What Physics and Astrophysics can we learn with Gravitational Waves?

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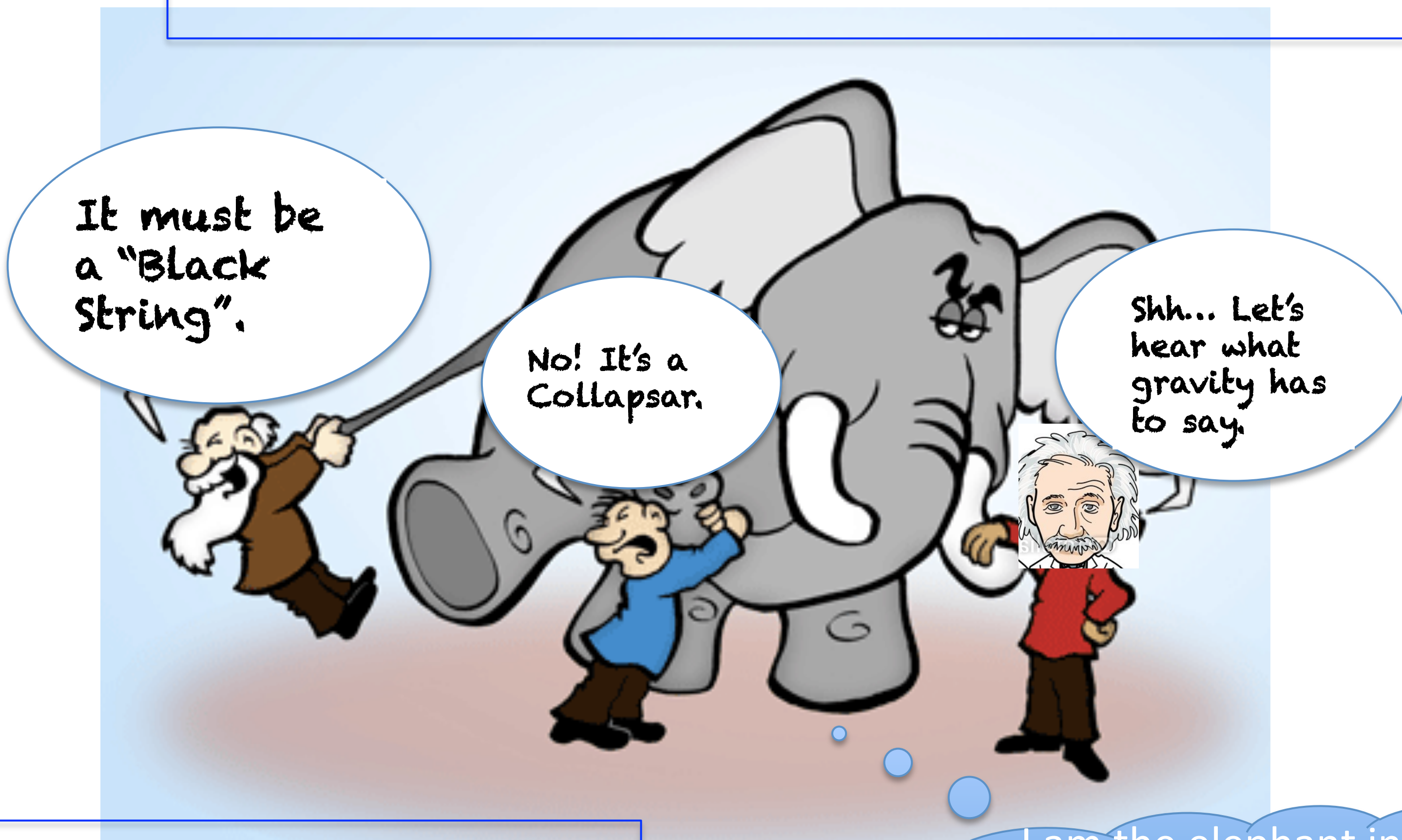

I am the elephant in the room (aka a "short GRB progenitor") guys!

Sukanta Bose (IUCAA / WSU)

CMI Silver Jubilee Workshop

WASHINGTON STATE UNIVERSITY

Talk plan

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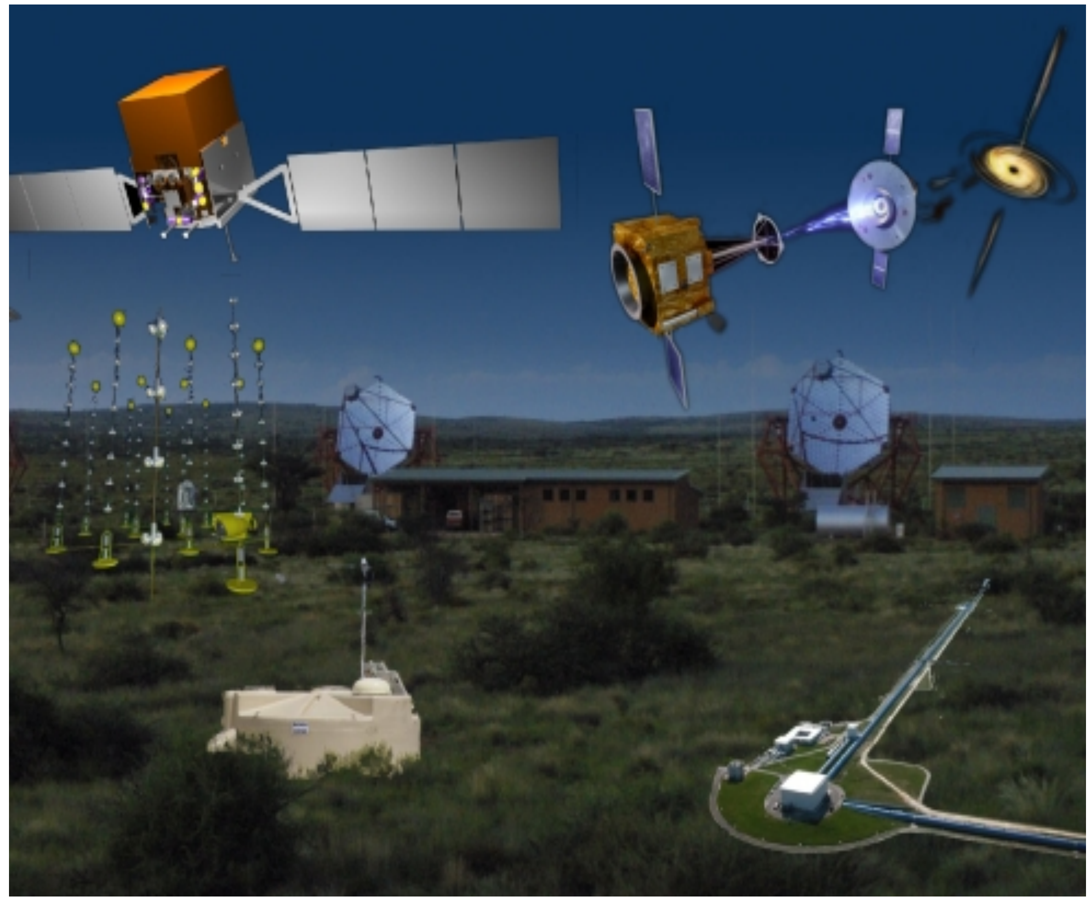
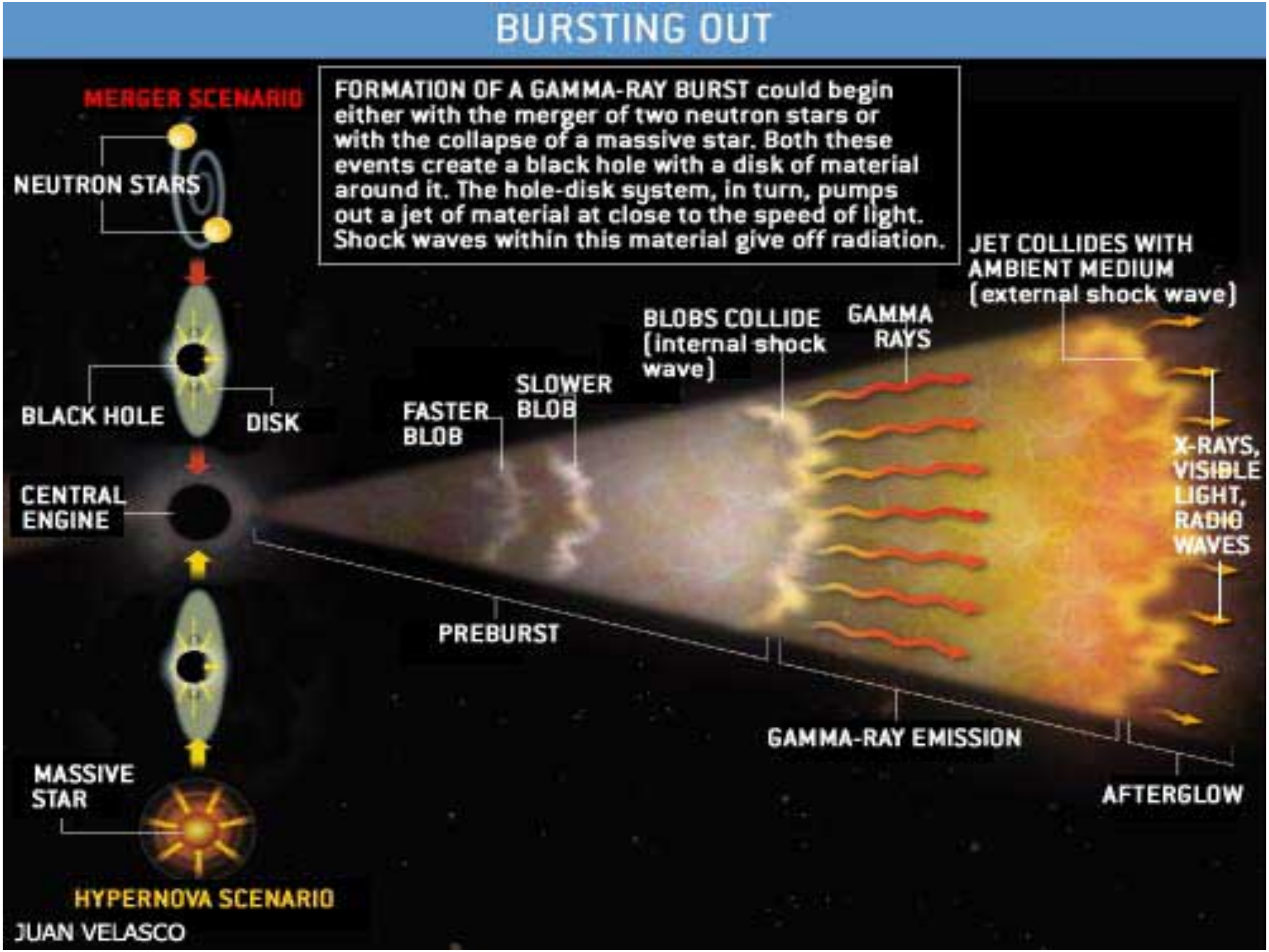
- Gravitational waves (GWs) as probes of compact object properties
- The elusive progenitor of short hard gamma-ray bursts (SGRBs)
- Following up electromagnetic (EM) counterparts of GW candidates
- Tackling the challenges inherent in this multi-messenger pursuit.




BURSTING OUT
MERGER SCENARIO
FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.
NEUTRON STARS
BLACK HOLE
DISK
CENTRAL ENGINE
MASSIVE STAR
HYPERNOVA SCENARIO
FASTER BLOB
SLOWER BLOB
BLOBS COLLIDE (internal shock wave)
GAMMA RAYS
JET COLLIDES WITH AMBIENT MEDIUM (external shock wave)
X-RAYS, VISIBLE LIGHT, RADIO WAVES
PREBURST
GAMMA-RAY EMISSION
AFTERGLOW
JUAN VELASCO

WASHINGTON STATE UNIVERSITY

Strength of gravitational waves

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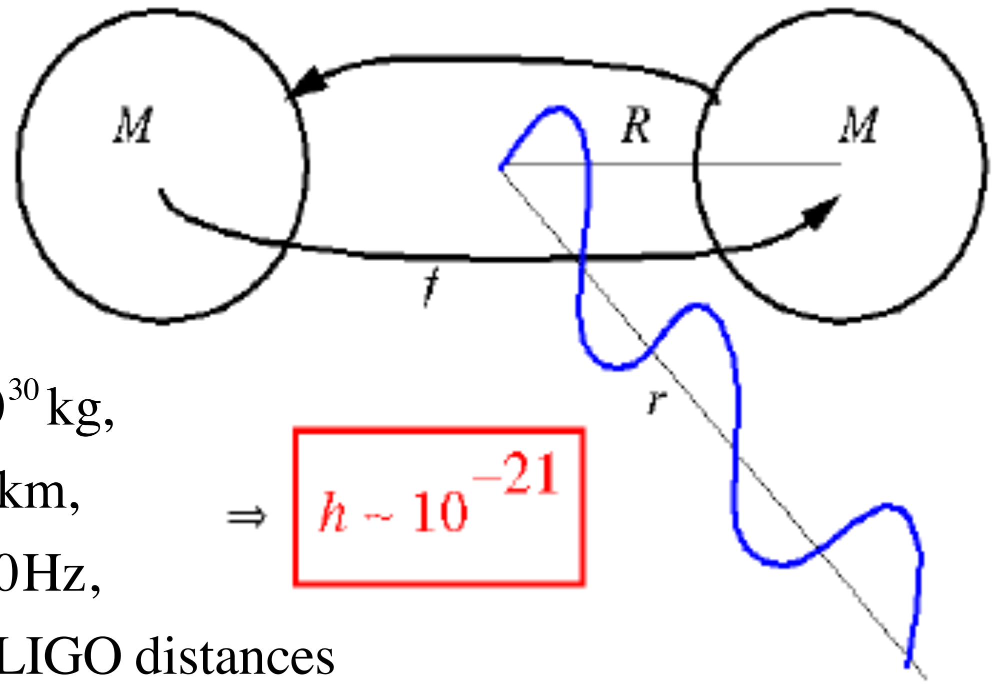
- GWs arise from a time-varying *quadrupole* moment, $Q \sim MR^2$
- GW strain amplitude depends on two time-derivatives of Q.
- Dimensional analysis then shows:

$$h \propto \frac{G\ddot{Q}}{c^4 r}.$$



$$M \sim 10^{30}\,\text{kg},$$
$$R \sim 20\,\text{km},$$
$$f \sim 400\,\text{Hz},$$

Initial LIGO distances

$$\Rightarrow \boxed{h \sim 10^{-21}}$$

Complete binary waveforms from pN and NR

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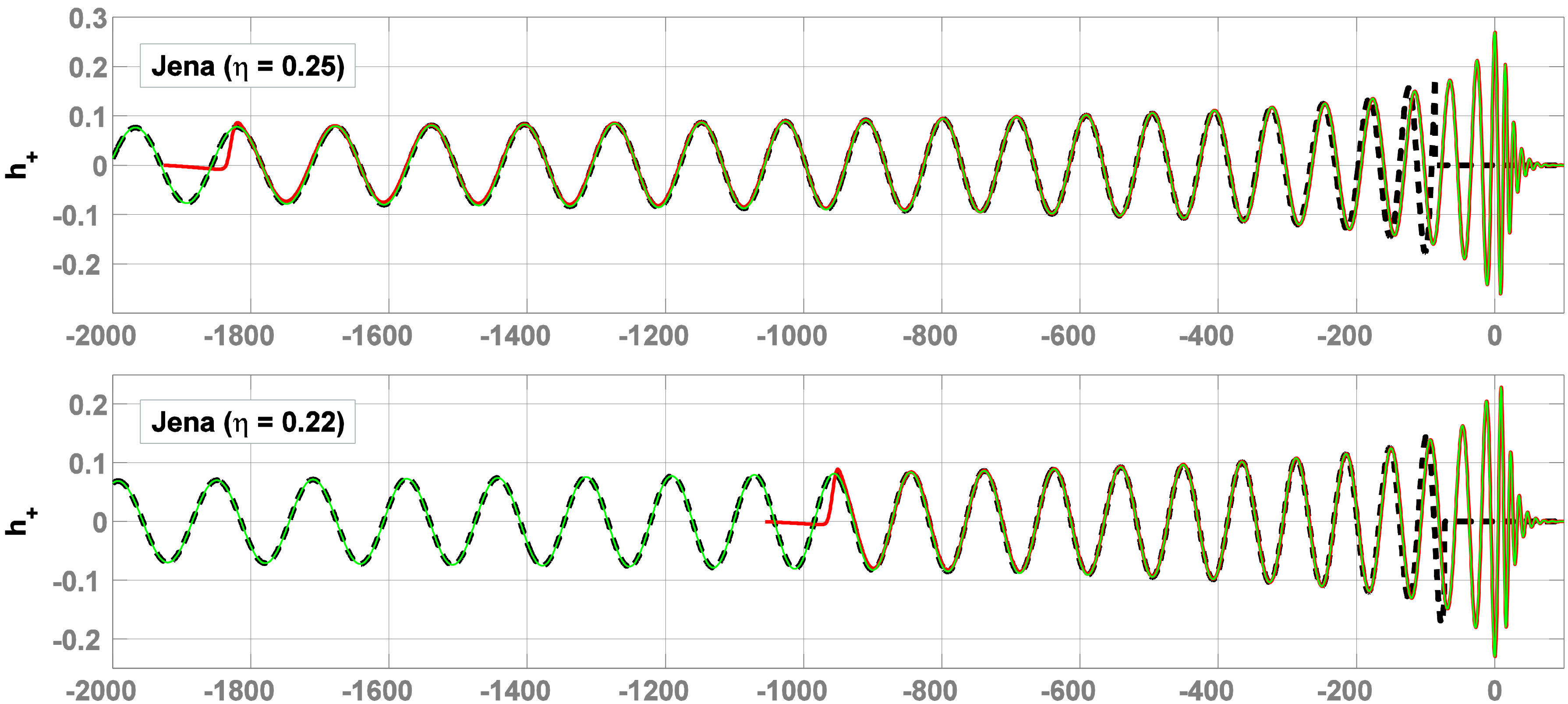

Black = inspiral; red = NR; green = analytical “phenomenological” complete waveforms

[P. Ajith et al, PRD ’08]

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Single detector (aLIGO) parameter accuracies

(SNR fixed to 10)

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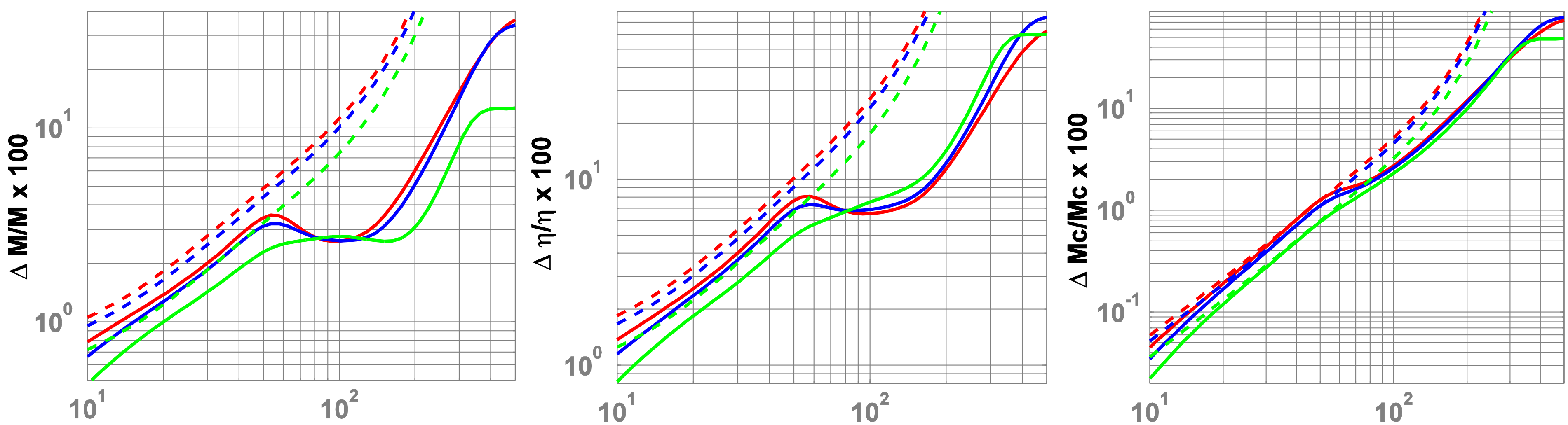
Total mass, symmetrized mass-ratio & chirp mass:

$$M = m_1 + m_2, \quad \eta = \frac{m_1 m_2}{M^2}, \quad M_c = \eta^{3/5} M \,.$$



Total mass (in M_{sun})

[P. Ajith & SB, PRD79, 084032 (2009).]

Single detector (aLIGO) parameter accuracies

(effective distance fixed at 1Gpc)

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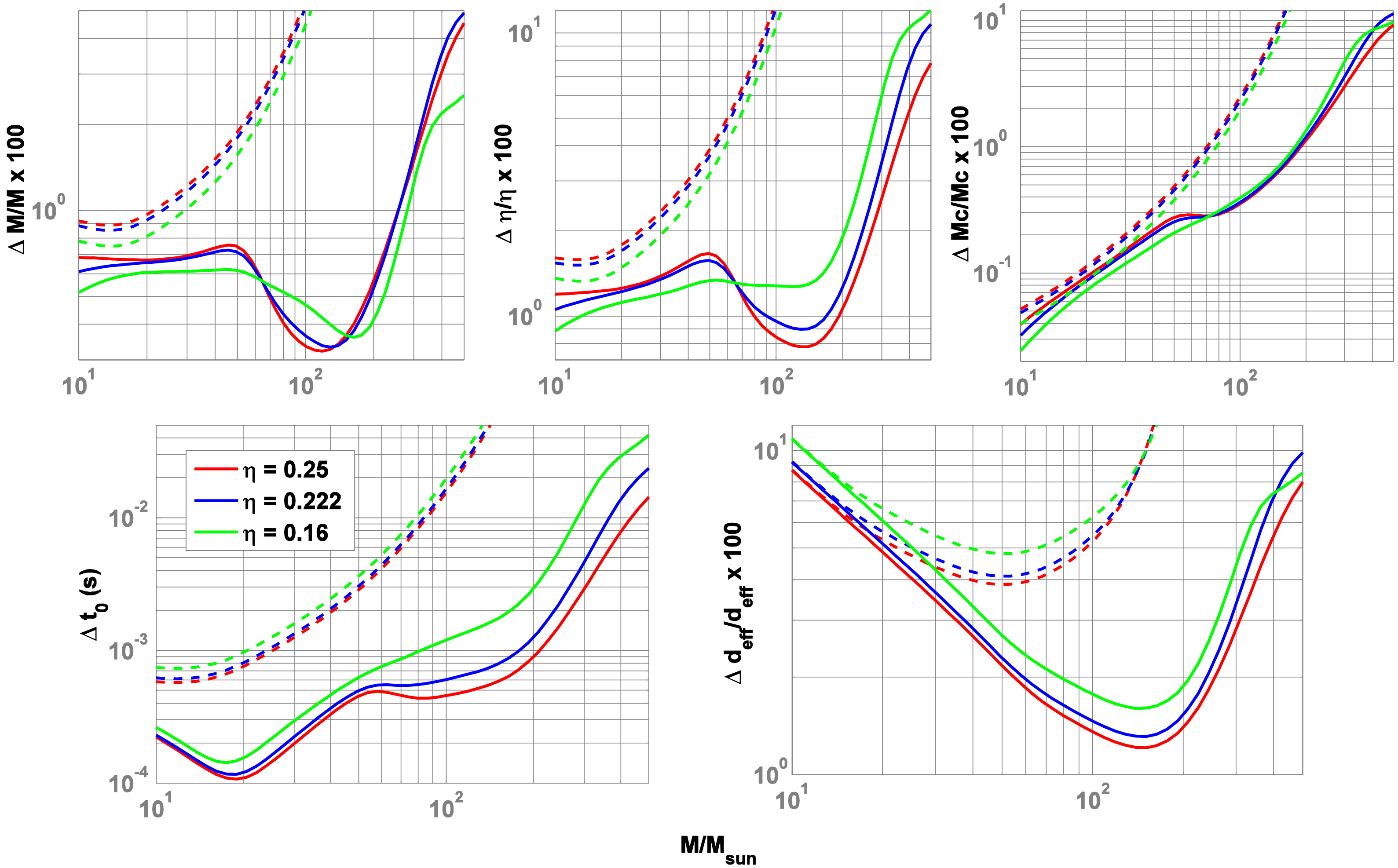

[P. Ajith & SB, PRD79, 084032 (2009).]

Gravitational wave detection

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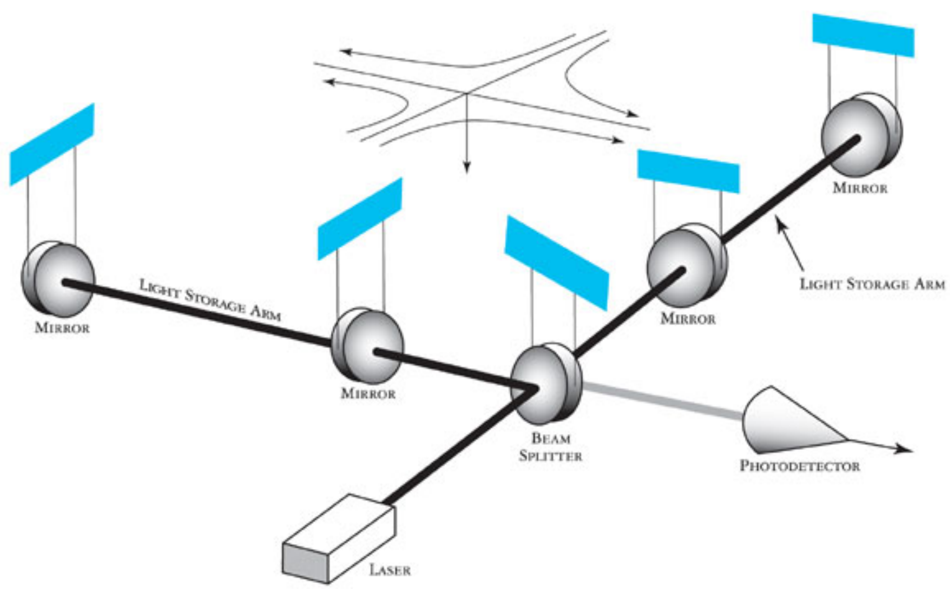
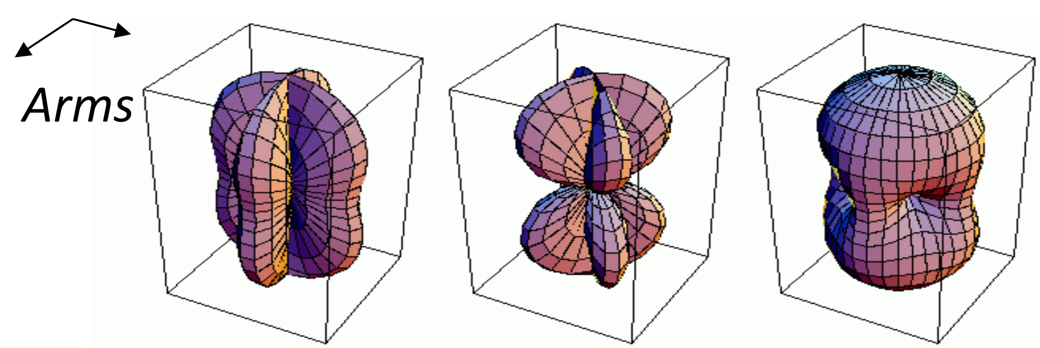


LIGO-Hanford, WA

The signal is the moving fringe at the photodiode

Sky response



+ polarization   *x polarization*   *unpolarized*

Gravitational-wave interferometers & their sources

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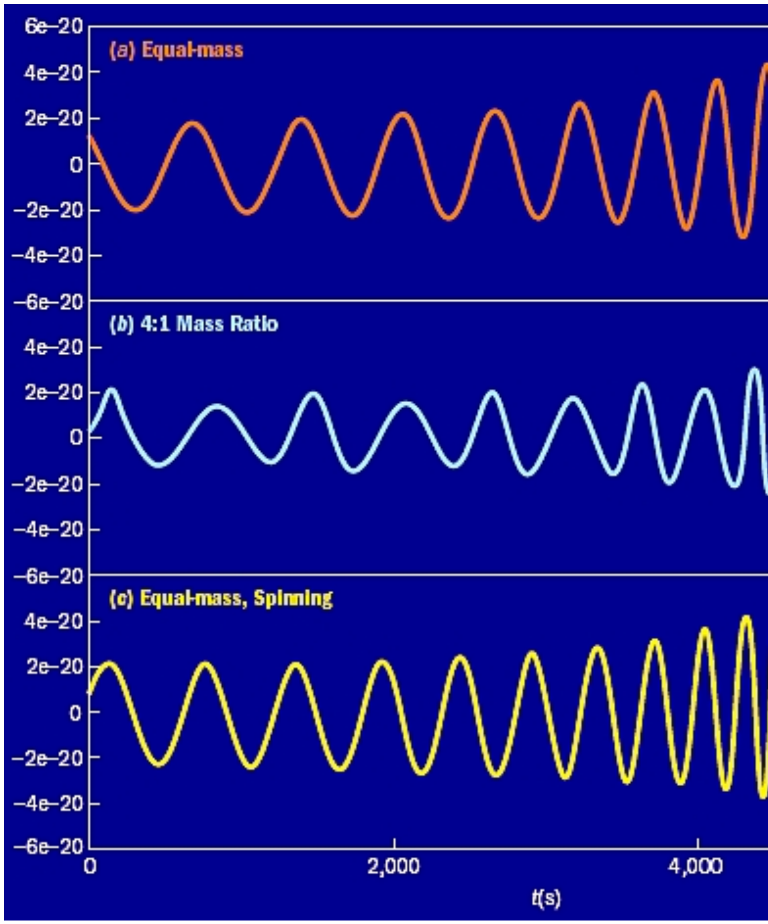
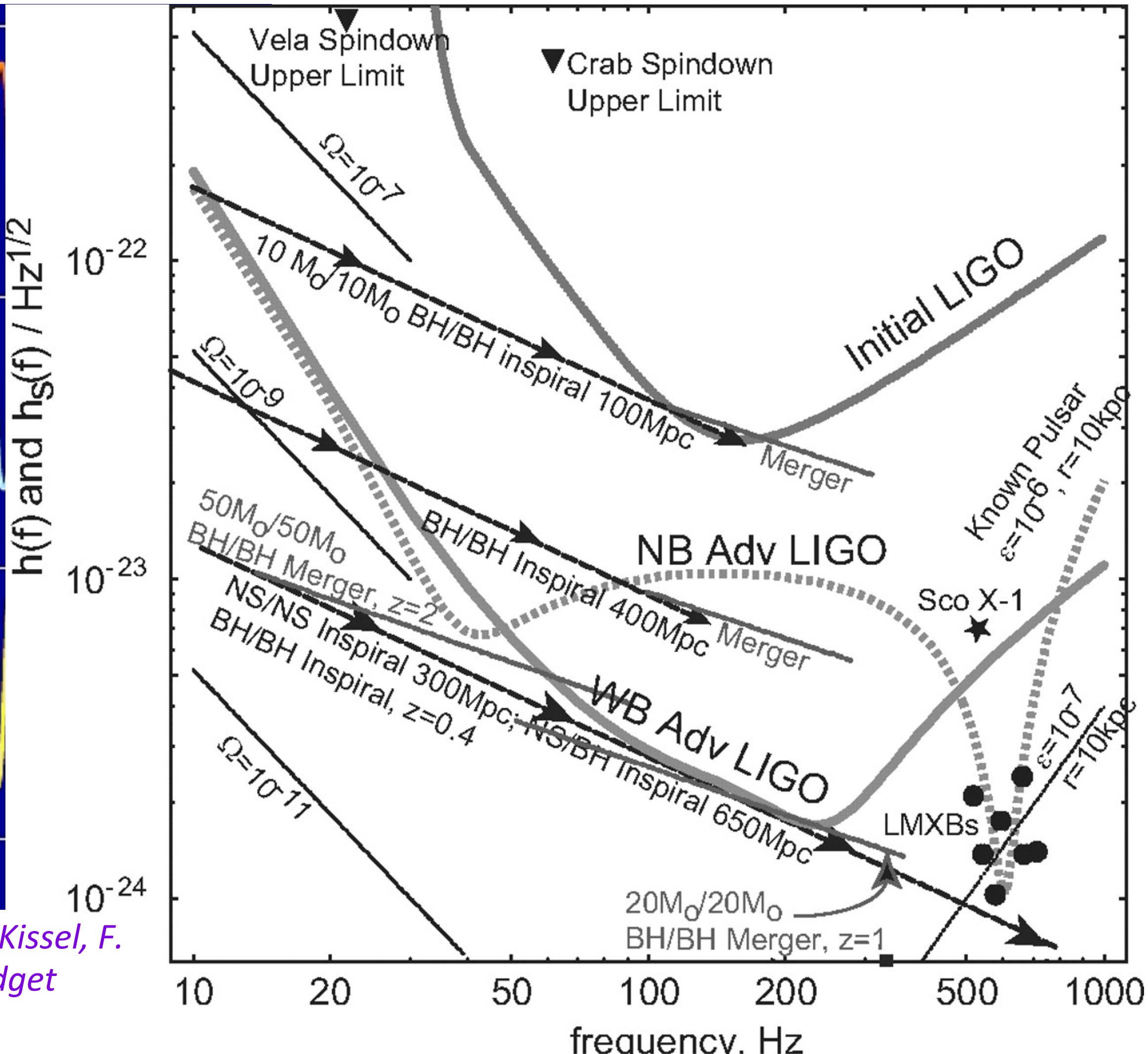


[Nairwita Mazumder, C. Wipf, J. Kissel, F. Raab, "Advanced LIGO Noise Budget estimation."]



[Cutler & Thorne, CQG (2002).]

Projected improvement in observation depth of GWOs

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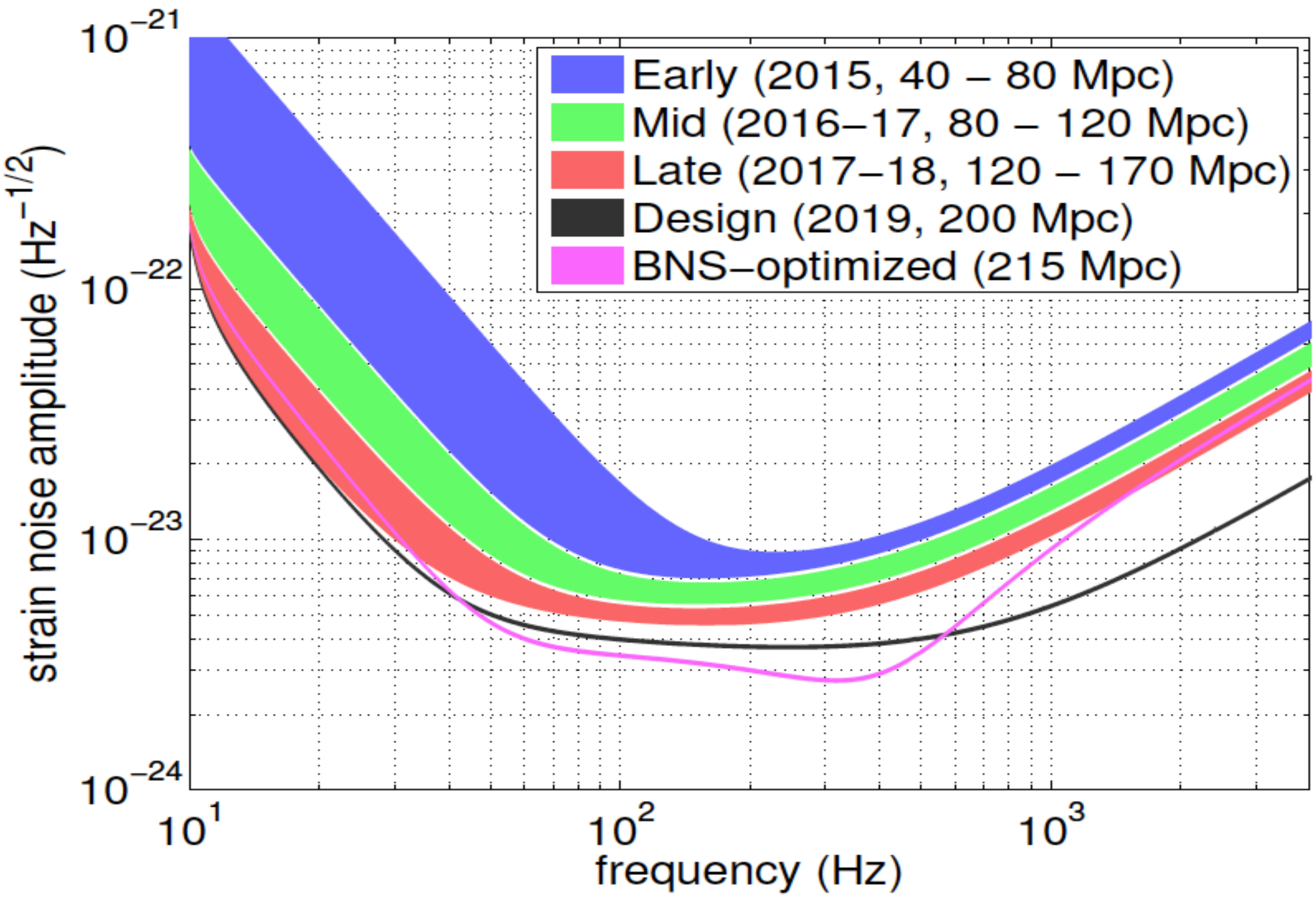

[J. Aasi et al., LIGO Scientific and Virgo Collaborations., arXiv:1304.0670 [gr-qc] (2013).]


Gravitational Wave Detectors
Interferometric
Resonant-Mass
eLISA
GEO
AURIGA
EXPLORER
VIRGO
NAUTILUS
KAGRA
LIGO
ALLEGRO
LIGO
LIGO-India
(proposed)
NIOBE

Global Network of Adv. GW Observatories

What fraction of the total number of CBC sources in a volume $4\pi r_H^3/3$ is detectable up to a distance of r?

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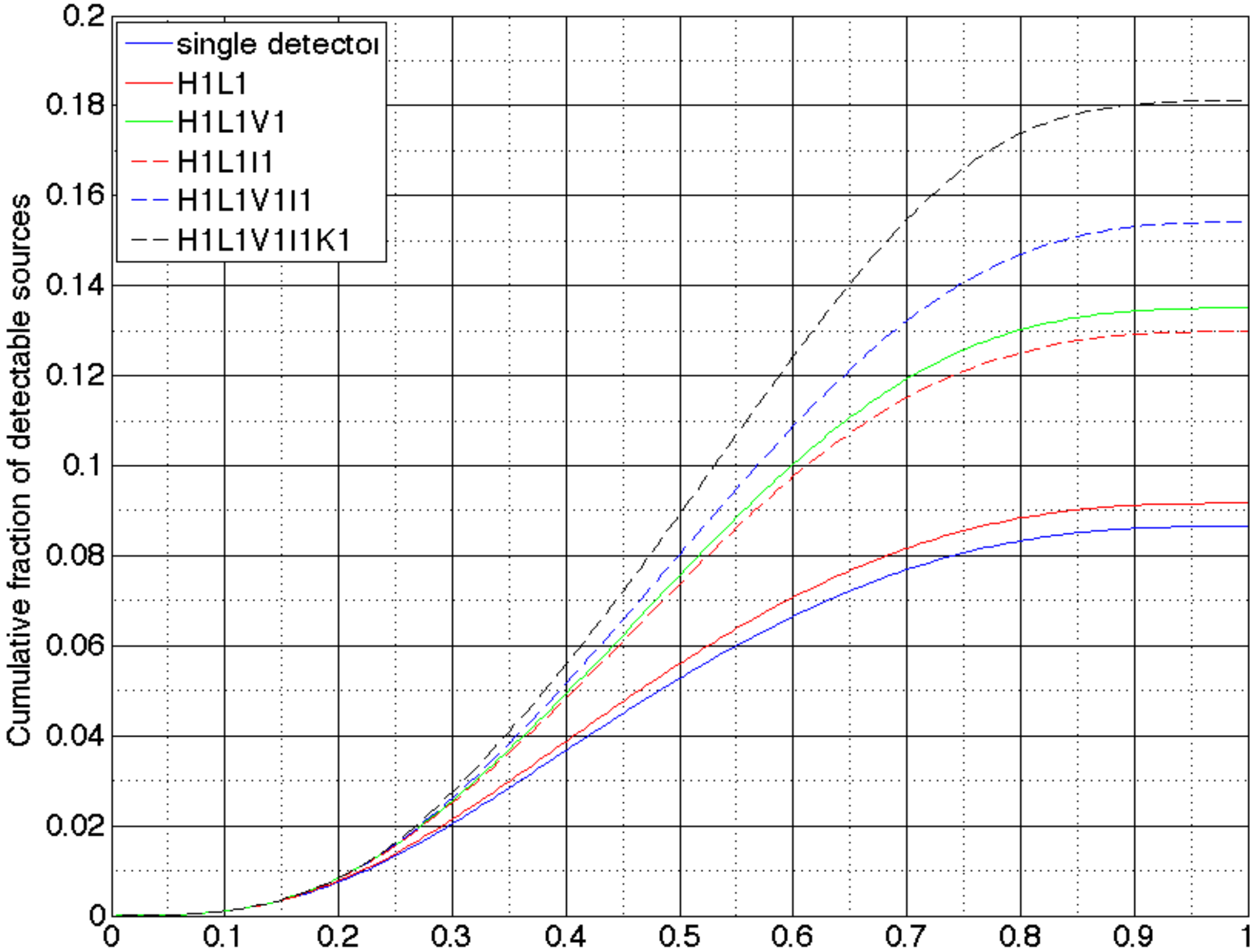

Distance *r* to the source (in units of horizon radius r_H)

The ratio of maximal to average distance sensitivity of *HLVIK* is $0.18^{-1/3} \approx 1.77$.

The ratio of maximal to average distance sensitivity of a *single detector* is $0.087^{-1/3} \approx 2.26$.

[Shaon Ghosh, SB, LIGO-P1200169 (2013)]

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Constraining the Neutron Star EOS

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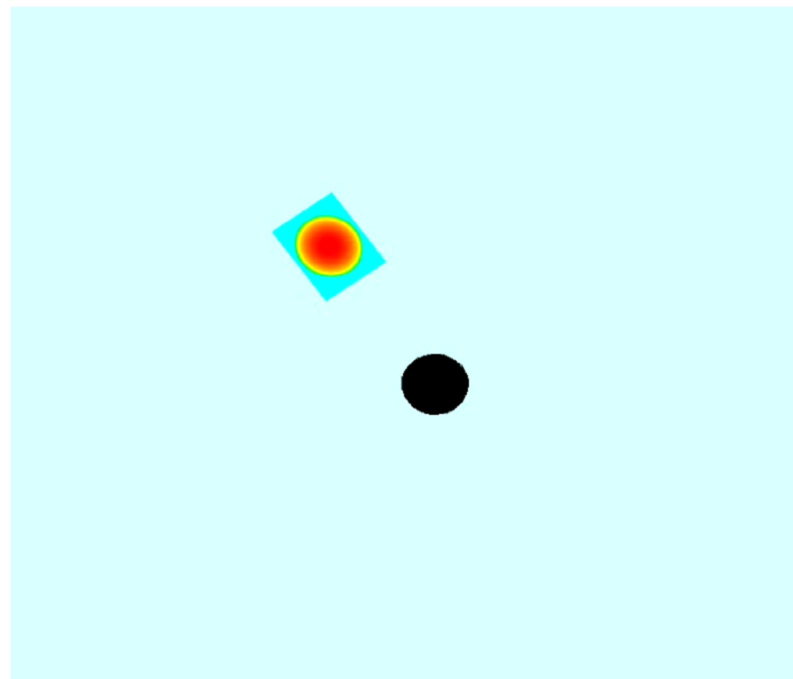
- Model merger @ ringdown with Caltech-Cornell-CITA-WSU **SpEC** code
  - Spectral evolution of metric, finite volume evolution of fluid
  - Comoving coordinates,
  - adaptive fluid grid, BH excised
- Sample case:
  - $M_{BH}:M_{NS}=3:1$
  - a/m=0.5,
  - Γ=2 EOS
- New physics in testing:
  - ν-leakage, MHD



Courtesy: Matt Duez.

[Kabir Chakravarti, A. Gupta, Matt Duez, SB, "Modeling NS-BH waveforms".]

Effect of NS EOS on GW signal

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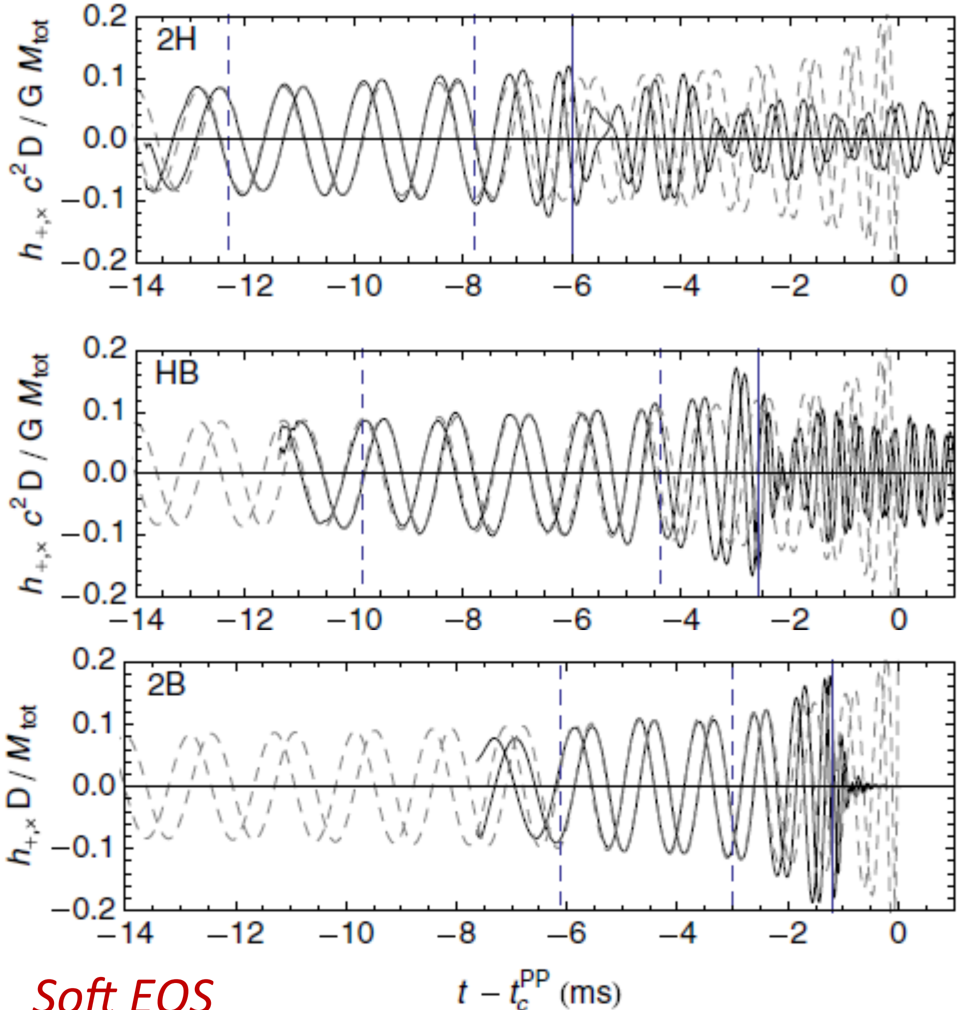
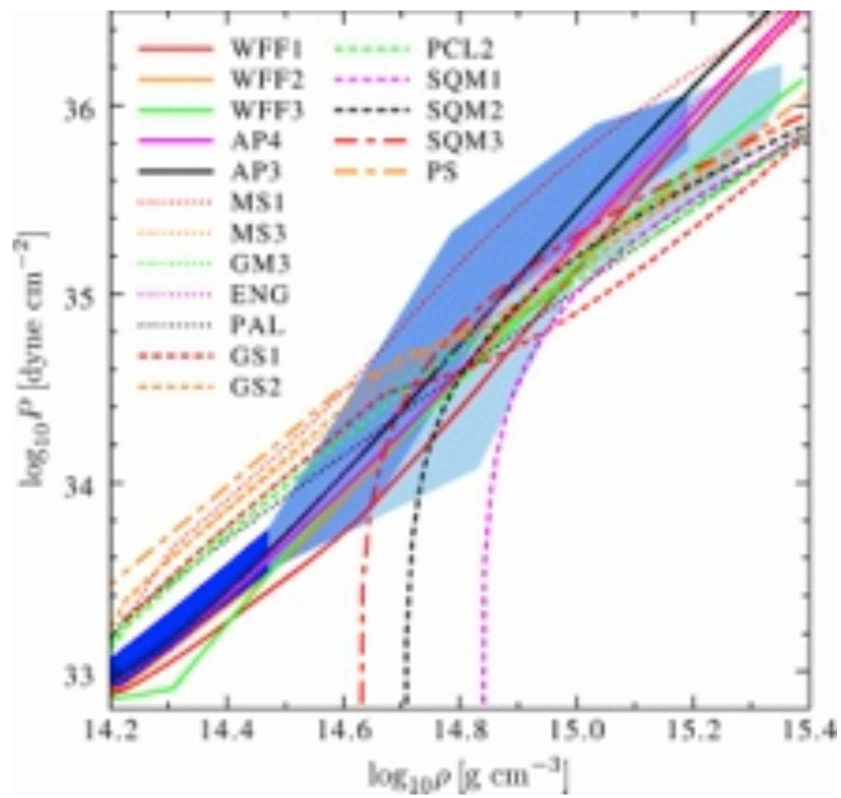
Stiff EOS



Soft EOS



[Read et al. Phys.Rev. D79 (2009) 124033;
Also see: Arunava Mukherjee, Shreya Shah, SB, arXiv:1409.6490 [astro-ph.HE]

Complementing LMXB observations

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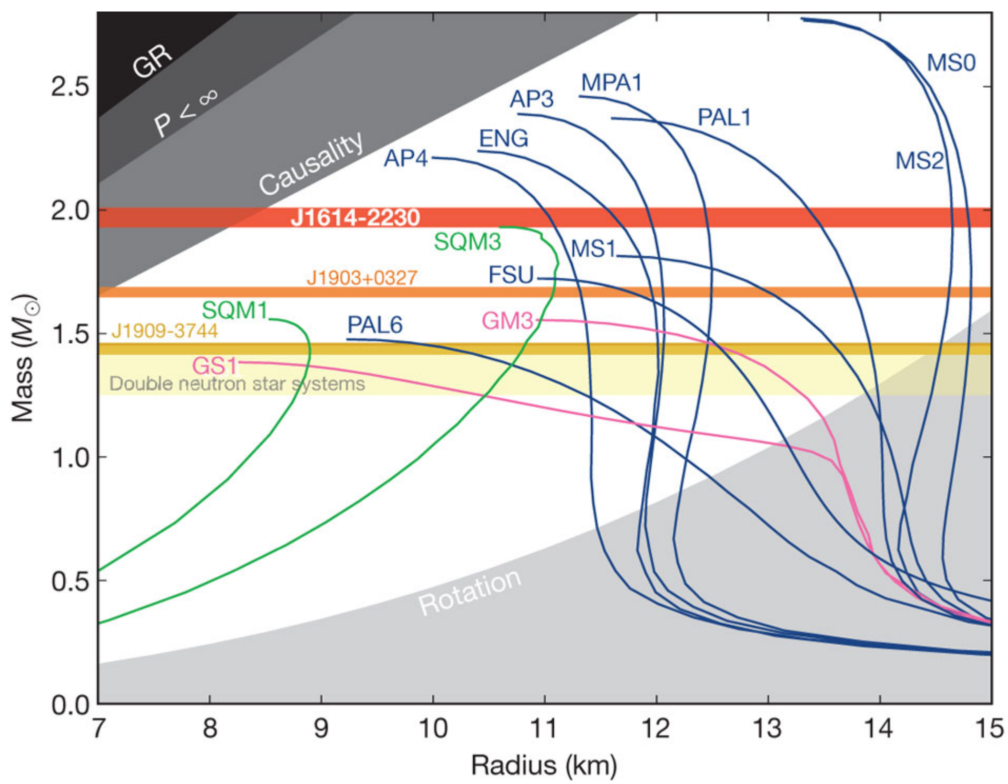

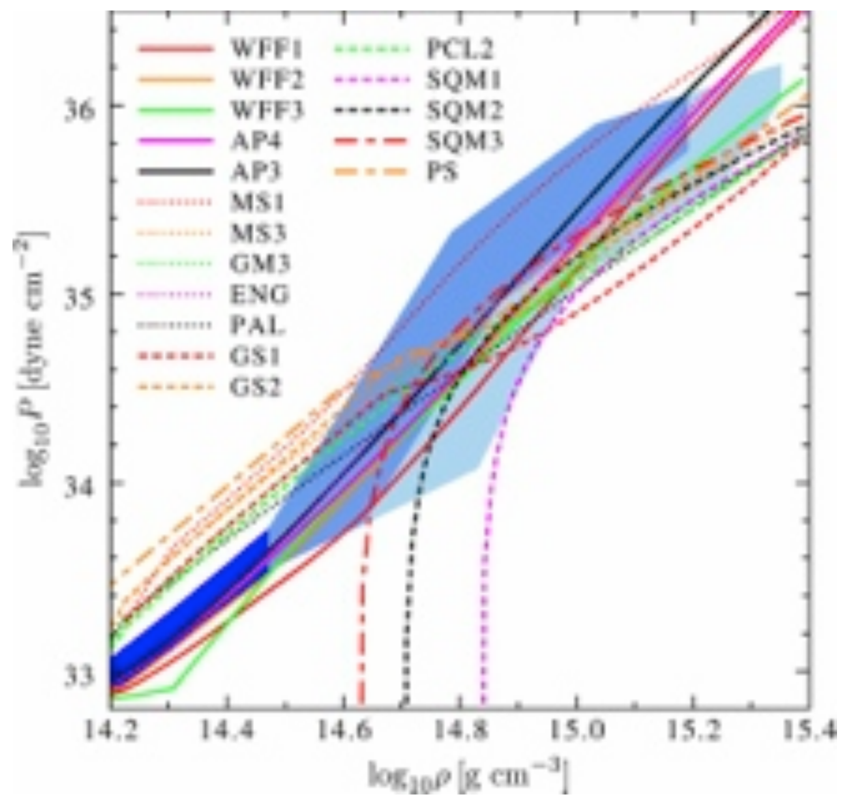

J. Lattimer, ApJ 2012.

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Searching for EM counterpart via GW sky localization

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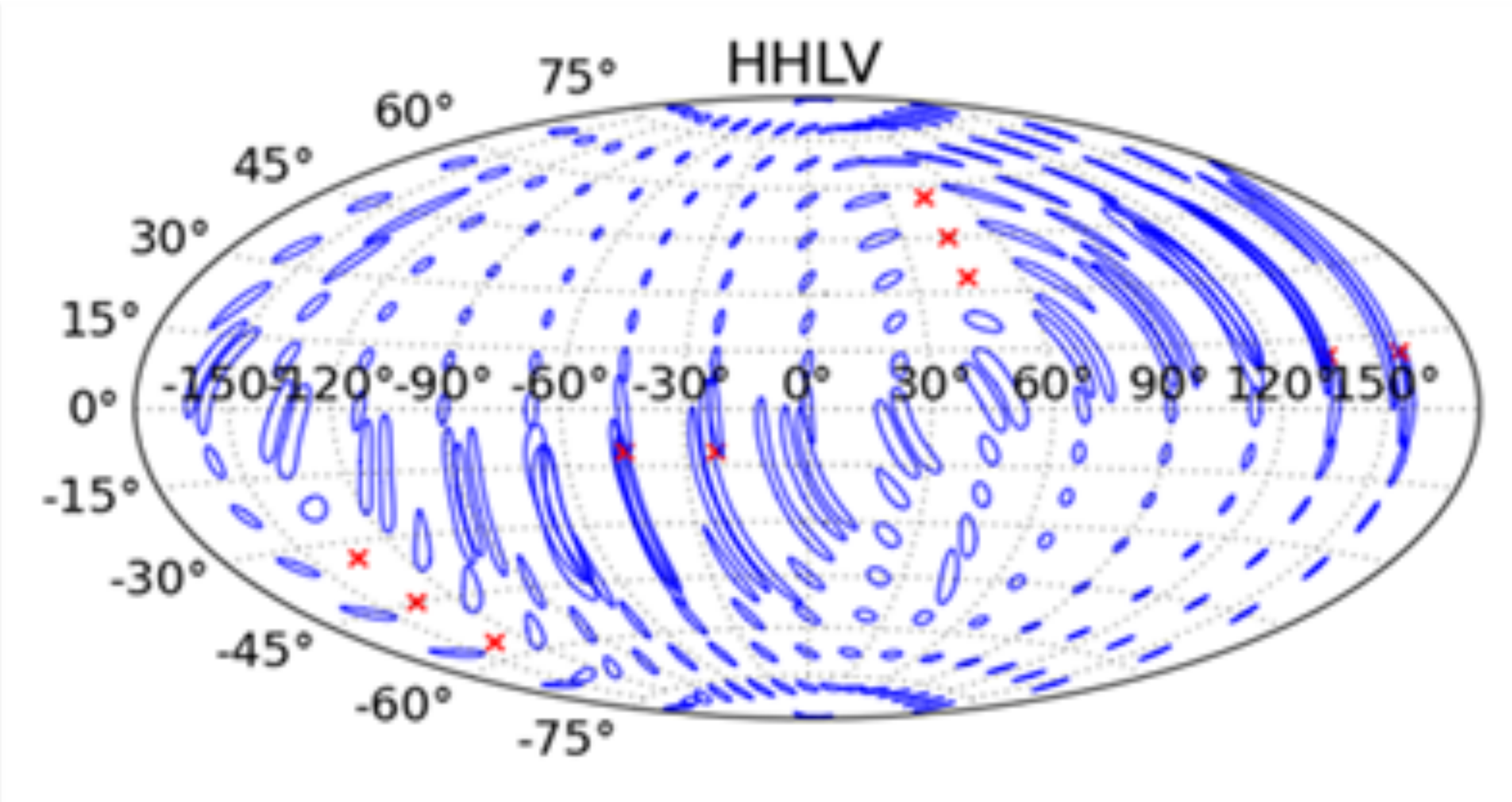

Original plan
2 +1 LIGO USA+ Virgo

Courtesy: S. Fairhurst

The Big Dog GW "event"

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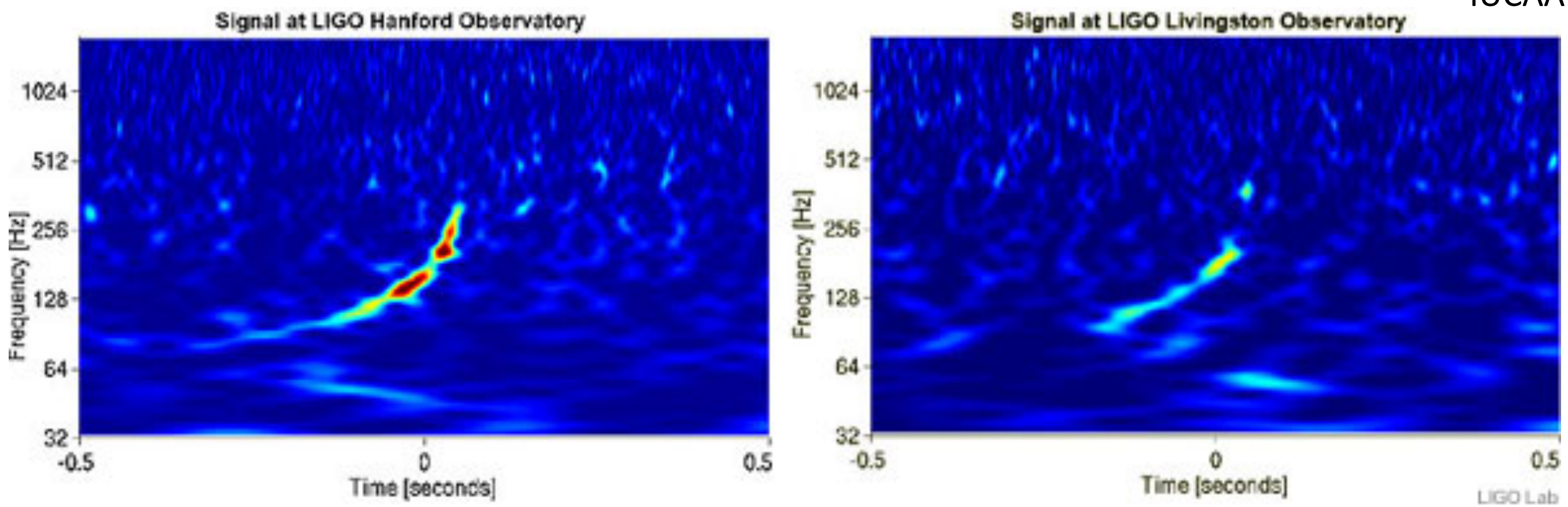

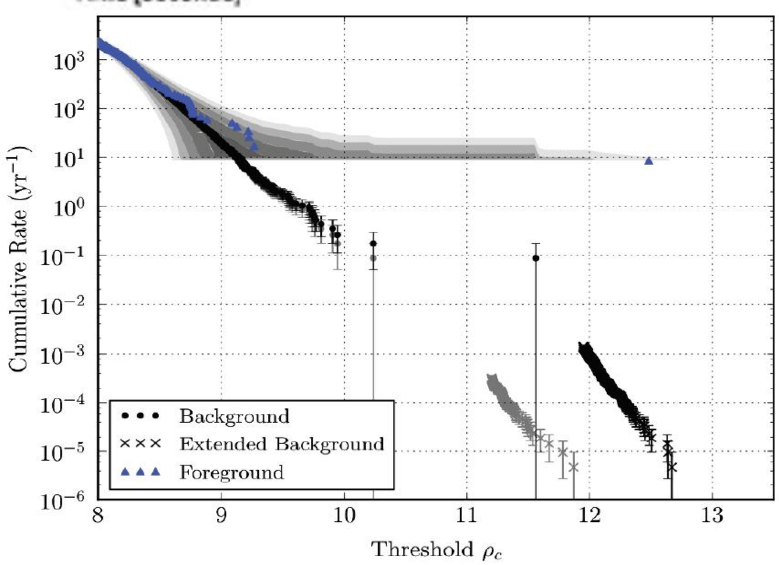

Abadie et al. (LVC), PRD 85, 082002 (2012).

S. Dhurandhar, A. Gupta, A. Pai, Sudhagar, K. S. Phukon, R. Dudi, SB, "Regressing the effect of Non-Gaussian noise artifacts on CBC searches."

N. Mukund, S. Mitra, R. Adhikari, "Adaptive noise cancellation."

The first EM follow-up of a GW candidate: G19377

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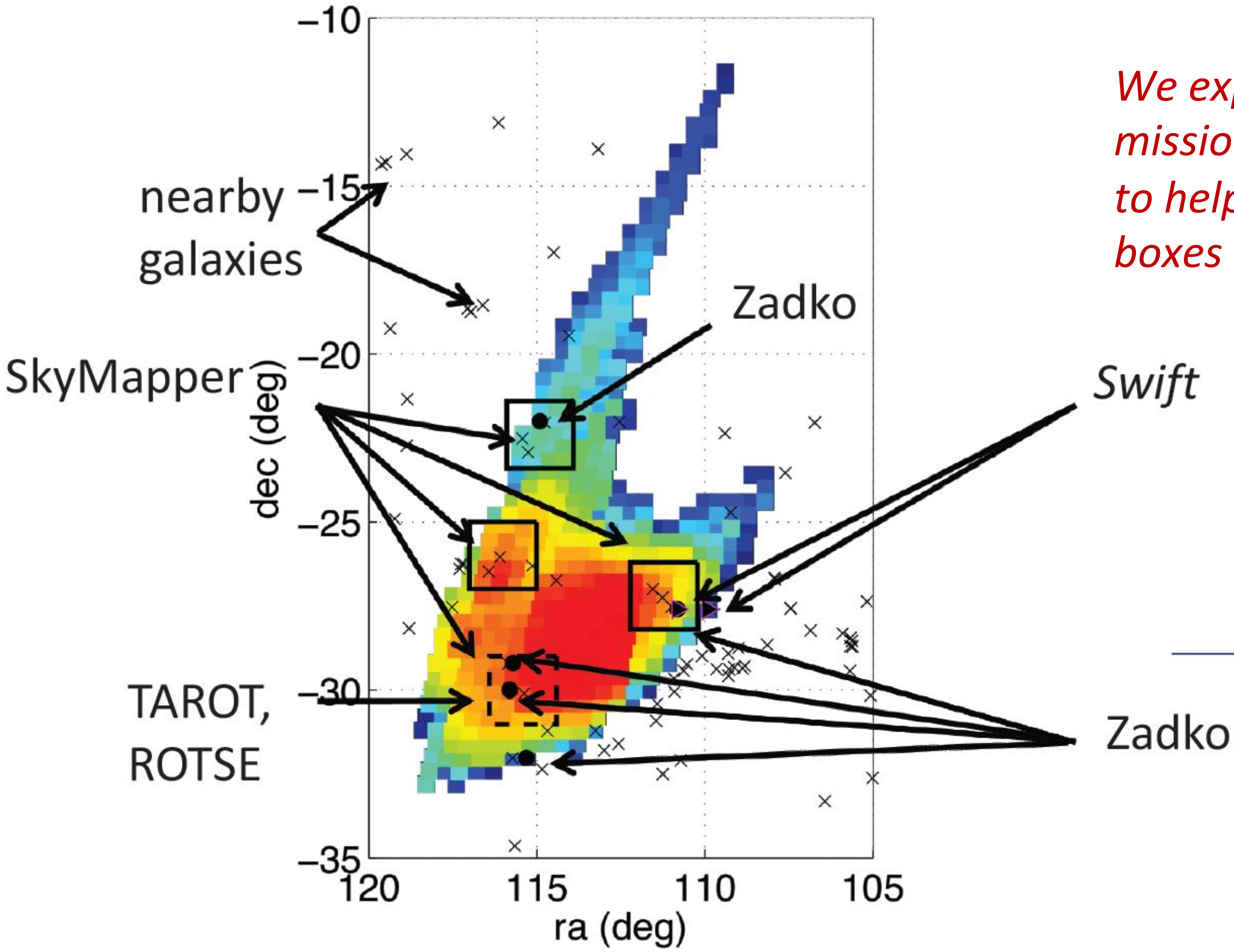
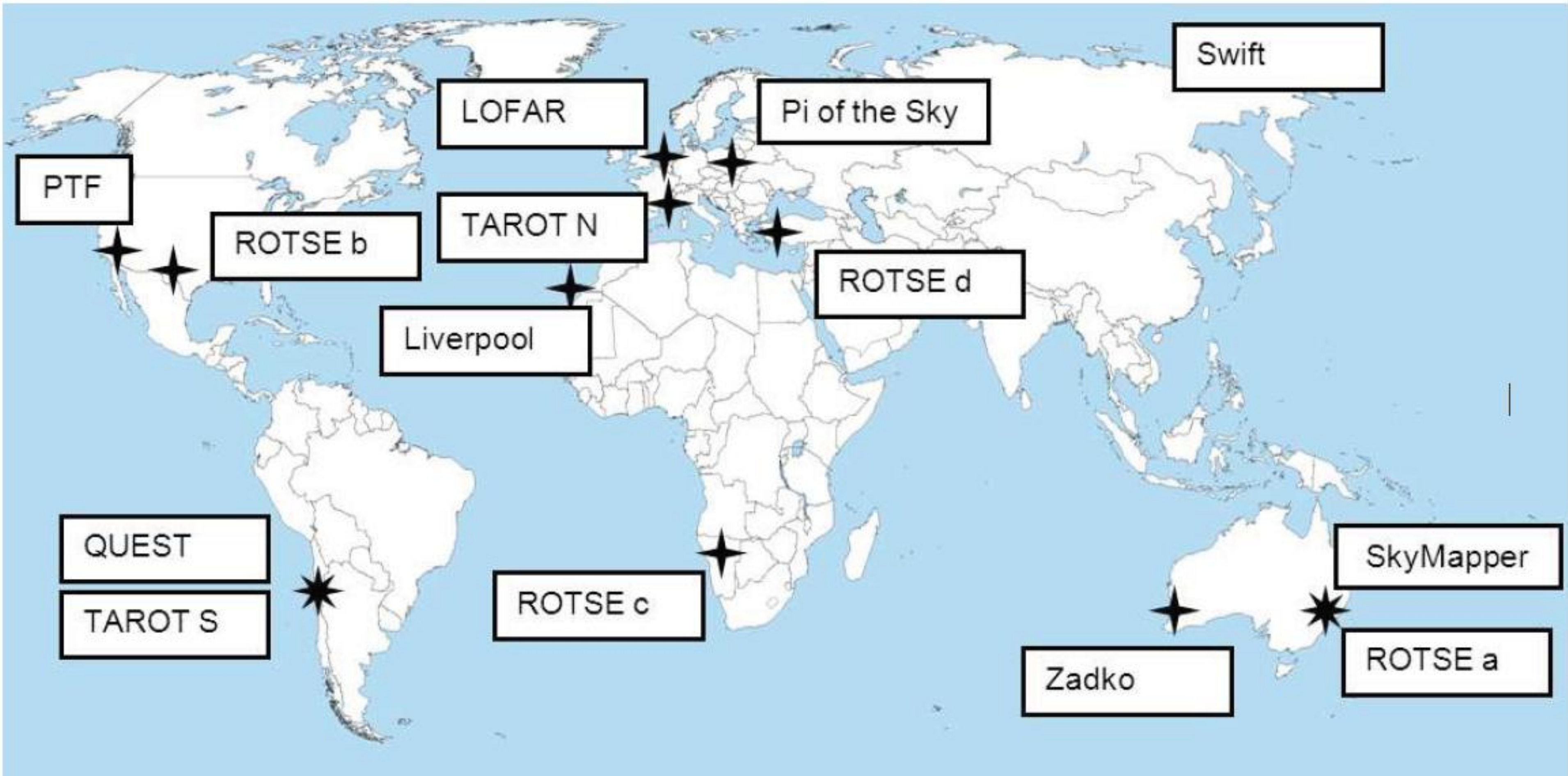


We expect future missions like BlackGEM to help cover the error boxes better.

[Aasi et al., LV collab., arXiv:1310.2314 (2013).]

The Big Dog: EM observatories as partners in crime



Some specs of the EM observatories

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Name	Locations	FOV (square degrees)	Aperture (m)	Exposure Time (s)	Limiting Magnitude	Tiles
Palomar Transient Factory	1	7.3	1.2	60	20.5	10
Pi of the Sky	1	400	0.072	10	11.5	1
QUEST	1	9.4	1	60	20.5	3
ROTSE III	4	3.4	0.45	20	17.5	1
SkyMapper	1	5.7	1.35	110	21.5	8
TAROT	2	3.4	0.25	180	17.5	1
Zadko Telescope	1	0.15	1	120	20.5	5
Liverpool Telescope - RATCam	1	0.0058	2	300	21	1
Liverpool Telescope - SkyCamZ	1	1	0.2	10	18	1

EM follow-up results: G19377

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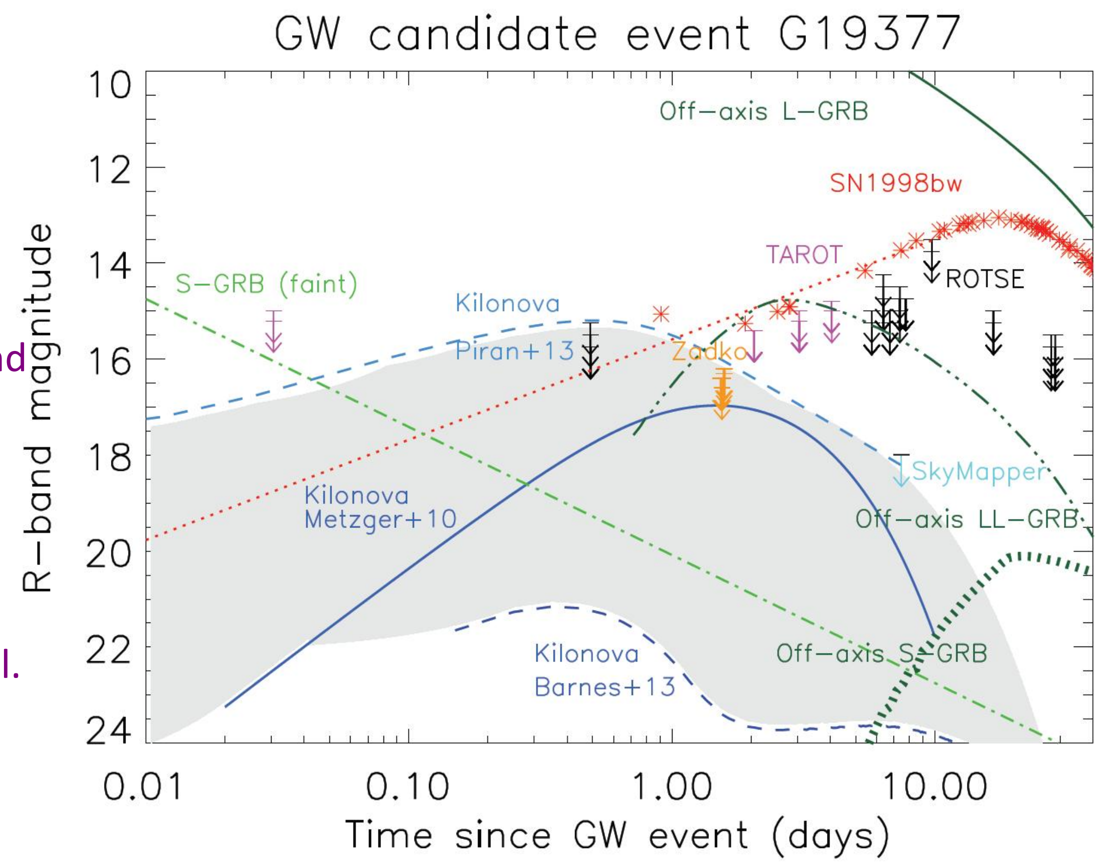
- These searches use post-Newtonian waveform modeling and matched-filtering techniques.*.

[At Indian institutions many new students and postdocs are now joining their senior counterparts B. Iyer, A. Gopakumar, K. G. Arun, C. K. Misra, A. Gupta et al. in the former effort and S. Dhurandhar, B. Sathyaprakash, K. Jotania, A. Pai, A. Sengupta, R. Nayak, S. Mitra, P. Ajith, SB et al. in the latter effort.]



- No GW counterpart detections made yet but are anticipated to happen in the aLIGO era.

Take-home messages

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- The first GW detections will likely happen within this decade.
- After the first few GW discoveries, there will be a strong push for doing astronomy with GWs.
- The transient nature of CBCs makes them well suited for complementing time-domain efforts being pursued by other telescopes.
- EM-GW coincidences will enrich our physical understanding of these sources much more than what they can do individually.
- Are we prepared well enough not to miss this opportunity?