Can GW multi-detector observation of CBC shine light on SGRB?

Archana Pai @ IISER TVM, Trivandrum

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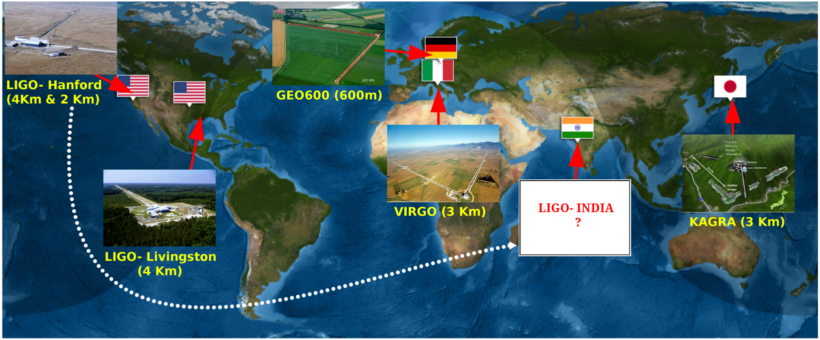
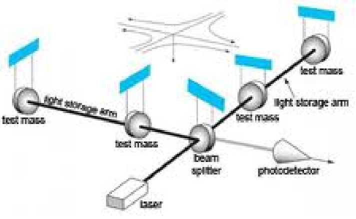
Overview

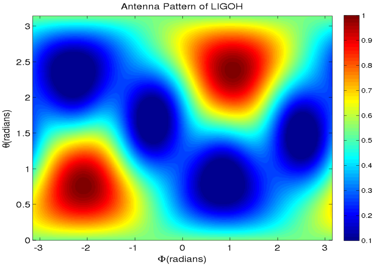
- Global Network of Interferometric GWave Detectors
- Compact binaries coalescence: SNRs, Detection rates in advanced detector era
- CBC probes Astrophysical/Cosmological information
- What are Short Gamma Ray bursts?
- Multi-detector parameter estimation of CBC source for Amplitude corrected waveform
- Joint EM-GW observation of SGRB: Astrophysically relevant scenario

Global Network of Ground Based GWave Detectors

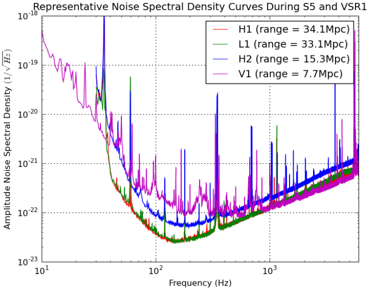


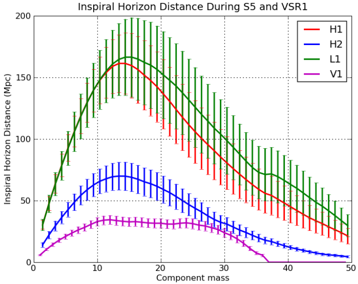
Suspended Michelson with Cavities

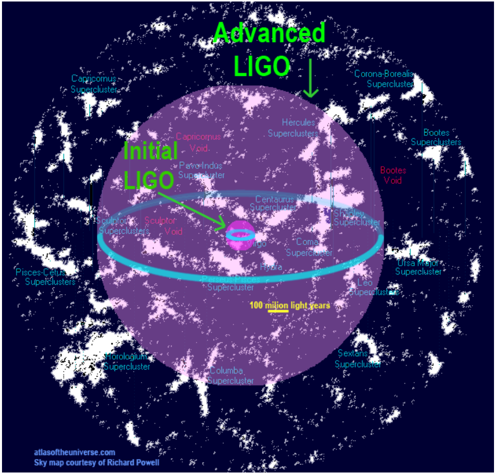




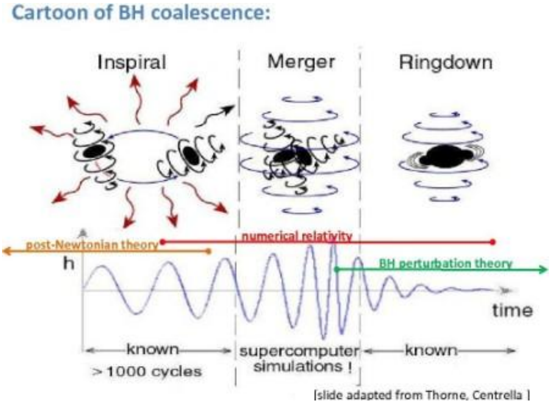
Detectable universe by iLIGO/aLIGO Interferometers







Compact Binary Coalescence: A Primary source



$Detection rates: CoalescenceRate/MWEG/year$ ×

N_G N_G: Number of MWEG up to the distance reach

[Source: Favata]

	iLIGO		aLIGO	
System	R(Mpc)	Rates P(O)	R (Mpc)	Rates P(O)
DNS	33	0.0002(0.2)	445	0.4(400)
NS-BH (10 $M_\odot$)	70	0.00007(0.1)	927	0.2(300)
BBH (10-10 $M_\odot$)	161	0.0002(0.5)	2187	0.4(1000)

[Source: Abadie 2010]

Coherent Detection of CBC

Advantages of Coherent multi-detector analysis of CBCs.

- Improved sky coverage – Antenna Pattern becomes fairly isotropic.
- Improved sky localisation – Time Delay information
- Consistency vetos to falsify the detection
- Improved detection volume – Due to increase in the distance reach
- Improved parameter accuracy due to increase in coherent SNR.

Max Likelihood Approach to Coherent detection: [AP, Bose, Dhurandhar 2001, Harry-Fairhurst 2011, Haris, AP 2014]

Construct 2 effective detectors: Captures the coherent multi-detector SNR.

$$\tilde{\tilde{\mathbf{z}}}_{+} = \sum_{\mathbf{k}}^{\mathbf{d}} \frac{\mathsf{F}^{\mathbf{DP}}_{+\mathbf{k}}}{\|\mathbf{F}'^{\mathbf{DP}}_{+}\|} \tilde{\tilde{\mathbf{X}}}_{\mathbf{jk}}, \qquad \tilde{\tilde{\mathbf{z}}}_{\times} = \sum_{\mathbf{k}}^{\mathbf{d}} \frac{\mathsf{F}^{\mathbf{DP}}_{\times\mathbf{k}}}{\|\mathbf{F}'^{\mathbf{DP}}_{\times}\|} \tilde{\tilde{\mathbf{X}}}_{\mathbf{jk}} \tag{1}$$

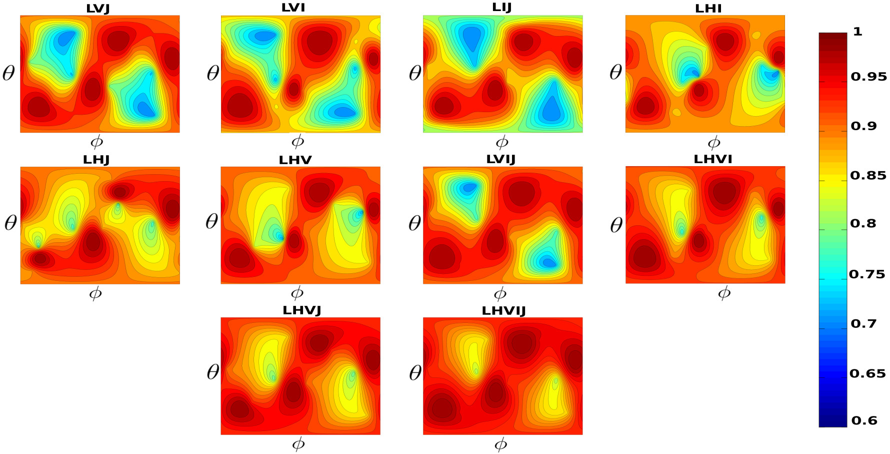
The net coherent SNR is the squared sum of the individual SNRs.

Full coherent search is computationally expensive.

Used for targetted search for GW follow-up of EM signals
(IPN GRB follow-up in the S5 and S6 data)

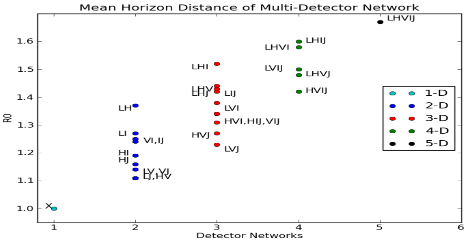
Fractional Improvement in Horizon Distance D_H Reach

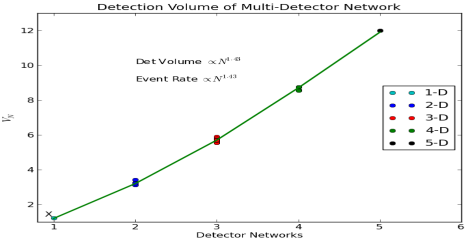
D_H = Distance at which the network gives the threshold SNR



[Figure Credit: Haris]

Fractional Improvement in Horizon Distance D_H Reach





Average Event Rate Improvement:

5.5 fold (3-Det Network)

8-fold (4-Det Network)

12-fold (5-Detector)

BNS: 1 detector rate 40/year

200/320/500 events per year with 3/4/5 detector networks

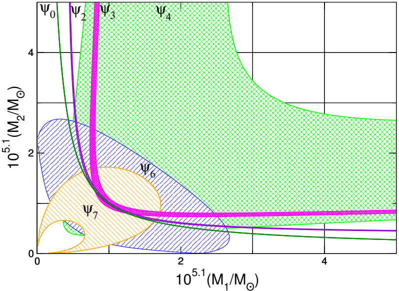
NS-BH: 1 detector rate - 20/year

100/160/250 events per year with 3/4/5 detector networks

Multi-detector analysis improves the detection rates as the distance reach improves with a multi-detector

CBC probe to Astrophysics/Cosmology

- **Chirping Binaries as Standard Sirens** [Proposal: Schutz 1987]
  The GWave signal $h \sim \mathcal{M}^{5/3}/D_L$.
  Estimation of $\mathcal{M}$ (through matched filter template)
  SNR would give the luminosity distance D_L. EM Observation gives redshift
  For low redshift: $D_L(z) \sim \frac{cz}{H_0}$
  Independent estimation of Hubble's constant through GW observations. [Nissanke et al 2013 , Walter del Pozzo 2012]
- **Test of PN theory:**



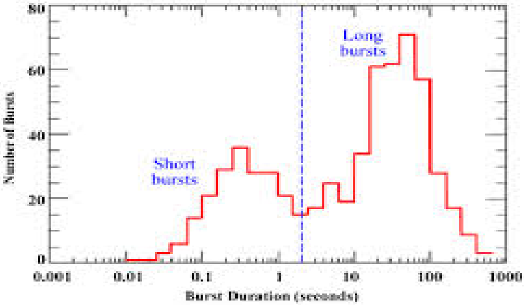
Alternative gravity theories predict different phase corrections in the CBC waveform
Consistency test in the mass parameter space [Blanchet, Sathyaprakash, PRL 1994, Arun, Iyer, Qusailah, Sathyaprakash, 2006 and 2006a]

CBC probe to Astrophysics/Cosmology

- **GW Polarization Measurement**:
  Two detectors needed to probe 2 polarisations ⇒ Orientation of the binary. (EM observations ⇒ Projected binary orbit).
- **Measuring BH spin** [Kameretsos et al, PRL 2013]
  Dominant Quasi-normal mode of the perturbed BH detection ⇒ Indications on the spin and mass ratio of the binary ⇒ Binary progenitors
- **Meauring EoS of the NS in binary system**
  NS with different EoS gives different signature waveforms in the inspiral phase. Detection of inspiral phase would contain this information.
- **EM-GWave joint observation**
  Joint observation in EM of a CBC event would improve the parameter estimation. Candidate astrophysical sources: Supernovae, Short GRB, X-ray binaries, Pulsars......

What are Gamma Ray Bursts?

- Most energetic ever since Big Bang. Typical $E_{iso} \sim 10^{49} - 10^{53} ergs$ in few seconds.
- Ultra relativistic jets $\Gamma > 100$.
- Varibility in light curve $\Rightarrow$ Compact star as the central engine



Bimodal distribution of burst duration

Short GRBs: $T_{90} < 2sec$

Long GRBs: $T_{90} > 2sec$

GRB features

Long GRBs

Long duration and spectrally soft

Largely associated with Core collapse SN. Star forming galaxies

Small offset from the galactic center (few kpc)

Large red shifts: $<z>=2$

Plausible progenitor:

Core collapse of massive star $>40M_{\odot}$, accretion powering jets.

Short GRBs

Short duration and spectrally hard

Associated with spiral/elliptical galaxies.

Significant offset from the galactic center (tens of kpc)

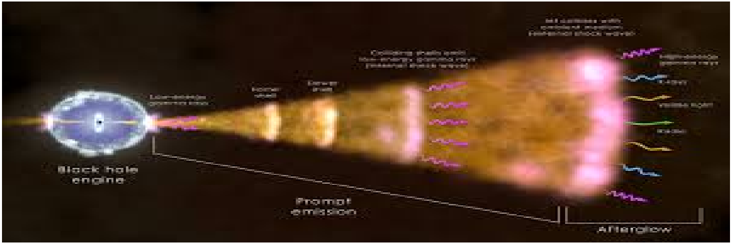
Small redshift of $<z>=0.5$

Plausible progenitor:

Collision of compact objects such NS-BH or DNS.

Can joint observation in EM+GW window shine light on SGRB?

Short GRBs: A candidate for GW+EM window



Features of the Fireball model

Prompt Emission : Internal Shocks

Afterglows (x-ray – radio): External Shocks.

Typical timescales: GW and SGRB coincides (??)

EM signatures:

Few seconds to 1000 seconds: X ray/ Optical afterglow

Few hours–days later — Kilonova

Few days – Months – Afterglow in radio

EM+GW Scenarios

Detection in GW window and Follow up in EM window:
Bayestar: rapid sky localisation pipeline for the EM follow-up of GW candidates in EM window. [Singer 2014]
Detection in EM Window and follow up in GW:
Follow-up of IPN GRB in the LIGO S5-S6 runs. Sky location error boxes from the IPN satellites were used for the GW follow up. [Aasi et al 2014]

Joint EM-GW observations

- No EM information : Beaming effect $\Rightarrow$ Selection bias, [viewing angle $\theta_v <$ Jet opening angle]. No event in Gamma rays
- 3D localised case: Host Galaxy is identified in EM observations (both distance and direction is localized) e.g. GRB070201 location coincidence with the spiral arm of andromeda

What can be probed from GWs?

- GW signal carries complimentary information.
- For DNS, NS-BH, inspiral phase carries the SNR.
- Inspiral phase: Luminosity distance, inclination angle, source location, polarisation angle, initial phase masses, spins, Equation of state.
- GW detection can probe only these parameters.

GW parameters and inferred astrophysical parameters

Improved distance estimates $\Rightarrow$ Probes cosmology

Improved inclination angle estimates $\Rightarrow$ Constraints jet opening angle

Improved source location $\Rightarrow$ Delay time between the SGRB and GW event

Astrophysical parameters estimation of CBC

- **Signal Model**: Post Newtonian waveform with GW phase corrected up to 3.5 PN order and amplitude corrected up to 2.5 PN order [Arun et al. 2004, Blanchet et. al 2008.].
  Why Amplitude corrections? Higher harmonics carry different functional dependence on the polarisation angles.
  Case study: Non-spinning DNS and NS-BH (1.4-10)
  Parameters (9): Distance, Initial phase, Source location, Inclination of binary orbit, Polarisation, Two masses, Time of arrival
- **Detectors**: Network using LIGO, VIRGO, KAGRA and proposed LIGO-India with advanced detector's designed sensitivities.
- **Semi-analytical Technique**: Fisher Information Matrix
  Covarince Matrix = Inverse of Fisher Information Matrix in parameter space

CBC Full Waveform: Amplitude and Phase correction

The signal is given by $h(t) = h_+ F_+ + h_x F_x$ $\quad F_{+,x}$: antenna pattern.
The two polarisations (amplitude correcions up to 2.5 PN order) is

$$h_{+,\times} = \frac{2M\nu}{D_L} x \left\{ H^{(0)}_{+,\times} + x^{1/2} H^{(1/2)}_{+,\times} + x H^{(1)}_{+,\times} + x^{3/2} H^{(3/2)}_{+,\times} + x^2 H^{(2)}_{+,\times} + x^{5/2} H^{(5/2)}_{+,\times} . \right\}$$

$x = (2\pi M F(t))^{2/3}$ $\quad H^{(n/2)}_{+,\times}$: function of inclination angle and various harmonics

$$H^{(n/2)}_{+,\times} = \sum_{k=1}^{n+2} [c^{(n/2)}_{+,\times,k} \cos(k\Psi(t)) + s^{(n/2)}_{+,\times,k} \sin(k\Psi(t))]$$

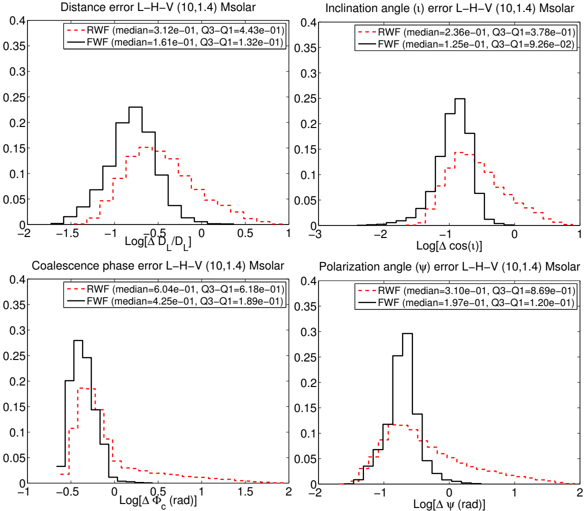
$c^{(n/2)}_{+,\times,k}, s^{(n/2)}_{+,\times,k}$: functions of inclination angle and massess
$\Psi(t)$: Orbital phase formula accurate up to 3.5 PN correction in phase.
The signal in a detector band is

$$h(t) = \frac{2M\nu}{D_L} x \sum_{a=+,x} \sum_{n=0}^{5} \sum_{k=1}^{7} x^{n/2} [F_a c^{(n/2)}_{a,k} \cos(k\Psi(t)) + F_a s^{(n/2)}_{a,k} \sin(k\Psi(t))]$$

RWF: No amplitude correction and phase correction up to 3.5 PN
FWF: Amplitude (2.5 PN) as well as phase correction up to 3.5 PN

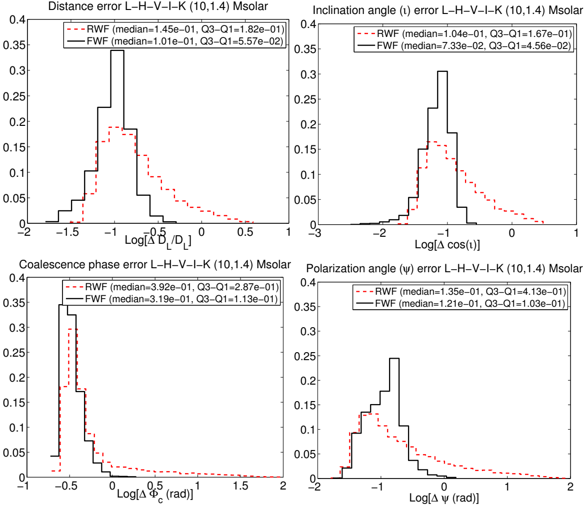
Multi-detector CBC parameter estimation with Higher Harmonics [Tagoshi, Mishra, Arun and AP, PRD2014]

Simulation Results: RWF vs FWF – LHV



Multi-detector CBC parameter estimation with Higher Harmonics [Tagoshi, Mishra, Arun and AP, PRD2014]

Simulation Results: RWF vs FWF – LHVKI



Multi-detector CBC parameter estimation with Higher Harmonics [Tagoshi, Mishra, Arun and AP, PRD2014]

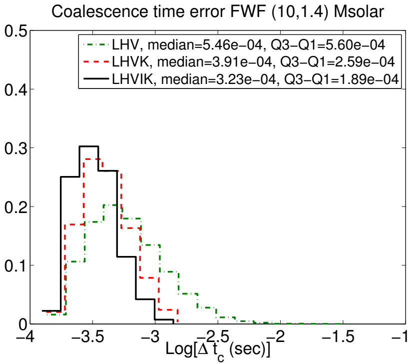
RWF-FWF Fisher Analysis features with Multi-Detectors

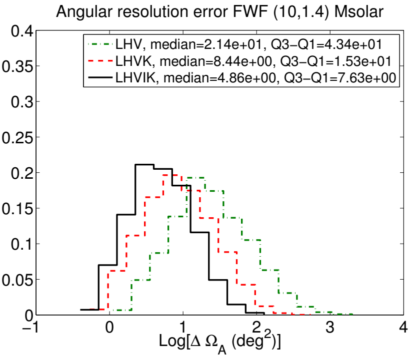
- Error distribution becomes narrower with FWF.
- $D_L - i$ **degeneracy breaks with HH**. More information from HH improves the accuracy in measurement of the inclination angle. This translates into improvement in the distance measurement (relative error: few percent).
- Φ_c **improvement:** Multiple harmonics entering the detector band at different times.
- $\Phi_c - \Psi$ correlation gives improvement in the Ψ parameter.

Multi-detector CBC parameter estimation with Higher Harmonics [Tagoshi, Mishra, Arun and AP, PRD2014]

RWF-FWF Fisher Analysis features with Multi-Detectors

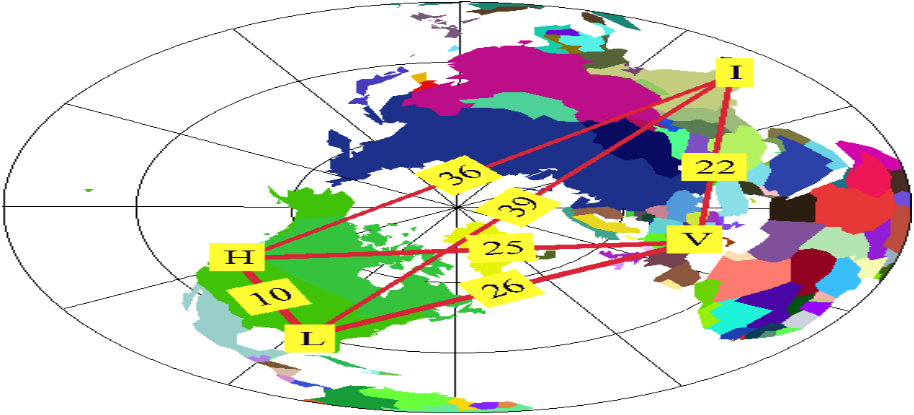
- Angular resolution depends on the time-delays. Main improvement comes because of using the multi-detector irrespective of RWF or FWF.





$\Delta\Omega_{95}$ level: 21sq deg. (LHV), 8.4sq deg. (LHVK), 4.8 sq. deg (LHVIK).

Global network of detectors with time delays

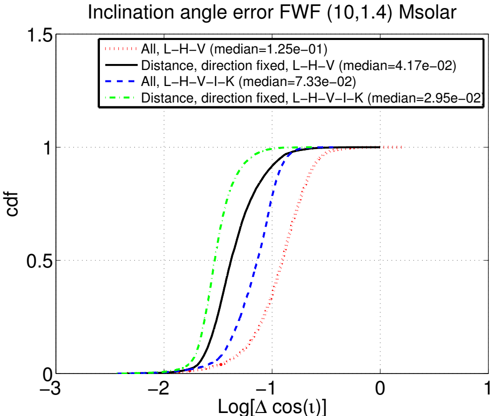


Implication: Both direction as well as distance uncertainty can be provided in the EM follow-up of GW candidates.

No EM information Vs 3D localized case ATPM, PRD 2014

Bracket (DNS) and unbracketted (NS-BH), distance at 200 Mpc.

Network	No EM information	Direction known	3D localized
LHV	9.3 (41.5)	8.3 (34.4)	3.3 (8.6)
LHVK	7.1 (24)	6.5 (21.0)	2.7 (6.4)
LHVKI	5.8 (15.5)	5.5 (14.3)	2.2 (5.1)



Knowledge of distance and source location, improves the error in the inclination angle. Additional effect with increase in the number of detectors.

90 % of injected NS-BH recovered wth $\Delta\cos(i) < 0.05$.

90 % of injected DNS recovered with $\Delta\cos(i) < 0.1$.

Implications of inclination angle accuracy on SGRB

- **GW event but no EM event**:
  Accurate inclination angle measurement would be used for consistency in observation.
  If $\theta_v > \theta_j$: Selection effect, Look for afterglows (optical/x-rays, radio)
  If $\theta_v < \theta_j$: Number statistics might tell us how many DNS, NS-BH events do not have associated SGRB?
  Observation: Not all Core Collapse SN have associated Long GRB!!
- **EM event but no GW event**:
  Do DNS/NS-BH mergers indeed form SGRB?
  Test formation channels of SGRB.

Future Prospects

- Advanced detector era would witness few colescence events per month for DNS/NS-BH systems.
- Operating multi-detector network in coherent mode would increase this by a factor of 10 with 5 detectors $\Rightarrow$ Sets stage for GW astronomy
- EM+GW observations of SGRB would shine light on **SGRB Progenitor, The formation channel (numerical relativity simulation), Jet models**
- **Ongoing Work:**
  Incorporate priors from EM observations in the analysis. [Saleem]
  Incorporate BH spin in the existing exercise.
  Explore the inclination angle improvement in the Bayesian framework.

Collaborators:

- K. G. Arun (Chennai Mathematical Institute)
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- Chandra Kant Mishra (ICTS-TIFR, Banglore)
- K. Haris (IISER TVM)
- Saleem Muhameed (IISER TVM)

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