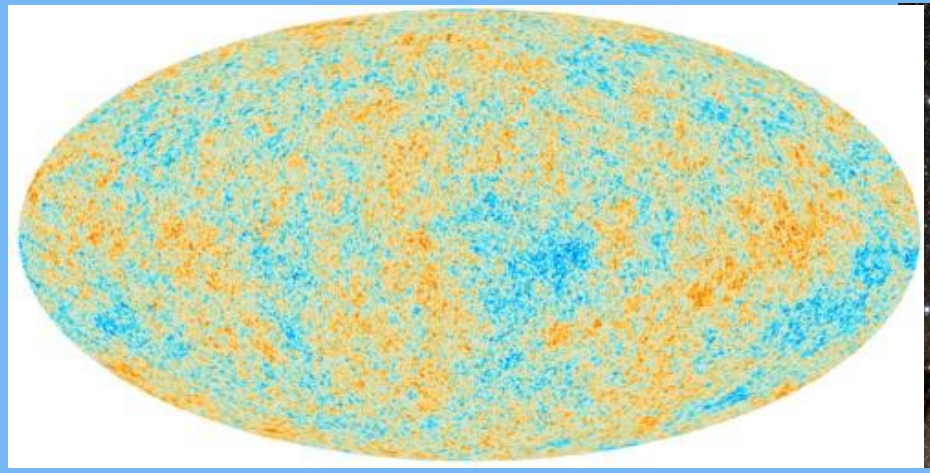
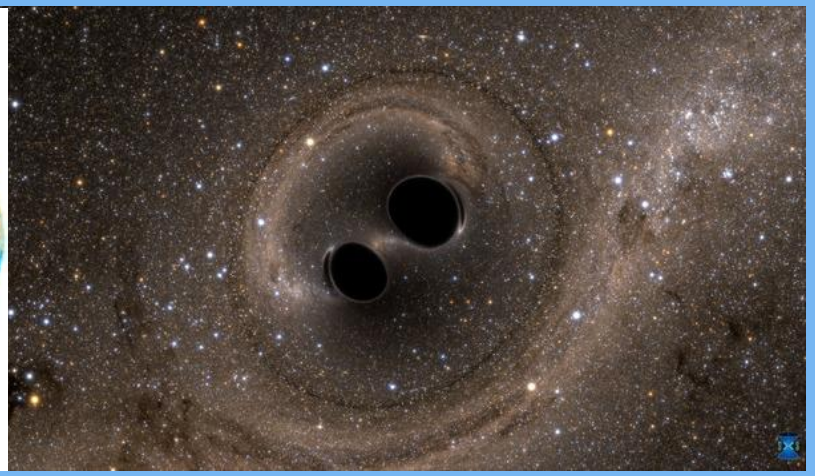
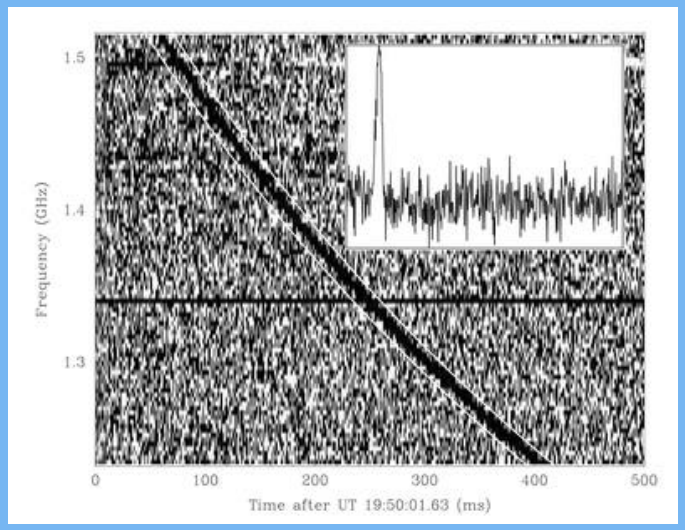






Black hole (and other) dark matter

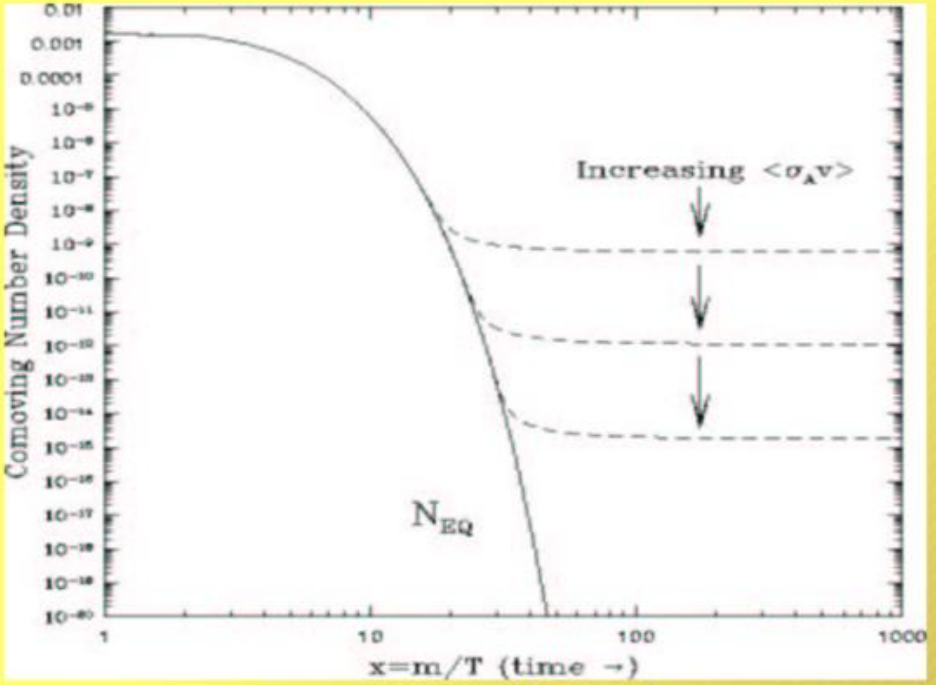
IDM 2018

Dark matter!!

What is it?

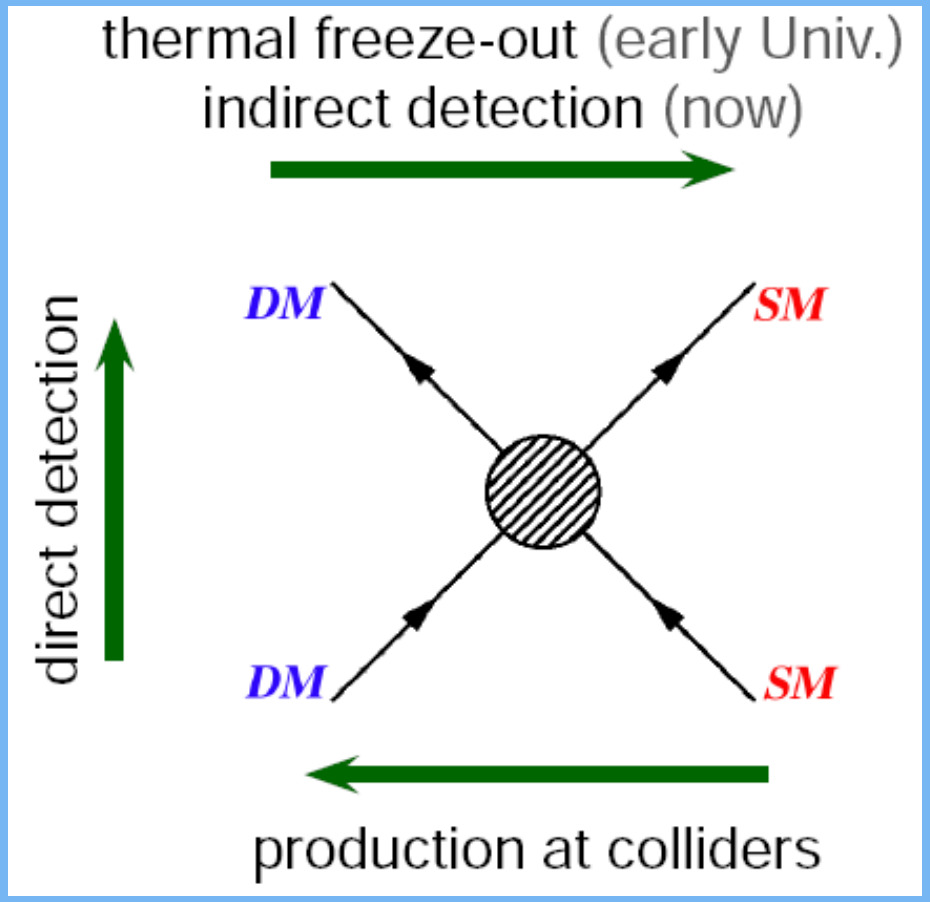
The Party line (~1985—2015)

- Weakly Interacting Massiv Particles (WIMPS). e.g.,neutralinos



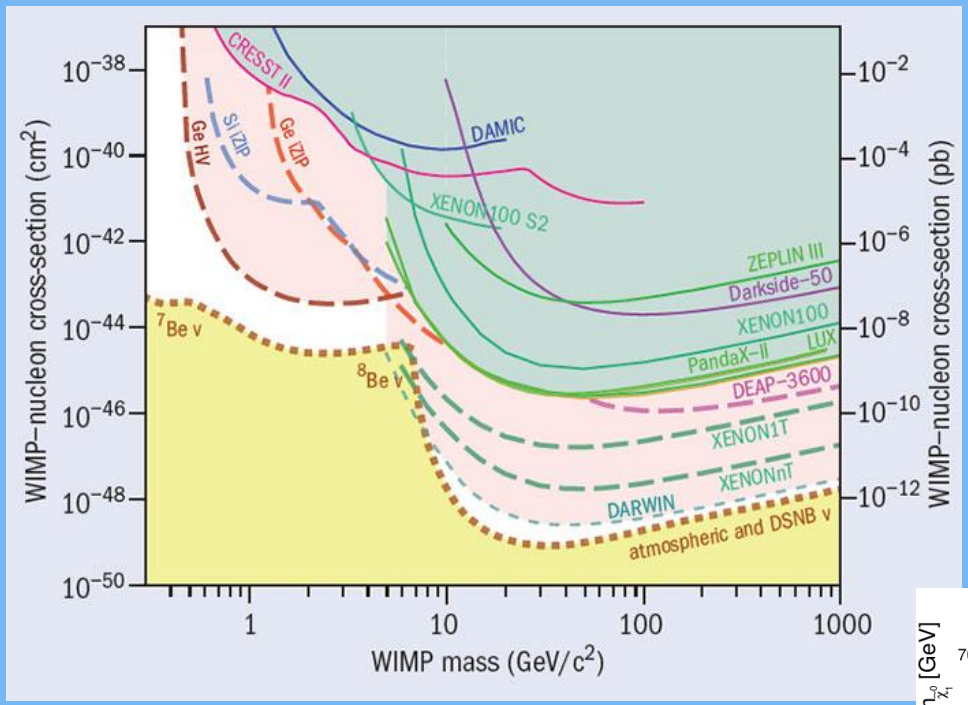
$$\Omega_\chi h^2 \approx \frac{3\times10^{-27} cm^3/\sec}{\langle \sigma v \rangle}$$

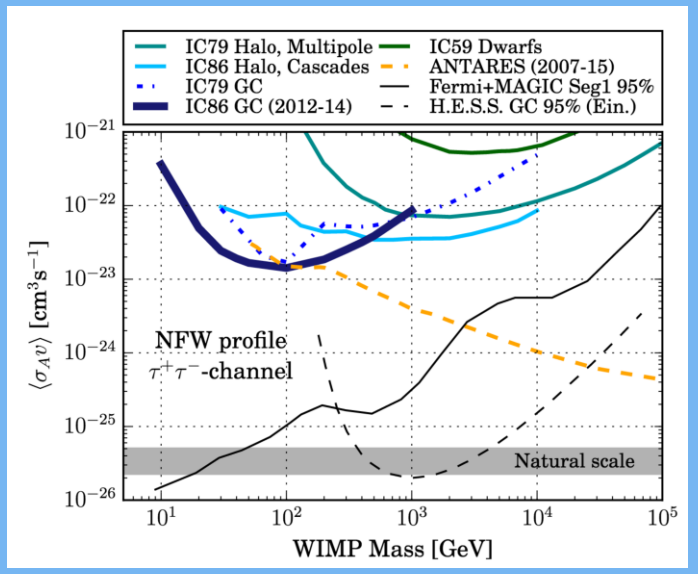
(e

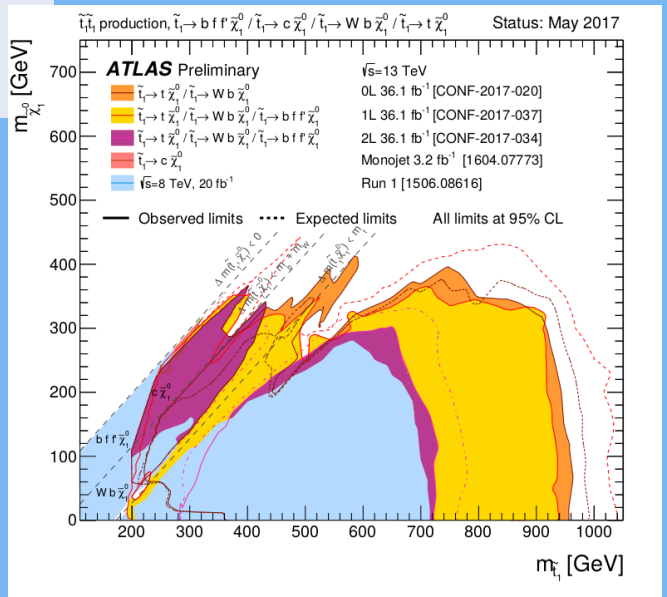


Simplicity/Elegance

Direct/indirect searches





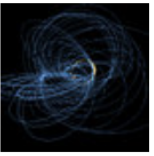


Inelastic, Sommerfeld-enhanced, momentum-dependent, leptophilic,co-annihilating, dipolar, millicharged, resonant, superheavy, sub-GeV, self-interacting, atomic, dark-sector, Higgs portal,…….

Inelastic, Sommerfeld-enhanced, momentum-dependent, leptophilic,co-annihilating, dipolar, millicharged, resonant, superheavy, sub-GeV, self-interacting, atomic, dark-sector…….

~~Simplicity/Elegance~~

Time to look elsewhere?



TRILOBITES
How Cassini Will Begin Its Date With Death on Saturn

TRILOBITES
Study Suggests 3.2 Million-Year-Old Lucy Spent a Lot of Time in Trees

A CONVERSATION WITH
C. Megan Urry, Peering Into Universe, Spots Bias on the Ground

SCIENCE

Gravitational Waves Detected, Confirming Einstein's Theory

Dennis Overbye
OUT THERE FEB. 11, 2016

986

Binary black hole

.

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

Where do these black holes come from?

Probably stellar remnants (binaries? globular clusters?)

Still….

- The two black holes in first system each had masses roughly 30 times that of the Sun!!

Did LIGO detect dark matter?

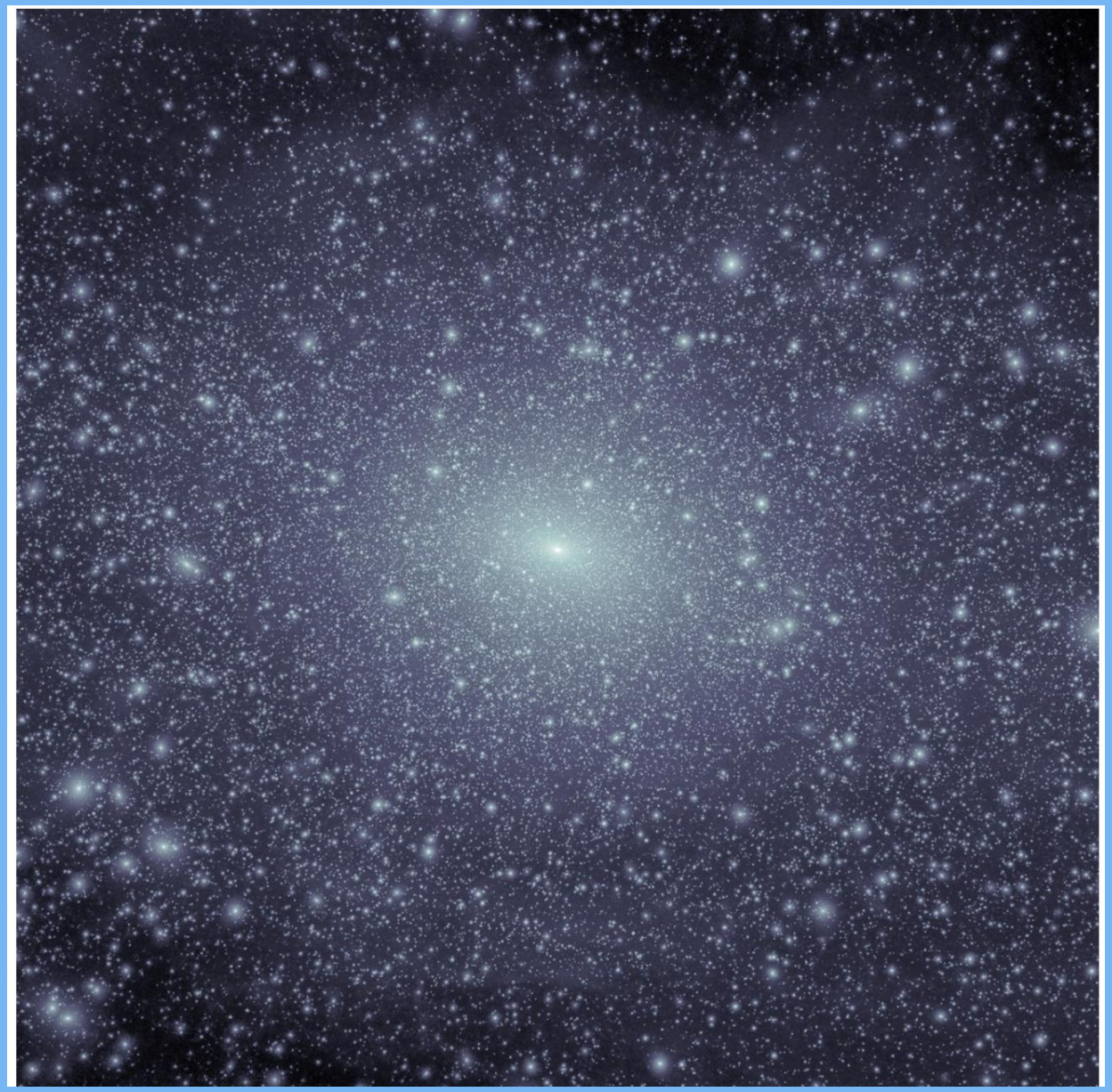
(Bird, Cholis, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli, Riess, 2016)

- highly speculative; not crazy
- Surprising coincidence: If black holes of 30 solar masses make up the dark matter, they merge with rate comparable to that inferred from the initial LIGO event! (Bird et al. 2016)

Suppose DM = 30-Msun BHs

Gravitational radiative recombination

$$\sigma = 2^{3/7}\,\pi \left(\frac{85\,\pi}{6\sqrt{2}}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$$
$$= 1.37 \times 10^{-14}\, M_{30}^2\, v_{\rm pbh-200}^{-18/7}\, {\rm pc}^2,$$



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

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

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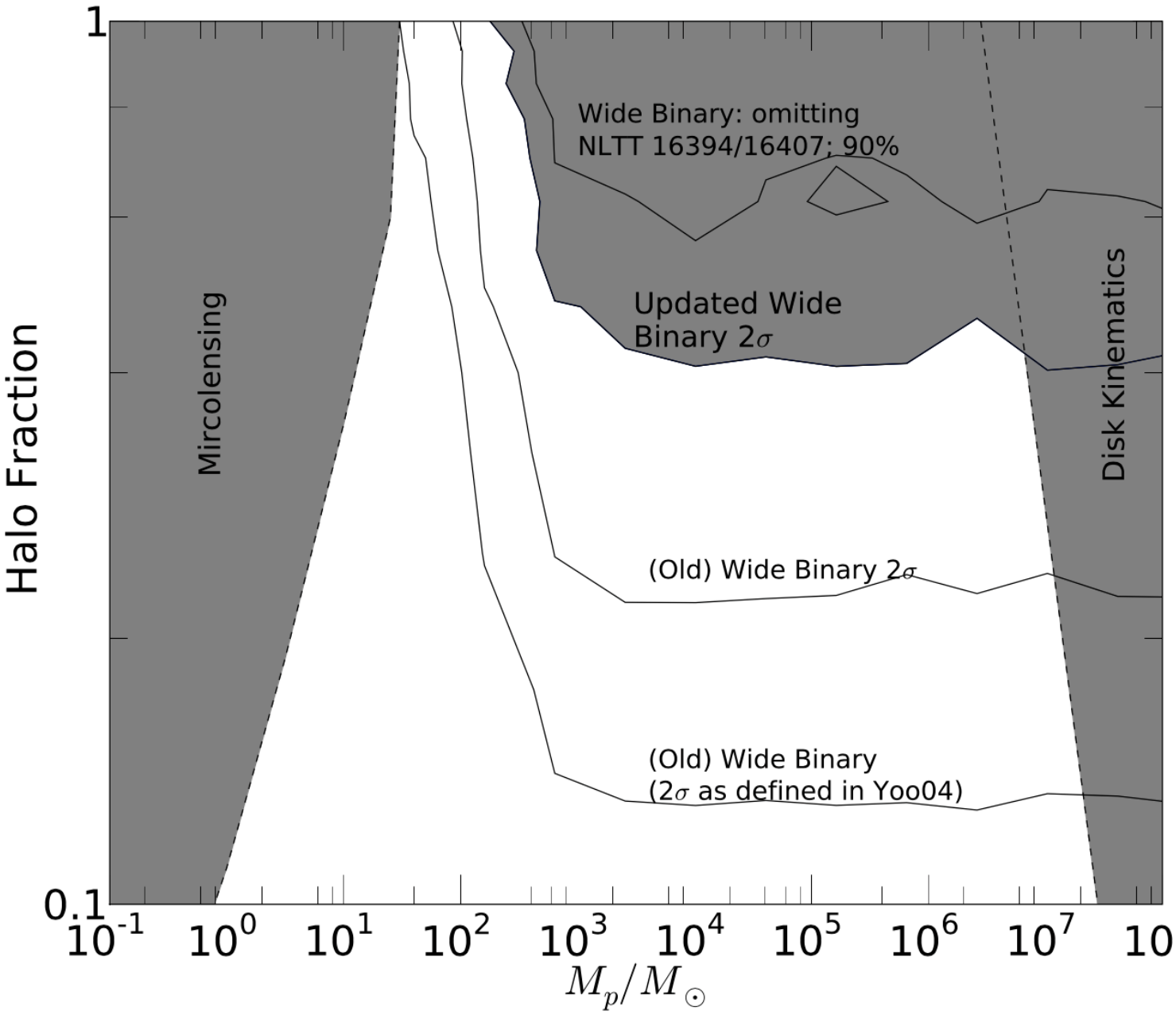
!!!!!!!



Quinn et al. 0903.1644

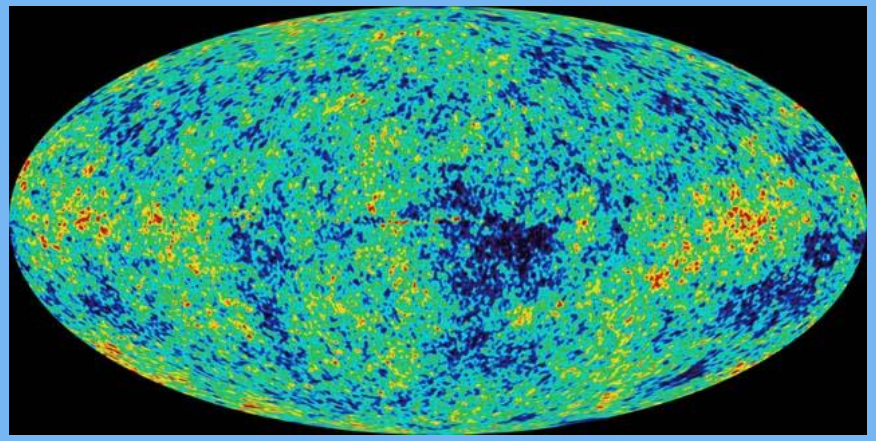
Since then….

Scenario ruled out (??) by:

- CMB (Ricotti, Ostriker, Mack 2007)
- Dwarf-galaxy dynamics (Brandt, 2016; Koushiappas et al. 2016)
- Quasar lensing (Mediavilla 2017)
- X rays from accretion of ISM (Gaggero et al. 2017; Inoue & Kusenko 2017)
- SN dispersions (Zumalcarregui & Seljak 2017)
- Pulsar timing (Schutz & Liu 2017)
- Good taste [[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)....]]

CMB fluctuations

Ricotti, Ostriker, and Mack (2008): heating of primordial plasma due to accretion onto PBHs leads to unacceptable fluctuations in CMB (by ~3-4 OoMs!!)



How does the CMB probe PBHs?

- PBHs accrete primordial plasma
- Accreted gas gets heated
- Heated gas radiates
- Radiation heats plasma → spectral distortions
- Radiation also affects ionization balance
  → changes recombination history
  → affects CMB power spectra

Our work

(Ali-Haimoud&MK 2017)

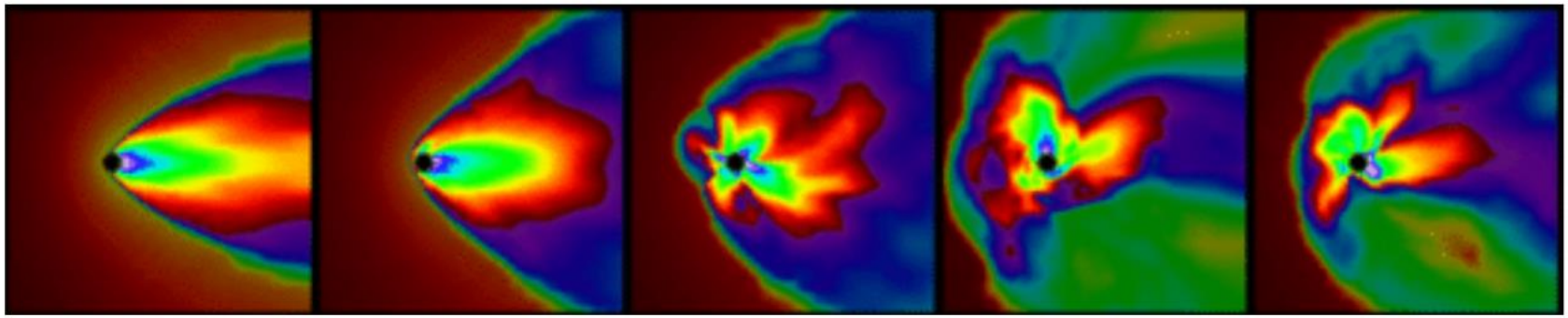
- first-principles calculation
- Given many uncertainties/complications, make simplest but most robust assumptions
- seek *bound*, not best estimate
- Self-consistently include DM-baryon relative velocities

Baryon-dark matter relative velocity

Baryons and dark matter have large-scale relative motions
(see e.g. Tseliakhovich & Hirata 2010 for effect on small-scale structure)

- before recombination $v_{\rm rel} \approx 30\ {\rm km/s} \approx 5\ c_s$
- after recombination: baryons become cold like DM. $v_{\rm rel} \propto 1/a$

Ricotti et al. 2008 assumed $v_{\rm rel} \approx 4\ {\rm km/s} \lesssim c_s$



Ruffert's website

Baryon-dark matter relative velocity

Simple fudge (à la Bondi-Hoyle): $c_s \rightarrow (c_s^2 + v_{rel}^2)^{1/2}$

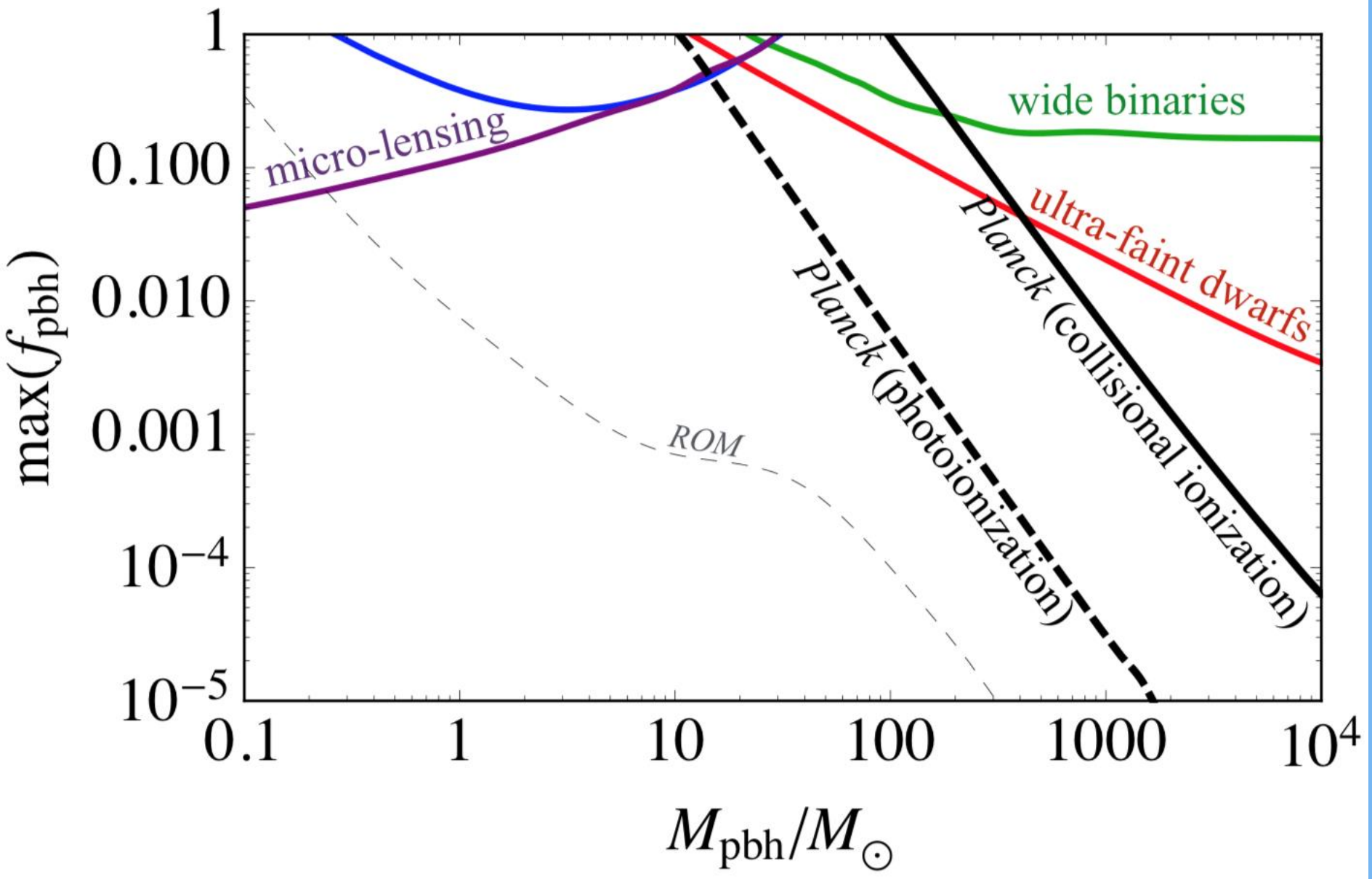
in the simple Bondi case: $$L \propto \dot{M}^2 \propto \frac{1}{(c_s^2 + v_{\rm rel}^2)^3}$$

$$\langle L \rangle \propto \left\langle \frac{1}{(c_s^2 + v_{\rm rel}^2)^3} \right\rangle \approx \frac{1}{c_s^3 \langle v_{\rm rel}^2 \rangle^{3/2}}, \quad \langle v_{\rm rel}^2 \rangle \gg c_s^2$$

$$\frac{\langle L \rangle}{L(v_{\rm rel} = 0)} \sim 10^{-2}$$

See also Horowitz 2016, Aloni, Blum & Flauger 2017

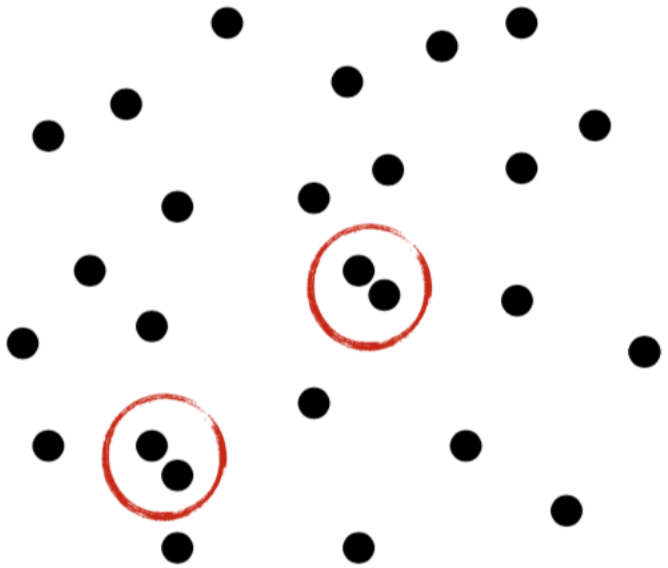
Notes: (1) detailed suppression is not highly relevant: average luminosity is dominated by subsonically accreting BHs.
(2) there are small-scale motions due to non-linear clustering.
We do not account for those.


1
0.100
0.010
0.001
10^{-4}
10^{-5}
$\max(f_{\rm pbh})$
micro-lensing
wide binaries
ultra-faint dwarfs
Planck (collisional ionization)
Planck (photoionization)
ROM
0.1
1
10
100
1000
10^4
$M_{\rm pbh}/M_\odot$

Does LIGO rule out PBH dark matter?

(Ali-Haimoud, Kovetz, MK 2017)

Basic idea: Nakamura, Sasaki, Tanaka & Thorne 1997



On small enough scales, PBHs are randomly distributed (or maybe not quite!)

Some PBH pairs happen to be close enough that they decouple from the Hubble flow deep in the radiation era.

As they fall towards one another, torqued by other PBHs result in a non-zero (but small) angular momentum

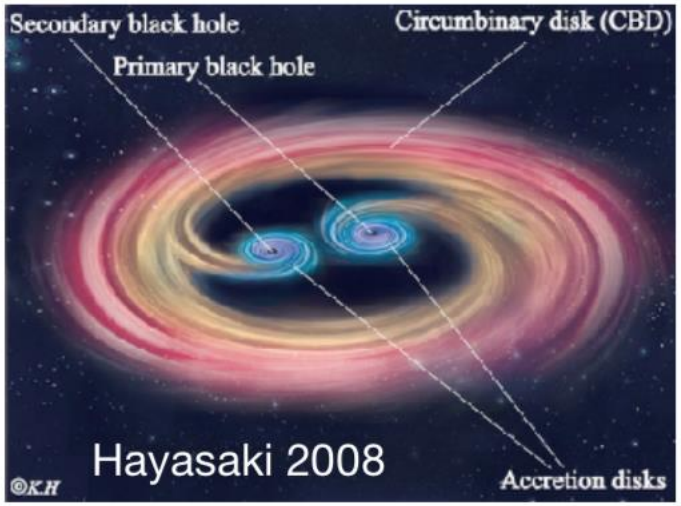
Inspiral through GW radiation, some merge at the present time.

Do binaries that form at $z \sim 10^4$ - 10^5 evolve only through GW radiation until the present time?

- Gravitational interactions with other PBHs and rest of dark matter

Using simple analytic estimates of the properties of the first structures, we found that torques due dark matter (PBHs or WIMPs) do not significantly affect PBH binaries.

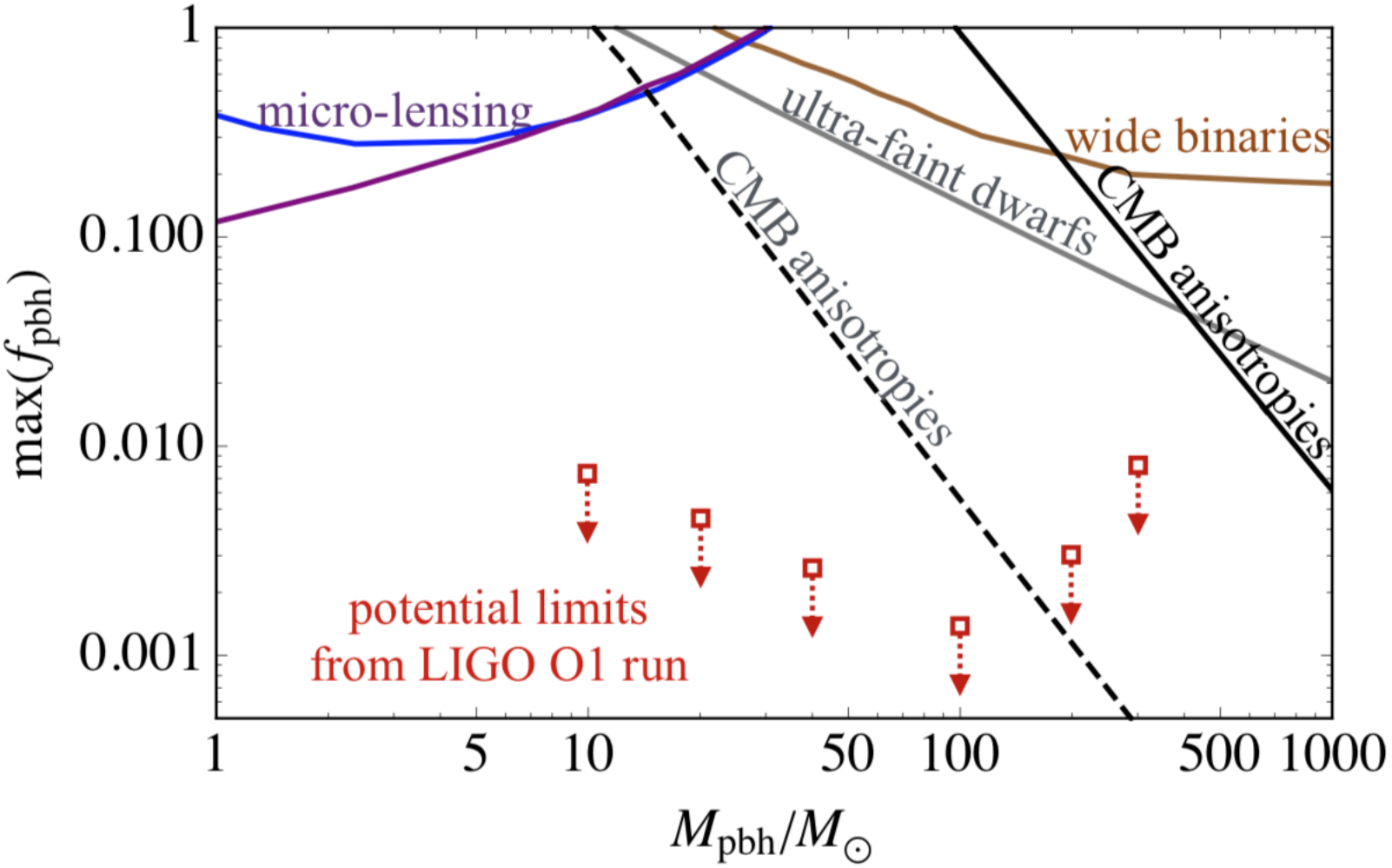
- Exchange of energy and angular momentum with accreting baryons



Most uncertain piece. Estimated that torques could be marginally relevant. Subject of active research (e.g. Tang, Haiman & MacFadyen 2018).

Does LIGO rule out PBH-dark matter?

Probably but more checks are needed

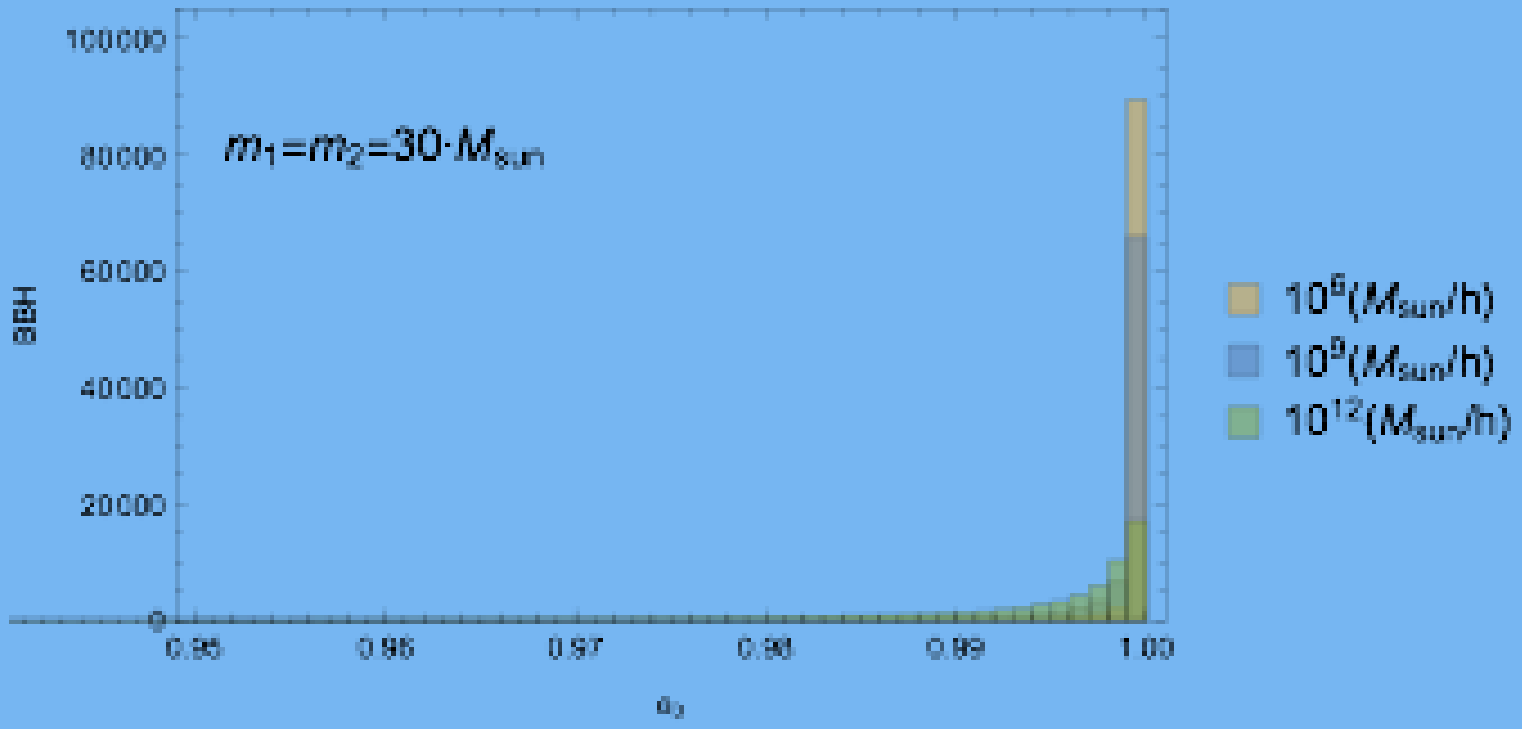


How to test PBH DM hypothesis?

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

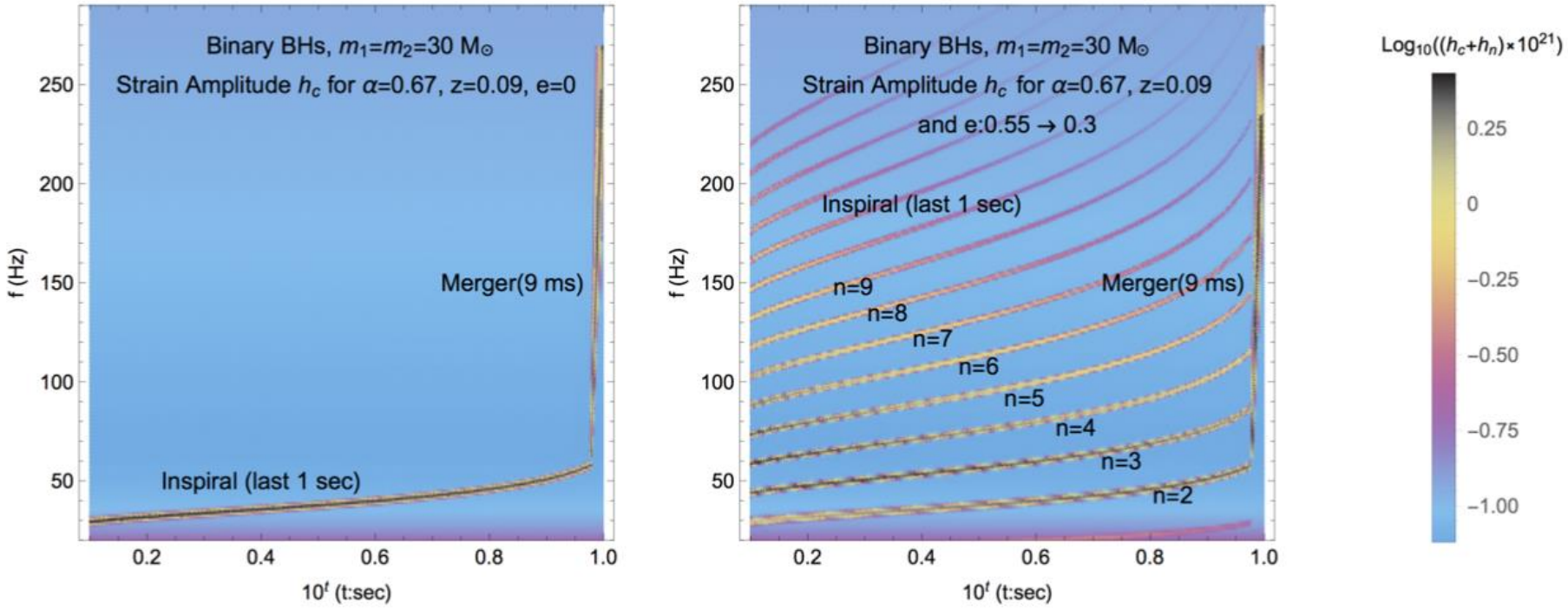
Given current LIGO rate, expect perhaps ~20,000 more BBH mergers in next decade!!

PBH binaries have high initial eccentricities:



see many more modes of grav. waves

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

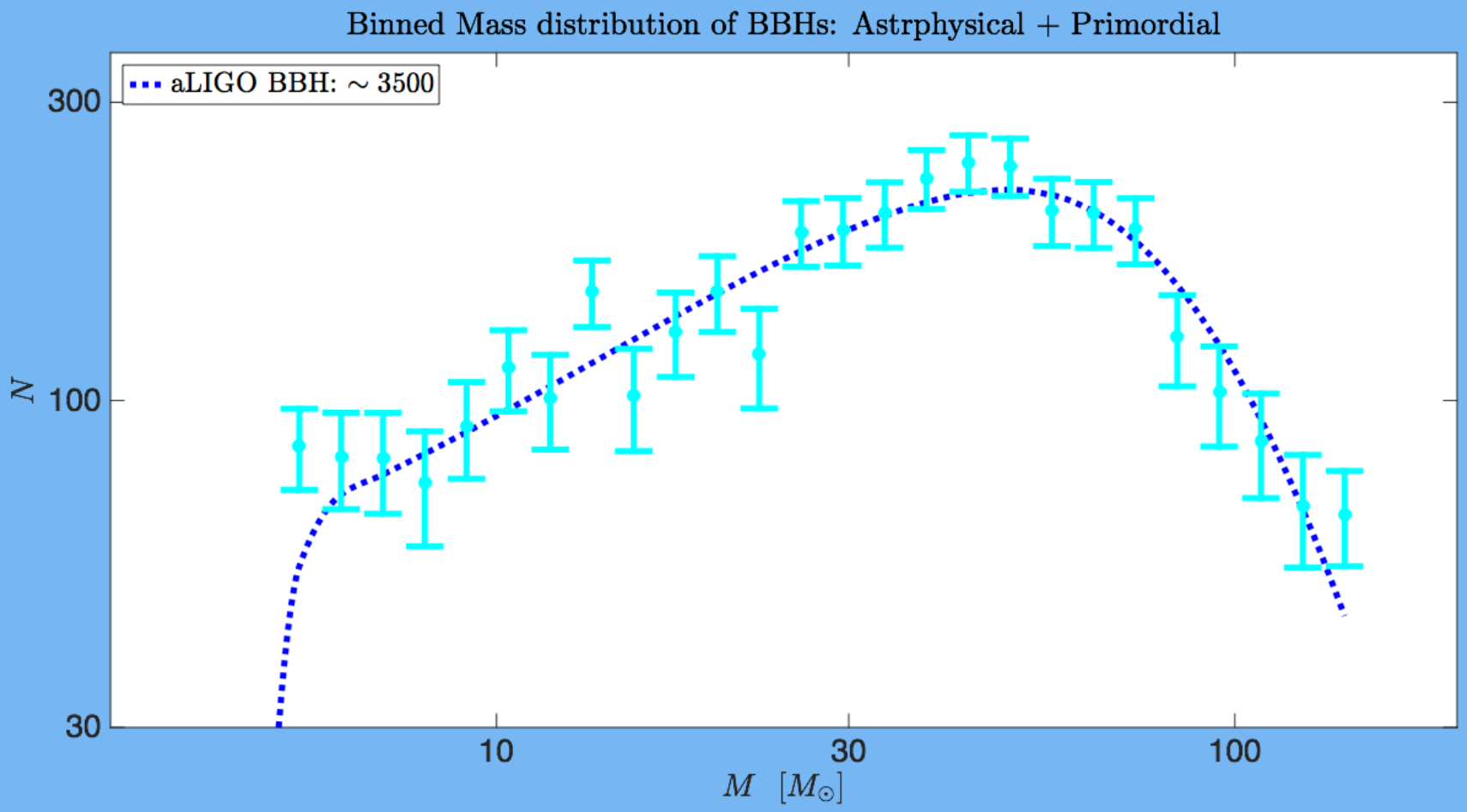


Cholis, Ali-Haimoud, Bird, Munoz,MK, Kovetz, and Raccanelli (2016)

The BH binary mass distribution

The Black-Hole Mass Function from GWs

with 5 years of aLIGO:

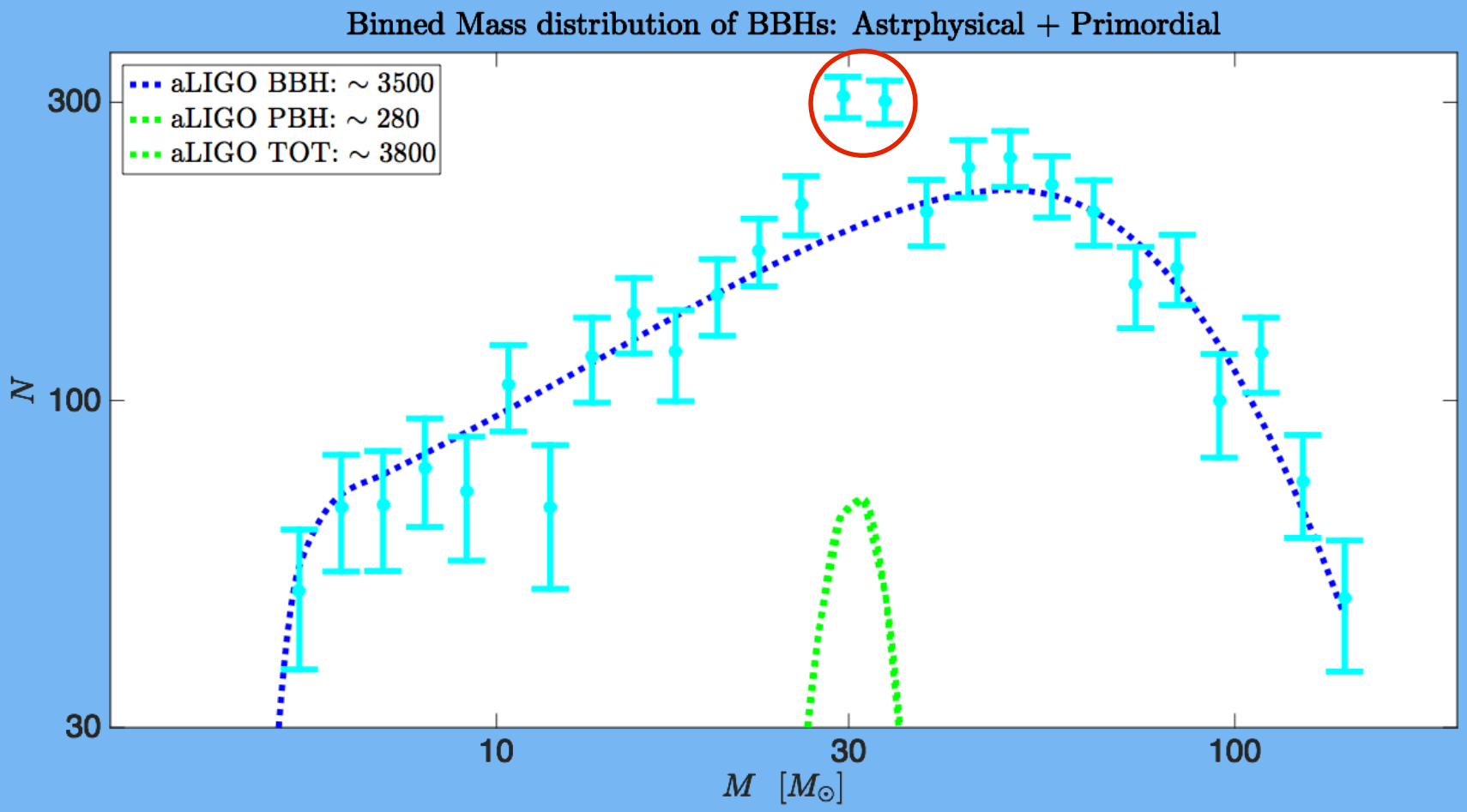


The Black-Hole Mass Function from GWs

with 5 years of aLIGO data:

Kovetz, Cholis, Breysse, MK 2017;
Kovetz, 2017

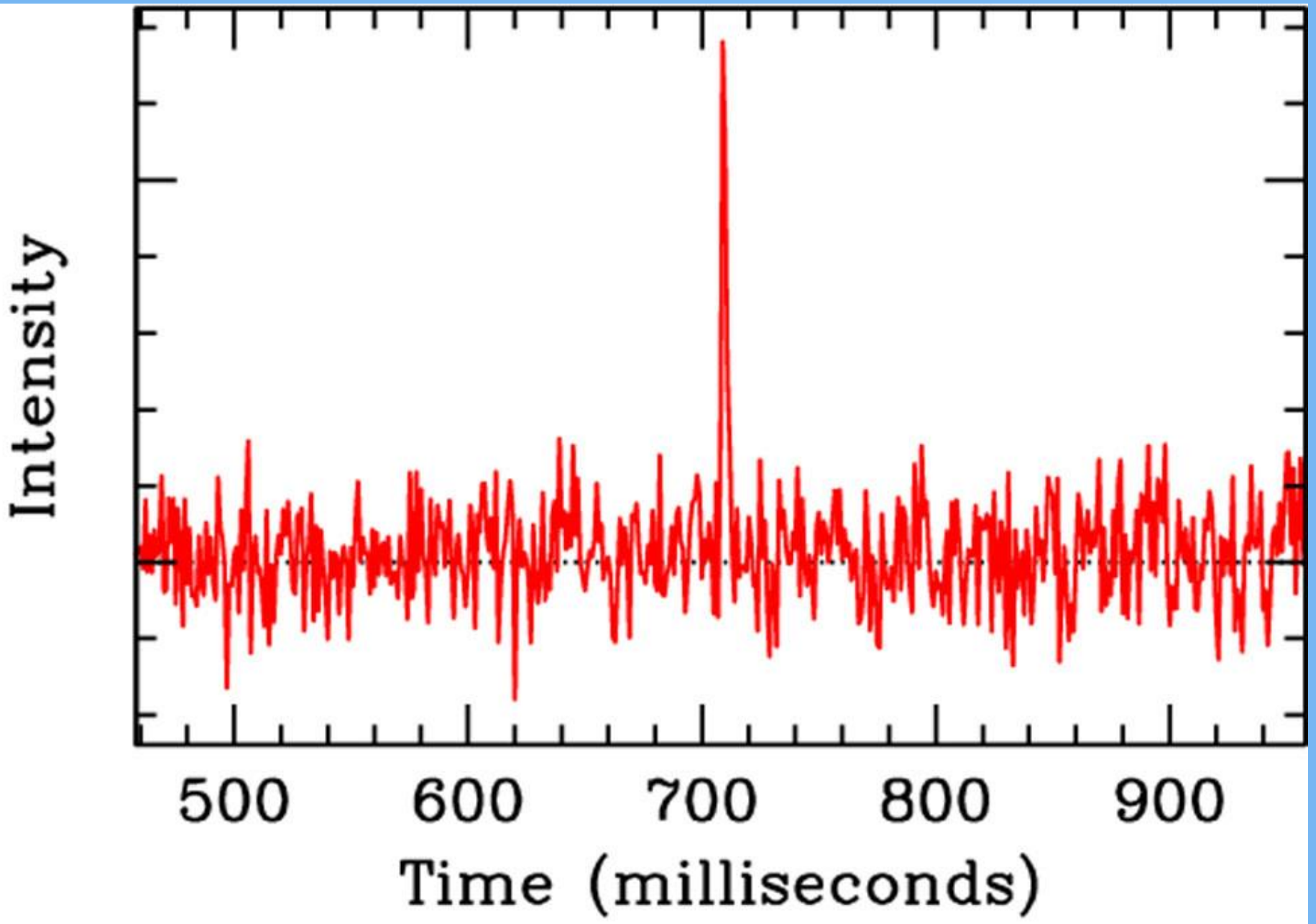
With Dark Matter PBHs:



Lensing of Fast Radio Bursts by Compact Objects

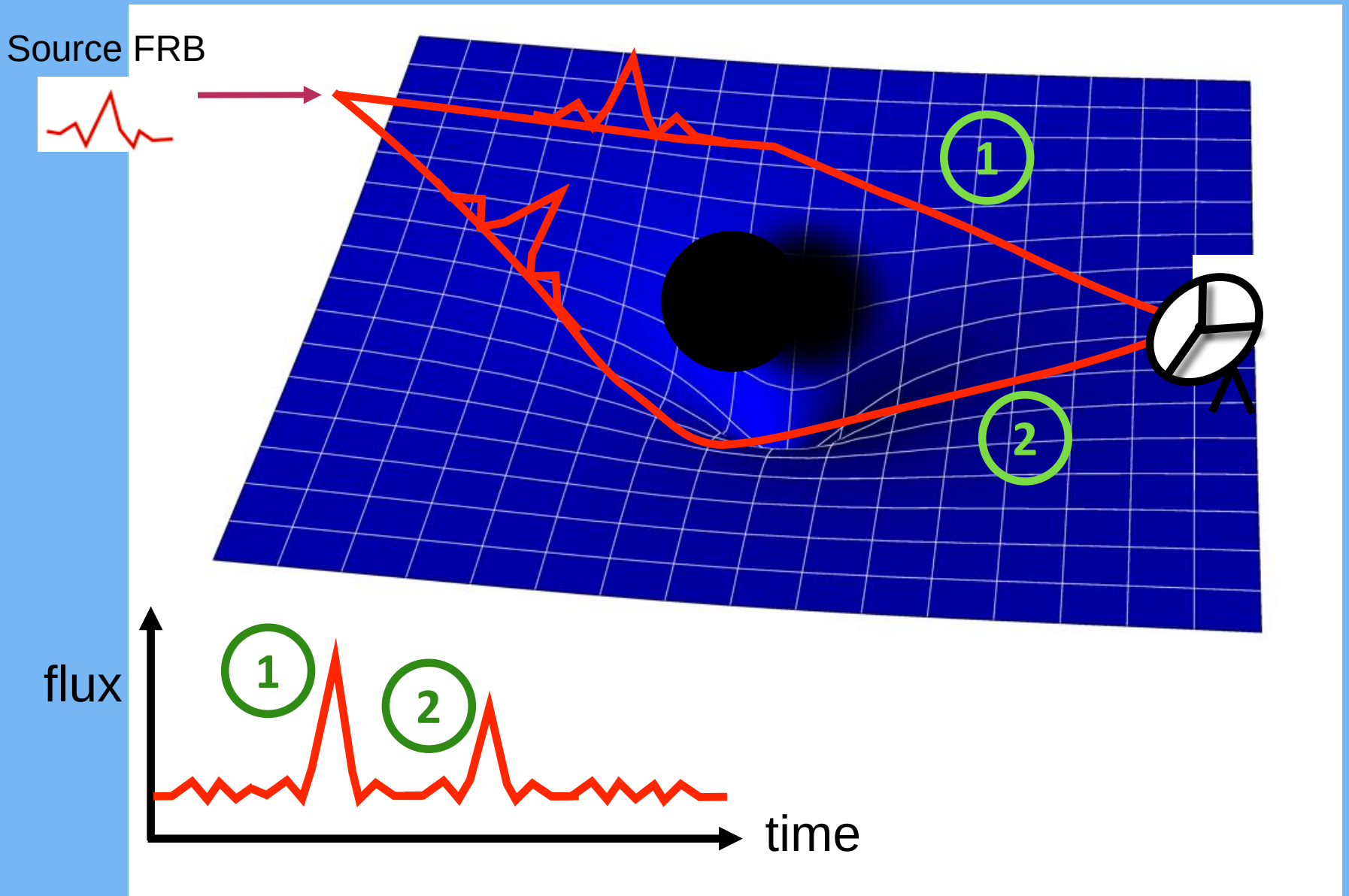
Munoz, Kovetz, Dai, MK, 1605.00008

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

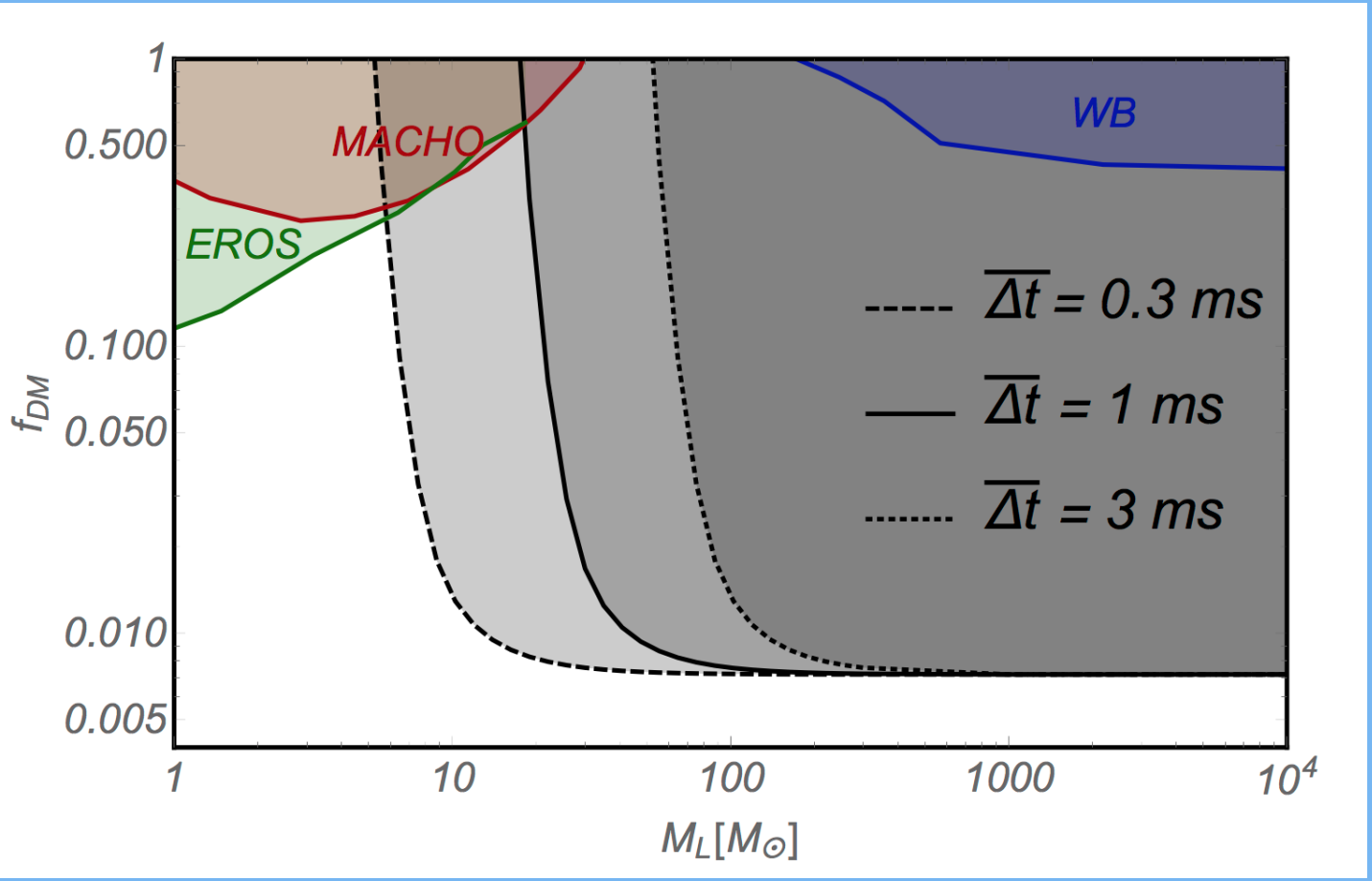

Intensity
500
600
700
800
900
Time (milliseconds)

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



In progress

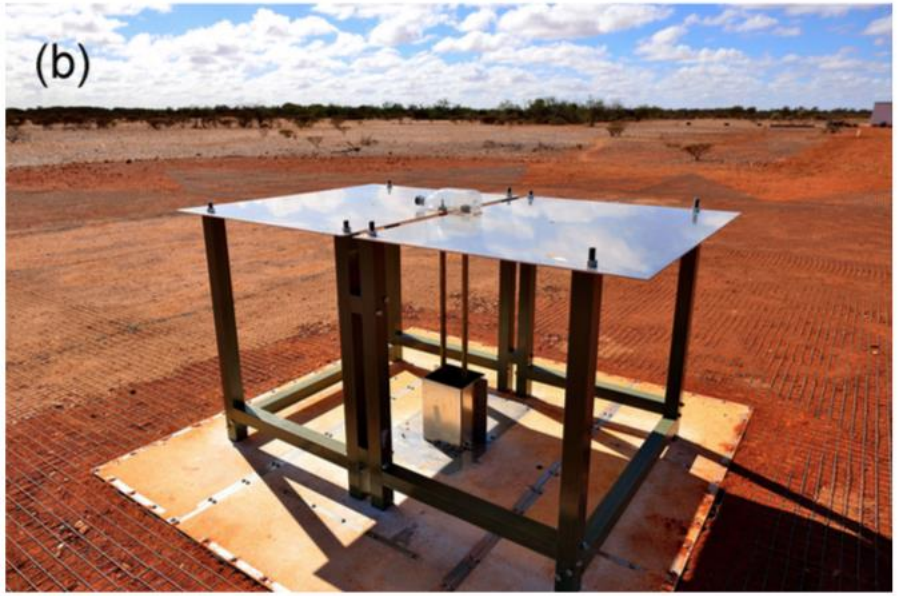
Can also seek echoes in gamma-ray-burst light curves

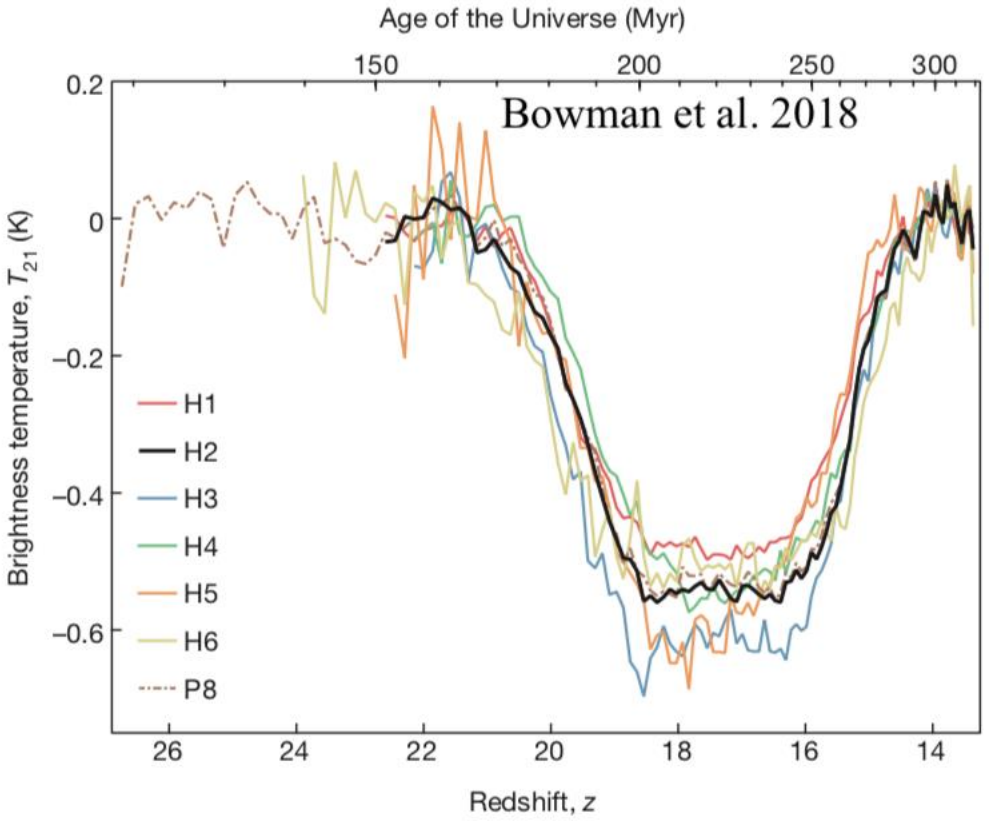
(Ji, Kovetz, MK)

Baryon—DM interactions from cosmic dawn?

(EDGES: Bowman et al. Nature 2018; Barkana, Nature 2018)

February 2018





Lots of neutral hydrogen

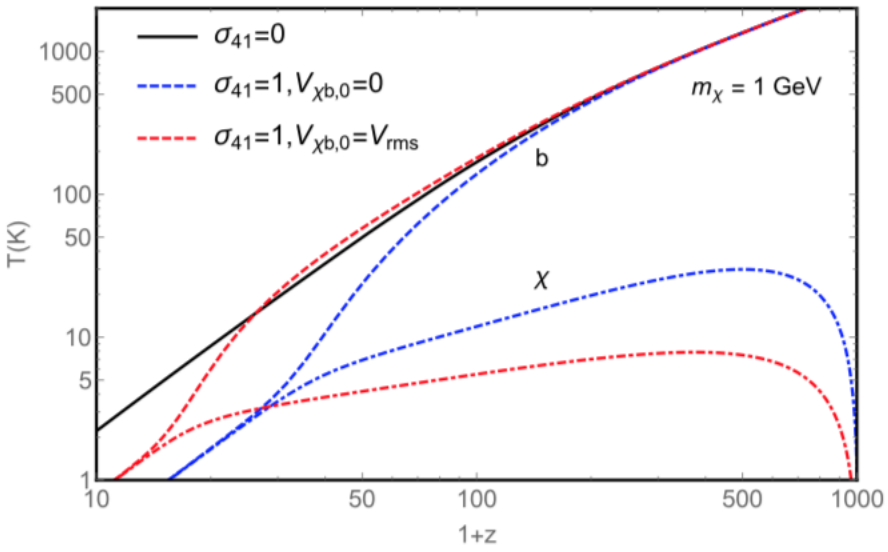
If DM-baryon interactions exist, they can mediate heat exchange between baryons and DM (Dvorkin, Blum, MK 2014)

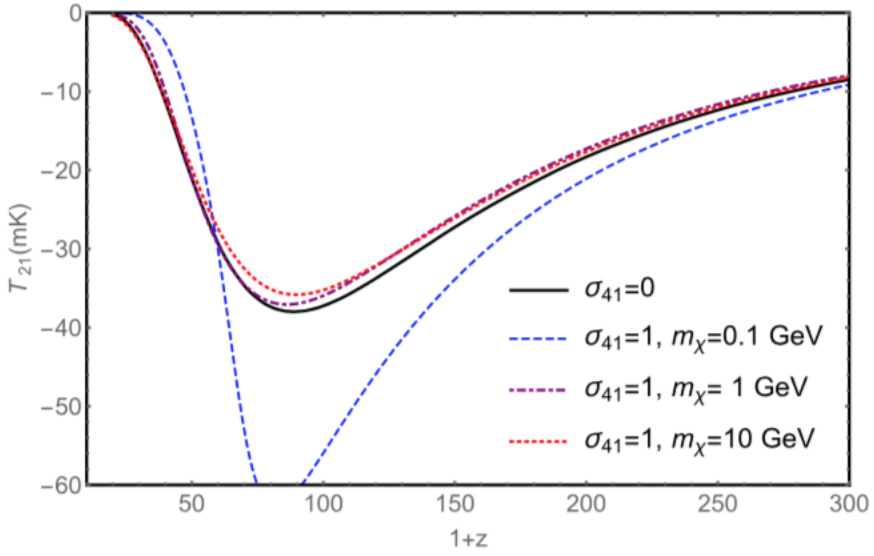
$$\frac{dT_\chi}{da} = -2\frac{T_\chi}{a} + \frac{2\dot{Q}_\chi}{3aH}, \qquad \frac{dT_b}{da} = -2\frac{T_b}{a} + \frac{\Gamma_C}{aH}(T_\gamma - T_b) + \frac{2\dot{Q}_b}{3aH}$$

Tashiro, Kadota, Silk 2014: DM can act as heat sink and cool neutral hydrogen in dark ages

Munoz, Kovetz, Ali-Haimoud 2015: included heating due to baryon-DM relative velocities and pointed out implications for global 21-cm signal

$$\dot{Q}_b = F(V_{\chi b})(T_\chi - T_b) - \frac{\rho_\chi}{\rho_m}\frac{m_\chi m_b}{m_\chi + m_b}\frac{d}{dt}\left(\frac{1}{2}V_{\chi b}^2\right)$$



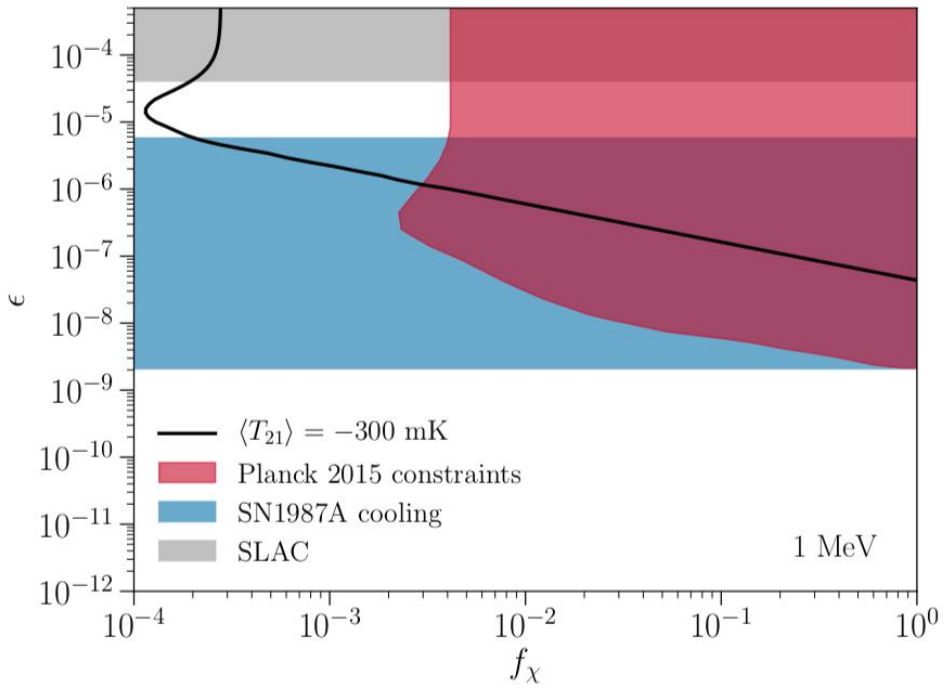


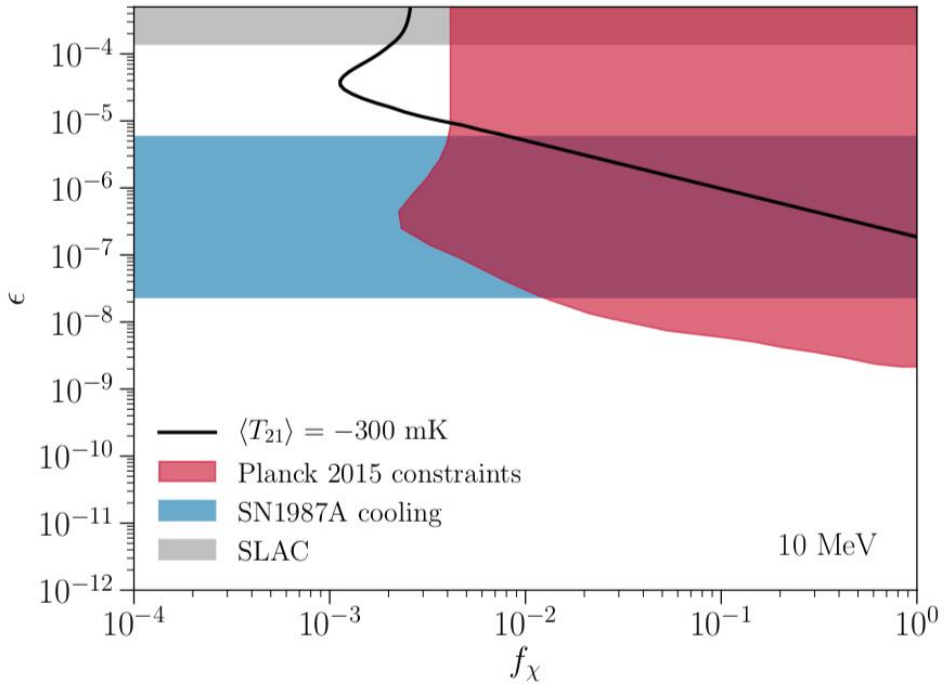
Issues/concerns/question:

Systematics (e.g., beam uncertainties)?

Required DM properties hard to come by theoretically (e.g., Munoz & Loeb; Berlin et al., Barkana et al.; Slatyer & Wu; Boddy et al. in prep; Kovetz et al., in prep)

Basic issue: CMB constraints (Dvorkin, MK, Blum 2013; Boddy&Gluscevic 2017; Slatyer-Wu 2018; Boddy et al. in prep) require $\sigma \propto \frac{1}{v^4}$ but required keV -- 100 MeV mass range constrained by SN1987 and stellar cooling. May still be window where only <1% of DM interacts

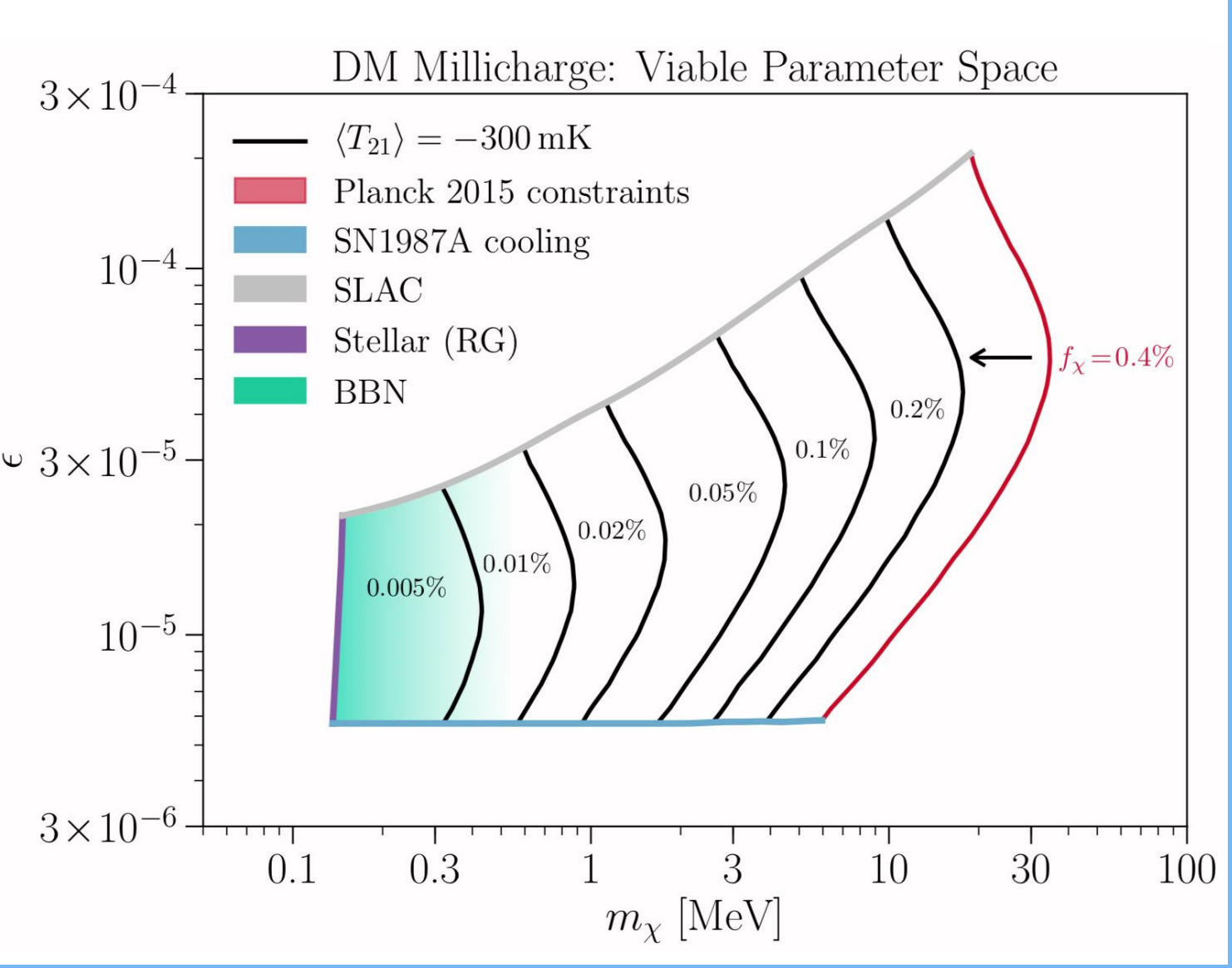




New constraints for millicharged DM!

(Boddy, Gluscevic, Poulin, Kovetz, MK, Barkana, any day now

Kovetz, Poulin, Gluscevic, Boddy, Barkana, MK, any day now)



Parameter space for millicharged-DM explanation for EDGES *very* constrained, but might account for $\sim 2\sigma$ discrepancy between CMB and BBN baryon densities

Dark-matter decay and line-intensity mapping

(Creque-Sarbinowski & MK, arXiv:1806.11119)

Intensity mapping

(review: Kovetz et al. 1709.09066)

Measure sky brightness of some emission line as function of angular position and frequency (a proxy for distance)

→ 3d distribution of emitters

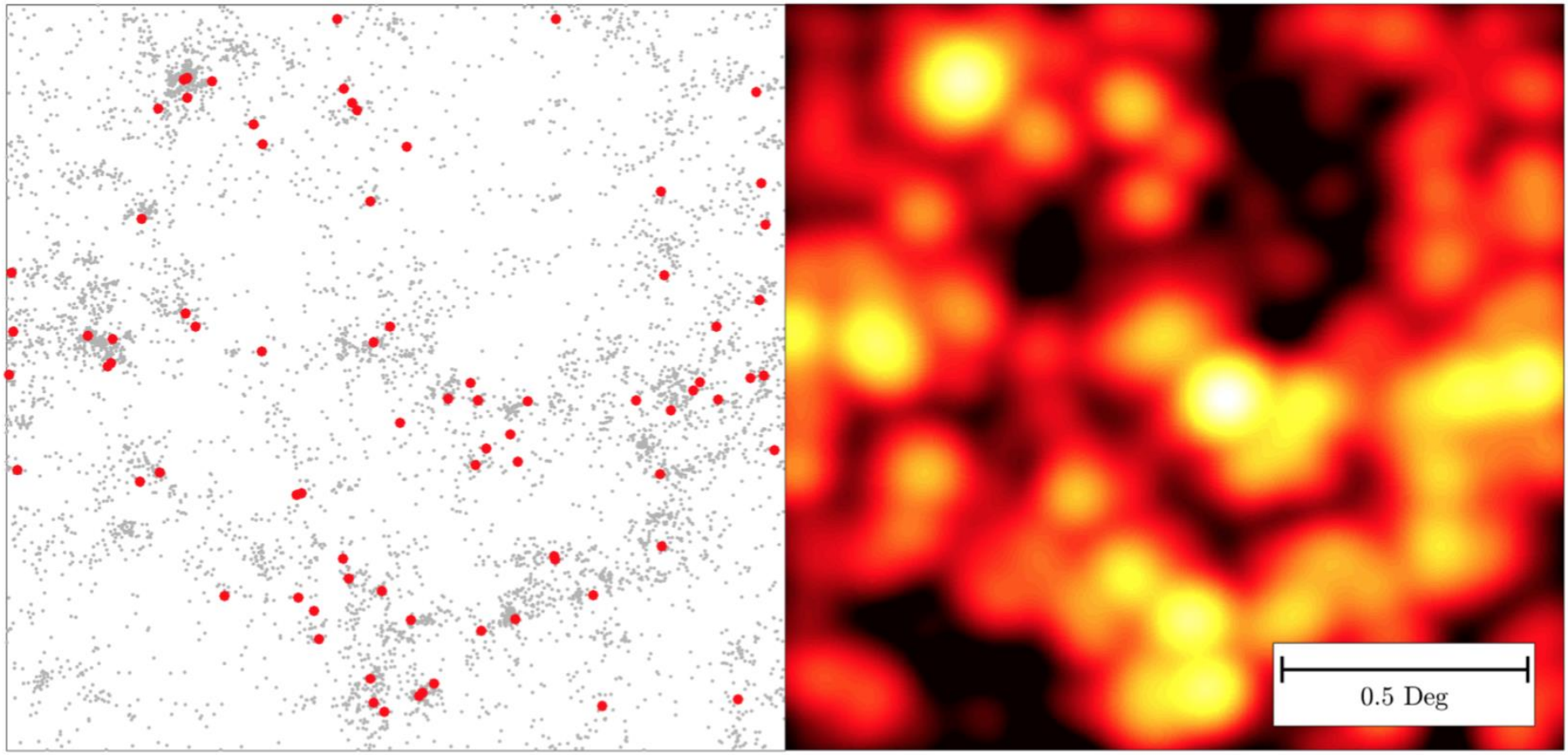


Fig credit: Patrick Breysse

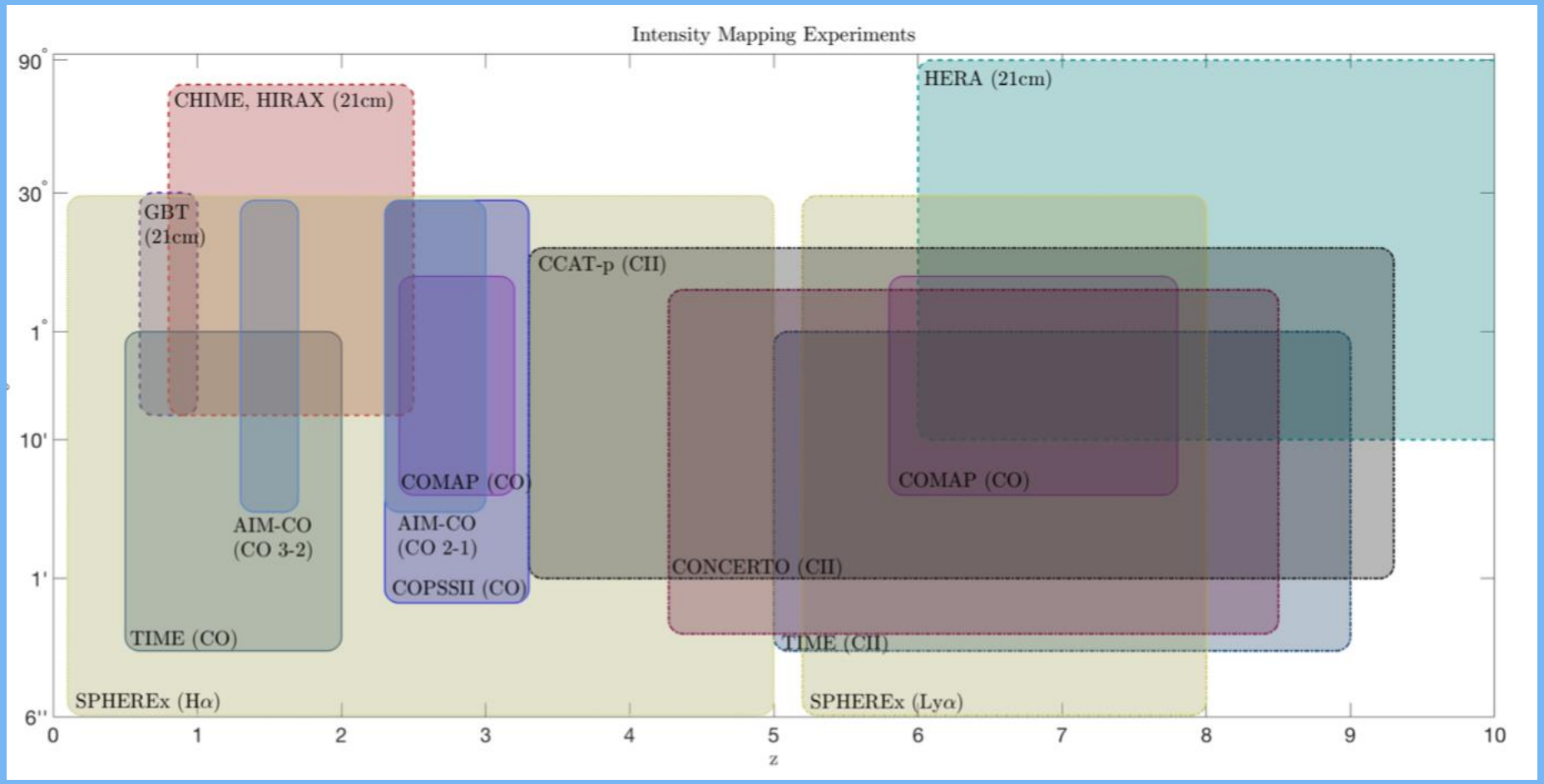
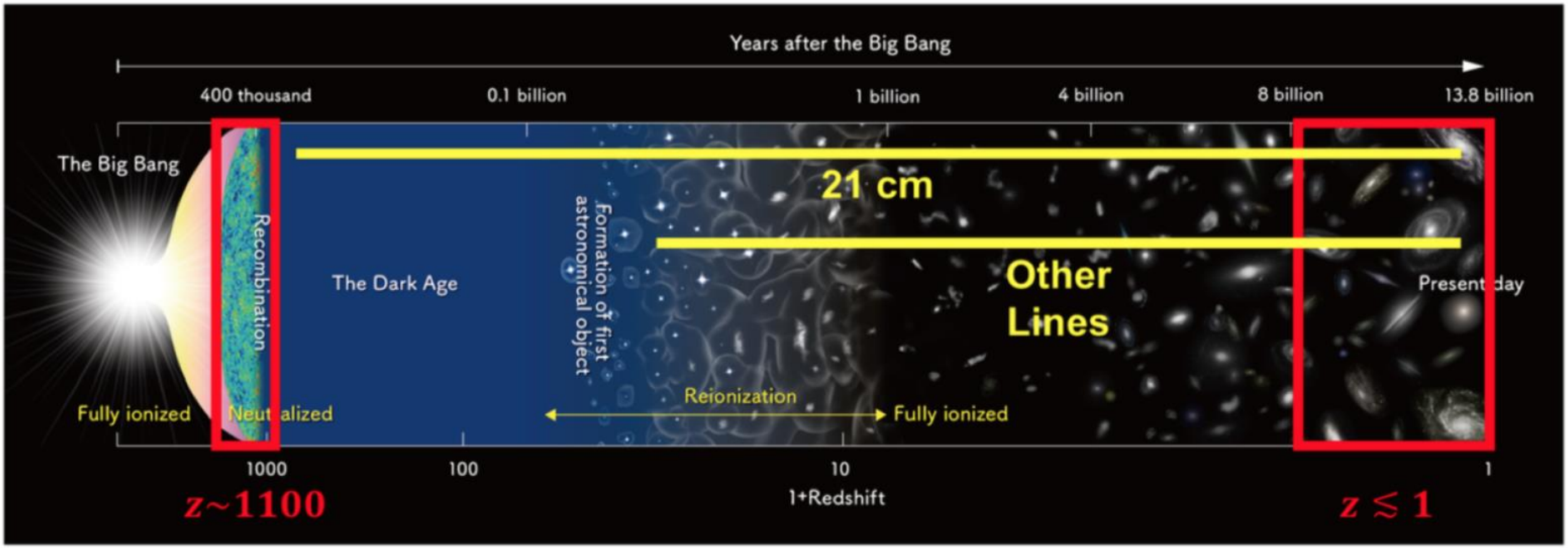
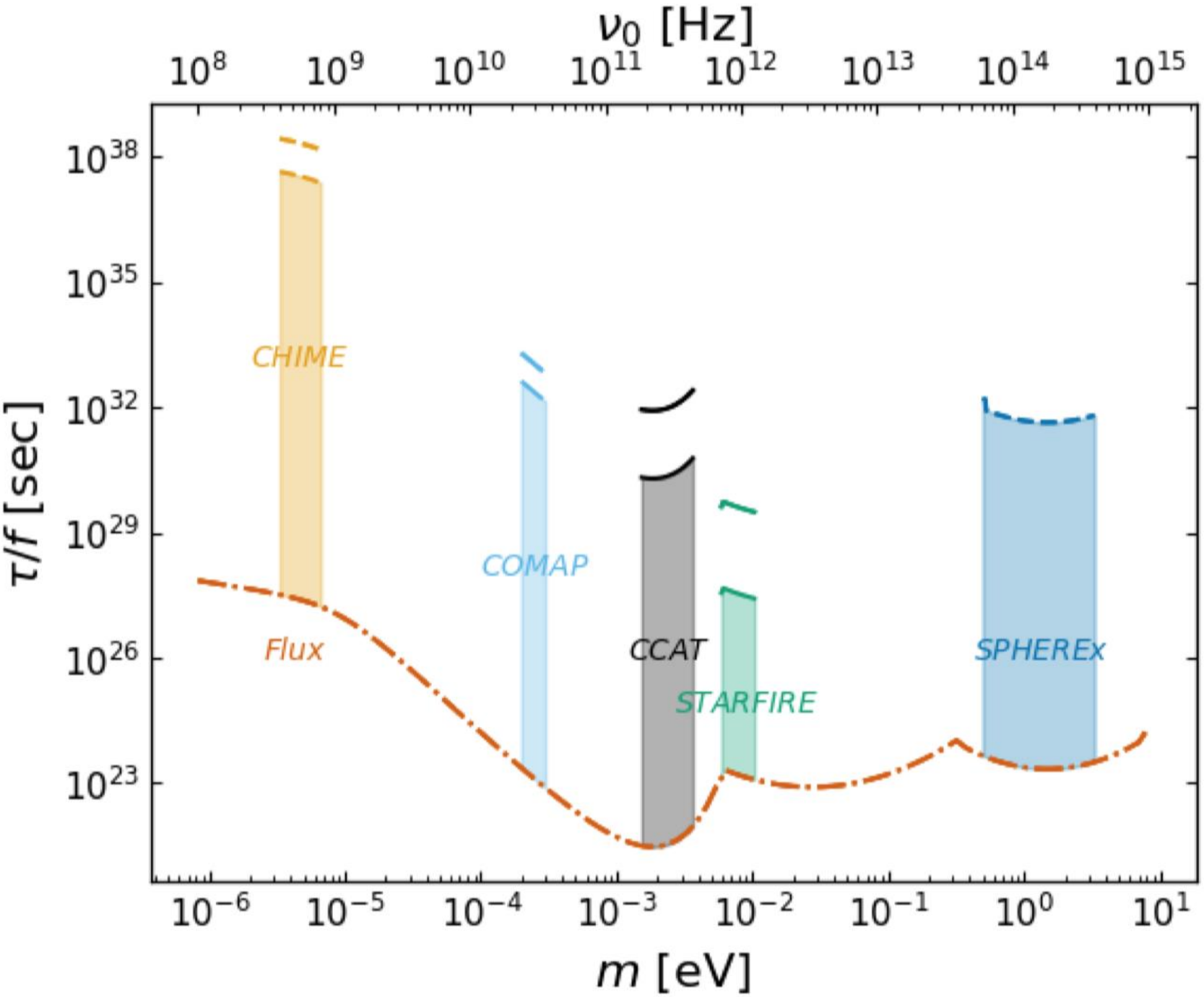


Fig. from Patrick Breysse and Ely Kovetz


Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
21 cm
Other Lines
Present day
Fully ionized
Neutralized
Reionization
Fully ionized
1000
100
10
1
1+Redshift
z~1100
z ≲ 1

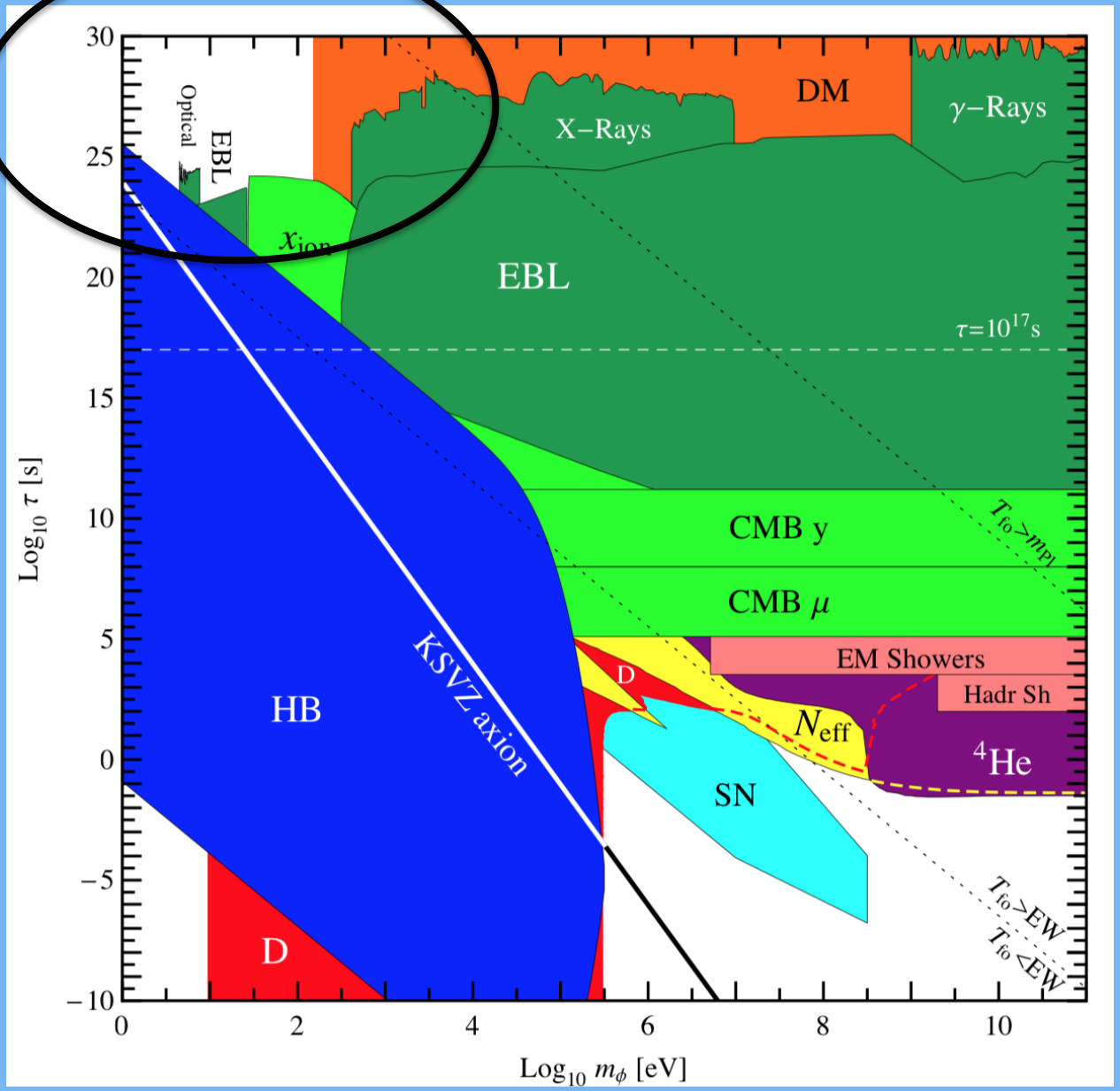
DM decay

- If DM decays to photon line, decay line will be correlated with large-scale structure


ν_0 [Hz]
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
τ/f [sec]
10^{38}
10^{35}
10^{32}
10^{29}
10^{26}
10^{23}
CHIME
COMAP
CCAT
STARFIRE
SPHEREx
Flux
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
m [eV]

Conclusions:

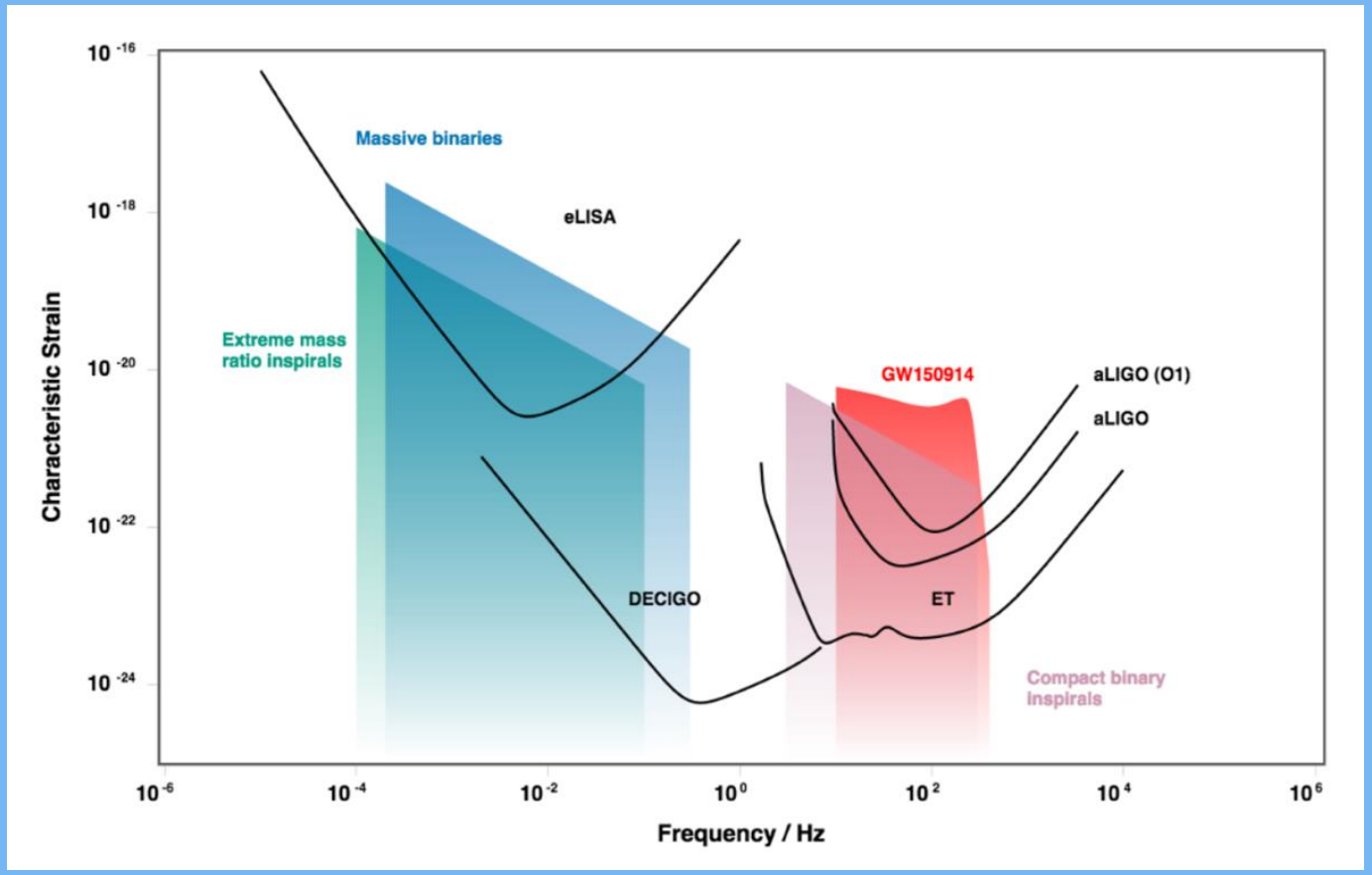
- Parameter space for canonical WIMP shrinking --- time to think anew?
- ~30-Msun PBHs face challenges: now guilty until prov en innocent
- EDGES signal is very intriguing, but cooling of hydrogen by scattering from DM hard to come by
- Intensity mapping provides one new astrophysical tool in arsenal of DM seekers



(Cadamuro & Redondo 2011)

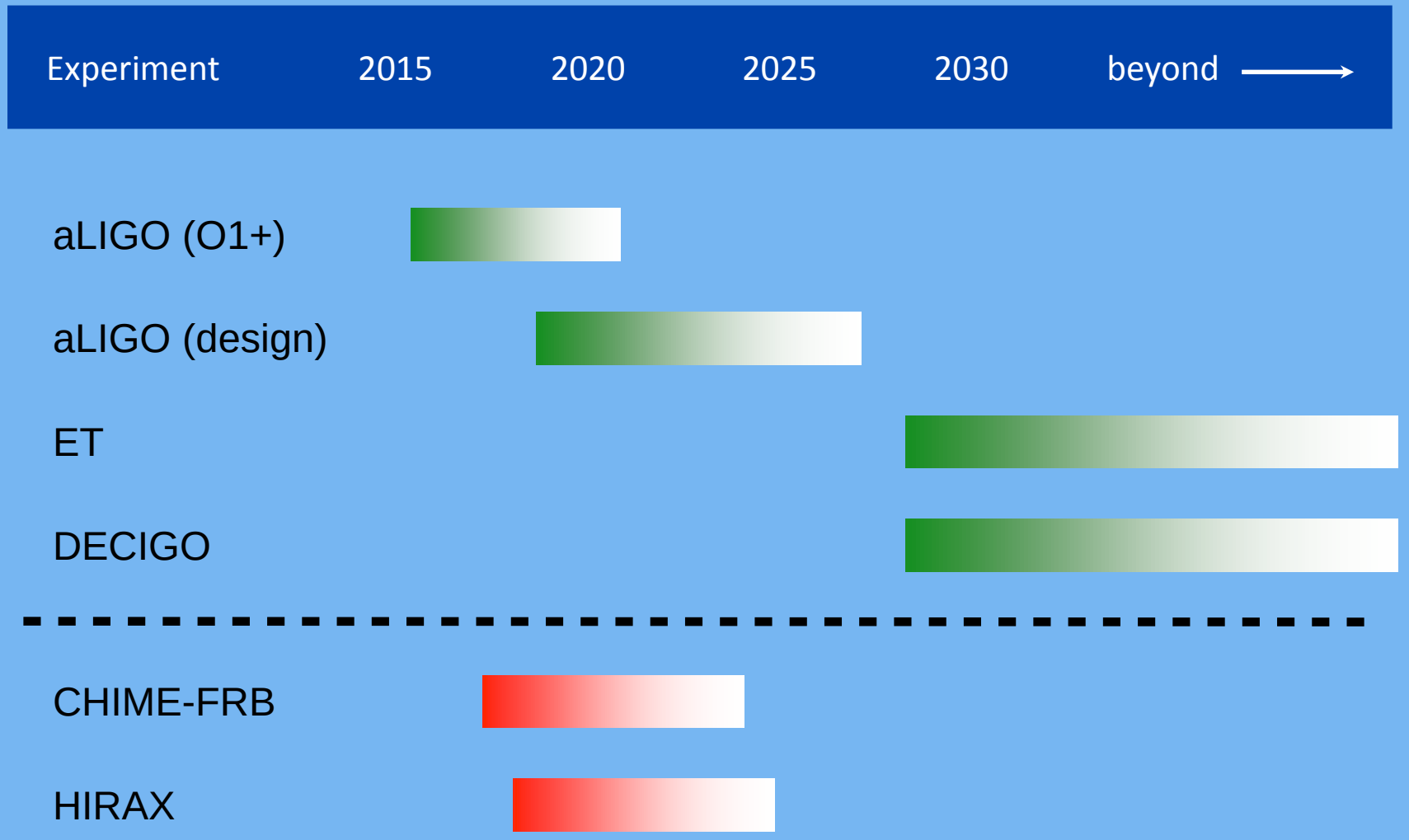
Observational Outlook

Gravitational waves:



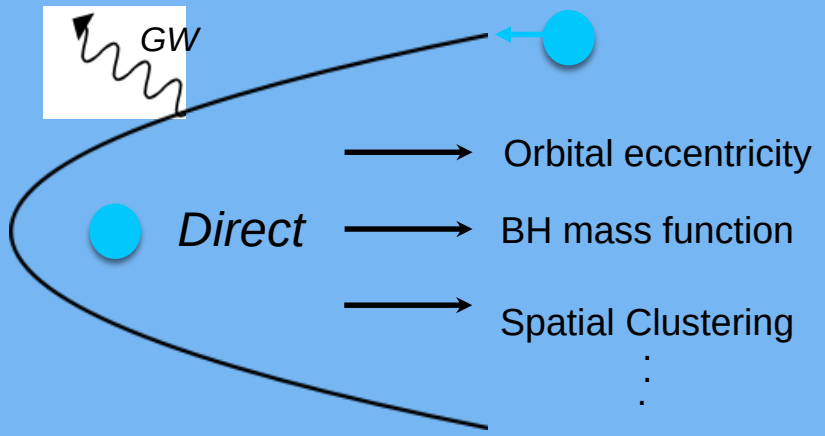
Fast Radio Bursts: **Lots of instruments, including CHIME, HIRAX...**

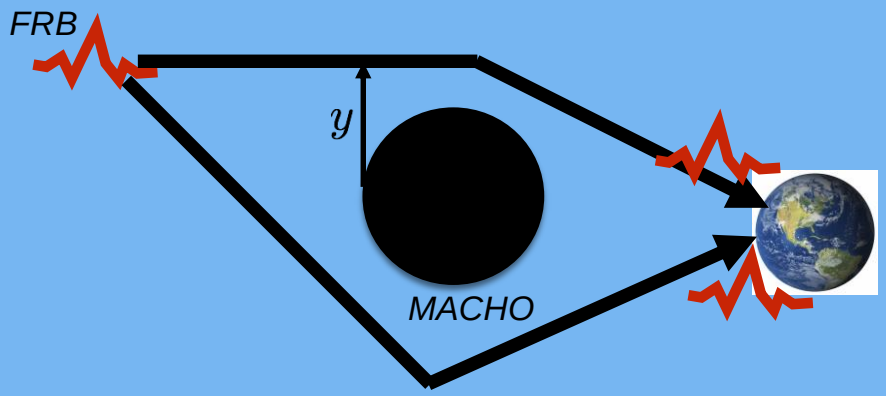
Observational Outlook: Experiment Timeline



Conclusion:

Theory





Indirect → FRB lensing time-delay + . . .

Experiment

Next Decade is promising!