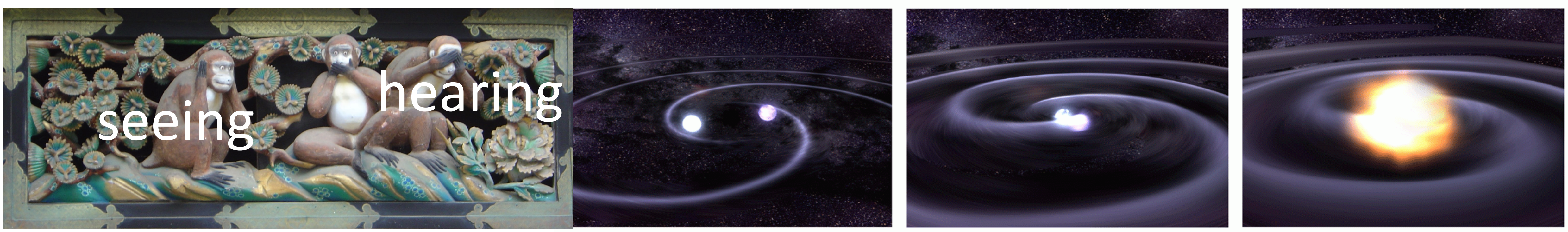
Status of Gravitational Wave Astronomy: listening and seeing the Violent Universe



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BlackGEM science team, Virgo Scientific Collaboration

TeVPA Conference, Kashiwa, Japan, 30th October 2015

Outline

Part 1: Introduction to Gravitational Wave (GW) astronomy

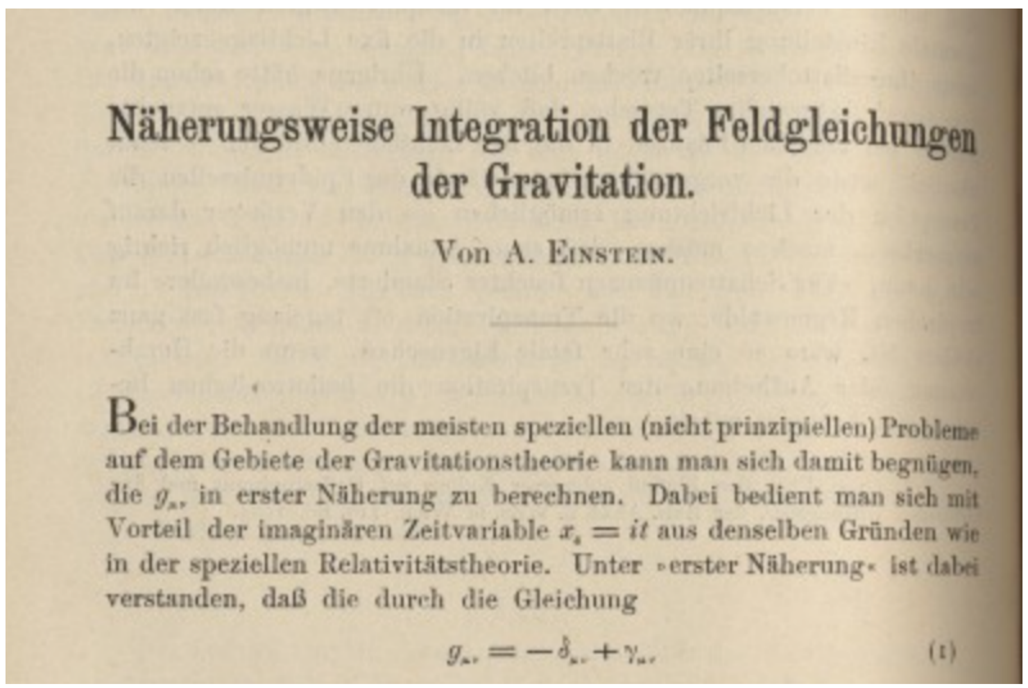
Part 2: Astrophysical Characterisation with GW and Electromagnetic (EM) and astroparticle measurements

Part 3: Challenges for EM/high-energy ν follow-up

GWs are perturbations in the fabric of spacetime

Accelerating quadrupole matter sources

Einstein, 1916

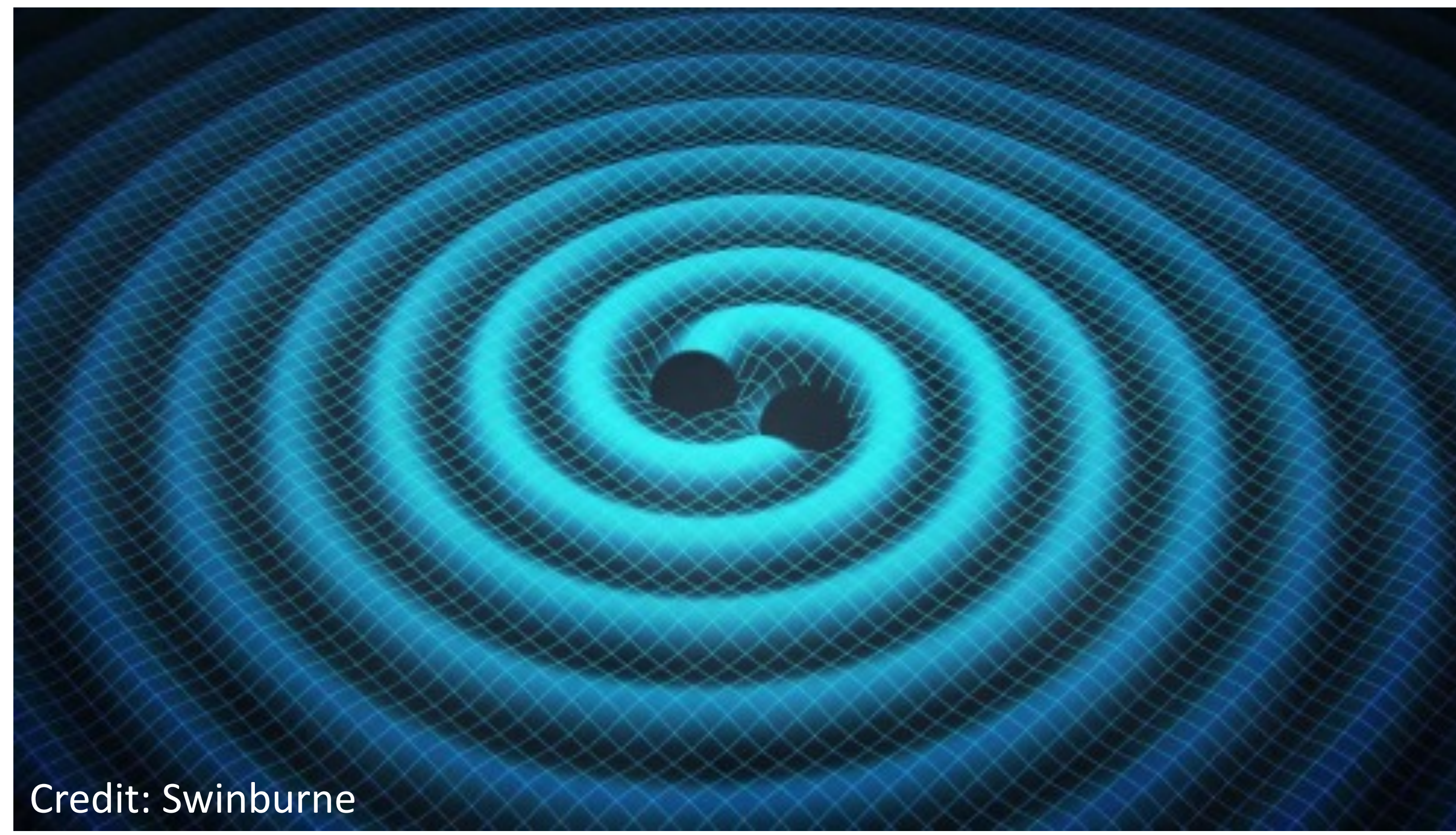


Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

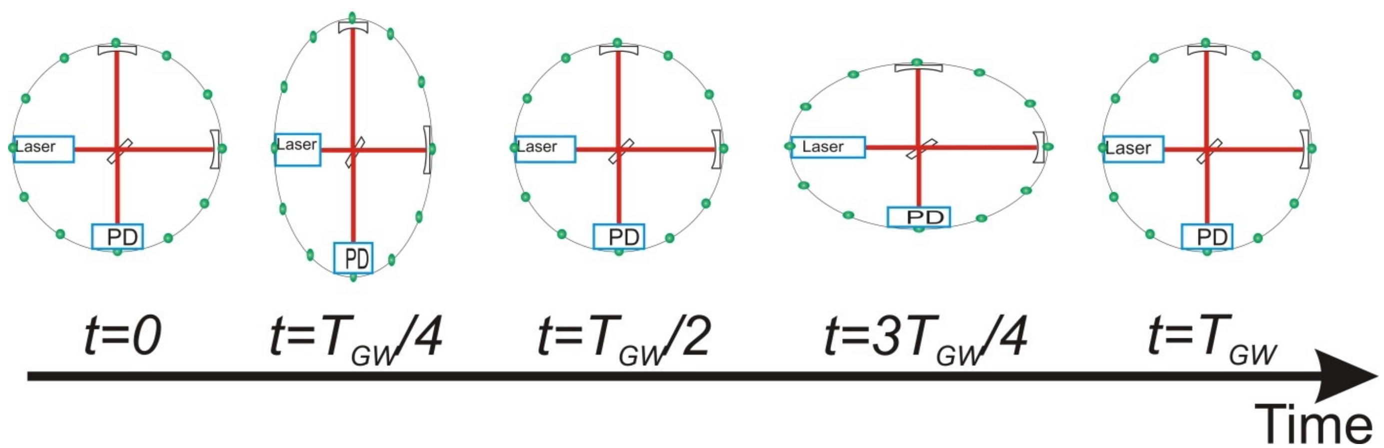


Coherent, weak, bulk dynamic properties of matter

Two polarizations h_+ and $h_\times$, transverse

Observable GW strain h (t) ~ 1/distance

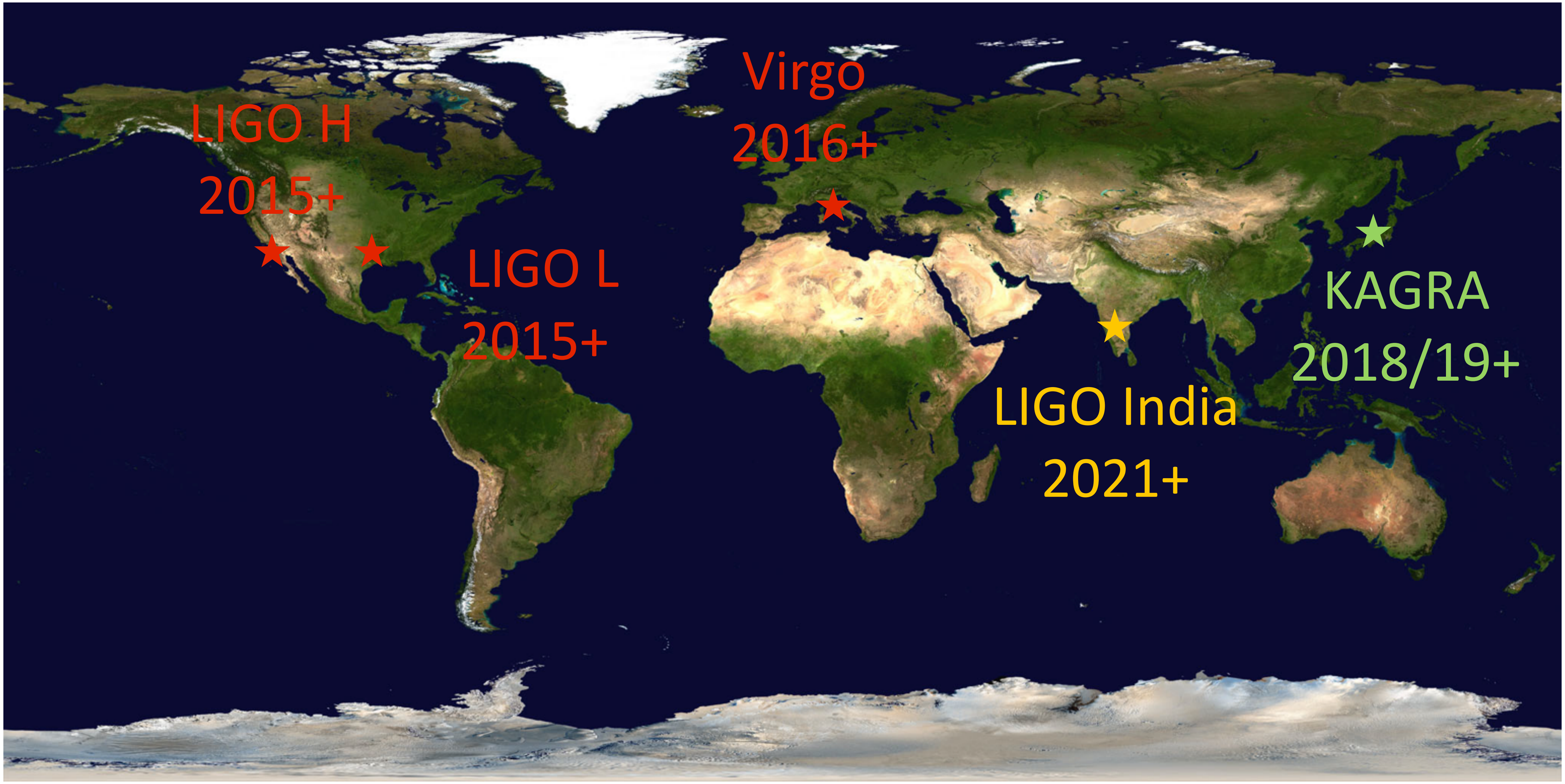
Advanced versions of kHz GW detectors began science runs last month !!



Michelson interferometers: acts as a transducer,
GWs → photocurrent ∝ the strain amplitude

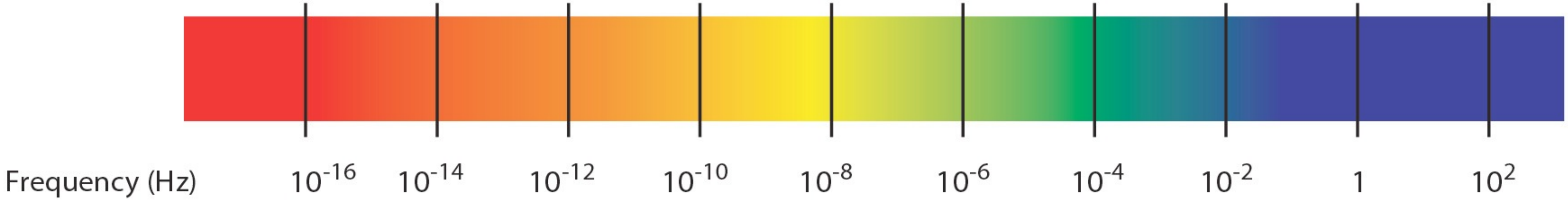
$$h \sim \frac{\Delta L}{L} \sim 10^{-21}$$

GW detector network: 2020s



[see roadmap in LSC and Virgo collaboration--arXiv:1304.0670]

Gravitational radiation opens up an entirely new window onto the Universe



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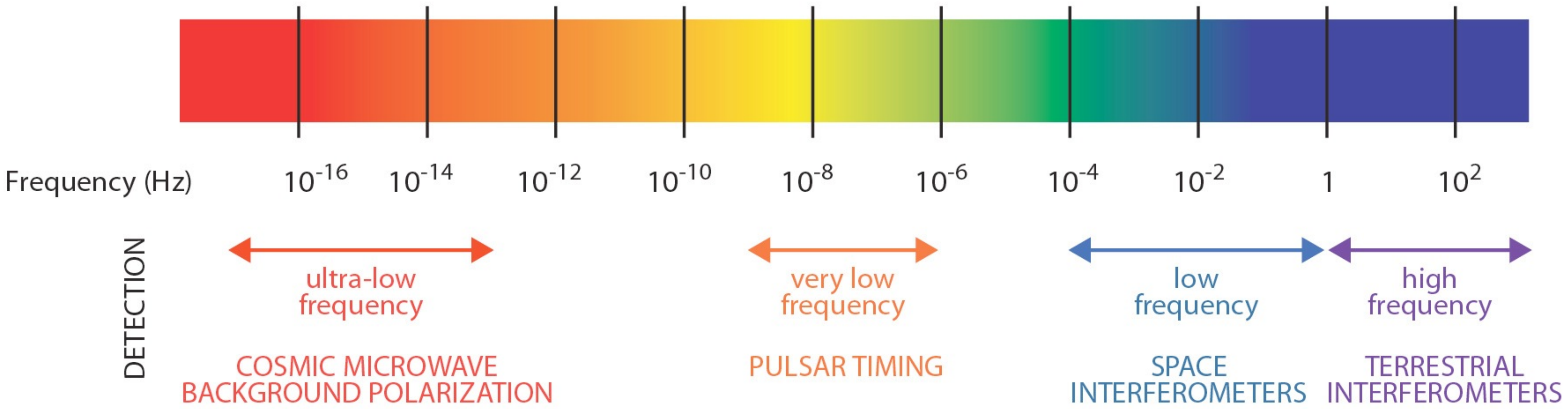
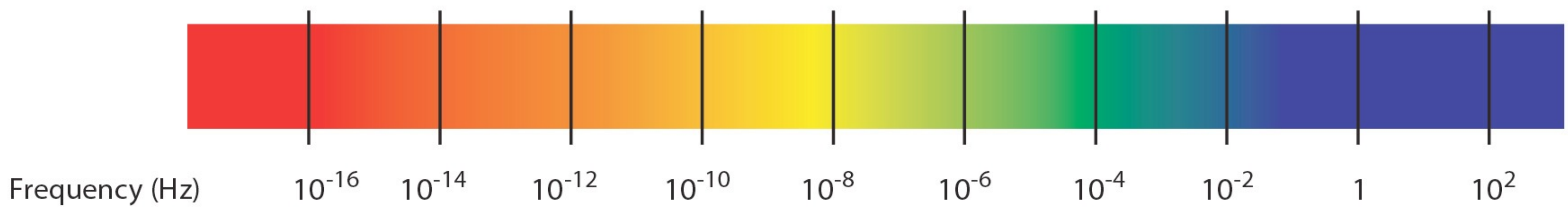
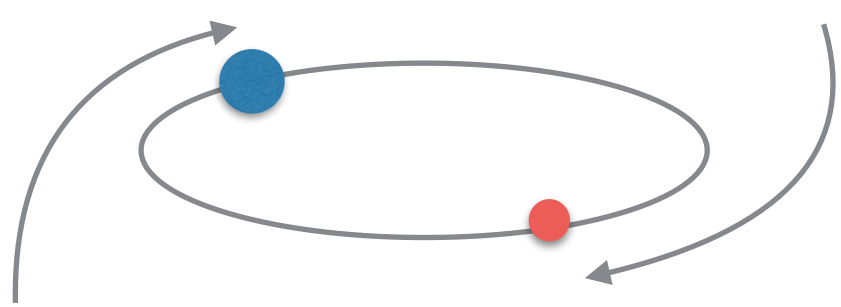


GW spectrum probes a diversity of astrophysical sources

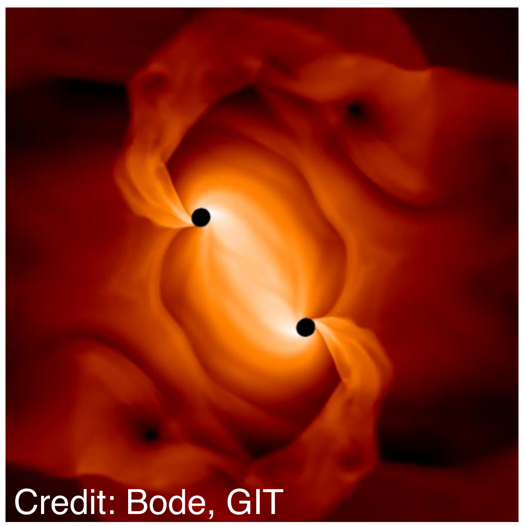




$$f_{\rm GW} \sim 2 f_{\rm orb} \sim \frac{1}{\pi}\sqrt{\frac{GM}{r_{12}^3}}$$

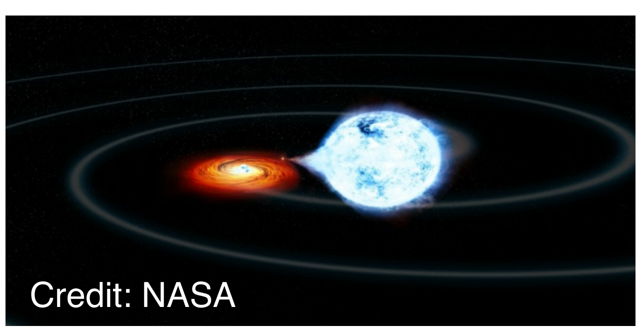
GW astrophysical sources

Low Frequency GWs



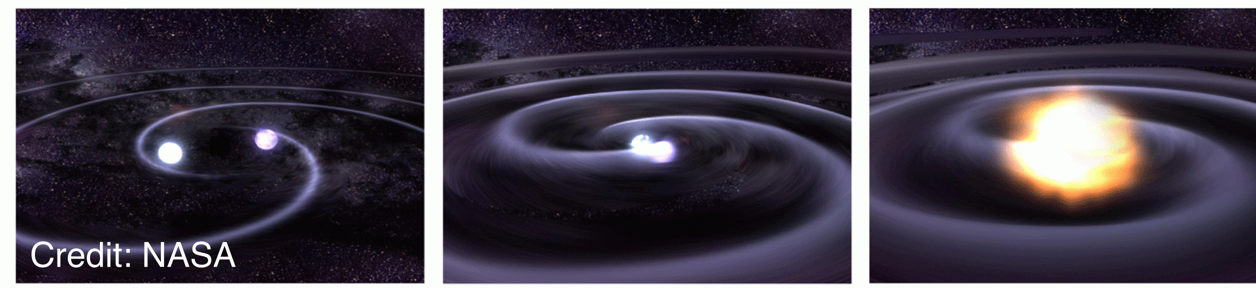
Supermassive Black Hole Binary Mergers
modelled

Mass-transferring or Detached White Dwarfs
modelled

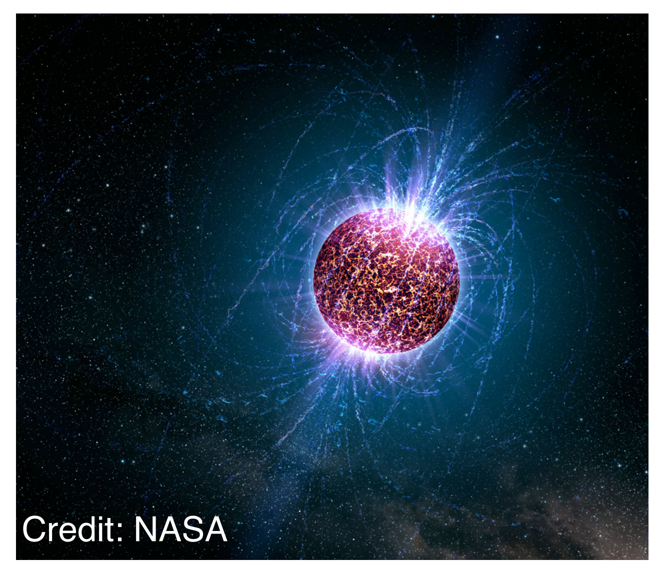


High Frequency GWs

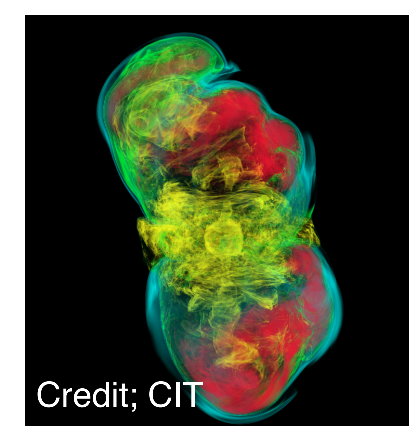
Neutron Star/Black Hole Binary Mergers
modelled



Pulsars:
continuous, ~ monotone



Asymmetric Core Collapse Supernova:
bursts, unmodelled

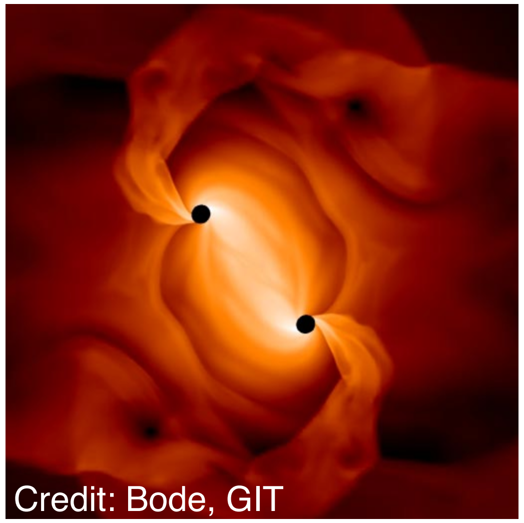


See Irene Di Palma’s talk

Strong quadrupole moment, compact, relativistic speeds

GW astrophysical sources

Low Frequency GWs



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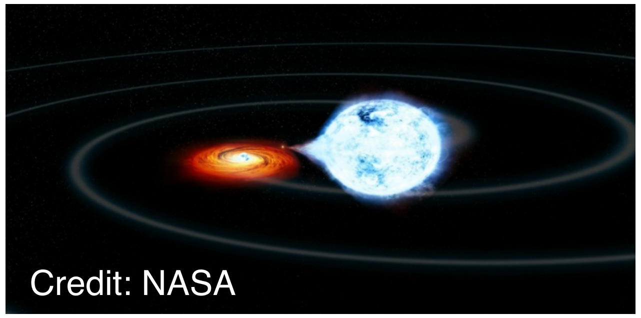

High Frequency GWs

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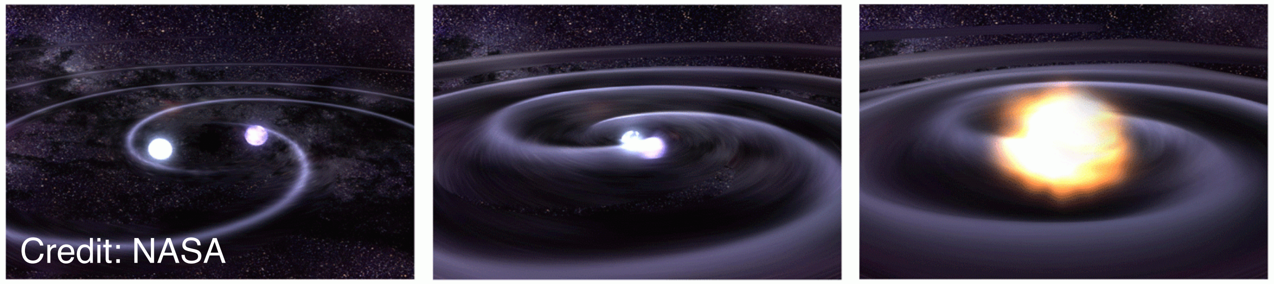

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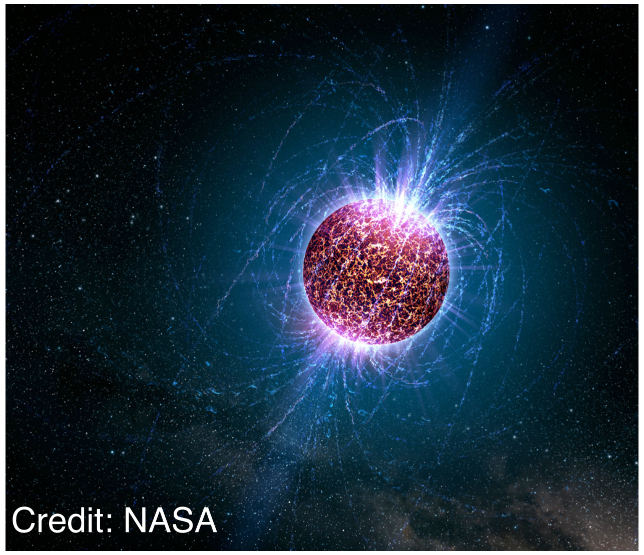

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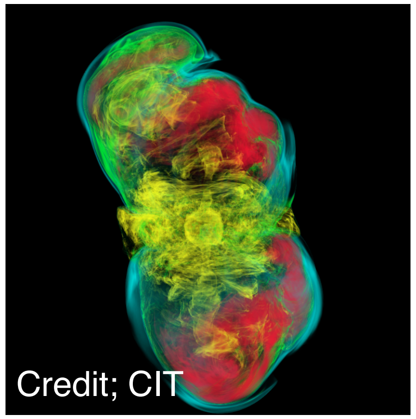
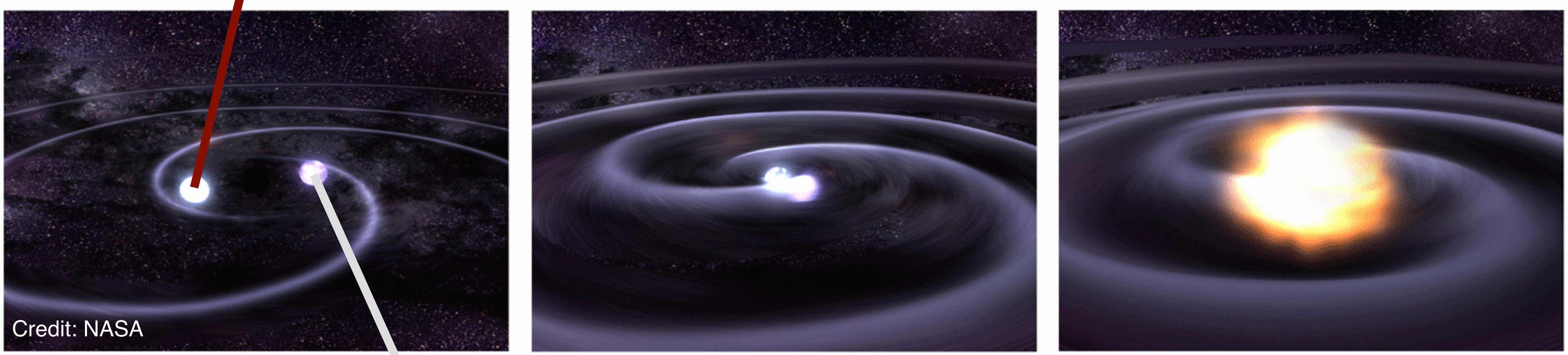


See Irene Di Palma's talk

Delayed matter outflows are responsible for EM signatures

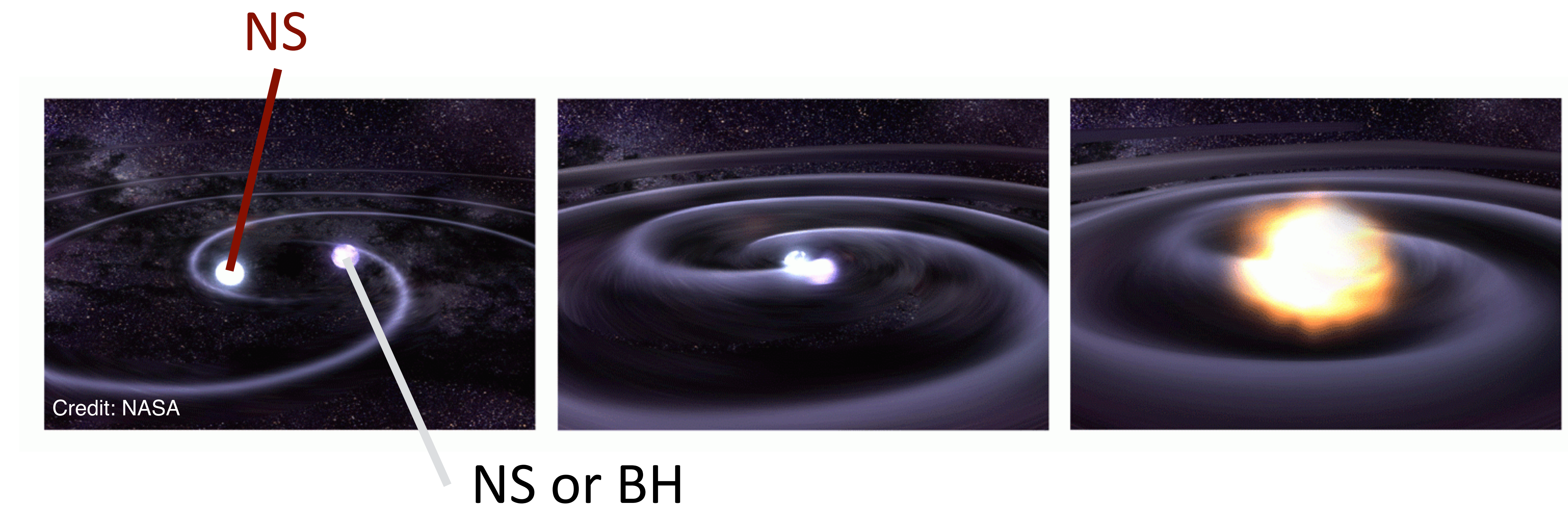
The astrophysics of compact object mergers

Neutron Stars (NS)



NS or Black Holes (BH)

The astrophysics of compact object mergers



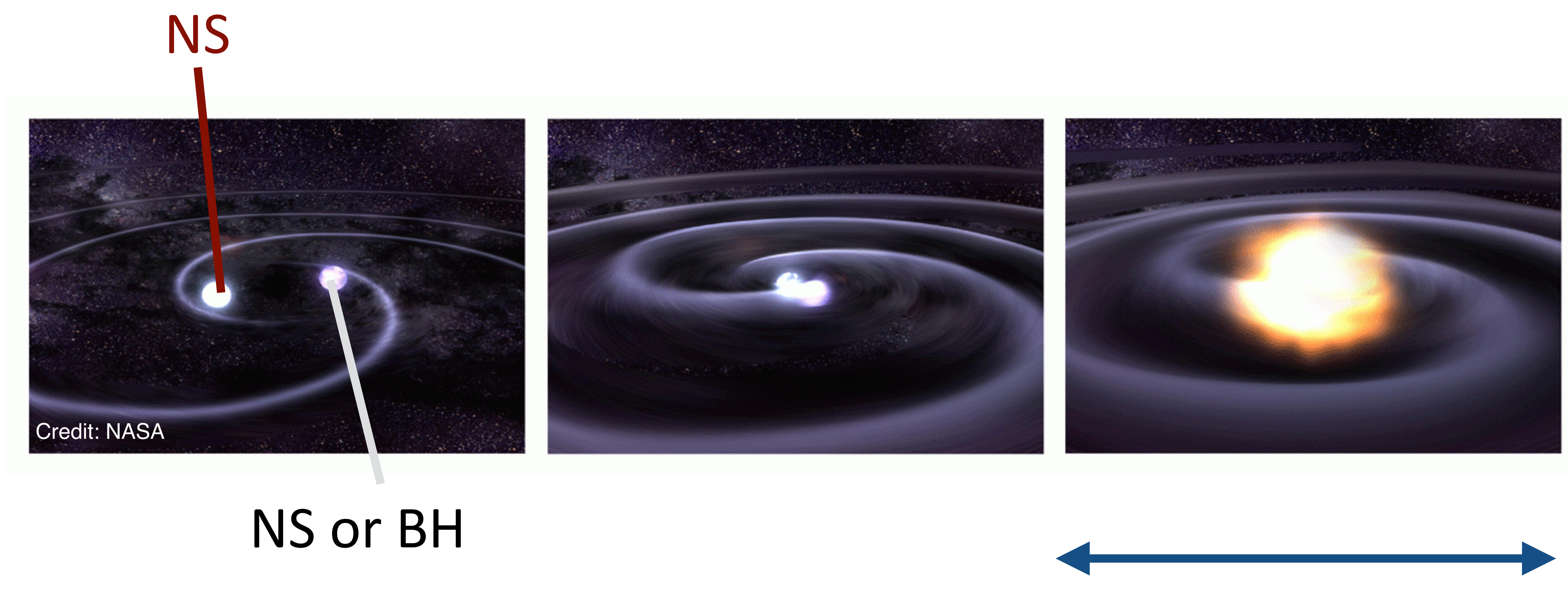
Gravitational Wave (GW) emission: 10^{57} ergs/s (final orbits)

10 mins pre-merger

~ Solar luminosity × 10^{24}

~ the visible Universe's galactic luminosity × 10

EM radiation probes the microphysics at play in extreme dynamical spacetimes

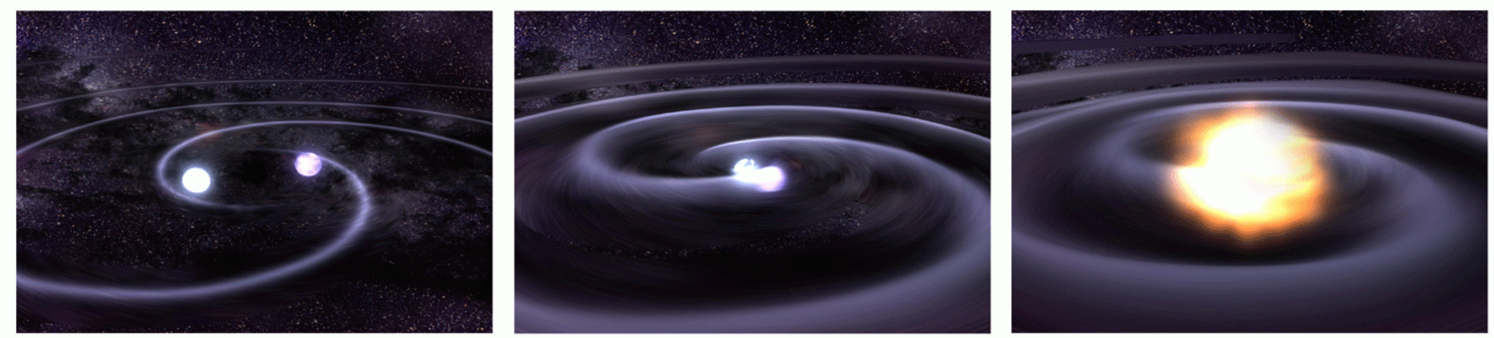


EM & ν emission + Outcome ??

10s pre-merger

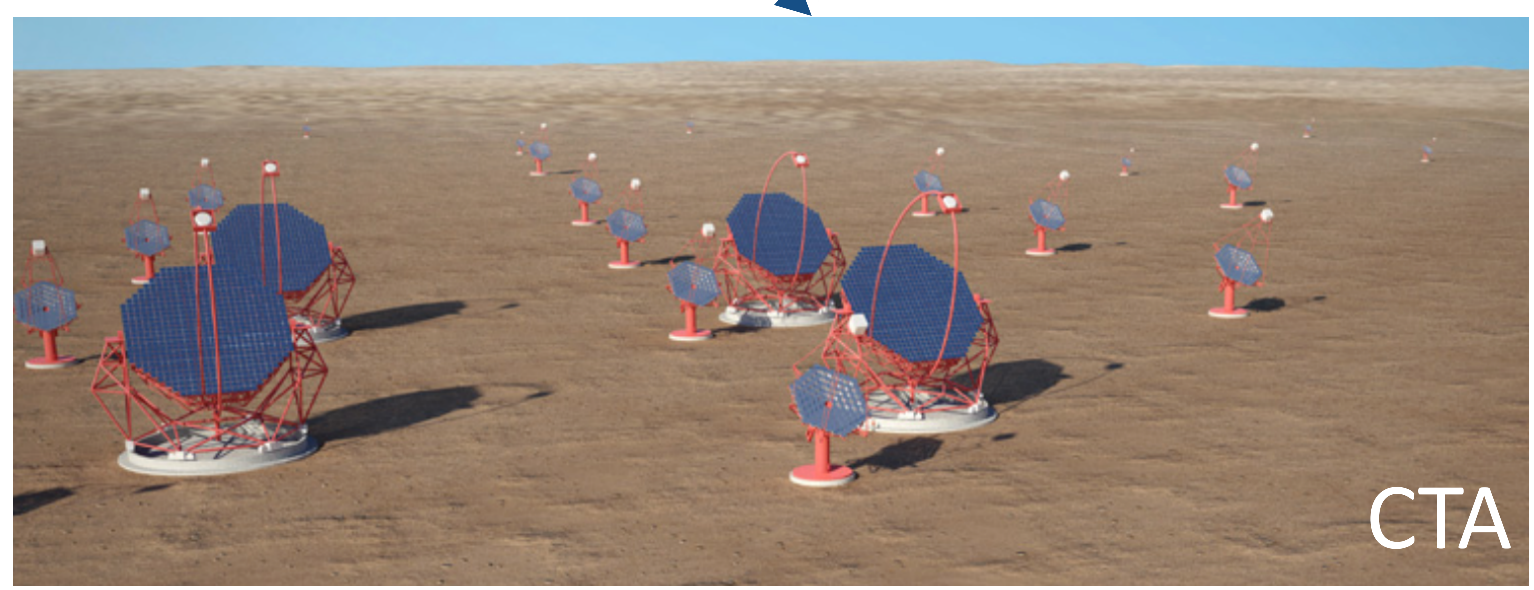
10ms post-merger

Recent Change: we now have the potential to detect multi-messenger radiation



Gravitational radiation

EM/ν radiation



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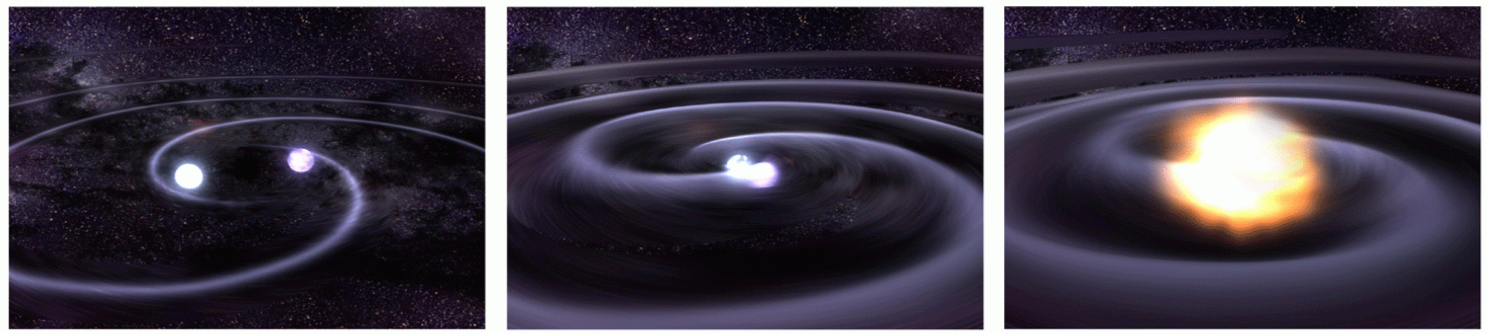
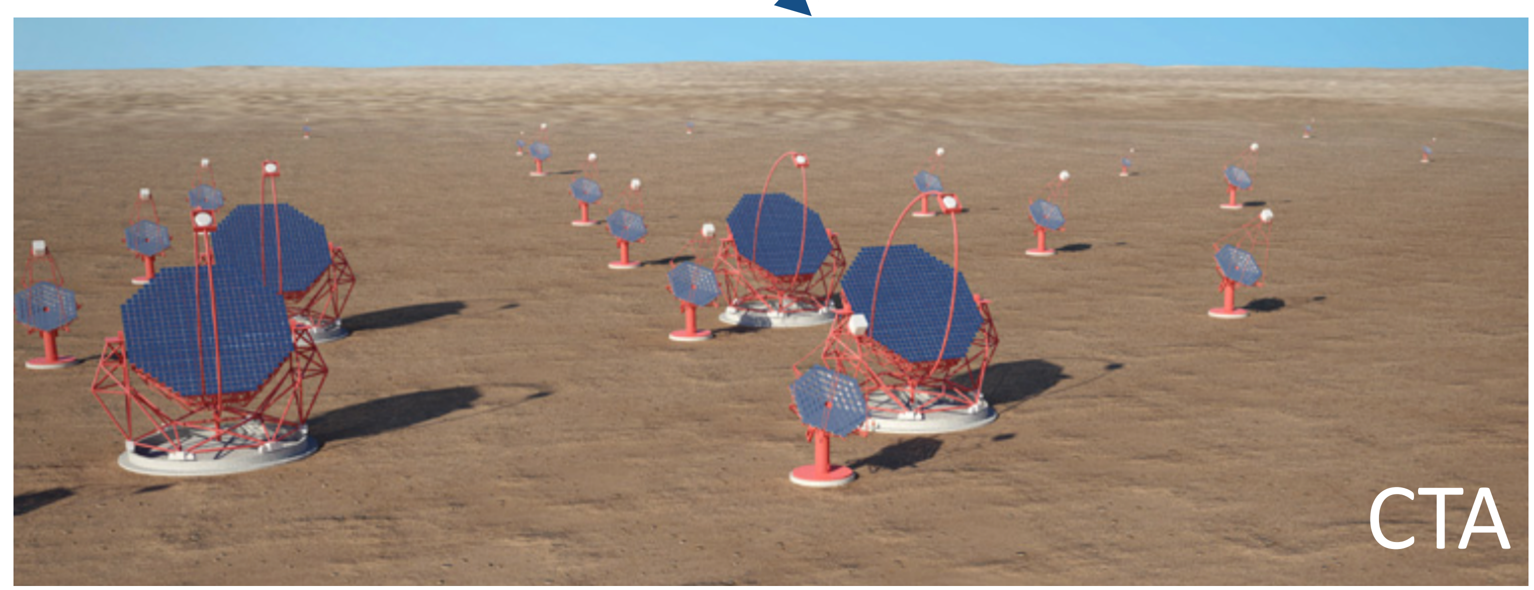


Gravitational radiation

EM/ν radiation



Learn about sources' <u>dynamic</u> and <u>fundamental properties</u>

Learn about sources' <u>environment</u> and <u>energetics</u>

Multimessenger astronomy: motivation

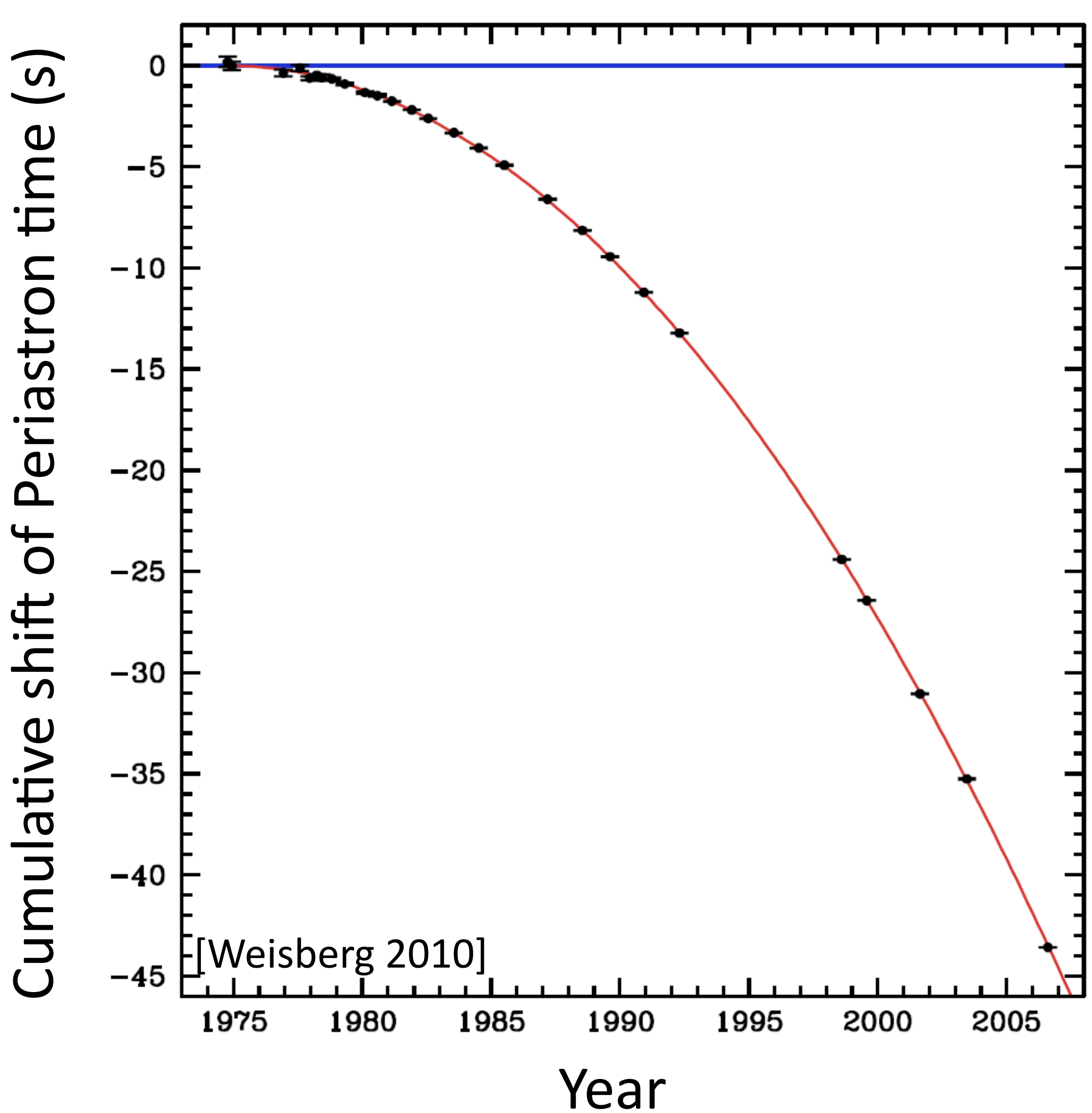
1. Strong field gravity astrophysics
   Physical processes in strongly curved space-times

2. Stellar Evolution
   Understanding the fate of compact binary stellar systems?

3. Cosmic Enrichment
   Sites of r-process nucleosynthesis

4. Cosmological Probes
   Measuring the expansion history of the Universe

NS-NS mergers are guaranteed kHz GW sources



Hulse-Taylor Binary (Nobel Prize 1993)
Confirms General Relativity prediction to 0.4%

<u>Predicted merger rates:</u>
13 Galactic NS-NS systems,
no known NS-BH system.

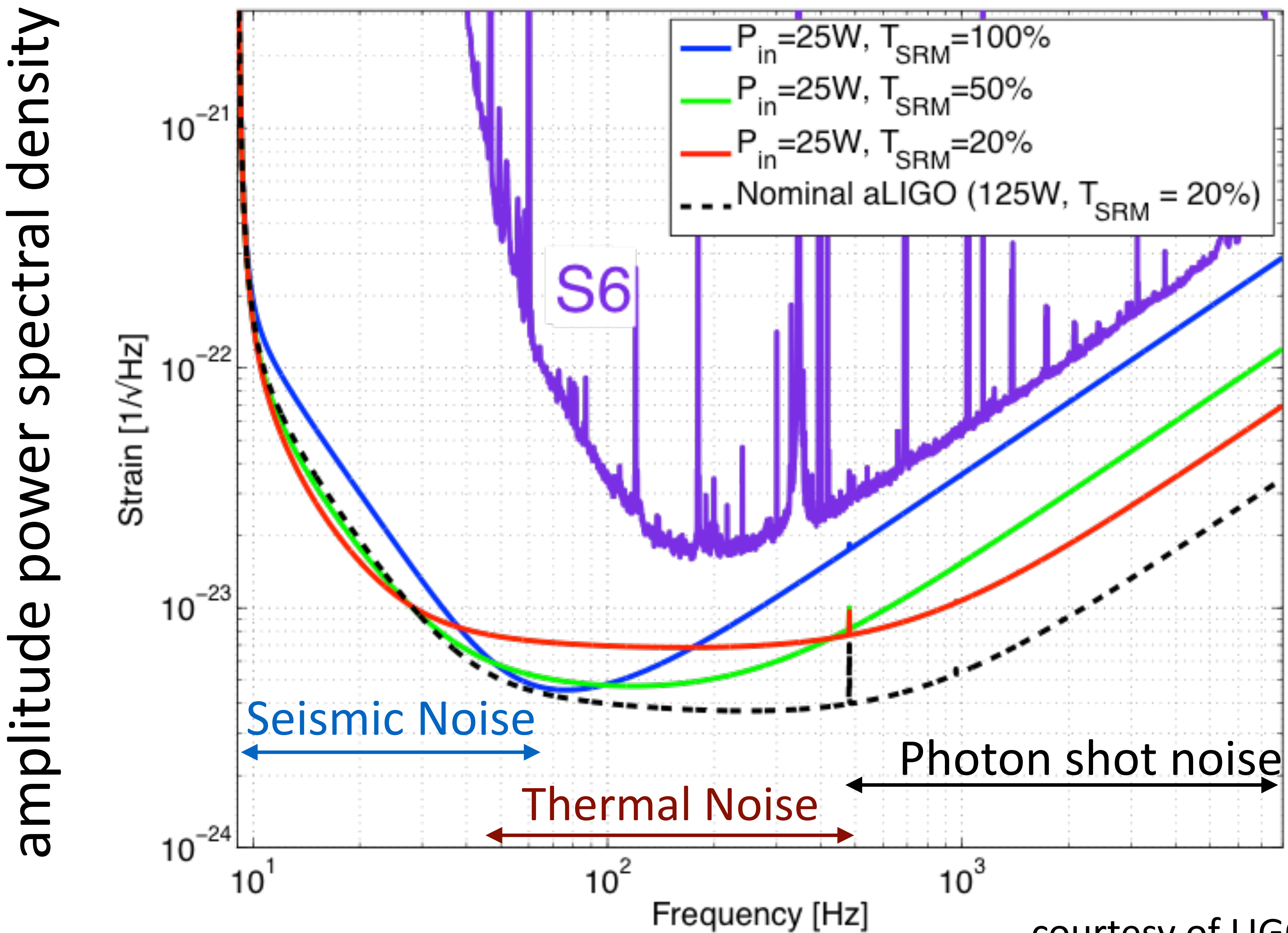
⇒ <u>Three orders of magnitude</u>

0.01 — 10 Mpc^{-3} Myr^{-1} (NS-NS)

[Lorimer 2006, Freire + 2015]

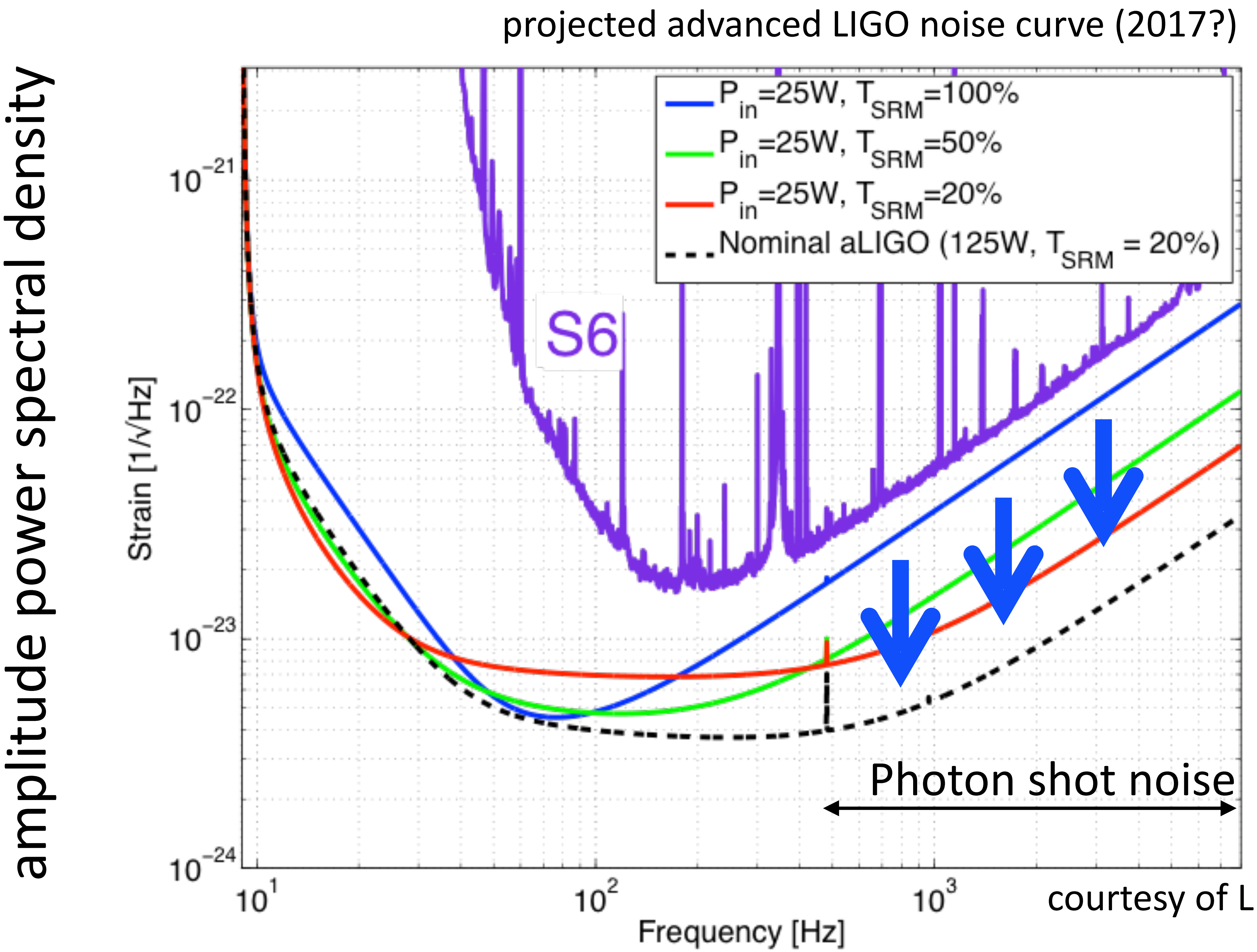
Understand the instrument noise very well

projected advanced LIGO noise curve (2017?)



courtesy of LIGO labs

Understand the instrument noise very well



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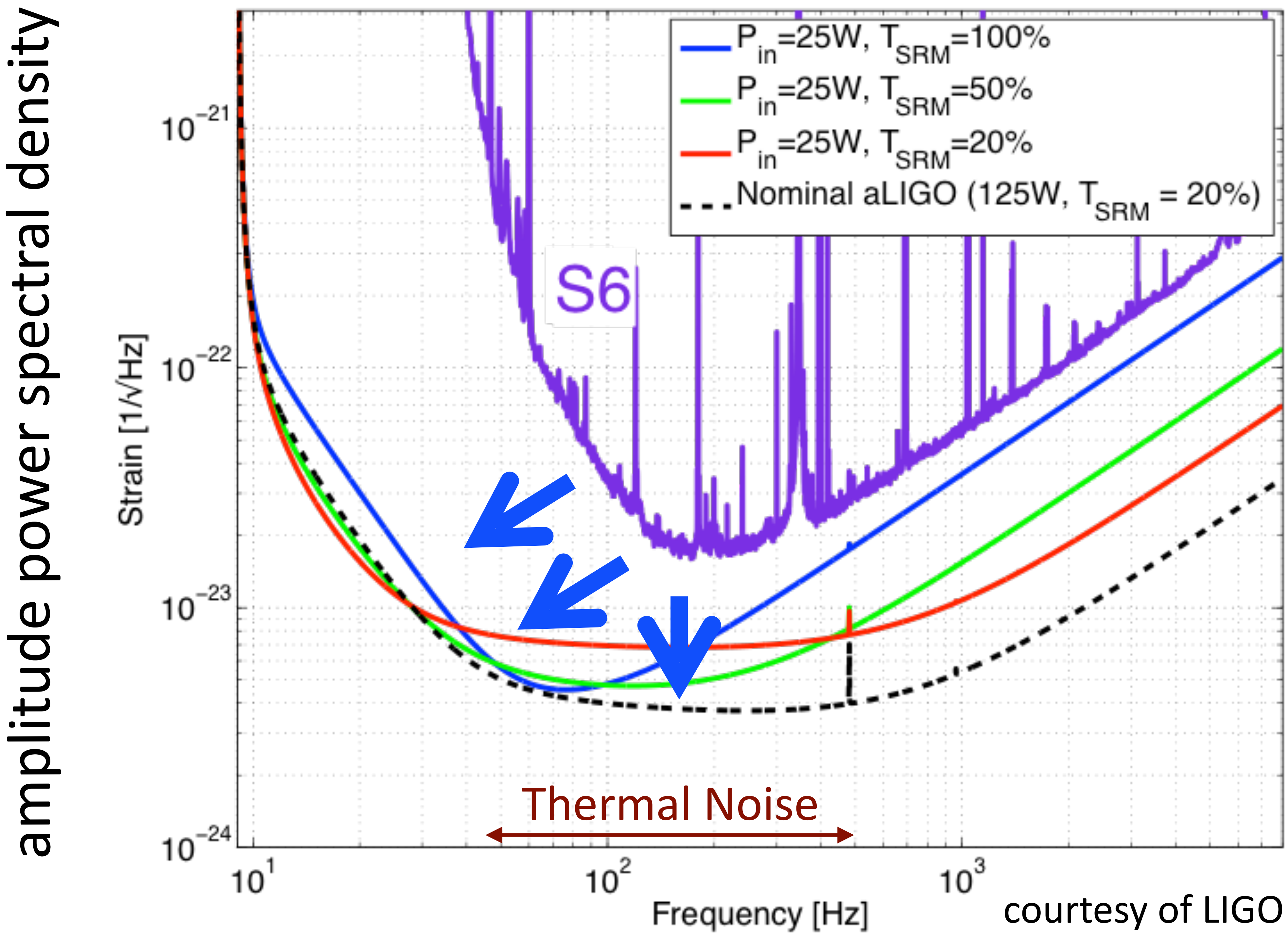

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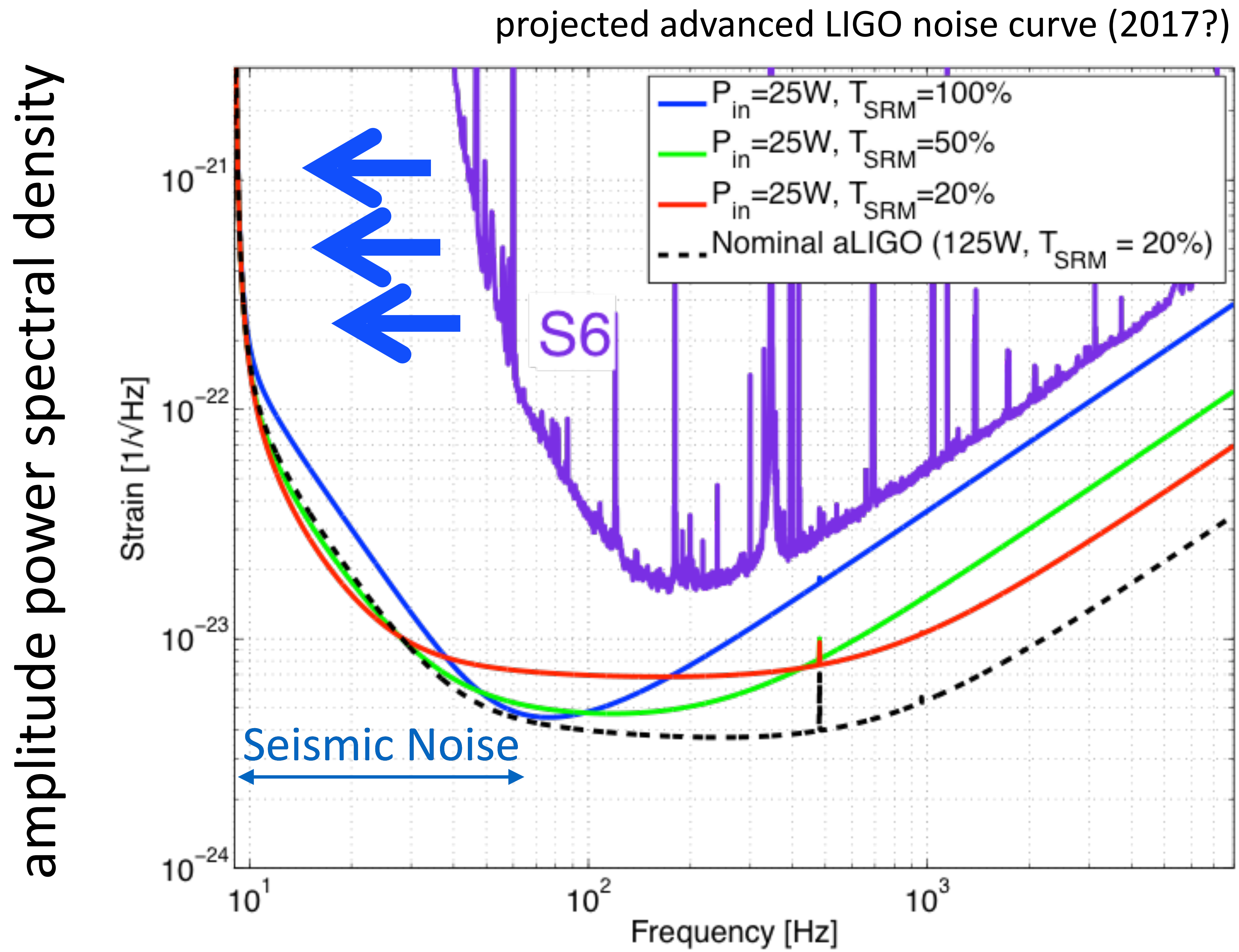
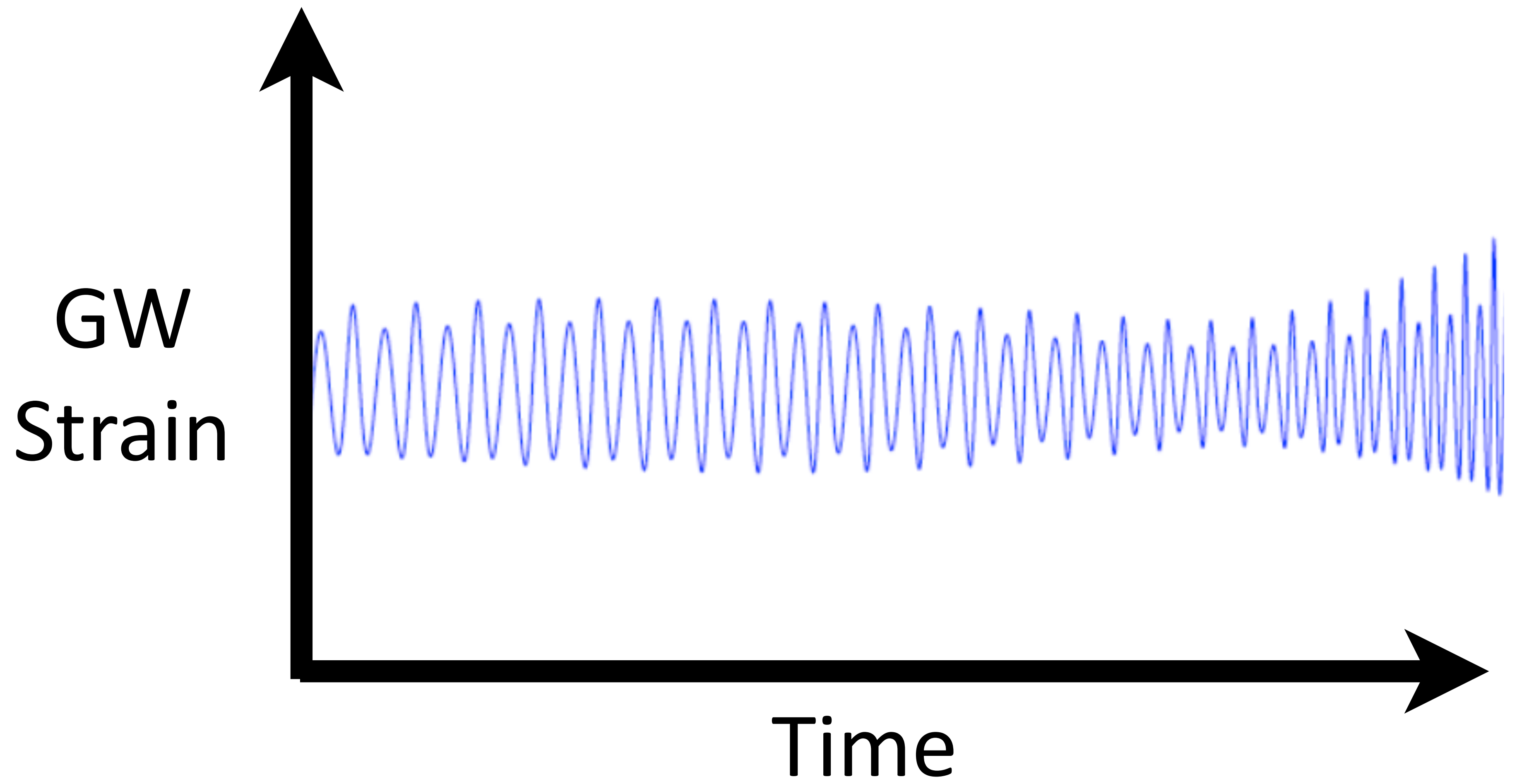


courtesy of LIGO labs

The GW chirp encodes source parameters



Weak field, perturbation theory of Einstein Field Equations

Chirp: ever-increasing amplitude and frequency

[see review by Blanchet 2015]

Extract source information from GWs

h(t): 9-16 dimensions

- Masses
- Spins
- NS radii
- Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

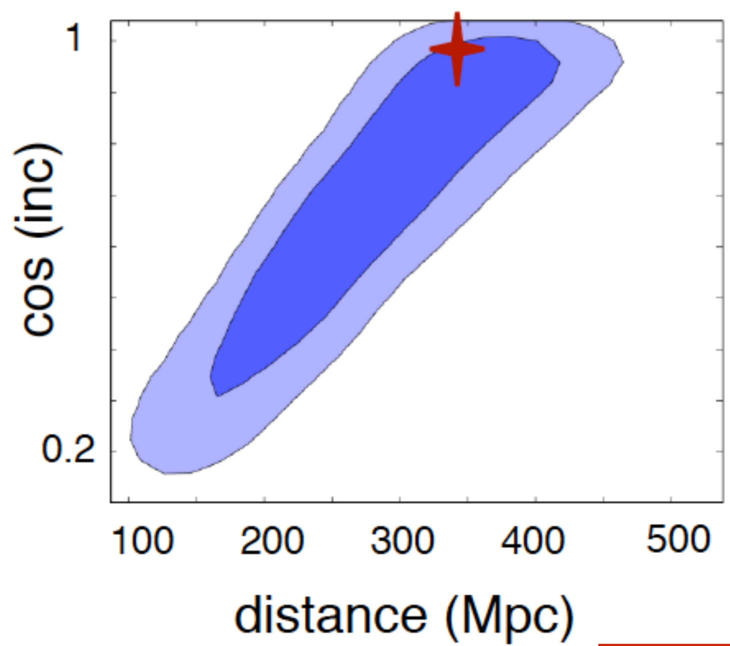
[see e.g. Cutler and Flanagan 1994, Poisson and Will 1996 …]

Extract source information from GWs

h(t): 9-16 dimensions

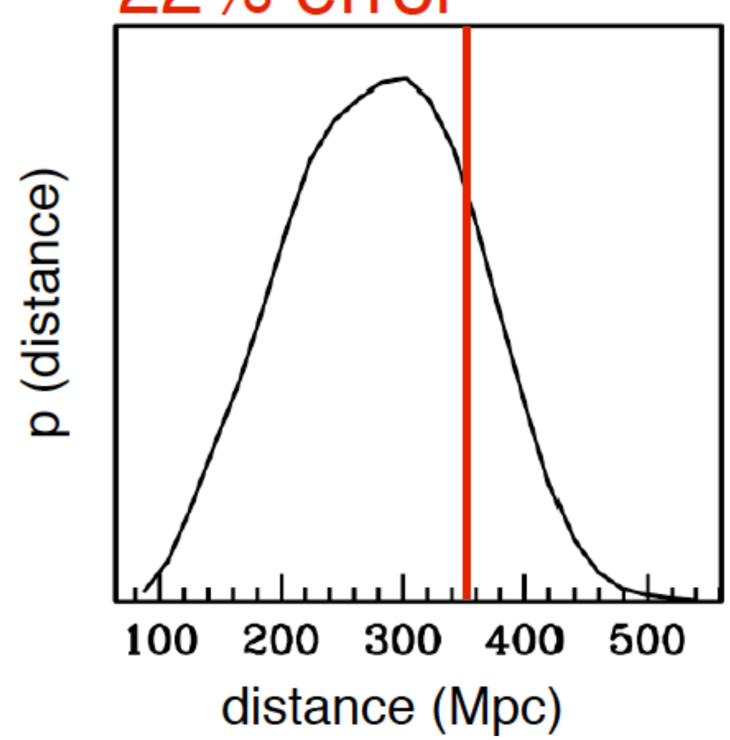
- Masses (few % to several %)
- Spins (several to tens of %)
- NS radii (tens of %)
- Geometric properties: (tens of %)
  - Inclination angle
  - Source Position
  - Luminosity distance

Nissanke et al. (2010)



Face-on binary

22% error



[see e.g., Nissanke et al. 2011, 2013, Veitch et al. 2012, 14, Rodriguez et al. 2013, Aasi et al. (LVC) 2013, 2014a, 2014b, Berry et al. 2014, Vitale et al. 2014, del Pozzo et al. 2013, O'Shaughnessy et al. 2013, del Canto et al. 2014, Grover et al., 2013, Singer et al. 2014, Lackay et al. 2014, Agathos et al. 2015 …]

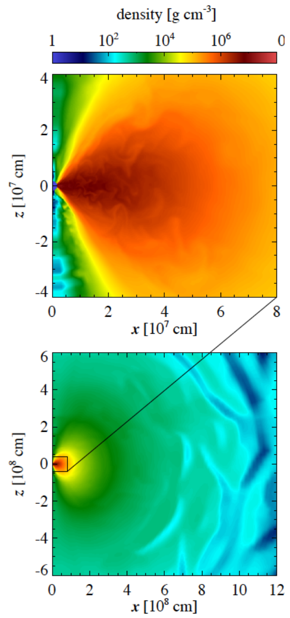
EM and ν from Two Types of Matter Outflows

1. Tidal Tails + Disk Winds

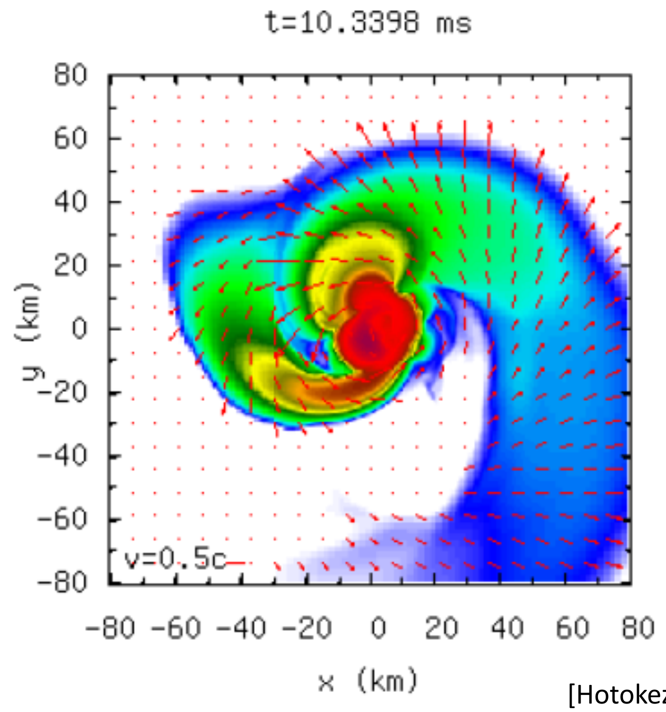
$M_{ej} \approx 10^{-4}$ - 0.01 $M_\odot$

E ≈10^{49}- 10^{50} ergs

v ≈ 0.1- 0.3c



[Fernandez & Metzger 2013]



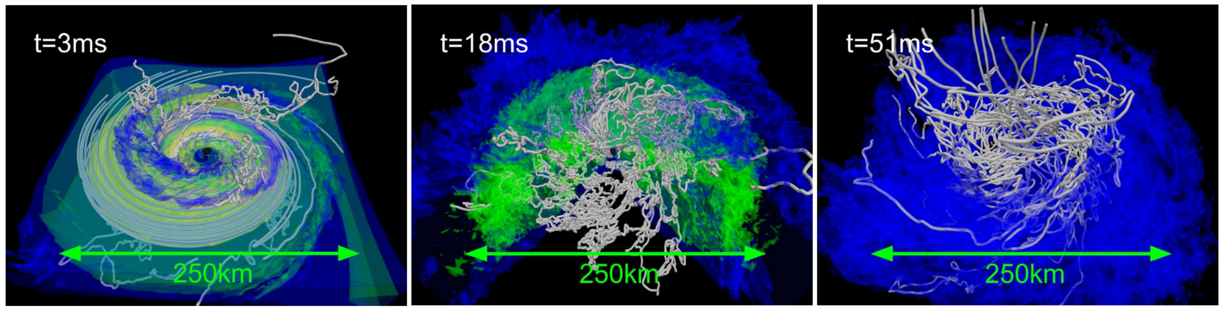
[Hotokezaka et al. 2012]

2. Ultra-relativistic Jet

$M_{ej} \approx 10^{-6}$ $M_\odot$

E ≈ 10^{49}- 10^{51} ergs

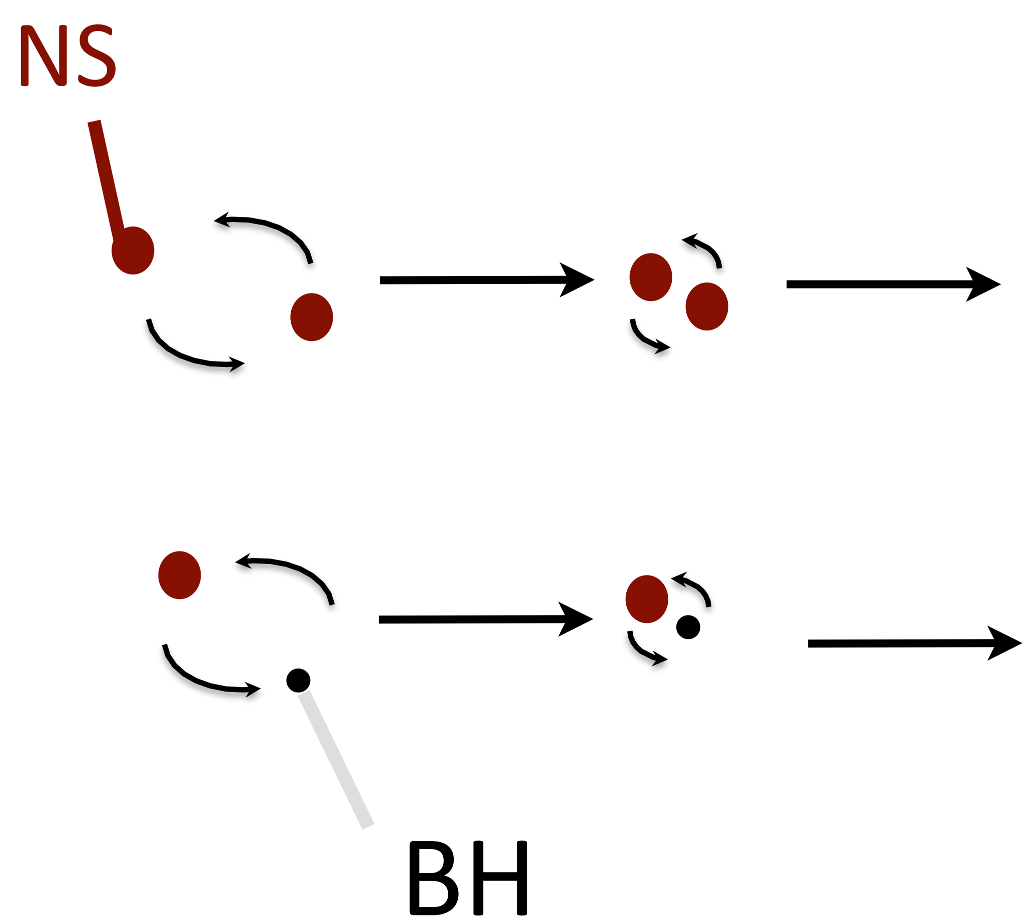
Γ ≈ 100

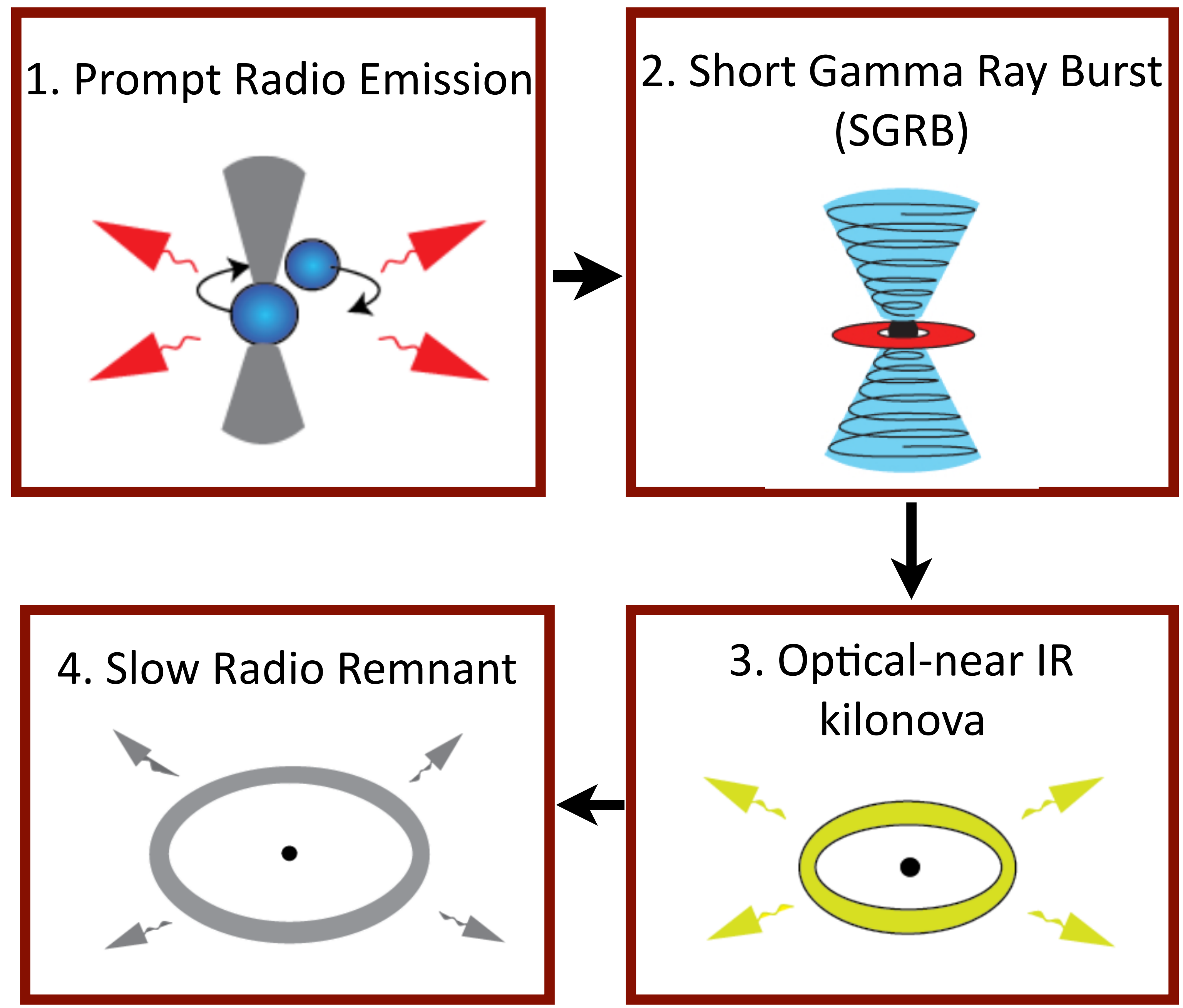


[Kiuchi et al. 2015]

Outflows' kinetic energy is converted into internal energy.
Expands, cools and heated by shocks or radioactivity.

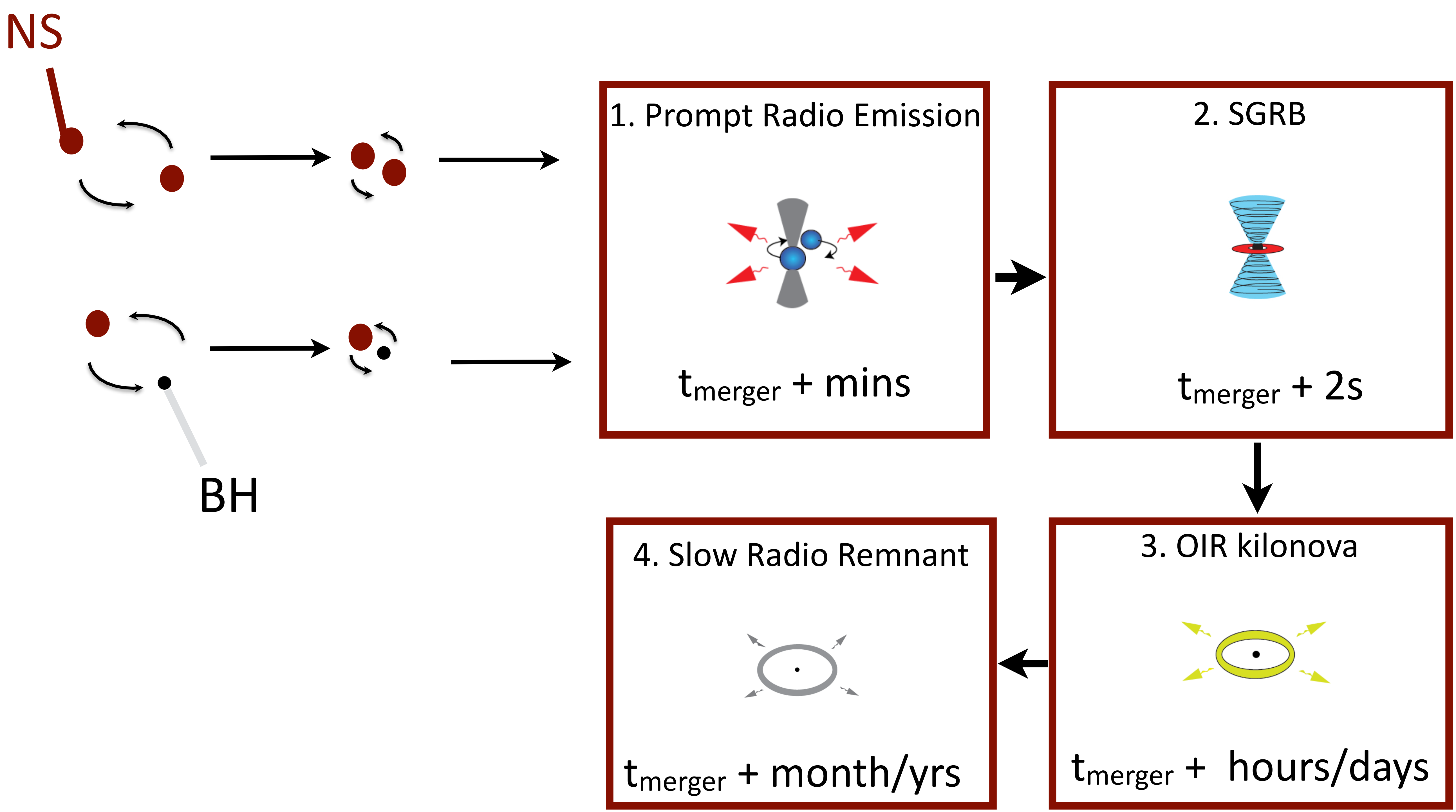
Four or more EM counterparts



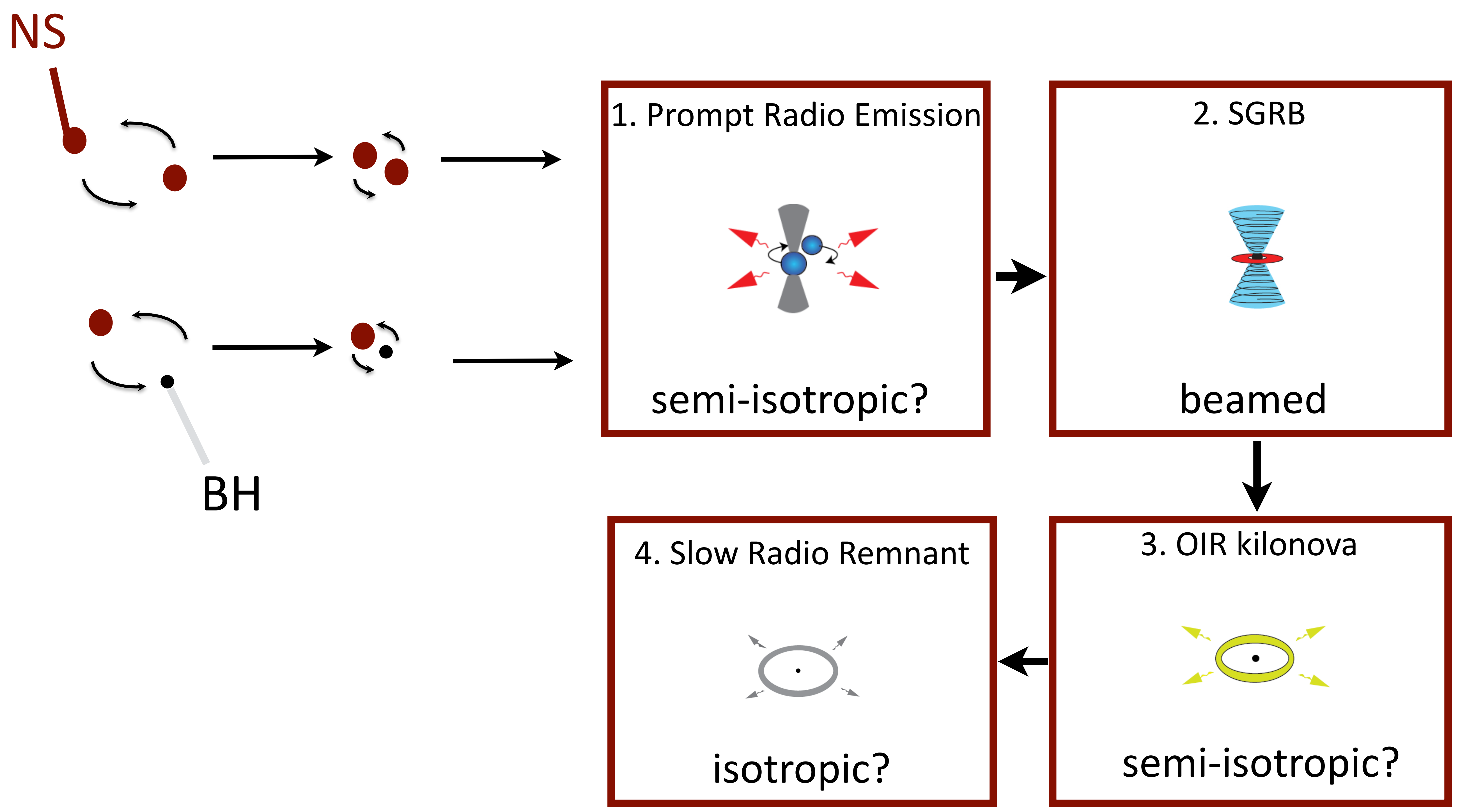


[e.g., prompt radio emission: Hansen & Lyutikov (2001), Moortgat and Kuipjers (2002,5,6), Postnov and Pshirkov (2010); kilonova: Li and Paczynski 1998, Kulkarni 2005, Metzger et al. 2010, Metzger & Berger 2012,...Barnes et al. 2013, Grossman et al. 2013, Tanaka et al. 2013, Tanvir et al. 2013, Berger et al. 2013, … ; slow radio: Nakar and Piran 2011, Hotokezaka et al., 2015]

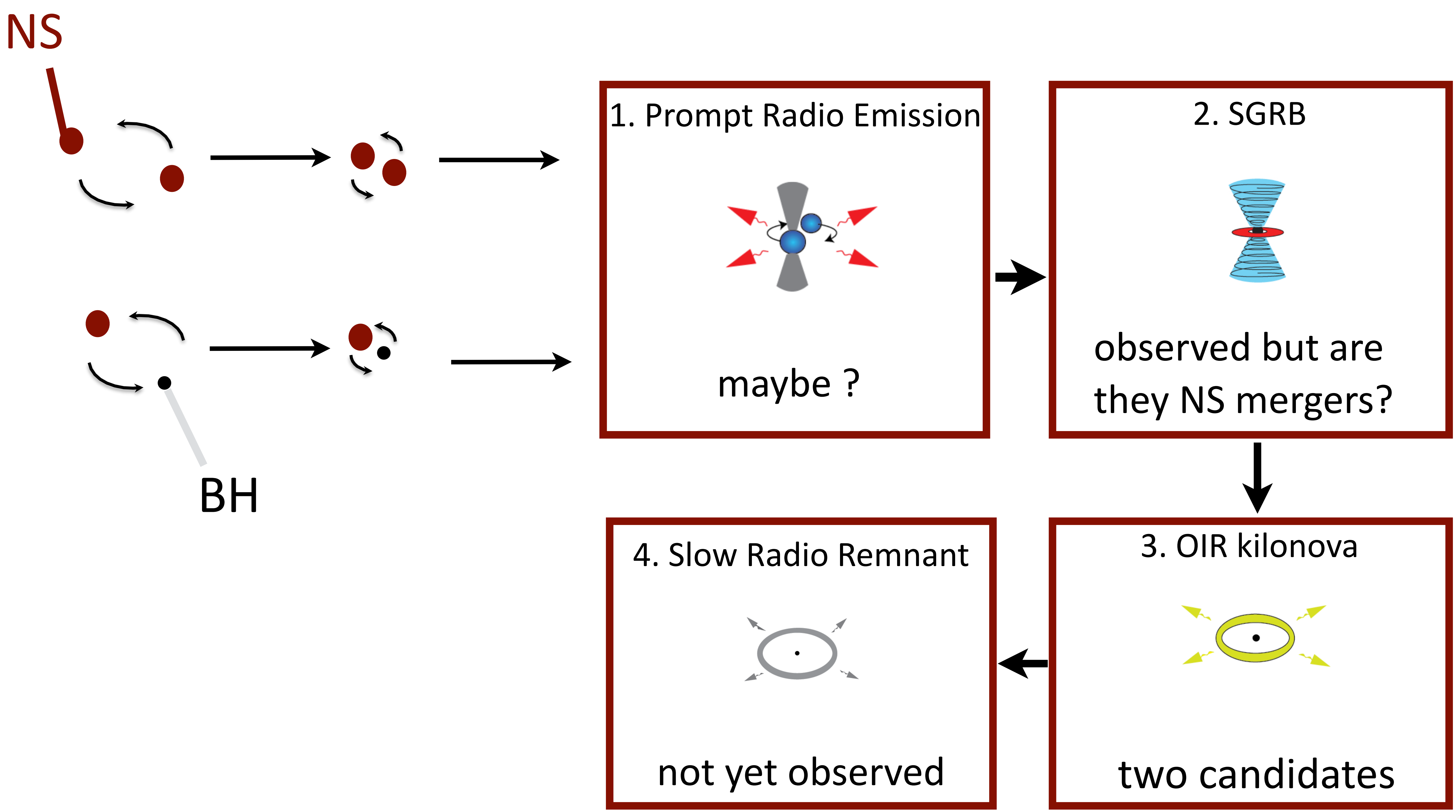
1. Four different EM observable timescales



2. EM emission geometry



3. EM counterparts already observed?



[e.g., fast radio bursts: Thornton + (2013), Spitler + (2013), Burke-Spolar + (2014), Petroff + (2015) …; kilonova: Tanvir + 2013, Berger + 2013, Yang et al. 2015]

Next step: combine & interpret GW + EM + ν

from the GW chirp

+ Masses (1% to several %)
+ Spins (several to tens of %)
+ NS radii (tens of %)
+ Geometric properties: (tens of %)
  - Inclination angle
  - Source Position
  - Luminosity distance

from EM + ν signature

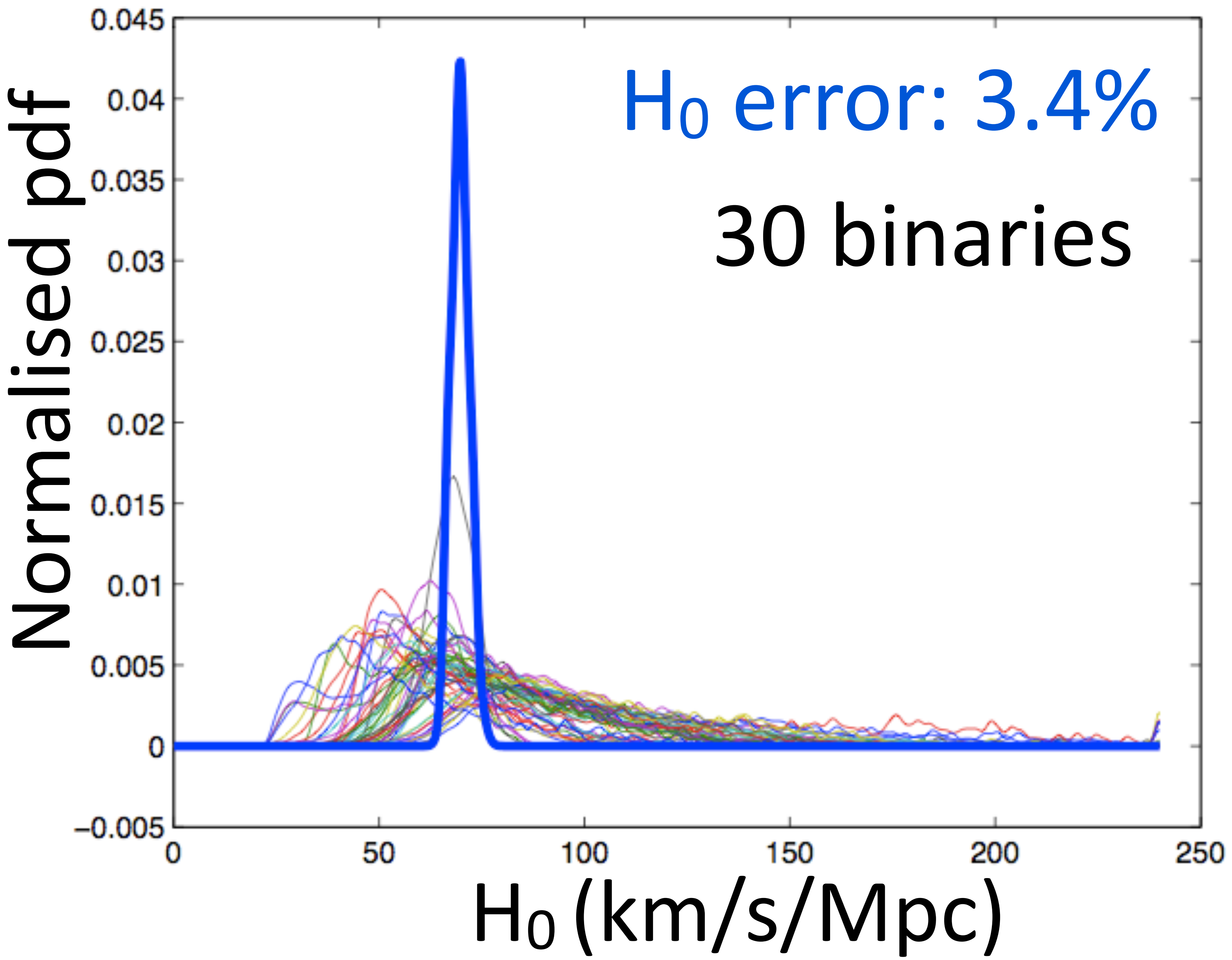
+ Energetics and beaming
+ R-process nucleosynthesis
+ Mass ejecta and velocity
+ Environment
+ Redshift, Accurate Position (1”)
+ Stellar populations
+ Magnetic field strength
+ Previous binary evolution & mass loss

→ Strong signal binary: Characterization

Population: Demographics, ecology and census

GW + EM enables few % error in Hubble constant

Nissanke et al. (2010, 2013)



[see also Schutz 1986, Dalal et al. 2006, del Pozzo 2012, Messenger et al. 2012, Taylor et al. 2012, …]

Challenges posed for multi-messenger astronomy

1. Observational (GW, optical, radio): faint, rare, and timescales & necessitates a multi-wavelength approach

2. Statistical: how to find the needle in the haystack of false positives?

3. Interpretational:

a) large parameter space & unidentified degeneracies in the GW-EM data sets
b) necessity of building a coherent model to describe GW-EM observables

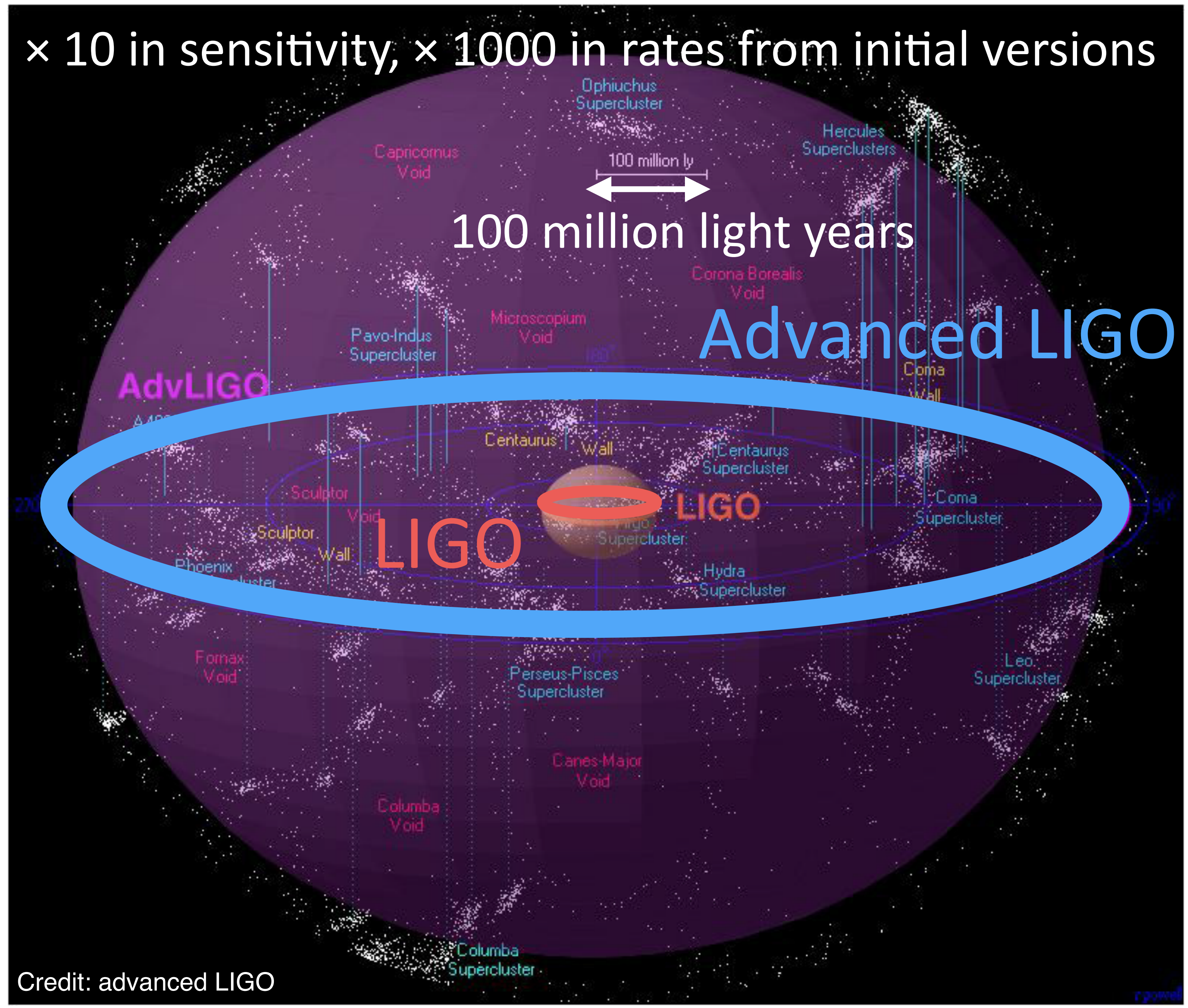
[See Irene Di Palma's talk for high-energy neutrinos]

1a. GW challenge: how many? how far?

2015 (3 months)
40-80 Mpc,
10^{-4}-3 (NS-NS)

2016 (6 months)
80 -120 Mpc,
0.006 - 20 (NS-NS)

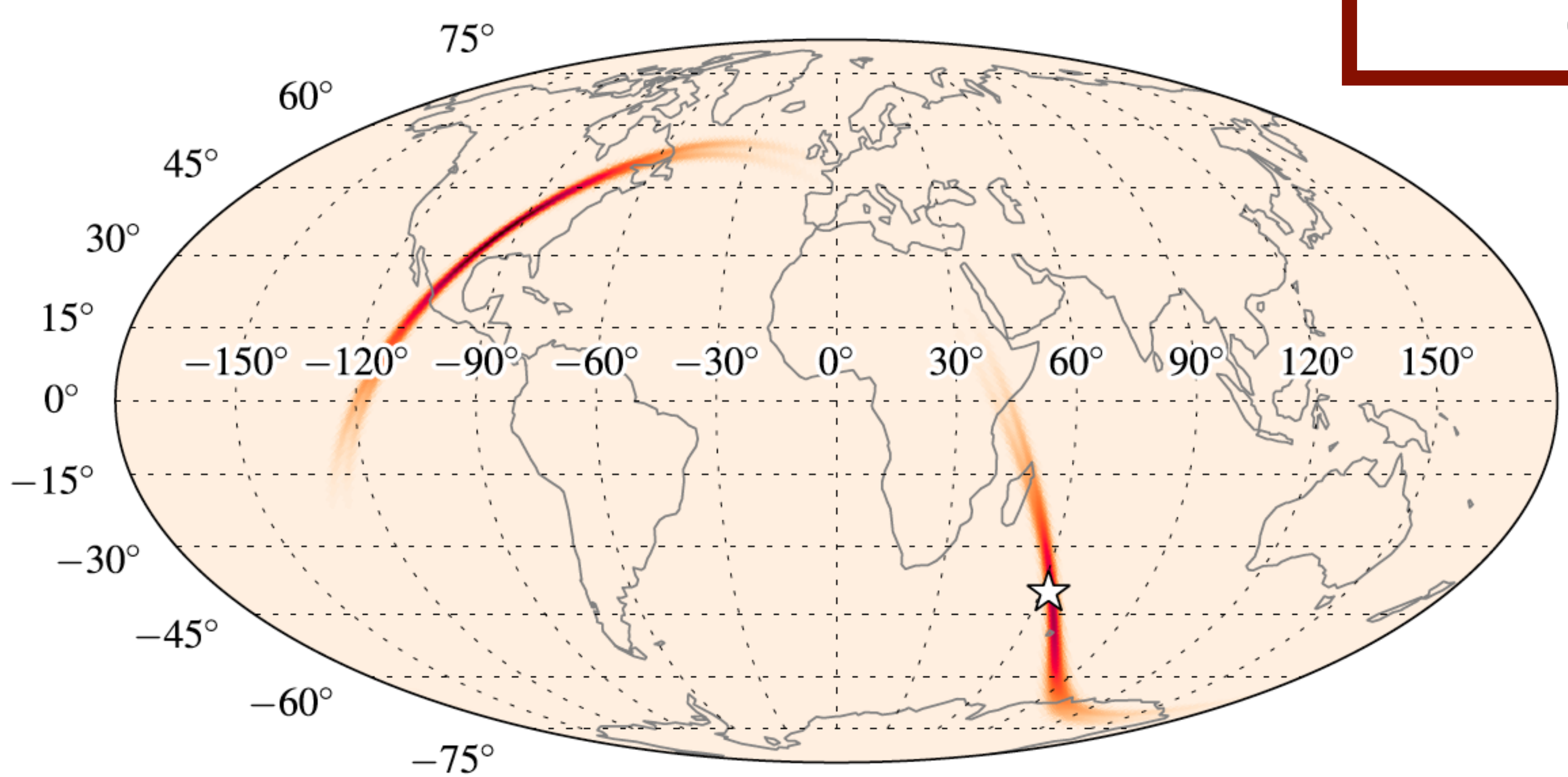
2017 - 19
200 Mpc,
0.04-200 yr^{-1} (NS-NS)



[LIGO-Virgo Scientific Collaboration, 1304.0770; for SNe see Gossan et al. 2015]

1a. GW challenge: how well?

Low rates, large sky errors
600 sq. deg.



[Singer et al. 2014]

Non-contiguous search islands with 10 to 100s sq. deg.

[see also Klimenko et al. 2011, Wen & Chen 2011, Fairhurst 2011, Nissanke et al. 2011, 13, Veitch et al. 2012, Aasi et al. 2013, Rodriguez et al. 2013, Sidery et al. 2014 …]

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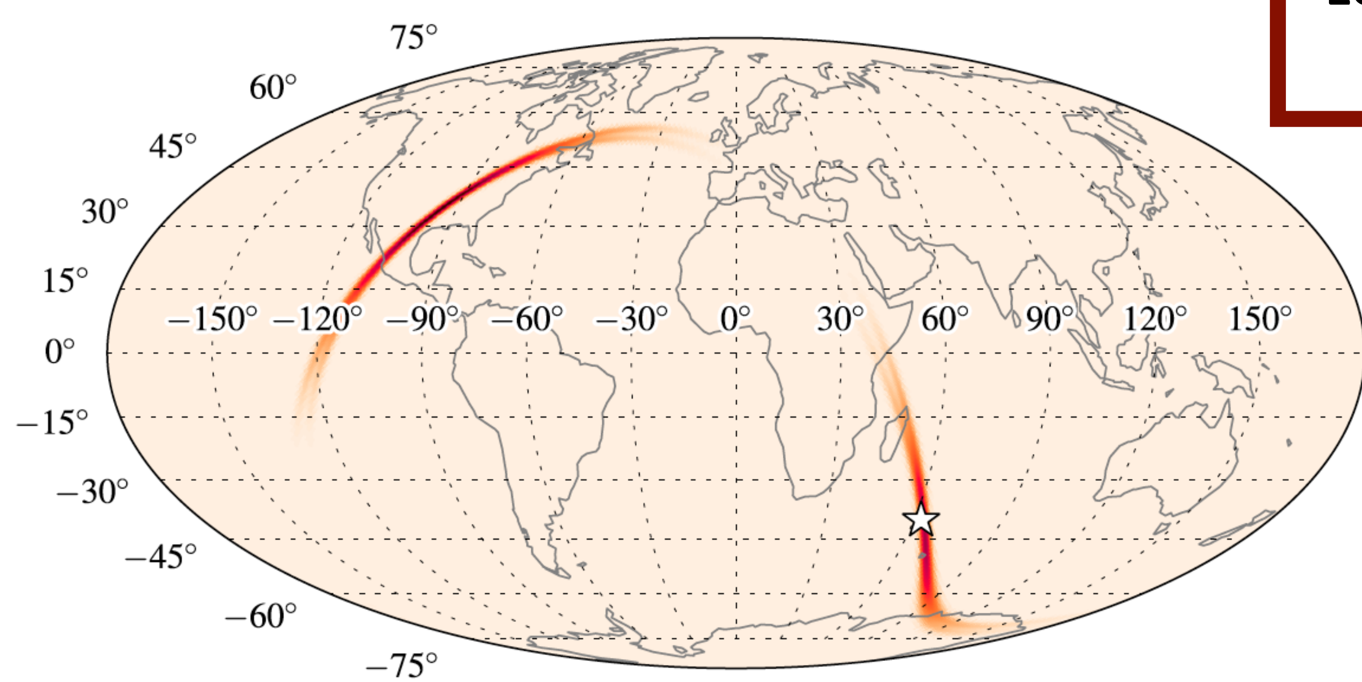


[Singer et al. 2014]

<u>2016-2019</u>
80 Mpc, 0.01 - 10 yr^{-1} (NSNS);
100s-1000 sq. deg.

→

<u>2019+</u>
200 Mpc, 0.2 - 200 yr^{-1} (NS-NS);
10s-100s sq. deg.

LVC Triggers are being released within thirty minutes (sky error, distance, SNR) to
60 EM partners in Science Run O1 (09/15-01/16)
see https://gw-astronomy.org/wiki/LV_EM/VOEventExamples

Optical follow-up

Wide, rare, faint , fast, red?

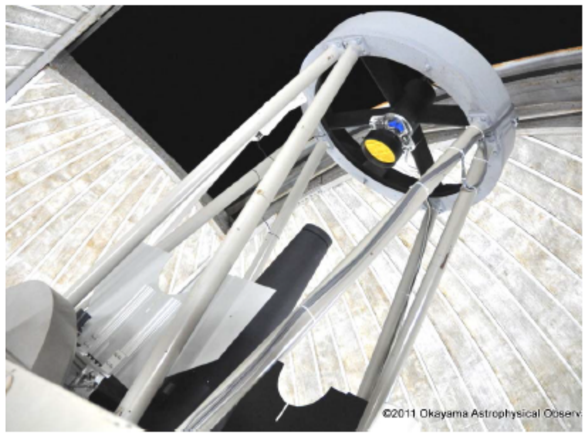
80 Mpc: 18-23.5 (r)
200 Mpc: 20-25.5 (r)

[e.g., kilo/macronova: Li and Paczynski 1998, Kulkarni 2005, Metzger et al. 2010, Metzger & Berger 2012,…Rosswog 2012, Piran et al. 2012, Tanaka et al. 2013, 2014, Kasen et al. 2013, Barnes et al. 2013, Grossman et al. 2013, Korobkin et al. 2012, Zhang et al., 2014, Fernandez et al. 2013, Metzger et al. 2014, Kasen et al. 2015, Fryer et al. 2015]

J-GEM

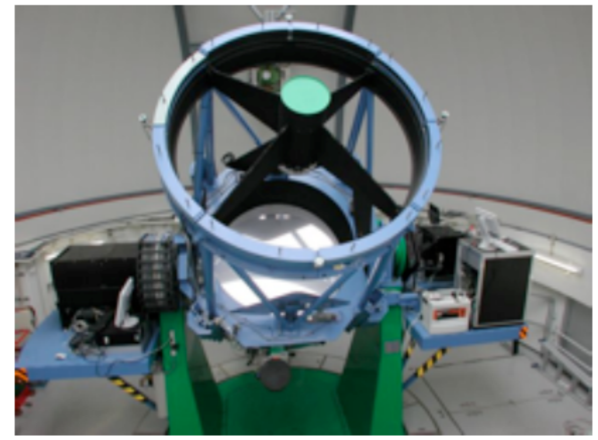
Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up

Okayama 0.91m

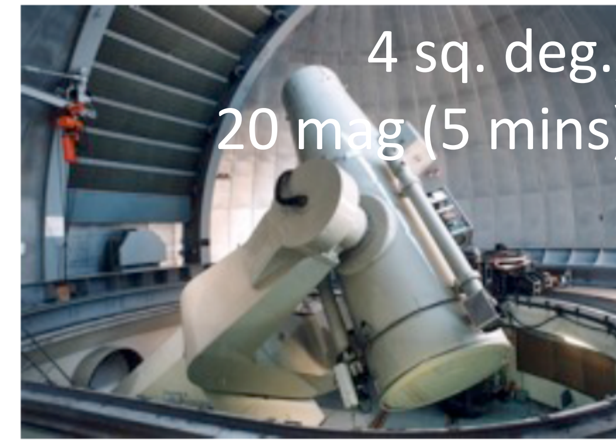


Okayama 1.88m

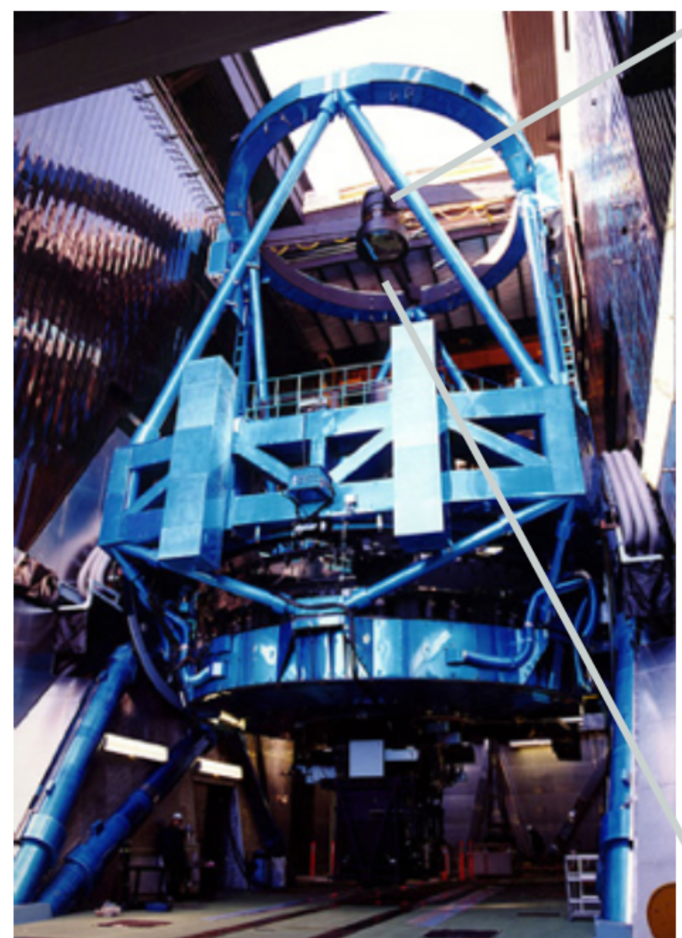
Hiroshima 1.5m



Kiso 1m (wide field)



Subaru 8.2m

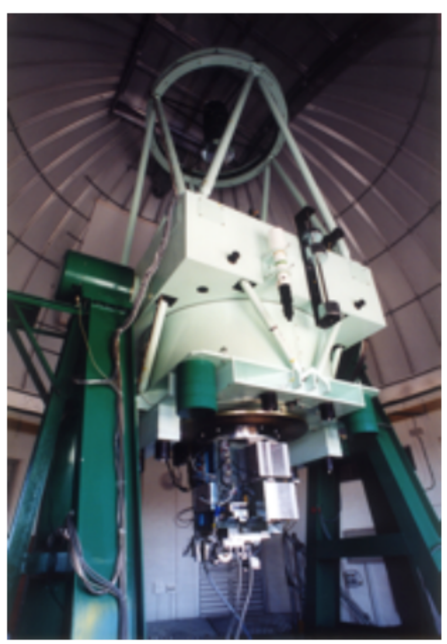


HSC (wide field)

1.5 sq. deg.,
24 mag (5 mins)

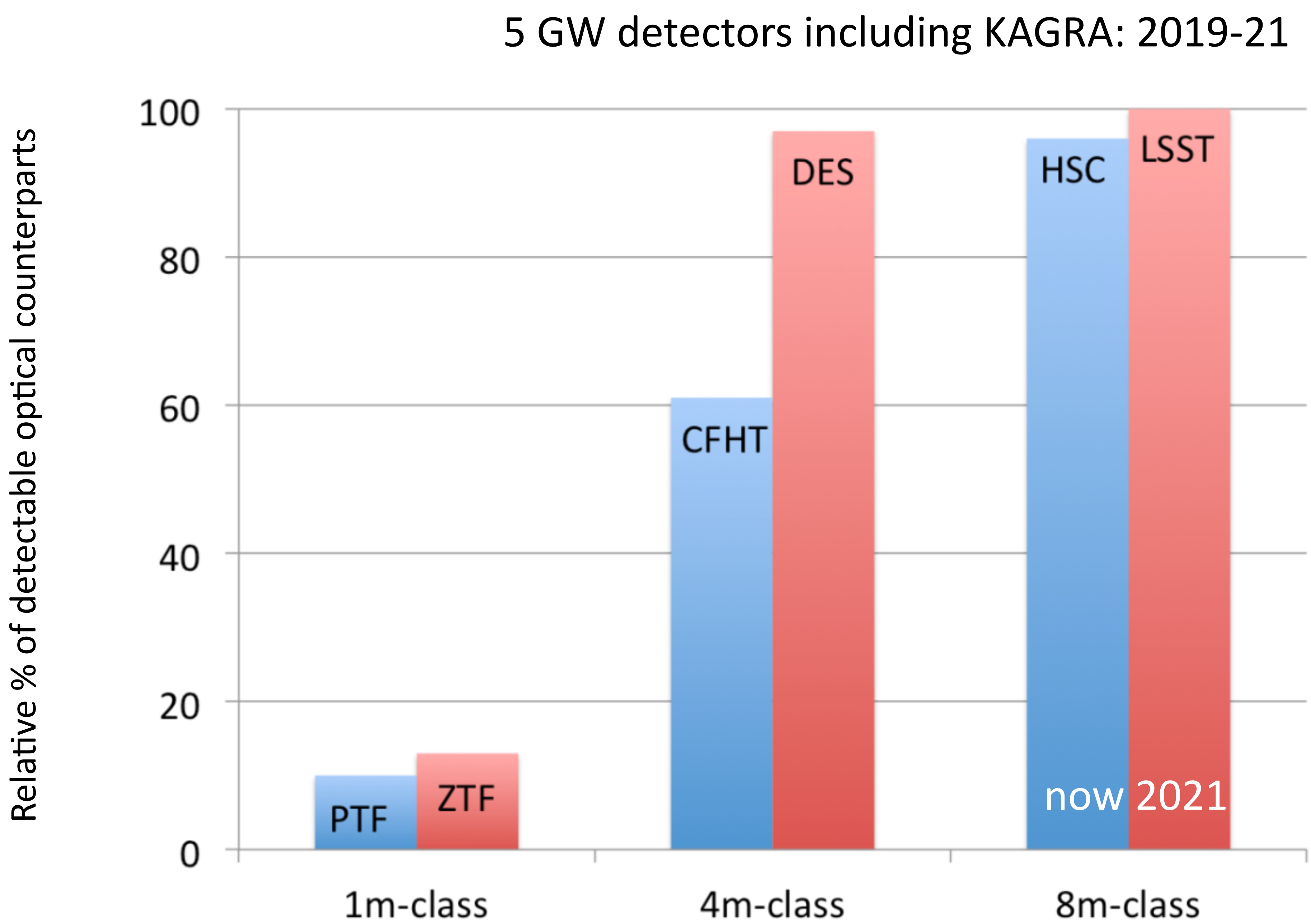
MOA-II 1.8m (wide field, south)

IRSF 1.4m (south)



slide courtesy of Masaomi Tanaka

1. Detection: monte carlo simulation of optical counterparts of GW sources



Nissanke, Kasliwal, Georgieva (2013); see Bartos et al. (2014) for CTA analysis

2. <u>Identification:</u> Statistical Challenge of Astrophysical False Positives

<u>Single Snapshot:</u>

100s SNe and AGNs

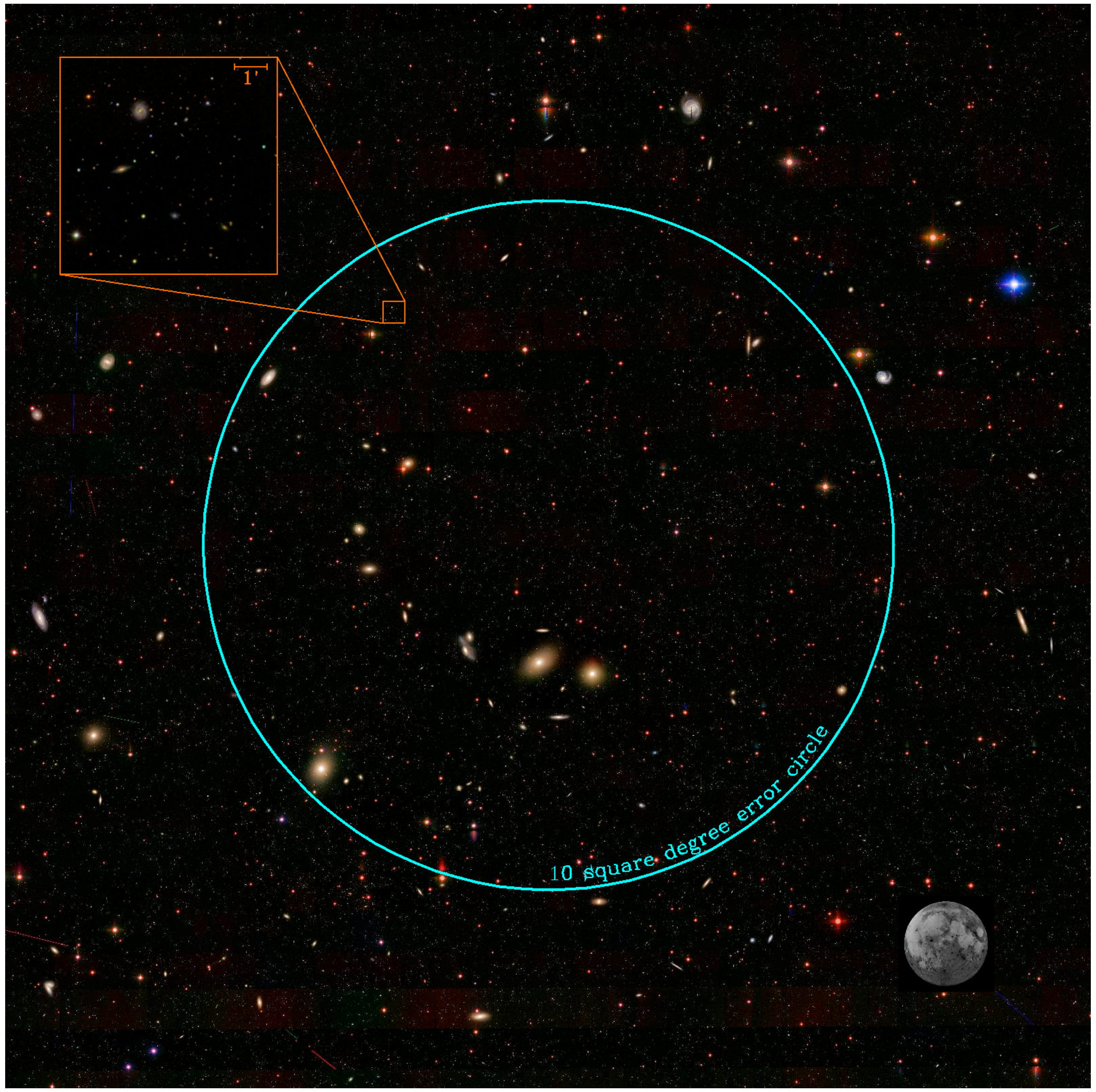
37 foreground flares/CVs

several dwarf nova

10-10000 asteroids

unknowns

[estimated at 24 mag.]



Kasliwal

[Nissanke, Kasliwal, Georgieva 2013]

2. Identification: Where is Wally/Charlie/Waldo? ウォーリーをさがせ!

Single Snapshot:

100s SNe and AGNs

37 foreground flares/CVs

several dwarf nova

10-10000 asteroids

unknowns

[estimated at 24 mag.]

[Nissanke, Kasliwal, Georgieva 2013]

2. Identification: Statistical Challenge of Astrophysical False Positives

Single Snapshot:

100s SNe and AGNs

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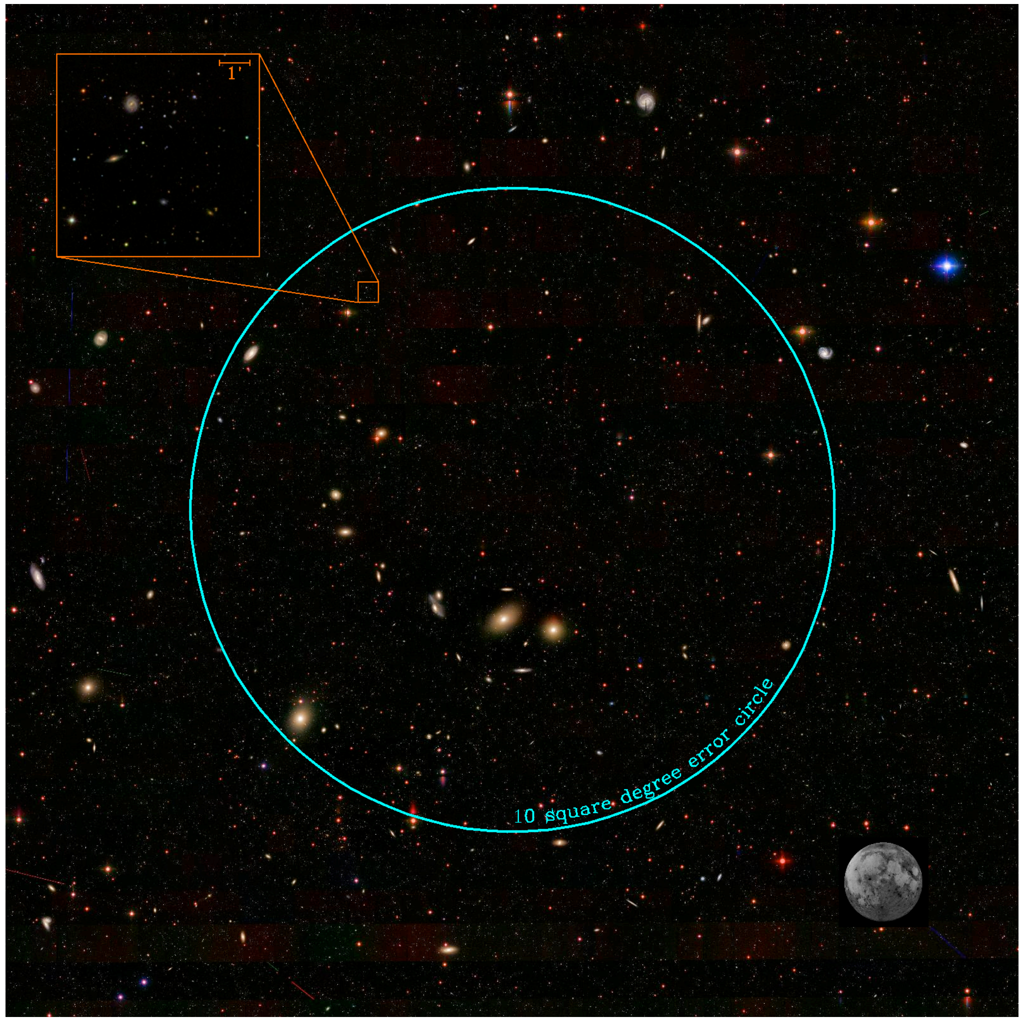


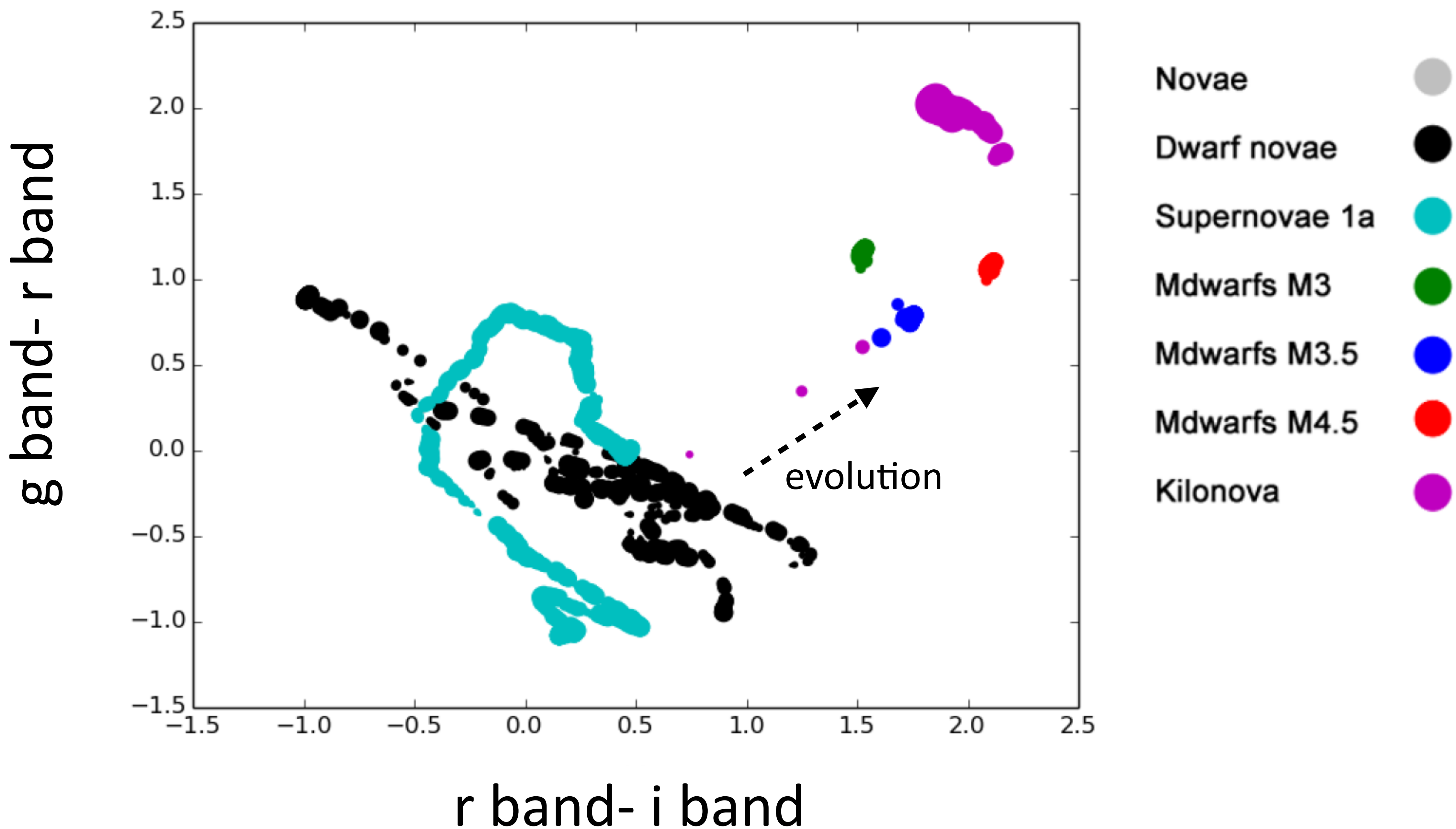
Opportunity: Timescales (different transients & variables have different timescales)

Empirical numbers/Dress rehearsals

[e.g., Drout et al. 2014, Singer et al. 2015]

Identification through different colors over 7 days

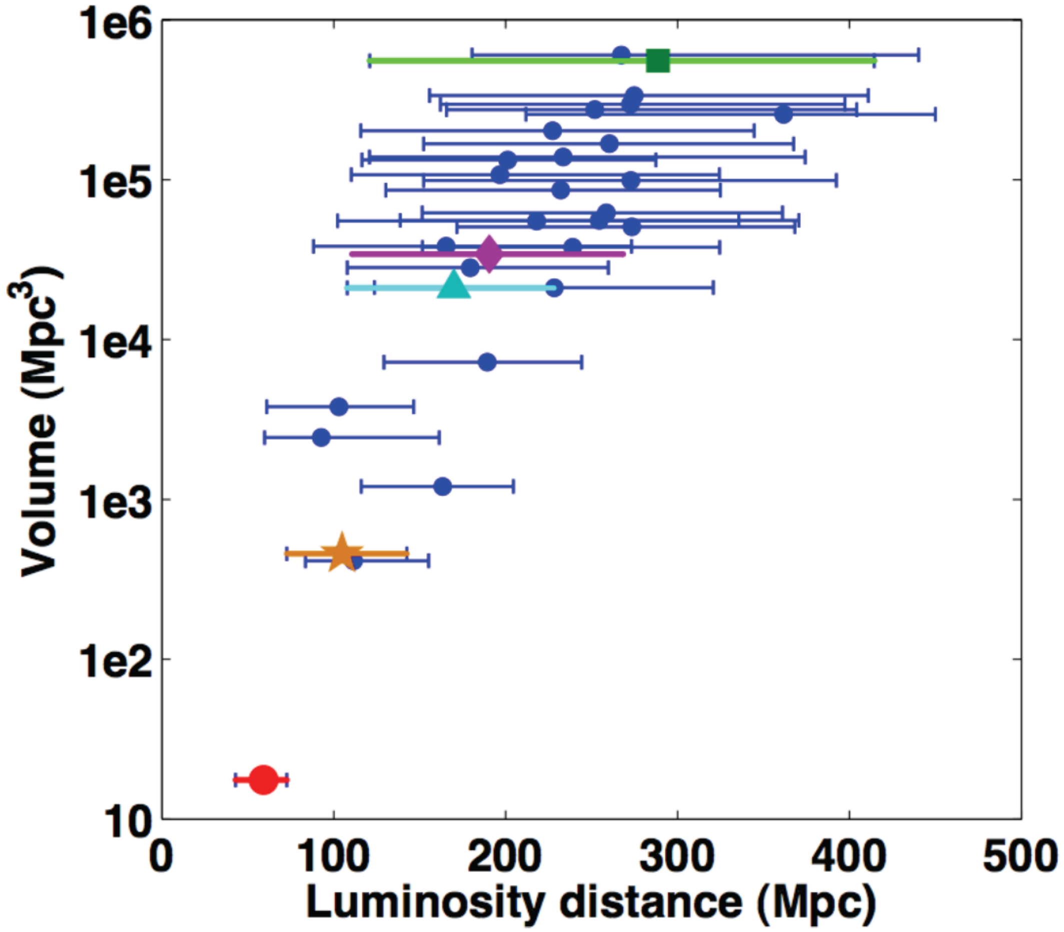
[Jacobs, Nissanke et al. in prep]



[Extragalactic only: see Tanaka & Hotokezaka 2014, Cowperthwaite and Berger 2015]

Reduce false-positive rate with GW volumes & galaxy catalog

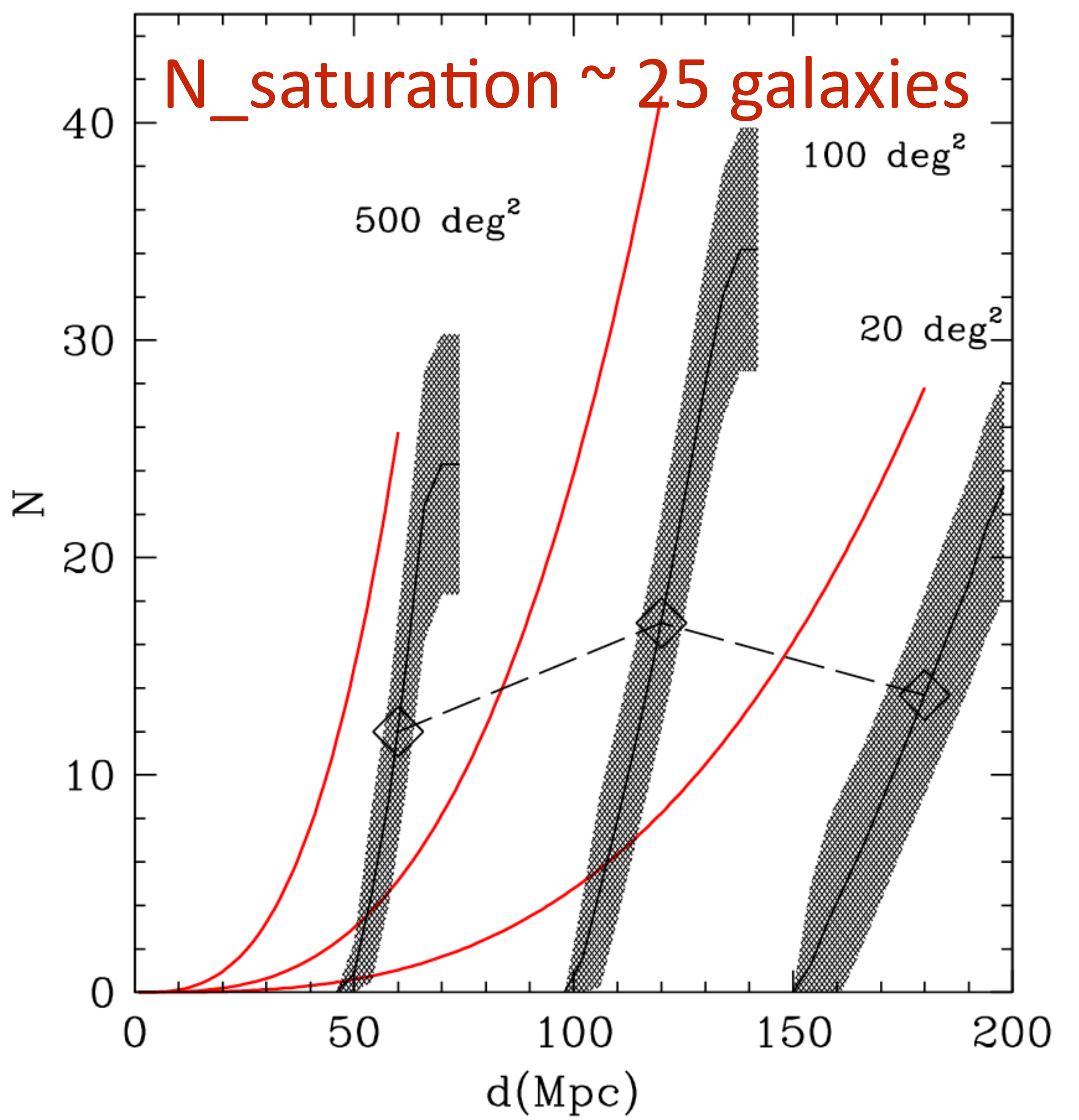
[LIGO, Virgo, advanced design sensitivity noise curves]



Reduce false positive x 10-1000

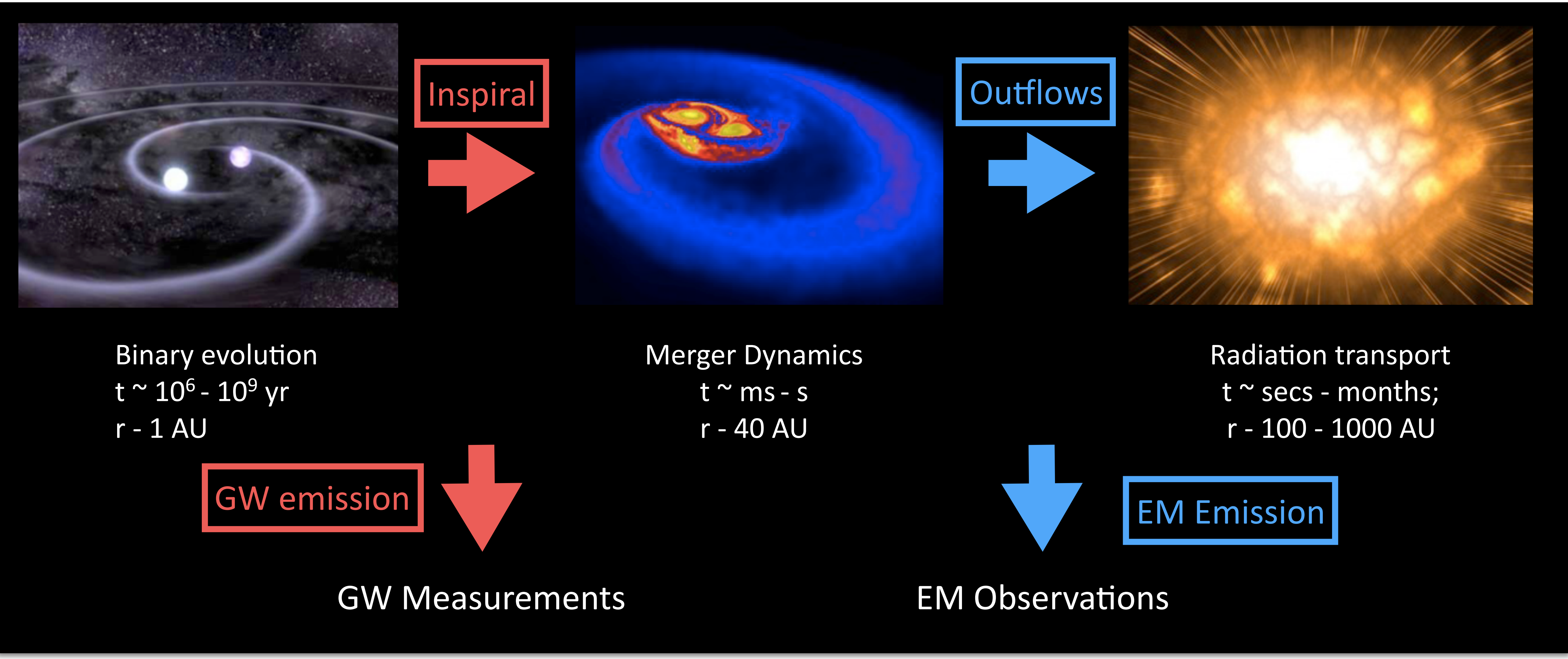
[Nissanke, Kasliwal, Georgieva 2013]

brightest galaxies that produce 50% of the light



[Gehrels, Canizzaro, Kanner, Kasliwal, Nissanke, Singer, 2015]

3. Interpretation challenge for GW+EM: we must build a coherent model of inspiral to EM



State of the Art: diverse models probing different microphysics, length and timescales

The future is loud and bright for multi-messenger astronomy

Witnessing BH & Magnetar formation

- First detections and identifications of EM counterparts
- First comprehensive joint characterisations of GW and EM sources