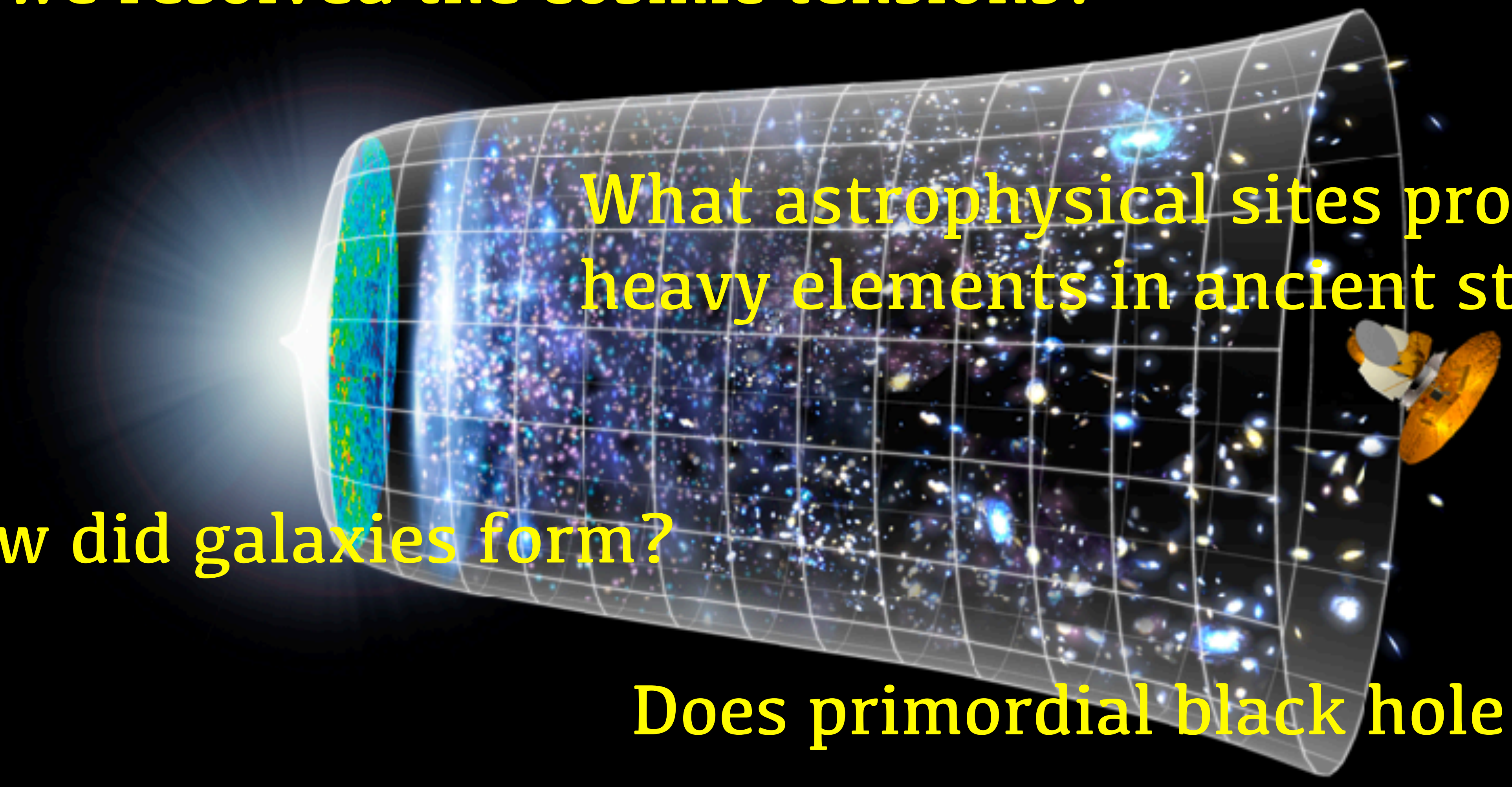
Prospects for multi-messenger observations with improved gravitational-wave detectors

Hsin-Yu Chen

(NASA Einstein Fellow, MIT)

INT-22-2a program on "Neutron Rich Matter on Heaven and Earth", July 2022

Have we resolved the cosmic tensions?



What astrophysical sites produced the heavy elements in ancient stars?

How did galaxies form?

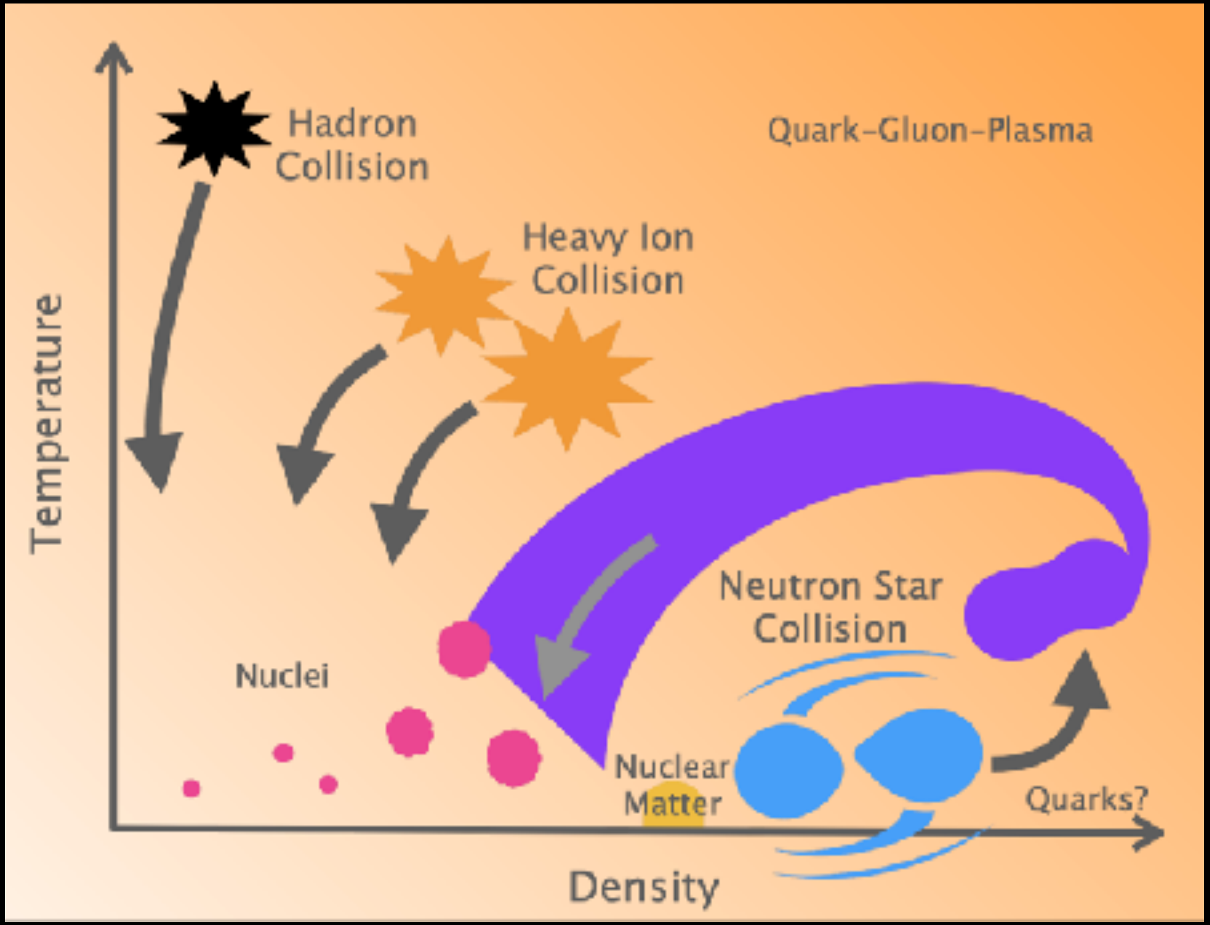
Does primordial black hole exist?

We have learned a lot about how the Universe work from theories, experiments and observations, but there are still big questions to be answered.

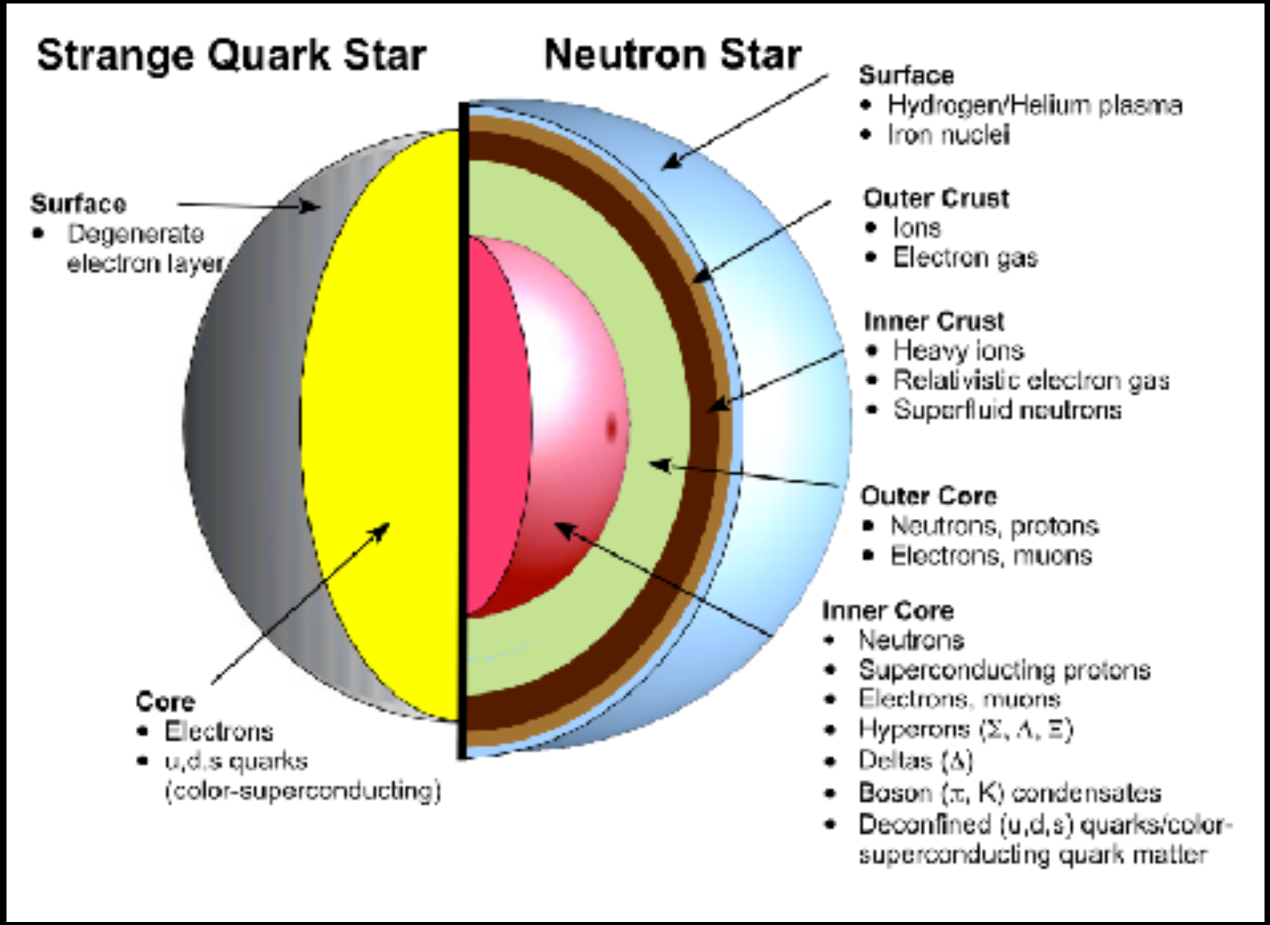
NASA/WMAP Science team

The properties of extreme matter in neutron stars

What are the properties of the ultra-dense and low/finite temperature matter in neutron stars? What is the structure of neutron star?



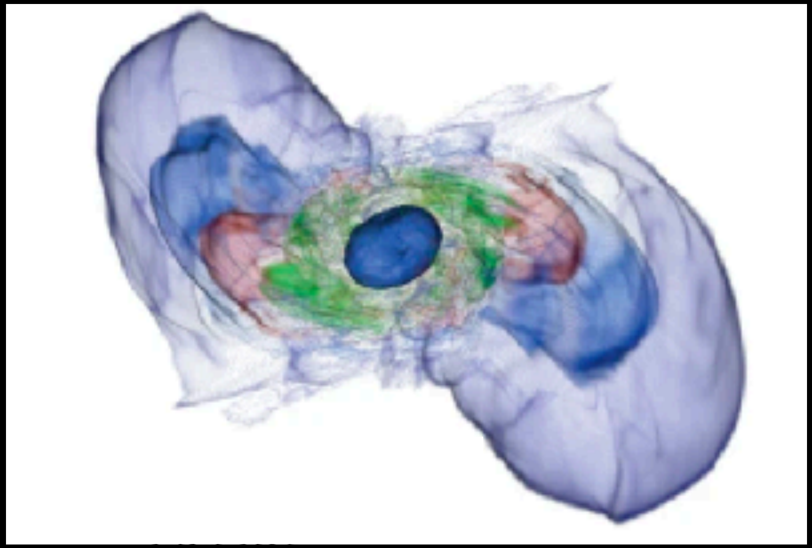
CE Horizon Study, arXiv:2109.09882



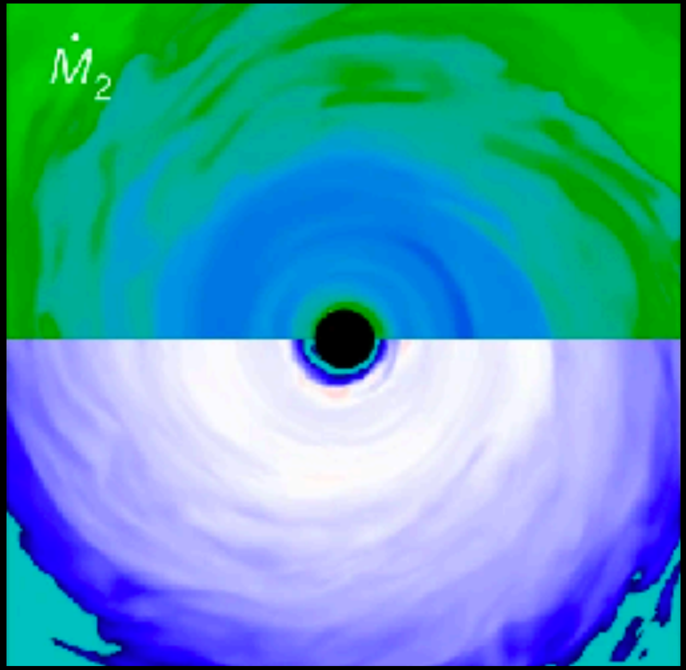
Weber et al., MPLA (2014)

The origin(s) of heavy elements

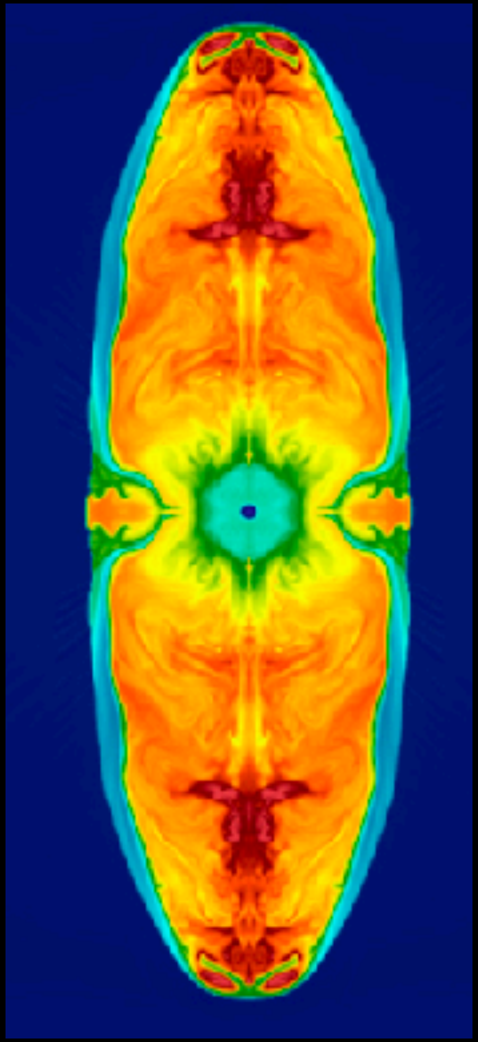
Where are the production sites of heavy elements: neutron star mergers, collapsars, magnetorotational core-collapse supernovae, or somewhere else?



Foucart, PRD (2014)

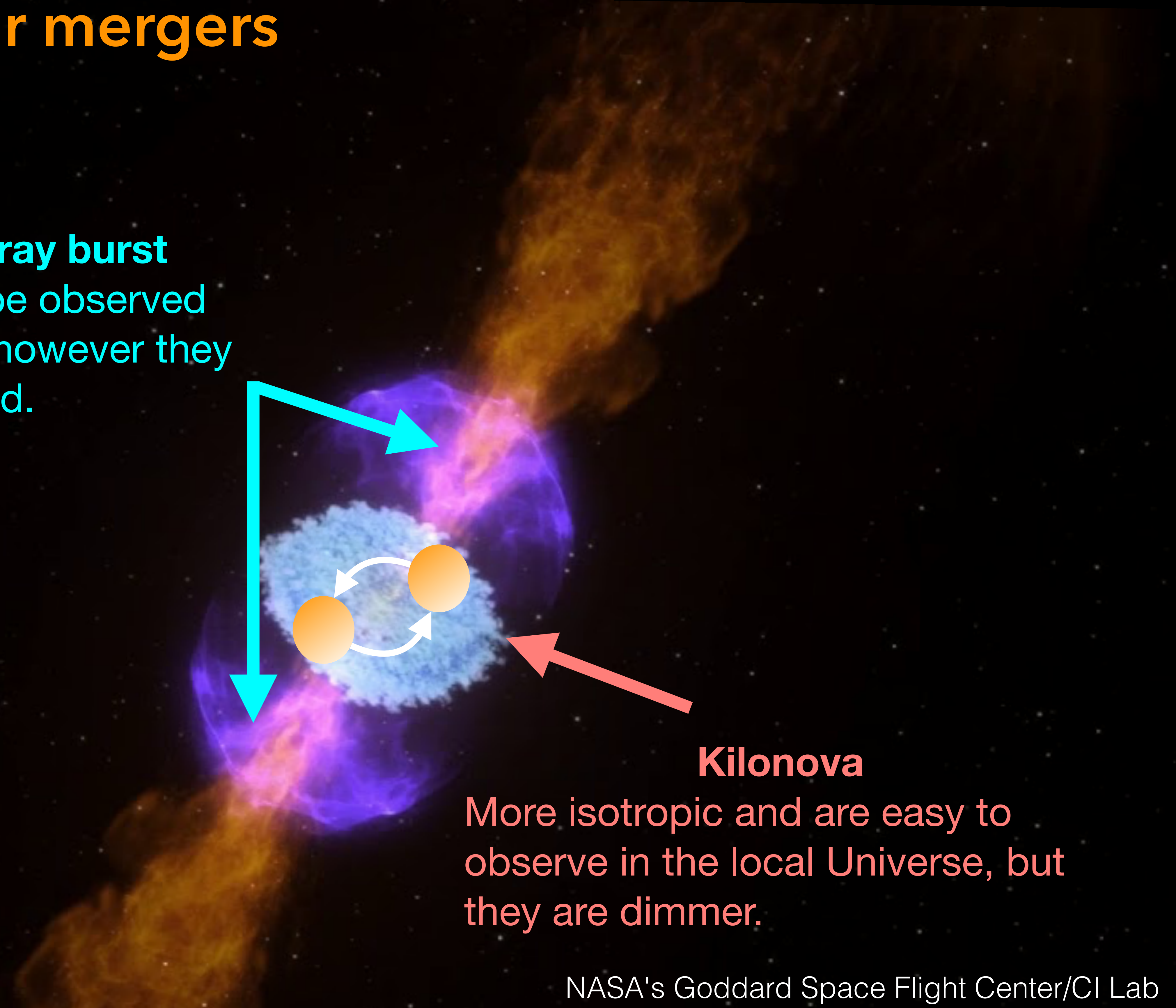


Siegel et al, Nature (2019)



Mösta et al., ApJ (2018)

Known electromagnetic emissions of neutron star mergers



Short gamma-ray burst
Energetic and can be observed at higher redshifts, however they are narrowly beamed.

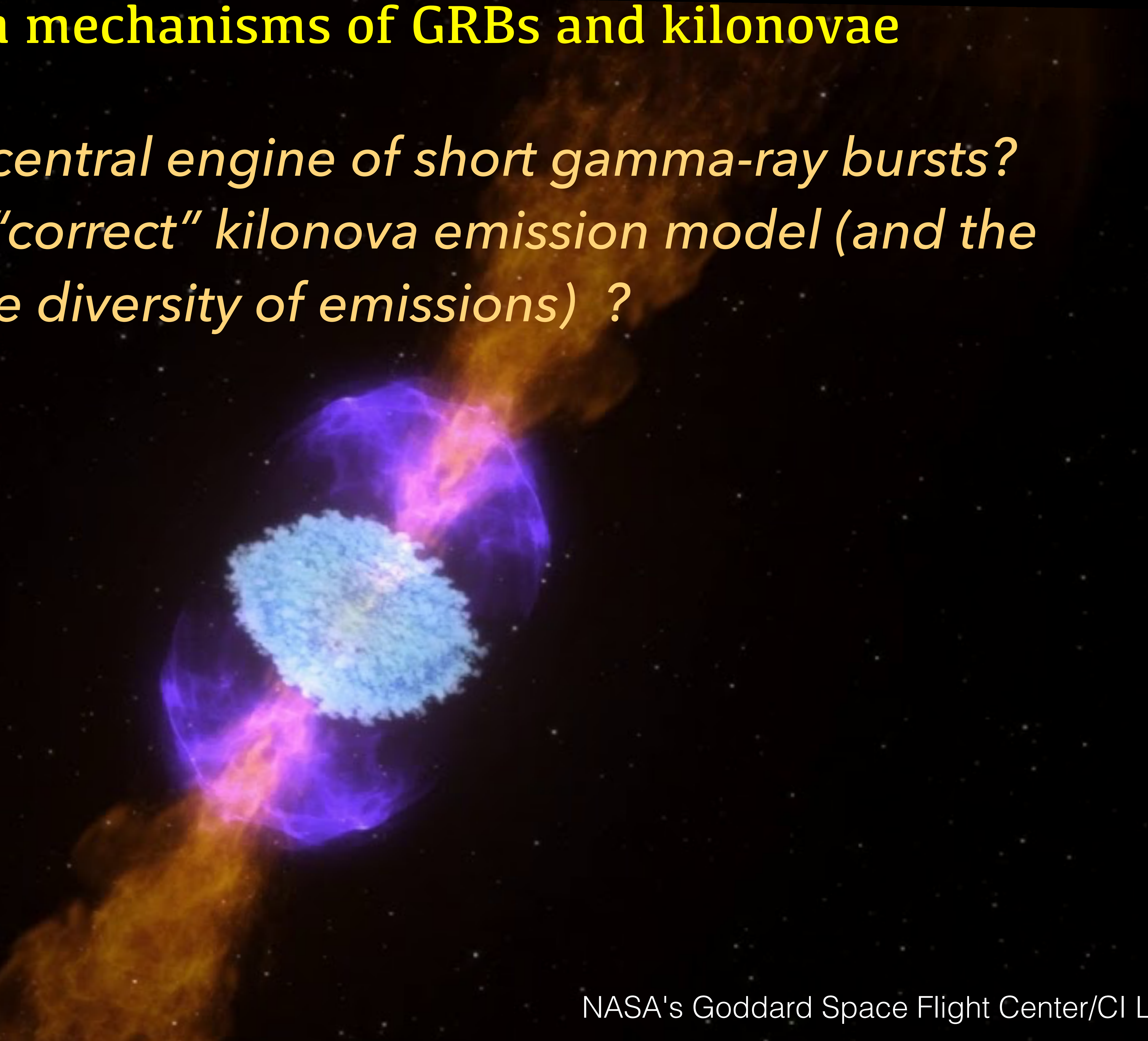
Kilonova
More isotropic and are easy to observe in the local Universe, but they are dimmer.

NASA's Goddard Space Flight Center/CI Lab

The emission mechanisms of GRBs and kilonovae

What is the central engine of short gamma-ray bursts?

What is the "correct" kilonova emission model (and the origins of the diversity of emissions) ?



NASA's Goddard Space Flight Center/CI Lab

Future gravitational-wave detectors
will be critical to address these questions.

Multi-band gravitational-wave observatories planned in 2G+

GW frequency

NanoHz **mHz** **deciHz** **>1Hz**

-Ground-based (nanoHz):

Next-generation pulsar timing array

-Space-based (mHz):

LISA, TianQin

-Ground-based, space-based (deciHz):

DECIGO, BBO, TianGO, Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS), Lunar Gravitational-Wave Antenna (LGWA)

-Ground-based (>1Hz):

Einstein Telescope, Cosmic Explorer, Voyager, Neutron Star Extreme Matter Observatory (NEMO)

Upgrade of ground-based detectors

2023 — O4

2025 — A+

2030 — Voyager

2040 — Cosmic Explorer/ Einstein Telescope

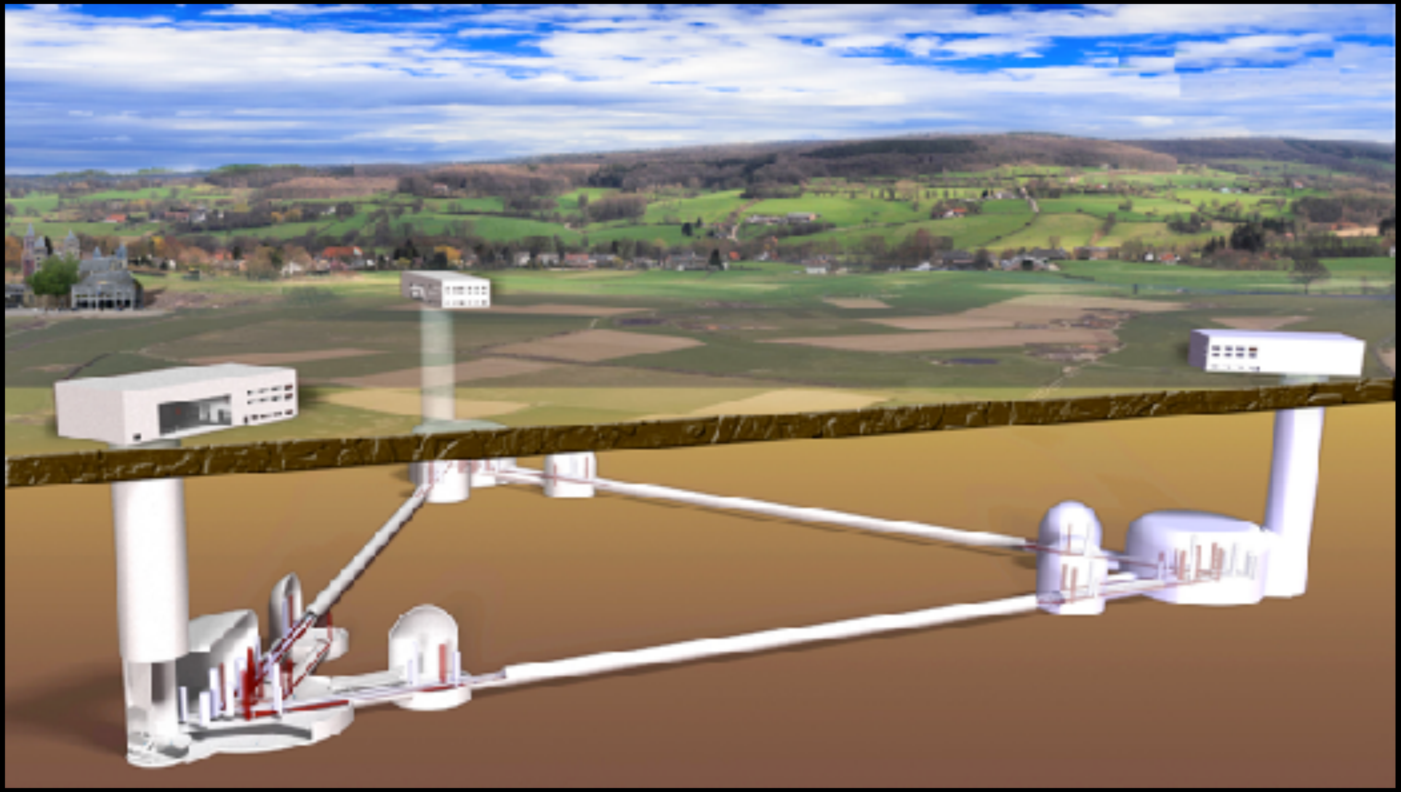
-Upgrade of LIGO facilities.

-Better handling of noises, e.g. better mirror coating, squeezing etc.

Upgrade of ground-based detectors

2023 2025 2030 2040

O4 → A+ → Voyager → Cosmic Explorer/ Einstein Telescope



-*Underground in Sardinia or Netherlands.*

-*Six detectors in a triangle (10-10-10km).*

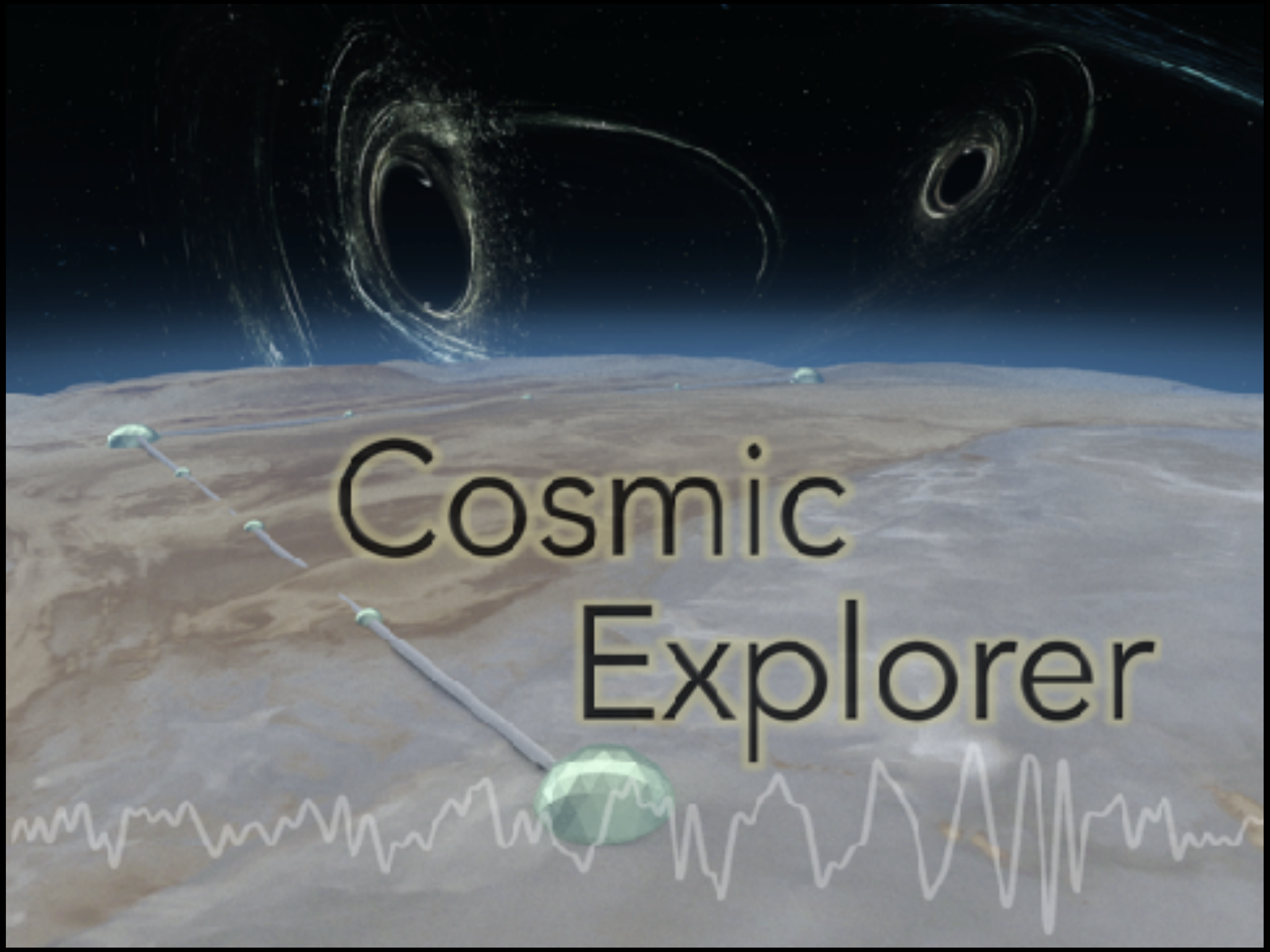
-*Can observe down to a few Hz.*

Upgrade of ground-based detectors

2023 2025 2030 2040

O4 → A+ → Voyager → Cosmic Explorer/ Einstein Telescope

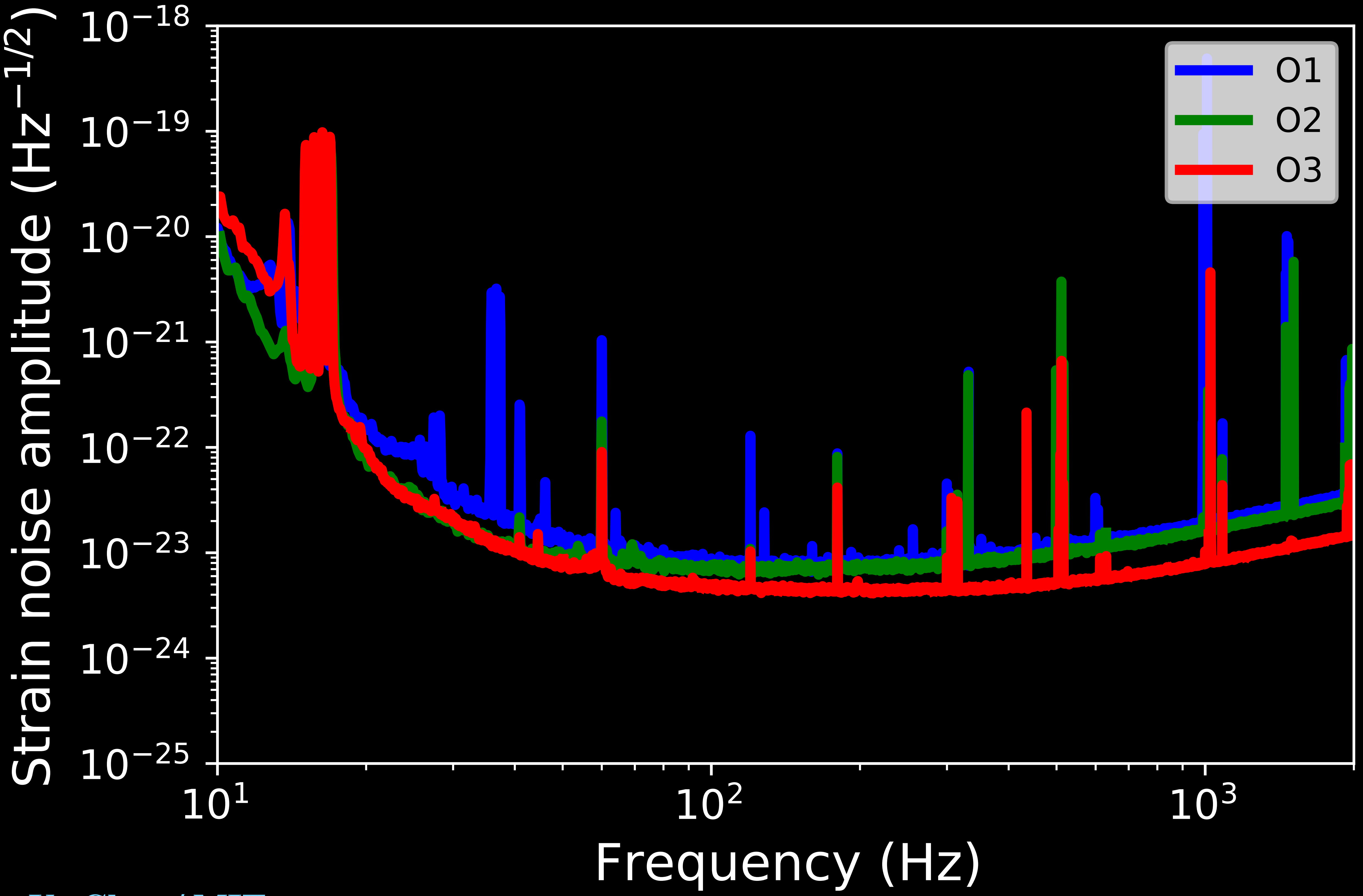
2G 2.5G 3G



-A scaled up of LIGO (40-40km, 20-20km).

-Use of mature technologies.

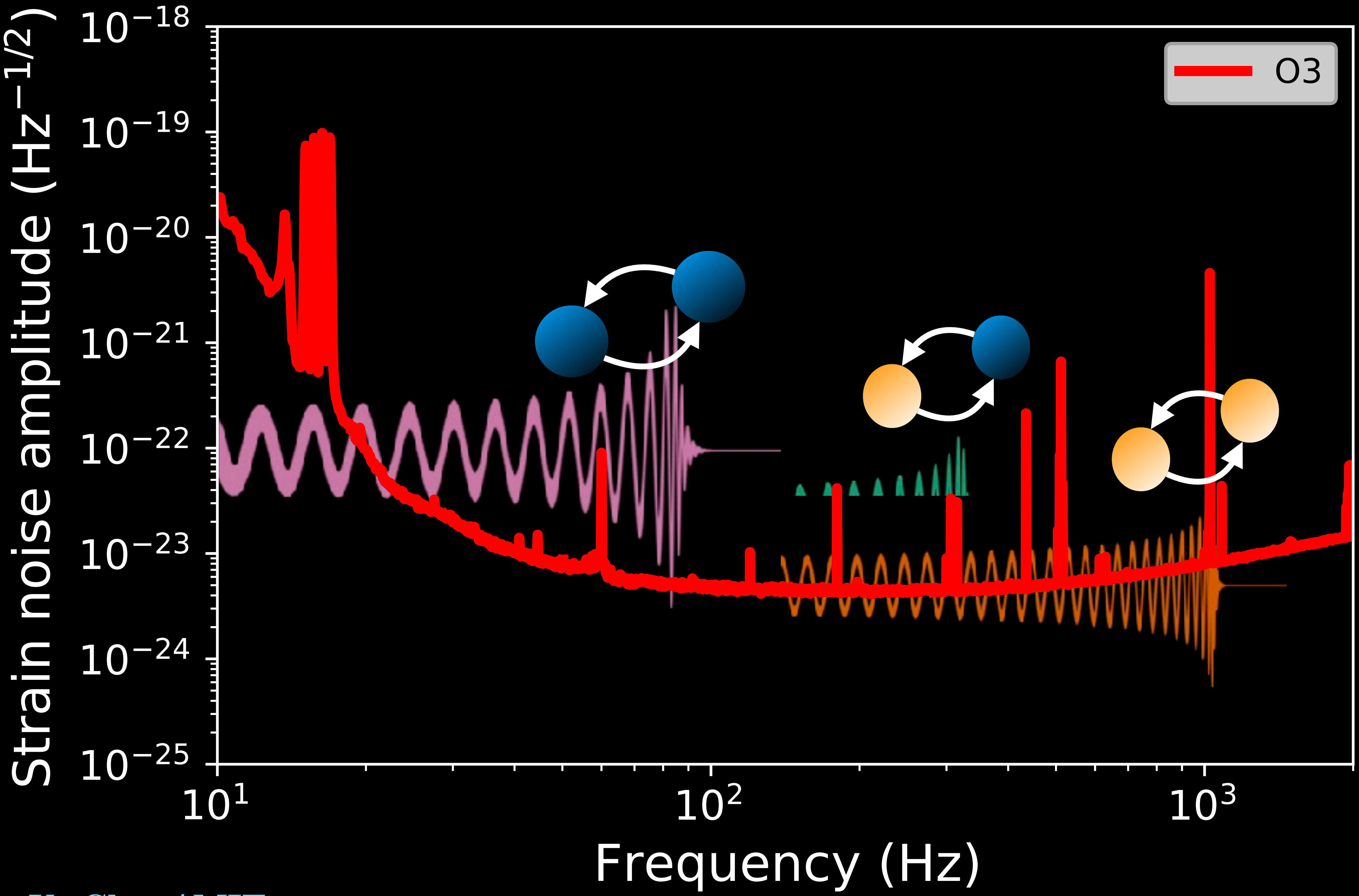
Gravitational-wave detector sensitivities



Hsin-Yu Chen / MIT

LIGO Lab/LIGO Document T1500293

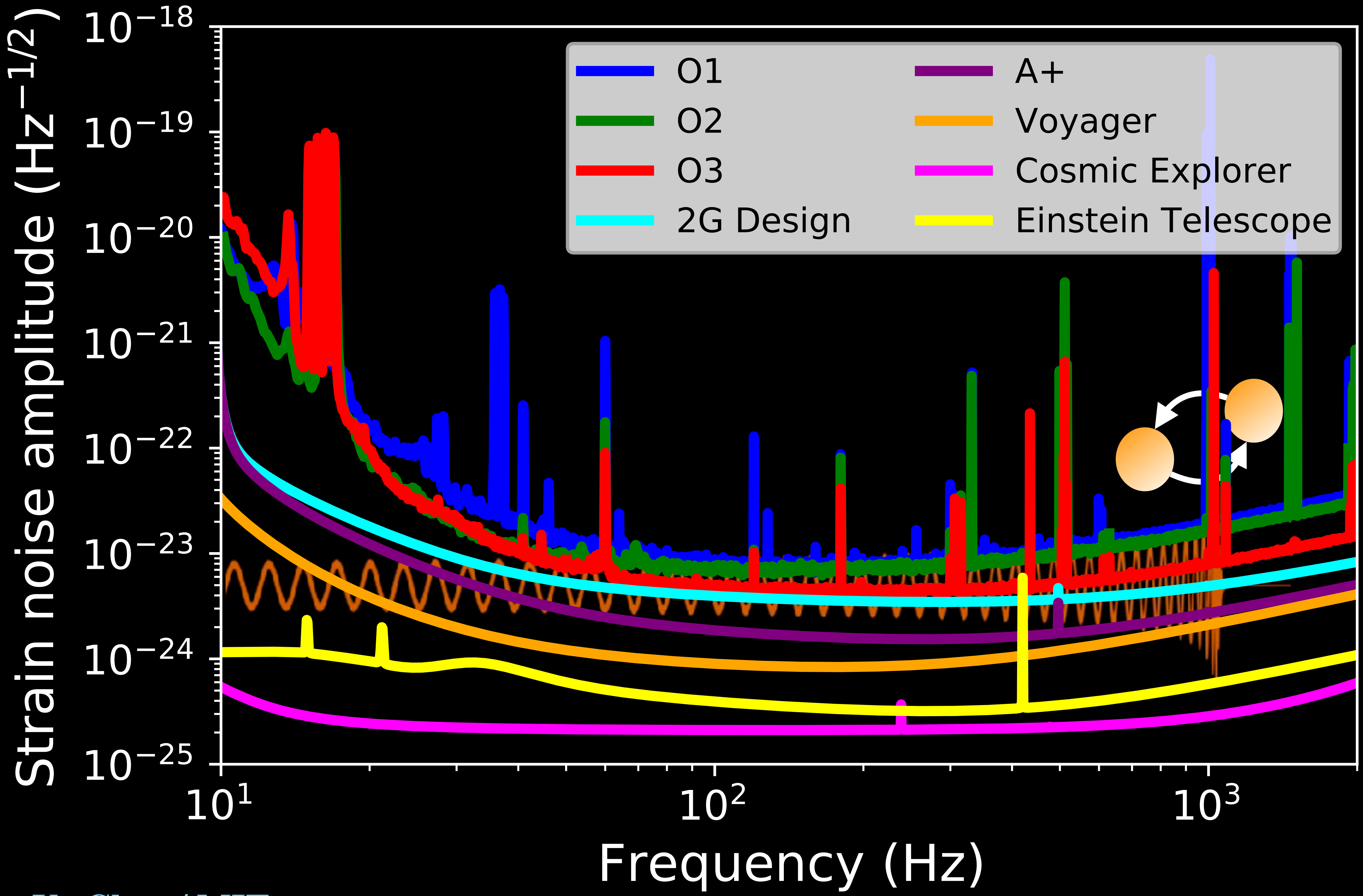
Gravitational-wave detector sensitivities



Hsin-Yu Chen / MIT

LIGO Lab/LIGO Document T1500293

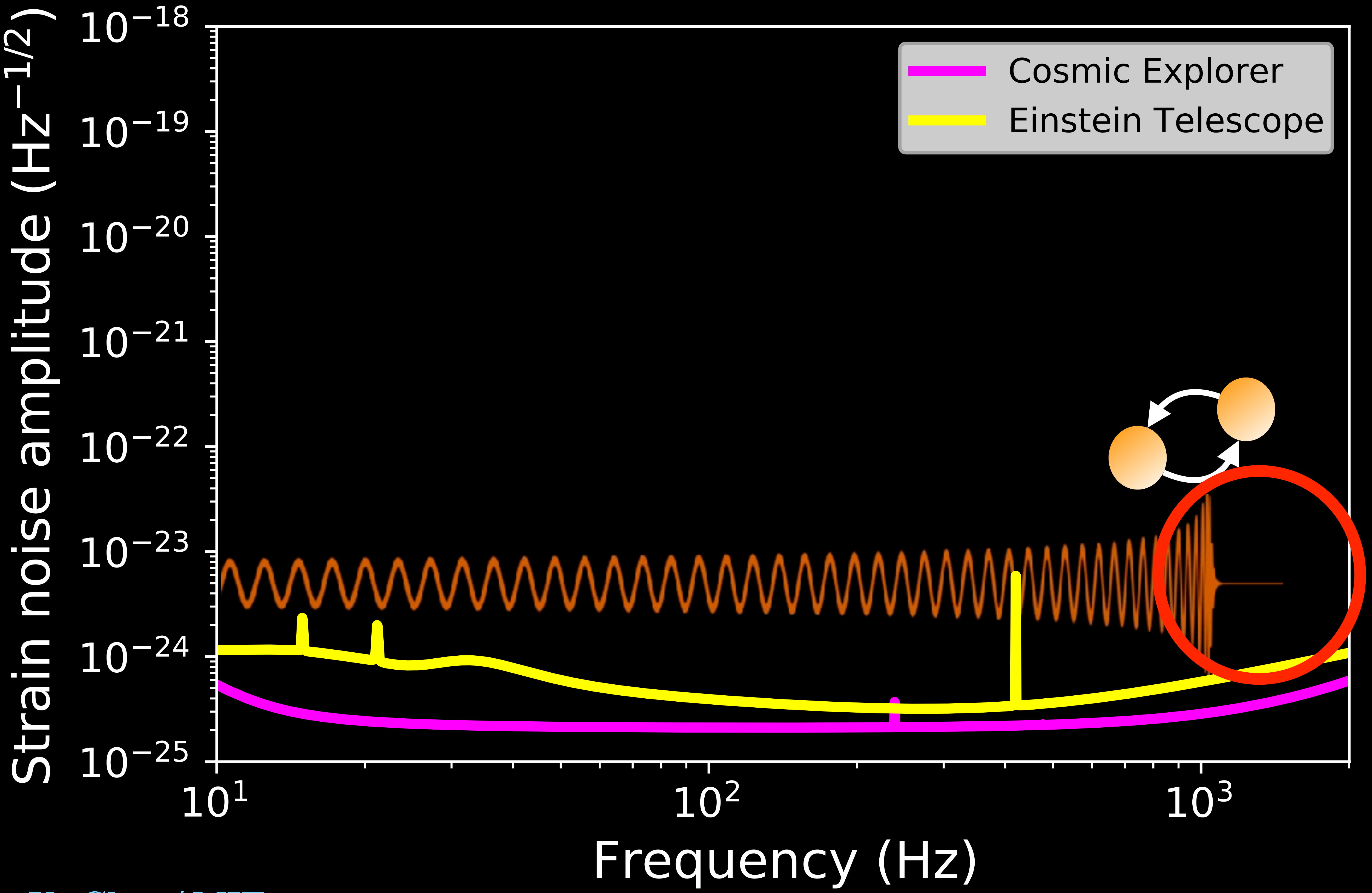
Gravitational-wave detector sensitivities



Hsin-Yu Chen / MIT

LIGO Lab/LIGO Document T1500293

Gravitational-wave detector sensitivities

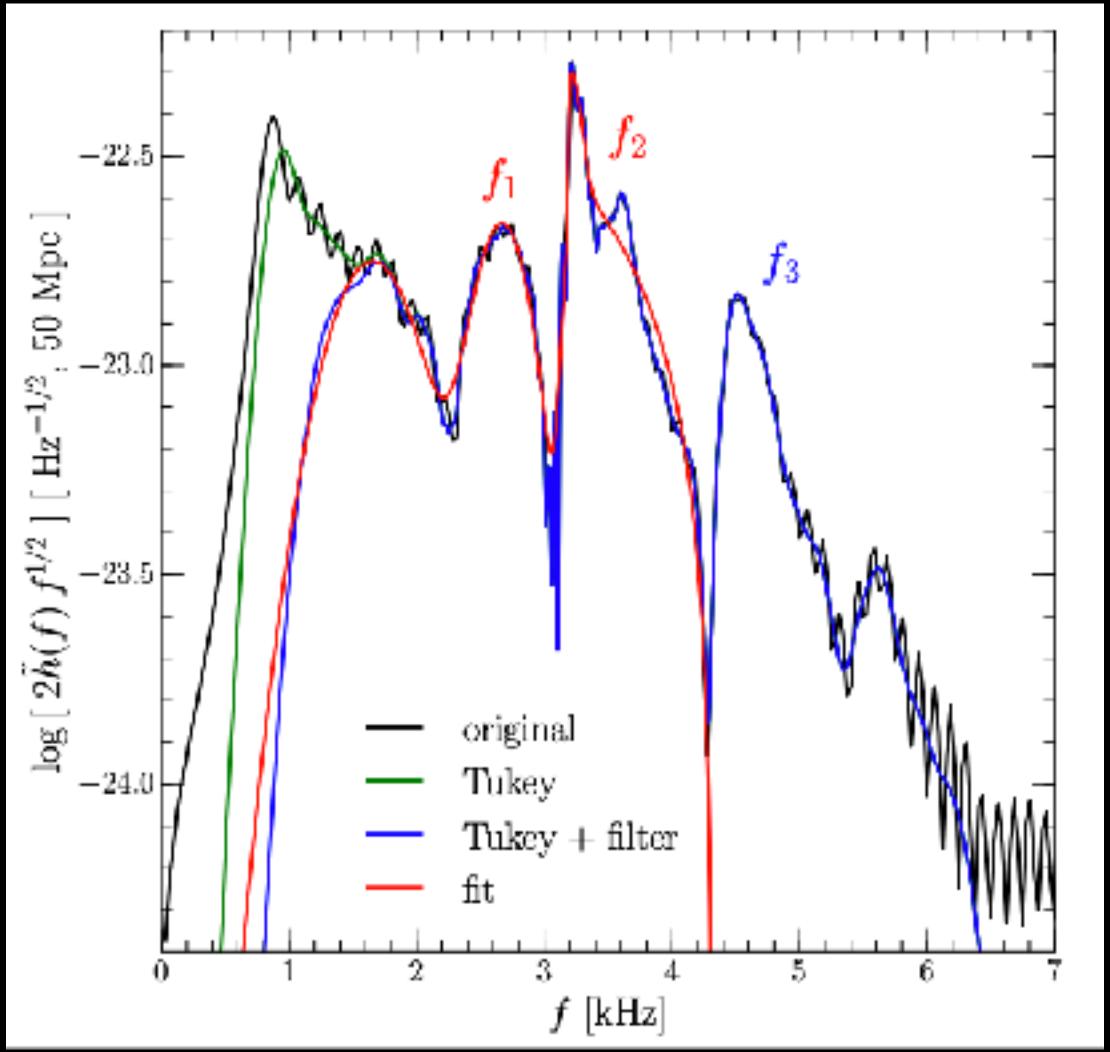


Hsin-Yu Chen / MIT

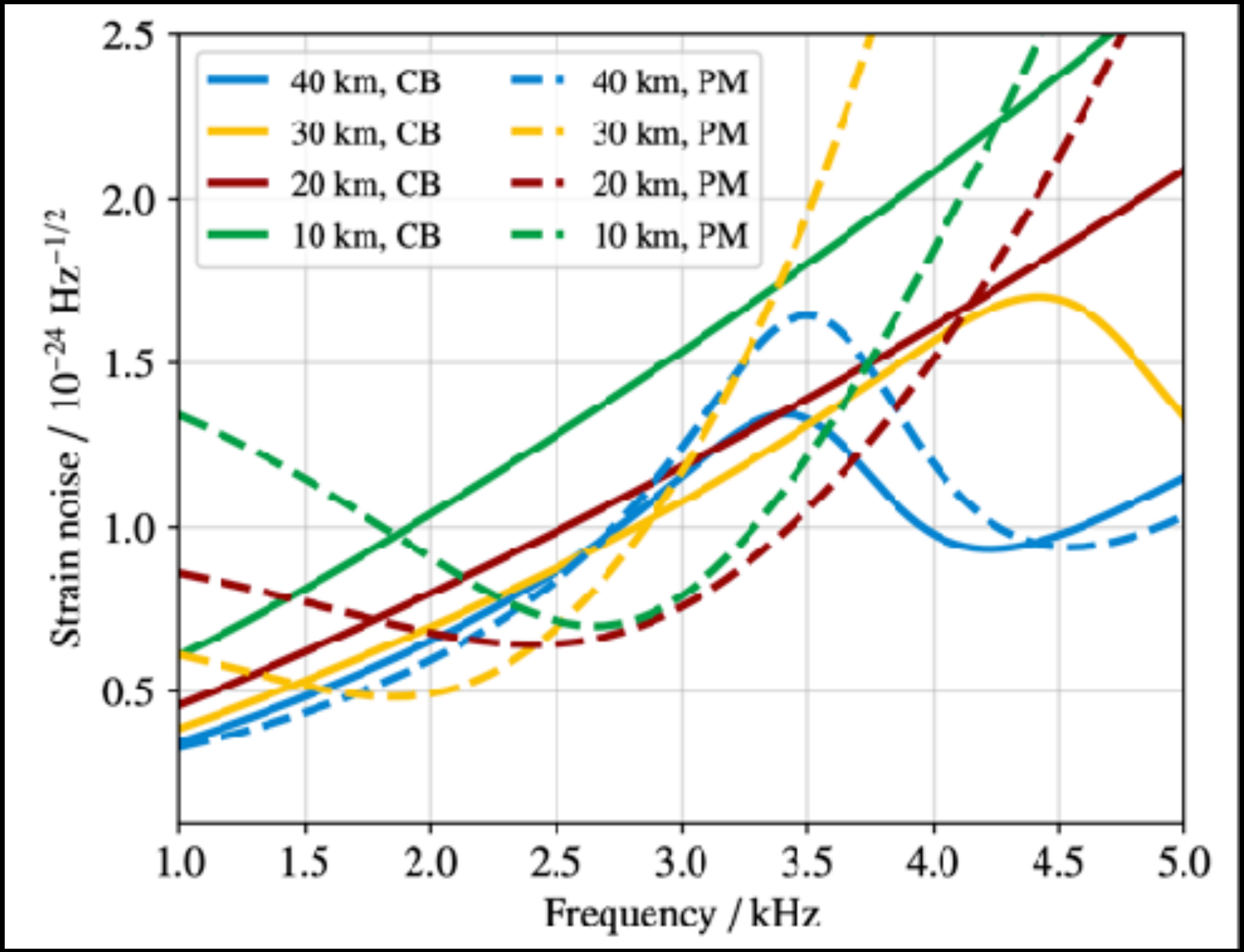
LIGO Lab/LIGO Document T1500293

The detection of post-merger signals

In 3G, we expect a few binary neutron star mergers a year with post-merger detections.

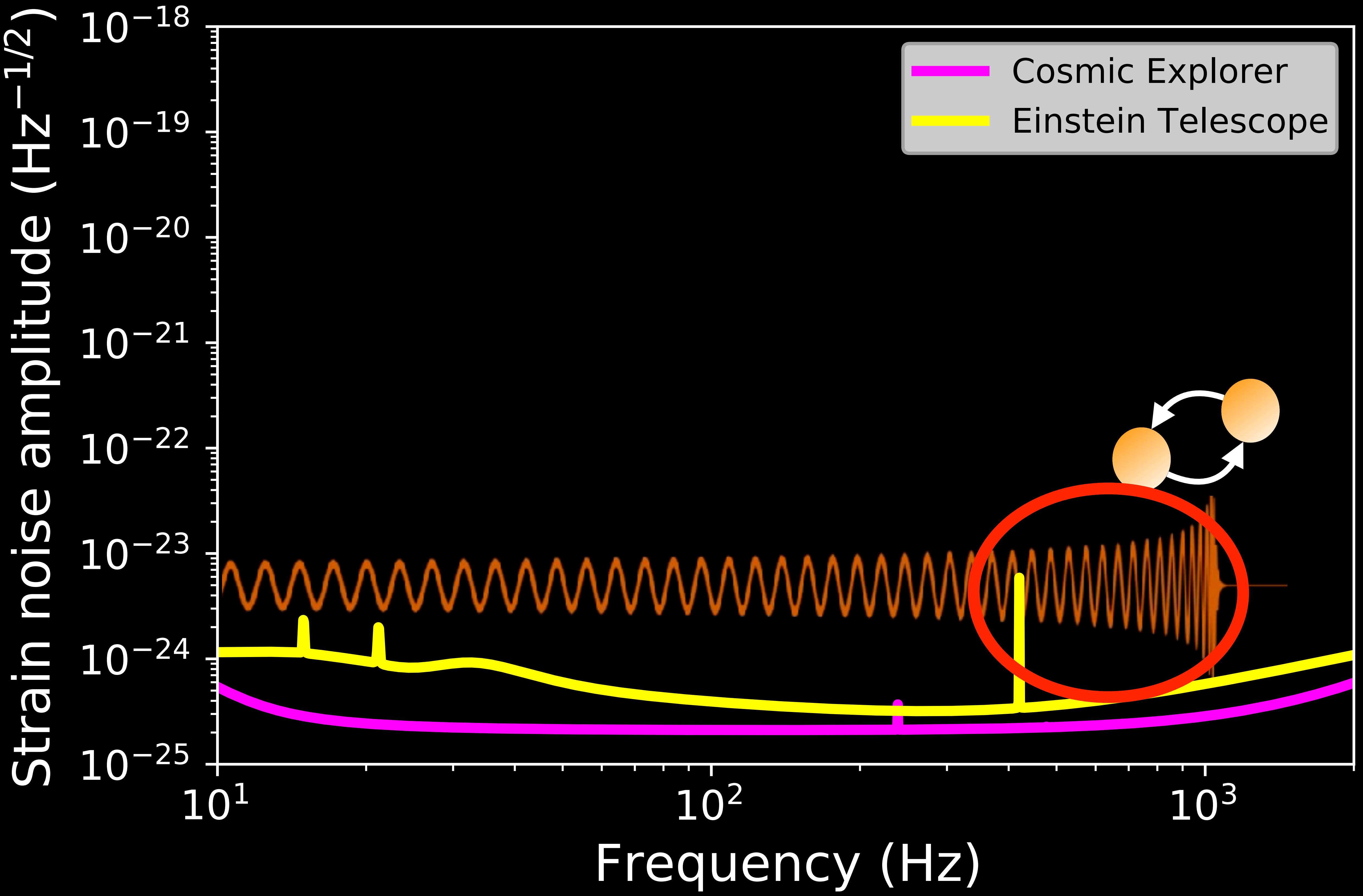


Takami et al, PRD (2015)

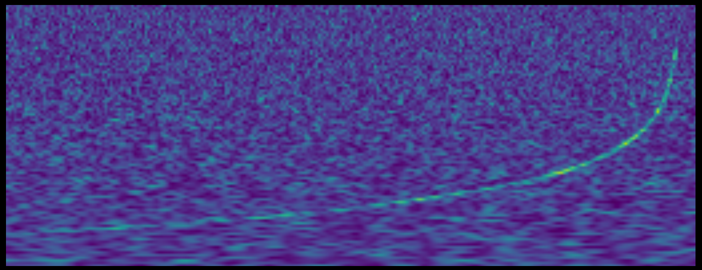


CE Horizon Study, arXiv:2109.09882

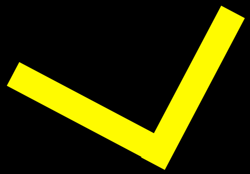
Gravitational-wave detector sensitivities



More precise measurements of the tides



GW170817



2.5G

3G

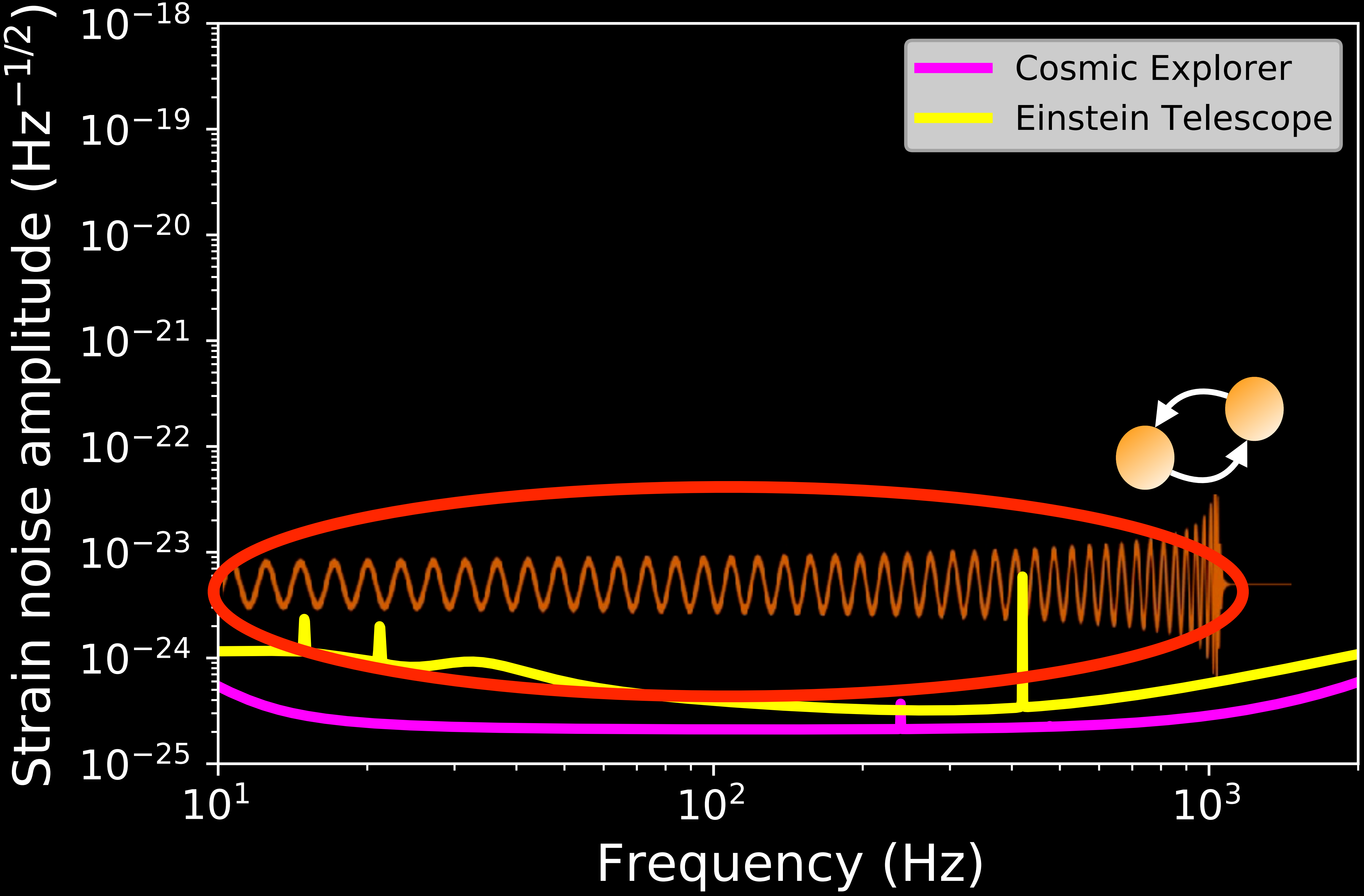
$\Delta\Lambda \sim 200$

$\Delta\Lambda \sim 100$

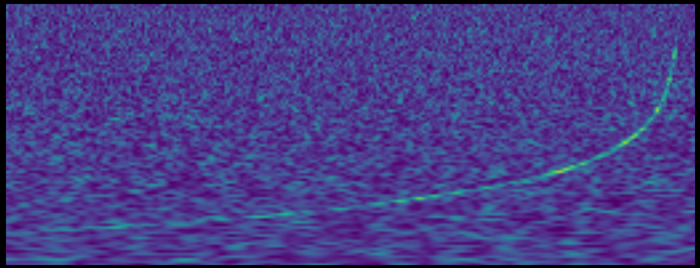
$\Delta\Lambda < 20$

Chatziioannou, PRD (2022)

Gravitational-wave detector sensitivities

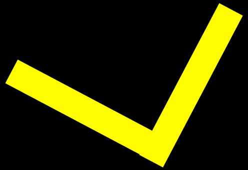


Louder signals



GW170817

SNR=32.4



2.5G

O(10-100) events/yr with SNR>100

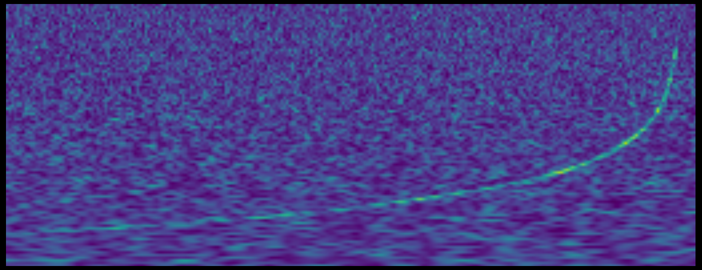
3G

O(100-1000) events/yr with SNR>100

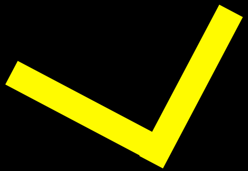
Borhanian&Sathyaprakash, arXiv:2202.11048

Golden events v.s. full populations

(Too) many detections



GW170817



2.5G

3G

1-2 events/yr *O(10-100) events/yr* *O(10^6) events/yr*

Chen et al, CQG (2021), Abbott et al., LRR (2020), Evans et al., 2109.09882

Use of the population properties

The origin(s) of heavy elements

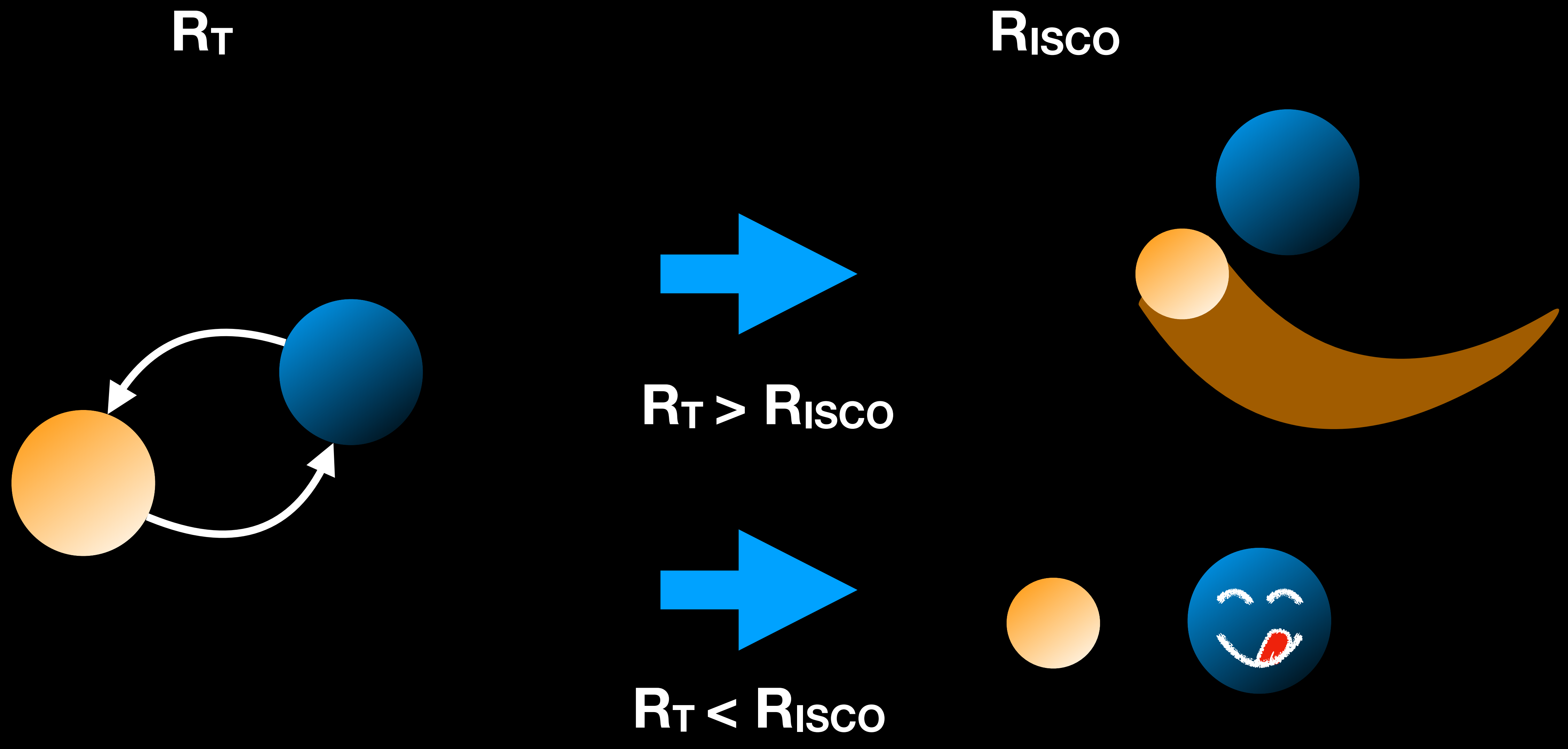
Neutron star-neutron star *Neutron star-black hole*

-What are the conditions for binary mergers to produce gold?

-Do LIGO-Virgo binary mergers satisfy these conditions?

What kind of neutron star-black hole mergers produce more heavy elements?

-Neutron star tidal radius > Black hole innermost stable circular orbit



R_T

R_{ISCO}

$R_T > R_{ISCO}$

$R_T < R_{ISCO}$

What kind of neutron star-black hole mergers produce more heavy elements?

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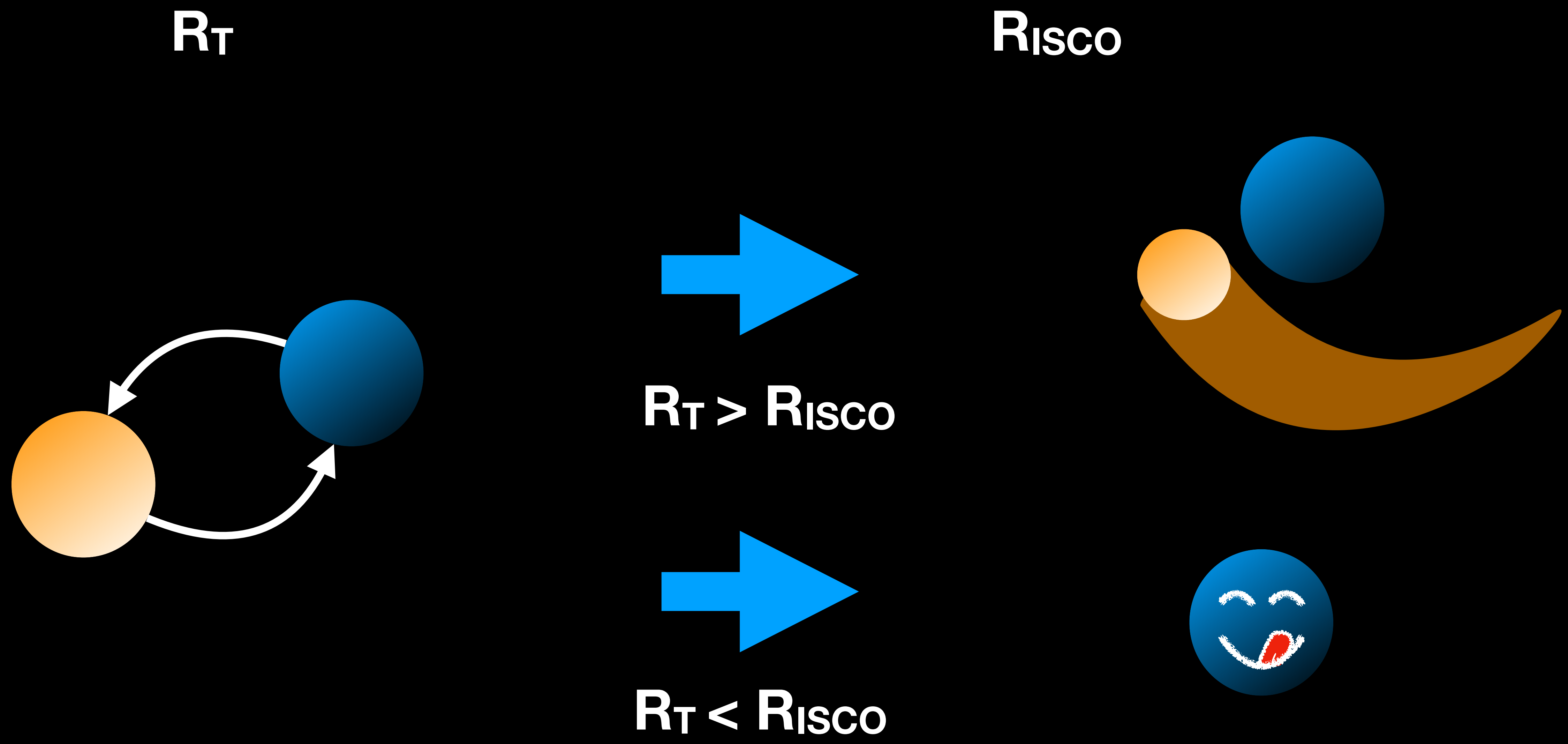


R_T

R_{ISCO}

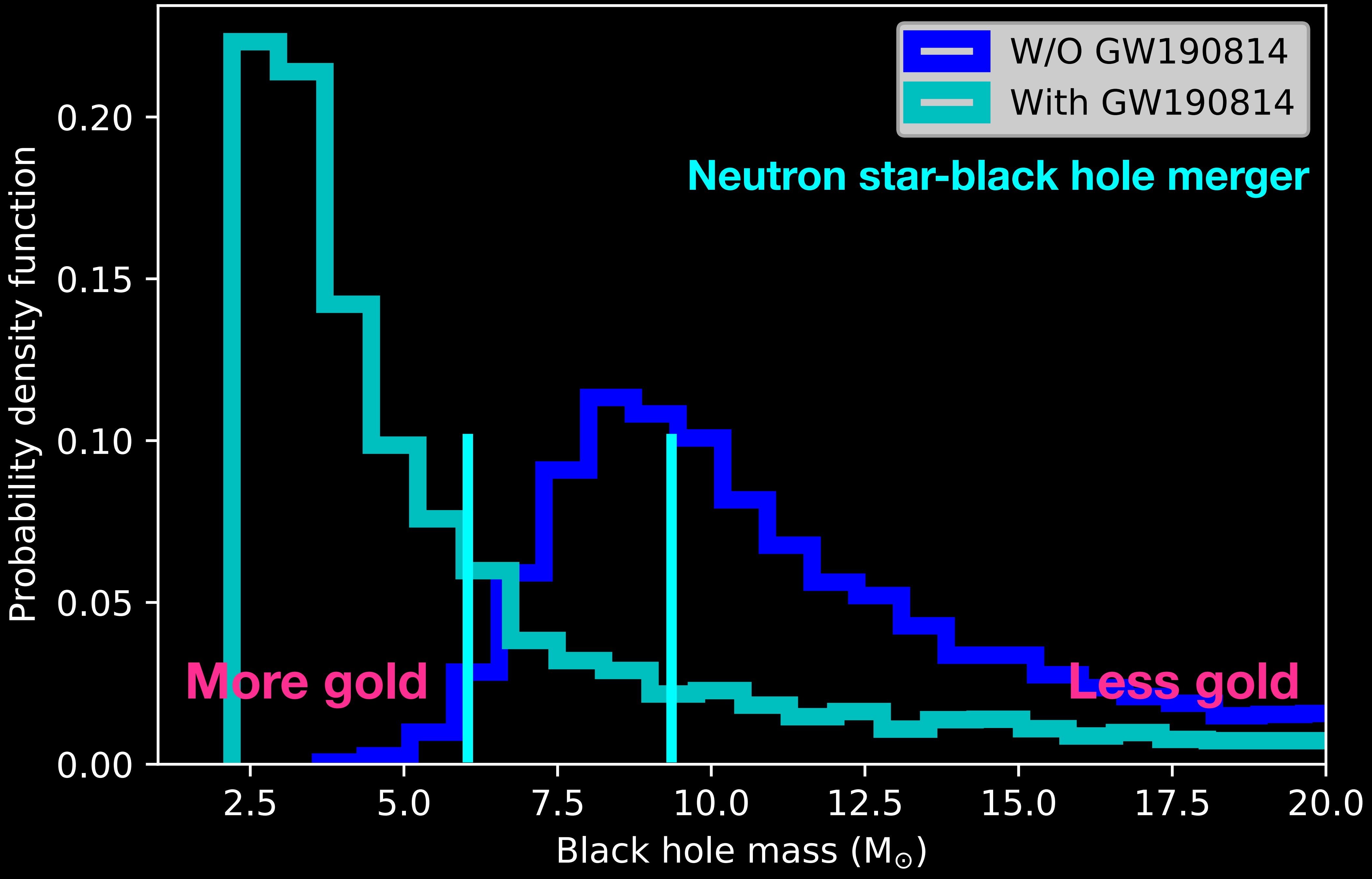
$R_T > R_{ISCO}$

$R_T < R_{ISCO}$

Smaller initial mass of the black hole

Black hole mass distribution

-Inferred from LIGO-Virgo binary black hole merger observations.



Abbott et al., ApJ (2021)

What kind of neutron star-black hole mergers produce more heavy elements?

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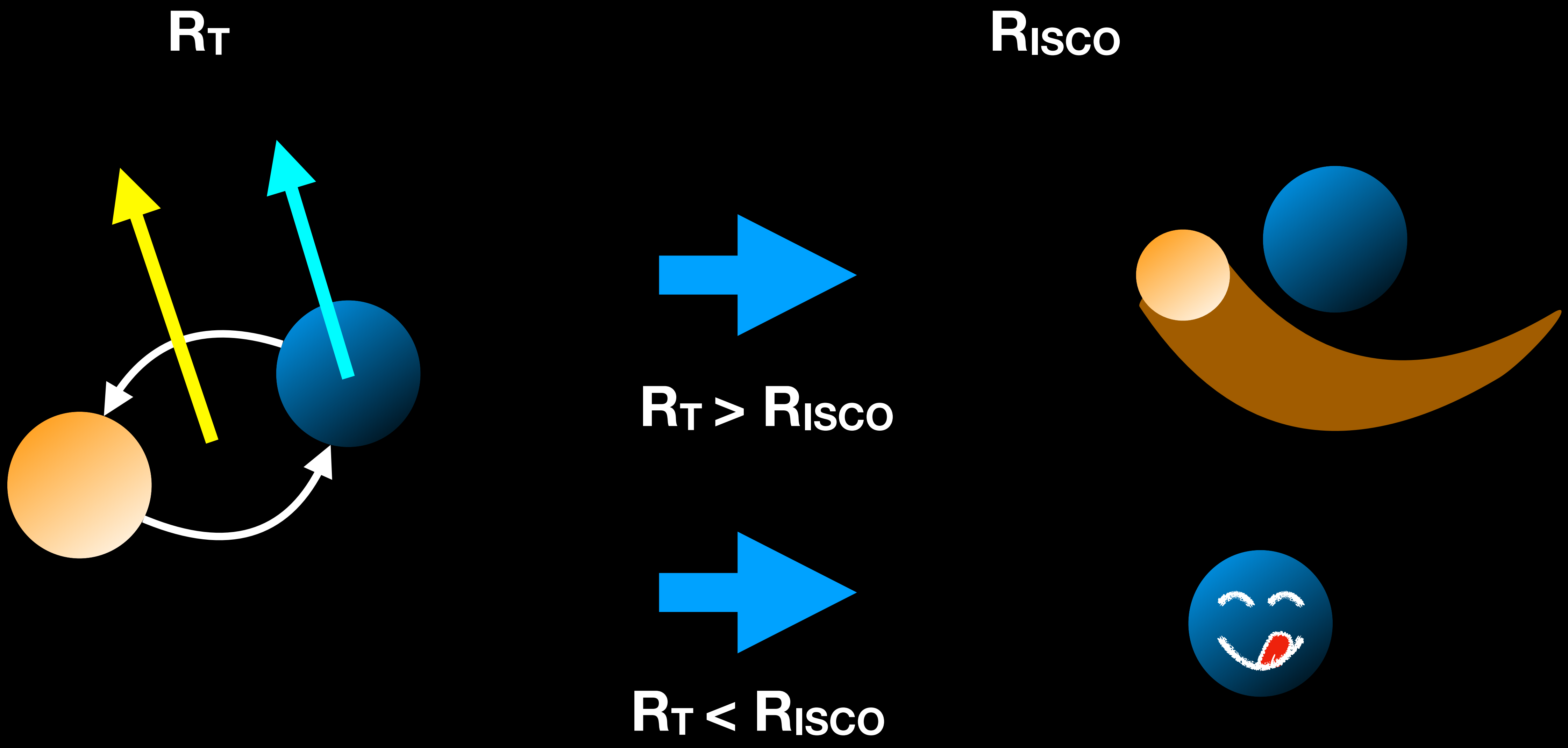


R_T

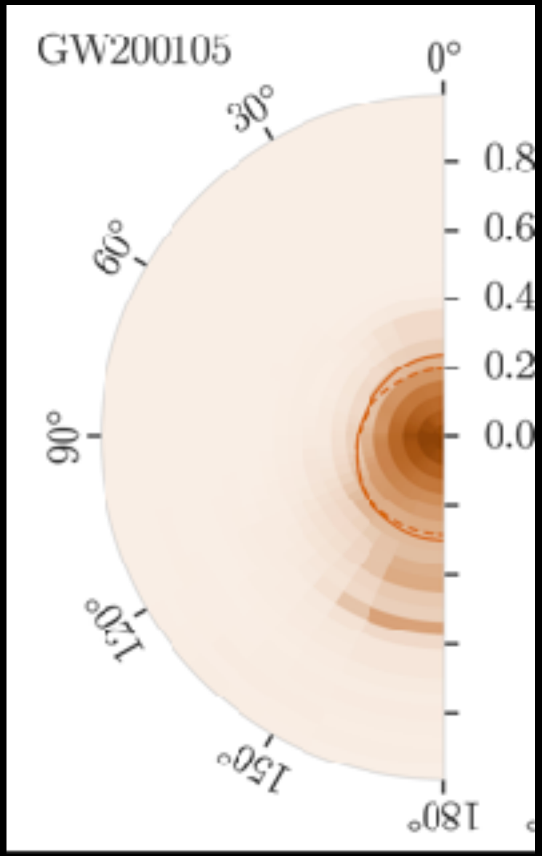
R_{ISCO}

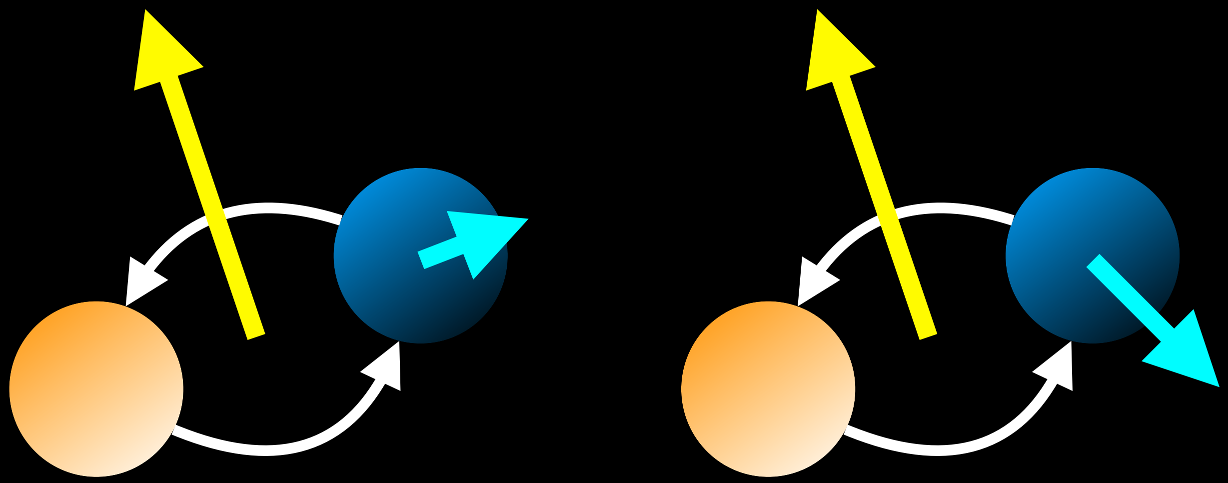
$R_T > R_{ISCO}$

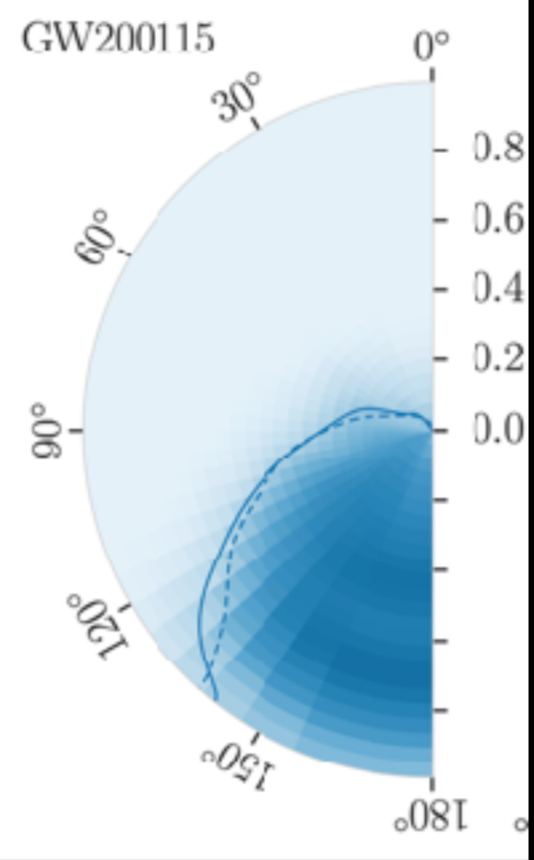
$R_T < R_{ISCO}$

Black hole spin aligned with the binary

Inferred black hole spins







Abbott et al., ApJL (2021)

The black hole spins didn't show too much support to the aligned component.

Different sources of uncertainties

-Numerical simulations of the amount of ejecta, and the analytical formula fitted to the simulations

-Neutron star equation-of-state.

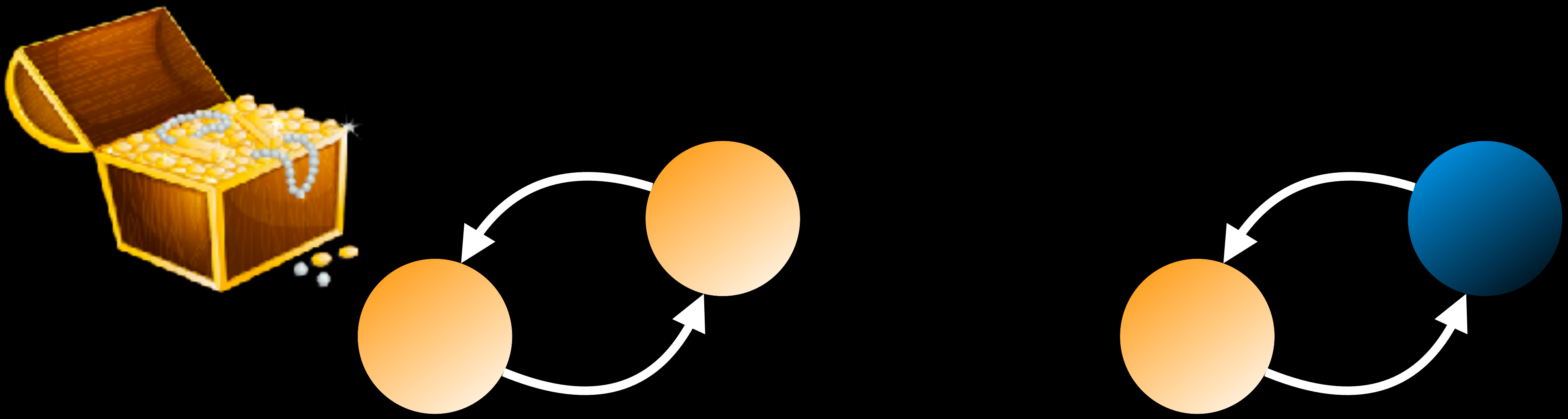
-Neutron star and black hole mass distribution.

-Black hole spin distribution.

-Astrophysical rate of binary neutron star and neutron star-black hole mergers.

Estimate the total amount of gold

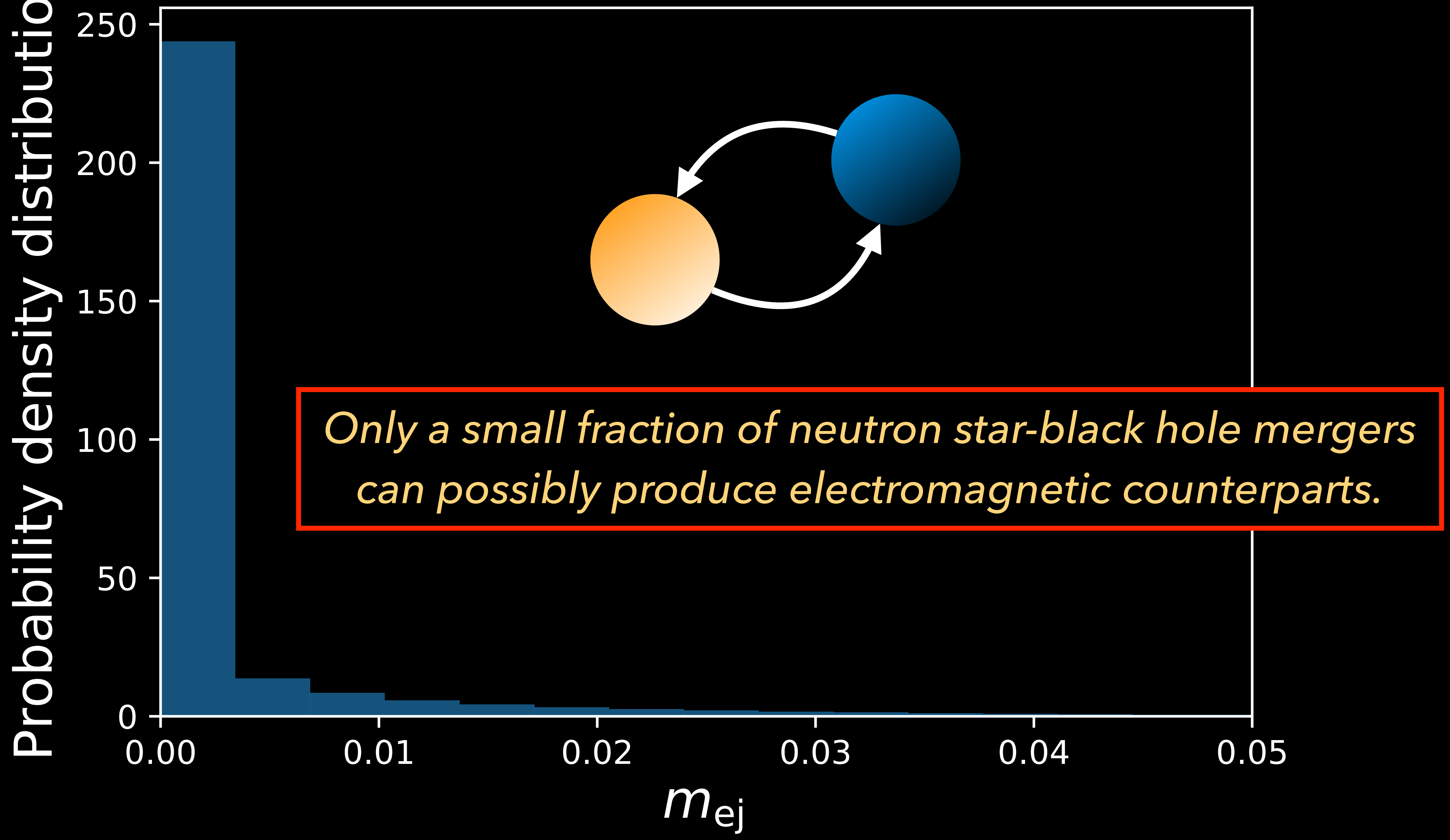
Chen, Vitale & Foucart, ApJL (2021)



Despite the uncertainties, binary neutron star mergers likely produce more heavy elements than neutron star-black hole mergers in the past 2.5 billion years.

Further implications on the electromagnetic emissions

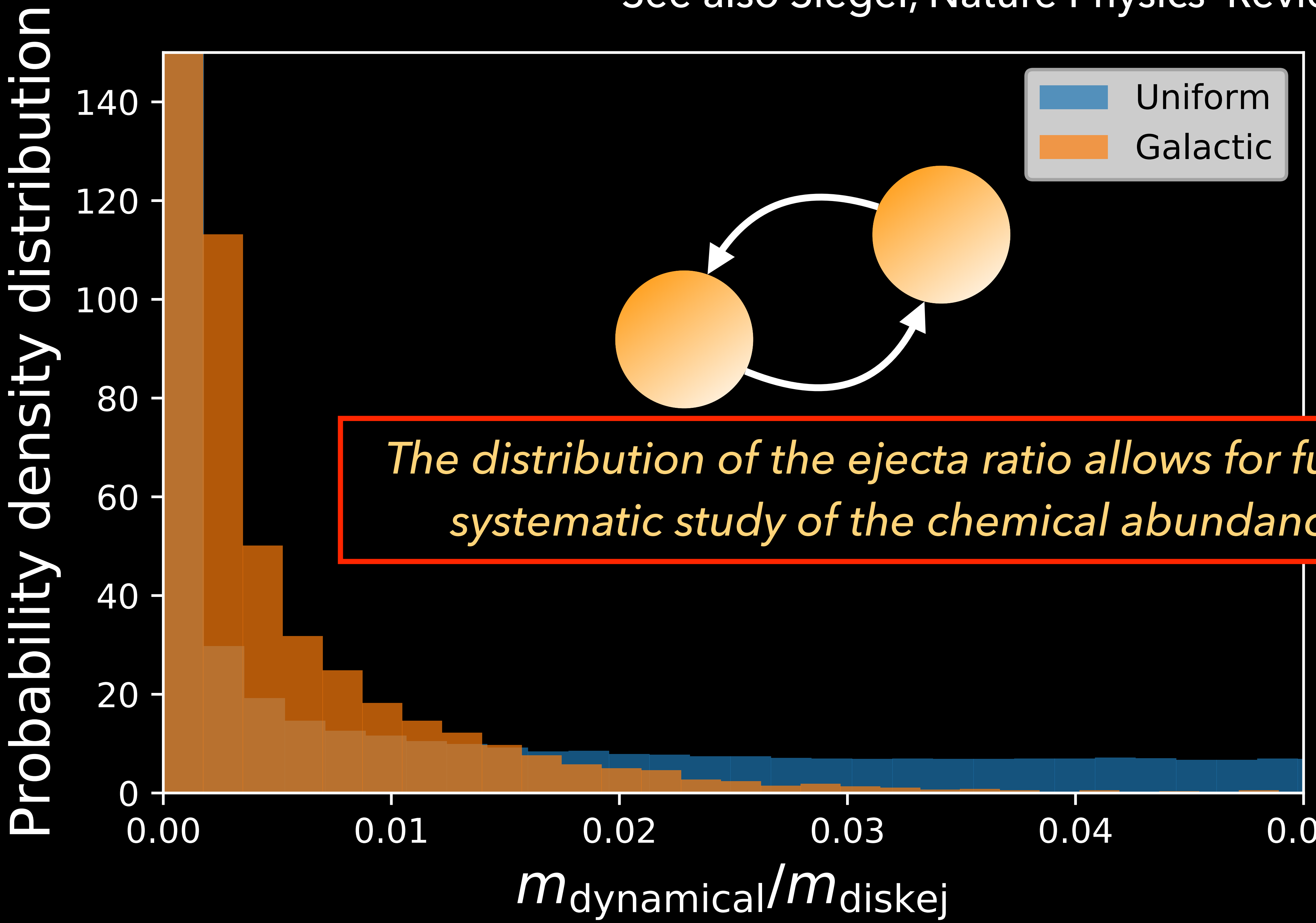
See also Fragione, ApJL (2021)



Only a small fraction of neutron star-black hole mergers can possibly produce electromagnetic counterparts.

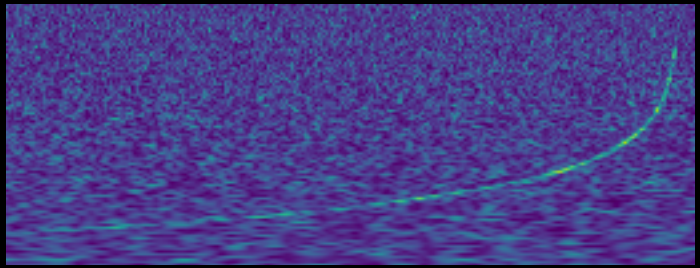
Relative ratio of different ejecta

See also Siegel, Nature Physics Reviews (2022)



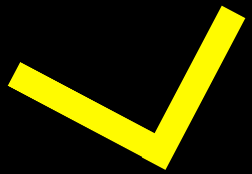
The distribution of the ejecta ratio allows for further systematic study of the chemical abundance.

Detections across different redshifts



GW170817

40 Mpc



2.5G

Median distance
200 Mpc (z~0.1)

Chen&Holz, arXiv:1612.01471

3G

Median distance
4 Gpc (z~1.5)

Chen et al., CQG (2021)

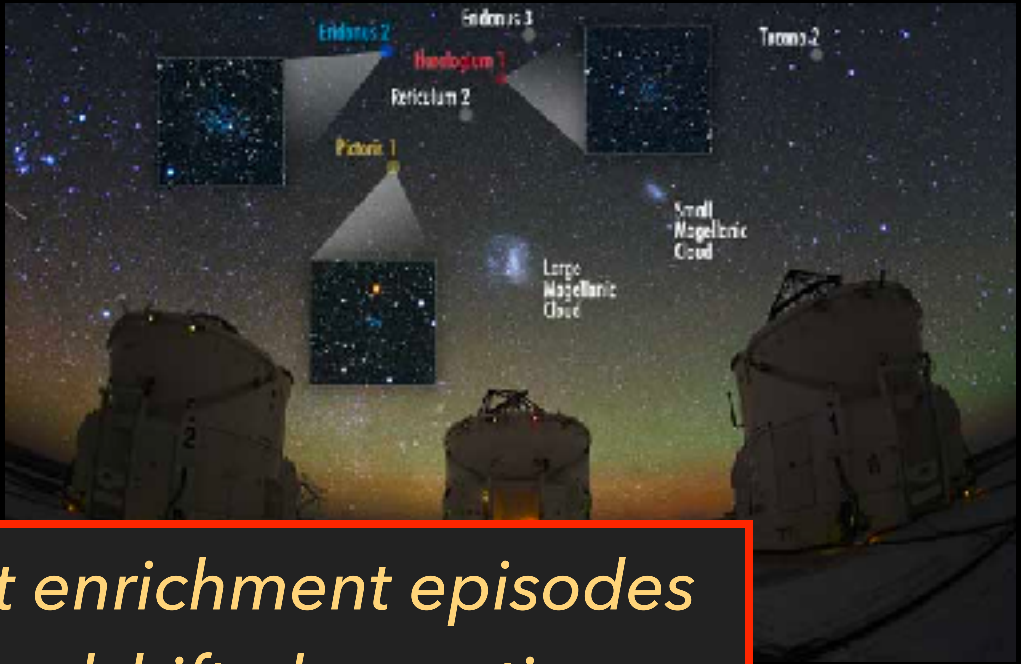
Are the GW and EM populations consistent across redshifts?

Reconstructing the heavy-element production history

-The Solar system is 4.6 billion years old.

Wallner et al., Nature Communications (2015)

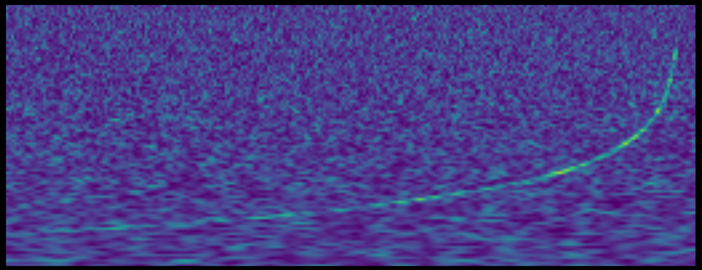
-The r-process element enriched stars in Reticulum II ultra-faint dwarf galaxy are >10 billion years old.



servatories)

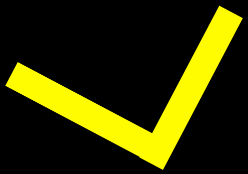
The origin of ancient enrichment episodes will require higher-redshift observations.

More precise measurements of masses



GW170817

$\Delta m \sim 0.1 M_\odot$



2.5G

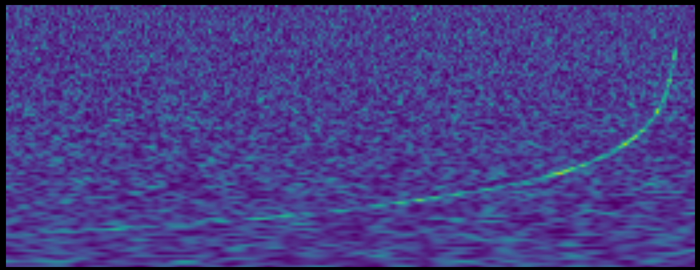
$\Delta m \sim O(10^{-2}) M_\odot$

3G

$\Delta m < O(10^{-3}) M_\odot$

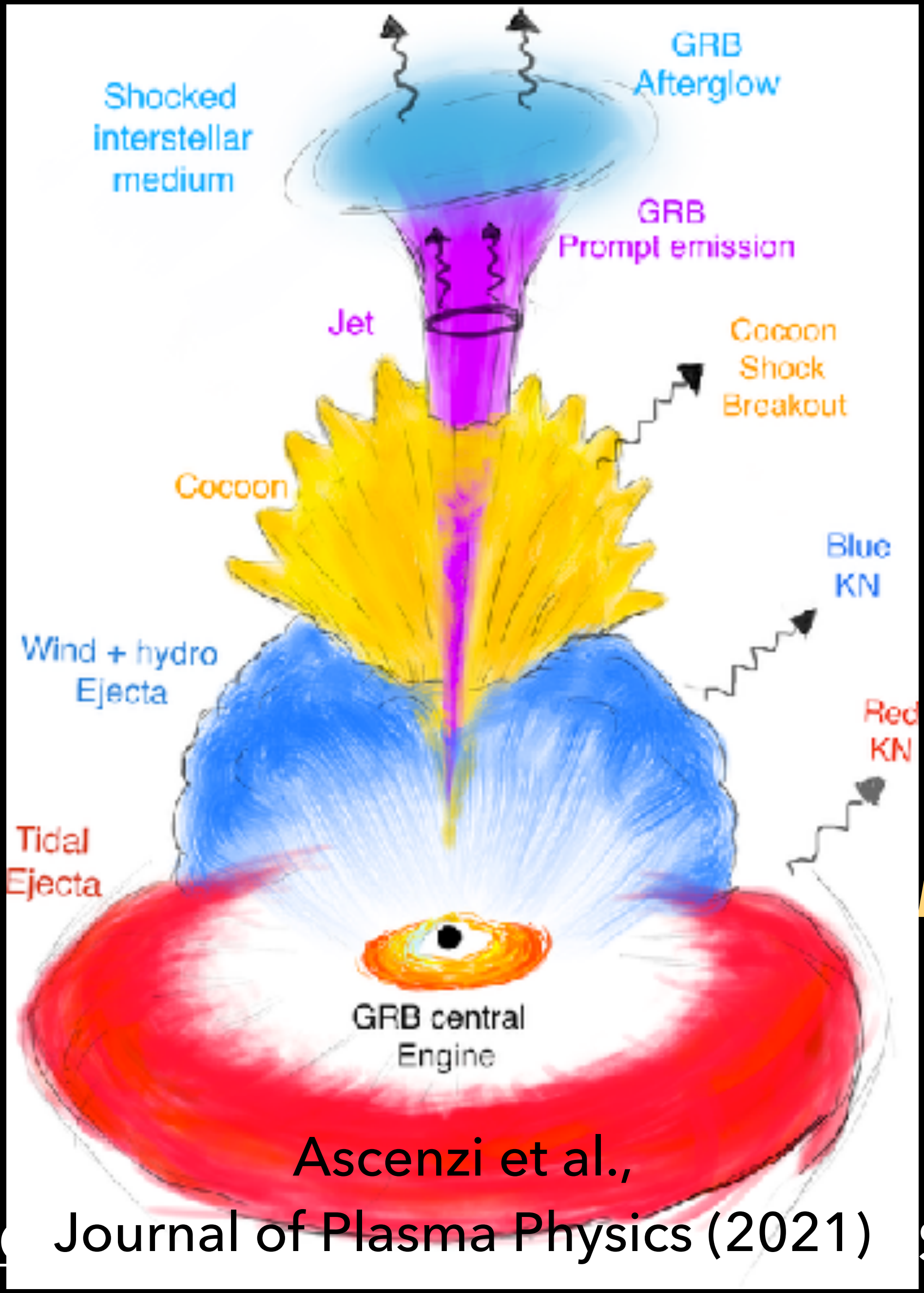
Smith et al., PRL (2021)
Borhanian&Sathyaprakash, arXiv:2202.11048

More precise measurement of inclination

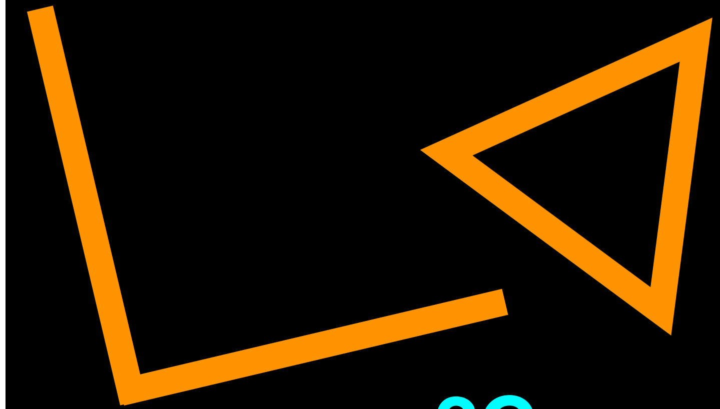


GW170817

25° uncertainty



Ascenzi et al.,
Journal of Plasma Physics (2021)



3G

Median uncertainty is 3°

Sathyaprakash, arXiv:2202.11048

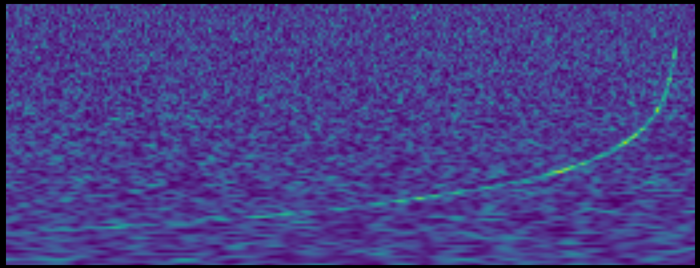
Can we resolve the emission geometry of short gamma-ray bursts and kilonovae?

Searching for electromagnetic counterparts is challenging

-We don’t know where it is on the sky.

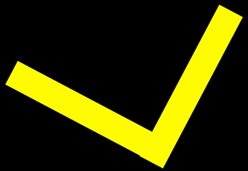
-The counterpart emissions fade away.

Search for counterparts: More precise localizations



GW170817

28 deg^2



2.5G

5 events localized in 10 deg^2 a year.

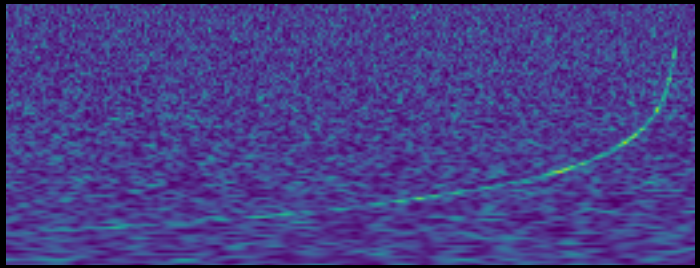
Chen&Holz, arXiv:1612.01471

3G

1,000 events localized in 1 deg^2, few thousands in 10 deg^2 a year.

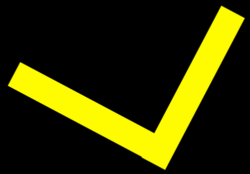
Mills et al., PRD (2018)

Search for counterparts: Early warnings



GW170817

40min after mergers.



2.5G

1 event localized within few hundred deg² 15s before merger.

Magee et al., ApJL (2021)

3G

O(1-10) events localized within 10 deg² 5min before mergers.

Nitz&Dal Canton, ApJL (2021)

Is there any precursor/early emission?

What kinds of electromagnetic facilities do we need?

Multi-band electromagnetic-wave telescopes in the future

-Radio: SKA, ngVLA

-Infared: JWST, Roman Space Telescope

-Optical: Vera Rubin Observatory

-UV: Hubble?

-X-ray: Athena, TAP

-γ-ray: Fermi-like–AMEGO-X / Swift-like–STAR-X

How do these telescopes help GW-EM multi-messenger science?

Which of these telescopes are more important?

Multi-band electromagnetic-wave telescopes in the future

-Radio: SKA, LOFAR, ngVLA

-Infared: JWST, Roman Space Telescope

-Optical: Vera Rubin Observatory

Kilonova

-UV: Hubble?

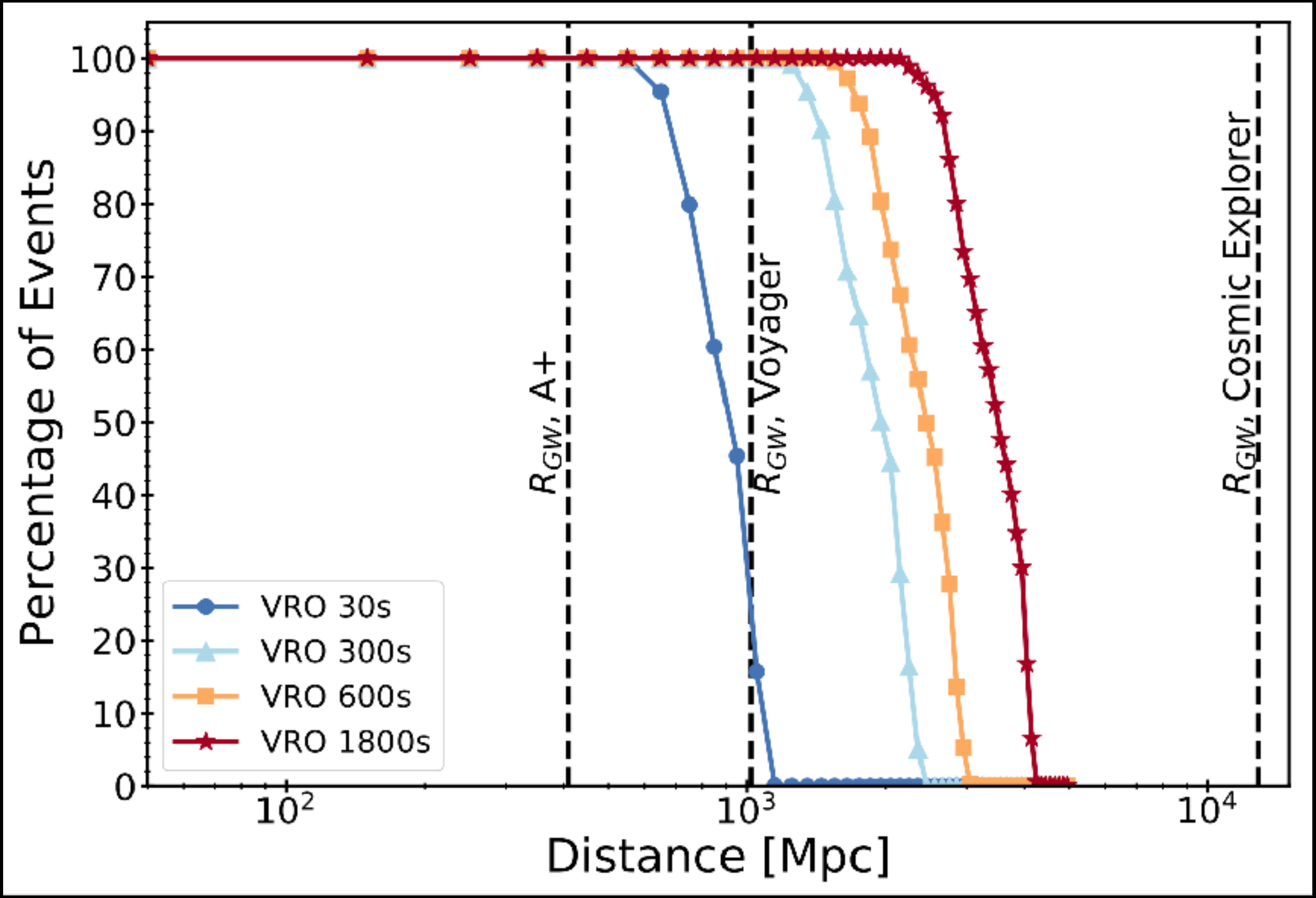
-X-ray: Athena, TAP

Short gamma-ray burst

-γ-ray: Fermi-like–AMEGO-X / Swift-like–STAR-X

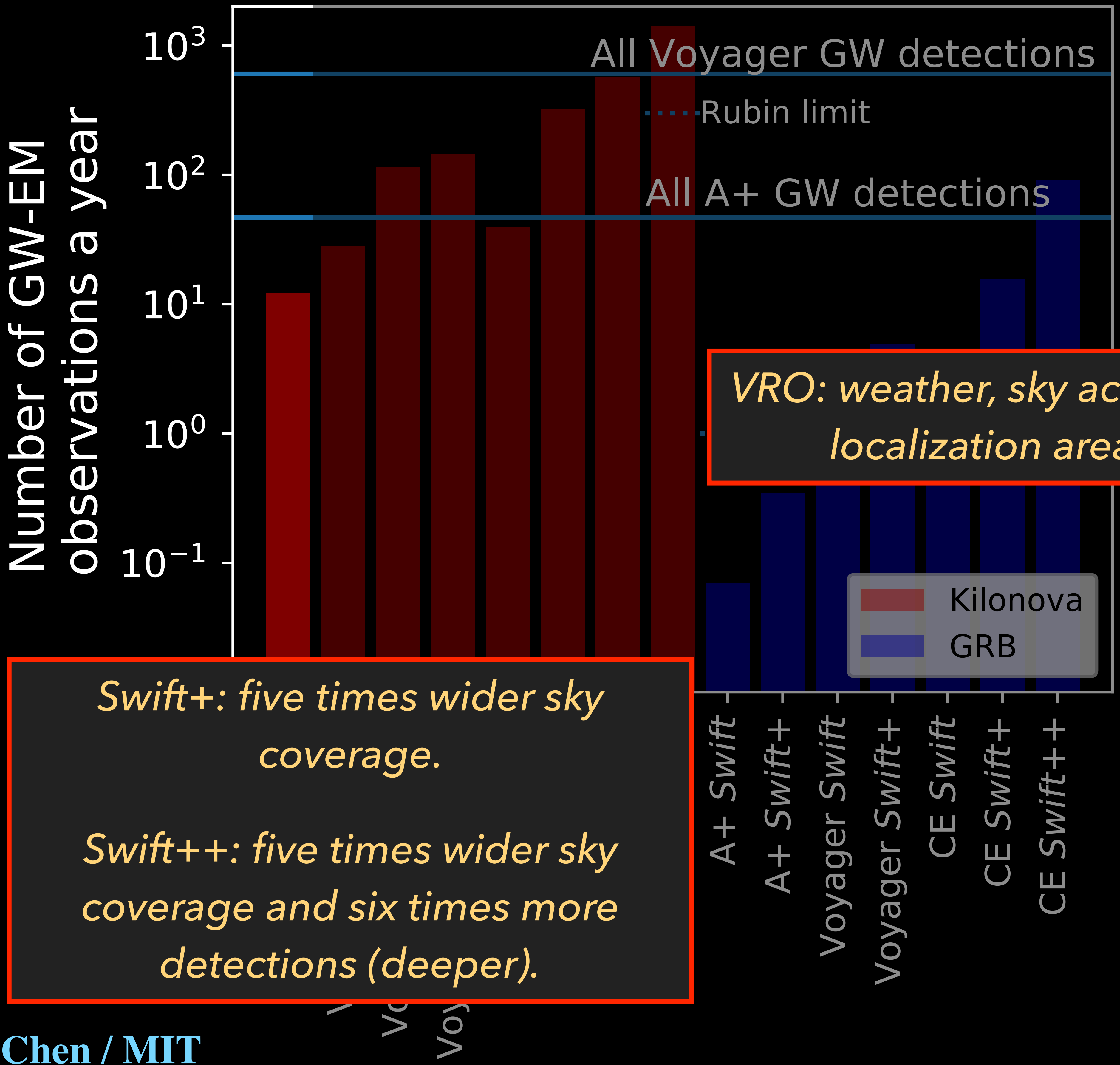
Chen, Cowperthwaite, Metzger, Berger, 2011.01211, ApJL (2021)

The EM detection efficiency drops rapidly as the distance increases



Chen, Cowperthwaite, Metzger, Berger, 2011.01211, ApJL (2021)

Number of joint detections in 2.5-3G era

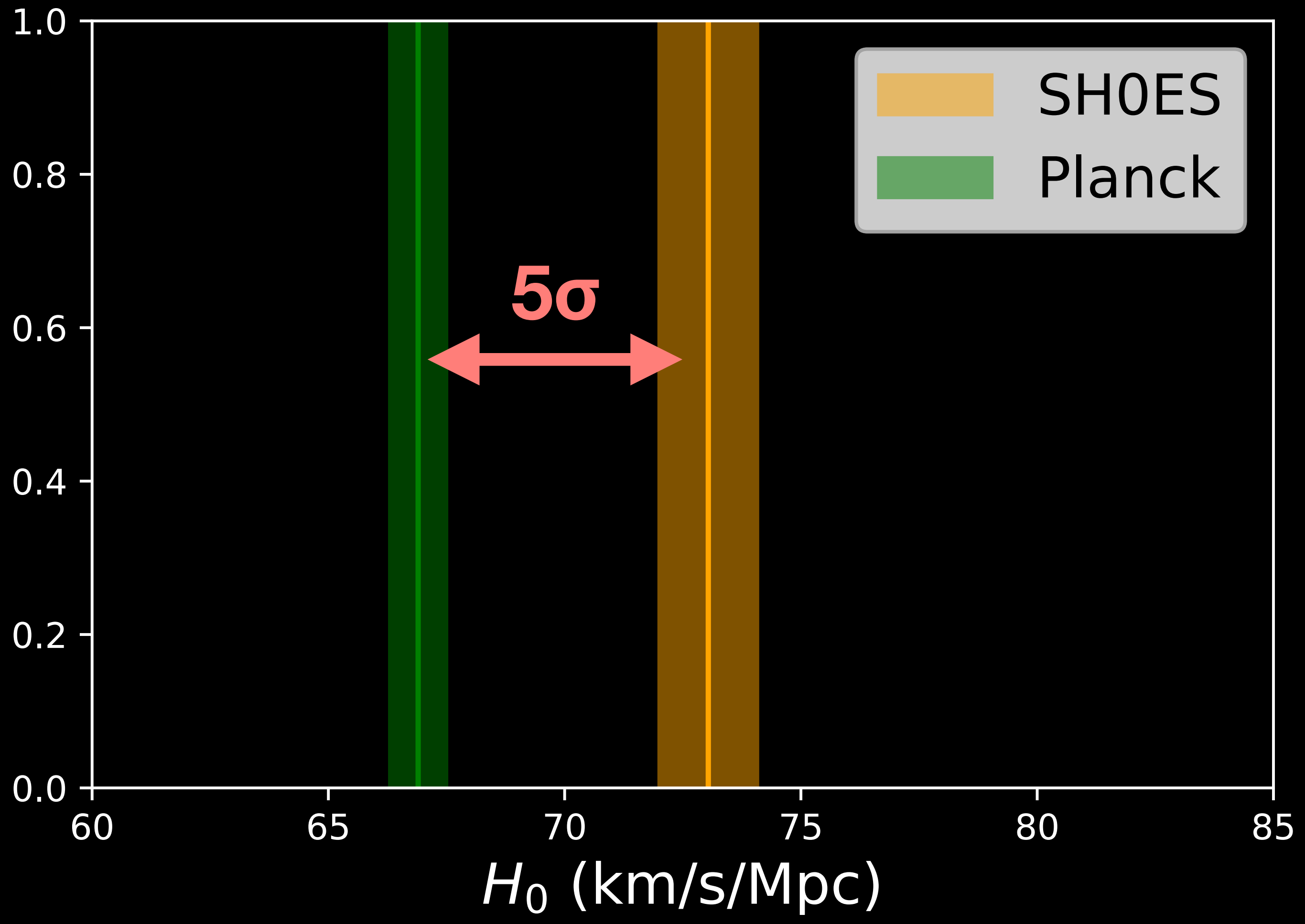


VRO: weather, sky accessibility, localization area etc.

Swift+: five times wider sky coverage.

Swift++: five times wider sky coverage and six times more detections (deeper).

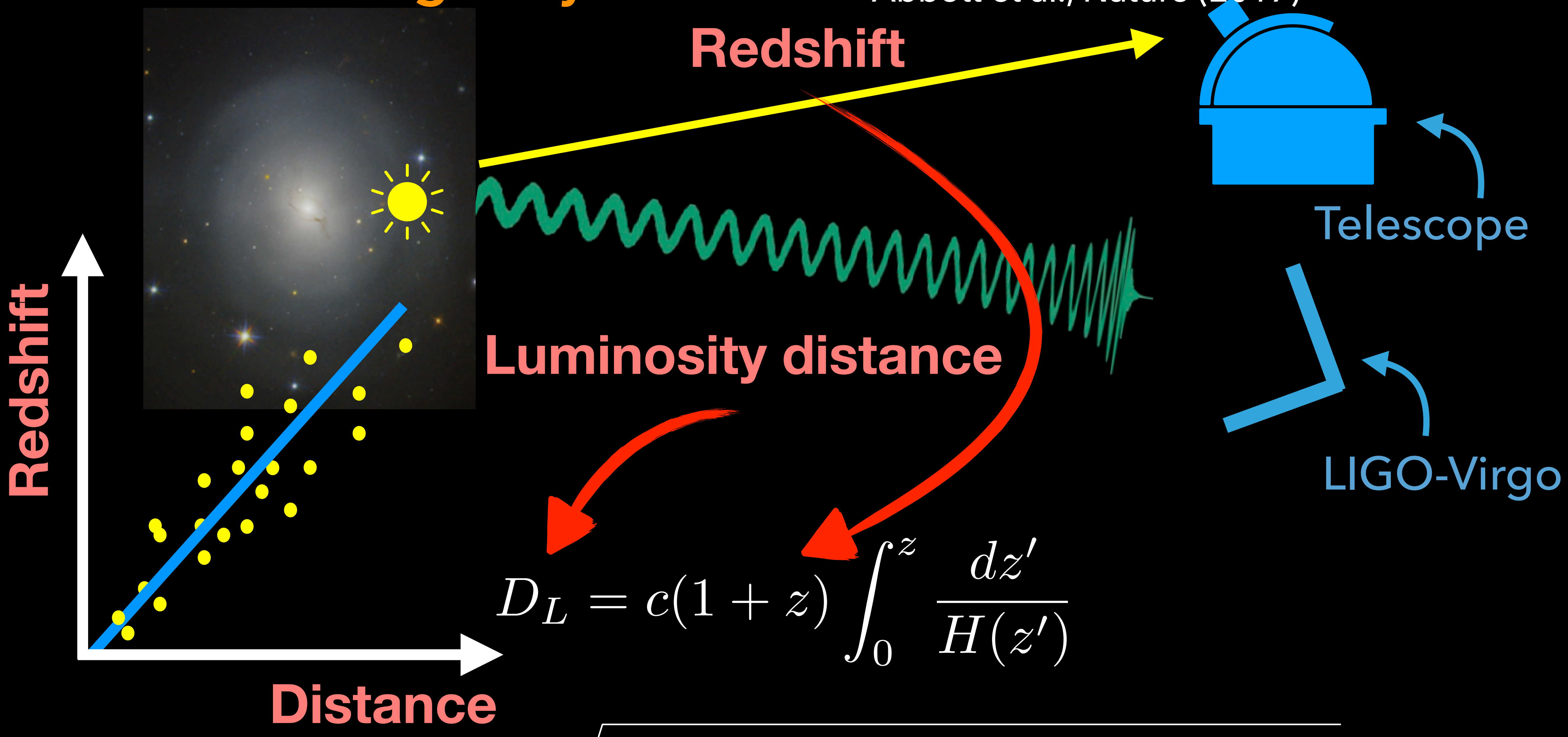
Tension in the Hubble constant measurement



Independent measurement of the cosmological parameters—Standard siren method

Standard siren with electromagnetic counterparts: Determine the redshift of gravitational-wave source with the host galaxy

Abbott et al., Nature (2017)

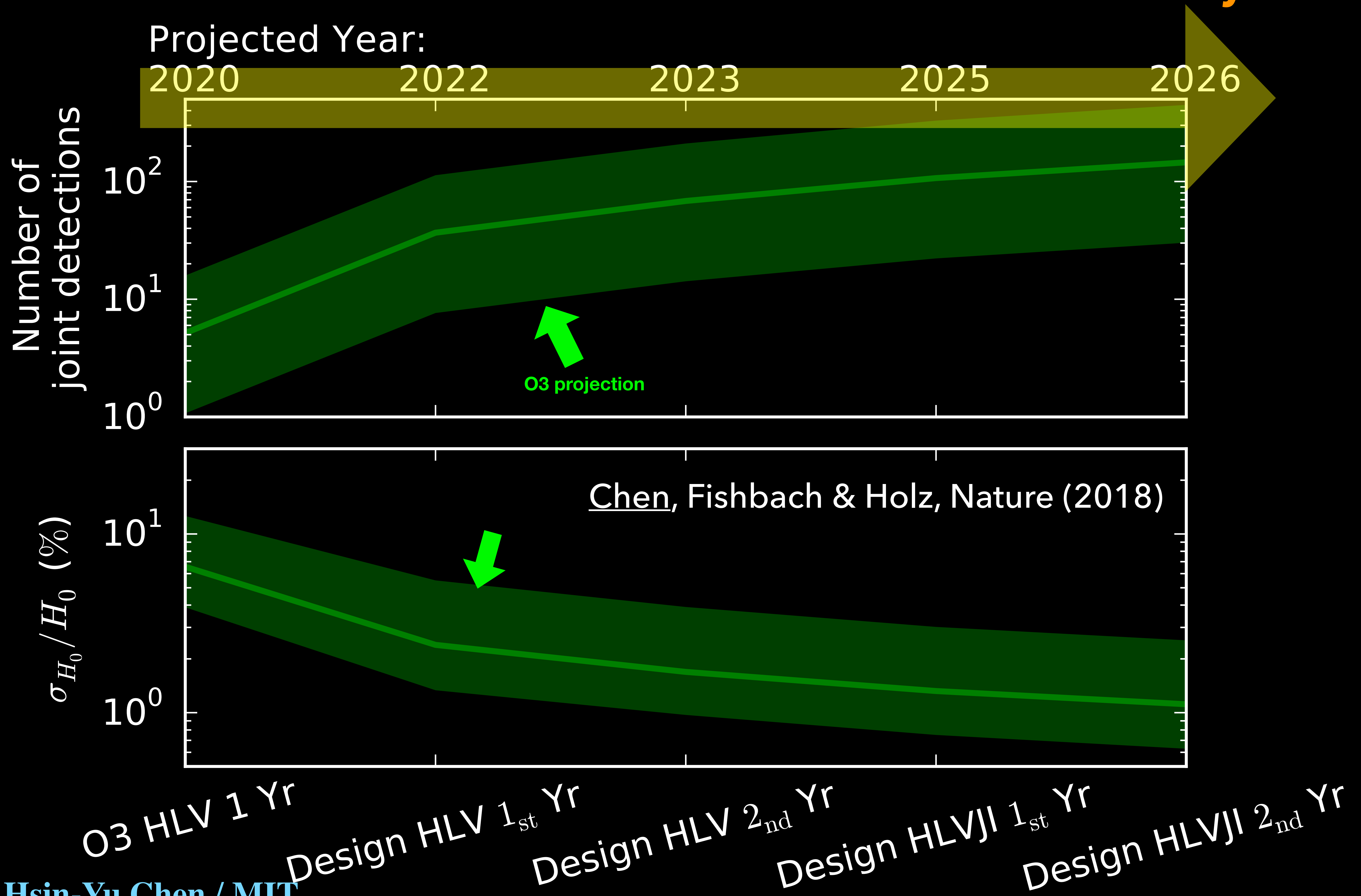


$$D_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w)}}$$

Schutz, Nature (1986) / Holz & Hughes, ApJ (2005)

Percent-level Hubble constant measurement within a few years

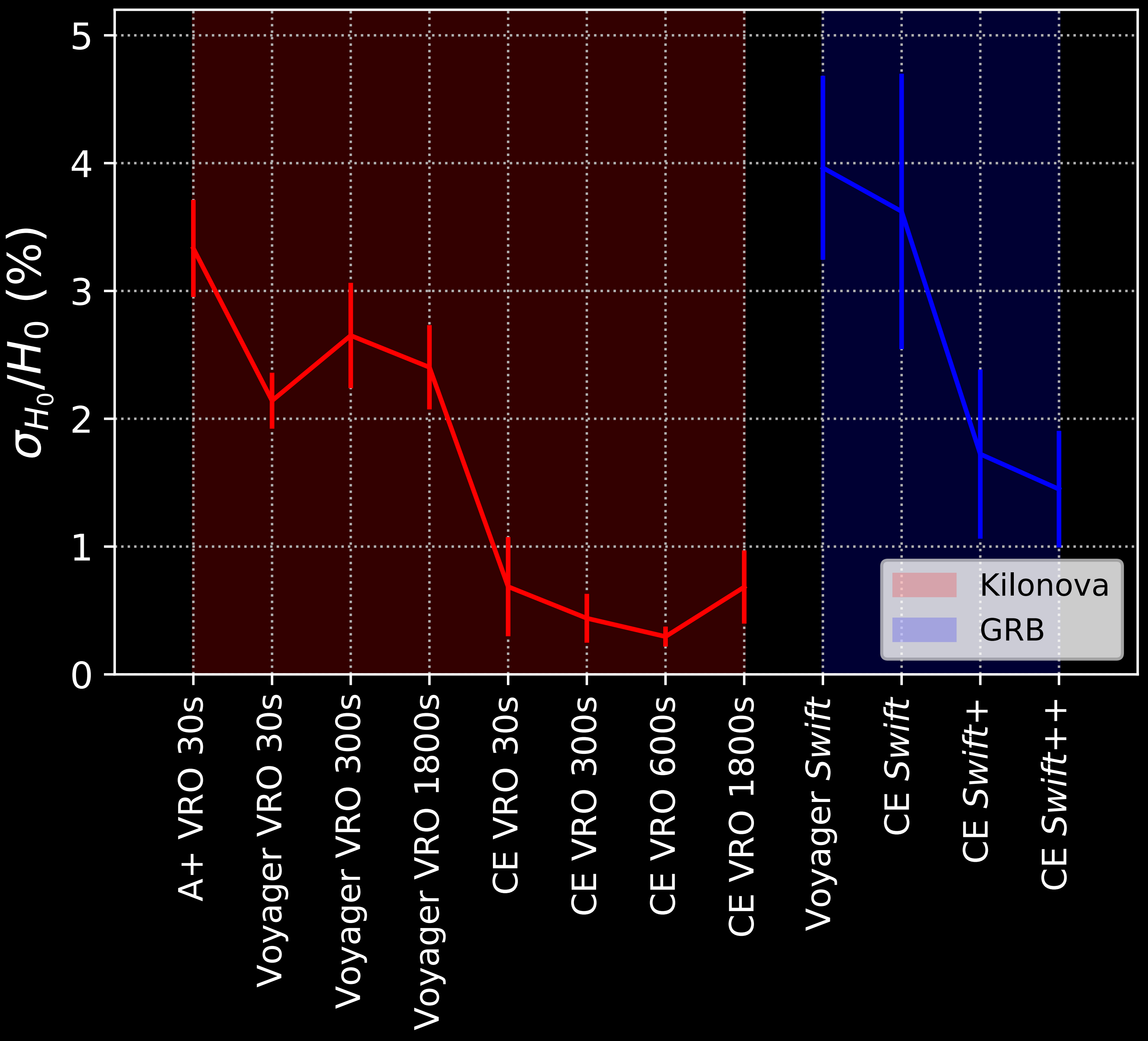


Chen, Fishbach & Holz, Nature (2018)

Hsin-Yu Chen / MIT

Chen, Cowperthwaite, Metzger, Berger, 2011.01211, ApJL (2021)

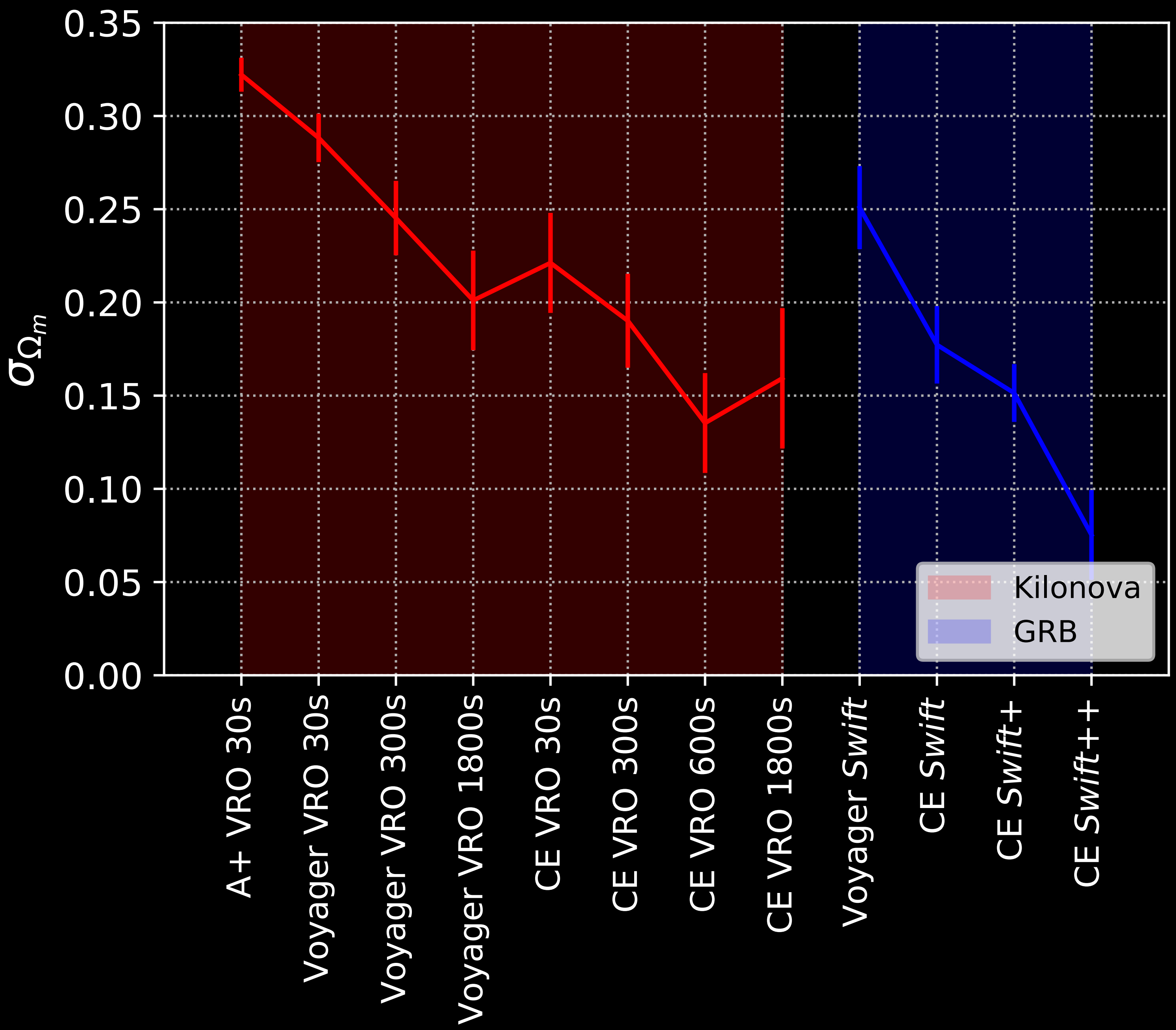
Cosmological constraints from bright sirens in 2.5-3G



-A+ and Voyager still at percent level. Sub-percent level precision is possible in CE era.

-Kilonovae are better than GRBs for H_0 constraint.

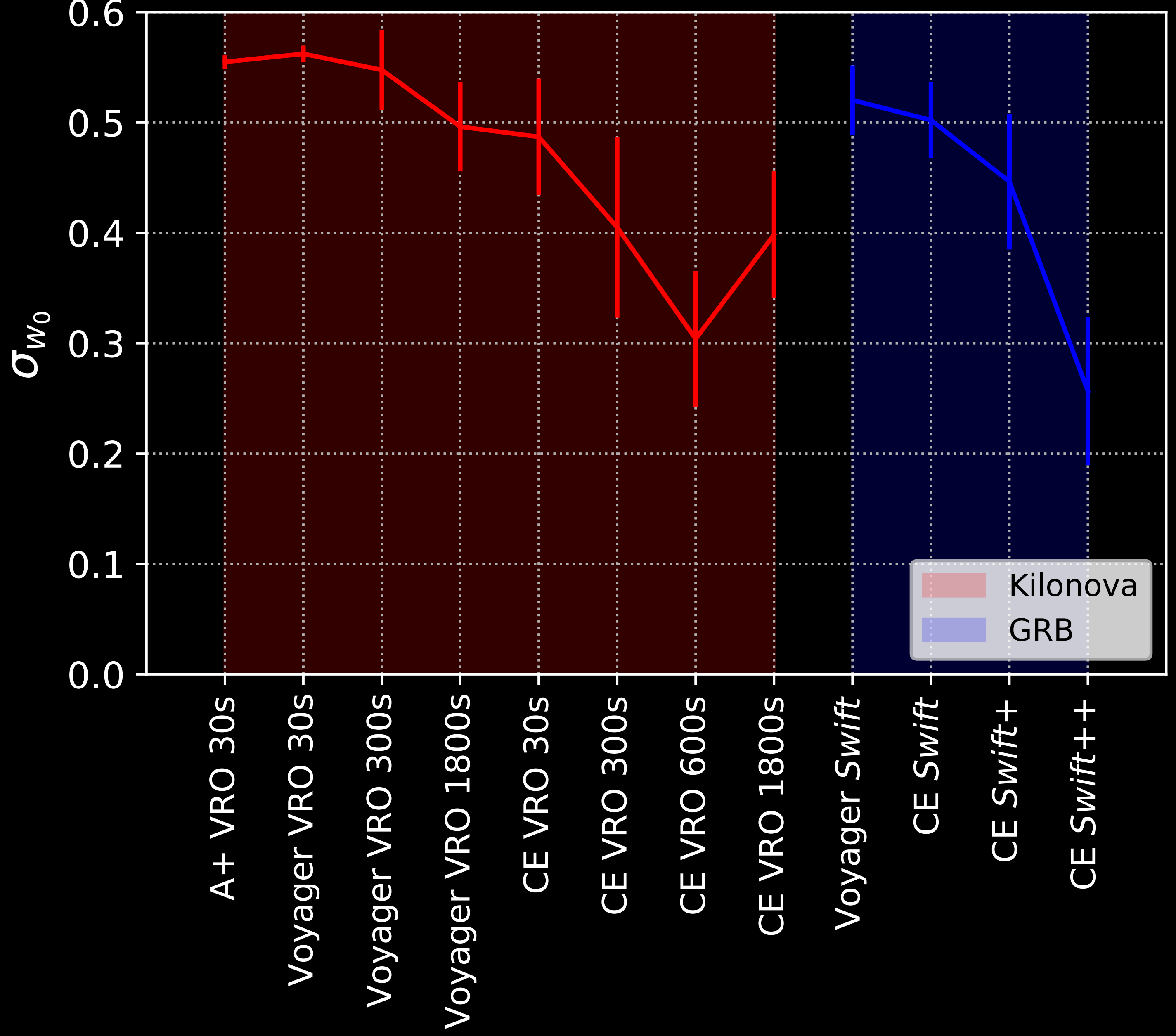
Cosmological constraints from bright sirens in 2.5-3G



-GRBs are better than kilonovae to constrain Ω_m and w.

-One order of magnitude fewer GRBs (with beaming) is needed to achieve the same precision as kilonovae.

Cosmological constraints from bright sirens in 2.5-3G



-Swift-like GRB telescope with larger field-of-view and better sensitivity is in need in the CE era.

-Otherwise, dedicated VRO-like telescope is needed in absence of the GRB telescope described above.

Final thoughts

-What will be the key EM facilities?

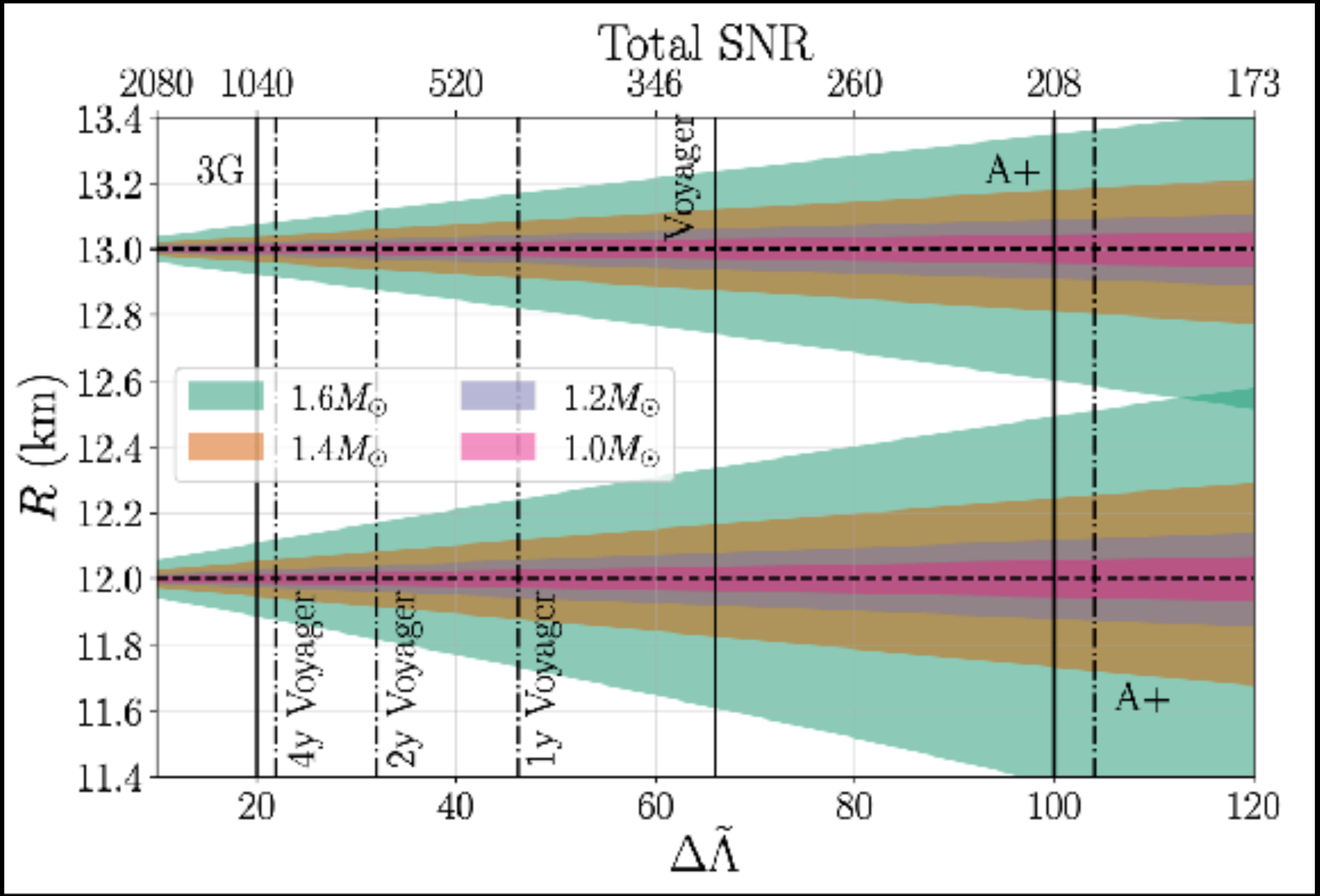
-What else can we learn from GW-EM multi-messenger nuclear physics?

-What will be the limitations in the 2.5G/3G era?

Thank you!

More precise measurements of the inspiral tides

GW170817-like event $\Delta\Lambda$~100 with A+, $\Delta\Lambda$<70 with Voyager, $\Delta\Lambda$<20 with CE/ET.

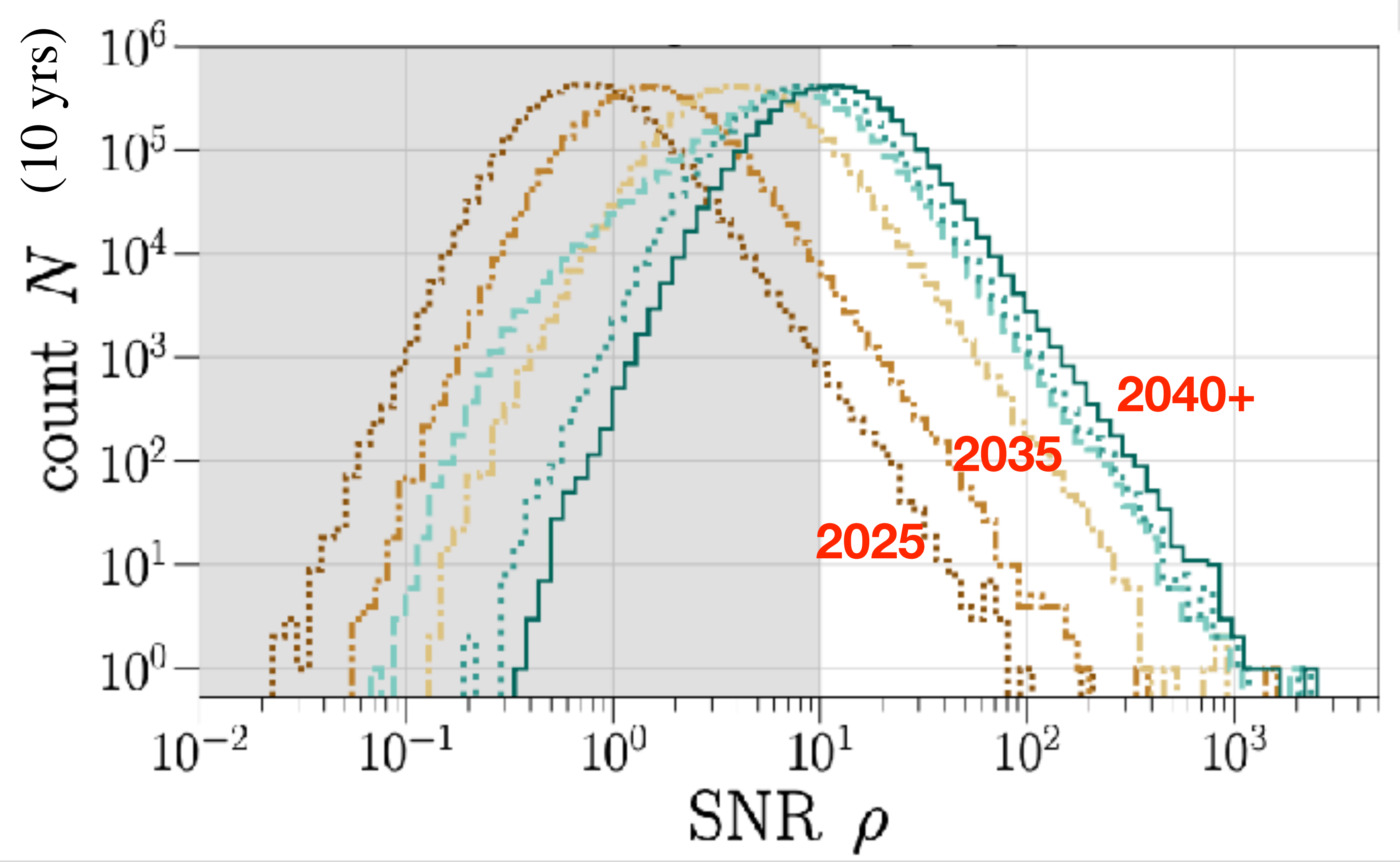


Chatziioannou, PRD (2022)

Hsin-Yu Chen / MIT

Louder signals

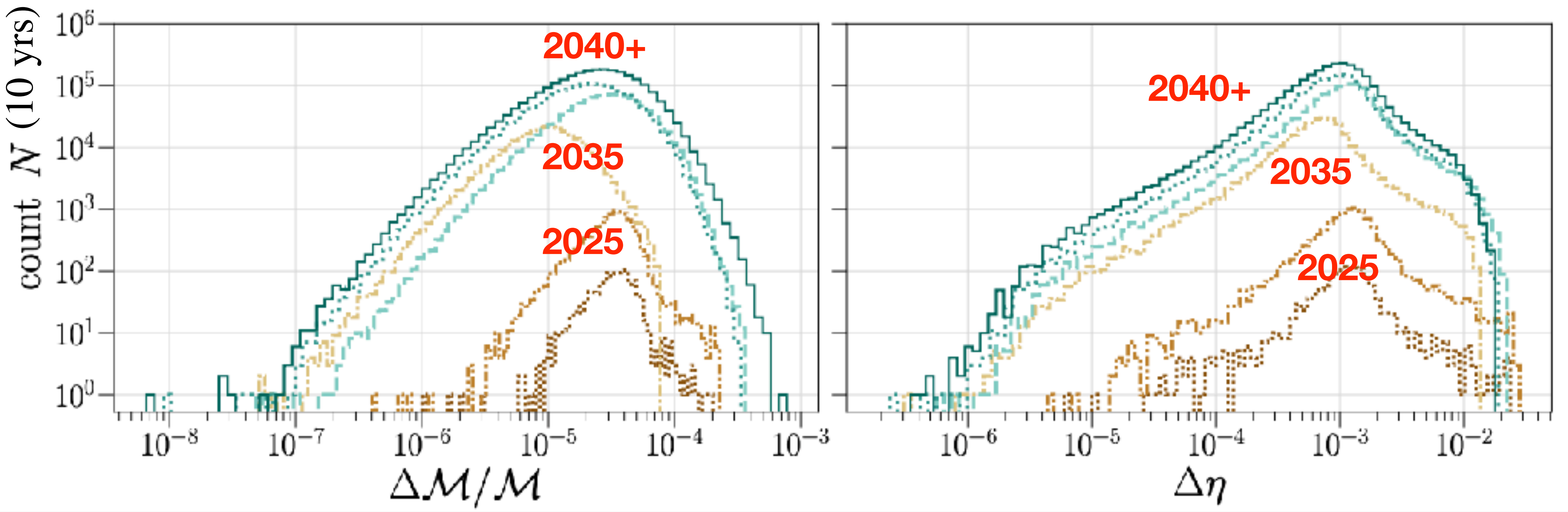
O(10-100) detections in 2G+ and O(100-1000) of detections in 3G every year with signal-to-noise ratio>100.



Borhanian&Sathyaprakash, arXiv:2202.11048

More precise measurements of masses

Most of the events will have better than O(10^{-2})$M_\odot$ mass measurements.

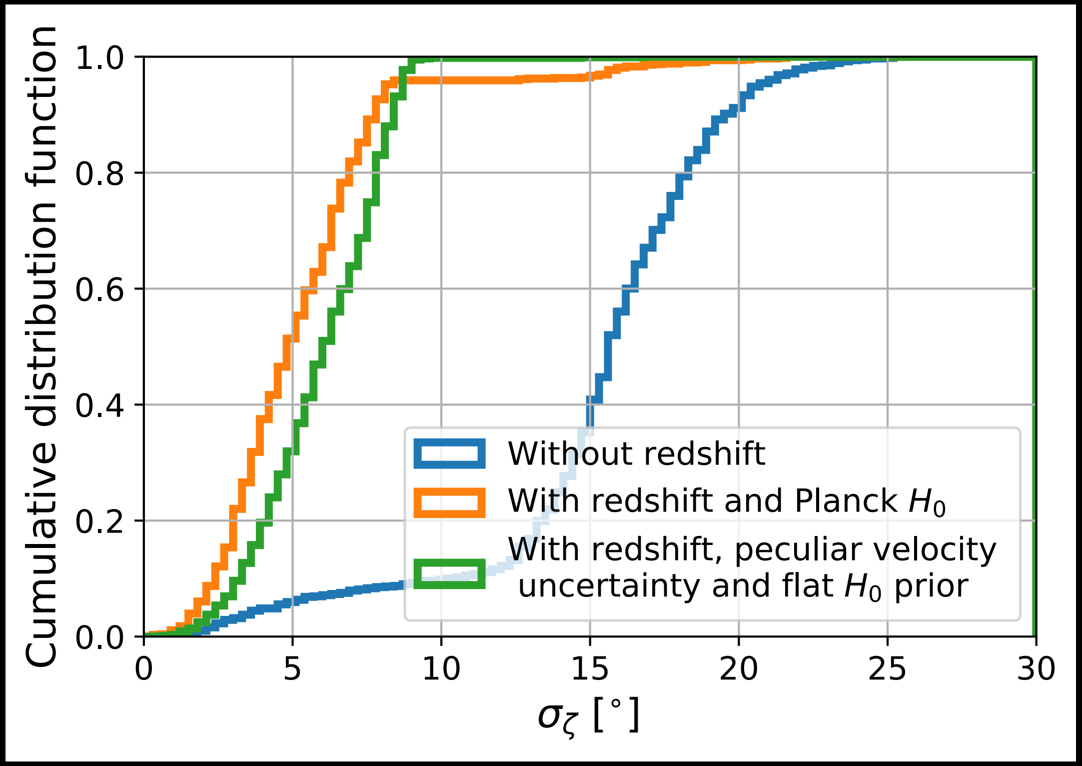


Borhanian&Sathyaprakash, arXiv:2202.11048

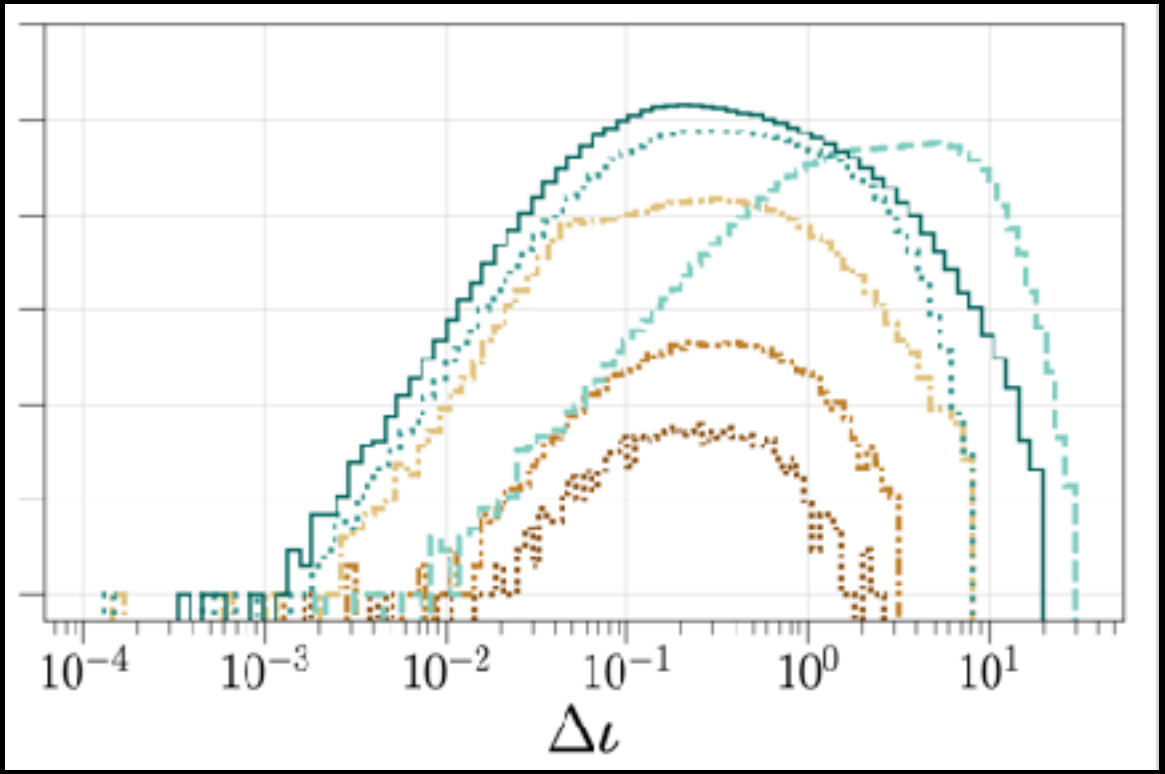
Multi-messenger: More precise inclination

Median uncertainty is 20°.

Median uncertainty is 3°.



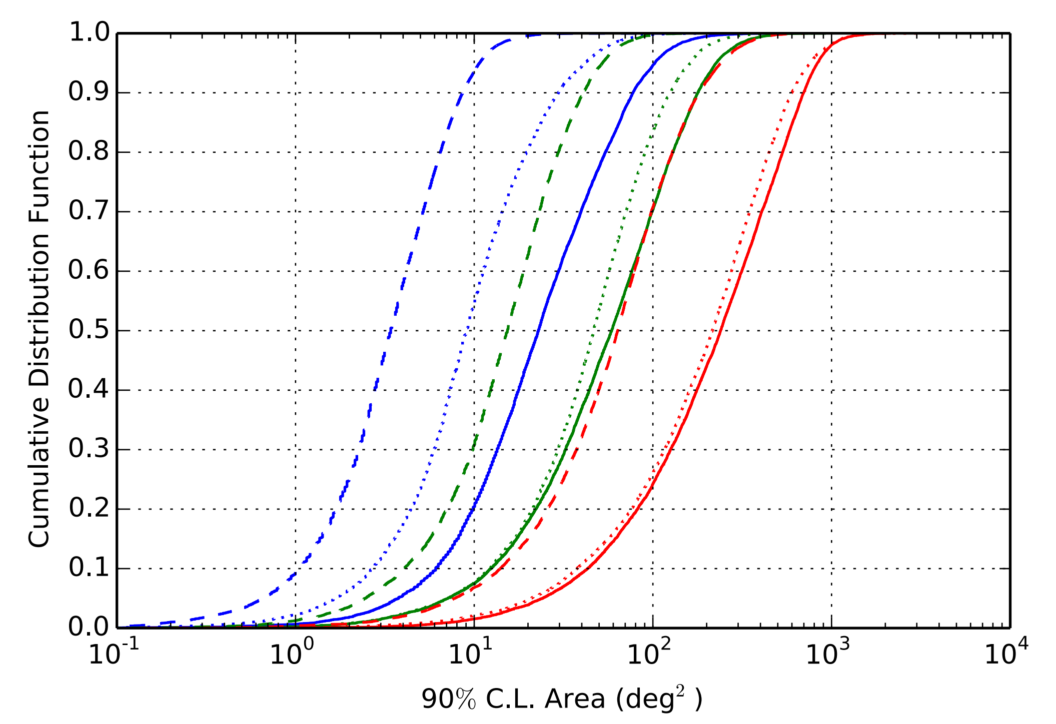
Chen et al., PRX (2019)



Borhanian&Sathyaprakash, arXiv:2202.11048

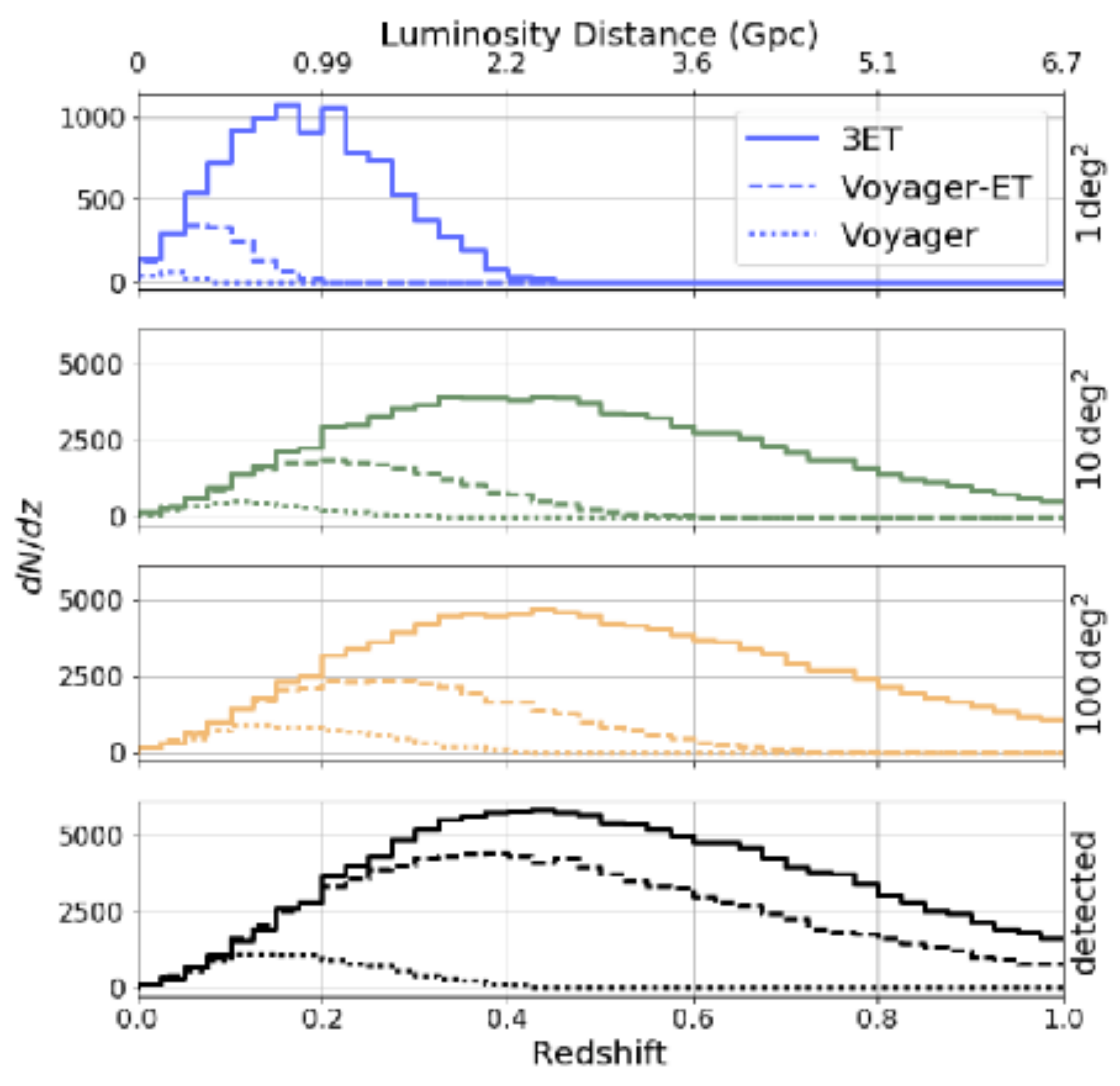
Multi-messenger: More precise localizations

5 events localized in 10 deg² every year.



Chen&Holz, arXiv:1612.01471

1,000 events localized in 1 deg² and a few thousands in 10 deg² every year.



Mills et al., PRD (2018)

Multi-messenger: More precise localizations

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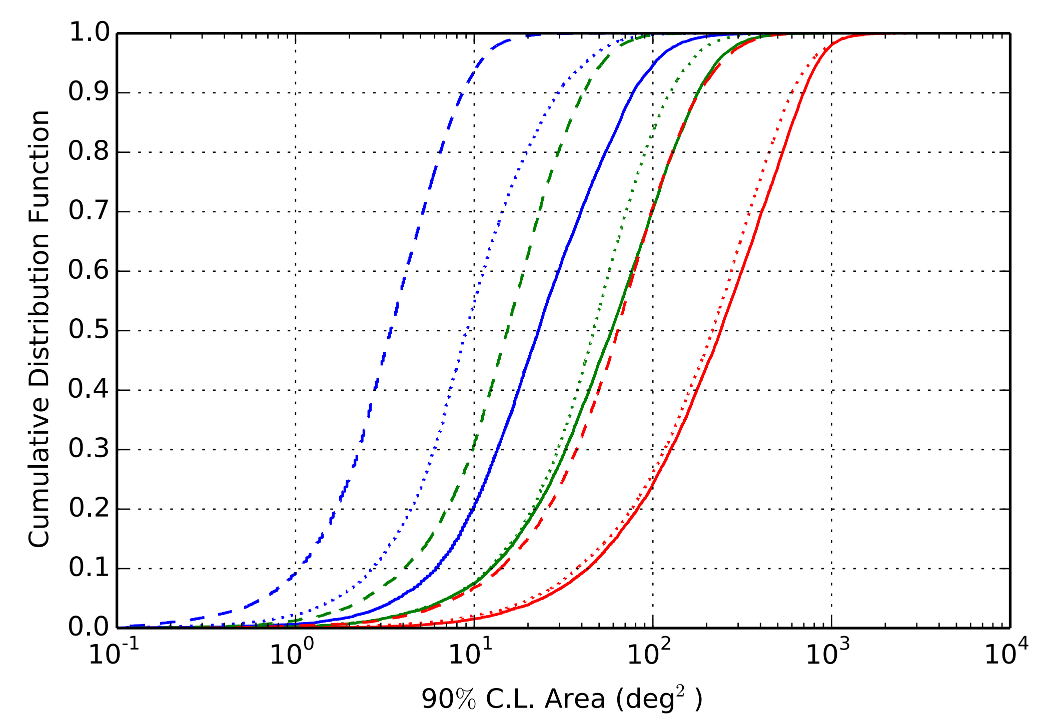

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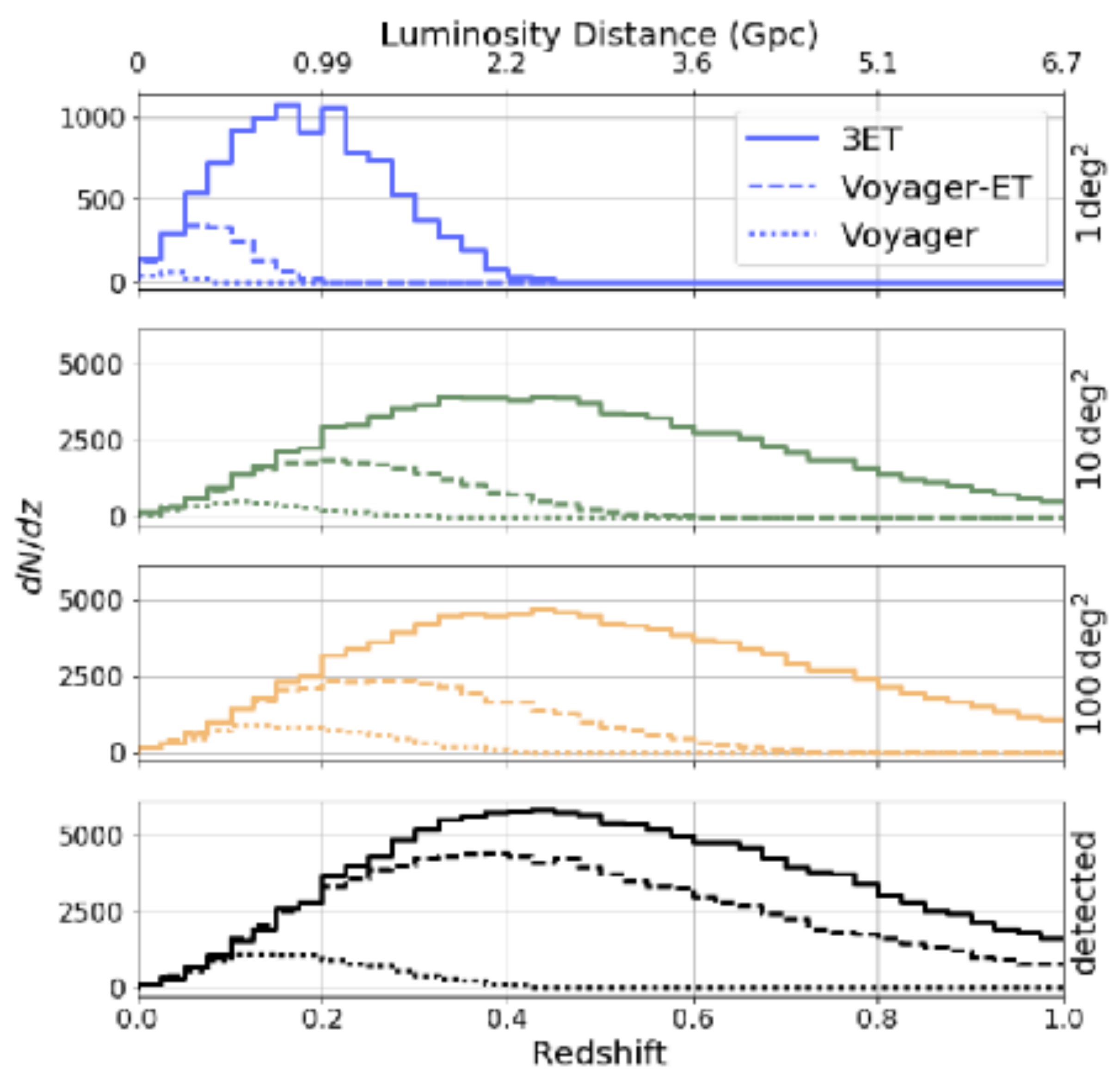

Mills et al., PRD (2018)

Different EM observing scenarios

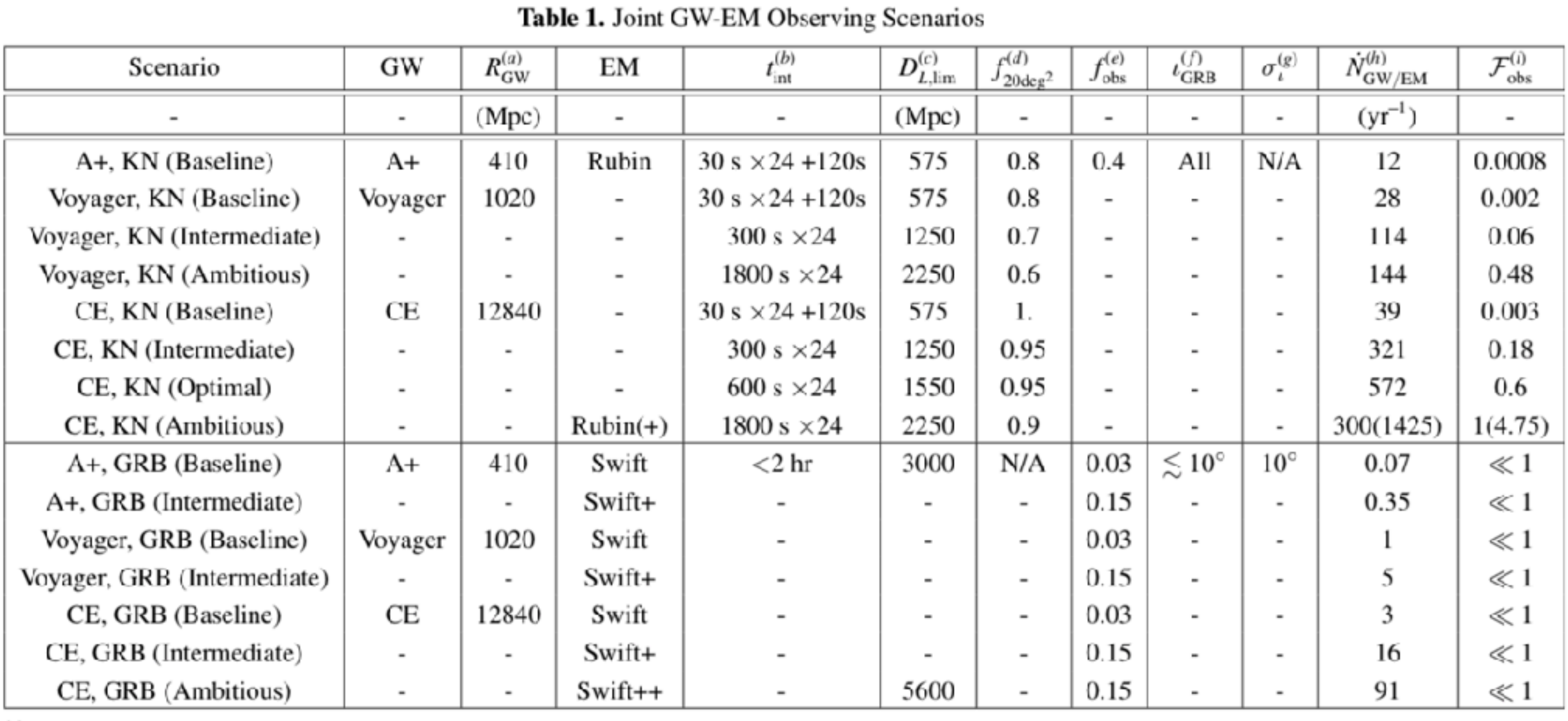

Table 1. Joint GW-EM Observing Scenarios

Scenario	GW	$R_{\rm GW}^{(a)}$	EM	$t_{\rm int}^{(b)}$	$D_{L,\rm lim}^{(c)}$	$f_{20\deg^2}^{(d)}$	$f_{\rm obs}^{(e)}$	$\iota_{\rm GRB}^{(f)}$	$\sigma_\iota^{(g)}$	$\dot{N}_{\rm GW/EM}^{(h)}$	$\mathcal{F}_{\rm obs}^{(i)}$
-	-	(Mpc)	-	-	(Mpc)	-	-	-	-	($\rm yr^{-1}$)	-
A+, KN (Baseline)	A+	410	Rubin	30 s $\times$24 +120s	575	0.8	0.4	All	N/A	12	0.0008
Voyager, KN (Baseline)	Voyager	1020	-	30 s $\times$24 +120s	575	0.8	-	-	-	28	0.002
Voyager, KN (Intermediate)	-	-	-	300 s $\times$24	1250	0.7	-	-	-	114	0.06
Voyager, KN (Ambitious)	-	-	-	1800 s $\times$24	2250	0.6	-	-	-	144	0.48
CE, KN (Baseline)	CE	12840	-	30 s $\times$24 +120s	575	1.	-	-	-	39	0.003
CE, KN (Intermediate)	-	-	-	300 s $\times$24	1250	0.95	-	-	-	321	0.18
CE, KN (Optimal)	-	-	-	600 s $\times$24	1550	0.95	-	-	-	572	0.6
CE, KN (Ambitious)	-	-	Rubin(+)	1800 s $\times$24	2250	0.9	-	-	-	300(1425)	1(4.75)
A+, GRB (Baseline)	A+	410	Swift	$<$2 hr	3000	N/A	0.03	$\lesssim 10^\circ$	10°	0.07	$\ll 1$
A+, GRB (Intermediate)	-	-	Swift+	-	-	-	0.15	-	-	0.35	$\ll 1$
Voyager, GRB (Baseline)	Voyager	1020	Swift	-	-	-	0.03	-	-	1	$\ll 1$
Voyager, GRB (Intermediate)	-	-	Swift+	-	-	-	0.15	-	-	5	$\ll 1$
CE, GRB (Baseline)	CE	12840	Swift	-	-	-	0.03	-	-	3	$\ll 1$
CE, GRB (Intermediate)	-	-	Swift+	-	-	-	0.15	-	-	16	$\ll 1$
CE, GRB (Ambitious)	-	-	Swift++	-	5600	-	0.15	-	-	91	$\ll 1$

Neutrino counterpart GW170817

-Non-detection consistent with an off-axis GRB model.

-20s: From the extended emission of GRB

-Days: Optically thick ejecta can retain the energy and lead to emission in the later stage.