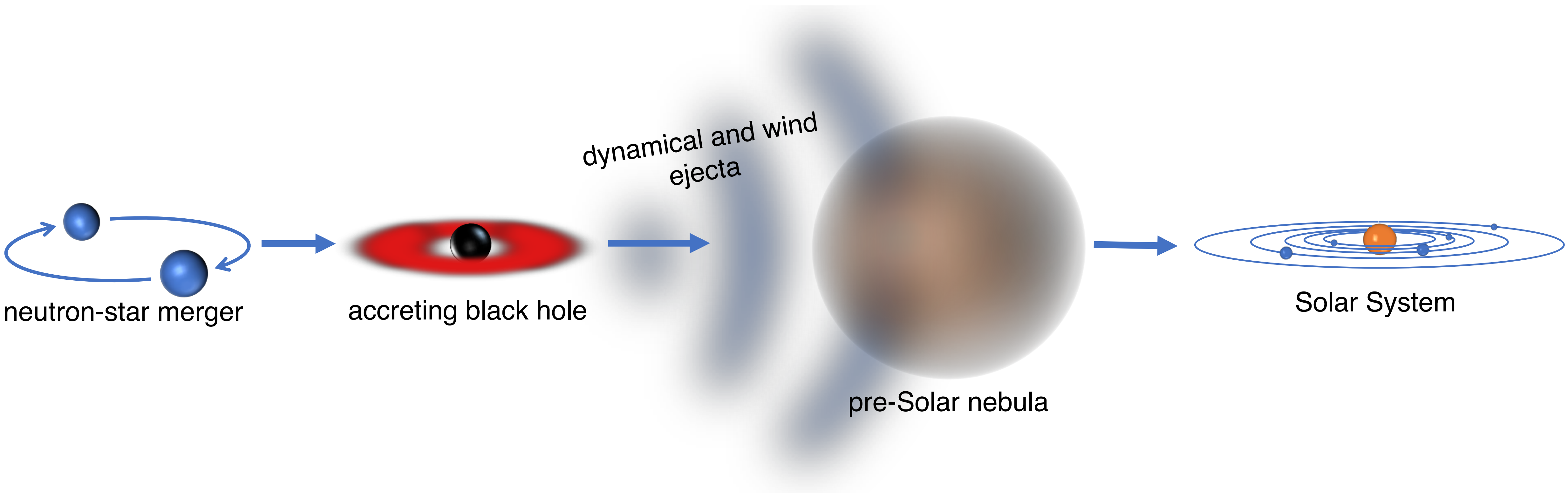
The r-process



- Rapid neutron capture
- The dominant process through which elements heavier than iron are formed (also s-process or slow neutron capture)
- Production site is still uncertain. Requires high neutron density, high temperature.
- Options: core collapse supernovae, neutron star mergers, collapsars.

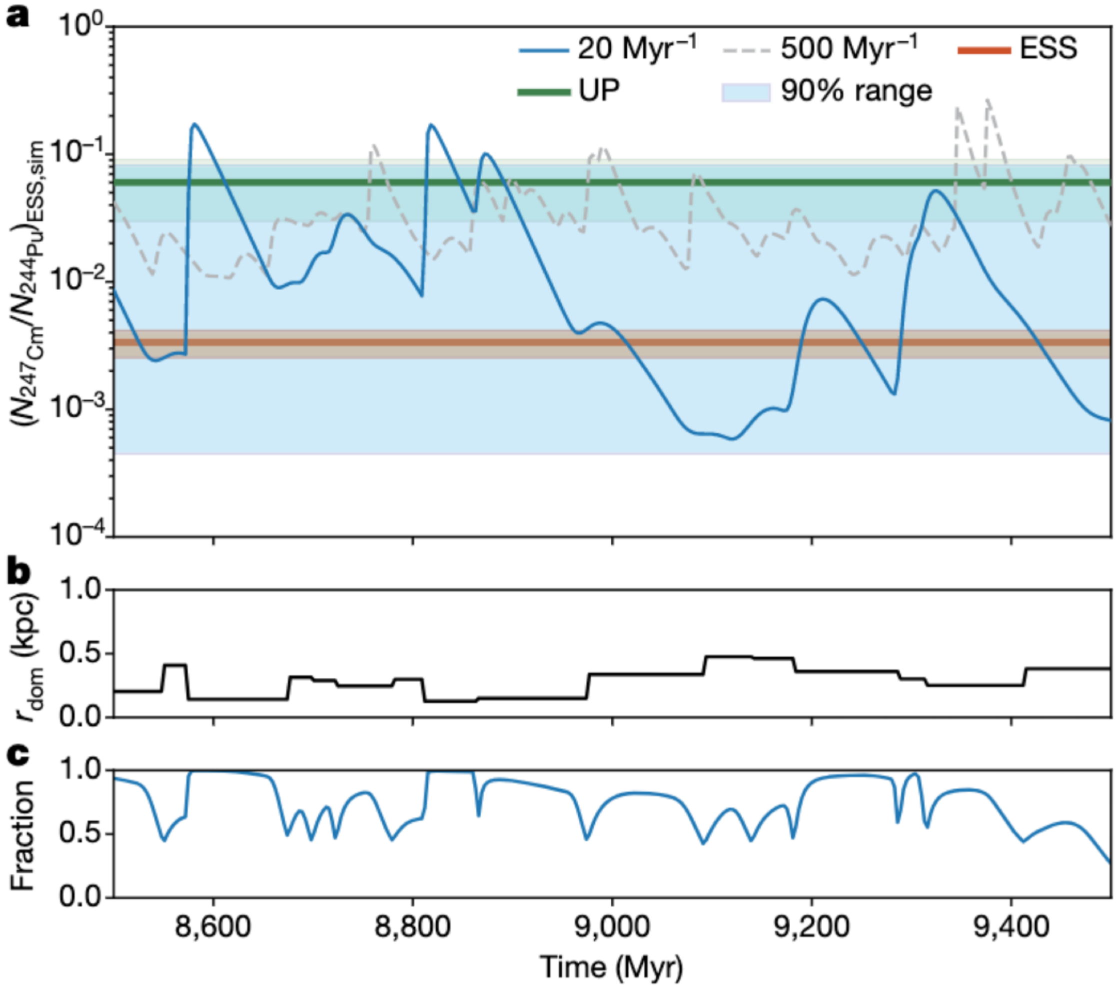
The origin of elements

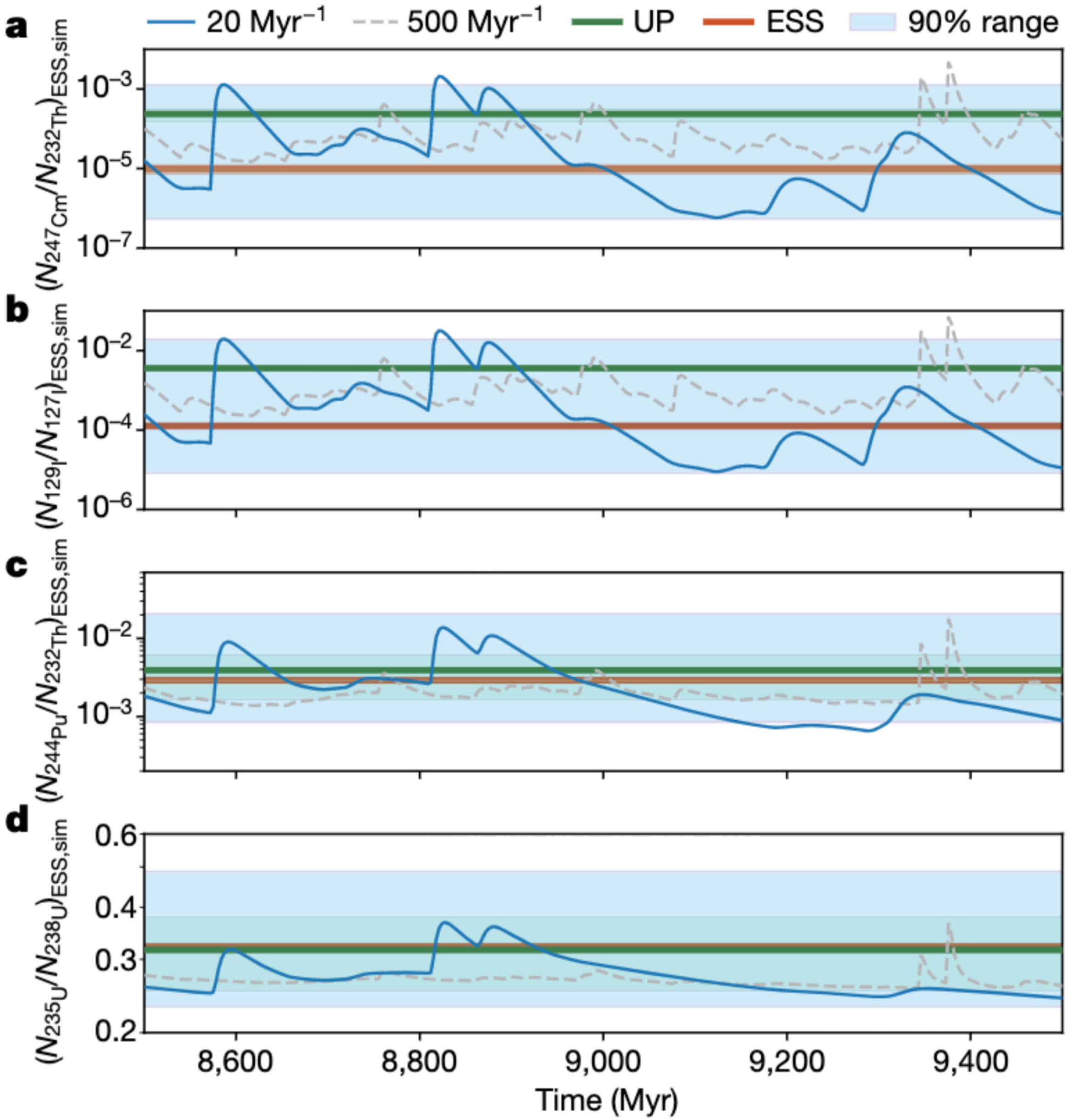




Bartos & Marka, Nature 2019

Numerical simulations of abundances in the ISM near the pre-Solar nebula





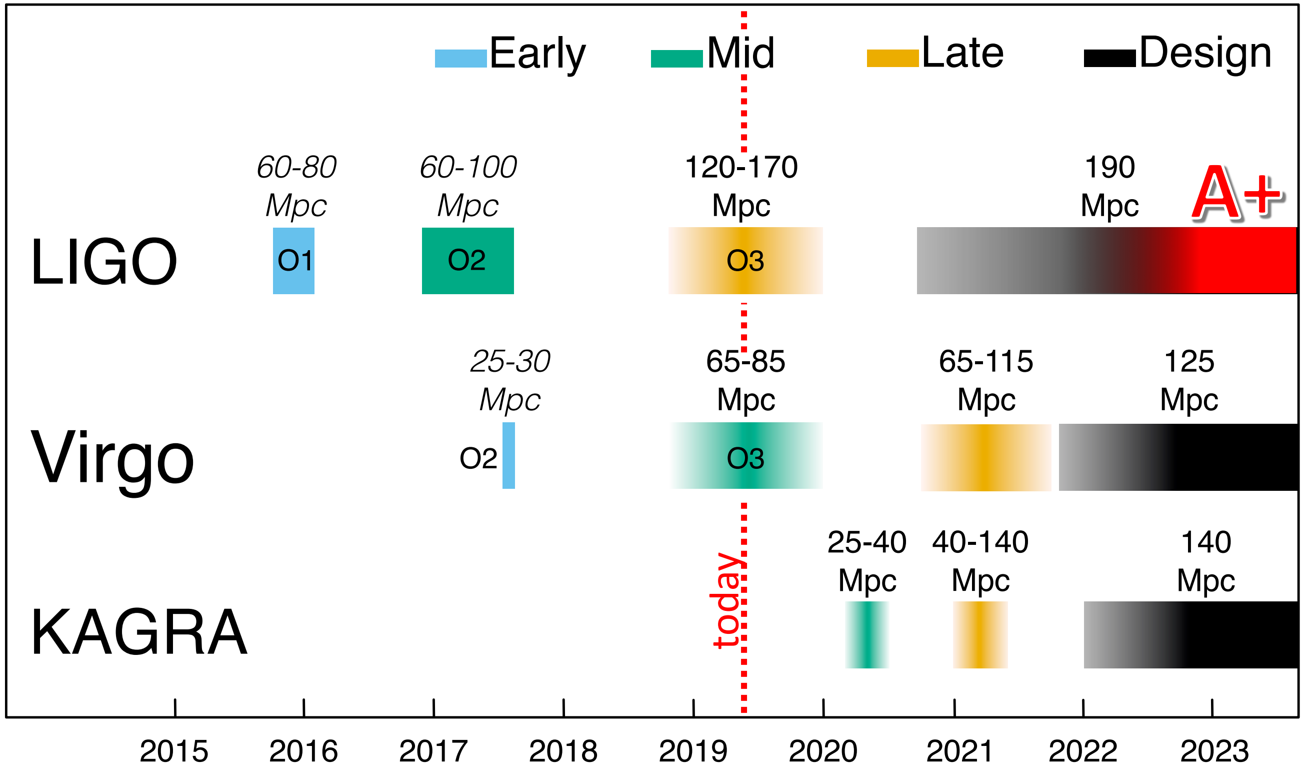
Bartos & Marka, Nature 2019

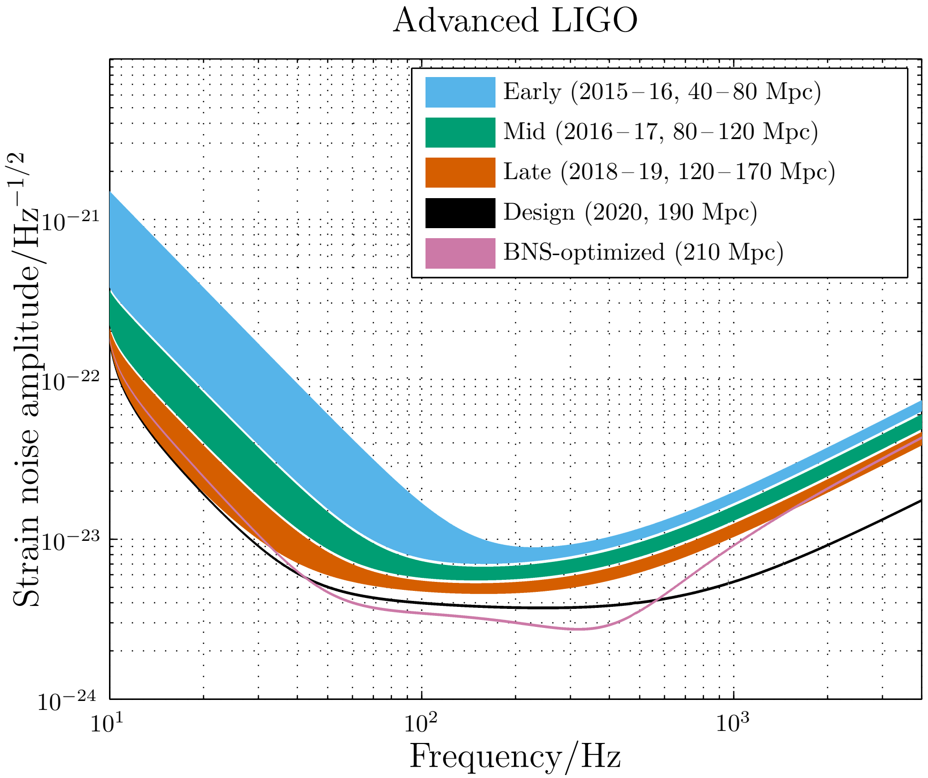
Single nearby event?

- Neutron star mergers are rare ~ 20 Myr^{-1} in the Milky Way
- For short lived isotopes only the most recent, nearby events will be relevant
  - Isotope will decay for older events
  - Isotope will not make it to the pre-Solar nebula in time for more distant events
- Contribution of single event was likely significant
  - Majority of isotopes with half lives <~ 15 Myr (e,g, Curium)
  - Large fraction of isotopes with half lives <~ 100 Myr (e.g. Plutonium)
  - Expected distance from pre-Solar nebula: 300 pc
  - Expected time before formation of Solar System: 100 Myr

Bartos & Marka, Nature 2019

sensitivity timeline





	LIGO		Virgo		KAGRA	
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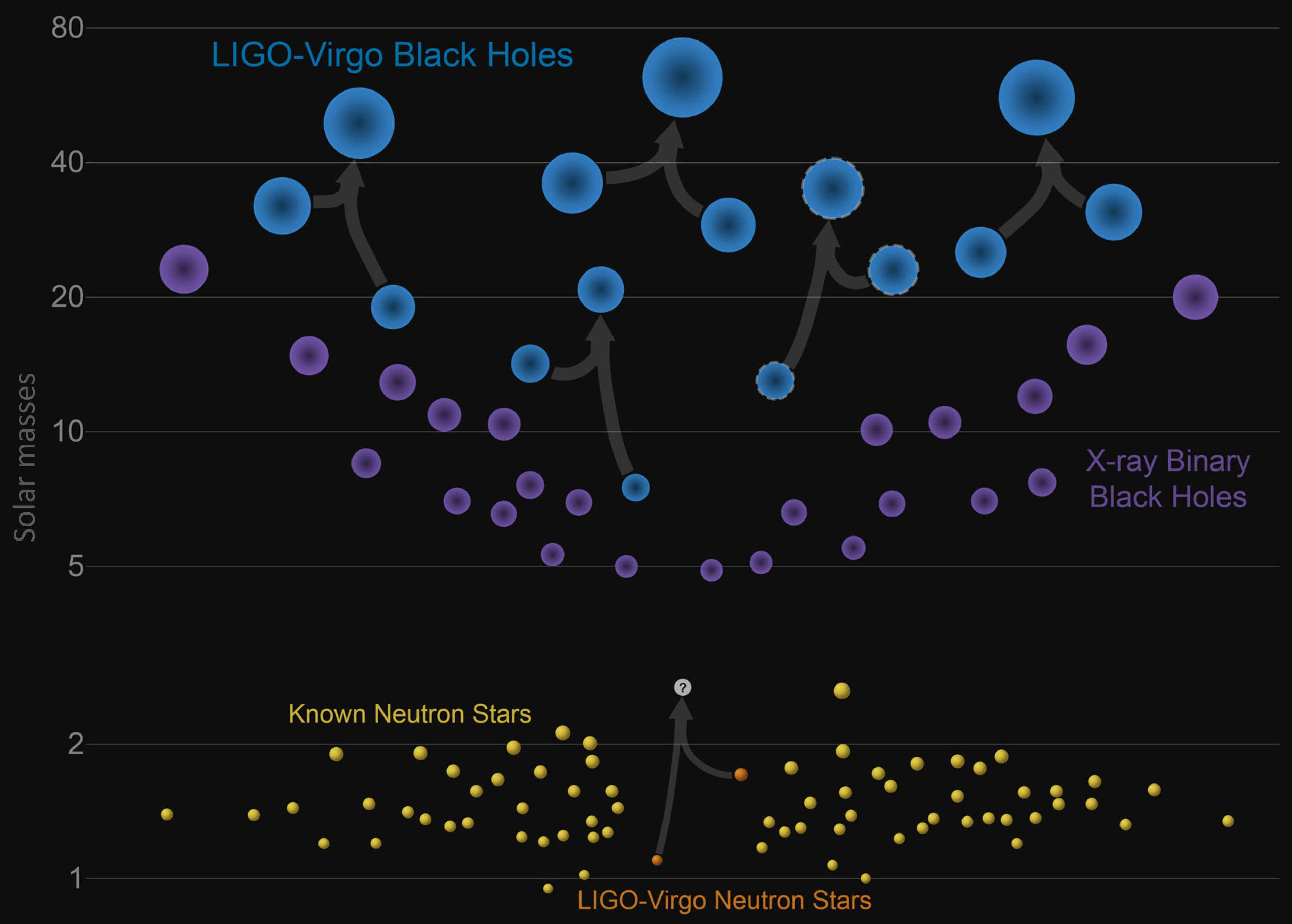
Design	190	1640	125	1130	140	1270
A+	325	2600				

KAGRA, LIGO, Virgo 2017, Barsotti+ 2018

- Currently: ~1 BBH / week
  ~1 BNS / month



Credit: LIGO-Virgo/Frank Elavsky/Northwestern University

Too many detections?!

LIGO A+ (325 Mpc range; Barsotti+ 2018), Virgo+

\+ neglect LIGO/Virgo duty cycle

\+ 100-4000 Gpc^{-3} yr^{-1} NS-NS detections (Abbott+ 2018)

10 – 600 NS-NS merger detections / year

→ for beaming with $\theta_{\mathbf{jet}} = 30^o$: 2 – 80 detections / year

→ for beaming with $\theta_{\mathbf{jet}} = 10^o$: 0.2 – 10 detections / year

→ for beaming with $\theta_{\mathbf{jet}} = 5^o$: 0 – 2 detections / year

(NS merger rate estimate will quickly improve with O3)

- Black hole – black hole
  - Range: ~2.5 Gpc with LIGO A+ (Barsotti+ 2018)
  - Rate: 10 – 100 Gpc^{-3} yr^{-1} (Abbott+ 2018)

  → detection rate: 600 – 6000 / year.

  → 10x more time would be needed than NS-NS…

- Neutron star – black hole: ?

- Sub-threshold events: ?

Summary

- ✓ Many new discoveries expected for O3
  - ➢ We will need to prioritize interpretation / EM follow-up
  - ➢ Statistics will be more difficult (large trial factor)
- ✓ First discoveries: Can we build on previous results or have to rethink everything?
- ✓ Incorporate astrophysical information in search and interpretation (e.g. GW waveforms)
- ✓ Coming large-scale instruments will completely change what is possible (CTA, LSST, SKA, DESI, IceCube-Gen2, Km3NET…, also LISA, ET, LIGO-CE)
- ✓ Need to prepare for this transformation now *(both as a community and as individual groups)*