Follow the chirp: seeing and listening to the transient Universe

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Follow the chirp: seeing and listening to the transient Universe

Seeing: *Electromagnetic Waves (EM).*

Listening to: *Gravitational Waves (GW).*

Transient Universe: *short timescales, extremely high energies.*

The fate of binary compact objects

The fate of binary compact objects

GW emission
~ 10^{57} ergs/s

EM emission

The fate of binary compact objects

Sun: ~10^{33} erg/s
galaxy: ~ 10^{44} erg/s

1.4 M_{sun}

1.4 M_{sun}

GW emission
~ 10^{57} erg/s

EM emission

My research goals

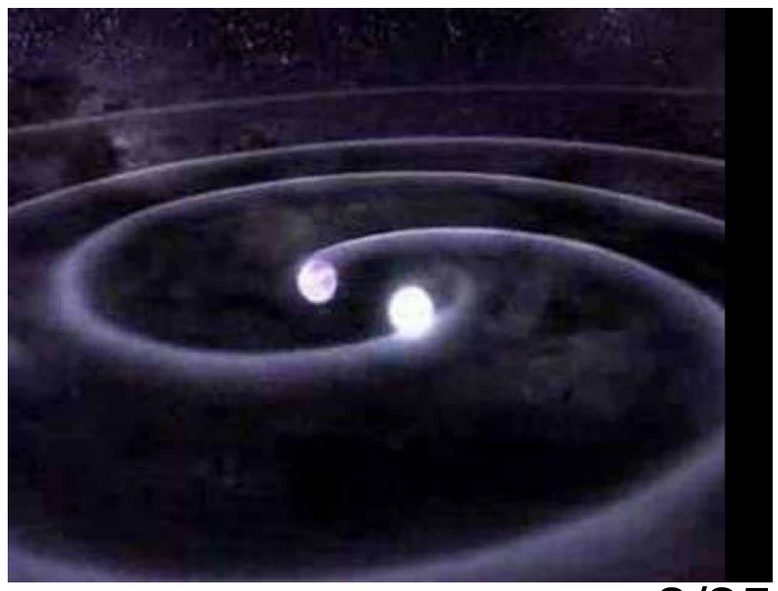
1.Strong-field gravity:

Astrophysical processes in jets, accretion disks, mergers and explosions?

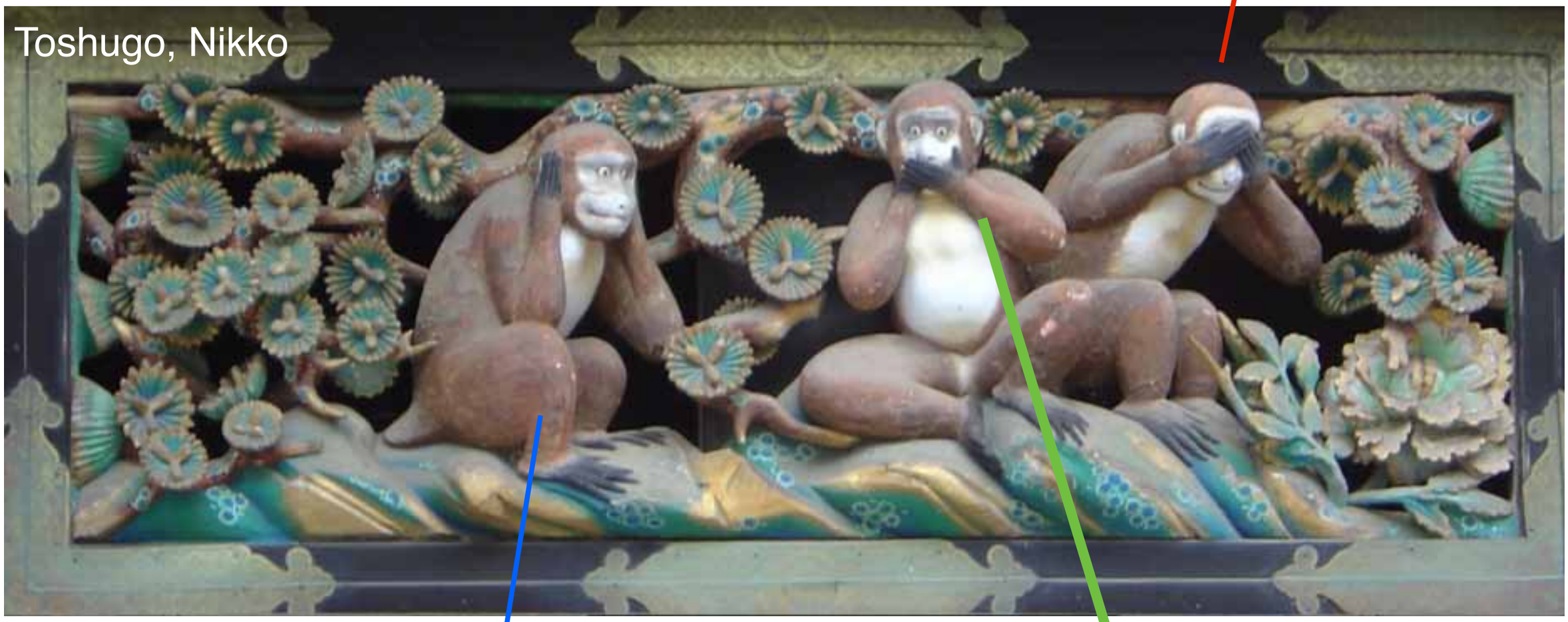
2. The fate of binary stellar evolution.

3. Cosmology:

luminous probes of the Universe's expansion history.



GW observer



EM observer

EM + GW

Talk Outline

Part 1: The fate of binary compact objects.

Part 2: Astrophysics in Strong-Field Gravity.

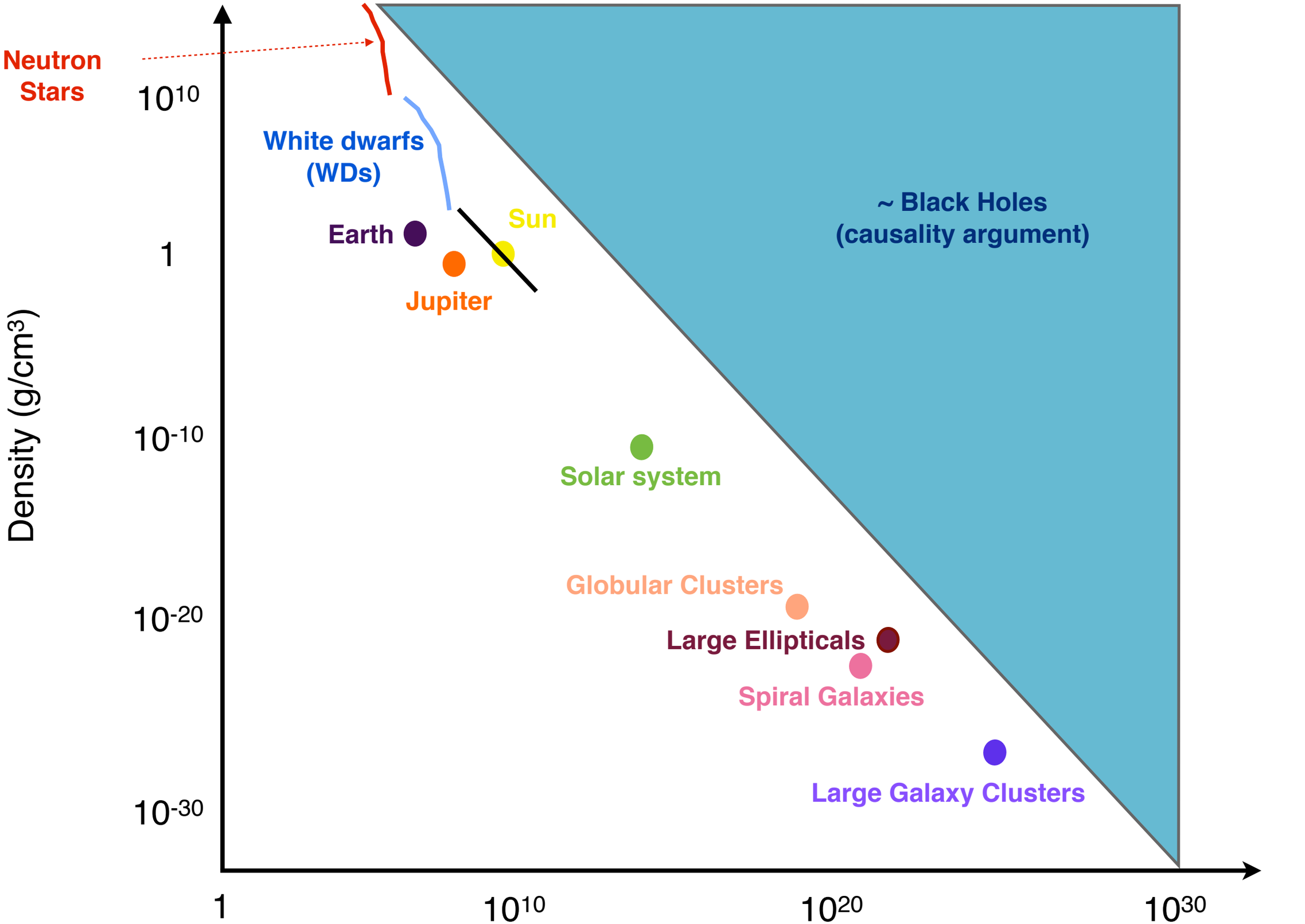
(Why?: GW + EM science.)

Part 3: Following the chirp.

(How?: GW + EM observations.)

Part 1: the fate of compact object mergers.

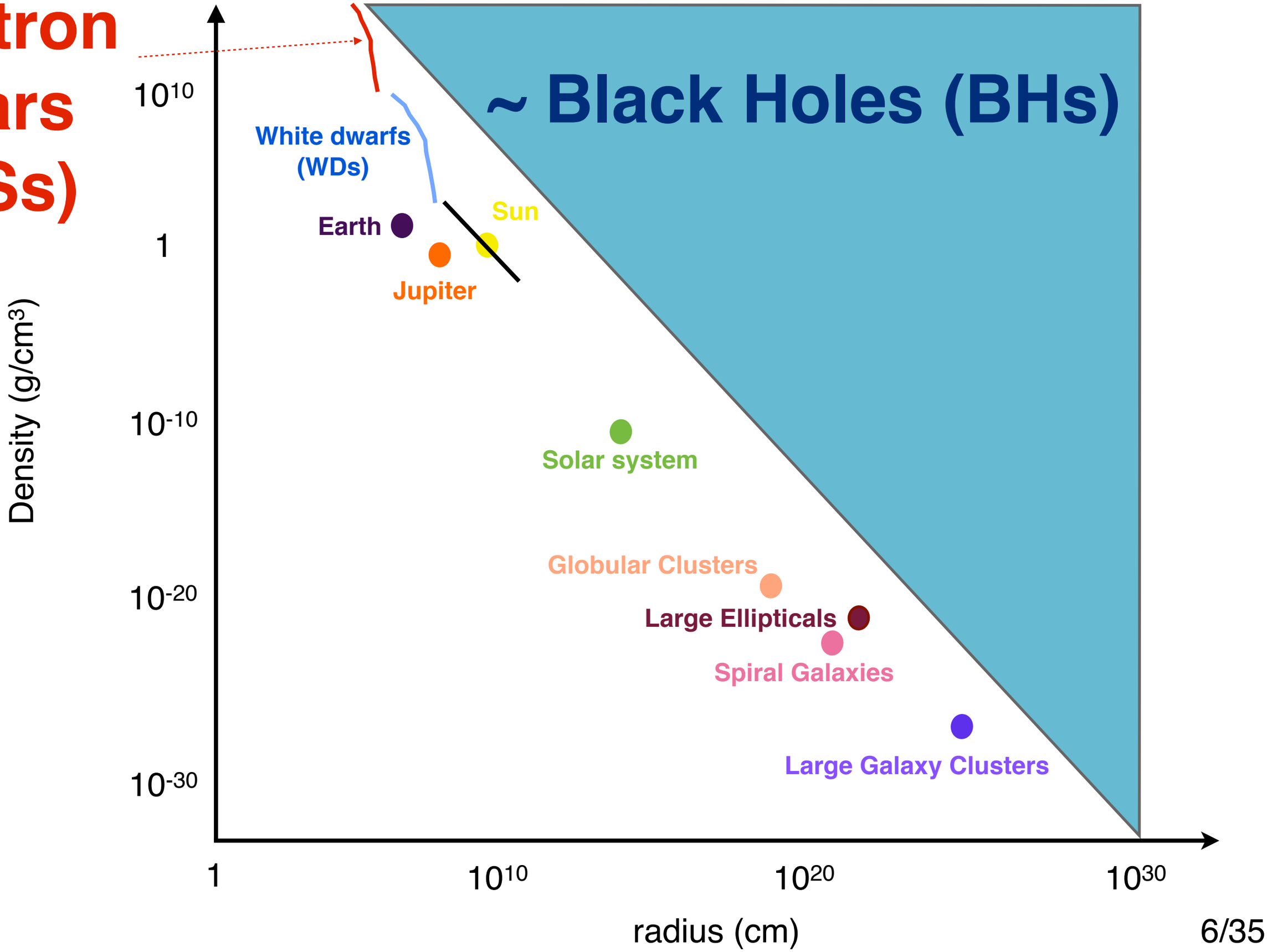
Density vs size



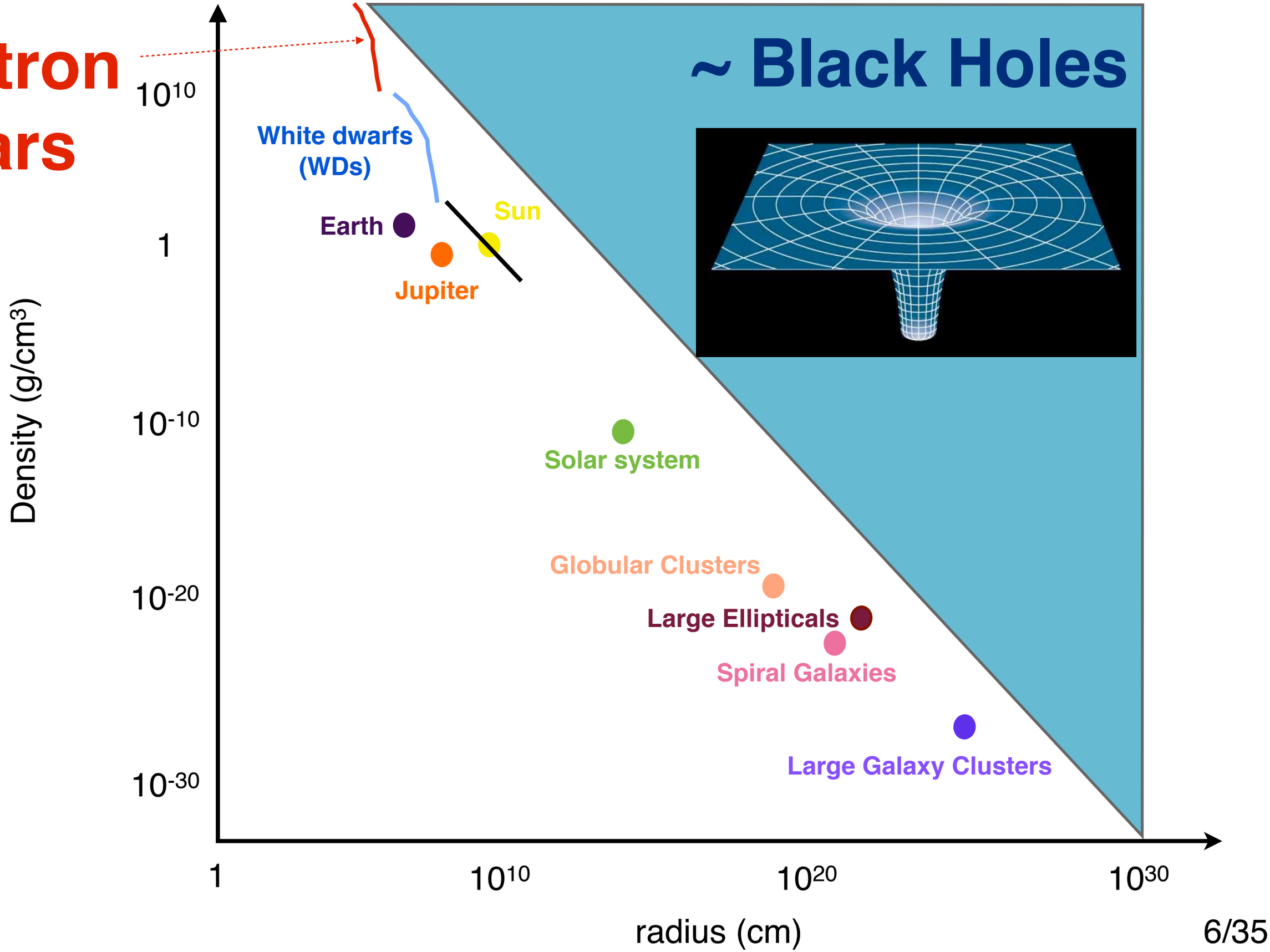
[adapted from Shapiro & Teukolsky]

Compact Objects

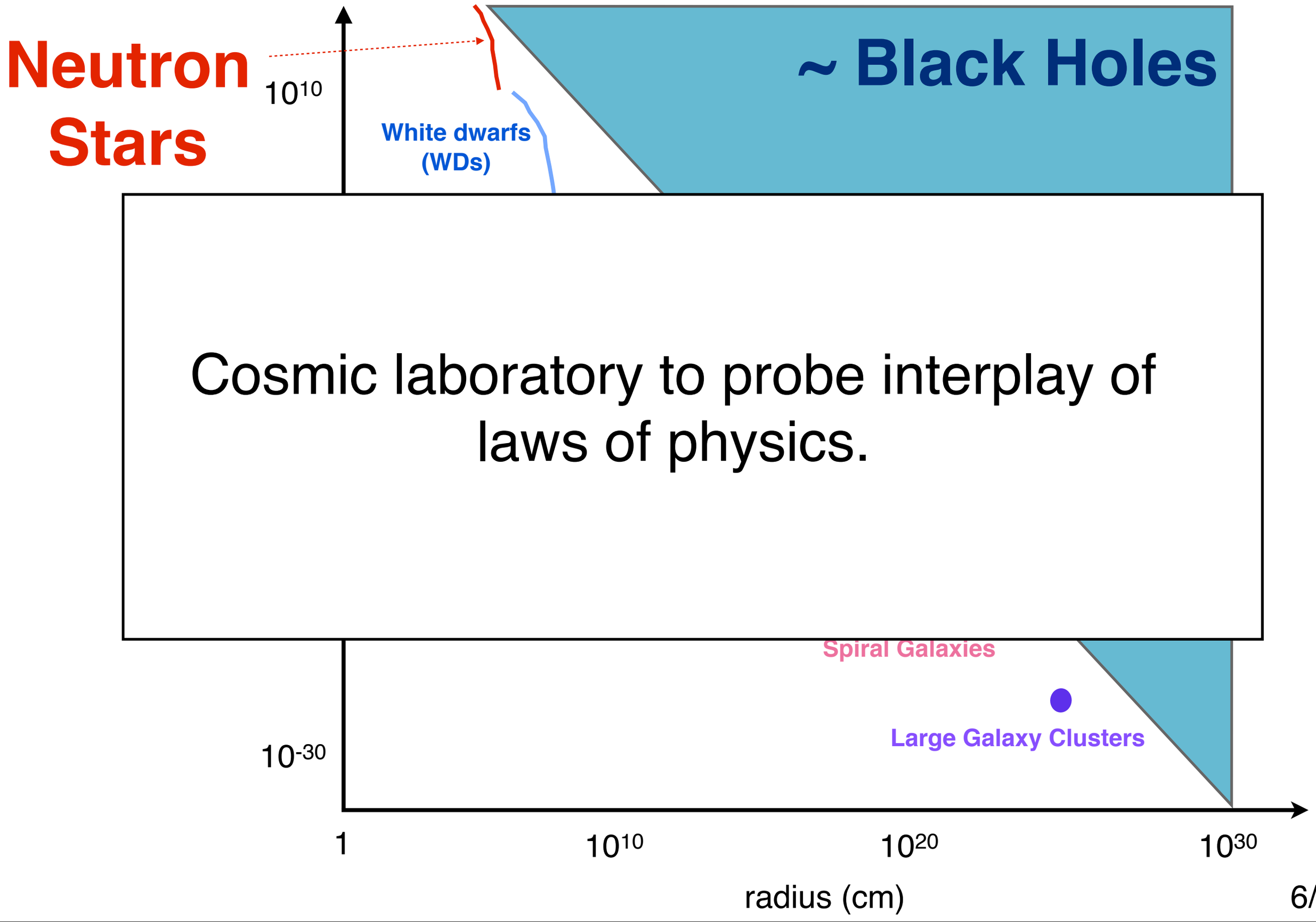
Neutron Stars (NSs)



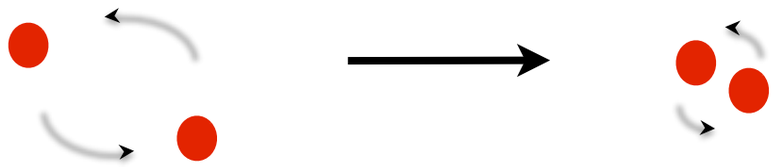
Compact Objects



Compact Objects



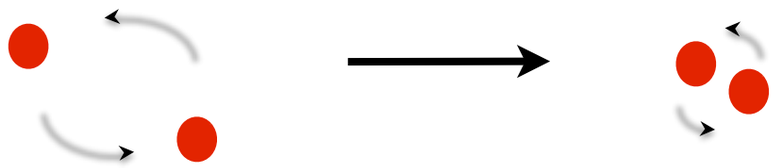
The tale of two binaries



NS - NS

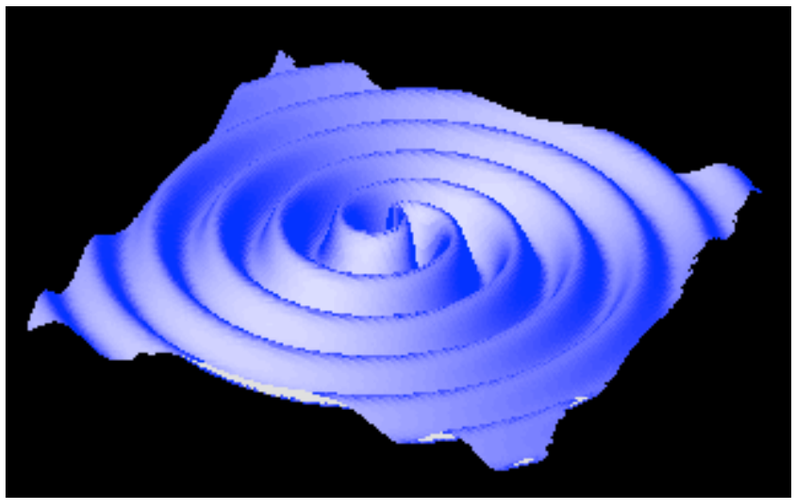
NS - BH

GWs: last few minutes pre-merger.



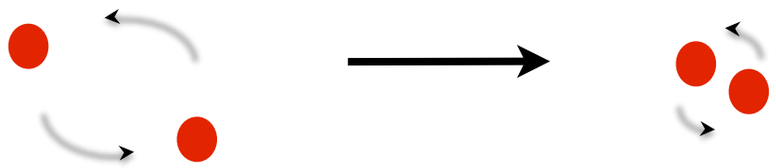
NS - NS

NS - BH



Gravitational Waves (GWs)

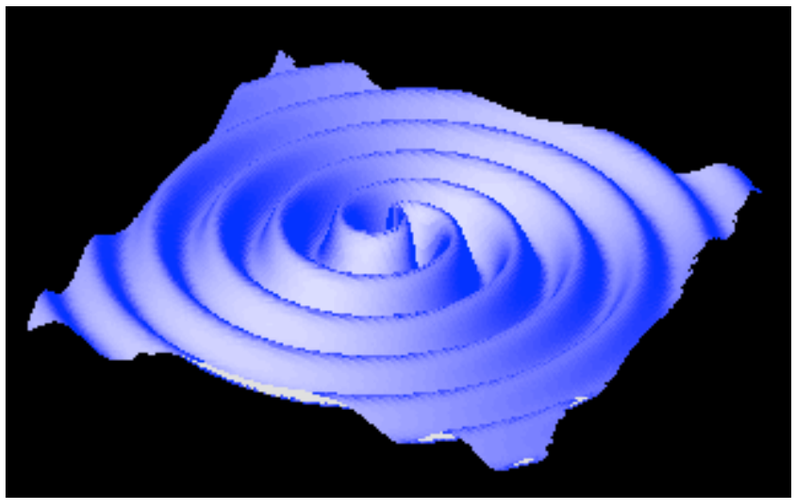
GWs: last few minutes pre-merger.



NS - NS

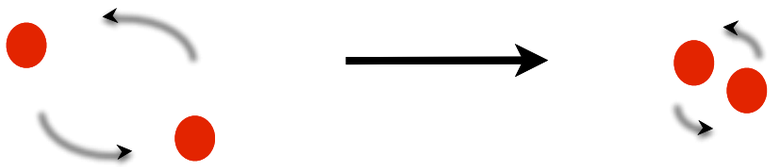
NS - BH

GWs: h(t)

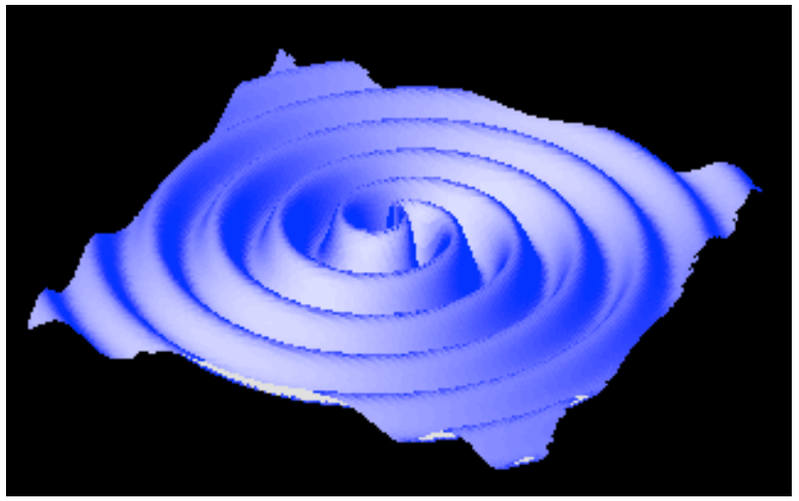


perturbations in the curvature of spacetime

GWs: last few minutes pre-merger.



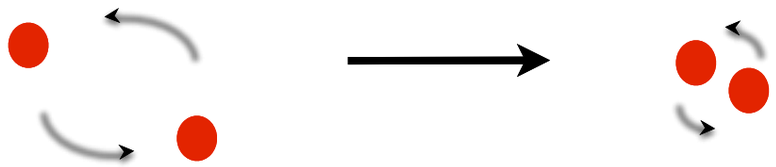
NS - NS



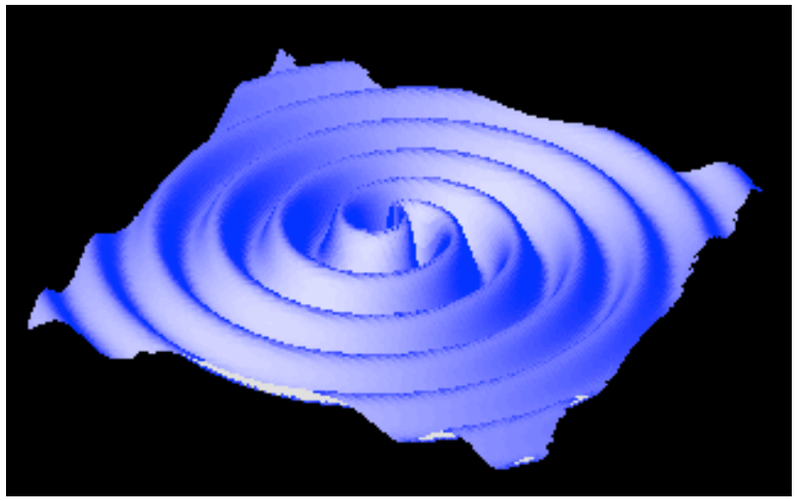
NS - BH

h ~ [d²Q/dt²]/distance

GWs: last few minutes pre-merger.



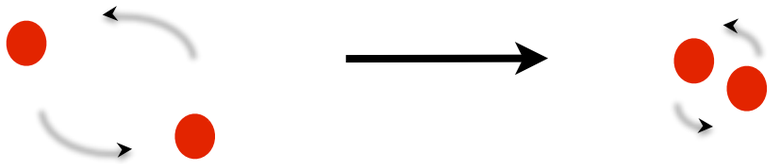
NS - NS



NS - BH

~ sound: coherent, weak, bulk properties of matter.

Outcome of mergers ?



NS - NS

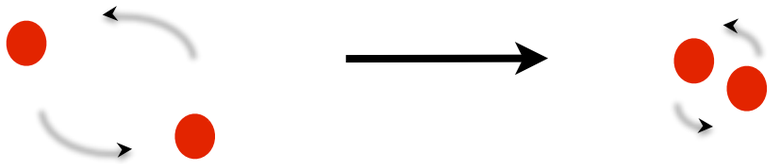
NS - BH

?

EM: current observational status.

OBSERVED

~ 6 Galactic disk binary pulsars
(including PSR 1913+16)



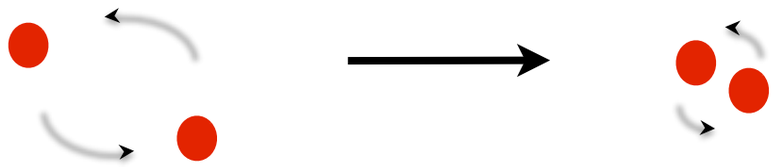
NS - NS

NS - BH

NOT- OBSERVED

?

EM counterparts



NS - NS

NS - BH

EM EMISSION !!!

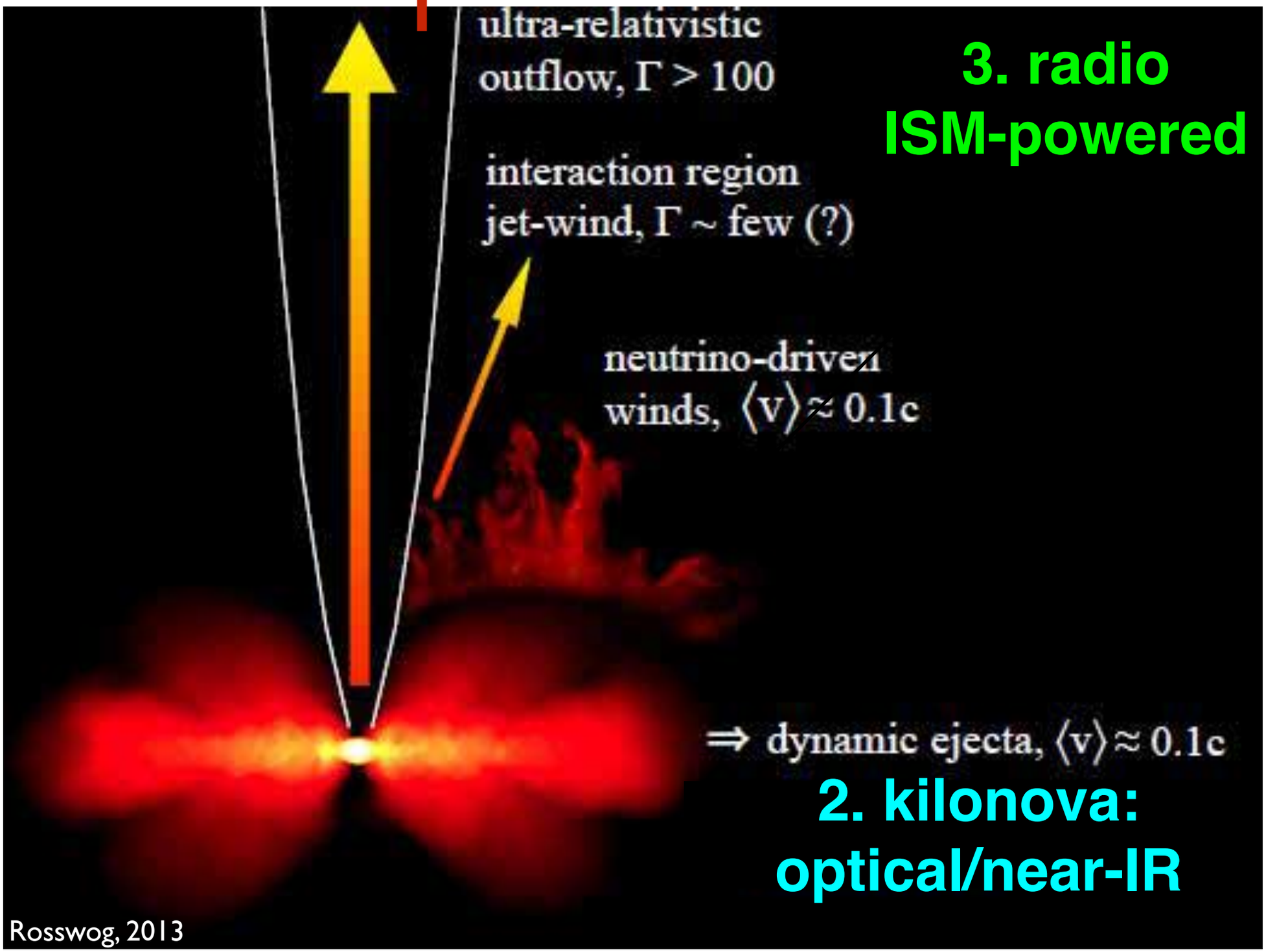
~ 10 s pre-merger

~ 10 ms post-merger

?

EM: Three post-merger counterparts

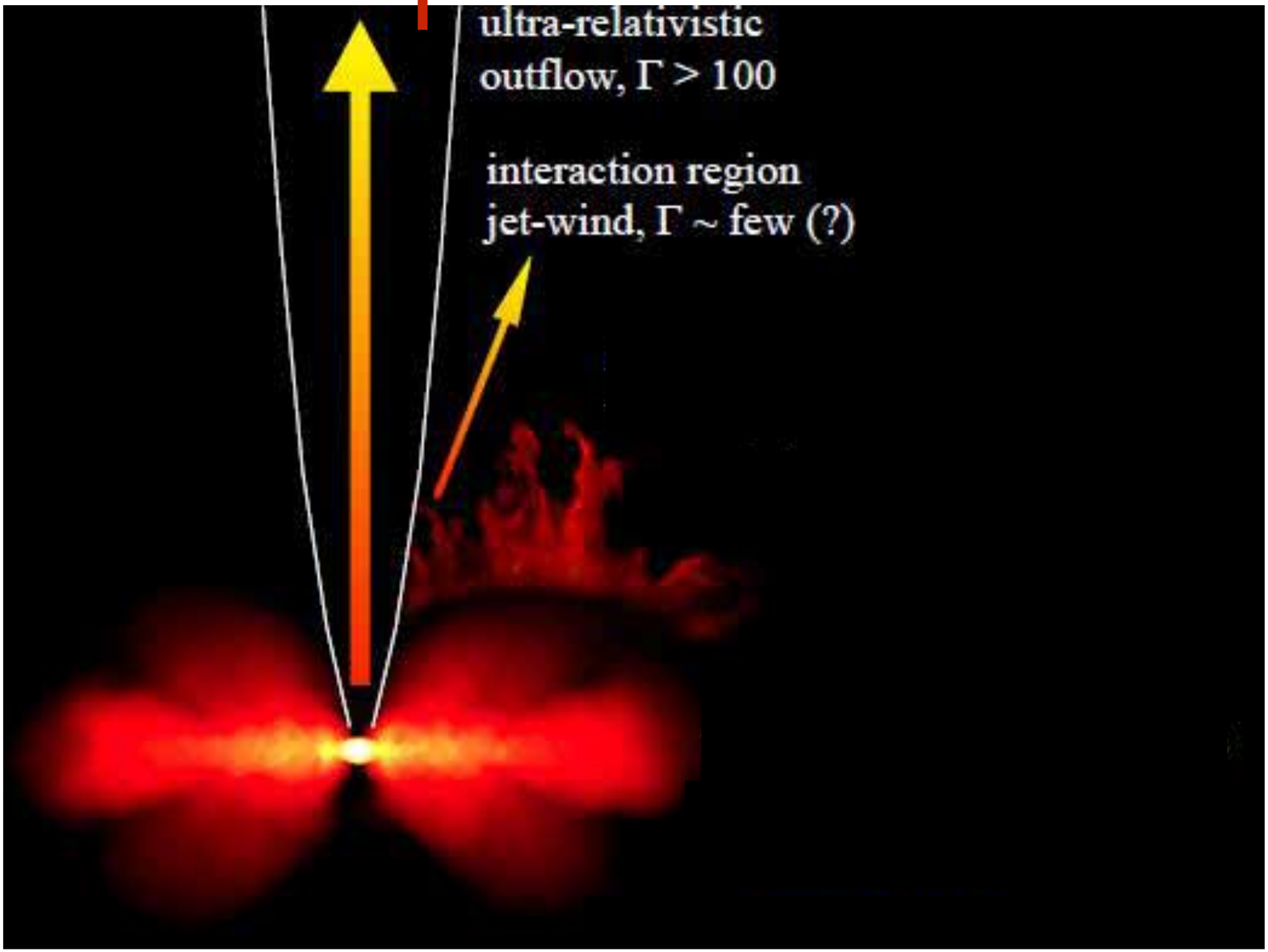
1. Short Gamma Ray Bursts (SGRBs): X/gamma - ray



Rosswog, 2013

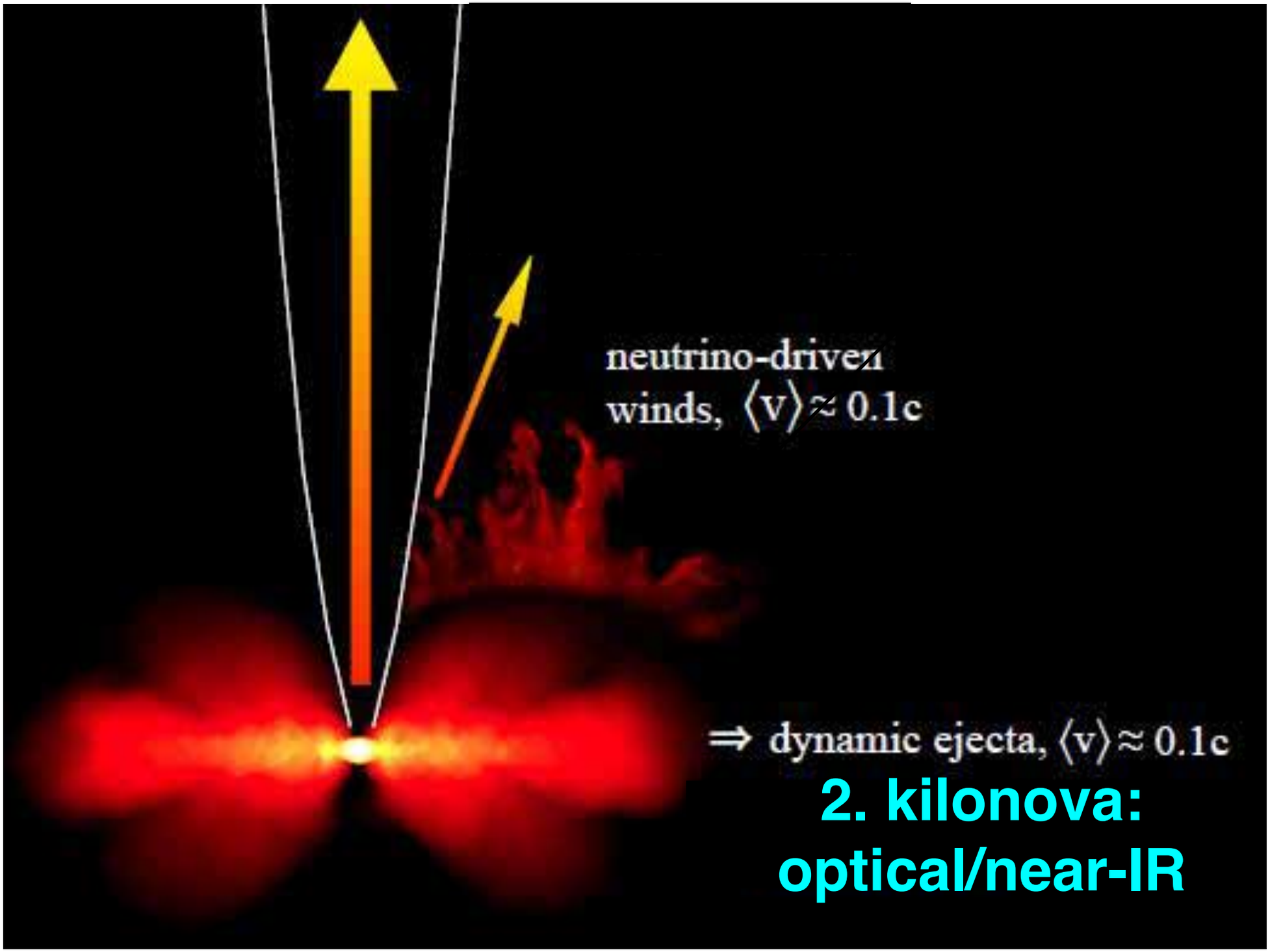
EM: Three post-merger counterparts

1. Short Gamma Ray Bursts (SGRBs): X/gamma - ray



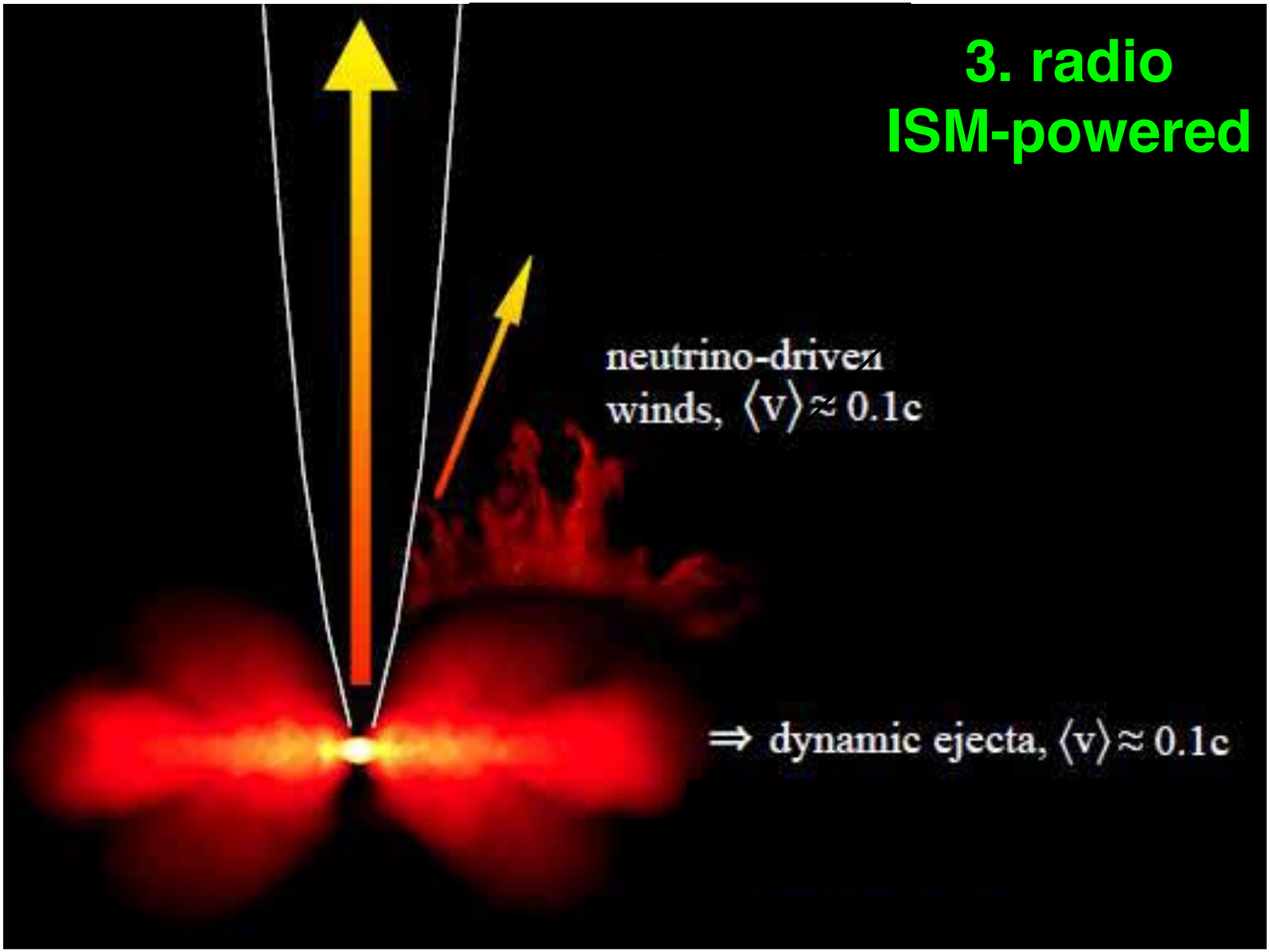
[see e.g. Atteia and Boer 2011…]

EM: Three post-merger counterparts



[e.g., Li and Paczynski 1998, Kulkarni 2005, Metzger et al. 2010,
…Barnes and Kasen 2013, Kasen et al 2013 …]

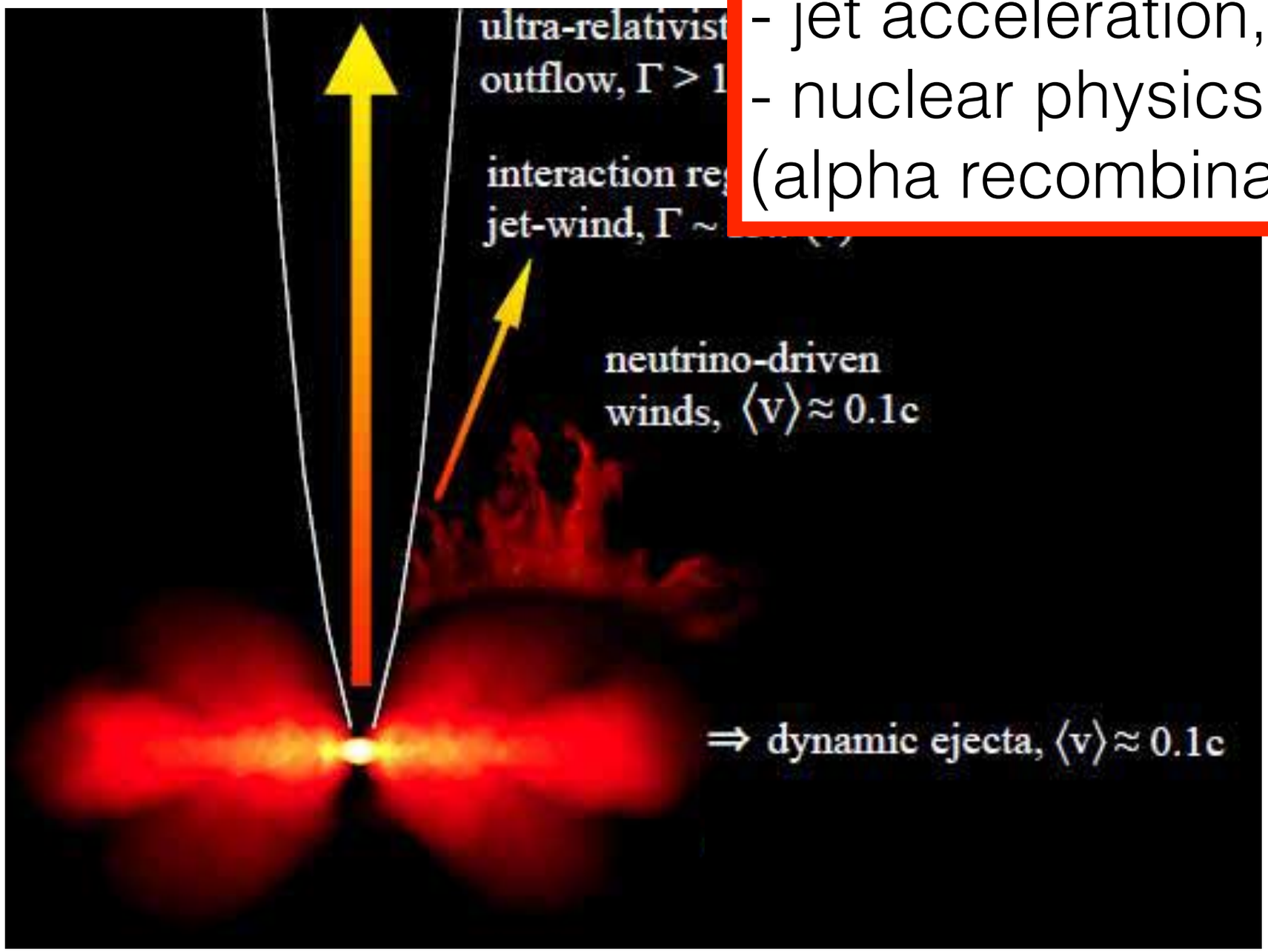
EM: Three post-merger counterparts



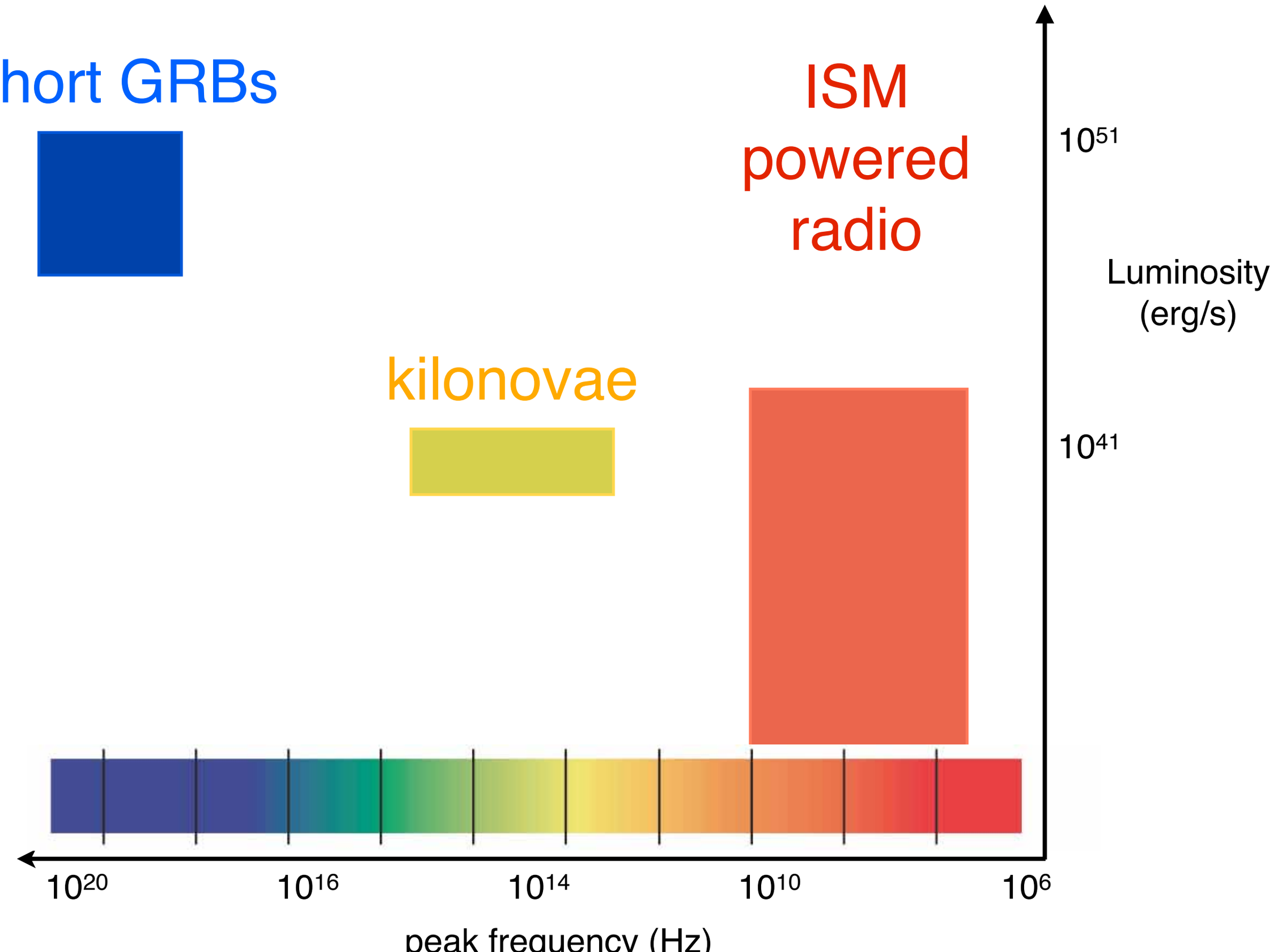
[e.g. Hansen and Lyutikov 2001, Nakar and Piran 2011]

Three post-merger EM counterparts

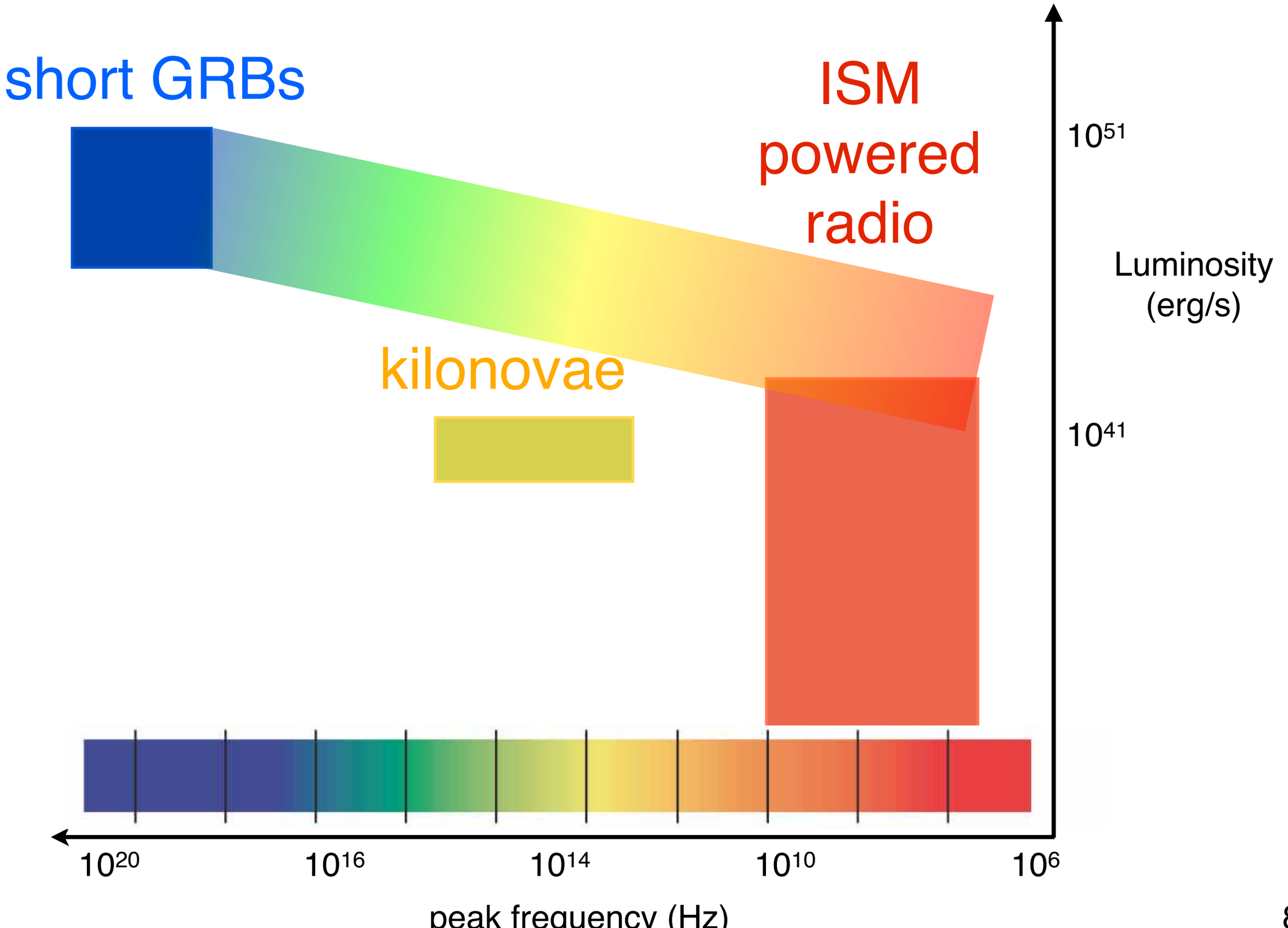
- standard accretion disk physics
- neutrino cooling,
- jet acceleration,
- nuclear physics in the outflows (alpha recombination, r process ...).



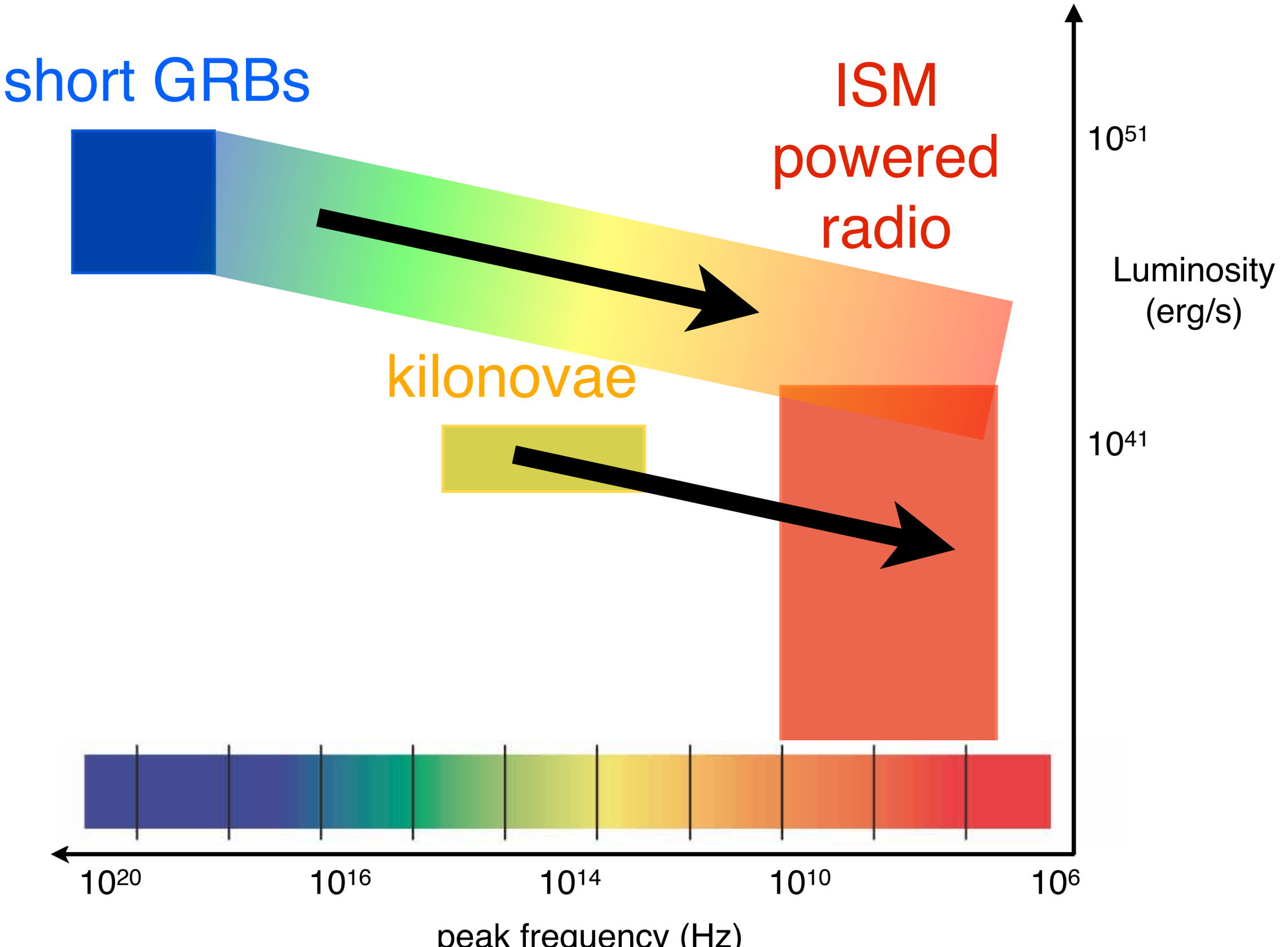
EM: Hertzprung-Russell for post-merger.



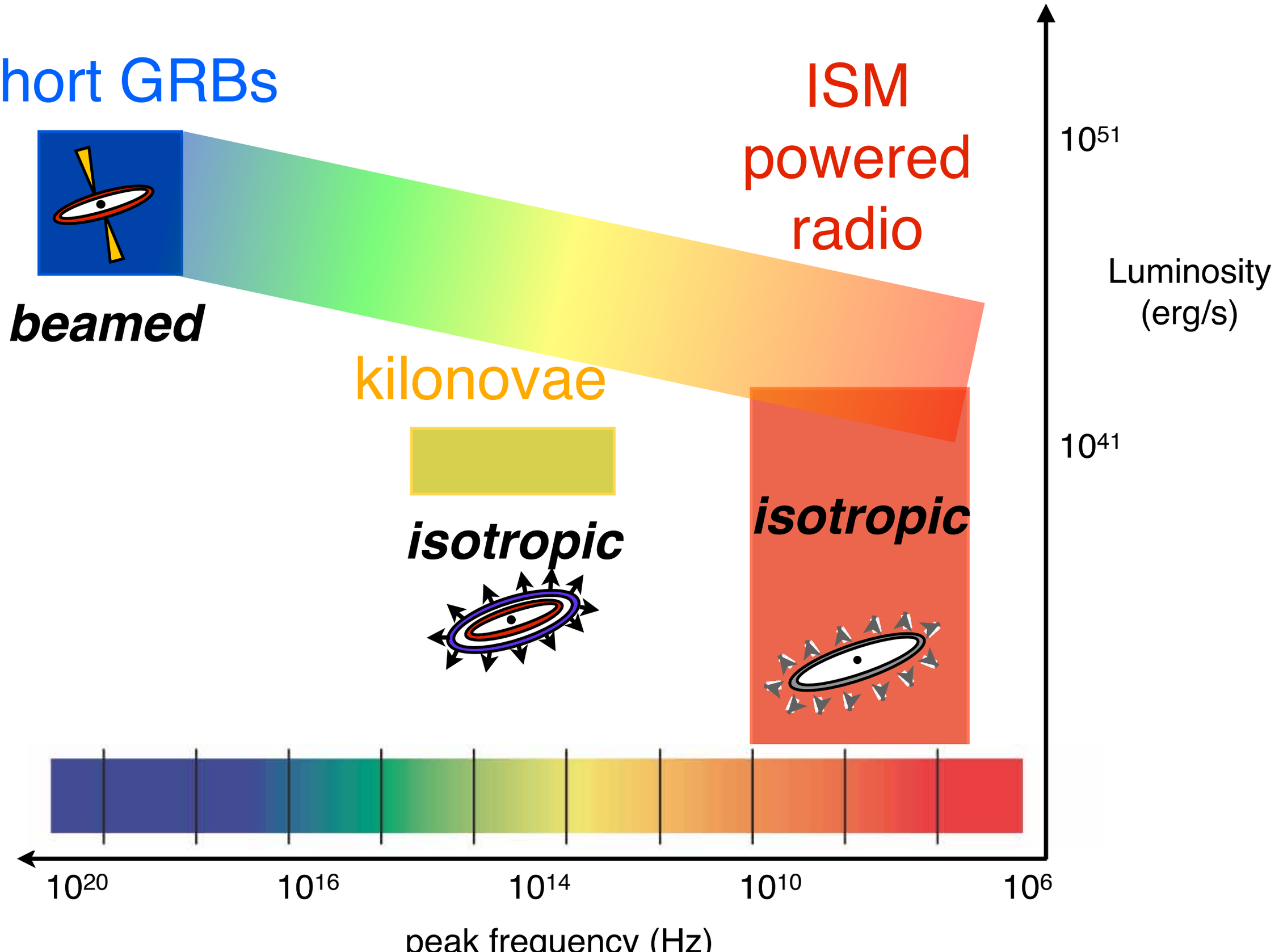
EM: H-R diagram for post-merger.



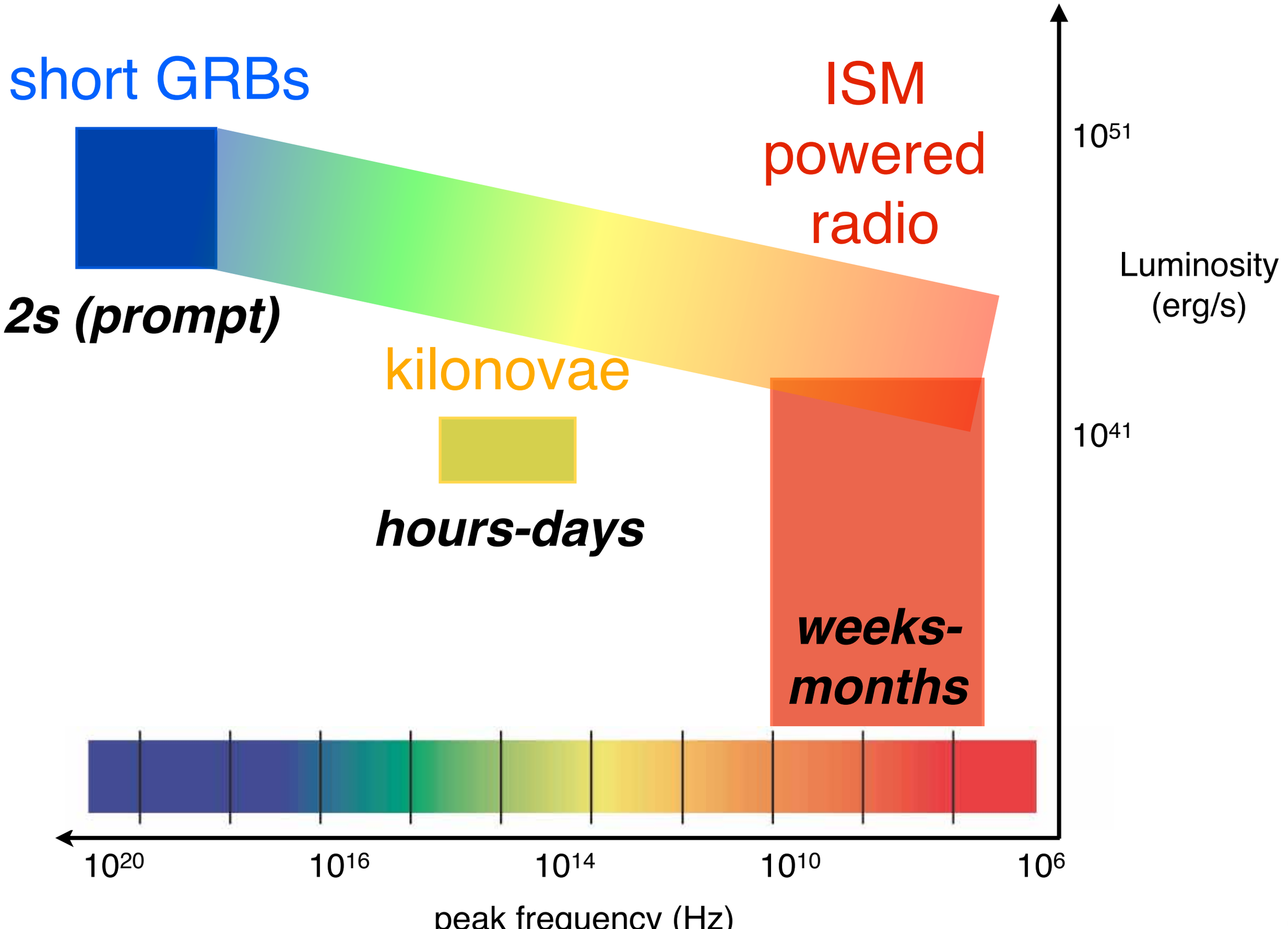
EM: Evolutionary tracks for post-merger.



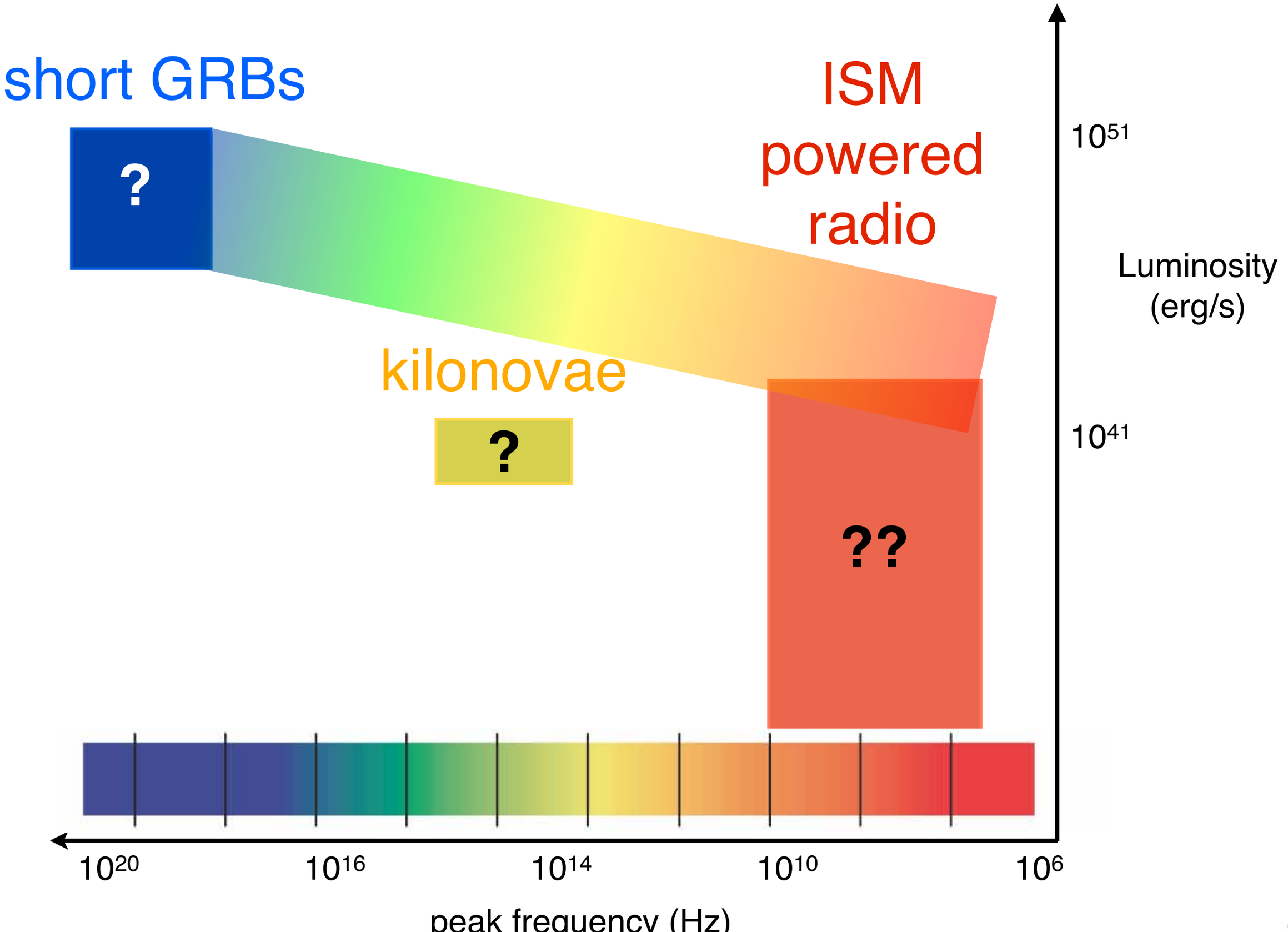
EM: isotropic or beamed emission.



EM: emission timescales.



EM: known and unknowns.



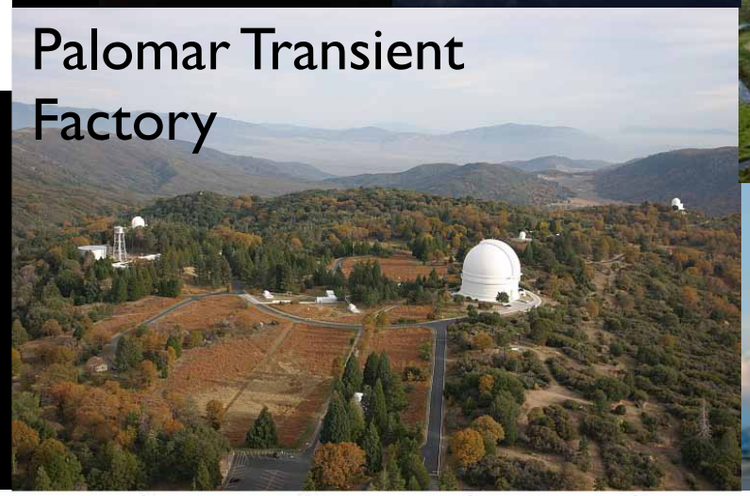
EM eyes wide open today.

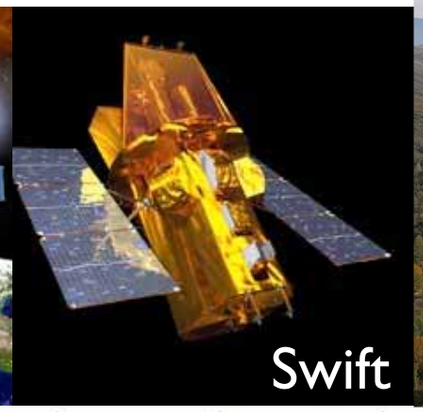
short GRBs

ISM powered radio

10^{51}

Luminosity (erg/s)

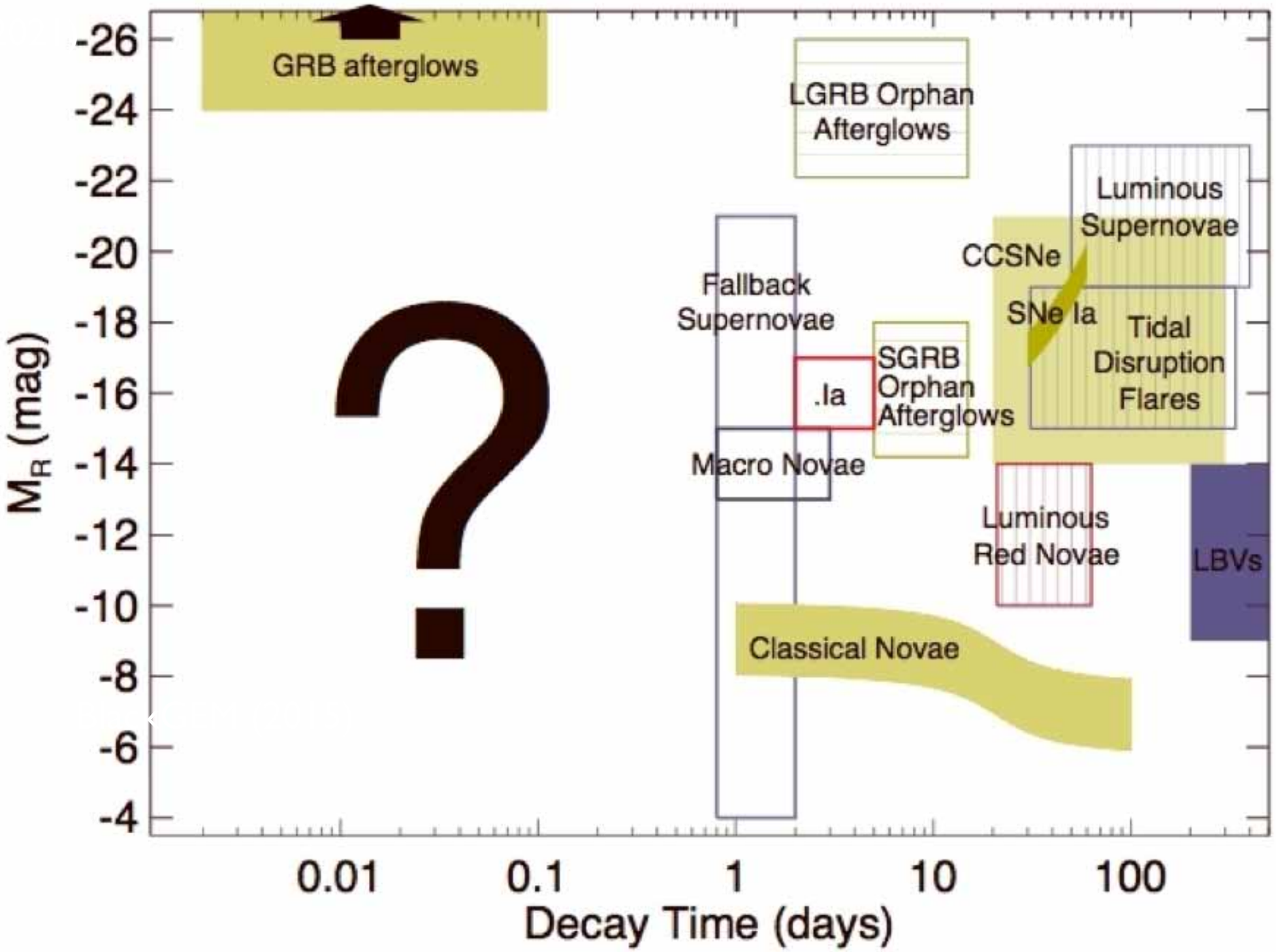




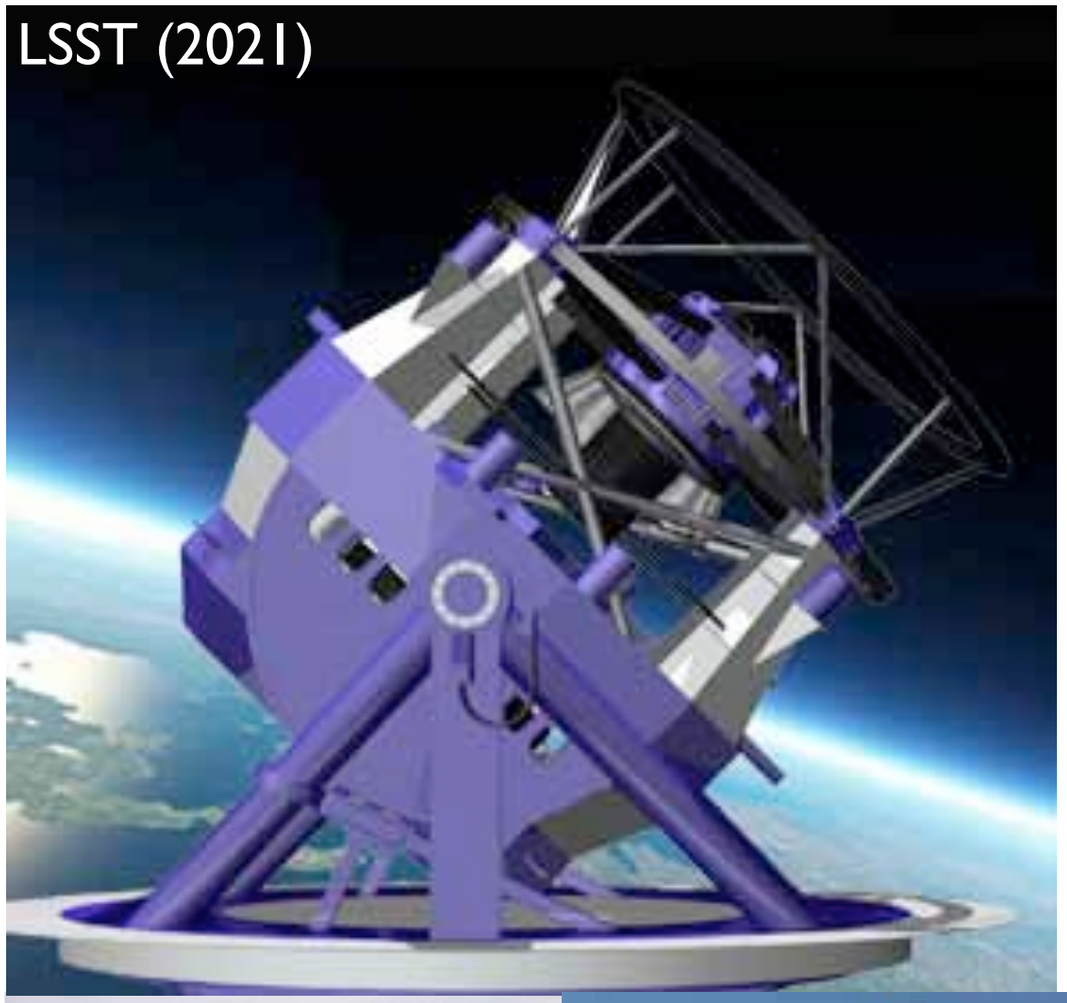
10^{20} 10^{16} 10^{14} 10^{10} 10^{6}

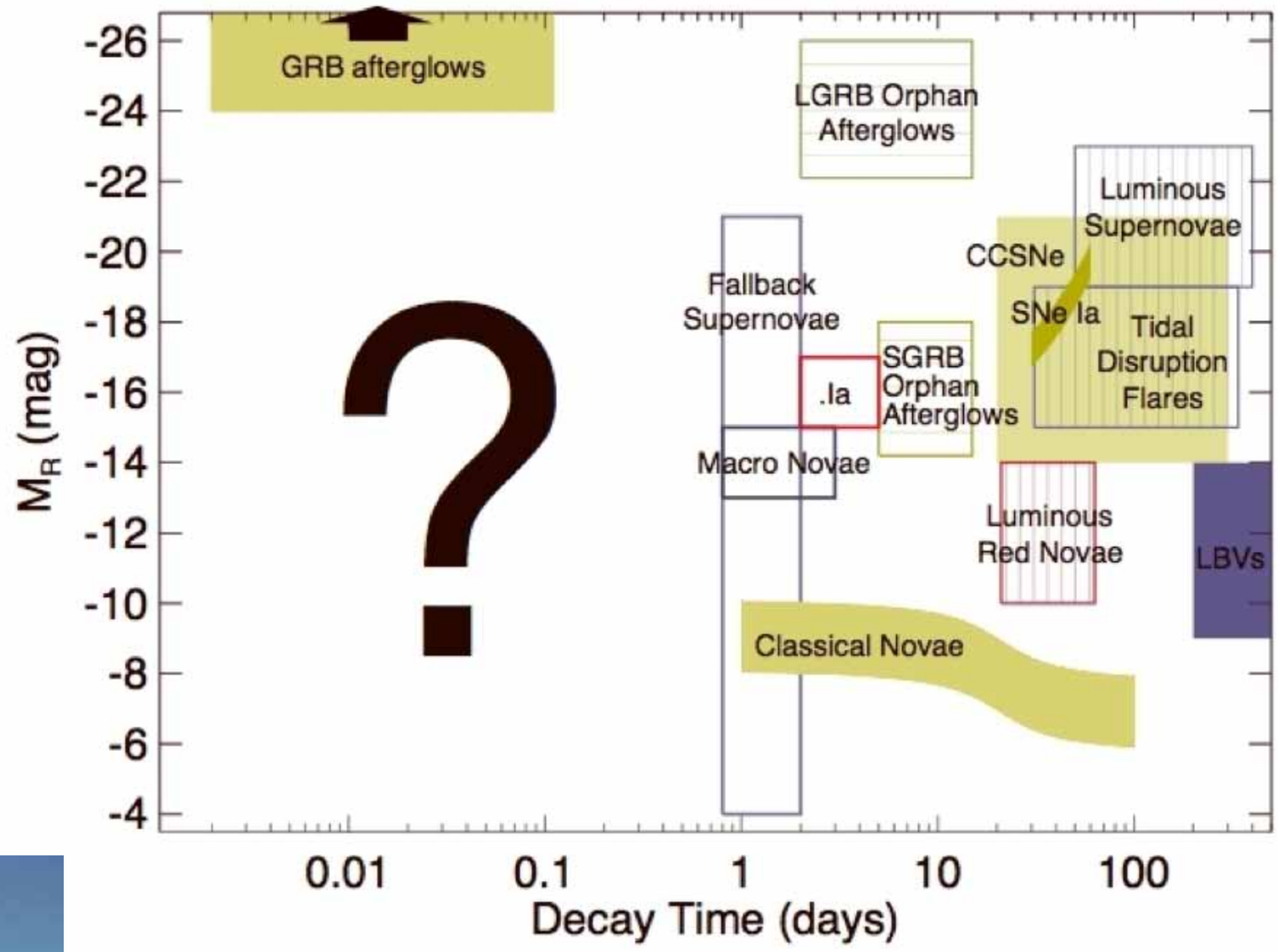
peak frequency (Hz)

EM optical: Transients in the Universe.



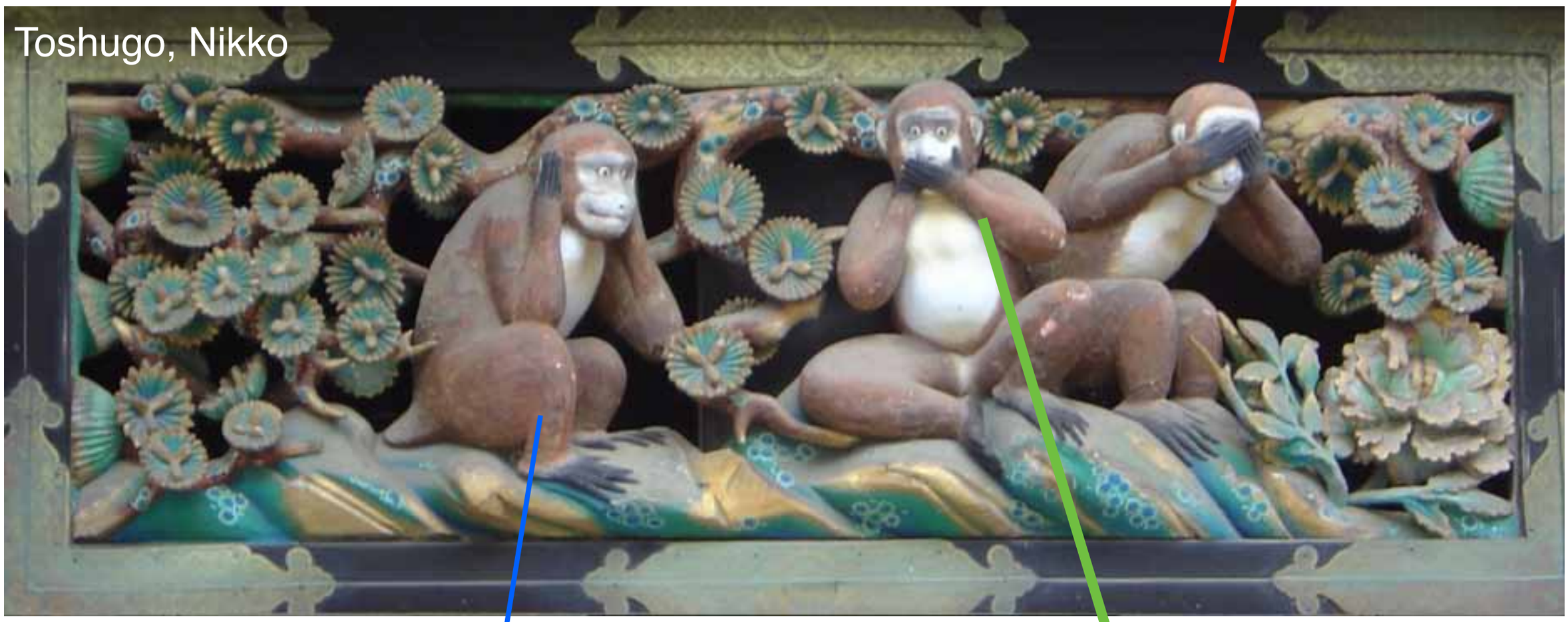
EM optical: Transients in the Universe.





LSST Science Book 2009

GW observer



EM observer

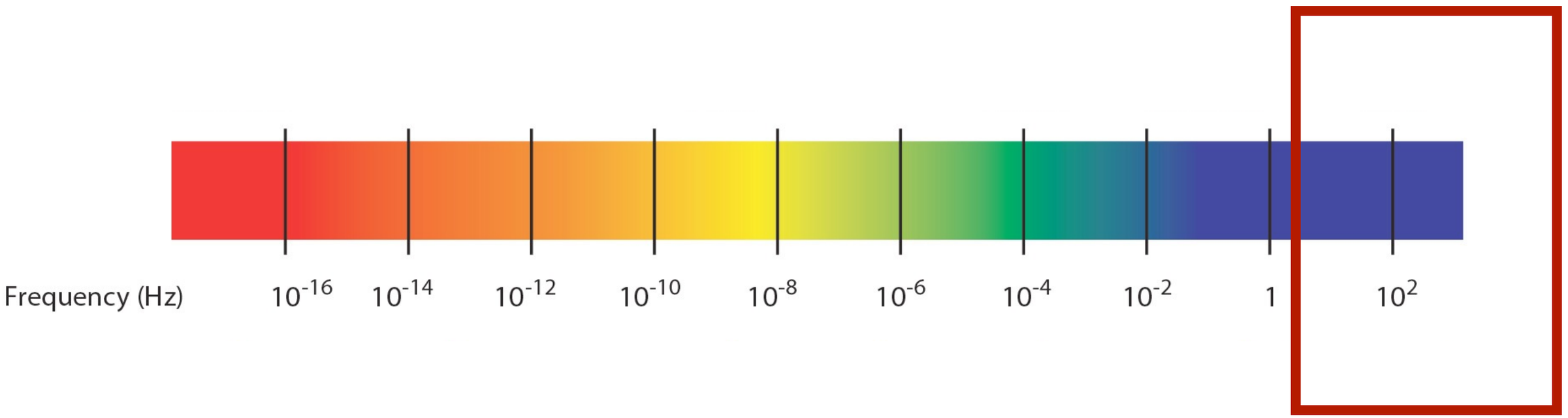
EM + GW

From EM eyes wide open...

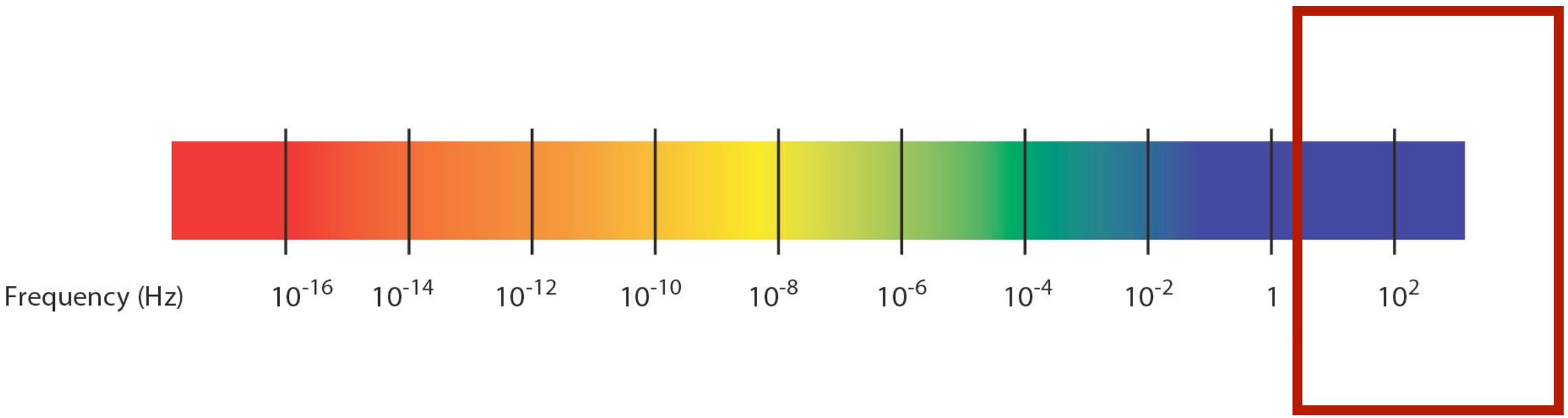
...to GW ears wide open…

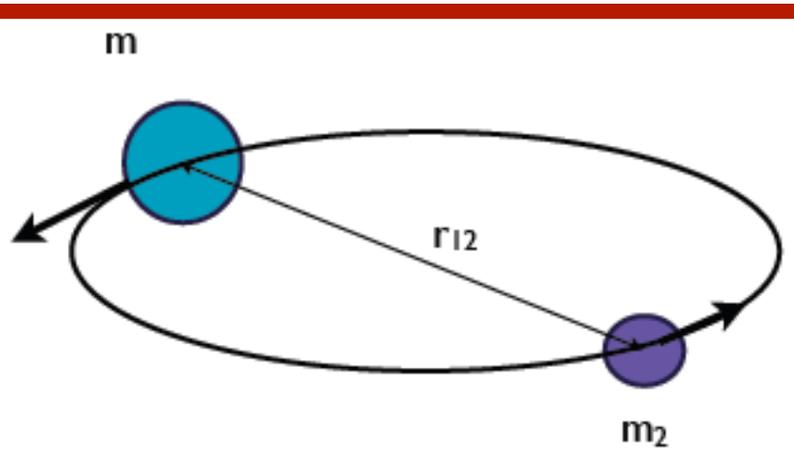
Progenitors (*masses*, *spins*, geometry, distance)

GW ears wide open for compact binaries.



GW ears wide open for compact binaries.

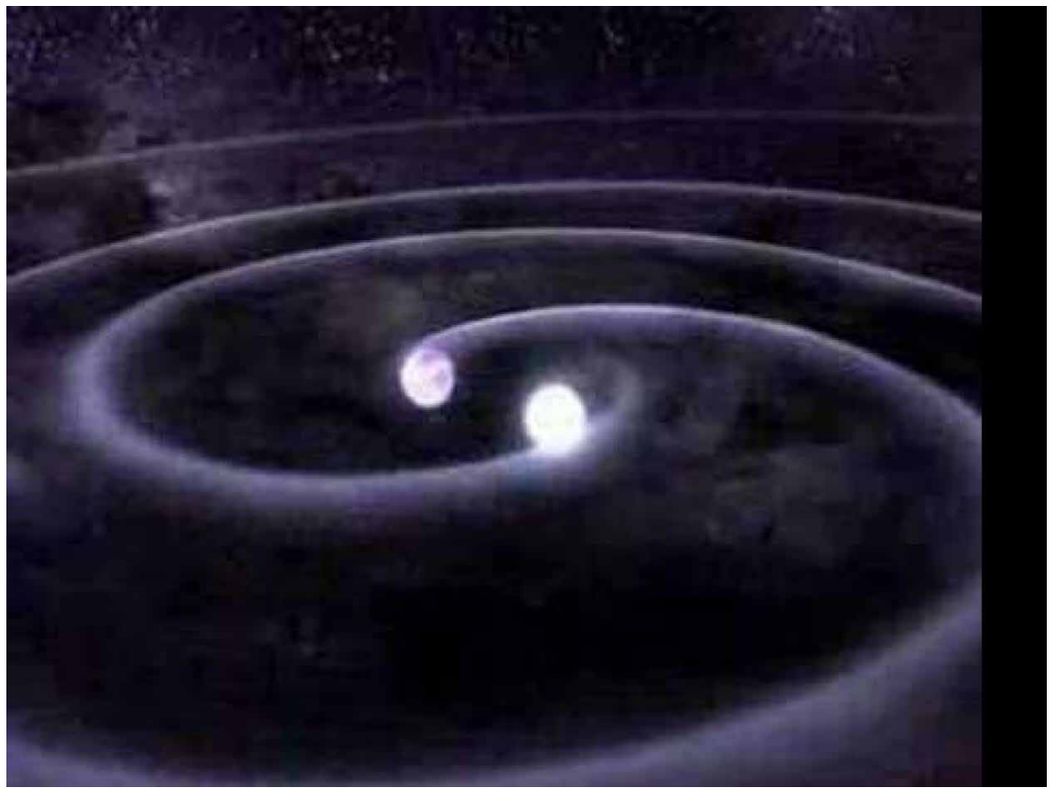




$$f_{\rm GW} \sim 2 f_{\rm orb} \sim \frac{1}{\pi}\sqrt{\frac{GM}{r_{12}^3}}$$

GW: High-frequency sources.

Accurate modelled h(t)

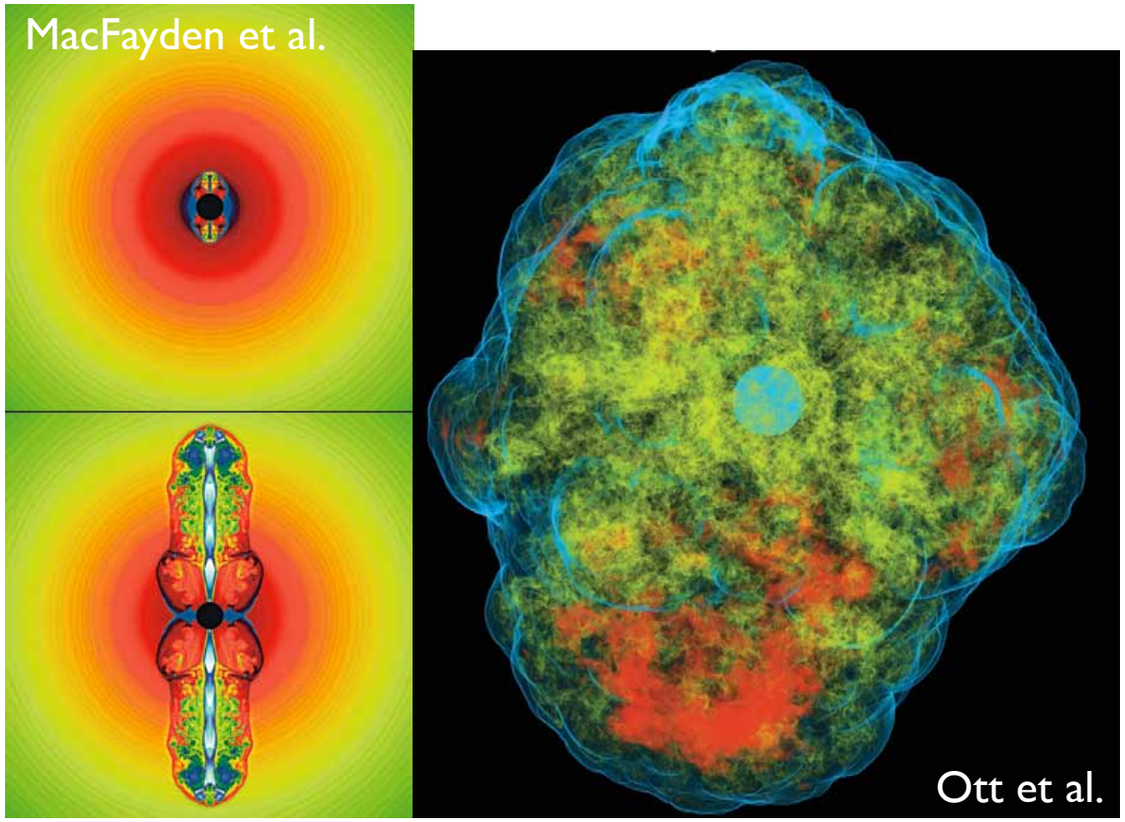


inspiralling NS - NS

inspiralling NS - BH

merging BH - BH

Excess powered burst

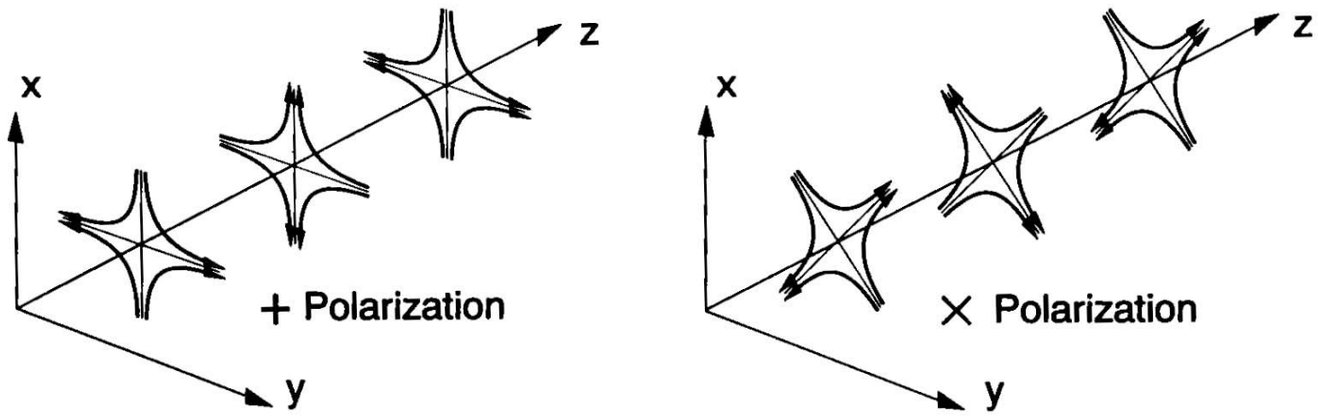


Supernova core-collapse

Unknown sources!

GW detection

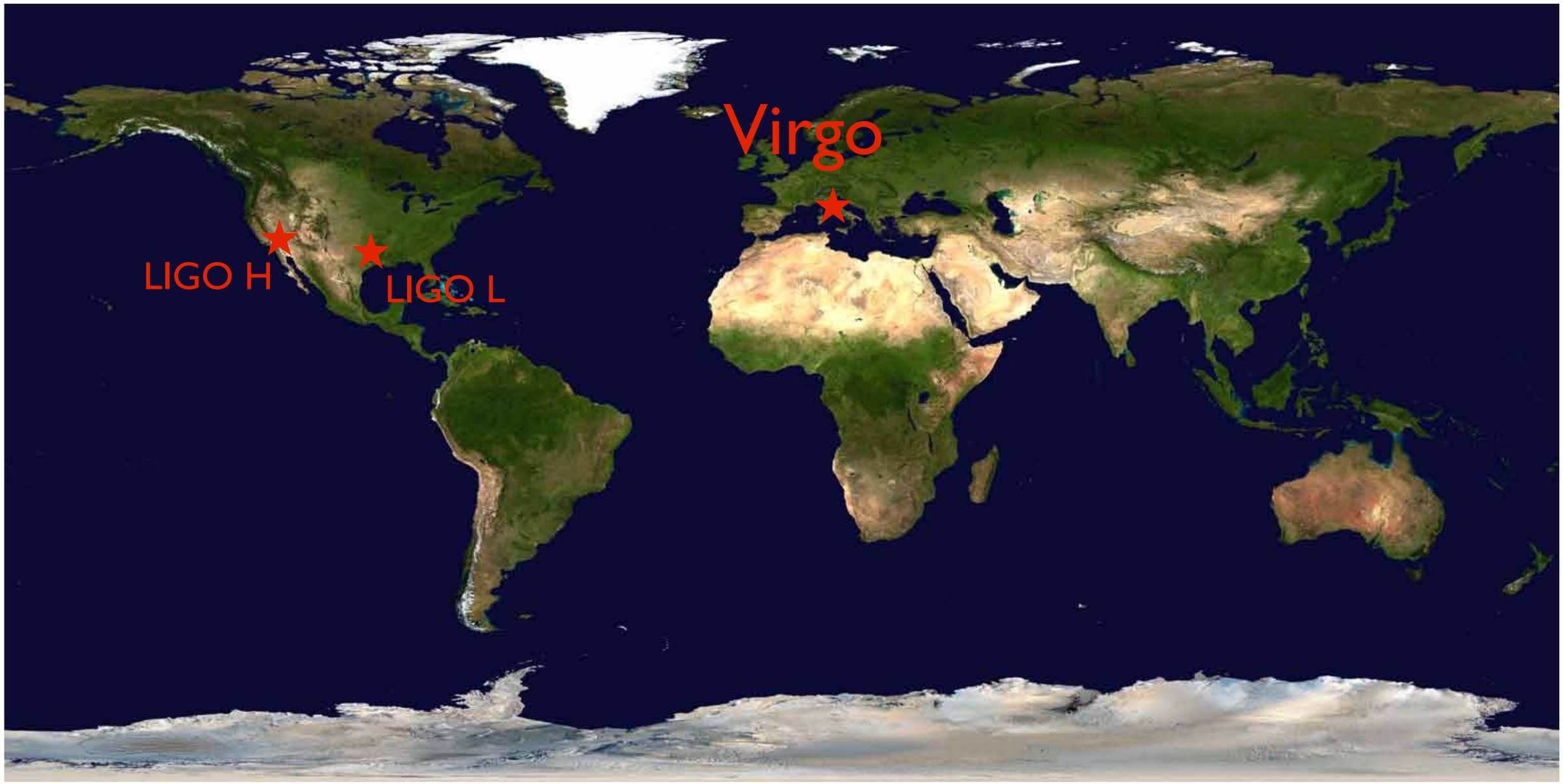
- Transverse, two polarization states:



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

[see Vinet et al. 1988 …]

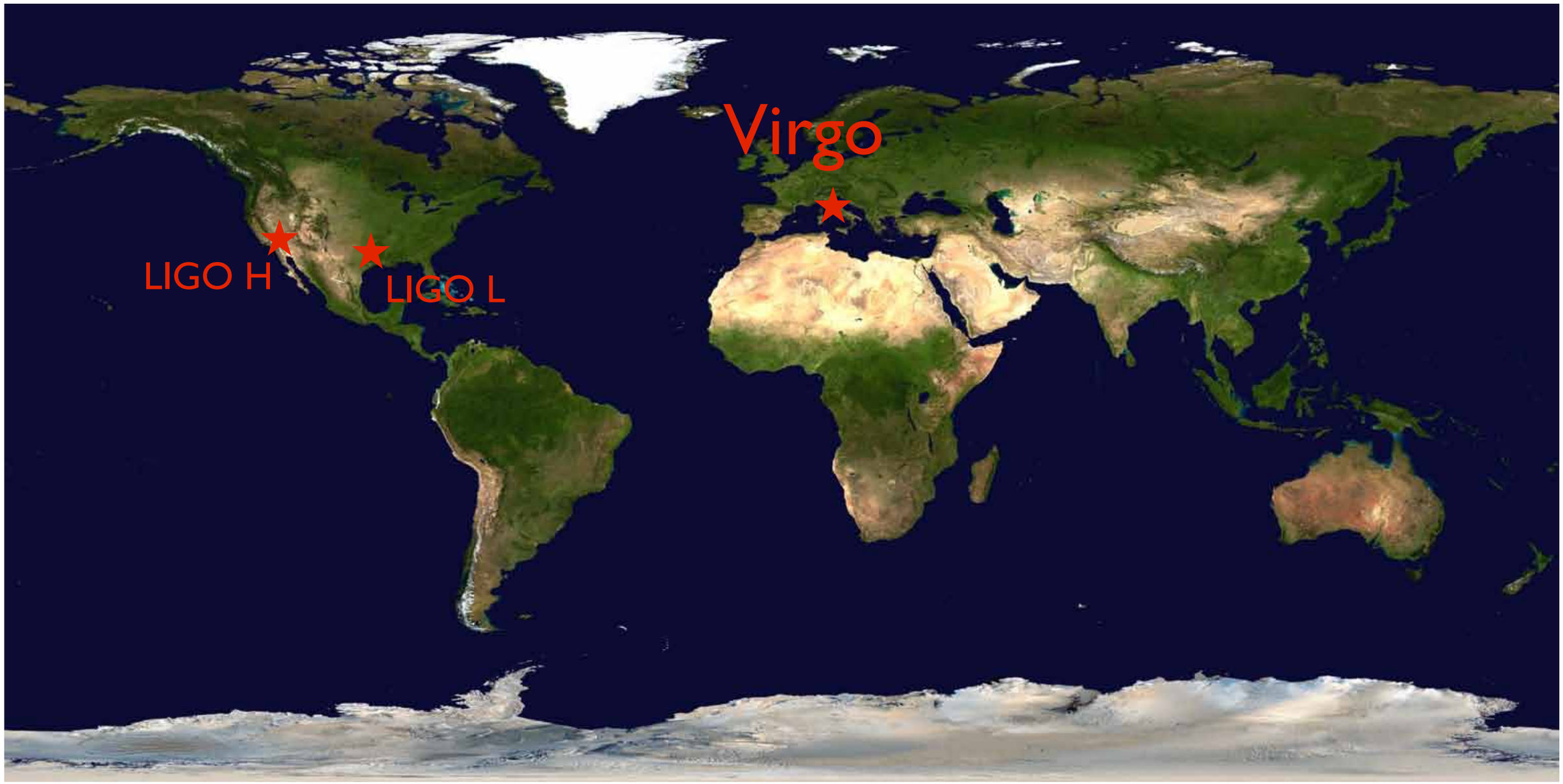
Network of GW interferometers: 2015-17



Factor of ten improvement in sensitivity.
average: 200 Mpc (NS-NS); 400 Mpc (NS-BH)

[see Nissanke et al. 2013 and Ligo and Virgo Scientific Collaborations et al. 2013]

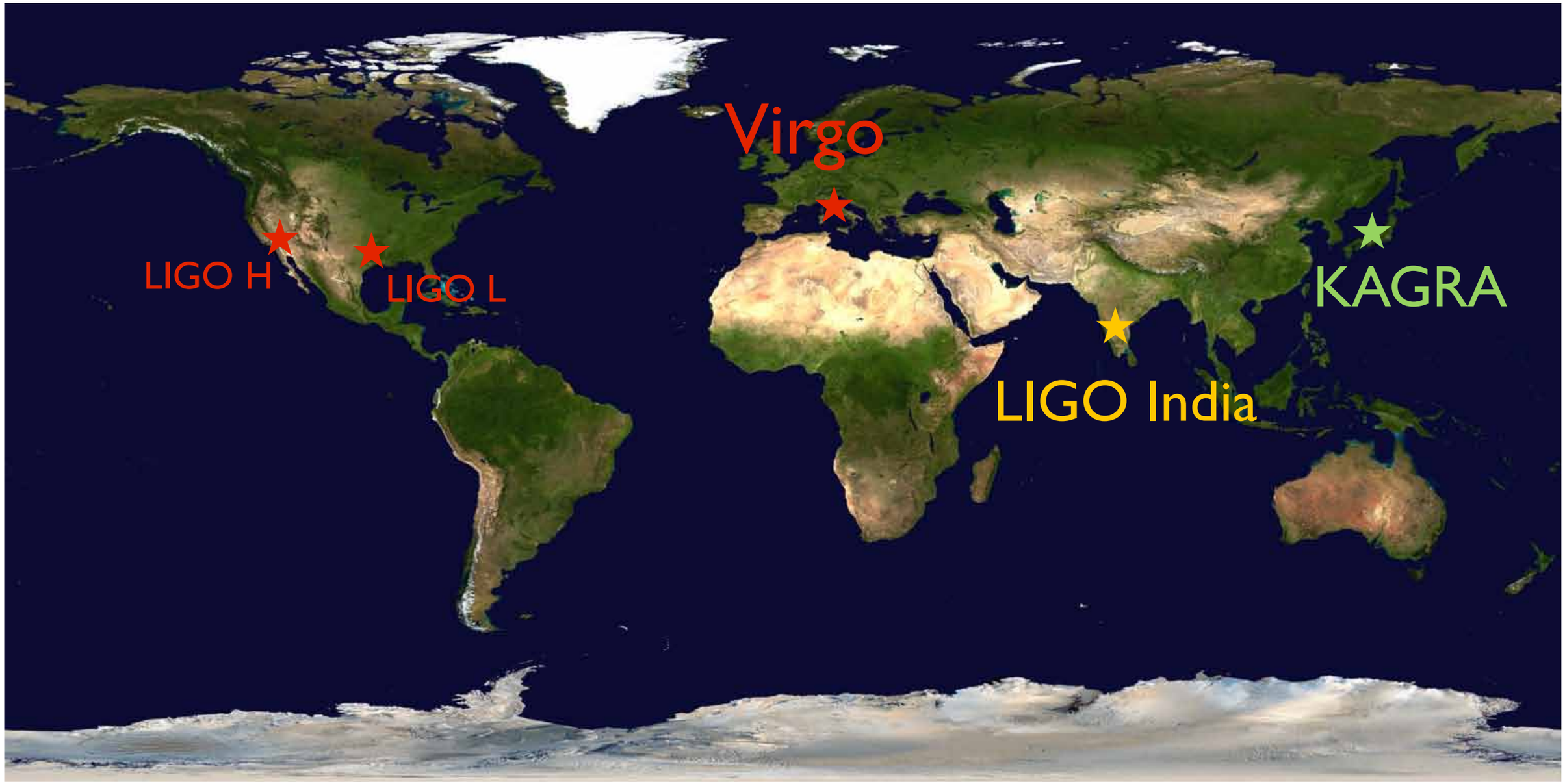
Network of GW interferometers: 2015-17



40 yr^{-1} (population synthesis); three orders of magnitude

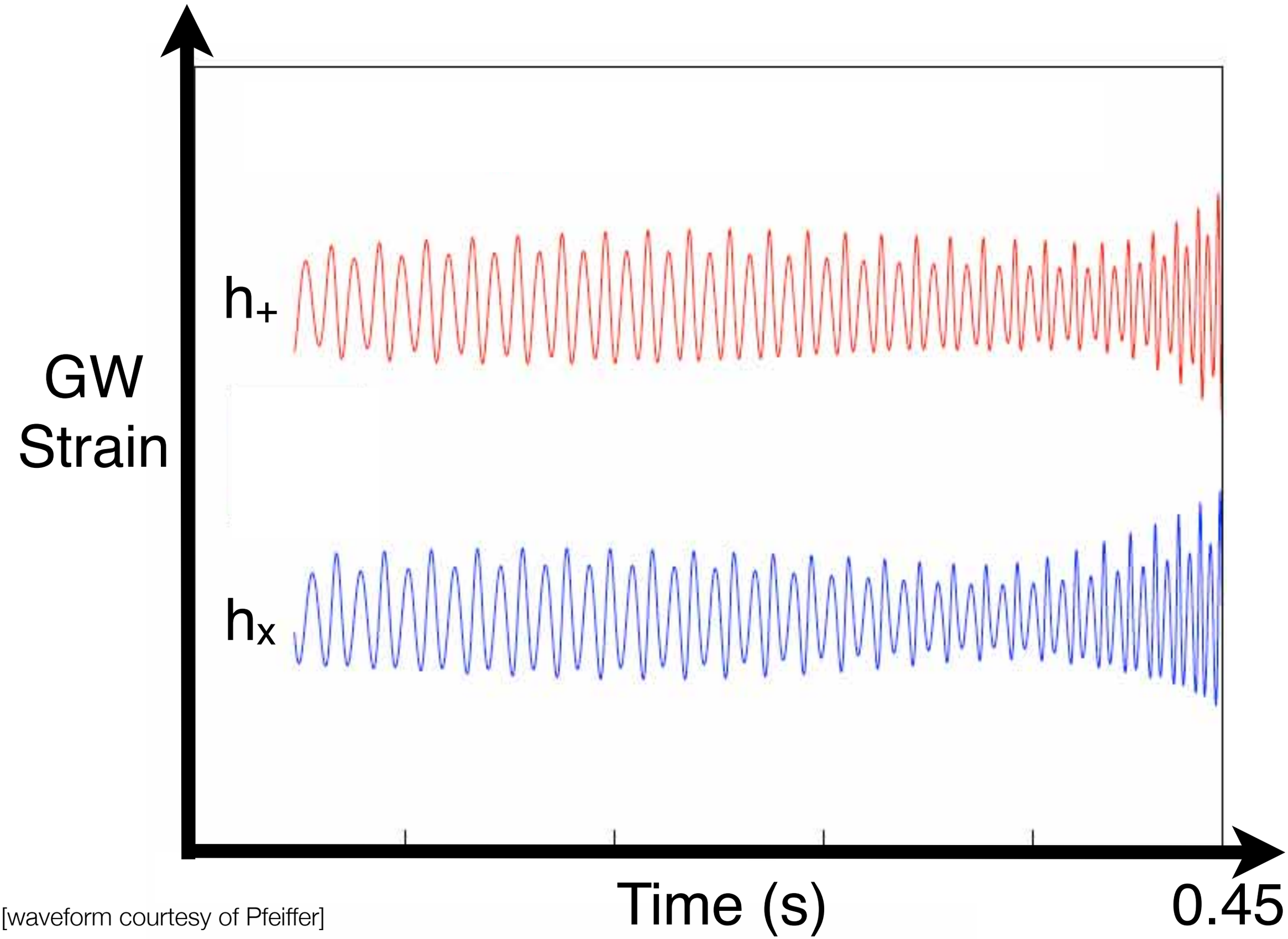
[see Aasi and Ligo and Virgo Scientific Collaborations et al. 2013, Regimbau et al. 2005]

Network of GW interferometers: 2020s



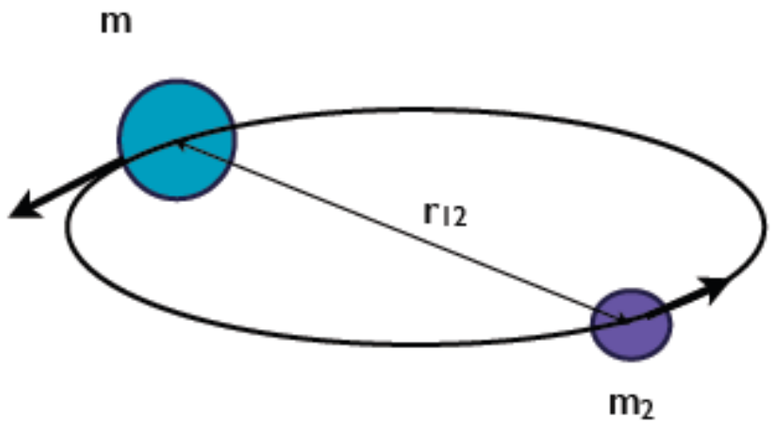
Part II: Information from EM+GW.

GW: Understand the signal - h(t) waveforms.

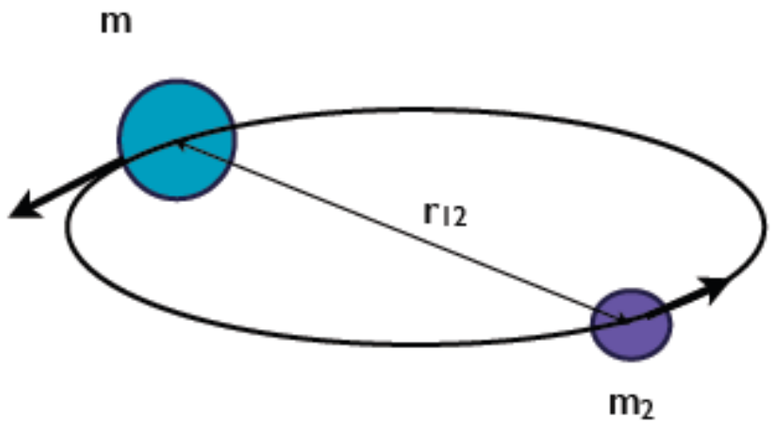


[waveform courtesy of Pfeiffer]

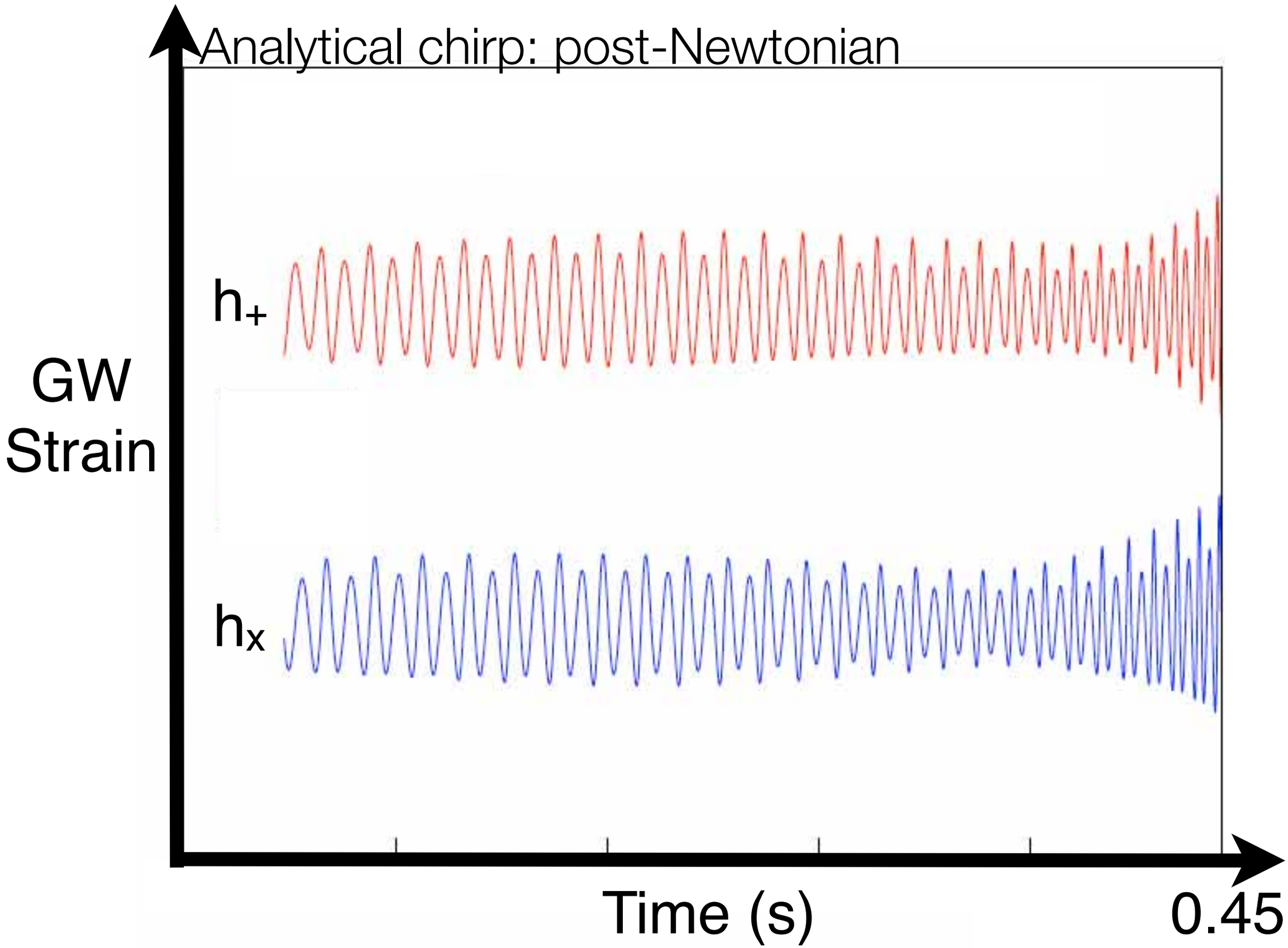
GW: Listen to the chirp.



GW: Listen to the chirp.



GW: Inspiral encodes source parameters.



GW: Wealth of information about the source.

GW

Stra

$$h_{+,\times} = \frac{2\,M\,\nu\,v^2}{D_L}\left[\hat{h}^{(0)}_{+,\times} + \left(\hat{h}^{(1/2)}_{+,\times} + \hat{h}^{(1/2,\mathrm{SO})}_{+,\times}\right) v + \left(\hat{h}^{(1)}_{+,\times} + \hat{h}^{(1,\mathrm{SO})}_{+,\times}\right) v^2 + \left(\hat{h}^{(3/2)}_{+,\times} + \hat{h}^{(3/2,\mathrm{SO})}_{+,\times}\right) v^3\right]$$

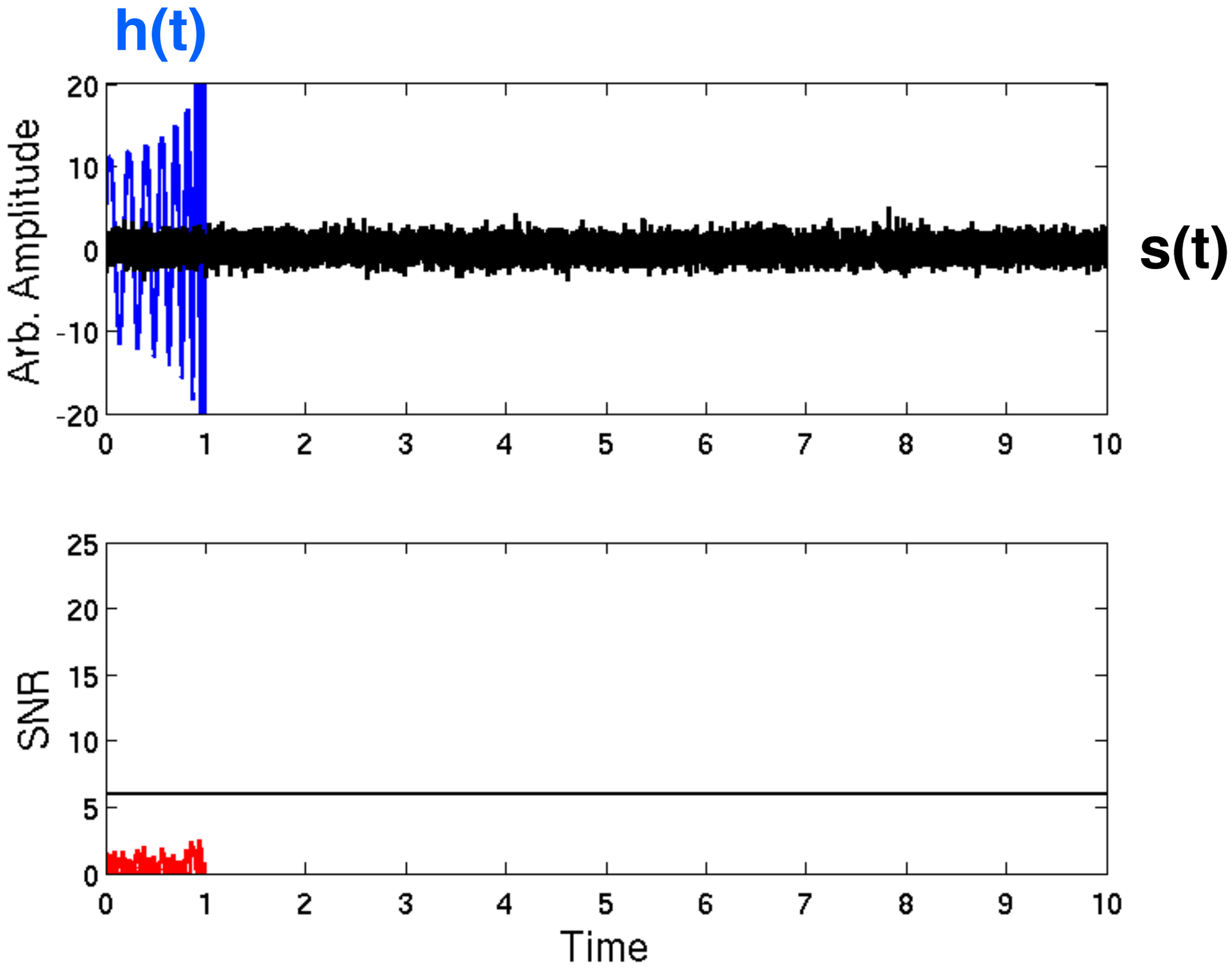
$$\begin{aligned}
\hat{h}^{(1/2)}_{+} = \delta\Bigg[& c_{\frac{\iota}{2}}^{6}\cos(3\alpha+3\Psi)\Big(-\frac{45s_\theta}{32}-\frac{9s_{3\theta}}{32}\Big) + c_{\frac{\iota}{2}}^{2}\cos(\alpha+\Psi)\Big(-\frac{175s_\theta}{256}+c_\iota\Big(\frac{87s_\theta}{64}-\frac{5s_{3\theta}}{64}\Big) \\
& + c_{2\iota}\Big(-\frac{5s_\theta}{256}+\frac{15s_{3\theta}}{256}\Big)+\frac{13s_{3\theta}}{256}\Big) + \cos(\alpha-\Psi)\Big(\frac{175s_\theta}{256}+c_\iota\Big(\frac{87s_\theta}{64}-\frac{5s_{3\theta}}{64}\Big) \\
& + c_{2\iota}\Big(\frac{5s_\theta}{256}-\frac{15s_{3\theta}}{256}\Big)-\frac{13s_{3\theta}}{256}\Big)s_{\frac{\iota}{2}}^{2} + c_{\frac{\iota}{2}}^{4}\cos(3\alpha+\Psi)\Big(-\frac{5s_\theta}{32}-\frac{s_{3\theta}}{32}\Big)s_{\frac{\iota}{2}}^{2} \\
& + c_{\frac{\iota}{2}}^{4}\cos(\alpha+3\Psi)\Big(-\frac{45s_\theta}{32}+\frac{135s_{3\theta}}{32}\Big)s_{\frac{\iota}{2}}^{2} + c_{\frac{\iota}{2}}^{2}\cos(\alpha-3\Psi)\Big(\frac{45s_\theta}{32}-\frac{135s_{3\theta}}{32}\Big)s_{\frac{\iota}{2}}^{4} \\
& + c_{\frac{\iota}{2}}^{2}\cos(3\alpha-\Psi)\Big(\frac{5s_\theta}{32}+\frac{s_{3\theta}}{32}\Big)s_{\frac{\iota}{2}}^{4} + \Big(\frac{27}{16}+\frac{9c_{2\theta}}{16}\Big)\cos(3\alpha-3\Psi)s_\theta s_{\frac{\iota}{2}}^{6} + \frac{45}{16}c_\theta\cos(3\Psi)s_\theta^2 s_\iota^3 \\
& + \cos(2\alpha+\Psi)\Big(\Big(-\frac{85c_\theta}{256}-\frac{1}{128}c_\theta c_{2\theta}-\frac{1}{32}c_\theta c_{2\theta}c_\iota-\frac{3}{128}c_\theta c_{2\theta}c_{2\iota}\Big)s_\iota-\frac{11}{64}c_\theta s_{2\iota}-\frac{1}{256}c_\theta s_{3\iota}\Big) \\
& + \cos(2\alpha+3\Psi)\Big(\Big(\frac{45c_\theta}{256}+\frac{81}{128}c_\theta c_{2\theta}+\frac{27}{32}c_\theta c_{2\theta}c_\iota+\frac{27}{128}c_\theta c_{2\theta}c_{2\iota}\Big)s_\iota+\frac{9}{64}c_\theta s_{2\iota}+\frac{9}{256}c_\theta s_{3\iota}\Big) \\
& + \cos(2\alpha-\Psi)\Big(\Big(-\frac{85c_\theta}{256}+\frac{1}{256}c_\theta c_{2\theta}\Big)s_\iota+\Big(\frac{11c_\theta}{64}+\frac{1}{64}c_\theta c_{2\theta}\Big)s_{2\iota}+\Big(-\frac{c_\theta}{256}-\frac{3}{256}c_\theta c_{2\theta}\Big)s_{3\iota}\Big) \\
& + \cos(2\alpha-3\Psi)\Big(\Big(\frac{45c_\theta}{256}+\frac{135}{256}c_\theta c_{2\theta}\Big)s_\iota+\Big(-\frac{9c_\theta}{64}-\frac{27}{64}c_\theta c_{2\theta}\Big)s_{2\iota}+\Big(\frac{9c_\theta}{256}+\frac{27}{256}c_\theta c_{2\theta}\Big)s_{3\iota}\Big) \\
& + \cos(\Psi)\Big(\frac{1}{64}c_\theta s_\theta^2 s_\iota+\frac{5}{64}c_\theta s_\theta^2 s_{3\iota}\Big)\Bigg],
\end{aligned}$$

[Arun et el. (2009)]

Time (s)

0.45

GW: Filter detector output with theoretical templates.



[animation courtesy of Chad Hanna]

GW: source characterization

Nissanke et al. (2010,11)

from the GW waveform

+ Masses ~ % - several %

+ Spins ~ several to tens %

+ Geometric properties:

- Inclination angle
- Source Position
- Luminosity distance

~ tens of %

[see Cutler and Flanagan (1994), Poisson and Will (1996)…]

GW + EM: Strong-field gravity astro. labs.

Nissanke et al. (2010,11)

from the GW waveform

+ Masses ~ % -several %

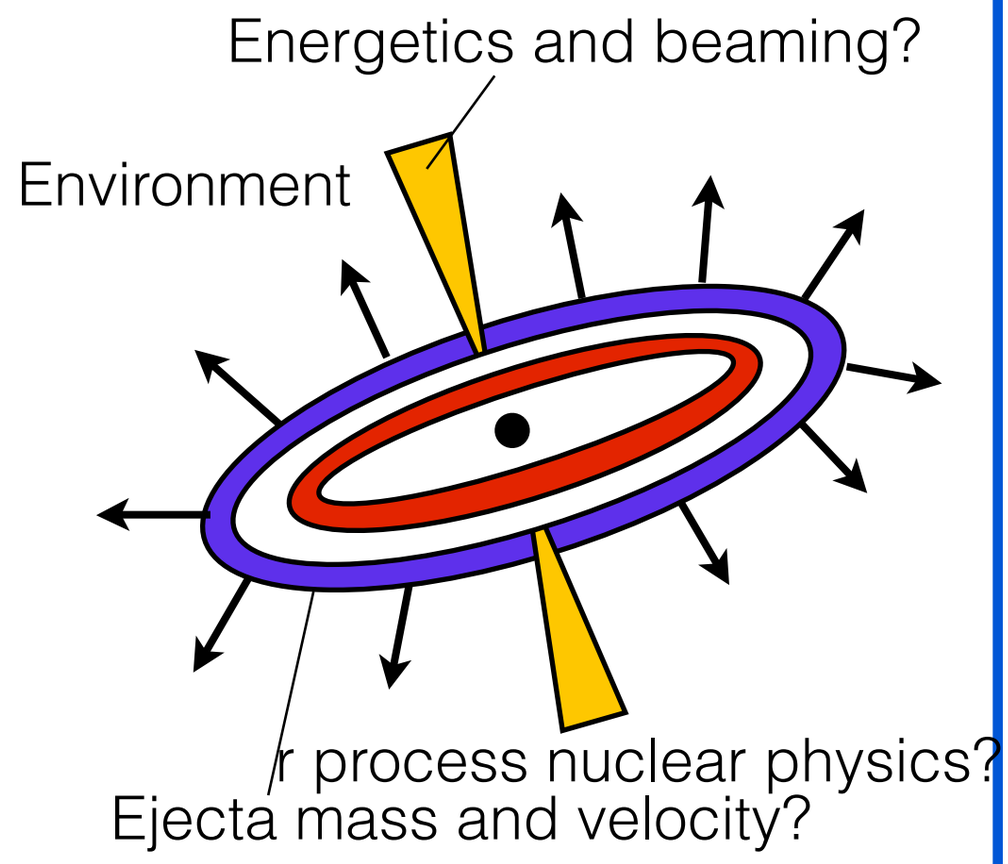
+ Spins ~ several to tens %

+ Geometric properties:

  - Inclination angle
  - Source Position
  - Luminosity distance

~ tens of %

from EM signature



GW + EM: Strong-field gravity astro. labs.

from the GW waveform

+ Masses ~ % -several %

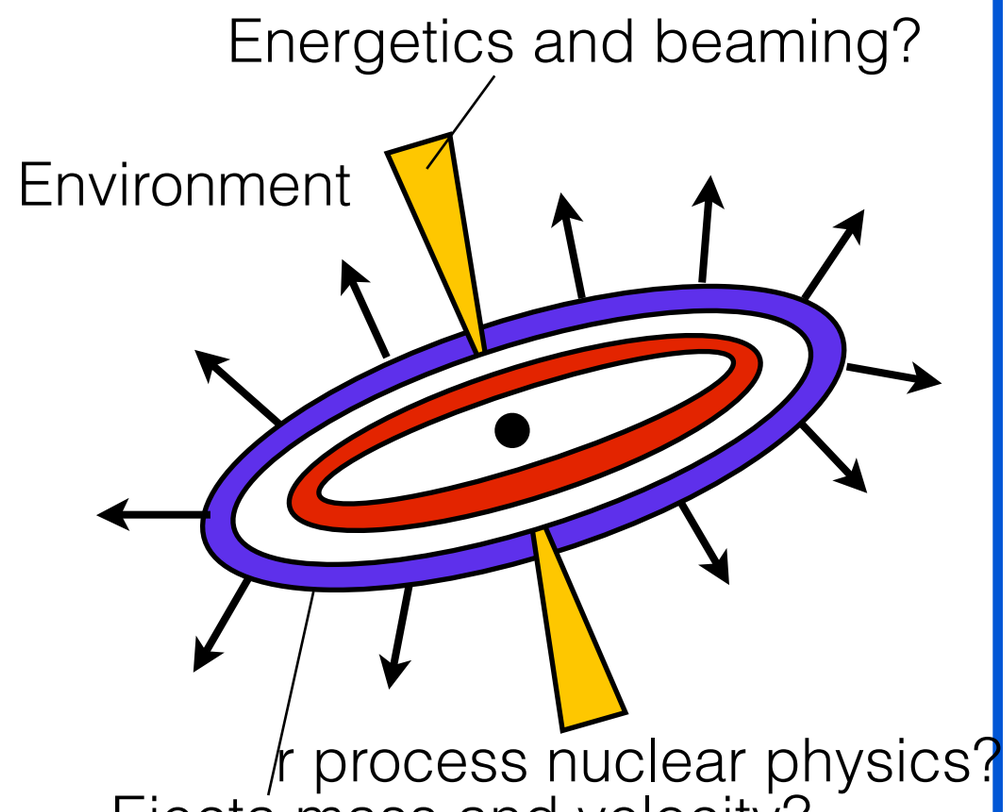
+ Spins ~ several to tens %

+ Geometric properties:

  - Inclination angle
  - Source Position
  - Luminosity distance

~ tens of %

from EM signature



NEXT: COMBINATION and Characterization.

GW + EM: Strong-field gravity astro. labs.

Nissanke et al. (2010,11)

from the GW waveform

+ Masses ~ % -several %

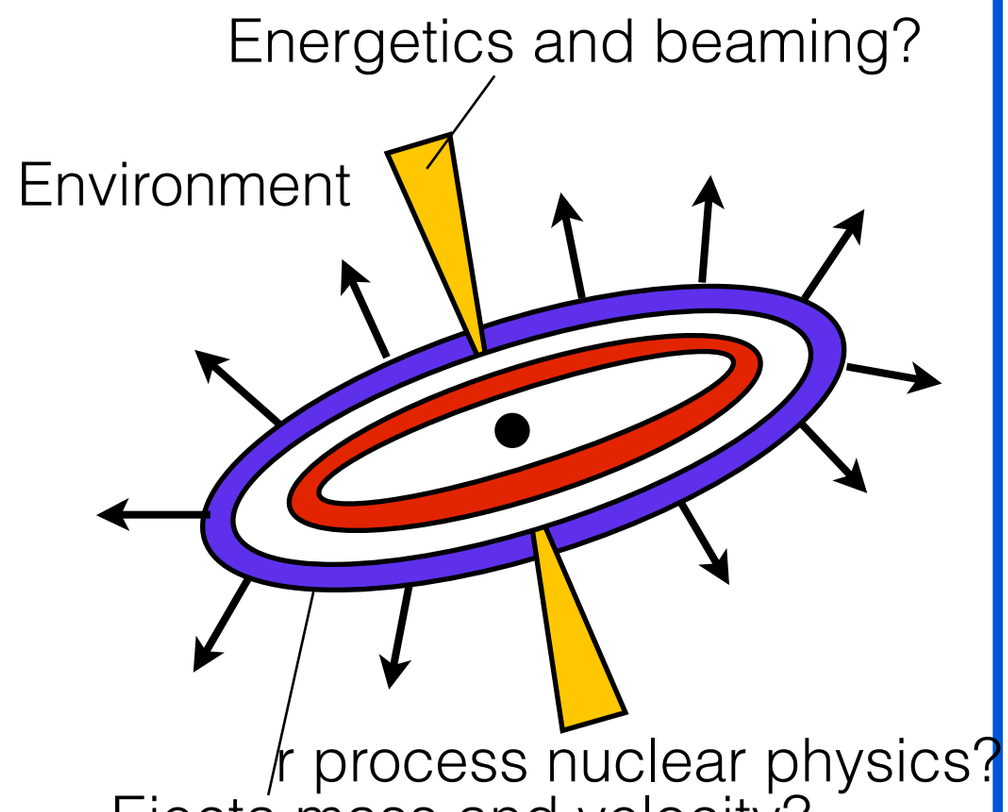
+ Spins ~ several to tens %

+ Geometric properties:

  - Inclination angle
  - Source Position
  - Luminosity distance

~ tens of %

from EM signature



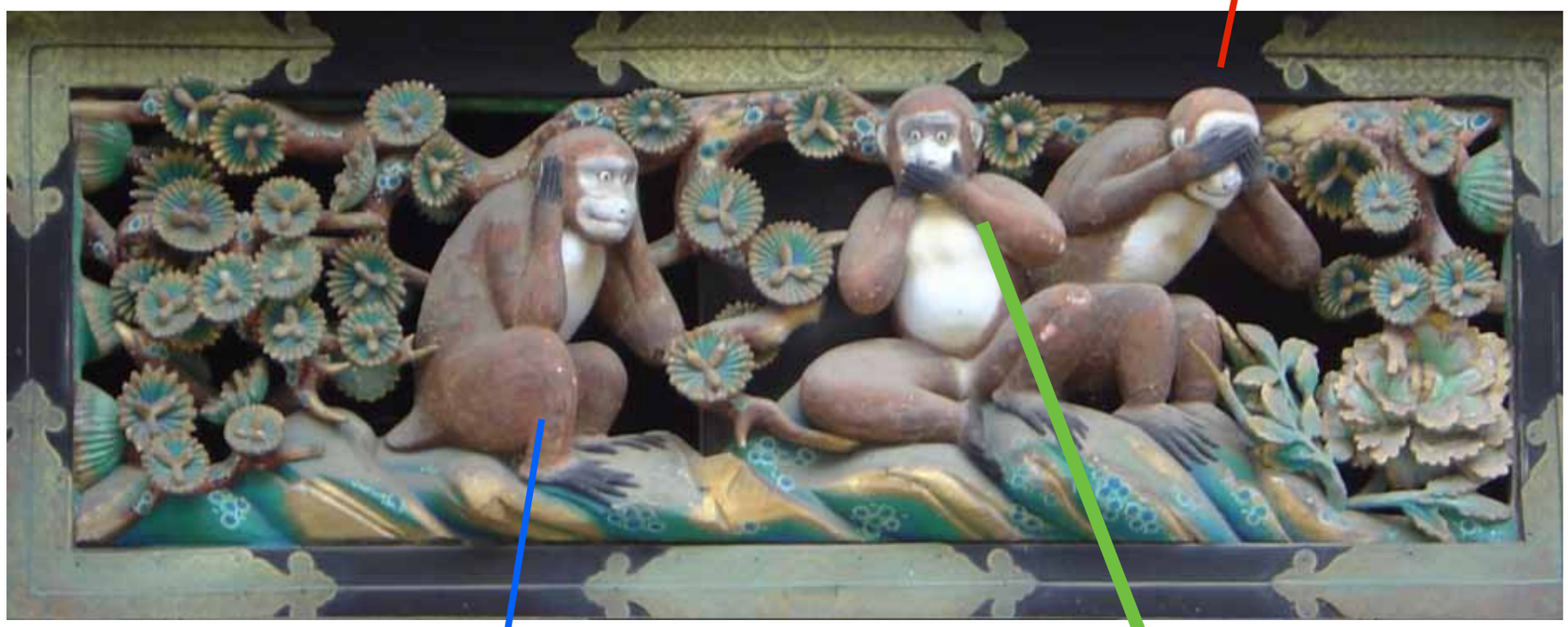
Golden binary: Characterization.

Population: Demographics, ecology and census.

[see e.g. Kowalska, Regimbau et al. 2012]

Part III: How can we obtain EM+GW?

GW observer



EM observer

EM + GW

EM+GW: how to follow the chirp?
First end-to-end simulation.

Nissanke, Kasliwal and Georgieva, ApJ 767, 124, 2013.
Kasliwal and Nissanke, 2013, arXiv: 1309.1535.

1: Catalog of NS binary mergers.

2: GW detectability & characterization (GW Malmquist bias).

3: EM detectability of GW mergers **(Wide field & depth)**.

4: Estimates of false-positives **(Spectroscopic)**.

5: GW volumes + Galaxy catalogs.

GWs: How many? 1-10s yr^{-1}.

GWs: How far? few hundred Mpc.

How well can we localize the GW events?

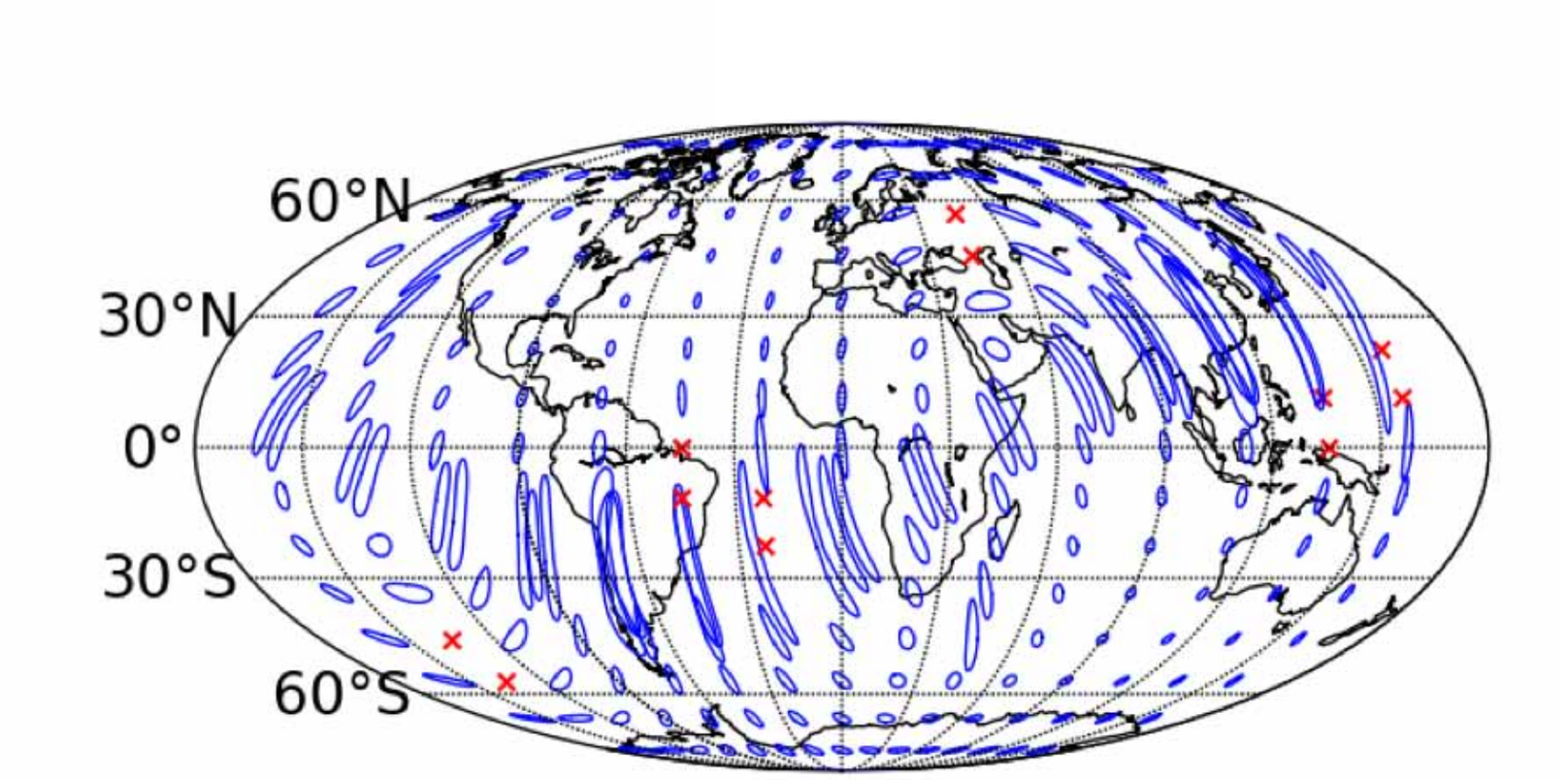
?

How well? GW interferometers: all-sky antenna.

$$\theta \sim \frac{\lambda}{D} \sim \frac{c}{fD} \sim 10 \text{ deg}$$

GW Sky Localization.

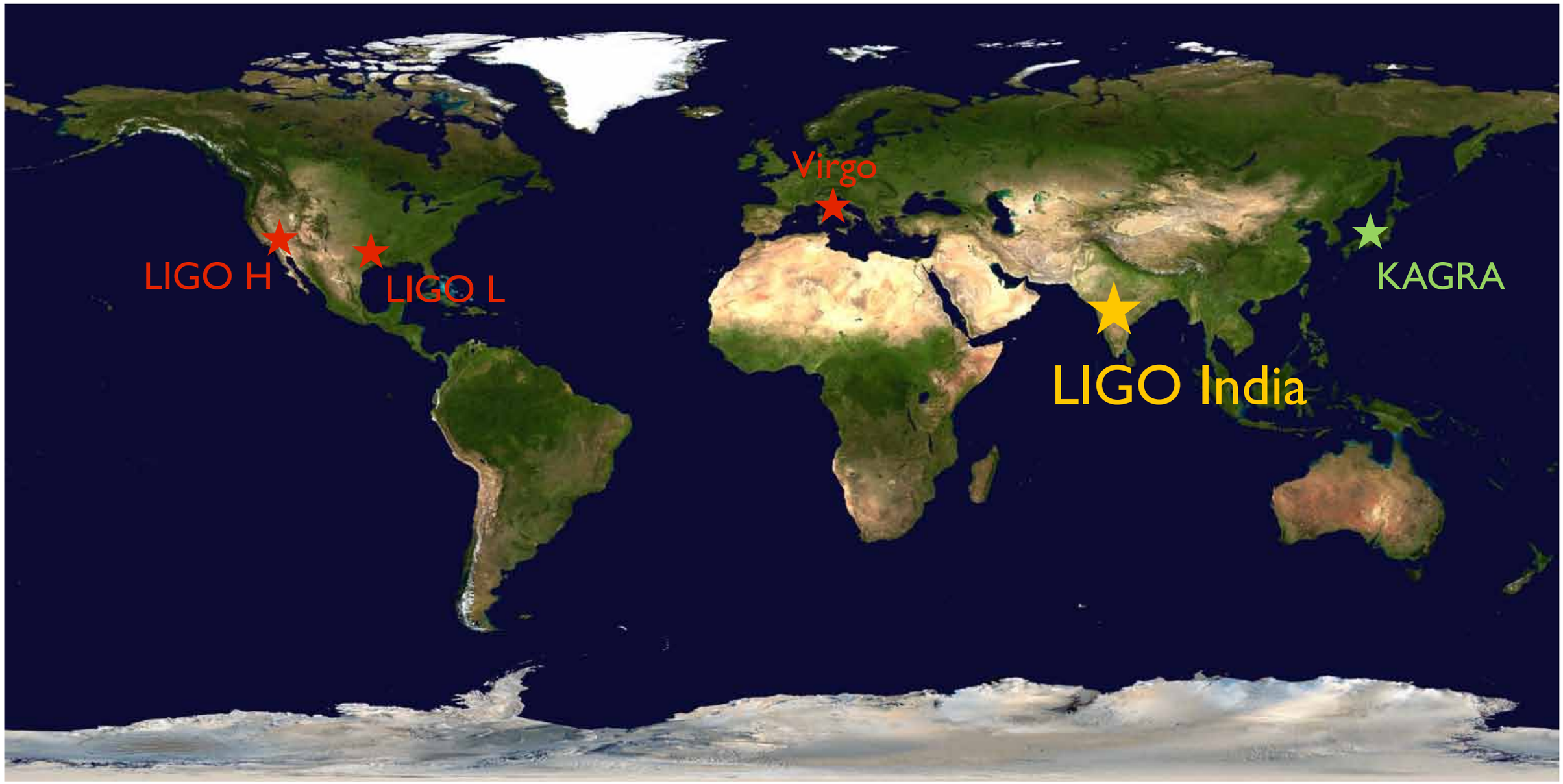
- 3+ detectors: Triangulation with arrival times



LIGO & Virgo

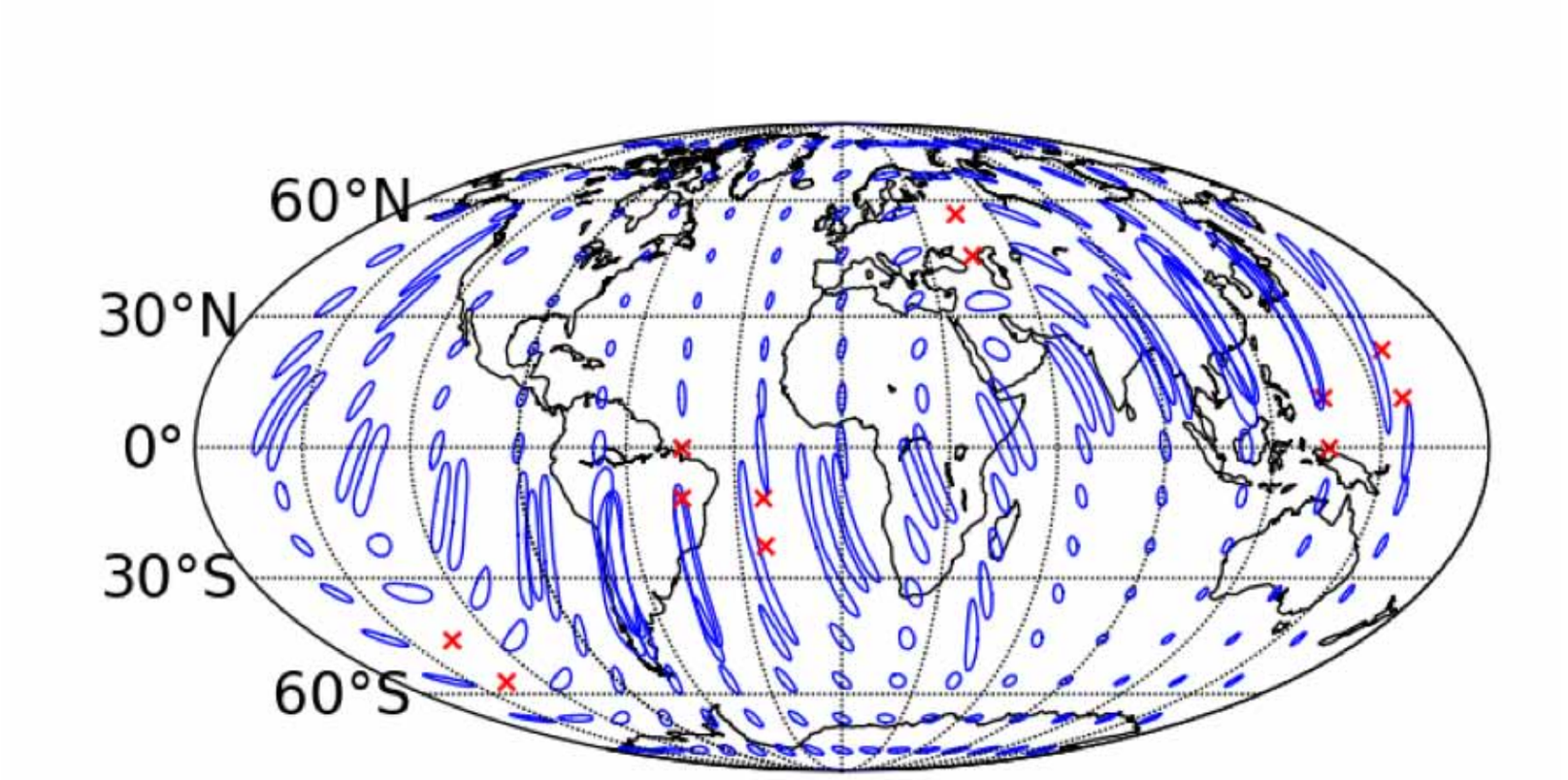
[LSC and Virgo collaboration—arXiv:1304.0670; see also Wen and Chen 2012]

The strength of an out-of-plane detector.



GW Sky Localization.

- 3+ detectors: Triangulation with arrival times

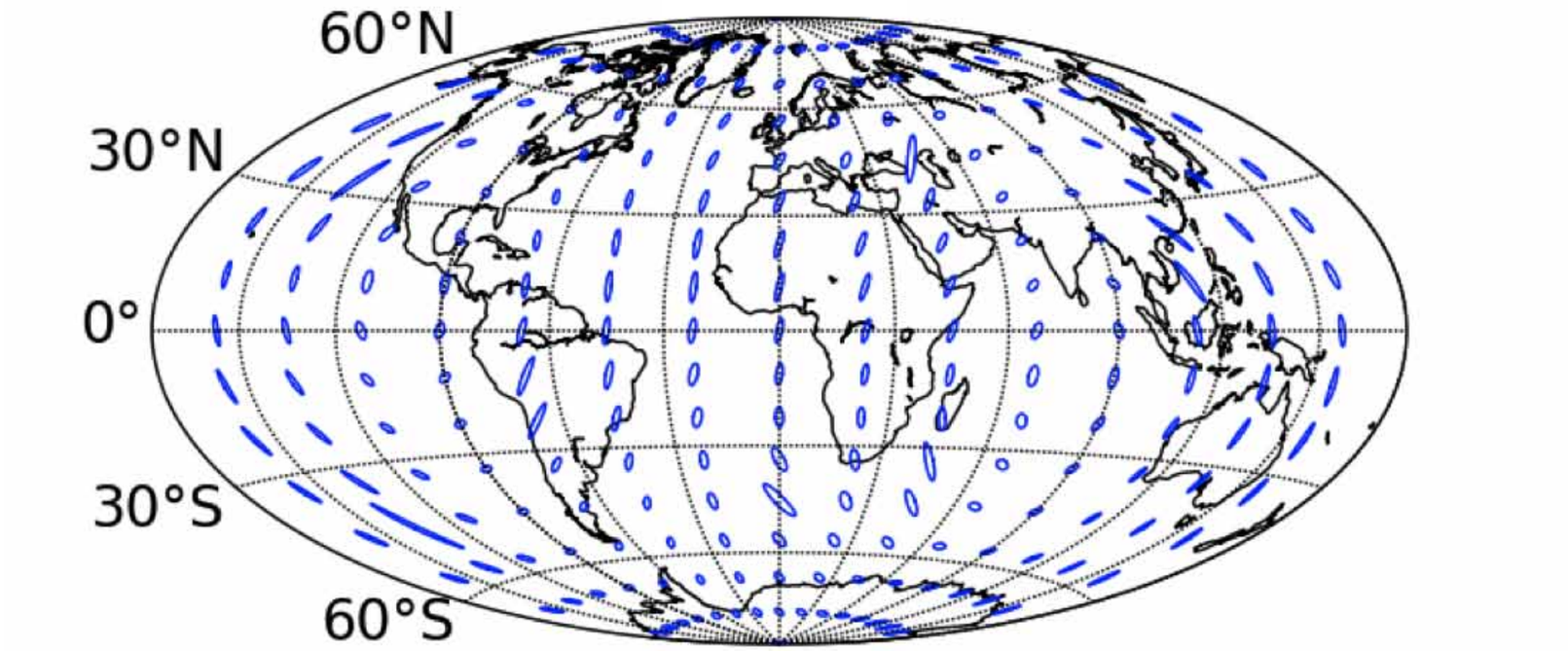


LIGO & Virgo

[LSC and Virgo collaboration--arXiv:1304.0670]

GW Sky Localization.

- 3 + out-of-plane interferometer: factor of 3 improvement in sky error.

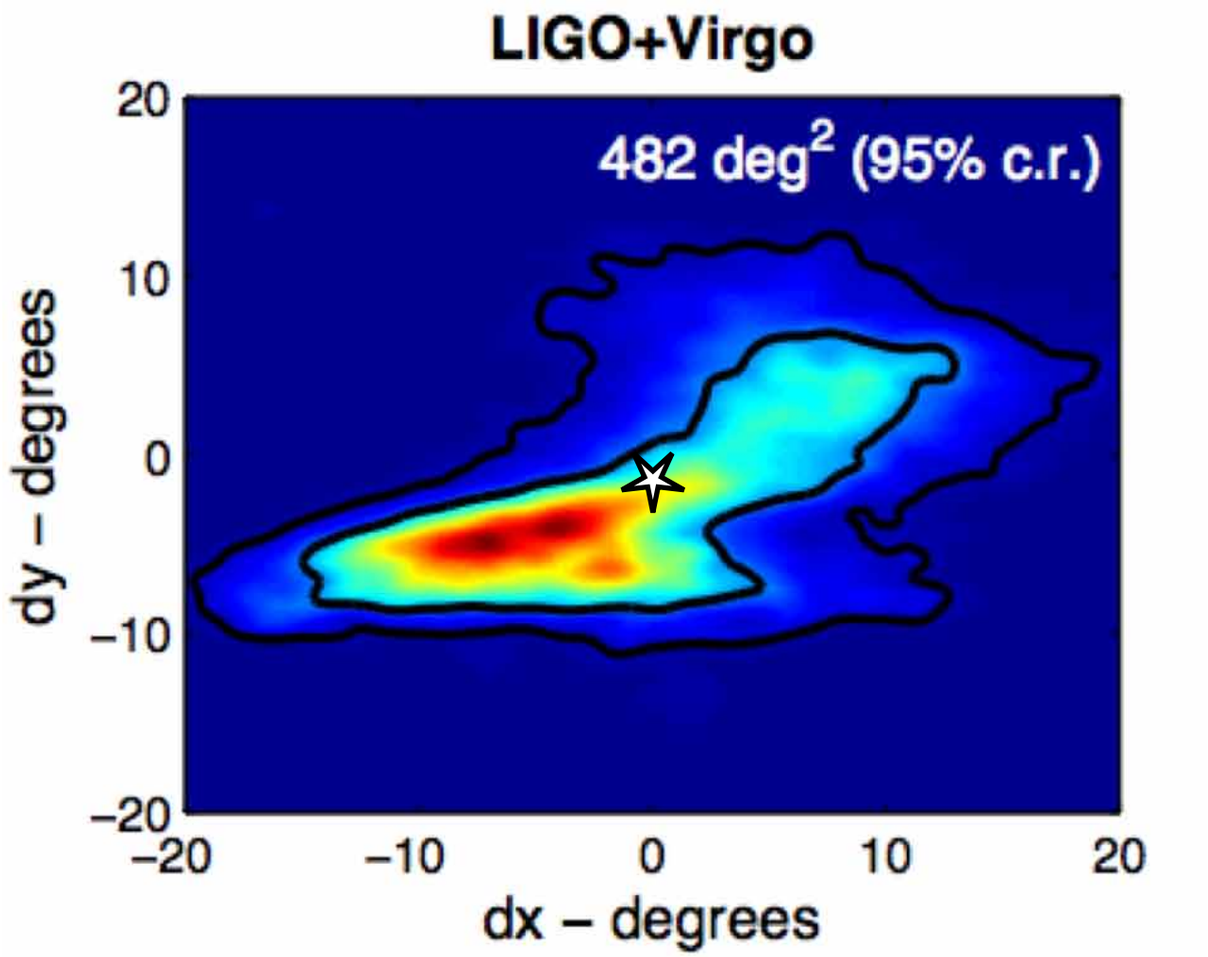


3 detectors + LIGO India.

[LSC and Virgo collaboration--arXiv:1304.0670]

Non-contiguous search islands.

Nissanke, Kasliwal, Georgieva (2013)

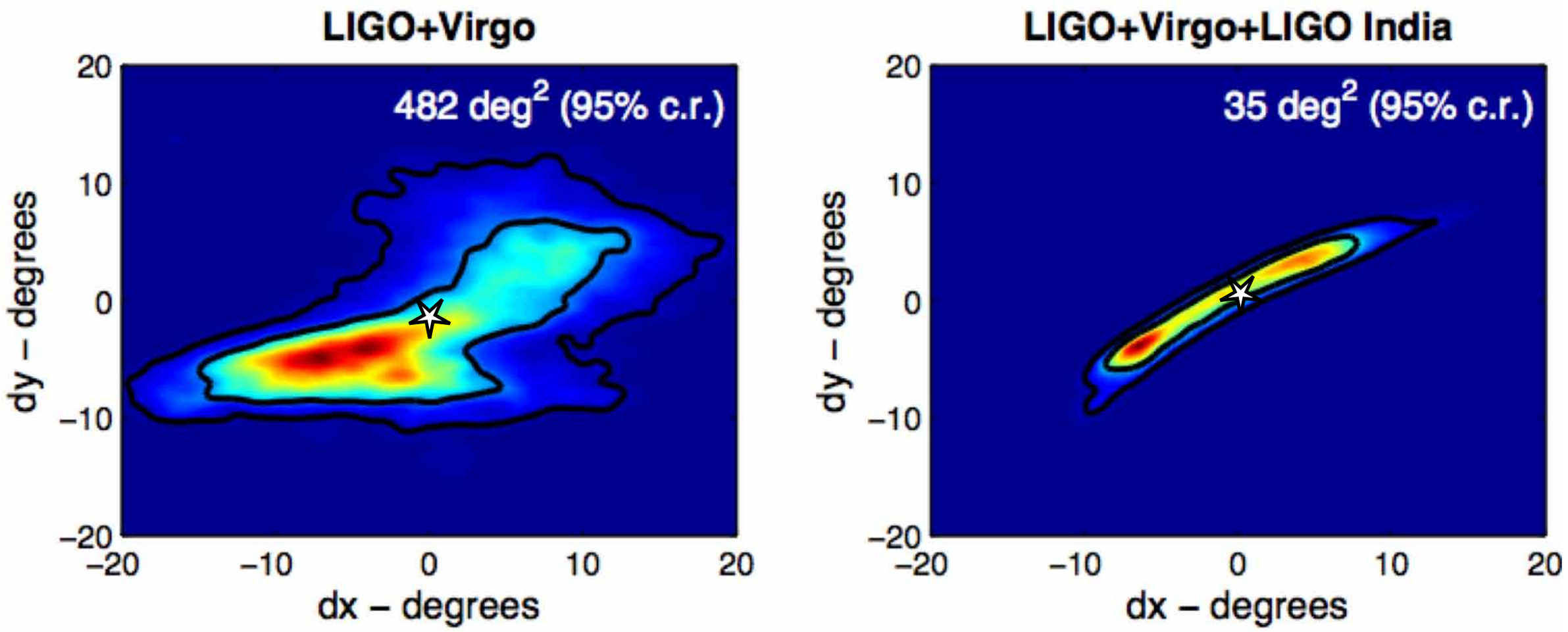


Very low threshold sources: Bayesian MCMC.

[Nissanke et al. (2011), see also Veitch et al. (2012), Aasi et al. (2013), Rodriguez et al. (2013)]

Non-contiguous search islands.

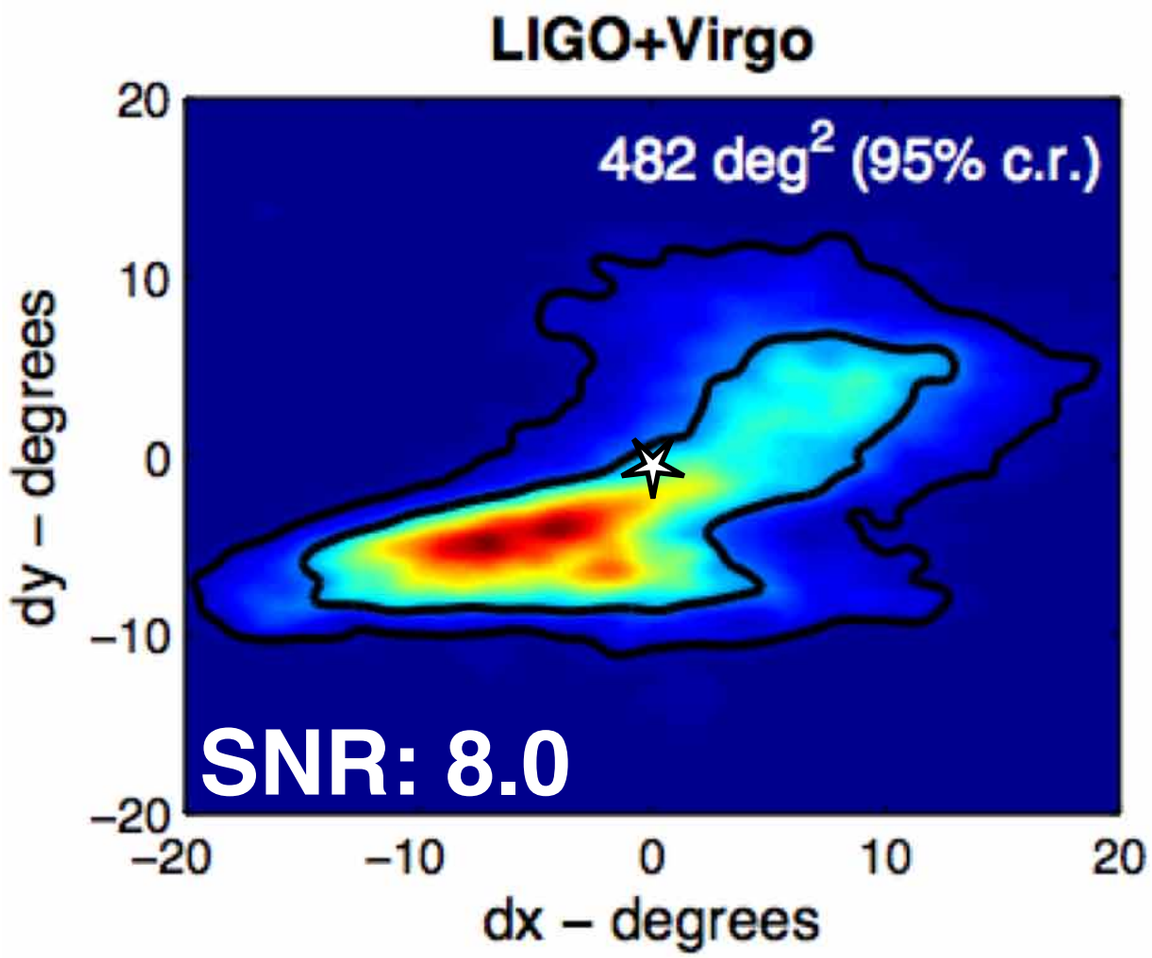
Nissanke, Kasliwal, Georgieva (2013)

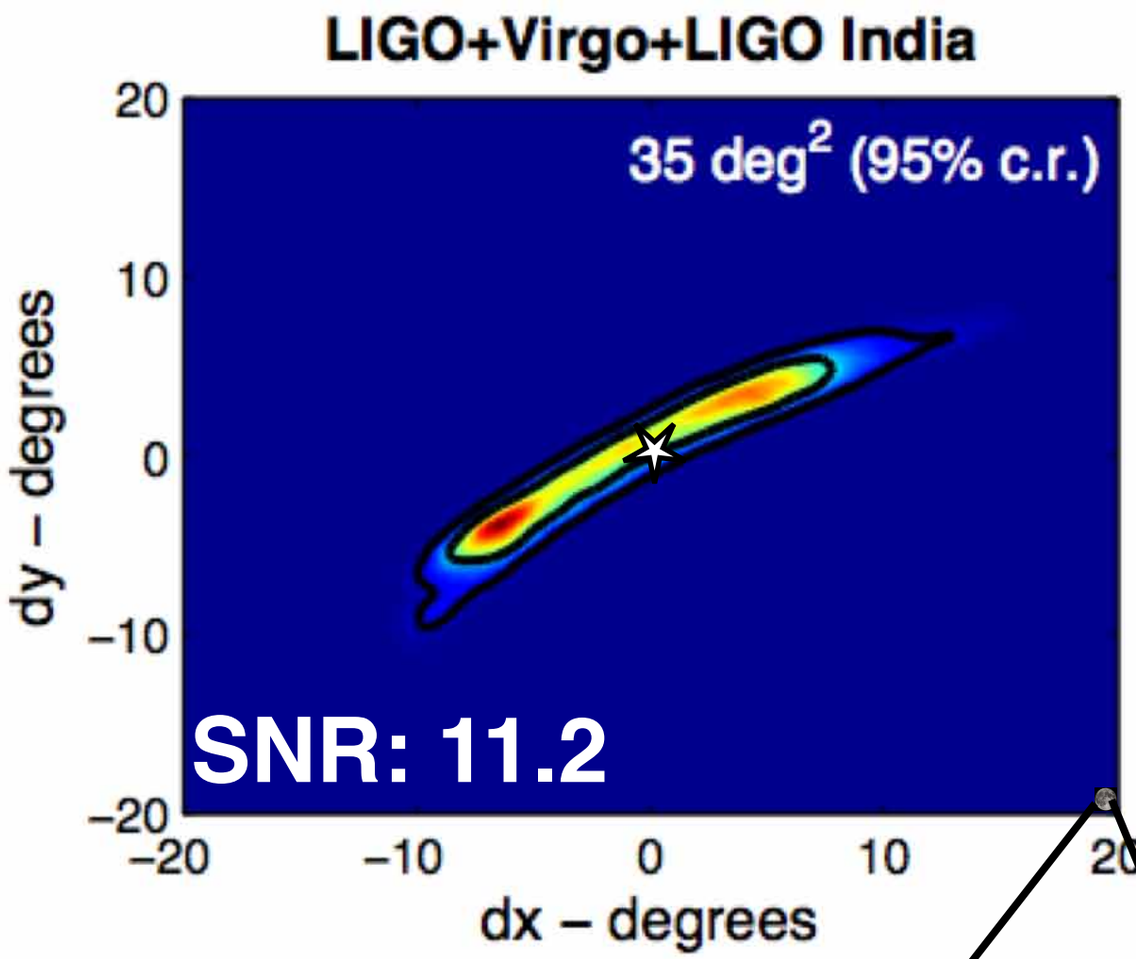


Very low threshold sources: Bayesian MCMC.

Non-contiguous search islands.

Nissanke, Kasliwal, Georgieva (2013)

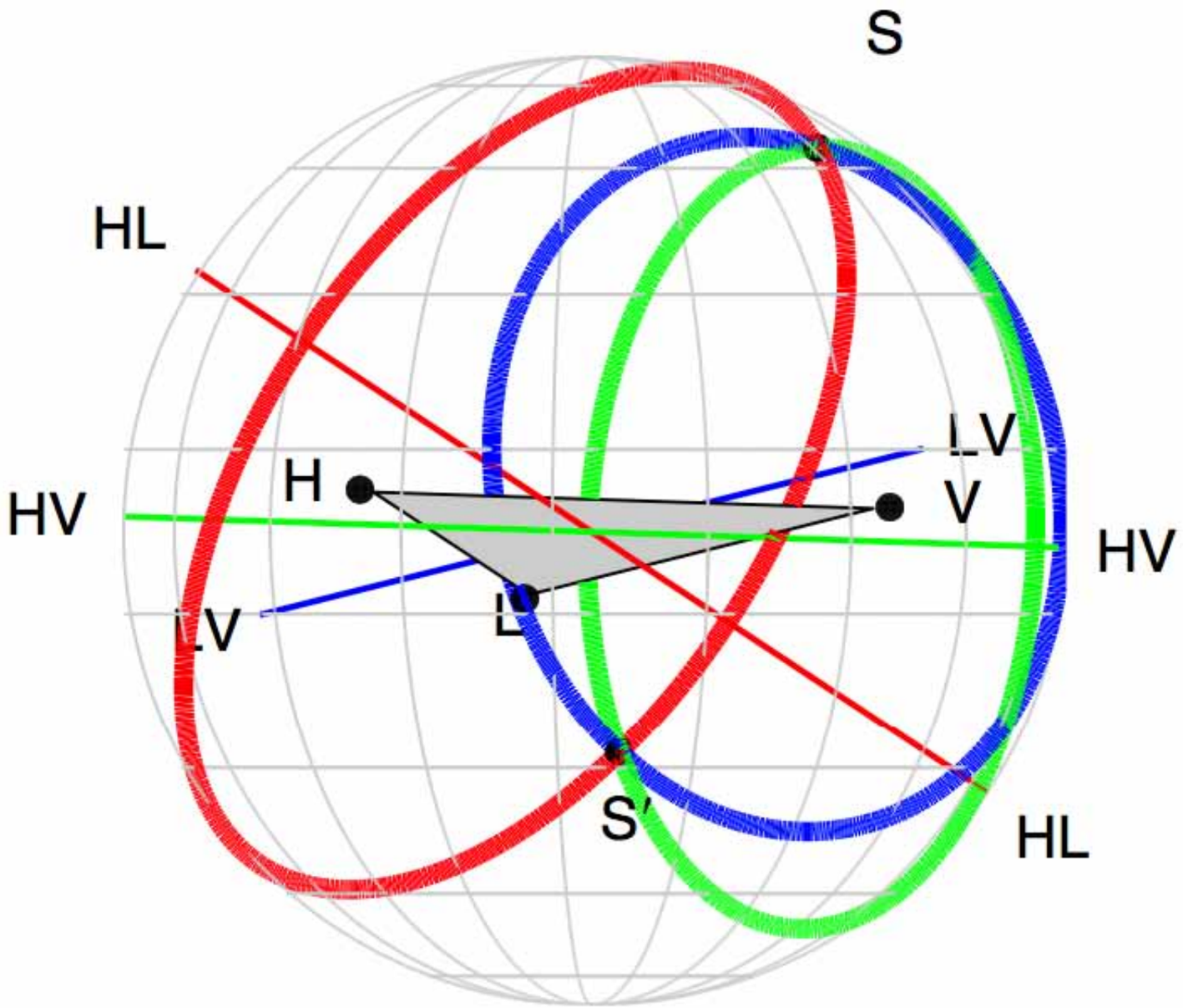




Very low threshold sources: Bayesian MCMC.

Timing rings in early years (2015+) ?

1000s sq. deg. ?

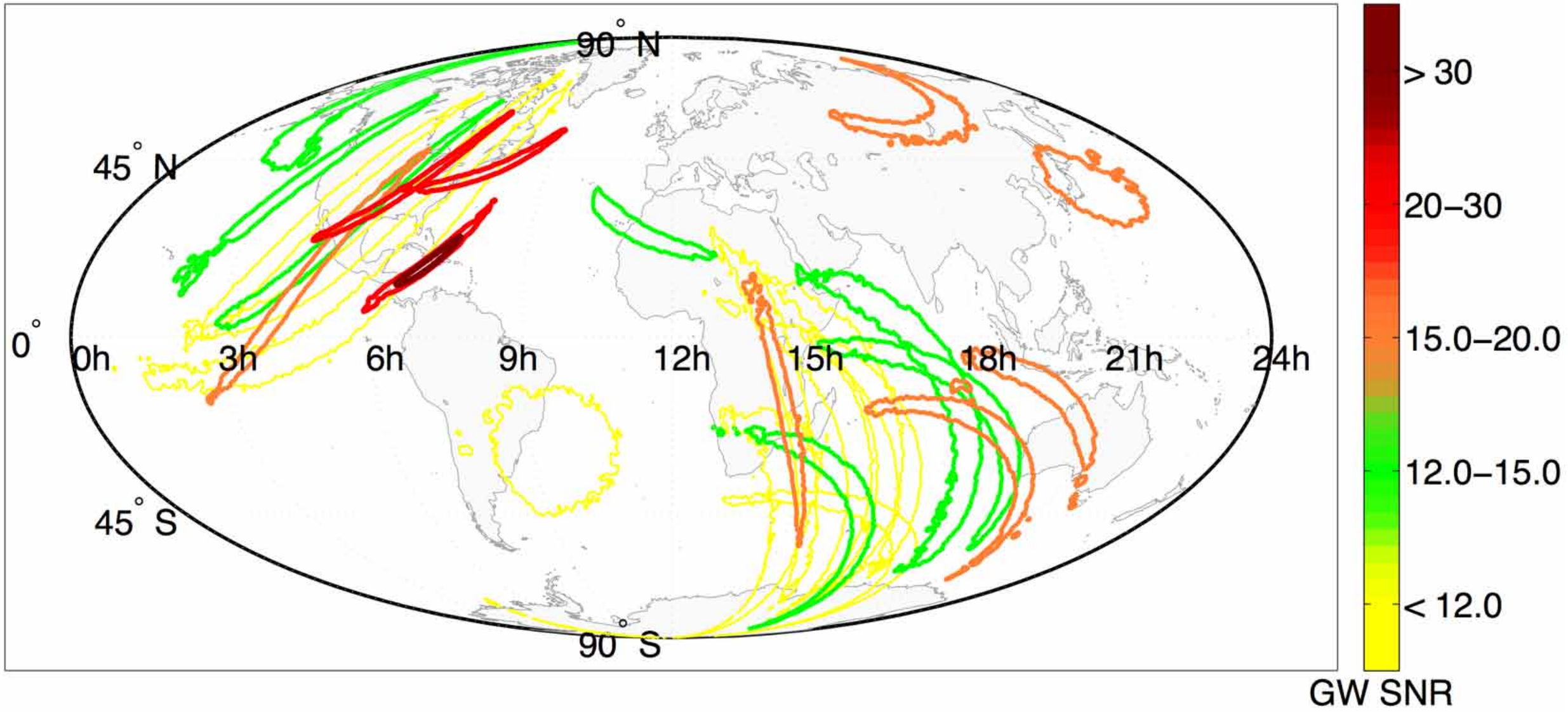


Aasi et al. 2013

Rainbow arcs in early years (2015+)

Kasliwal and Nissanke 2013

2 US-based LIGO.



100s sq. deg.

GWs: How many? 1-10s yr^{-1}.

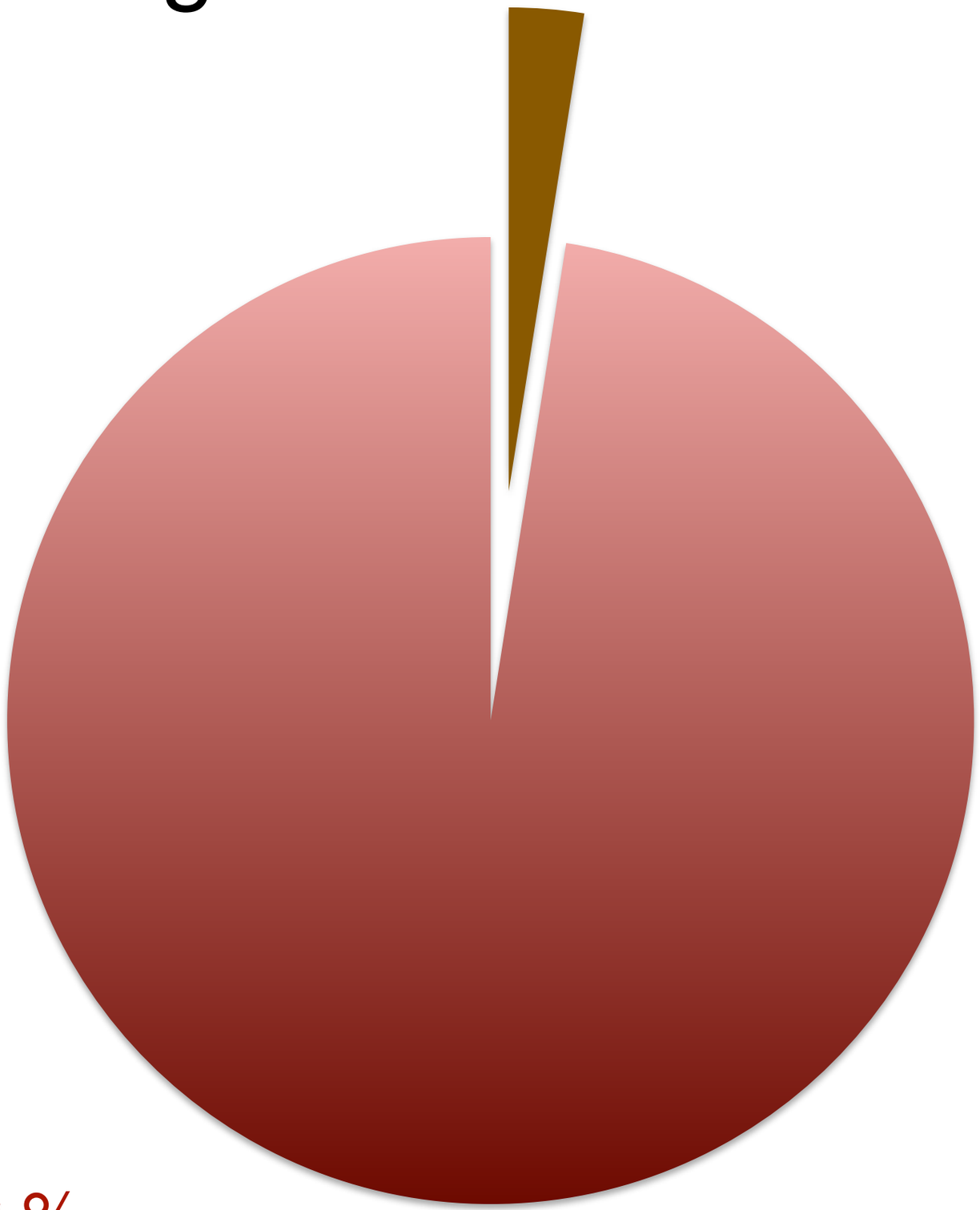
GWs: How far? few hundred Mpc.

How well can we localize the GW events?

10-100s deg^2.

Part IIIb: Challenges for EM follow-up.

3a. High energy: Timing!

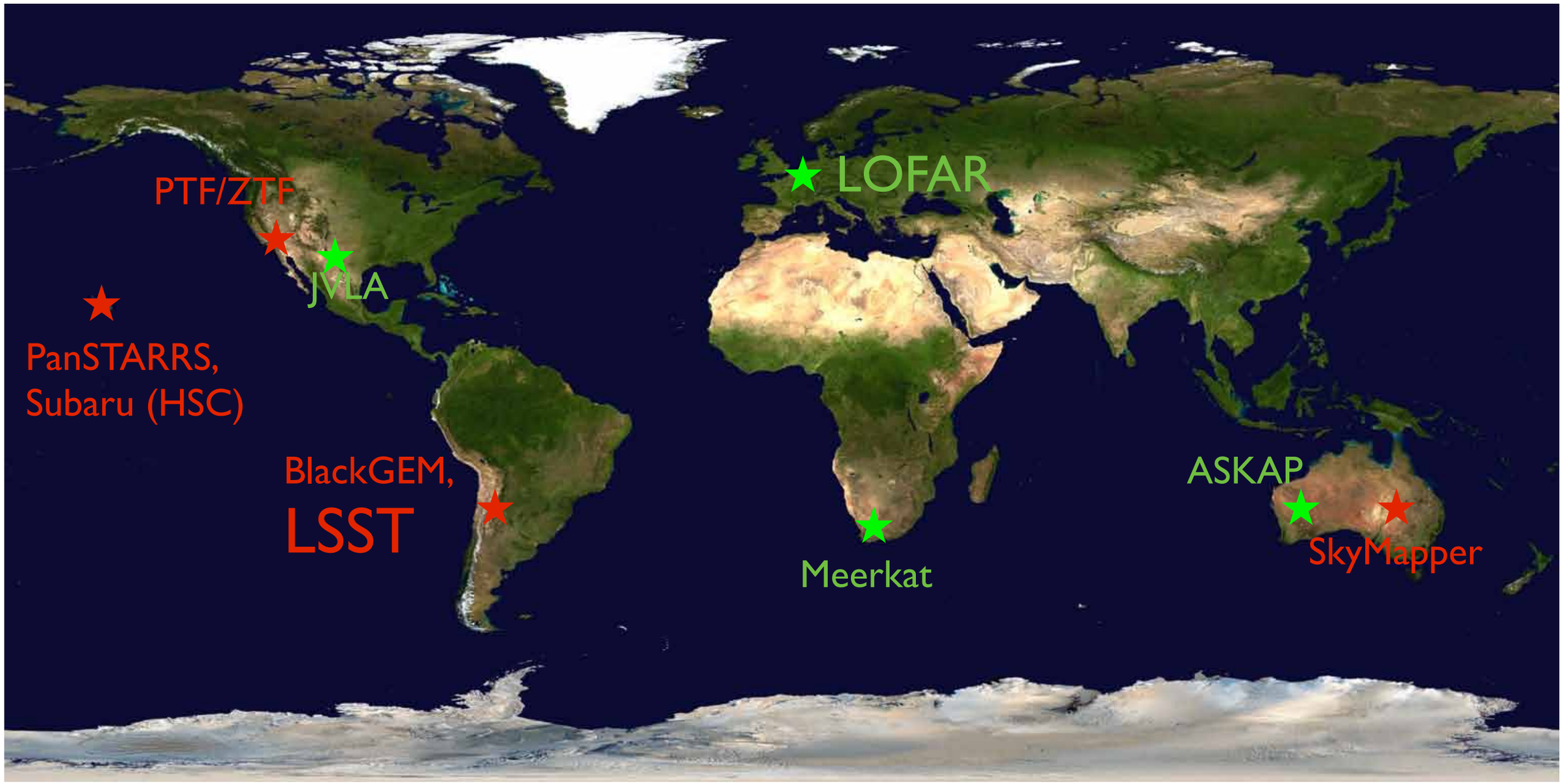


BUT…
Only for Beamed <~few %

Nissanke et al. 2013

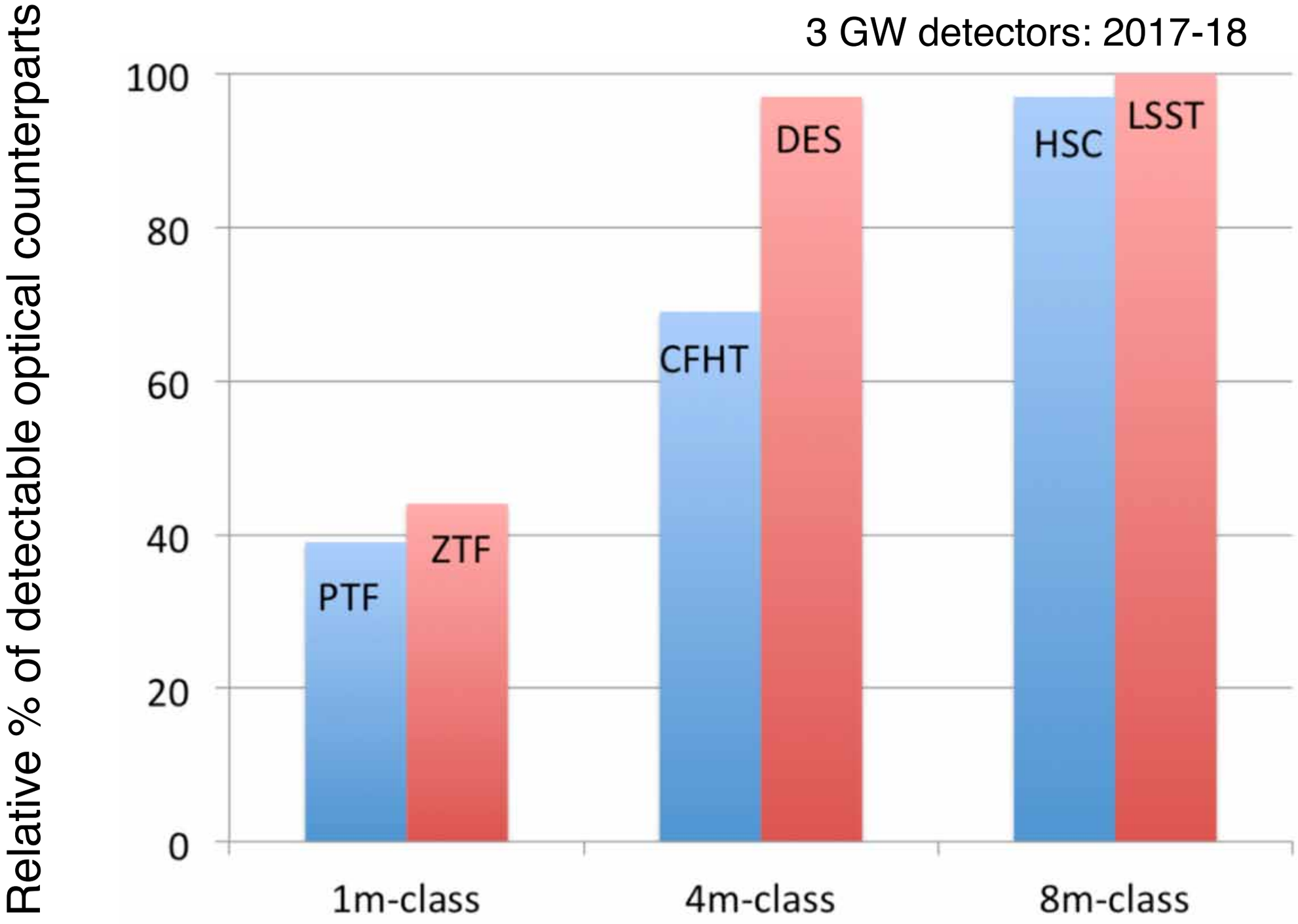
[see also Metzger and Berger 2012, Siellez et al. 2013, …]

3b. Global network of telescopes & arrays



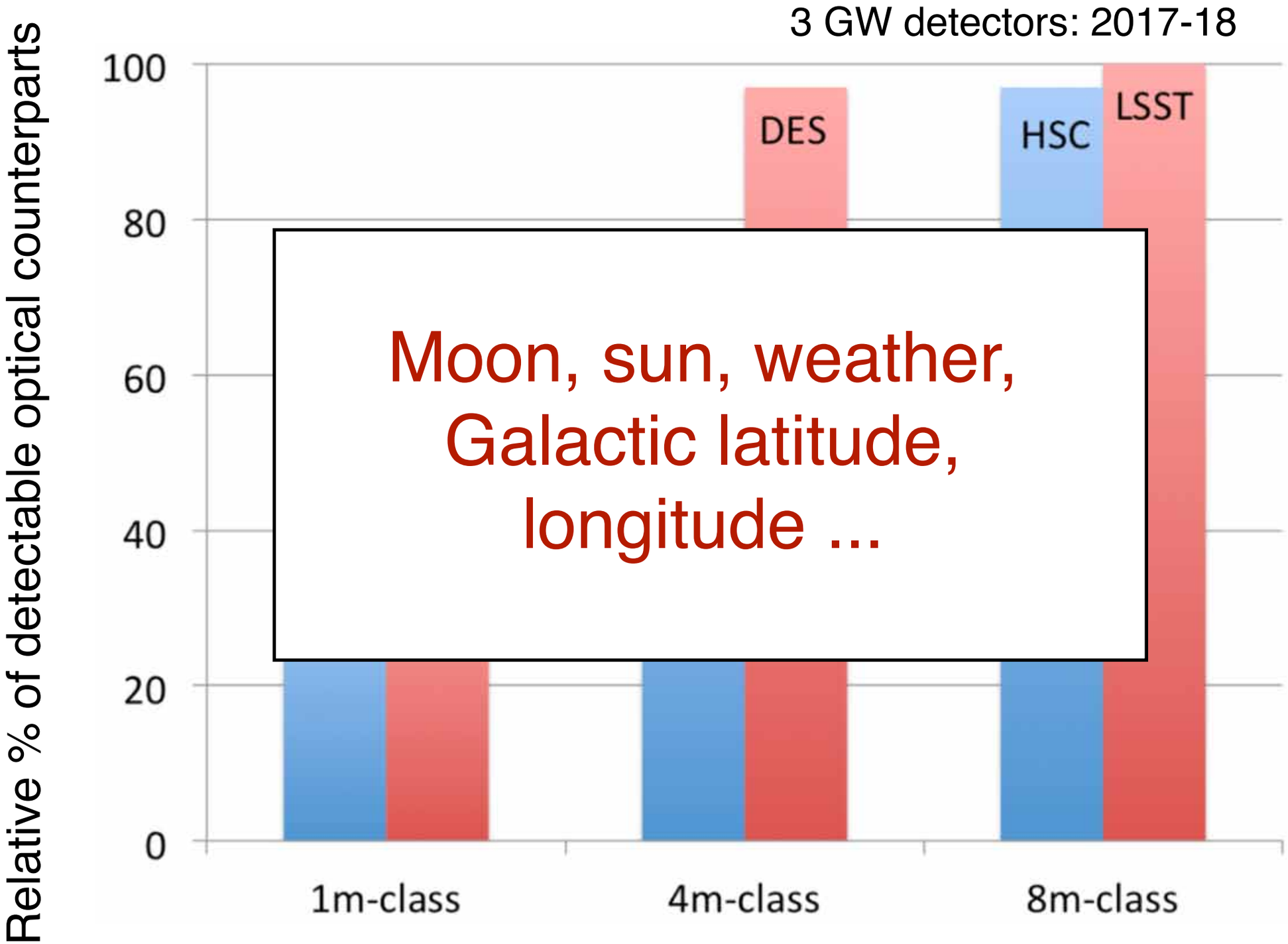
[see also Coward,..Regimbau,..Boer et al. 2011]

3. ZERO SUM GAME:
depth vs. area vs. cadence.



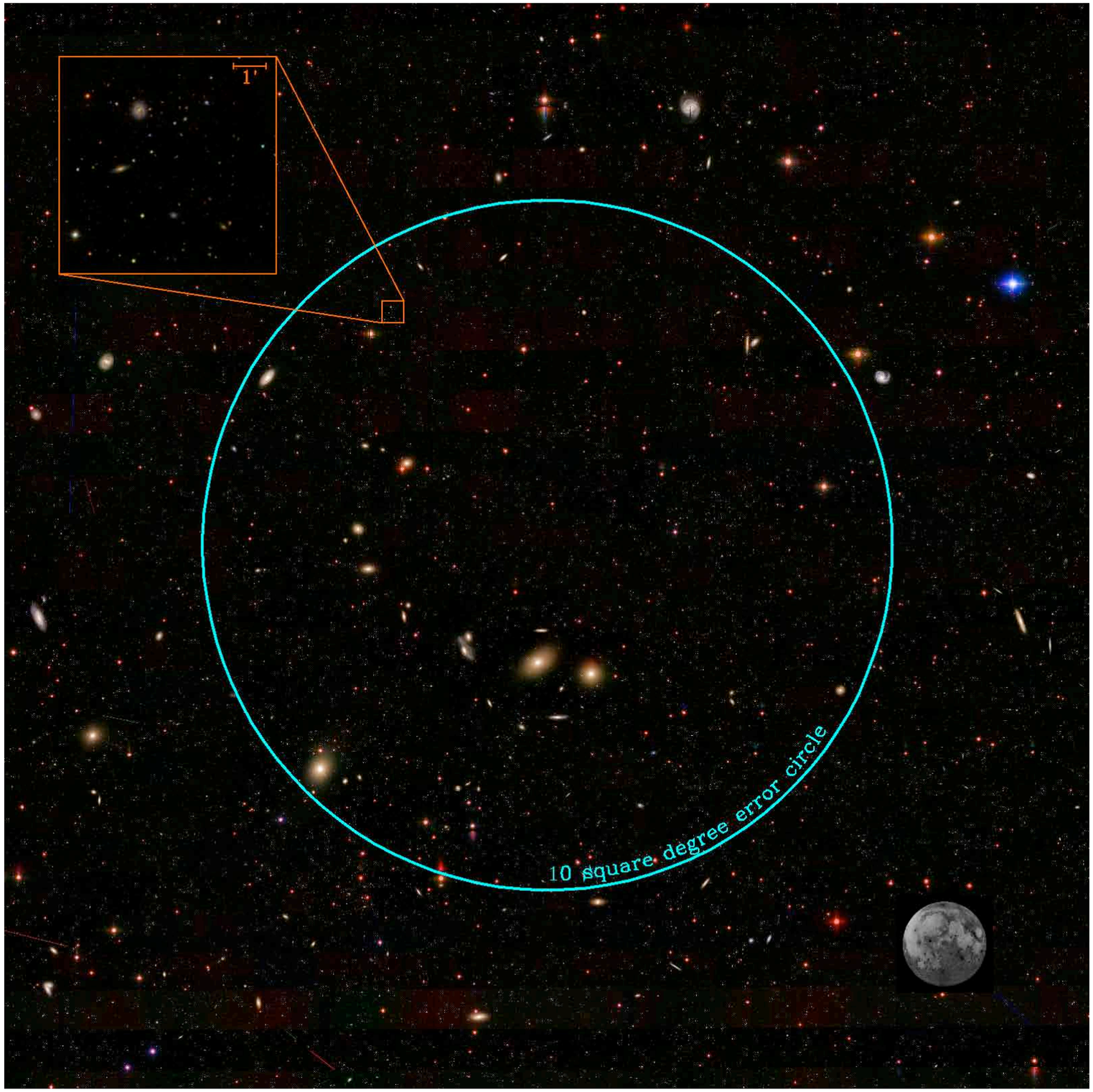
Nissanke, Kasliwal, Georgieva (2013)

3. ZERO SUM GAME:
depth vs. area vs. cadence.



Nissanke, Kasliwal, Georgieva (2013)

4. Snapshot of the dynamic universe.



courtesy Kasliwal

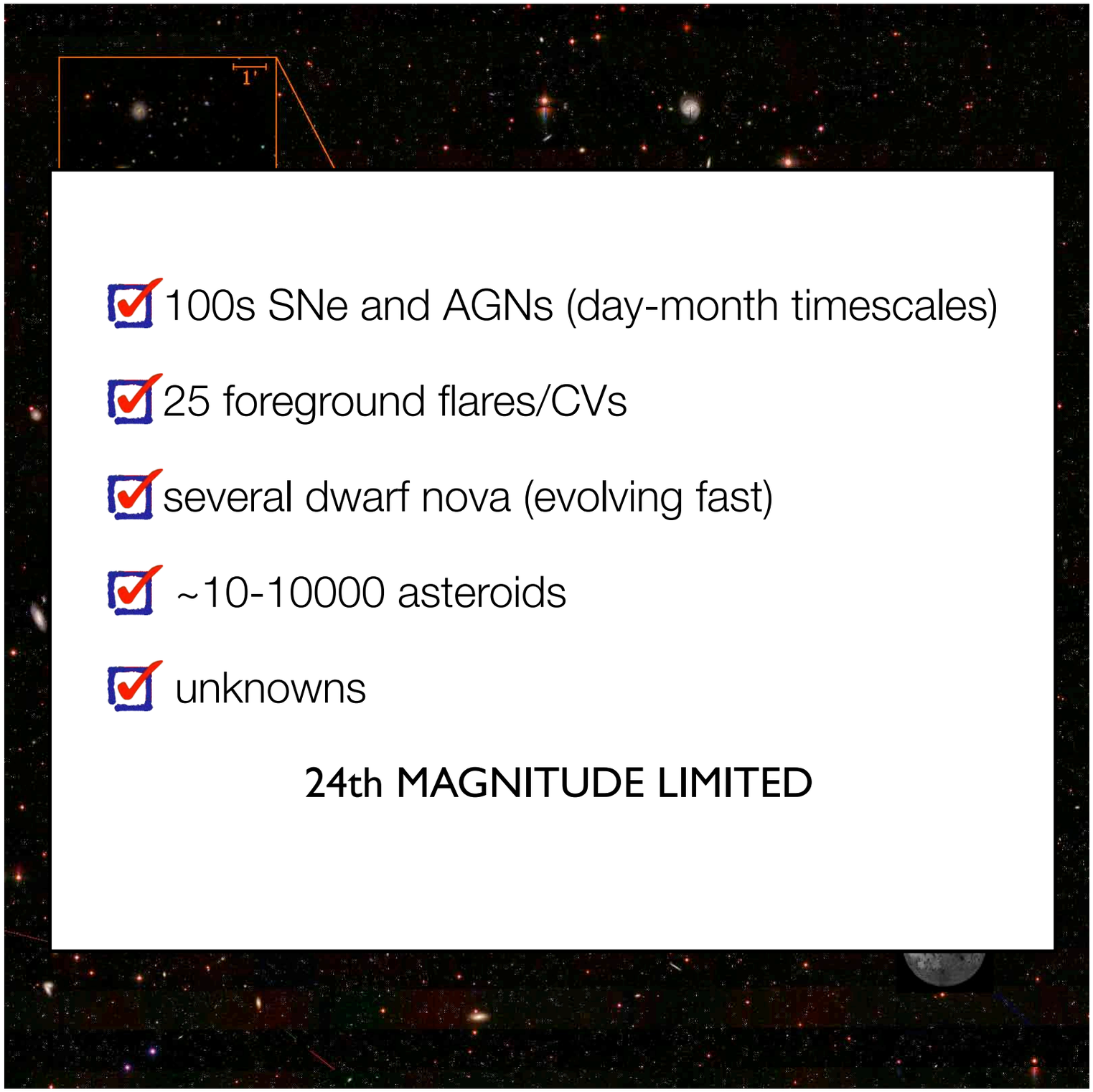
Finding the needle in the haystack

Kulkarni and Kasliwal (2009)
Nissanke, Kasliwal, Georgieva (2012)

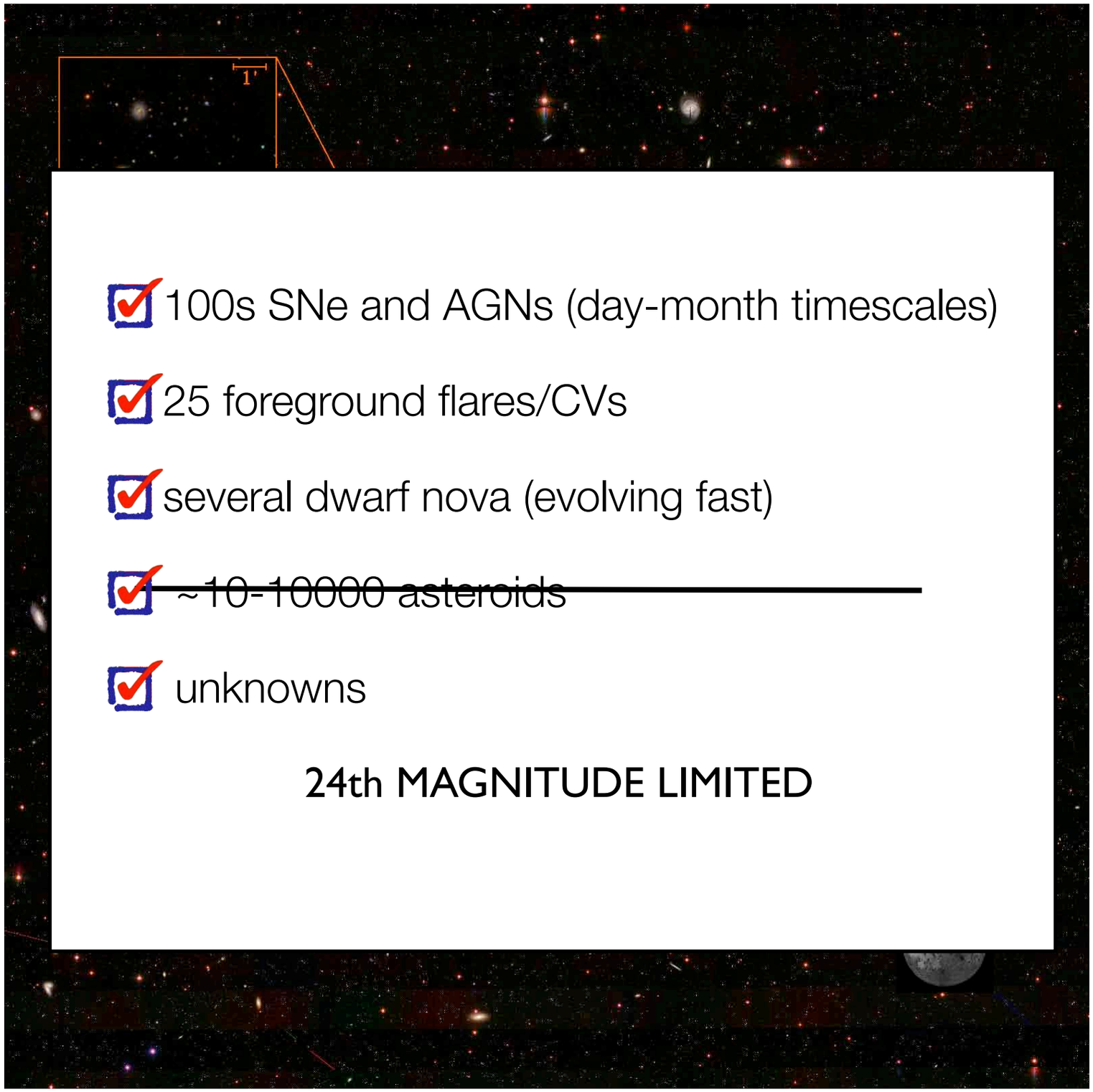
~ Where's Wally?/Ou est Charlie?

Kulkarni and Kasliwal (2009)
Nissanke, Kasliwal, Georgieva (2012)

Finding the needle in the haystack: dynamic.



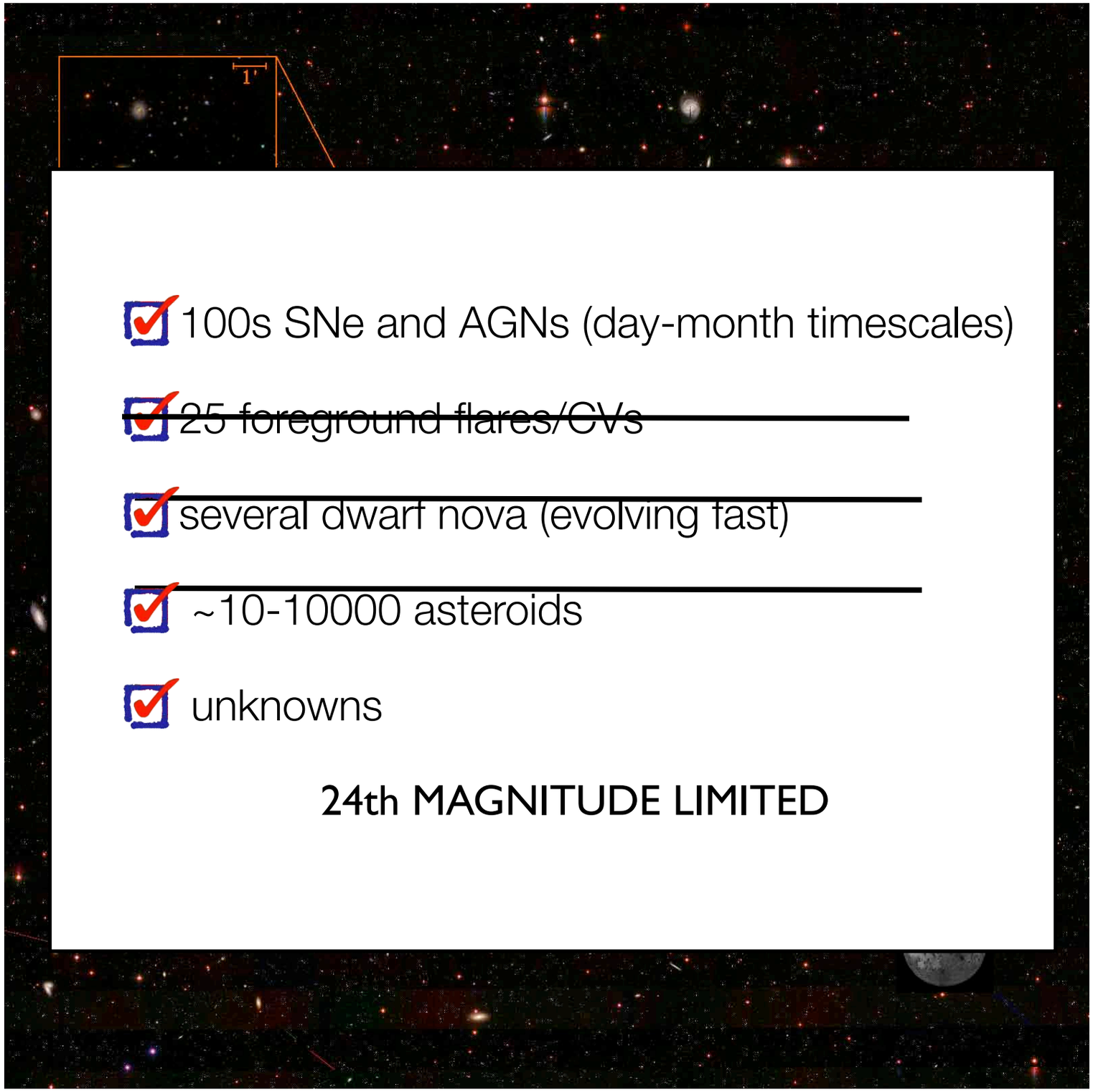
Finding the needle in the haystack: dynamic.



Finding the needle in the haystack: dynamic.

variable star catalogs

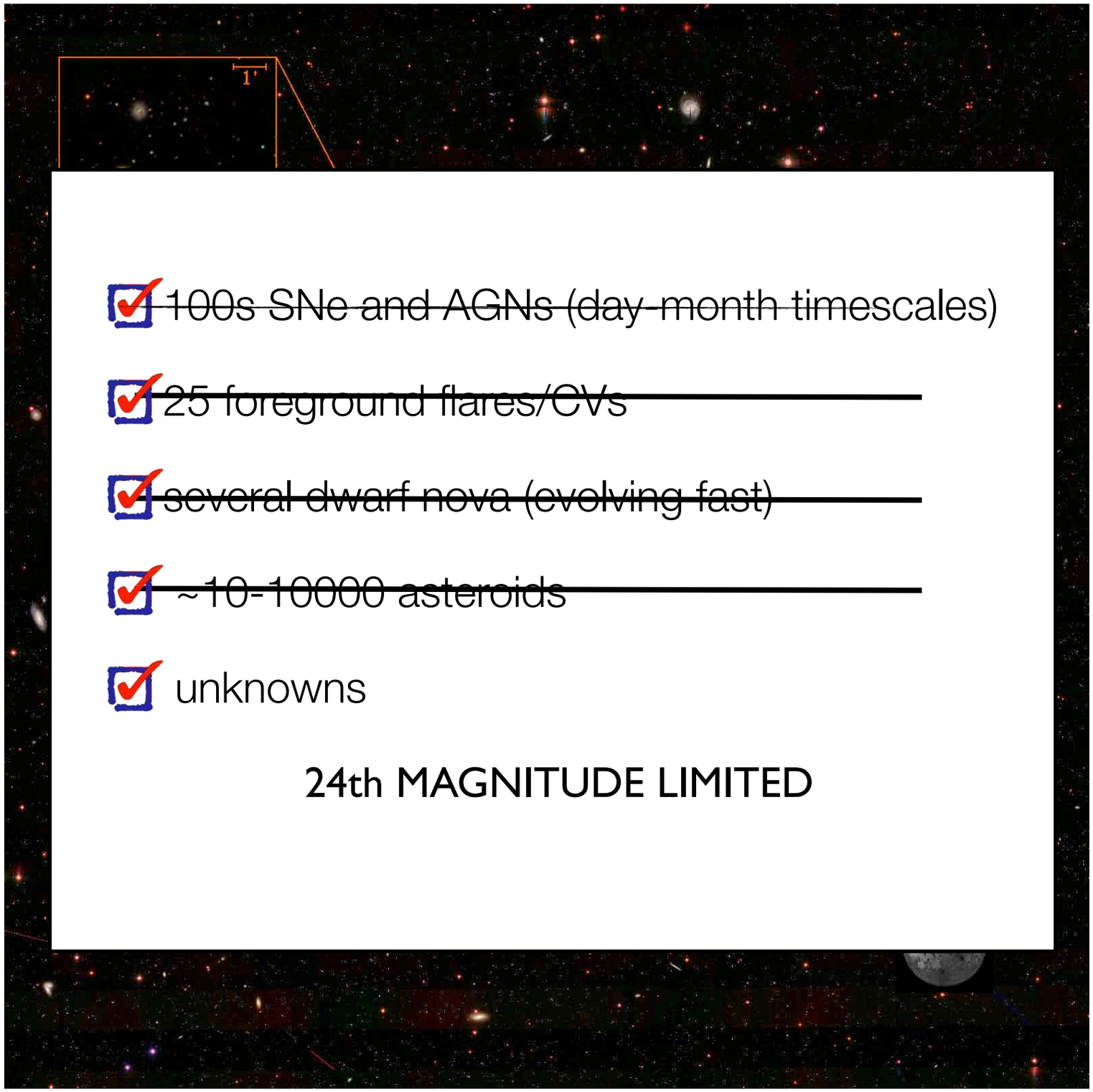
e.g. GAIA & LSST.



Finding the needle in the haystack: dynamic.

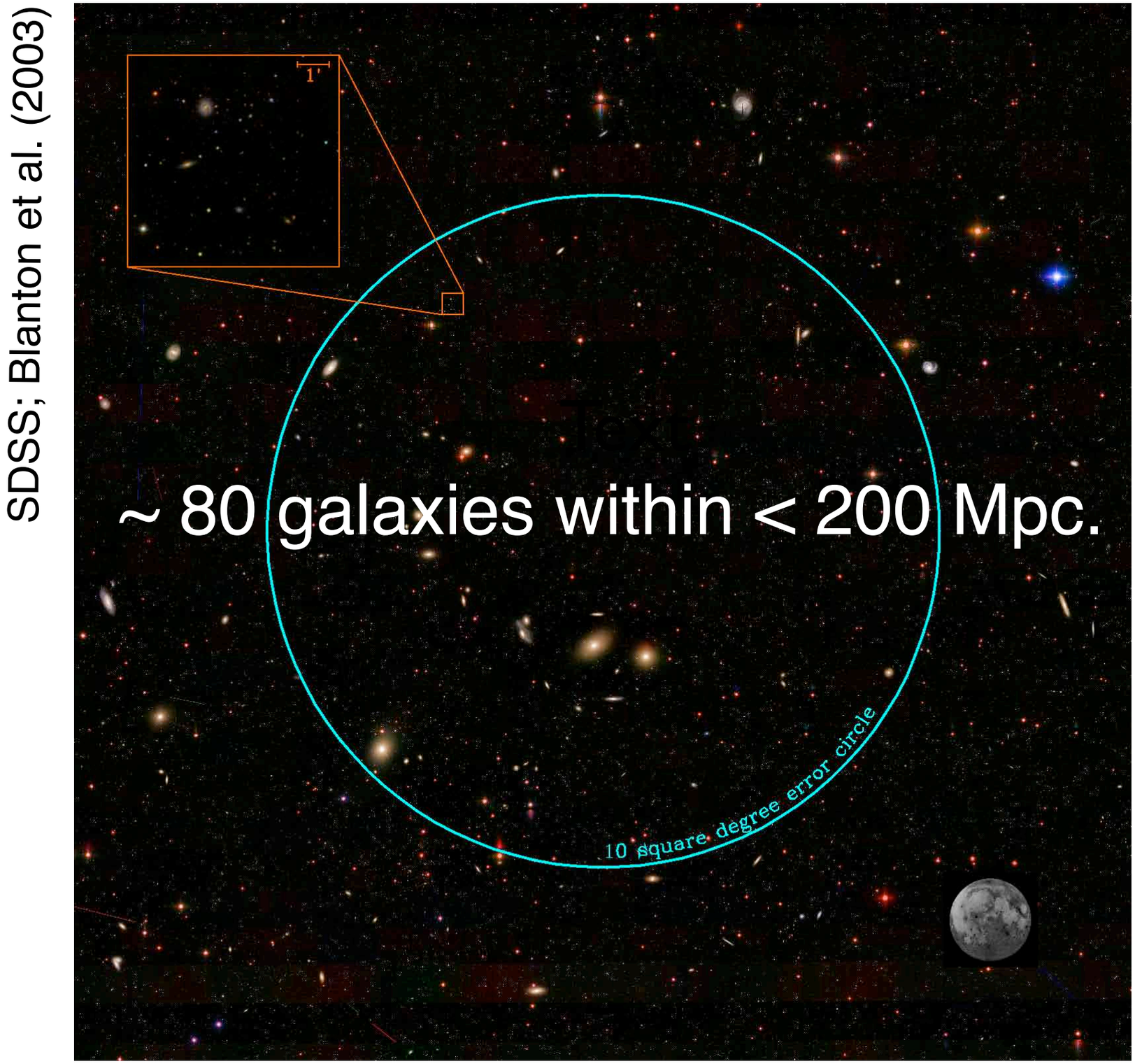
pre-existing surveys:

e.g. LSST

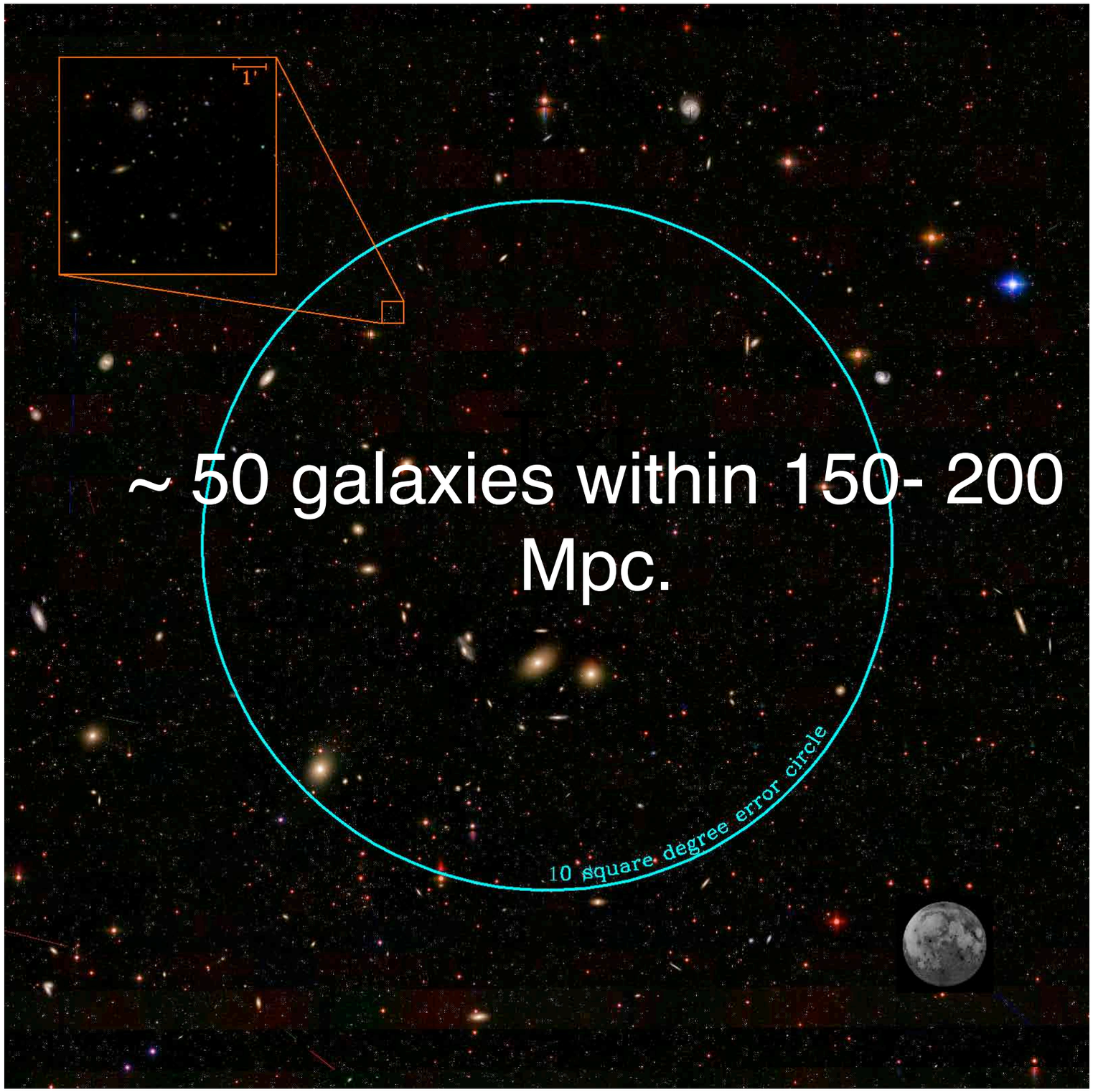


5a. Need for a galaxy catalog.

Kulkarni and Kasliwal (2009)
Nissanke, Kasliwal, Georgieva (2012)

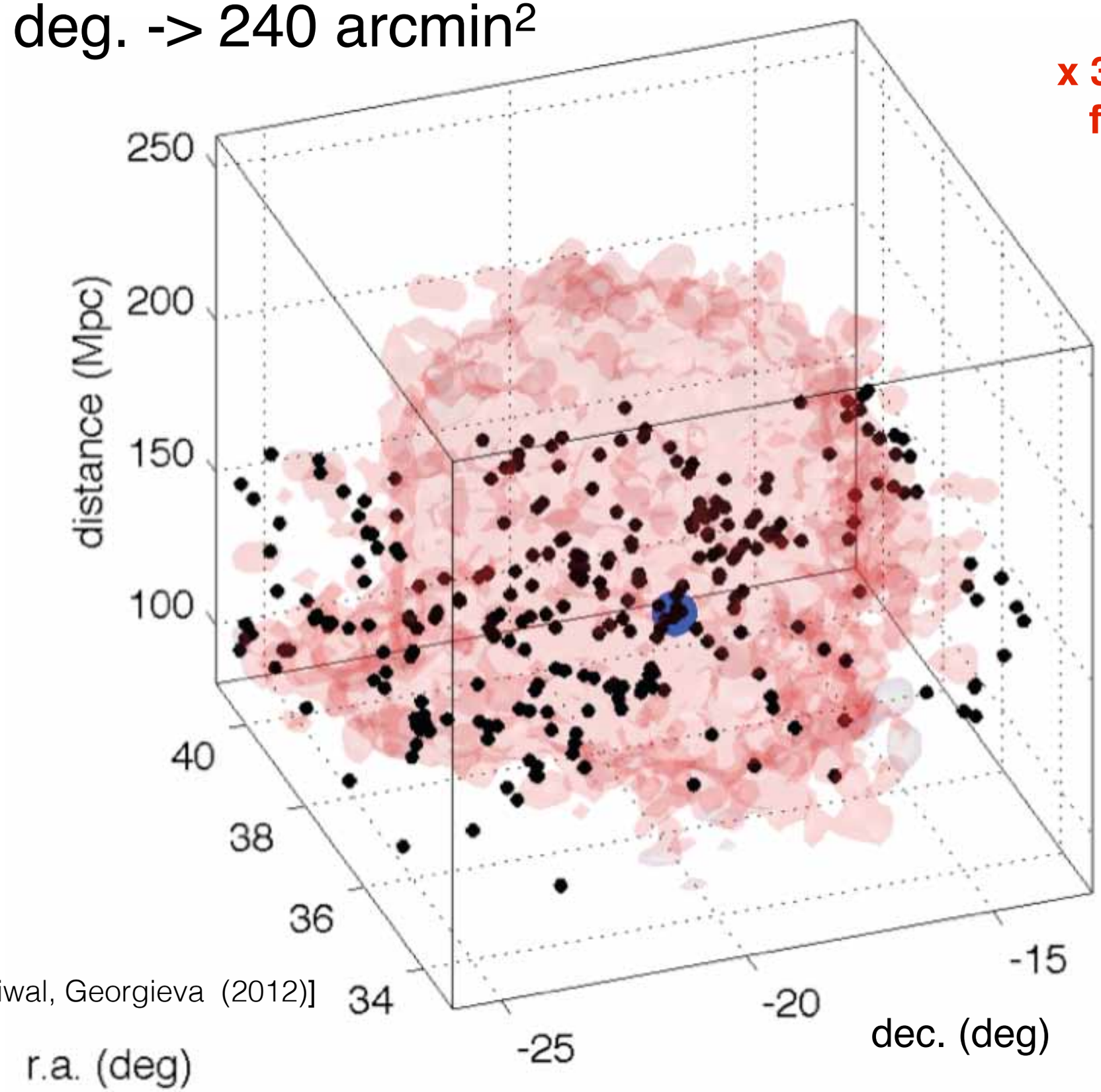


5b. Leverage GW distance.



GW + EM:...and Galaxy Catalogs.

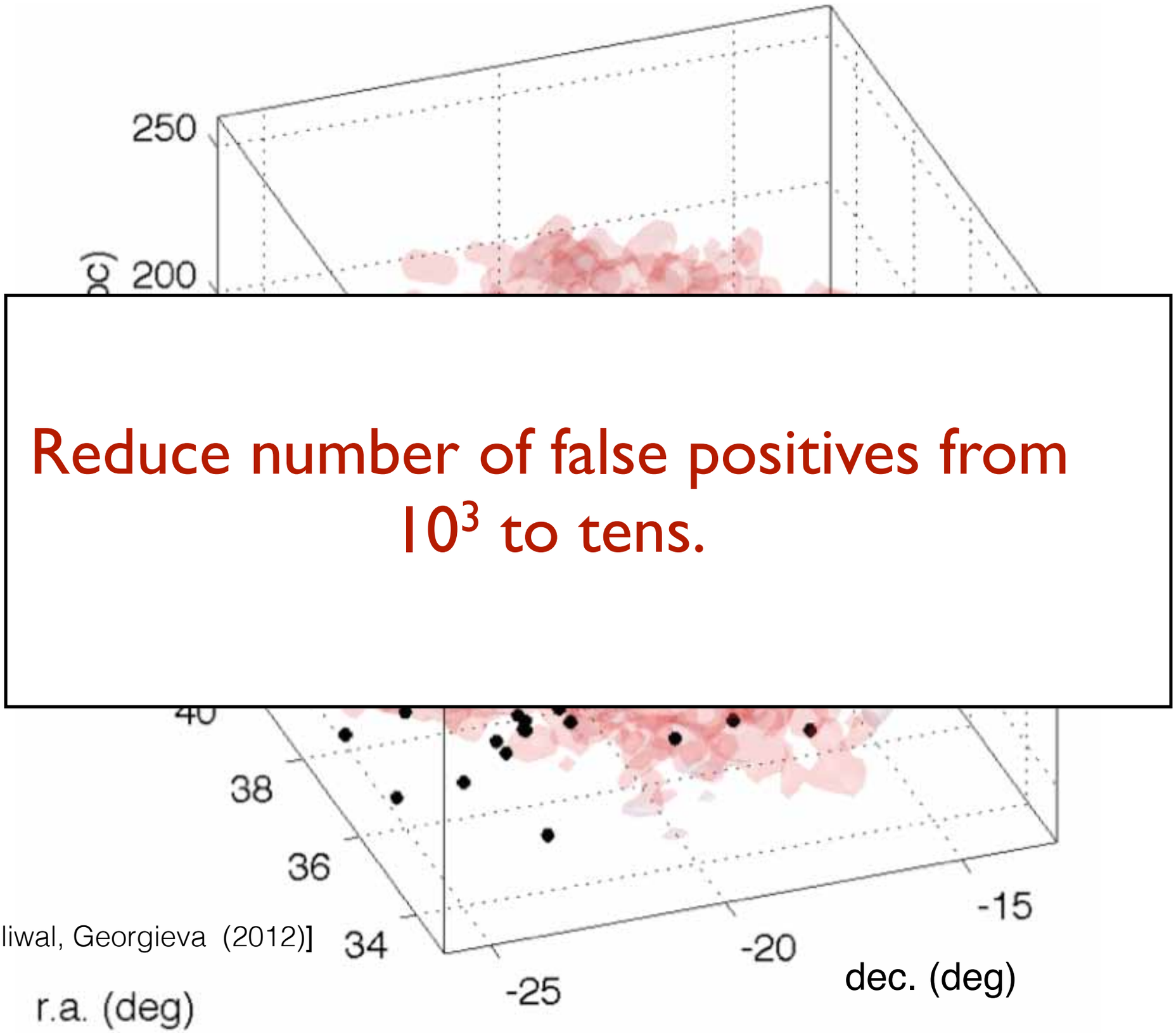
20 sq. deg. -> 240 arcmin^2



550 galaxies:
x 300 reduction in false positives

[Nissanke, Kasliwal, Georgieva (2012)]

GW + EM:…and distance.



Reduce number of false positives from 10^3 to tens.

[Nissanke, Kasliwal, Georgieva (2012)]

Three great pyramids of EM + GW

The next decade of EM + GW

EM:

e.g. PTF
GAIA

e.g. BlackGEM
ZTF, …

LSST

e.g. JVLA
LOFAR

e.g. MeerKAT

SKA

GW:

LIGO Virgo

LIGO India

KAGRA

Theoretical:

i. False Positive Classification
ii. Merger Characterization
iii. Population Statistics

1. Identify the first EM counterparts of GW mergers

- Galaxy catalogs (e.g. SDSS IV): completeness.

- False positive rate at different magnitudes and short cadences (e.g. with SNe rates, ZTF, BlackGEM, HSC)

- Variable star catalogs (e.g. GAIA).

2. EM+GW Source Characterization

- Combining macroscopic EM and GW observables to elucidate microphysics of merger.

3. Population Demographics and Ecology of Binary Stars

- Constraining our understanding of binary stellar evolution with GW and EM mergers.