Multi-messenger standard siren cosmology and high-redshift black hole formation history with next generation gravitational-wave observatories

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

Chen, Ricarte & Pacucci, 2202.04764

Hsin-Yu Chen

(NASA Einstein Fellow, MIT)

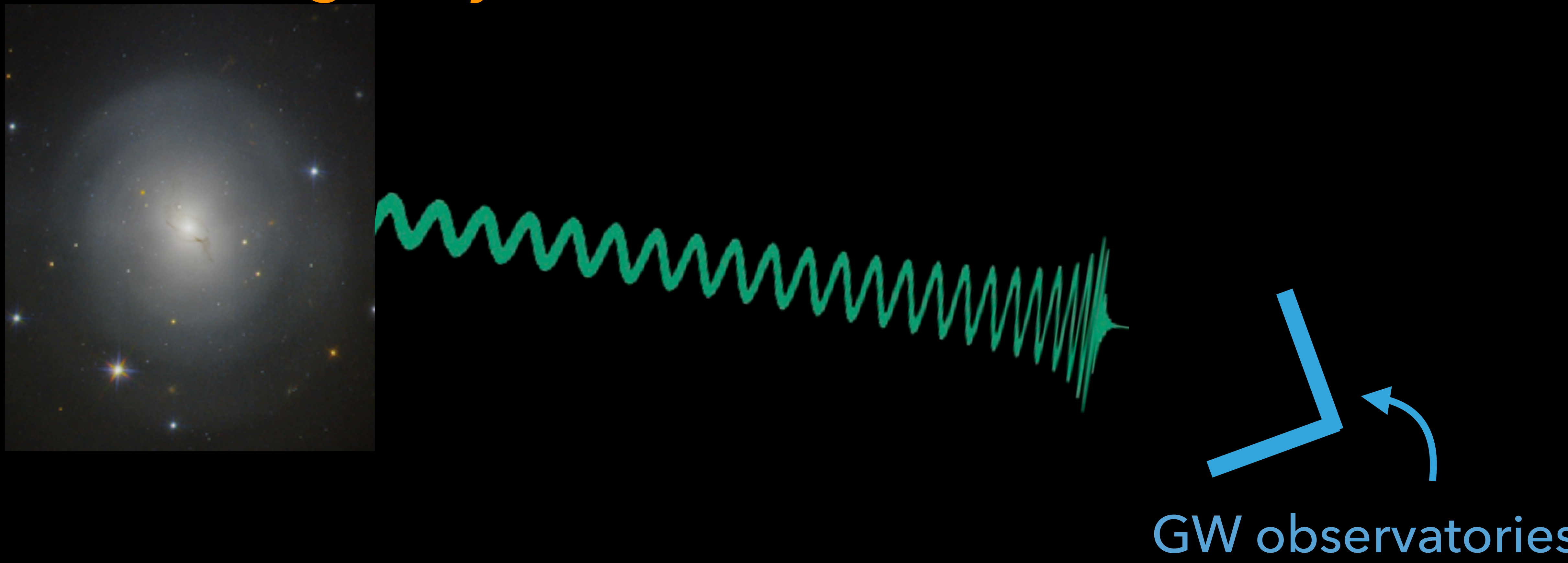
Cosmic Explorer Science Call, March 2022

Bright siren in 3G era

Bright siren in 3G era

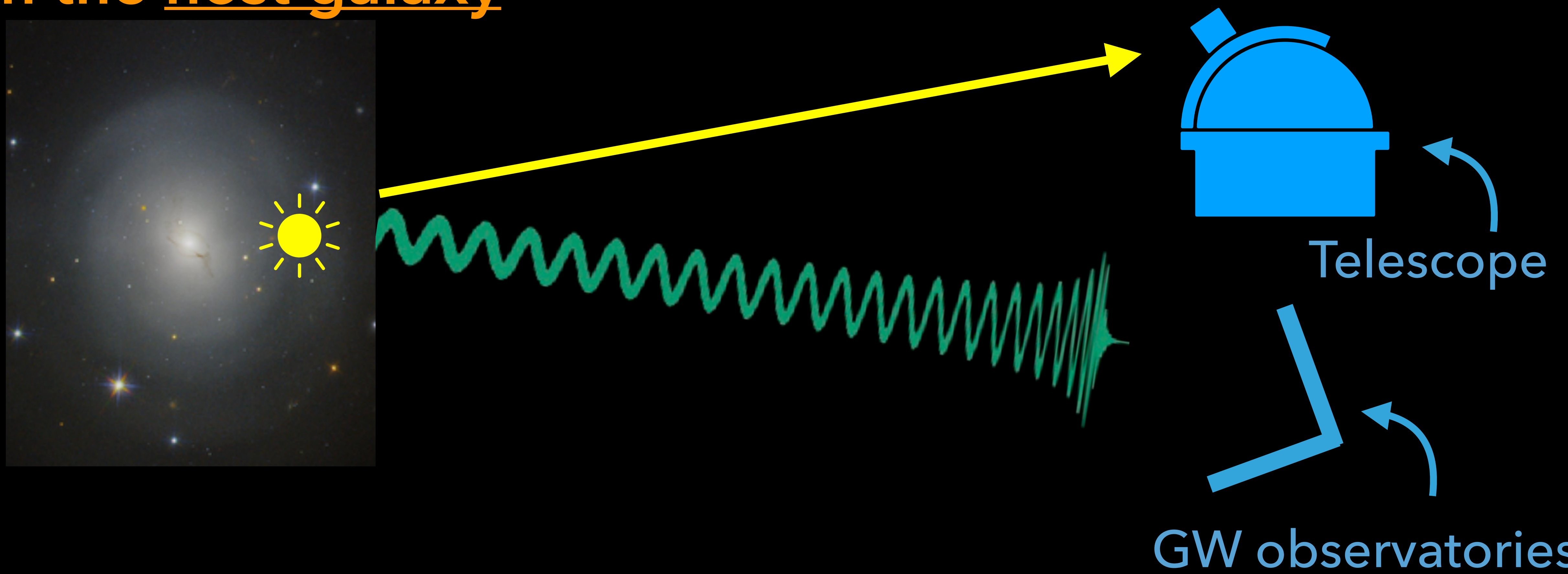
The limiting factor is the
electromagnetic counterpart observations.

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



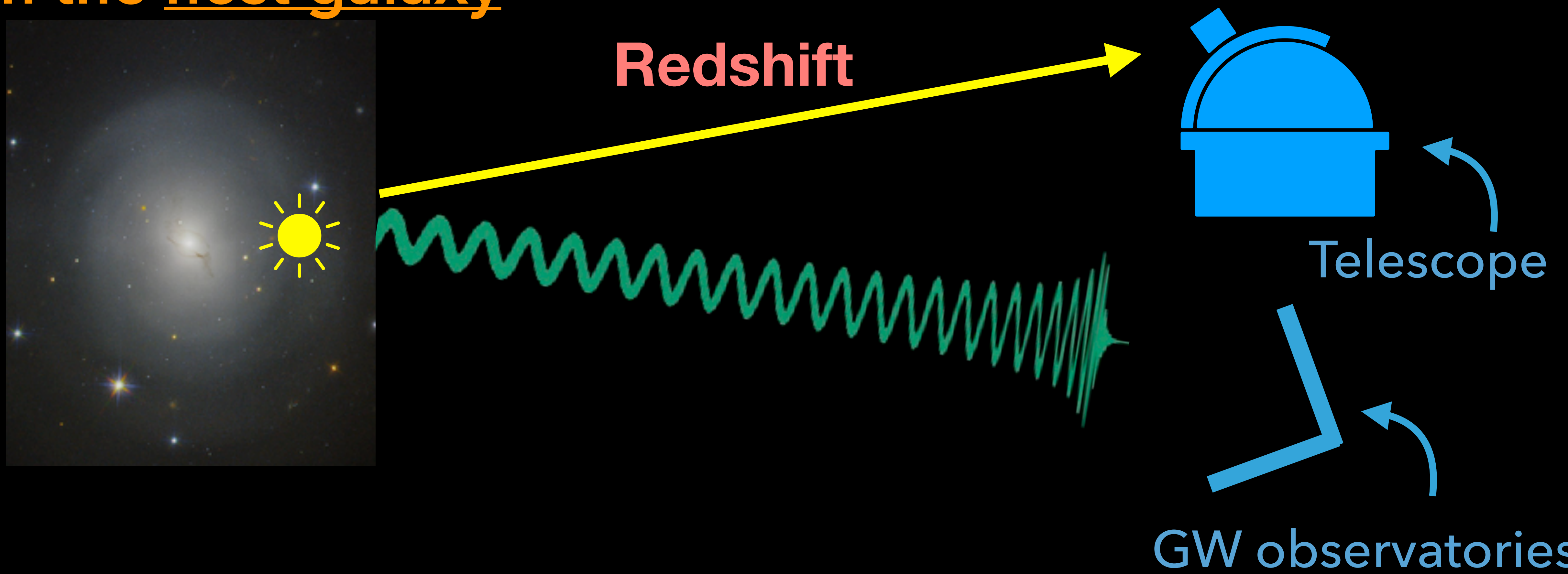
Schutz, Nature (1986) / Holz & Hughes, ApJ (2005)

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



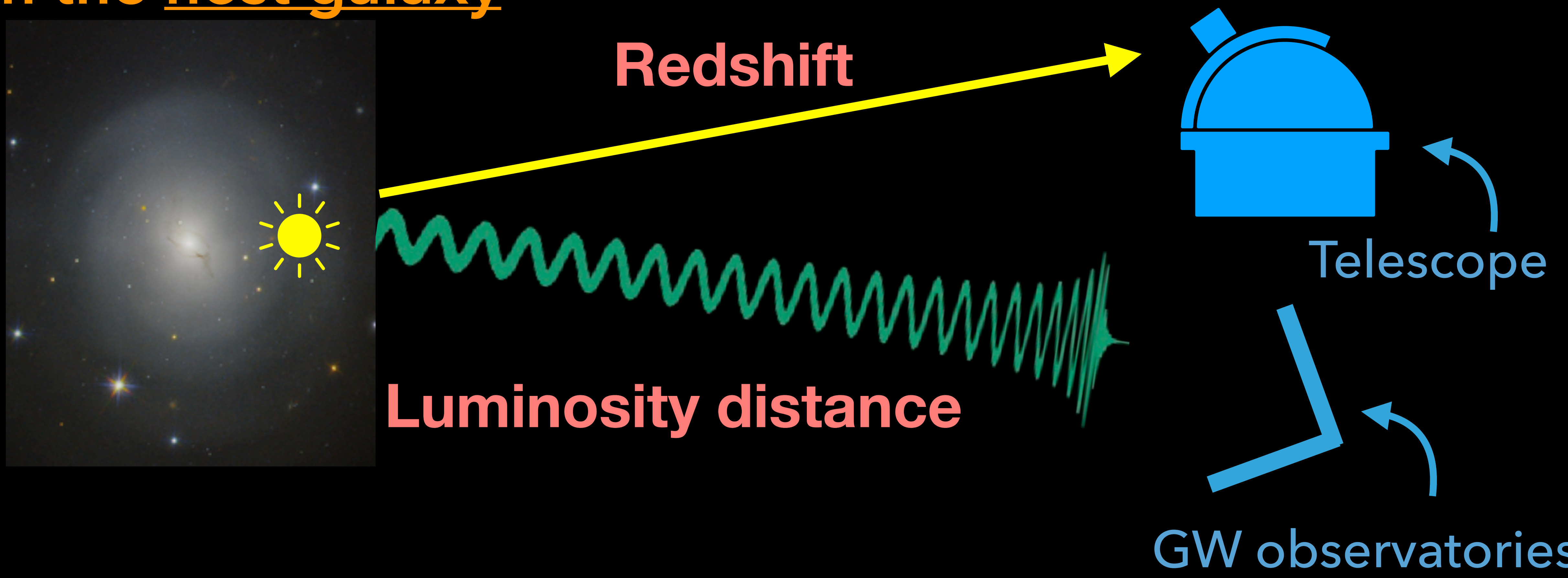
Schutz, Nature (1986) / Holz & Hughes, ApJ (2005)

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



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

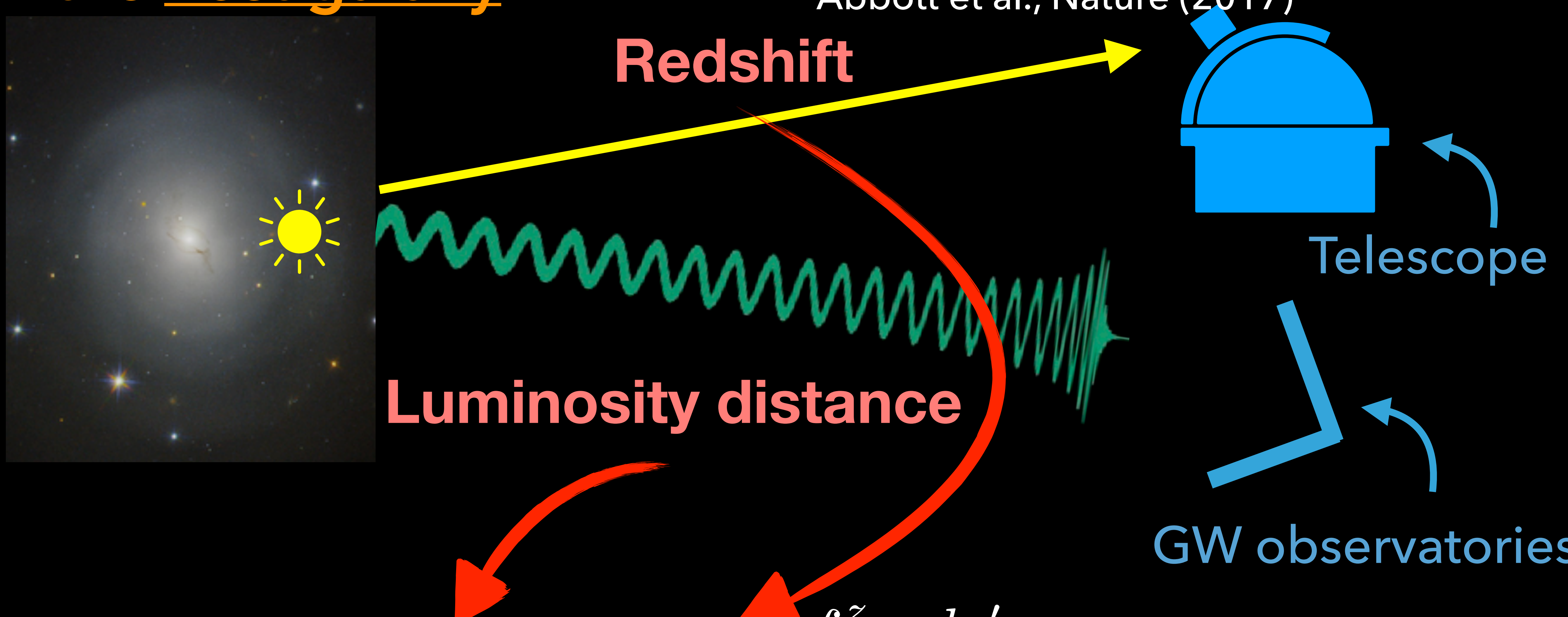
Standard siren with electromagnetic counterparts: Determine the redshift of gravitational-wave source with the host galaxy



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

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

Abbott et al., Nature (2017)



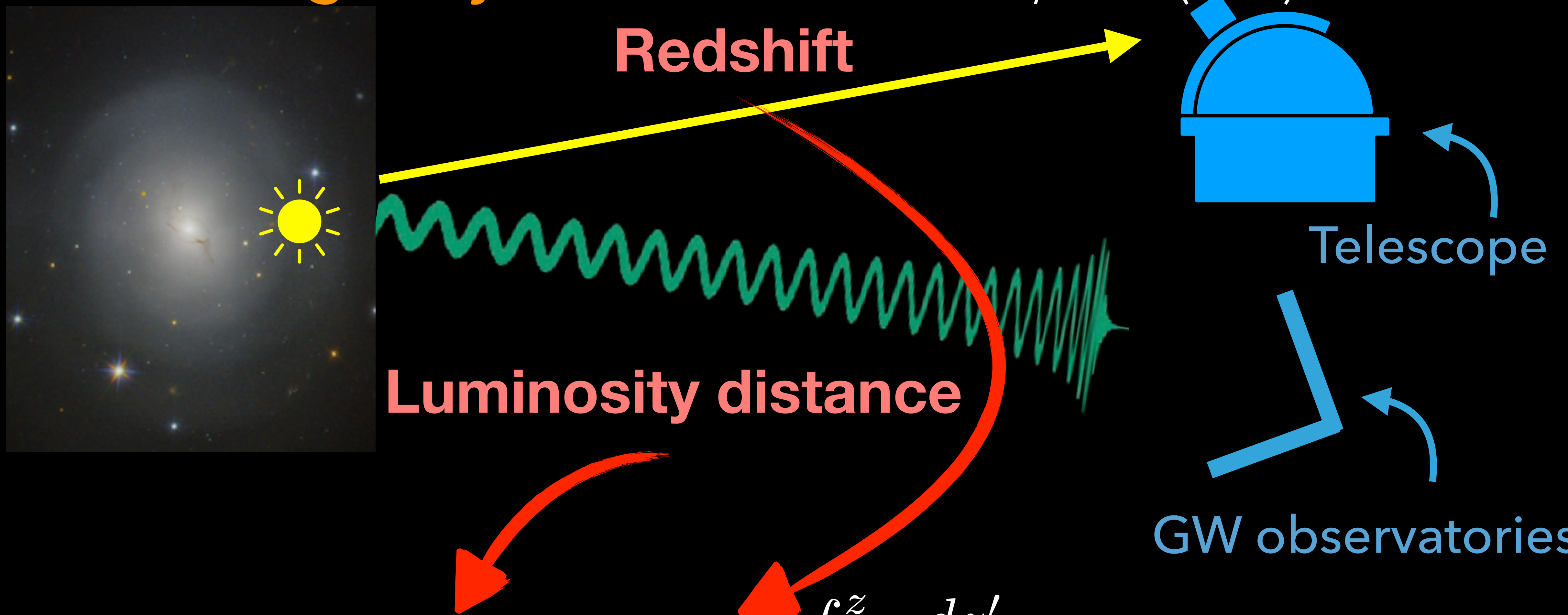
$$D_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

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

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

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

Abbott et al., Nature (2017)



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

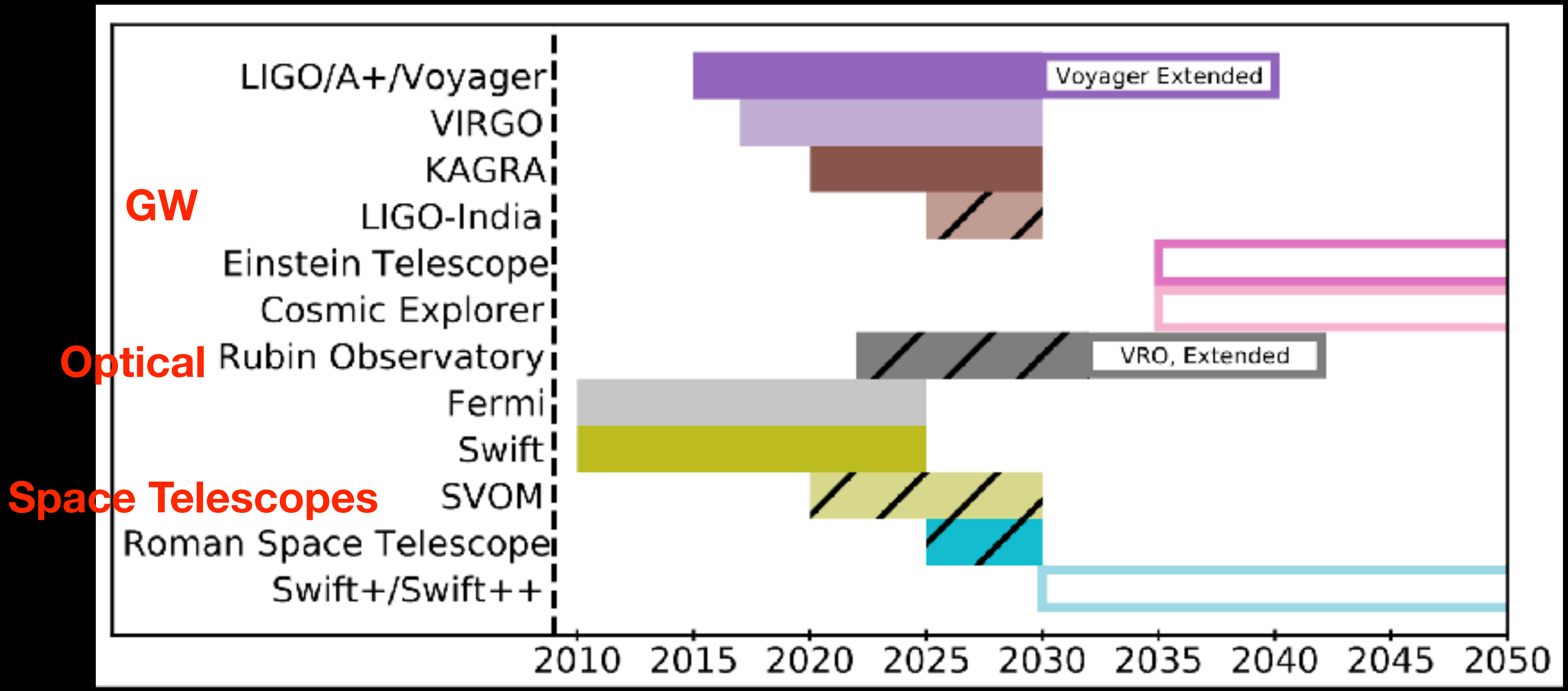
Percent-level precision in H_0 is expected in 2G.

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

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

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

Electromagnetic observations in 2.5-3G era

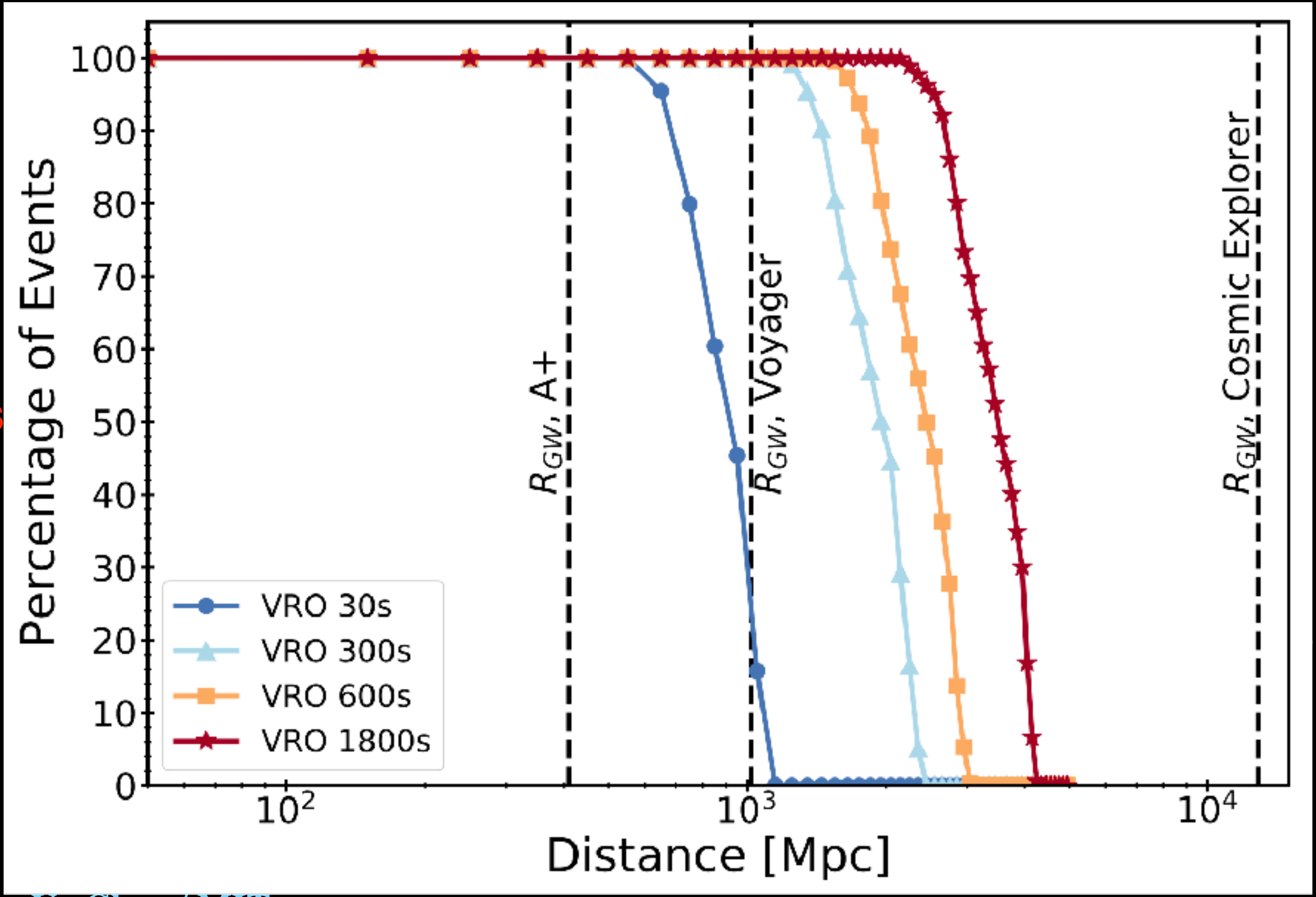


-There are more GW events than the telescopes can follow.

-The detection efficiency drops rapidly as the distance increases.

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

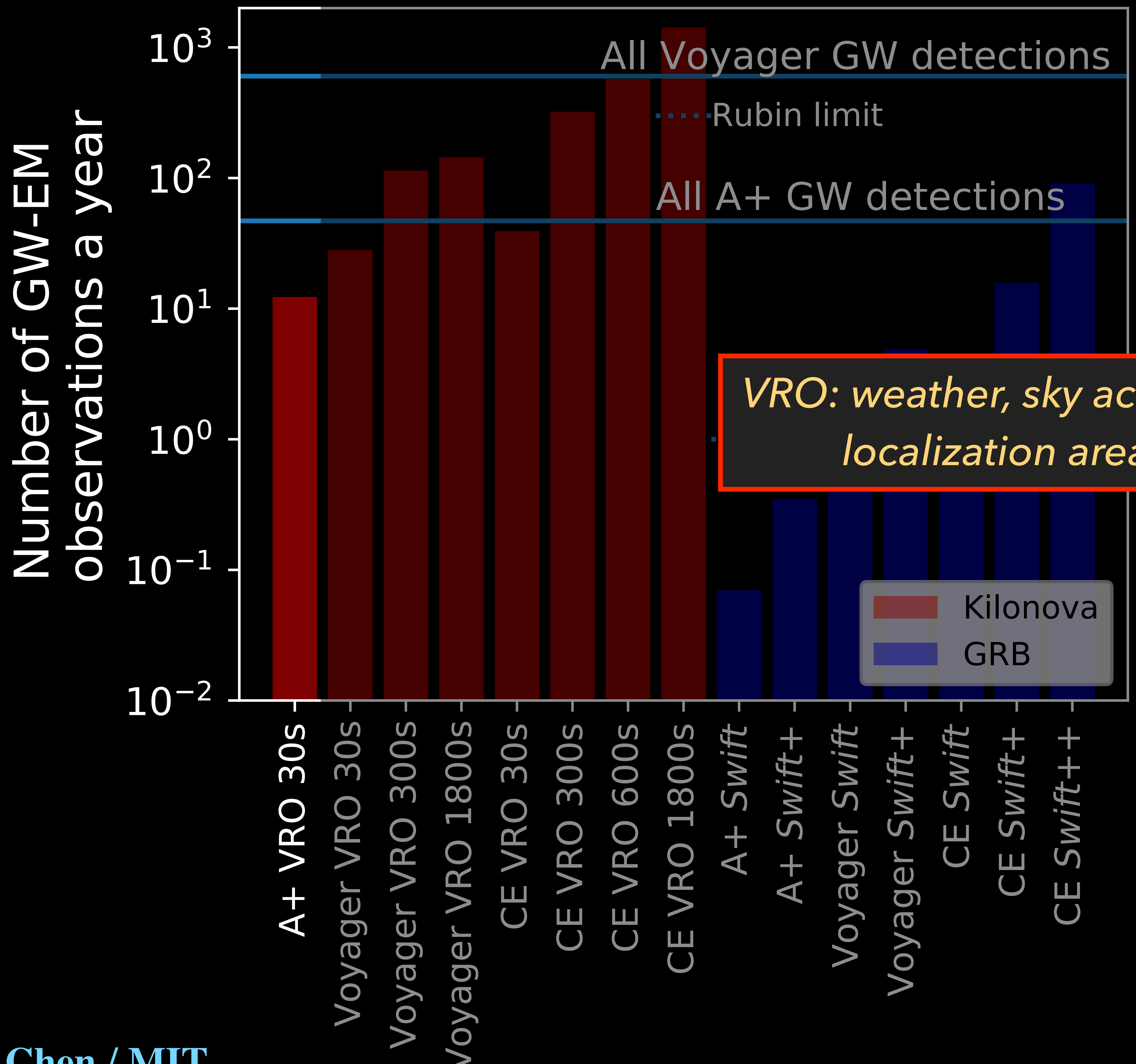
Electromagnetic observations in 2.5-3G era



s

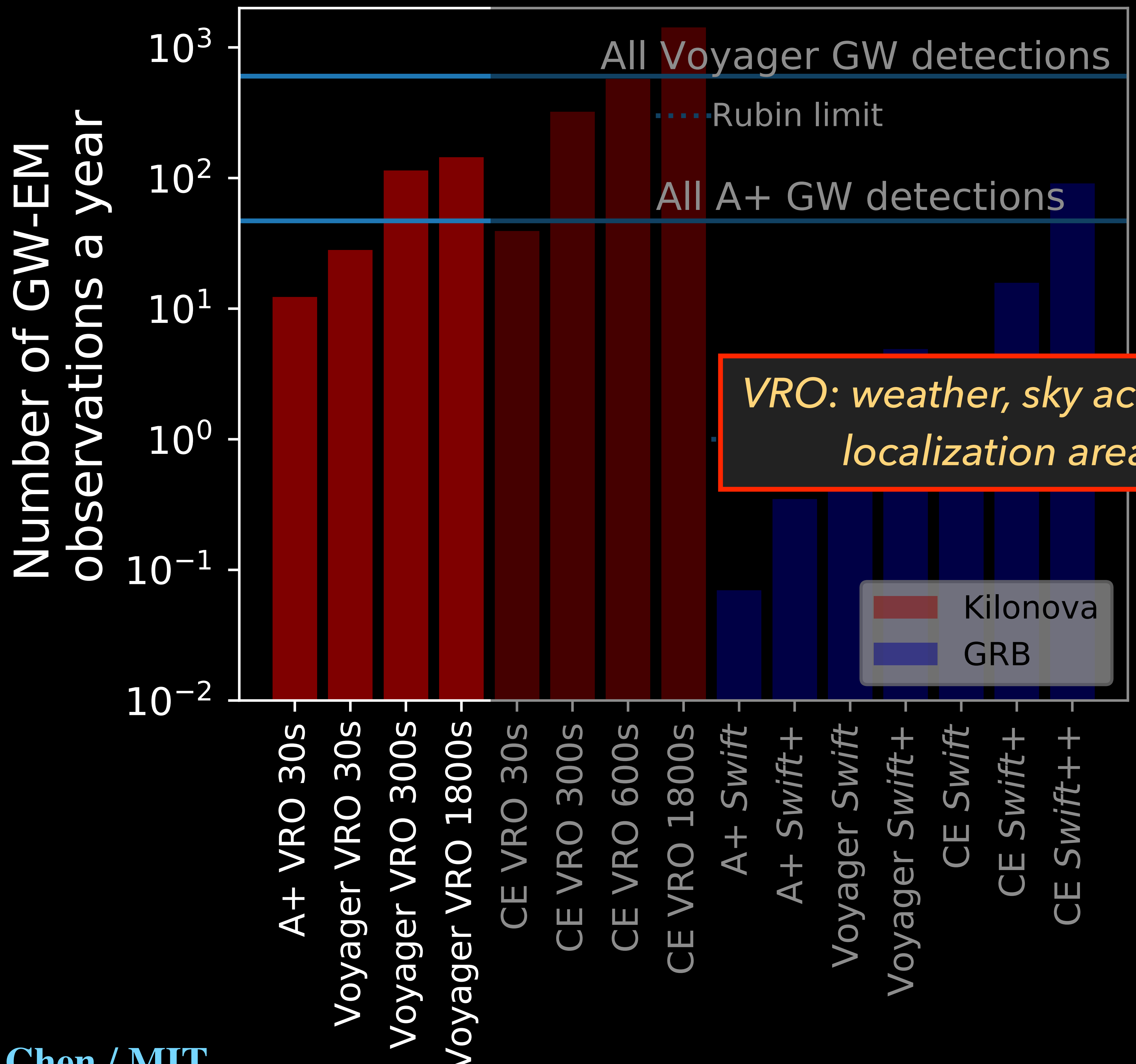
w.

Number of joint detections in 2.5-3G era



VRO: weather, sky accessibility, localization area etc.

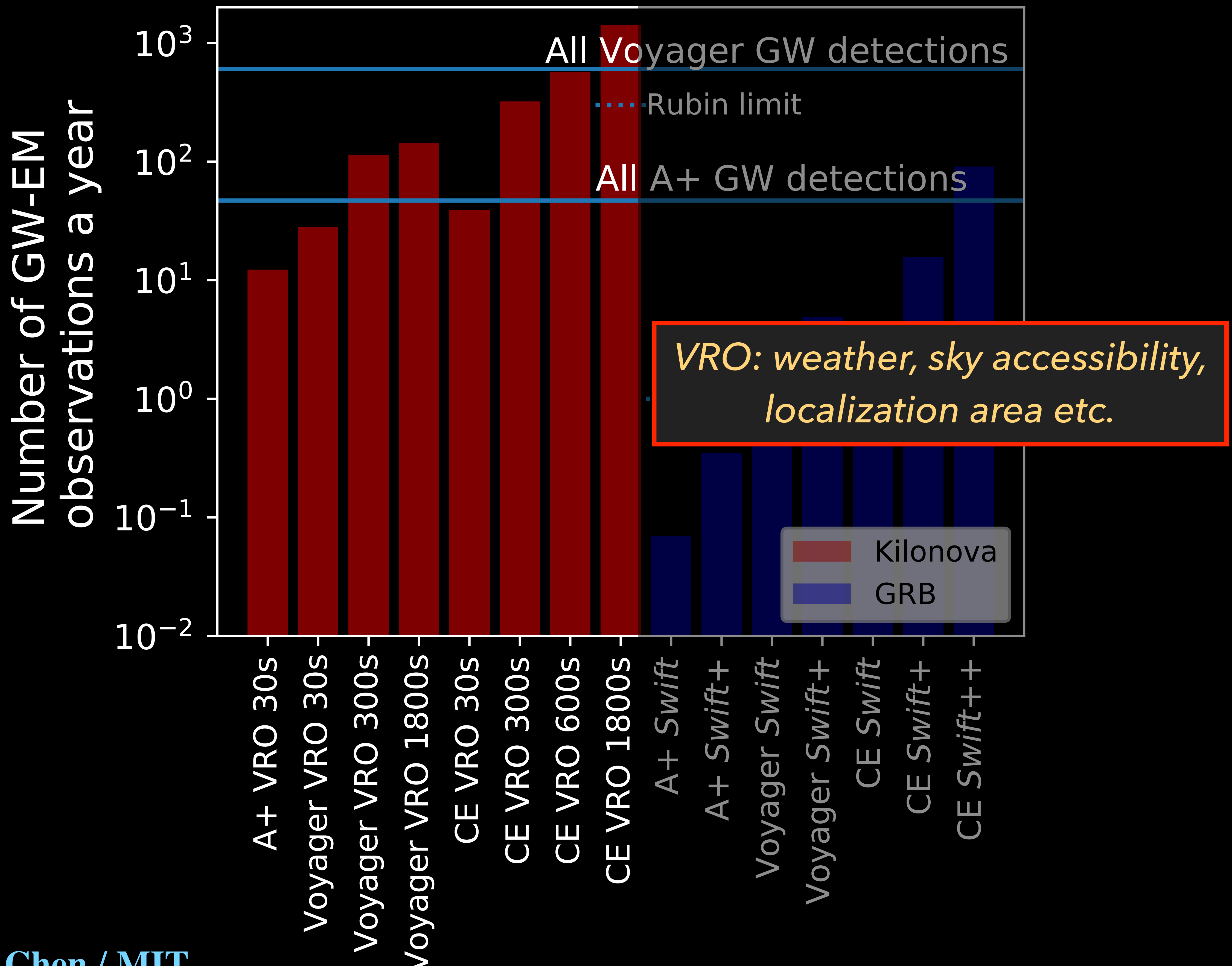
Number of joint detections in 2.5-3G era



VRO: weather, sky accessibility, localization area etc.

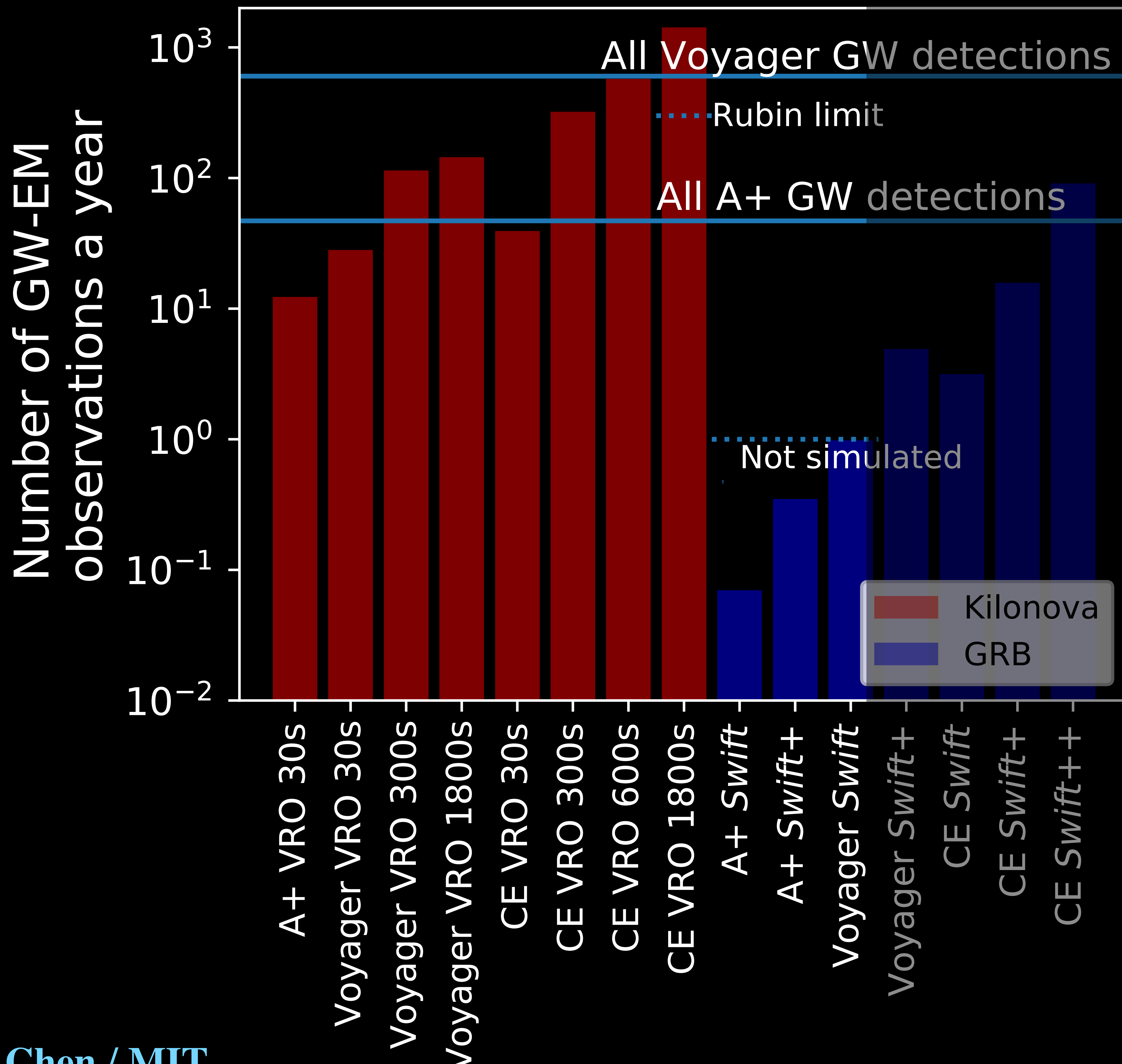
Chen, Cowperthwaite, Metzger, Berger, 2011.01211, ApJL (2021)

Number of joint detections in 2.5-3G era



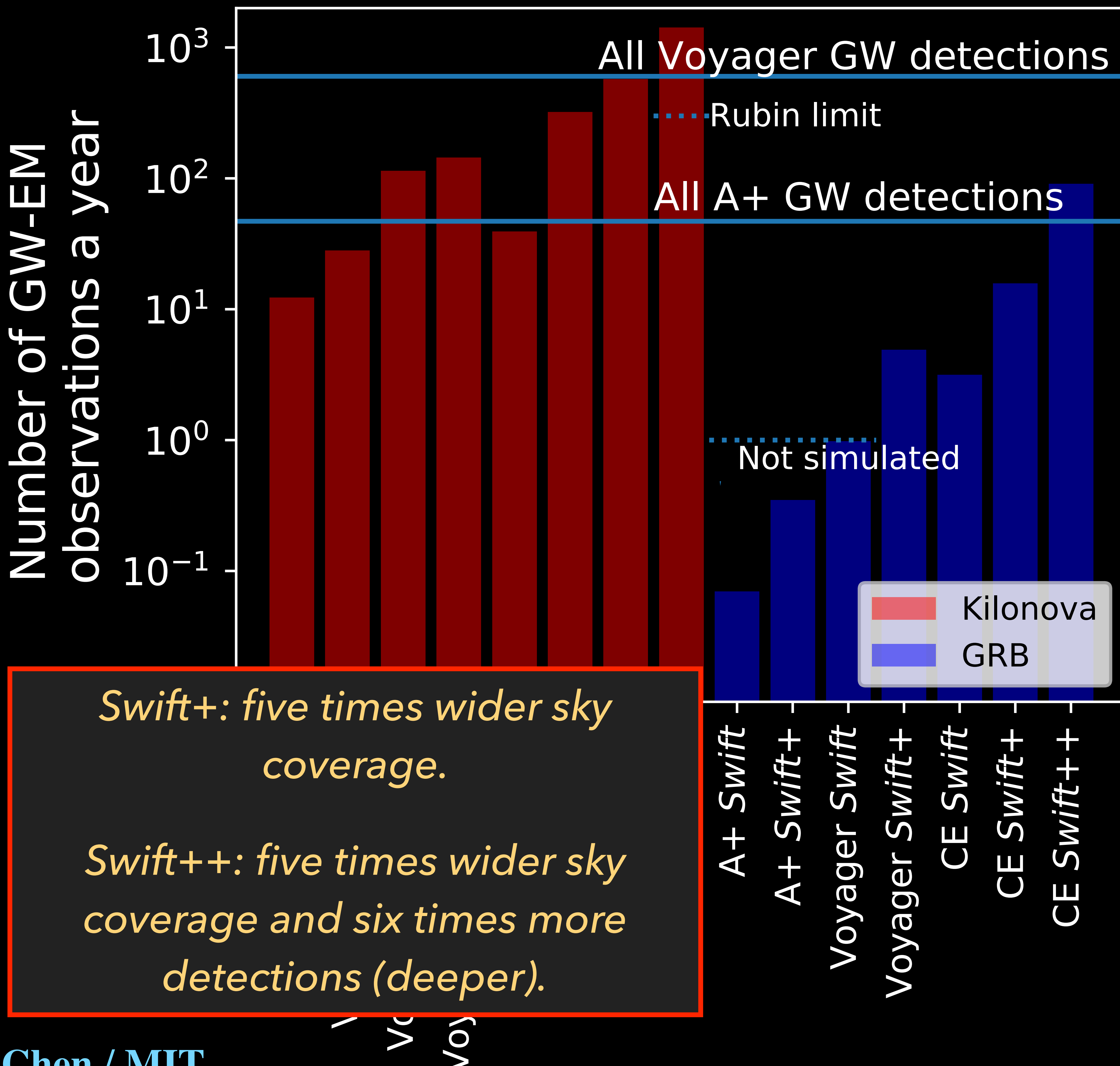
Chen, Cowperthwaite, Metzger, Berger, 2011.01211, ApJL (2021)

Number of joint detections in 2.5-3G era



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

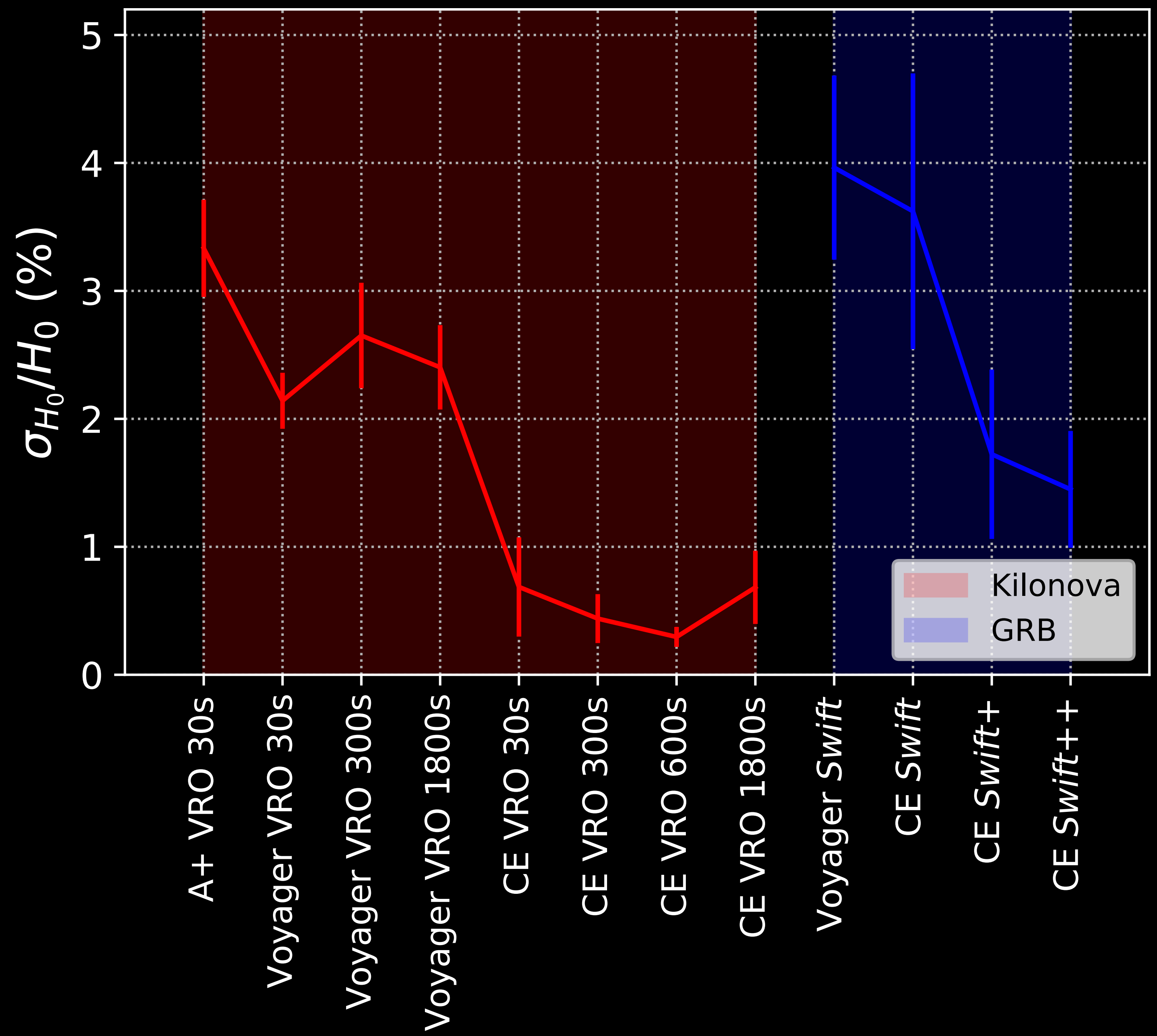
Number of joint detections in 2.5-3G era



Swift+: five times wider sky coverage.

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

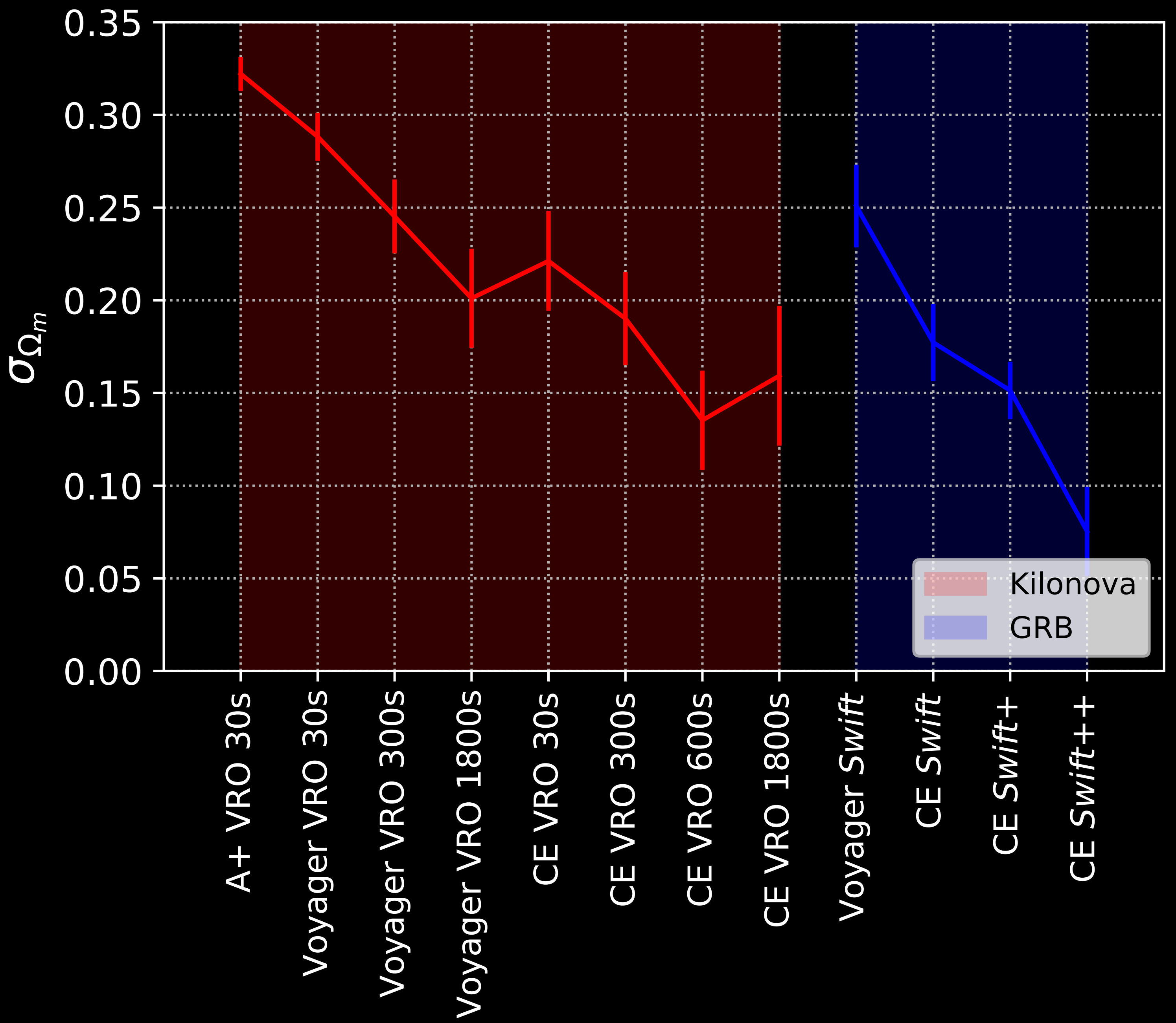
Cosmological constraints from bright sirens in 2.5-3G



-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.

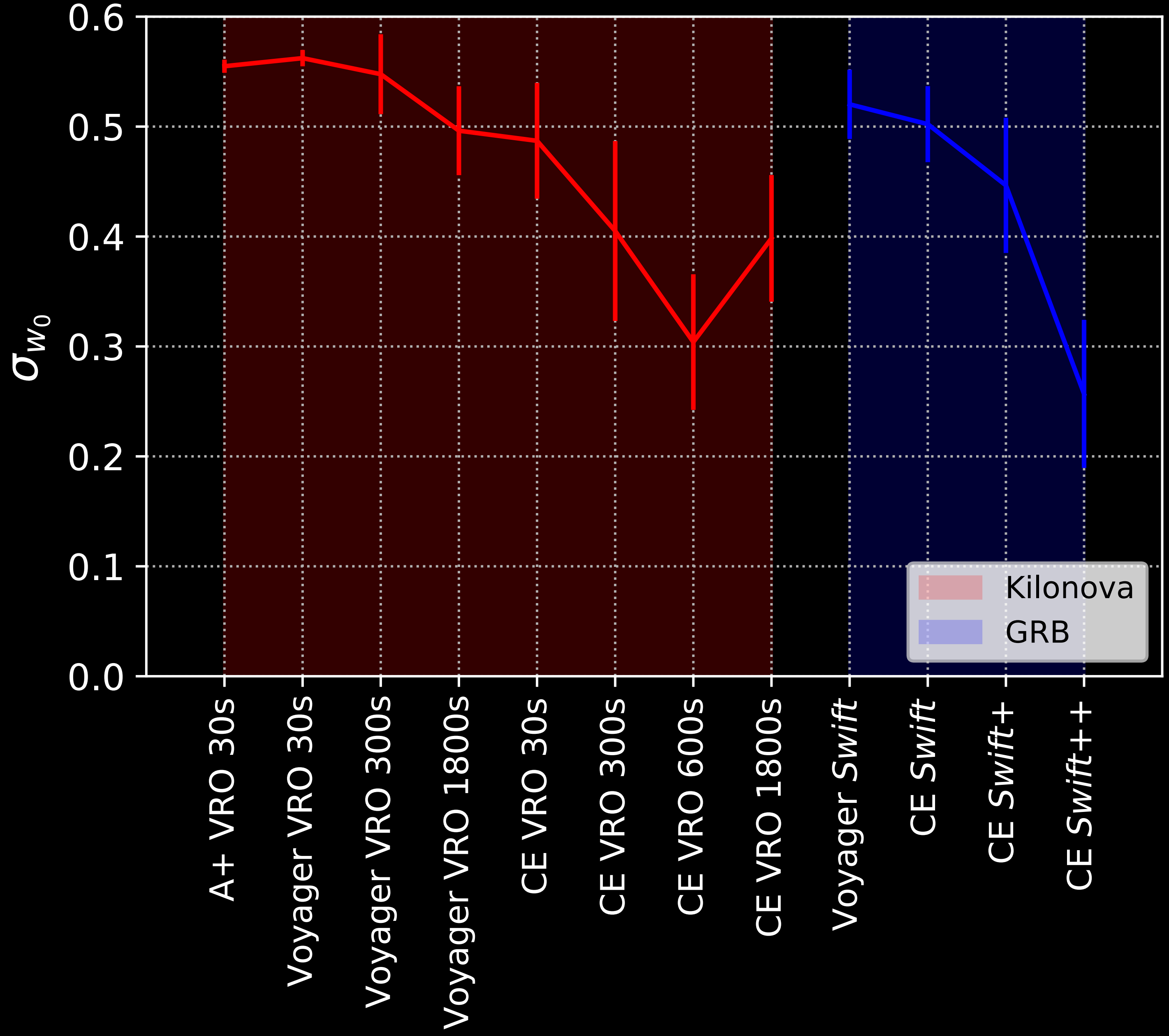
Cosmological constraints from bright sirens in 2.5-3G



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

-GRBs (with beaming) only need an order of magnitude fewer events to achieve the same precision than 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.

How did massive black holes at the center of galaxies formed?

How did massive black holes at the center of galaxies formed?

Mergers of black holes

Accretion

Seeding by binary black hole mergers

-Light seed [O(10-10^3) $M_\odot$]: Remnants of Pop III stars

-Heavy seed [O(10^4-10^6) $M_\odot$]: Direct collapse of dense and massive cloud

Seeding by binary black hole mergers

-Light seed [O(10-10^3) $M_\odot$]: Remnants of Pop III stars

-Heavy seed [O(10^4-10^6) $M_\odot$]: Direct collapse of dense and massive cloud

The abundance of seeds and their merging mechanism is highly uncertain.

Dominated uncertainties for the seeding models

-The relative ratio of light v.s heavy seeds that contribute to the central black hole formation

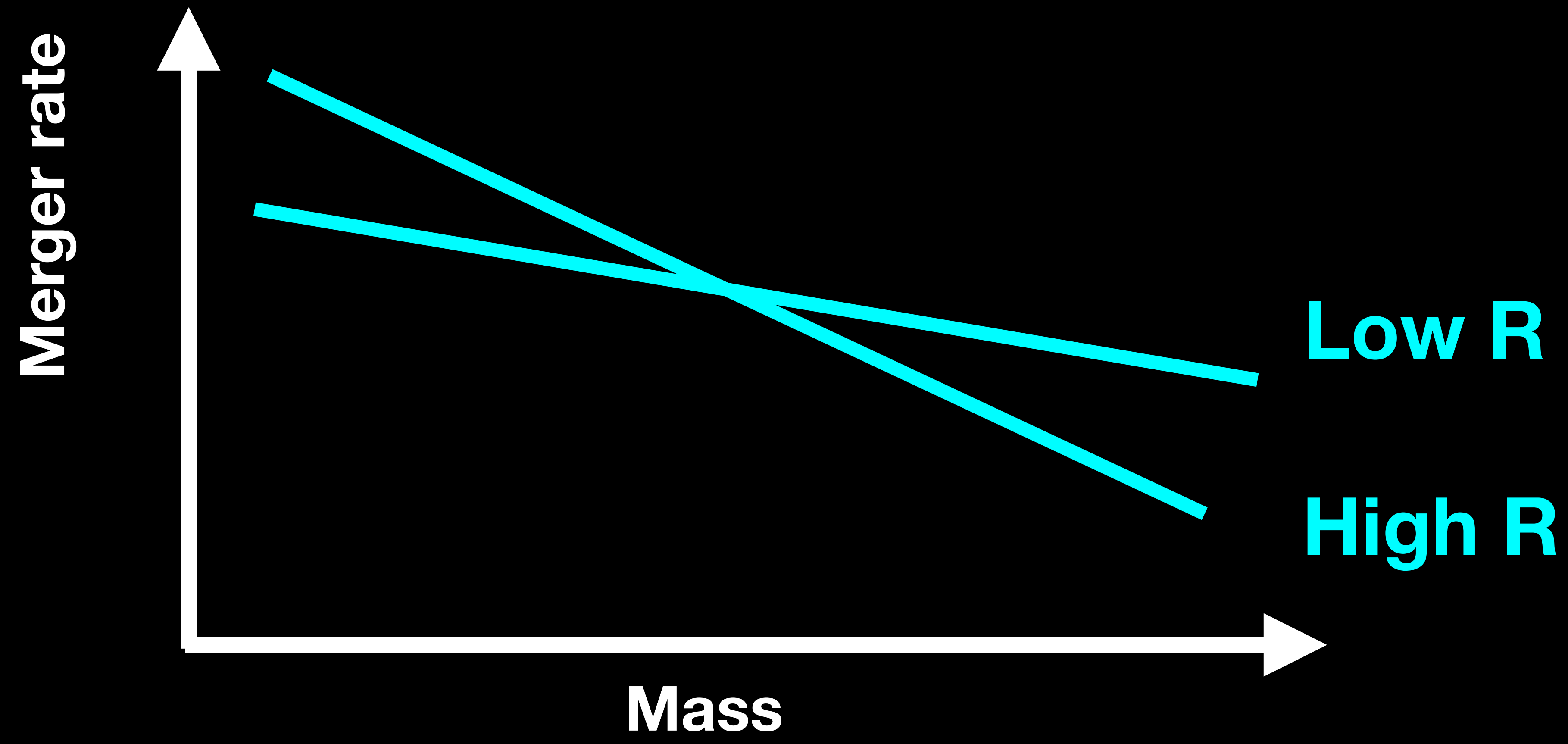
$\Longrightarrow$ ***Light/heavy seed mixture ratio R***

Chen, Ricarte & Pacucci, 2202.04764

Dominated uncertainties for the seeding models

-The relative ratio of light v.s heavy seeds that contribute to the central black hole formation

⟹ ***Light/heavy seed mixture ratio R***



Dominated uncertainties for the seeding models

-The relative ratio of light v.s heavy seeds that contribute to the central black hole formation

$\Longrightarrow$ ***Light/heavy seed mixture ratio R***

-How likely the central black holes merge after their galaxies merge?

$\Longrightarrow$ ***Merging probability P***

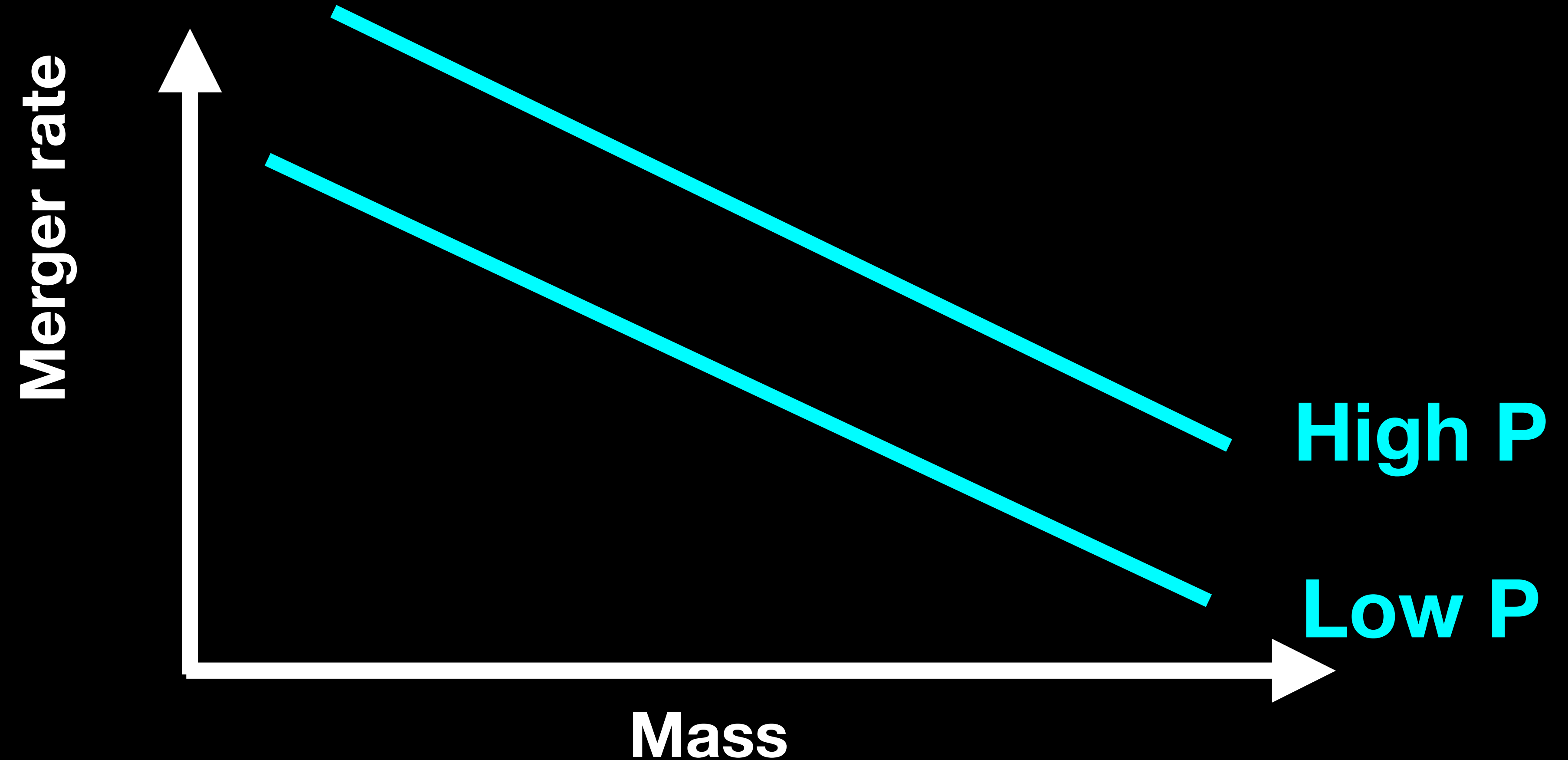
Dominated uncertainties for the seeding models

-The relative ratio of light v.s heavy seeds that contribute to the central black hole formation

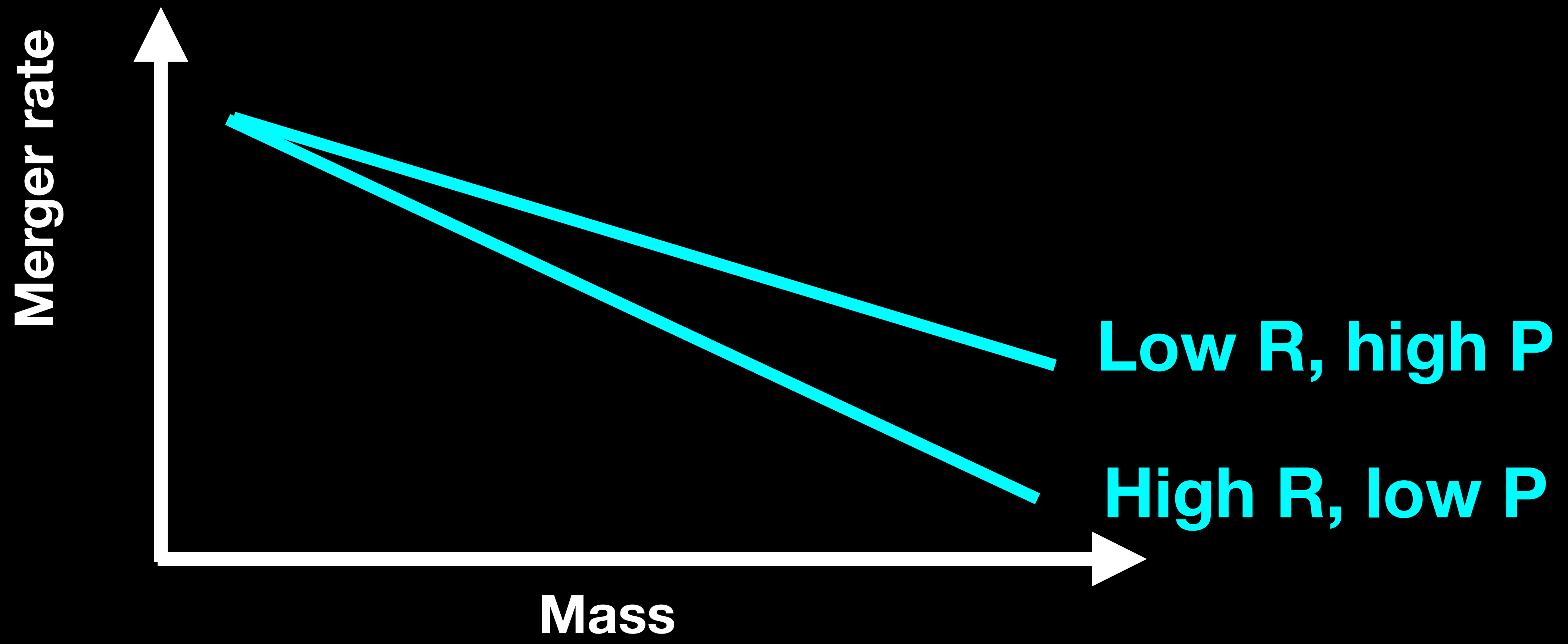
$\Longrightarrow$ ***Light/heavy seed mixture ratio R***

-How likely the central black holes merge after their galaxies merge?

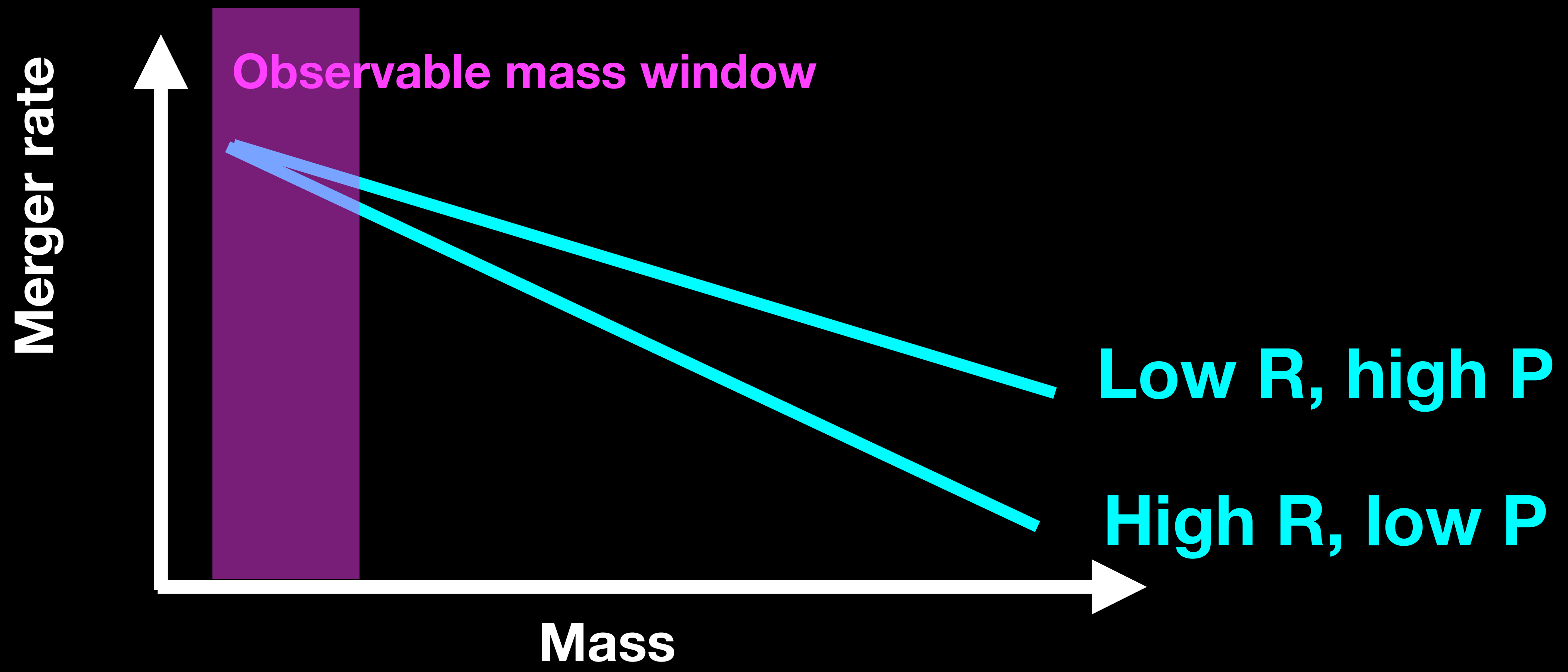
$\Longrightarrow$ ***Merging probability P***



To constrain R and P from observations

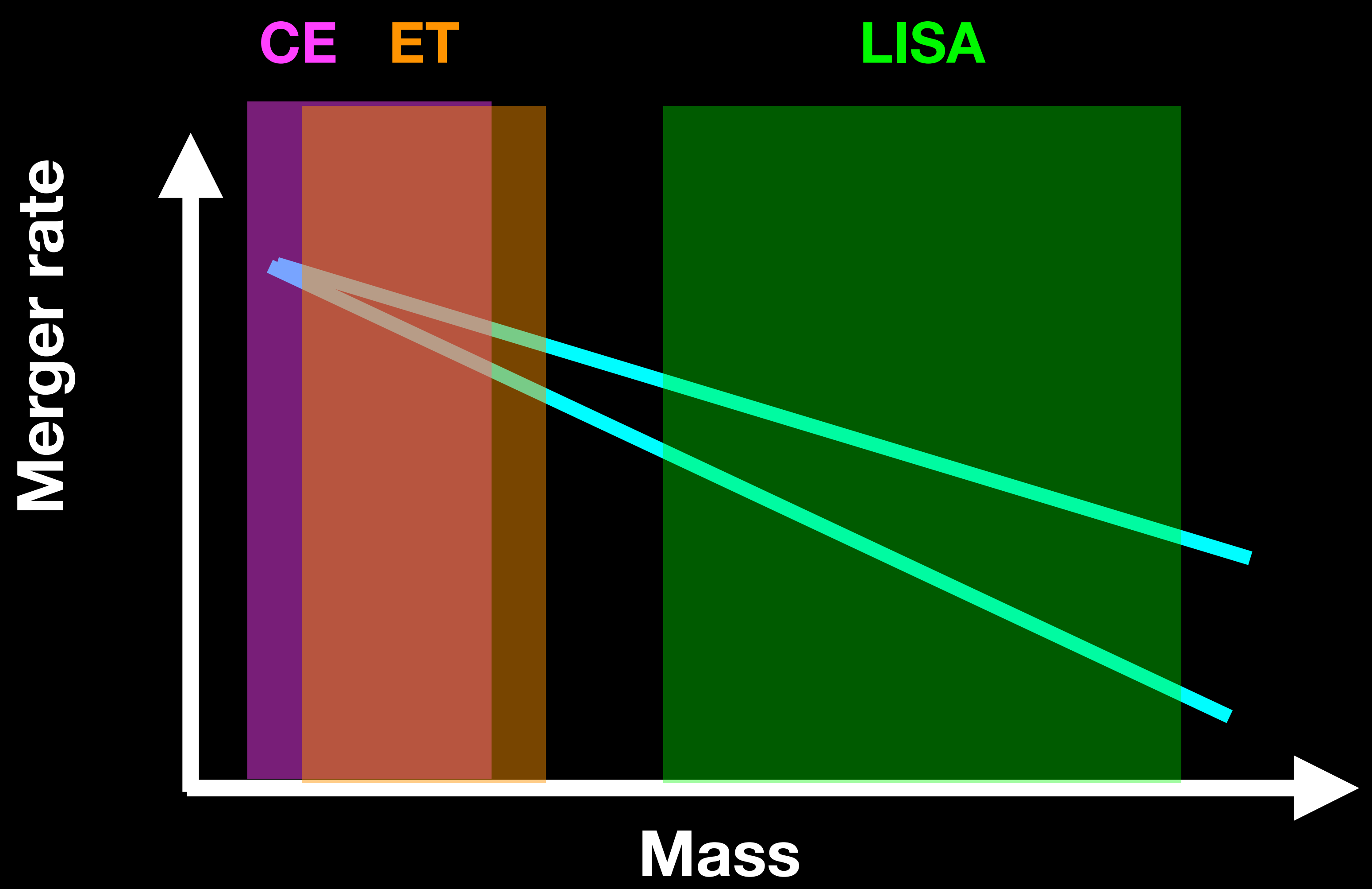


To constrain R and P from observations



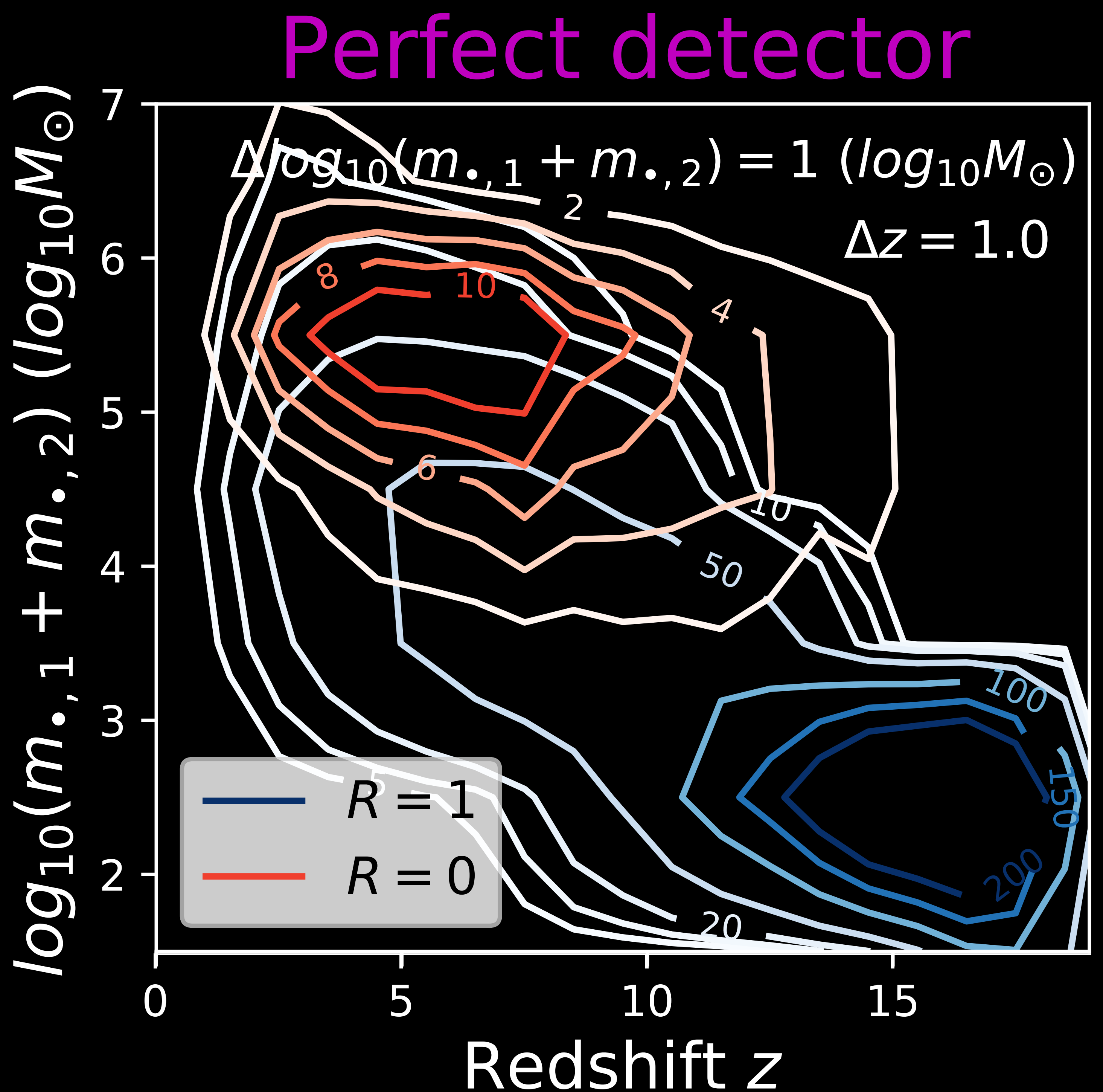
Limited observable mass window can limit the constraining power to R and P due to the degeneracy.

To constrain R and P from observations

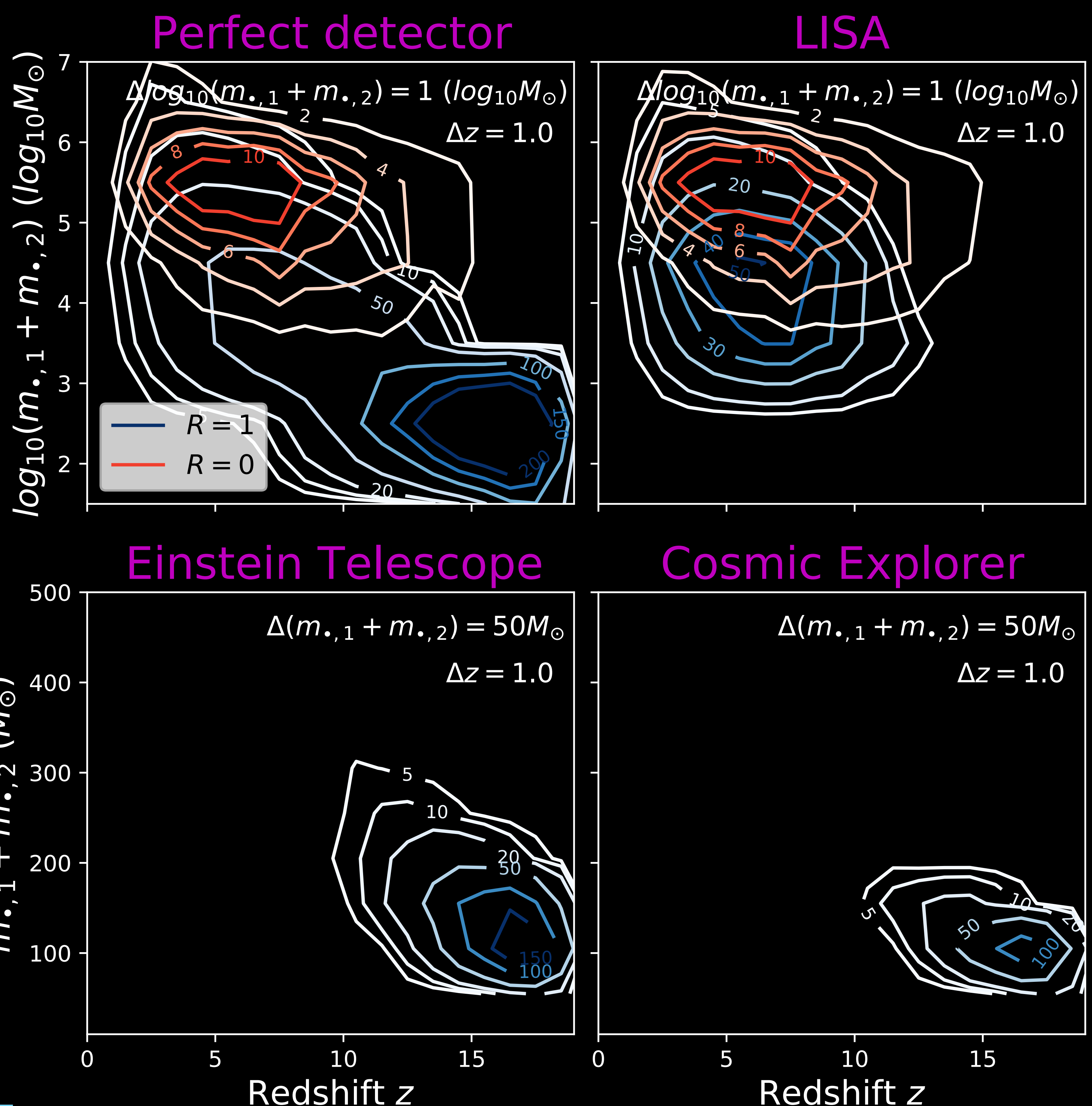


Limited observable mass window can limit the constraining power to R and P due to the degeneracy.

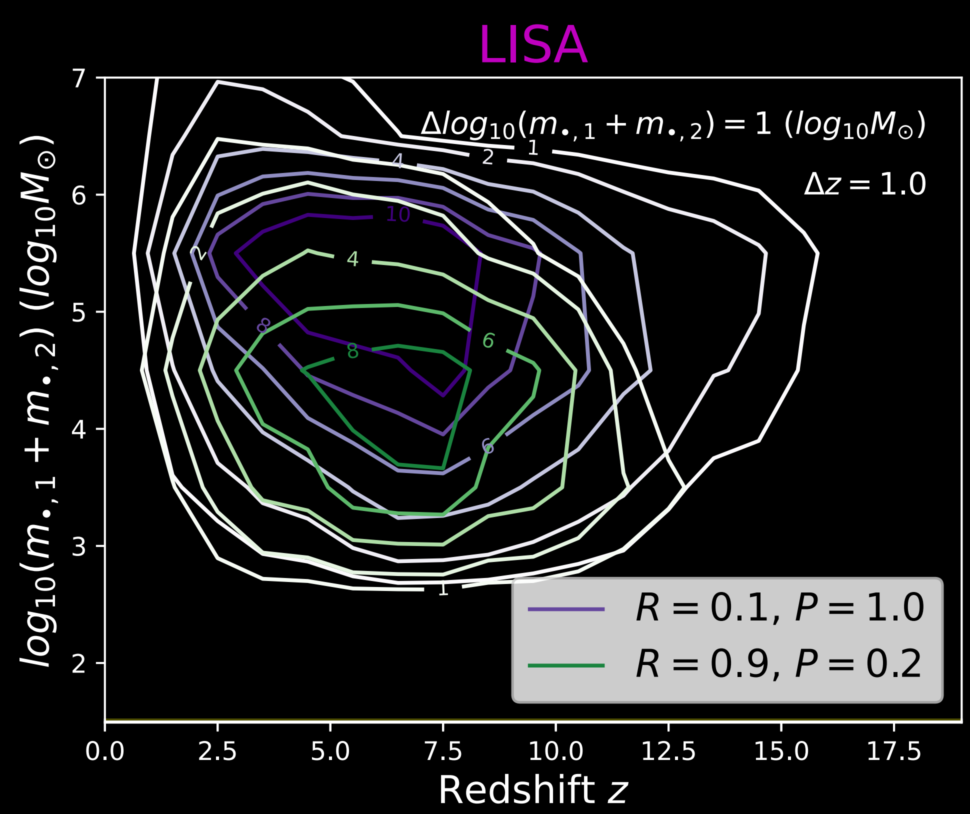
Mass-redshift distribution of mergers

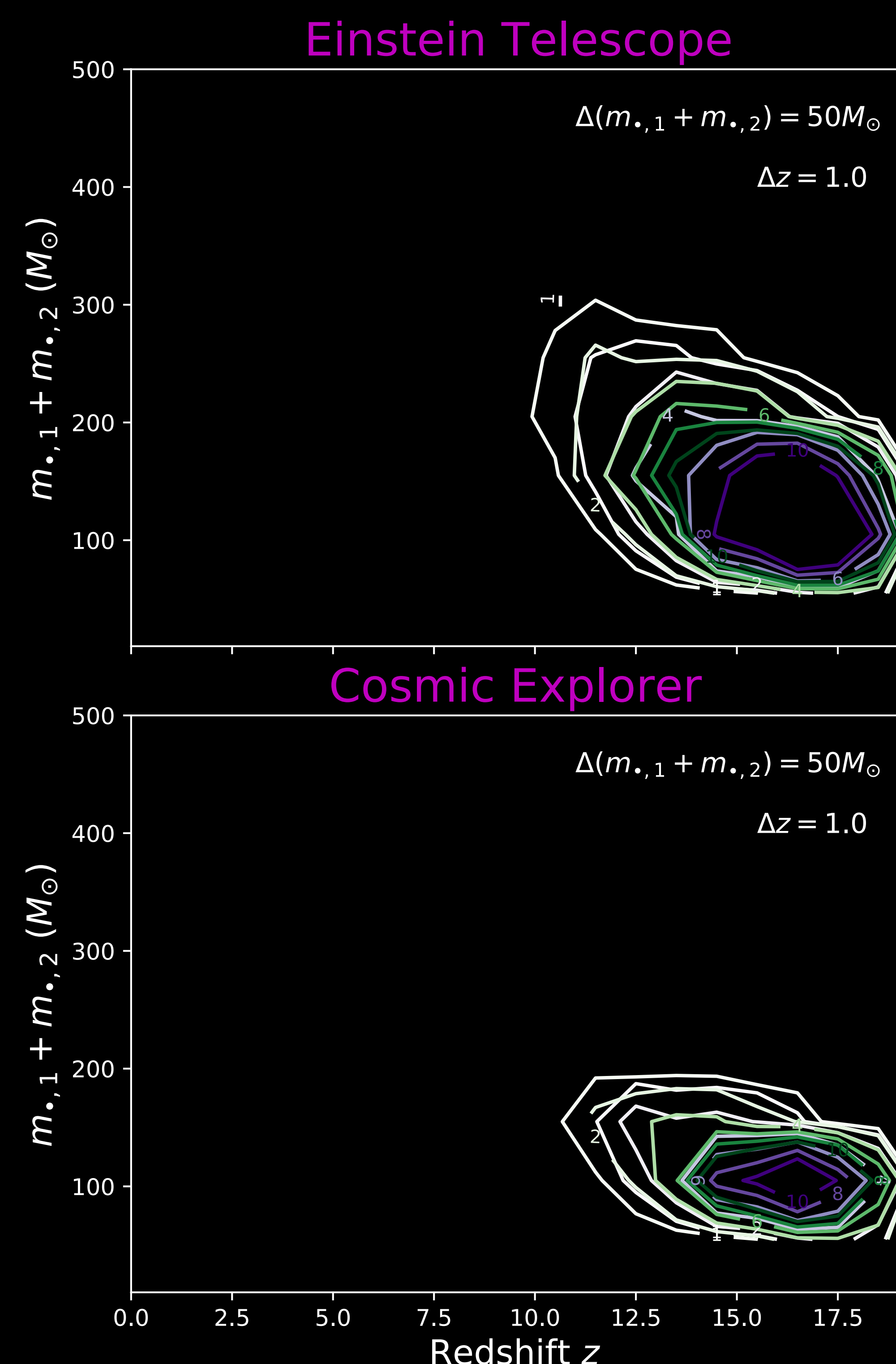


Mass-redshift distribution of mergers



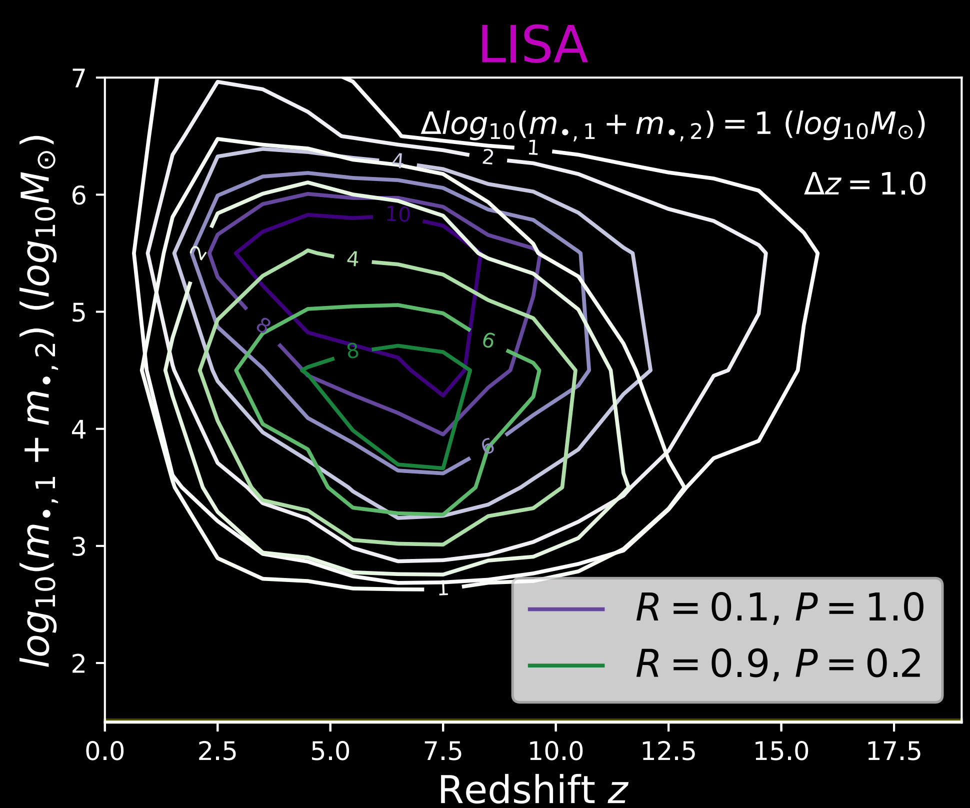
Limited scenario 1:
Heavy-seed-dominated, high merging probability v.s. Light-seed-dominated, low merging probability

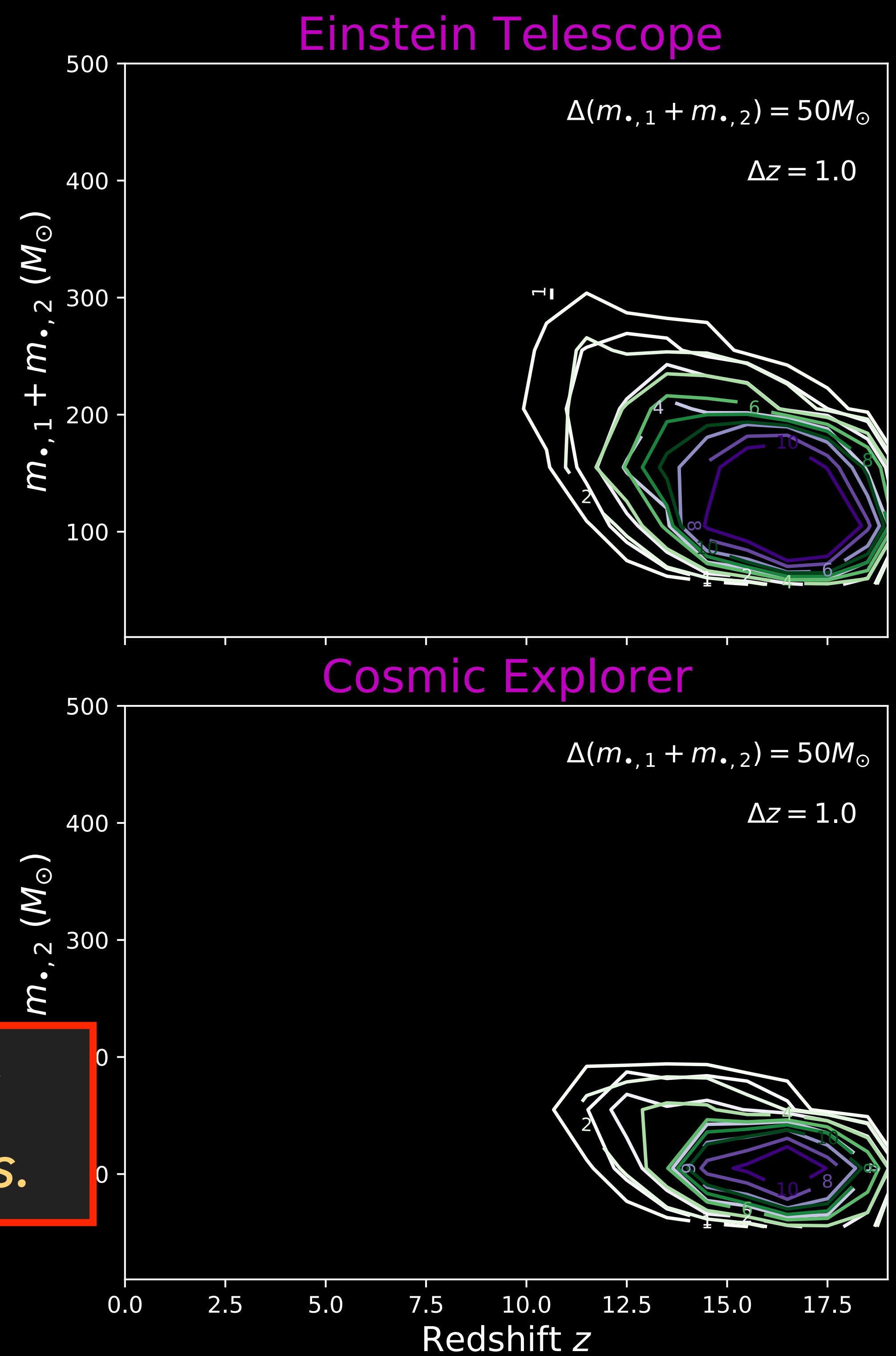




Chen, Ricarte & Pacucci, 2202.04764

Limited scenario 1: Heavy-seed-dominated, high merging probability v.s. Light-seed-dominated, low merging probability

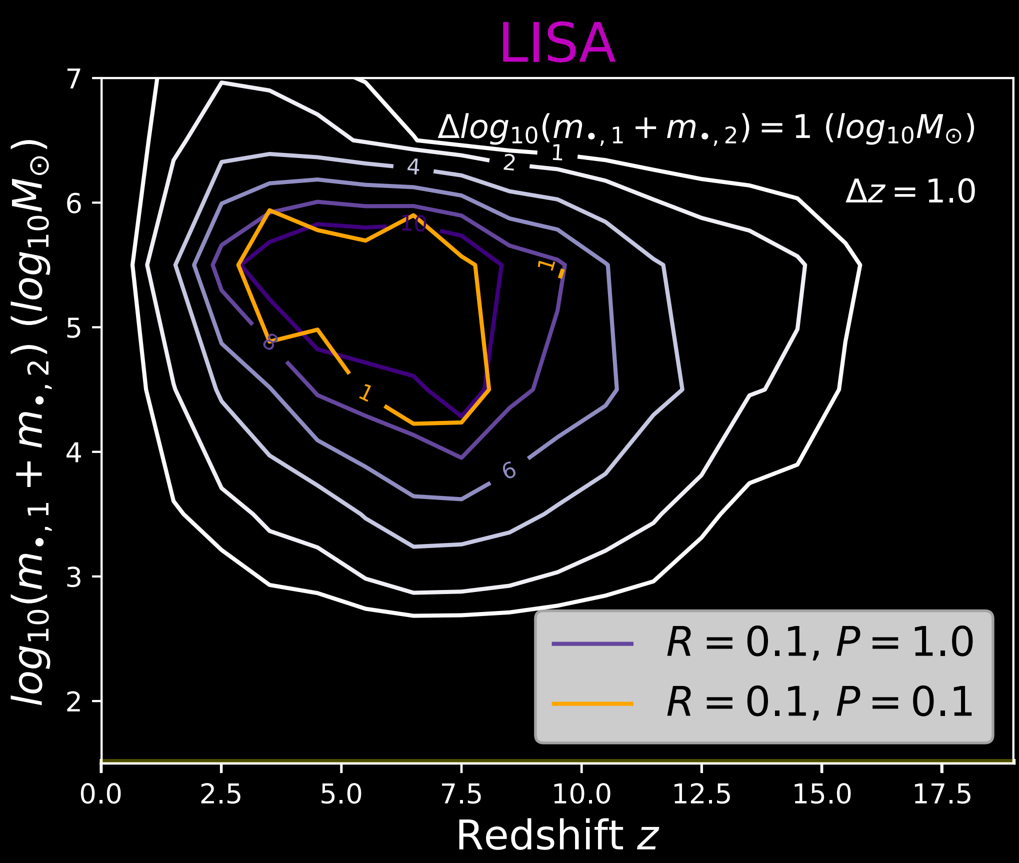


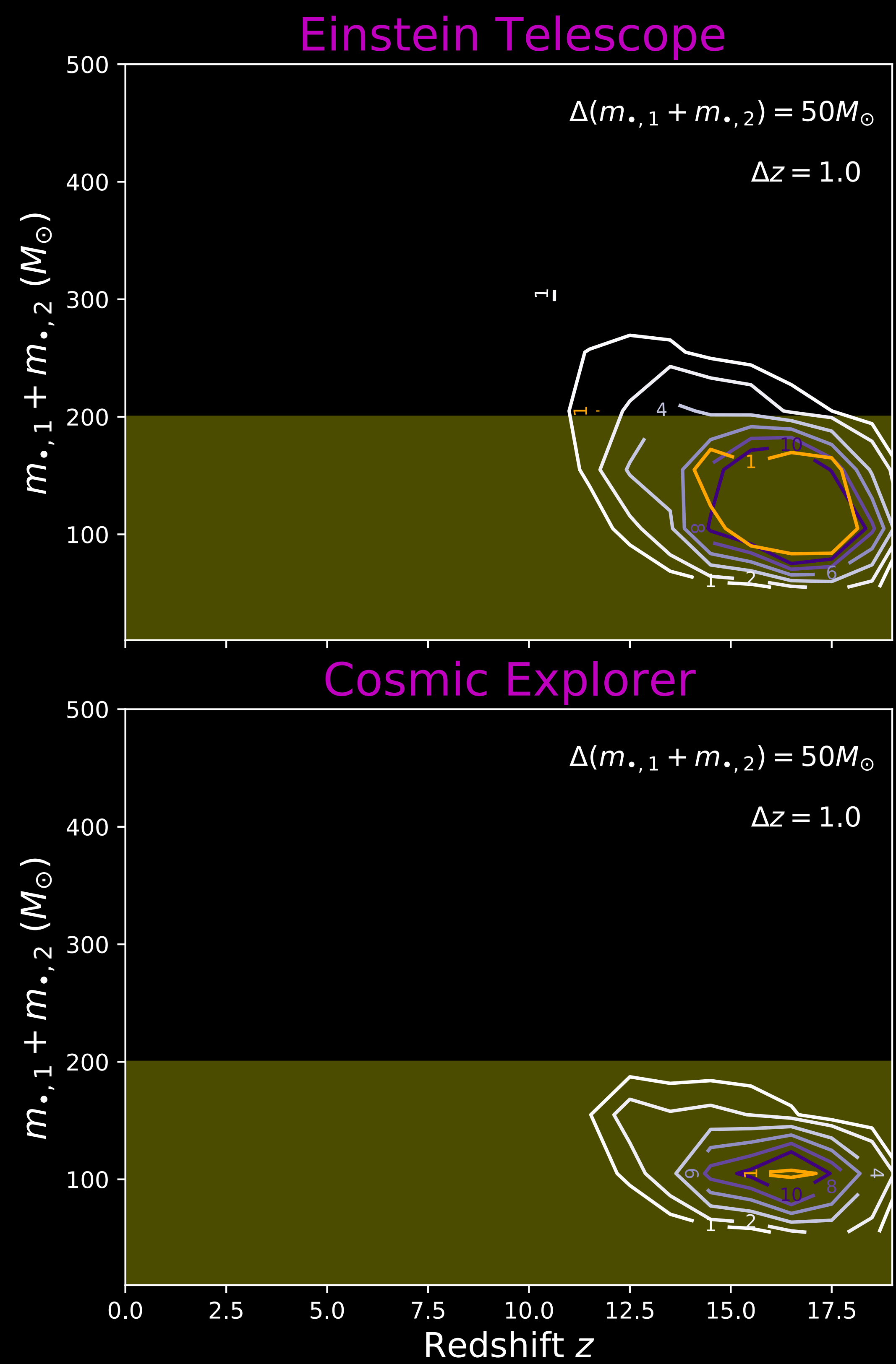


CE and ET can't distinguish the two cases since they can only observe the light seeds.

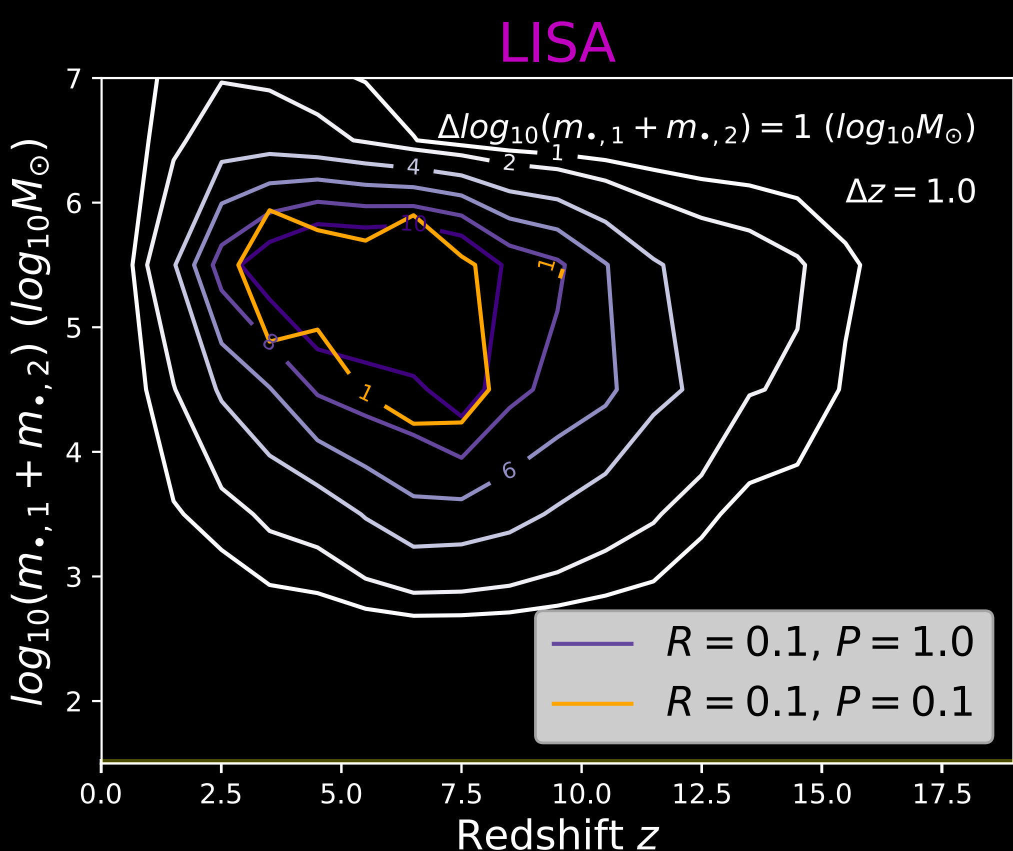
Hsin-Yu Chen / MIT

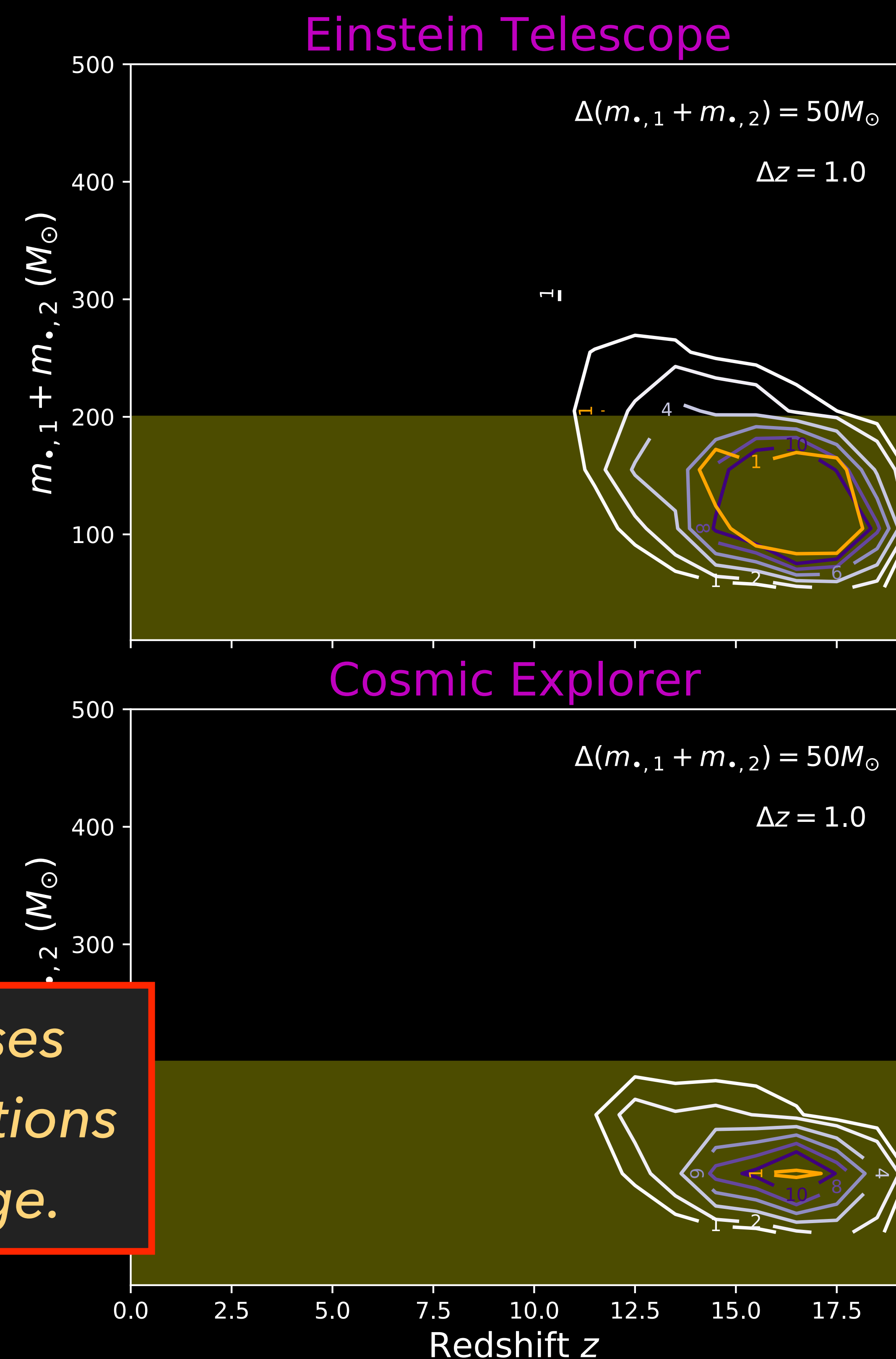
Limited scenario 2:
Heavy-seed-dominated, different merging probabilities





Limited scenario 2: Heavy-seed-dominated, different merging probabilities





CE and ET can't distinguish the two cases since the nuclear and off-nuclear populations merged at the same mass-redshift range.

Summary

Summary

-Even if the uncertainties of parameter estimations are ignored, there are still scenarios CE/ET can't properly constrain.

Summary

-Even if the uncertainties of parameter estimations are ignored, there are still scenarios CE/ET can't properly constrain.

-We need better ways to distinguish between nuclear and off-nuclear black hole mergers, e.g. spin?

Summary

-Even if the uncertainties of parameter estimations are ignored, there are still scenarios CE/ET can't properly constrain.

-We need better ways to distinguish between nuclear and off-nuclear black hole mergers, e.g. spin?

-If the parameter estimation uncertainties are considered, we may need multi-band multi-messenger (LISA+3G+EM) observations to study the black hole seeding problems.

Different EM observing scenarios

Table 1. Joint GW-EM Observing Scenarios

Scenario	GW	$R_{\rm GW}^{(a)}$	EM	$t_{\rm int}^{(b)}$	$D_{L,\rm lim}^{(c)}$	$f_{\rm 20deg^2}^{(d)}$	$f_{\rm obs}^{(e)}$	$\iota_{\rm GRB}^{(f)}$	$\sigma_{\iota}^{(g)}$	$\dot{N}_{\rm GW/EM}^{(h)}$	$\mathcal{F}_{\rm obs}^{(i)}$
-	-	(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	$\ll 1$