Multimessenger Observations

PAX IX, King's College London, UK, July 23-25

Andrea Maselli

Gran Sasso Science Intitute

Gravitational wave fundamental physics, strong gravity, black hole physics

Zsuzska Marka

Columbia Astrophysics Laboratory

Gravitational-wave multi-messenger astrophysics, joint high-energy neutrino & GW searches

Nikhil Sarin

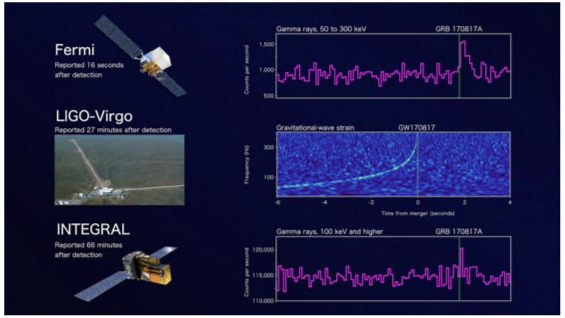
Oskar Klein Center at Stockholm University and Nordita Institute

GRBs/kilonovae/supernovae. Neutron star astrophysics. Gravitational-wave and electromagnetic transient and population inference

GW170817

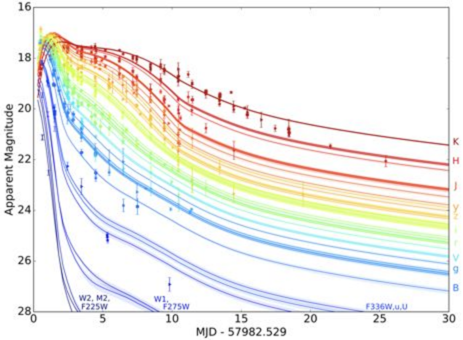
Binary neutron star mergers as progenitors of short GRB

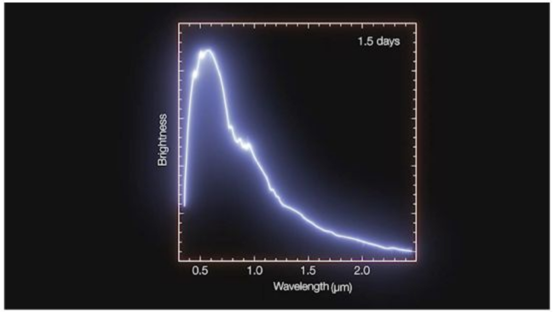
- Multi-wavelength afterglow observations
  - The primary first short GRB observed off-axis
  - Structured off-axis jet



BNS mergers are a major channel of formation of heavy elements

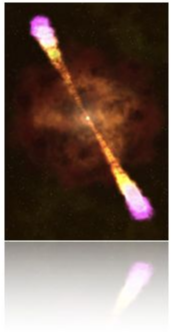
E. Pian +, Nature 551 (2017)
S. J. Smartt +, Nature 551 (2017)



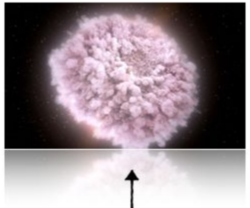


Multimessenger physics

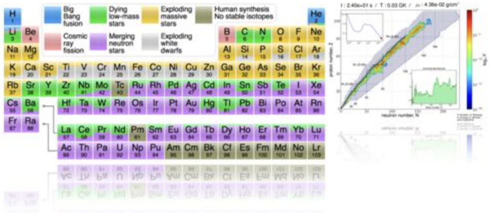
Relativistic astrophysics



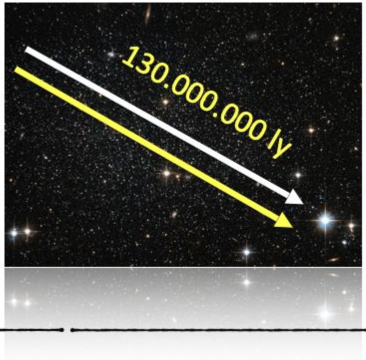
Radioactively powered transients



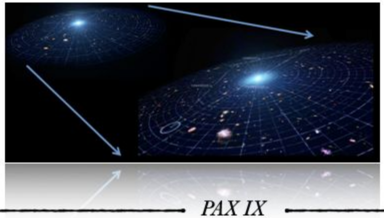
Nucleosynthesis and enrichment of the Universe



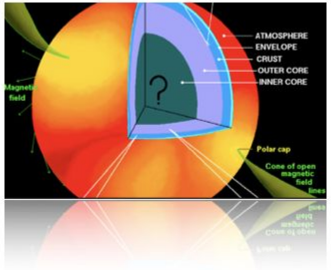
Fundamental Physics



Cosmology



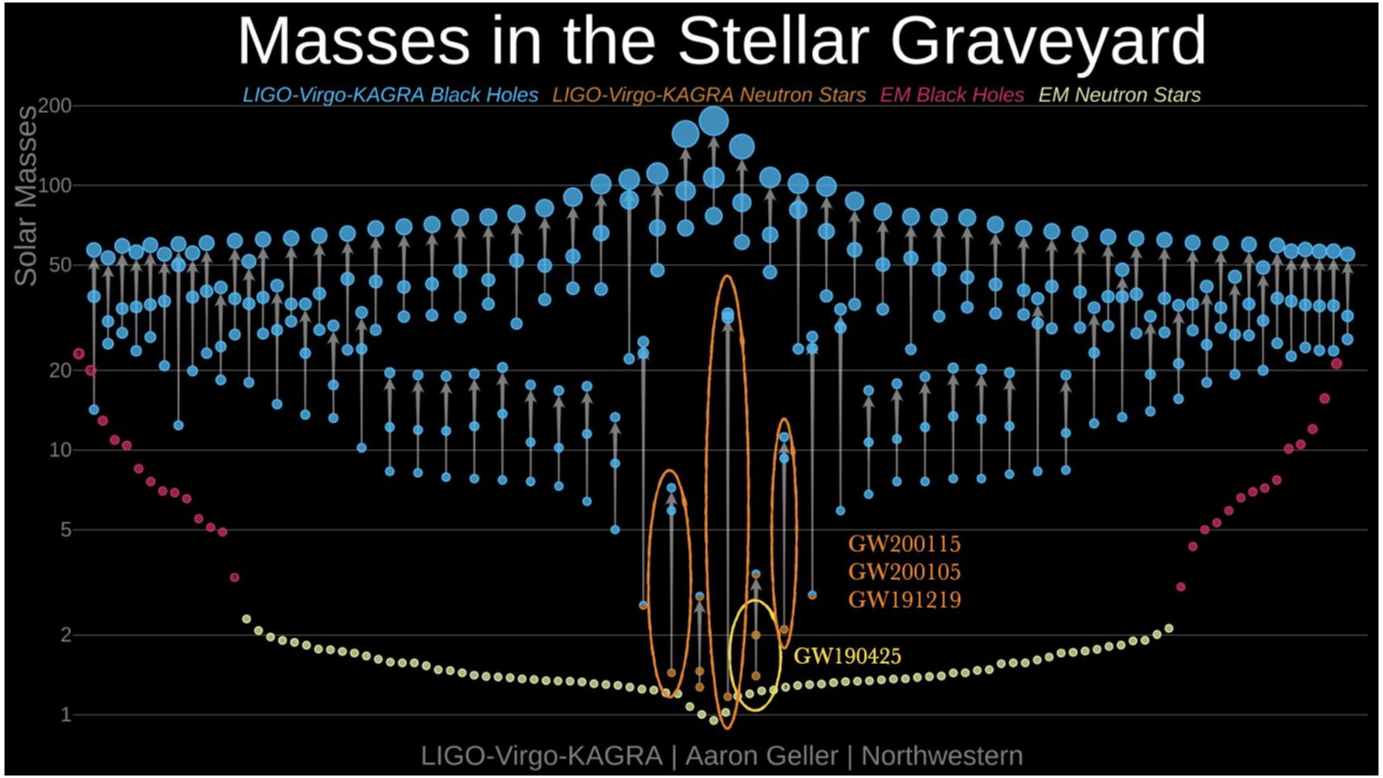
Nuclear matter physics



BNS so far

Life after GW170817

LVK, PRX 13 041039, (2023)
Abbott +, ApJL 915 (2021),
LVK, PRX 13, 011048 (2023)



90+ events

vast majority BBHs

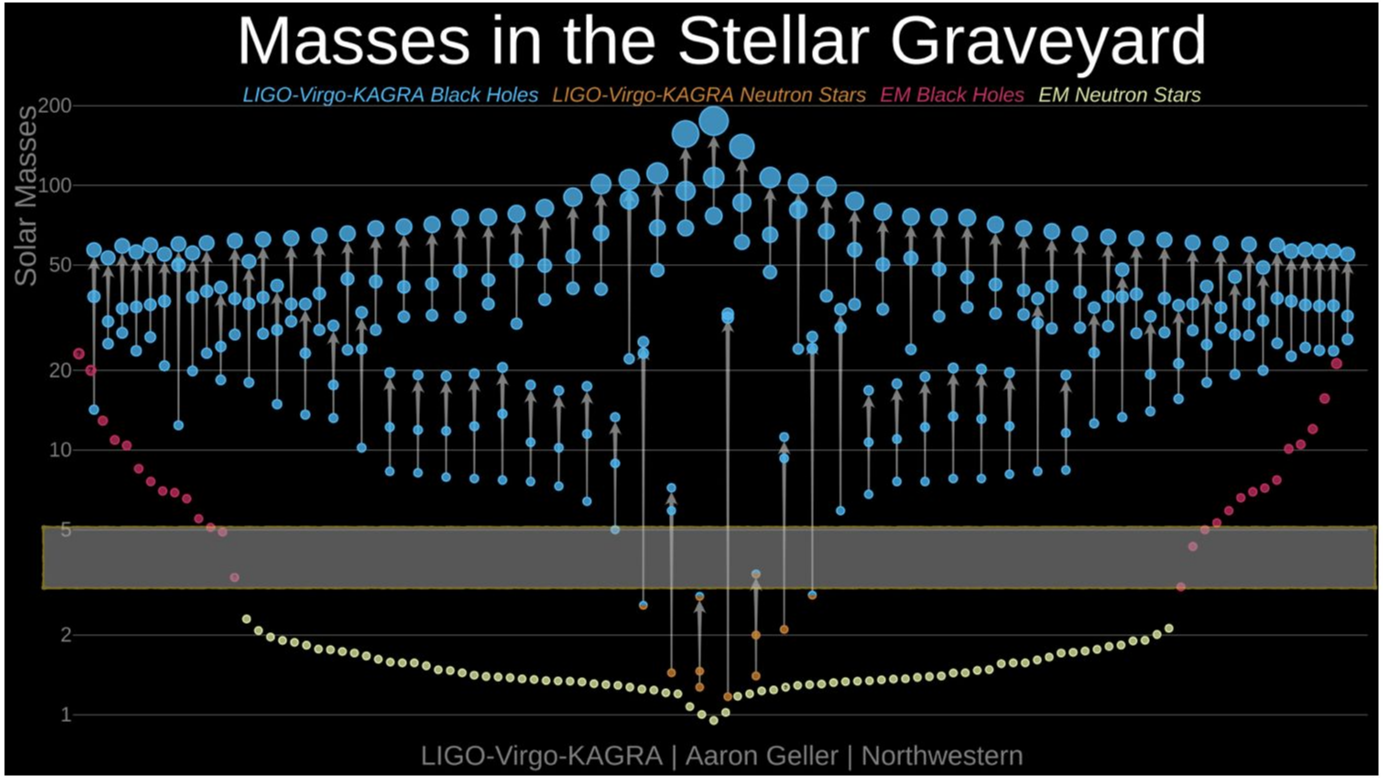
BH-NS events

BNS detection with total mass larger than any known BNS (5σ from Galactic BNS mean)

BNS so far

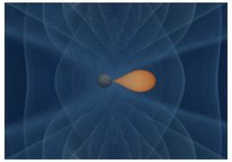
Life after GW170817

LVK, PRX 13 041039, (2023)
Abbott +, ApJL 915 (2021),
LVK, PRX 13, 011048 (2023)



mass gap?

GW230529



- Likely a neutron star merging with a mass-gap compact object, and possibly a tidal disruption event
- The primary component of the source has a mass less than $5M_\odot$ at 99% credibility
  - Updated local NSBH merger rate to $30 - 200\text{Gpc}^{-3}\text{yr}^{-1}$
  - No EM counterpart: poor sky-localisation

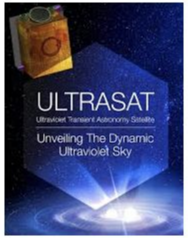
Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$
Primary spin magnitude χ_1	$0.44^{+0.40}_{-0.37}$
Effective inspiral-spin parameter $\chi_{\rm eff}$	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter $\chi_{\rm p}$	$0.40^{+0.39}_{-0.30}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$

- Expected hundreds of BNS detections and a few GRB/GW detections per year with the current GW detectors (at design sensitivity) up to z = 0.2
- Two long GRBs with kilonova emission, GRB 211211A and GRB 230307A within the current GW detector reach

J. Rastinejad +, Nature 612, 7939 (2022)
A. Mei +, Nature 612, 7939 (2022)
E. Troja +, Nature 612, 7939 (2022)
A. Levan +, Nature Astron. 7, 8 (2023)

To the future

SVOM



NEW OBSERVATORIES

LIGO INDIA

SKA
SQUARE KILOMETRE ARRAY

make all events a GW170817

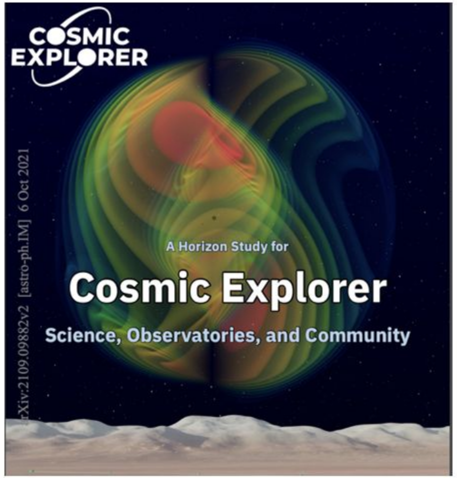
Einstein Telescope and Cosmic Explorer next generation of ground based interferometers

M. Branchesi +, JCAP 07, 068 (2023)

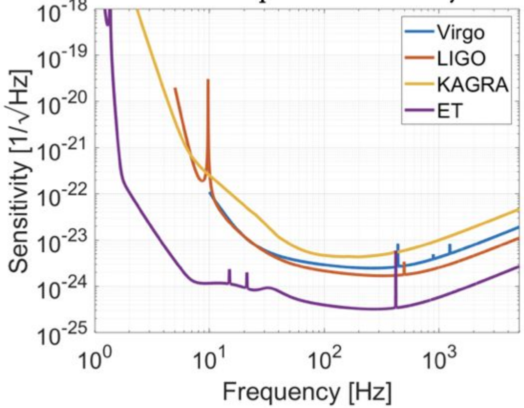
Science with the Einstein Telescope: a comparison of different designs

Marica Branchesi,[1,2] Michele Maggiore,[3,4] David Alonso,[5] Charles Badger,[6] Biswajit Banerjee,[1,2] Freija Beirnaert,[7] Swetha Bhagwat,[8,9] Guillaume Boileau,[10,11] Ssohrab Borhanian,[12] Daniel David Brown,[13] Man Leong Chan,[14] Giulia Cusin,[15,3,4] Stefan L. Danilishin,[16,17] Jerome Degallaix,[18] Valerio De Luca,[19] Arnab Dhani,[20] Tim Dietrich,[21,22] Ulyana Dupletsa,[1,2] Stefano Foffa,[3,4] Gabriele Franciolini,[8] Andreas Freise,[23,16] Gianluca Gemme,[24] Boris Goncharov,[1,2] Archisman Ghosh,[7] Francesca Gulminelli,[25] Ish Gupta,[20] Pawan Kumar Gupta,[16,26] Jan Harms,[1,2] Nandini Hazra,[1,2,27] Stefan Hild,[16,17] Tanja Hinderer,[28] Ik Siong Heng,[29] Francesco Iacovelli,[3,4] Justin Janquart,[16,26] Kamiel Janssens,[10,11] Alexander C. Jenkins,[30] Chinmay Kalaghatgi,[16,26,31] Xhesika Koroveshi,[32,33] Tjonnie G. F. Li,[34,35] Yufeng Li,[36] Eleonora Loffredo,[1,2] Elisa Maggio,[22] Michele Mancarella,[3,4,37,38] Michela Mapelli,[39,40,41] Katarina Martinovic,[6] Andrea Maselli,[1,2] Patrick Meyers,[42] Andrew L. Miller,[43,16,26] Chiranjib Mondal,[25] Niccolò Muttoni,[3,4] Harsh Narola,[16,26] Micaela Oertel,[44] Gor Oganesyan,[1,2] Costantino Pacilio,[8,37,38] Cristiano Palomba,[45] Paolo Pani,[8] Antonio Pasqualetti,[46] Albino Perego,[47,48] Carole Périgois,[39,40,41] Mauro Pieroni,[49,50] Ornella Juliana Piccinni,[51] Anna Puecher,[16,26] Paola Puppo,[45] Angelo Ricciardone,[52,39,40] Antonio Riotto,[3,4] Samuele Ronchini,[1,2] Mairi Sakellariadou,[6] Anuradha Samajdar,[21] Filippo Santoliquido,[39,40,41] B.S. Sathyaprakash,[20,53,54] Jessica Steinlechner,[16,17] Sebastian Steinlechner,[16,17] Andrei Utina,[16,17] Chris Van Den Broeck,[16,26] and Teng Zhang[9,17]

M. Evans + arXiv gr-qc: 2109.09882



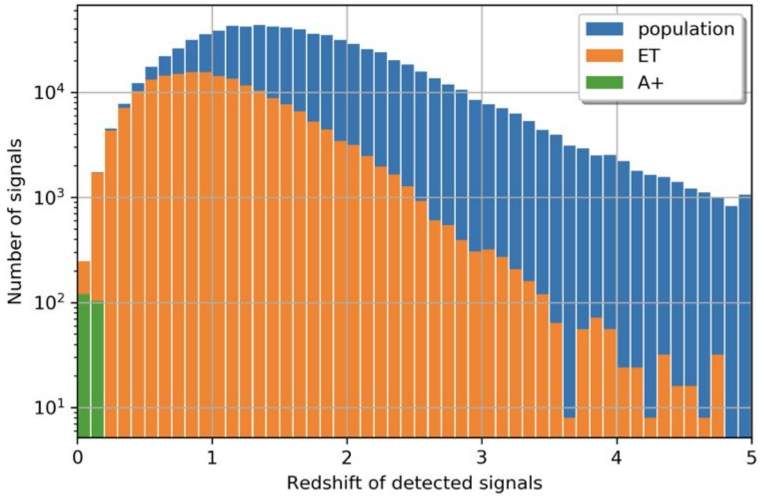
ET expected sensitivity



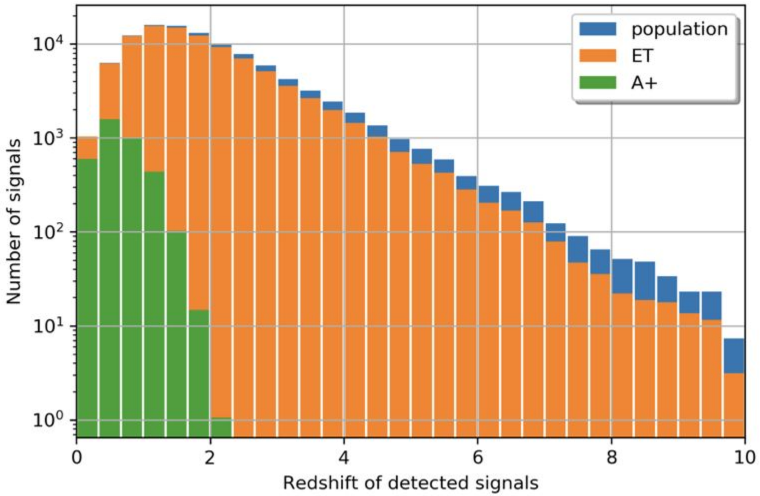
Populations of events

M. Branchesi +, JCAP 07, 068 (2023)

binary neutron star mergers



binary black hole mergers



10^5 *detections/yr*

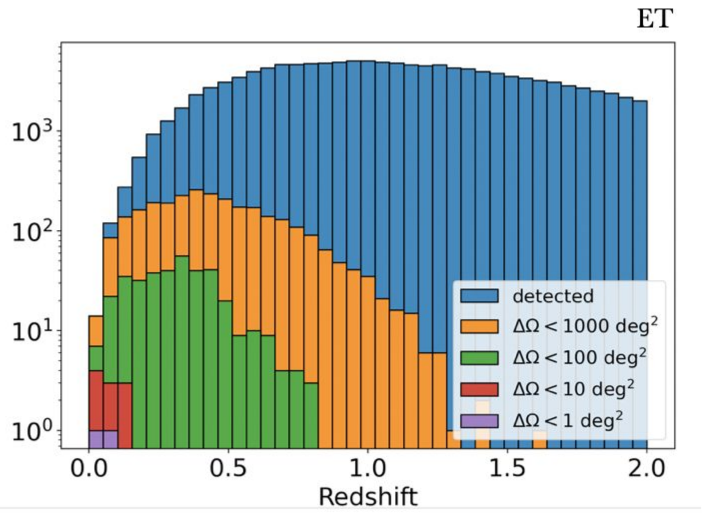
10^5 *detections/yr*

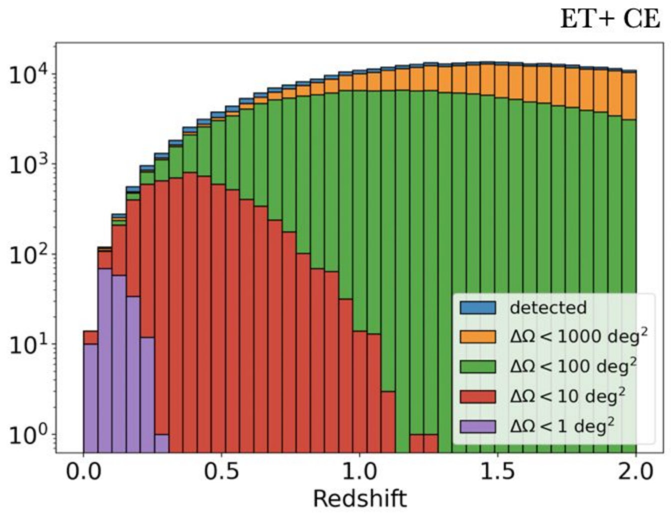
- Sampling astrophysical populations of binary system of compact objects along the cosmic history of the Universe

Some numbers: ET

S. Ronchini +, A&A 665, A97 (2022)

ET sky localisation capabilities

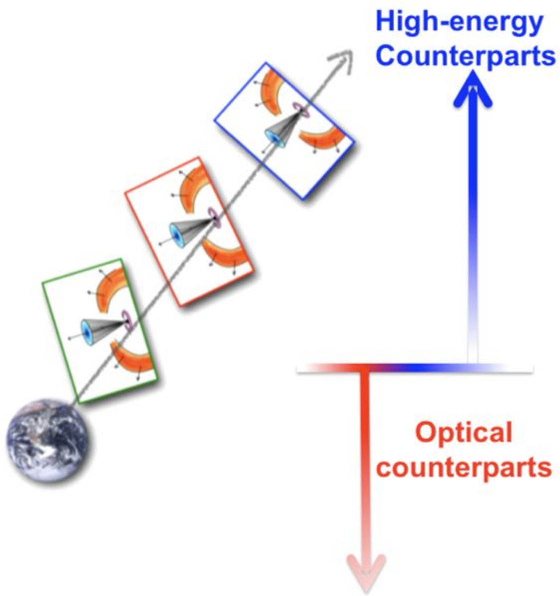


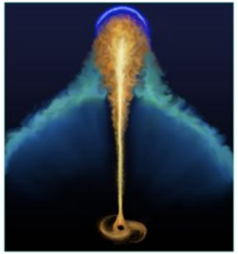


- ET: $\mathcal{O}(100)$ detections/yr with sky-localisation $\lesssim 100$ deg^2
  - Chances for early warning alerts
- ET + CE: $\mathcal{O}(1000)$ detections/yr with sky-localisation $\lesssim 10$ deg^2

GW & light

Multimessenger observations, where do we look? nearby and far Universe





high redshift: Gamma Ray Bursts

relativistic jet physics, GRB emission mechanisms, cosmology…

low redshift: kilonovae

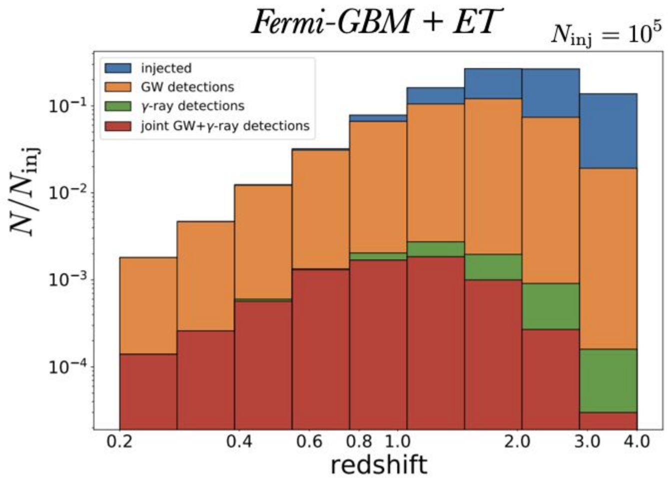
kilnovae physics, nucleosynthesis, nuclear physics…

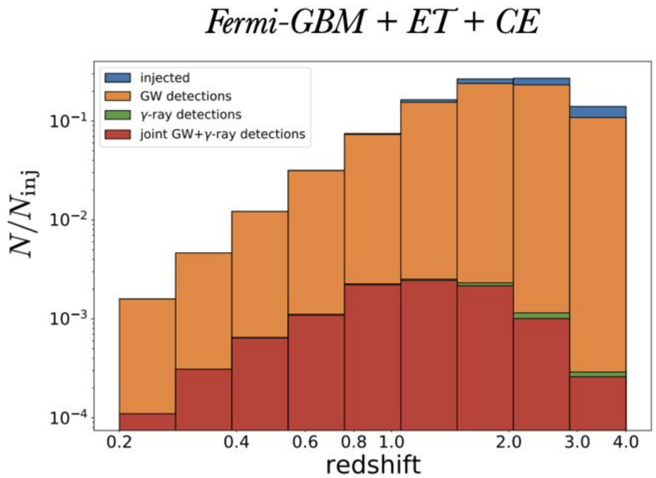
Image credit: NASA Goddard Space Flight Center

GW & light

S. Ronchini +, A&A 665, A97 (2022)

GW + γ-ray joint detections per year





- Almost all detected GRBs will have a counterpart
  - From tens (THESEUS) to hundreds (HERMES) detections/yr depending on the detector
- Crucial instruments able to localise at arcmin-arcsec level and drive ground-based follow-ups

GW & light

GW + X-ray joint detections per year

S. Ronchini +, A&A 665, A97 (2022)

- X-ray wide-FoV satellites, such as THESEUS, will be able to detect several tens per year

Sky localisation from GW → 100 s of slewing time (like Swift-XRT) → Detection with wide field X-ray telescopes

$\Delta\Omega < 100\ \mathrm{deg}^2$

survey mode

	ET	ET+2CE
SVOM-ECLAIRs	4 ± 2	5 ± 2
Einstein Probe	50^{+15}_{-16}	64^{+12}_{-20}
Gamow	9^{+2}_{-2}	10^{+3}_{-3}
THESEUS-SXI	11^{+3}_{-3}	13^{+4}_{-3}
THESEUS-(SXI+XGIS)	23^{+6}_{-5}	27^{+7}_{-5}
TAP-WFI	16^{+3}_{-4}	17^{+6}_{-3}

pointing mode

	ET	ET+CE	ET+2CE
EP	9^{+5}_{-3}	294^{+80}_{-59}	359^{+168}_{-110}
THESEUS-SXI/ Gamow	7^{+5}_{-3}	95^{+43}_{-14}	122^{+41}_{-23}
TAP-WFI	8^{+5}_{-3}	182^{+43}_{-31}	225^{+76}_{-72}

- An order of magnitude less detection if 1 hour later on source
  - Fast response to GW alert is crucial

	100 s	1 h	4 h
Einstein Probe	359^{+168}_{-110}	48^{+24}_{-15}	17^{+15}_{-10}
THESEUS-SXI/ Gamow	122^{+41}_{-23}	12 ± 7	<9
TAP-WFI	225^{+76}_{-72}	50^{+20}_{-10}	17^{+10}_{-5}

Prioritisation

A lot of events coming. Too many for a full follow up: need for prioritisation strategies

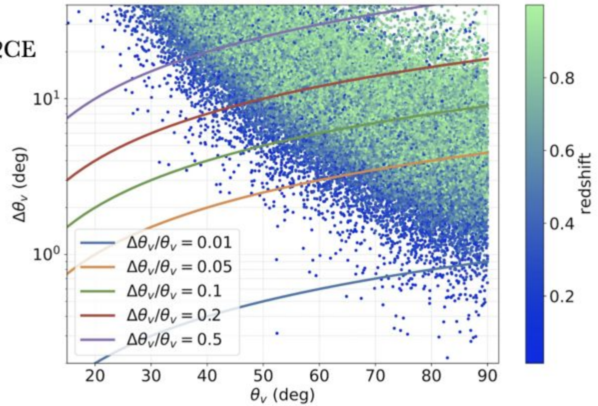
Sky-localization

	ET	ET+CE	ET+2CE
$N_{\rm det}$	143970	458801	592565
$N_{\rm det}(\Delta\Omega < 1 \text{ deg}^2)$	2	184	5009
$N_{\rm det}(\Delta\Omega < 10 \text{ deg}^2)$	10	6797	154167
$N_{\rm det}(\Delta\Omega < 100 \text{ deg}^2)$	370	192468	493819
$N_{\rm det}(\Delta\Omega < 1000 \text{ deg}^2)$	2791	428484	585317

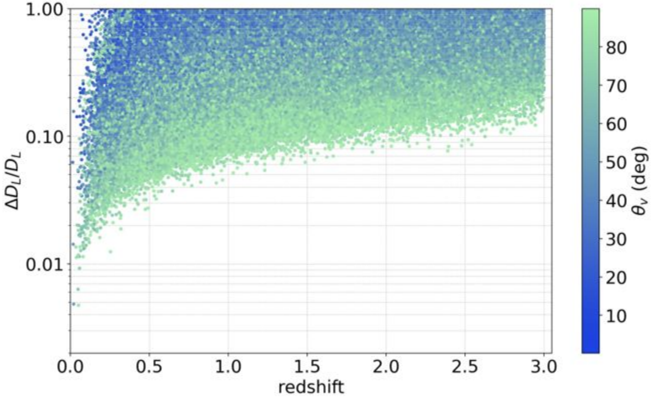
- Choose a subset of samples to follow up based on expected constraints

Viewing angle

ET+2CE



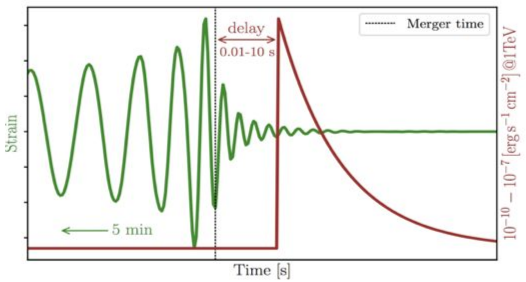
Distance



Pre-merger detections

M. Branchesi +, JCAP 07, 068 (2023)

3g low-frequency improvement is key for pre-merger alerts



Einstein Telescope alone

Configuration	$\Delta\Omega_{90\%}$	All orientation BNSs			BNSs with $\Theta_v < 15°$		
	[deg^2]	30 min	10 min	1 min	30 min	10 min	1 min
Δ10km	10	0	1	5	0	0	0
	100	10	39	113	2	8	20
	1000	85	293	819	10	34	132
	All detected	905	4343	23597	81	393	2312
2L 15 km misaligned	10	0	1	8	0	0	0
	100	20	54	169	2	7	26
	1000	194	565	1399	23	73	199
	All detected	2172	9598	39499	198	863	3432

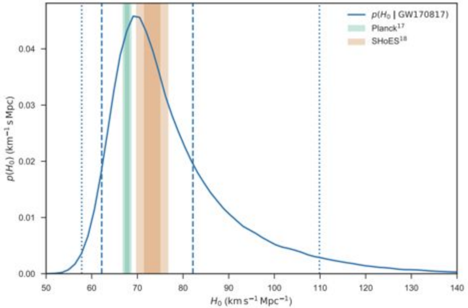
- Five minutes before the merger, a factor 10 higher number of well-localisaed events when ET operates in a network of next generation GW detectors

Fundamental physics

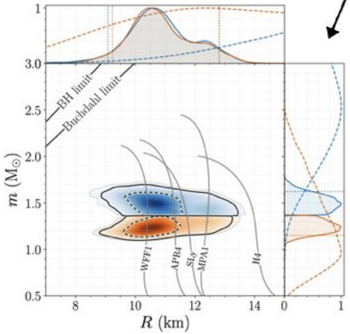
P. Creminelli & F. Vernizzi, PRL 119, 251302 (2017)
J. M. Ezquiaga & M. Zumalacarregui, PRL 119, 251304 (2017)
J. Sakstein & B. Jain, PRL 119, 251303 (2017)
T. Baker +, PRL 119, 251301 (2017)
….

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [51], $f(\phi)$·Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

LVK, Nature 551, 7678 (2017)



LVK, PRL 121 (2018) 16, 161101



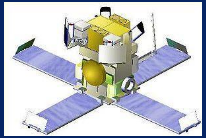
- GRBs, kilonova
- maximum mass bound
- bounds on tidal deformability from below

Rezzolla +, The Astroph. J. 852, 2018
Magalit+, The Astroph. J.850, 2017
Ruiz +, Phys. Rev. D 97, 2017
Most +, Phys. Rev Lett. 120, 2018
Bauswein +, The Astroph. J.850, 2017
Coughlin +, Mon. Not. R. Astr. 480, 2018
Radice & Lai, Eur. Phys. J. 55 , 2019
Radice +, The Astroph. J. 852, 2018
Coughlin +, Mon. Not. R. Astr. 489, 2019
LVC, Class. Quant. Grav.37, 2020
Ai +, The Astroph. J. 893, 2020
Shibata+, Phys. Rev. D 96, 2017
Annala +, Phys. Rev. Lett. 120, 2018
Shibata+, Phys. Rev. D 100, 2019
Shao + , Phys. Rev. D 101, 2020
Carson +, Phys. Rev. D 100, 2019
……..

Basic Glossary: Multimessenger Approaches

Two decades of MMA searches with GWs

HETE-2



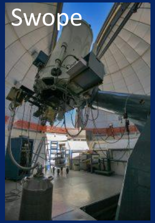
"ExtTrig" strategy:

Telescopes, Satellites
or other external entities → (Flow of trigger information) → GW Search

First exttrig search
GRB030329

"Follow-Up" strategy:

GW Data → (Flow of trigger information) → Telescopes, Satellites
or other external entities



First EM follow campaign:
summer 2007
pilot project

"joint search" strategy:

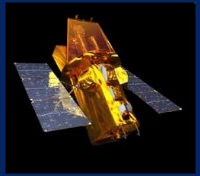
GW detector
(GRB detector)
HEN detector
++

→

Low
Latency
Algorithm for
Multimessenger
Astrophysics

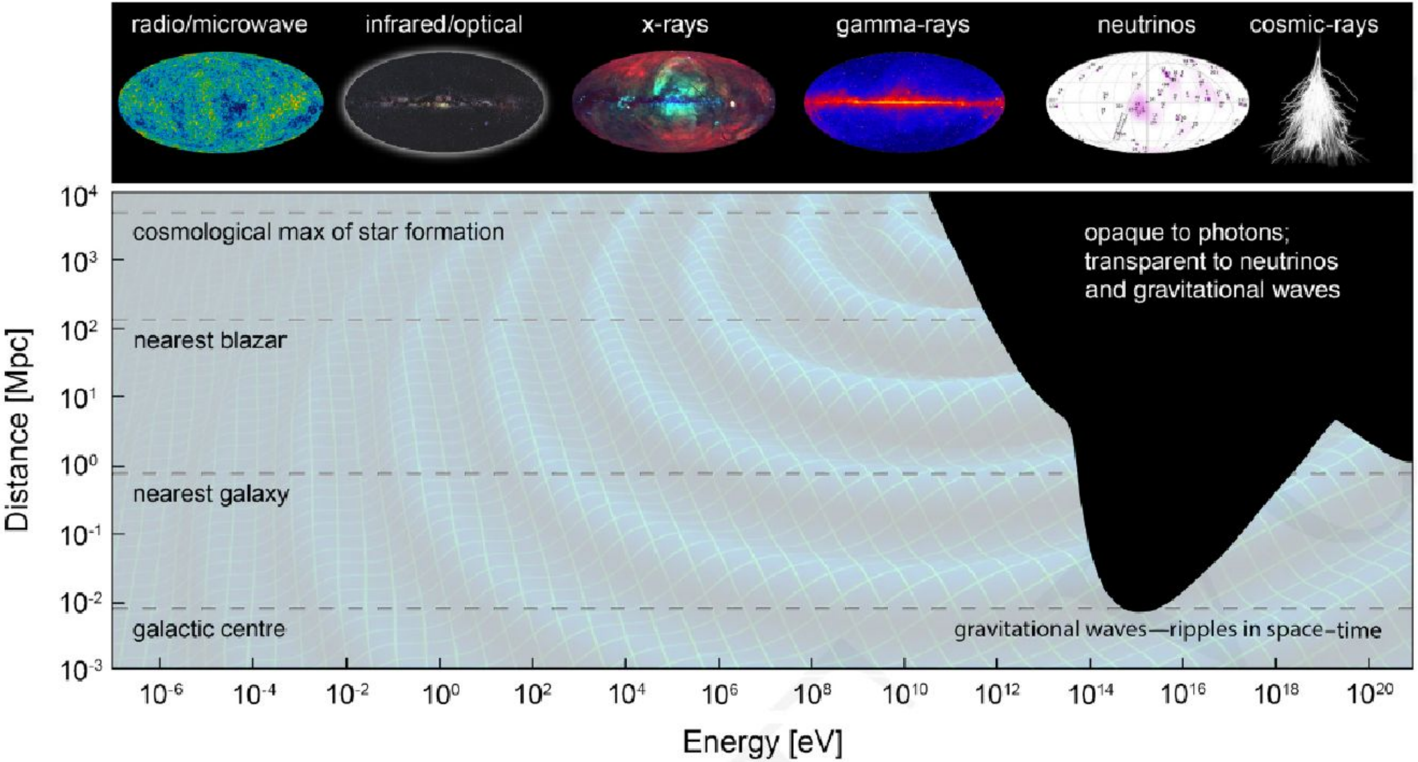
→

→



First search concept: 2006
in ***low-latency***
since O2 (2017)

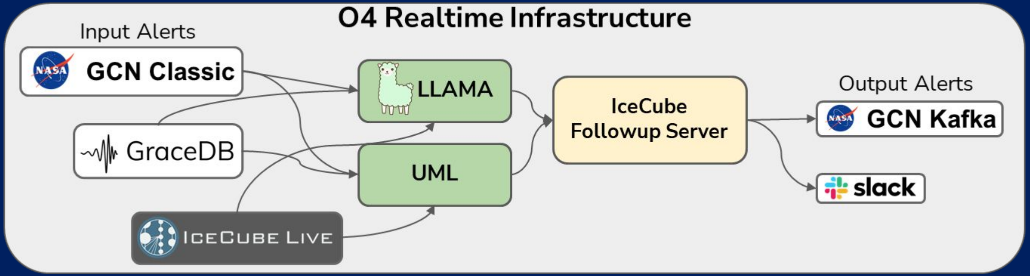
The multimessenger energy-distance scale

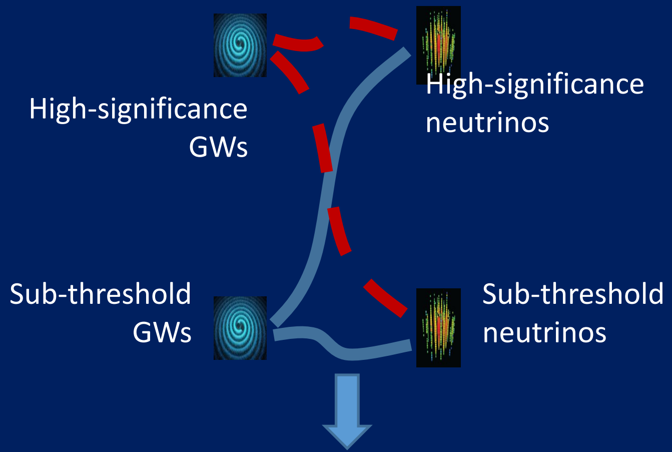


Bartos and Kowalski

Future of MMA: rich in observational data

- More sensitive detectors across all messenger types
  - More triggers from more detectors at all levels
- Proliferation of open science
  - Public data for multiple observatories
  - Multitudes of open-source software
- Proliferation of real-time analysis capabilities
  - Receive information from MMA cyberinfrastructures
  - Multitudes of open-source software
  - Even subthreshold triggers are released publicly

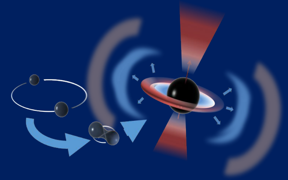




Alert EM community of significant temporal+spatial overlaps

=>Coincident observation of triggers for two or more messengers (gravitational-waves, electromagnetic, neutrinos) will become increasingly frequent

Ingredients of an MMA search



- detector data for each messenger (arrival time, localization ..)
- understanding the detector’s behavior (sensitivity – distance reach, noise trigger rate ..)

- source model (emission delay between messengers, distribution of sources in the Universe, source energetics) or no model (unknown unknown)

Time of the transient
Localization of the transient

Find **spatial** and *temporal* overlap

Energetics of the observed excess
-signalness of GW trigger candidate
-neutrino energy
-GRB energetics
-optical signatures

Understand the detectors’ behavior (sensitivity – distance reach, noise trigger rate ..)

Model independent optimal multimessenger search doesn't exist!

Veske et al., The Astrophysical Journal (2021), Volume 908, Number 2, 216

Model dependent optimal test statistic with Bayesian statistics:

$$\mathrm{TS}(\mathbf{x}) = \frac{P(\mathbf{x}|H_s)}{P(\mathbf{x}|H_n)} = \frac{\sum_i P(\mathbf{x}|H_s^i)P(H_s^i)}{\sum_j P(\mathbf{x}|H_n^j)P(H_n^j)} \times \frac{\sum_j P(H_n^j)}{\sum_i P(H_s^i)}$$

Combined signal hypothesis

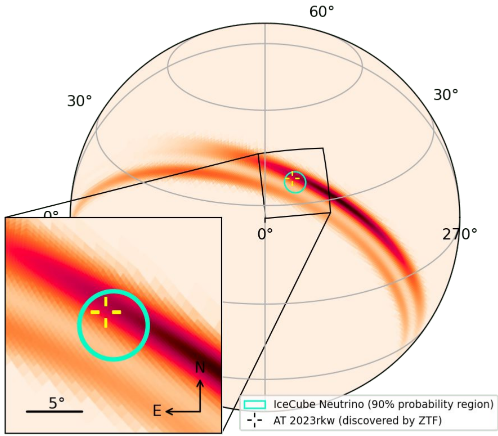
Model dependent prior probability

Independent of **x**

Detection outcomes

Combined null hypothesis

Sub-hypothesis likelihoods



GW+HEN+GRB example

SEARCH INPUTS

(different for each multi-messenger trigger)

GW

1 GW trigger

- Skymap (Ω)
- Mean distance (r_{GW})
- SNR (ρ)
- Time

Neutrino

Multiple neutrino triggers

- Sky position mean (RA, Dec)
- Sky position std. dev. (σ)
- Energy
- Time

GRB

1 GRB trigger

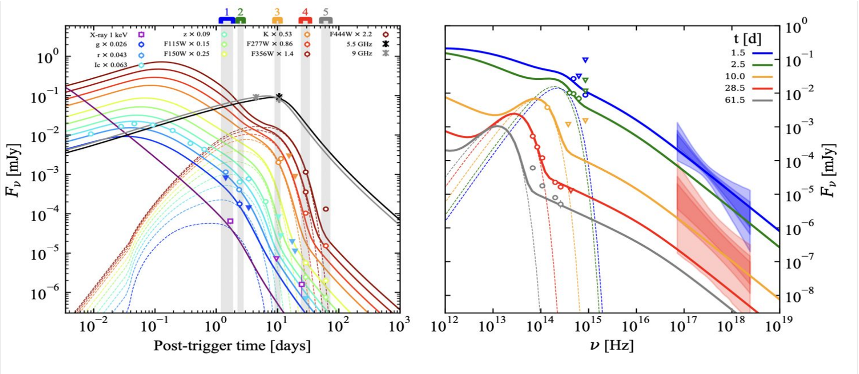
- Sky position
- Angular uncertainty
- Time
- Duration, Significance, Fluence

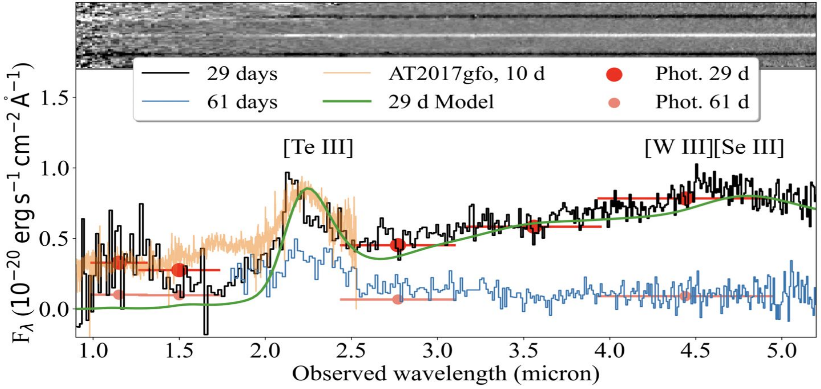
Common source relation through a source parameter: $P(\mathbf{x}|H_a^b) = \int P(\mathbf{x}|\boldsymbol{\theta}, H_a^b)P(\boldsymbol{\theta}|H_a^b)d\boldsymbol{\theta}$

Nikhil Sarin (Nordita/Stockholm University)

Multi-messenger is not just joint/coincident observations.

- GW170817 was of course, a watershed event. But we should not limit ourselves to looking at ‘joint’ observations.
  - We should be thinking about what Supernova/GRB/kilonova observations independently tell us about CBCs.
- Long GRBs with kilonova pointing suggestive of merger origin
  - GRB211211A, GRB230307A
    - How do you actually get the long duration?
    - Same feature as AT2017gfo at 2.1 micron, but at 30 days. Should that happen?
    - What element is it?

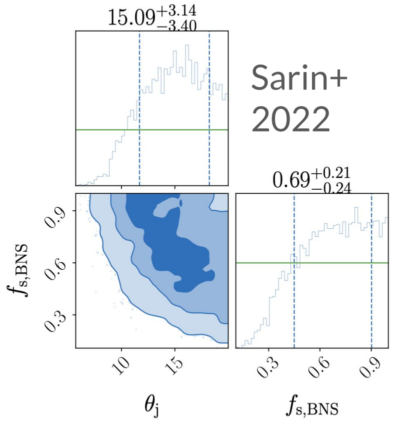




Levan+ (incl NS) 2024

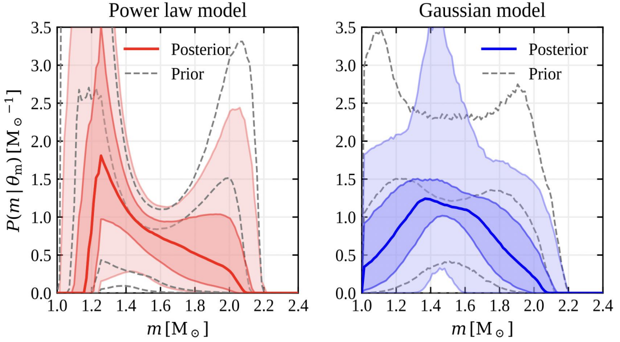
Multi-messenger is not just joint/coincident observations.

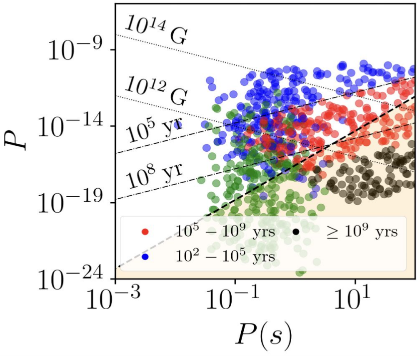
- SN2018ibb - Best candidate of a pair-instability supernova. Can we extract things like rates/properties and relate it to BBH population?
- What can we extract from other CCSNs?
- What do galactic pulsars/neutron stars tell us about neutron star evolution/formation?
- Gaia
- What does the GRB + DNS population tell us?
- What does chemical properties of stars + expectations of kilonovae yields tell us?



Sarin+ 2022

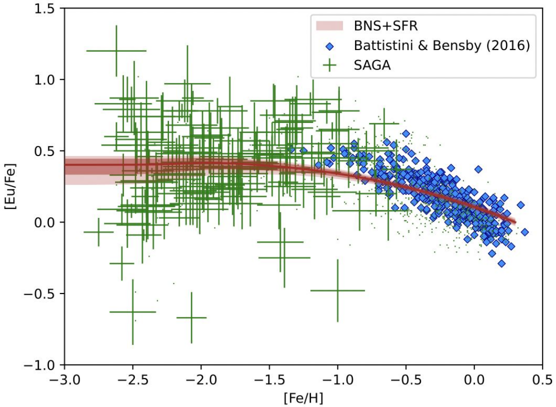
Salafia+ 2022





Sarin+ 2023

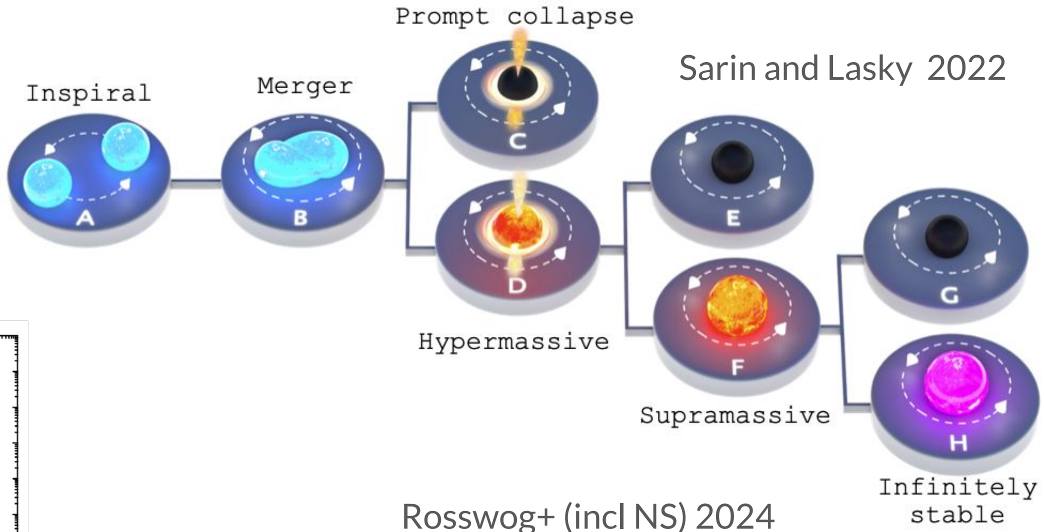
Hsin-Yu Chen+ 2024



Nikhil Sarin (Nordita/Stockholm University)

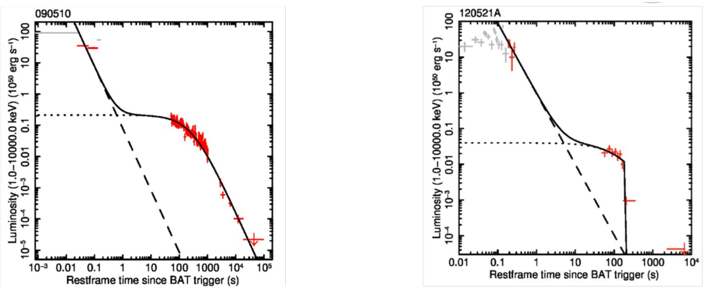
What is the diversity of counterparts to a merger?

- How do properties of kilonovae/GRB/afterglow change as a function of progenitor mass/spin, viewing angle?

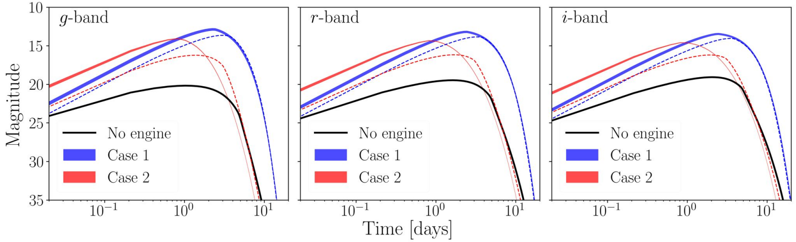


Sarin and Lasky 2022

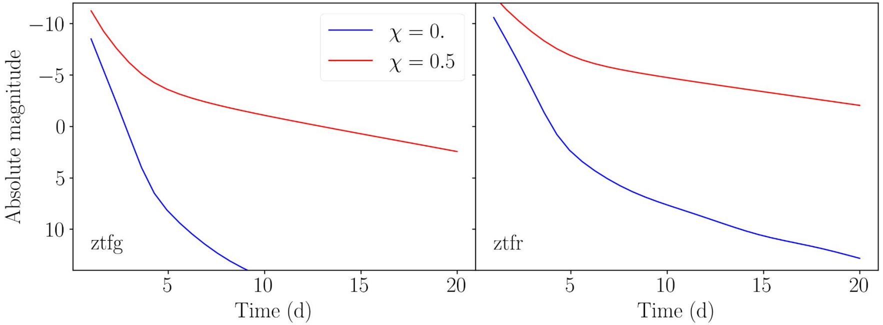
Rowlinson+13



Sarin+ 2022



Rosswog+ (incl NS) 2024

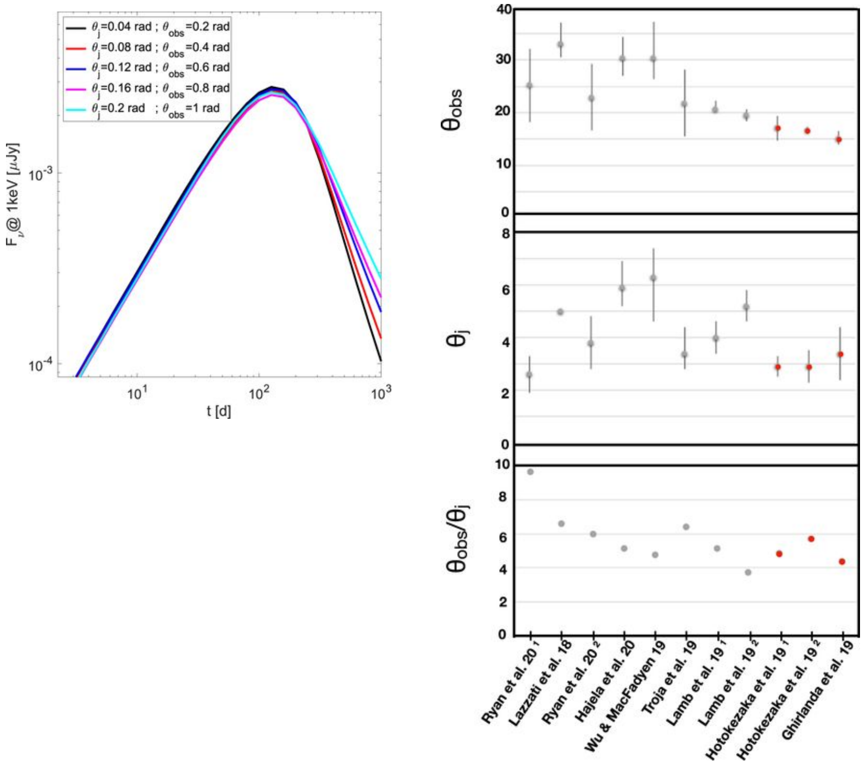


Nikhil Sarin (Nordita/Stockholm University)

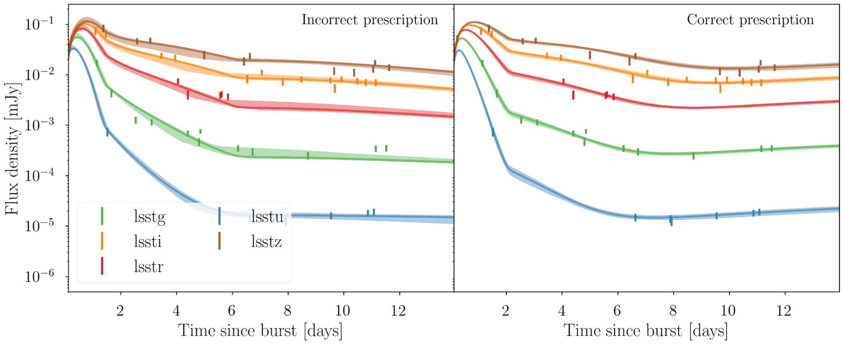
What can we actually “robustly” extract from current/future observations?

- A number of works have pointed out that ‘inferring’ these from observations is fraught with difficulty/systematics.
  - Viewing angle/core angle degeneracy in afterglows e.g., Nakar and Piran 2020
  - Heating rate uncertainties in kilonovae e.g., Zhu+ 2021, Barnes+2022, Shenar+2024.
- GW side already covered/will be covered by other panels.

Nakar and Piran 2021



Sarin and Rosswog 2024



What EM facilities do we need/require in 3G era?

- What does multi-messenger science look like in ET/CE era when we have too many things to follow-up.
  - Most events are too far so we only expect to see GRB emission (if on axis)
  - What can we extract from just the GRB + GW signal?