Multimessenger & Multi-band

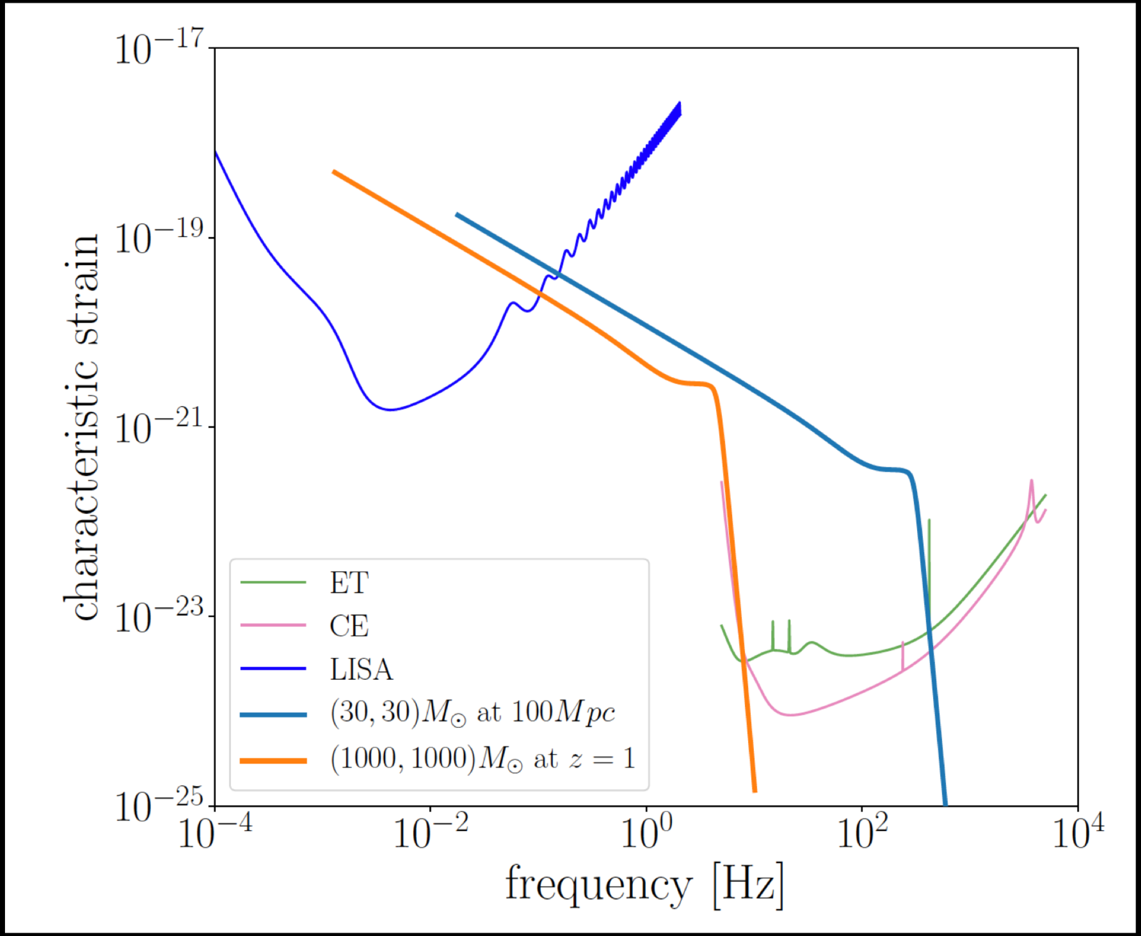
M. Branchesi, L. Cadonati
PANEL: S. Bernuzzi, M. Branchesi, D. Verkindt, C. Palomba, G. Prodi, S. Vitale

- Salvo "Multi-band perspectives"
- Sebastiano "GW/EM modeling and joint analysis"
- Marica "Challenges and perspectives for multi-messenger observational campaigns"
- Giovanni: "Supernovae (and other unmodeled signals)"
- Didier: "Challenges in detecting SNe and other unmodeled transients"
- Cristiano "GW Continuous waves (+ EM) to infer NS properties"

Some considerations on multibanding

Salvatore Vitale
MIT
PAX VI
May 2019

What are we talking about?



Cutler+, 1903.04069

- Sesana, PRL 116 231102, noticed an heavy BBH *à la* GW150914 would have been detected by LISA ~years in advance
  - Up to z~0.3
  - 10s to 100s sources in a 5 years mission
- The same is true for IMBHs
- Multibanding is the idea that the same source can be seen in multiple bands

Why is this useful? (1)

- Sesana, PRL 116 231102
  – LISA can provide merger time and sky location with small uncertainty
  – Can be sure all telescopes of the world are pointing at that patch of sky
  – Can be sure ground-based detectors are online (and that it’s not a Tuesday ;-))
- Caveats:
  – These are BBH, probably they don’t emit light. This will be funny a few times until this is firmly established. Then?

Why is this useful? (2)

- Vitale, PRL 117 051102
  - LISA can provide precise estimates for masses (mchirp and mass ratio), not so much spins
  - Can use LISA's posteriors on masses as Bayesian priors for the ground-based parameter estimation, breaking mass-spin degeneracies. Factor of ~2 improvement
  - Also improvements for unmodeled tests of GR
- Caveats:
  - Assumed ground-based is made of advanced detectors, very pessimistic/depressing given that LISA flies ~2034

Why is this useful? (3)

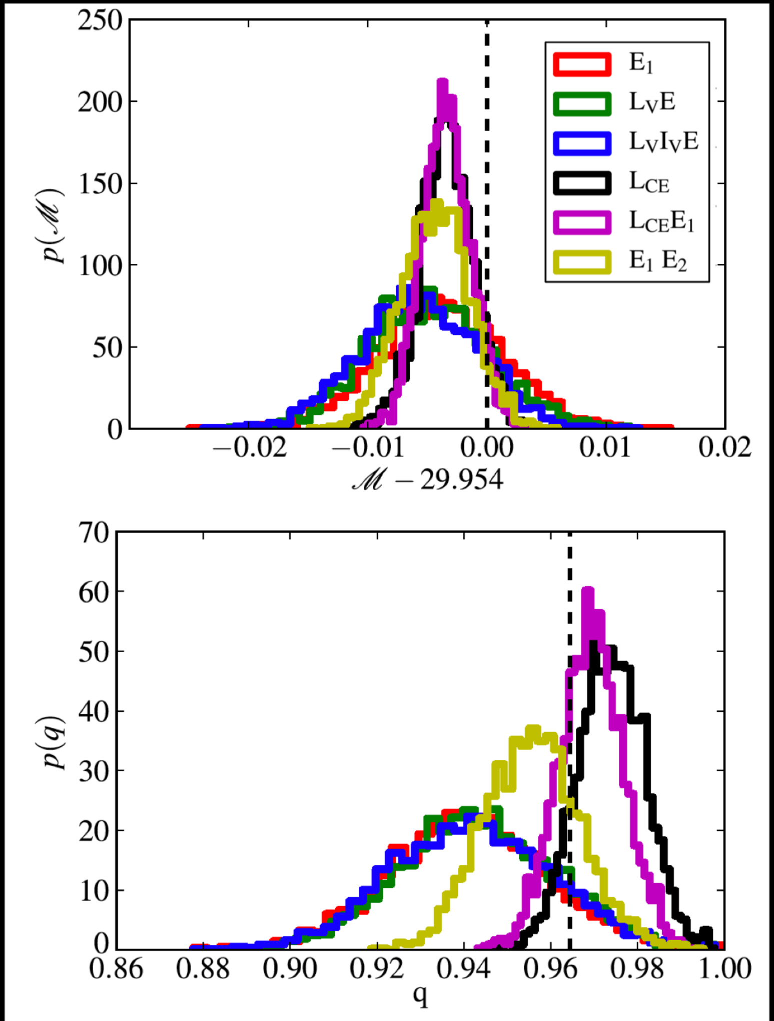
- Barausse+, PRL 116 241104
  - Tests of GR of dipolar emission improves by 10^6 (low PN from LISA, merger time from the ground)
- Caveats:
  - Assumed ground-based is made of advanced detectors, very pessimistic/depressing given that LISA flies ~2034

Why is this useful? (4)

- Other ideas I'm aware of (certainly not complete)
  - Detune ground-based detectors in preparation for a golden BBH that LISA saw earlier on + ringdown tests (Tso, 1807.00075)
  - "Rewind it": use ground-based detectors to remove marginal BBH from the LISA noise (Wong+, PRL 121, 251102)
  - IMR consistency tests (I cannot believe nobody has done this??? We should)

But what if we have 3G (1)

- Cutler+ (2020 Decadal WP, Scientific paper in prep, MIT+JHU+Friends)
  - If 3G is up and running (>=2 sites) the SNR of a GW150914 would be so high (Vitale+, PRD 98 024029) that LISA's priors don't really buy you anything for parameter estimation



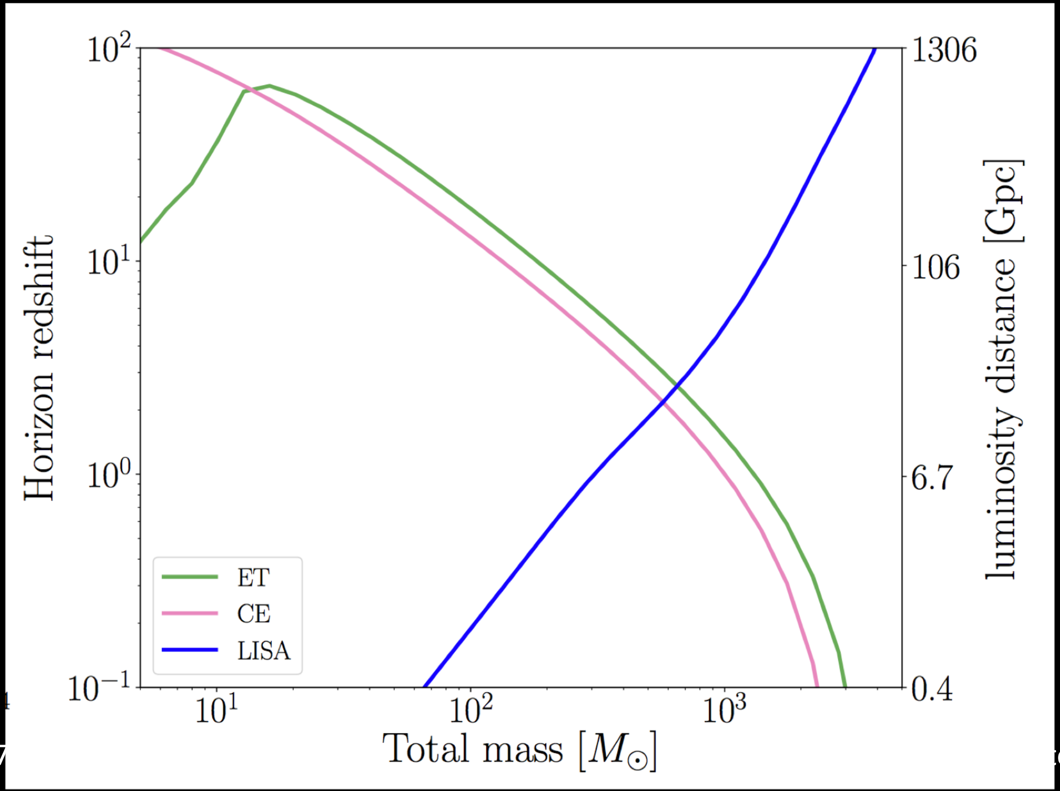
Vitale+, PRD 98 024029

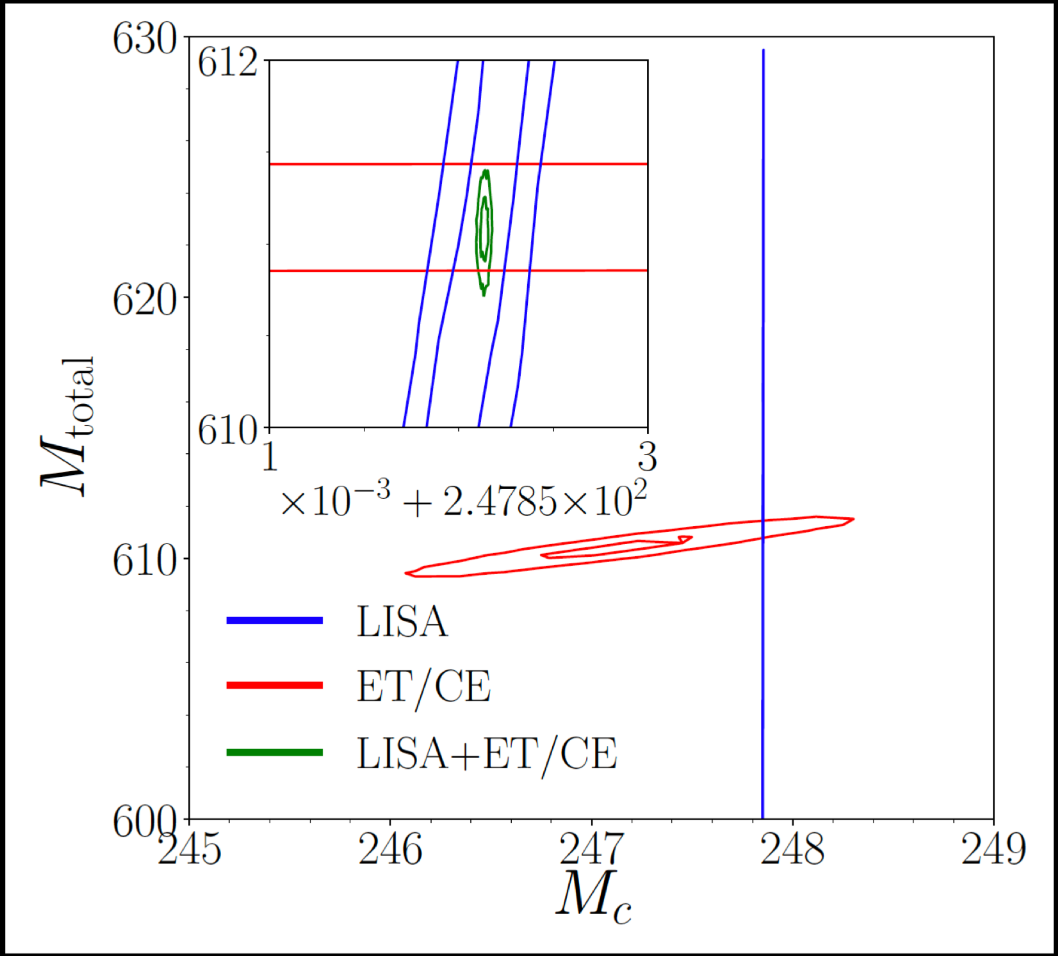
But what if we have 3G (2)

- Cutler+ (2020 Decadal WP, Scientific paper in prep, MIT+JHU+Friends)
  - If 3G is up and running (>=2 sites) the SNR of a GW150914 would be so high (Vitale+, PRD 98 024029) that LISA's priors don't really buy you anything for parameter estimation
  - Might still help for *some* tests of GR
  - However, as the mass of the systems increase (i.e. less and less inspiral on the ground) the benefit of having LISA becomes more important

But what if we have 3G (3)

- If IMBHs exist, they could be the sources that benefit the most from multibanding
-

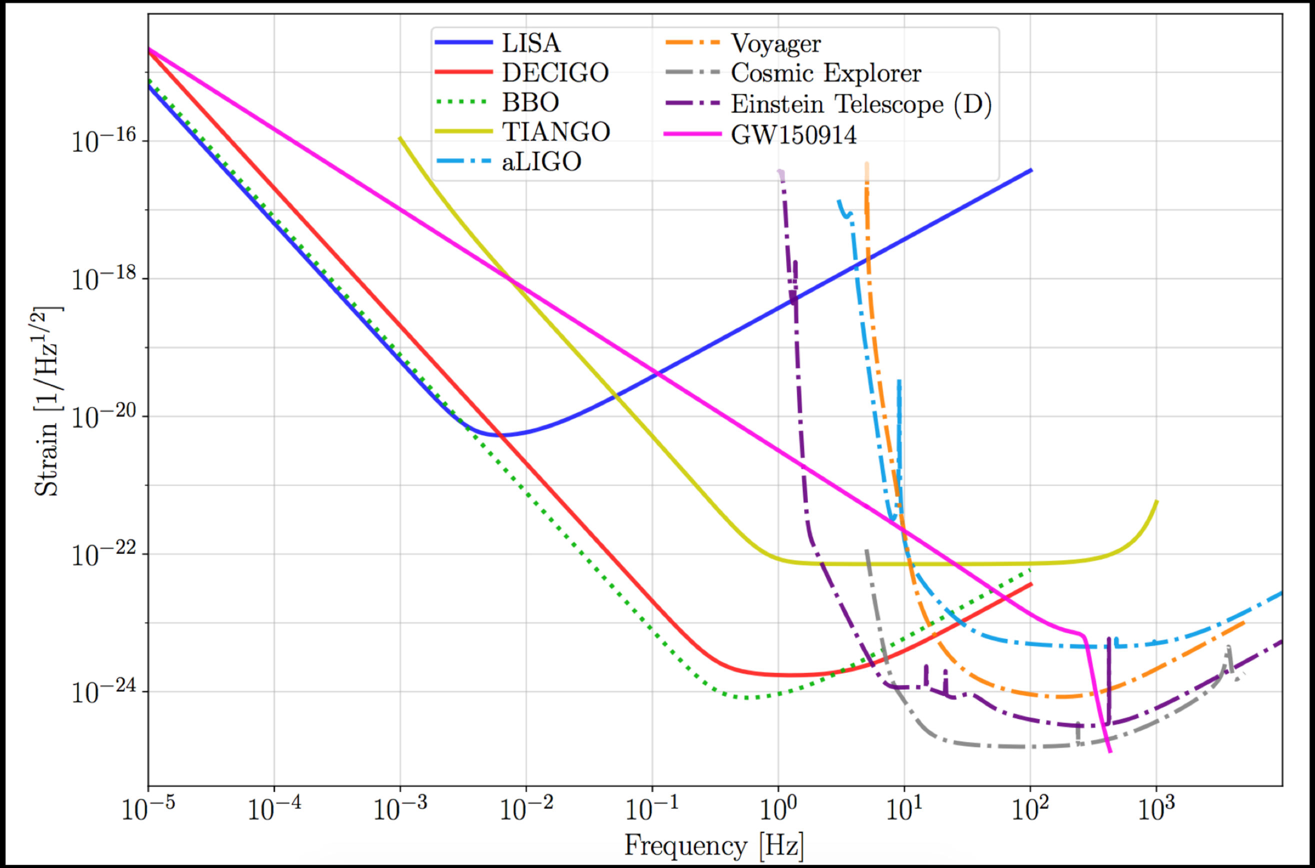




Cutler+, 1903.04069

Do we need anything in 0.1Hz range?

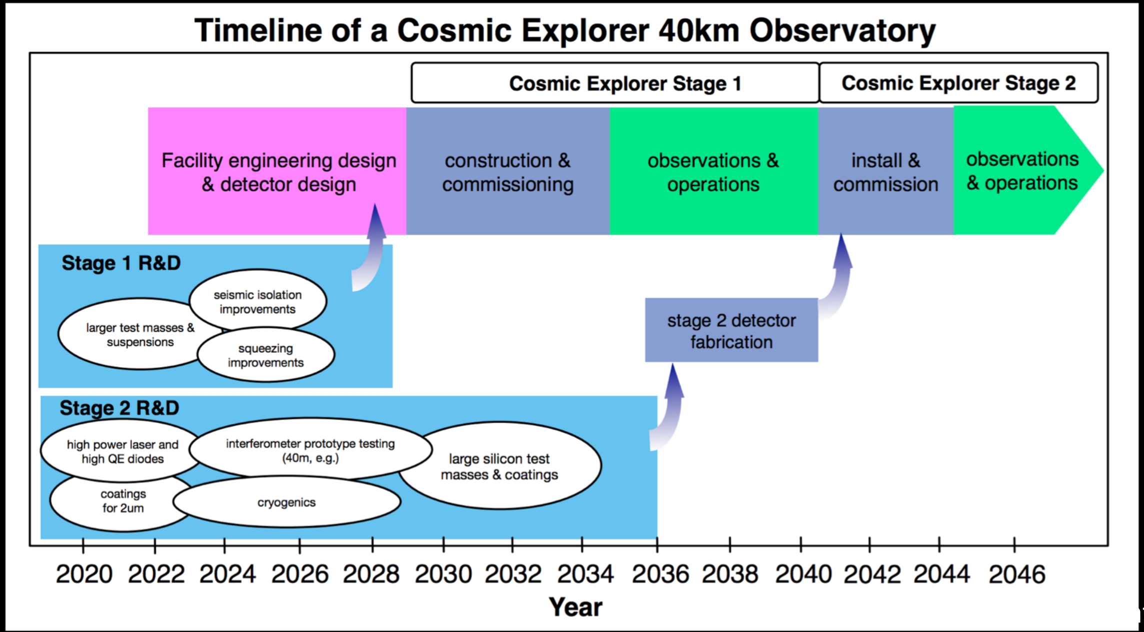
- There are proposals for "cheap" space-based instruments that could fill the LISA-ground frequency gap
  - I'm not aware of any study to quantify the science case for these instruments, specifically in a multibanding context
- Questions to ask ourselves:
  - Would these add something that LISA+ground won't give us for BBH?
  - Would they allow for multibanding of sources that LISA won't see?



Kuns+, DCC G1801071

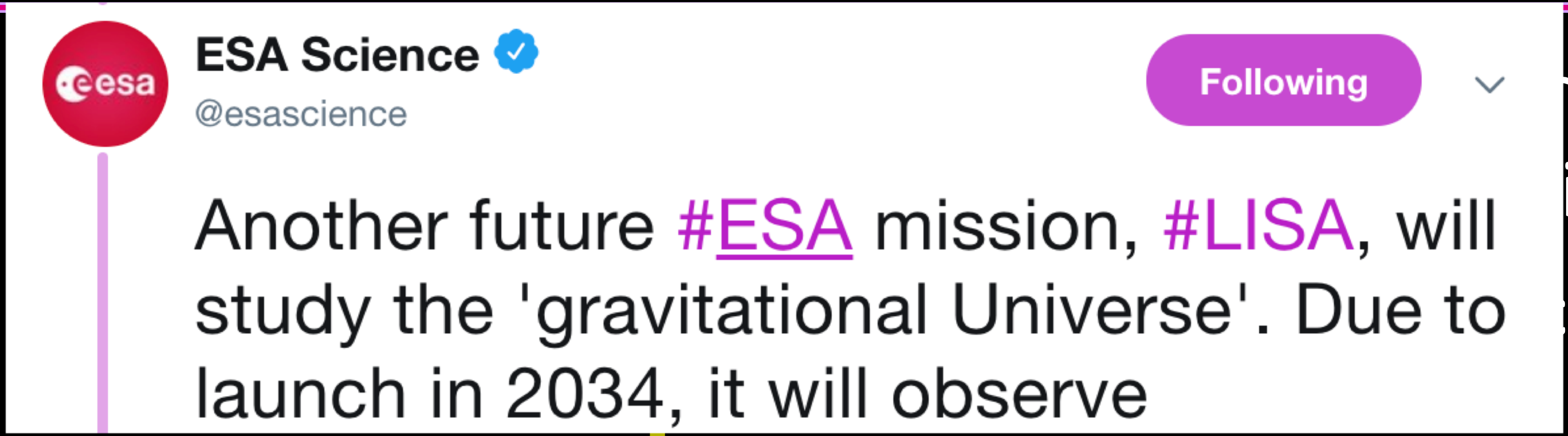
Timeline considerations

- Should we take into account at all the prospects of multibanding and fold it in 3G timeline (if possible at all)?
- What if we are still stuck with <3G detectors?

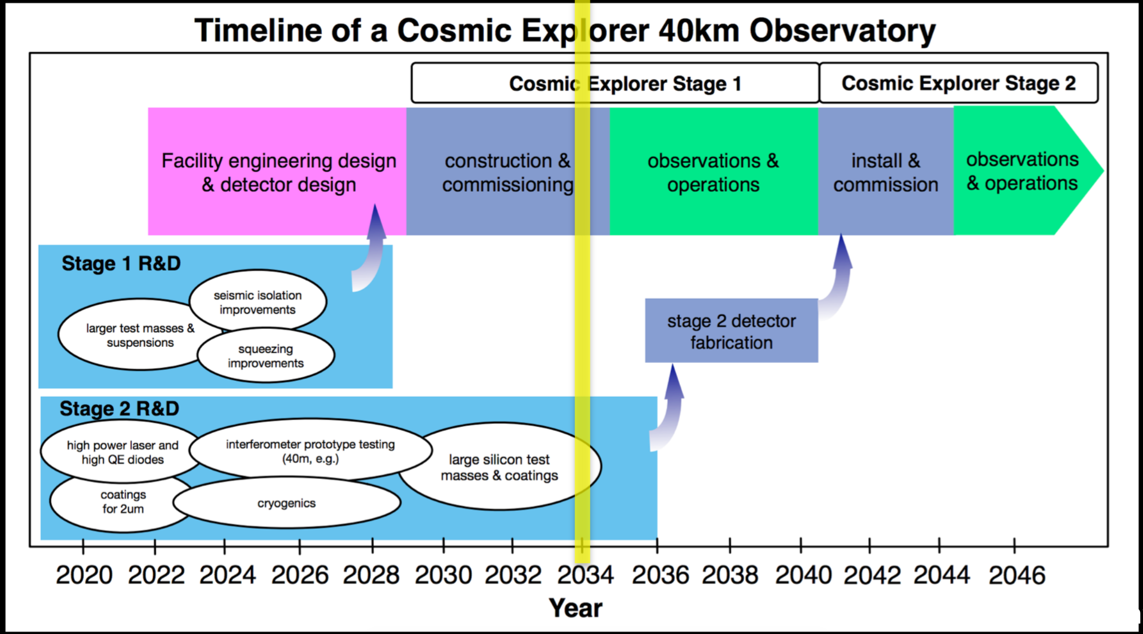


LIGO Lab 1903.04615

Timeline considerations



rospects of
(if possible at all)?
tors?



LIGO Lab 1903.04615

Timeline considerations

ESA Science @esascience

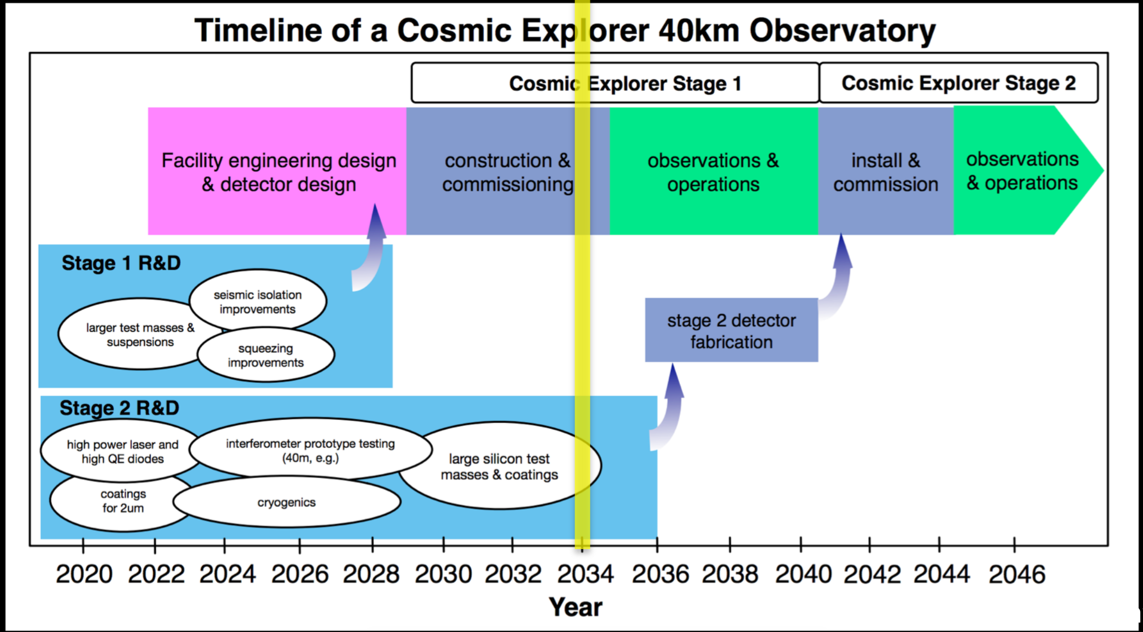
Following

Another future #ESA mission, #LISA, will study the 'gravitational Universe'. Due to launch in 2034, it will observe

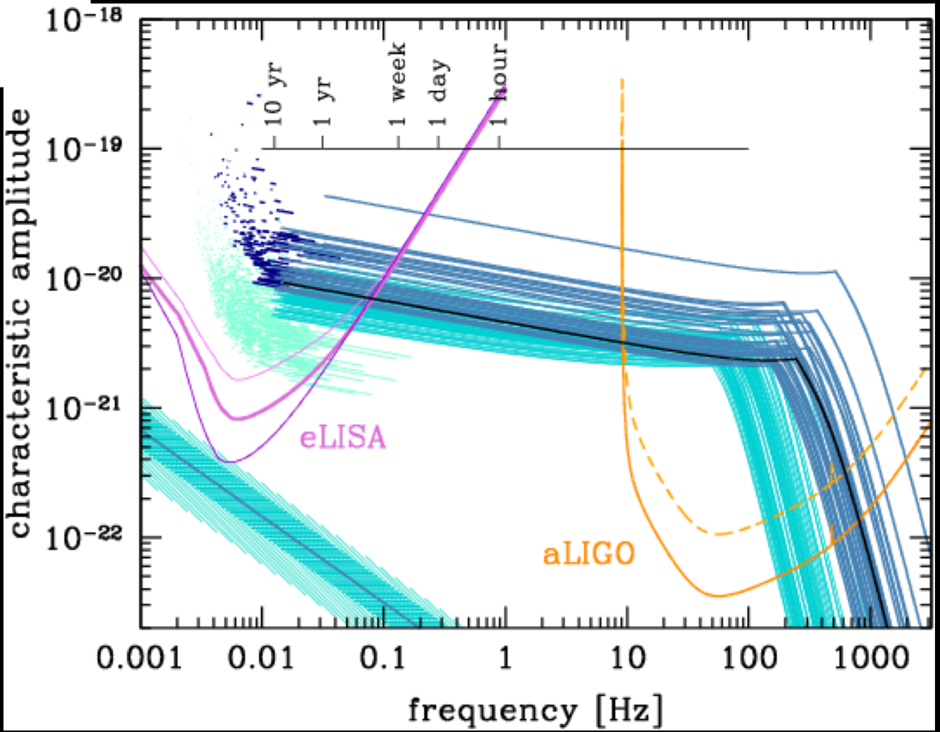
…rospects of

…if possible at all)?

…tors?



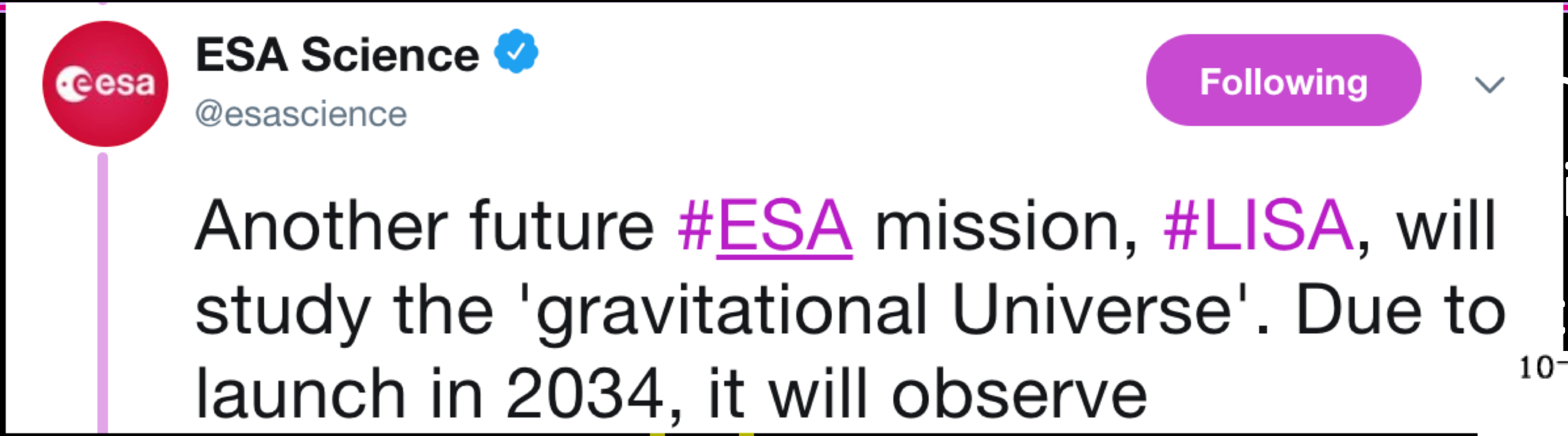
…tore Vitale



LIGO Lab 1903.04615

Sesana, PRL 116 231102

Timeline considerations



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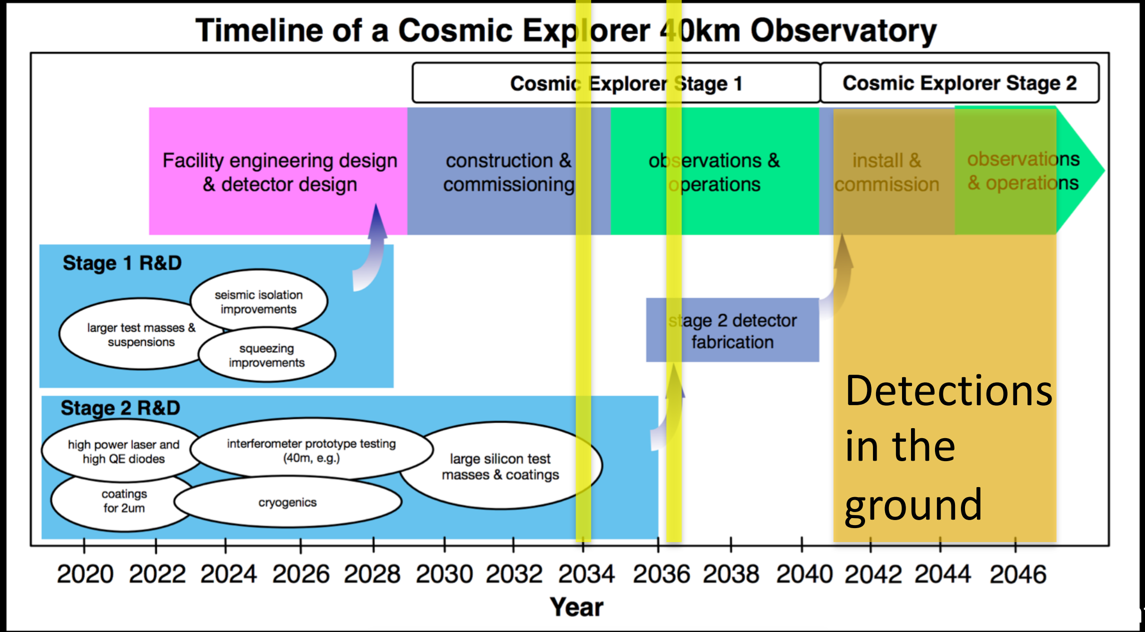

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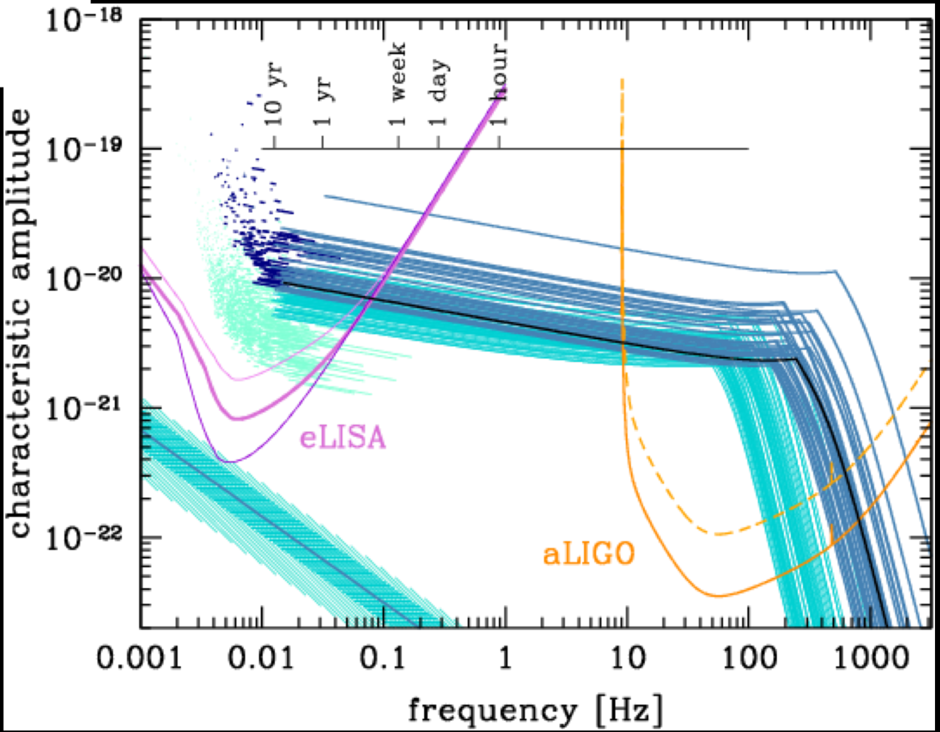

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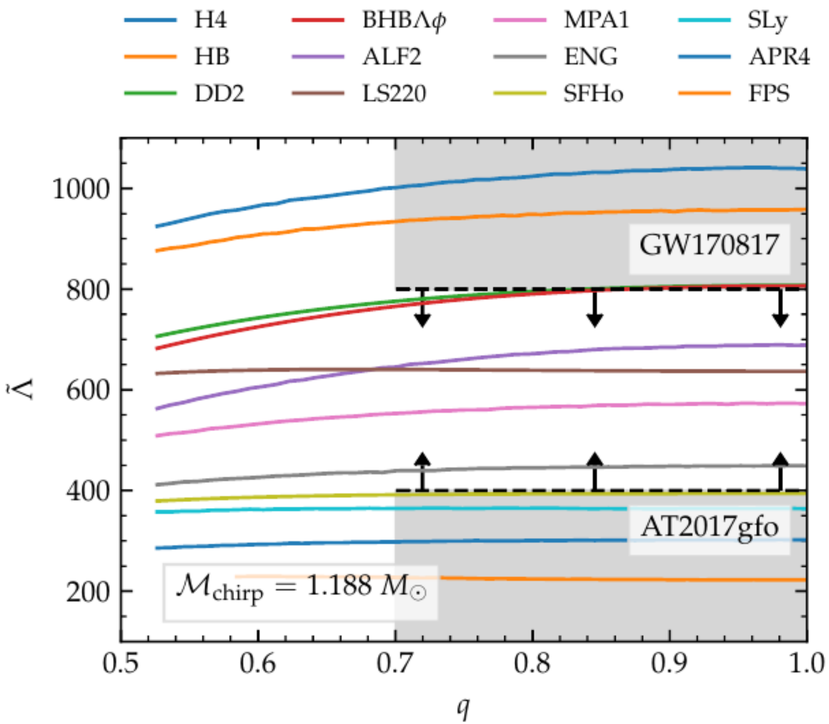
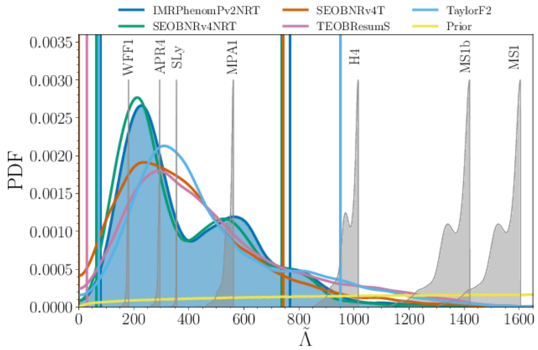
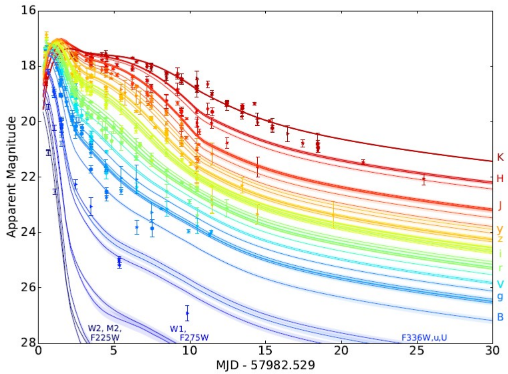
Joint constraints on the neutron star EOS from multi-messenger observations



[Radice, Perego, Zappa, SB ApJL (2018)]

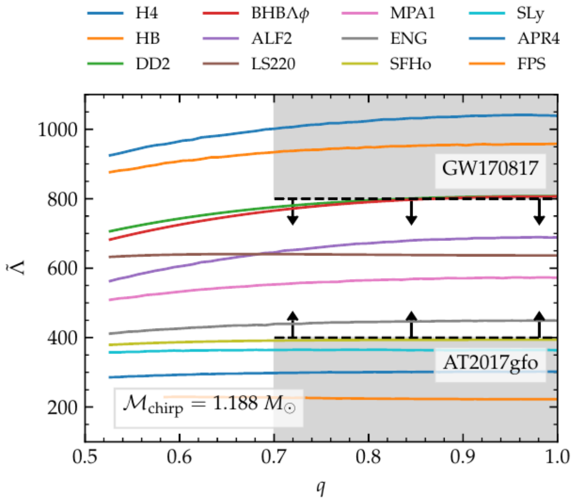


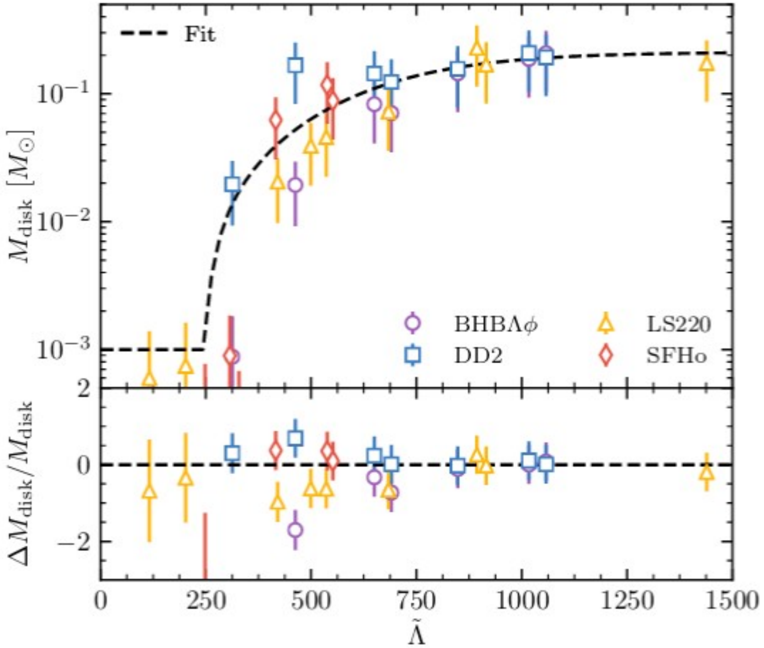
GW170817



AT2017gfo

Joint constraints on the neutron star EOS from multi-messenger observations



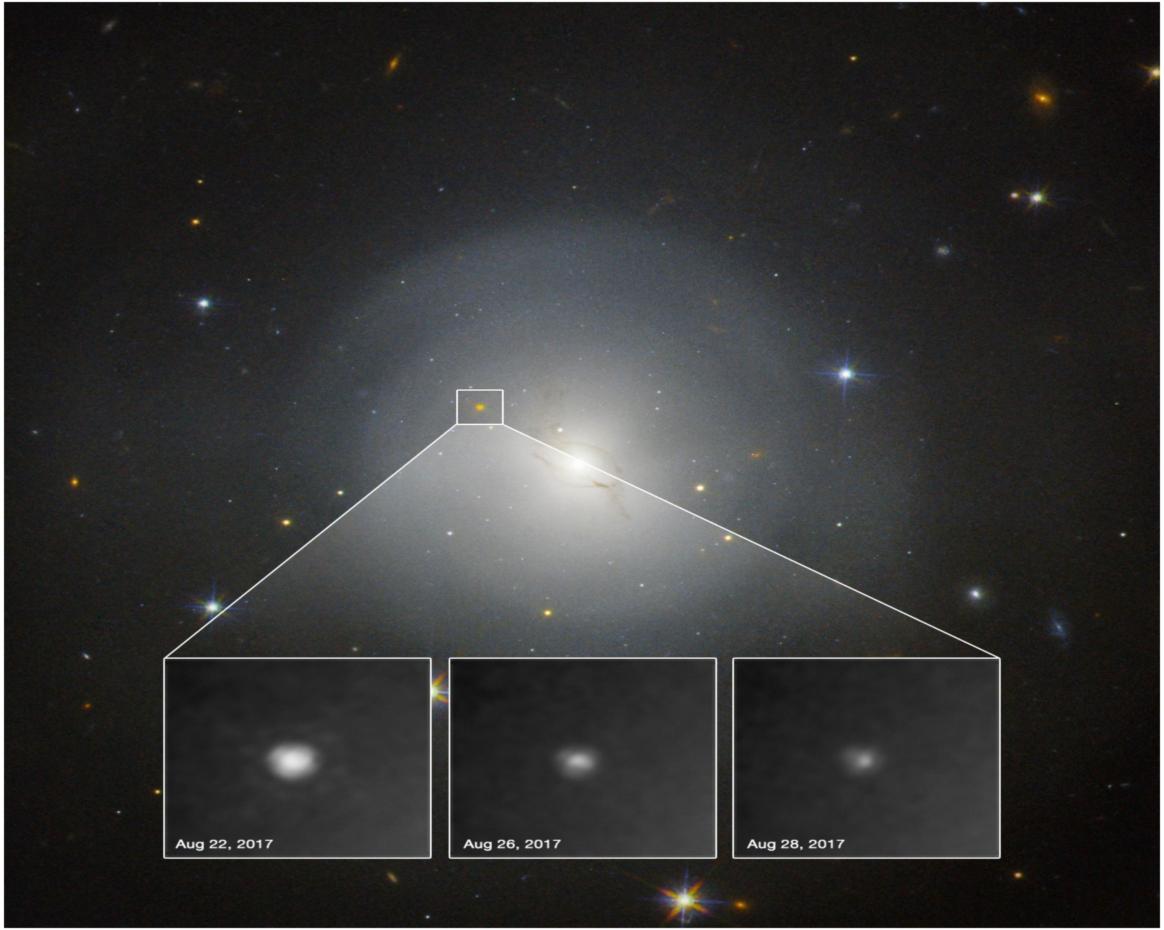


- Numerical relativity →
  - Collapse threshold in Λ <~300-400
  - Trend in Λ : $M_{disk}(\Lambda)$ [Other parameters are possible]
- EOS dependent

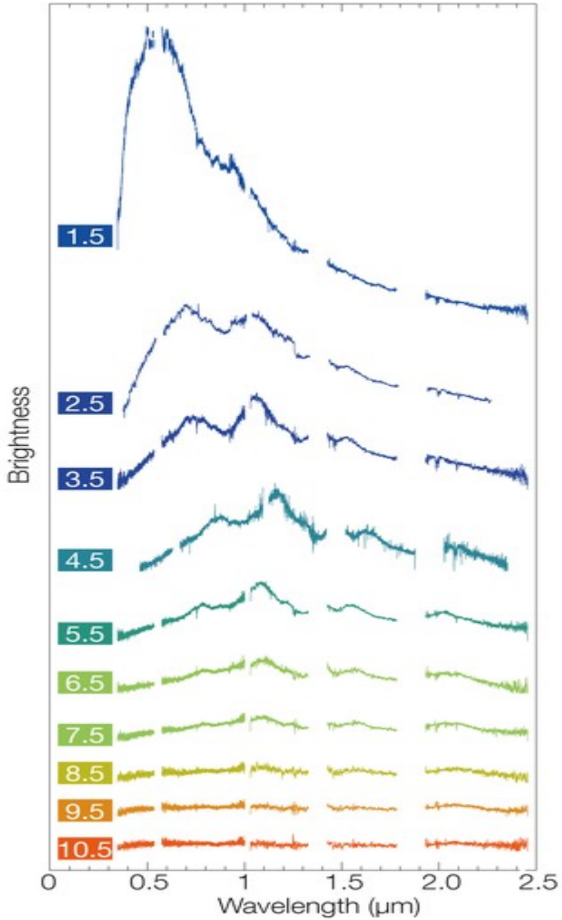
[Radice,Perego,Hotokezaka,Fromm,SB,Roberts 2018]

[Radice, Perego, Zappa, SB ApJL (2018)]

Kilonova

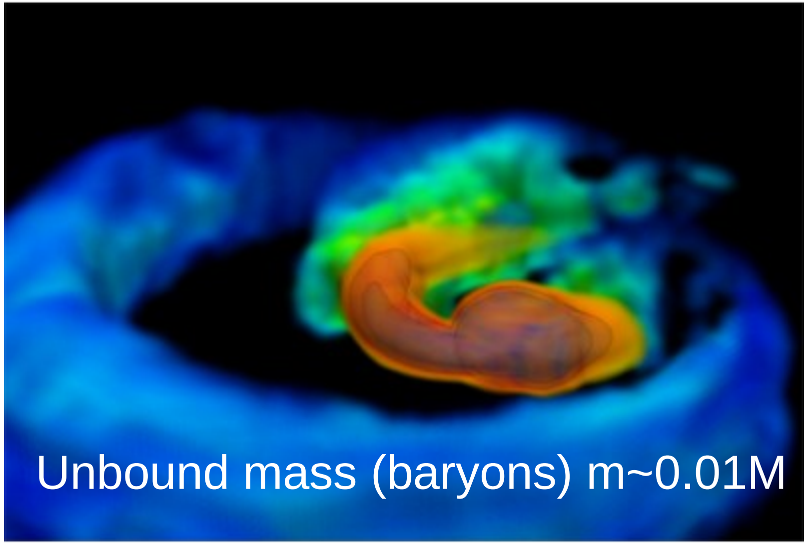


Aug 22, 2017
Aug 26, 2017
Aug 28, 2017



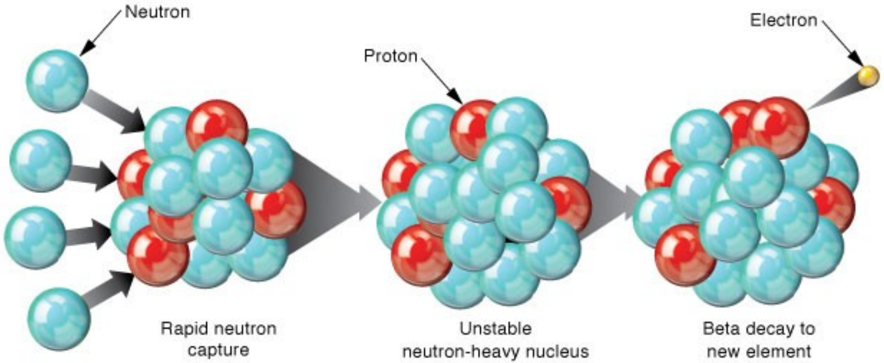
Brightness
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
0
0.5
1
1.5
2.0
2.5
Wavelength (µm)

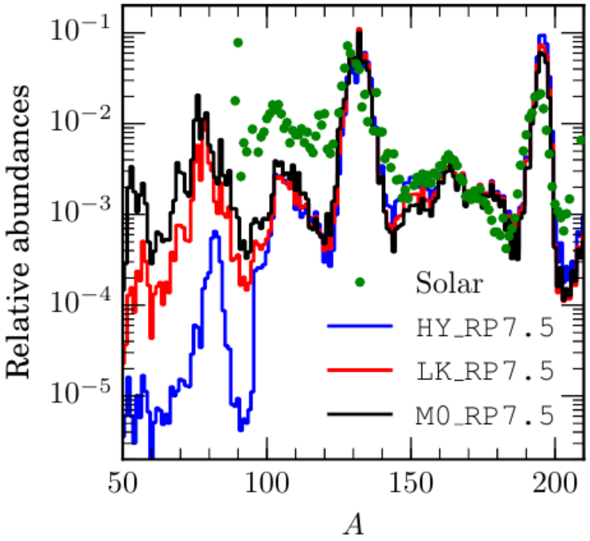
Mass ejecta from mergers



NS-BH collisions (1974) Decompression of cold neutron star matter

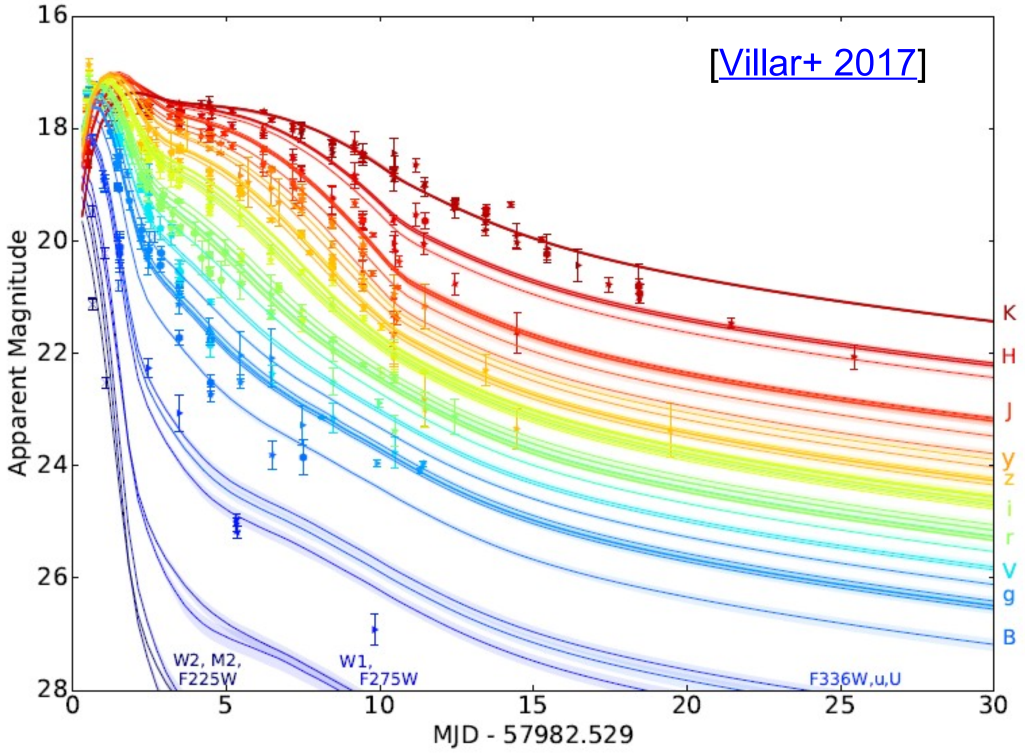
D. Schramm, J. Lattimer, D. Eichler, T. Piran, F. Thielemann, S. Rosswog and many others





Kilonova

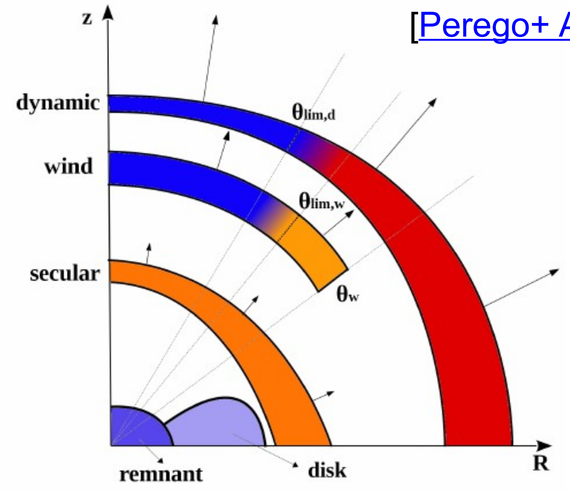
UV/optical/IR transient powered by the radioactive decay of freshly synthesized *r*-process elements
[Li&Paczynski 1998,Kulkani 2005,Metzger+ 2010,Kasen+ 2013,Grossmann+ 2014,Metzger LRR (2017)]



[Lattimer&Schramm 1974, Symbalisty&Schramm 1982]
[Freiburghaus+ 1999,Korobkin+ 2012, ...]

- High energy photons from nuclear decay
- Photon thermalization in expanding ejecta
- Emission: t_diffusion ~ t_expansion
- Key parameters:
  - ejecta velocity (v)
  - mass (m)
  - opacity (k)

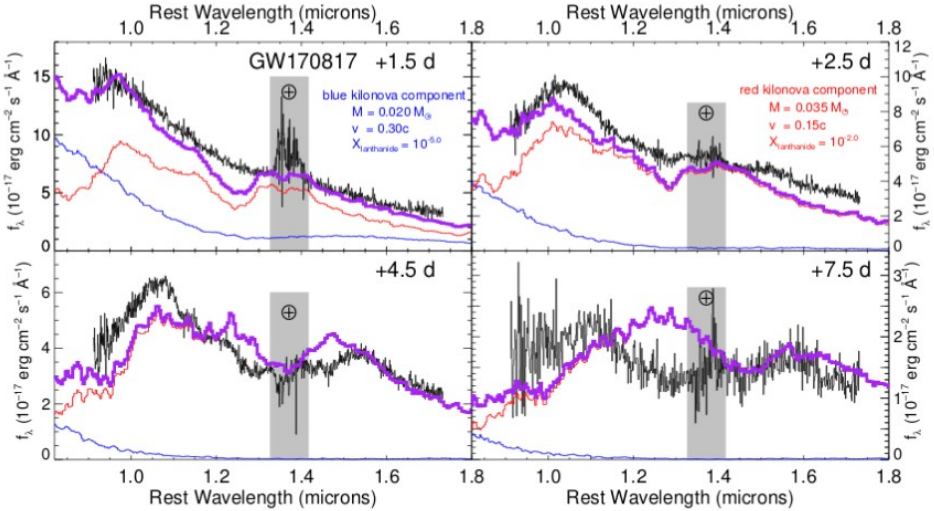
[Perego+ ApJL (2017)]



Light curves: complementary approaches

Semi-analytical models
[e.g. Grossmann+ 2014, Perego+ 2017, Villar+ 2017]

- Fast for DA
- Flexible to account several mechanisms & components
- Less accurate

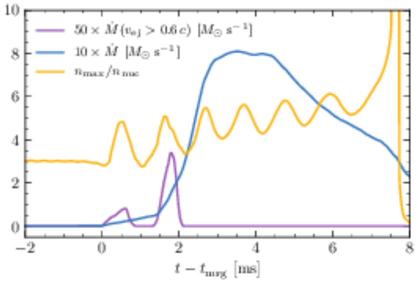


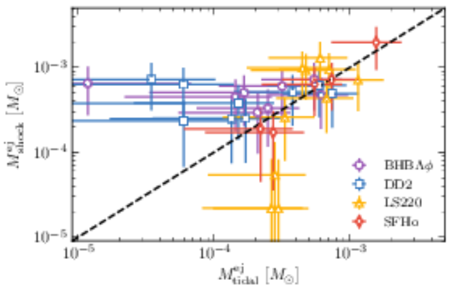
Radiative transfer simulations
[e.g. Kasen+ 2013,Tanaka&Hotokezaka 2013, Fontes+ 2017]

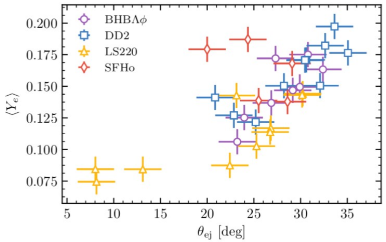
- Newtonian/SR, 1D o 2D
- More accurate, complete
- More expensive
- Require ejecta mass input (mostly sph.sym.)

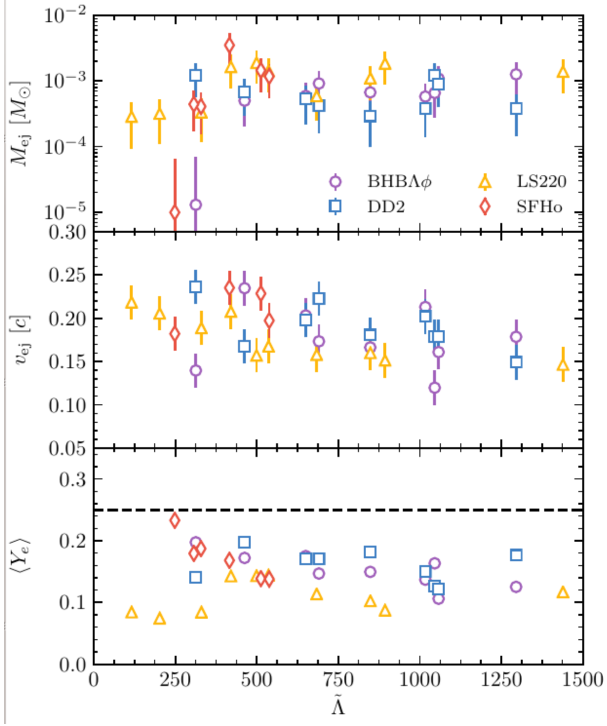
Dynamical ejecta

[Davies+ 1994, Rosswog+ 1999, … (Newtonian SPH, Stiff EOS)
Hotokezaka+ 2013, Bauswein+ 2013, Wanajo+ 2014, Sekiguchi+ 2015,2016, Foucart+ 2016, Radice+ 2016]





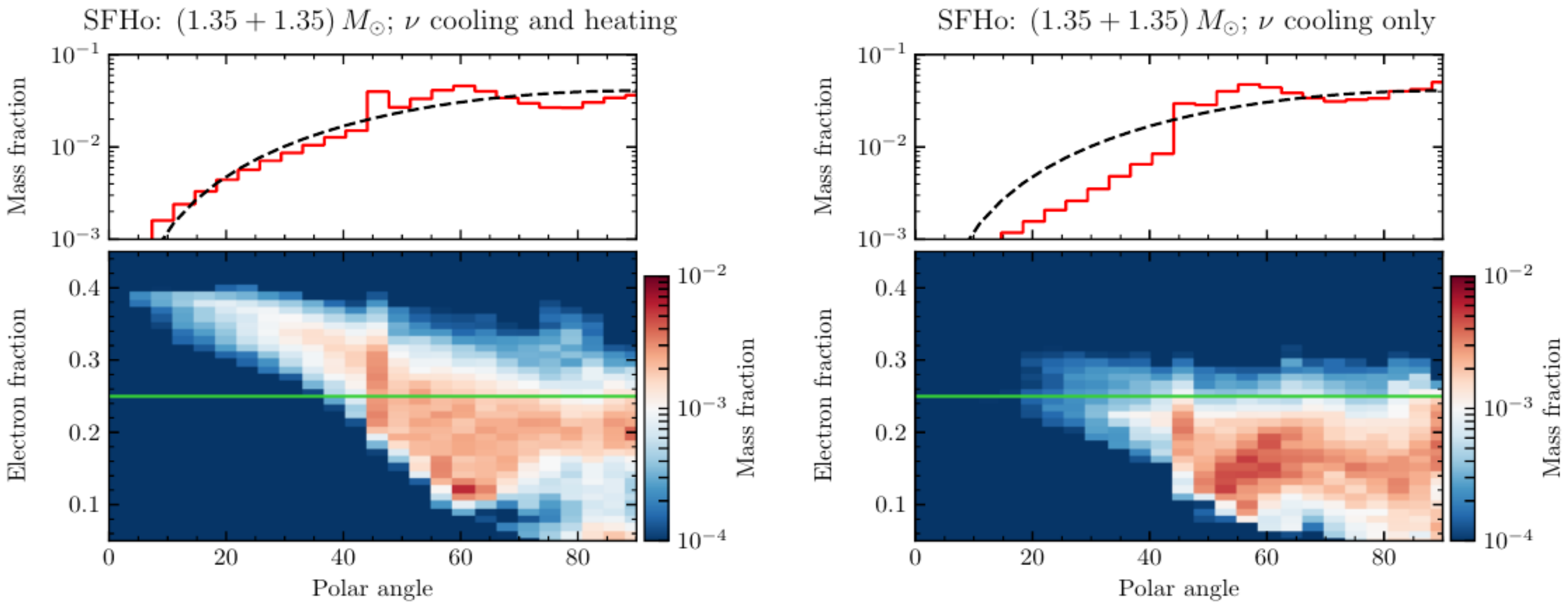




- Tidal component (low Ye, ~equatorial)
- Shocked component (high Ye, ~"polar")
- Mass < 10^-2 Mo; <v> <~ 0.2*c*, w\ high speed tail (<0.6*c*)
- ~ Independent on binary properties and EOS
- GR simulations needed (soft EOS, high speed. etc)

[Radice,Perego,Hotokezaka,Fromm,SB,Roberts 2018]

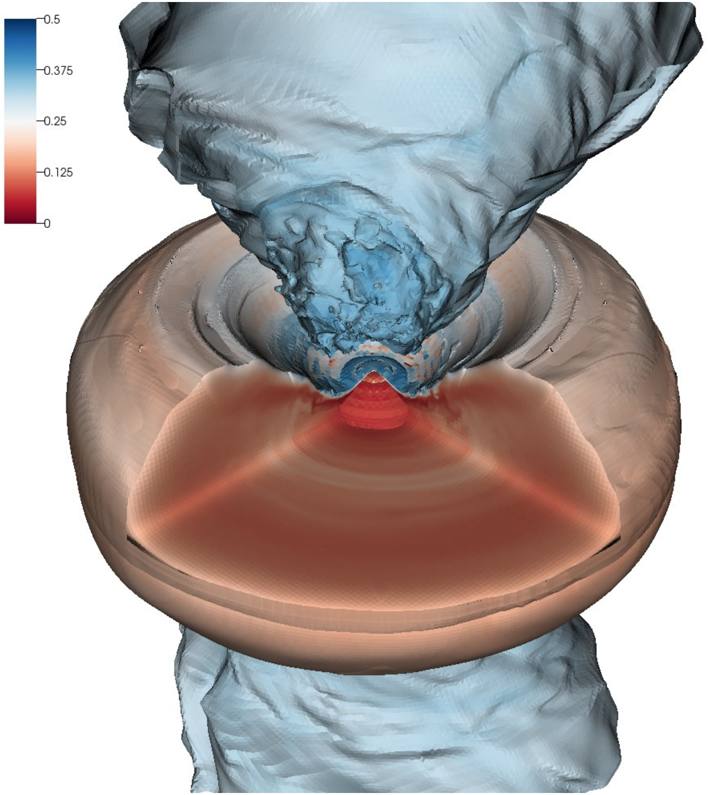
Impact of neutrino absorption on ejecta composition



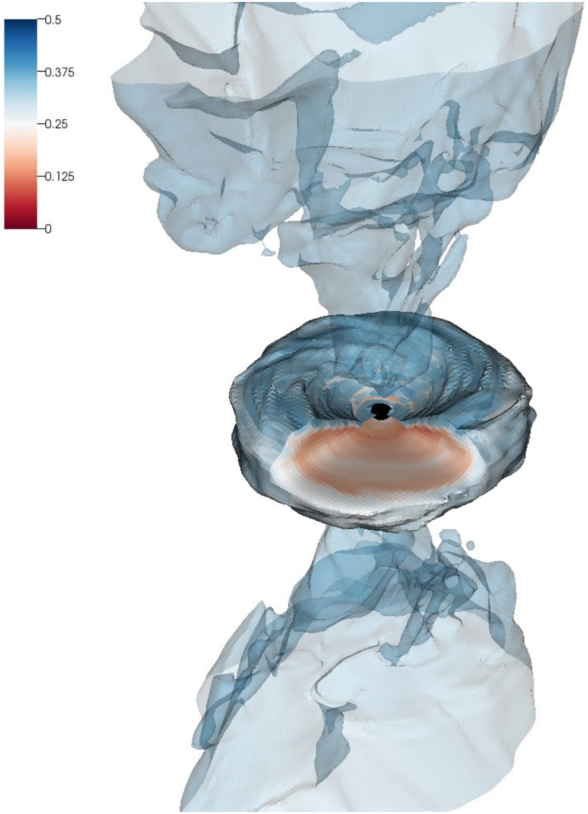
[Perego, Radice, SB 2017 ApJL]

Remnant discs around NS and BH

3D rendering: Electron fraction



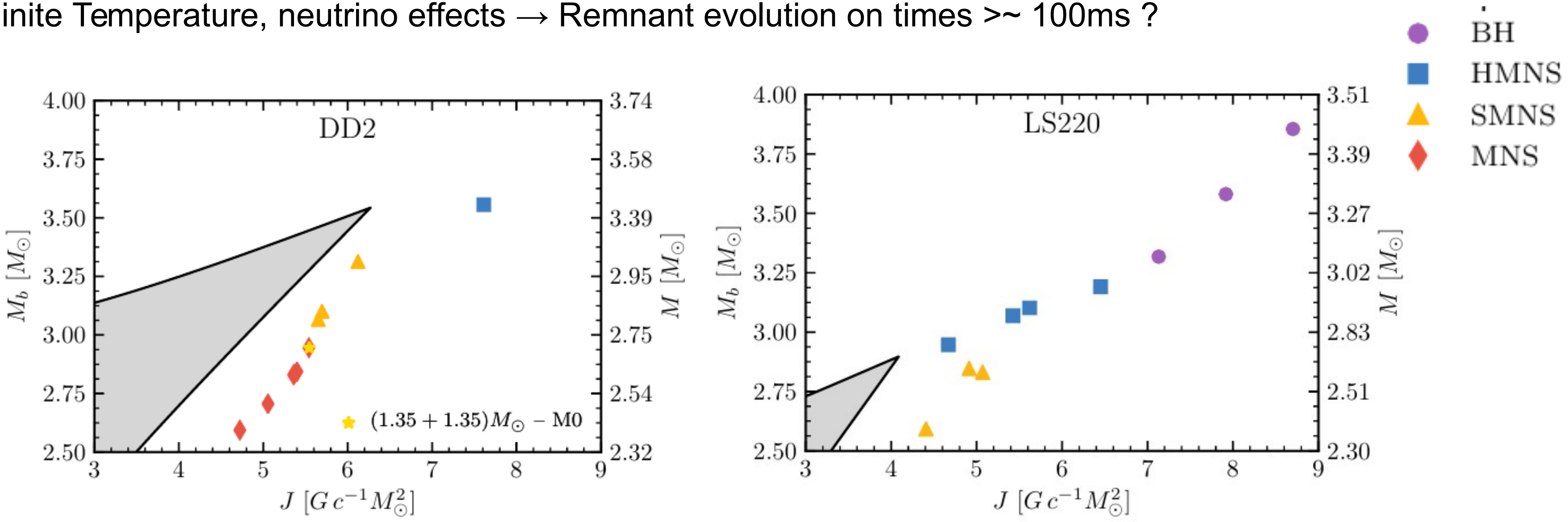
More massive & extended, optically thicker



Less massive & extended, optically thinner

Merger remnant: angular momentum

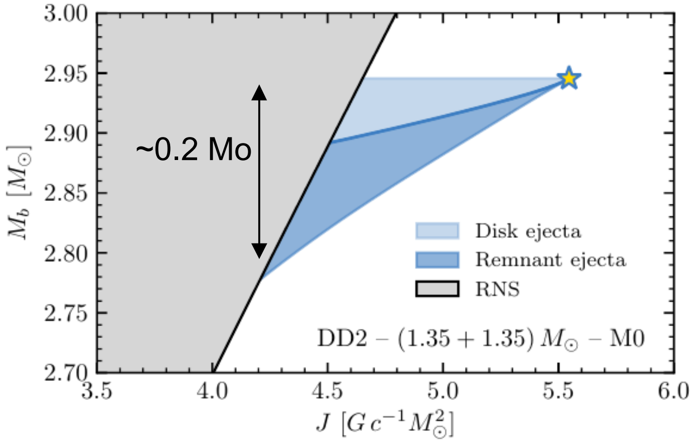
- BH: 0.6 <~ J/M^2 <~ 0.8 (HMNS → 0.6-0.7, Prompt BH → 0.7-0.8) [Kiuchi+ 2009, Kastaun+ 2013, SB+ 2016, Zappa+ 2018]
- NS: “super Keplerian” and grav. mass excess [Zappa+ 2018, Radice+ 2018]
- Remarks:
  - BH is always sub-Kerr
  - inite Temperature, neutrino effects → Remnant evolution on times >~ 100ms ?



[Radice, Perego, SB, Zhang 2018]

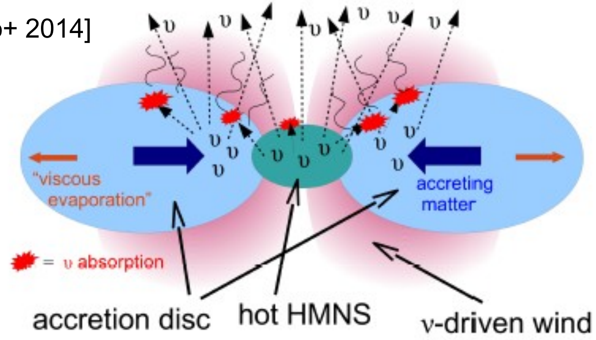
Disc remnant evolution on viscous timescale

[Radice, Perego, SB, Zhang 2018]

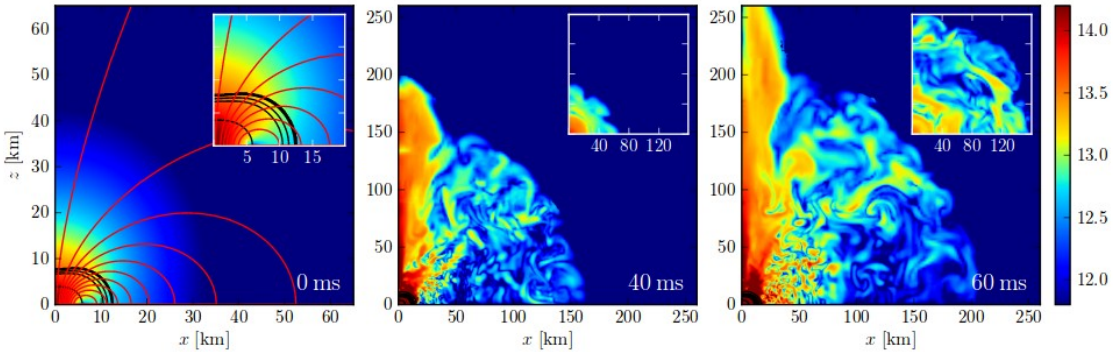


- After an initial GW transient (t ~ 10s ms) , GW timescale >~ sec
- Disk cooling/expansion → outflows:
  - Neutrino absorption (t ~ 10s ms)
    [Dessart+2008, Perego+2014, Martin+2015, Metzger&Fernandez 2014]
  - Magnetic processes (t ~ 10s ms)
    [Siegel+2014]
  - Viscous processes (t ~ 100s ms)
    [Fernandez&Metzger 2013, Just+ 2015, Siegel&Metzger 2017]
- Nuclear recombination energy unbind matter (+ 8 MeV/baryon)
  [Lee+ 2009, Fernandez&Metzger 2013]

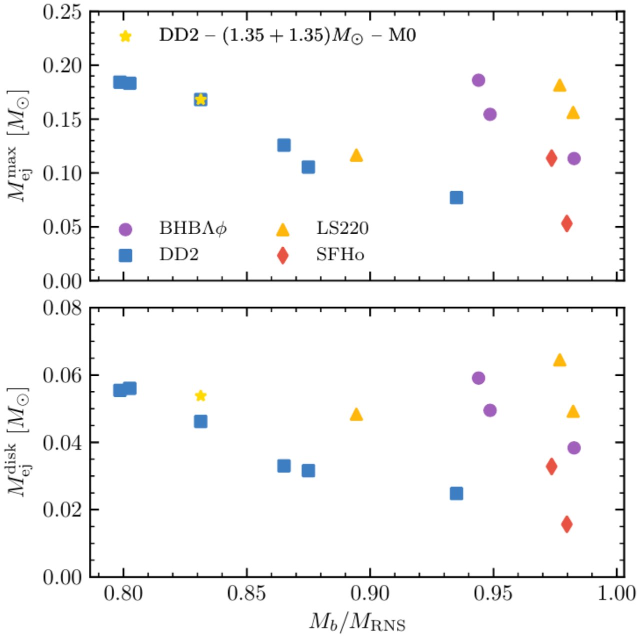
[Perego+ 2014]



[Siegel+ 2014]



Secular ejecta: Mass outflow from remnant disk



Upper limits from 3D hydro+M0 simulations
[Radice, Perego, SB, Zhang 2018]

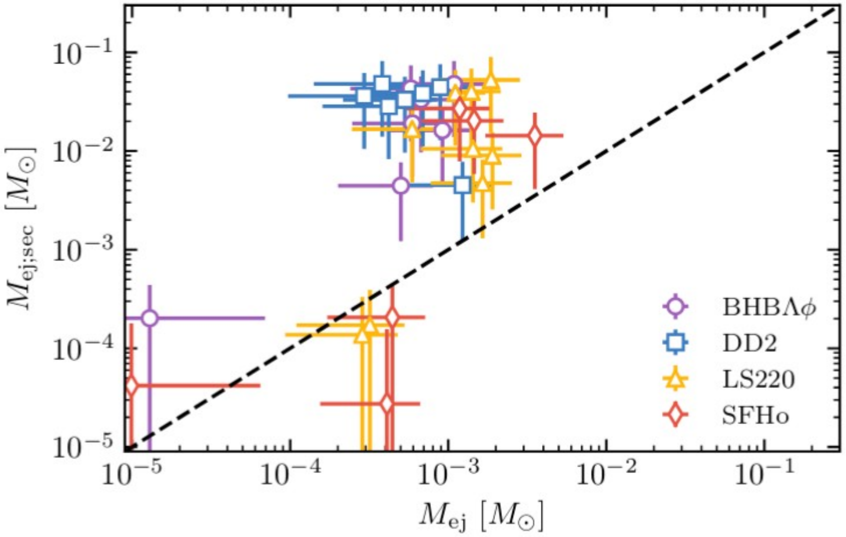


Figure 16. Dynamical ejecta $M_{\rm ej;dyn}$ versus secular ejecta masses $M_{\rm ej;sec}$. With the exception of the prompt BH formation cases that are able to expel at least a few $10^{-4}\ M_\odot$ in dynamical ejecta, the secular ejecta dominate over the dynamical ejecta.

[Radice,Perego,Hotokezaka,Fromm,SB,Roberts 2018]

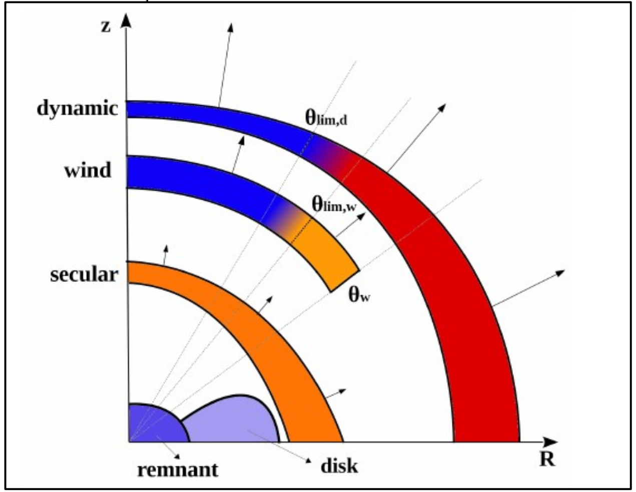
See also 2D remnant simulations by
[Fujibayashi+ 2017]

How much ejecta?

Table 1. Left: Parameters for the exploration of the model. Right: Parameters of the best fits to AT2017gfo.

	Parameter range	BF	BF_c	$BF_{c,\epsilon}$
χ^2	-	759	1263	1448
M_{disk} [$M_\odot$]	{0.01; 0.08; 0.1; 0.12; 0.15; 0.2}	0.08	0.1	0.12
$m_{ej,d}$ [$10^{-2} M_\odot$]	{0.05; 0.5; 1.0; 2.0; 5.0}	1.0	0.5	0.5
ξ_w	{0.001; 0.05; 0.1; 0.15; 0.2}	0.001	0.15	0.2
ξ_s	{0.001; 0.1; 0.2; 0.3; 0.4}	0.4	0.2	0.4
$\theta_{lim,d}$	{$\pi/6$; $\pi/4$}	$\pi/4$	$\pi/6$	$\pi/6$
$\theta_{lim,w}$	{$\pi/6$; $\pi/4$}	$\pi/6$	$\pi/6$	$\pi/4$
$v_{rms,d}$ [c]	{0.1; 0.13; 0.17; 0.2; 0.23}	0.2	0.23	0.2
$v_{rms,w}$ [c]	{0.033; 0.05; 0.067}	0.067	0.067	0.067
$v_{rms,s}$ [c]	{0.017; 0.027; 0.033; 0.04}	0.027	0.04	0.04
κ_d [$cm\,g^{-1}$]	{(0.5, 30); (1, 30)}	(1,30)	(1,30)	(1,30)
κ_w [$cm\,g^{-1}$]	{(0.5, 5); (0.1, 1)}	(0.1,1)	(0.5,5)	(0.5,5)
κ_s [$cm\,g^{-1}$]	{1; 5; 10; 30}	1	5	5
θ_{obs}	$n\pi/36$ for $n = 0 \ldots 11$	$\pi/12$	$5\pi/36$	$7\pi/36$
ϵ_o[$10^{18} erg\,g^{-1}\,s^{-1}$]	{2; 6; 12; 16; 20}	16	20	12

3-components anisotropic model
[Perego, Radice, SB ApJL (2017)]



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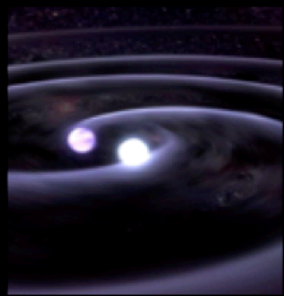
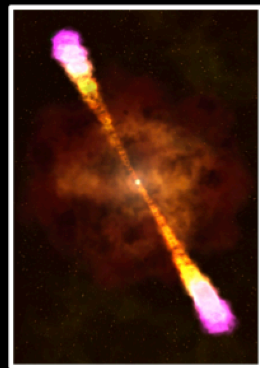
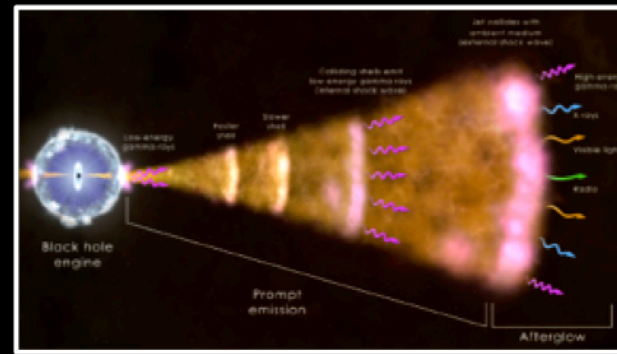
GW170817



NS merger



Short GRB



X-ray

Radio afterglow

t0

Info missed

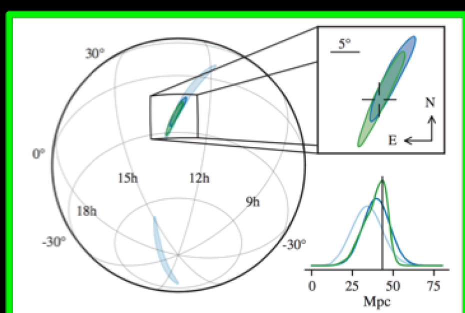
+5.23hrs

+10.87 hrs

+9 days

+16 days

LHV sky localization



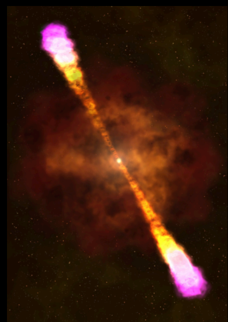
UV/Optical/NIR Kilonova

LVC + astronomers, ApJL, 848, L12

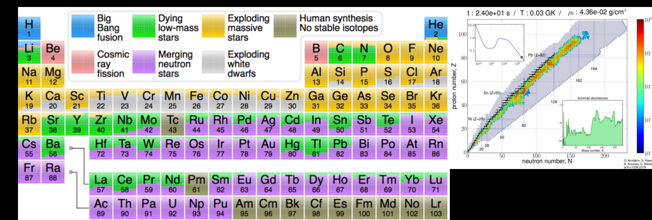
X-ray, optical, radio (months, yrs)

Radioactively powered transients

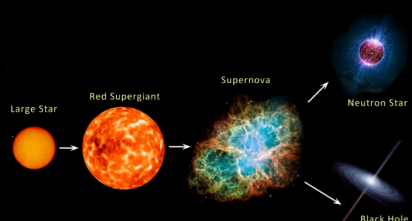
Relativistic astrophysics



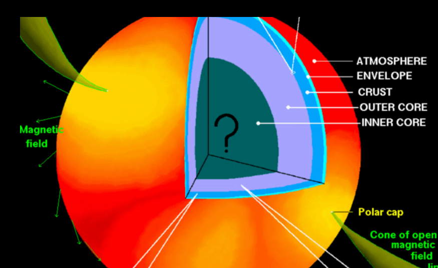
Nucleosynthesis and enrichment of the Universe



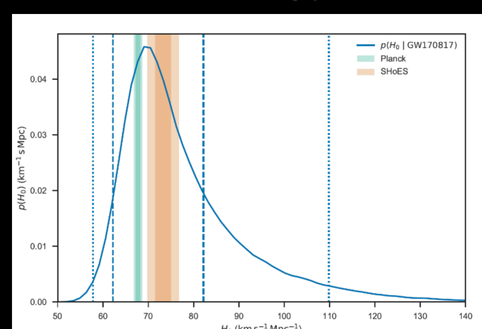
Compact object formation and evolution



Nuclear matter physics

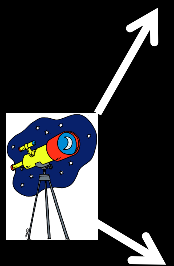


Cosmology



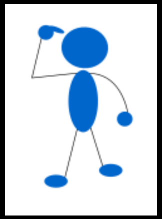
Next decades multi-messenger observatories

Hunt the elusive EM-counterpart!



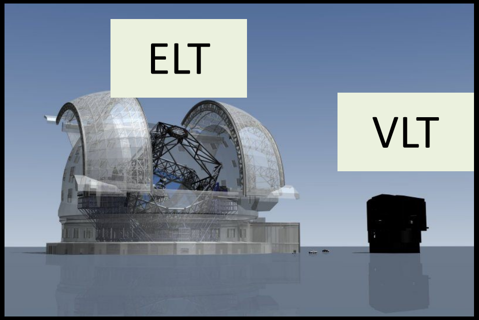
Wide-field telescope
FOV >1 sq.degree

to cover hundreds/thousands of square degrees



"Fast" and "smart" software to select a sample of candidate counterparts

to remove transients contaminants

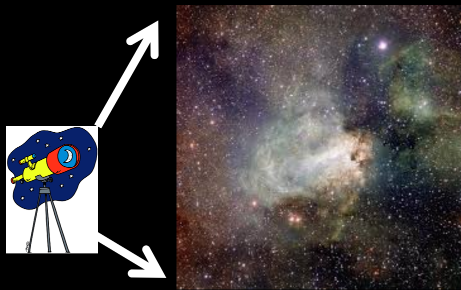


Larger telescope to **characterize** the candidate nature

To obtain observational time for the characterization

The EM Counterpart!

Hunt the elusive EM-counterpart!

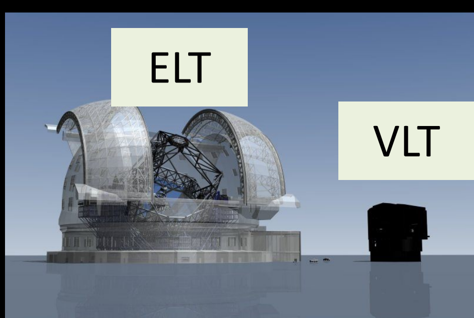


Wide-field telescope
FOV >1 sq.degree

“Fast” and “smart” software to select a sample of candidate counterparts

Discovery phase

☹ **Sky localization!**



Larger telescope to **characterize** the candidate nature

Characterization phase

☹ **Limited time at the telescopes!**

The EM Counterpart!

- What are the MM-MB science goals for A+/3G?
- What are the MM-MB instruments?
- Will the 3G MM science limited by EM observatory capabilities?
- How can help coordination/collaboration?

To answer is crucial to have a clear scenario about:
→ Sky localization and sensitivity capabilities of A+ and 3G
→ Alert latency, early warning

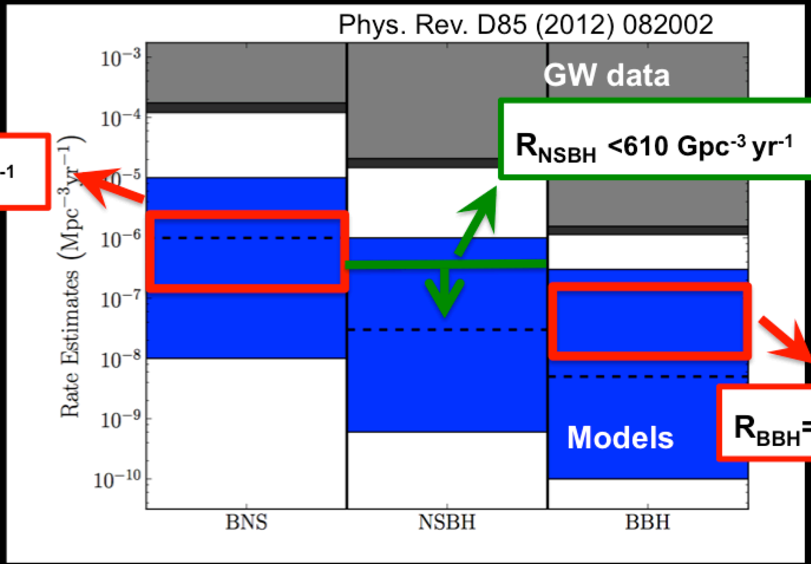
Astrophysical rate

BNS

R_{BNS}=110-3840 Gpc^{-3} yr^{-1}

LVC, arXiv:1811.12940

LVC, arXiv:1811.12907



R_{NSBH} <610 Gpc^{-3} yr^{-1} **NSBH**

BBH

R_{BBH}=9.7-101 Gpc^{-3} yr^{-1}

EXPECTED NUMBER OD DETECTIONS FOR O3

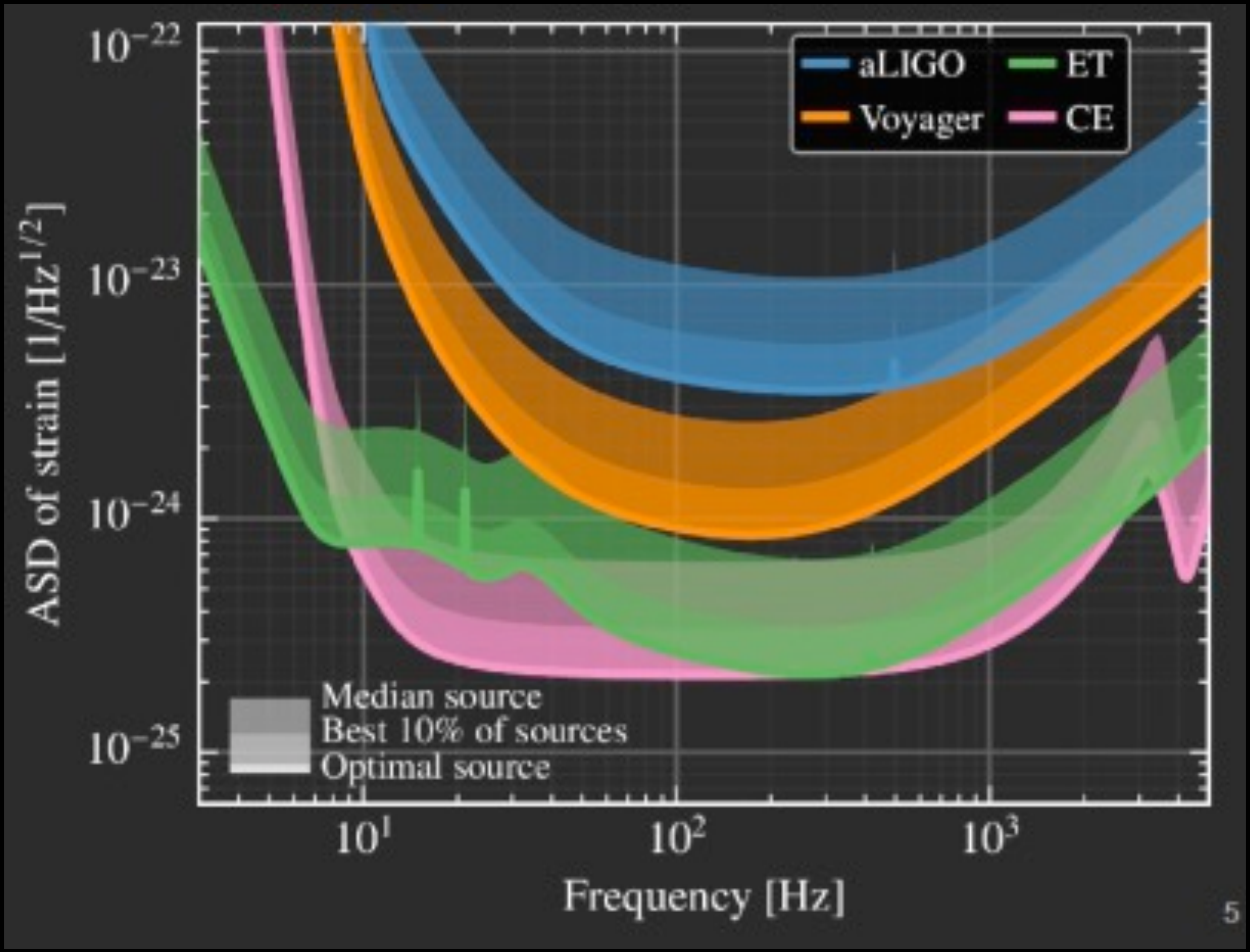
- NS-NS → Up to 1/month of data taken
  median is 2/year of data taken
- BH-BH → 1/month to 1/week of data taken
- NS-BH & other transients → Uncertain & unknown

LIGO BNSrange 120 Mpc
Virgo BNS range 60 Mpc

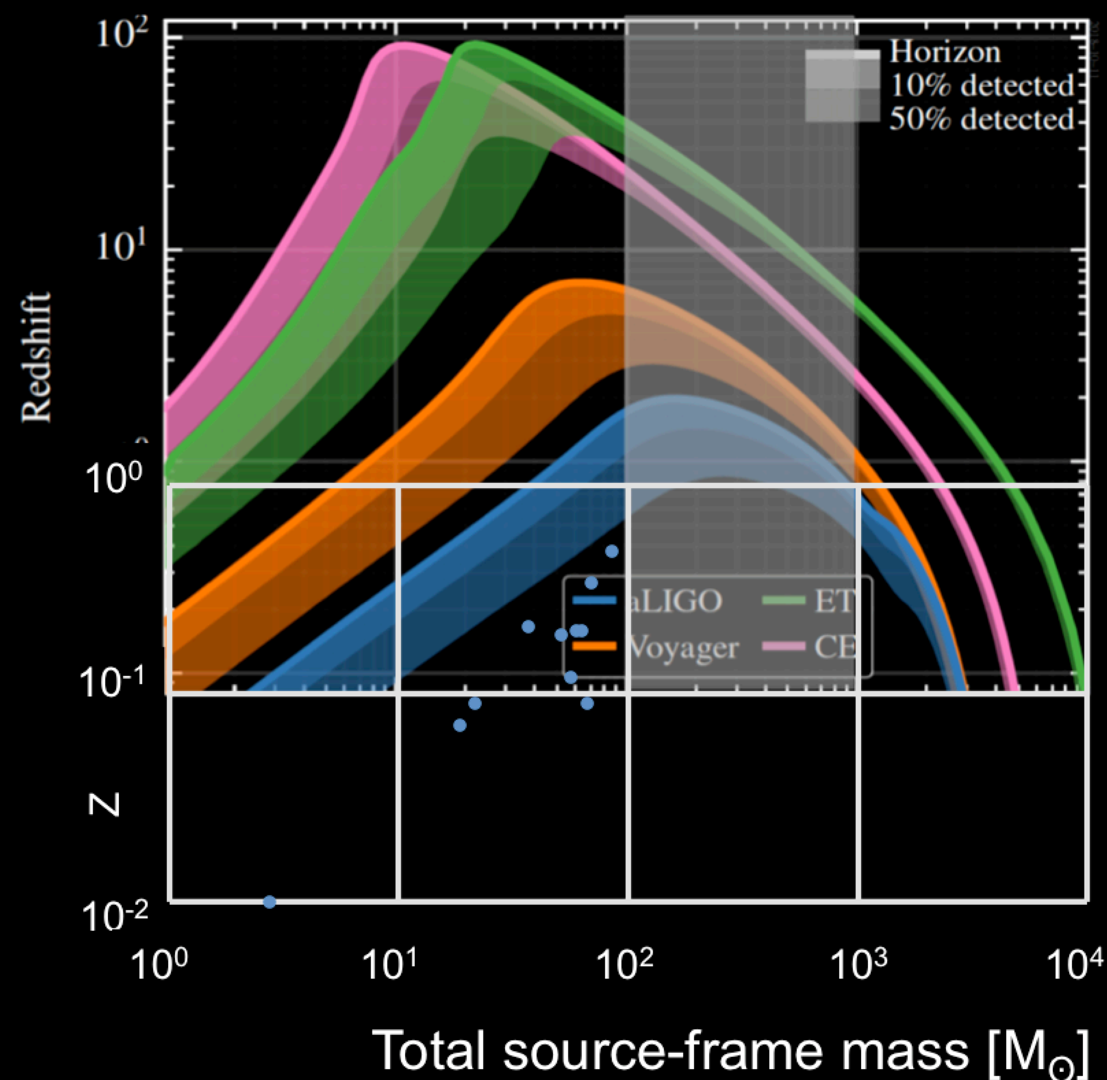
Median sky localization:
O3 a few hundreds deg^2
O4 (HLVK) a few tens deg^2

A+ about a factor 2.5 better sensitivity wrt O3, a factor 15 in volume!

3G DETECTORS: Einstein Telescope and Cosmic Explorer



Binary systems of Compact Objects



3G Science case WP

MM-MB SCIENCE GOALS OF 3G DETECTORS

- Binary system population studies
- Connection with GRBs/Star formation history/POP III
- Intermediate massive BH – seeds of supermassive BH

- Probing the physics of the merger remnant
- Probing the EOS of neutron stars

- Cosmology and Cosmography with GWs
- Explosion mechanism and remnant in Supernovae

STEPS FORWARD WRT ADVANCED DETECTORS

- Close astrophysical sources → high SNR

Going to larger distances → sample of detections:

- origin and evolution of compact objects in connection with SFH
- disentangle viewing effects (geometry) and energetics

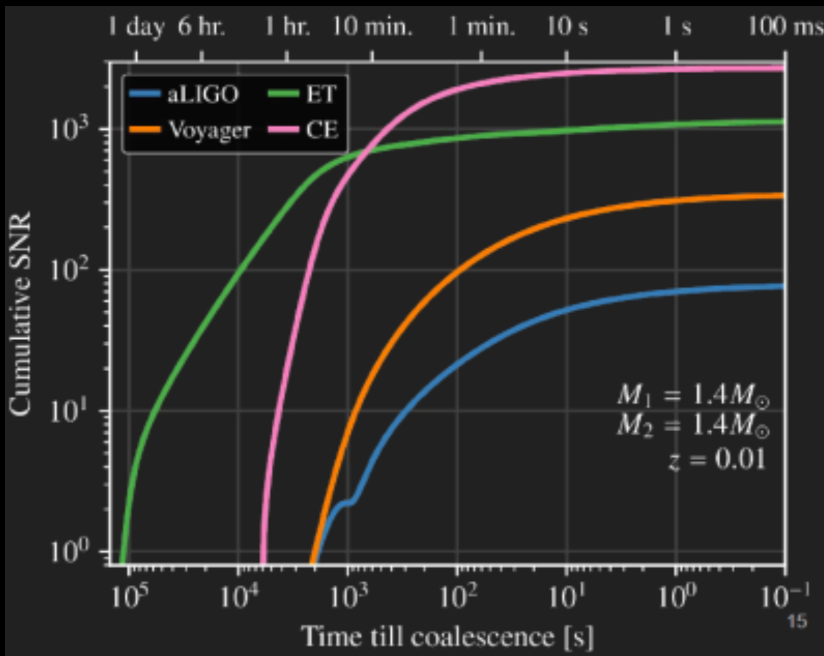
Detection Capability of 3G Network

Table 2.1: Expected BNS detections per year N; number detected with a resolution of < 1, < 10 and < 100 sq. deg. N_1, N_{10} and N_{100}, respectively, and median localization error M in sq. deg., in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV, KAGRA and LIGO-India (HLVKI) and 1 Einstein Telescope and 2 Cosmic Explorer detectors (1ET+2CE).

Network	N	N_1	N_{10}	N_{100}	M
HLV	48	0	16	48	19
HLVKI	48	0	48	48	7
1ET+2CE	990k	14k	410k	970k	12

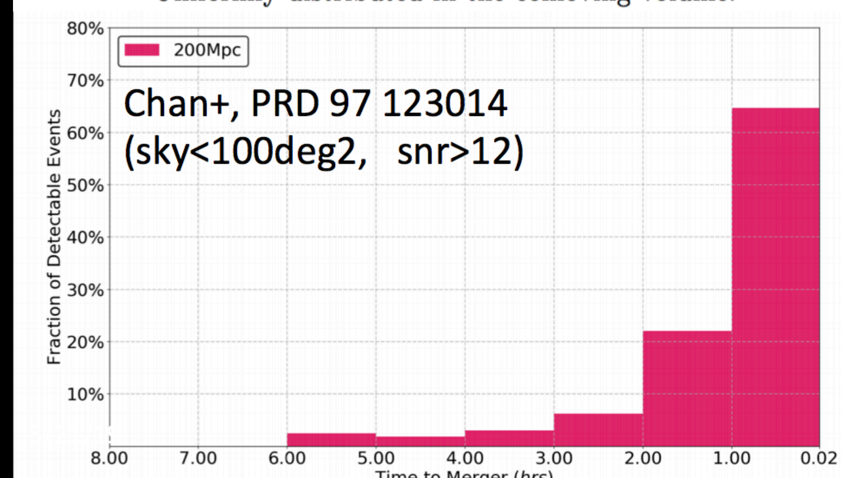
No need of wide-FoV surveys?
Important: to add 1ET+CE expectations and duty cycle
Expectations for close and distant objects

Trigger before the merger



Network	d (Mpc)	n	100 sec	0.5 hrs	2 hrs	5 hrs	10 hrs
ET & CE	40	500	100%	100%	99%	66%	18%
	200		100%	74%	13.4%	2%	0%
	400		98%	27%	4%	0%	0%
	800		51%	4%	0%	0%	0%
	1600		5%	1%	0%	0%	0%
	Uniform [1]	5000	4%	1%	0%	0%	0%

[1] Uniformly distributed in the comoving volume.



Cosmic Explorer

ET EINSTEIN TELESCOPE

3G Science case WP

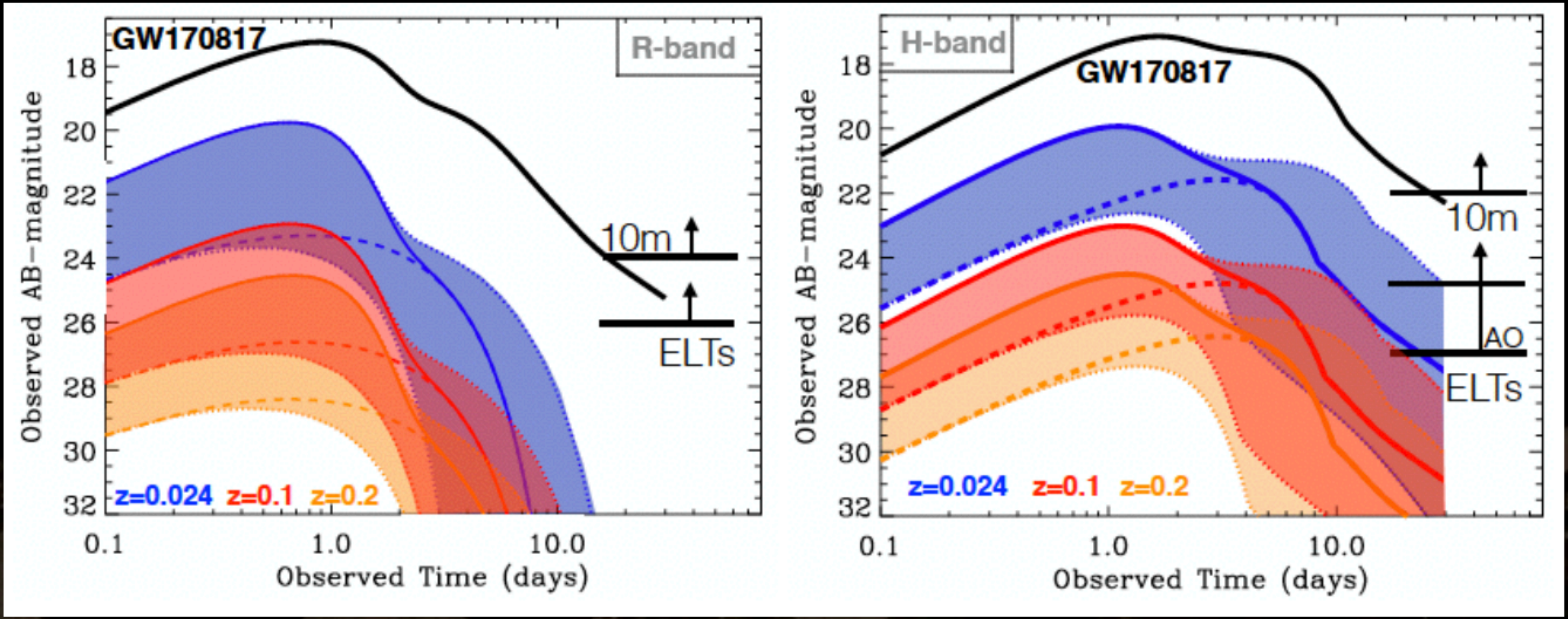
When the early warning is a big advantage?

Large sky-localization → optical band many contaminants and faint signals

High-energy?

ELT - ET era: kilonova

Chornock+2019



May 2018: THESEUS selected within ESA Cosmic Vision science programme with SPICA and EnVision Venus

IF SELECTED LAUNCH 2032!

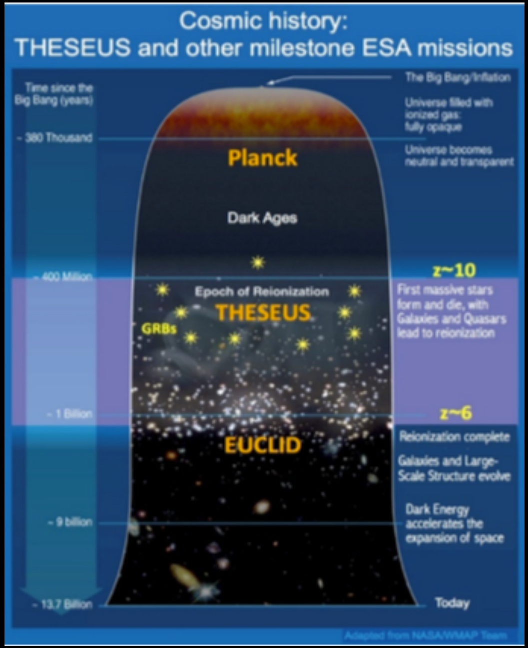
- **Lead Proposer (ESA/M5)**: Lorenzo Amati (INAF – IASF Bologna, Italy)
- **Coordinators (ESA/M5)**: Lorenzo Amati, Paul O'Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), C. Tenzer (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)
- **Payload consortium**: Italy, UK, France, Germany, Switzerland, Spain, Poland, Czech Republic, Denmark, Ireland, Hungary, Slovenia, ESA
- **Interested international partners**: USA, China, Brazil

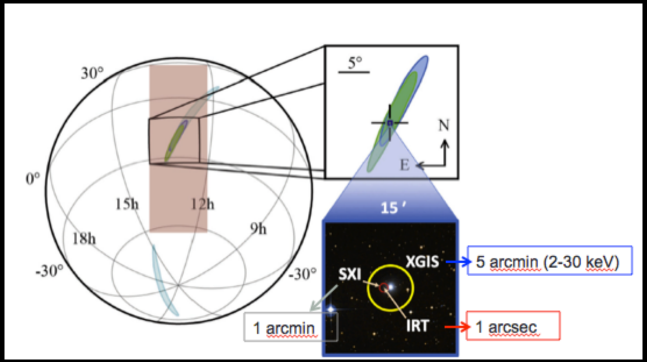
Courtesy of G. Stratta

Transient HE Sky and Early Universe Surveyor: main science goals

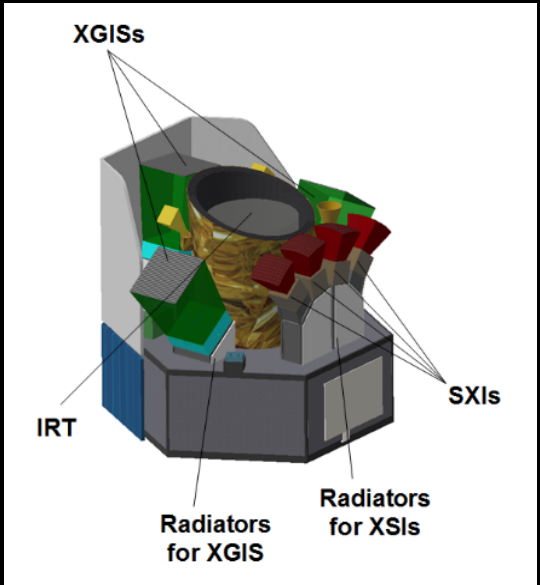
- Explore the physical conditions of **the early Universe by unveiling the Gamma-Ray Burst** population in the first billion years

- Perform unprecedented **deep monitoring of the X-ray transient Universe** playing a fundamental role in the coming era of **multi-messenger and time-domain astronomy**





These goals will be achieved through a unique combination of instruments:

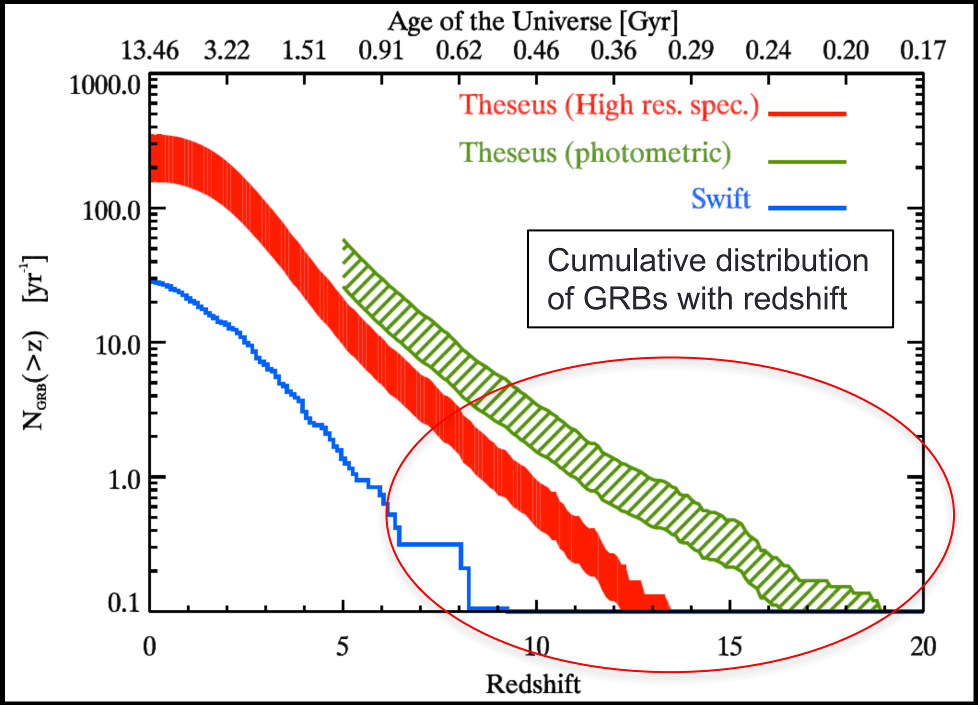


Amati et al. 2018

- **Soft X-ray Imagers (SXI)**
  - 4 Lobster-eye telescopes
  - **0.3-5 keV**
  - FoV ~ 1 sr
  - Location accuracy ~ 0.5’-1’
- **X-Gamma-ray Imager Spectrometer (XGIS)**
  - 3 Coded mask telescopes + X(Si) – Gamma(CsI) ray cameras
  - **2 keV – 10 MeV**
  - FoV ~ 2 - 4 sr (overlapping SXI)
  - Location accuracy ~ 5’
- **InfraRed Telescope (IRT)**
  - 0.7mt class telescope
  - 0.7-1.8 mm (ZYJH)
  - FoV: 10’x10’
  - Imaging (H=20.6;300s) and medium resolution spectroscopy (H=17.5;1800s) capabilities (→ redshift)

- **BROAD FIELD OF VIEW (more than 1sr) with ACCURATE LOCALIZATION (down to 0.5’-1’ in the X-rays)**
- **LARGE SPECTRAL COVERAGE from 0.3 keV up to several MeV**
- **an on-board prompt (few minutes) follow-up with a 0.7 m CLASS IR TELESCOPE** with both imaging and spectroscopic capabilities

GRB expected detection rate vs z

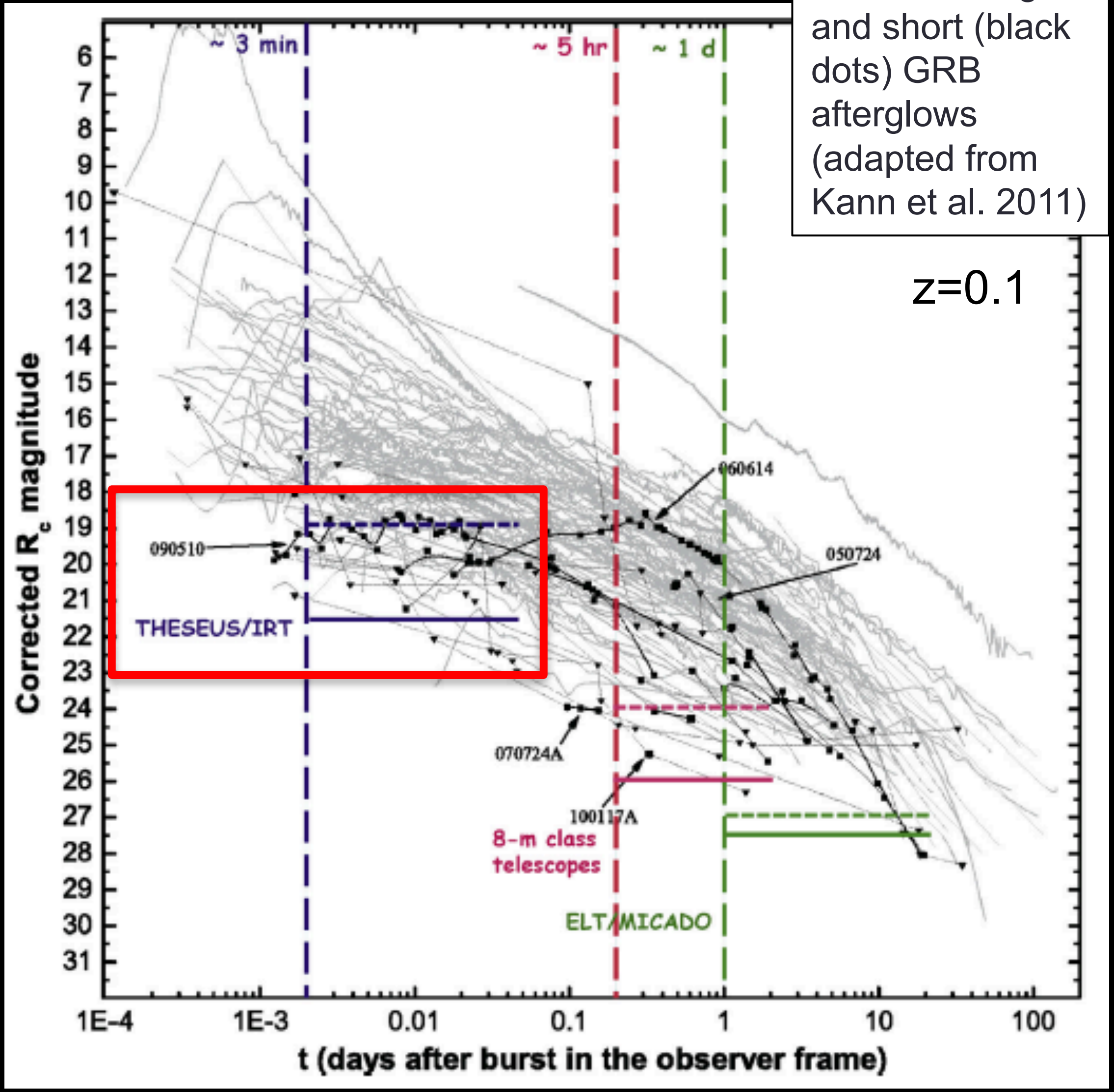


Amati et al. 2018

THESEUS GRB#/yr	All	z > 5	z > 8	z > 10
Detections	387 - 870	25 – 60	4 – 10	2 - 4
Photometric z		25 – 60	4 – 10	2 - 4
Spectroscopic z	156 - 350	10 - 20	1 - 3	0.5 - 1

Optical afterglow detection with THESEUS/IRT

Stratta et al. 2018



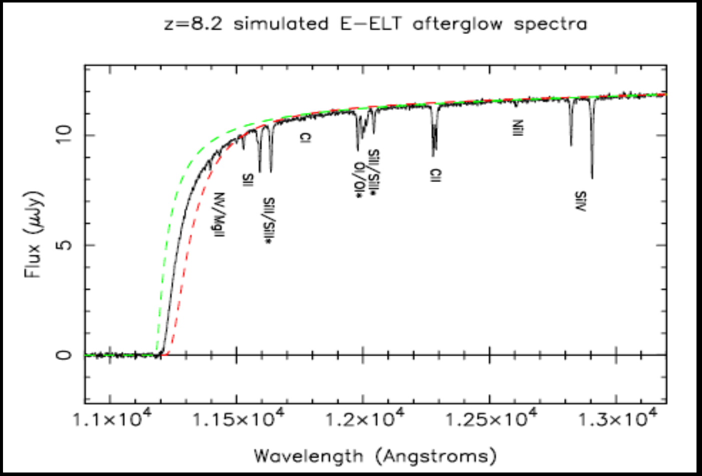
R-band light curves of long and short (black dots) GRB afterglows (adapted from Kann et al. 2011)

IR Telescope will provide:

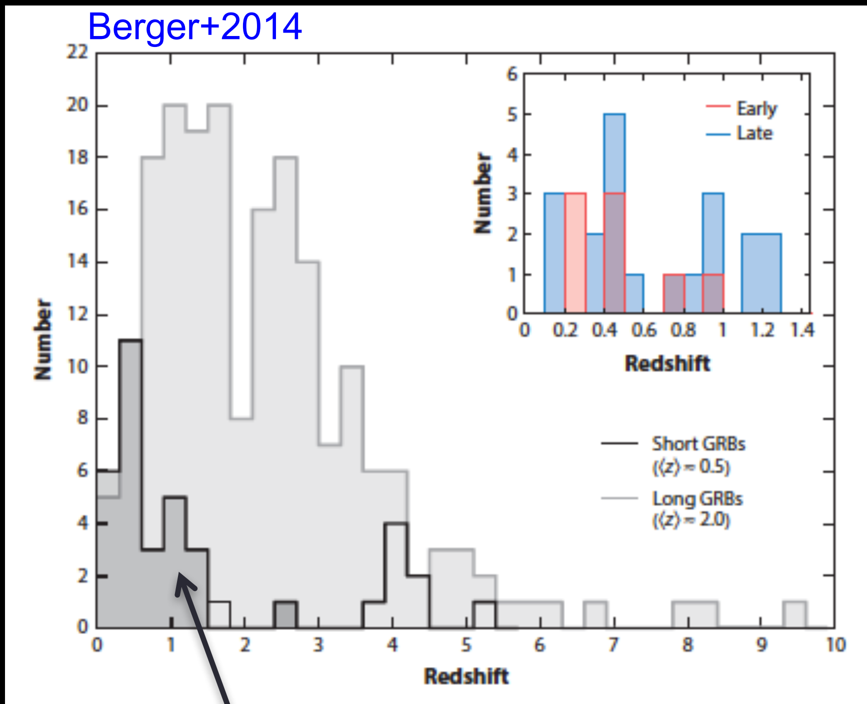
- arcsec localizations
- Redshift measures
- Luminosity estimates

These information will be used to optimise follow-up high S/N spectroscopy

E-ELT

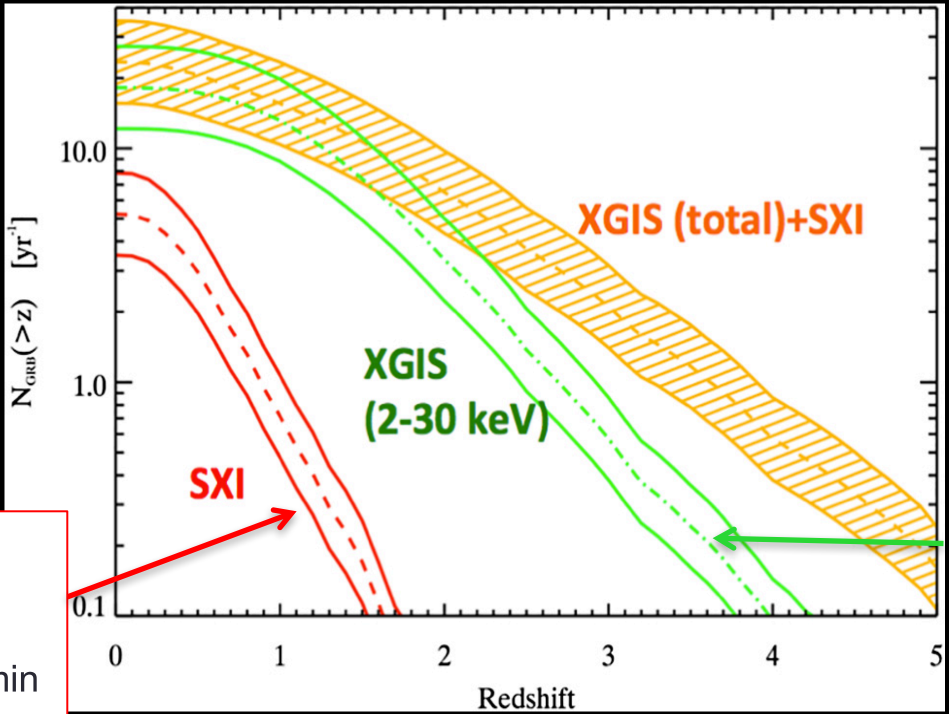


Short GRB detections



Short GRB z distribution,<z> ~ 0.5

Short GRB detections with THESEUS



Stratta et al. 2018

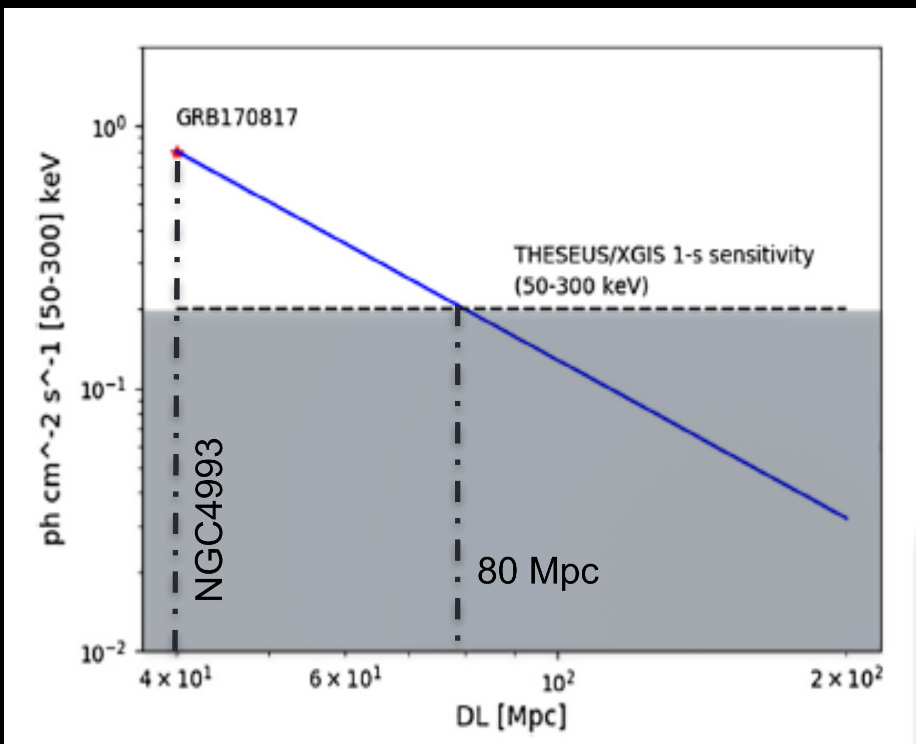
short GRB detected and localized down to 5 arcmin by XGIS only

short GRB detected and localized down to 1 arcmin with SXI only

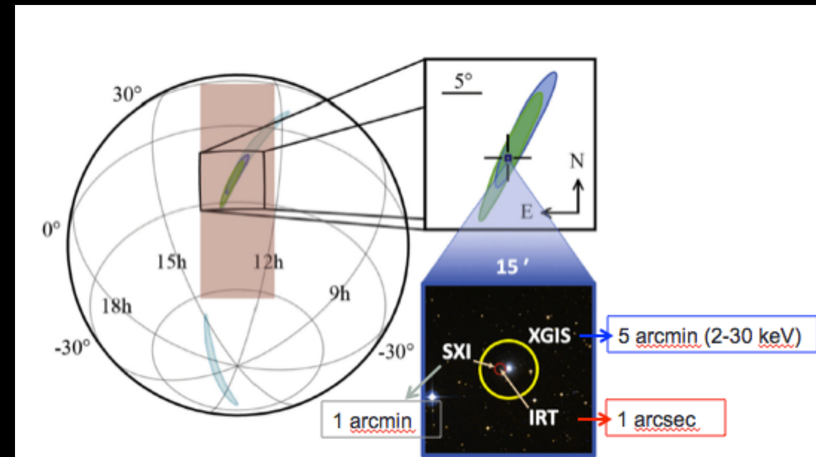
THESEUS will provide accurate localization for
20-40 short GRB/year within 1' - 5'

THESEUS and GW170817/gamma-rays

GRB 170817



Stratta et al. 2018



THESEUS/XGIS would had detected the off-axis GRB170817 up to ~ 80 Mpc

→ NOT SO DISTANT! ☹

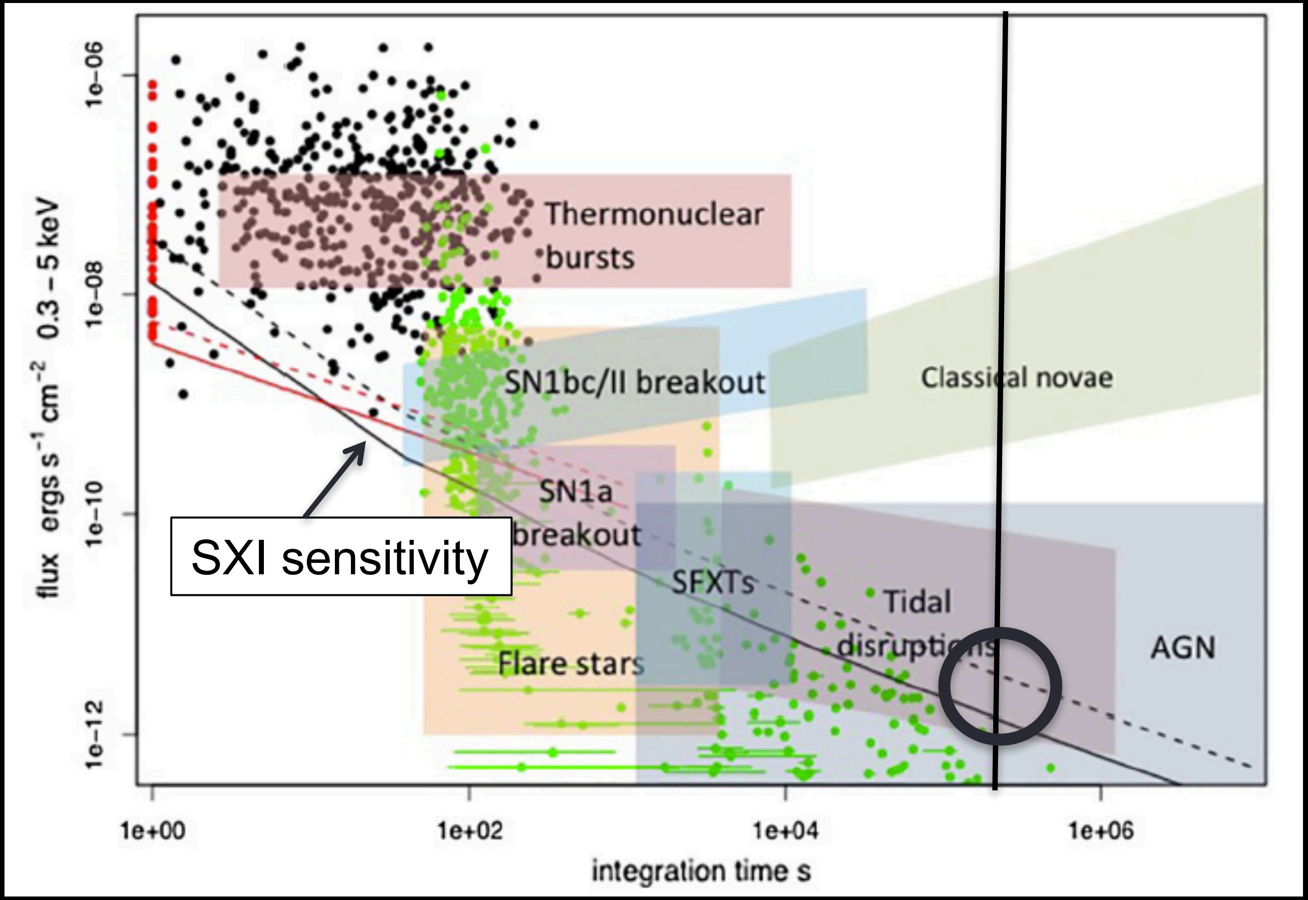
BUT

→ THESEUS would had accurately localized GW170817 from 5 arcmins down to arcsec

→ with 3G interferometers, HUNDREDS OF DISTANT GW/ON-AXIS SHORT GRBs will be detected, localized and studied with THESEUS ☺

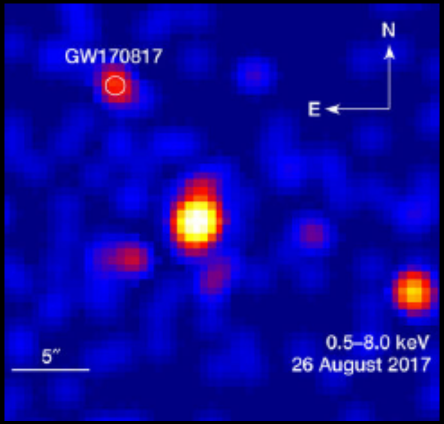
THESEUS and GW170817-X-ray

50 ks of integration



SXI >~10^{-12} erg/s cm^2 for Texp=50 ks

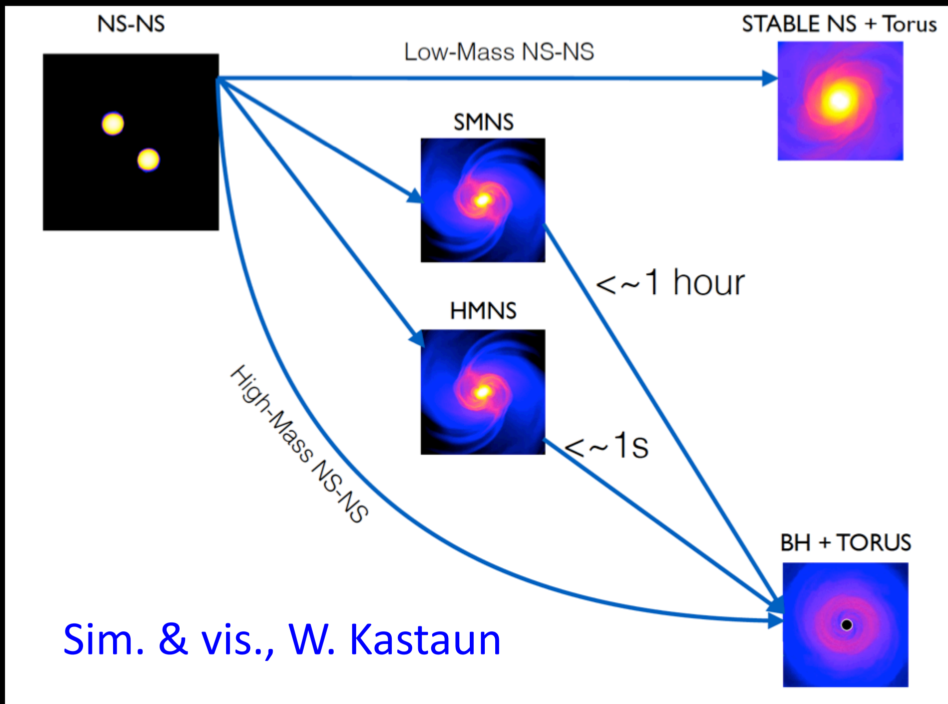
→ Much higher than the Chandra X-ray first detection of GW170817 ~4 x 10^{-15} erg/s cm^2 (50ks, Troja+2017)



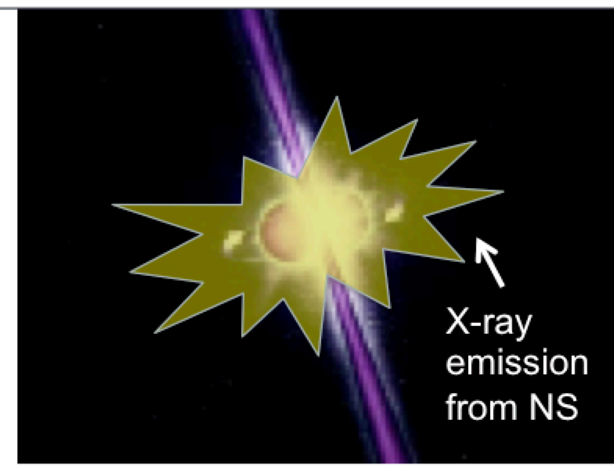
ATHENA will be necessary…

BUT…

ISOTROPIC X-RAY EMISSION FROM NS-NS MERGER



Nearly isotropic magnetar-powered X-ray emission from long-lived NS-NS merger remnants

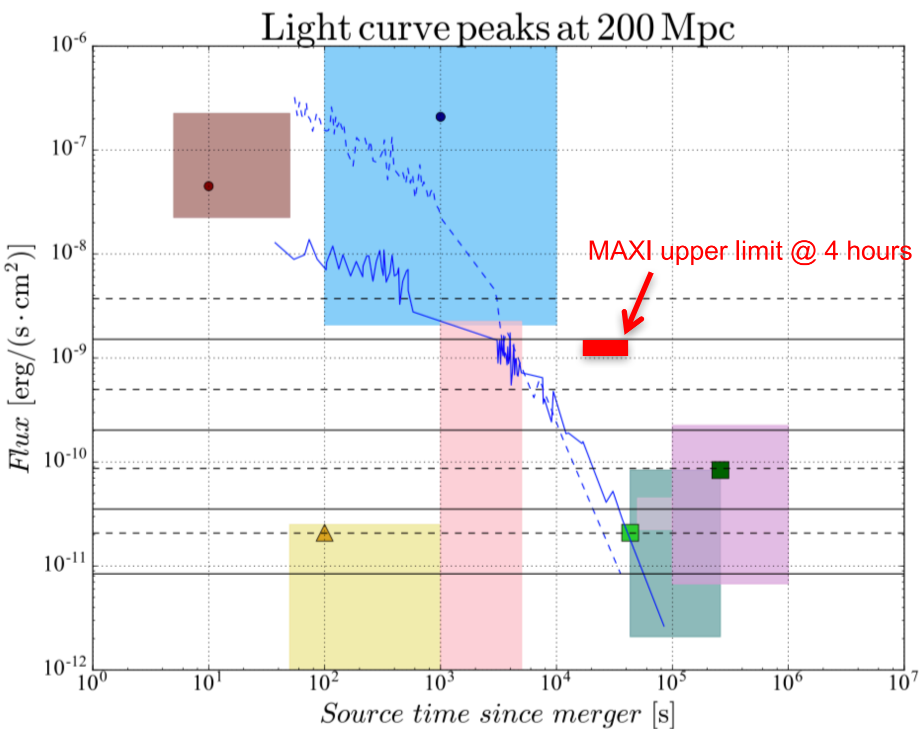


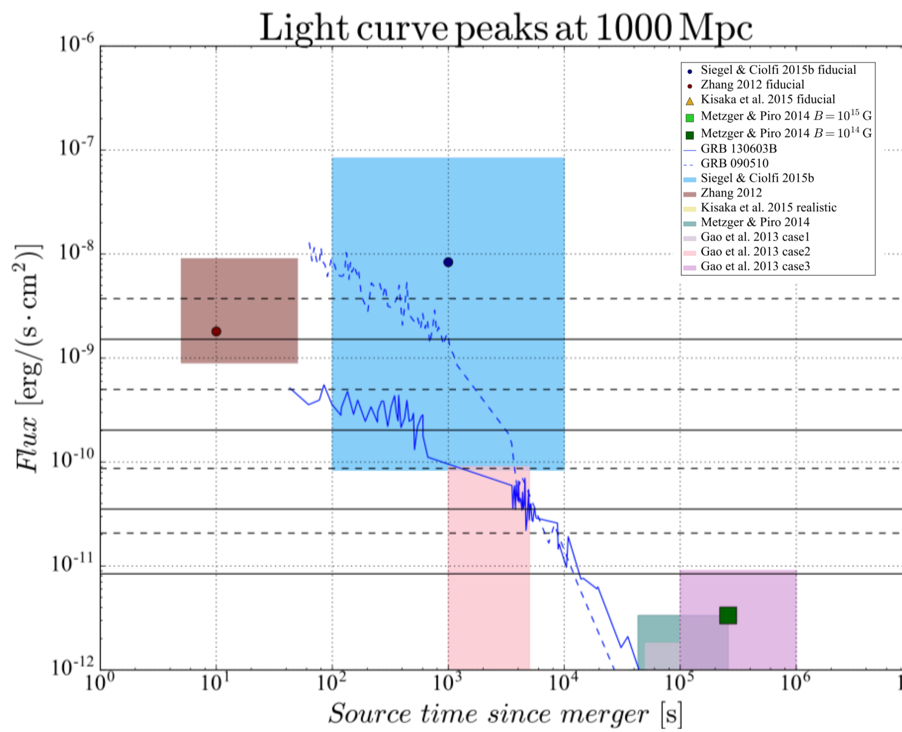
$L_X \sim 10^{43} - 10^{48}$ erg/s

NS-NS merger detections with THESEUS

Distance (range) for 2G GW network

Distance for 3G GW detectors





Solid and dashed horizontal lines: SXI limits for 10s, 100s, 1ks and 10ks exposure time for two different column densities

Almost all X-ray flux predictions will be detected with THESEUS

Brightest X-ray flux predictions will be detected with THESEUS up to 1 Gpc

Stratta 2018, Vinciguerra 2019

Summary open questions

- Multi-messenger approach is fundamental
- What are the EM observatories which are necessary for the GW science?
- Will sky localization be so good to avoid the wide-FOV instruments' discovery phase?
- When the early warning is a big advantage?
- Will the 3G MM science be limited by EM observatory capabilities?
- How can help coordination/collaboration?

Multimessenger & Multi-band

M. Branchesi, L. Cadonati
PANEL: S. Bernuzzi, M. Branchesi, D. Verkindt, C. Palomba, G. Prodi, S. Vitale

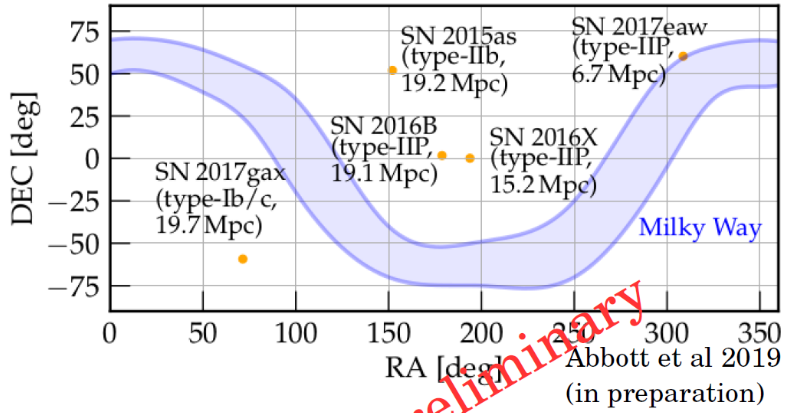
- Salvo "Multi-band perspectives"
- Sebastiano "GW/EM modeling and joint analysis"
- Marica "Challenges and perspectives for multi-messenger observational campaigns"
- Giovanni: "Supernovae (and other unmodeled signals)"
- Didier: "Challenges in detecting SNe and other unmodeled transients"
- Cristiano "GW Continuous waves (+ EM) to infer NS properties"

some GW data analysis challenges posed by ccSN

on the need for loosely modeled GW searches

latest optically triggered GW observations:

from the presentation at APS 2019
by Marek S. on behalf of LVC



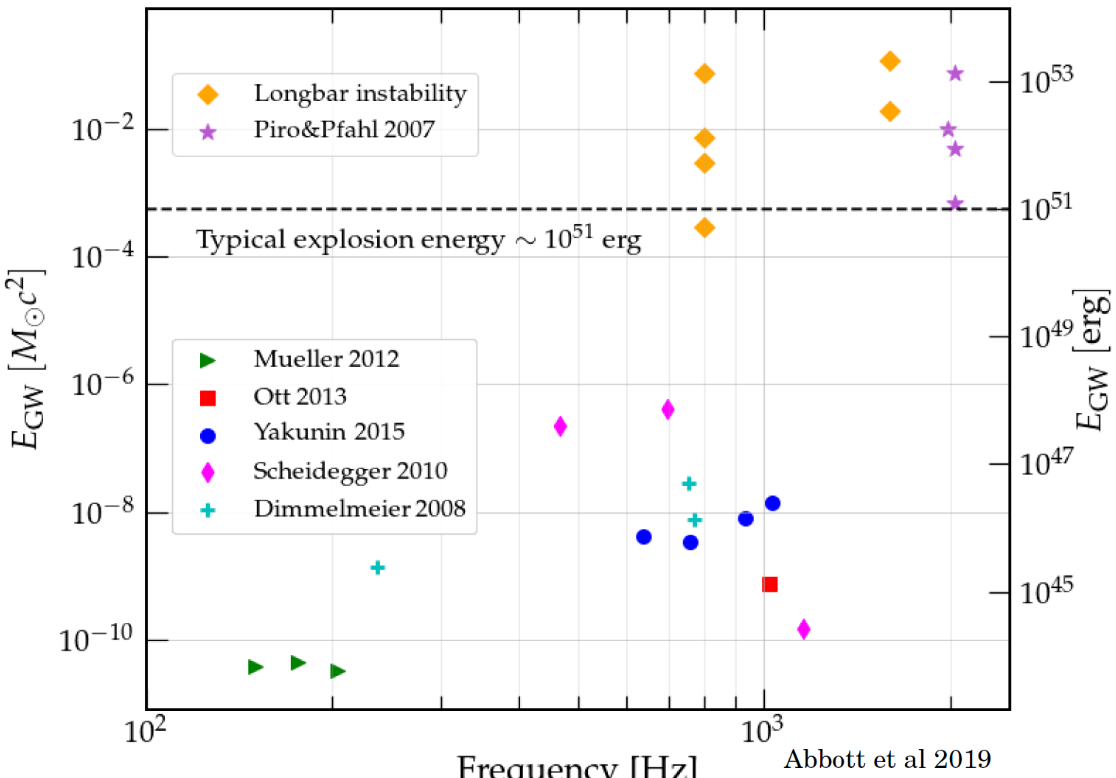
5 CCSN within 20 Mpc

e.g.

- Detection ranges for SN 2017gax (19.7 Mpc):
  5 kpc (neutrino-driven explosions),
  54 kpc (MHD-driven explosions),
  28 Mpc (extreme emission models)

O1-O2 Optically Targeted CCSN Search
GW Energy constraints

Preliminary



Abbott et al 2019
(in preparation)

- Constraint on the GW energy emitted by a CCSN source
- Isotropic emission assumed
- iLIGO SN Search Egw constraints: 5.8×10^{-2} Msun (235Hz) and 26Msun (1304Hz)
- Typical explosion energy (~10^{51}erg) and typical kinetic energy of the ejecta (~10^{51}erg)
- Models:
  - Longbar: Ott, dcc: T1000553
  - Piro&Pfahl, ApJ 658, 1173 (2007)
  - Mueller et al, ApJ 537, A63 (2012)
  - Ott et al, ApJ 768, 115 (2013)
  - Yakunin et al Submitted to PRD (2015)
  - Scheidegger et al, CQG 27, 114101 1405 (2010)
  - Dimmelmeier et al, PRD 78, 064056 (2008)

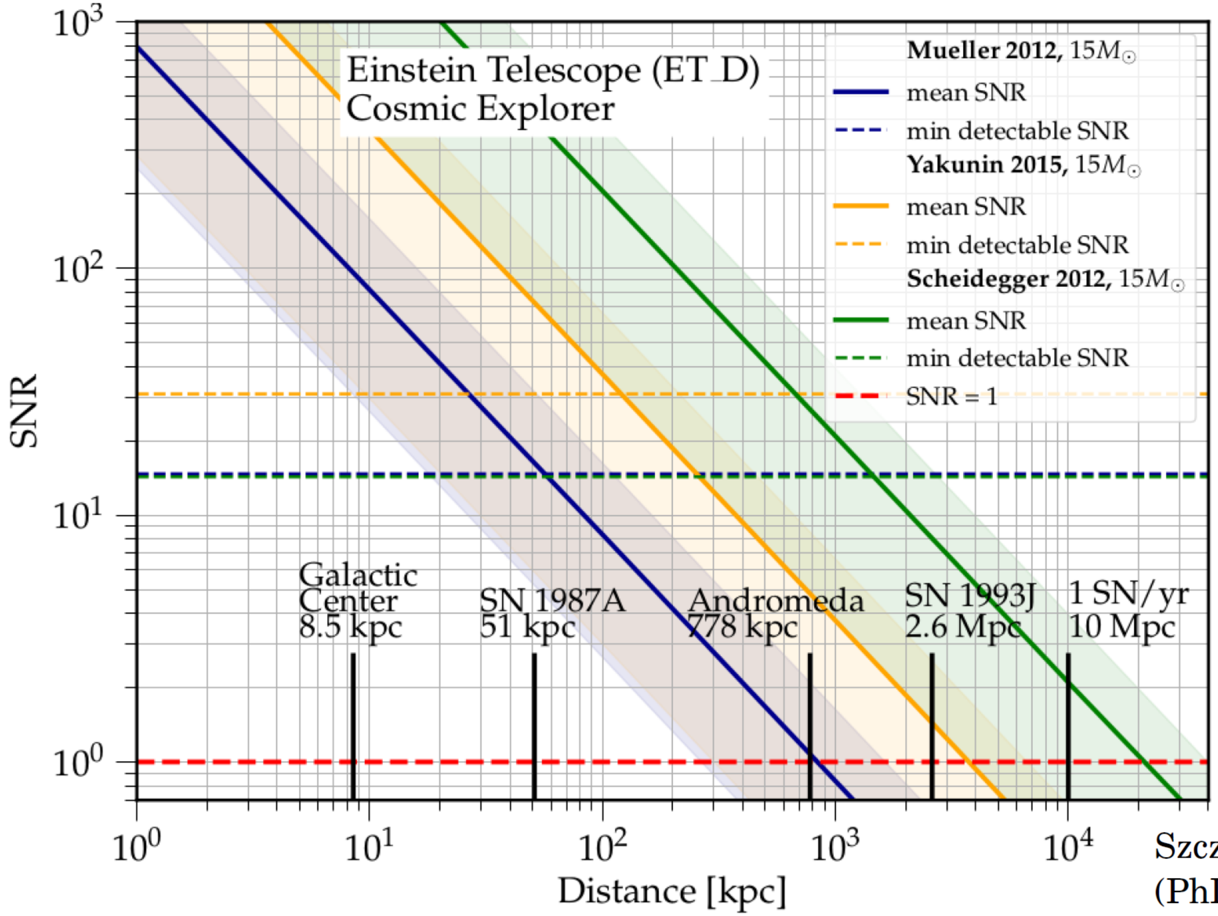
GW observations with 3G: Detectability with Future Generation Interferometers – R&D project

from the presentation at APS 2019
by Marek S. on behalf of LVC

- association with long GRBs ?
- neutrinos

low Signal to Noise ratio for extragalactic CCSN

- Extensive studies on detectability of the CCSN waveforms with proposed Future interferometers:
  - Einstein Telescope (ET) – proposed European triangular 10 km arm interferometer
  - Cosmic Explorer (CE) – proposed L-shape US 40km arm interferometer

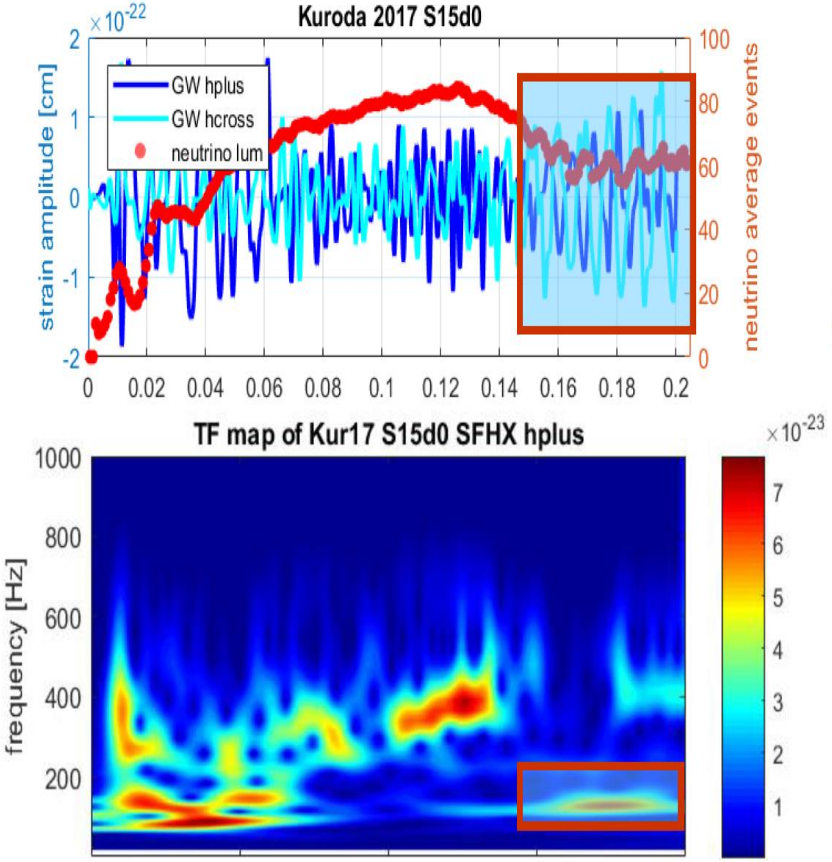


Szczepańczyk 2018 (PhD Dissertation)

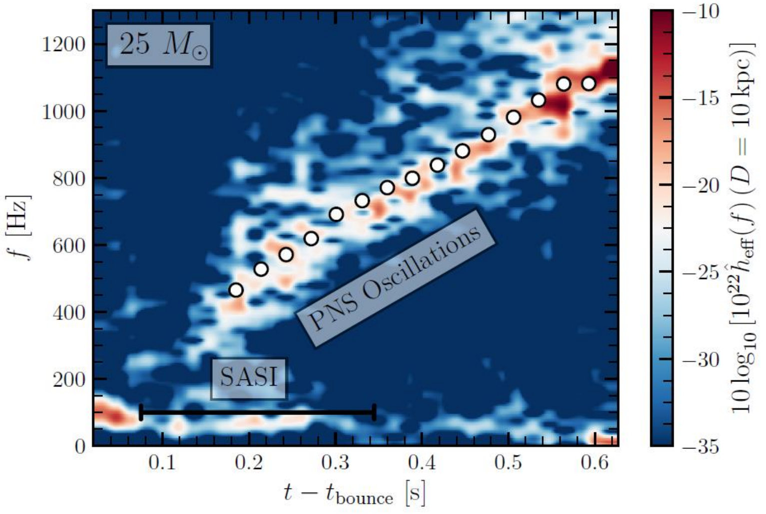
a variety of mechanisms for GW emission

models provide approximate morphological properties of the GW waveforms

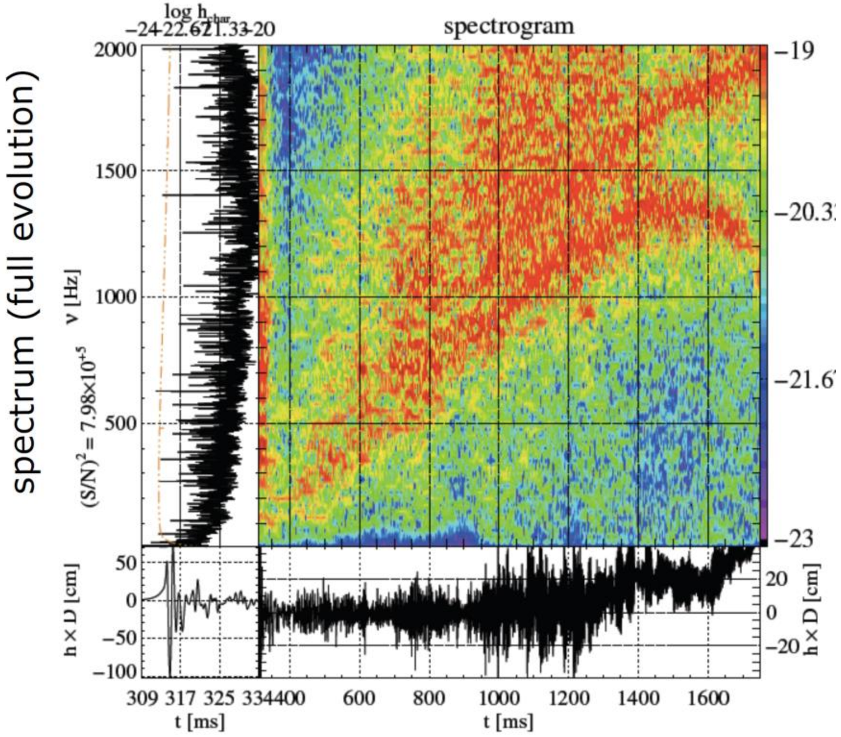
- core bounce forming proto-NS
- post-bounce: stochastic behavior dominated by mode oscillations of the proto-NS + ….



Marie Bals, Marek Szczepańczyk, Sergei Klimenko and Michele Zanolin, based on Kuroda+ arXiv:1708.05252



Radice+ ApJL 876:L9 (2019)



strain @ bounce full strain evolution

Cerdá-Durán+ 2013

ccSN Detection and interpretation

detection challenges:

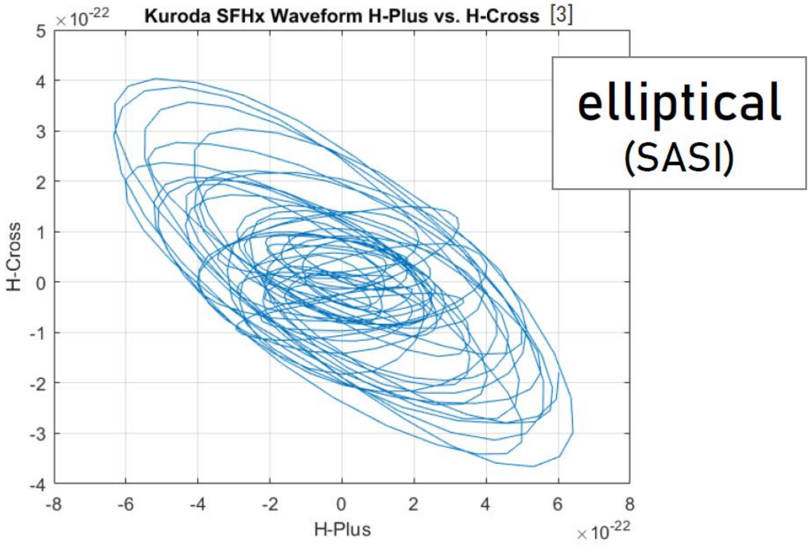
- un-modeled or loosely modeled methods looking for a coherent response from the detector network
- Signal to Noise ratio is dispersed on a large time-frequency volume
- help from other messengers

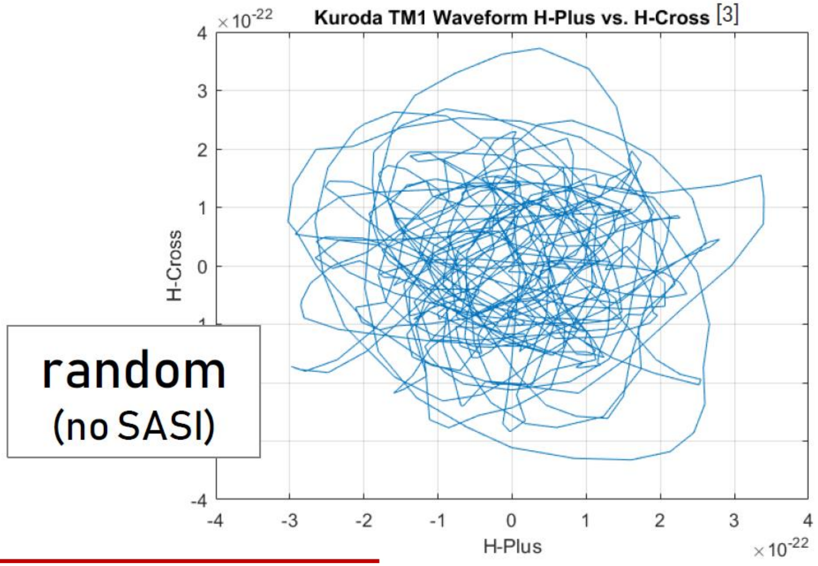
interpretation challenges:

- different morphological features are present
- help from models of asteroseismology for the proto-NS modes, SASI
- polarization of the GW: "evolving elliptically polarized" vs "stochastic polarization"

on each detected feature:
which uncertainty ?
which significance ?
understand prob. of dismissing features ..

Marie Bals, Marek Szczepańczyk, Sergei Klimenko and Michele Zanolin, recent LVC presentation:





ccSN Detection and interpretation

interpretation challenges continued:

- Bayesian model selection:

Supernova Model Evidence Extractor (SMEE)

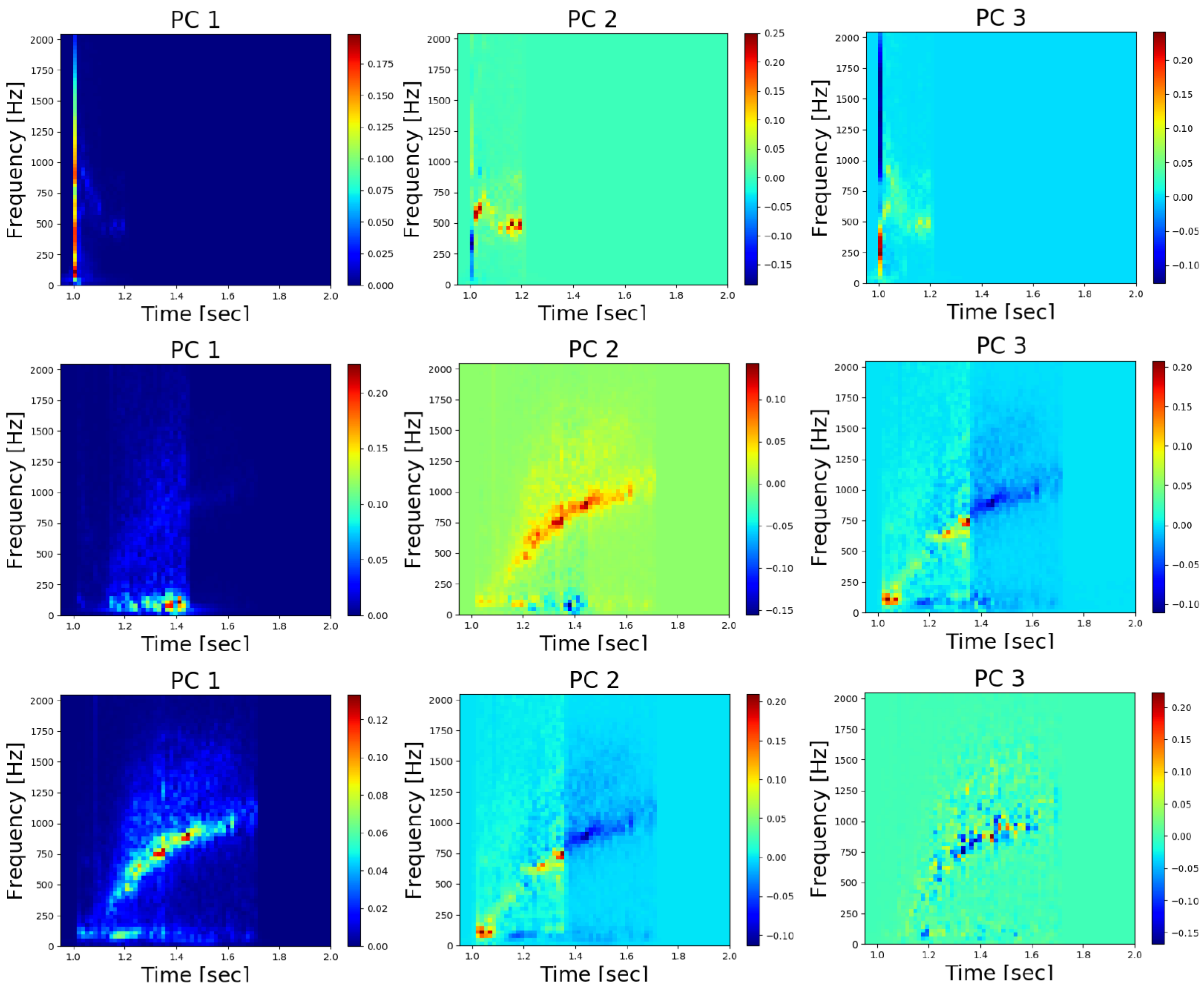
Roma+ PRD2019

using Principal Component Analysis

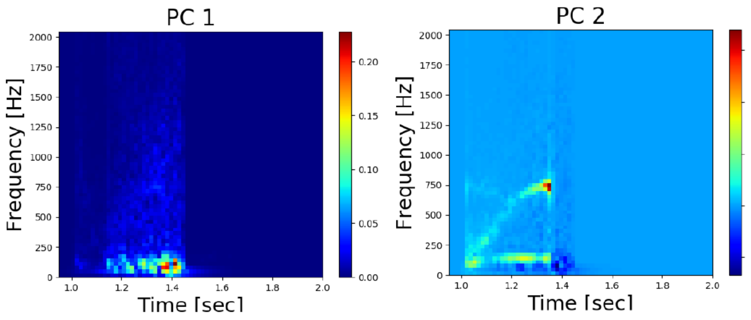
Magneto-rotational

Neutrino

G-Mode



SASI



GW search for the possible NS remnant

- **power-law spindown of a massive magnetar-like remnant**

transient chirp-down signal of ***hours-days duration,*** GW emission from non-axisymmetric fast-rotating NS

spindown GW-dominated at early times ? and then transition into EM dominance

2017 advanced LIGO-Virgo reach ≈ 1 Mpc [Astrophys. J. **875**, 160 (2019)]

> analysis methods benefit from different techniques (unmodeled bursts, unmodeled narrowband correlation radiometer-like, tracking emission lines which are slowly evolving, …)

- **glitching NS :** possible further excitations of oscillation modes of hot NS (related to "pulsar glitches" phenomena ?)

duration 1-1000s

also in surveys of galactic pulsars and magnetars e.g. SGRs, QPOs in AXPs

Multimessenger & Multi-band

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- Salvo “Multi-band perspectives”
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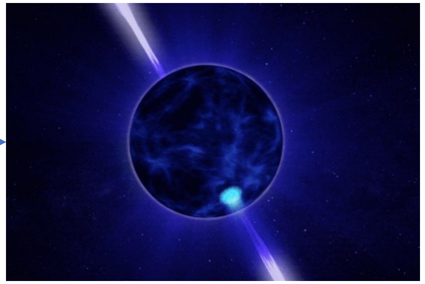
From GW detector noise to Supernovae

D. Verkindt, LAPP, CNRS, Virgo

Preliminary remark

Core-Collapse Supernovae

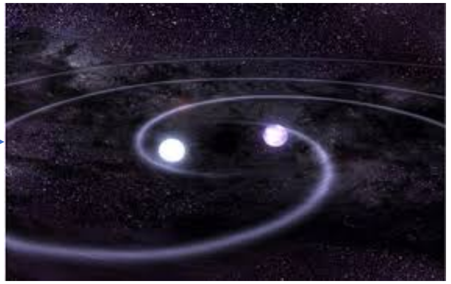
Neutron star



Pulsar

CCSNe

Black Hole



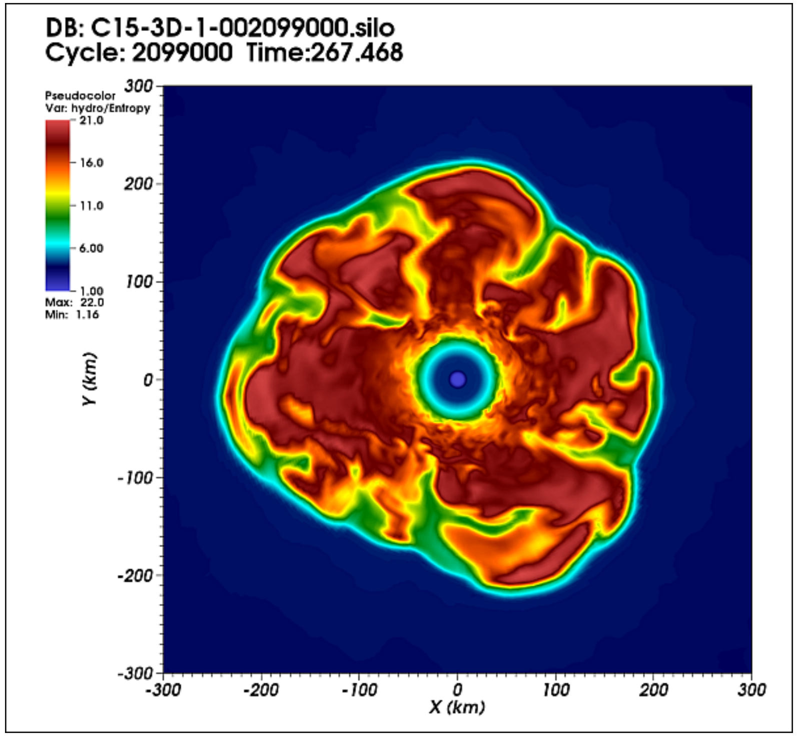
BNS, NSBH , BBH

Extreme Matter

Extreme Gravitational Field

Extreme Speed

No stable modelisation

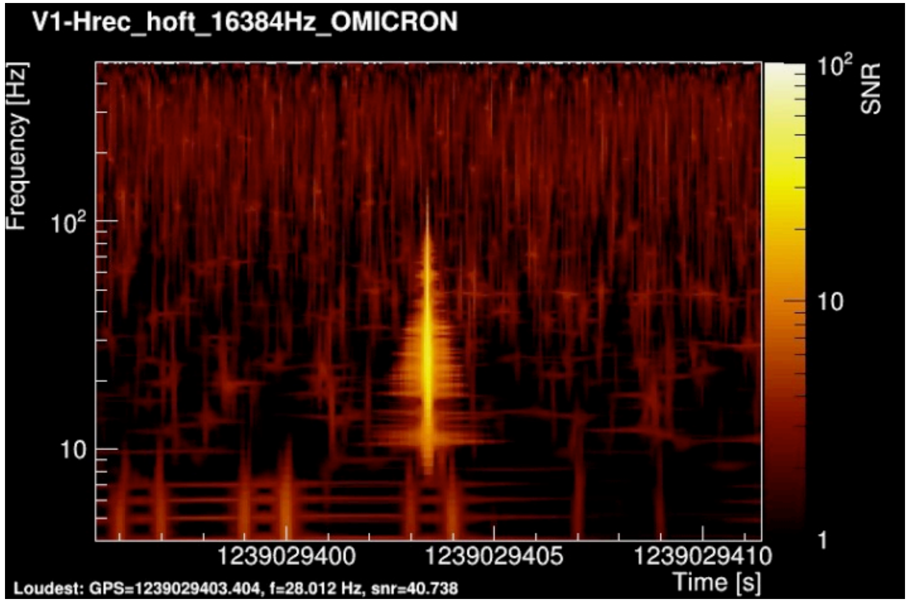


CCSNe simulation of standing accretion shock instability (SASI)
Credit: Eric Lentz, University of Tennessee, Knoxville.

To go from detection to physics study of the source: need modelisation

Core-Collapse Supernovae
Many efforts of modelisation
But not yet well defined GW theoretical signals
→ No template (or too many templates) to be used for matched filtering detection or for Parameters Estimation

Many transient noises



Virgo glitch due to magnetic transient

Despite concident or coherent detection by LIGO+Virgo detectors
A lot of transient noises builds a background against the detection and can mimic CCSNe GW signal

Most of them (with SNR<8) can not be vetoed

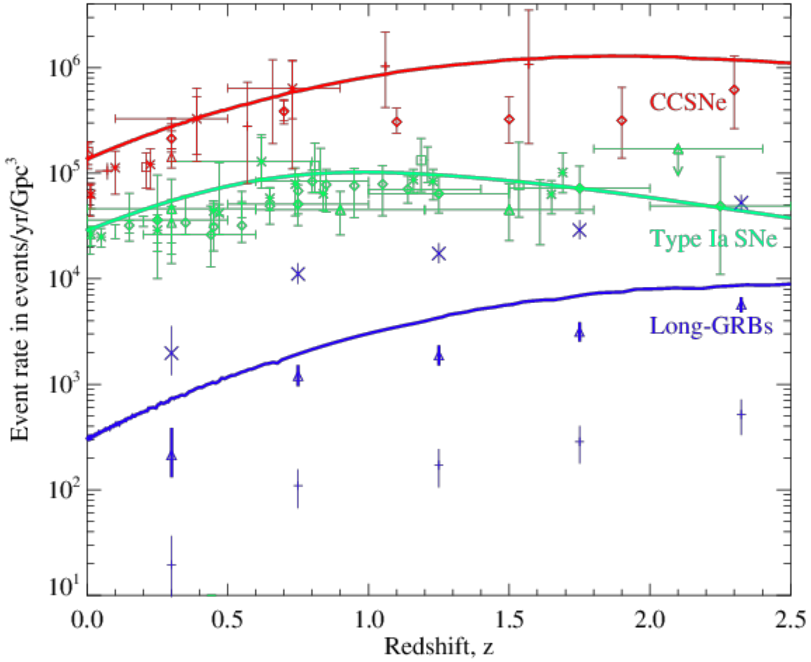
Low probability to get an event

Feb 23rd 1987

Gravitational Waves signal expected to be detectable only if CCSNe is in our galaxy.

Galactic CCSNe rate (about 2 per century)
+ LIGO-Virgo « 3 detectors-duty cycle » of about 50% during a 1-year run
+ about 1 run every 2-3 years

→ Small probability to have a triple detection of a galactic CCSNe

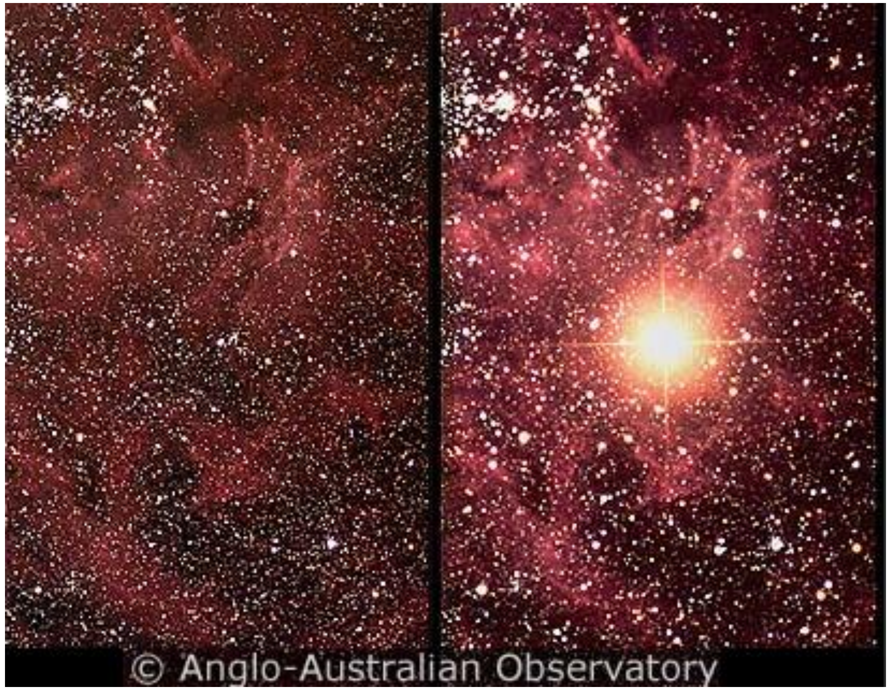


CCSNe rate

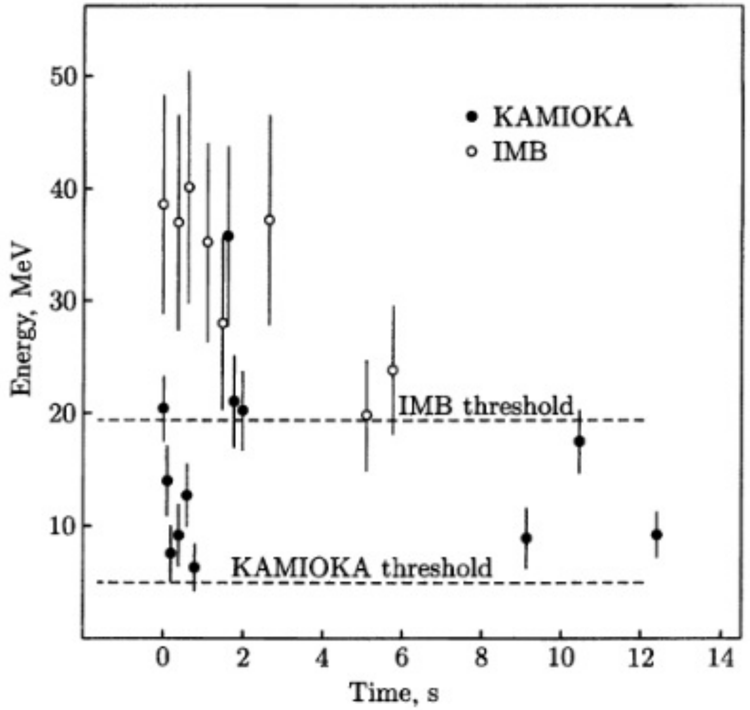
Elridge et al, Mon.Not.Roy.Astron.Soc. 482 (2019) no.1, 870-880
https://arxiv.org/abs/1807.07659

Typical multi-messenger detection

Neutrino and optical counterparts are guaranteed
and could help in understanding the physics of CCSNe behind the GW waveform



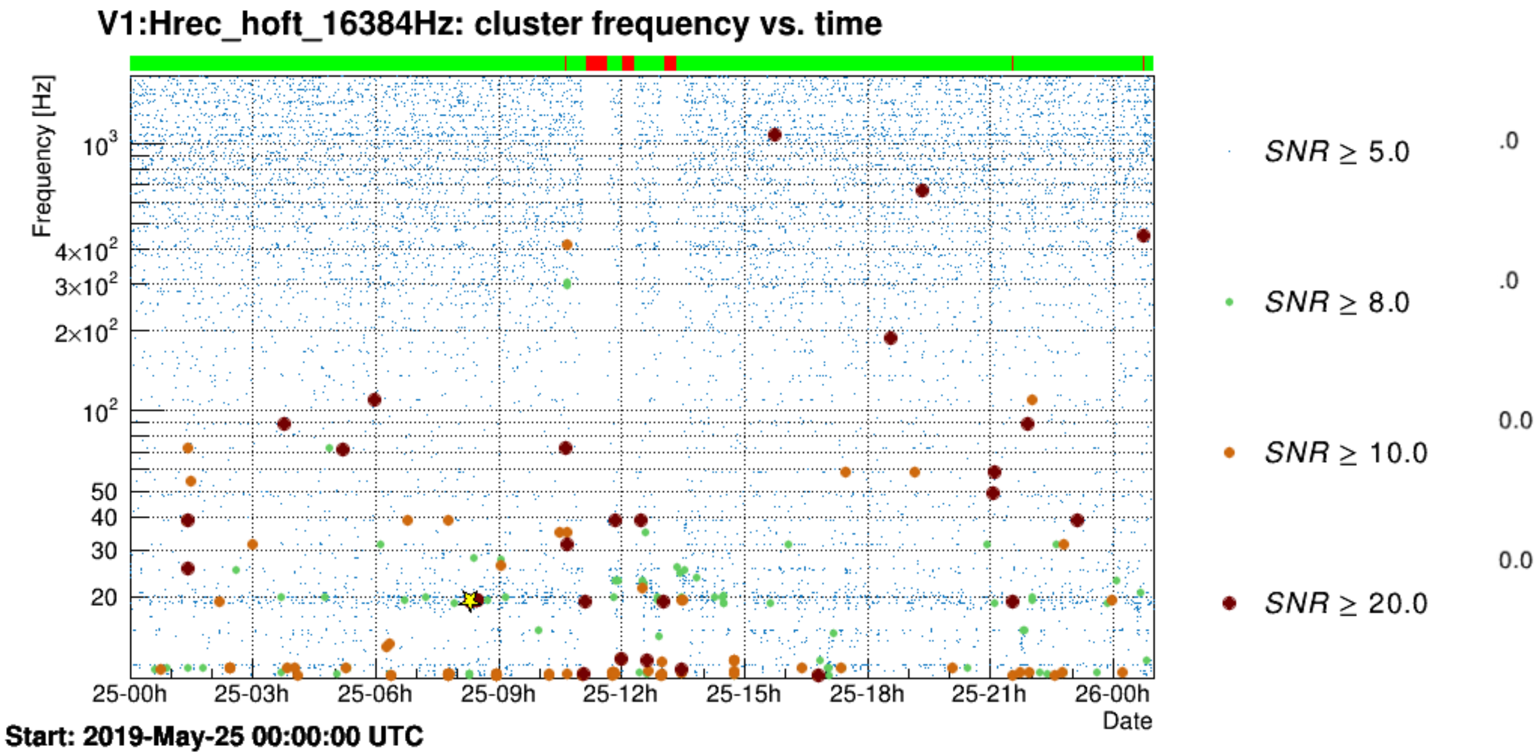
Feb 23rd 1987



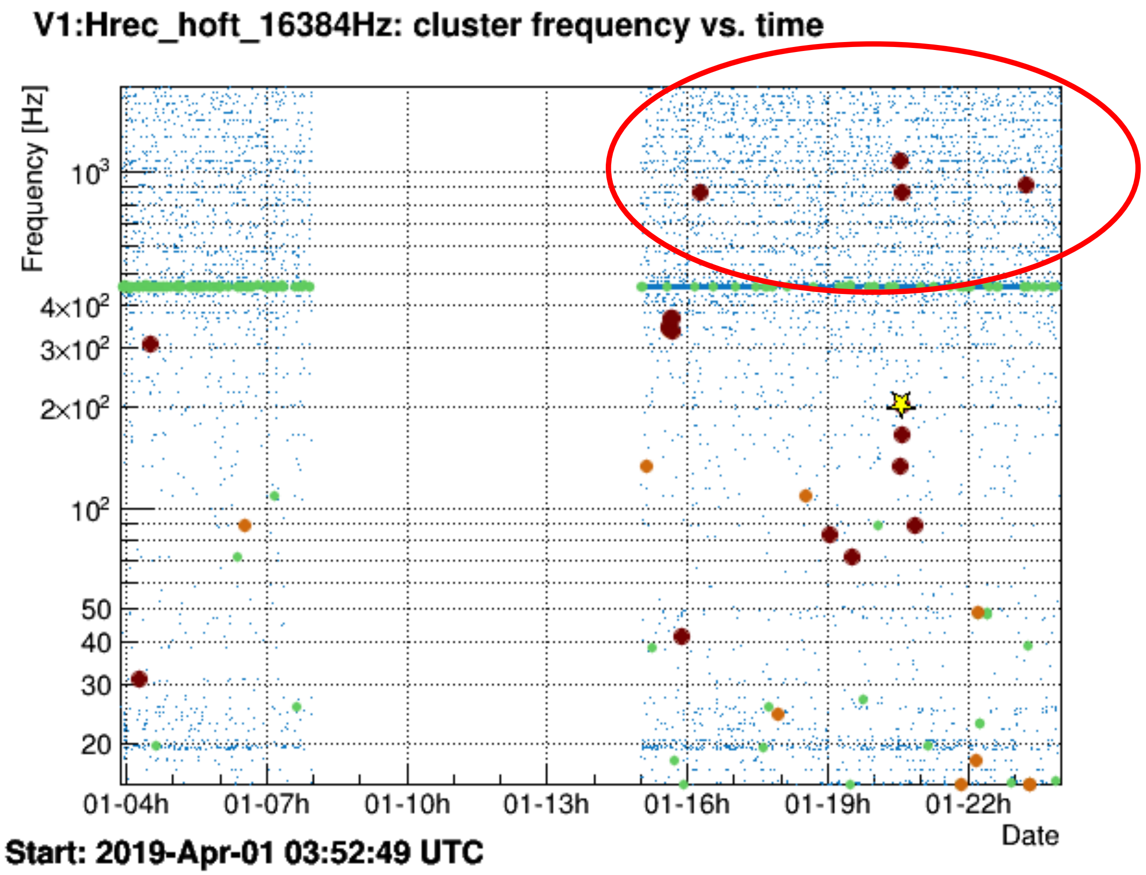
Clean frequency-band detection

CCSNe are expected in the upper frequency band (> 500 Hz) where
- glitchiness is much lower
- calibration uncertainties may be better under control

Omicron triggers
1 detector

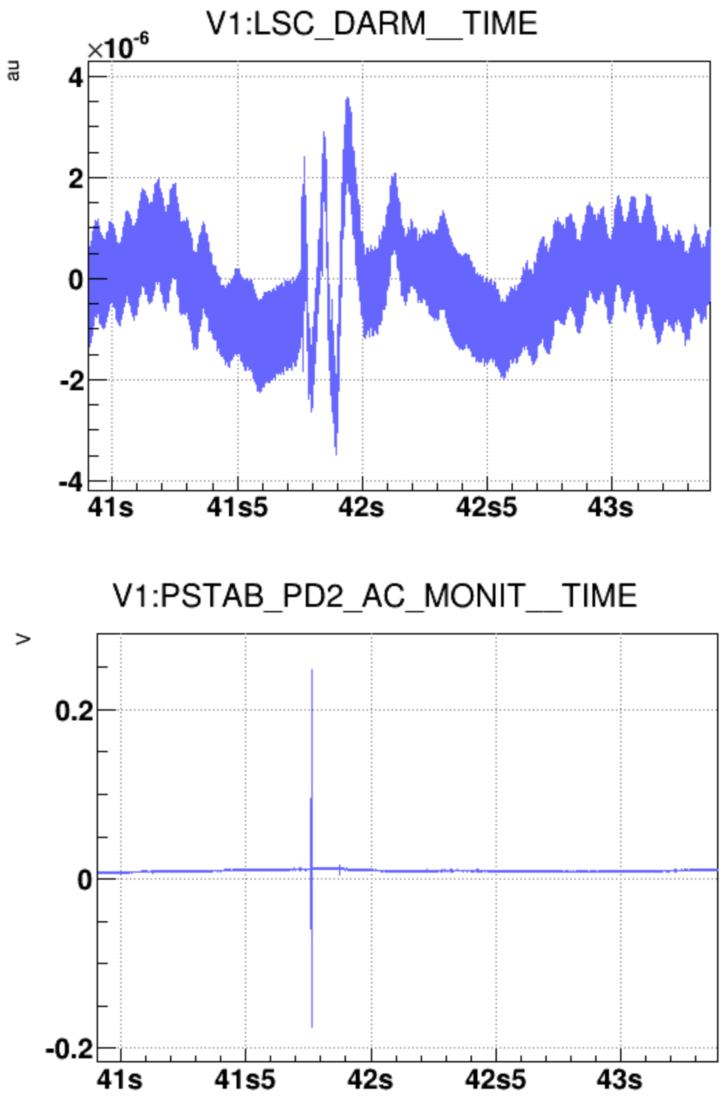


Rogue transient noises

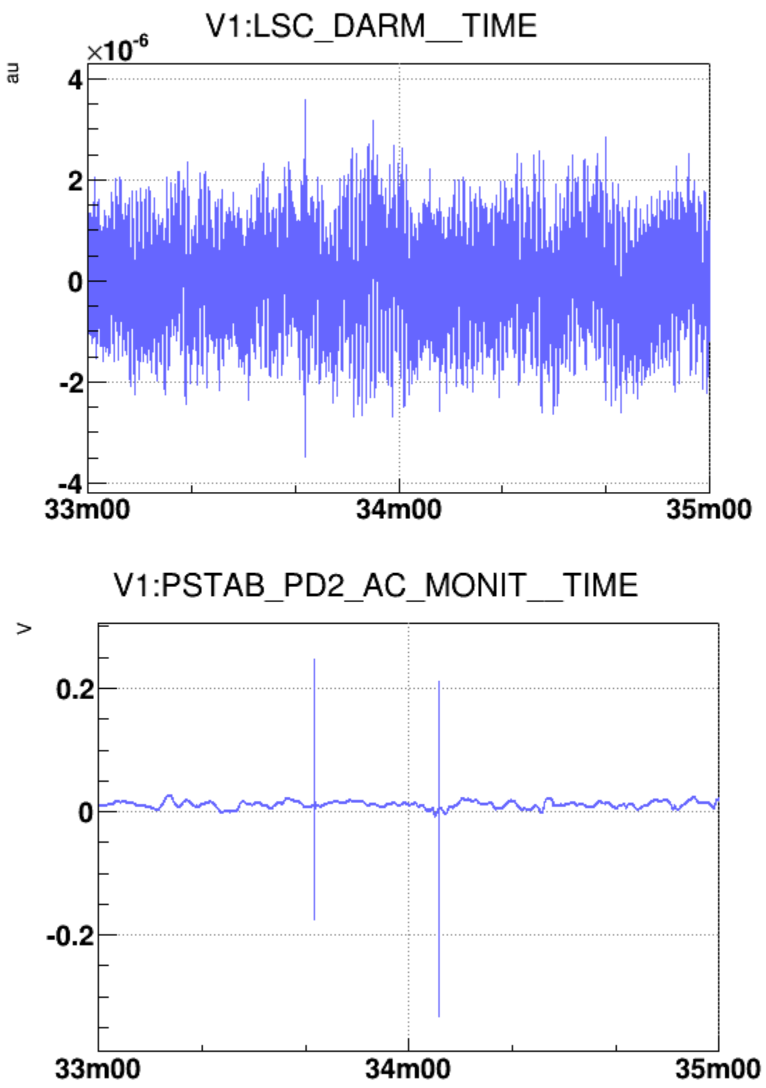


Some transient noises have no evident origin and no veto:
sparse in time
not always at the same frequency
just look like a glitch « family »

Rogue transient noises

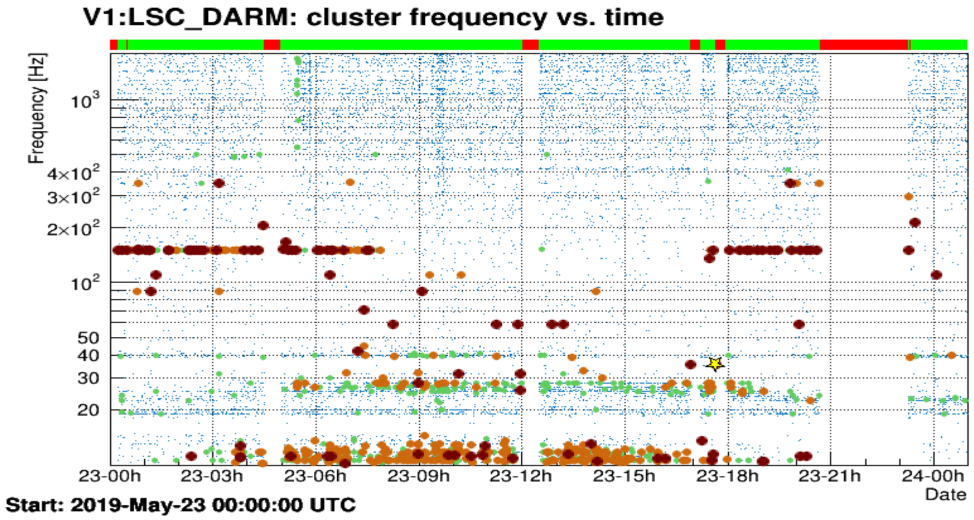


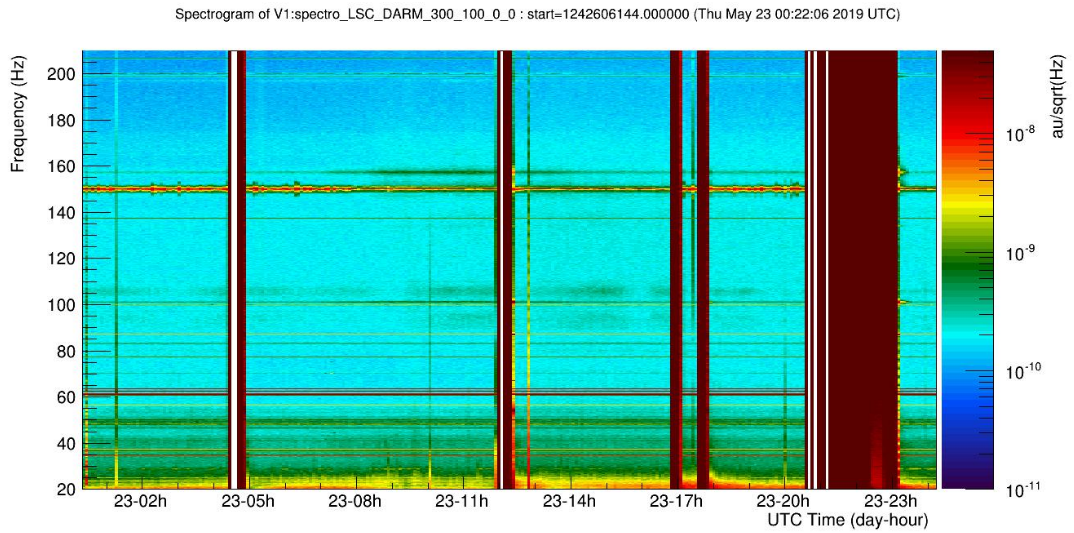
1238186038.9067 : Apr 1 2019 20:33:40 UTC



1238185998.0000 : Apr 1 2019 20:33:00 UTC

Nice transient noises

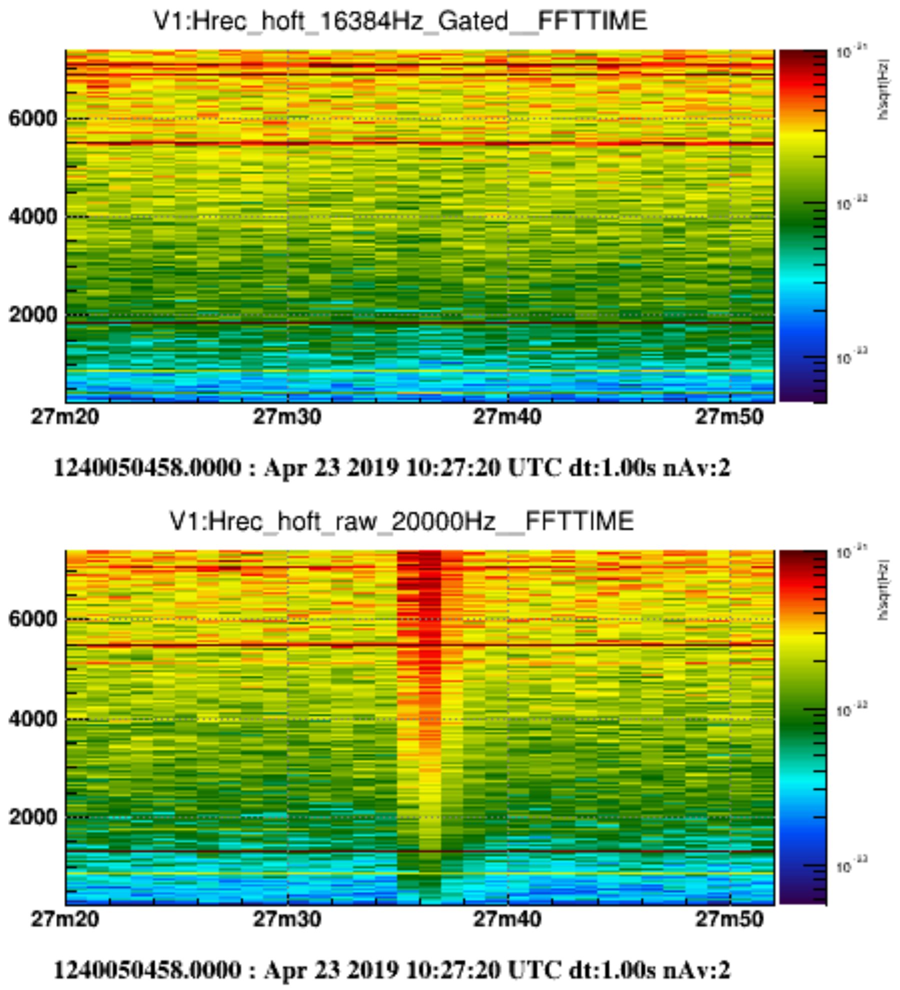




Some transient noises can be vetoed even without vetoes:

- frequent in time
- always same signature
- always same frequency

Nice transient noises



Some transient noises can be vetoed by a gating:

- Large frequency band
- high SNR

Conclusion

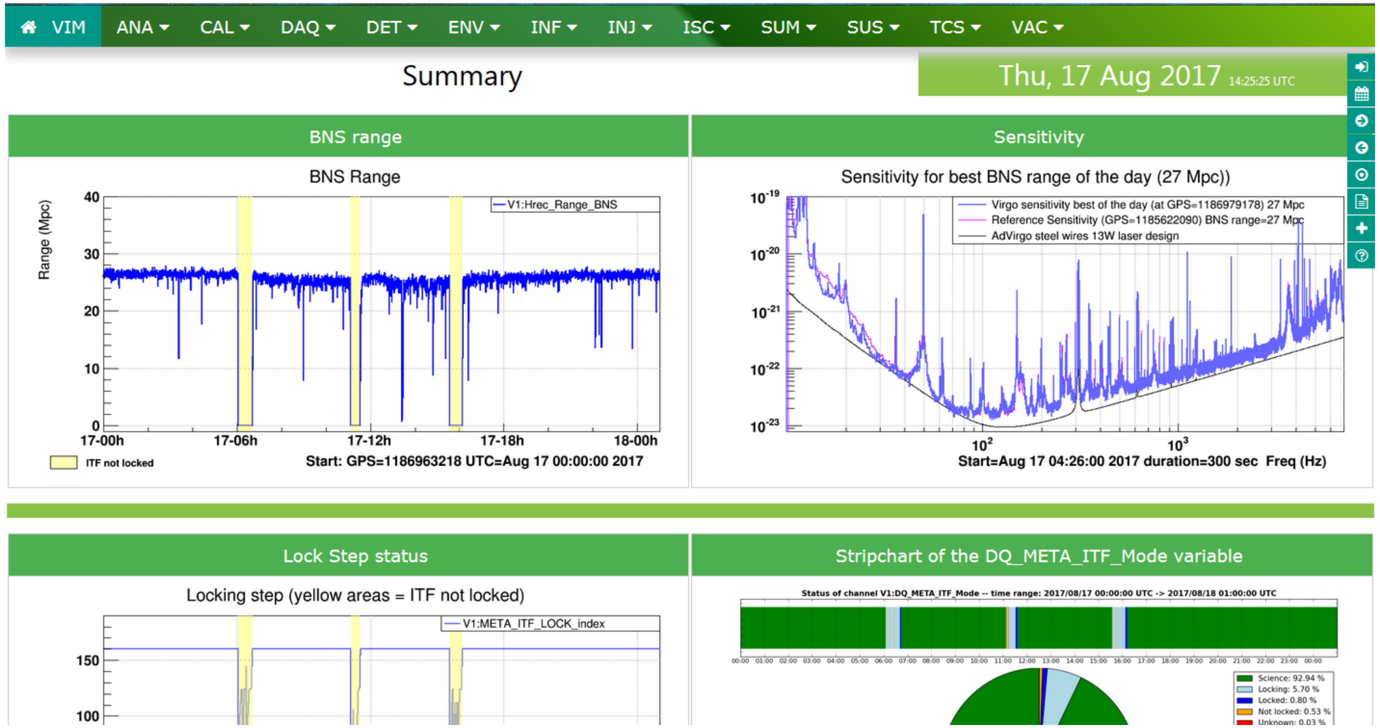
- Galactic CCSNe are rare detectable events (only one in our life!)

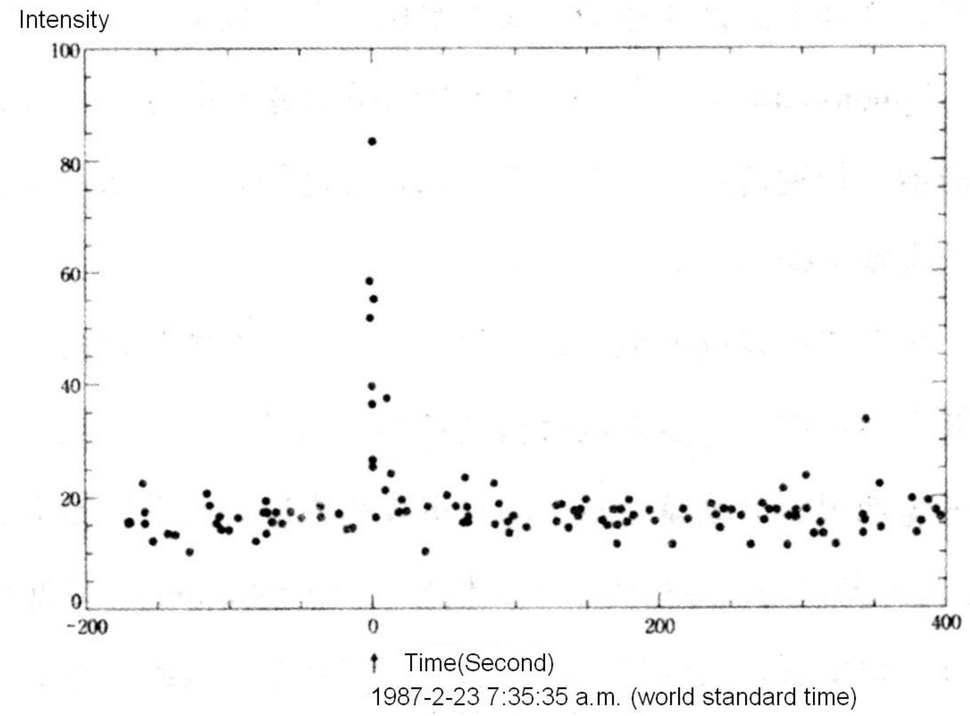
→ We push for sensitivity improvements and low glitchiness. We should push also for high duty cycle

- Even if detected, studying their physics still requires a large effort of modelisation

- Transient noises hunting is a permanent effort in order to not miss THE galactic CCSNe GW detection

END


VIM
ANA
CAL
DAQ
DET
ENV
INF
INJ
ISC
SUM
SUS
TCS
VAC
Summary
Thu, 17 Aug 2017 14:25:25 UTC
BNS range
BNS Range
Range (Mpc)
V1:Hrec_Range_BNS
17-00h
17-06h
17-12h
17-18h
18-00h
ITF not locked
Start: GPS=1186963218 UTC=Aug 17 00:00:00 2017
Sensitivity
Sensitivity for best BNS range of the day (27 Mpc))
Virgo sensitivity best of the day (at GPS=1186979178) 27 Mpc
Reference Sensitivity (GPS=1185622090) BNS range=27 Mpc
AdVirgo steel wires 13W laser design
Start=Aug 17 04:26:00 2017 duration=300 sec Freq (Hz)
Lock Step status
Locking step (yellow areas = ITF not locked)
V1:META_ITF_LOCK_index
Stripchart of the DQ_META_ITF_Mode variable
Status of channel V1:DQ_META_ITF_Mode -- time range: 2017/08/17 00:00:00 UTC -> 2017/08/18 01:00:00 UTC
Science: 92.94 %
Locking: 5.70 %
Locked: 0.80 %
Not locked: 0.53 %
Unknown: 0.03 %


Intensity
Time(Second)
1987-2-23 7:35:35 a.m. (world standard time)

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MM input for Continuous Waves searches

Cristiano Palomba – INFN Roma

- **It is well known that MM observations of neutron stars help CW searches**. E.g.:

pulsar ephemeris → targeted/narrow-band searches

SN remnant/CCO position → directed searches

BNS merger → (very) long-transient searches

- The relation can become bi-directional. E.g:

CW detection in all-sky or galactic center search will trigger the search for an EM counterpart

- **Future observations/facilities (and modelling) may prove crucial to increase the chance of detection of CWs and to infer NS properties.**

Two examples follow

Restrict parameter space for long-transient searches of long-lived newborn NSs

- initial spin frequency, braking index, early time evolution, signal duration,…
  - Make more sensitive searches → increase the distance reach (but robustness is an issue as well → DAC discussion)
- X-ray light curve shallow decay and/or plateau in GRBs are interpreted as due to the formation of a long-lived magnetars [e.g. Rowlinson+, MNRAS 430, 1061 (2013)]

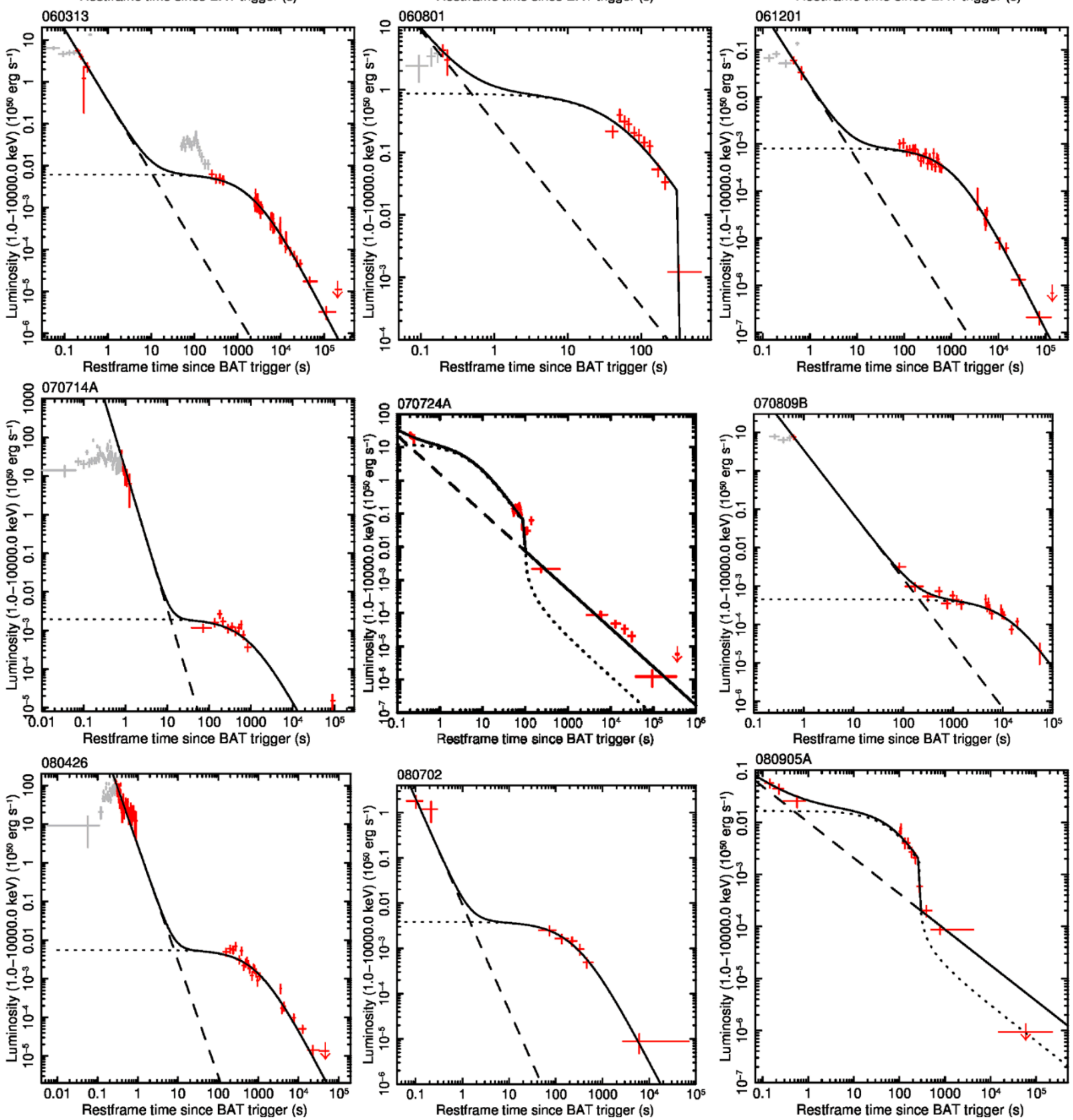


Figure 8. SGRB BAT–XRT rest-frame light curves fitted with the magnetar model. The light grey data points have been excluded from the fit. The dashed line shows the power-law component and the dotted line shows the magnetar component.

Rowlinson+, MNRAS 430, 1061 (2013)

- GW emission on timescales of 10^3-10^5 s due to EM field – induced distortion, bar-mode or r-mode excitation [e.g Corsi & Mézsáros 2009, Sarin+ 2018, Dall'Osso, Stella & CP 2018]

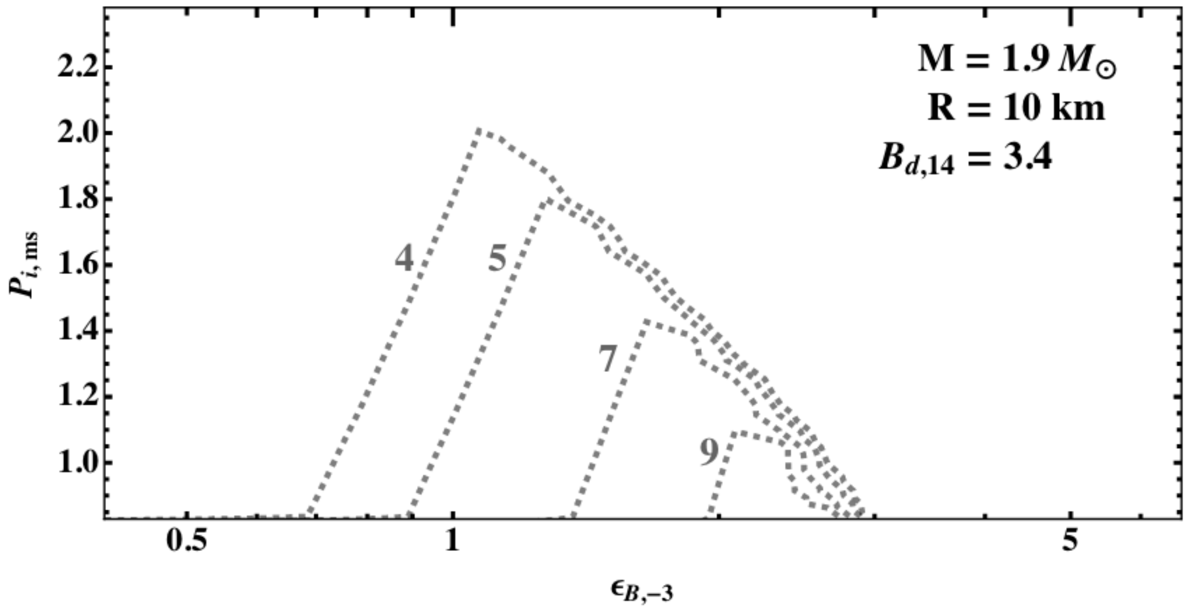


Figure 4. The orientation- and position-averaged S/N of a new-born magnetar at 20 Mpc, for EoS *II* and a single-detector matched-filter search, as a function of P_{ms} and ϵ_B. Signals are

ALIGO sensitivity, assuming **matched filtering**

Dall'Osso, Stella, CP, MNRAS 480, 1353 (2018)

➢ Use EM observations to constrain magnetar parameters

$$L(t) = L_0 \left(1 + \frac{t}{\tau}\right)^{\frac{1+n}{1-n}} .$$

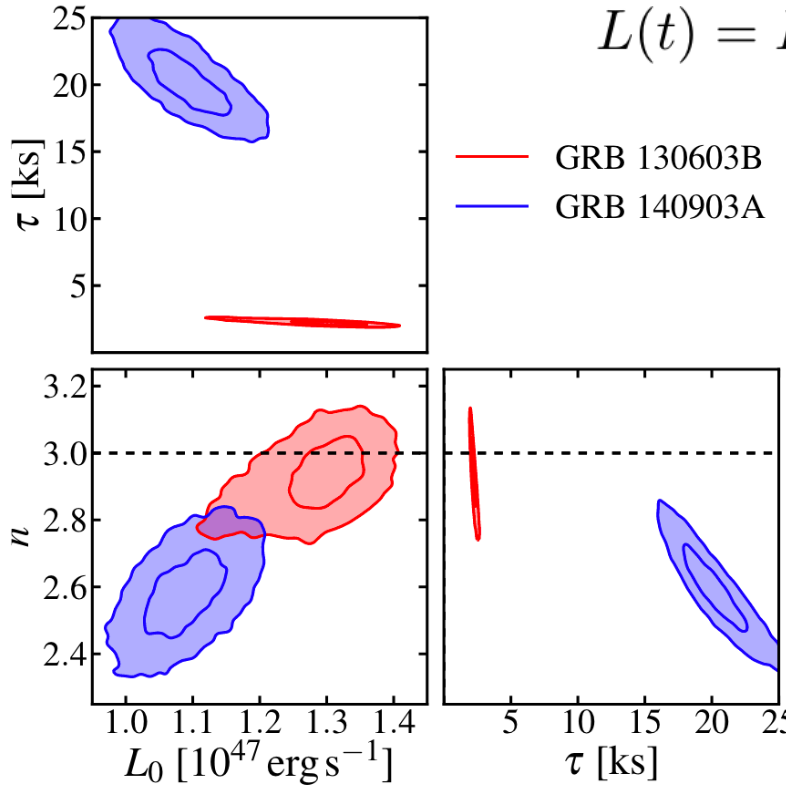


FIG. 2.— Posterior probability distributions for the parameters in Eq. (2) for GRB 130603B (red) and GRB 140903A (blue). The contours show the one- and two-sigma confidence intervals, and the dashed line indicates the fiducial value of $n = 3$.

Lasky+, ApJL 843, 1, 2017

- Model uncertainties
- Early times evolution difficult to infer

Measuring NS moment of inertia with pulsar's CW emission

- Given a NS which evolution is dominated by GW emission (a *gravitar*): $h_0 \sim h_{sd}$ (spin-down limit)

$$I_{zz} = \frac{2}{5}\frac{c^3}{G}\frac{f}{|\dot{f}|}(h_0^{sd})^2 d^2 = 1.54 \cdot 10^{37} \left(\frac{f}{100\,\mathrm{Hz}}\right)\left(\frac{|\dot{f}|}{10^{-11}\,\mathrm{Hz\,s^{-1}}}\right)^{-1}\left(\frac{h_0^{sd}}{10^{-25}}\right)^2\left(\frac{d}{1\,\mathrm{kpc}}\right)^2$$

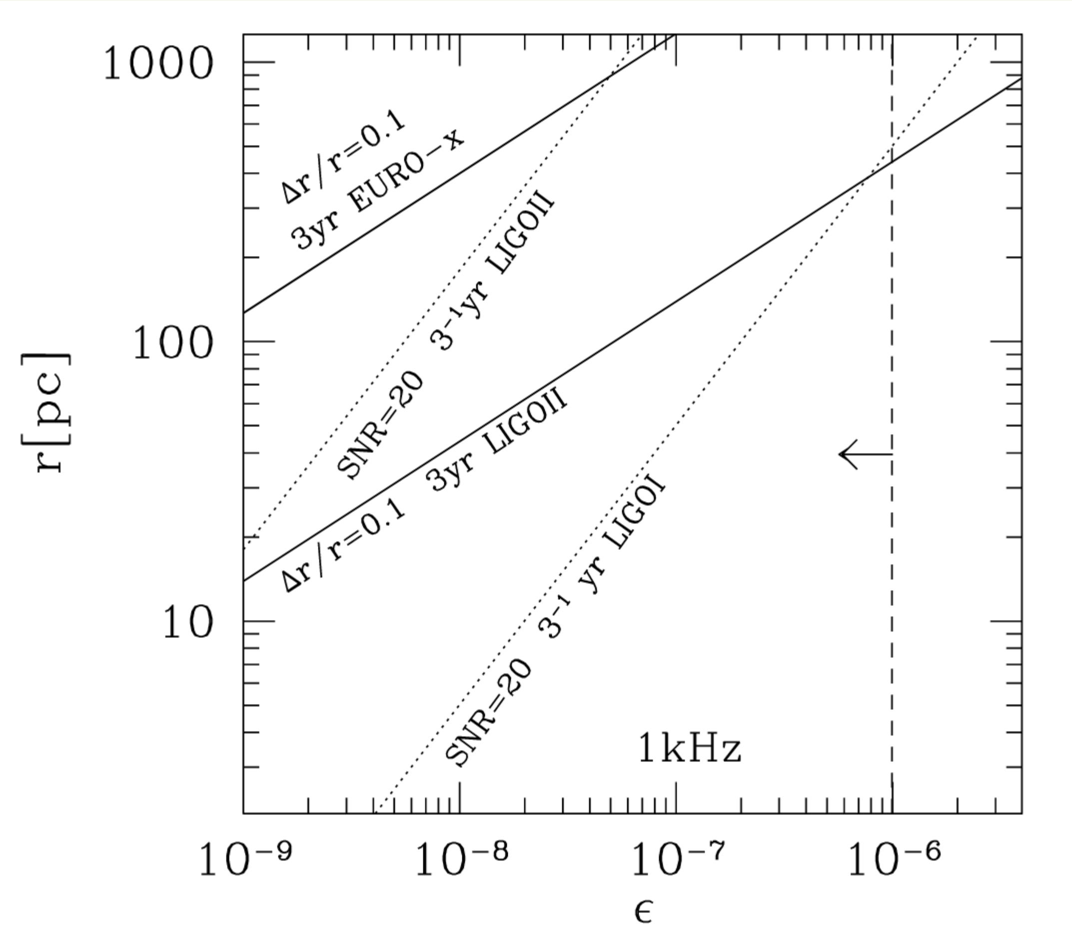
Meaured (with high accuracy) in the analysis

- The accuracy in I_{zz} mainly depends on that on the distance

  → SKA

  → GW wave-front curvature (parallax-induced phase shift)

Lines of constant Dr/r=0.1 [Seto PRD 71, 123003 (2005)



- Best suited for 3G detectors

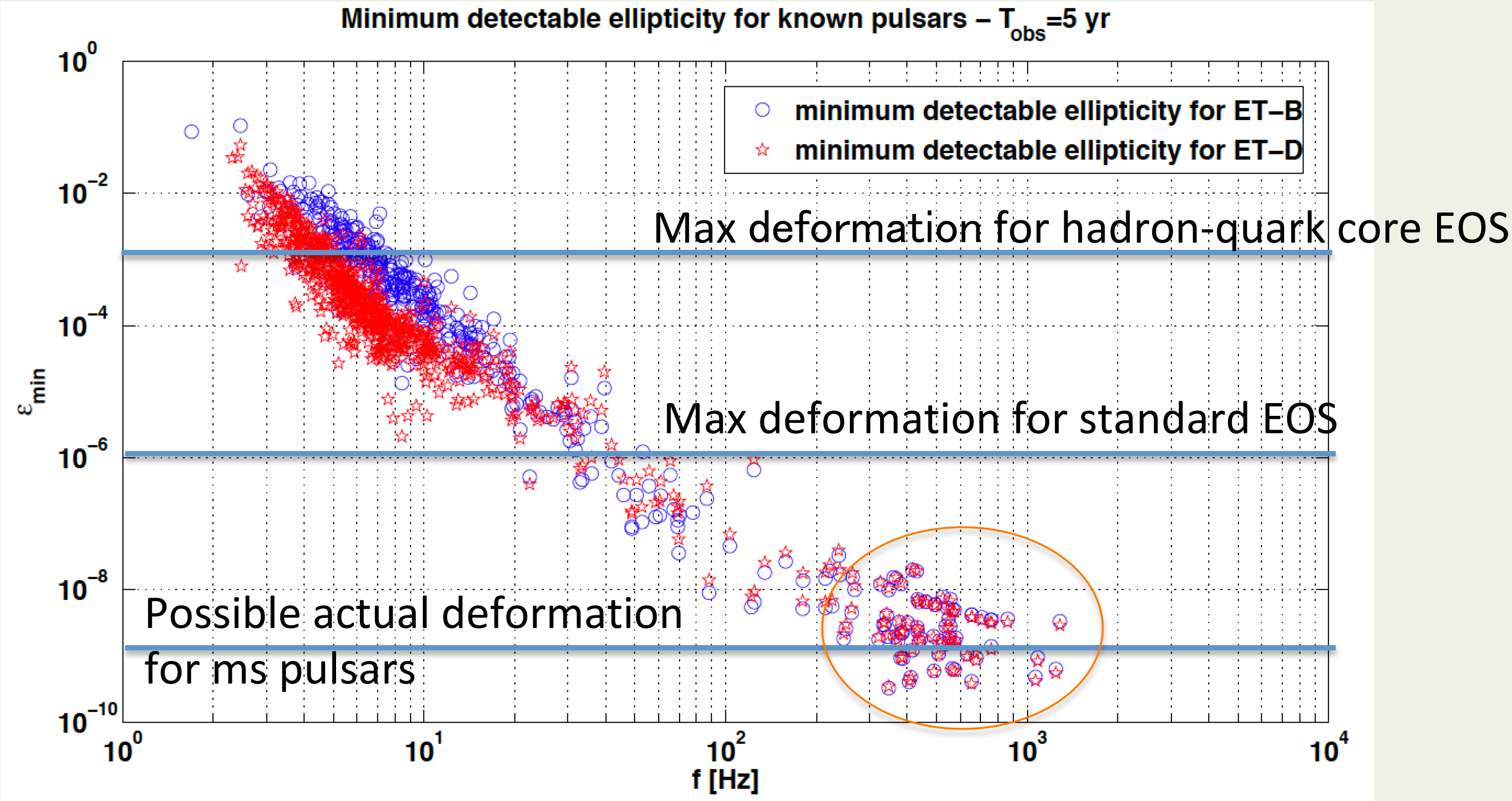
- A potential target: J0437-4715

  $f_{rot} = 173.7$ Hz
  $r = (156 \pm 3)$ pc [Deller+, 2008]

- It could be a ~gravitar [Woan+, ApJL 863, L40 (2018)]
- Also the mass is well known: $(1.76 \pm 0.2) M_{sun}$

  → EOS reconstruction [CP+, in prep.]

- Competitive with NICER's measures of M and R (based on X-ray pulse profile modelling), but less model dependent



- DAC discussion for more details