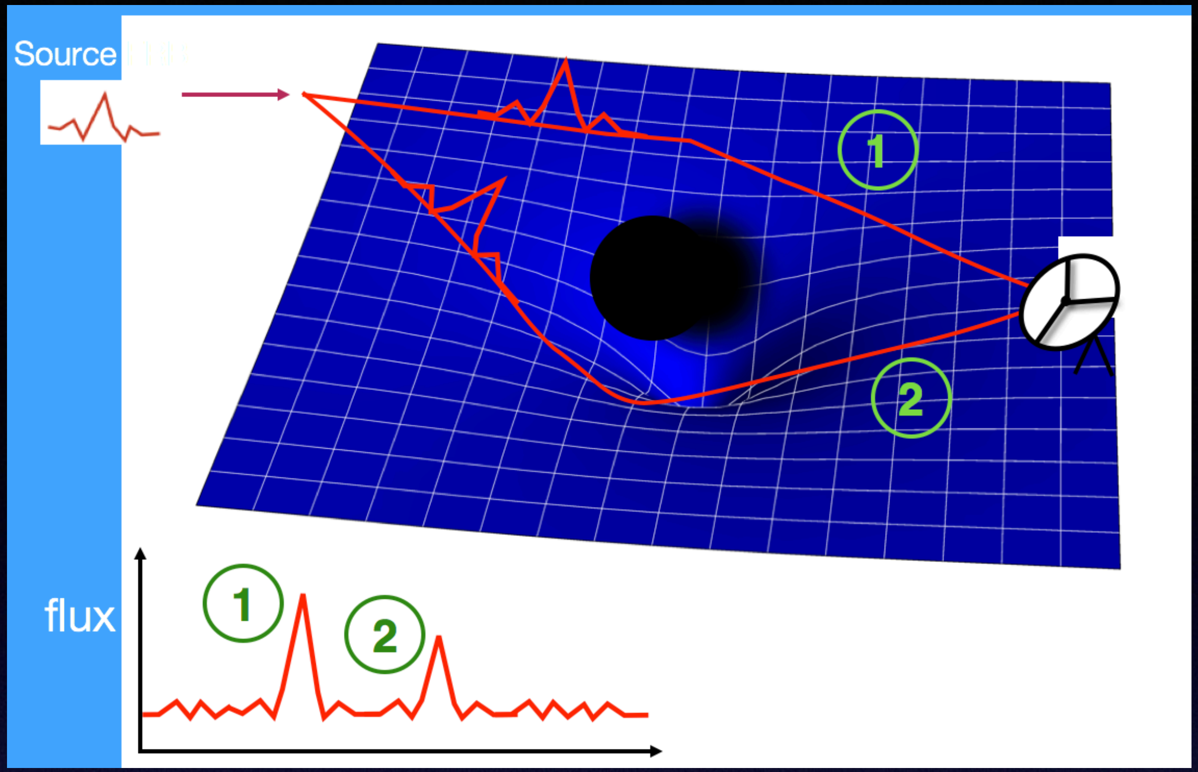
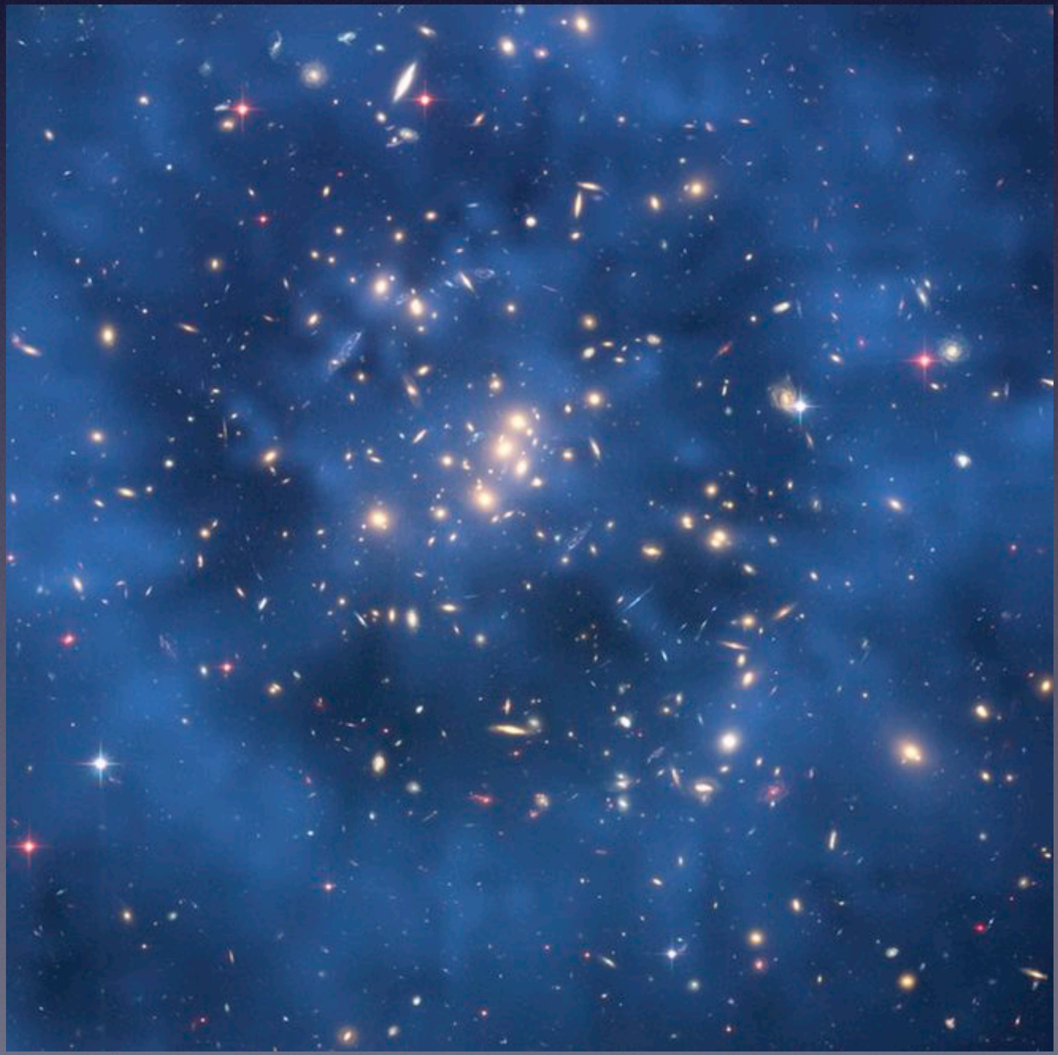




Gravitational waves and compact dark matter

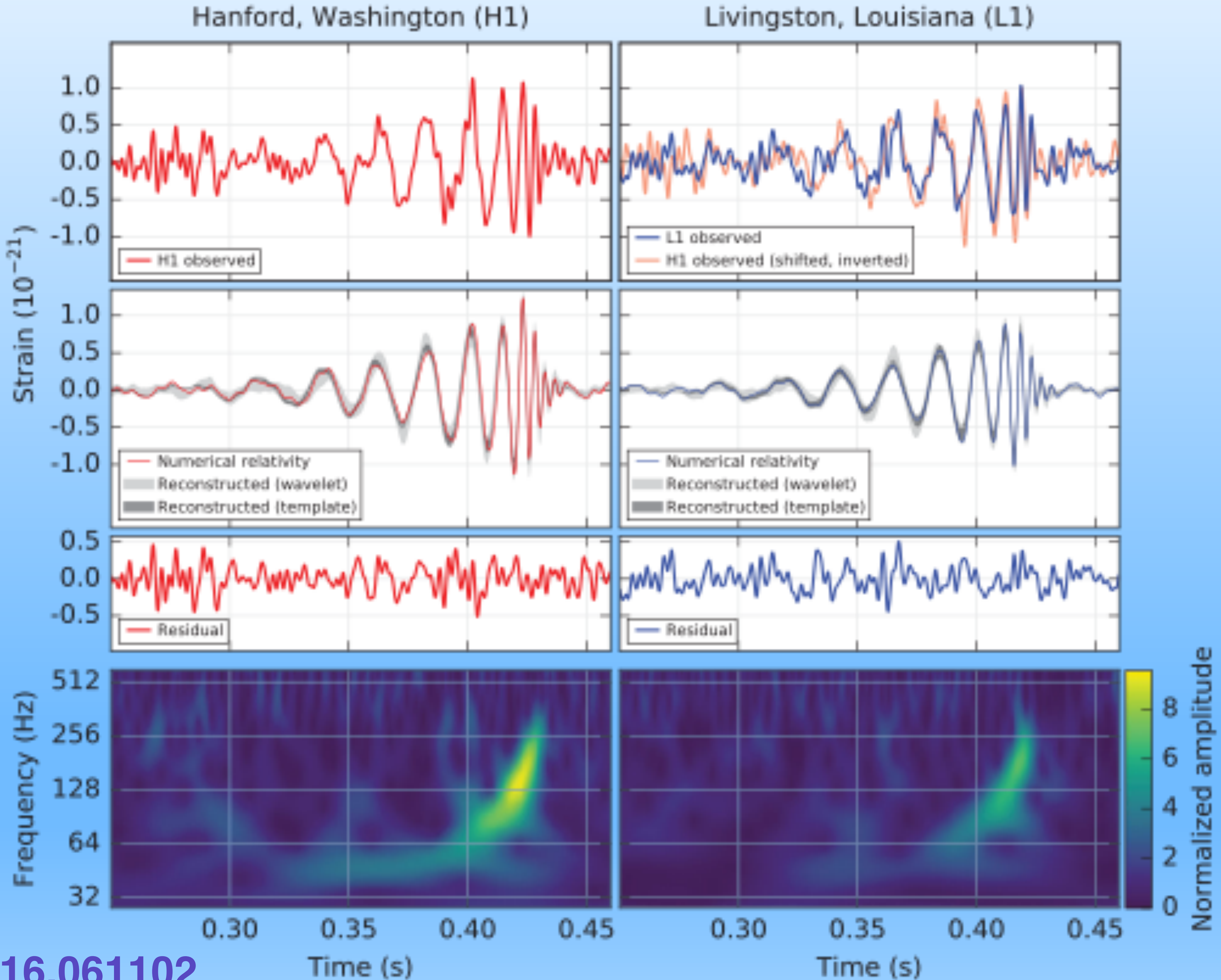
Marc Kamionkowski

Collaborators

Simeon Bird (JH postdoc → UCR faculty)
Yacine Ali-Haimoud (JH postdoc → NYU faculty)
Ilias Cholis (JH postdoc)
Julian Munoz (JH PhD → Harvard)
Ely Kovetz (JH postdoc)
Alvise Raccanelli (JH postdoc → Barcelona)
Adam Riess

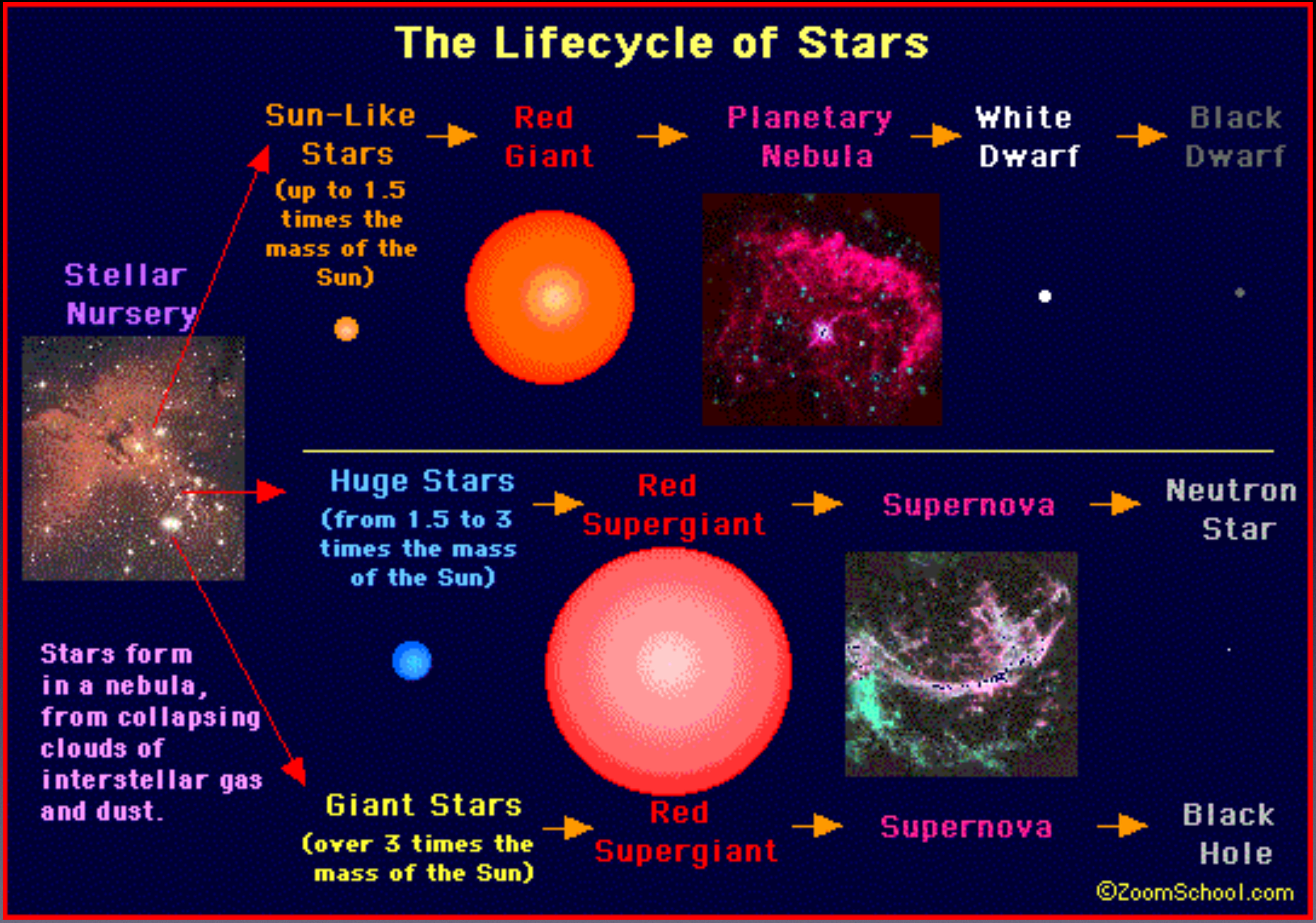
Liang Dai (JH PhD → IAS)
Tomohiro Nakama (JH postdoc)
Patrick Breysse (JH PhD → CITA)
Joe Silk

The GW150914 event



PRL 116.061102

$$m_1 = 36^{+5}_{-4} M_\odot \qquad m_2 = 29^{+4}_{-4} M_\odot$$


The Lifecycle of Stars
Sun-Like Stars
(up to 1.5 times the mass of the Sun)
Red Giant
Planetary Nebula
White Dwarf
Black Dwarf
Stellar Nursery
Huge Stars
(from 1.5 to 3 times the mass of the Sun)
Red Supergiant
Supernova
Neutron Star
Stars form in a nebula, from collapsing clouds of interstellar gas and dust.
Giant Stars
(over 3 times the mass of the Sun)
Red Supergiant
Supernova
Black Hole
©ZoomSchool.com

$$m_1 = 36^{+5}_{-4} M_\odot \qquad m_2 = 29^{+4}_{-4} M_\odot$$

?????

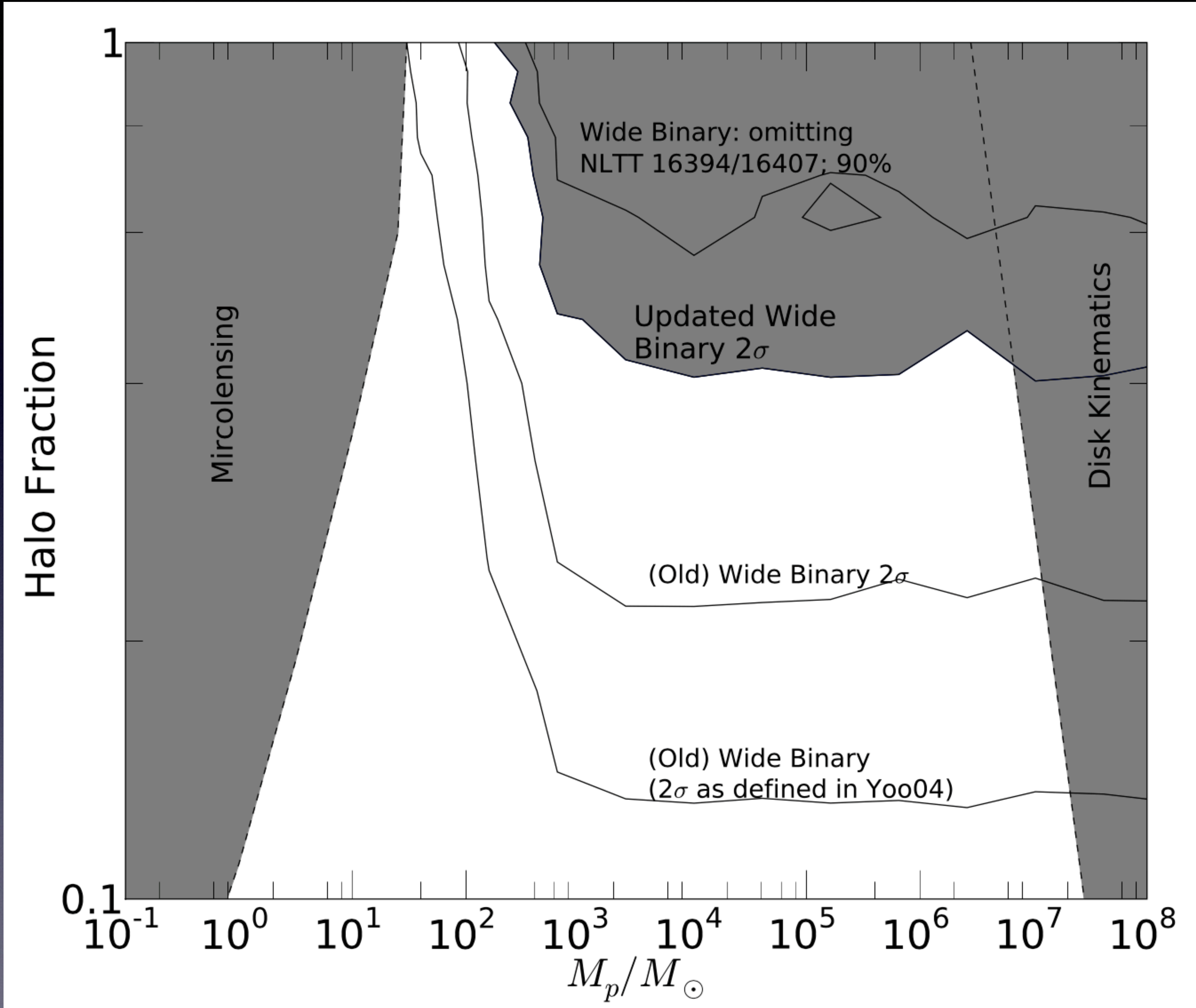
$$m_1 = 36^{+5}_{-4} M_\odot \qquad m_2 = 29^{+4}_{-4} M_\odot$$

Why such massive stellar remnants?

Can 30 Msun primordial black holes (PBHs) be the dark matter?

Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, Adam G. Riess (Johns Hopkins U.)

arXiv:1603.00464



Quinn et al. 0903.1644

Suppose DM = 30-Msun BHs

Two BHs in galactic halo can form binary by emission of soft-GW brehmsstrahlung if they undergo sufficiently hard scatter

$$\sigma = 2^{3/7}\,\pi\left(\frac{85\,\pi}{6\sqrt{2}}\right)^{2/7} R_s^2\left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$$
$$= 1.37\times10^{-14}\,M_{30}^2\,v_{\rm pbh-200}^{-18/7}\,{\rm pc}^2,$$

$$N \simeq (1/2)V(\rho/M_{\rm pbh})^2\sigma v$$
$$\simeq 3.10 \times 10^{-12}\, M_{12}\, \rho_{0.002}\, v_{\rm pbh-200}^{-11/7}\, {\rm yr}^{-1},$$

$$\Gamma \simeq 1.1 \times 10^{-4}\, \rho_{0.002}\, v_{\rm pbh-200}^{-11/7}\, {\rm Gpc}^{-3}\, {\rm yr}^{-1}$$

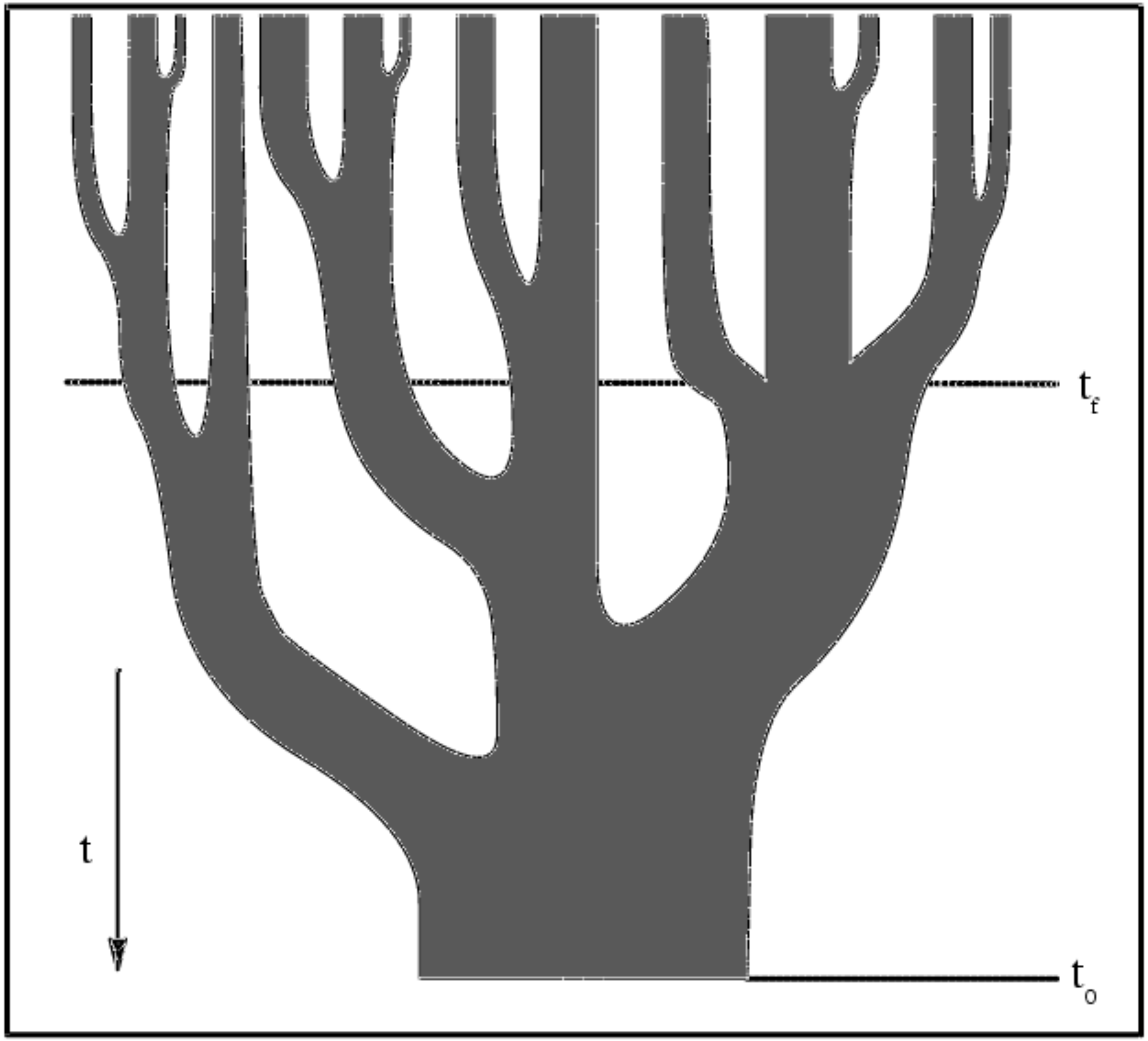
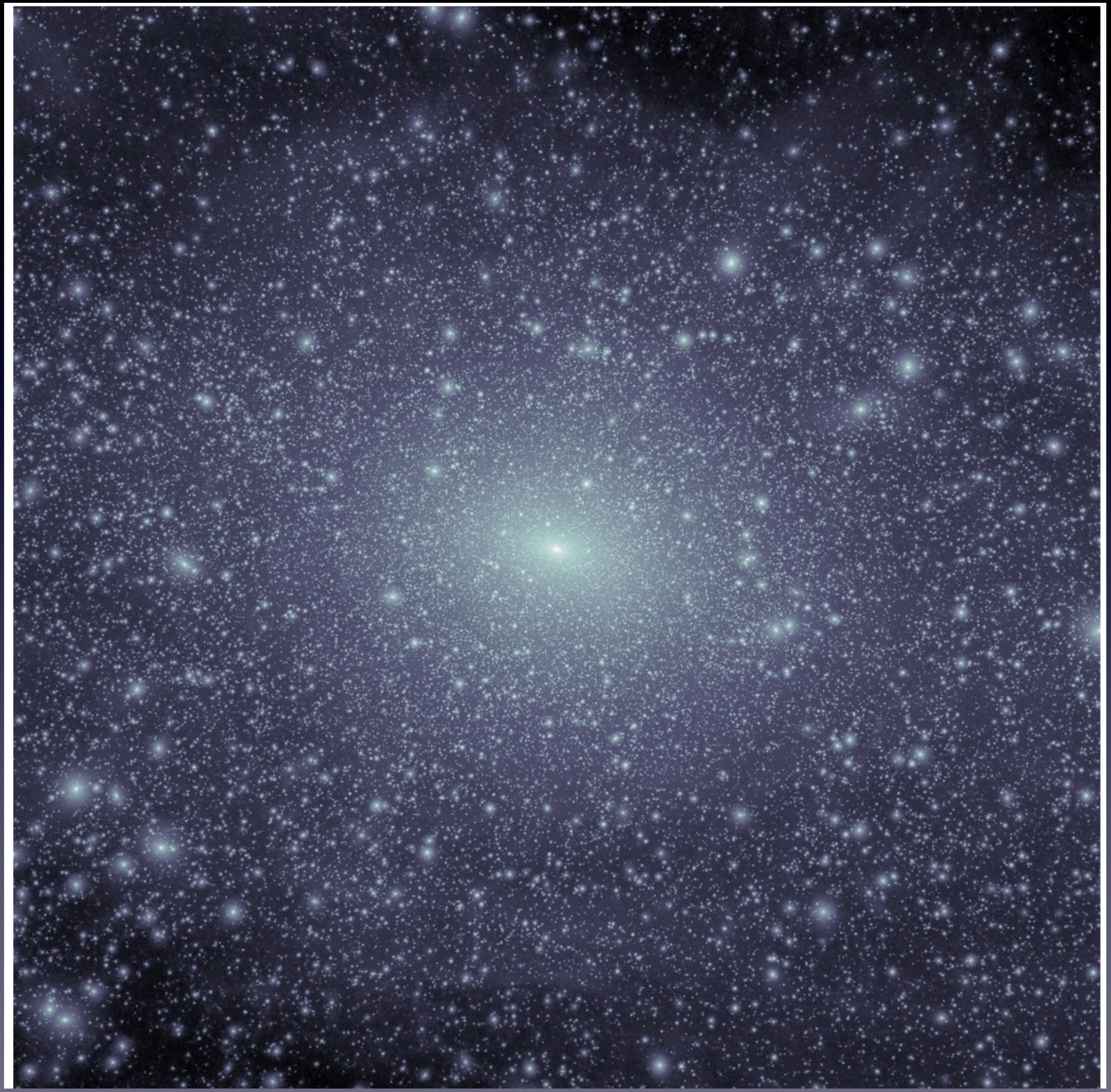


Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.



$$\Gamma \simeq 1400\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}.$$

More carefully….

Integrate over halo mass function

$$\mathcal{V} = 5\, f (M_c / 500\, M_\odot)^{-11/21}\, \mathrm{Gpc}^{-3}\, \mathrm{yr}^{-1}$$

$$\mathcal{V} = 5\, f(M_c/500\, M_\odot)^{-11/21}\ \mathrm{Gpc}^{-3}\, \mathrm{yr}^{-1}$$

assuming that the BBH merger rate is constant in the comoving frame, we infer a 90% credible range of 2–53 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (comoving frame). Incorporating all triggers that pass the search threshold while

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!!!!!!!

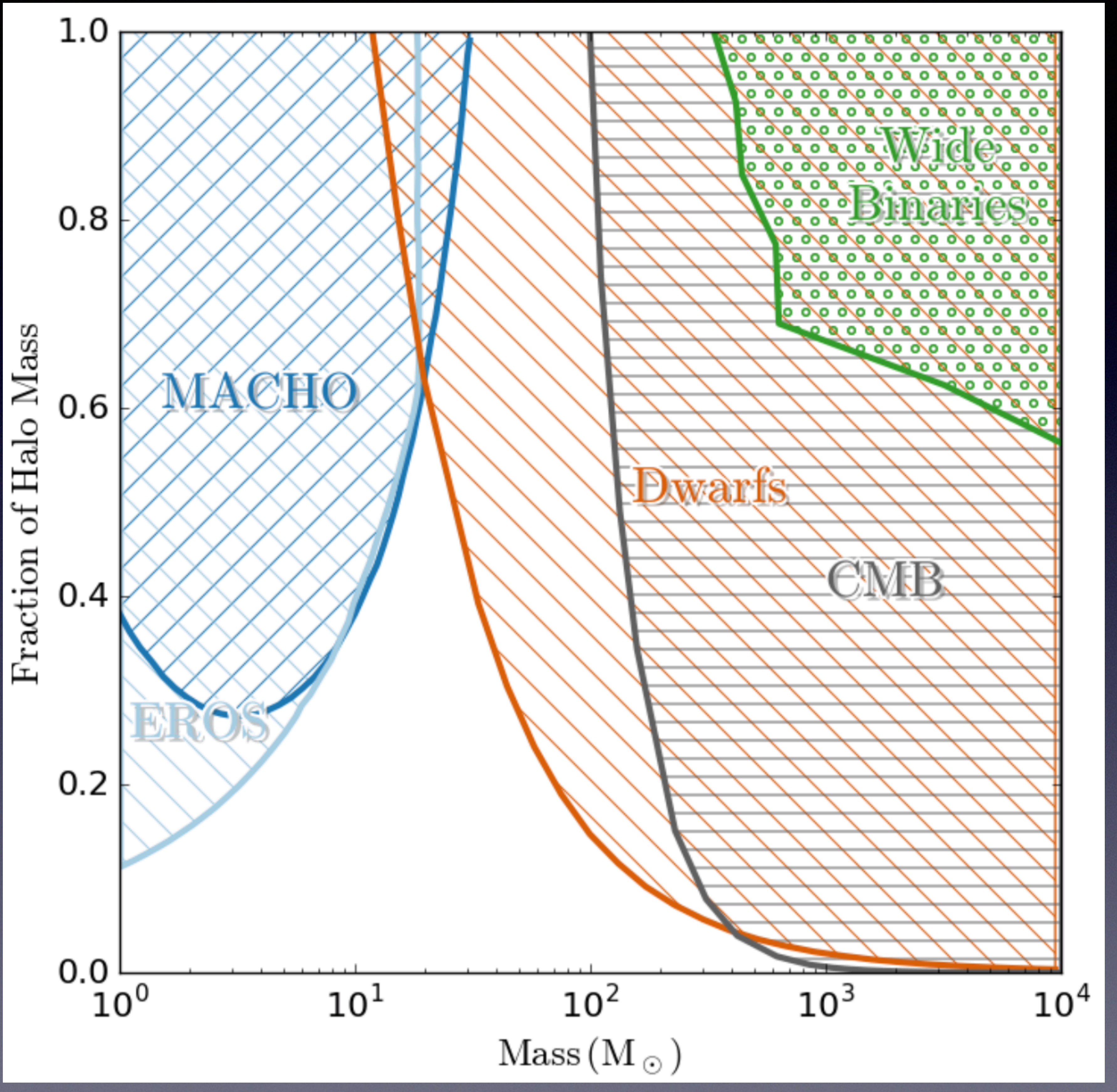
PBH dark matter Report Card

Test	Grade	Comments
Merger rate	A	Amazing coincidence with LIGO-inferred rate

Astrophysical constraints?

I. Dwarf galaxy dynamics

Brandt (1605.03665): 30-Msun DM would heat up cold stellar cluster at center of Eridanis II



1.0
0.8
0.6
0.4
0.2
0.0
Fraction of Halo Mass
MACHO
EROS
Dwarfs
CMB
Wide Binaries
10^0
10^1
10^2
10^3
10^4
Mass ($M_\odot$)

Brandt (1605.03665): 30-Msun DM would heat up Eridanis II stellar cluster

but there are caveats:

No central massive black hole (Kilizman et al. 2017 found 2200 $M_\odot$ BH at the center of a star cluster; Li et al. 2017 show ~30 decrease in constraint if 1500 $M_\odot$ BH in center

Eri II cluster assumed to be at center of the dark matter halo

Satellites assumed to have had same mass for 10 billion years

Cluster assumed to be at center of DM halo (Bird/Pfeffer, in prep)

Crnojevic et al. 2016 note evidence for tidal stripping due to Milky Way

Assumes monochromatic stellar mass function

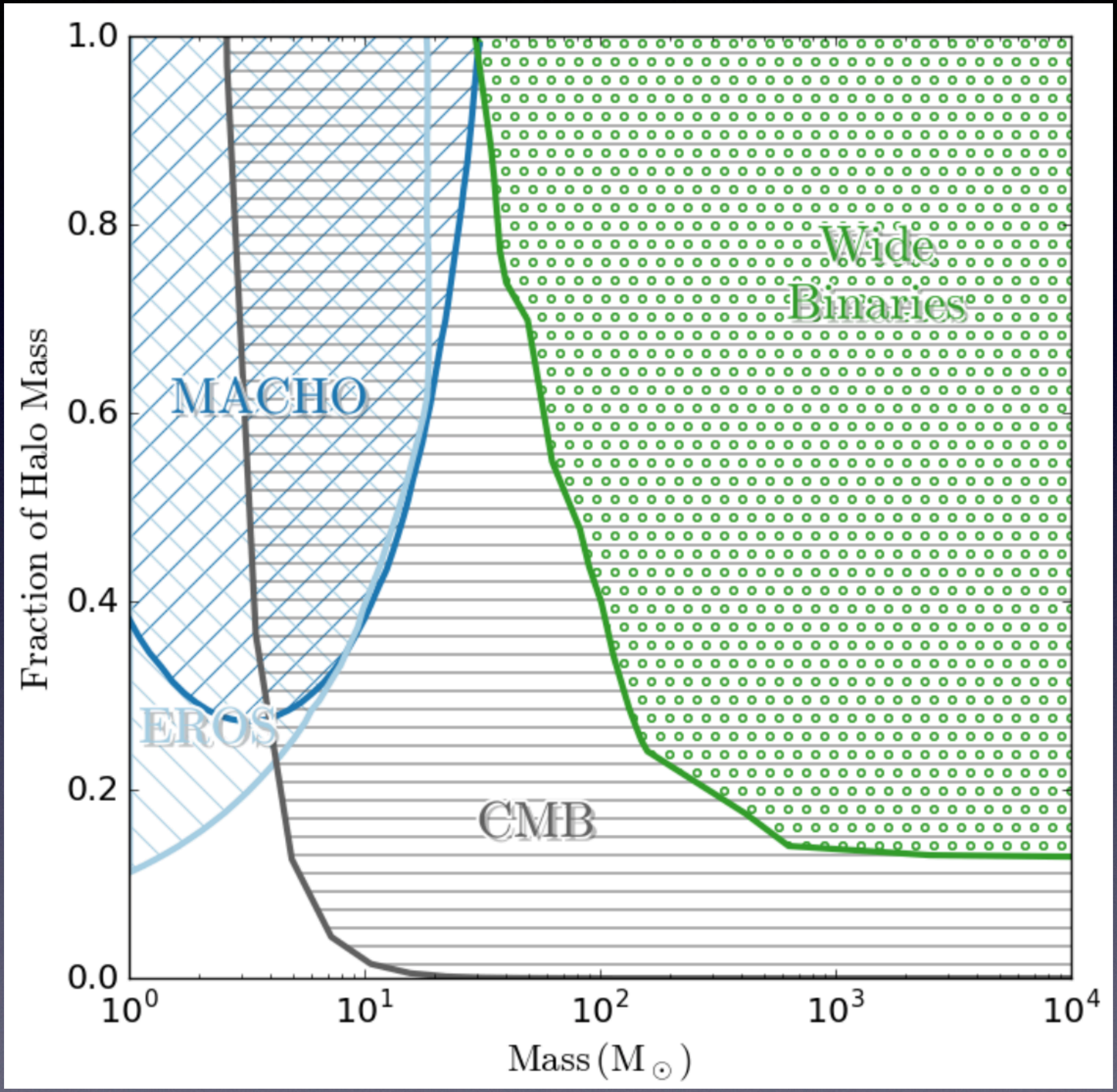
PBH dark matter Report Card

Test	Grade	Comments
Merger rate	A	Amazing coincidence with LIGO-inferred rate
Dwarf galaxies	A-	Great idea from Brandt with lots of promise, but current constraint to PBH DM not robust

Astrophysical constraints?

II. CMB fluctuations and spectral distortions

Ricotti, Ostriker, and Mack (2007): heating of primordial plasma due to accretion onto PBHs leads to spectral distortions and angular fluctuations in CMB. WMAP/FIRAS bound heating rate <0.0001 of that from 30 Msun PBHs



MACHO
EROS
CMB
Wide Binaries
Fraction of Halo Mass
Mass (M☉)
1.0
0.8
0.6
0.4
0.2
0.0
10^0
10^1
10^2
10^3
10^4

II. CMB fluctuations and spectral distortions

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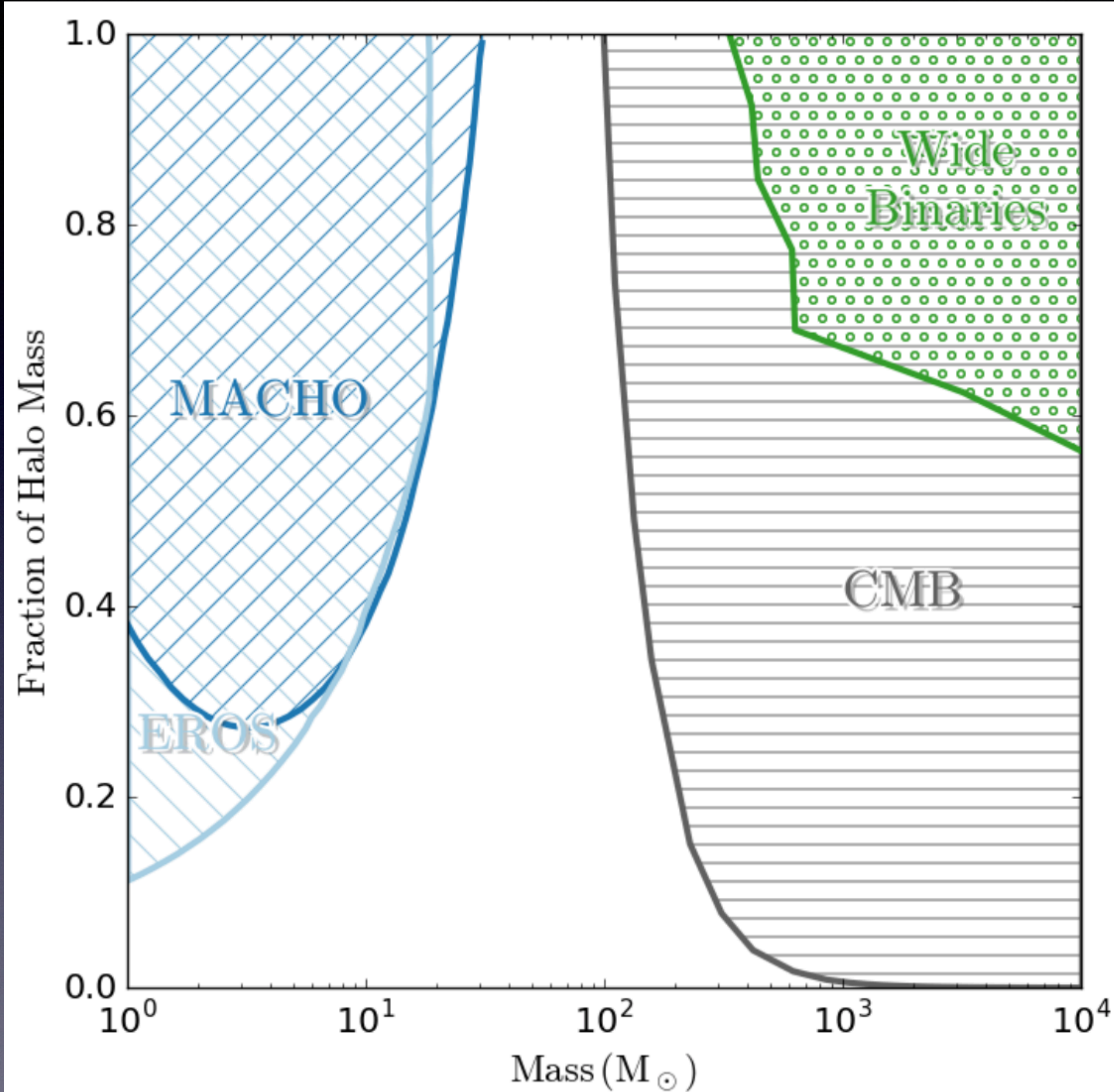
Ali-Haimoud & MK (2017; see also Horowitz 2017 and Aloni, Blum & Flauger 2017): Re-do analysis including Compton drag and cooling of accreting gas, careful treatment of radiative feedback, proper treatment of peculiar velocities, and Planck data. No spectral-distortion bound; fluctuations consistent with Planck



1.0
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Fraction of Halo Mass
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10^0
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PBH dark matter report card

Test	Grade	Comments
Merger rate	A+	Amazing coincidence with LIGO-inferred rate
Dwarf galaxies	B+	Great idea from Brandt with lots of promise, but current constraint to PBH DM not robust
CMB	A	Earlier claims were overstated, but are pushing up against current bounds

Astrophysical constraints?

III. Quasar lensing (Mediavilla et al. 2017)

Consistency of smooth-lens model for strong-lensing systems constrains 30-Msun DM

Astrophysical constraints?

III. Quasar lensing (Mediavilla et al. 2017)

Consistency of smooth-lens model for strong-lensing systems constrains 30-Msun DM

….but need more details, discussion, systematics….

PBH dark matter Report Card

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Merger rate	A+	Amazing coincidence with LIGO-inferred rate
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CMB	A	Earlier claims were overstated, but are pushing up against current bounds
Quasar lensing	I	Constraints need more study

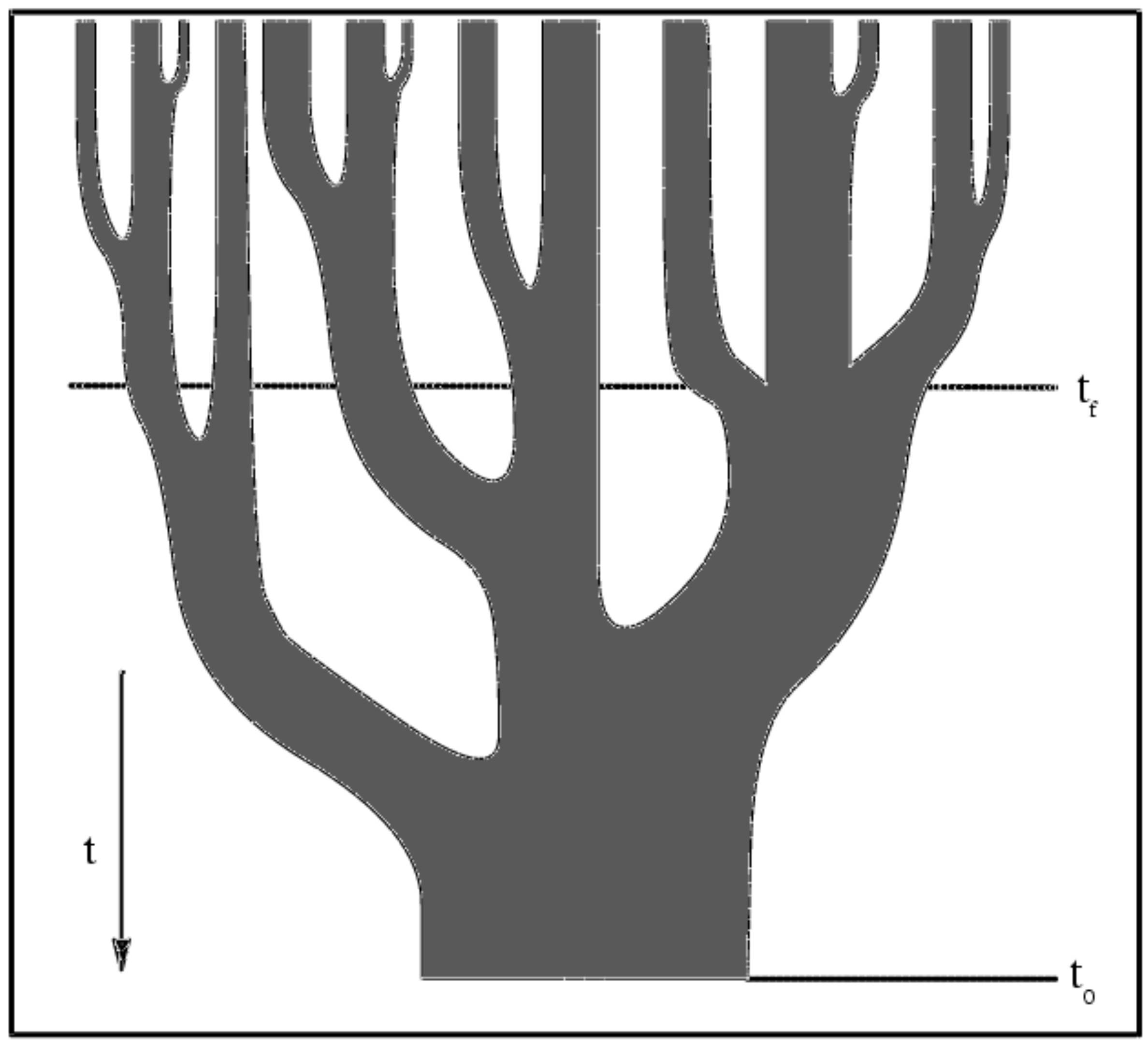
Astrophysical constraints?

IV. Primordial binaries (Sasaki et al. 2016)

Primordial binaries form as first stage of hierarchical clustering. Enough survive to produce ~10^4 times as many LIGO-like events as are observed

Astrophysical constraints?

IV. Primordial binaries (Sasaki et al. 2016



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Astrophysical constraints?

IV. Primordial binaries (Sasaki et al. 2016)

Primordial binaries form as first stage of hierarchical clustering. Enough survive to produce $\sim 10^4$ times as many LIGO-like events as are observed

But survival of primordial binaries is uncertain either from accretion or dynamical processes in subsequent generations of structure formation (Hayasaki et al. 2016; Ali-Haimoud, Kovetz & MK, in prep)

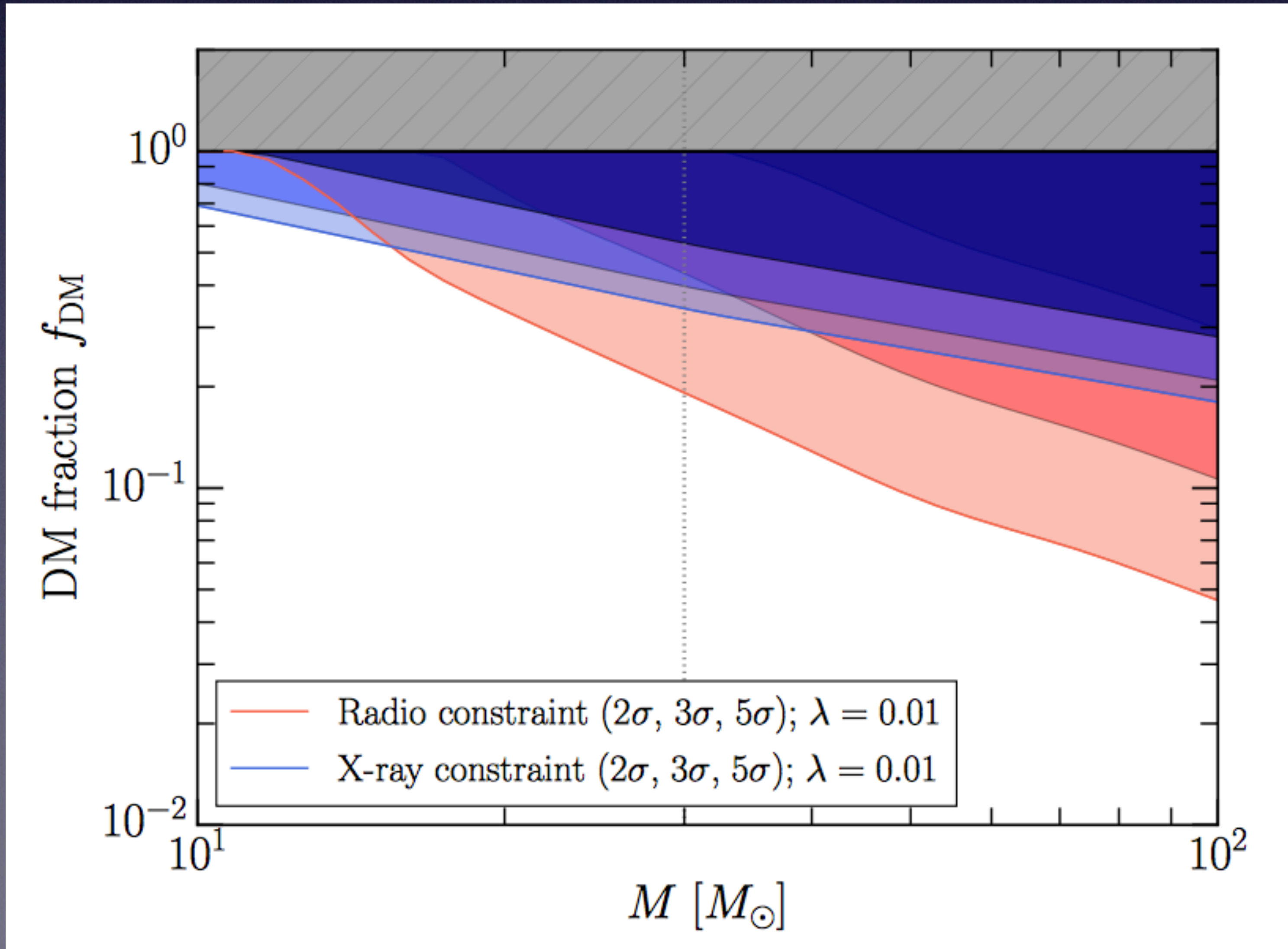
PBH dark matter Report Card

Test	Grade	Comments
Merger rate	A+	Amazing coincidence with LIGO-inferred rate
Dwarf galaxies	B+	Great idea from Brandt with lots of promise, but current constraint to PBH DM not robust
CMB	A	Earlier claims were overstated, but are pushing up against current bounds
Quasar lensing	I	Constraints need more study
Primordial binaries	I	The survival of these fragile objects is uncertain

Astrophysical constraints?

V. X rays from accretion of ISM (Gaggero et al. 2017; Inoue & Kusenko 2017)

Claim that EM emission from accretion of ISM onto PBHs excludes PBH DM in Milky Way



Astrophysical constraints?

….but predictions of accretion rates are highly uncertain (cf., Ali-Haimoud & MK 2017; Agol & MK 2002)

PBH dark matter Report Card

Test	Grade	Comments
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Dwarf galaxies	B+	Great idea from Brandt with lots of promise, but current constraint to PBH DM not robust
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Primordial binaries	I	The survival of these fragile objects is uncertain
X-rays from accretion of ISM	A	Assumed accretion rates are very uncertain

Where do 30-Msun PBHs come from?

Where do these things come from?

??????

Where do these things come from?

Supergravity inflation (1606.07361,1612.02529); axion inflation (1610.03763; 1704.03464); broken scale invariance (1611.06130,1702.03901);non-thermal histories (1703.04825); trapped inflation (1606.00206); double inflation (1705.06225); axion stars (0609.04724); critical Higgs inflation (0705.04861); contracting Universe (0609.02556)....

PBH dark matter Report Card

Test	Grade	Comments
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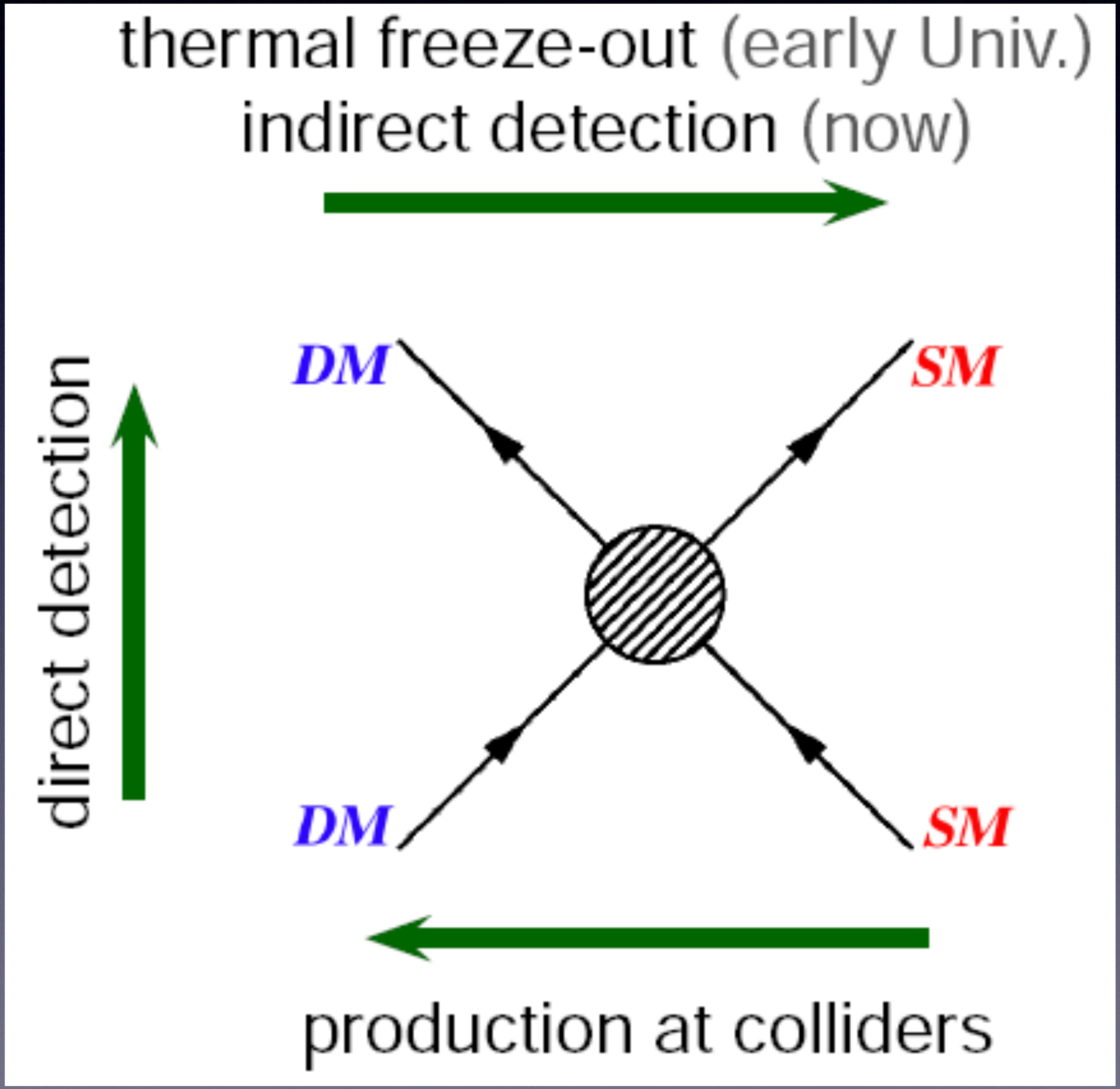
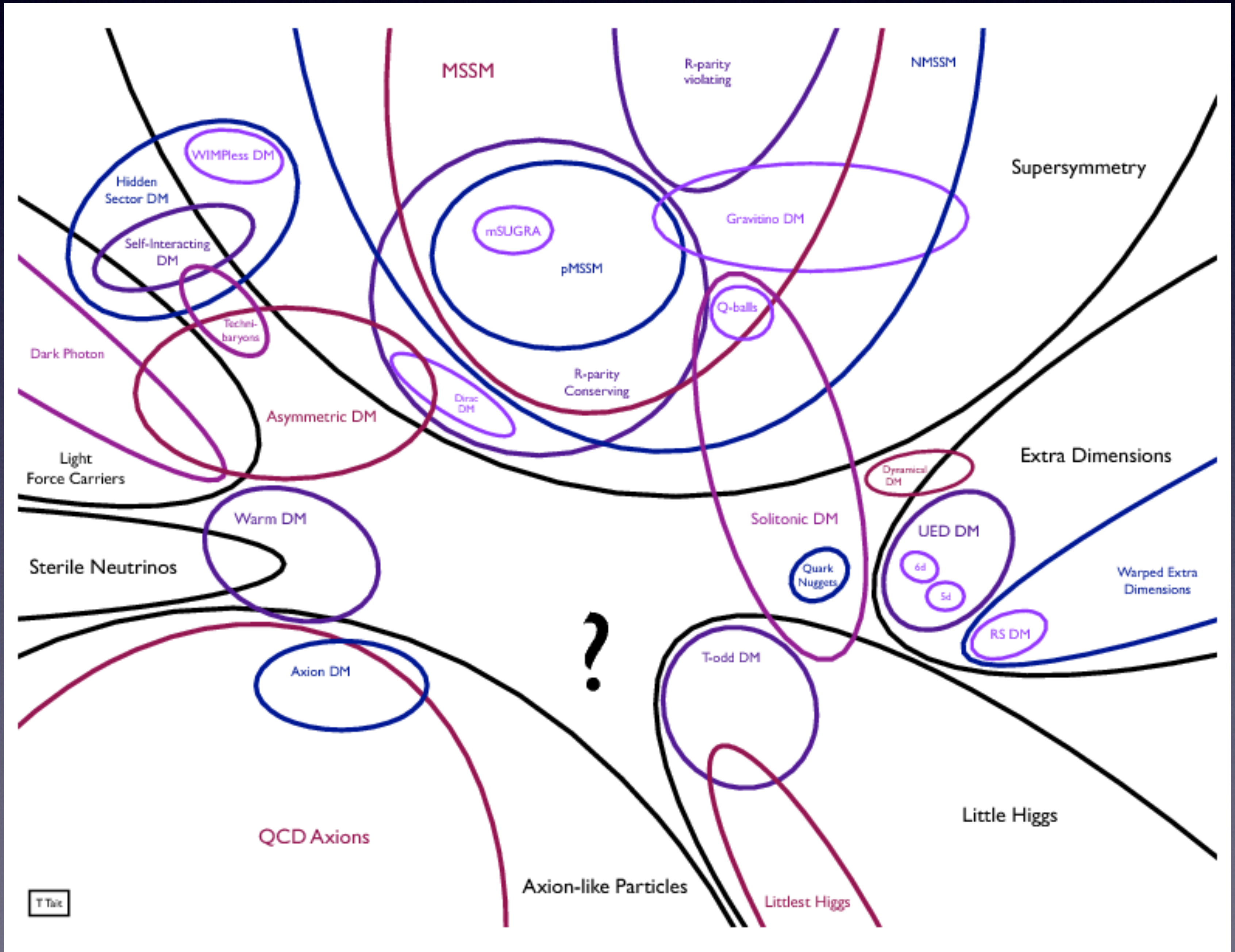
Dwarf galaxies	B+	Great idea from Brandt with lots of promise, but current constraint to PBH DM not robust
CMB	A	Earlier claims were overstated, but are pushing up against current bounds
Quasar lensing	I	Constraints need more study
Primordial binaries	I	The survival of these fragile objects is uncertain
X-rays from accretion of ISM	A	Assumed accretion rates are very uncertain
Primordial production mechanism	D	Scenarios require multiple highly skilled tooth fairies

Dark matter: 1987



Dark matter: 2017



Dark matter:1987

Dark matter:2017

D 17

So, if we grade on a curve

PBH dark matter Report Card

Test	Grade	Comments
Merger rate	A+	Amazing coincidence with LIGO-inferred rate
Dwarf galaxies	B+	Great idea from Brandt with lots of promise, but current constraint to PBH DM not robust
CMB	A	Earlier claims were overstated, but are pushing up against current bounds
Quasar lensing	I	Constraints need more study
Primordial binaries	I	The survival of these fragile objects is uncertain
X-rays from accretion of ISM	A	Assumed accretion rates are very uncertain
Primordial production mechanism	~~D~~ **A**	Scenarios require multiple highly skilled tooth fairies…..but that's ok

Predictions/tests of scenario

- BBH mass spectrum
- BBH eccentricity No EM/neutrino counterparts!
- Clustering with DM
- Stochastic GW background
- Lensing echoes of fast radio bursts

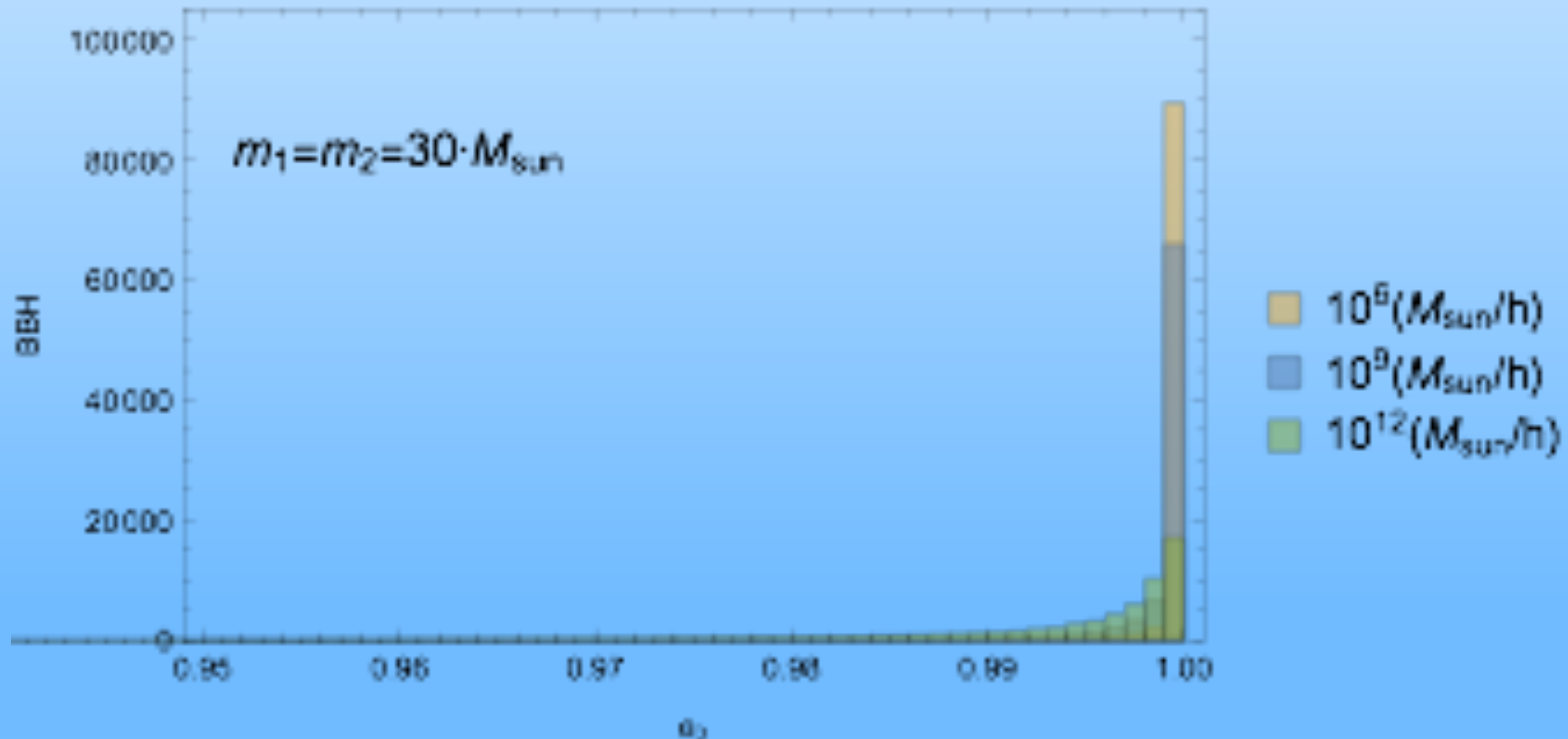
With more GWs

Given current LIGO rate, expect perhaps ~20,000 more BBH mergers in next decade!!

PBH binaries will be eccentric

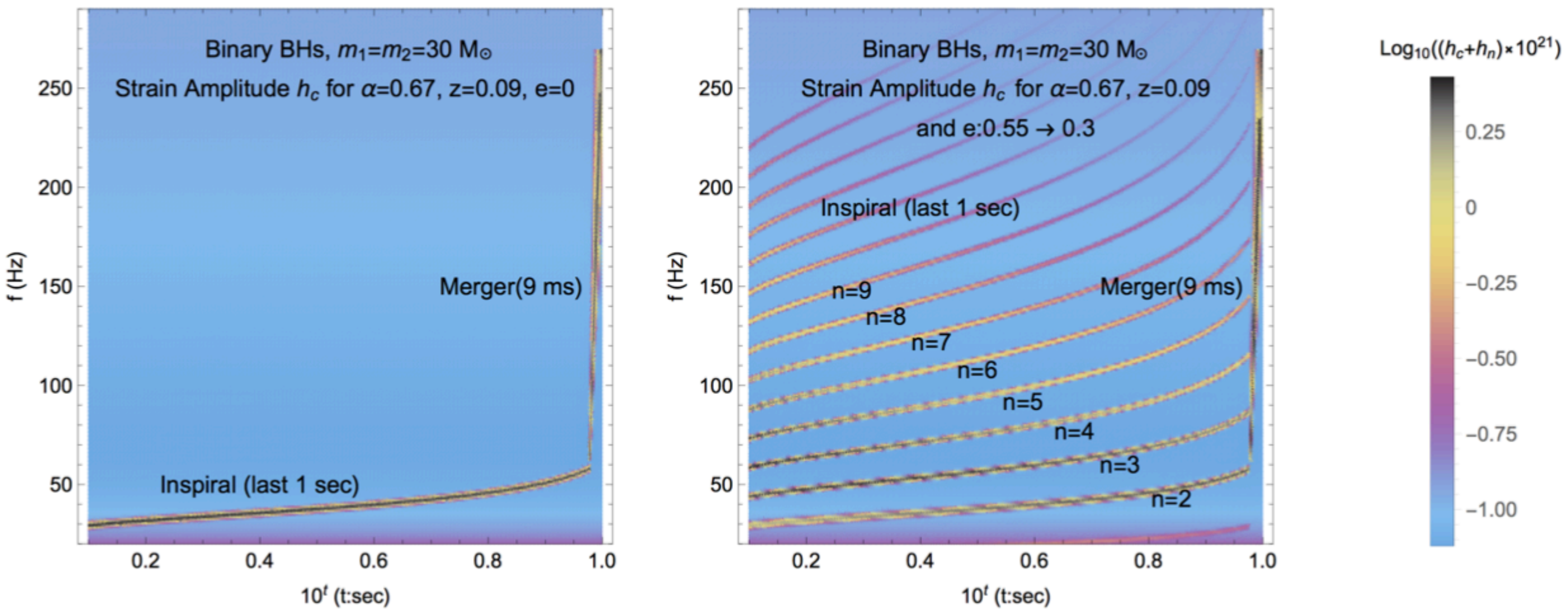
Future directions for DM by PBHs

When binaries form that have high initial eccentricities:



see many more modes of grav. waves

~1 such event in LIGO; ~10 in Einstein Telescope



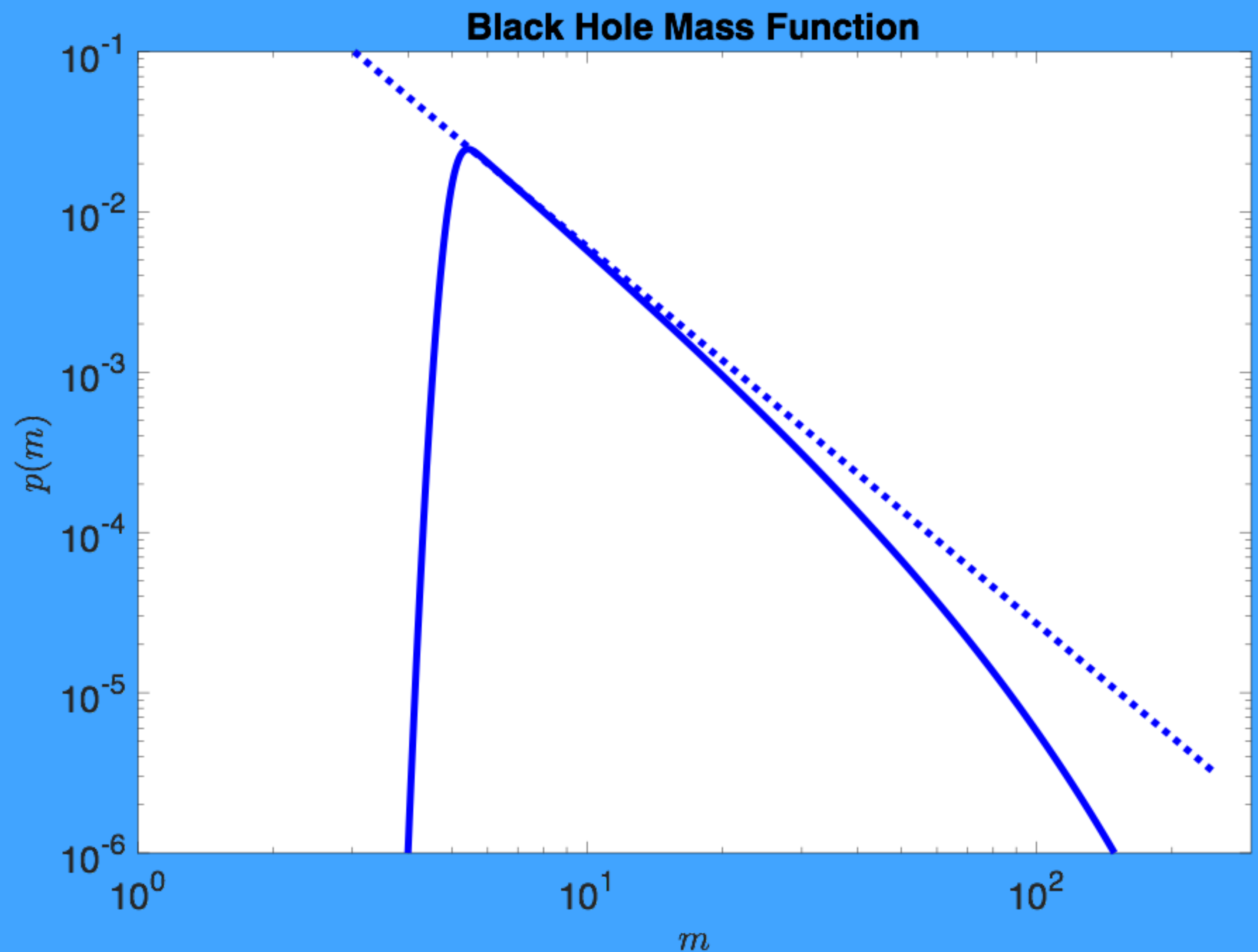
Cholis, Ali-Haimoud, S. Bird, J. Munoz,MK, E. Kovetz, and A. Raccanelli (2016)

The BH binary mass distribution

The Black-Hole Mass Function from GWs

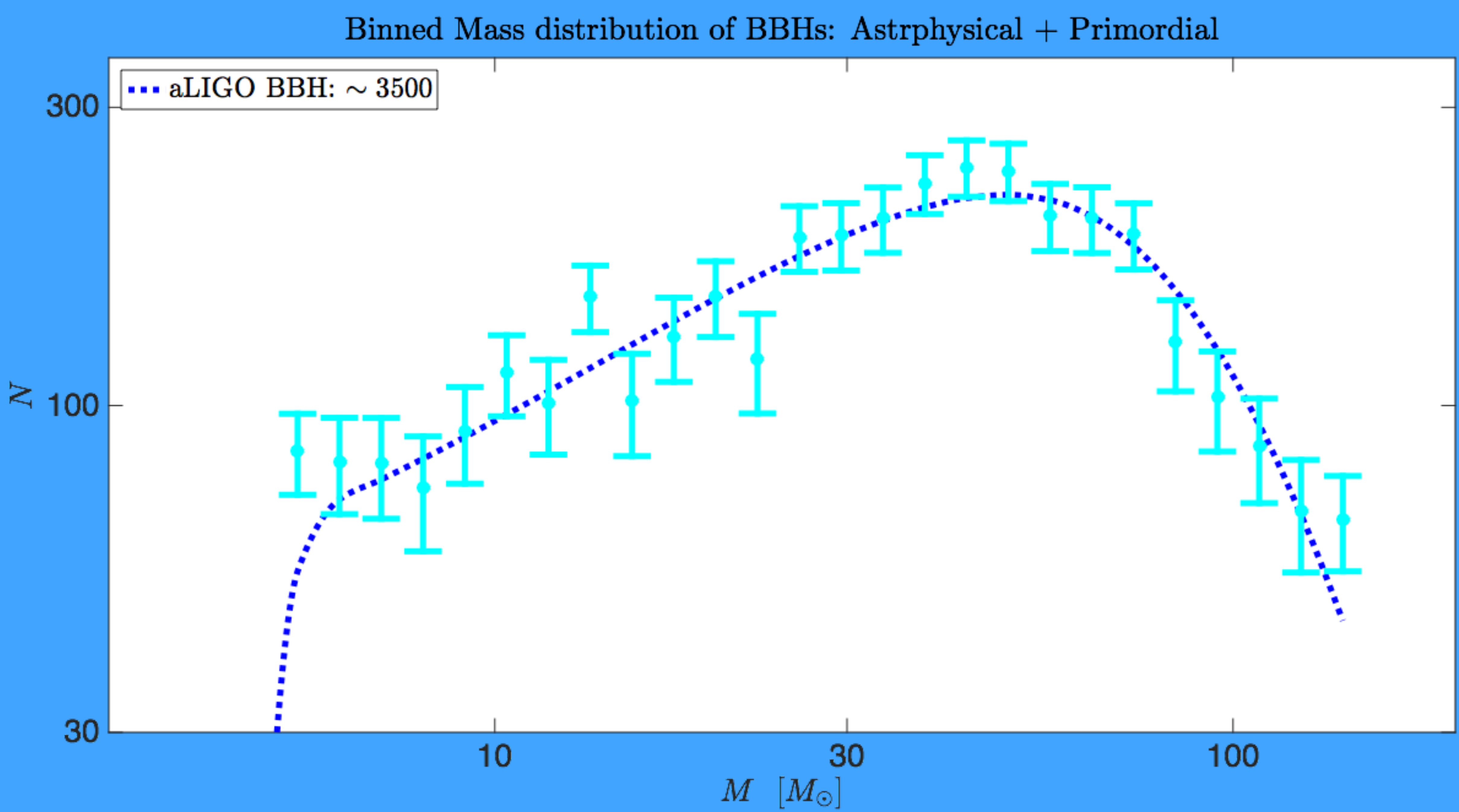
(Kovetz et al., arXiv:1611.01157)

$$p(m) \propto m^{-\alpha}\mathcal{H}(m - m_{\rm Gap})e^{-m/m_{\rm Cap}}$$



The Black-Hole Mass Function from GWs

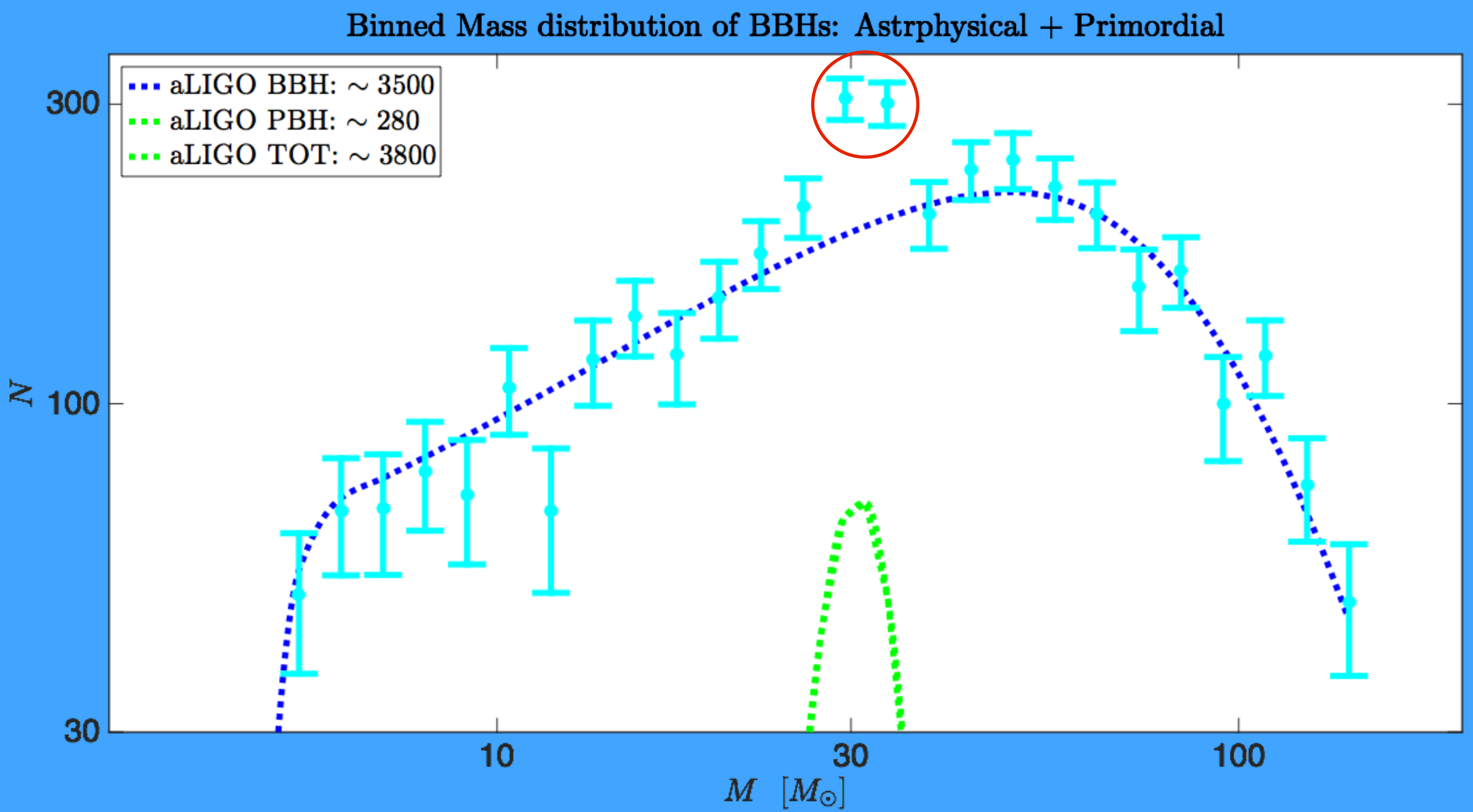
Observed mass spectrum with 5 years of advanced LIGO data:



The Black-Hole Mass Function from GWs

Observed mass spectrum with 5 years of advanced LIGO data:

if we add Dark Matter PBHs: $M_{\rm PBH} \sim \mathcal{N}(30 M_\odot, \sigma_M^2)$

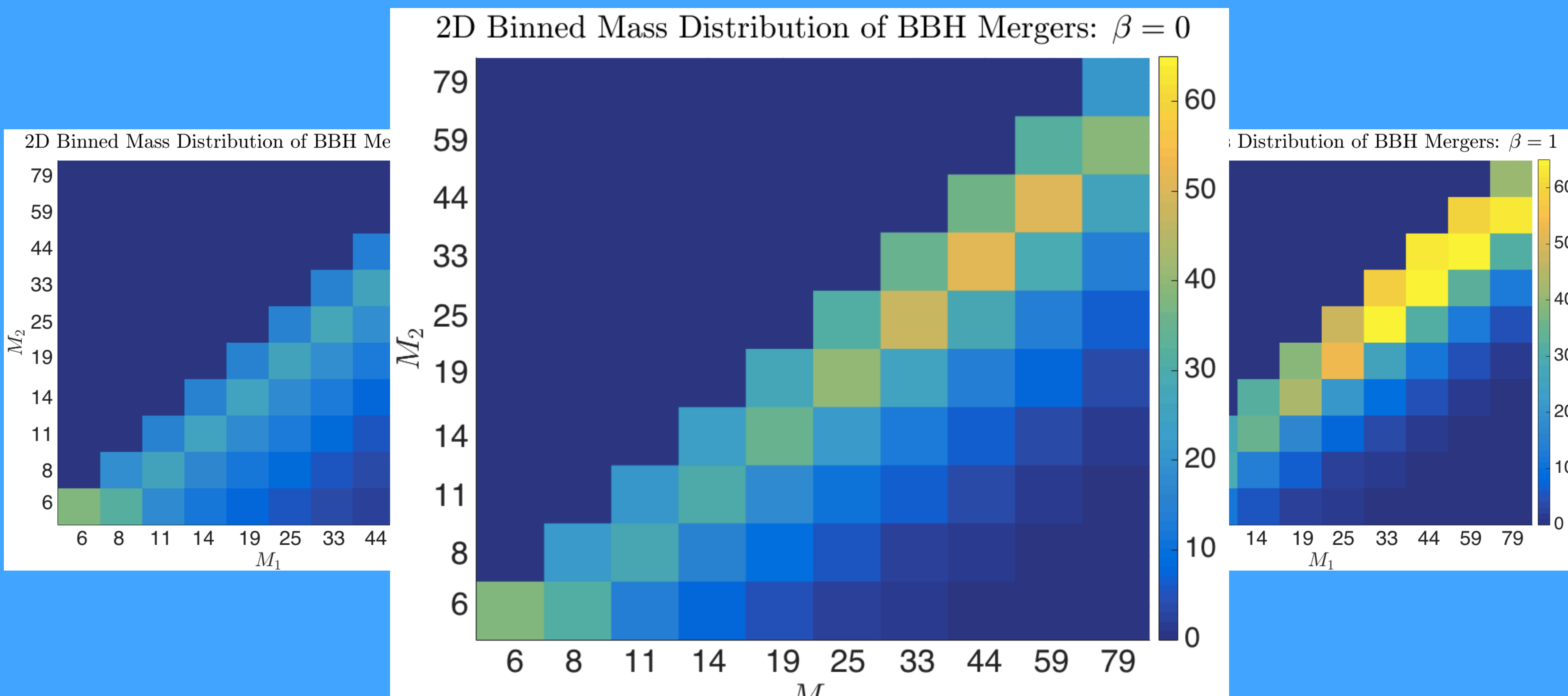


The Black Hole Mass Function from GWs: 2D

Probing the MF parameters:

Heavier mass: $p(m) \propto m^{-\alpha} \mathcal{H}(m - m_{\rm Gap}) e^{-m/m_{\rm Cap}}$

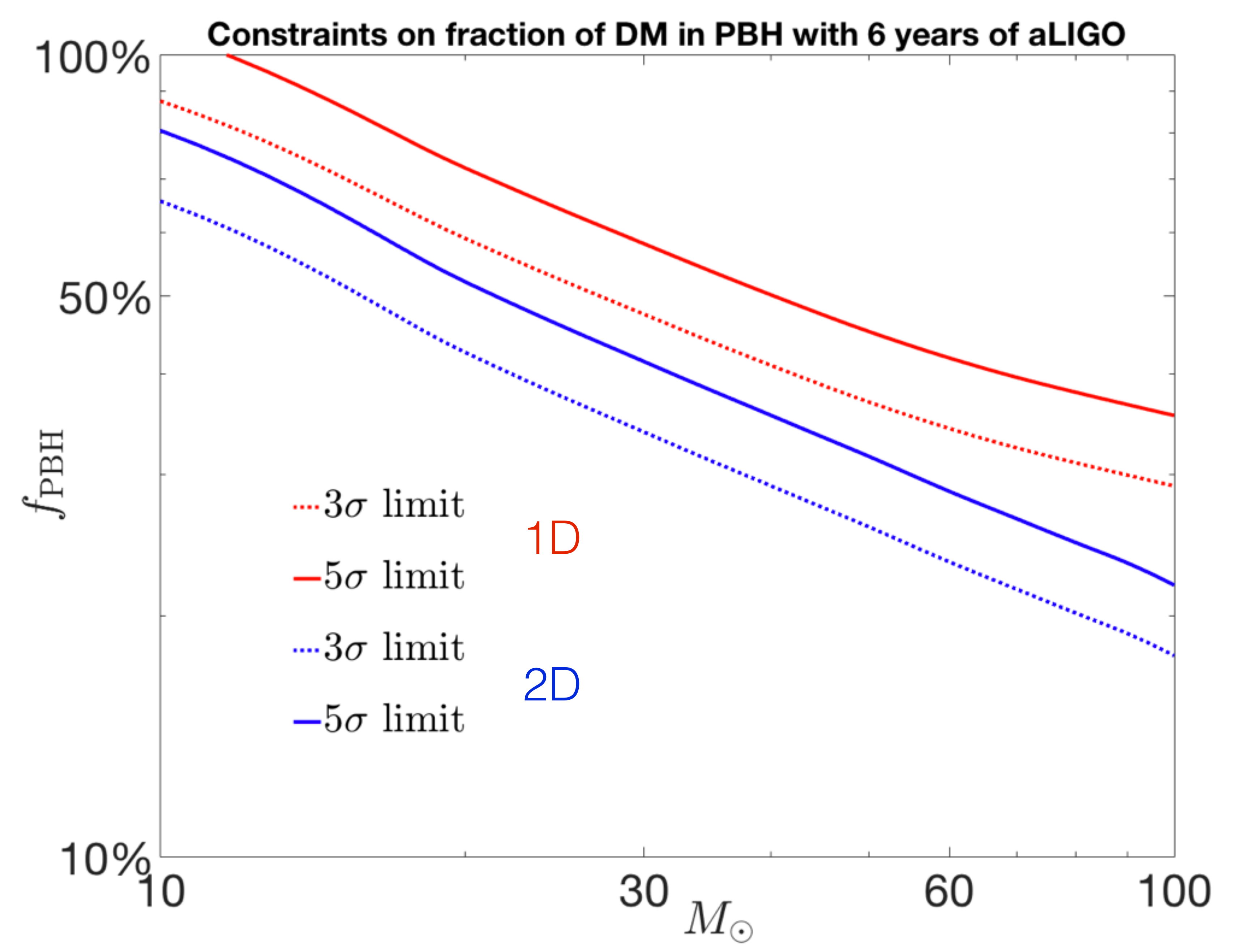
Lighter mass: $p(m') \propto (m'/m)^{\beta}$ ← Mass Ratio



Probing PBH Dark Matter with GWs

(Kovetz, 1705.09182)

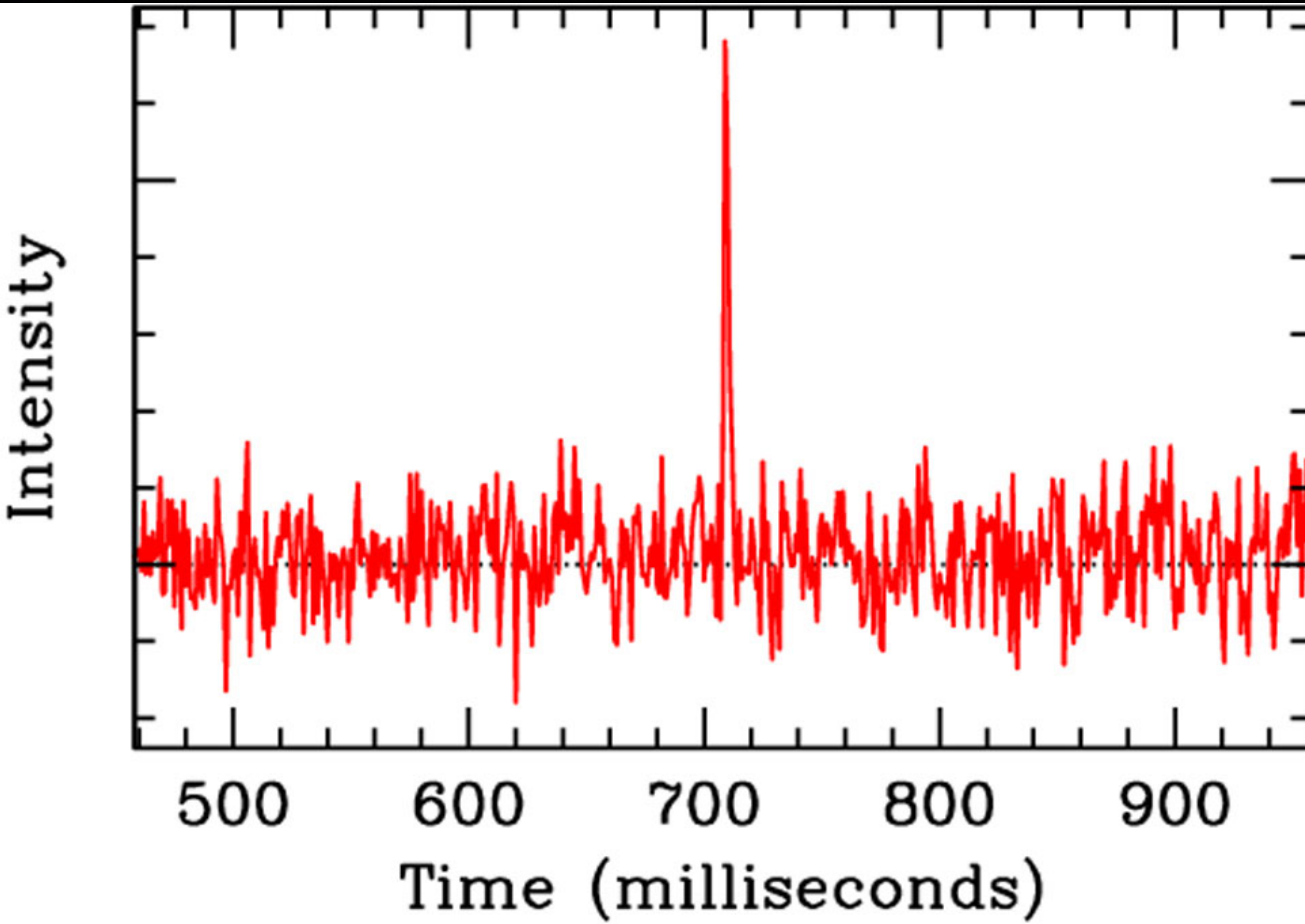
Probing the LIGO window with gravitational waves:

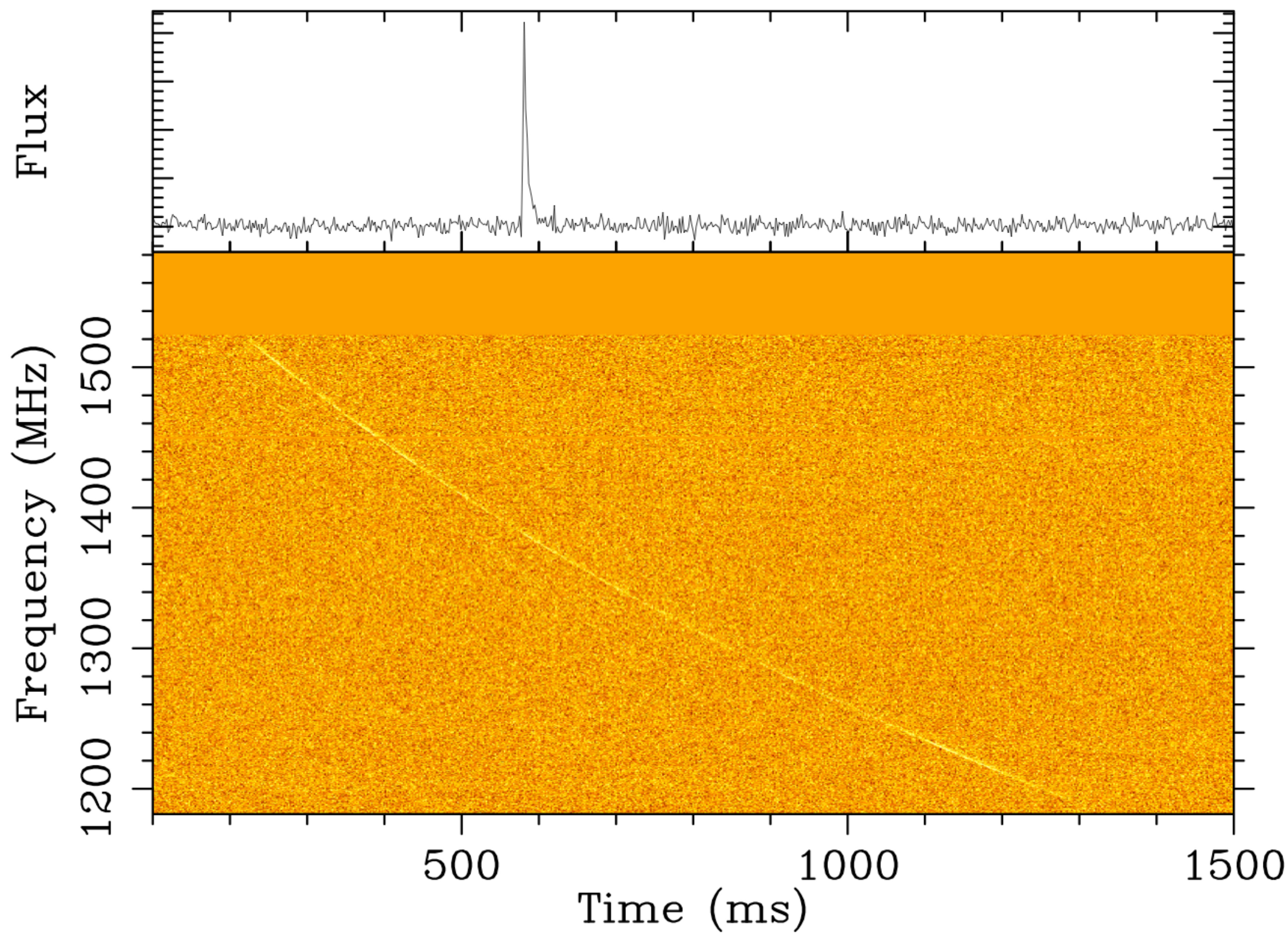


Lensing of Fast Radio Bursts by Compact Objects

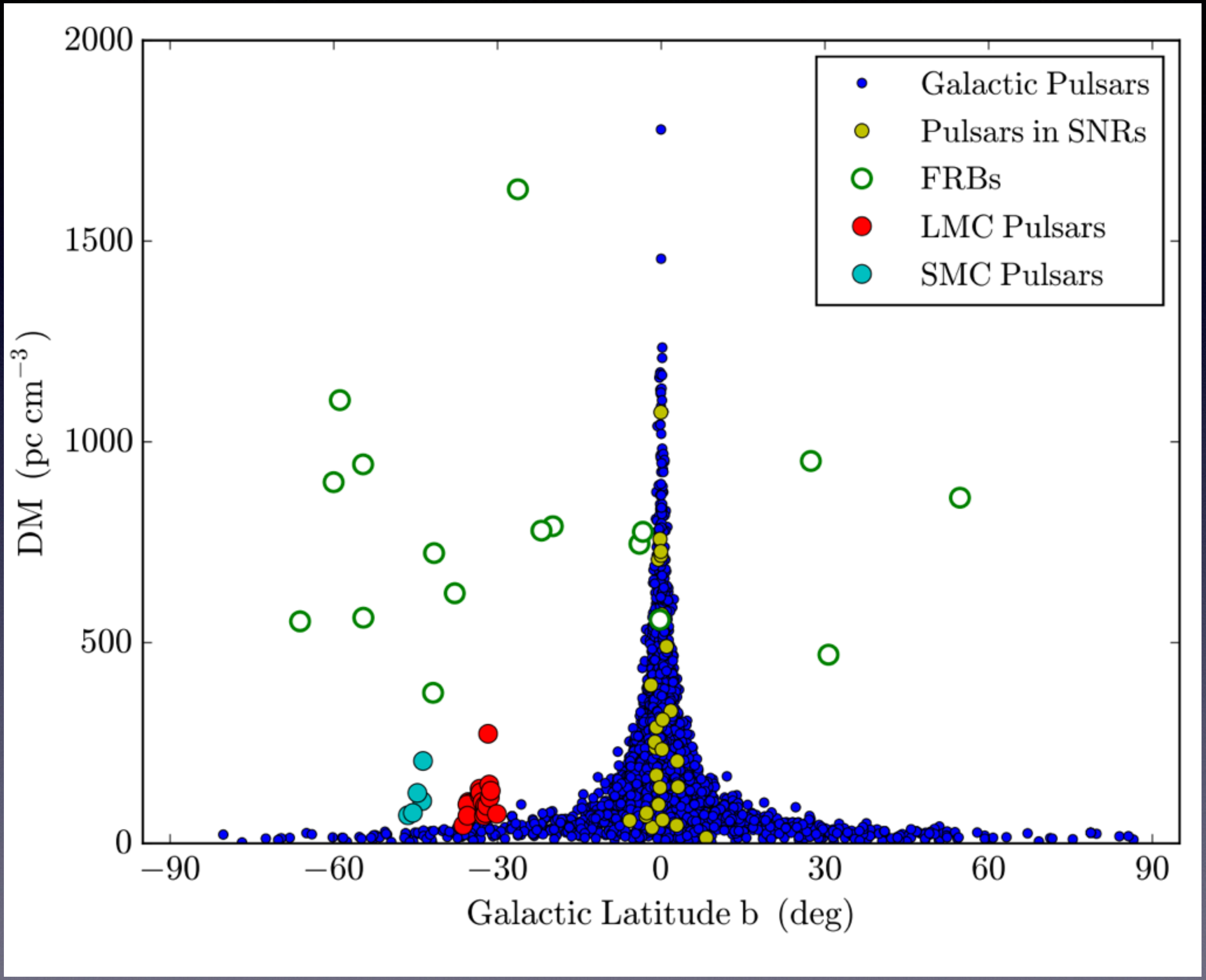
Munoz, Kovetz, Dai, MK, 1605.00008

- FRBs = <millisecond ~GHz radio bursts
- ~10,000 on sky per day
- Large dispersion measures imply cosmological dist
ances
- Forthcoming experiments (e.g., CHIME) should dete
ct thousands


Intensity
500
600
700
800
900
Time (milliseconds)



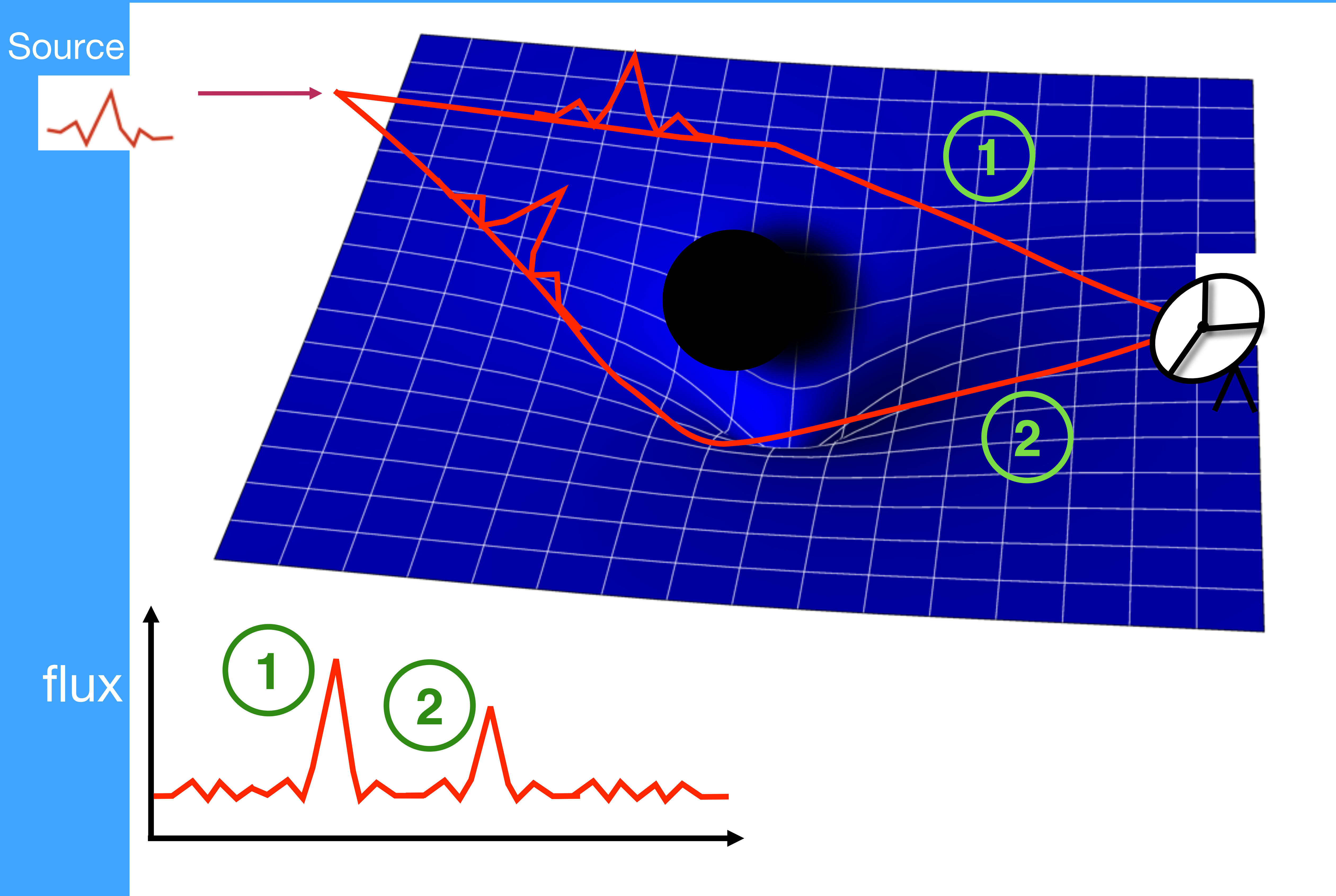
Flux
Frequency (MHz)
1200
1300
1400
1500
500
1000
1500
Time (ms)



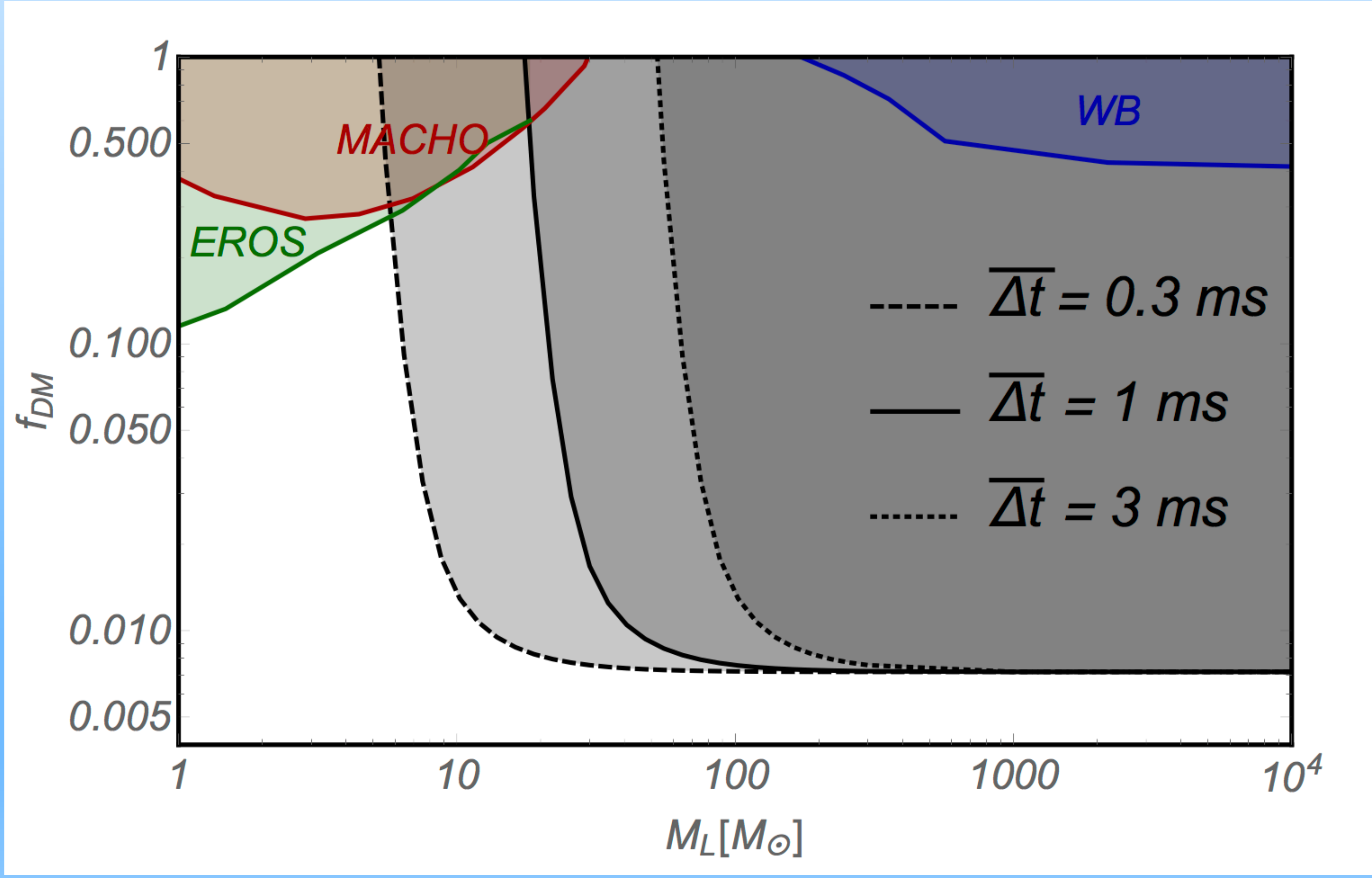
Galactic Pulsars
Pulsars in SNRs
FRBs
LMC Pulsars
SMC Pulsars
DM (pc cm^{-3})
Galactic Latitude b (deg)
2000
1500
1000
500
0
−90
−60
−30
0
30
60
90

FRB Lensing

(Muñoz, Kovetz, Dai, Kamionkowski, PRL 117 (2016))



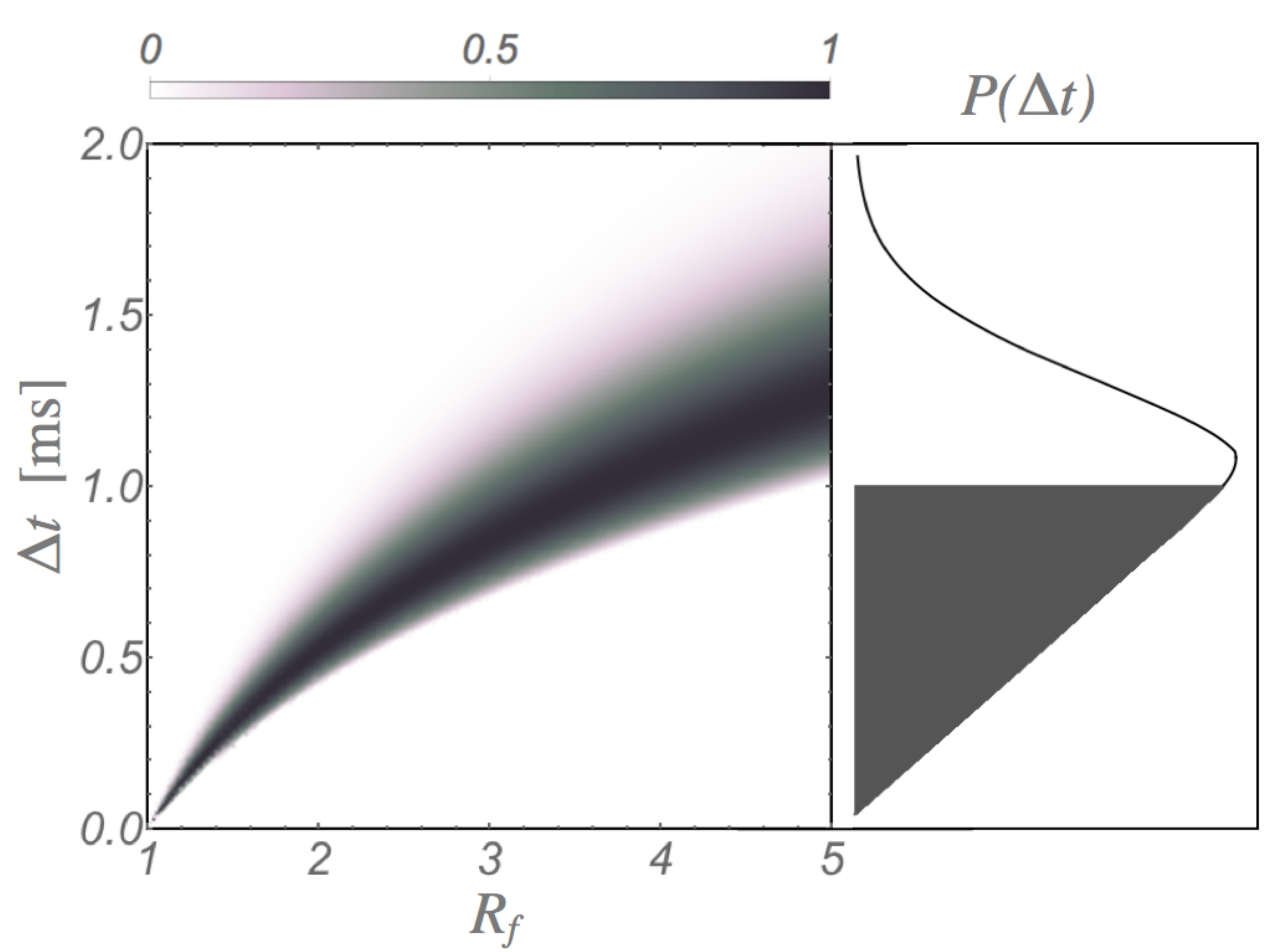
Images separation (~nano-arcsec) too small to be detected, but there can be a >ms time delay



Strong Lensing of FRBs

(Muñoz, Kovetz, Dai, MK, PRL 117 (2016))

Joint PDF of time delay and flux ratio:



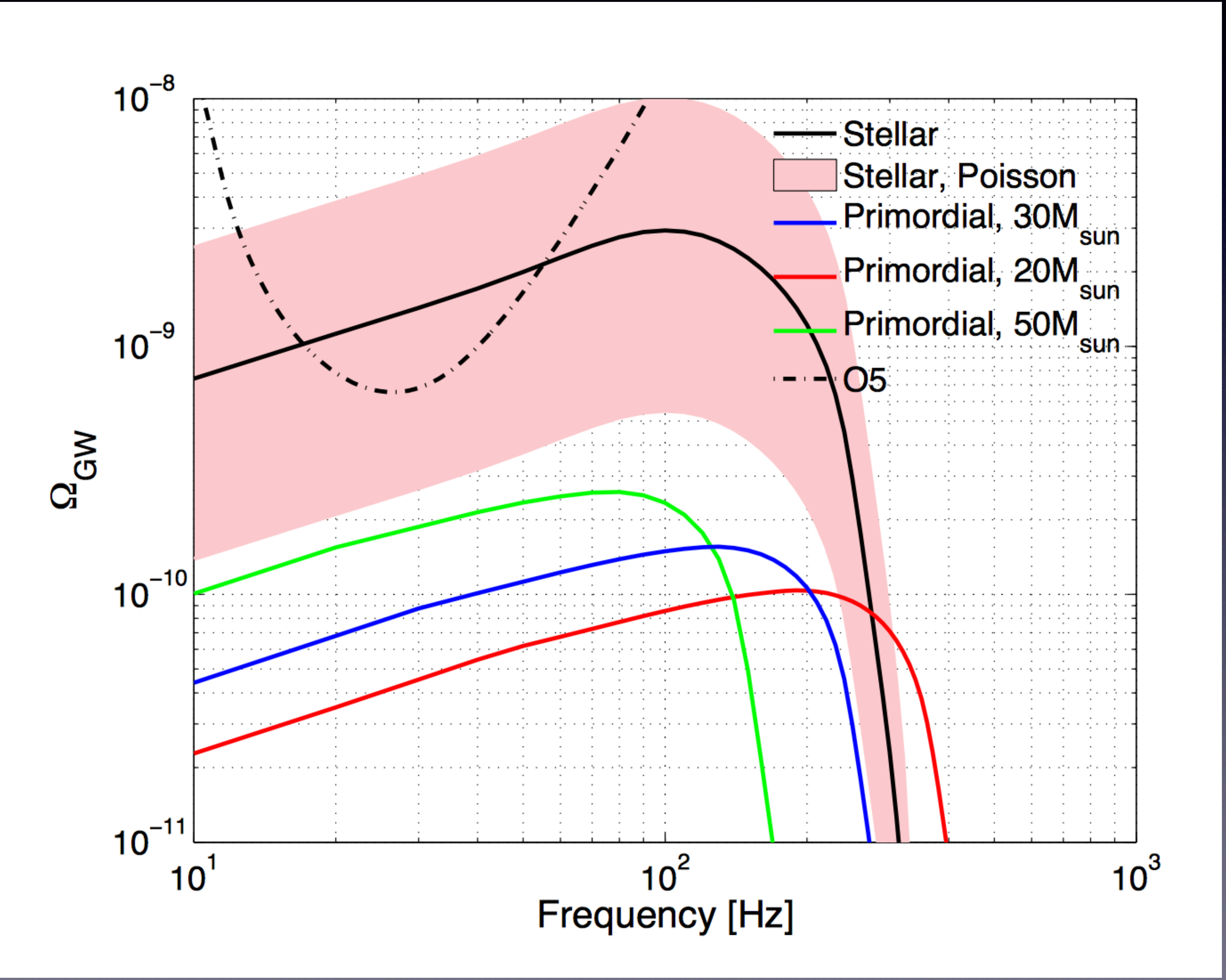
Cross-Correlations with Galaxies

Alvise Raccanelli Yacine Ali-Haimoud Simeon Bird, Ilias Cholis, Julian B Munoz, Ely D. Kovetz, 1605.01405

PBH mergers in lowest-mass halos, GW-galaxy clustering weaker than almost any other GW source

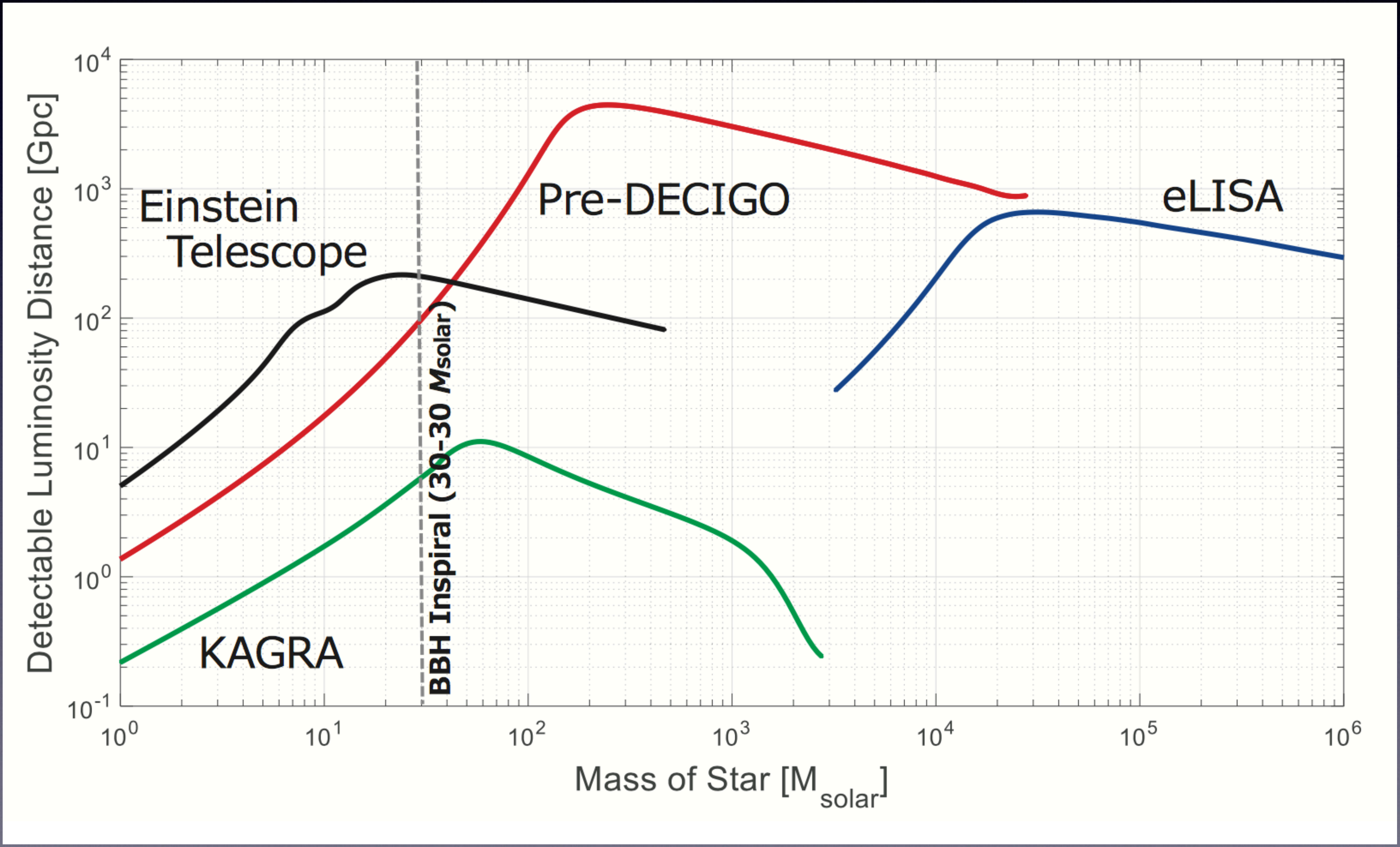
PBH Dark Matter: The Stochastic GW Background

Pen&Turok; **Mandic-Bird-Cholis**; Cholis; Clesse-Garcia-Bellido; Wang et al.

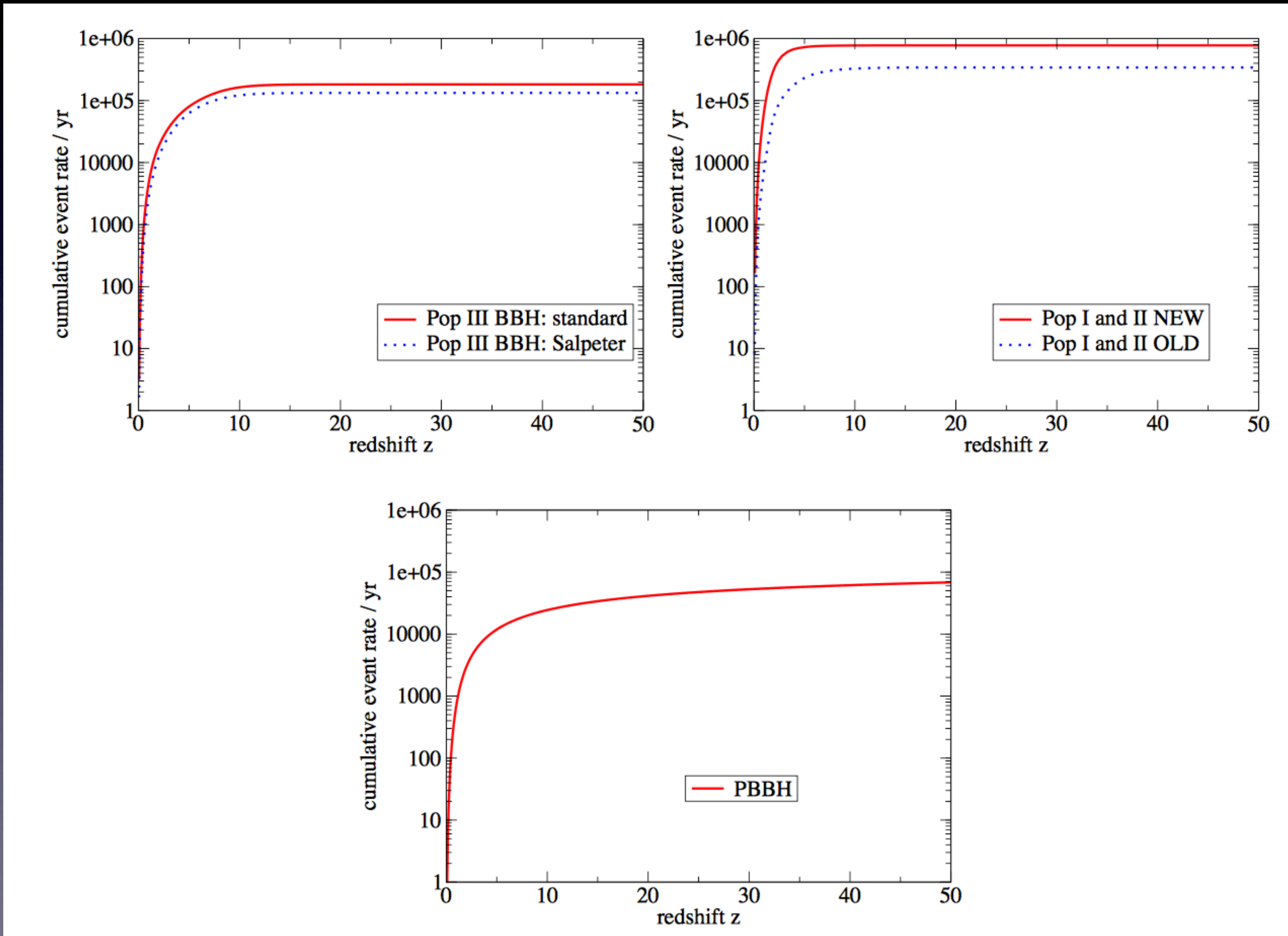


PBH Dark Matter: The Redshift Distribution

Nakamura et al. (with pre-DECIGO)

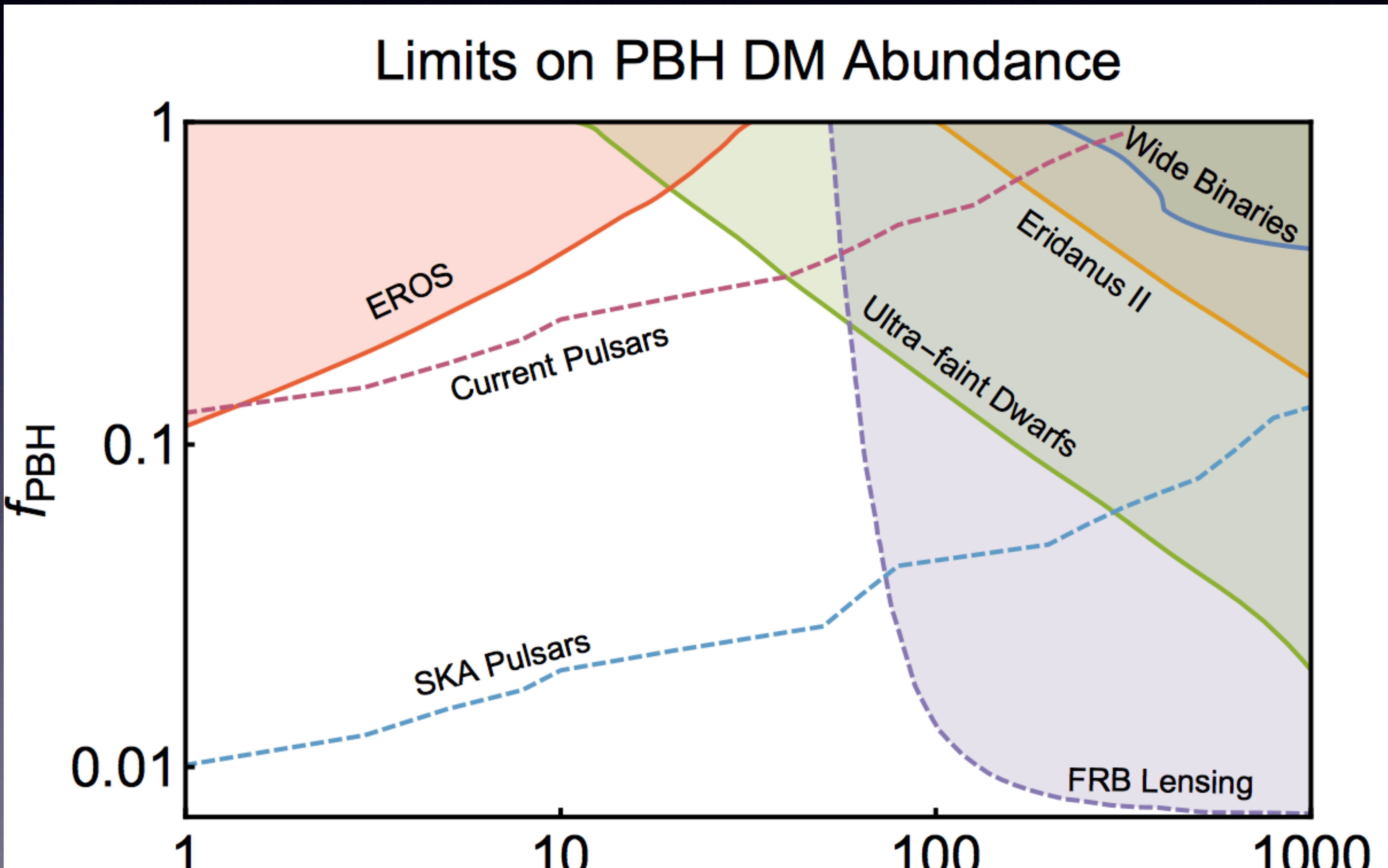


PBH Dark Matter: The Redshift Distribution



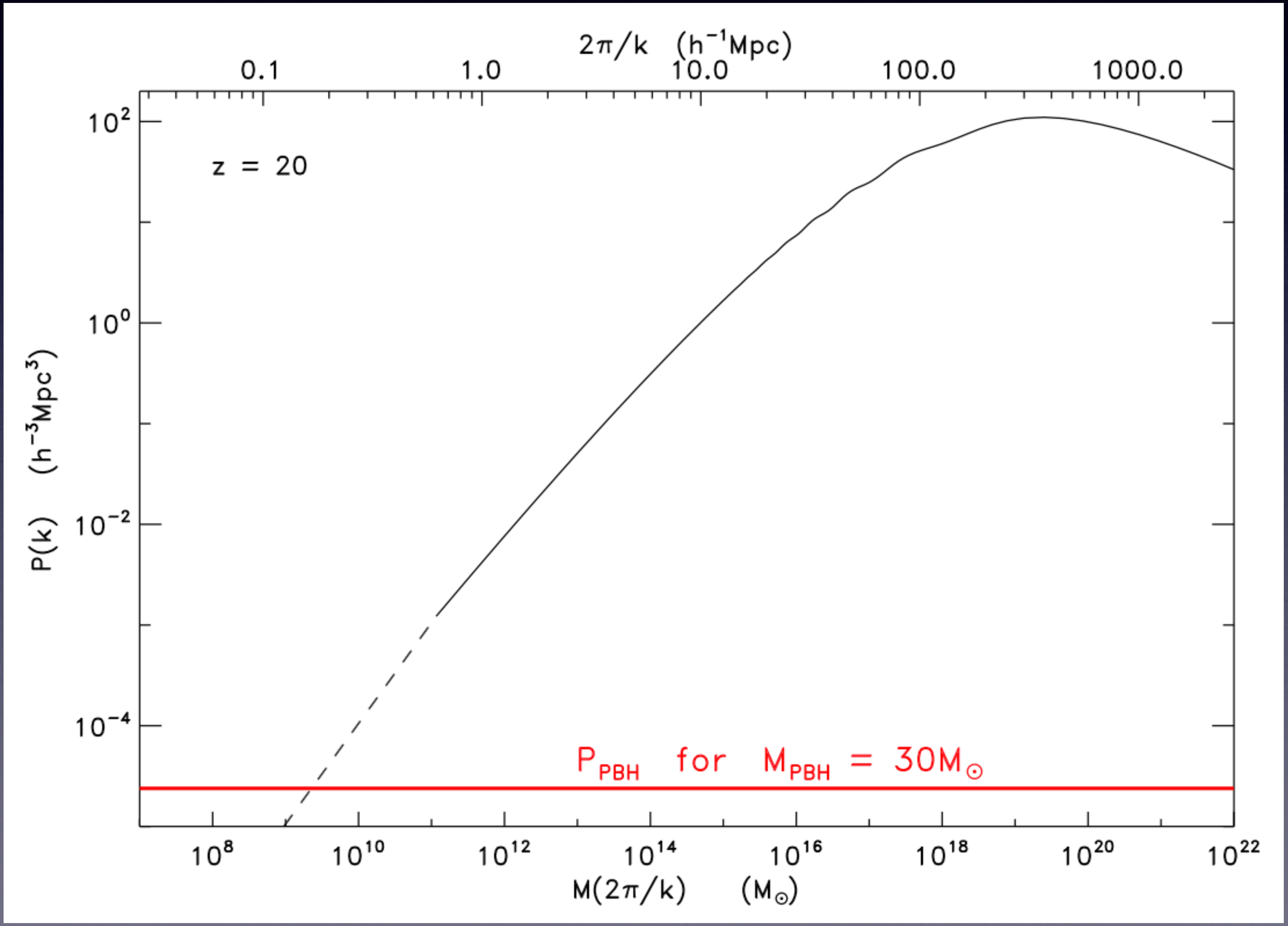
PBH Dark Matter: Pulsar timing

Schutz&Liu; Inomata et al.



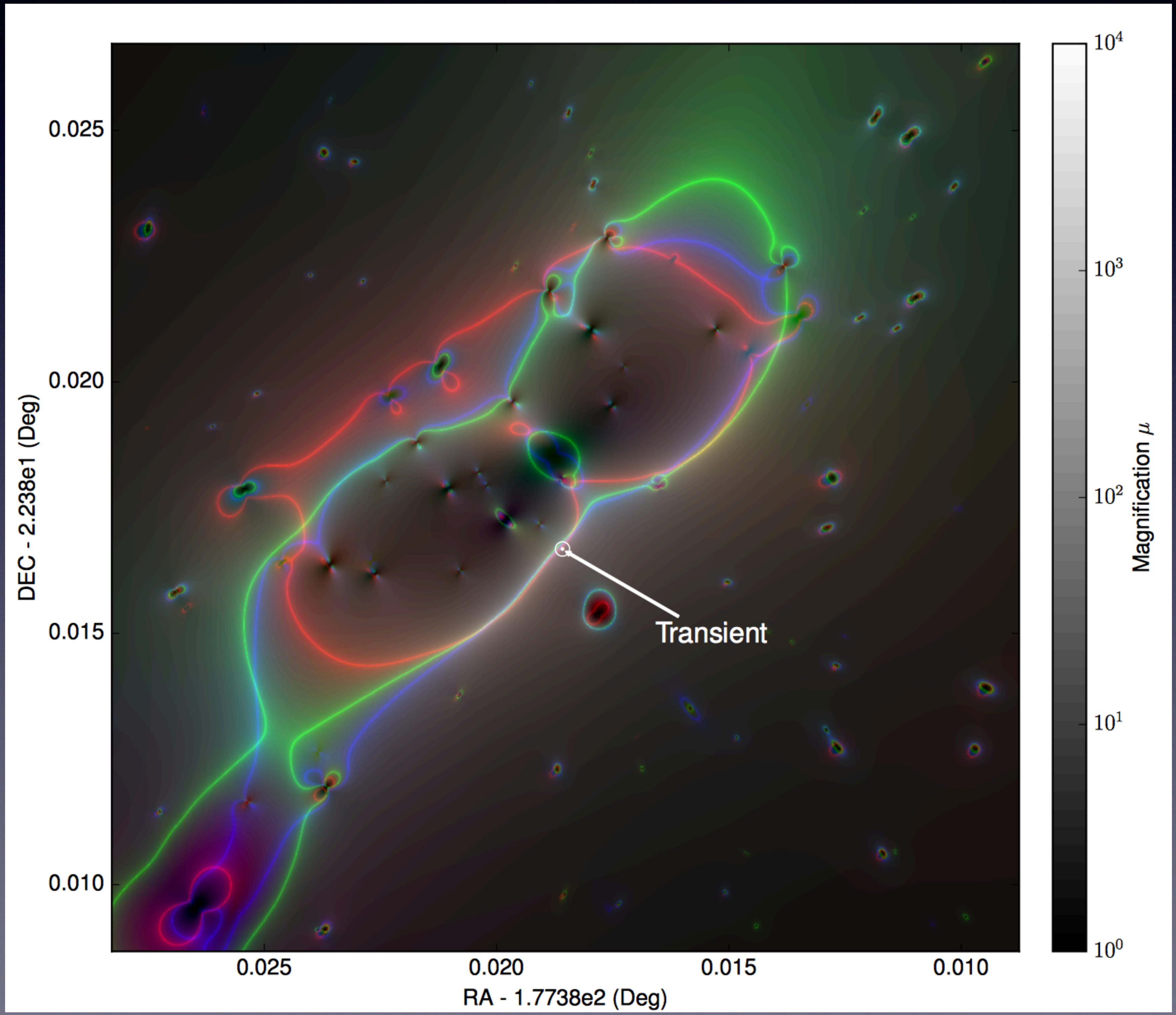
PBH Dark Matter: infrared backgrounds

Kashlinsky



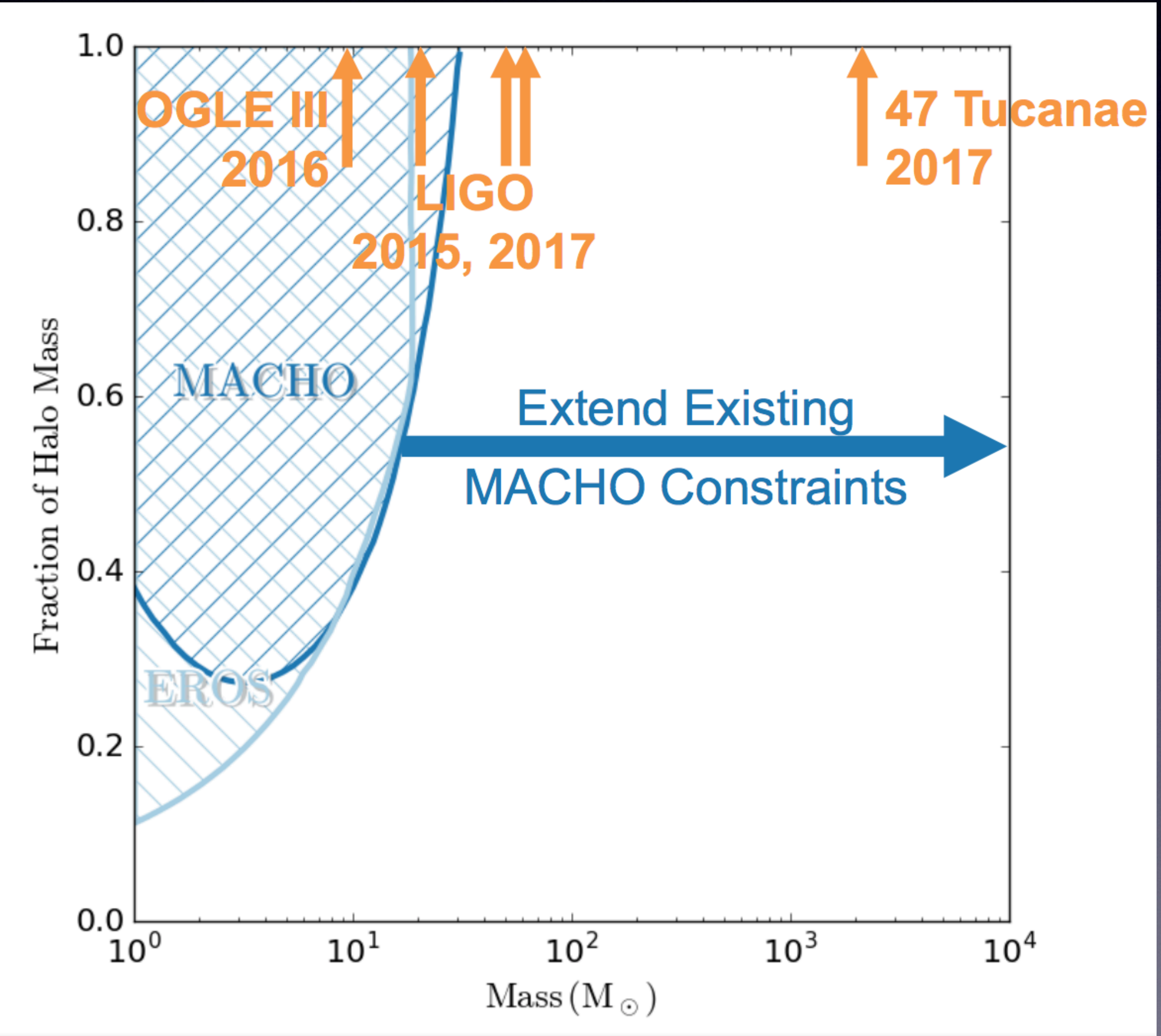
PBH Dark Matter: caustic microlensing

Dai, Venumadhav, Miralda-Escude 2017; Diego et al. 2017



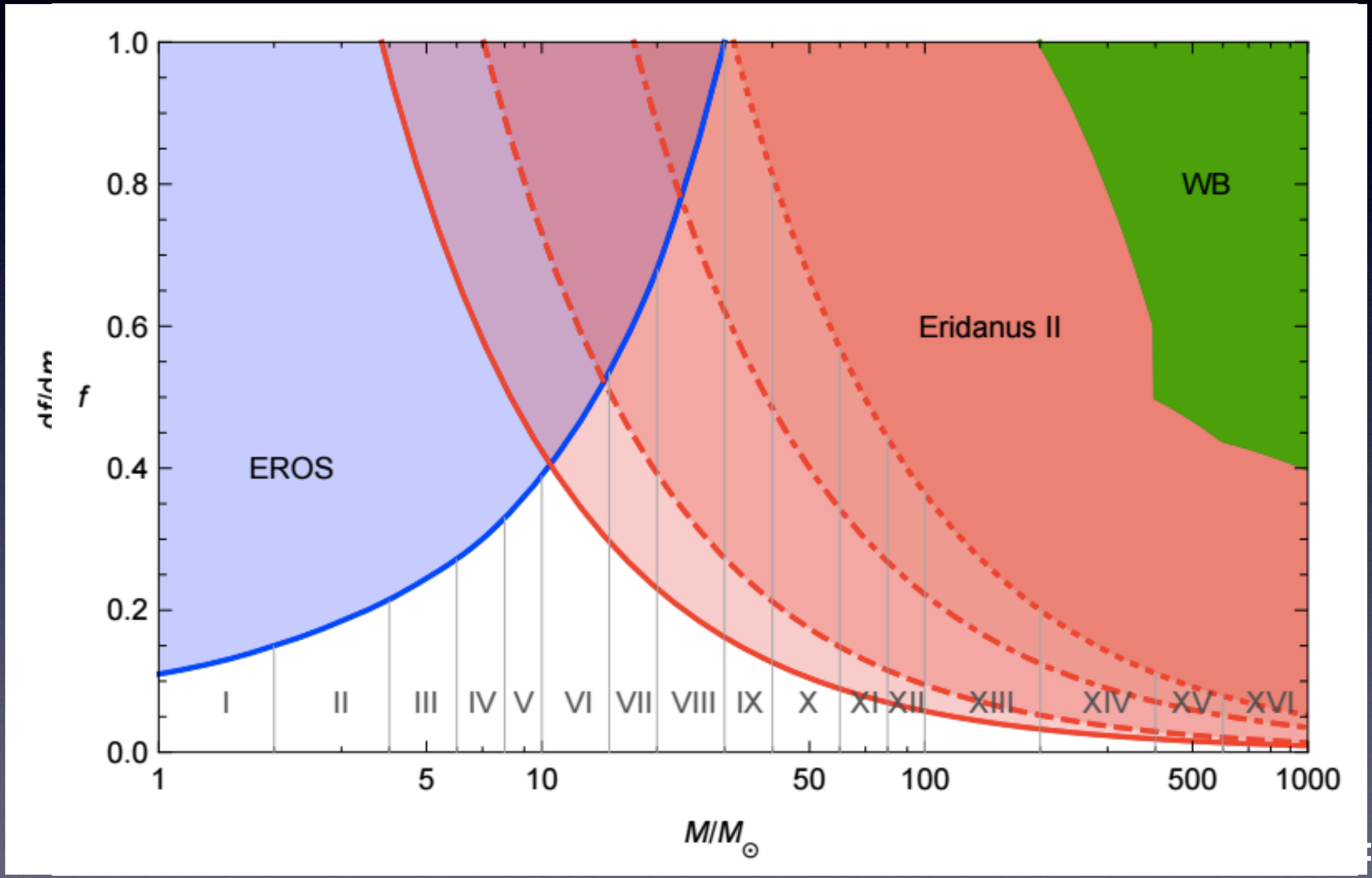
PBH Dark Matter: microlensing with WFIRST

W. Dawson 2017; US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report



PBH DM LIGO Window: Extended Mass Function?

Constraints may be evaded if the PBHs have an extended mass function:



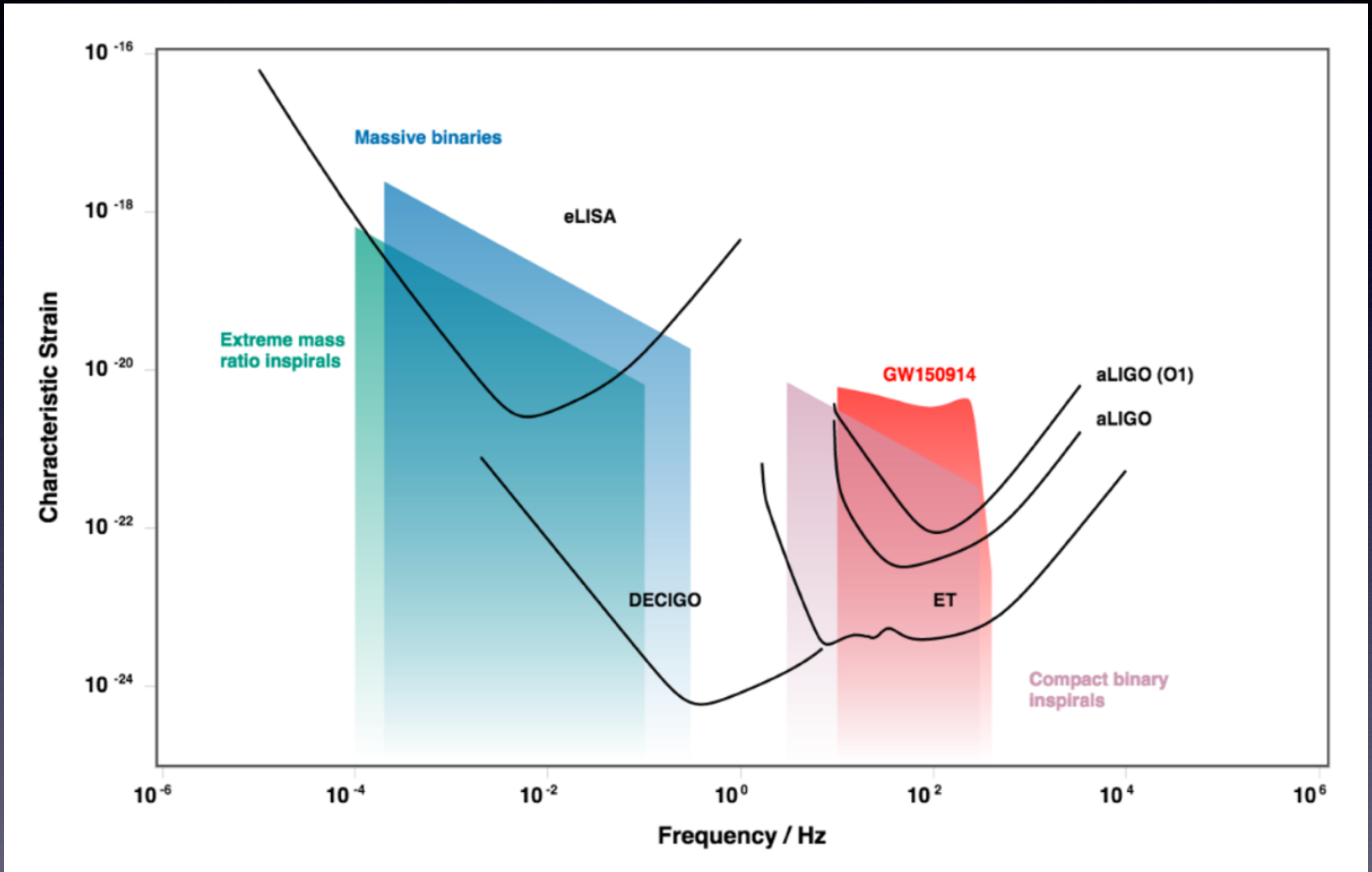
:1607.06077

Needs to be done carefully: constraints assume delta-function mass function.

Green arXiv:1609.01143

Observational Outlook

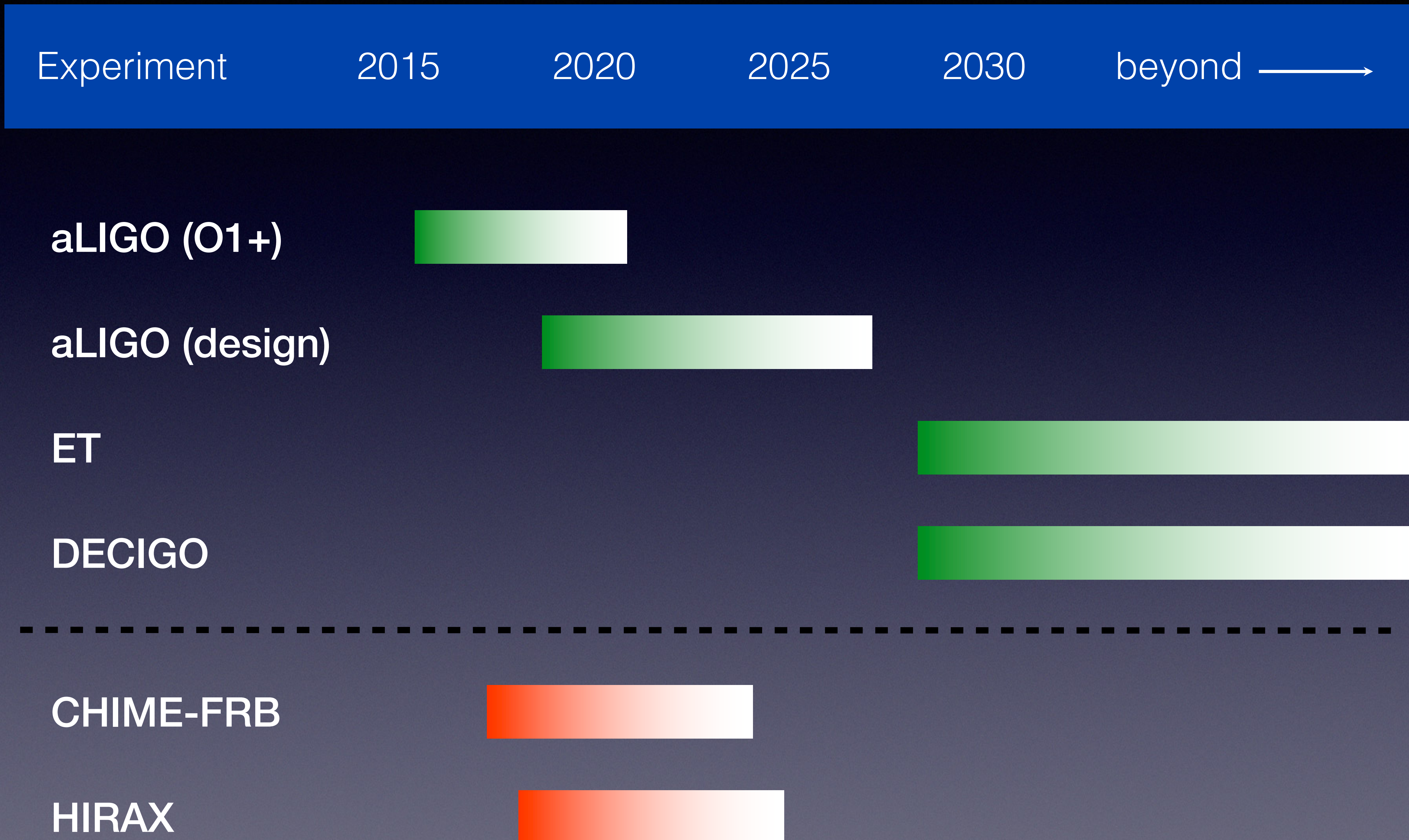
Gravitational waves:



Fast Radio Bursts:

Lots of instruments, including CHIME, HIRAX...

Observational Outlook: Experiment Timeline



Conclusion:

- Dark matter = one of science's biggest que stions but no simple/obvious solutions
- 30-Msun PBHs are nutty but not crazy
- Several tensions with astrophysical observ ations reported, but no silver bullets
- Great synergies with GWs, early Universe, l ensing/microlensing, high-energy astrophy sics, galactic dynamics…..