THESEUS IN THE ERA OF MULTI-MESSENGER ASTRONOMY

G. Stratta

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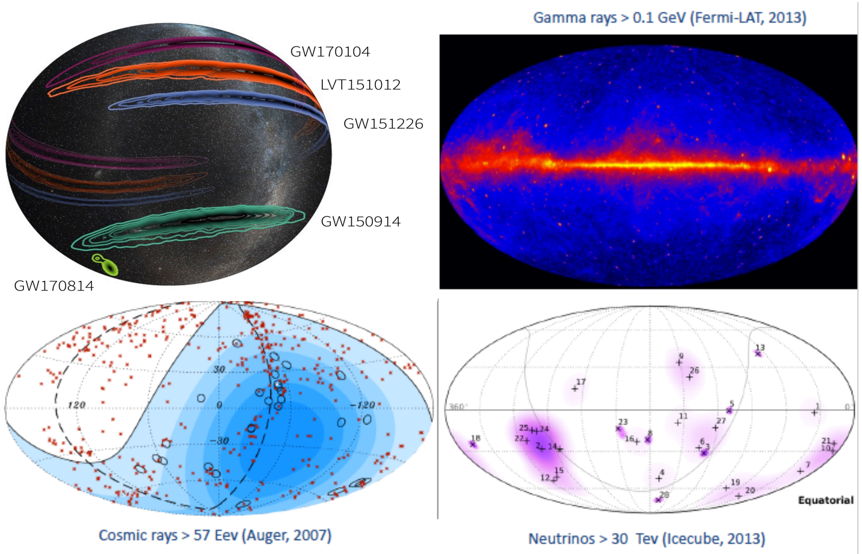


THESEUS WORKSHOP, NAPOLI (ITALY), 5-6 Oct 2017

Outline

- Overview of neutrino and gravitational wave (GW) detectors during ‘20s and ‘30s
- Promising multi-messenger sources for THESEUS
- The case of NS-NS mergers: expected THESEUS detection rates
- Conclusions

Multi-messenger observations

Two main goals of multimessenger observations are:

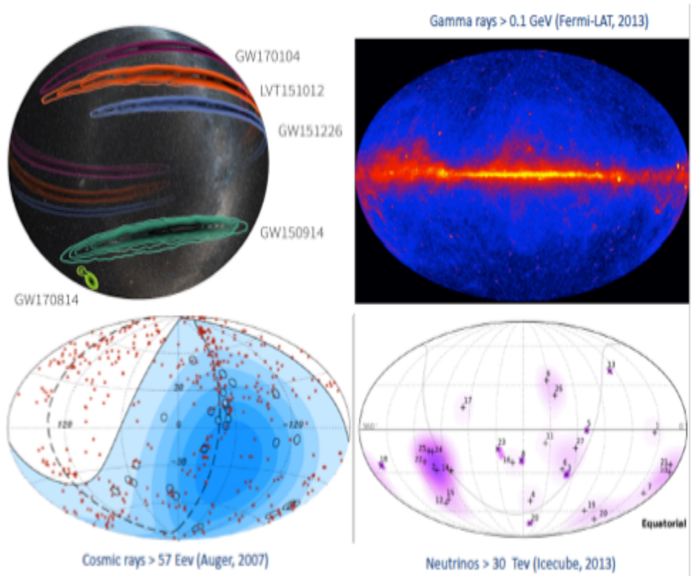
- **to provide a more complete phenomenological picture of several astrophysical phenomena by combining information from different probes**

E.g. for GRBs only:

- short Gamma Ray Burst **progenitors** (→ see D'Avanzo talk)
- From HE neutrino detection/not detection → hints on physics of **the prompt emission**
- From GW polarization → orbital plane inclination → hints **on jet opening angle → accurate energy estimates**
- From GW luminosity distance + EM cosmological redshift → **constrain cosmological parameters**

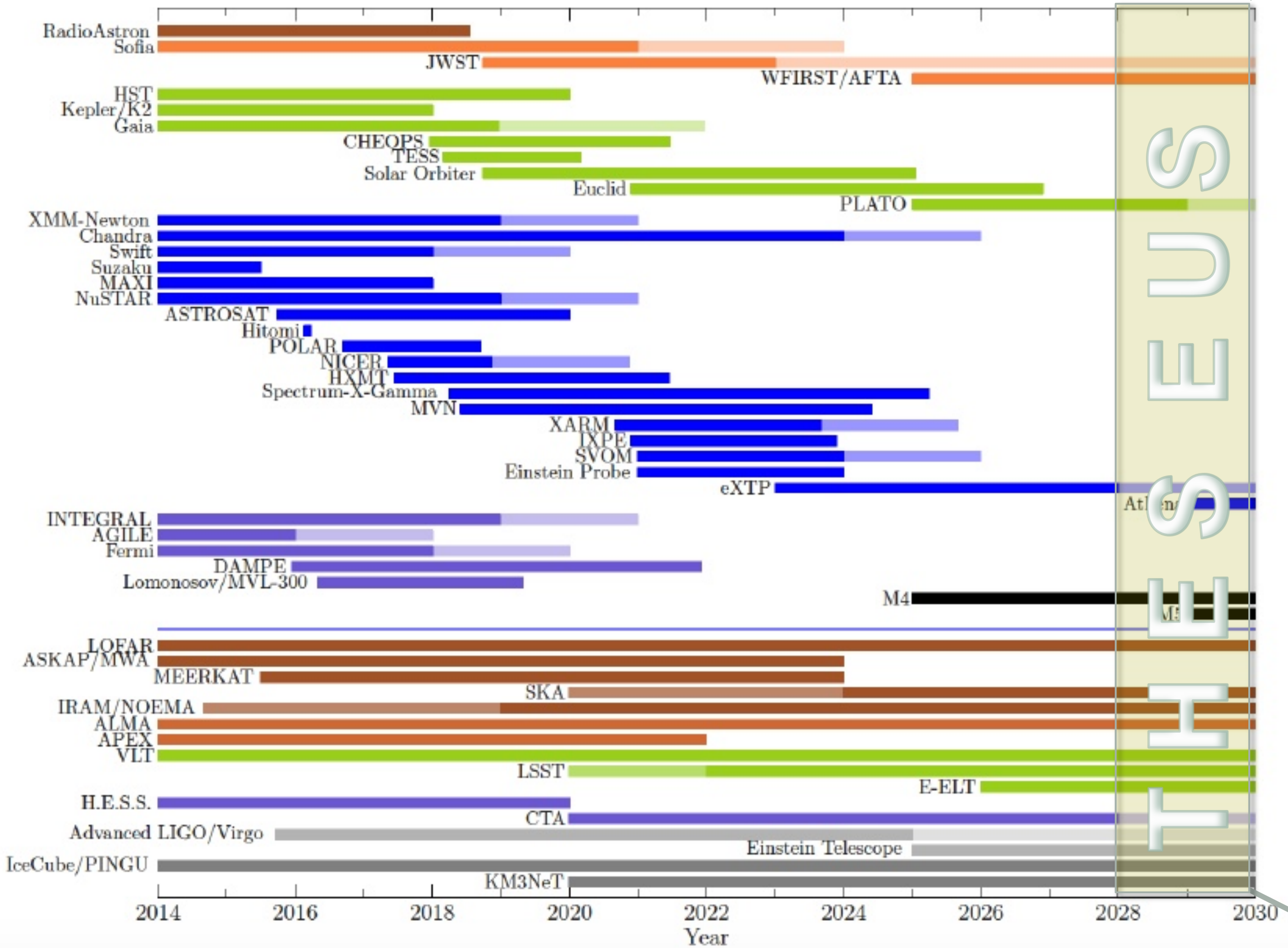
- **to increase the search sensitivity available by using just a single messenger**

  - Low SNR GW event searches can use neutrino and/or EM detection epoch/sky position as priors in data anlysis



The multi-messenger sky

Golden era of multi-messenger astronomy



2028+

JWST
WFIRST

eXTP*
ATHENA*

SKA*

E-ELT*

CTA*

2G and 3G GW detectors

IceCubeGen2
+
KM3Net

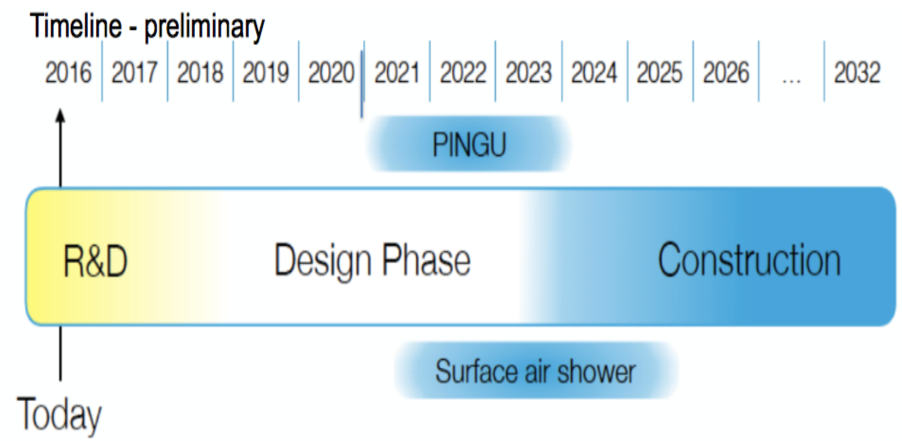
Neutrino detectors

During the '20s, km3 detectors in both emispheres:

- **IceCube** - km^3 facility in the South Pole
- **ANTARES** in the Mediterrean Sea
- **KM3Net** in the Mediterrean Sea (construction started by 2015)
- **Lake Baikal Neutrino Telescope GVD** (upgrading to km3)

During the '30s, 10 km3 detectors as IceCubeGen2 will collect high-statistics sample of HE neutrinos (arXiv:1412.5106)

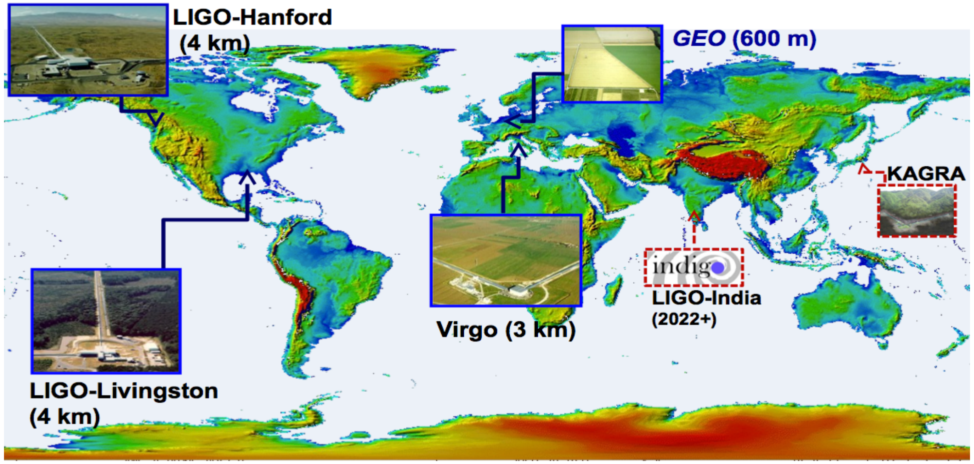
IceCubeGen2 construction timeline



Gravitational Wave detectors

2025+: network of 2G completed

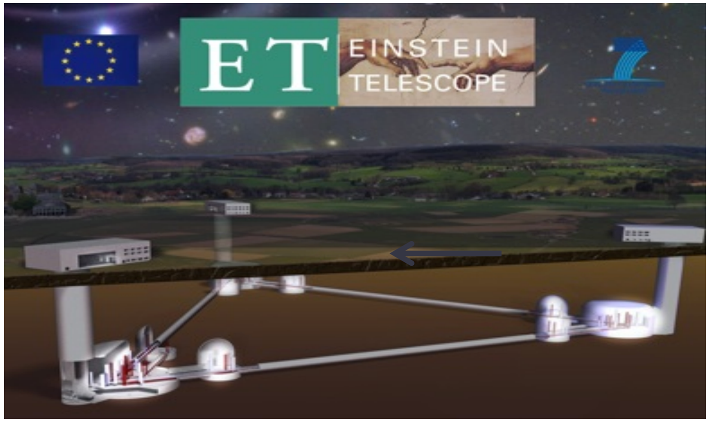
- 2 Advanced LIGO (H+L, USA)
- Advanced Virgo (Italy)
- LIGO-India
- Kagra (Japan)



2030+: 3G (**Einstein Telescope, Cosmic Explorer**):

~10 times more sensitive --> GW sources 10 times more distant!

(e.g. Sathyaprakash 2015)



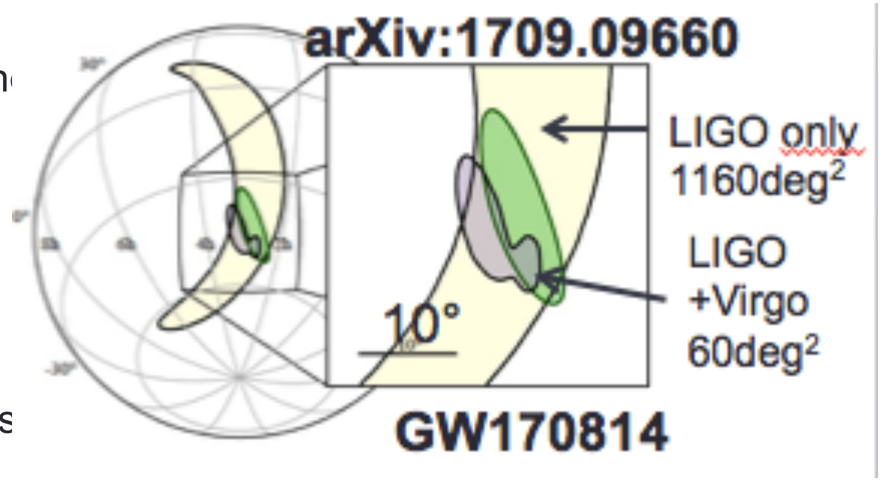
Source sky localization

GW detectors sky localization
triangulation methods → strongly depends on th number of detectors (with similar sensitivity) observing simultaneously (duty cycle 80% each) (Abbott+2016 LLR,1)**.**

- For example: GW170814
  - ~1160 deg2 with 2 detectors
  - ~60 deg2 with 3 detectors

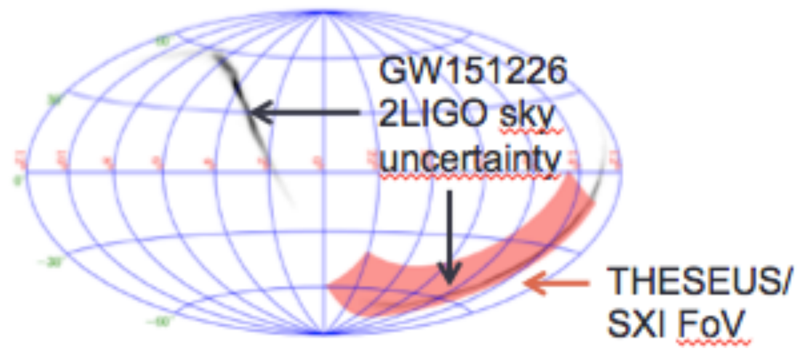
- Even with full 2G detector network, uncertainties will not be less than **few square degrees**

- **3G detectors may be just one or two → uncertainties of the order of ~100-1000 deg2**

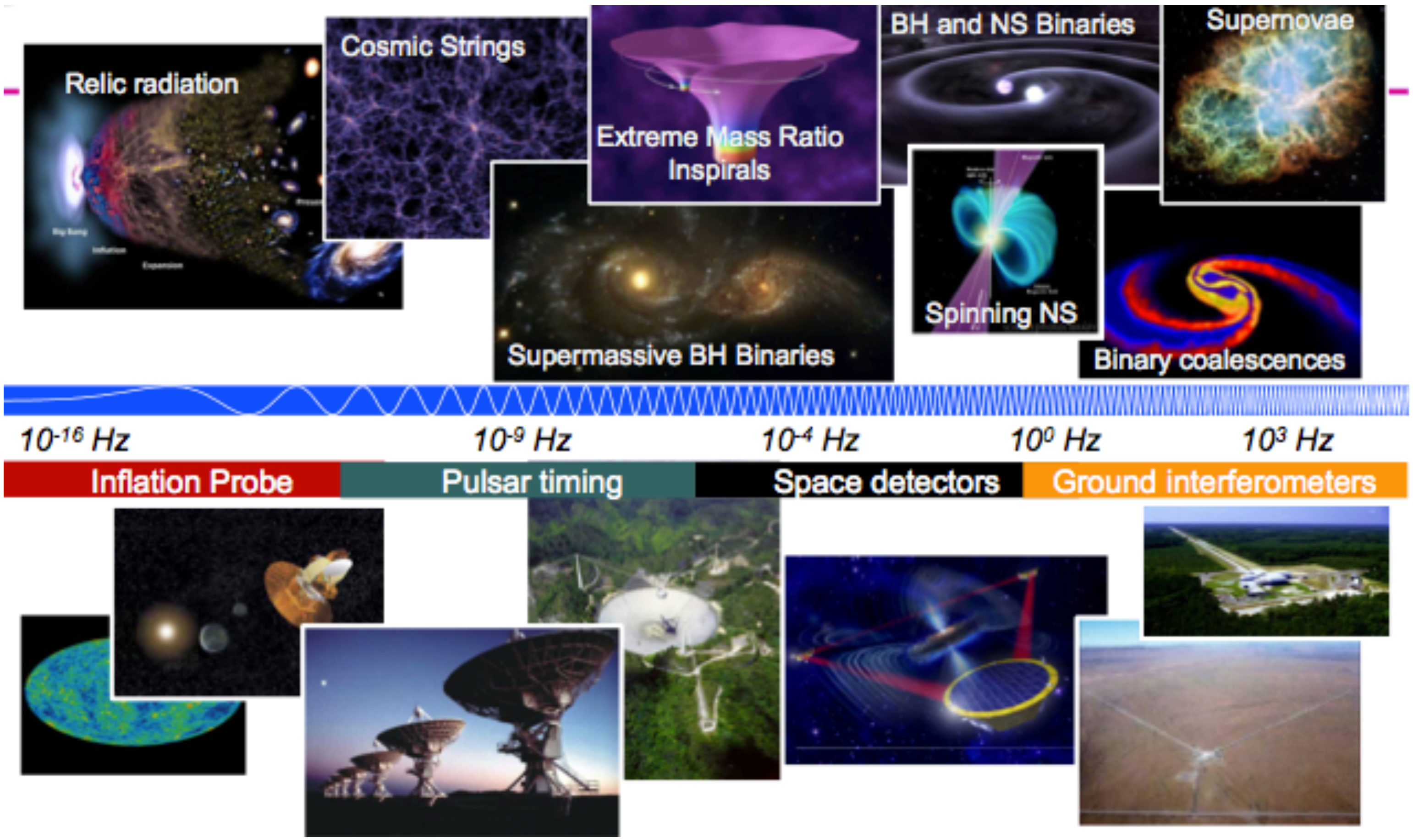


Neutrino detector sky localization uncertainty:
~ 1° or less

→ Survey EM telescopes as THESEUS will play a crucial role in accurately localize MM sources down to arcmin/arcsec level, thus enabling multi-band follow up campaign with ground-based telescopes

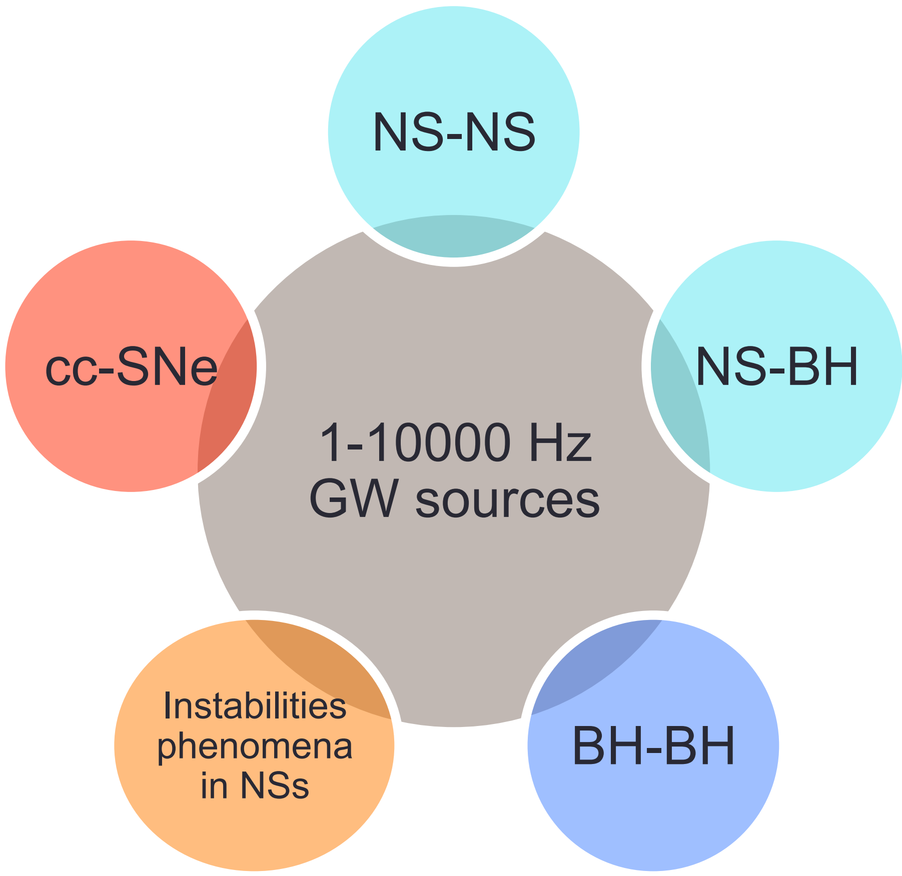


GW sources in the THESEUS era



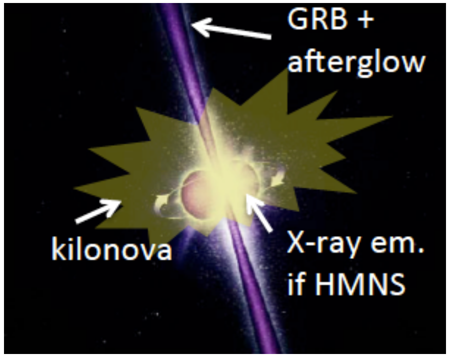
Credit: A. Weinstein

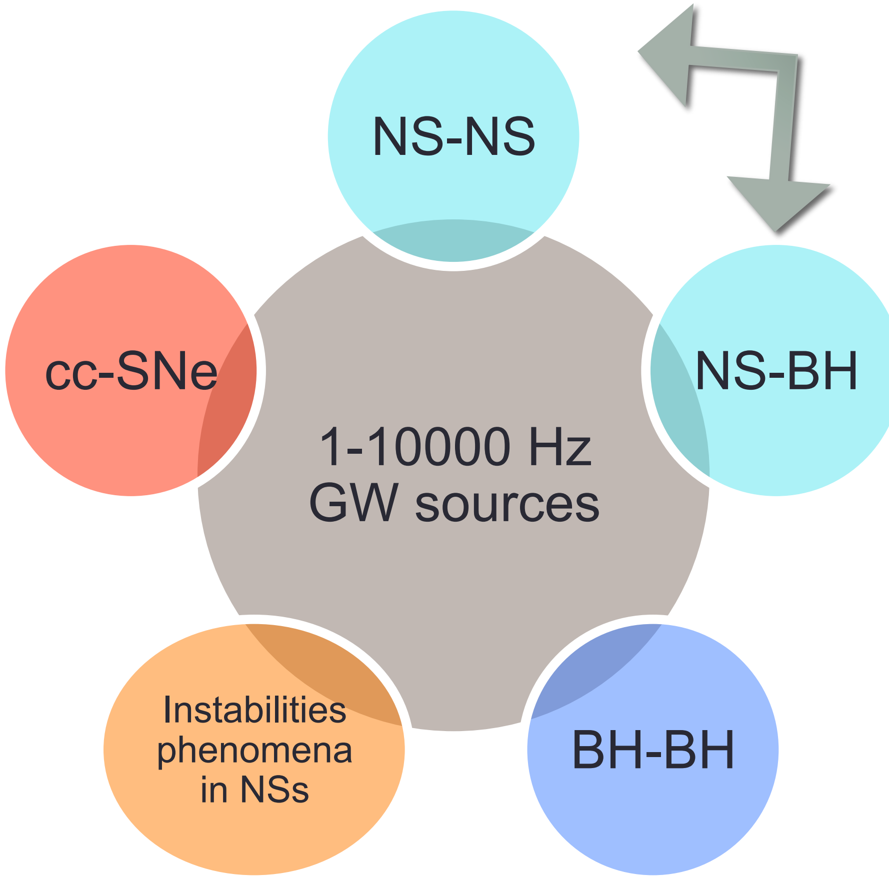
GW sources in the THESEUS era



...are MM sources!

- Collimated short GRBs
- isotropic X-ray emission
- isotropic kilonova + radio delayed emission
- Neutrinos?





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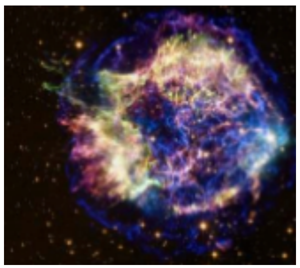
- Collimated long GRBs
- X-ray shock breakout
- Type II, Ibc SNe
- Neutrinos



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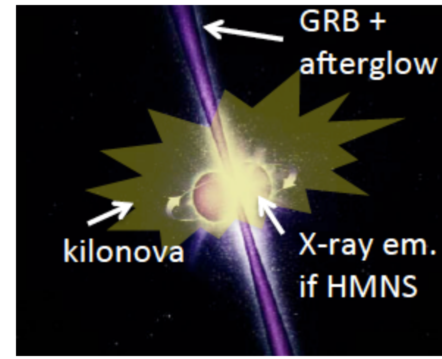

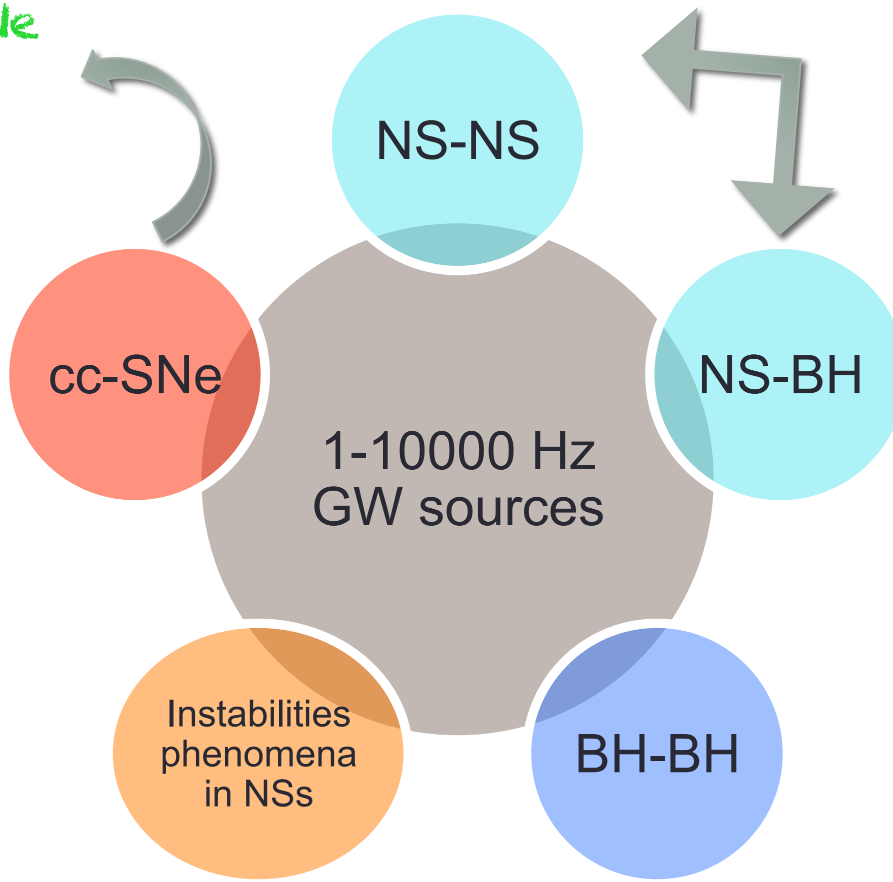

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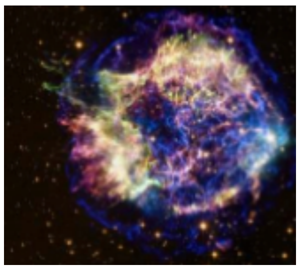
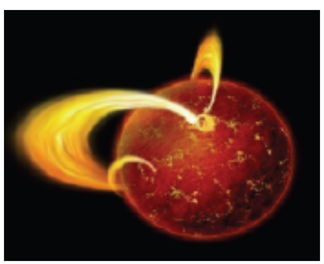
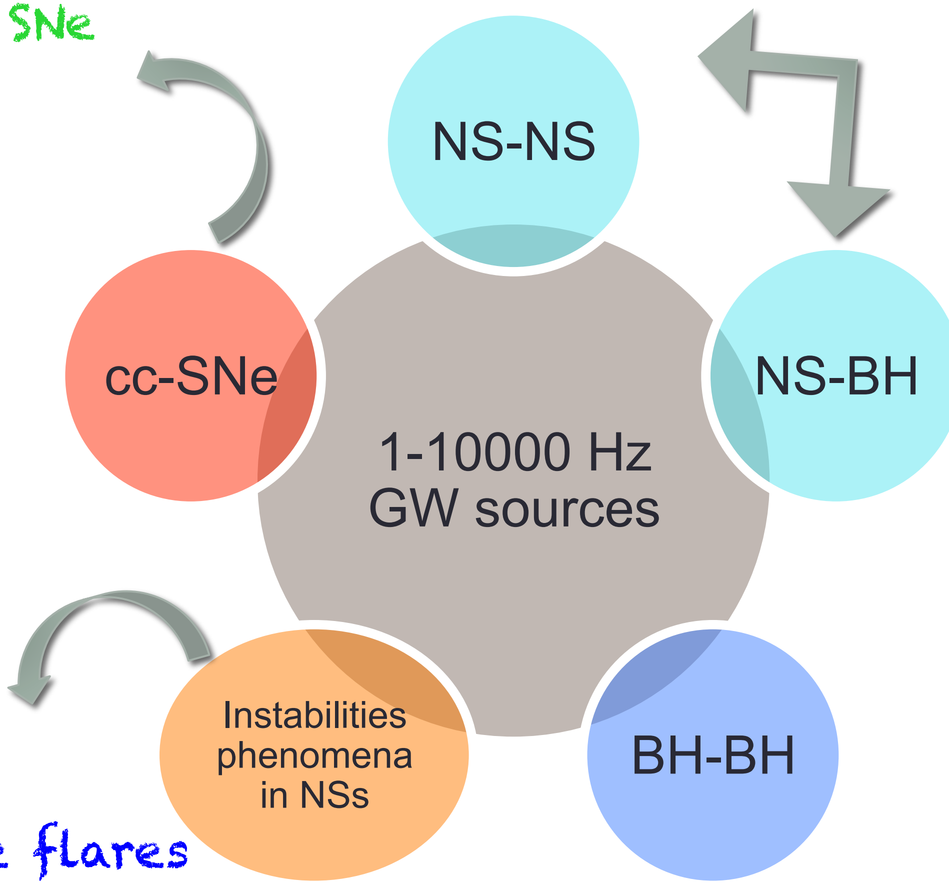




- SGRs/giant+ intermediate flares
- Neutrinos?



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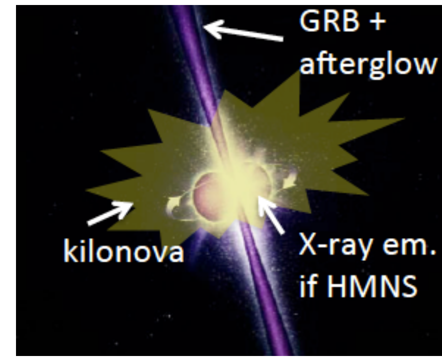

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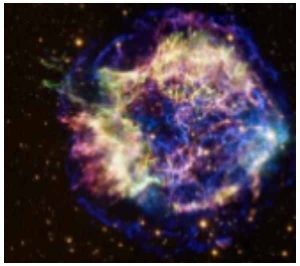

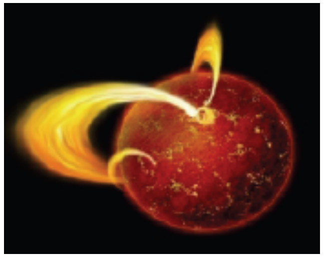

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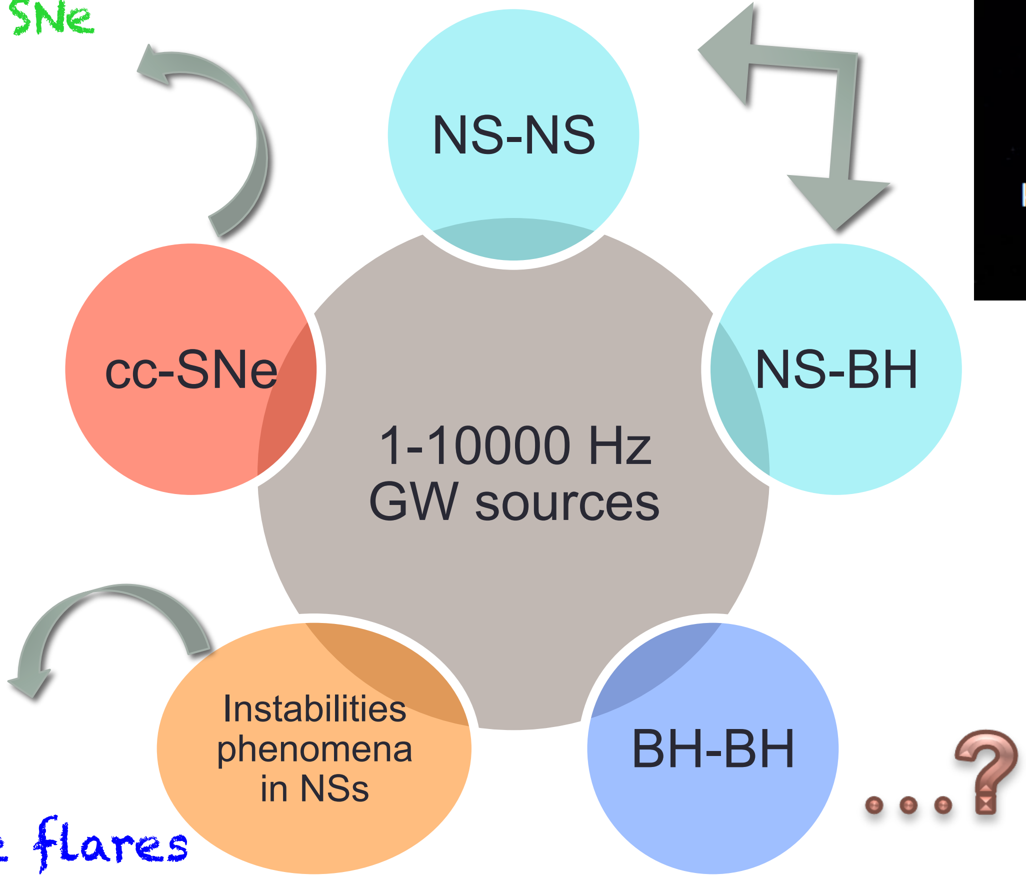

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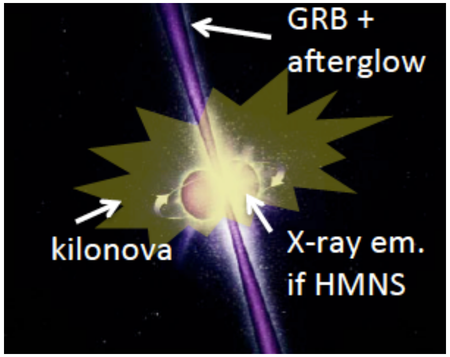

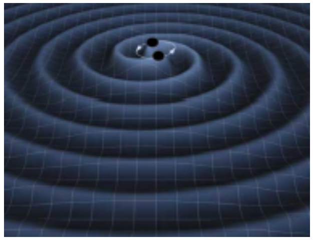

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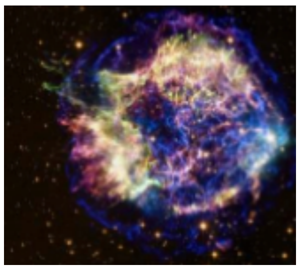

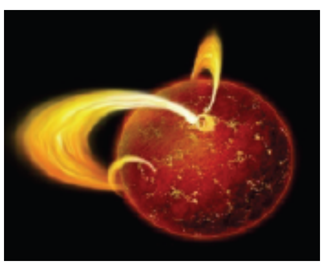

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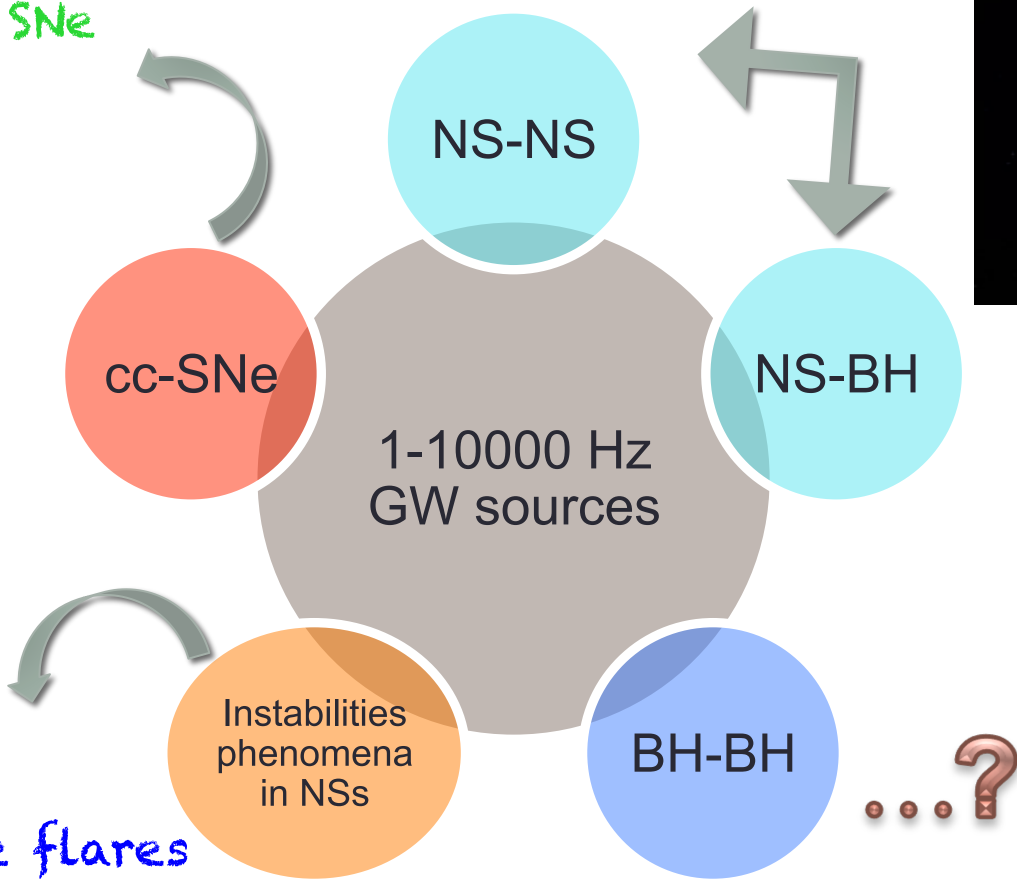

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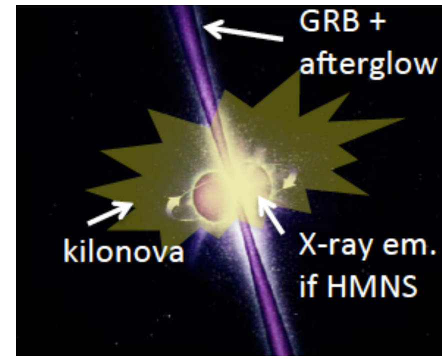
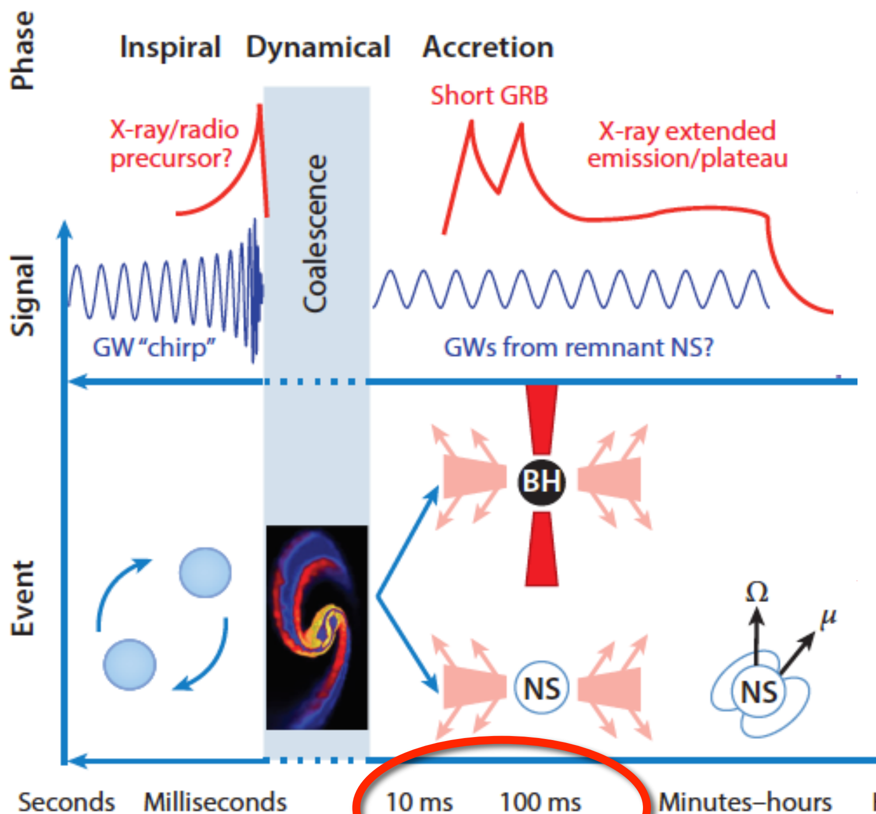
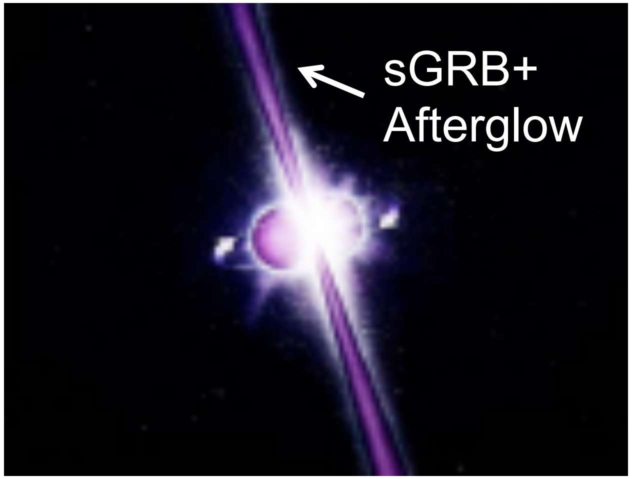


Short GRBs from NS-NS mergers

See D'Avanzo's talk

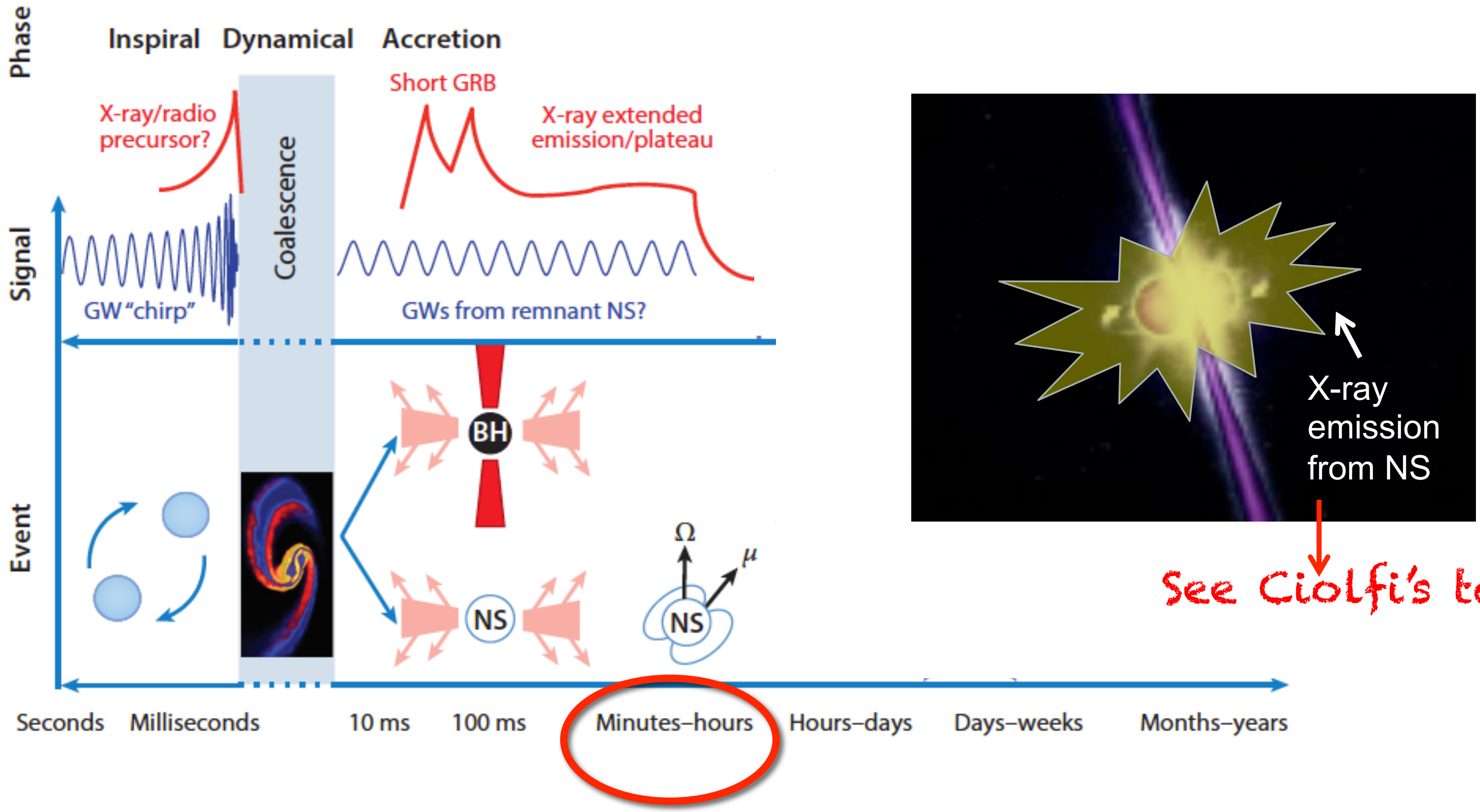




Short GRB duration < 2 sec

From Fernandez & Metzger 2017

X-ray emission from NS-NS mergers



See Ciolfi's talk

From Fernandez & Metzger 2017

X-ray emission peak ~ min/hours

Expected rate of joint **sGRB+GW** detection with THESEUS/XGIS

NS-NS rate

10-10000 $Gpc^{-3}yr^{-1}$

Abadie et al. 2010

Expected rate of joint **sGRB+GW** detection with THESEUS/XGIS

NS-NS rate
10-10000 $Gpc^{-3}yr^{-1}$

Abadie et al. 2010

40/yr
up to 0.4-0.5 Gpc

2G GW detectors

Expected rate of joint **sGRB+GW** detection with THESEUS/XGIS

NS-NS rate

10-10000 $Gpc^{-3}yr^{-1}$

Fraction collimated towards us

2G GW detectors

40/yr
up to 0.4-0.5 Gpc

2%-20%
(assuming a half-jet angle θ_{jet}=[10°- 40°], e.g. Rezzolla+2011)

Expected rate of joint **sGRB+GW** detection with THESEUS/XGIS

NS-NS rate 10-10000 $Gpc^{-3}yr^{-1}$	2G GW detectors	**40/yr up to 0.4-0.5 Gpc**
Fraction collimated towards us		**2%-20%** (assuming a half-jet angle θ_{jet}=[10°- 40°], e.g. Rezzolla+2011)
Fraction within XGIS FoV		**FoV_{XGIS} → 50%**
		~[0.5-5]/yr

Expected rate of joint **sGRB+GW** detection with THESEUS/XGIS

NS-NS rate

10-10000 $Gpc^{-3}yr^{-1}$

↓

Fraction collimated towards us

↓

Fraction within XGIS FoV

2G GW detectors

40/yr
up to 0.4-0.5 Gpc

2%-20%
(assuming a half-jet angle θ_{jet}=[10°- 40°], e.g. Rezzolla+2011)

FoV_{XGIS} → 50%

~[0.5-5]/yr

+ off-axis GRB detection !

Expected rate of joint **X-ray+GW** detection with THESEUS/SXI

NS-NS rate

10-10000 $Gpc^{-3}yr^{-1}$

2G GW detectors

40/yr
up to 0.4-0.5 Gpc

Expected rate of joint **X-ray+GW** detection with THESEUS/SXI

NS-NS rate

10-10000 $Gpc^{-3}yr^{-1}$

↓

Fraction with isotropic X-ray emission

2G GW detectors

40/yr
up to 0.4-0.5 Gpc

30%-60%
(see Gao+2016, Piro+2017)

Expected rate of joint **X-ray+GW** detection with THESEUS/SXI

NS-NS rate

10-10000 $Gpc^{-3}yr^{-1}$

↓

Fraction with isotropic X-ray emission

↓

Fraction within SXI FoV + ~60% can be followed up

2G GW detectors

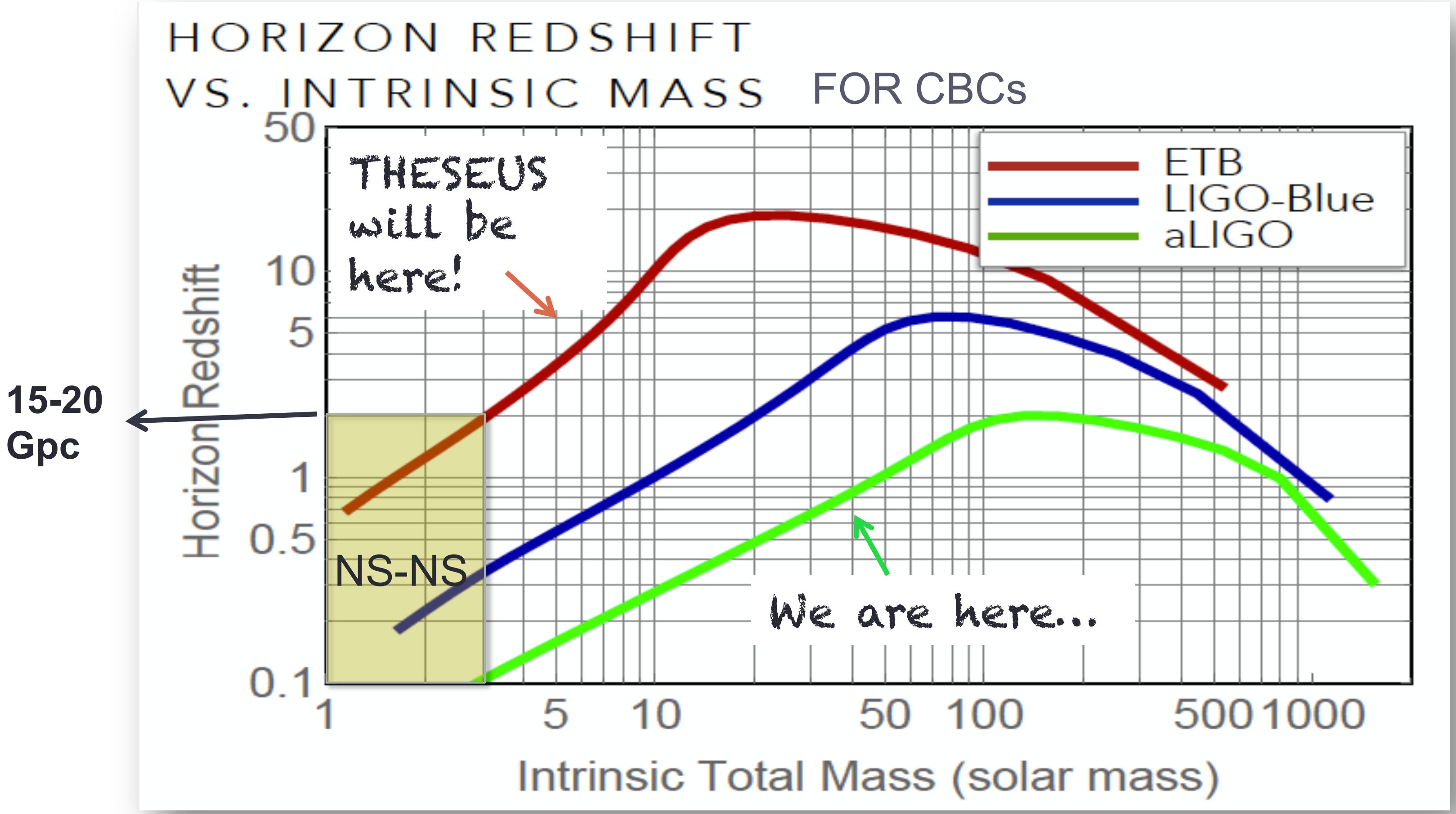
40/yr
up to 0.4-0.5 Gpc

30%-60%
(see Gao+2016, Piro+2017)

FoV_{SXI} → 8%
+
60% in FoR → 40%

[6-12]/yr

3G GW detector's distance reach of CBC



Credit: Sathyaprakash - 7th ET Symposium 2016

Expected rate of joint **sGRB+GW** detection with THESEUS/XGIS

NS-NS rate
10-10000 $Gpc^{-3}yr^{-1}$

↓

Fraction collimated towards us

↓

Fraction within XGIS FoV

2G GW detectors

40/yr
up to 0.4-0.5 Gpc

2%-20%
(assuming a half-jet angle θ_{jet}=[10°- 40°], e.g. Rezzolla+2011)

FoV_{XGIS} → 50%

~[0.5-5]/yr

3G GW detectors

>10000/yr
up to 15-20 Gpc

↓

By 2030+ the number of joint short GRB+GW with THESEUS depends on XGIS sensitivity to short GRBs, estimated to be of
~[15-25] / yr

Expected rate of joint **X-ray+GW** detection with THESEUS/SXI

NS-NS rate
$10\text{-}10000\ Gpc^{-3}yr^{-1}$

↓

Fraction with isotropic X-ray emission

↓

Fraction within SXI FoV + those that can be followed up

2G GW detectors

40/yr
up to 0.4-0.5 Mpc

30%-60%
(see Gao+2016, Piro+2017)

FoV_{SXI} → 8%
+
60% in FoR → 40%

[6-12]/yr

3G GW detectors

>10000/yr
up to 15-20 Gpc

30%-60%
(see Gao+2016, Piro+2017)

~30% detected with SXI

FoV_{SXI}=1/12
+
60% in FoR → 40%

[100-300]/yr

Summary

- **THESEUS will fly in the golden era of multi-messenger astronomy**

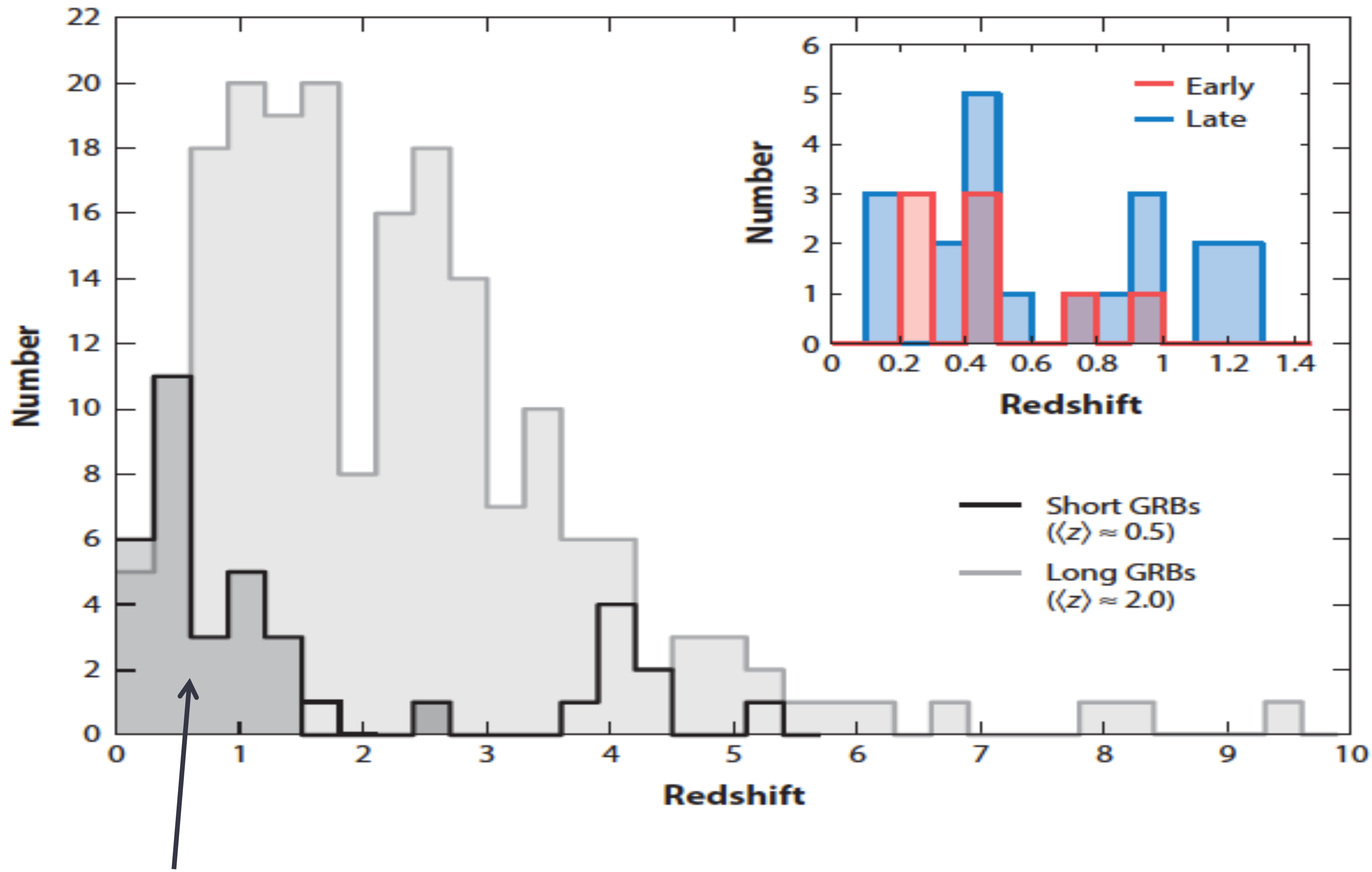
- MM sources that THESEUS can potentially detect in X-rays and gamma-rays are:
  - **NS-NS/NS-BH mergers,**
  - **core collapse massive stars and**
  - **SGR/intermediate+giant flares**

- **NS-NS mergers** are expected to produce a **collimated short GRB** and an **isotropic X-ray emission** if a NS remnant is formed after the merger

- **During 2G GW detectors era**, due to their limited distance reaches (NS-NS at $z<0.1$), **isotropic X-ray emission from NS-NS maybe the dominant MM target for THESEUS/SXI**

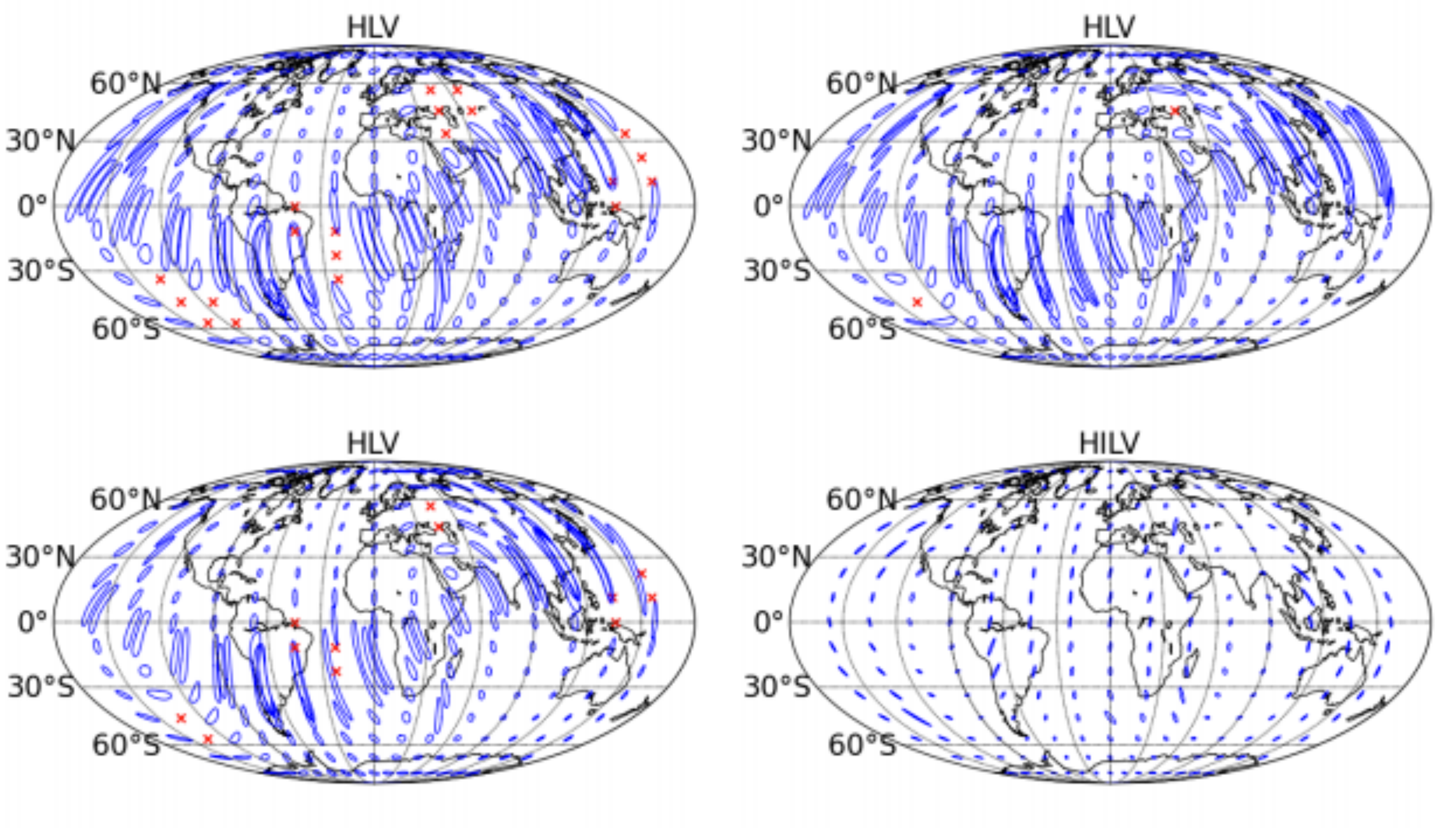
- **During 3G GW detectors era,** thousands of NS-NS systems will be detected up to $z\sim2$ and **short GRBs + space missions capable to detect and localize them as THESEUS, will play a fundamental role in MM astronomy by that time**

Extra slides

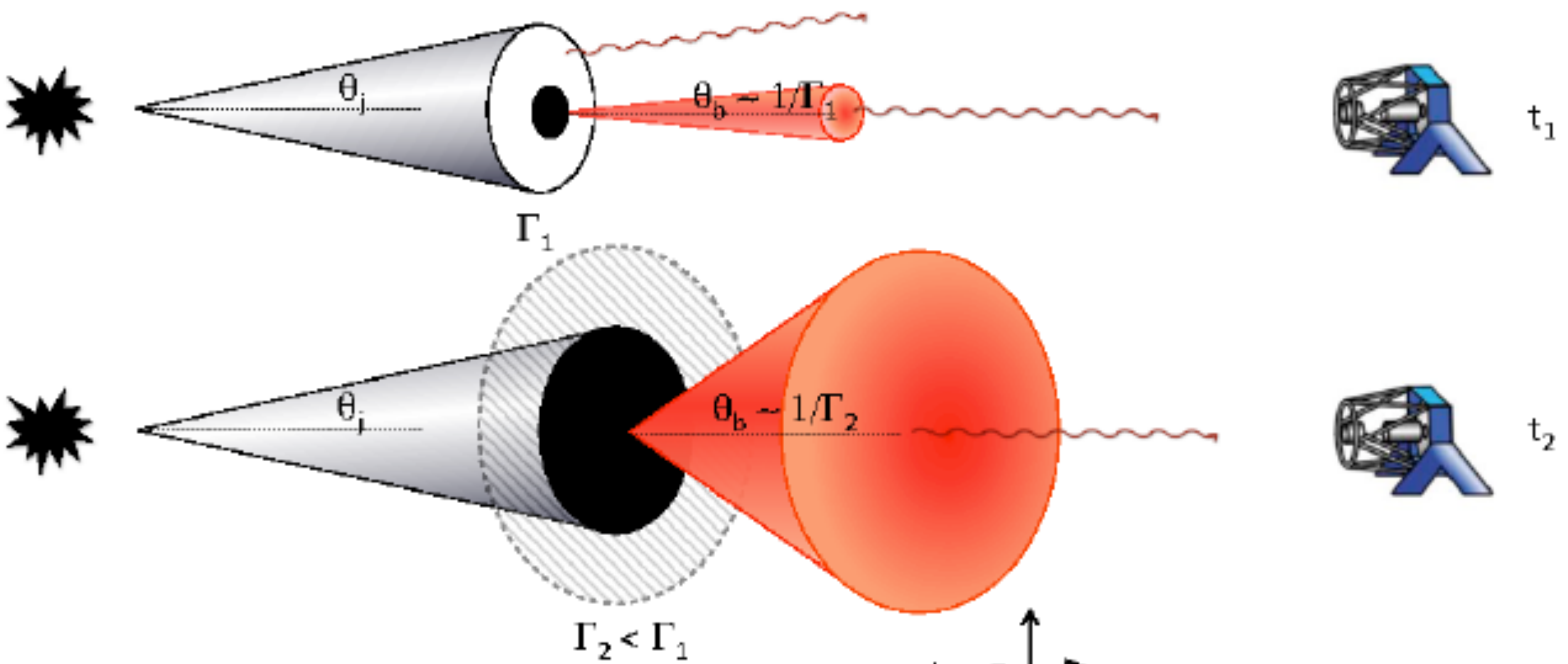


Short GRB redshift distribution (Berger 2014)

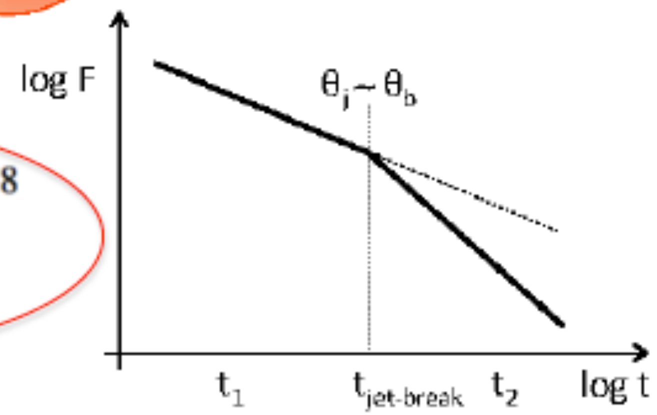
GW source sky localization accuracy



The "jet-break" is produced when the relativistic opening angle within which ejecta radiates (that increases due to the ejecta deceleration) equals the jet cone aperture.

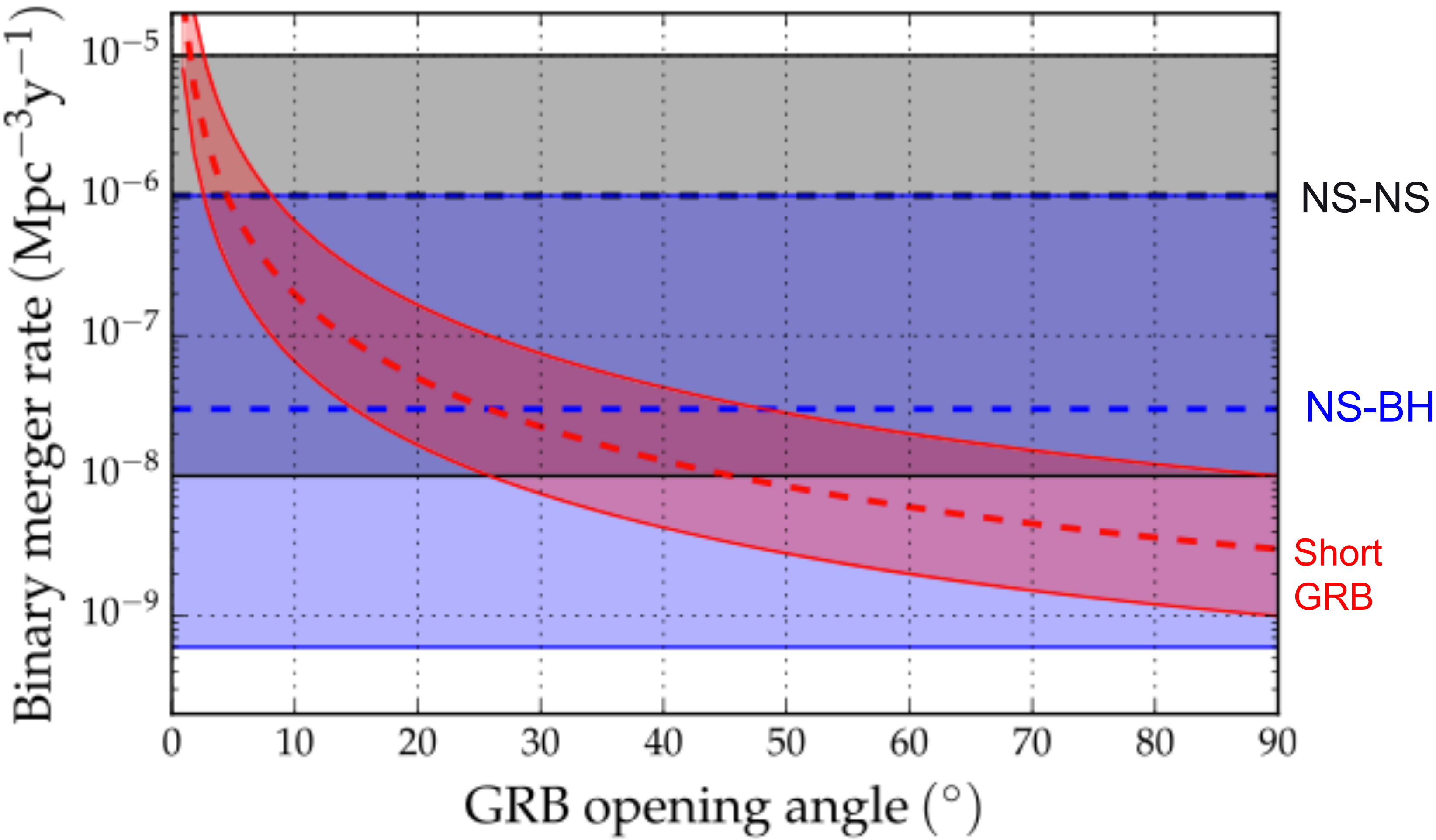


$$1/\Gamma(t_{\text{jet-break}}) = \theta_j = 0.13\left(\frac{t_{j,d}}{1+z}\right)^{3/8}\left(\frac{n_0}{E_{52}}\right)^{1/8}$$



Sari, Piran and Halpern 1999

Clark+2015



Binary merger rate ($Mpc^{-3}y^{-1}$)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
10
20
30
40
50
60
70
80
90
GRB opening angle (°)
NS-NS
NS-BH
Short
GRB

Can a binary black hole merger produce a detectable EM transient?

We don't expect a stellar-mass binary black hole system to have enough matter around for the final BH to accrete and form a relativistic jet [e.g., Lyutikov, arXiv:1602.07352] — or can it?

Various models have been proposed:

Single star [Fryer+ 2001; Reisswig+ 2013; Loeb 2016, ApJL 819]: collapse of a very massive, rapidly rotating stellar core, which fissions into a pair of black holes which then merge; but see Woosley, arXiv:1603.00511v2 for modeling that does not support

Instant BBH [Janiuk+ 2013, A&A 560; arXiv:1604.07132]: massive star-BH binary triggers collapse of star to BH, then immediate inspiral and merger; final BH can be kicked into circumbinary disk and accrete from it

BBH with fossil disk [Perna+ 2016, ApJL 821]: activates and accretes long-lived cool disk

BBH embedded in AGN disk [Bartos+, arXiv:1602.03831; Stone+ 2016, MNRAS]: binary merger assisted by gas drag and/or 3-body interactions in AGN disk, which provides material to accrete

Third body [Seto&Muto 2011, cited in Murase+ 2016, ApJL 822]: tidal disruption of a star in a hierarchical triple with the BBH at time of merger

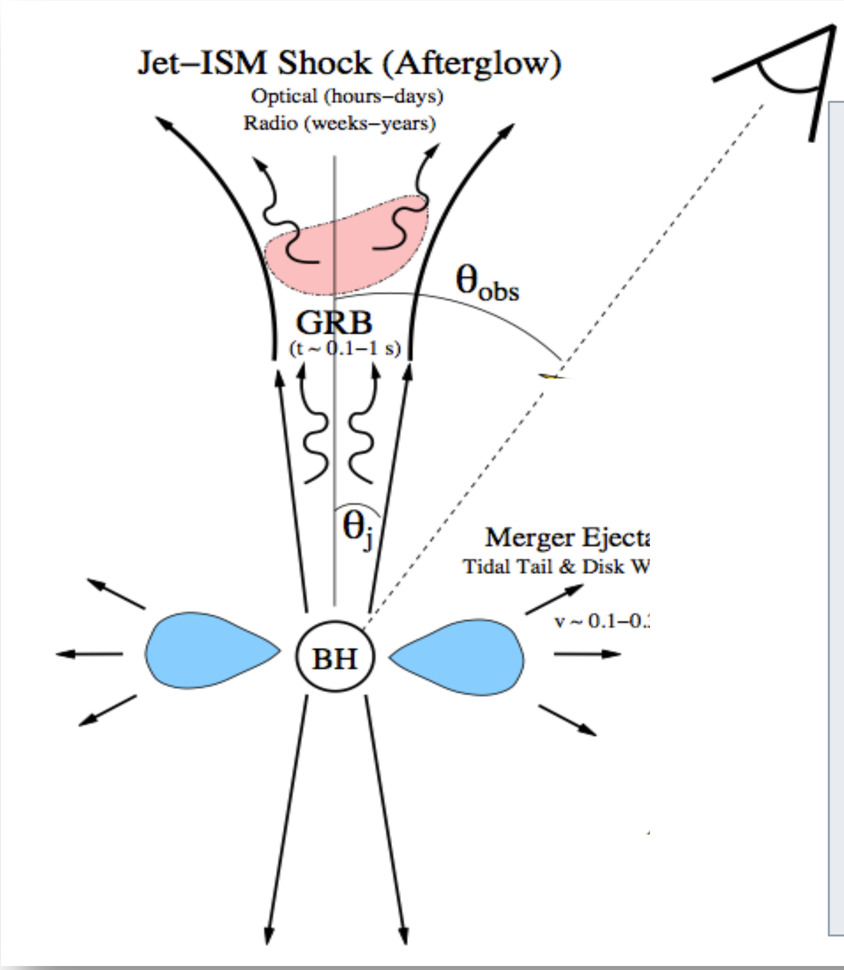
Charged BHs [Zhang 2016, ApJL 827; Liebling&Palenzuela 2016, PRD 84]: Merging BHs with electric (or magnetic monopole!) charge could produce a detectable EM transient

Magnetic reconnection [Fraschetti, arXiv:1603.01950]

Also models for high-energy neutrino and ultra-high energy cosmic ray emission

Review – courtasy of Peter Shawhan (Maryland)

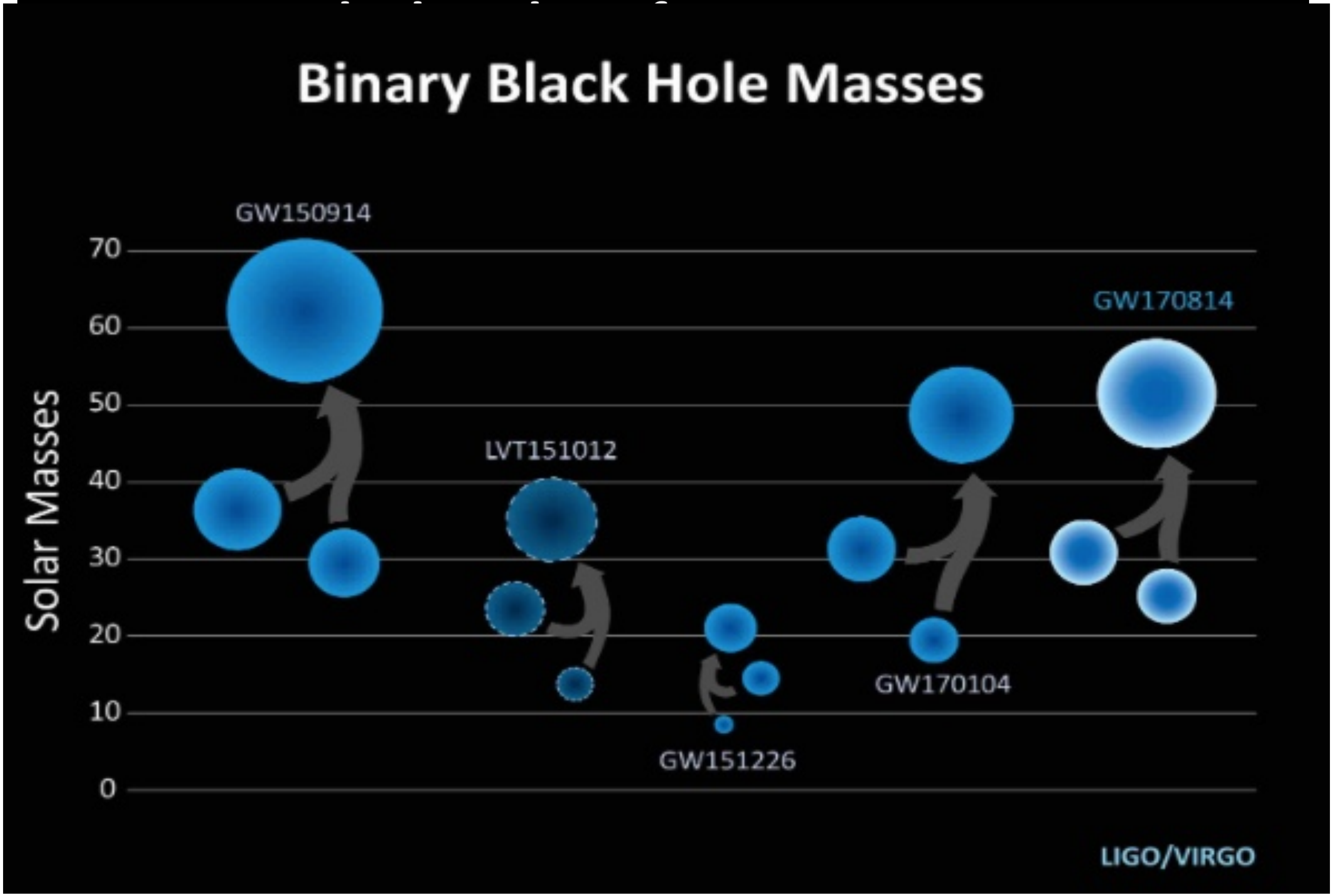
NS-NS/NS-BH EM counterparts



Off-axis GRB

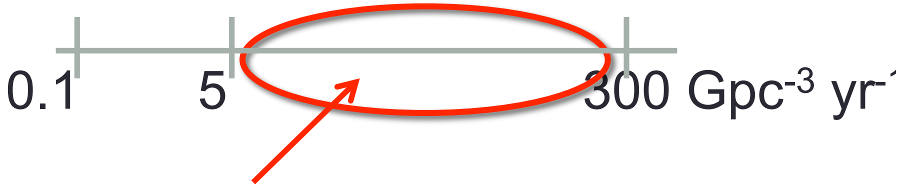
- Jets slows down and expands laterally
- Afterglow emission enters in the line of sight of an off-axis observer → rising + decaying temporal behavior
- ...not detectable for θobs>>2θjet (e.g. Ghirlanda et al. 2016)

Metzger & Berger 2012


Binary Black Hole Masses
Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170814
LIGO/VIRGO

Expected BBH rate

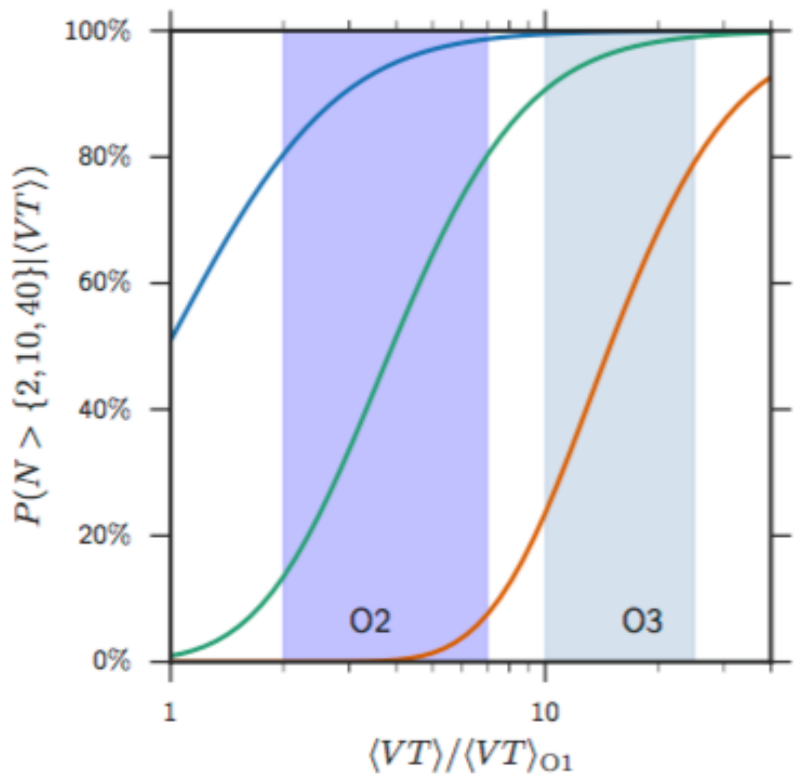
BBH rate from Abadie+2010



New constraints from O1 for BBH population are: **9-240 Gpc^{-3} yr^{-1}**

High significance BBH detections:

- **O2:**
  - **~90% probability to see >2 BBH**
  - **~50% to see >10 BBH**
- **O3:**
  - **~90% of probability to see > 10 BBH**
  - **~60% of probability to see >40 BBH**



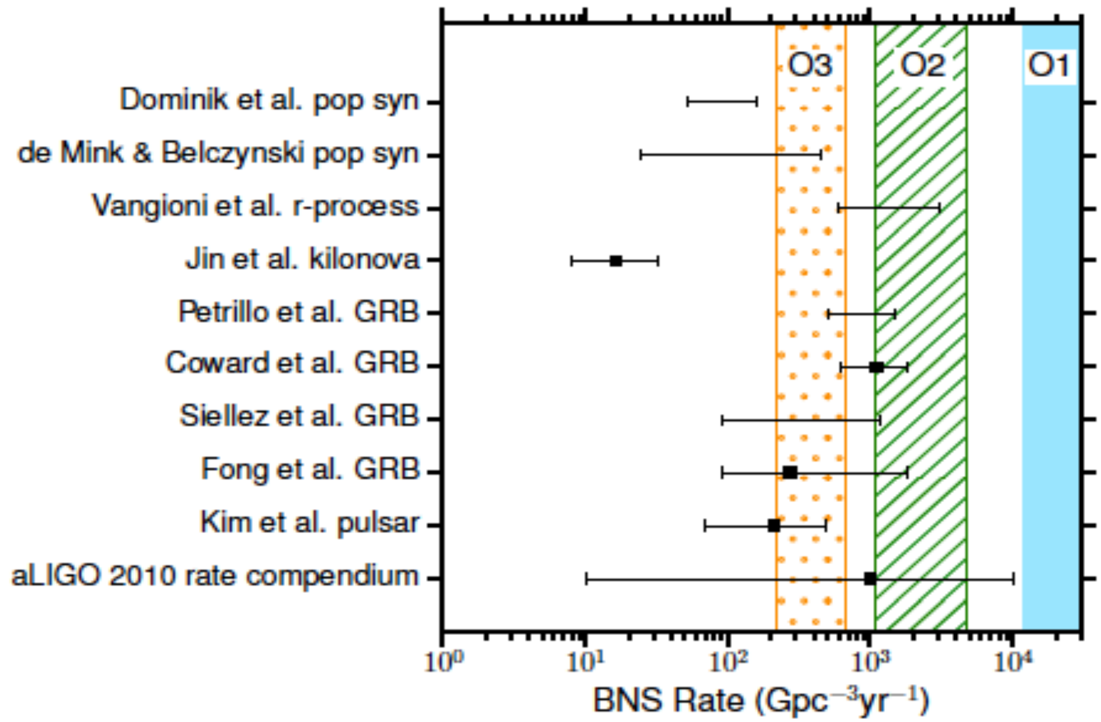
“BBH Mergers in the first aLIGO observing run” Abbott+2016, ApJL in press

Expected BNS rate

O1 no BNS detections still consistent with expectations

R_BNS < 12600 $Gpc^{-3}\ yr^{-1}$

O2 expected number of BNS is: 0.006-20 (Abbott+2016 LRR, for 6 months of LIGO+Virgo)



"Upper limits on the rates of BNS and NSBH from aLIGO first observing run" Abbott+2016 arXiv: 1607.07456v1.

TABLE IV: Compact binary coalescence rates per Mpc^3 per Myr.[a]

Source	R_{low}	R_{re}	R_{high}	R_{max}
NS-NS (Mpc^{-3} Myr^{-1})	0.01 [1]	1 [1]	10 [1]	50 [16]
NS-BH (Mpc^{-3} Myr^{-1})	6×10^{-4} [18]	0.03 [18]	1 [18]	
BH-BH (Mpc^{-3} Myr^{-1})	1×10^{-4} [14]	0.005 [14]	0.3 [14]	

TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{high}$ yr^{-1}	$\dot{N}_{max}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			< 0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

Abadie et al. 2010