Title: Multi-band GW observation from the third-generation detectors

Speakers: Hsin-Yu Chen

Collection: Gravitational Waves Beyond the Boxes II

Date: April 05, 2022 - 1:15 PM

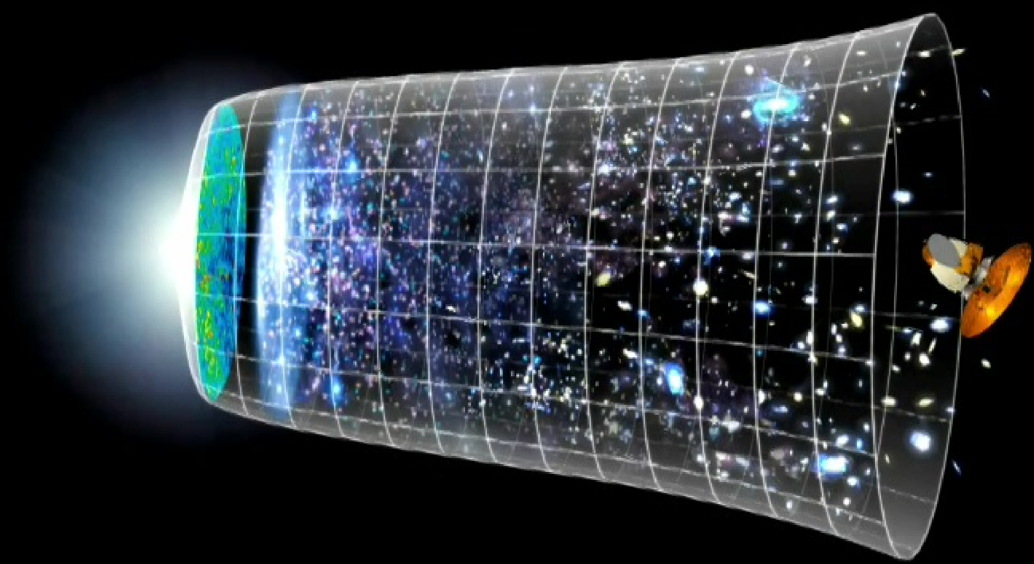
URL: https://pirsa.org/22040028

Multi-band Gravitational-wave cosmology with next-generation detectors

Hsin-Yu Chen

(NASA Einstein Fellow, MIT)

Gravitational Waves Beyond the Boxes II, April 2022

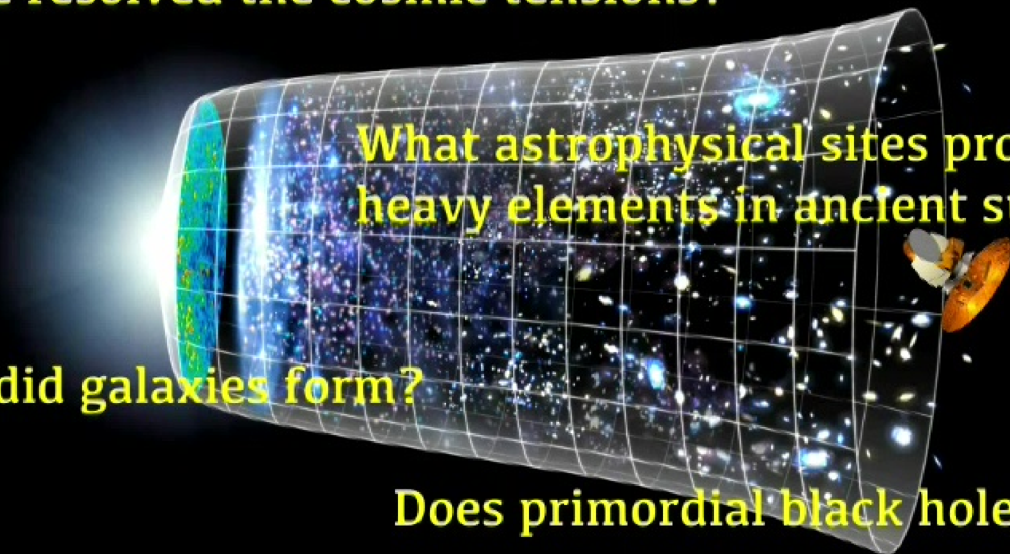


We are going to learn a lot about how the Universe work from the LIGO-Virgo-KAGRA observations, but there will still be big questions to be answered after the 2G era.

Hsin-Yu Chen / MIT

NASA/WMAP Science team

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 are going to learn a lot about how the Universe work from the LIGO-Virgo-KAGRA observations, but there will still be big questions to be answered after the 2G era.

Hsin-Yu Chen / MIT

NASA/WMAP Science team

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

GW frequenc

NanoHz **mHz** **deciHz**

-*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)

Hsin-Yu Chen / MIT

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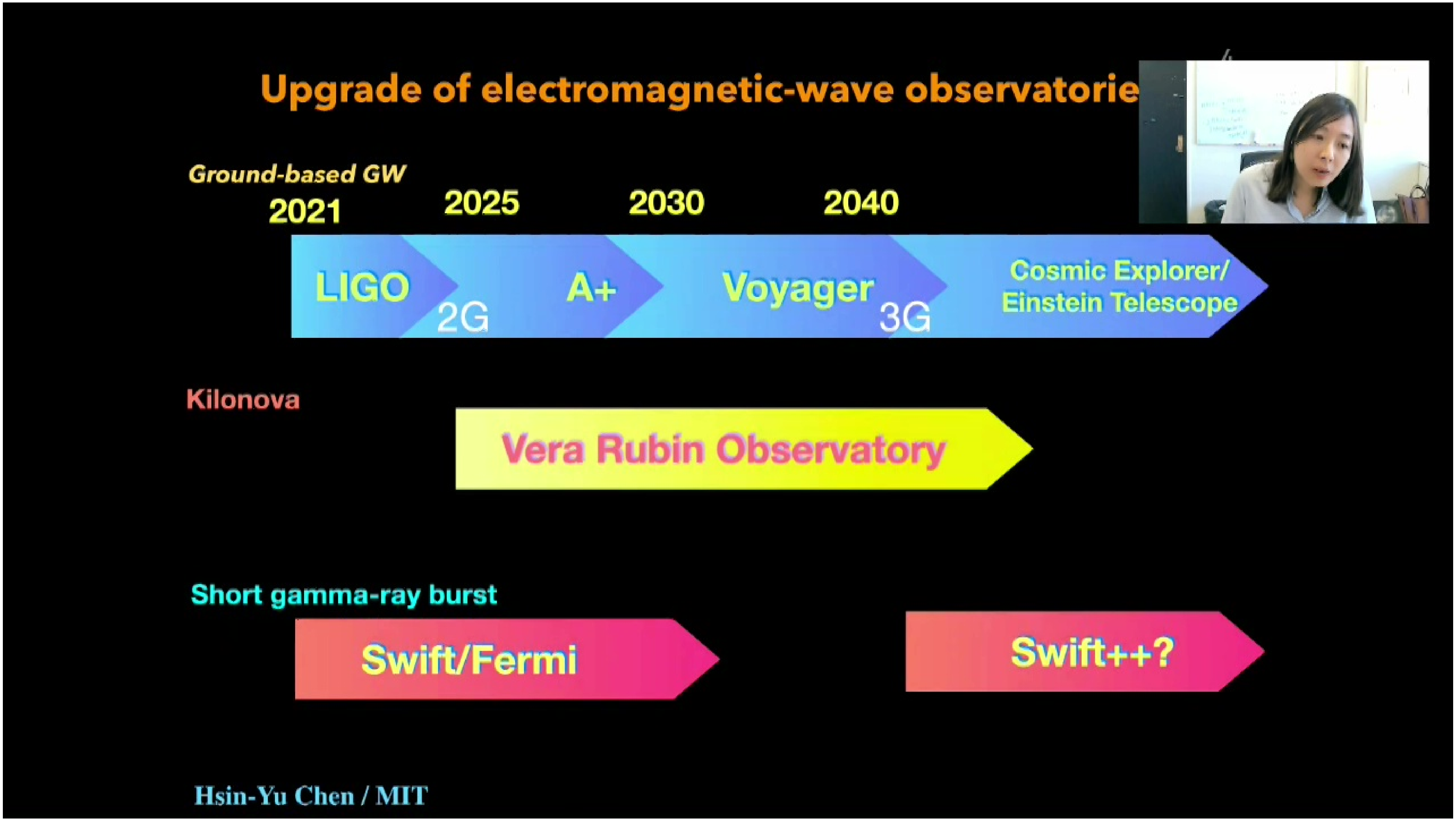
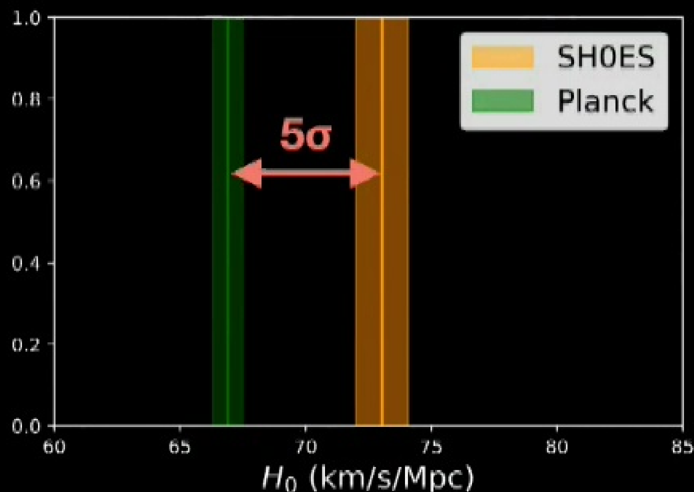
-*Ground-based (>1Hz):*
Einstein Telescope, Cosmic Explorer, Voyager, Neutron Star Extreme Matter Observatory (NEMO)

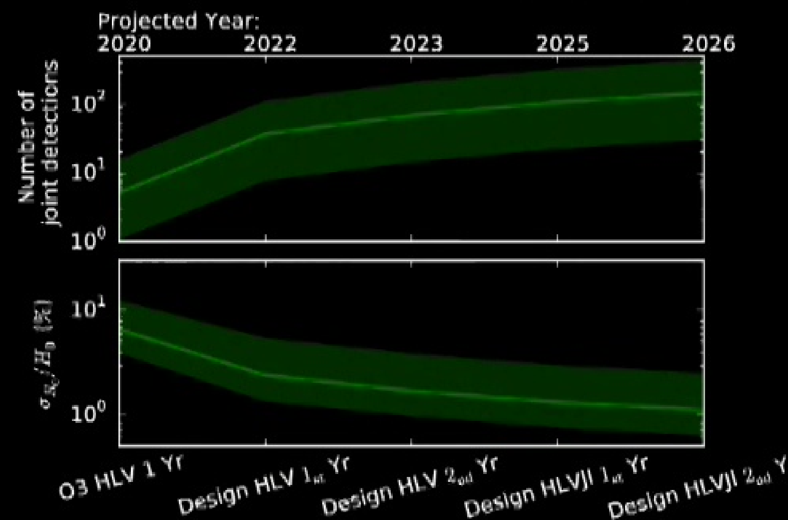
Hsin-Yu Chen / MIT


Upgrade of electromagnetic-wave observatorie
Ground-based GW
2021
2025
2030
2040
LIGO
2G
A+
Voyager
3G
Cosmic Explorer/
Einstein Telescope
Kilonova
Vera Rubin Observatory
Short gamma-ray burst
Swift/Fermi
Swift++?
Hsin-Yu Chen / MIT

Independent measurement to resolve the tension in the Hubble constant measurement

Chen, Fishbach & Holz, Nature (2018)





What is the potential and challenges for bright siren measurements in the 3G era?

Hsin-Yu Chen / MIT

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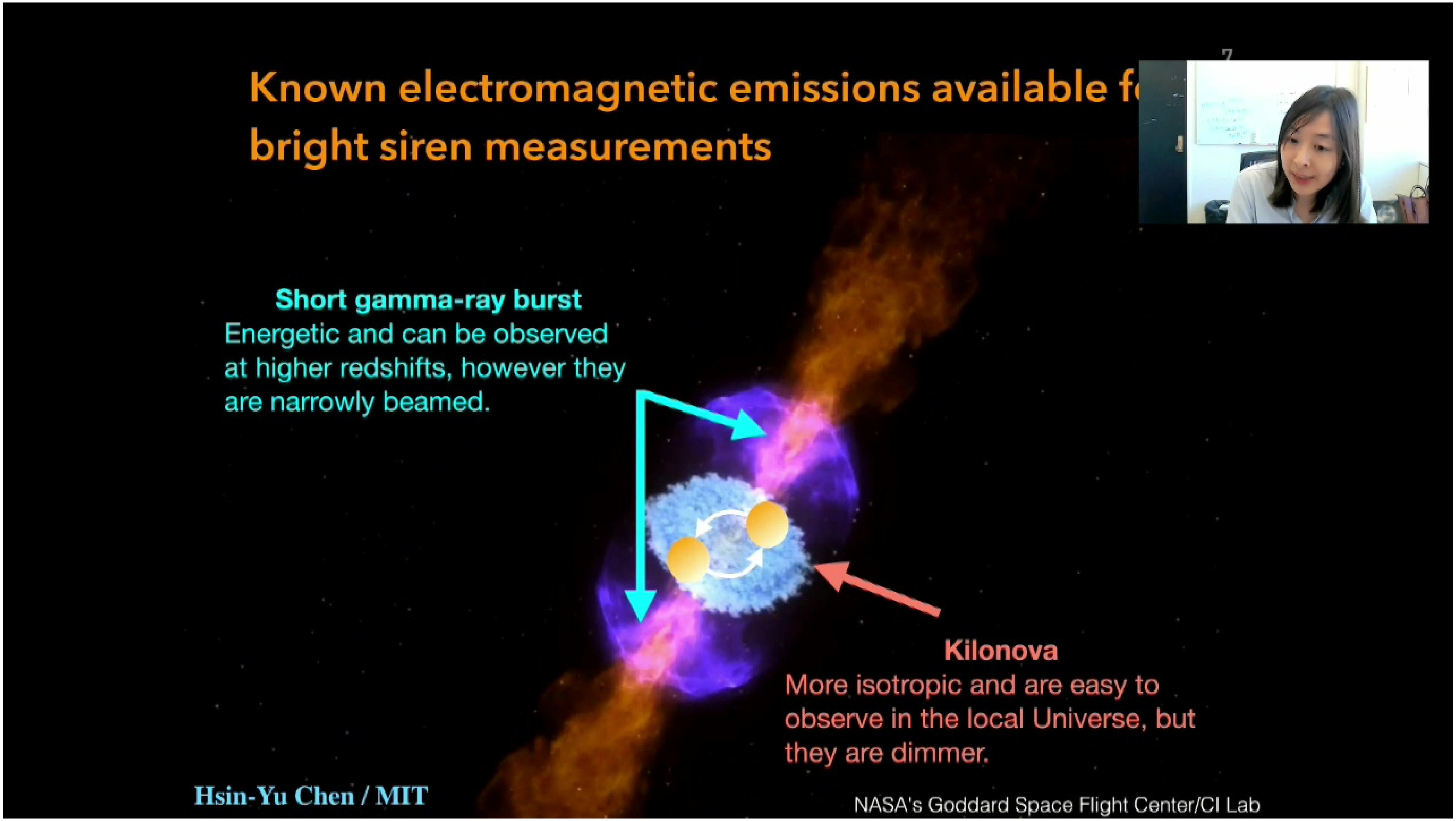
Bright siren in 3G era

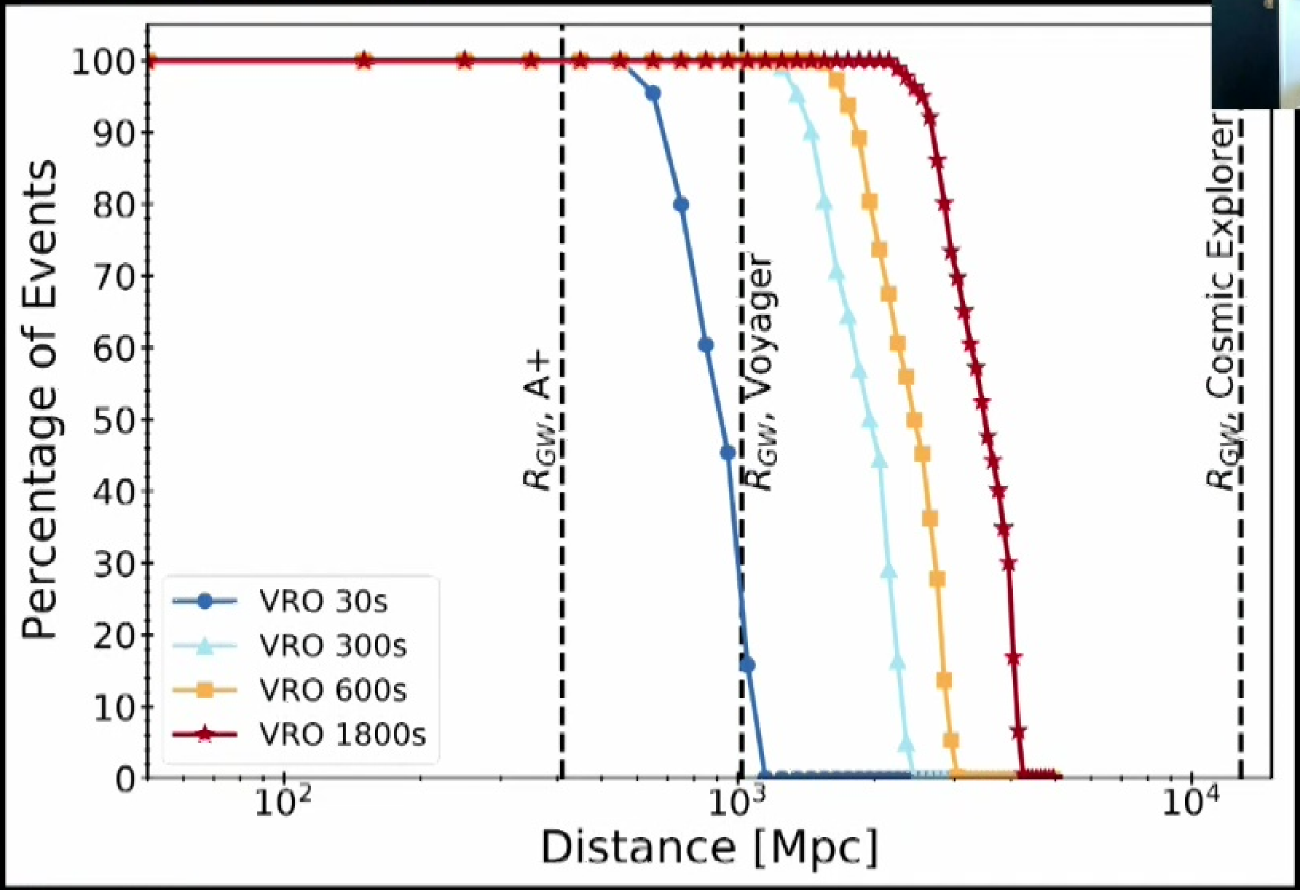
The limiting factor is the
electromagnetic counterpart observations.

Hsin-Yu Chen / MIT


Known electromagnetic emissions available f
bright siren measurements
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.
Hsin-Yu Chen / MIT
NASA's Goddard Space Flight Center/CI Lab

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

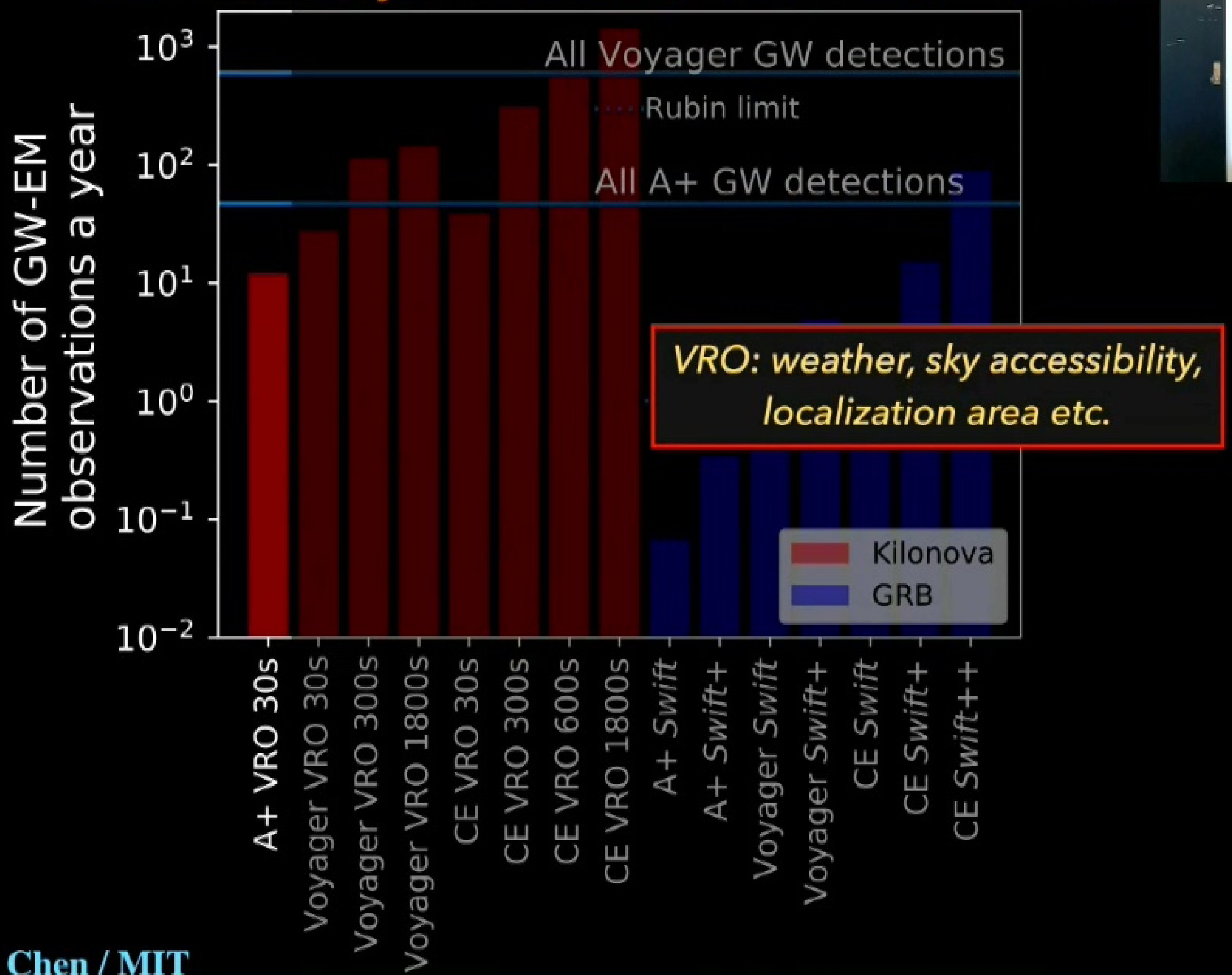
The EM detection efficiency drops rapidly as the distance increases



Hsin-Yu Chen / MIT

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

Number of joint detections in 2.5-3G era



Hsin-Yu Chen / MIT

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

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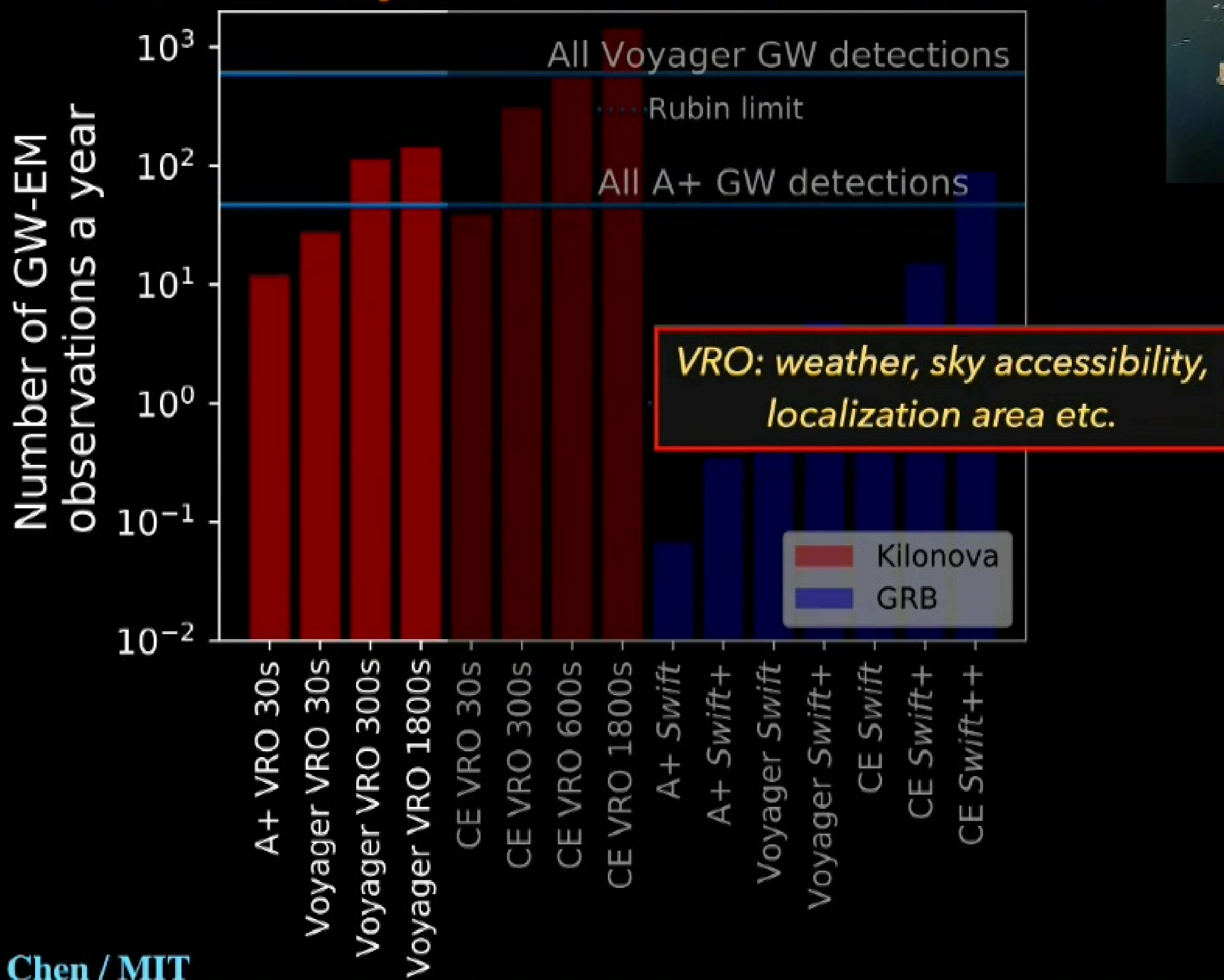
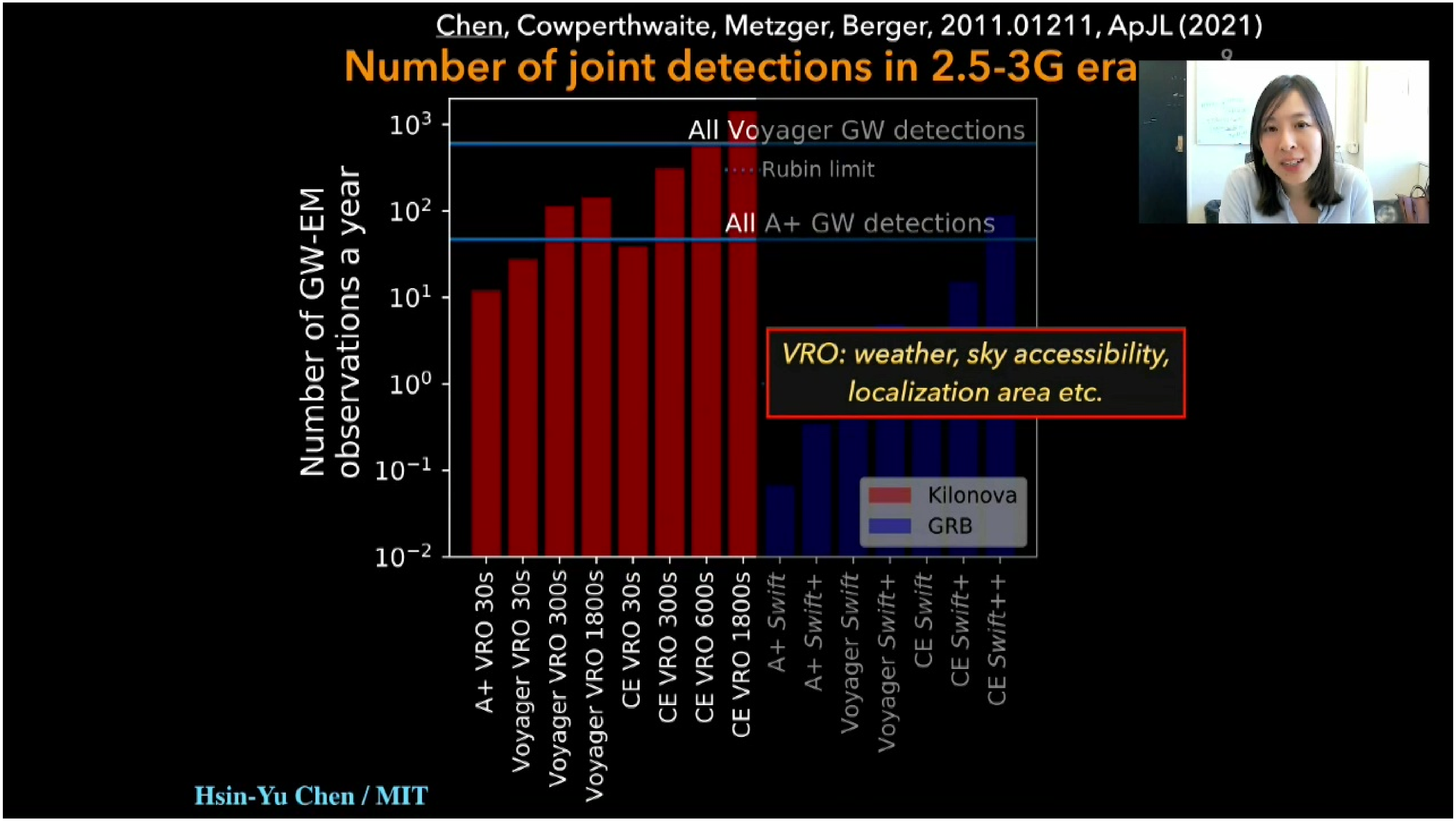
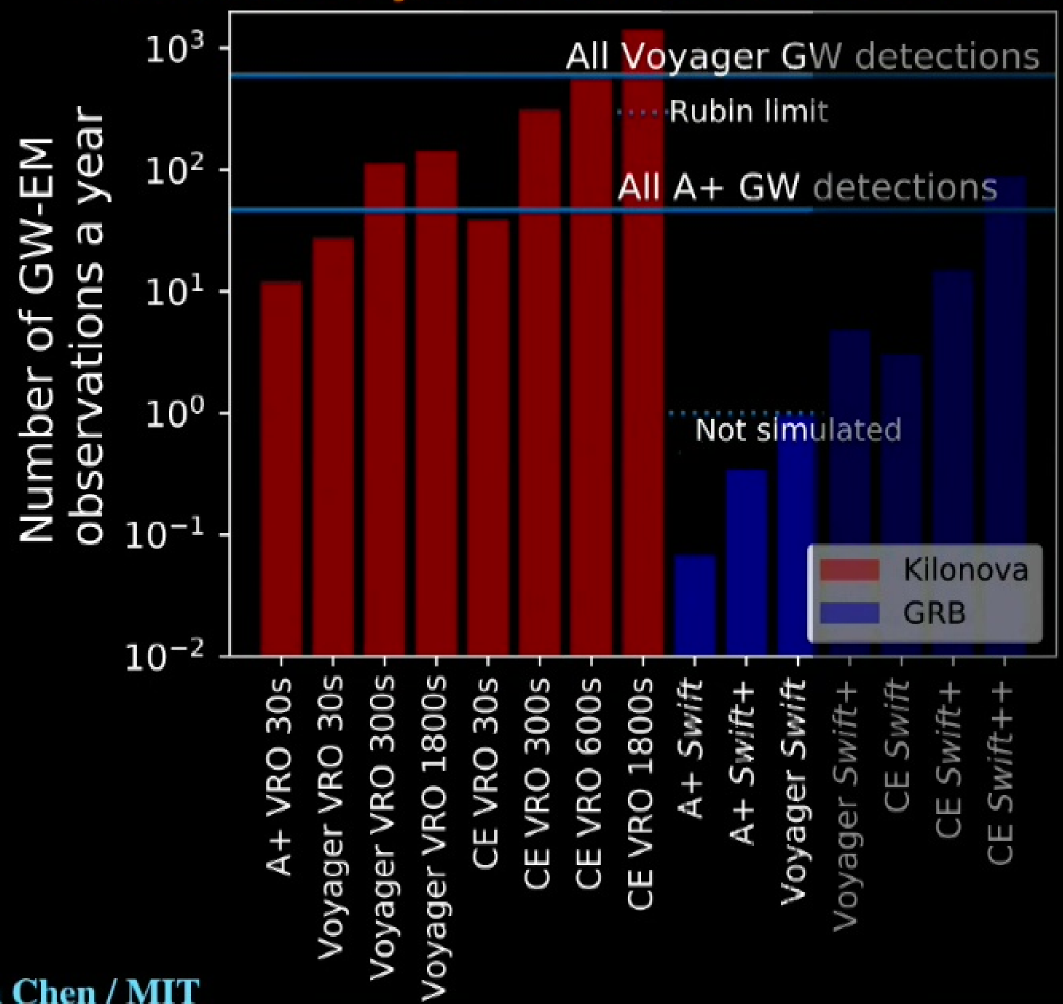


Hsin-Yu Chen / MIT

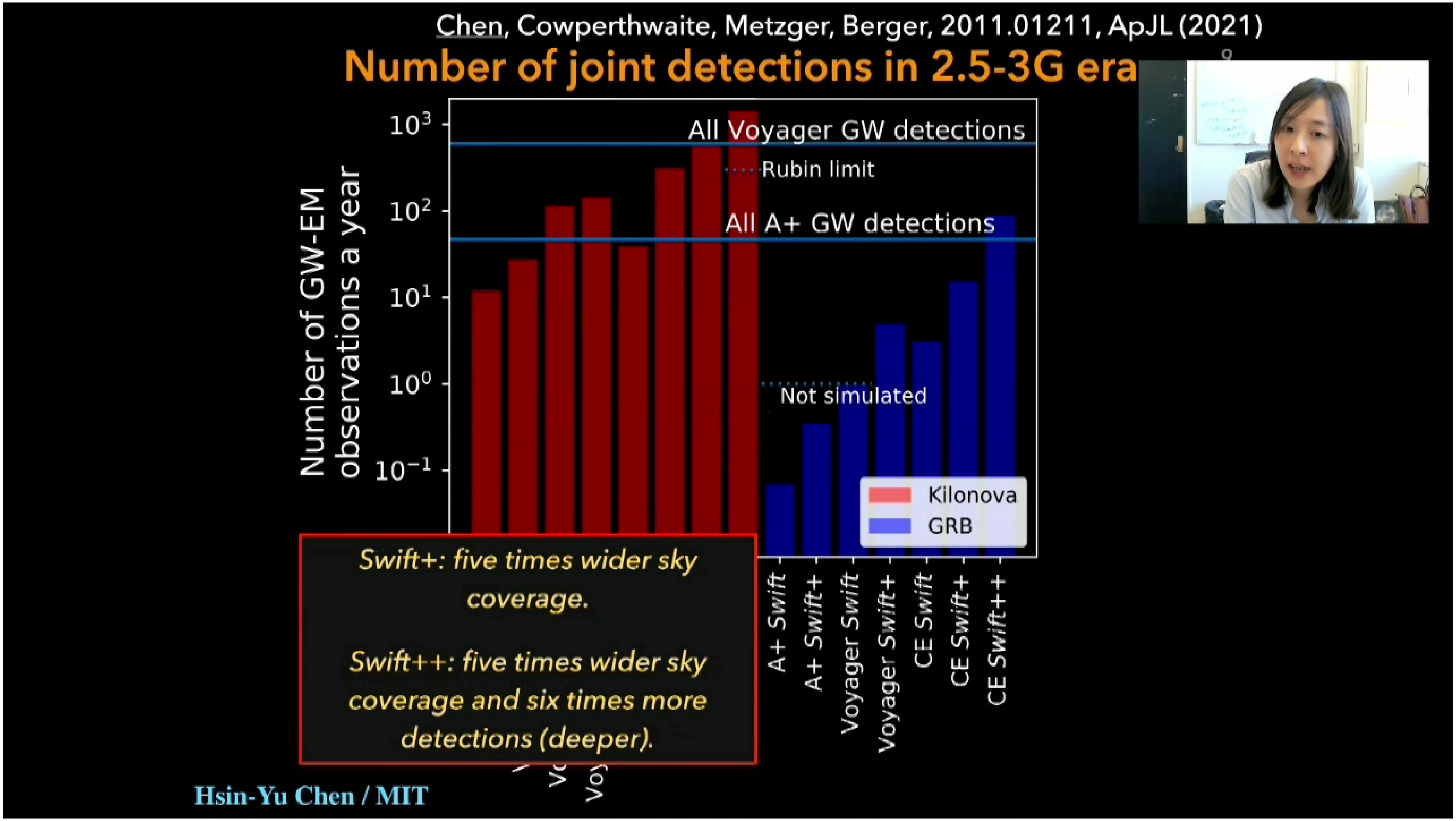

Chen, Cowperthwaite, Metzger, Berger, 2011.01211, ApJL (2021)
Number of joint detections in 2.5-3G era
Number of GW-EM observations a year
All Voyager GW detections
Rubin limit
All A+ GW detections
VRO: weather, sky accessibility, localization area etc.
Kilonova
GRB
A+ VRO 30s
Voyager VRO 30s
Voyager VRO 300s
Voyager VRO 1800s
CE VRO 30s
CE VRO 300s
CE VRO 600s
CE VRO 1800s
A+ Swift
A+ Swift+
Voyager Swift
Voyager Swift+
CE Swift
CE Swift+
CE Swift++
Hsin-Yu Chen / MIT

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

Number of joint detections in 2.5-3G era

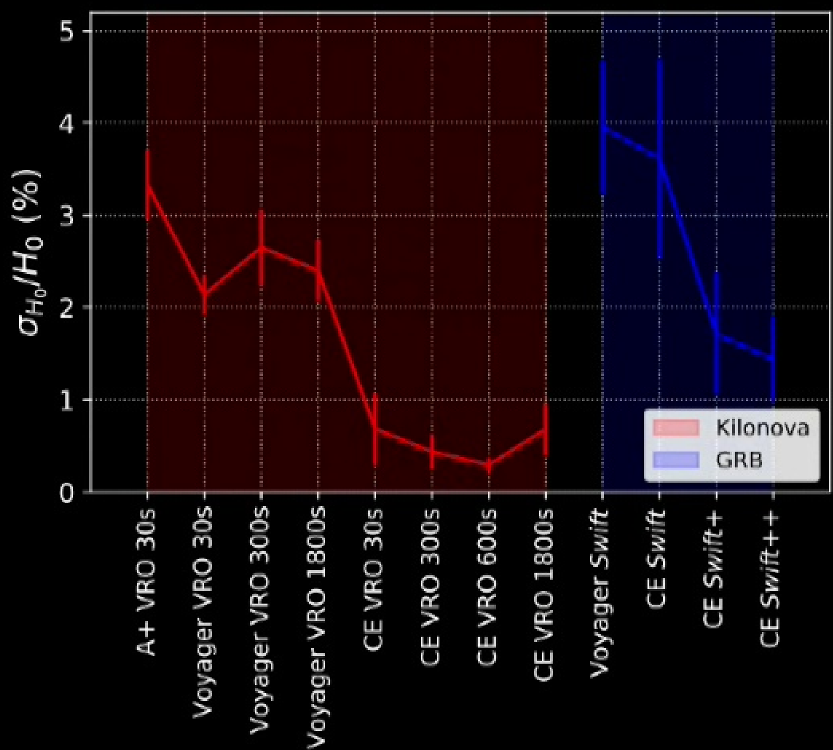


Hsin-Yu Chen / MIT


Chen, Cowperthwaite, Metzger, Berger, 2011.01211, ApJL (2021)
Number of joint detections in 2.5-3G era
Number of GW-EM observations a year
All Voyager GW detections
Rubin limit
All A+ GW detections
Not simulated
Kilonova
GRB
A+ Swift
A+ Swift+
Voyager Swift
Voyager Swift+
CE Swift
CE Swift+
CE Swift++
Swift+: five times wider sky coverage.
Swift++: five times wider sky coverage and six times more detections (deeper).
Hsin-Yu Chen / MIT

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

Cosmological constraints from bright sirens in 2.



Hsin-Yu Chen / MIT

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

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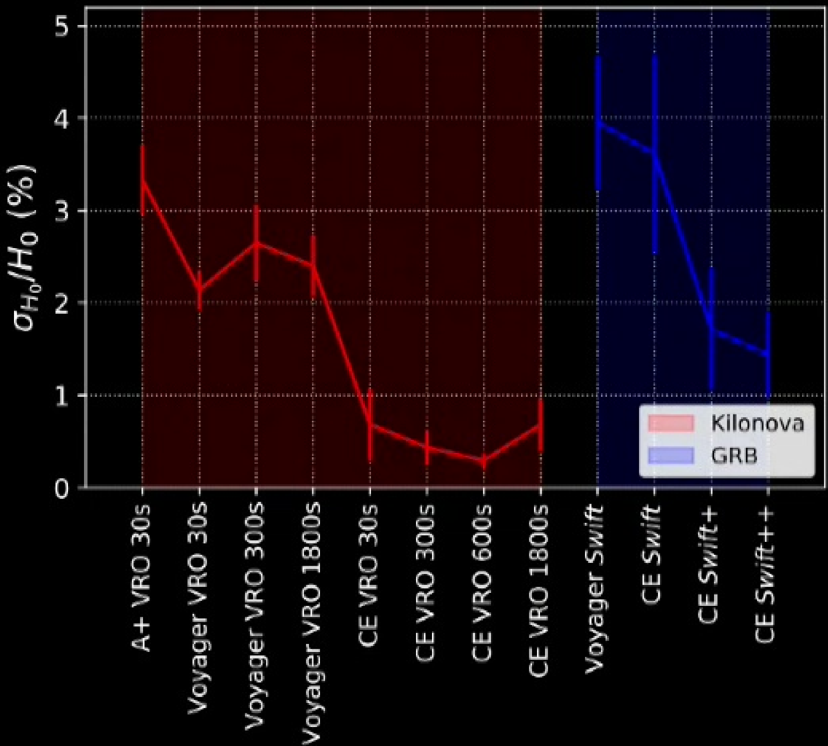

-A+ and Voyager still at percent level. Sub-percent level precision is possible in CE era.

-Kilonovae are better than GRBs for H_0 constraint.

Hsin-Yu Chen / MIT

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

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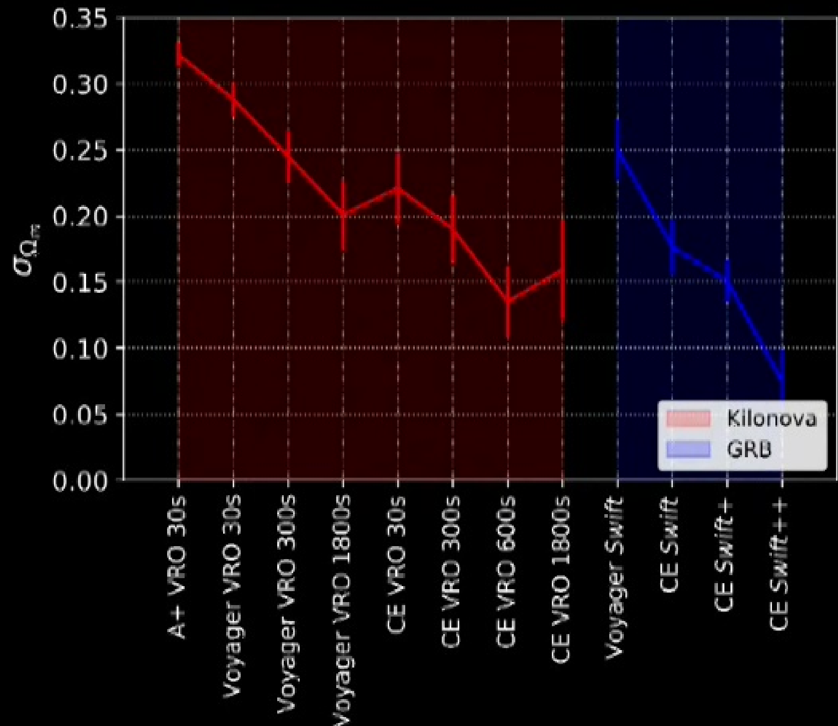

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Hsin-Yu Chen / MIT

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

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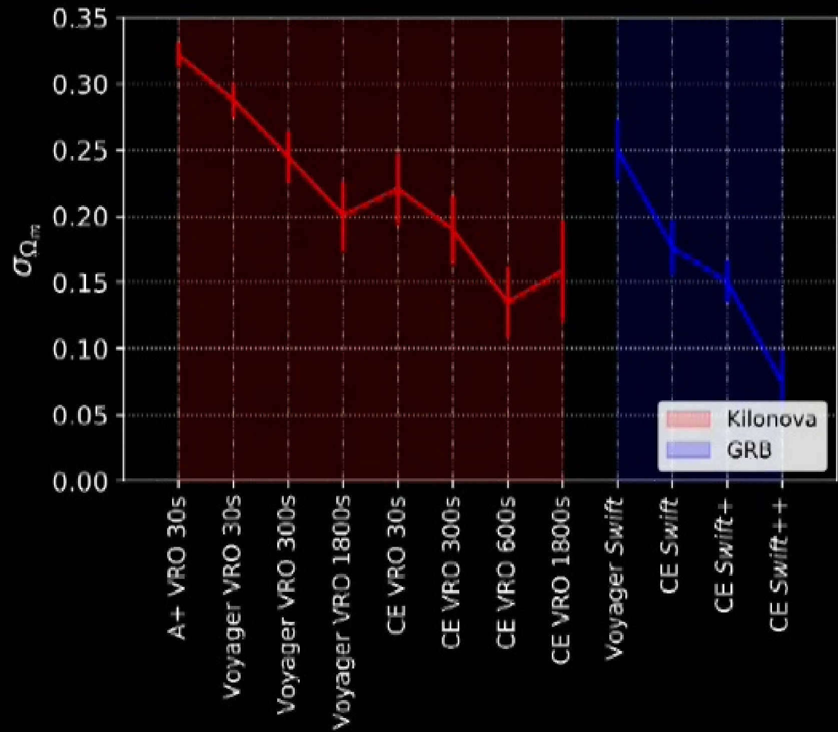

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Hsin-Yu Chen / MIT

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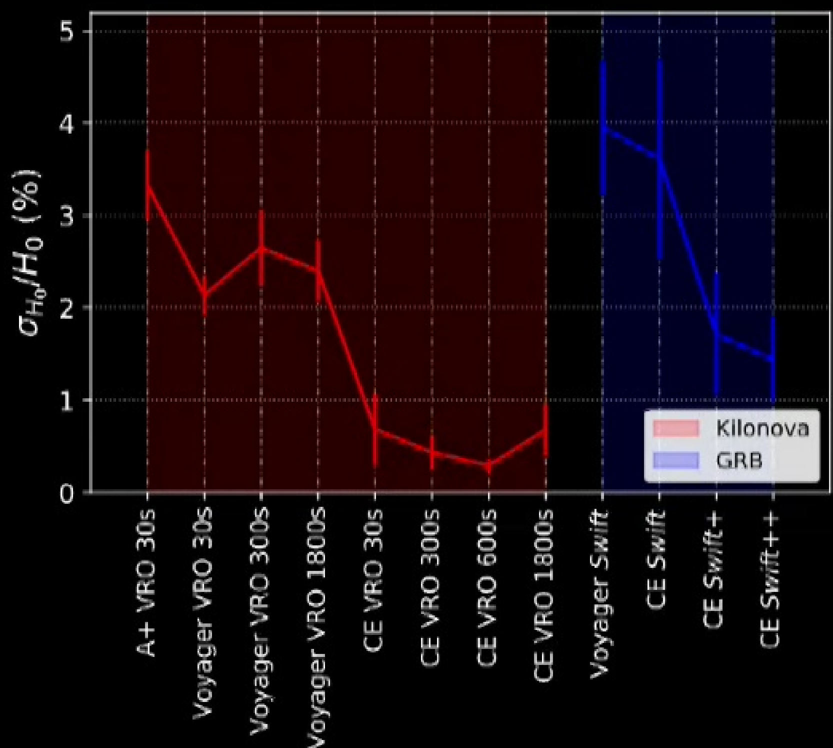

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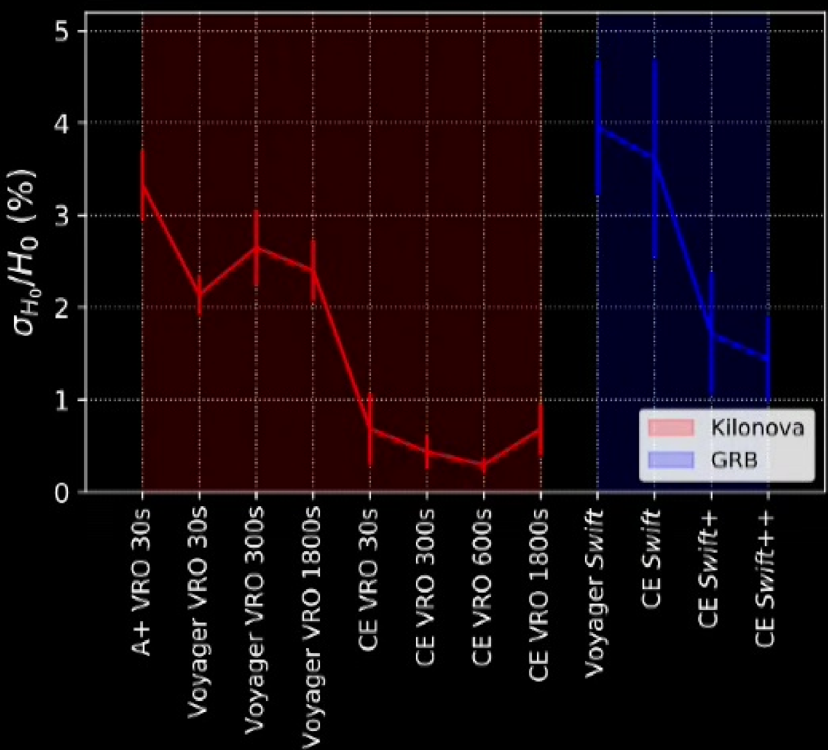

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Hsin-Yu Chen / MIT

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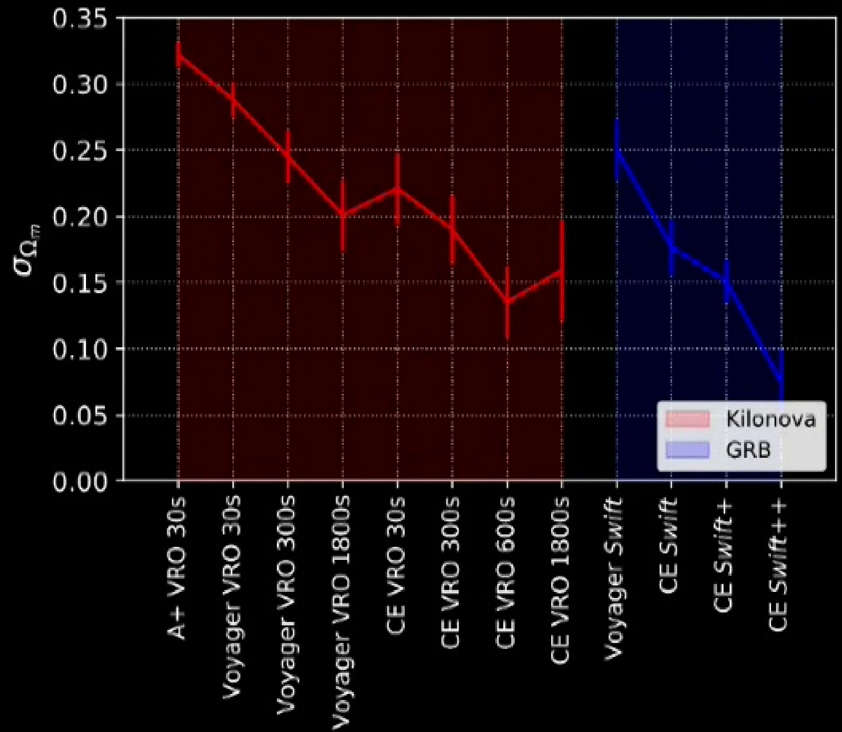

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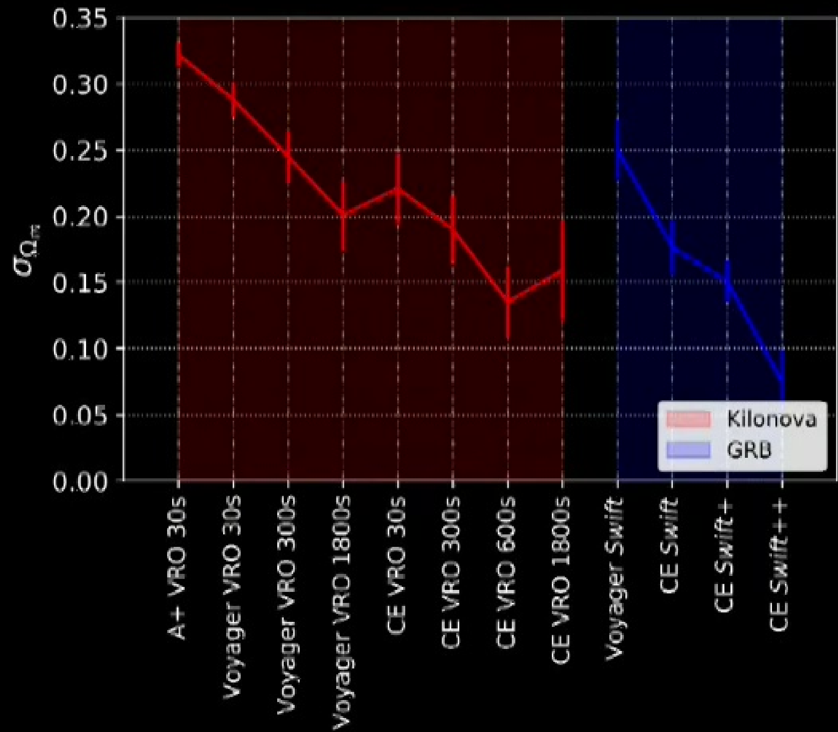
Different EM observing scenarios

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 ×24 +120s	575	0.8	0.4	All	N/A	12	0.0008
Voyager, KN (Baseline)	Voyager	1020	-	30 s ×24 +120s	575	0.8	-	-	-	28	0.002
Voyager, KN (Intermediate)	-	-	-	300 s ×24	1250	0.7	-	-	-	114	0.06
Voyager, KN (Ambitious)	-	-	-	1800 s ×24	2250	0.6	-	-	-	144	0.48
CE, KN (Baseline)	CE	12840	-	30 s ×24 +120s	575	1.	-	-	-	39	0.003
CE, KN (Intermediate)	-	-	-	300 s ×24	1250	0.95	-	-	-	321	0.18
CE, KN (Optimal)	-	-	-	600 s ×24	1550	0.95	-	-	-	572	0.6
CE, KN (Ambitious)	-	-	Rubin(+)	1800 s ×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	$\ll 1$

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

Cosmological constraints from bright sirens in 2.



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Hsin-Yu Chen / MIT

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

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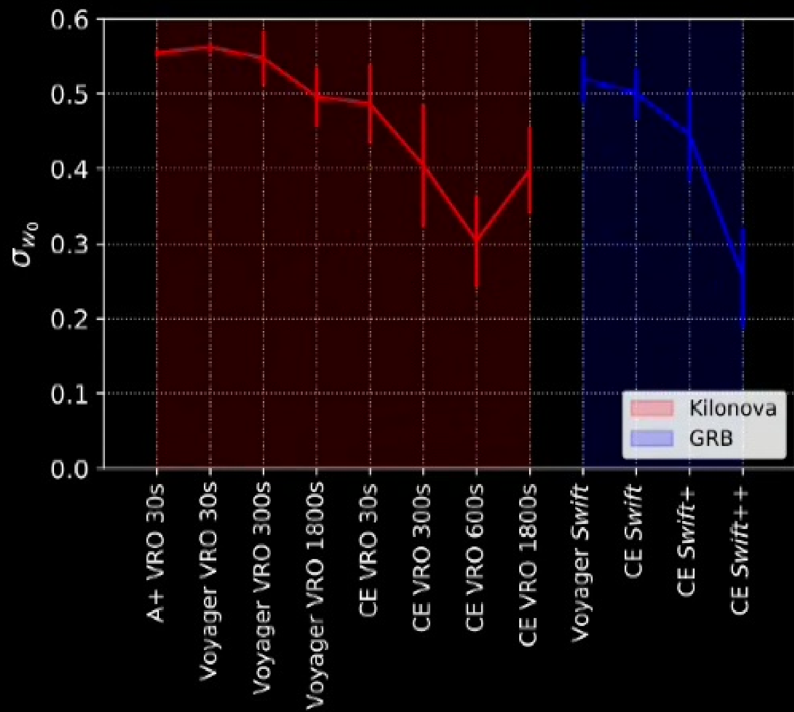
Cosmological constraints from bright sirens in 2.



-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.

Hsin-Yu Chen / MIT

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

Mergers of black holes

Accretion

Hsin-Yu Chen / MIT

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.

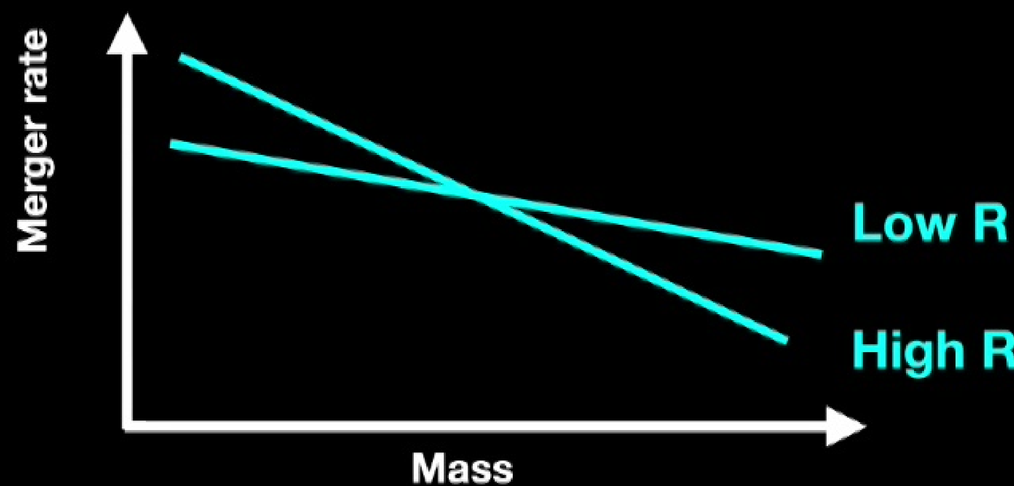
Hsin-Yu Chen / MIT

Chen, Ricarte & Pacucci, 2202.04764

Dominated uncertainties for the seeding mod

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

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



Hsin-Yu Chen / MIT

Chen, Ricarte & Pacucci, 2202.04764

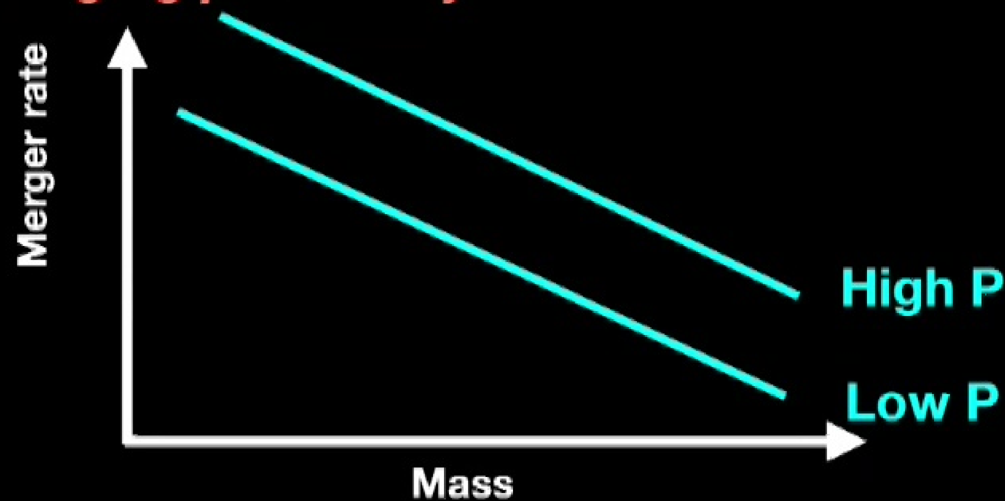
Dominated uncertainties for the seeding mod

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

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

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

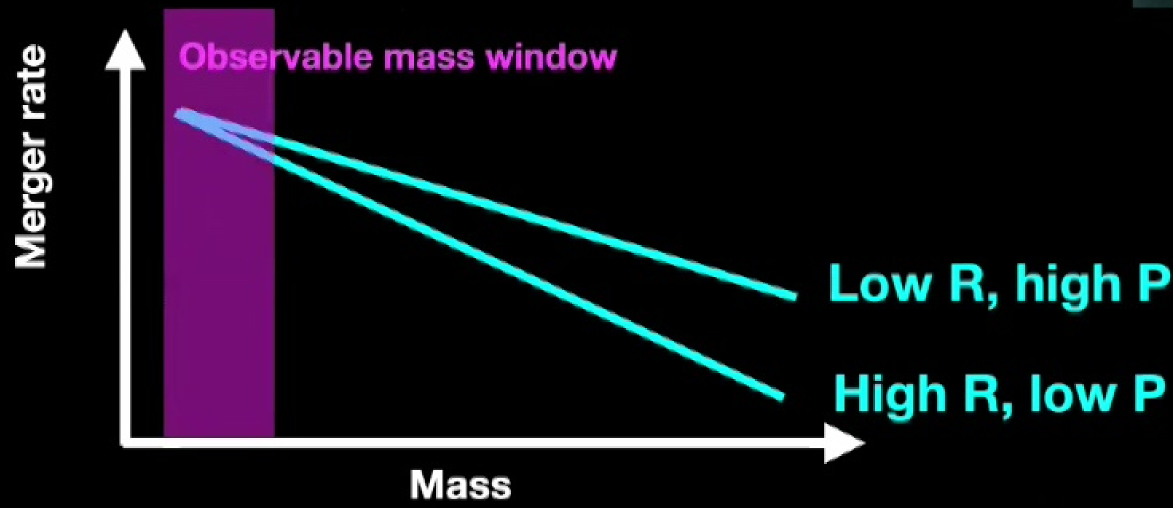
⟹ ***Merging probability P***



Hsin-Yu Chen / MIT

Chen, Ricarte & Pacucci, 2202.04764

To constrain R and P from observations

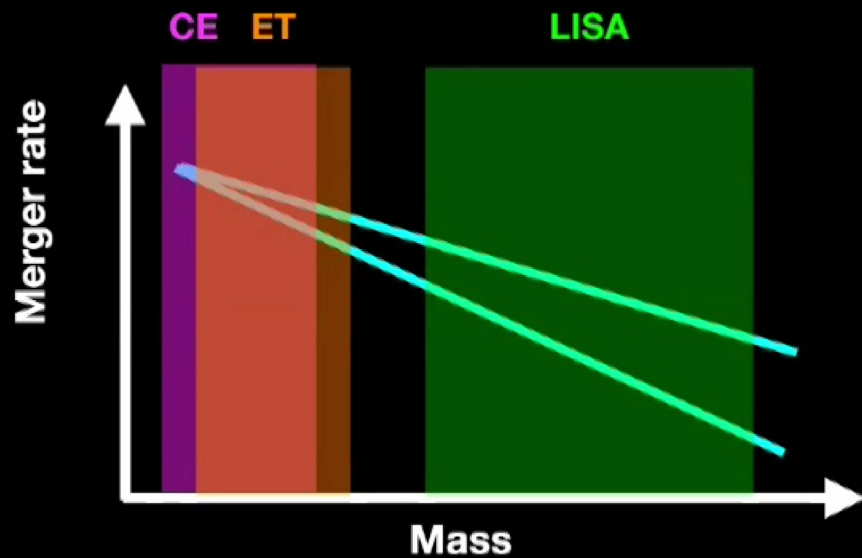


Limited observable mass window can limit the constraining power to R and P due to the degeneracy.

Hsin-Yu Chen / MIT

Chen, Ricarte & Pacucci, 2202.04764

To constrain R and P from observations



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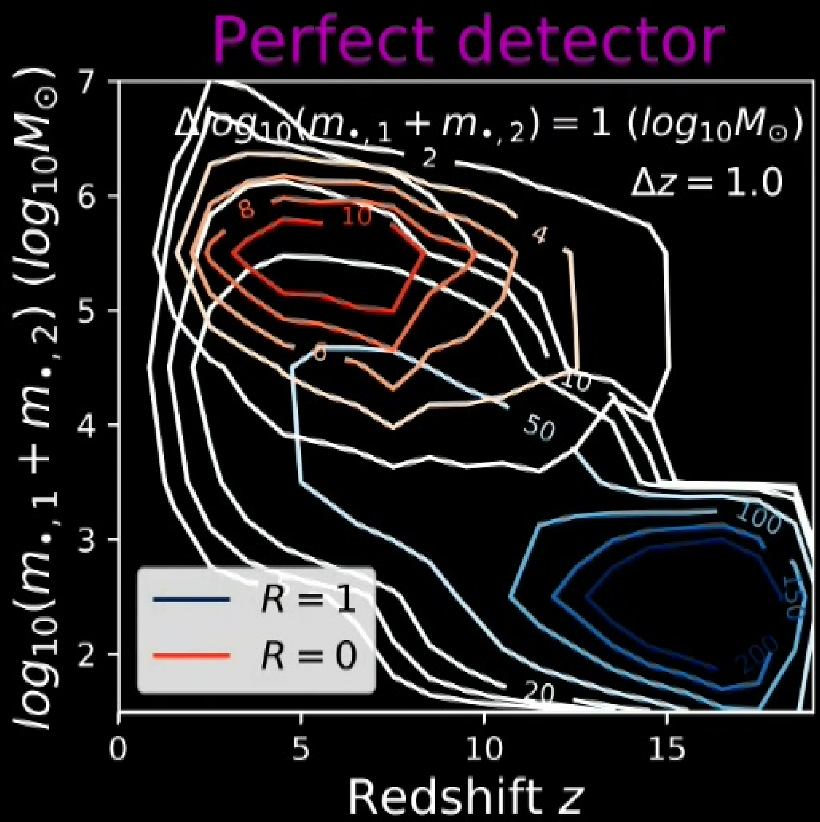
Mass-redshift distribution of mergers



Hsin-Yu Chen / MIT

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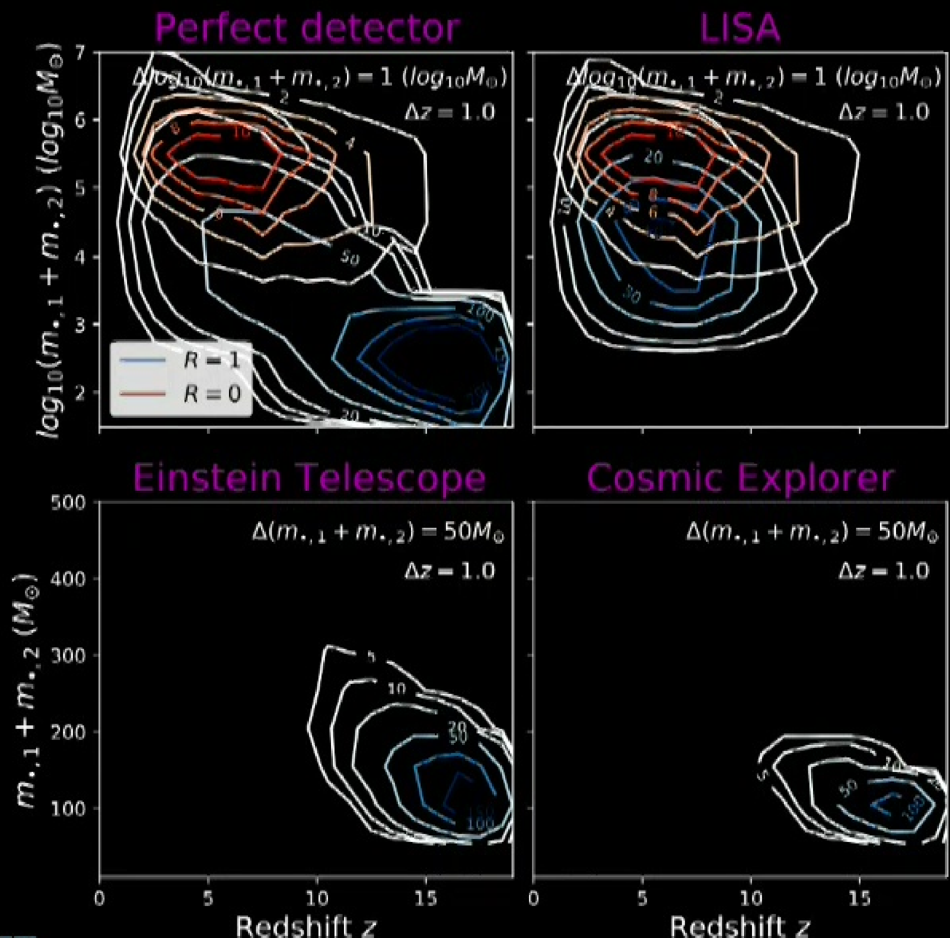

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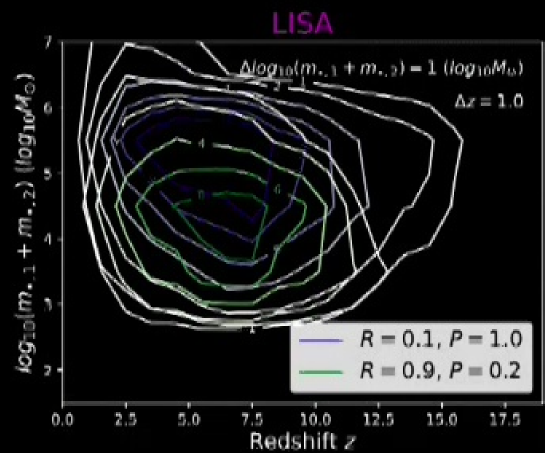
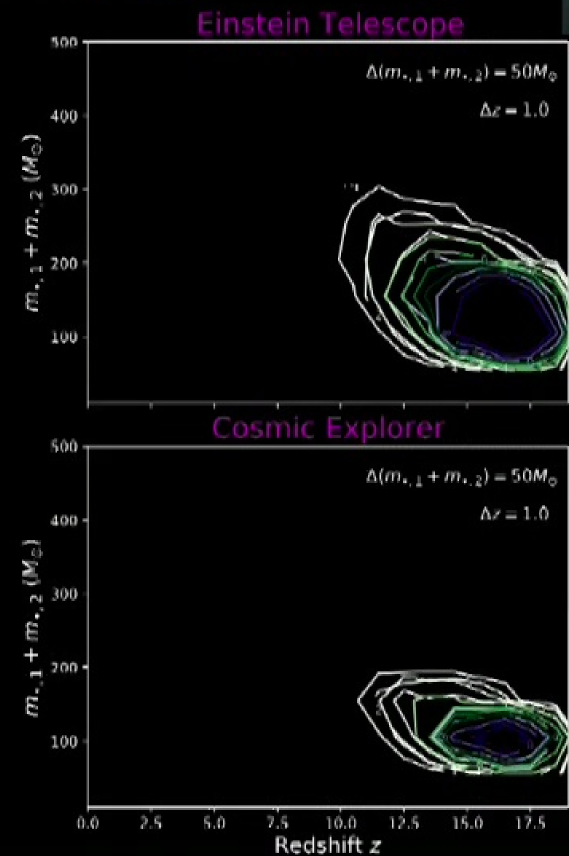
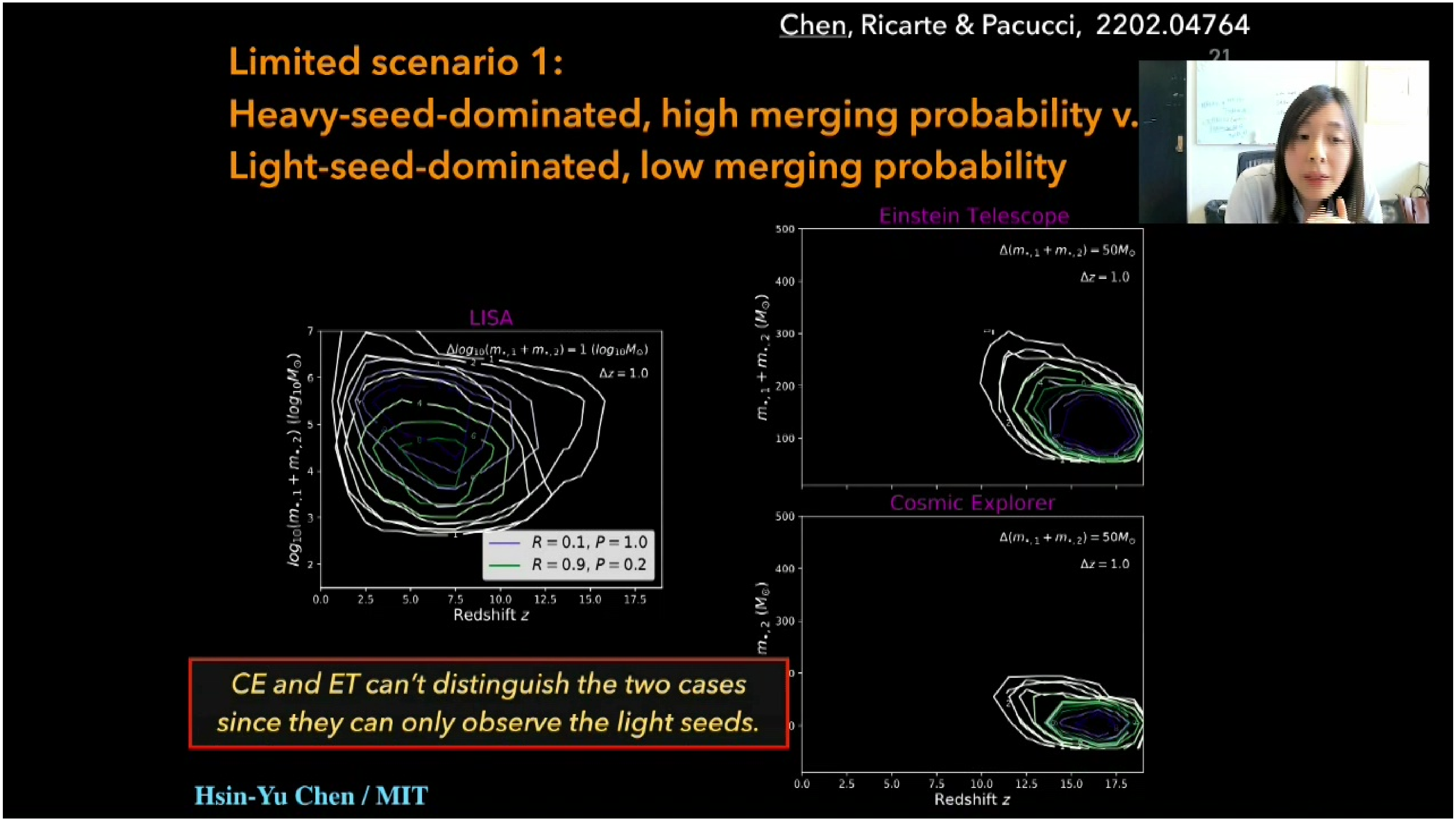
Chen, Ricarte & Pacucci, 2202.04764

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

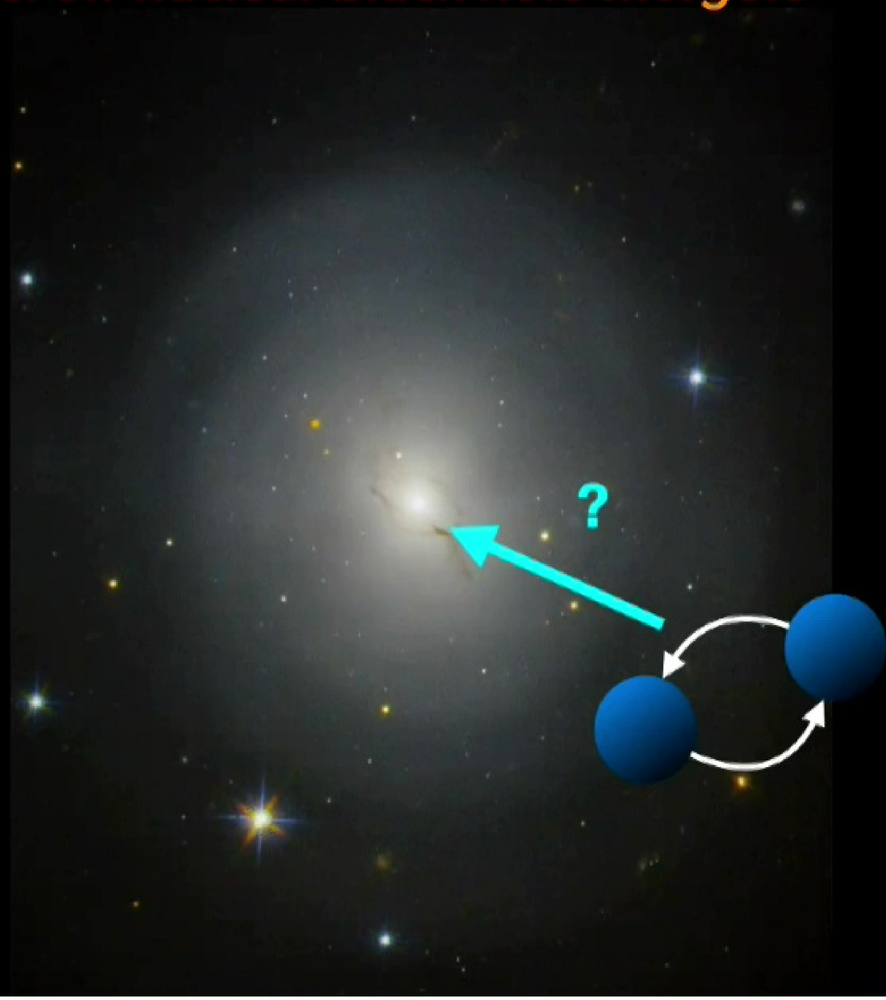




Hsin-Yu Chen / MIT


Chen, Ricarte & Pacucci, 2202.04764
Limited scenario 1:
Heavy-seed-dominated, high merging probability v.
Light-seed-dominated, low merging probability
LISA
Einstein Telescope
Cosmic Explorer
Redshift z
R = 0.1, P = 1.0
R = 0.9, P = 0.2
CE and ET can't distinguish the two cases since they can only observe the light seeds.
Hsin-Yu Chen / MIT

Nuclear v.s. off-nuclear black hole mergers



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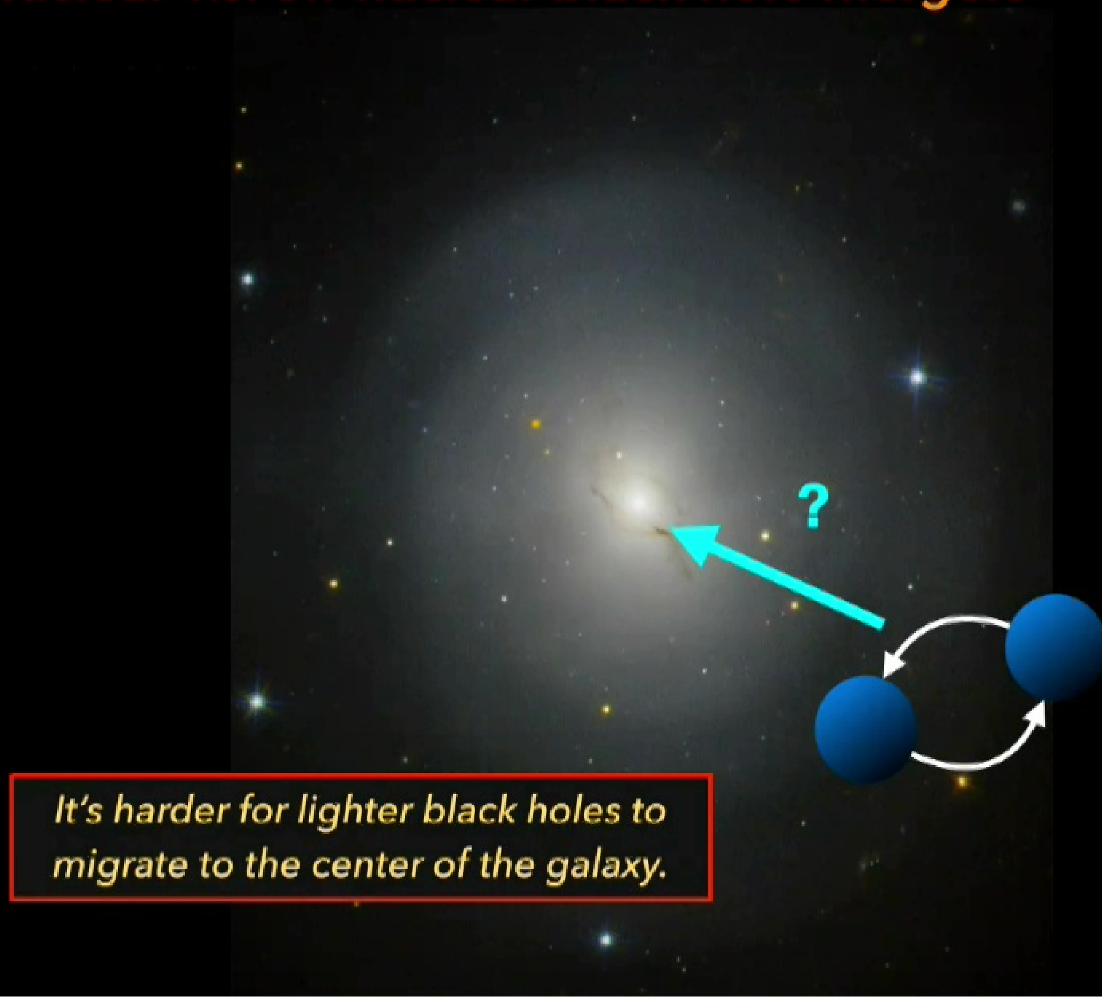

Chen, Ricarte & Pacucci, 2202.04764

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

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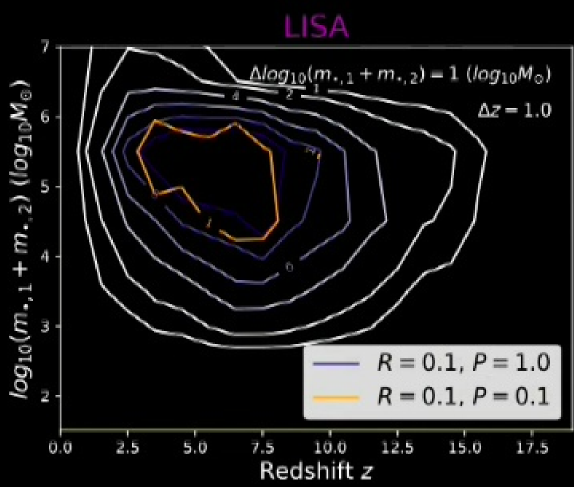
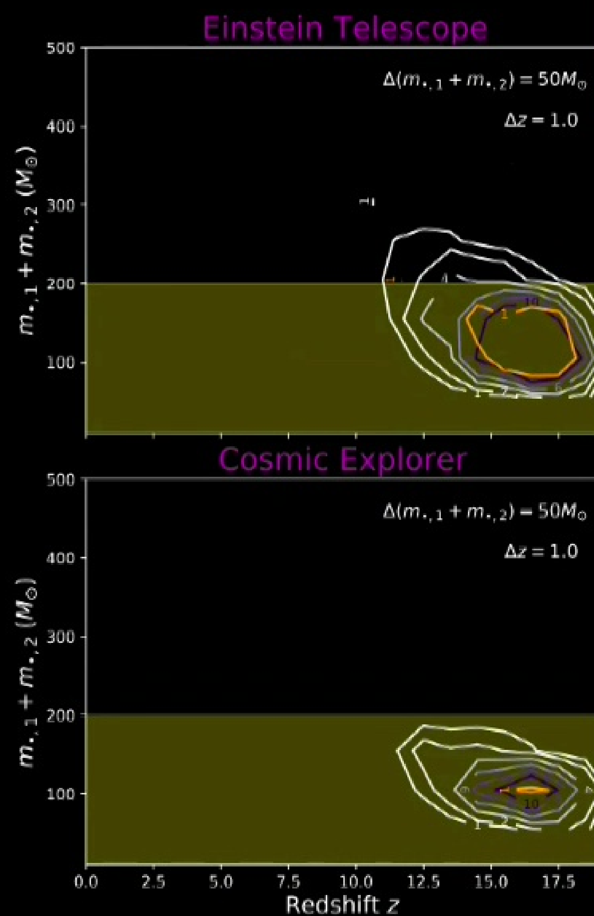
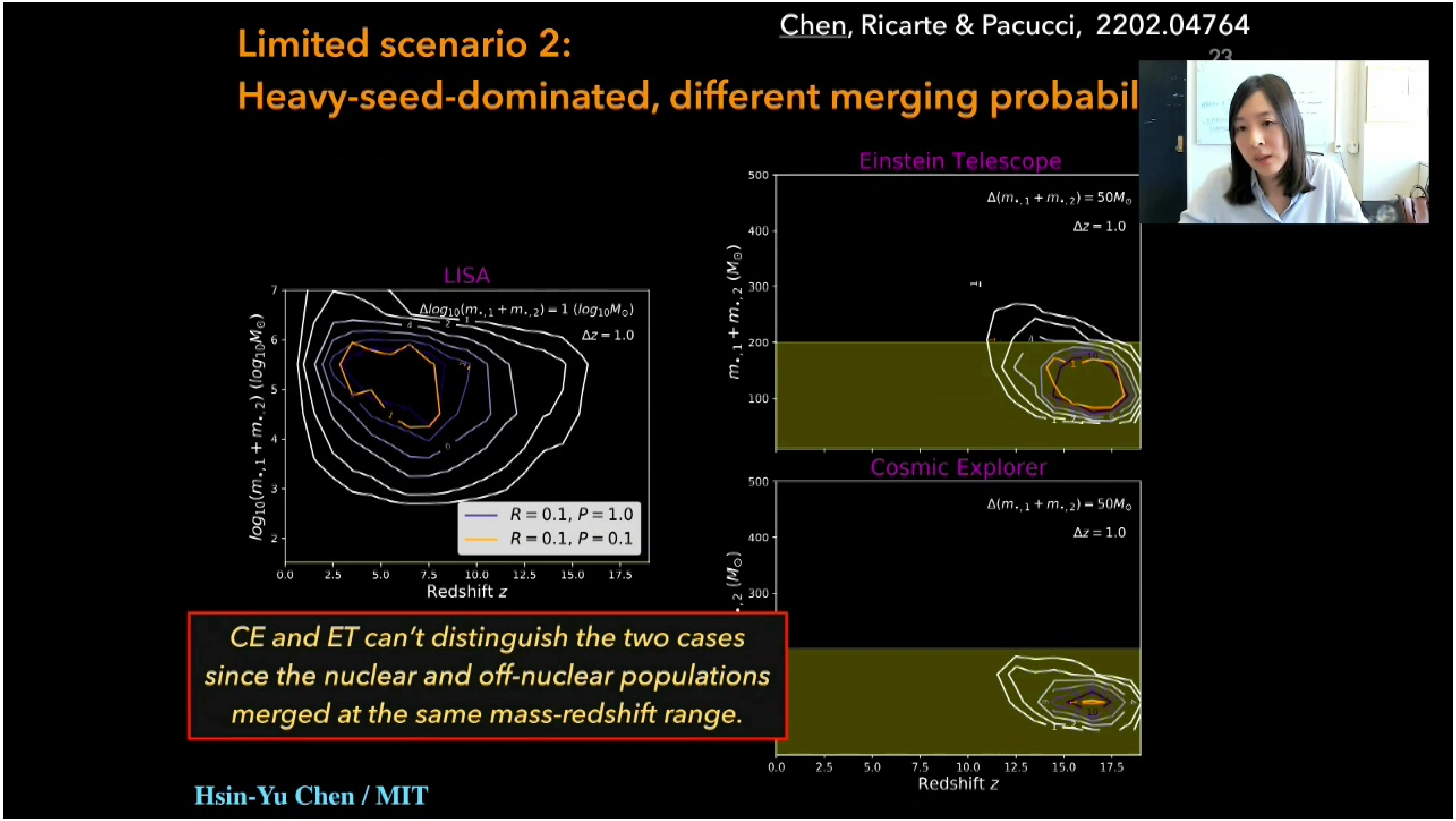




Hsin-Yu Chen / MIT



Chen, Ricarte & Pacucci, 2202.04764
Limited scenario 2:
Heavy-seed-dominated, different merging probabil
LISA
$\Delta log_{10}(m_{\bullet,1}+m_{\bullet,2}) = 1\ (log_{10}M_\odot)$
$\Delta z = 1.0$
$R = 0.1, P = 1.0$
$R = 0.1, P = 0.1$
Redshift z
$log_{10}(m_{\bullet,1}+m_{\bullet,2})\ (log_{10}M_\odot)$
Einstein Telescope
$\Delta(m_{\bullet,1}+m_{\bullet,2}) = 50M_\odot$
$\Delta z = 1.0$
$m_{\bullet,1}+m_{\bullet,2}\ (M_\odot)$
Cosmic Explorer
$\Delta(m_{\bullet,1}+m_{\bullet,2}) = 50M_\odot$
$\Delta z = 1.0$
Redshift z
CE and ET can't distinguish the two cases since the nuclear and off-nuclear populations merged at the same mass-redshift range.
Hsin-Yu Chen / MIT

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.

Hsin-Yu Chen / MIT


Thank you!
Hsin-Yu Chen / MIT