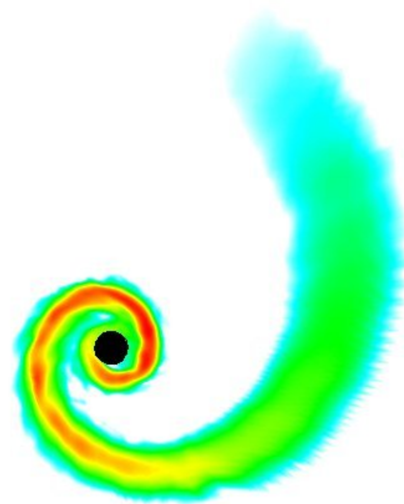
From GW detection challenges to GW astrophysics

(How well can GWs from coalescing binaries constrain NS EOS?)



Sukanta Bose

Supported in part by NSF grant PHY-1206108 & IUSSTF(India).
LIGO-DCC-G1500499

Talk plan

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- GW detection challenge 1: Searching for a needle in a haystack – fast.
- Challenge 2: Is that a real signal or just the detector whistling?
- Beyond detection: Constraining the neutron star EOS with GW observations.
- Astronomy challenge (#3): Turning a GW detection into a coincidence with an EM / particle counterpart → Case for LIGO-India & collaboration with astronomy / particle physics community.

Strength of gravitational waves

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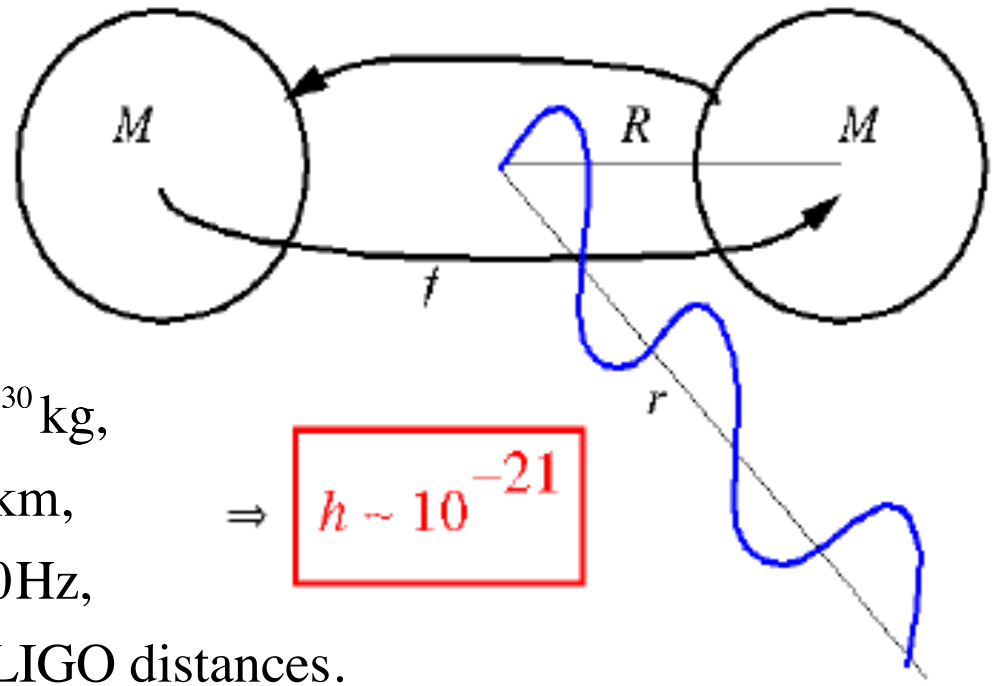
- GWs arise from a time-varying *quadrupole* moment, $Q \sim MR^2$
- GW strain amplitude depends on two time-derivatives of Q.
- Dimensional analysis then shows:

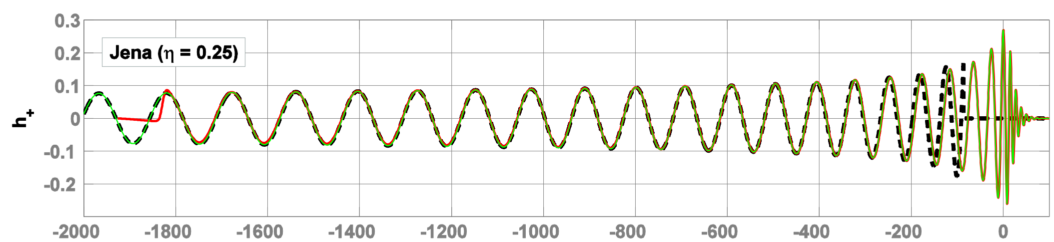
$$h \propto \frac{G\ddot{Q}}{c^4 r}.$$



$M \sim 10^{30}\,\mathrm{kg}$,
$R \sim 20\,\mathrm{km}$,
$f \sim 400\,\mathrm{Hz}$,
Initial LIGO distances.

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

Compact Binary Coalescence (CBC) waveform.



Gravitational wave polarizations

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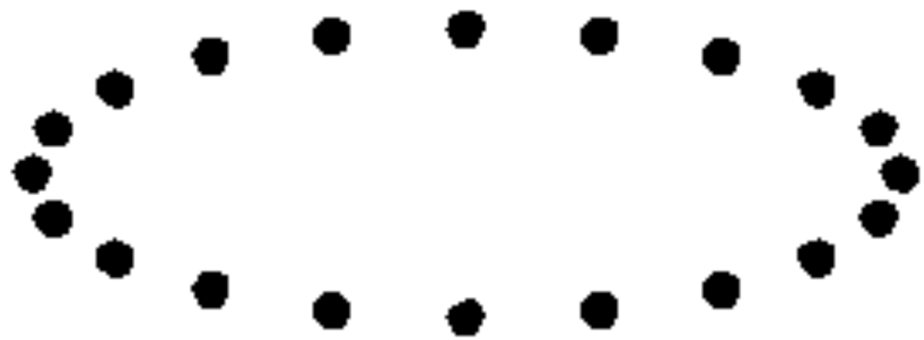

The Plus (+) polarization

Gravitational wave polarizations

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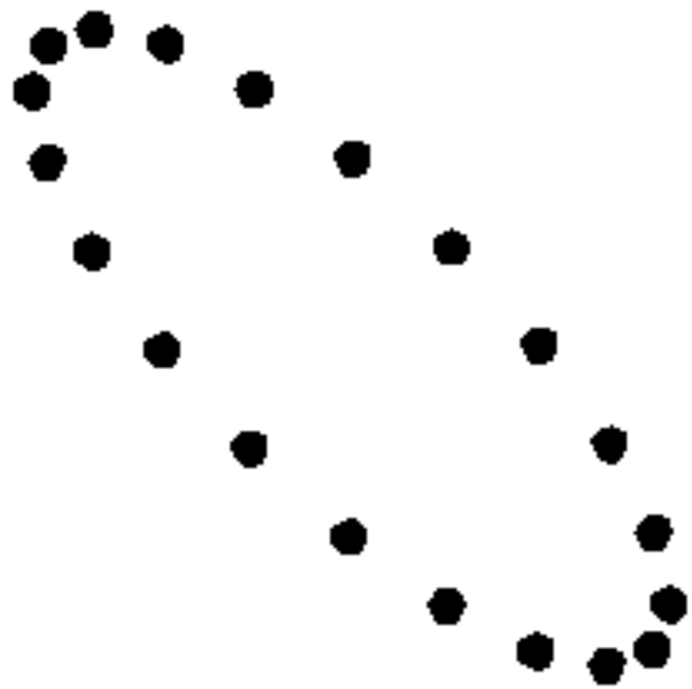

The Cross (x) polarization

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Gravitational wave detection

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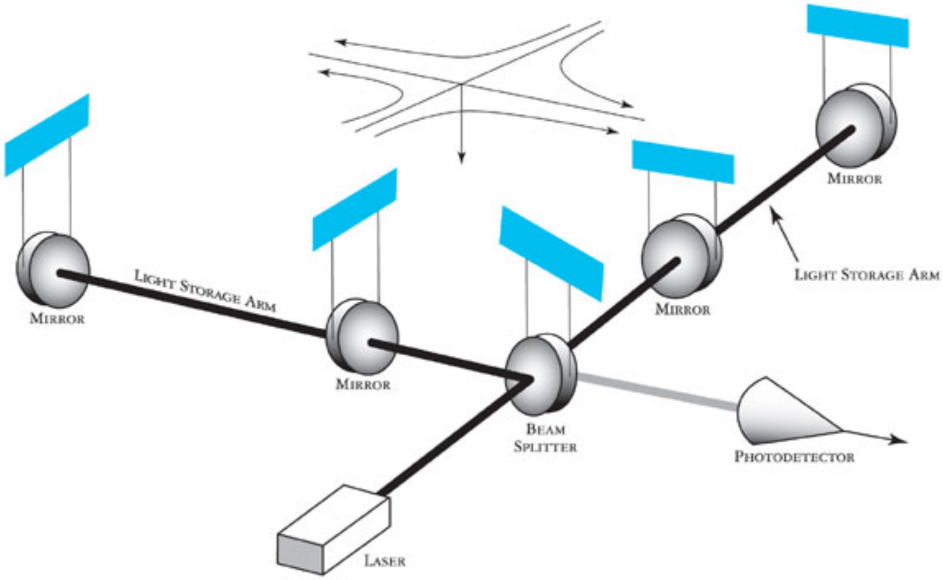
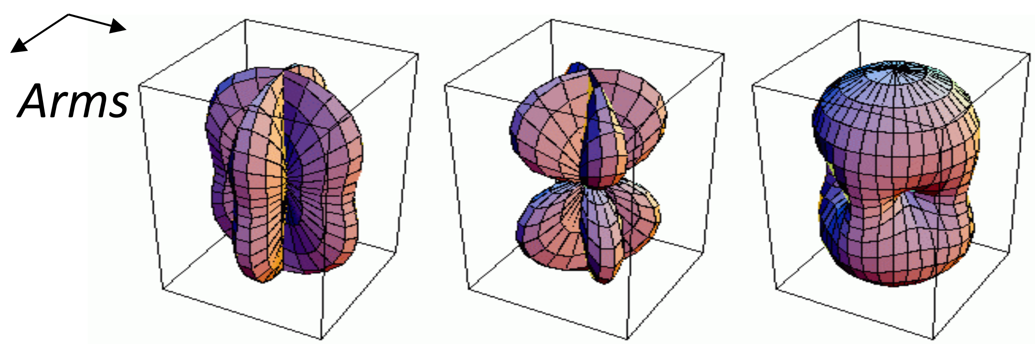


LIGO-Hanford, WA

The signal is the moving fringe at the photodiode

Sky response



+ polarization *x polarization* *unpolarized*

What Limits the Sensitivity of the *Earth-based* Interferometers?

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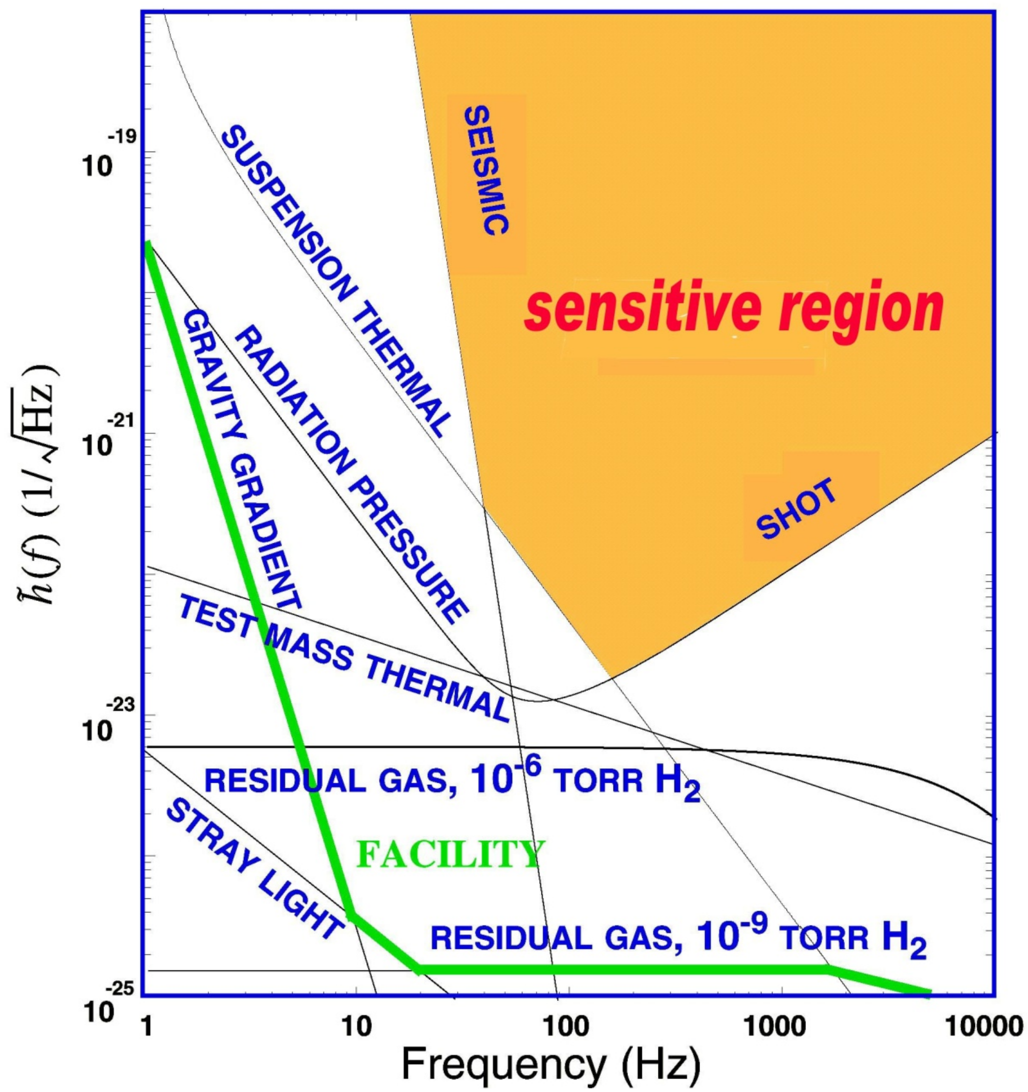
- Seismic noise & vibration limit at low frequencies
- Thermal noise of suspensions and test masses at mid frequencies
- Quantum nature of light (shot noise) limits at high frequencies
- Limitations of facilities much lower

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



Gravitational-wave interferometers & their sources

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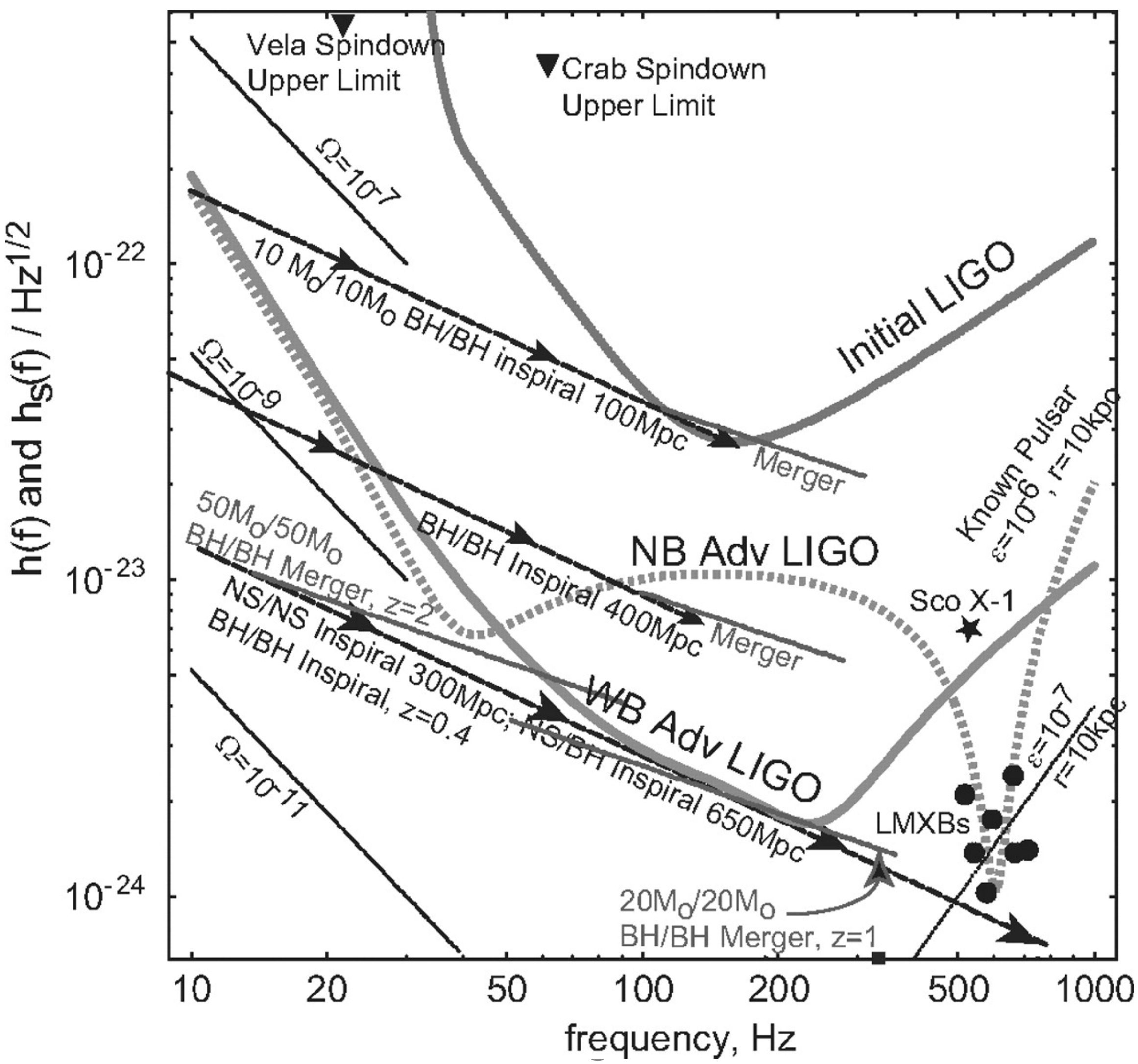

[Cutler & Thorne, CQG (2002).]

Projected improvement in observation depth of GWOs

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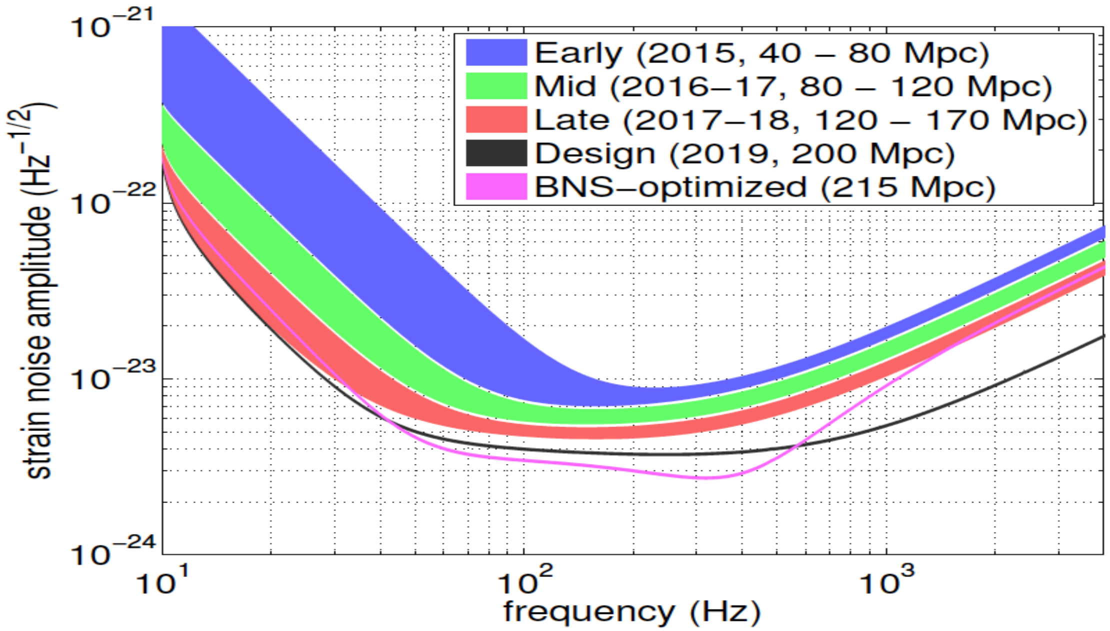

[J. Aasi et al., LIGO Scientific and Virgo Collaborations., arXiv:1304.0670 [gr-qc] (2013).]

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Detection Challenge 1: High Computational Costs

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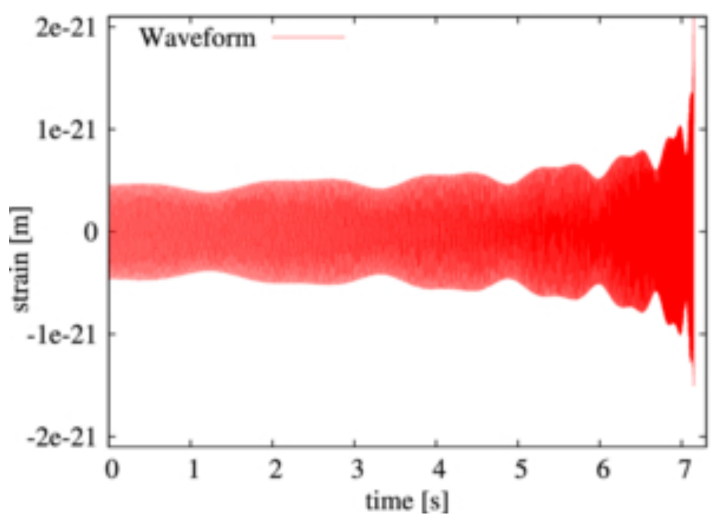
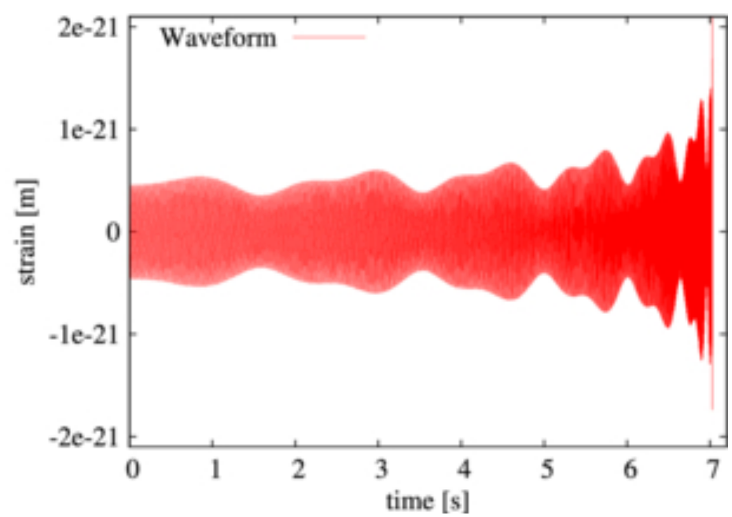
Bank	Number of templates
Non-spinning templates	72,000
Single spin templates	750,000





[Shaon Ghosh, I. Harry, SB, LIGO-DCC-G-1300550 (2013).]

A speed-up idea: Singular value decomposition of "CBC" template banks

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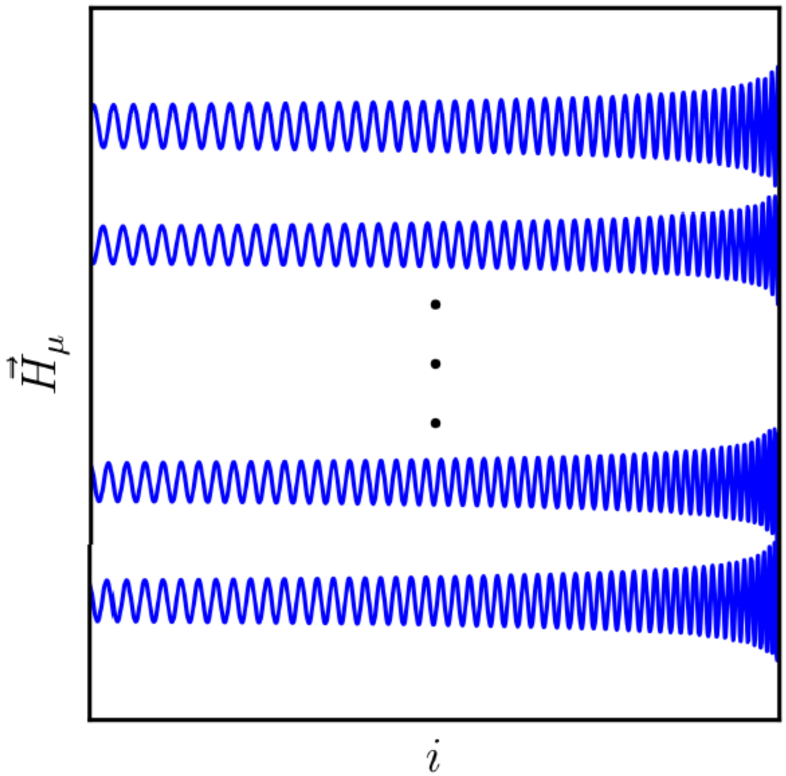
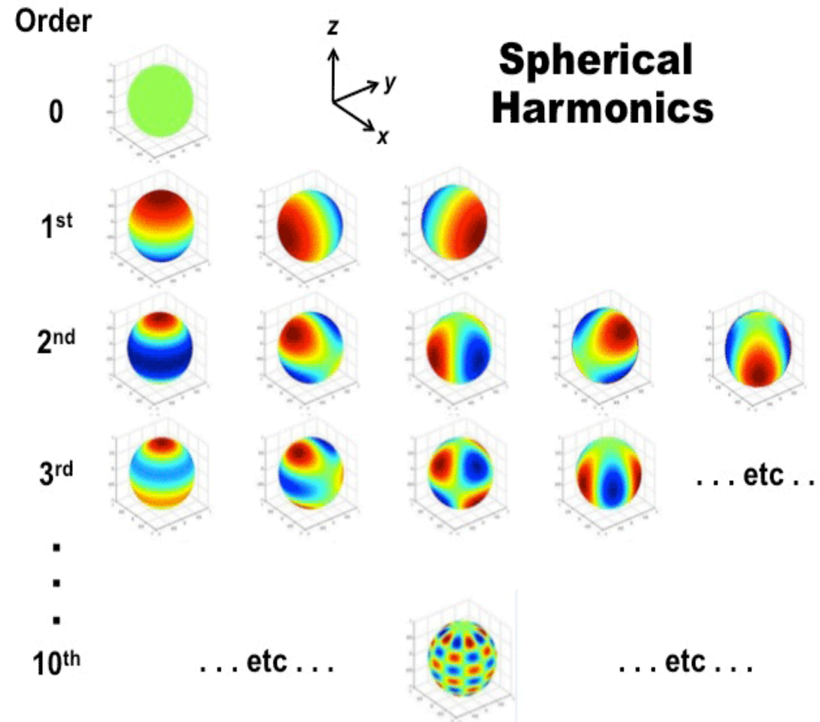


Compact binary coalescence (CBC) templates H_μ ; i is the time-series index.



A basis for patterns in the sky.

A speed-up idea: Singular value decomposition of "CBC" template banks

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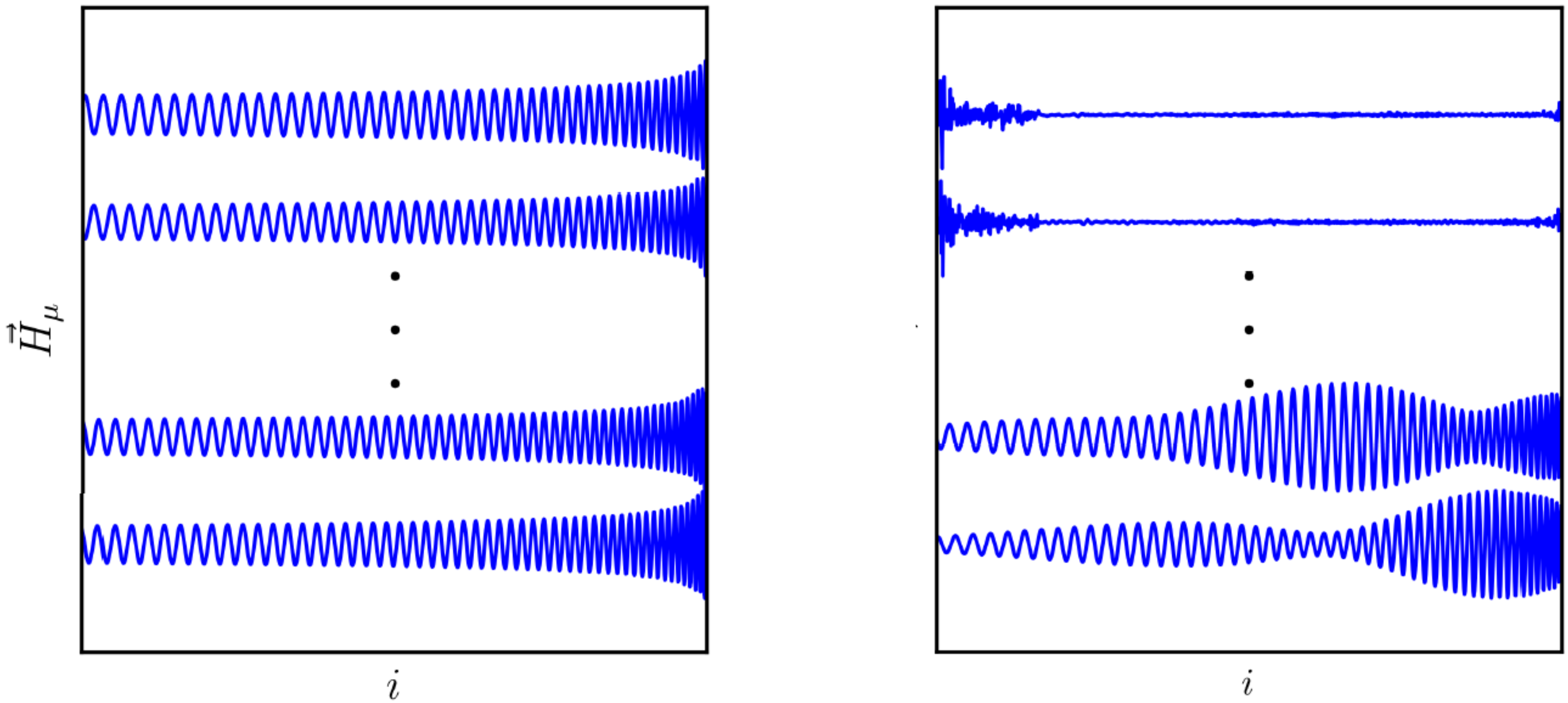


Compact binary coalescence (CBC) templates H_μ ; i is the time-series index.

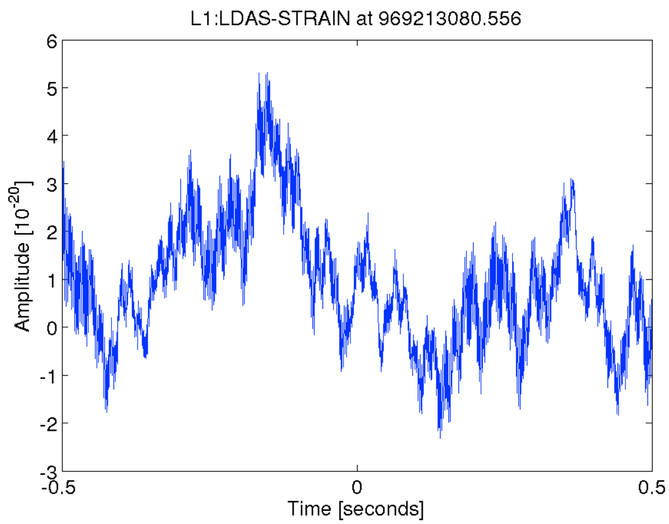
[Cannon et al., PRD82, 044025 (2010); Nairwita Mazumder, LIGO-DCC-G1401030 (2014).]

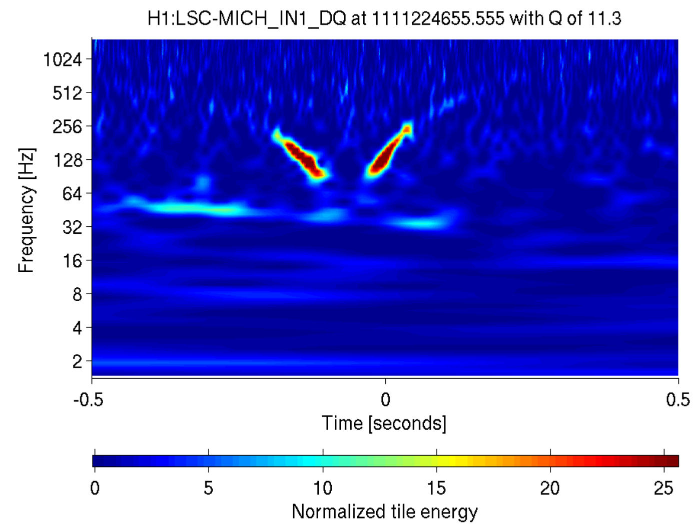
SVD basis vectors R_μ .

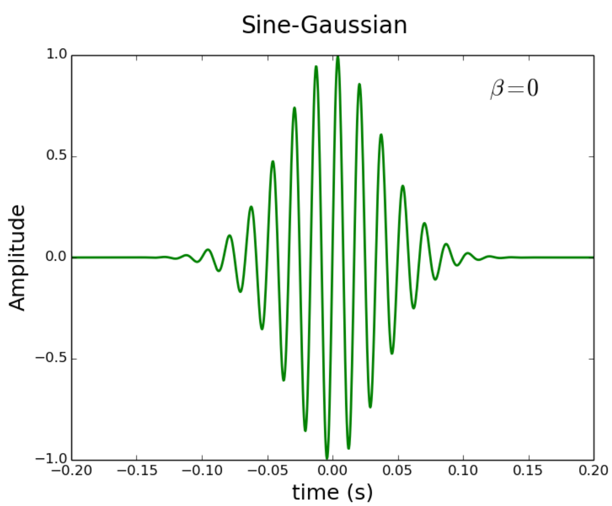
[For GPU speed up, see SB, Pandey, Phukon, LIGO-1500194; Yuan Liu et al 2012 Class. Quantum Grav. 29 235018]

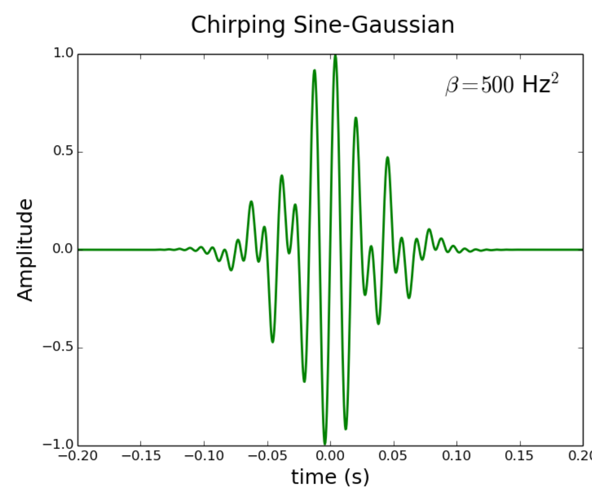
IUCAA Data Centre

Challenge 2: Noise transients









Bernard Hall, Nairwita Mazumder, LIGO-DCC-G1500496 (2015)

The Big Dog GW "event"

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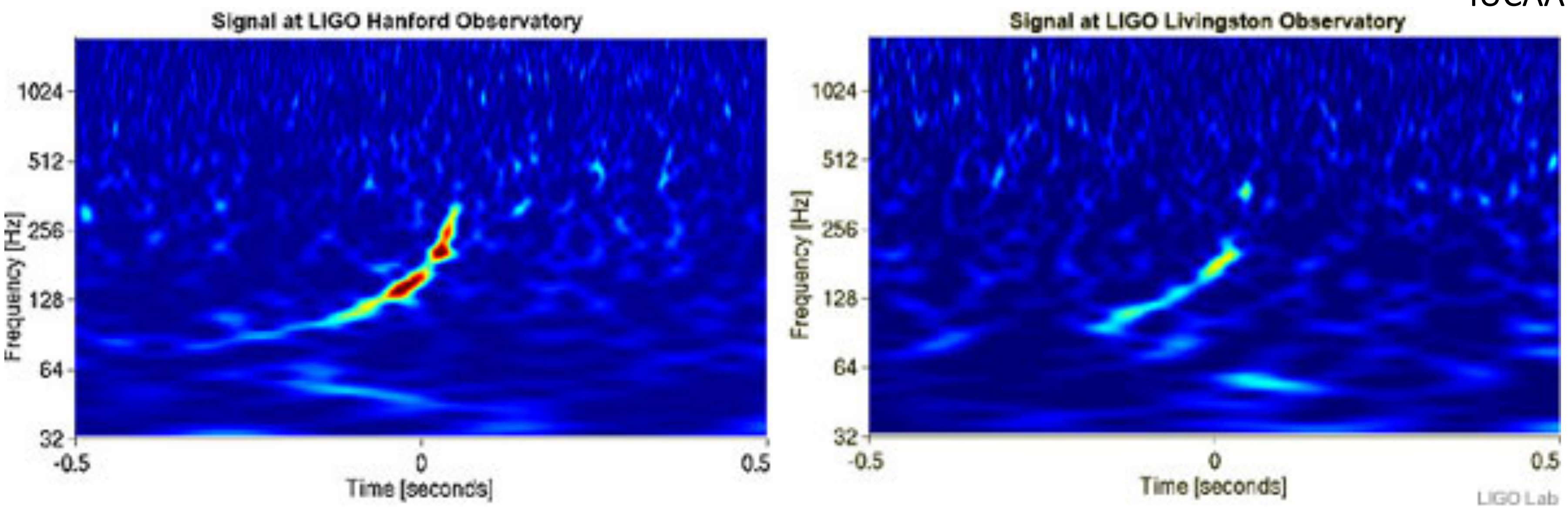
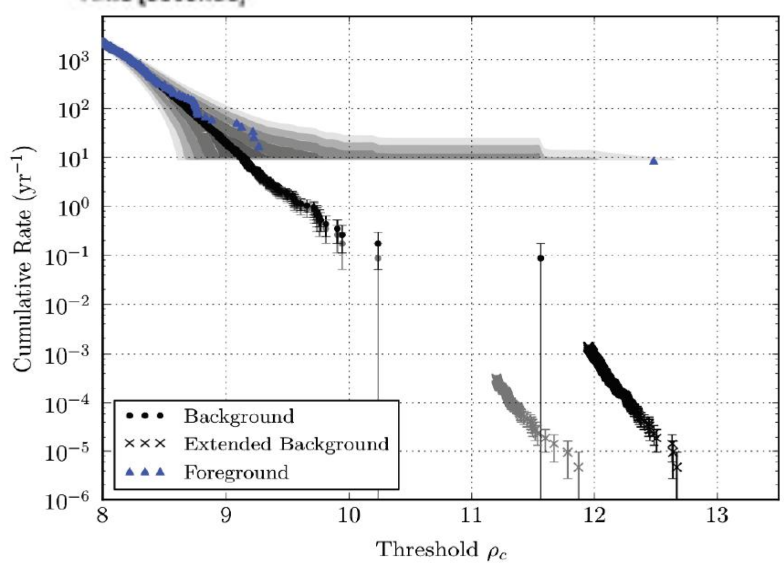




Abadie et al. (LVC),
PRD 85, 082002 (2012).

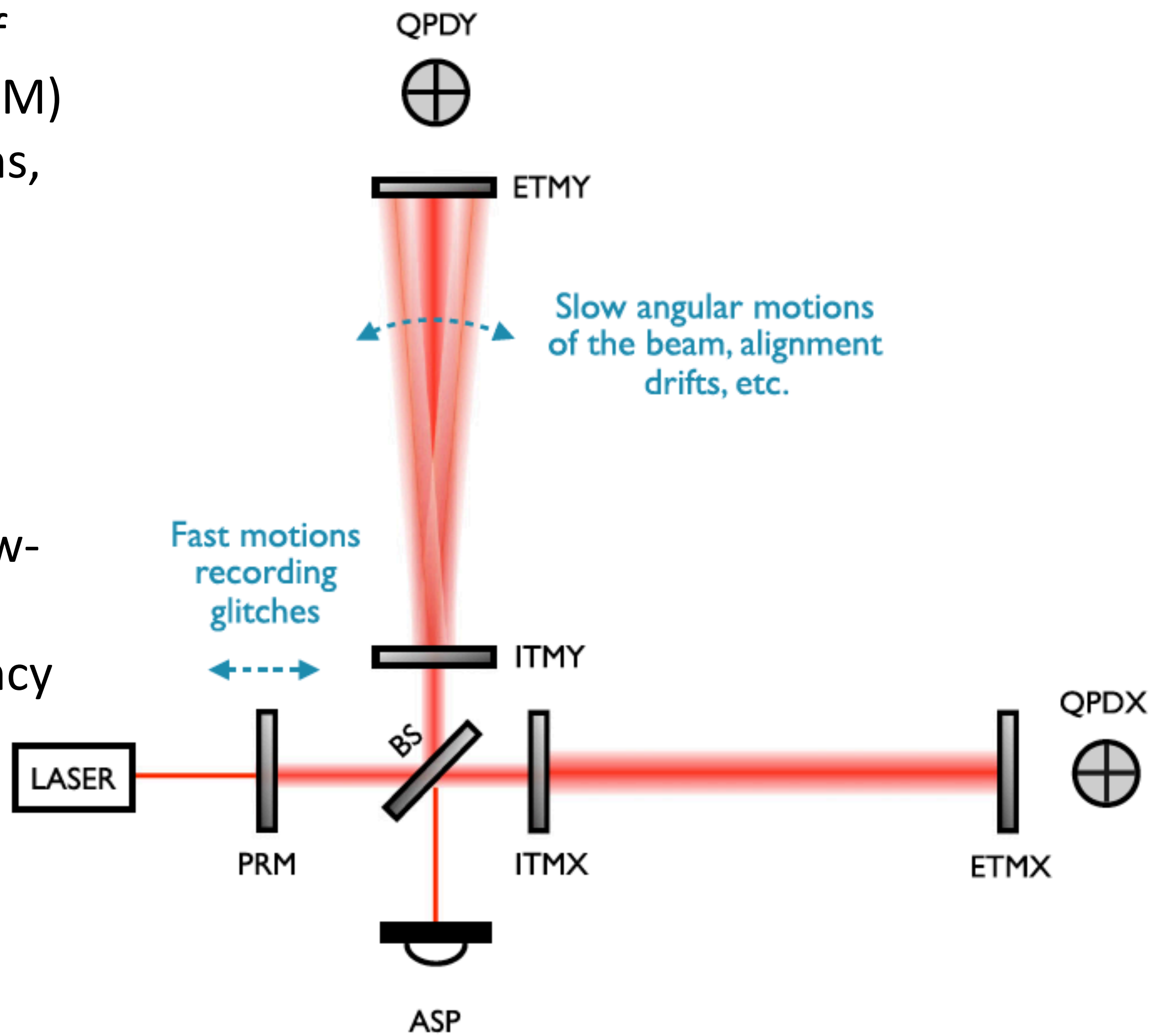
A mechanism for bilinear coupling

- The fast low-amplitude jitter of the power-recycling mirror (PRM) can create intensity fluctuations, which in turn can ride on with low-frequency motion of the end-test mass.

- Length of cavity is quadratic in mirror rotation angle. Large low-frequency angular fluctuations couple with small high-frequency fluctuations to create strain noise:

$$L \approx L_o + \alpha\theta^2,$$

$$\Delta L(\omega) \approx \alpha\theta(\omega_{low})\theta(\omega_{high})$$



S. Whitcomb, https://dcc.ligo.org/LIGO-G000336/public.

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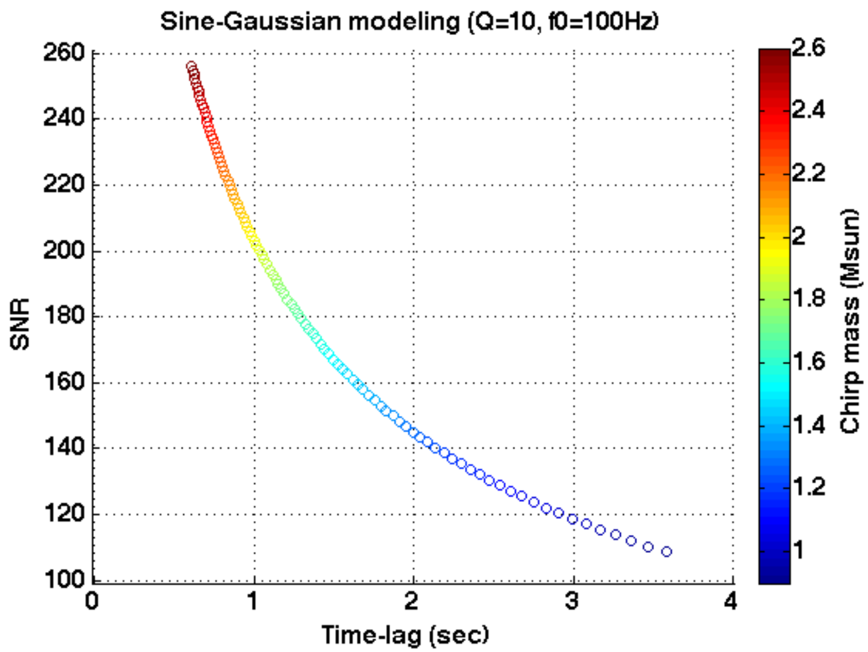
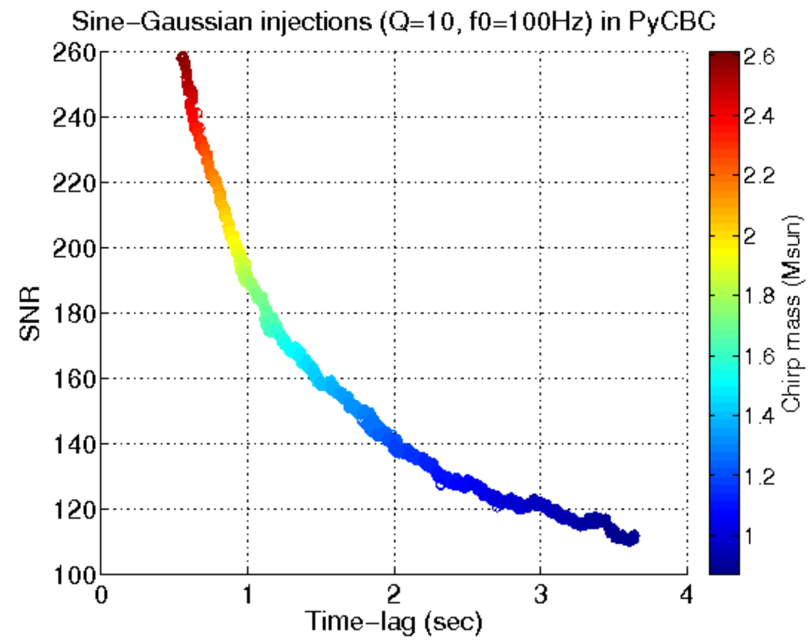
Response of a CBC template-bank to a sine-Gaussian glitch





Prediction from theoretical modeling of effect of a sine-Gaussian glitch on *Compact Binary Coalescence (CBC)* template SNRs and time-lags.

The above plot shows what a search pipeline produces for a CBC template bank.

Dhurandhar, Gupta, Lundgren, SB, LIGO-DCC-G1500545 (2015)

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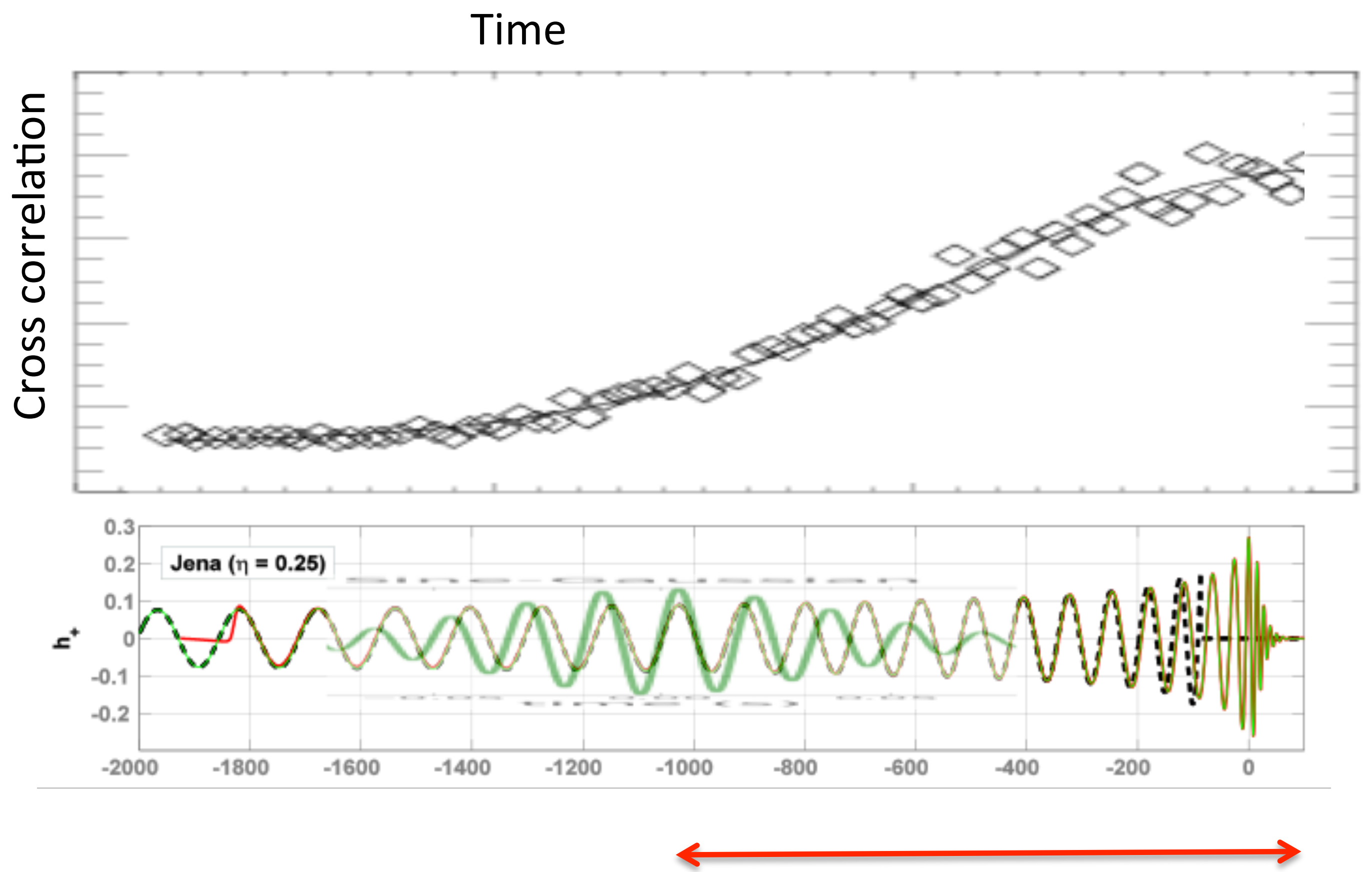
Why the time-lag?



Time lag

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Response of a CBC template-bank to a *CBC signal*

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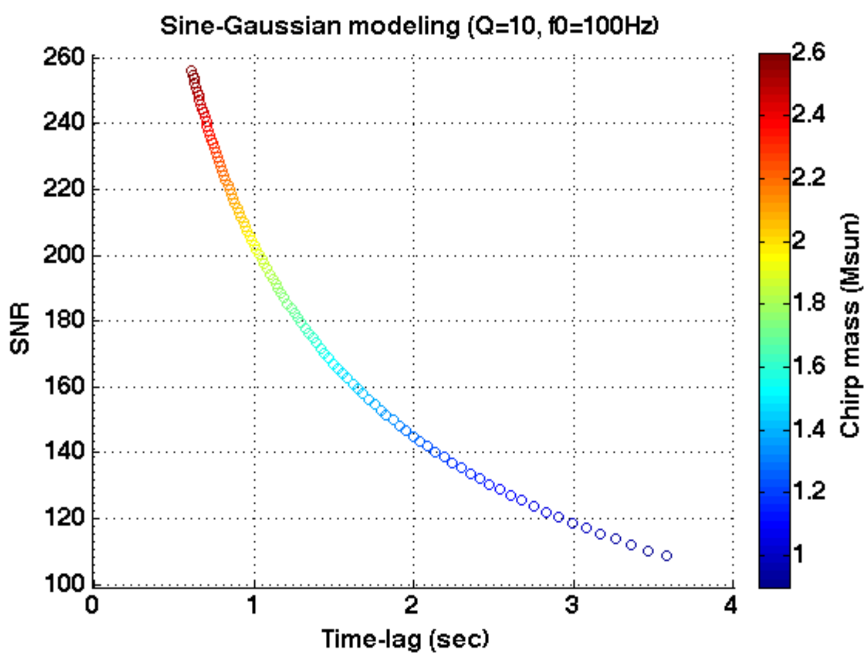

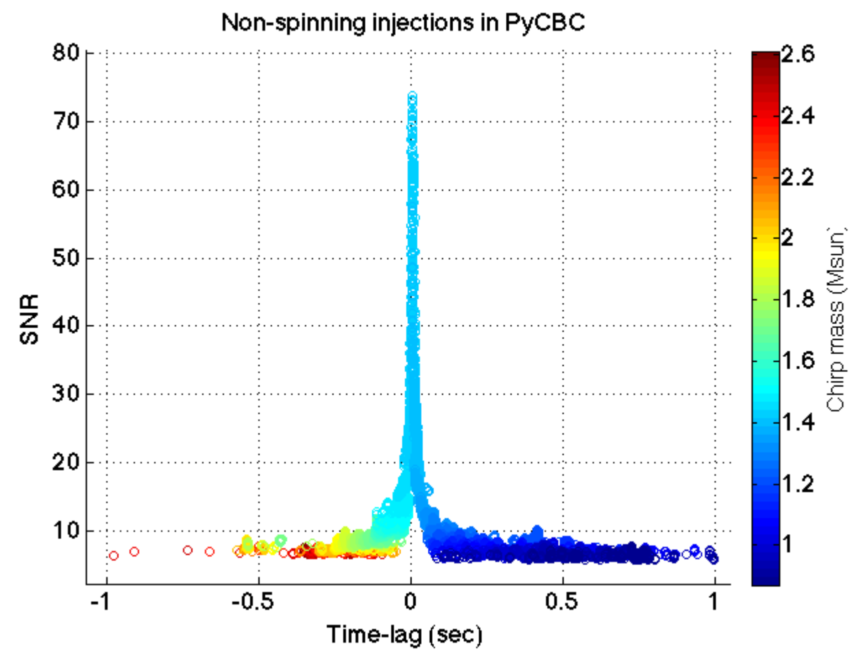

Prediction from theoretical modeling of effect of a sine-Gaussian glitch on CBC template SNRs and time-lags.

The above plot shows what a search pipeline produces *for a CBC signal.*

Dhurandhar, Gupta, Lundgren, SB, LIGO-DCC-G1500545 (2015)

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GW applications in other areas of science?

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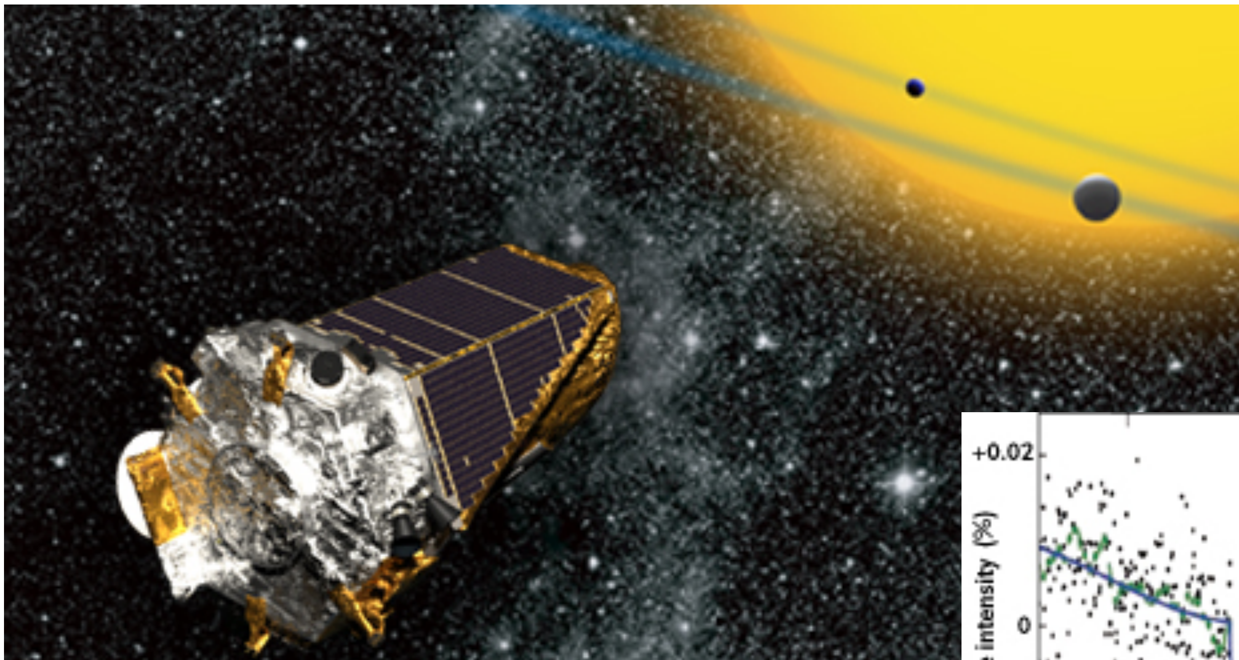

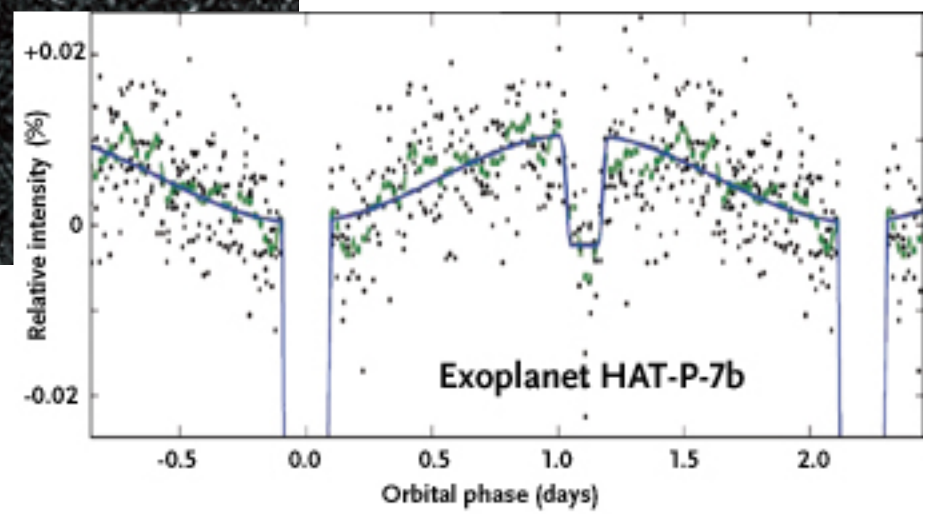

The Kepler mission

GW methods have aided exo-planet discoveries!

S. Seader et al., Astrophys.J.Sup. 206 (2013) 25.

GWs & Neutron star EOS:
Why is NS EOS important?

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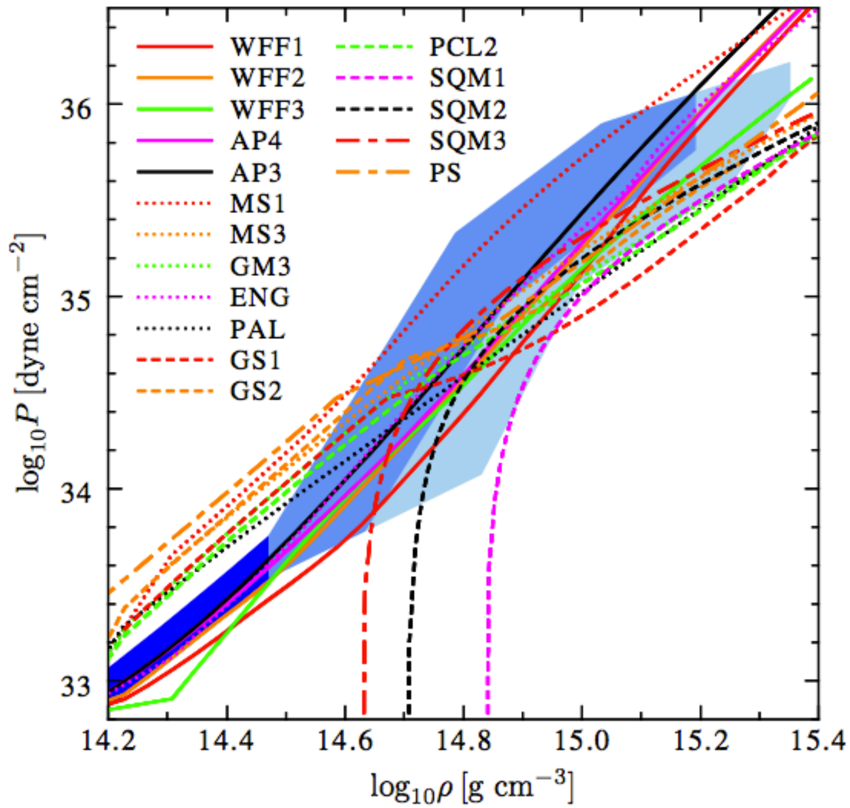
- The NS EOS depends on the *nuclear composition and interactions* in a neutron star.

- Observational constraints on NS EOS will shed light on the nature of many-body nucleon interactions that cannot be probed in terrestrial experiments in the foreseeable future.



J. Lattimer, ApJ 2012.

How can GWs constrain the NS EOS?

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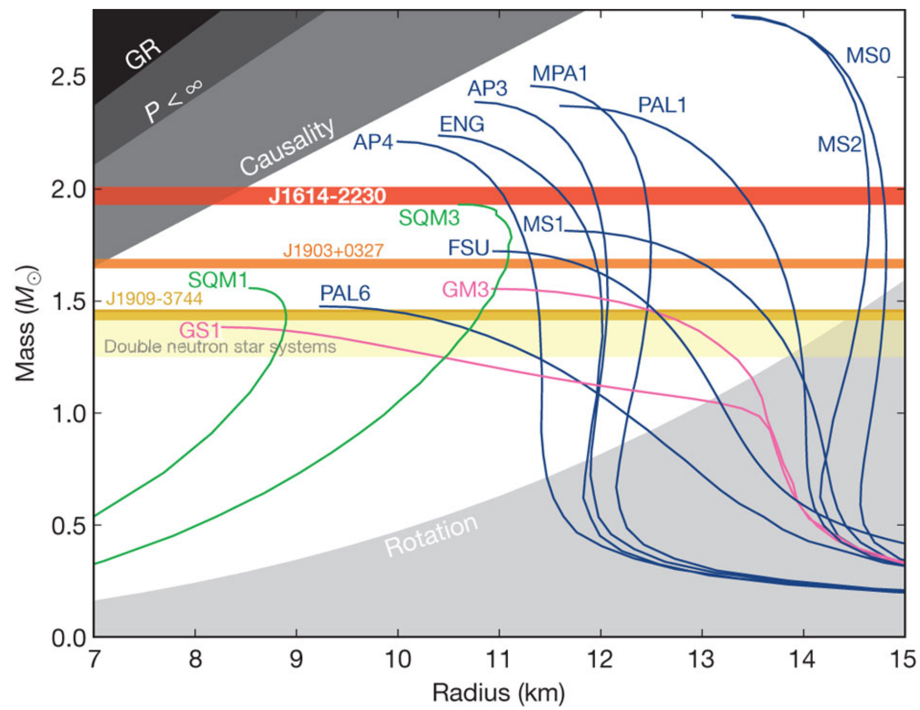
- How stiff or soft the NS EOS is determines how much the NS will flex (with quadrupole moment Q_{ij}) in an external tidal field, E_{ij} .

The EOS parameter to be measured is λ, where $Q_{ij} = -\lambda E_{ij}$, and

$$\frac{\lambda}{M^5} = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5 \approx 10^2 - 10^5.$$

k_2 is the second Love number. It is bigger for stiffer EOS.

- The flexing of a neutron star affects the GW emitted by it.



J. Lattimer, ApJ 2012.

NS-NS and NS-Black Hole coalescences as probes of NS EOS?

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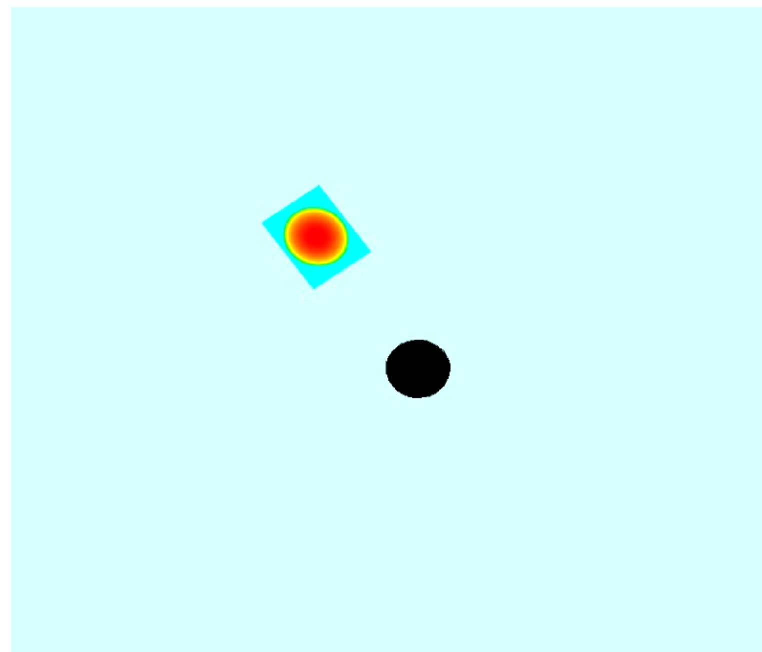
- Non-extreme case:
  low mass, non-extremal spin hole
- NS: M/R=0.144 (R=14km for $M=1.4M_{\odot}$); BH: $M=4M_{\odot}$, **S=0.5**
- Polytrope (toy matter);
- $P=\kappa\rho^{\Gamma}$; $\Gamma=2$;
- neutrinos/MHD off.
- Result: Moderate sized accretion disk.



[Lovelace, Duez et al. PRD 2013;
K. Chakravarti, A. Gupta, SB, in prep.]

Courtesy: Matt Duez

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Effect of EOS on GWs

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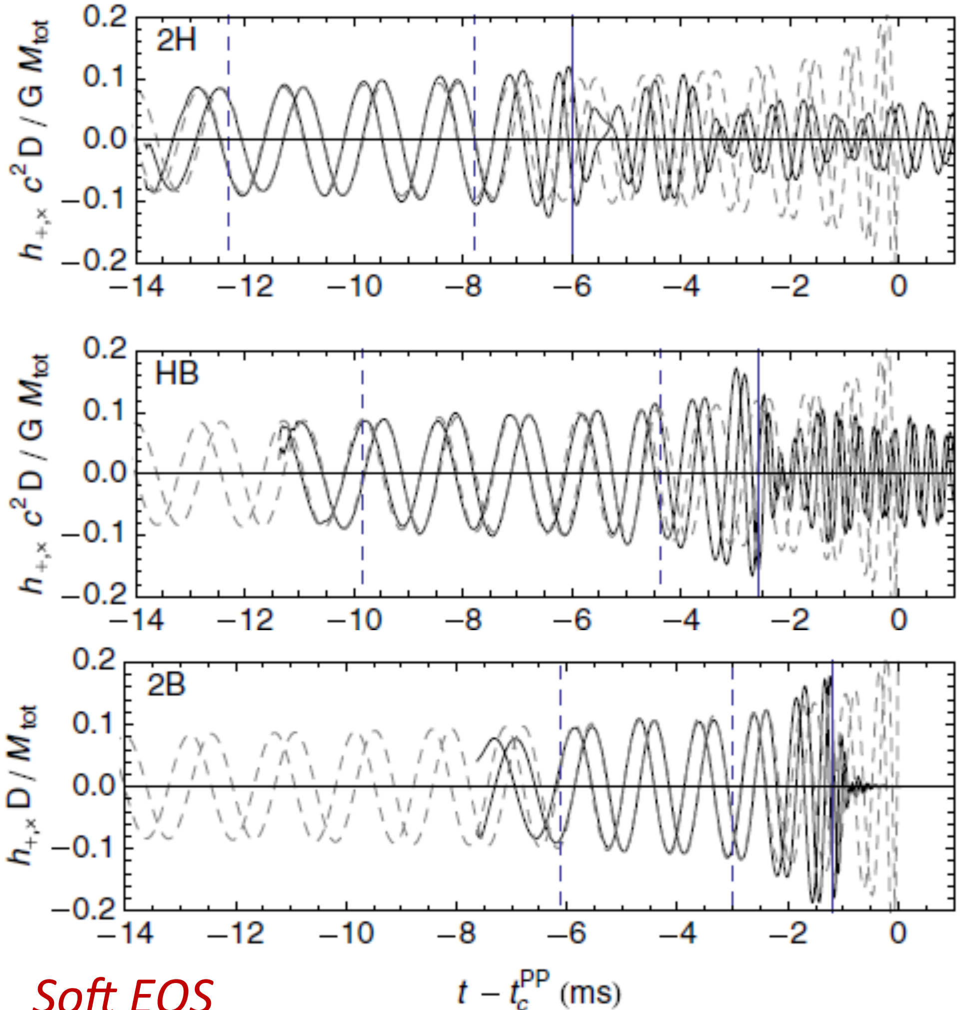
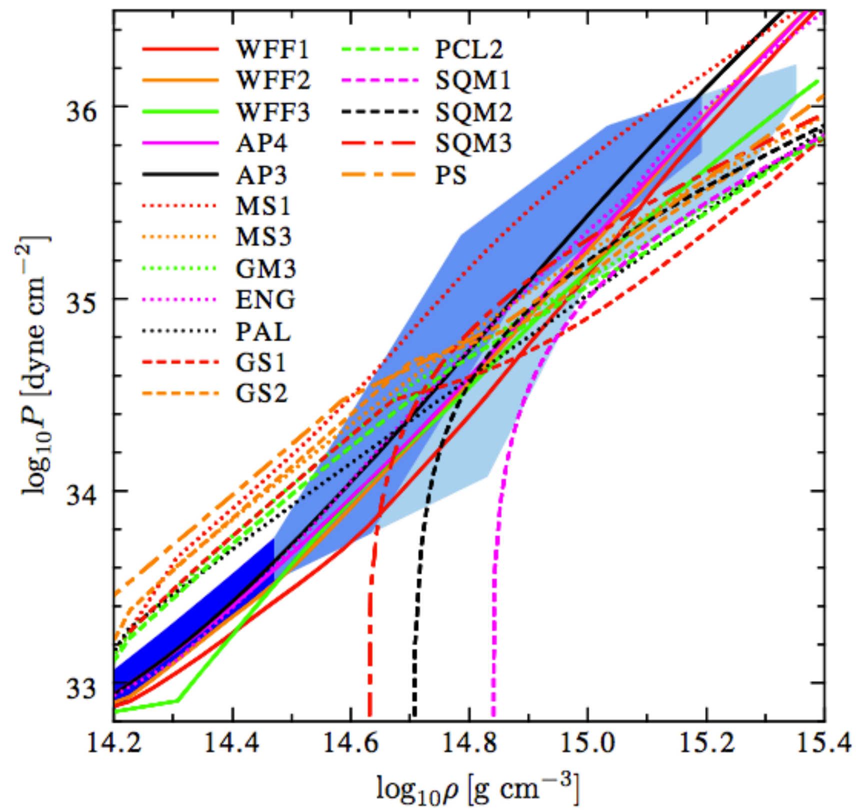
Stiff EOS



Soft EOS



[Read et al. Phys.Rev. D79 (2009) 124033;
Hebeler, Schwenk, Eur.Phys.J. A50 (2014) 11]

NS tide in waveforms

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Total phase = Point-particle phase + Tidal phase-correction.

Point-particle phase has non-spinning and spinning (aligned or anti-aligned) terms up to 3.5pN. We add test-particle non-spinning corrections for 4pN to 6pN to bridge the gap up to the terms where tidal corrections are present (5pN and 6pN).

Tidal phase-correction is:

$$\Phi_{\text{tidal}} = \sum_{i=1}^{2} \frac{3\lambda_i}{128\eta M^5} \left[-\frac{24}{\chi_i}\left(1+\frac{11\eta}{\chi_i}\right)\left(\frac{v}{c}\right)^5 - \frac{5}{28\chi_i}\left(3179 - 919\chi_i - 2286\chi_i^2 + 260\chi_i^3\right)\left(\frac{v}{c}\right)^7 \right],$$

[Vines, Flanagan, Hinderer, arXiv:1101.1673v1.; Damour, Nagar, Villain, PRD85, 123007 (2012).

where $v = (M\omega)^{1/3}$, $\chi_i = m_i / M$ and "i" is binary component index.

$M = m_1 + m_2$ and $\eta = m_1 m_2 / M^2$.

Double neutron star systems: Populations

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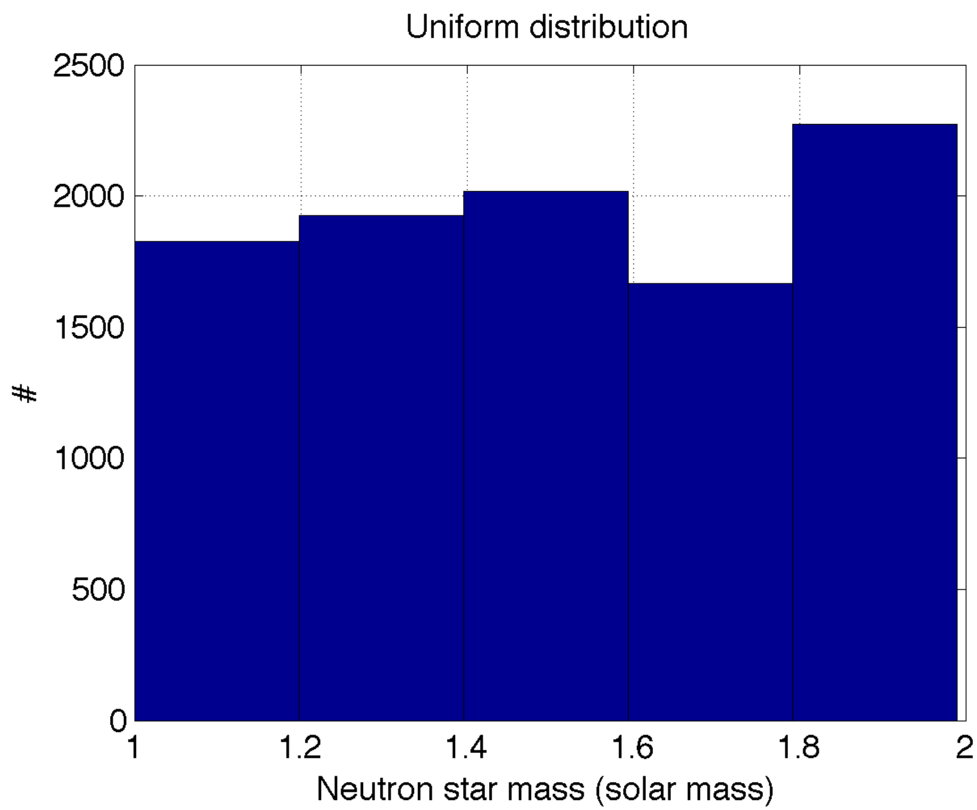
- Uniform distribution of NS masses, limited to the range [1, 2] M_sun.



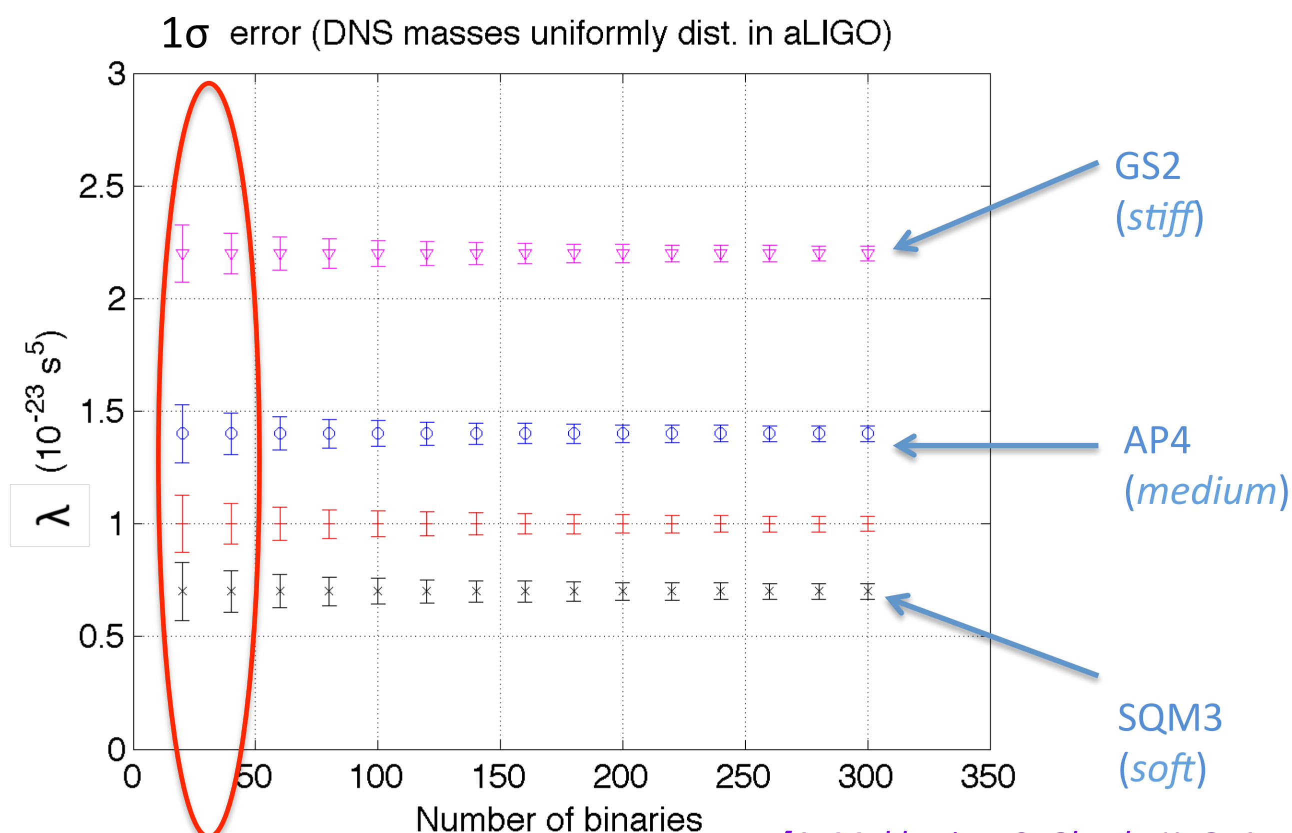
[A. Mukherjee, S. Ghosh, K. G. Arun, S. De, SB, in preparation.]

Error in determining λ

Double neutron star systems

IUCAA

- ***Uniform*** distribution of NS masses, limited to the range [1, 2] M_sun.



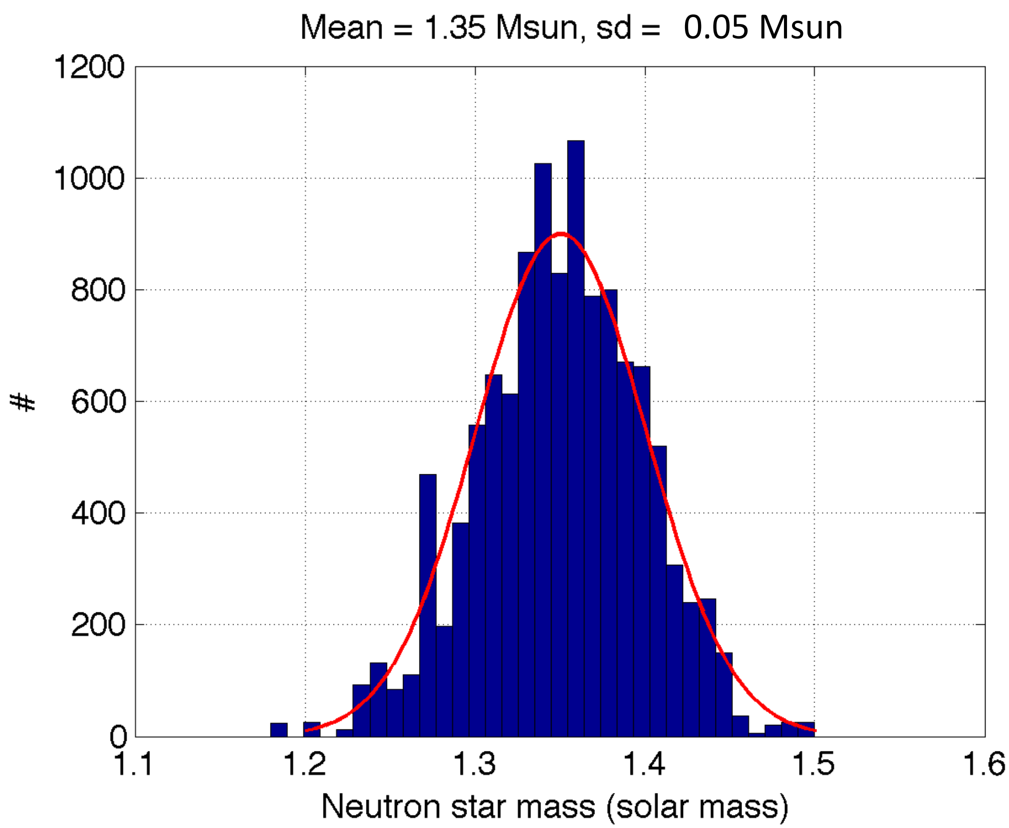
[A. Mukherjee, S. Ghosh, K. G. Arun, S. De, SB, in preparation; see also: Agathos et al., arXiv:1503.05405 (2015).]

Double neutron star systems

Populations

IUCAA

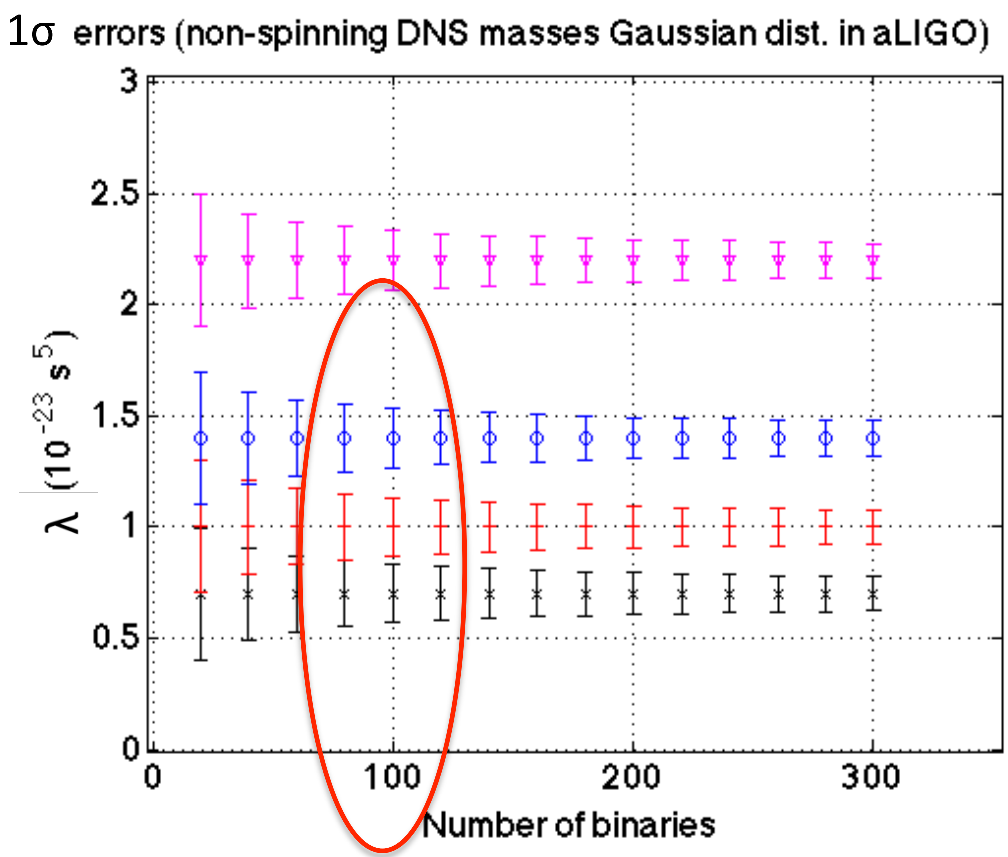
- Gaussian distribution of NS masses with mean = 1.35Msun, sd = 0.05Msun:



Error in determining λ
Double neutron star systems

IUCAA

- ***Gaussian*** distribution of NS masses, with mean = 1.35Msun, sd = 0.05Msun.



Effect of mass distribution

Double neutron star systems

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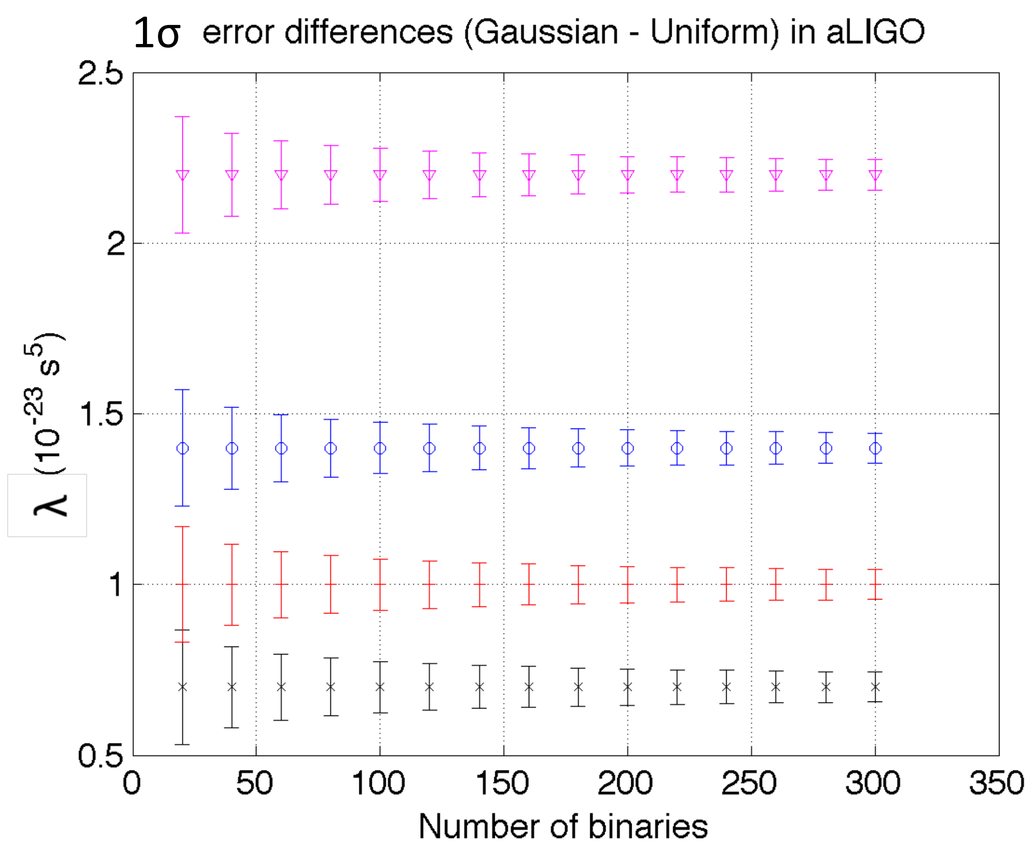
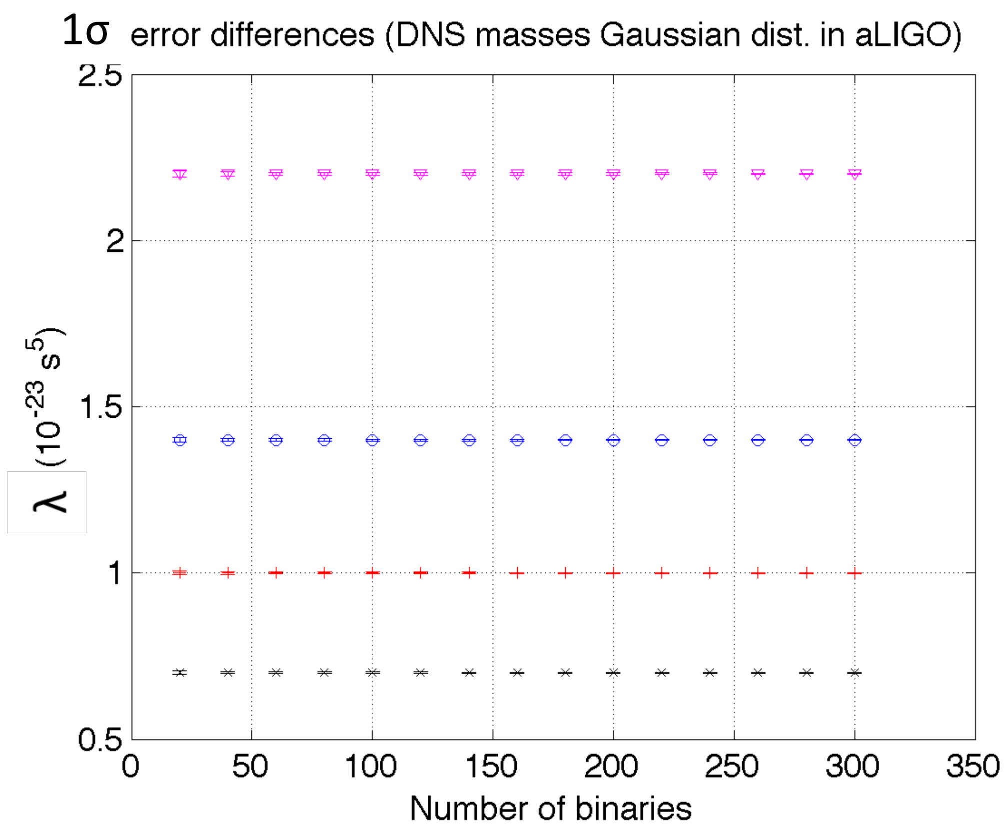
- Error due to choice of distribution:



Effect of spin

Double neutron star systems

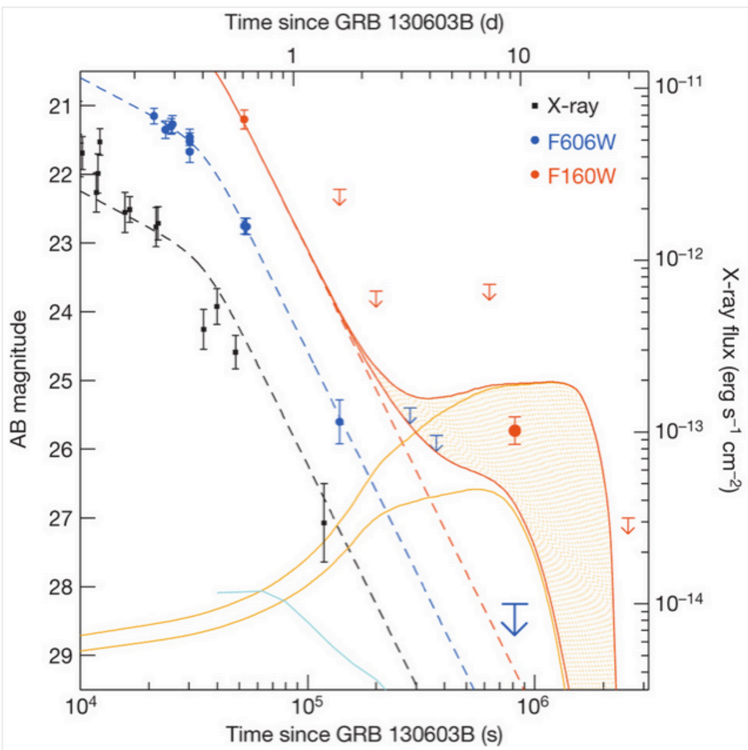
- Error in spinning DNS – error in non-spinning DNS:

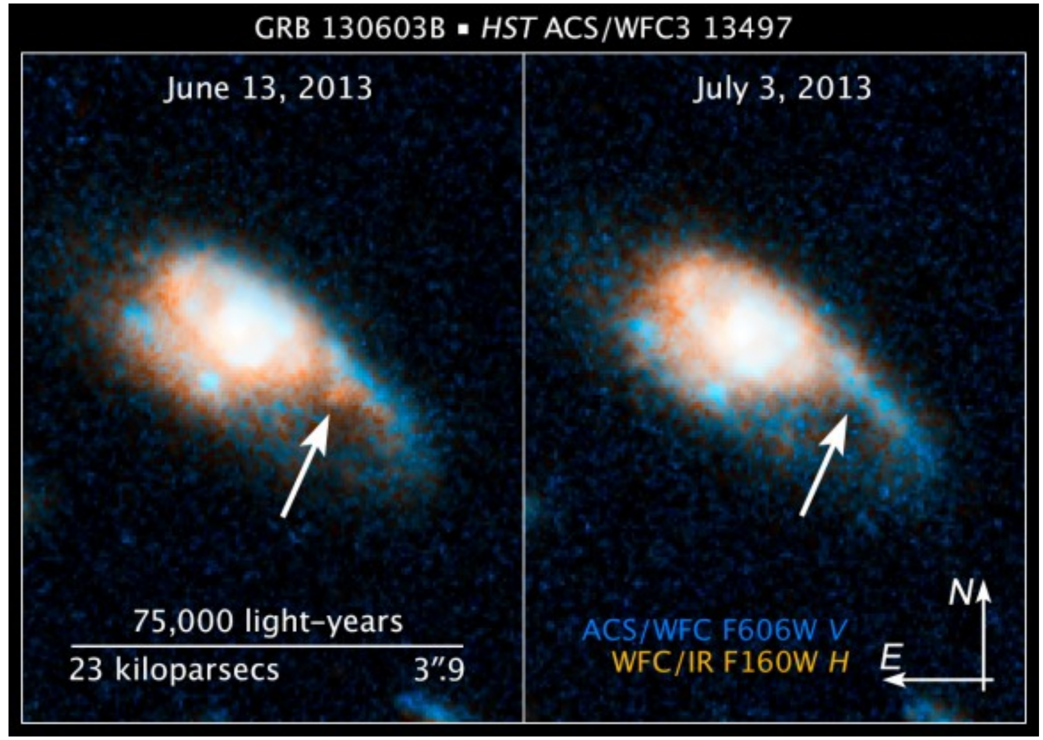


Is that a neutron star?

(Is GRB 130603B the first ever kilonova detection?)

- Late-type galaxy at z ~ 0.35
- No late-time optical counterpart (rules out Ni-decay emission as in a supernova)
- Single late-time near-infrared emission.





- N-IR emission consistent with kilonova models of CBC-NS with ejected mass ~ $10^{-2} – 10^{-1}$ Msun.

[Tanvir et al., , Nature doi:10.1038/nature12505 (2013).

The first kilonova in GRB 130603B?

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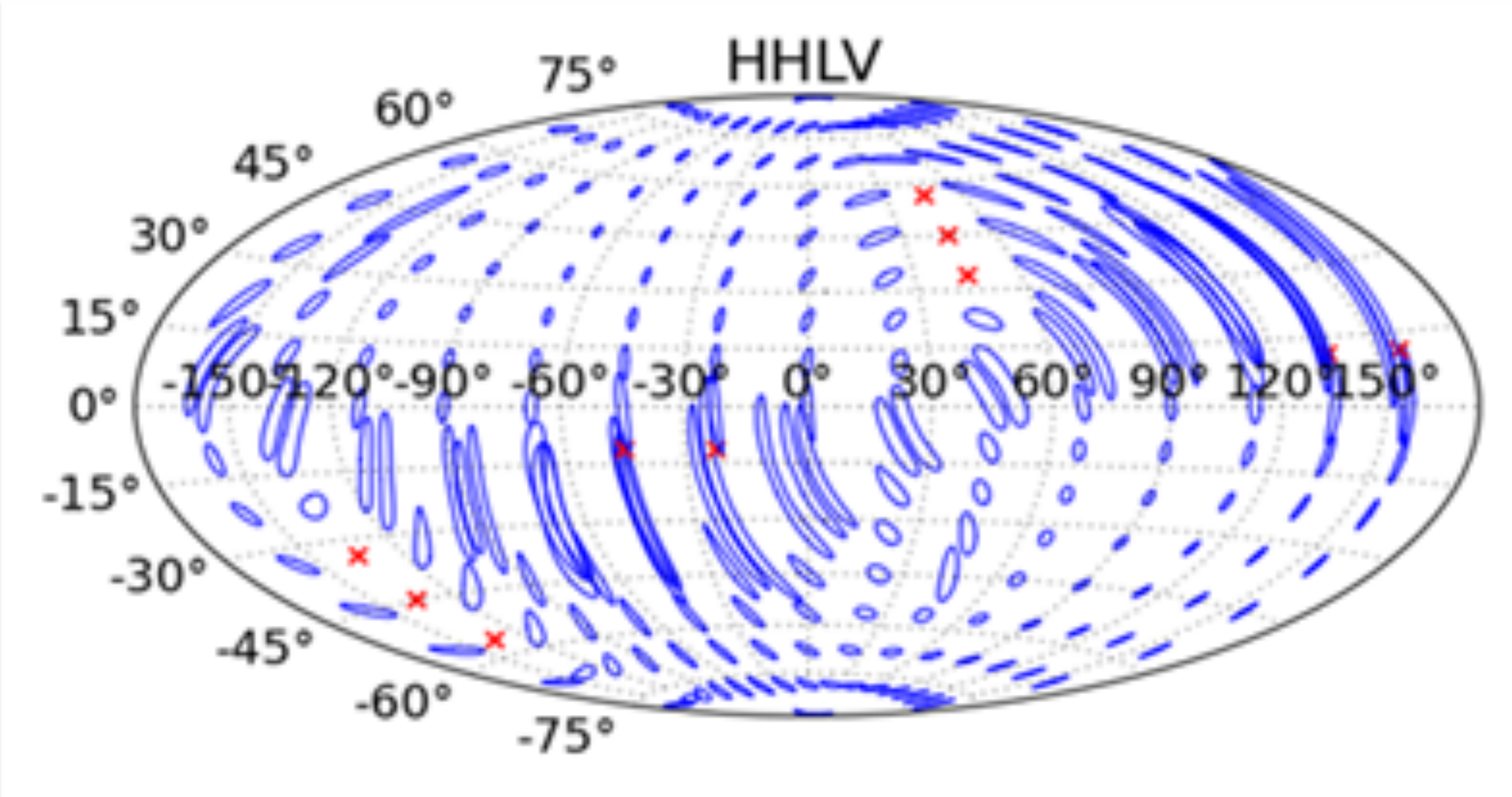
Gravitational Wave Detectors

Sky localization

IUCAA

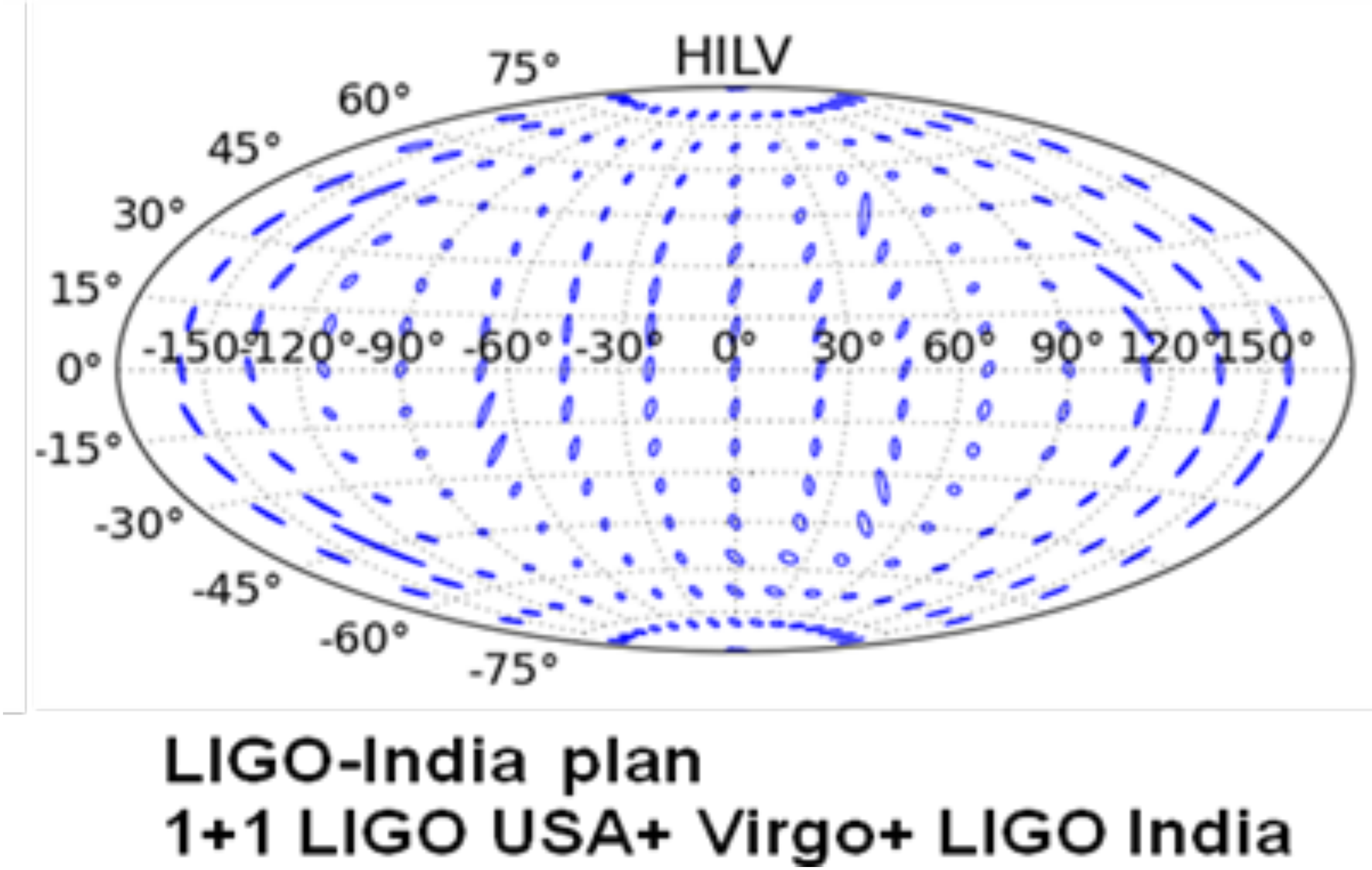


Original plan
2 +1 LIGO USA+ Virgo

Fairhurst, J. Phys.: Conf. Ser. 484 012007 (2014).

Sky localization: Case for longer baselines

IUCAA



Fairhurst, J. Phys.: Conf. Ser. 484 012007 (2014).

Any EM counterpart search yet? E.g., the Big Dog GW “event”

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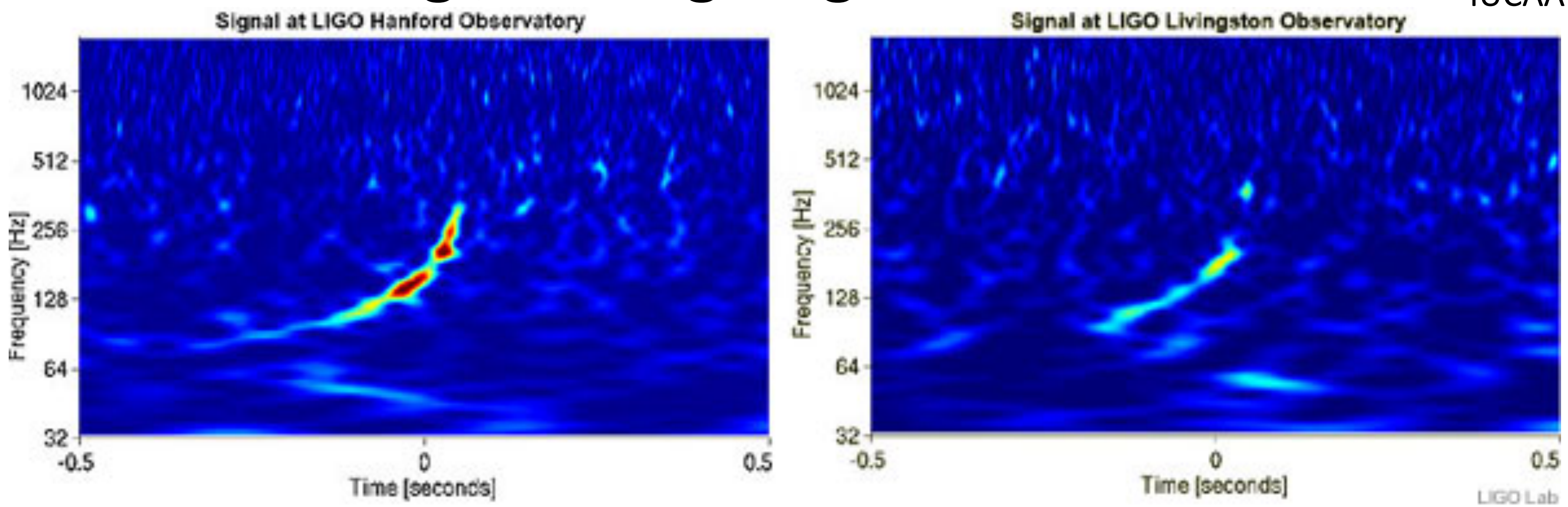

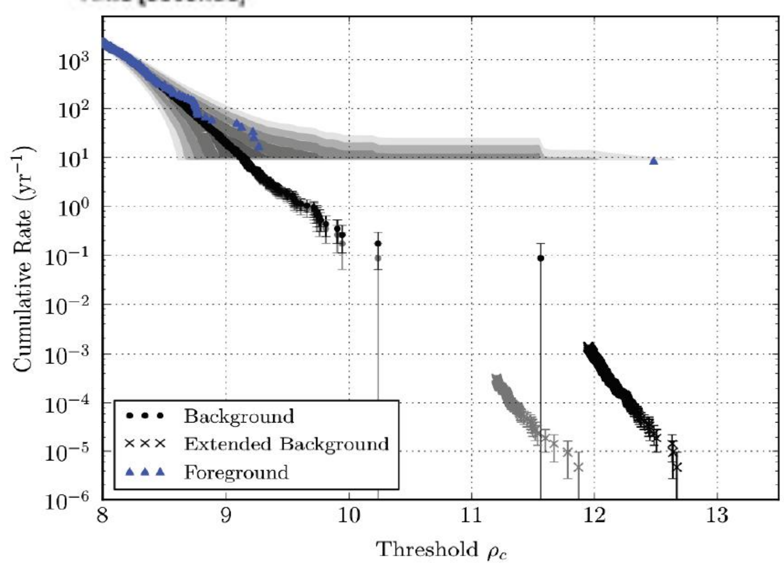

Abadie et al. (LVC),
PRD 85, 082002 (2012).

Challenge 3: EM Follow up E.g.: GW candidate G19377

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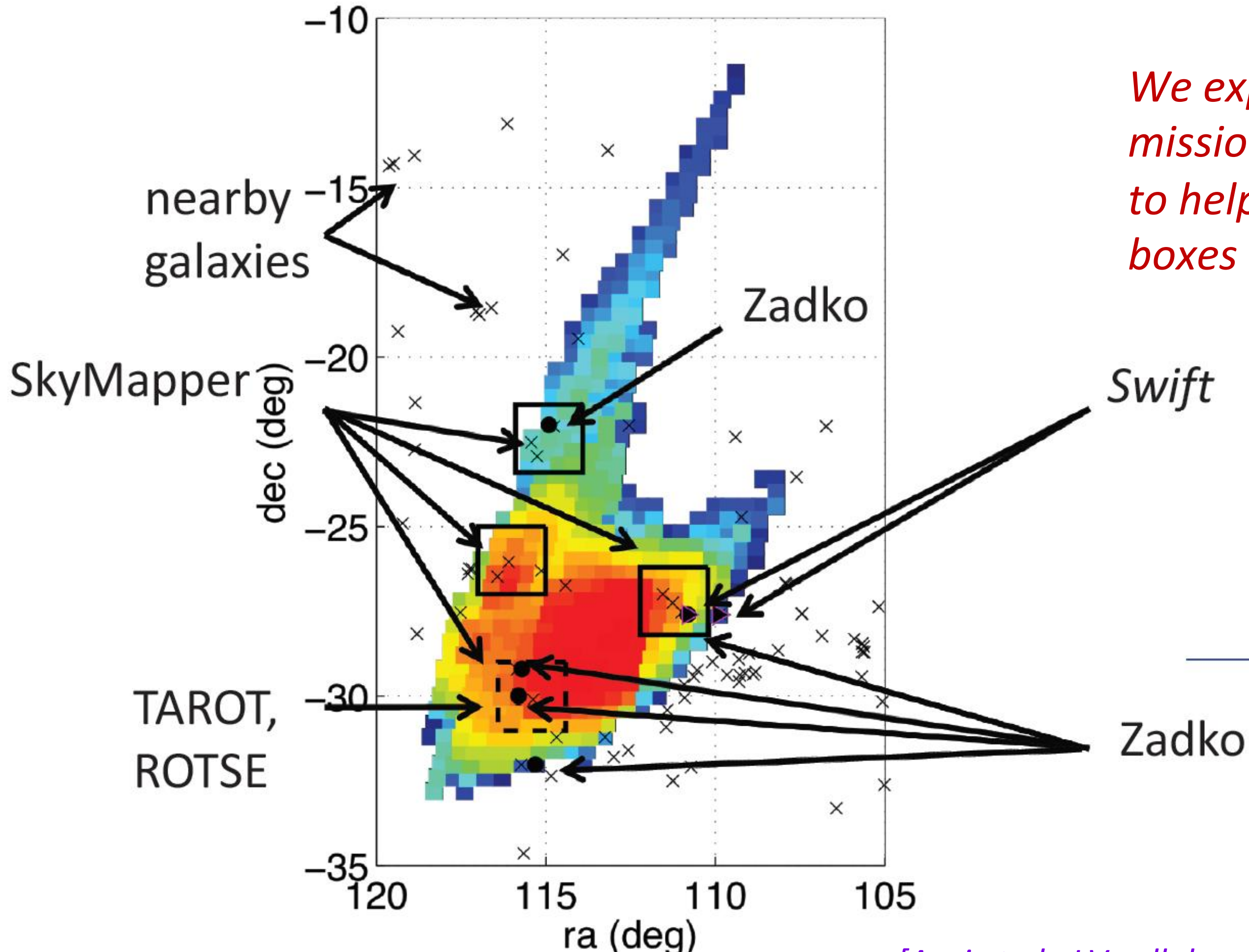
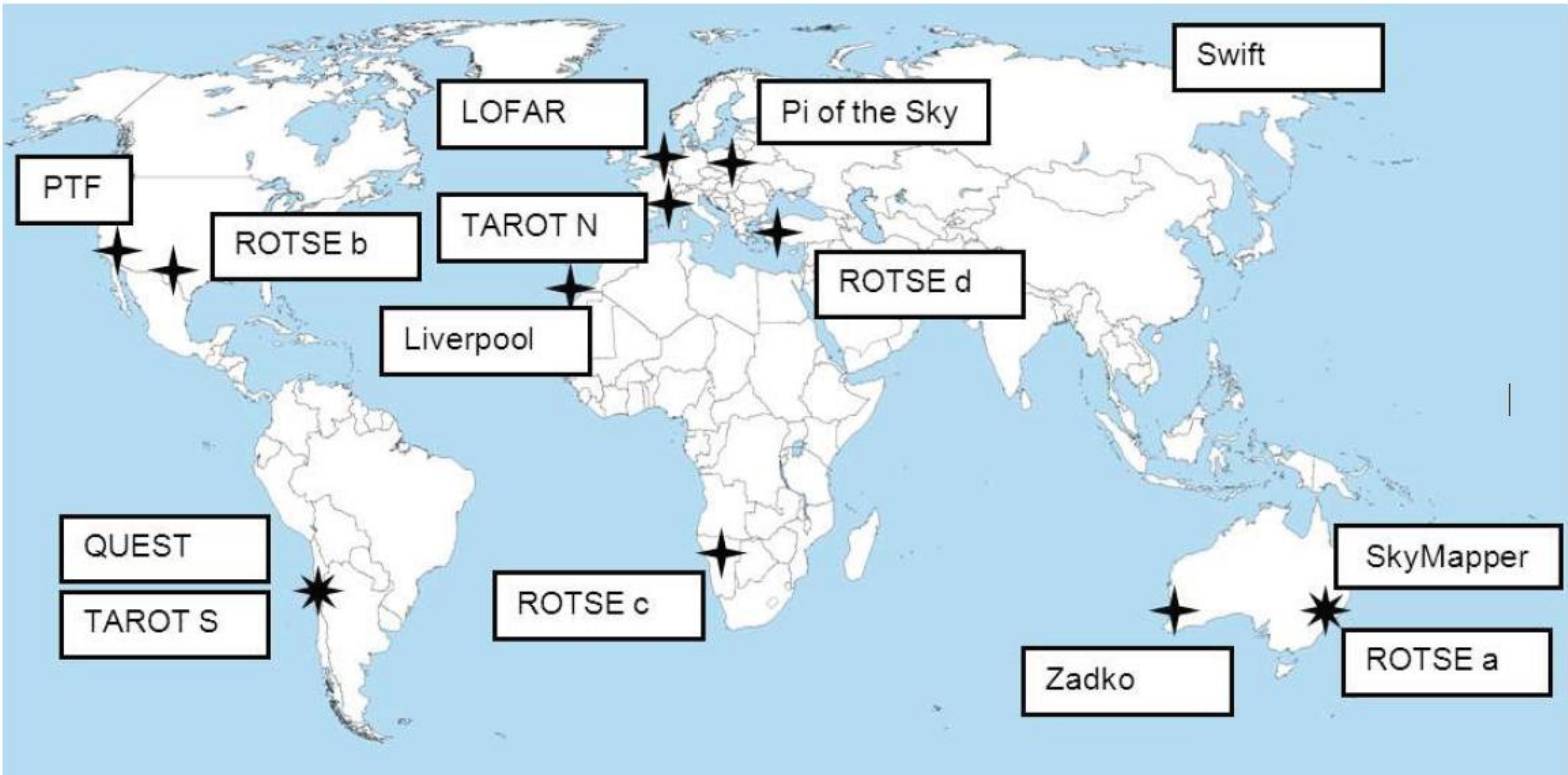


We expect future missions like BlackGEM to help cover the error boxes better.

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

EM observatories as "partners in crime"

IUCAA



Tiling a GW error region for multiple pointings

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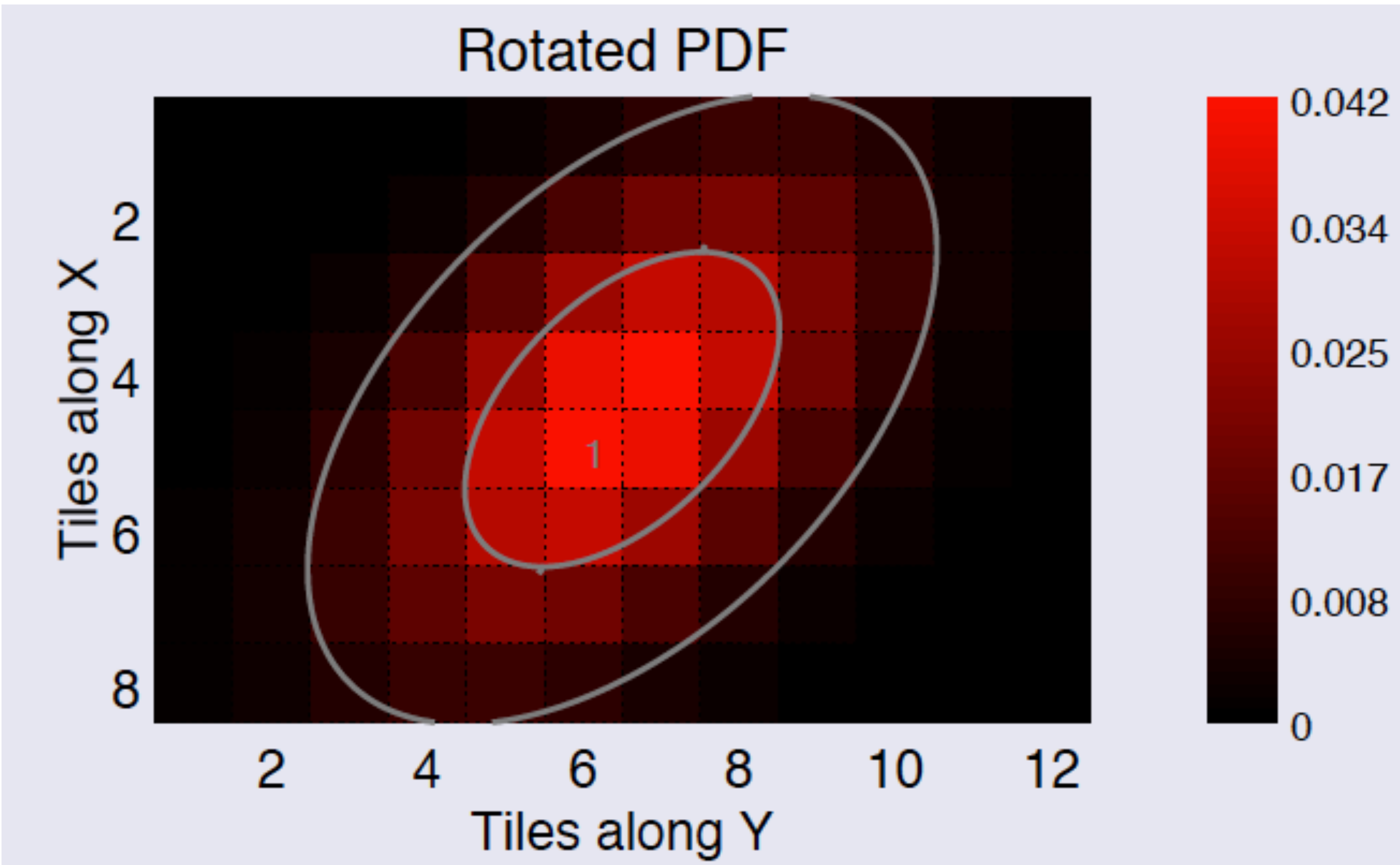

Javed Rana, A. Singhal, V. Bhalerao, SB, "Tiling gravitational wave error boxes for EM counterpart searches," in preparation.

L. Singer et al., ApJ 795 105 (2014);

S. Ghosh, G. Nelemans, Astrop.Space Sci.Proc. 40 (2015) 51-58.

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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

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

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IUCAA Girawali Observatory

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- Median seeing: 1.5"
- ~180 nights/year
  - 90 photometric
  - 140 spectroscopic
  - Closed in Jul-Oct

Instruments mounted on an instrument cube and available all the time.

http://www.iucaa.ernet.in/~itp/igoweb/igo_in_out_observatory.htm

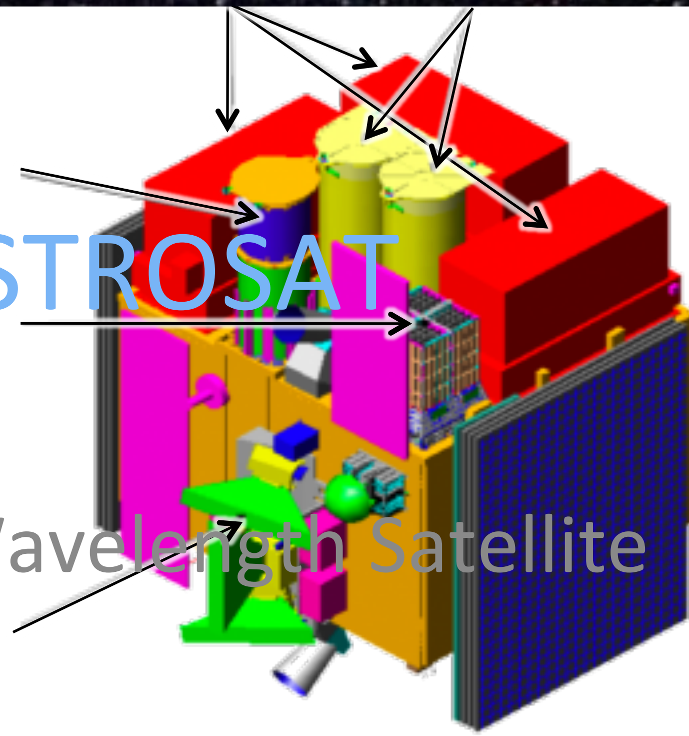
ASTROSAT

A Multi-Wavelength Satellite

SXT

CZTI

SSM



[Courtesy: Varun Bhalerao]

Take-home messages

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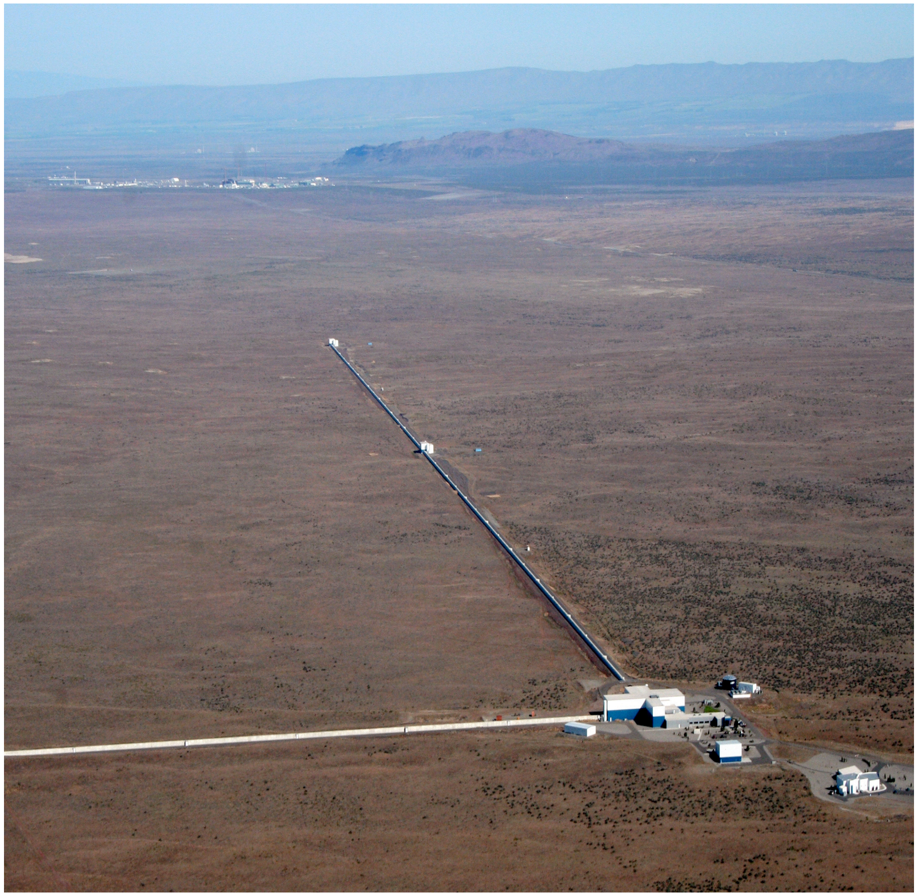
- The first GW detections will likely happen within this decade.
- After the first few GW discoveries, there will be a strong push for pursuing physics and astrophysics with GWs.
- EM-GW coincidences will enrich our physical understanding of compact objects (e.g., the NS EOS) much more than what they can do individually.
- The transient nature of compact binaries makes them well suited for complementing time-domain efforts being pursued by other telescopes.
- Are we prepared well enough not to miss this opportunity?



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