Australian Government
Australian Research Council

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

3G Multi-messenger Observations

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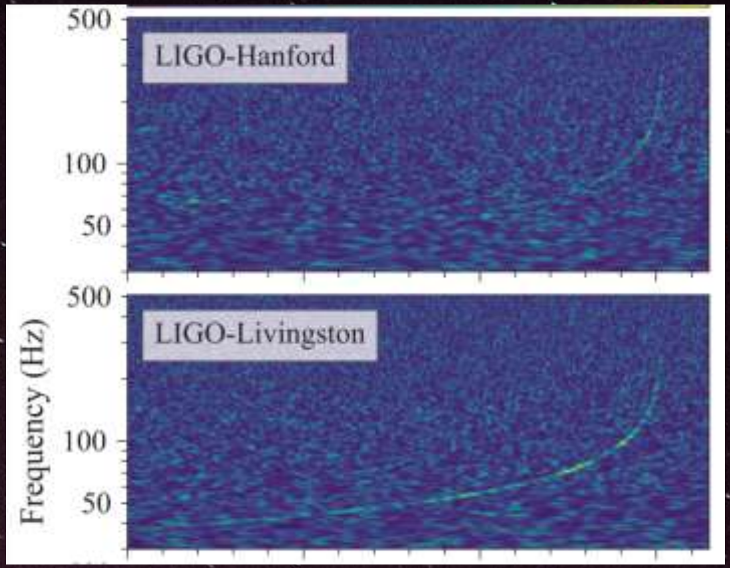
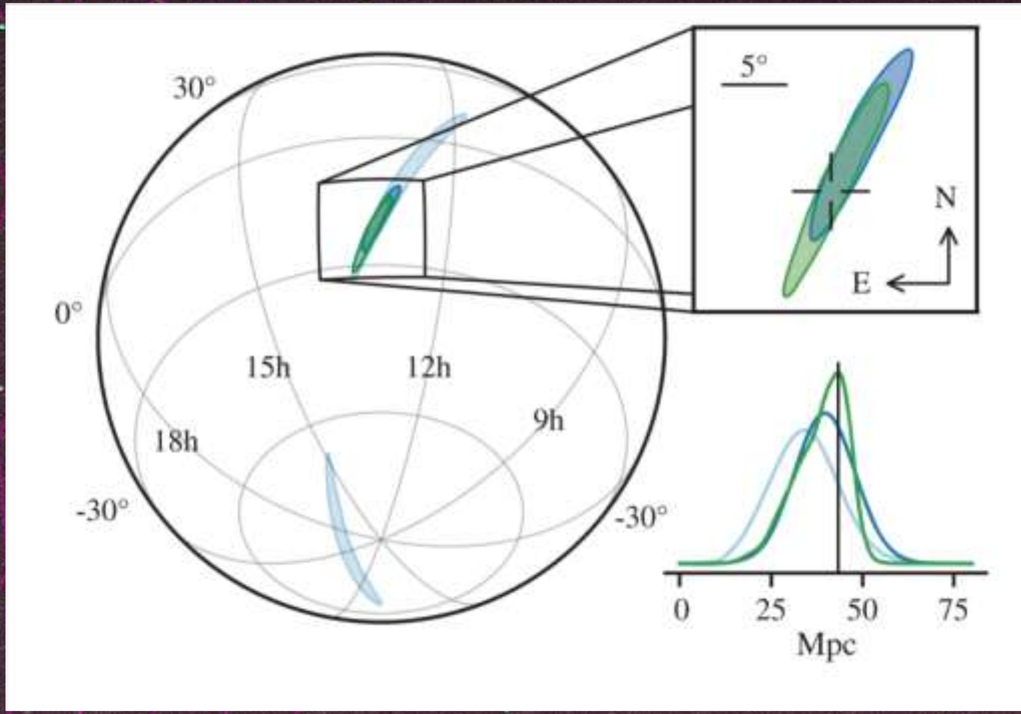
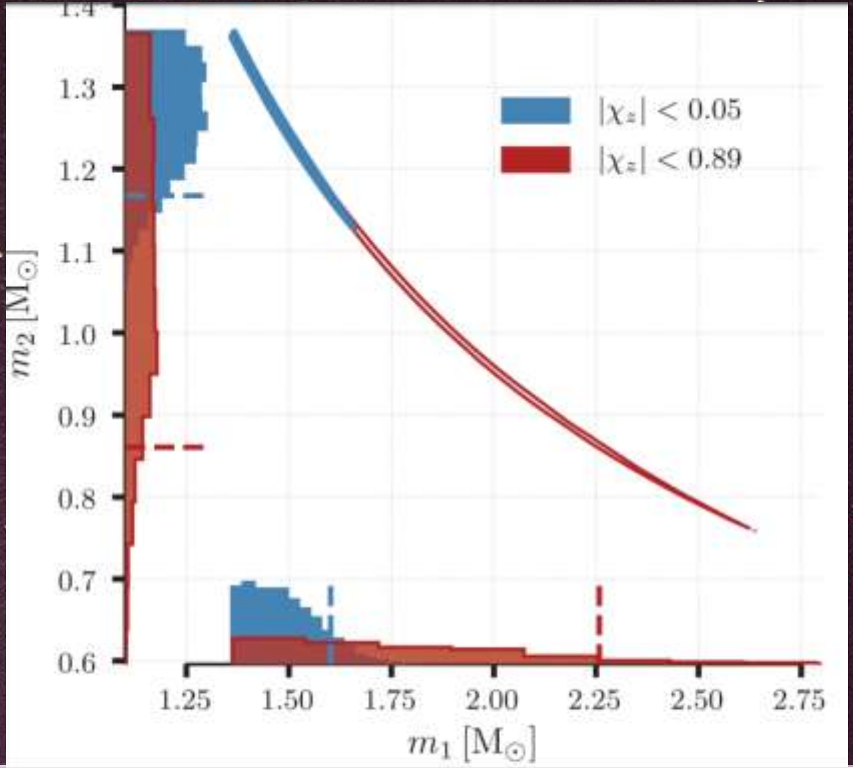
- GW 170817
  - localisation ~28 deg^2,
  - 26 Mpc < d < 48 Mpc,
  - Total Mass ~2% accuracy







GW 170817

- Wealth of insights:
  - Speed of light vs GWs
  - Nature of GRBs
    - Jets
    - Luminosities
  - Kilonovae/r-process elements
    - Distance/Luminosity SD^2
  - Hubble Constant

- Without an optical companion/GRB:
  - ~~Speed of light vs GWs~~
  - ~~Nature of GRBs~~
    - ~~Jets~~
    - ~~Luminosities~~
  - ~~Kilonovae/~~r-process elements?
    - ~~Distance/Luminosity SD^2~~
  - ~~Hubble Constant~~

GW Multi-Messenger Observations more than BNS

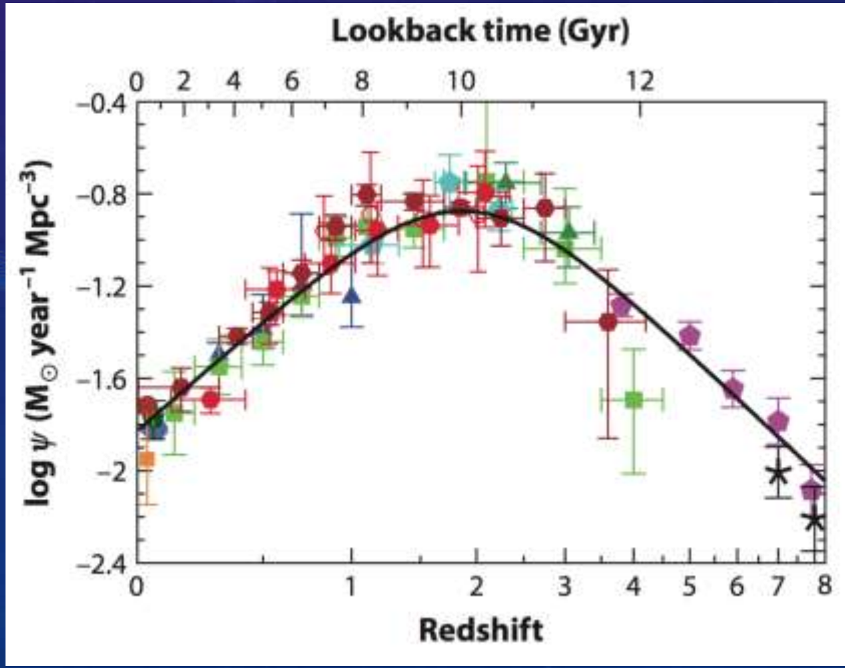
- Close Binary Coalescence (CBC):
  - BNS
  - BHNS
  - BBH
- Continuous Waves (CW):
  - MSPs
  - LMXBs
- Burst:
  - SNe? – *Neutrinos*?
  - PSR Glitches?? - *Radio*
  - FRBs???? - *Radio*

3G Killer Apps?

- Things GWs can do better than anything else:
  - Extreme Gravity Dynamics
    - $0.1c < v < c$
  - Black Holes
  - BNS & BHNS & BBH mergers
    - r-process elemental creation (z)
    - Merger rate (z, m1, m2, Mc)
  - Cosmology?
    - H_0??
  - GRB engines

Key Questions:

- Nucleosynthesis
  - Where/how much
- Cosmology
  - Ho, et al.
- Which Galaxies produce what type of merger (z)
  - Where in the host? Kicks, lifetimes etc.
- Multiband Multi-messenger and Rapid Response Options
  - Can we lie in wait for the event?
- Equation of State of Nuclear Matter
  - What is the mass-radius relation of nuclear matter?
- Supernovae
  - Are they hidden – do they rotate rapidly?
- GRB Jet physics



GW-EM "Curse"

- *In radio:*
- $SNR = \frac{SG\sqrt{BNpt}}{T_{rec}+T\_\{sky\}}$; S=$\frac{L}{d^2}$
- t=d^4

- GW 170817 –> z=0.01
- z=1 -> 10^8 x (before cosmology)

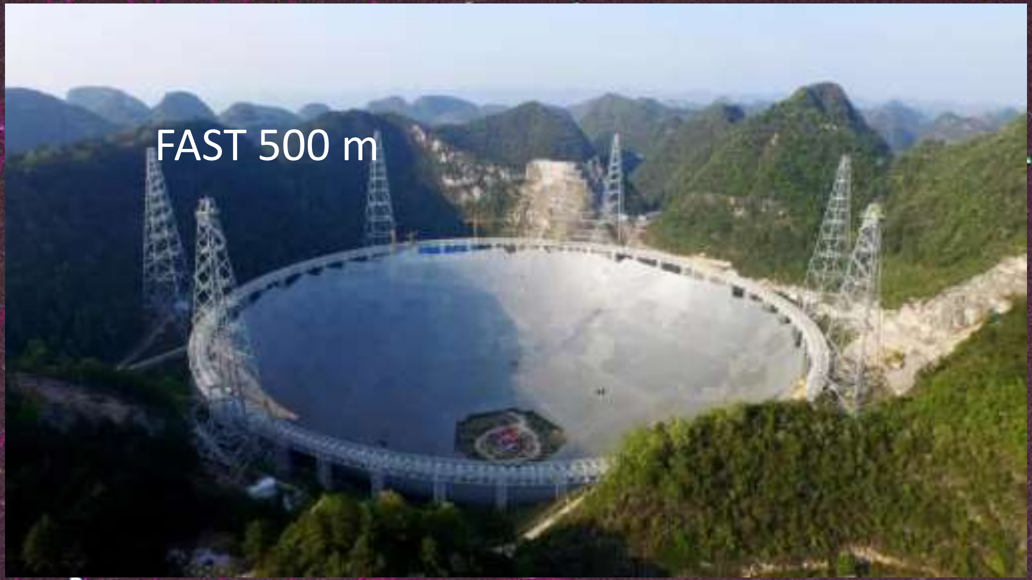
CW: Millisecond Pulsars

Current Pulsar Numbers: ~2600

Period < 10 ms = 315

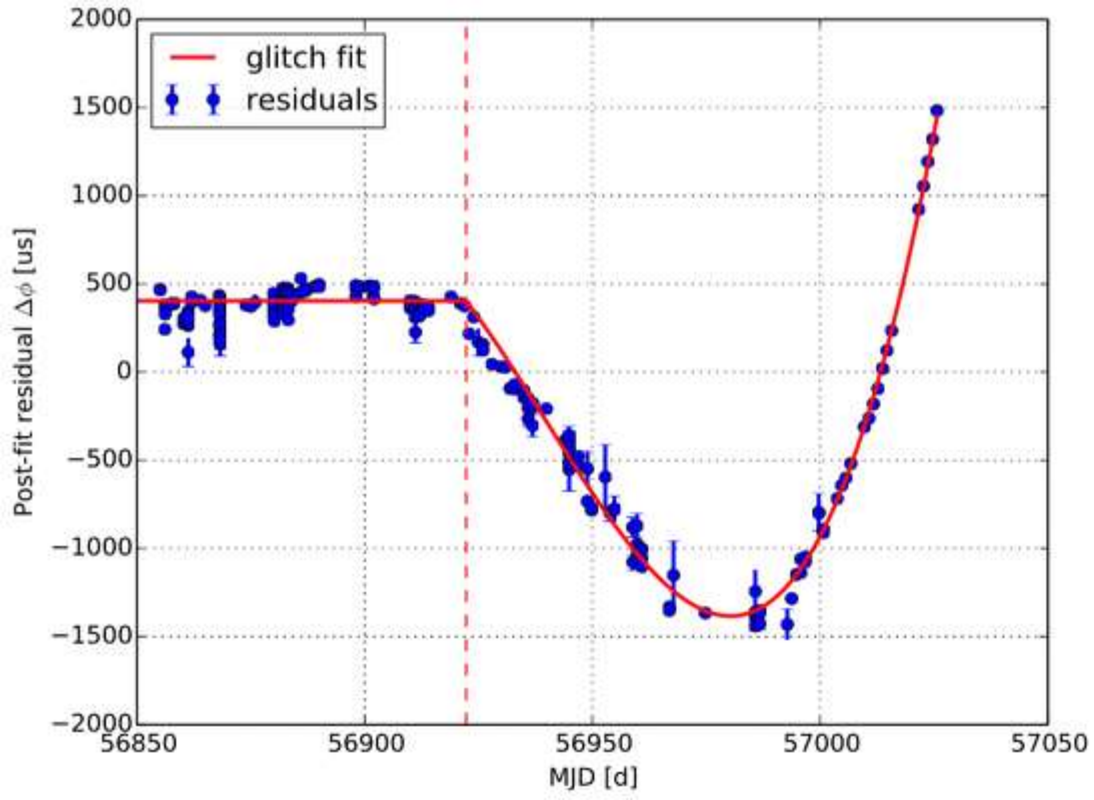
MeerKAT, Arecibo, FAST, SKA

Total = 10,000
MSPs > 1200



Not a guaranteed source of GWs!

Pulsar Glitches

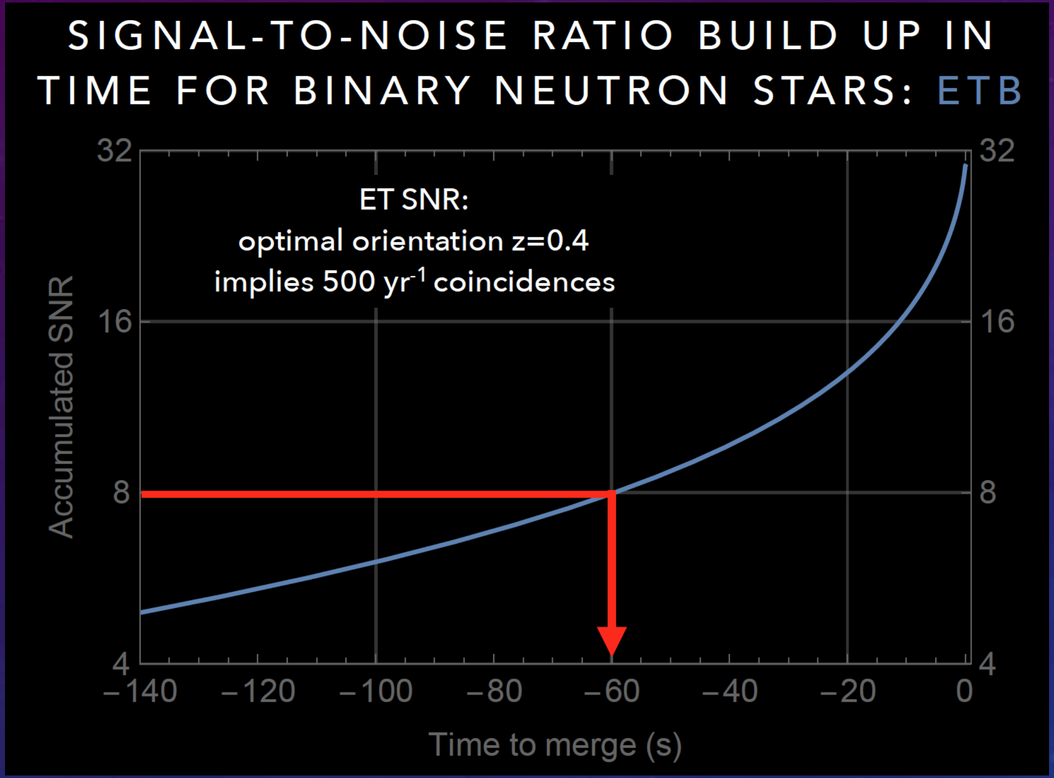


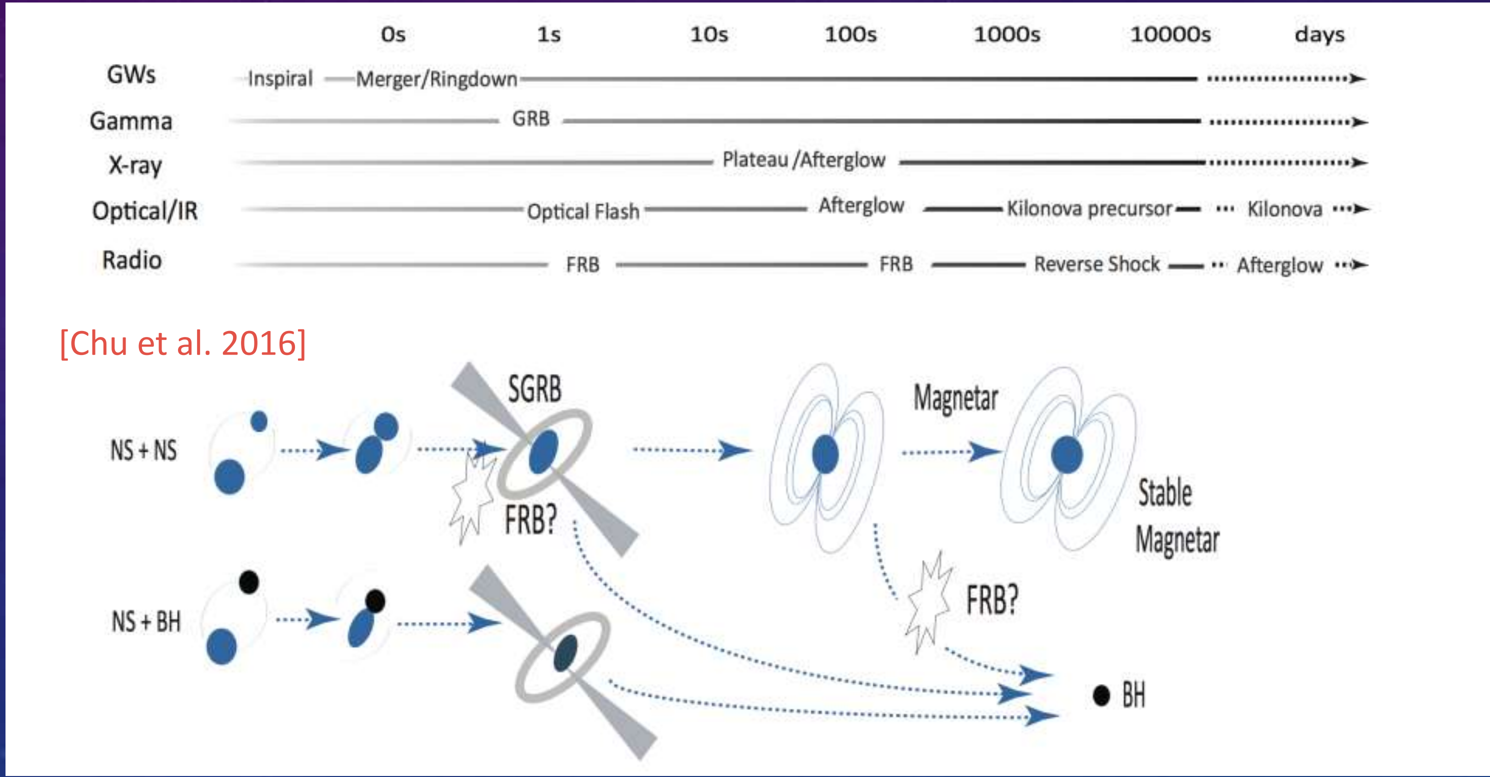
Glitches can be found:

- Via Bursts
- Reverse-searches
- Expect 2030 glitch detection rate > 10x current

Not a guaranteed source of GWs!

Necessity for early warning signals for EM precursor signals





Fast Radio Bursts (FRBs)
"Prompt" emission

$$t_* = 0.86 \text{ day} \left(\frac{1.21 \text{ M}_\odot}{\mathcal{M}_c} \right)^{5/3} \left(\frac{2 \text{ Hz}}{f_\text{low}} \right)^{8/3},$$

- Not all FRBs can cause GWs
  - "Repeater" removed catastrophic models like BNS
  - Some BNS *may* cause FRBs?
  - -ve latency BNS GWs can allow "wait and capture" in radio
  - Can be an hour or more?
- ASKAP in fly's eye mode: 36 * 30 = 1080 deg^2
- MeerKAT in fly's eye mode: 64 * 1 = 64 deg^2
- SKA in fly's eye mode: 200 * 1 = 200 deg^2

⚠ *Not a guaranteed source of GWs!* ⚠

CCSNe Supernovae

Good Questions:

- GWs help distinguish between neutrino-driven and rotation-driven CCSNe
- Can Neutrinos & GWs find "electromagnetically dark" "failed Sne"
  - Estimated up to 30% of supernovae "fail"
- Rotation rate of SNe cores

CCSNe Supernovae Neutrinos

ICE Cube (3 Mpc?)

- 1-3 per Century ☹

Megaton Facilities (5 Mpc?)

- 10 per Century? 😐

Our Galaxy?

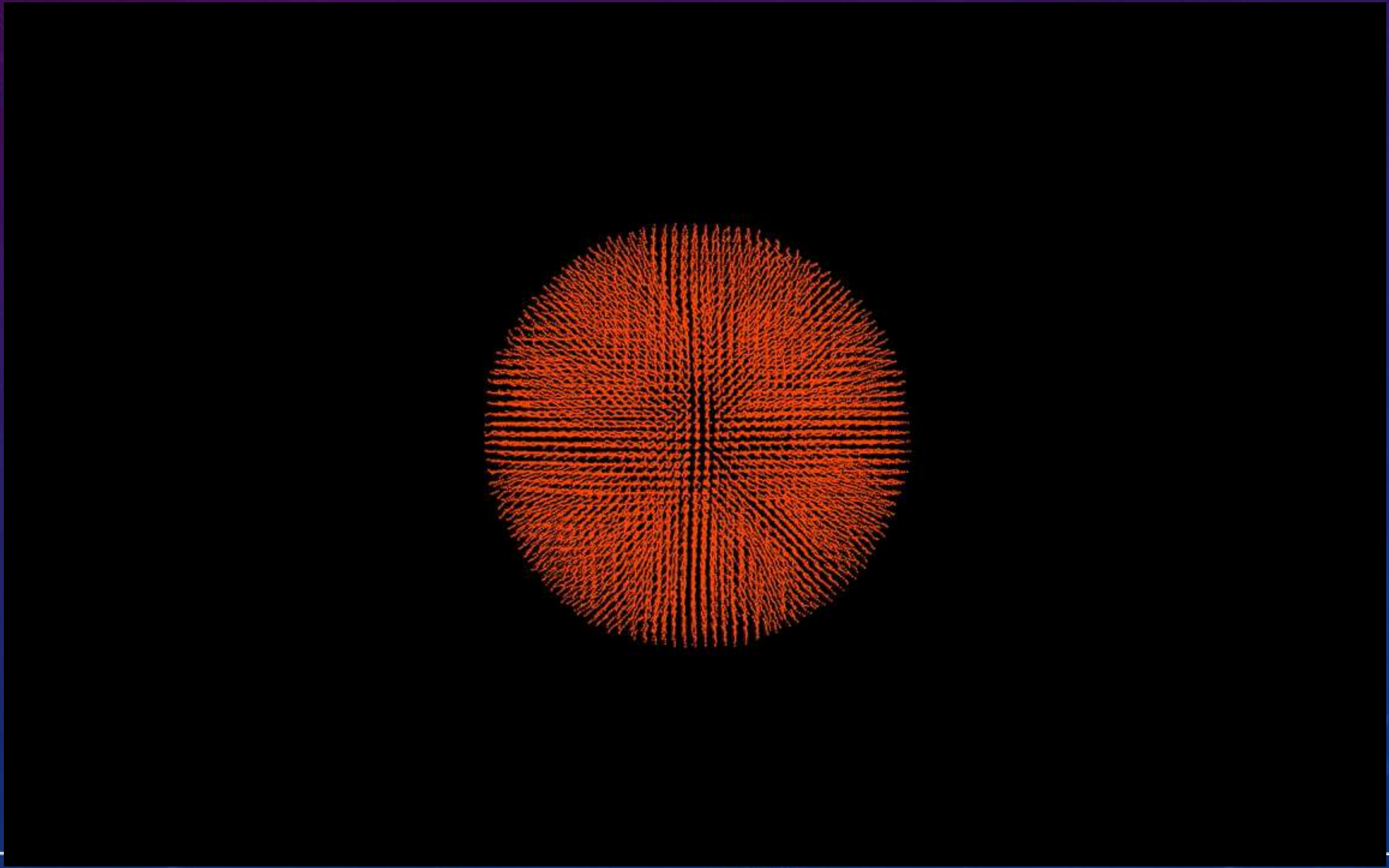
- How Many per Century? 😐
- Optical/IR – ~30% via naked eye?
- Radio Trivial – but 3G?

⚠ *Not a guaranteed source of GWs!* ⚠

BBH Mergers and MMO

Galaxy Formation:

- Build-up of building blocks
- Friction for BBH negligible



BBH Mergers and MMO

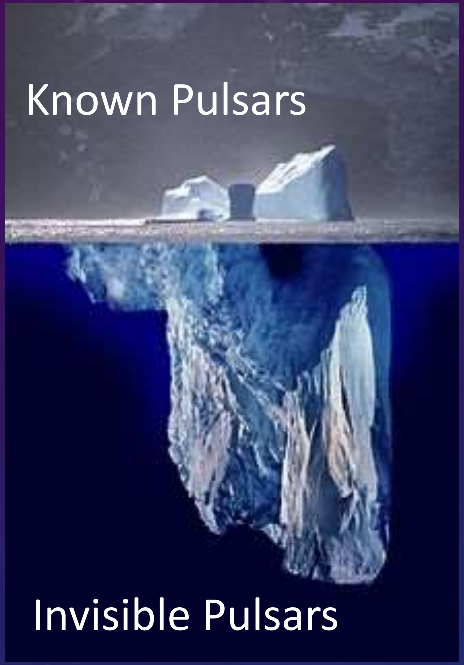
Can we localise to a Galaxy?

- Maybe ~few / year?
- Which type of Galaxy – not where in the Galaxy!
  - @z=0.01 1' = 12 kpc ~Galactic Radius
- Won't answer Globular Cluster vs Binary origin

But so what?

- All Galaxies once had stars
  - #Ellipticals: #Spiral: #Irregular

BNS Merger Rates



Binary Pulsar Rate

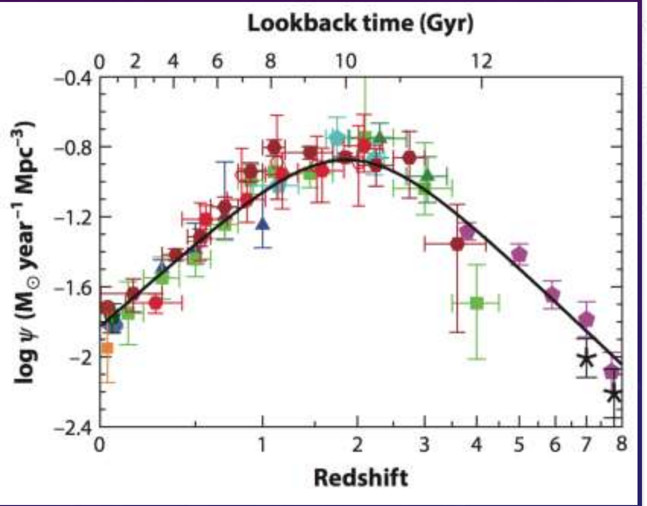
- Number of ns+ns in Galaxy that merge in t<t_Hubble (now 10)
- Guess beaming fraction
- Guess luminosity function
  - Unknown at the low end…
- Get a "merger rate"
  - ~10 / Milky Way/ Myr
- Milky Ways/Mpc^3 ~ 0.01
- PSR Rate therefore > 100 $Gpc^{-3}\ yr^{-1}$

LIGO rate

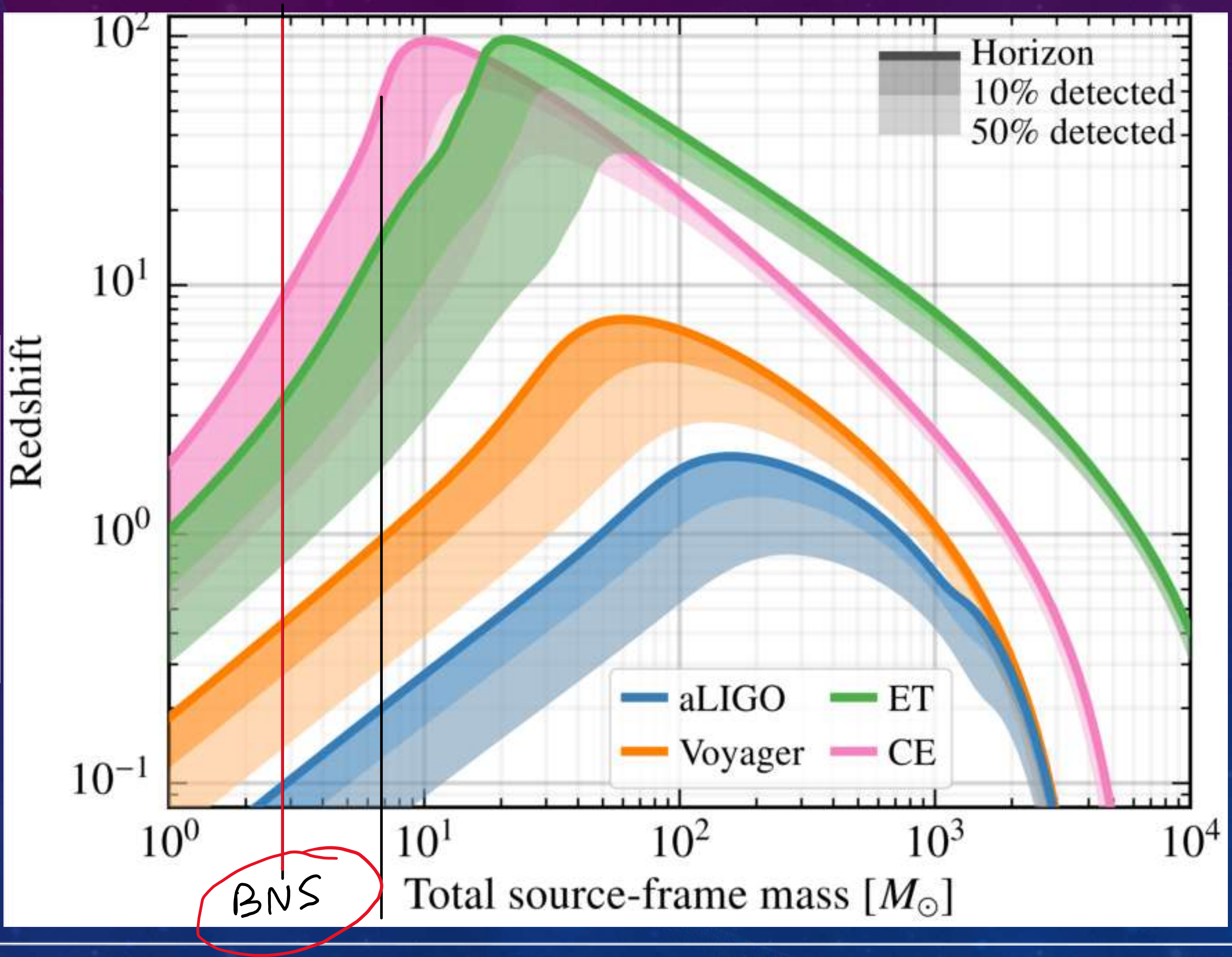
- Number of Mergers seen
  - Determine time
  - Range
- Rate ~ 1500 $Gpc^{-3}\ yr^{-1}$!!!
- GW170817 masses a lot like galactic ns+ns

100 vs 1500!?

Kilonova Detection Distances?



BNS dN/dz



GW170817 Kilonova Radio Detection Range

Radio:

SKA z~0.15

VLBI jet trick:

z~0.03??

Chinese VLBI network?

z~0.06?

Strongly density-dependent?

Dynamic range considerations…

	Facility	Det. limit	D (Mpc)	Status
Gamma–rays	*Fermi*	S/N 5	80	Present
	AMEGO	S/N 5	130	Future
	e-ASTROGAM	?	130	Future
X–rays	*Swift*	S/N 5	∼80	Present
	Chandra	3×10^{-15} erg s^{-1} cm^2	150	Present
	ATHENA	3×10^{-16} erg s^{-1} cm^2	480	Future
	Lynx	6×10^{-16} erg s^{-1} cm^2	450	Future
	STROBE-X	S/N 5	120	Future
Ultraviolet	HST (im)	26 mag	1460com z=0.370	Present
	HST (spec)	23 mag	368com z=0.087	Present
	LUVOIR			Future
Optical Imaging	Subaru	27 mag	2066com z=0.548	Present
	LSST	27 mag	2066com z=0.548	Future
Optical Spectroscopy	Keck/VLT	23 mag	450com z=0.107	Present
	GMT	25 mag	1013com z=0.249	Future
	TMT	25.5 mag	1223com z=0.305	Future
	E-ELT	26 mag	1464com z=0.371	Future
Infrared Imaging	WFIRST	27.5 mag	2725com z=0.765	Future
	Euclid	25.2 mag	1286com z=0.322	Future
Infrared Spectroscopy	Keck/VLT	21.5 mag	438com ~~z=0.114~~	Present
	GMT	23.5 mag	657com z=0.158	Future
	TMT	24 mag	803com z=0.195	Future
	E-ELT	24.5 mag	974com z=0.239	Future
Radio	VLA (S)	23 μJy	91	Present
	ATCA (CX)	42 μJy	51	Present
	ngVLA (S)	1.5 μJy	353	Future
	SKA-mid (L)	0.72 μJy	634	Future

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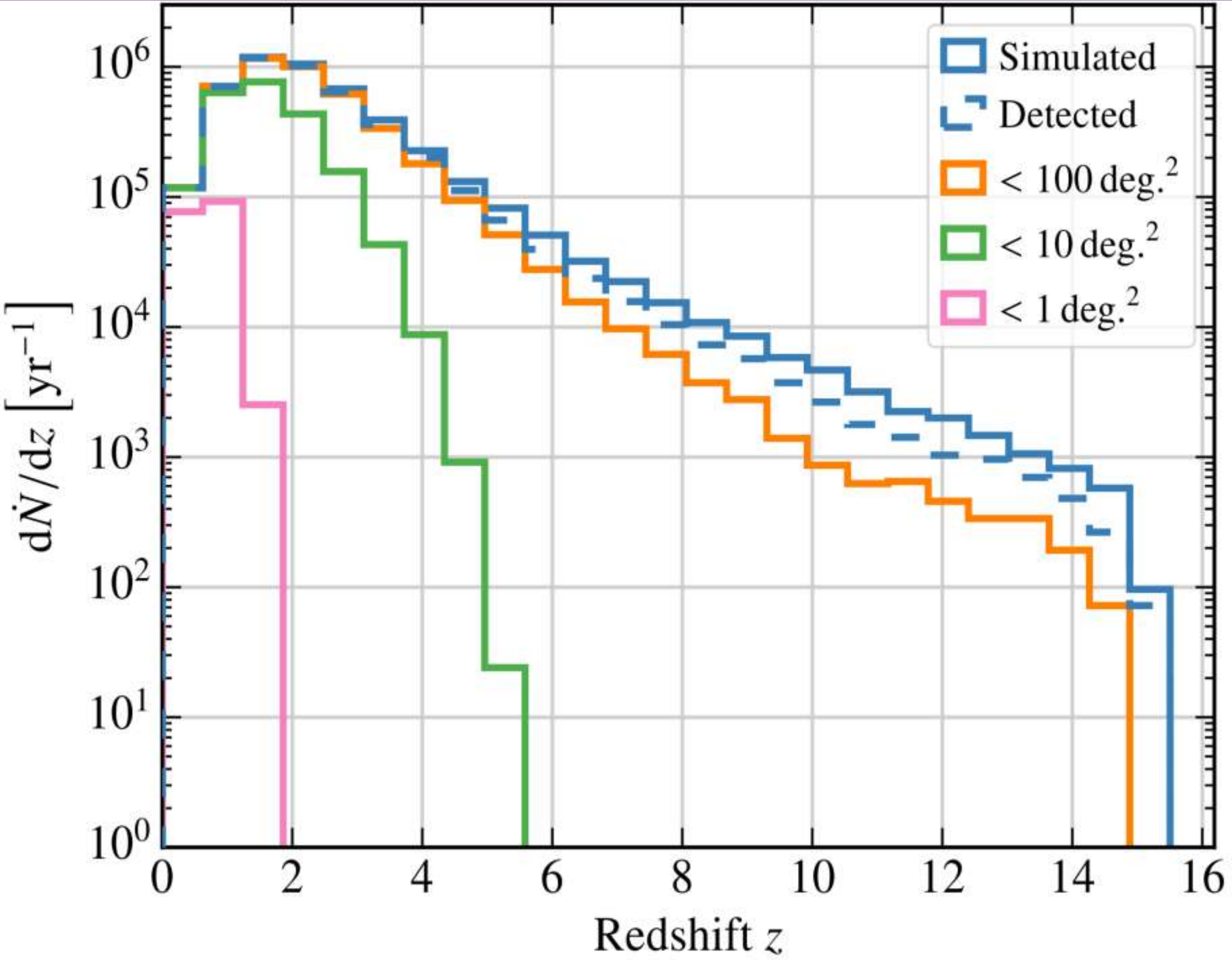
Kilonova Localisation

(Evan Hall)

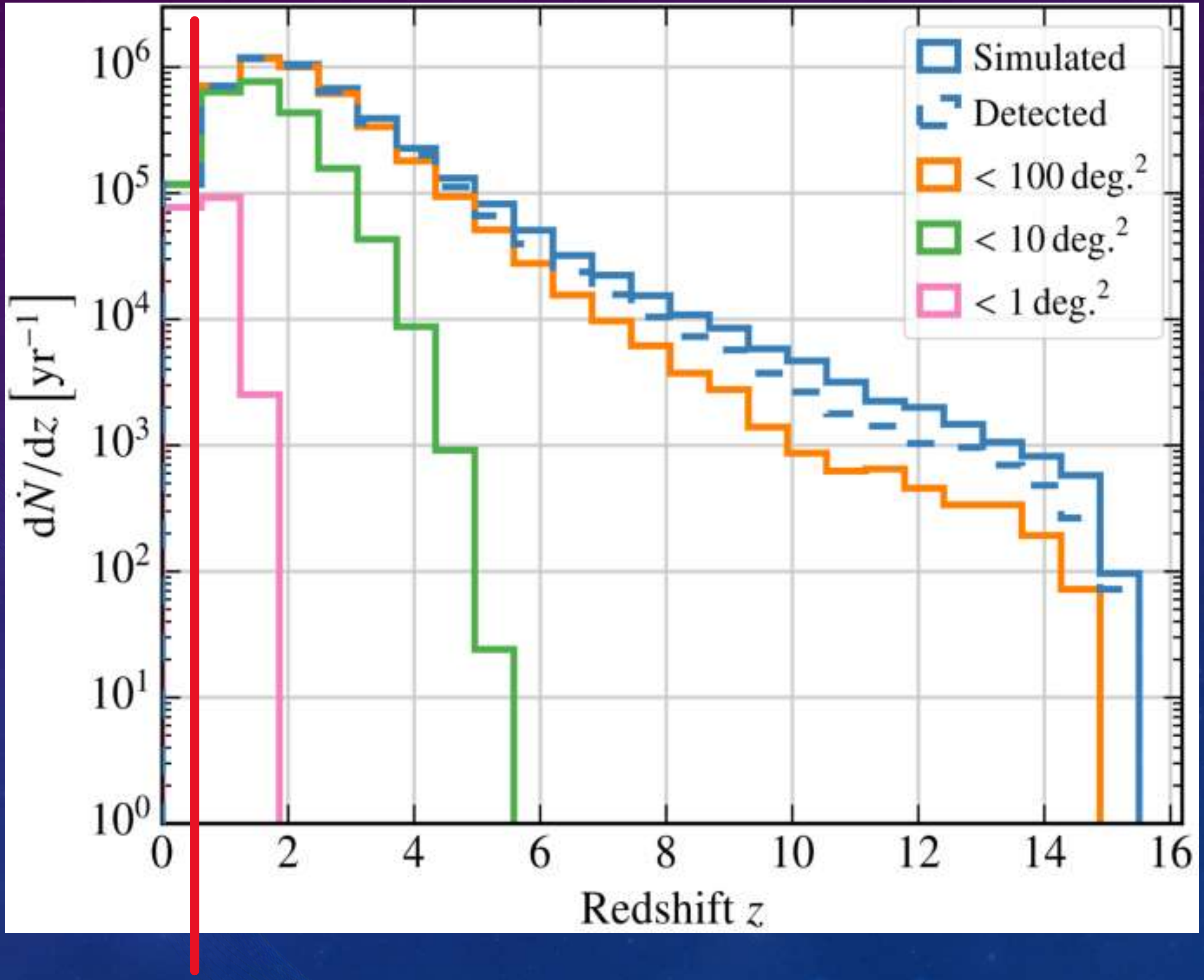
BNS dN/dz

1CE+1ET+1V



Kilonova Detection Distances

- LSST:
  - 27^{th} Magnitude
  - 1h
  - 3.5 deg x 3.5 deg?
  - Need 2-3 epochs
  - 2100 Mpc (z~0.55)
  - ~60K/Host @z~1



What produces BNS and BHNS mergers?

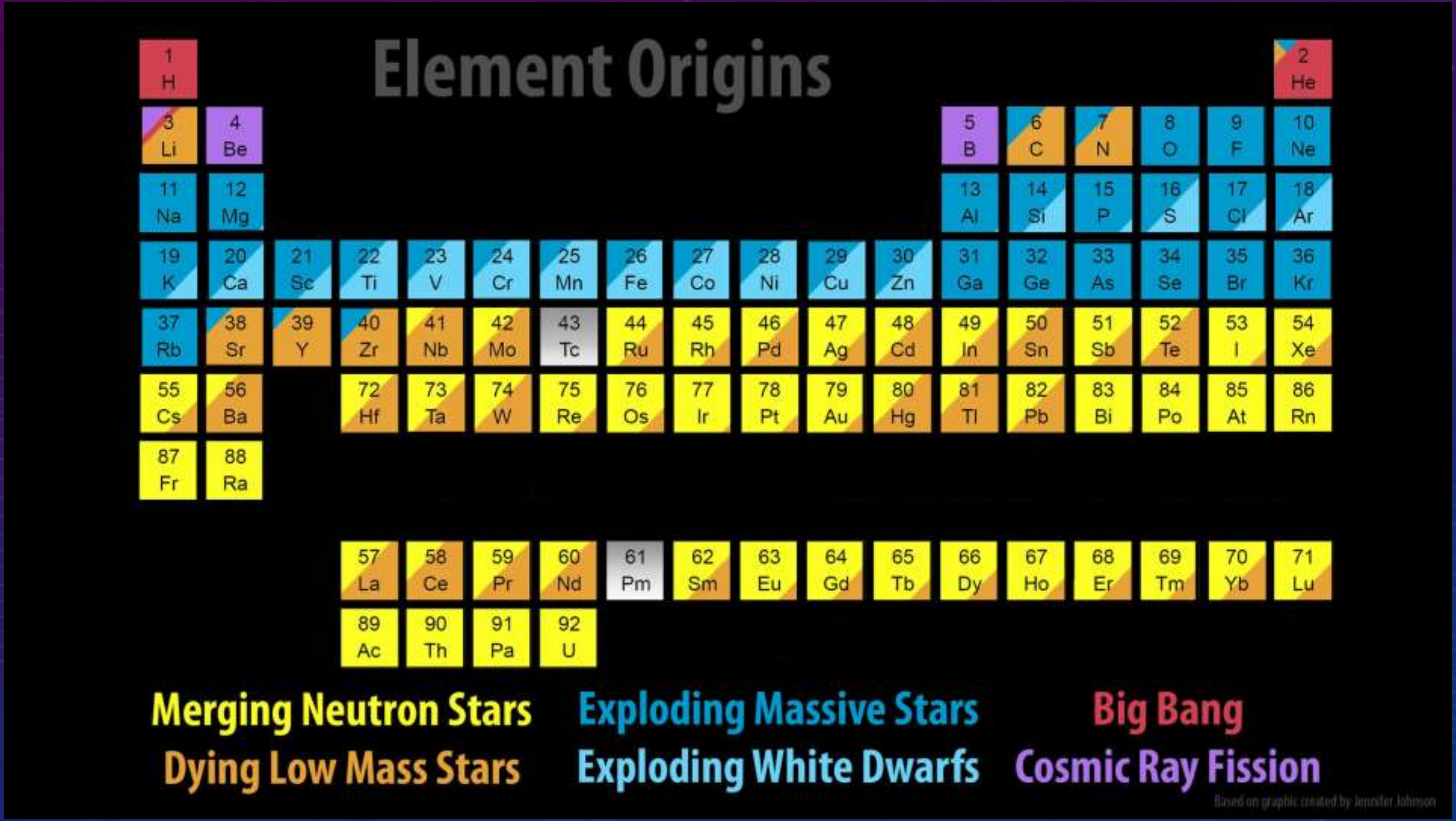
- Cost of 1000@z~0.55 with LSST = 60M?
  - 1 year of LSST dark time!
- But - BNS ~200/year (LSST blind survey – strategy dependent statement)
- Localisation cost @z~0.1 << 1% of z~0.55
  - Expect 100-1000s/year
- Answers the "where are they question?"

I. Nucleosynthesis

Are neutron star mergers indeed the long-sought sites of heavy element production?

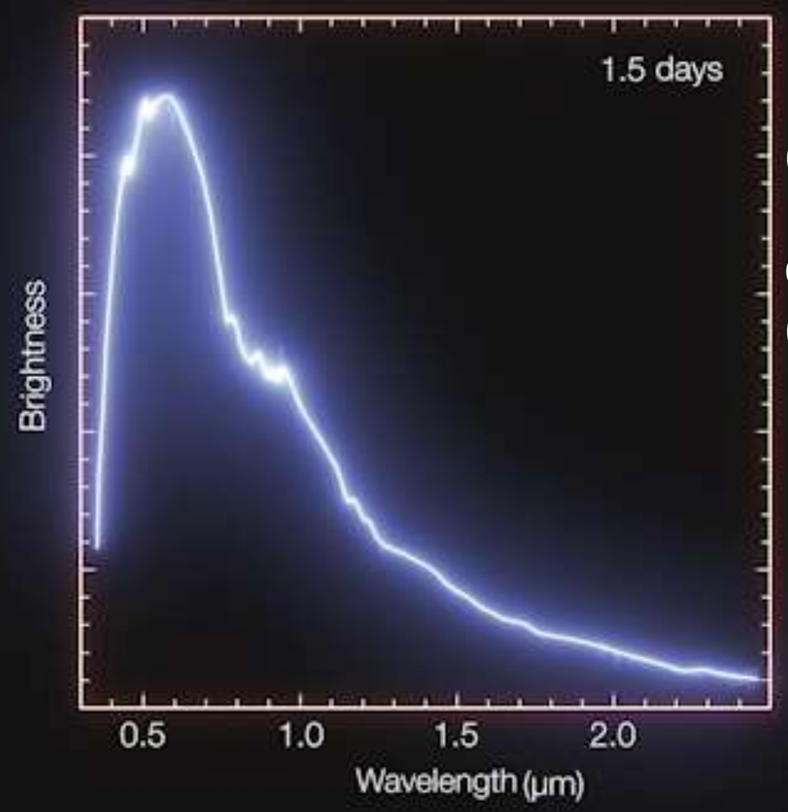
Lattimer & Schramm 1974

Cosmic Mines



Credit: J. Johnson

Spectroscopic Evolution (up to z~0.1 with ELTs)



Neodymium?
(Kasen et al. 2017)

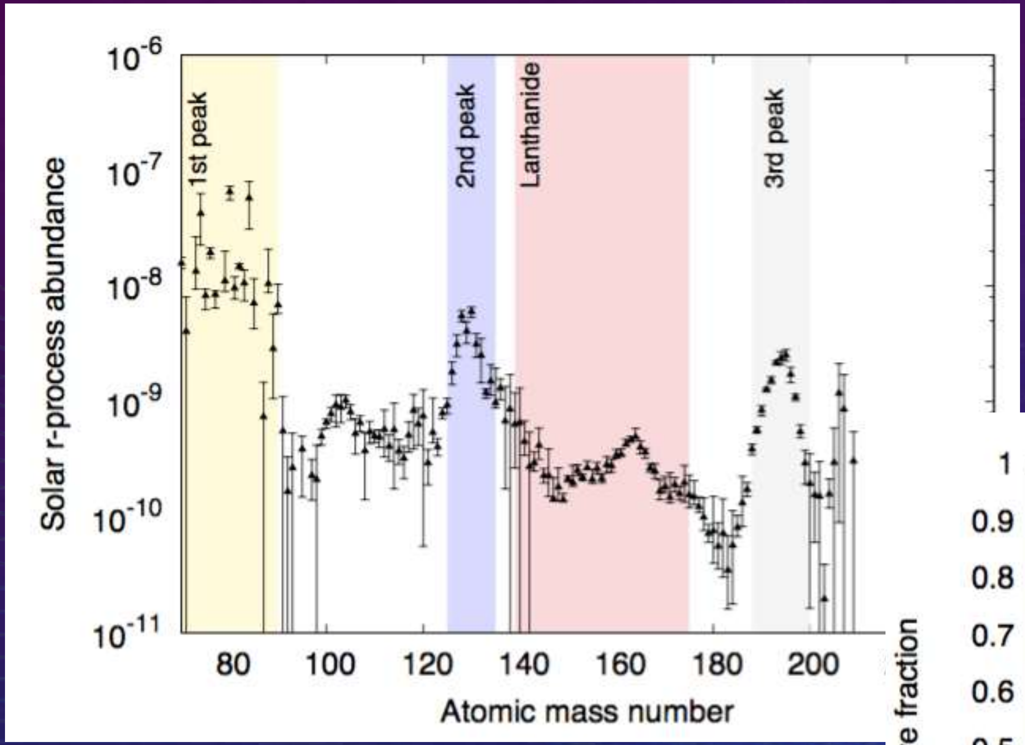
Cs I, Te I?
(Smartt et al. 2017)

Se, Ru, Te, Nd, and Er (Tanaka et al. 2017)

Pian et al. 2017, Nature

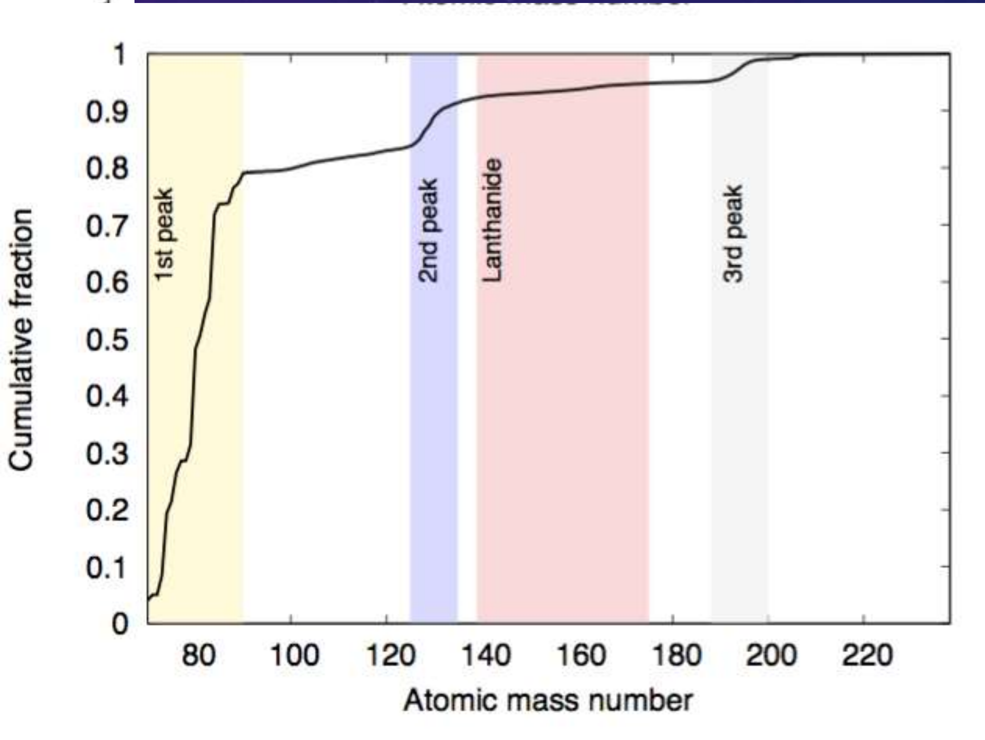
Additional spectroscopic evolution datasets:
Shappee et al . 2017, Chornock et al. 2017, Smartt et al. 2017, Nicholl et al. 2017
McCullly et al. 2017, Buckley et al. 2017, Kasliwal et al. 2017

Solar abundance of Heavy Elements (up to z<0.1 ELT)



Rate / 500 Gpc^-3 / yr
X Ejecta / 0.05 Msun
= Observed Solar Abundance

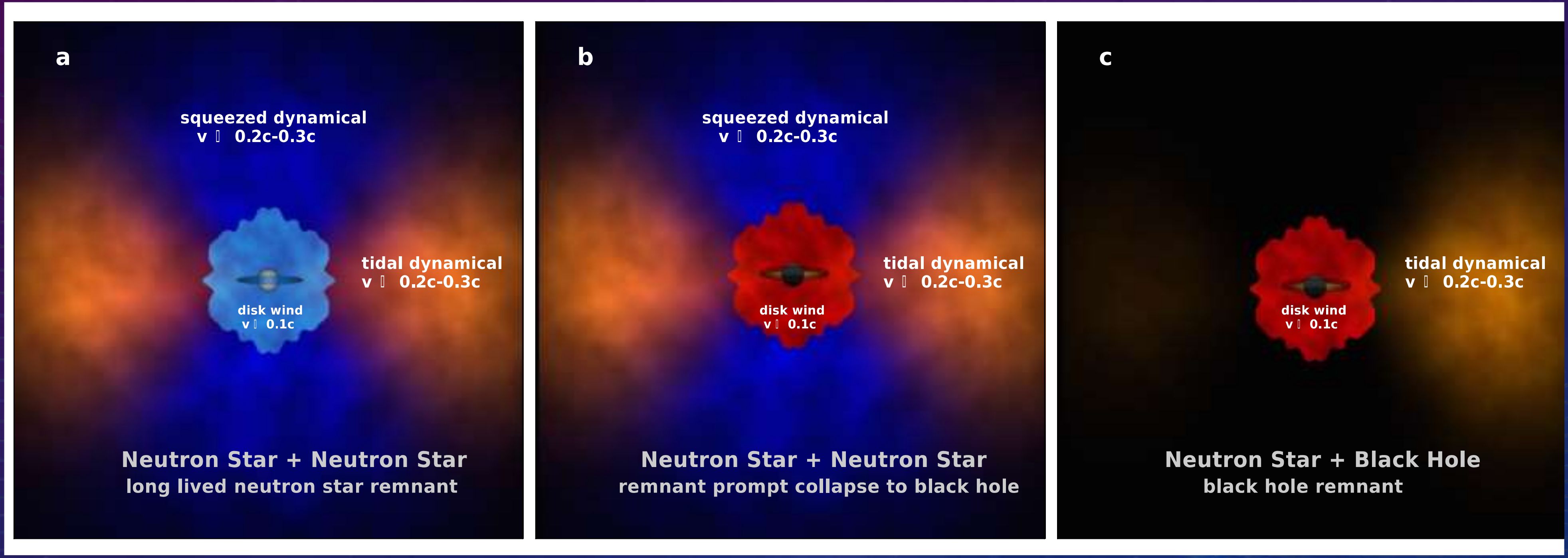
LIGO lower limit: > 320 / Gpc^3 / yr
PTF upper limit: < 800 / Gpc^3 / yr



A Site or The Site?

e.g. Hotokezaka et al. 2018

Parameter Space:
Viewing Angle, Mass ratio, Remnant Lifetime, EoS, Accretion MHD, neutrino physics...



Kasen et al. 2017

LSST can only identify kilonovae to 3 Gpc

ELTs and JWST can only follow-up kilonovae to 1 Gpc

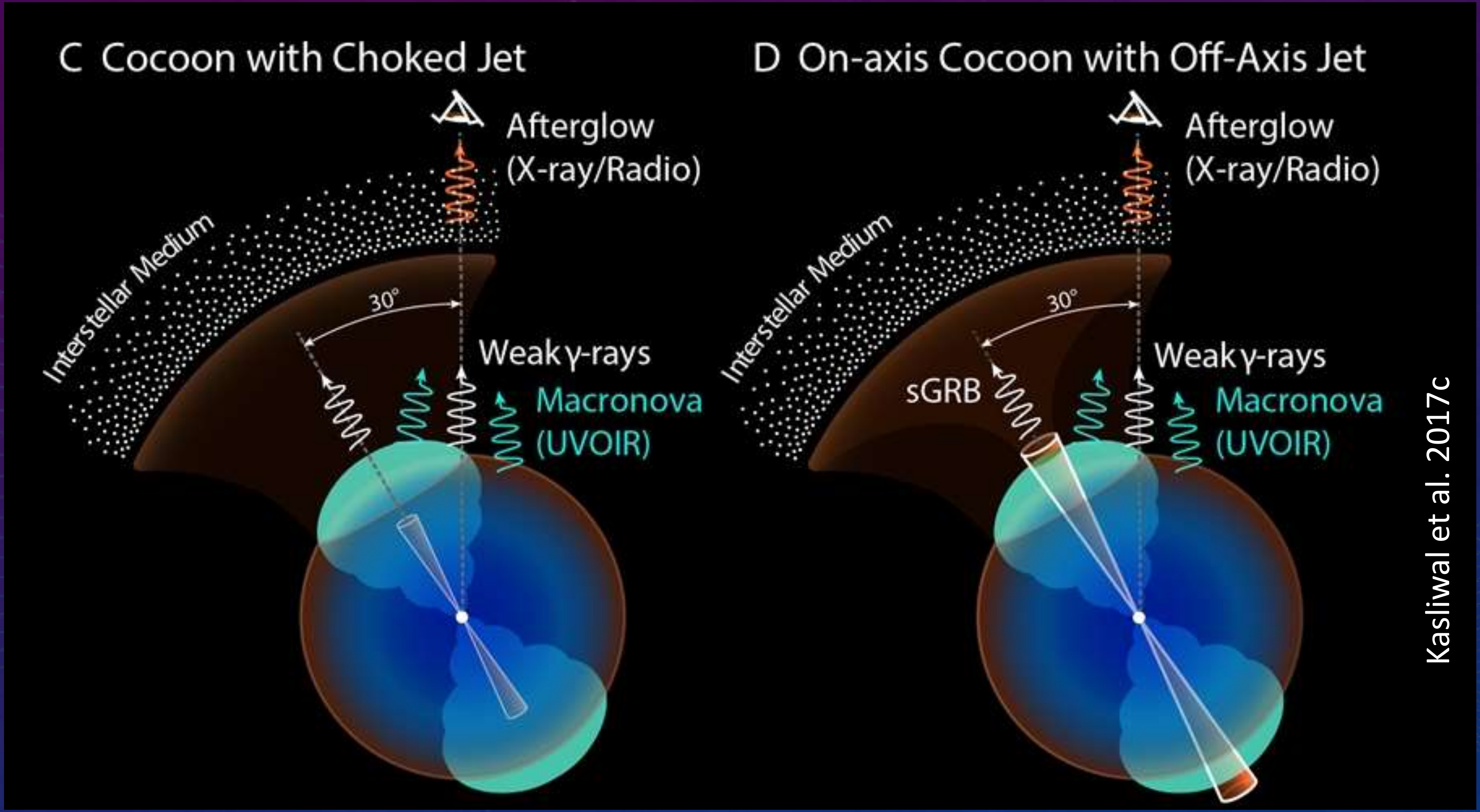
3 Voyagers will give the sample of 1000 events to chart this parameter space!

II. Jet Physics

Are neutron star mergers progenitors of short hard gamma-ray bursts?

Eichler et al. 1989, Paczynski 1989

What is the fate of the jet-cocoon system?



Kasliwal et al. 2017c

Also referred to as "structured jet"
e.g. Lazzati et al. 2017c, Lyman et al. 2018

We have learned so much…
but this is just the beginning!

What is the connection to the class of cosmological short hard gamma-ray bursts?

Does a wide-angle mildly relativistic cocoon always accompany a BNS merger?

Does the jet always successfully escape the cocoon or can it get choked?

How do the observed jet properties vary as a function of viewing angle, mass ratio, remnant lifetime, black hole spins, and ejecta mass?

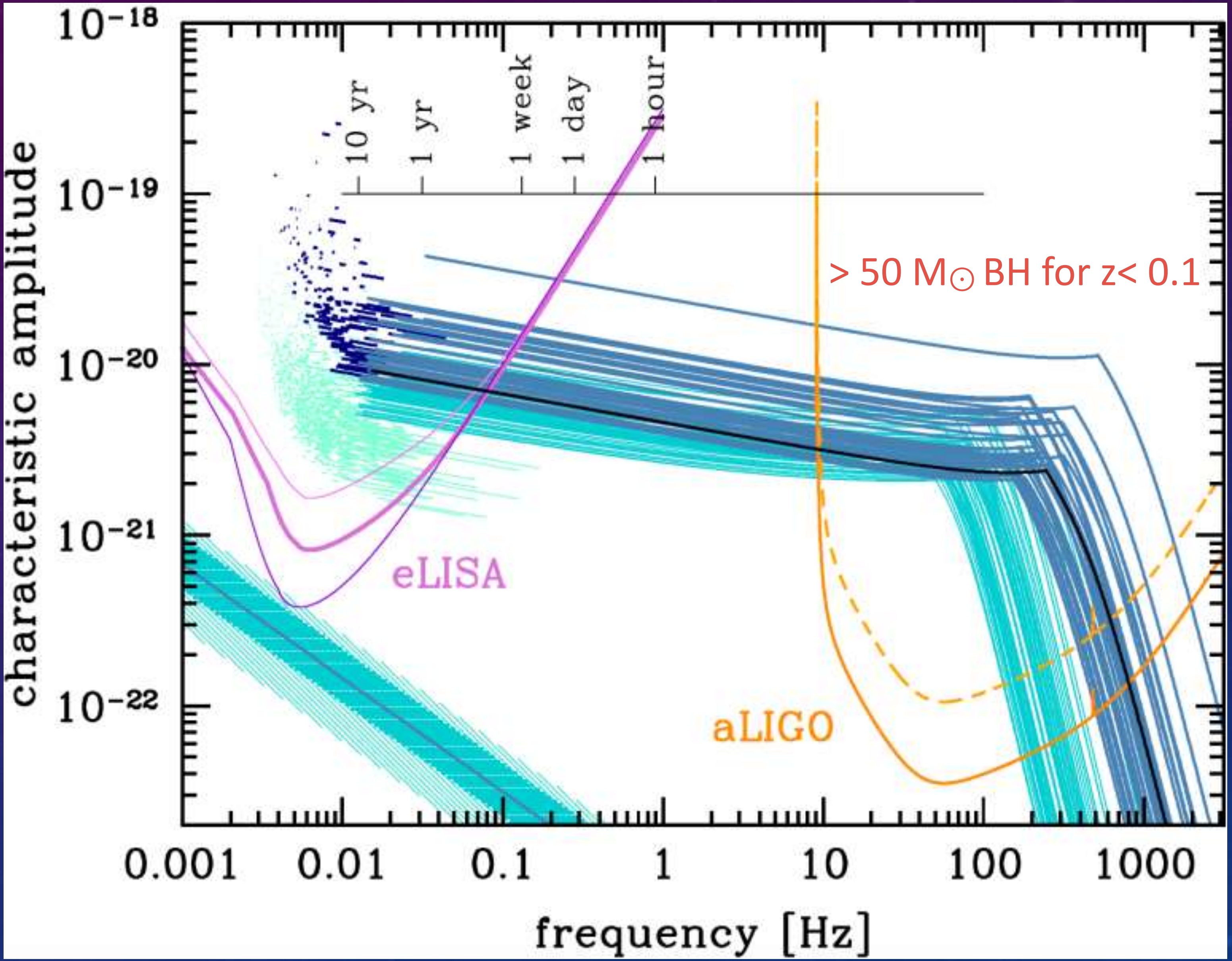
What is the distribution of time delays between the EM and GW signal arrival times?

What are the characteristics of a jet from a NS-BH merger?

Future Gamma-ray, X-ray and Radio facilities limited to < 0.5 Gpc.
Three Voyagers are enough to build a sample of 1000 events.

LISA-3G

A hundred resolvable stellar-mass BBHs by space-based GW detectors before they enter LIGO-Virgo band



- sky localization to 1 deg.^{2}
- time of coalescence to 1 min
- mass and eccentricity to better than 0.01 and 0.001

Conclusions

- BBH hosts poorly determined
- Many key questions can be answered by a 3x Voyager network
- BNS after z>1 never found via kilonovae
  - GRBs better for large z
- SNe risky science case – small or zero N
- LISA a nice complement
  - Provides “triggers”

3G too good!

Thank-yous:

Samaya Nissanke
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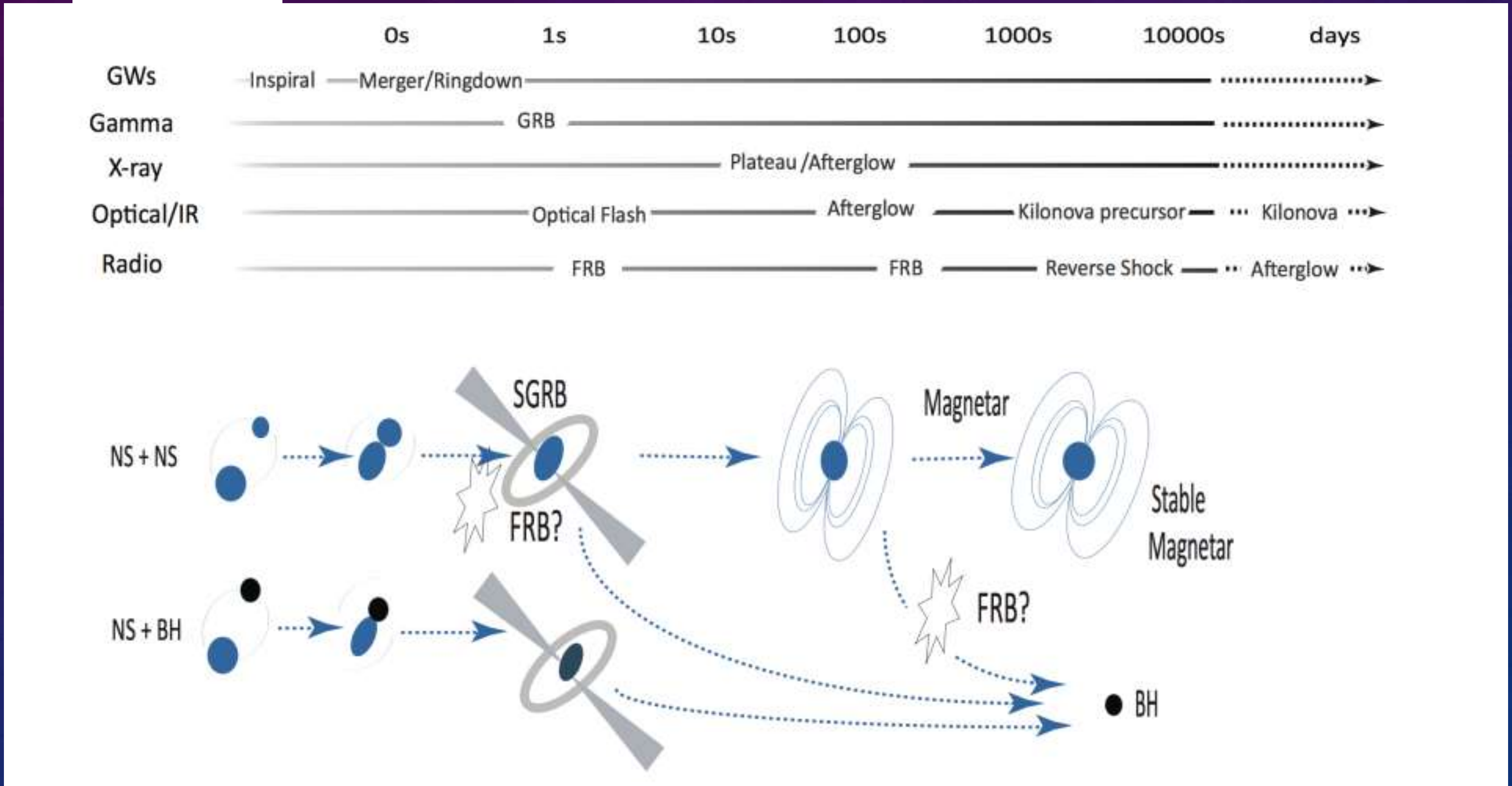
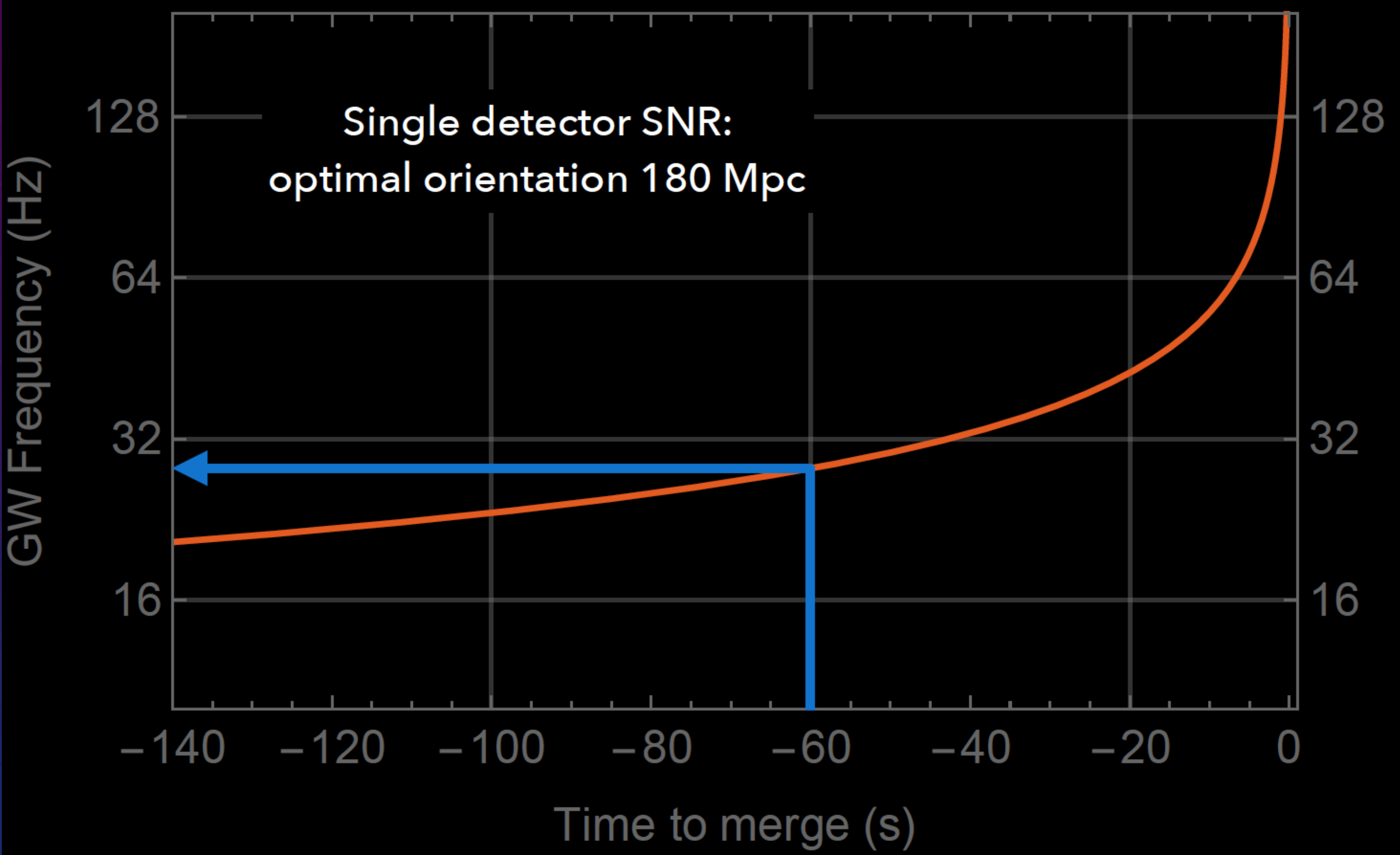
Igor Andreoni
Antonia Rowlinson
David Kaplan
Tara Murphy
Alberto Sesana
Eric Howell
Dougal Dobie

Bonus Slides

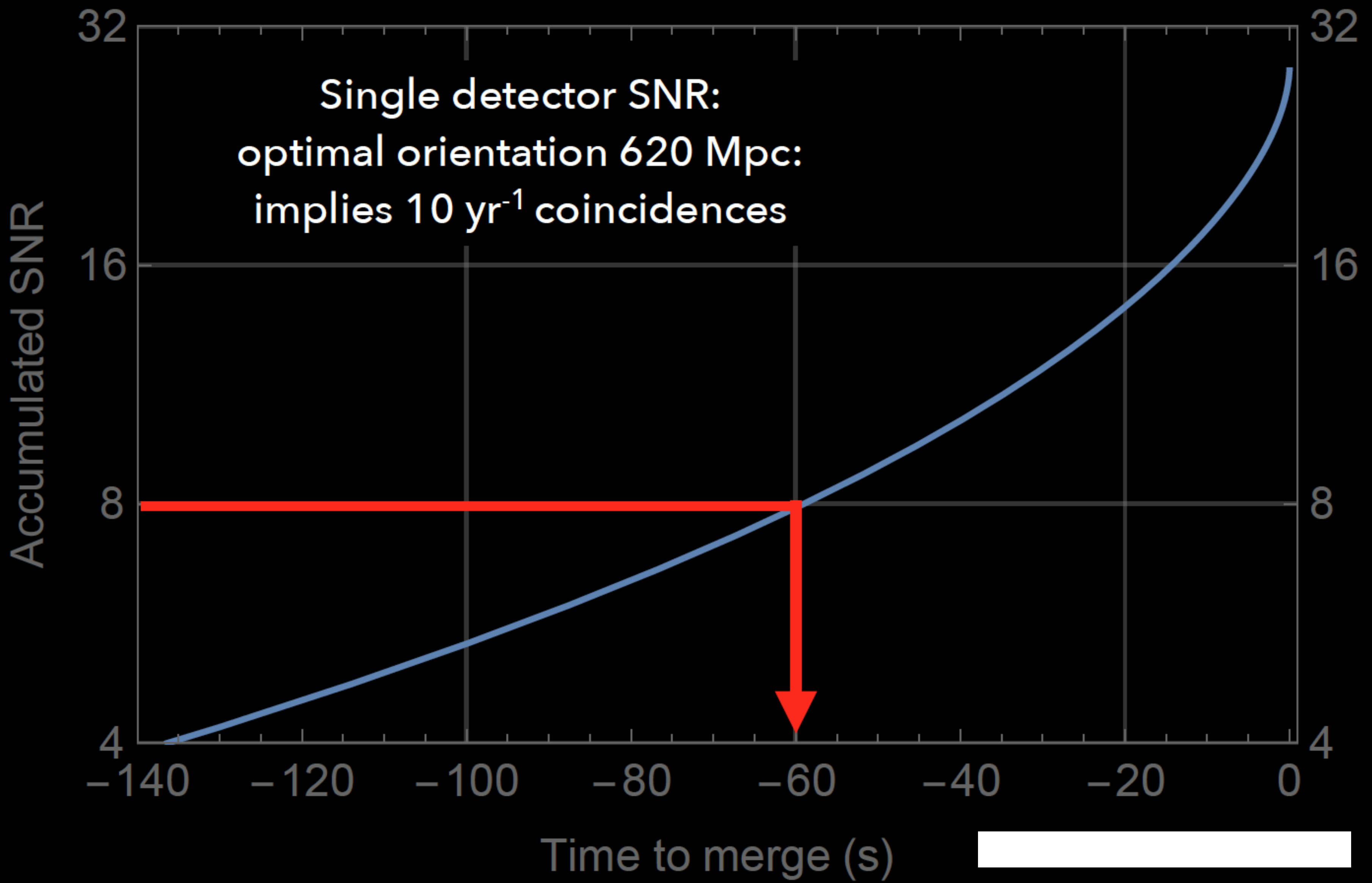
Necessity for early warning signals for EM precursor signals



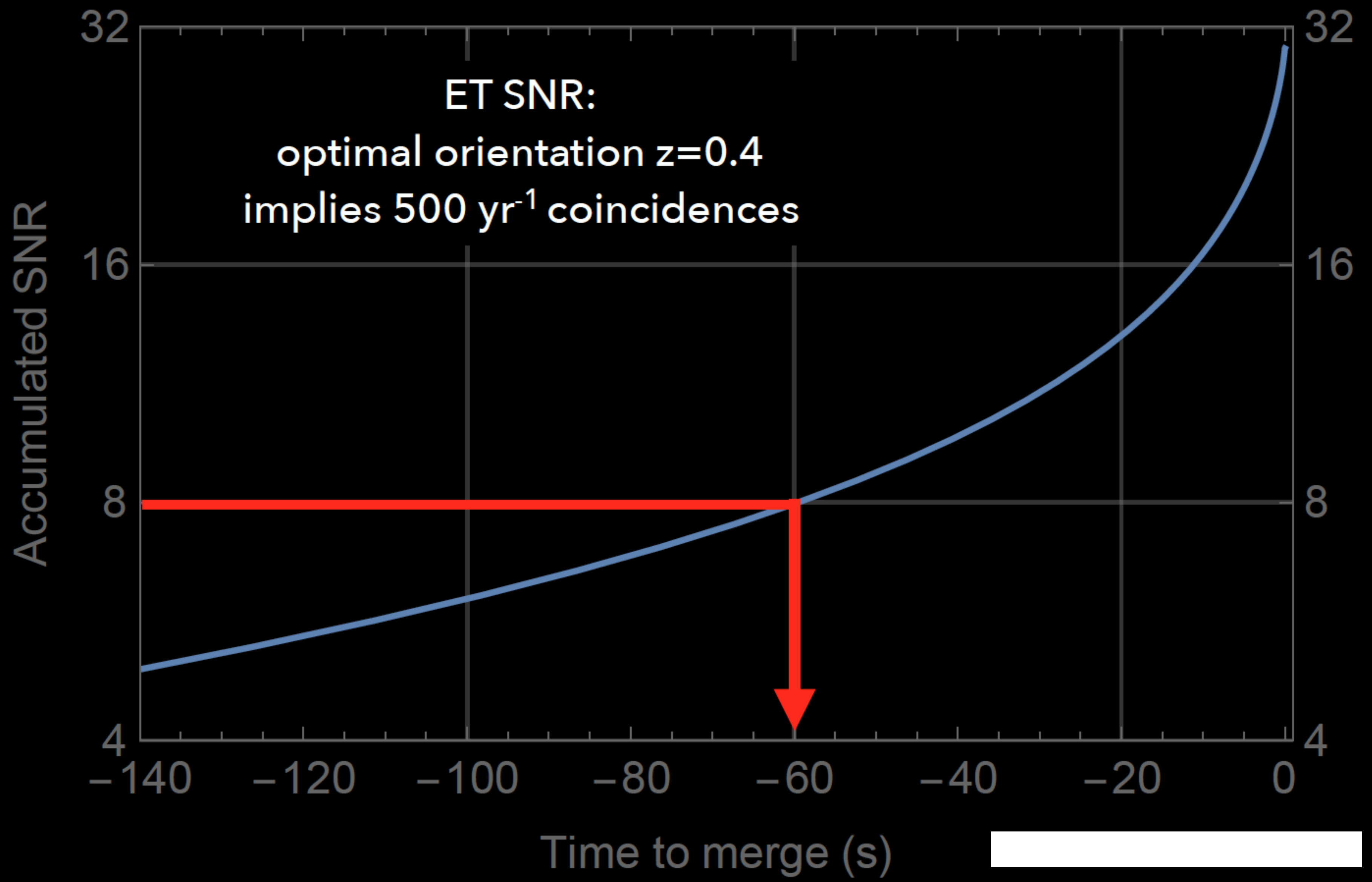
GW FREQUENCY AS A FUNCTION OF TIME



SIGNAL-TO-NOISE RATIO BUILD UP IN TIME FOR BINARY NEUTRON STARS: LIGO-BLUE

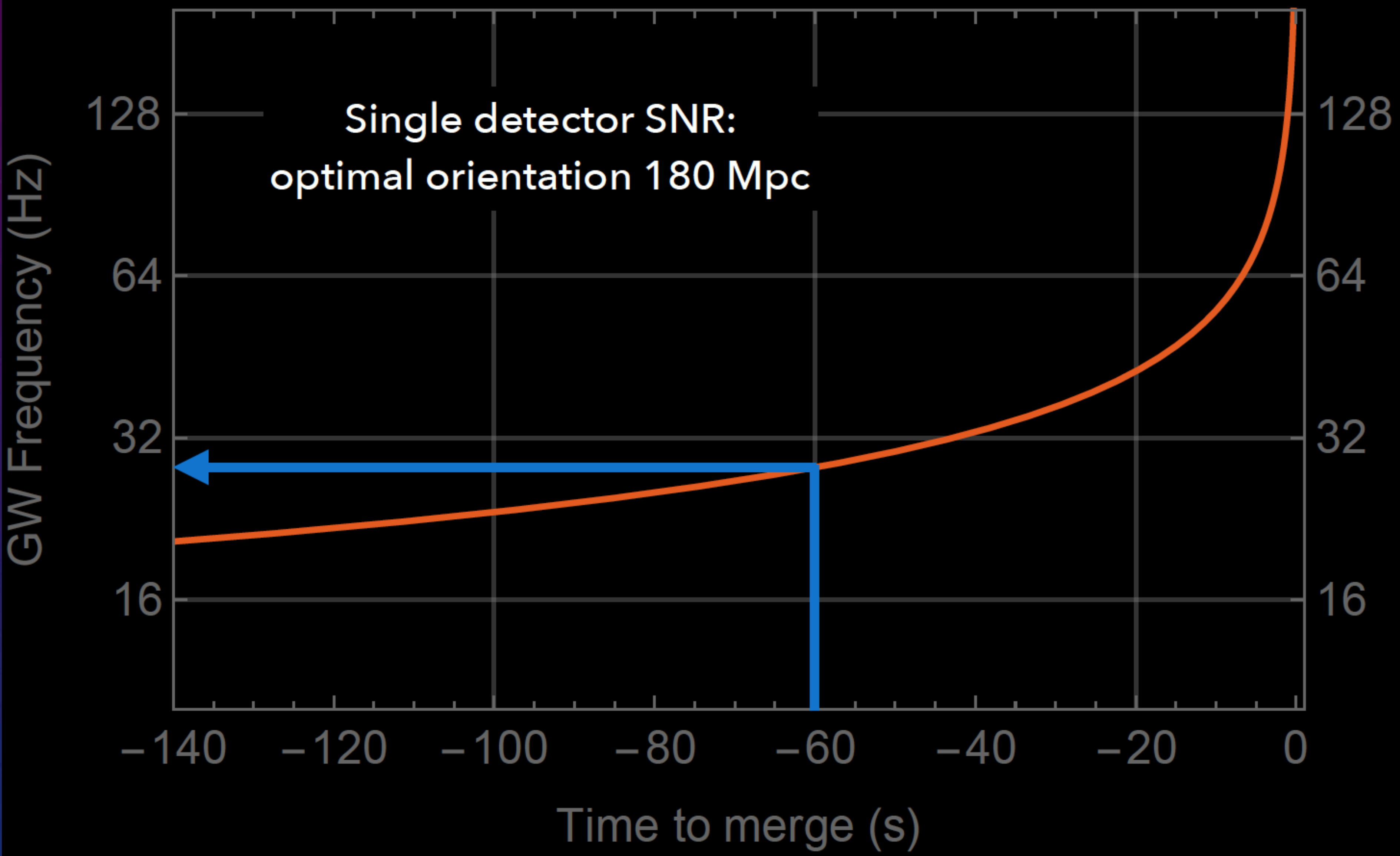


SIGNAL-TO-NOISE RATIO BUILD UP IN TIME FOR BINARY NEUTRON STARS: ETB

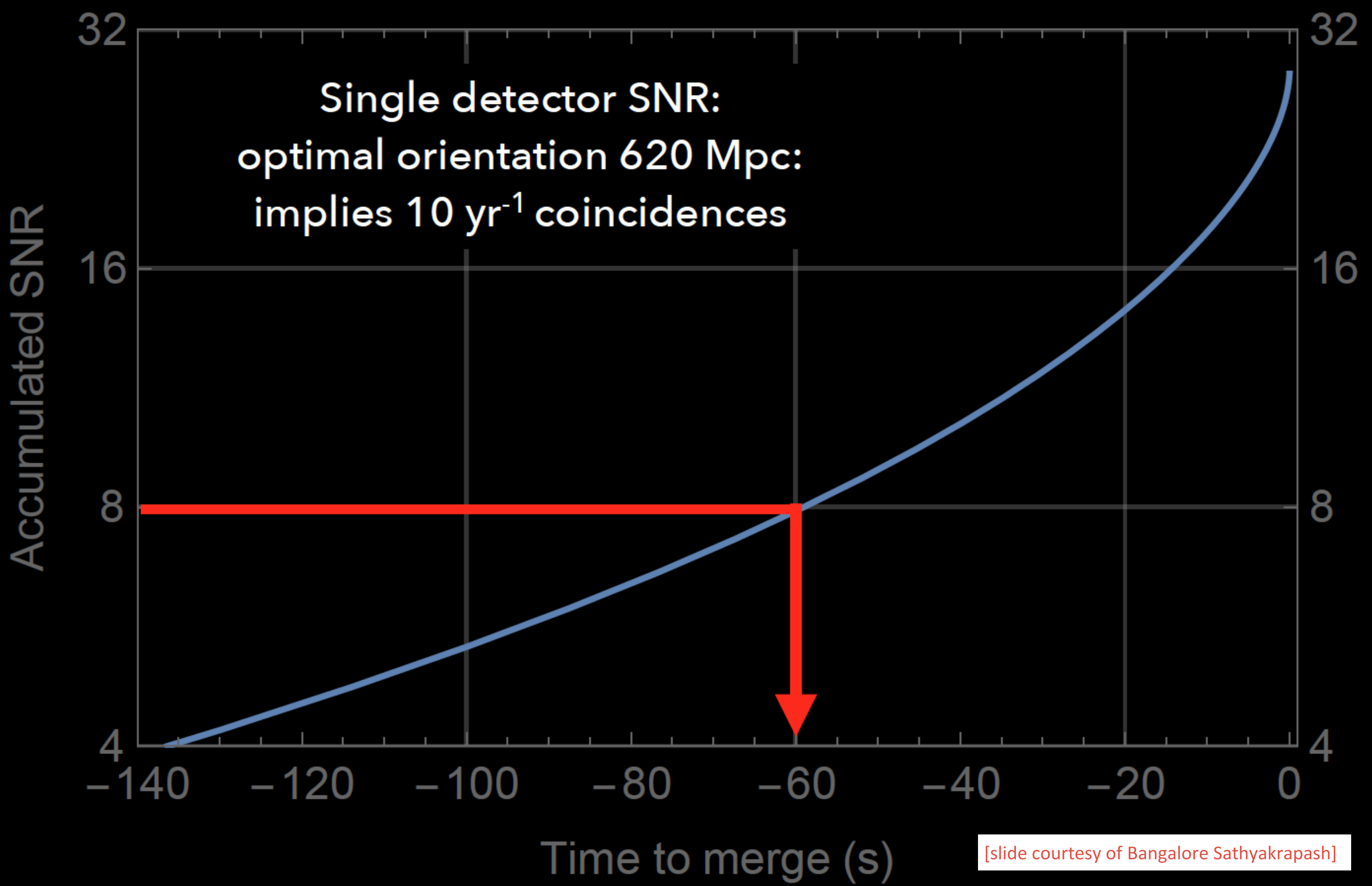


GW FREQUENCY AS A FUNCTION OF TIME

[slide courtesy of Bangalore Sathyakrapash]



SIGNAL-TO-NOISE RATIO BUILD UP IN TIME FOR BINARY NEUTRON STARS: LIGO-BLUE



[slide courtesy of Bangalore Sathyakrapash]

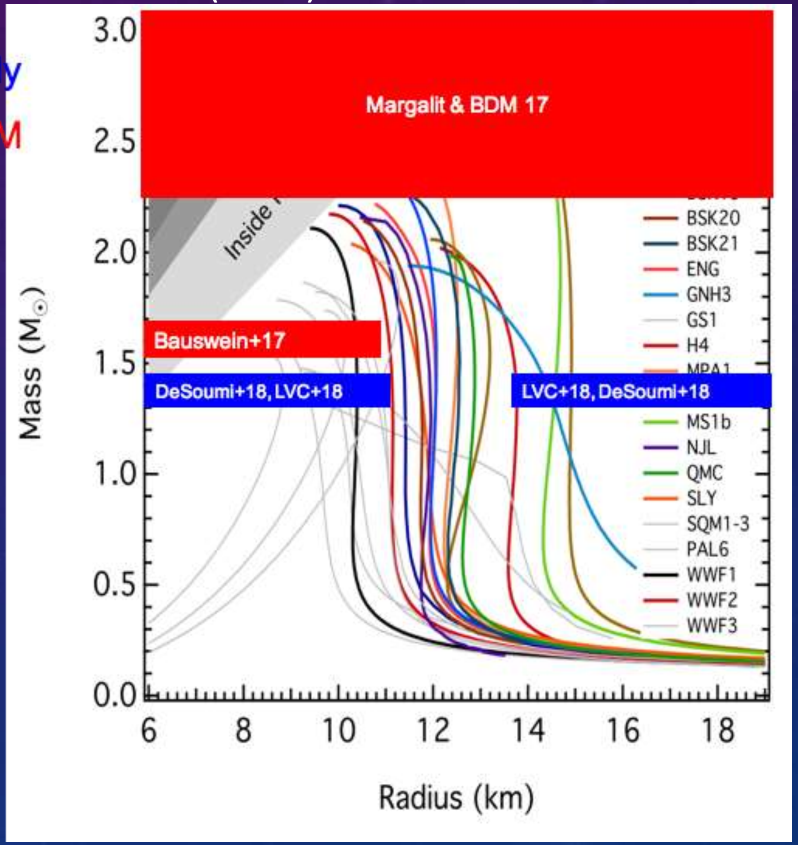
[slide courtesy of Bangalore Sathyakrapash]

Equation of State with MMO: NS binary mergers

figure courtesy of Metzger based on Ozel et al. (2016)

GW only

GW+EM



GW + EM (post-merger)

[see also Radice et al. 2018, Rezzolla et al. 2018, etc]

EoS temperature Effects

Equation of State with MMO: Single Source

Slide to be finished

What can be inferred about crust physics from magnetar flares and outbursts?

For continuous wave sources, if GW and EM signals are in or out of phase, what does this tell us about the crust and magnetosphere?