What is needed from other communities?

Alessandra Corsi, Katie Breivik, Michael Pürrer, Mike Zevin

What can population synthesis bring to the table for 3G?

Katie Breivik
Carnegie Mellon University | McWilliams Center for Astrophysics and Cosmology

There are *MANY* population synthesis tools

SEVN
Up-to-date Stellar Evolution
Up-to-date SN models (5 models)
Versatile easy-to-change input stellar evolution tables
Ready for N-body sims Starlab HiGPUs-R

SeBa

METISSE

StarTrack

BPASS

COSMIC

CMC Cluster Monte Carlo

POSYDON

BSE

MSE

binary_c

TRES

MOBSE

ComBinE

MOCCA

*rapid isolated binary, *hybrid isolated, *detailed isolated, *triple, *globular cluster

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Each code has strengths and weaknesses

→ a healthy population synthesis landscape is one with a diverse tool set that enables comparisons of outputs from each code

→ support for development and maintenance of population synthesis (both through funding agencies and mentorship of junior devs) is critical to maintain this diverse toolset into the 3G era

SEVN

StarTr

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ComBinE

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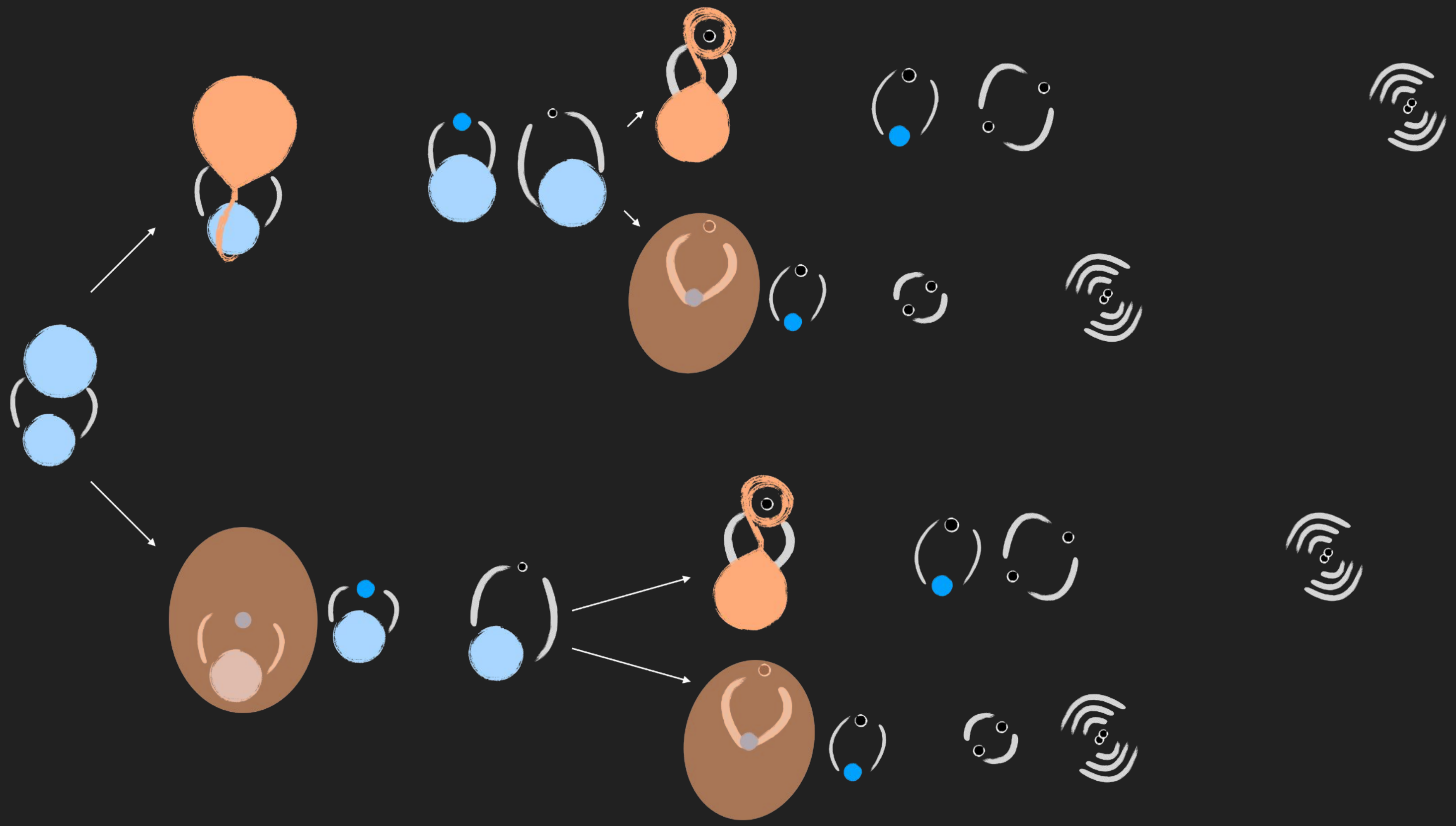
binary c

In preparation for 3G, we can learn from current population studies

- Incorporation of pop synth results from multiple codes and/or channels in local ($z \lesssim 1$) population studies is difficult due to differences in data formats and output choices
  - One potential solution to this is a single population synthesis format
    - BinCodex (arXiv:2311.03431) developed by Ruggero Valli and Luca Graziani in collaboration with the Synthetic UCB Catalog Project within the LISA Astrophysics Working Group could be a wider community standard
- Pop synth and wider community should agree on when to apply selection effects (KB thinks this should be *never* for pop synth open datasets but let's discuss!!)
  - Recent studies which apply selection effects of current detectors can't be used for 3G forecasts

every merging DCO carries other phases of evolution with it!



These are clues for distinguishing between formation channels – we should keep them in mind for all formation environments

The complex landscape of compact binary formation channels: Can we navigate it with 3G?

Mike Zevin
The Adler Planetarium

“We will know everything about BBH formation by the end of O3/O4” – many of us ~5 years ago

“We show that solely with chirp mass measurements, it is possible to constrain natal kick prescriptions and the relative fraction of systems originating from each formation channel with O(100) of confident detections.” –Zevin et al. 2017b

“With 100 observations, it will be possible to infer the relative fraction of coalescing BBHs with isotropic spin directions (corresponding to dynamical formation in our models) with a fractional uncertainty of ~40 per cent.” –Stevenson, Berry, & Mandel 2017

“We show that with ~10 additional LIGO-Virgo BBH detections, fitting the BH mass distribution will provide strong evidence for an upper mass gap if one exists.” –Fishbach & Holz 2017

“We show how the fraction of aligned systems can be accurately estimated using Bayesian parameter estimation, with 1 σ uncertainties of the order of 10% after 100–200 sources are detected.” –Vitale et al. 2017a

“We find that ~1000 observations would constrain [CE efficiency, kick-velocity dispersion, mass loss during LBV and WR phases] to a fractional accuracy of a few percent.” –Barrett et al. 2018

“...using 200 detections at design sensitivity…we will be able to identify the presence of an excess due to PPSN at ~3σ and constrain the fraction of black holes forming through PPSN to within ~0.05 at 95% confidence. –Talbot & Thrane 2018

“Our results show that the fingerprints of different BBH formation channels will emerge as soon as LIGO detects more than ~10^2 merger events.” –Arca Sedda & Benacquista 2019

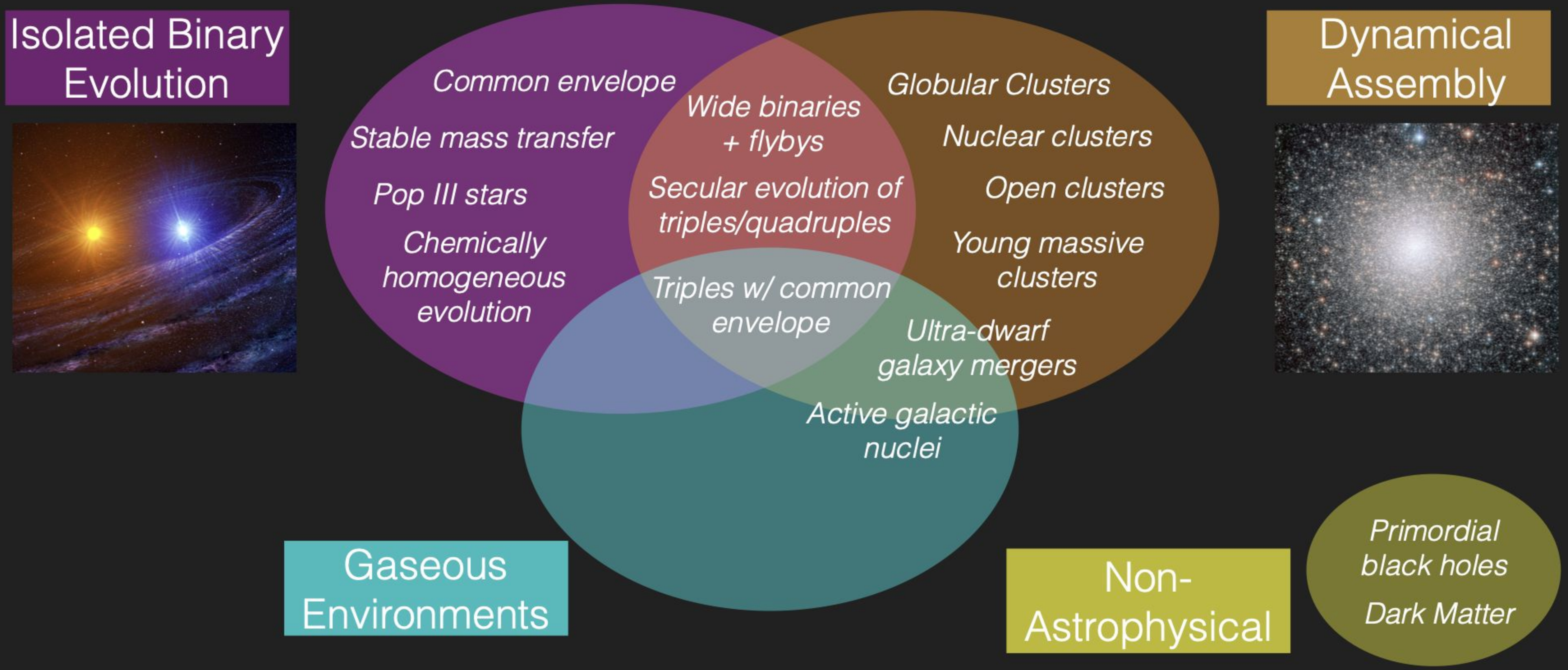
“We demonstrate that only a few tens of events can enable astrophysically significant constraints on the spin magnitude and orientation distribution of BHs in merging binaries.” –Wysocki, Lange, & O’Shaughnessy 2019

“...we show that, although current advanced LIGO/Virgo observations only mildly constrain the mixing fraction between the two formation channels, we expect to narrow down the fractional errors to 10%–20% after a few hundreds of detections.” –Bouffanais et al. 2019a

“...we show that in the 10 BBHs detected by LIGO/Virgo the contribution of the dynamically assembled BBHs to be more than about 50% with 90% confidence” –Safarzadeh 2020

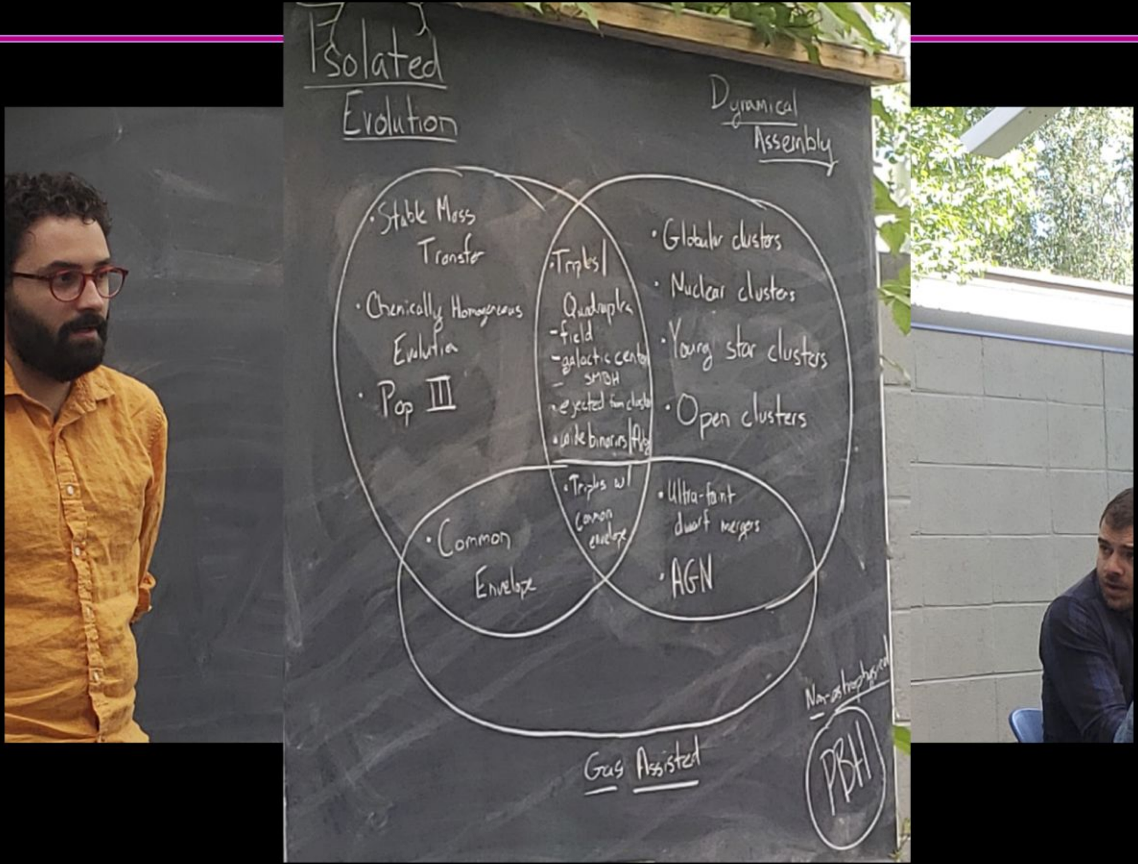
Isolated Binary Evolution

Dynamical Assembly

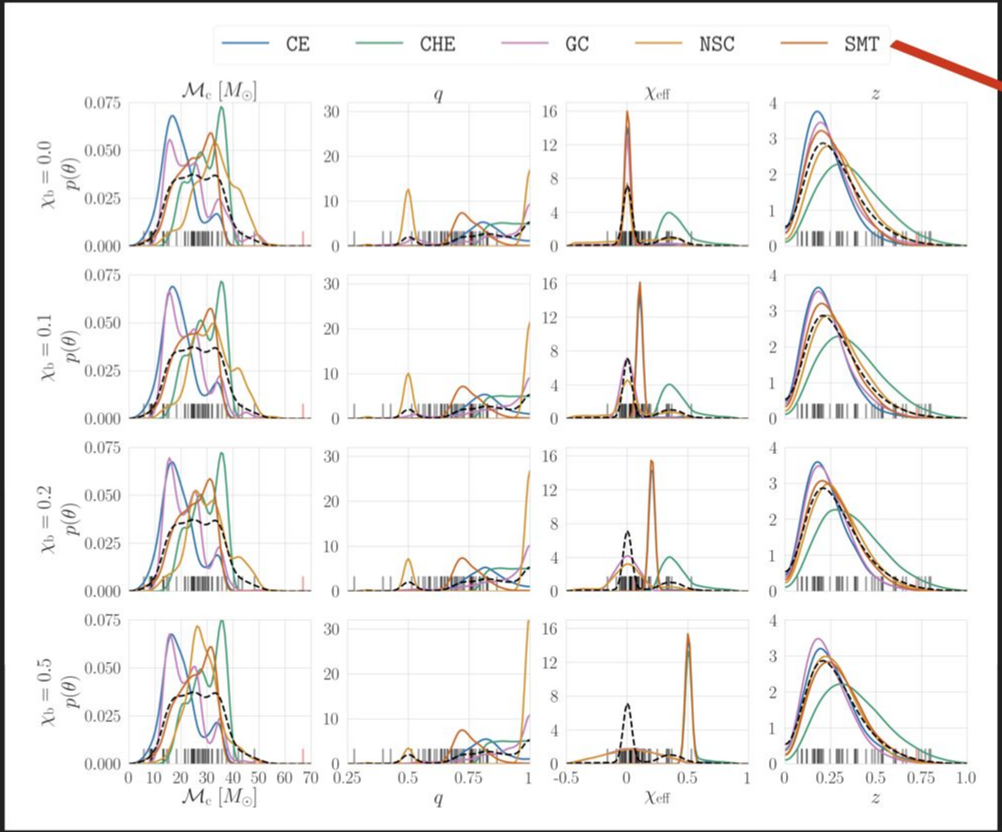

Isolated Binary Evolution
Dynamical Assembly
Common envelope
Stable mass transfer
Pop III stars
Chemically homogeneous evolution
Wide binaries + flybys
Secular evolution of triples/quadruples
Triples w/ common envelope
Globular Clusters
Nuclear clusters
Open clusters
Young massive clusters
Ultra-dwarf galaxy mergers
Active galactic nuclei
Gaseous Environments
Non-Astrophysical
Primordial black holes
Dark Matter

CBC formation channels

Concerned astrophysicist



Skeptical astrophysicist



Varying natal spins of black holes born in isolation

Predictions from various models for binary black hole formation:

CE: Common Envelope

CHE: Chemically Homogeneous Evolution

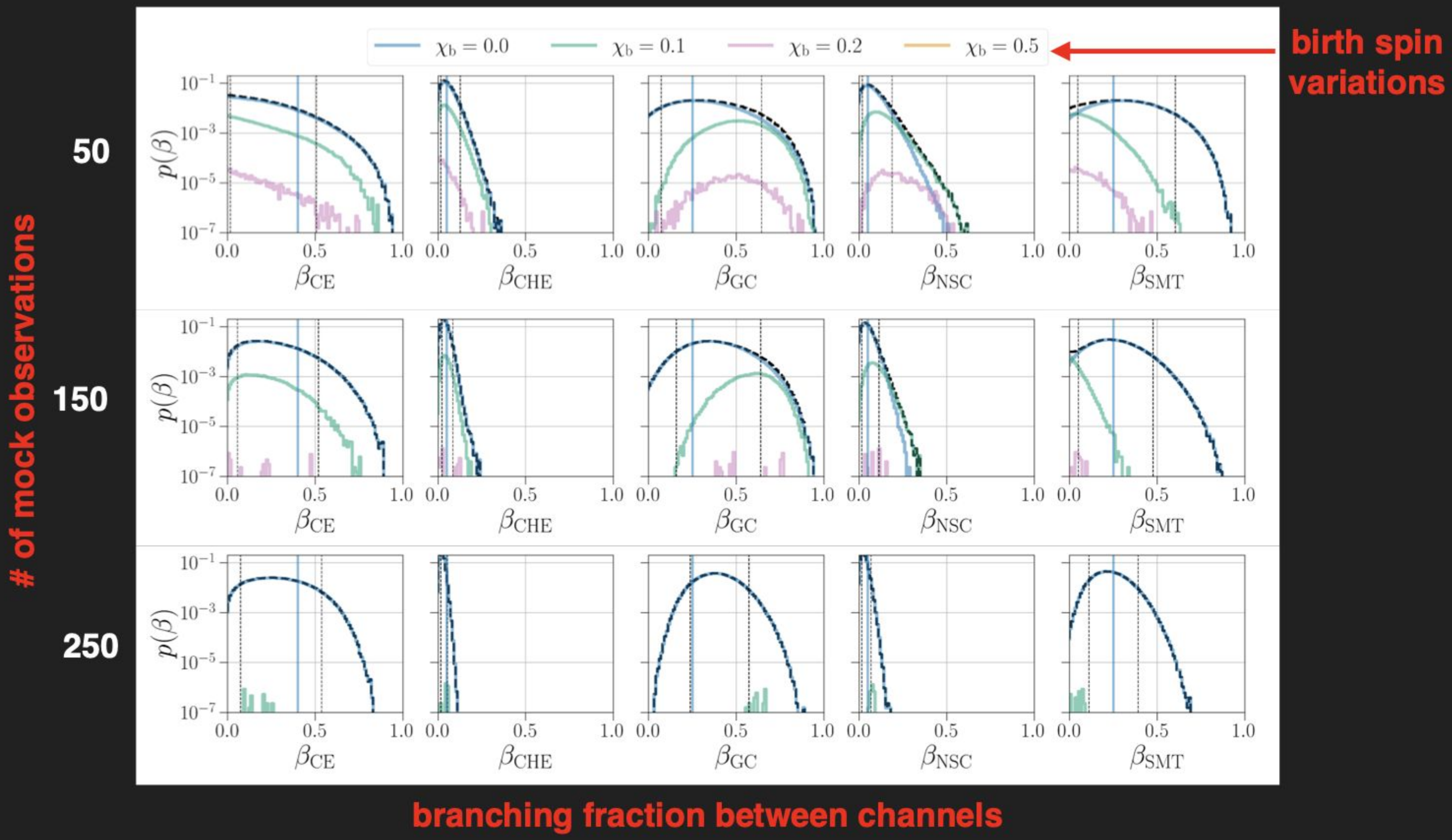
GC: Globular Clusters

NSC: Nuclear Star Clusters

SMT: Stable Mass Transfer

MZ+ 2021 [2011.10057]

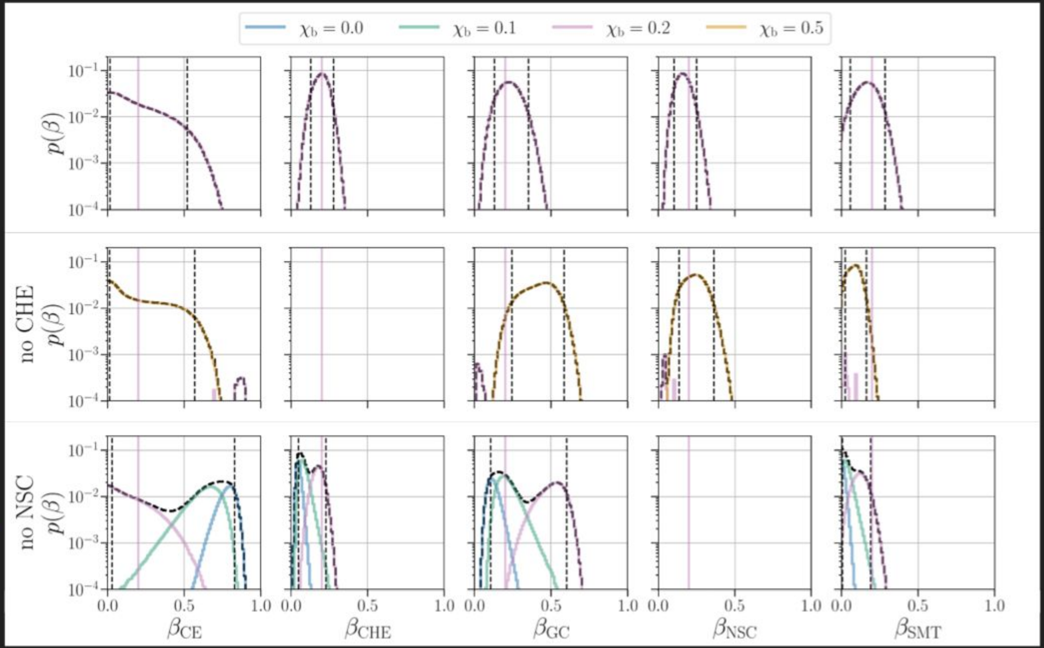
In a mock universe consisting of these 5 channels, we quickly recover the correct physics and branching fractions!



Cheng, MZ, & Vitale 2023 [2307.03129]

But…excluding relevant formation channels in such analyses can ***severely bias inference***

For example, let's consider 250 observations from a mock universe…



excluding chemically homogeneous evolution

excluding nuclear star clusters

Cheng, MZ, & Vitale 2023 [2307.03129]

Waveform modeling and inference for 3G

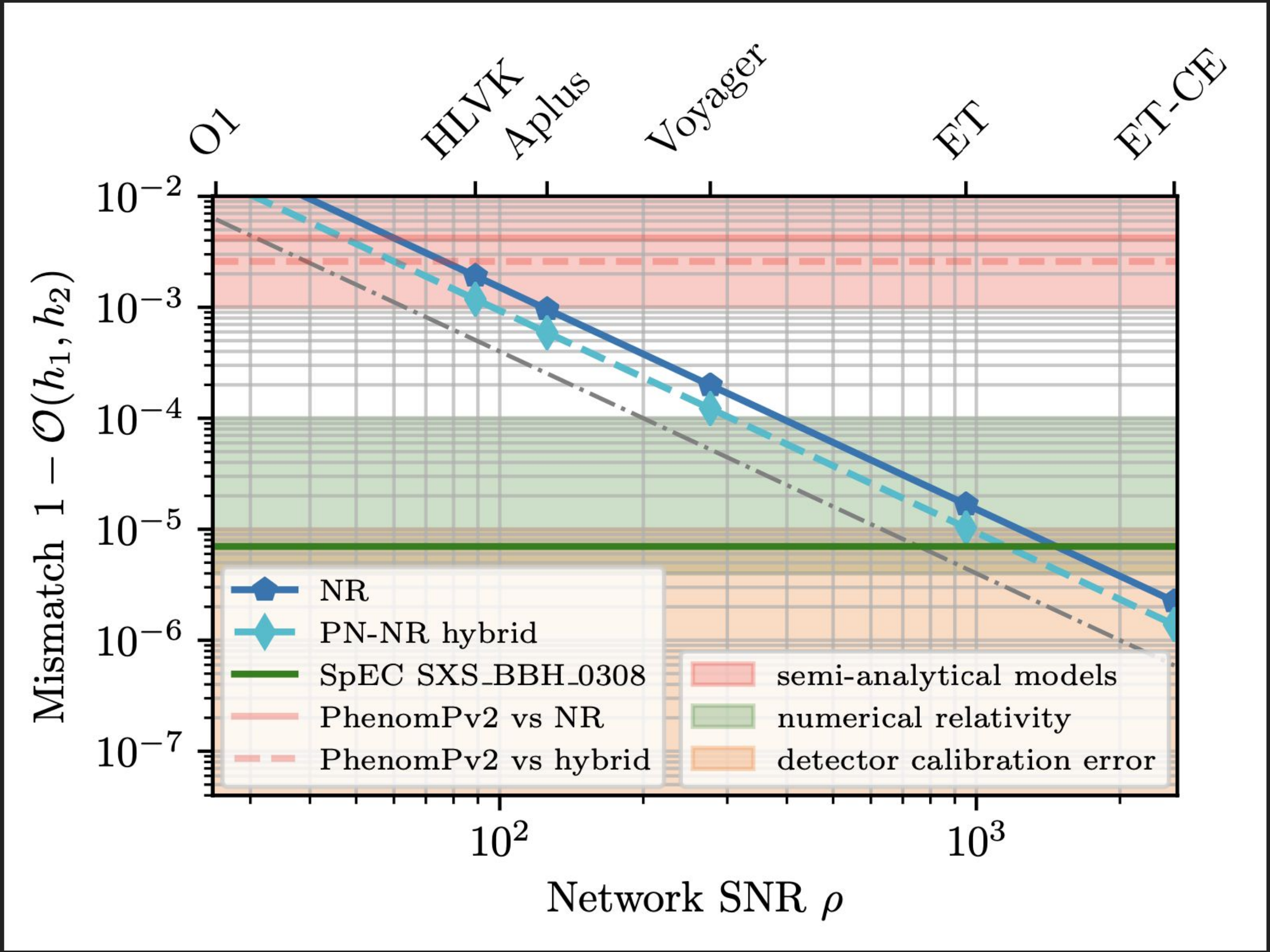
Michael Pürrer, University of Rhode Island

Waveform accuracy requirements (BBHs)

- MP & Haster 20 (see also Ferguson+21, Hu+22, Jan+23, Dhani+24)
  - Analyze NR-hybrid mock signals for 2G / 3G networks
  - Find SNR at which statistical errors ~ systematic errors (mismatch of WF template with NR-hybrid)
  - Tune indistinguishability estimate

- Indistinguishability criterion: [Flanagan&Hughes 97, Lindblom+08, McWilliams+10, Chatziioannou+17, Toubiana+24]

$$1 - \mathcal{O}(h_1, h_2) < D/(2\rho^2)$$


O1
HLVK
Aplus
Voyager
ET
ET-CE
Mismatch $1-\mathcal{O}(h_1,h_2)$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{2}
10^{3}
Network SNR ρ
NR
PN-NR hybrid
SpEC SXS_BBH_0308
PhenomPv2 vs NR
PhenomPv2 vs hybrid
semi-analytical models
numerical relativity
detector calibration error

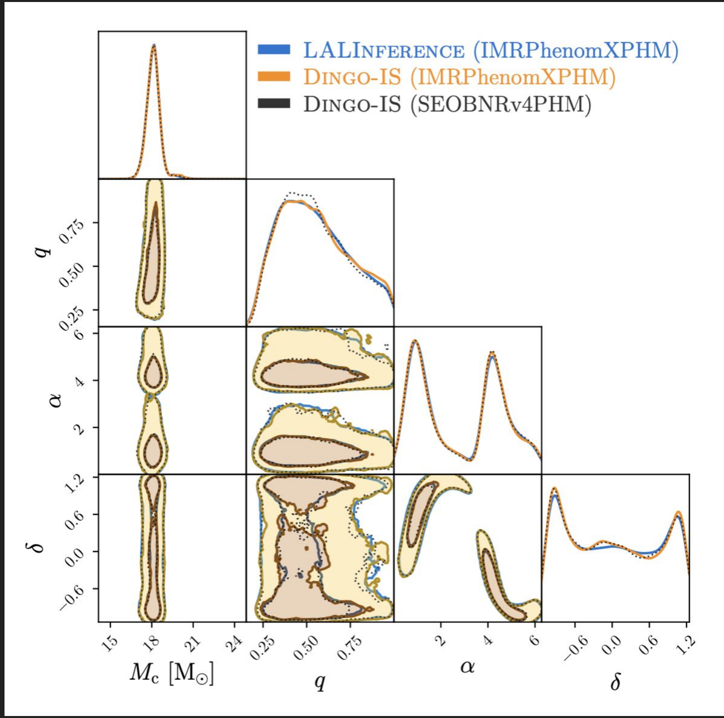
MP & Haster 20

Computation for Parameter Inference

- 3G sensitivity increase:
  - much *louder* and *longer* CBC signals
- Scaling and cost of stochastic sampling methods (MCMC, nested sampling):
  - Sampling time for a GW150914-like signal increases by O(10) from HLVK design to 3G sensitivity
- Likelihood acceleration techniques:
  - ROQ [Canizares+15, Smith+(MP)16, Morisaki+20, Smith+21] $O(10^2 - 10^5)$
  - Heterodyning / Relative binning [Cornish 21, Zackay+18] $O(10^2 - 10^4)$
  - Auto-diff'ed (jaxified) waveforms on GPU [Wong+23] O(10) & normalizing-flow enhanced MCMC [Edwards+23]

Computation for Parameter Inference

- Neural posterior estimation (Dingo): [Dax+21, Dax+(MP)23]
- Deep learning method to train conditional density estimator (e.g. normalizing flow) on noisy training data
- Training: O(week)
- Inference: O(minutes)
- Robust results: importance sampling O(hours)
- Proven technique for BBHs
- Extension to BNS and study of performance at SNRs > 100 under way



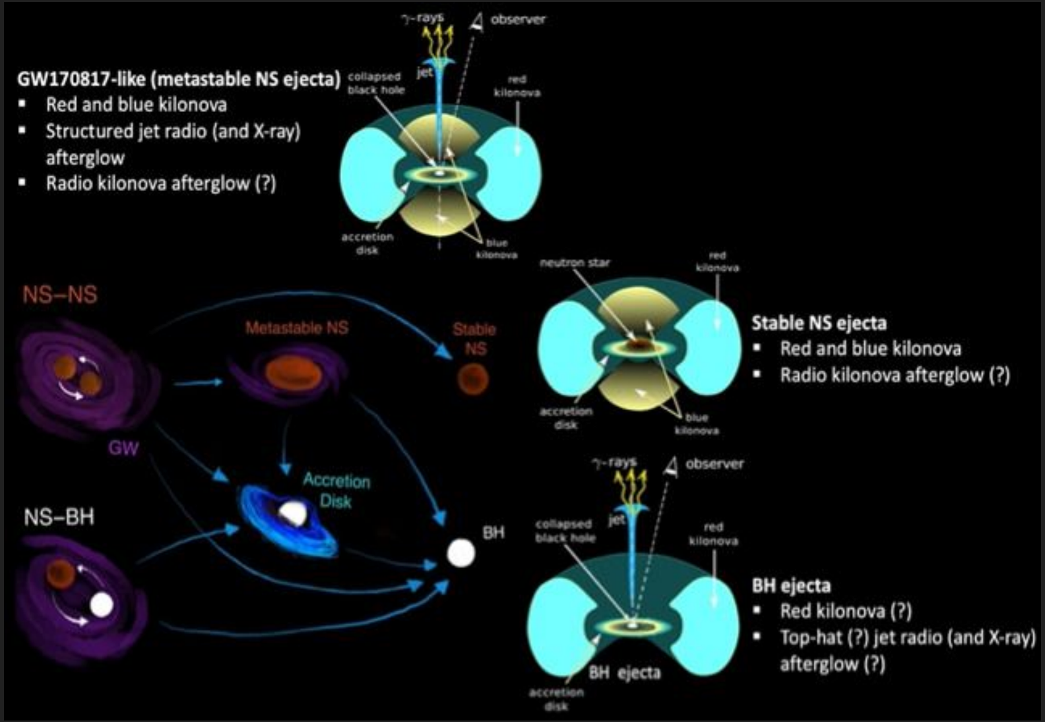
How can we be ready for the 3G era?

- Steep demands for 3G analyses x deluge of events (~10^5 BBHs / yr):
  - "golden events" will be the hardest to analyze accurately
  - need to efficiently analyze high number of vanilla CBCs (SNR~100)
- Extend NR-simulation catalogs:
  - length: reducing starting frequency by 2: ~ *5 x cost*
  - coverage: doubling mass-ratio: ~ *4 x cost*
  - accuracy: reduce mismatch by 10: ~*2 x cost*
- Build more accurate models (surrogate & semi-analytical models) including all relevant physics (higher modes, precession, eccentricity, tides)
- Consider marginalizing over WF uncertainty - limiting precision of inference
- Further develop inference acceleration techniques (samplers, DL methods)

Multi-messenger astrophysics in the ngGW era

Alessandra Corsi
Texas Tech University
(moving soon to Johns Hopkins University)

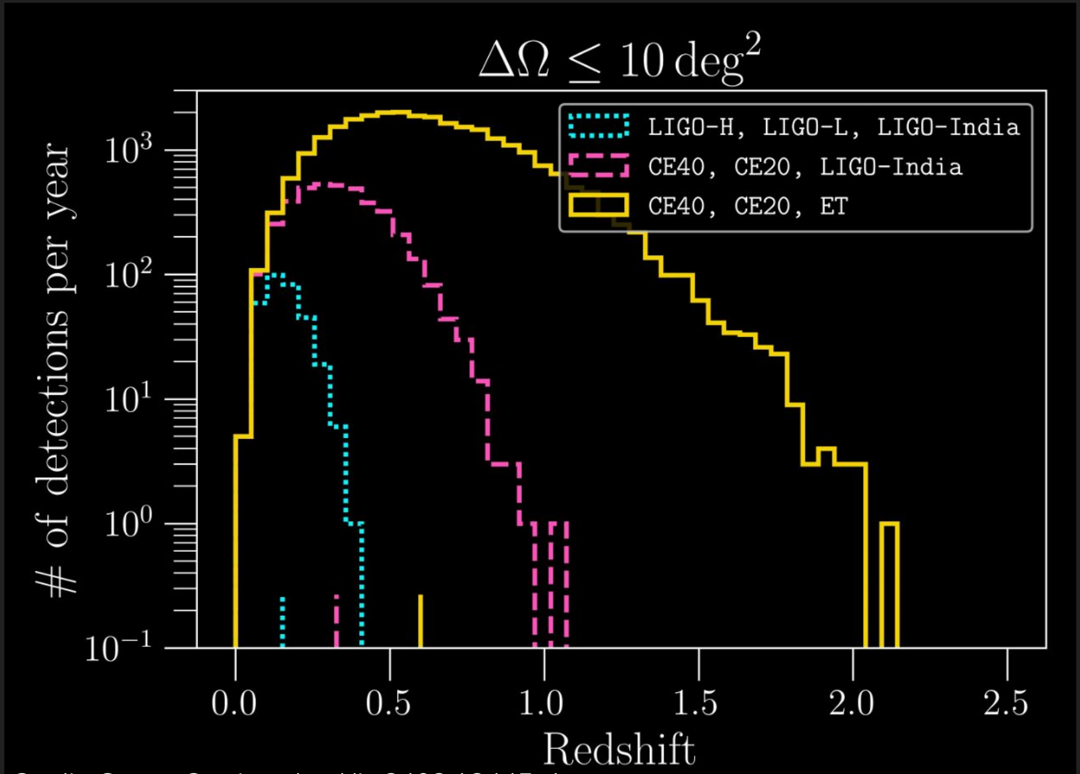
Key Questions needing answers



Observations and simulation/numerical/modelling work all critically needed! Observations will not happen without instruments that can follow the progress in GW horizon distance reach and detection rates.

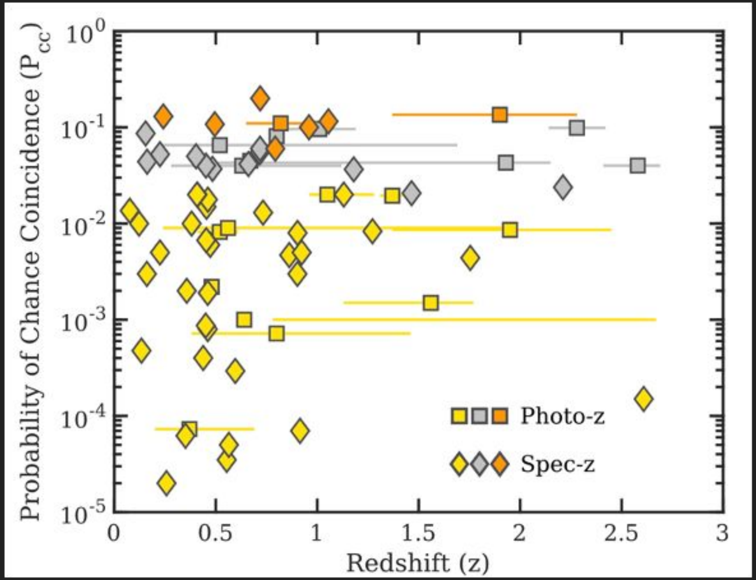
- What is the **mass distribution** of NS-NS and BH-NS binaries?
- Are BNS mergers the **only site of r-process nucleosynthesis or one of many sites**? Are the heaviest of the heavy elements synthesized?
- **What are the properties of their outflows?** (geometry, energy and speed distribution, particle acceleration, magnetic field amplification, ISM density, ...)
- What are the central engines of and what is the physics behind r**elativistic jets**?
- **What is the nature of the merger remnant** (max NS mass and EoS of state of neutron matter)?

ngGW era brings the opportunity to answer these questions via better localizations nearby and farther reach



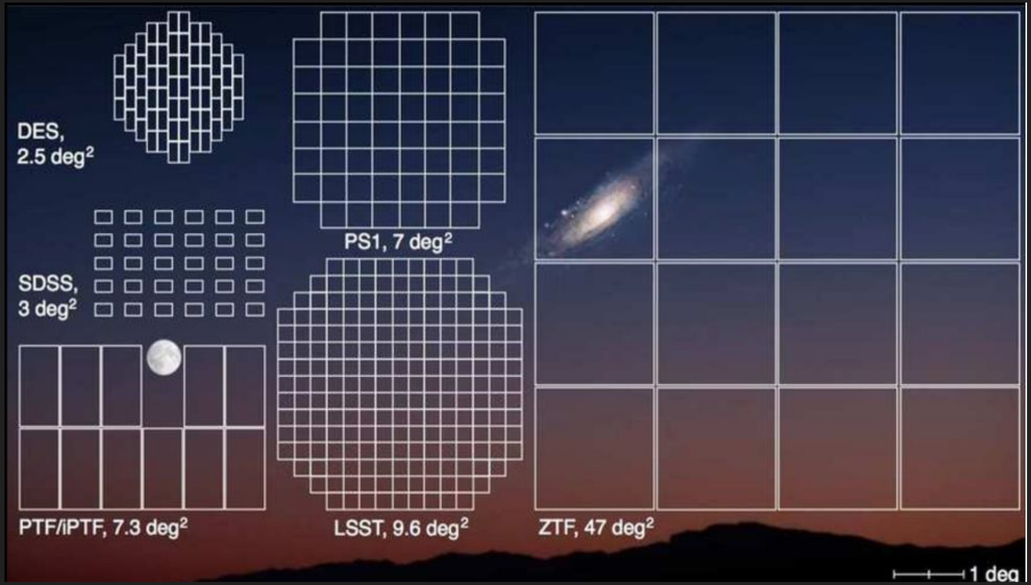
Credit: Gupta; Corsi et al. arXiv:2402.13445v1

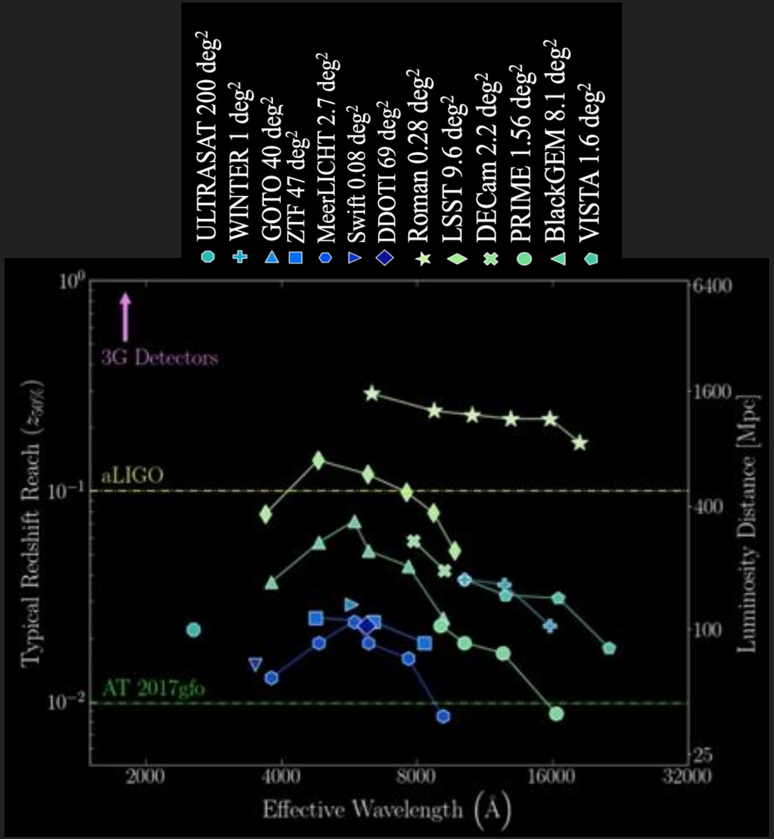
Assumed NS-NS rate is 320 $Gpc^{-3}\ yr^{-1}$
GWTC-3 90% credible interval is 10-1700 $Gpc^{-3}\ yr^{-1}$



Fong et al. 2022 ApJ 940 56

Finding kilonovae in GW error areas: Facilities such as Rubin and Roman are key

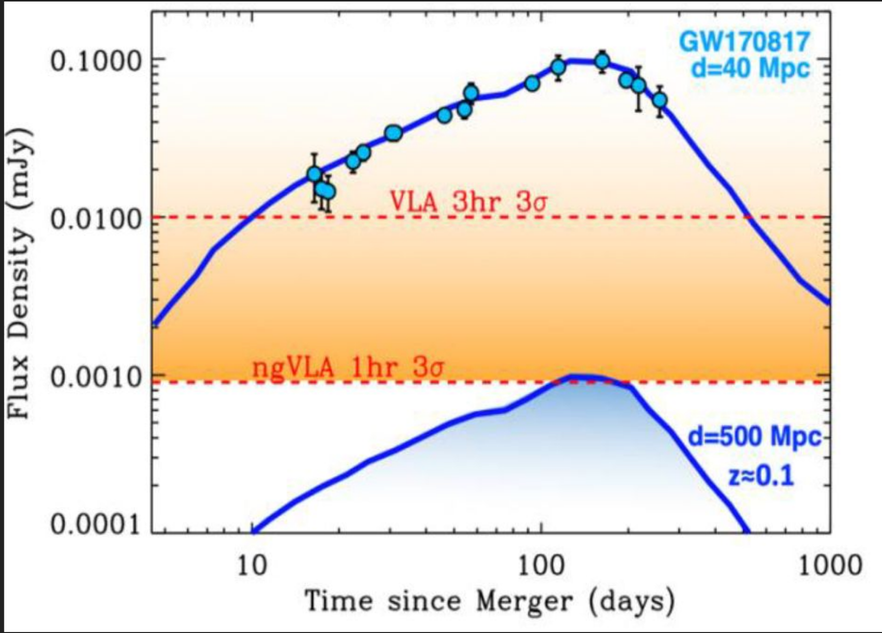




Chase et al. 2022, ApJ, 927, 163

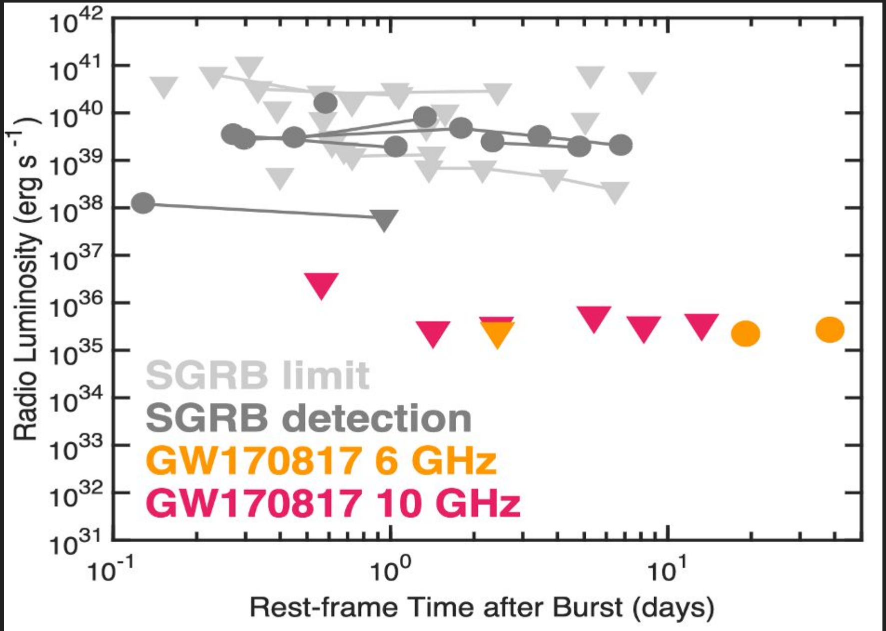
From fast ejecta tails to farther jets: ngVLA will be key

Beasley et al. Astro2020 White Paper



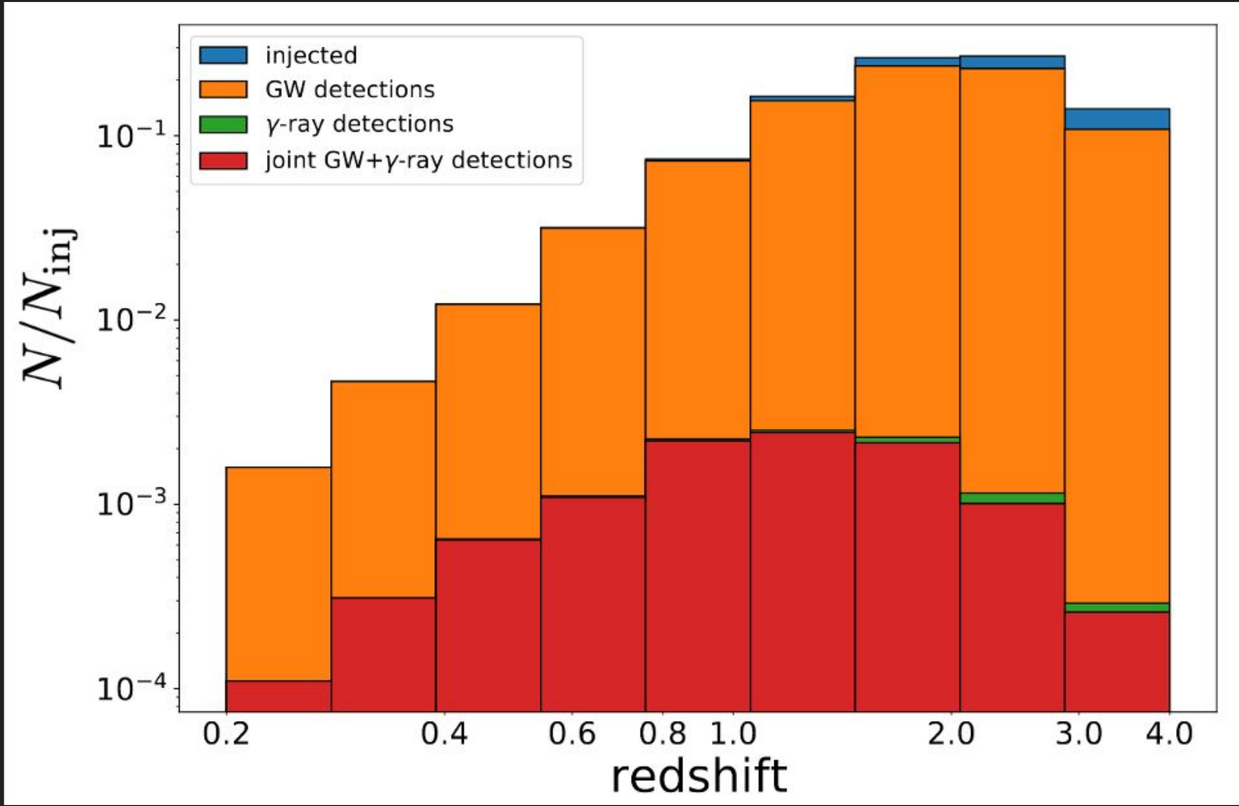
Quantity	0 XG	1 XG			2 XG			3 XG
	HLA	HLET	20LA	40LA	20LET	40LET	4020A	4020ET
	$\Delta\Omega \leq 1$ deg^2							
Number	5	24	17	18	157	247	97	754
Median z	0.056	0.090	0.072	0.082	0.102	0.128	0.108	0.185
Maximum z	0.101	0.156	0.126	0.126	0.230	0.287	0.243	0.503

Fong et al. 2017, ApJL, 848, L23



Quantity	0 XG	1 XG			2 XG			3 XG
	HLA	HLET	20LA	40LA	20LET	40LET	4020A	4020ET
	$\Delta\Omega \leq 10$ deg^2							
Number	317	1216	866	976	6211	9440	4004	27771
Median z	0.152	0.208	0.216	0.199	0.360	0.410	0.327	0.599
Maximum z	0.359	0.535	0.522	0.535	1.08	1.30	1.06	2.12

NASA's roadmap for the future of gamma-ray astronomy will be very important



Ronchini et al. A&A 665, A97 (2022) - Fermi-GBM+(ET+CE)

Future Innovations in Gamma Rays(FIG SAG):

https://pcos.gsfc.nasa.gov/sags/figsag.php