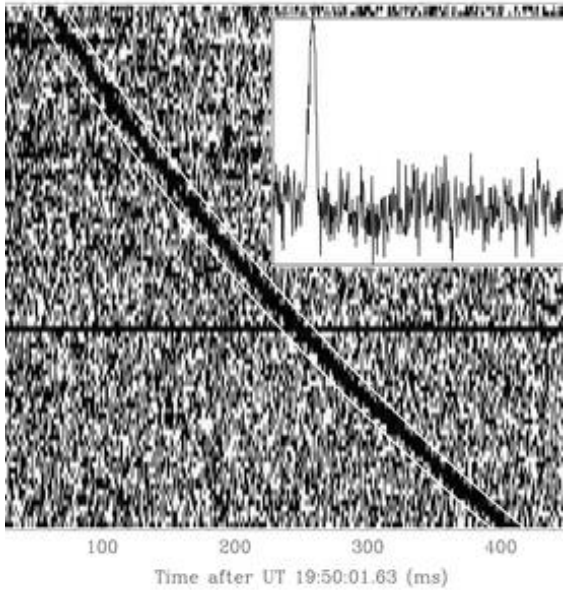
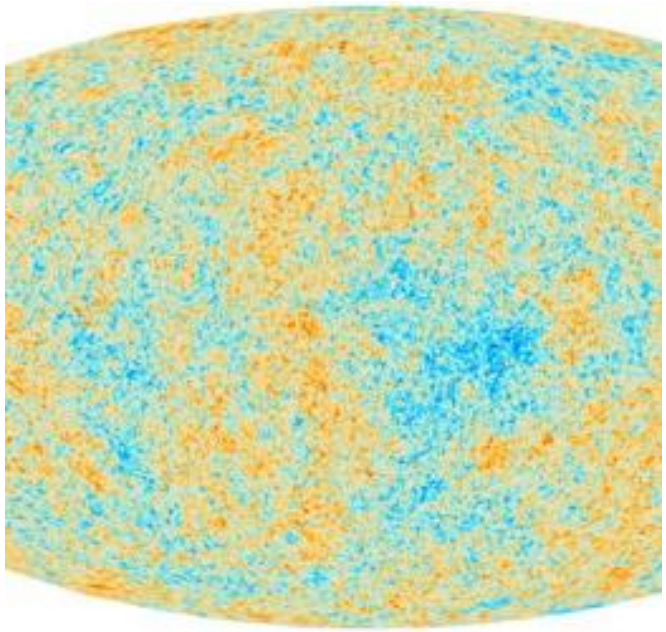




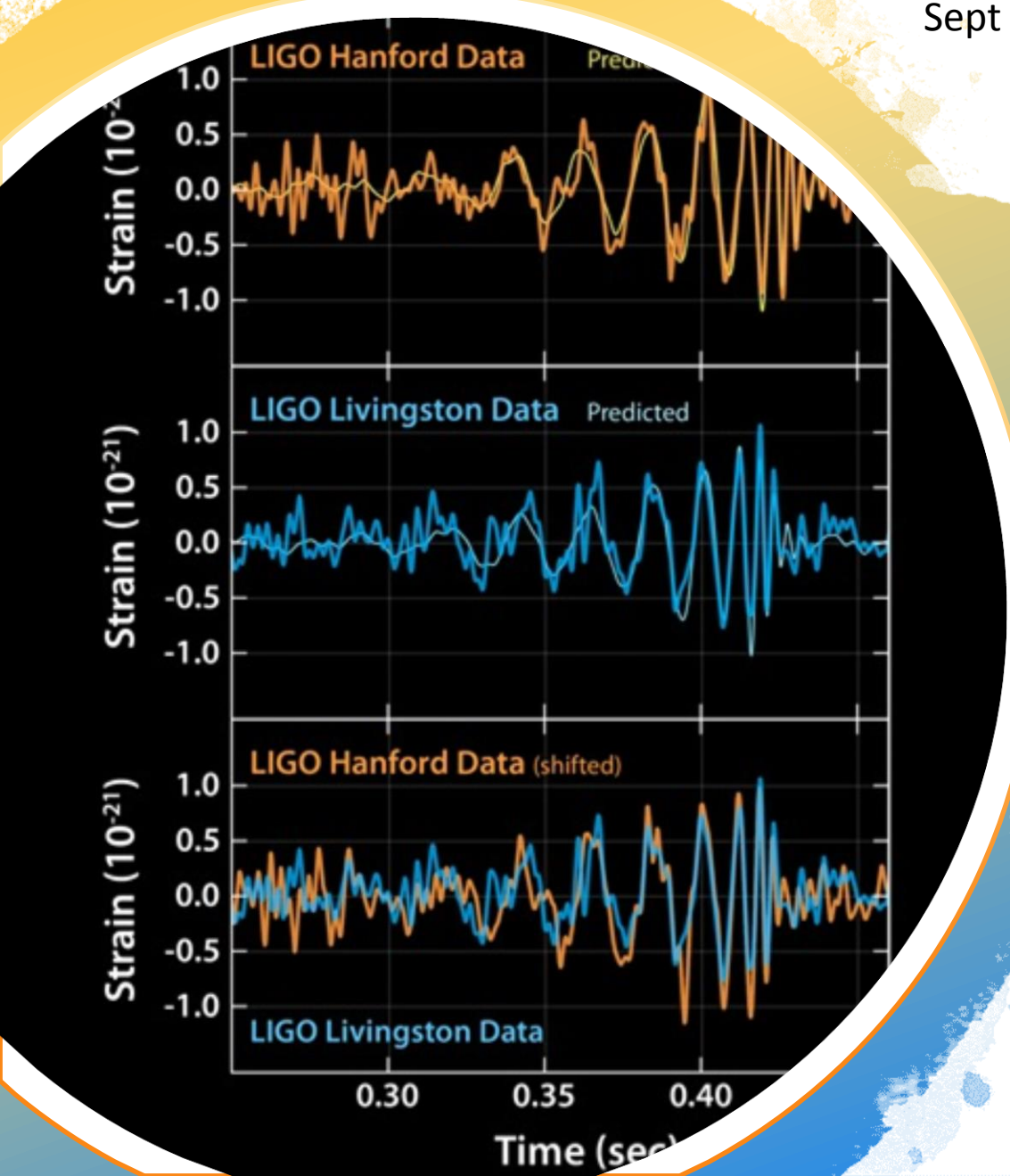
Black holes, gravitational waves, and avenues to new physics

Marc Kamionkowski
(Johns Hopkins University)

Dark matter: A Cosmic mystery

Sept 14, 2015 (announced Feb 10, 2016):

Gravitational waves detected!!



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!!

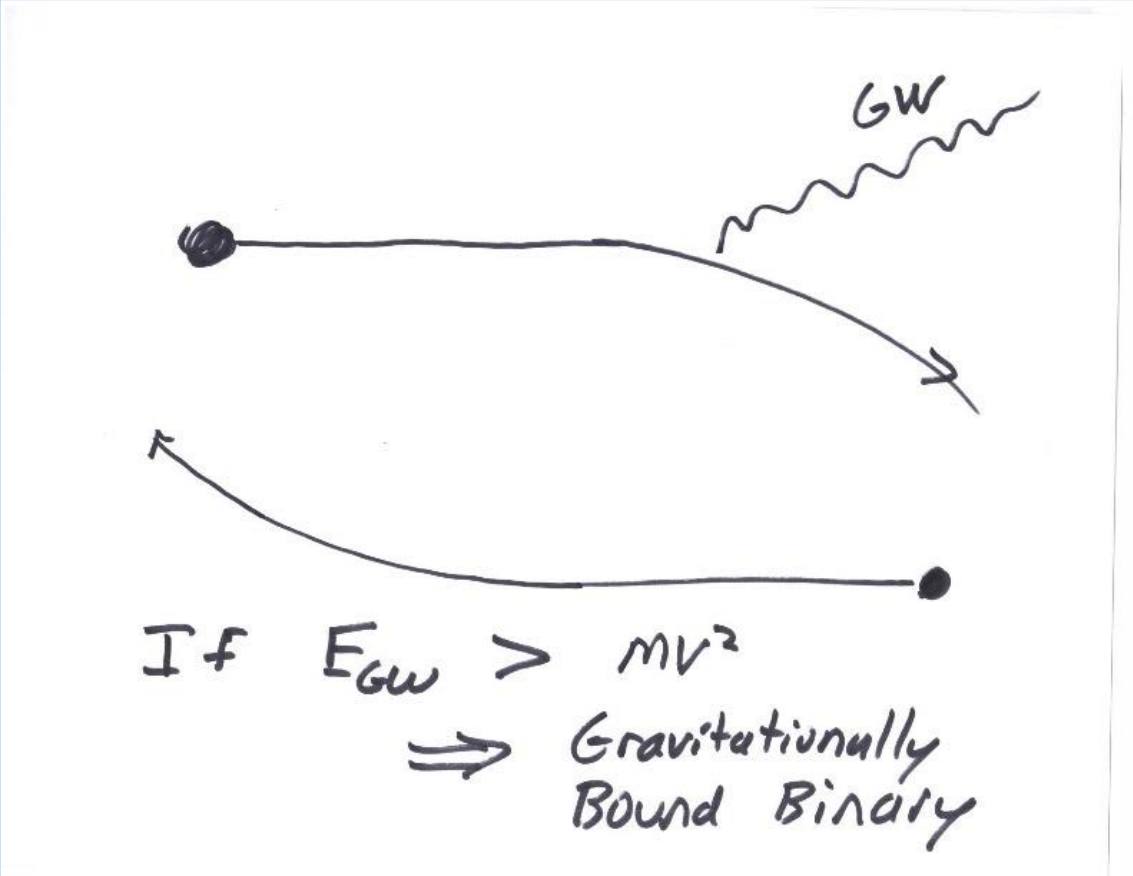
Did LIGO detect dark matter?

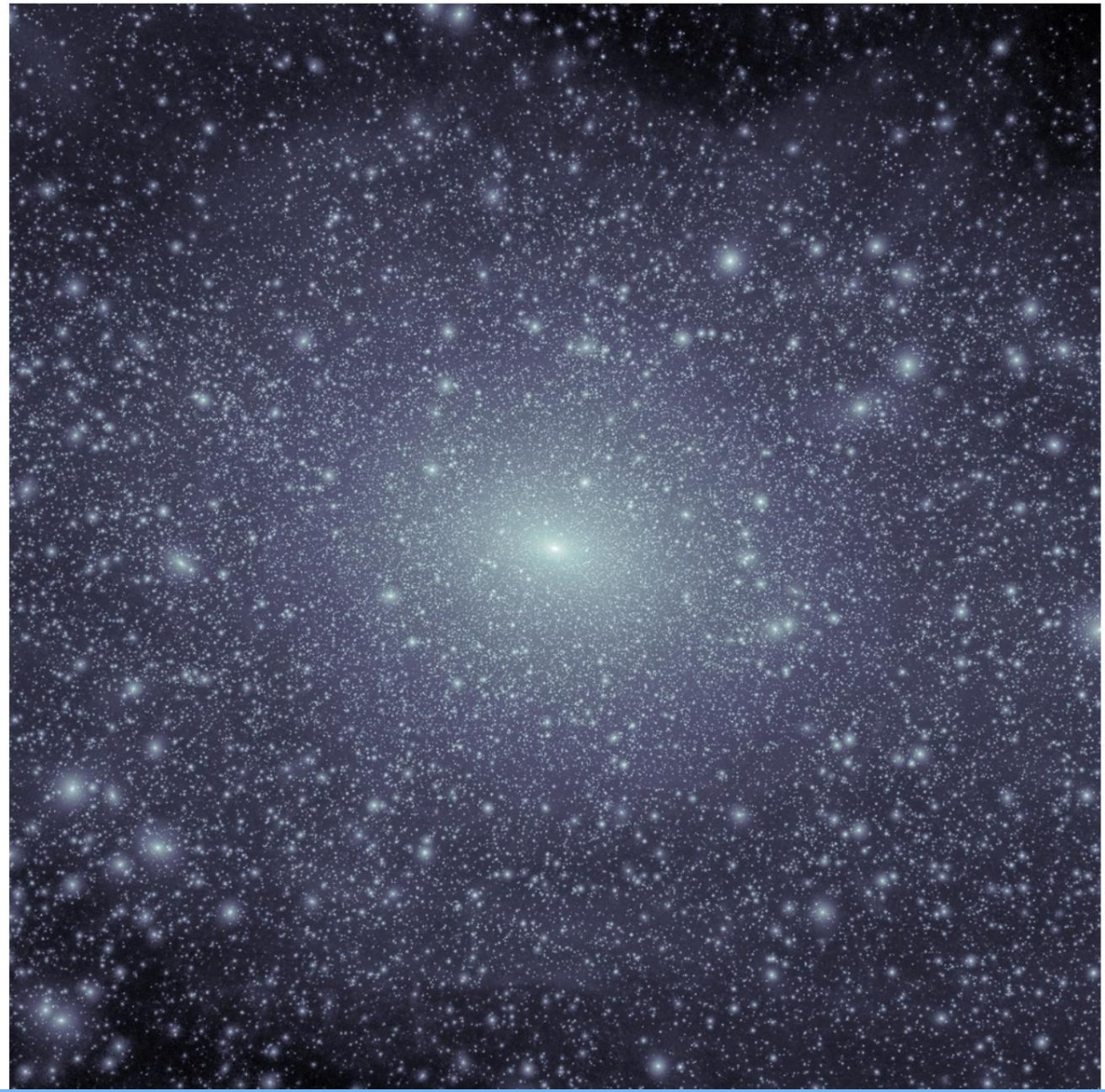
(Bird, Cholis, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli, Riess, 2016)

- 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





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

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

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

!!!!!!!

Since then….

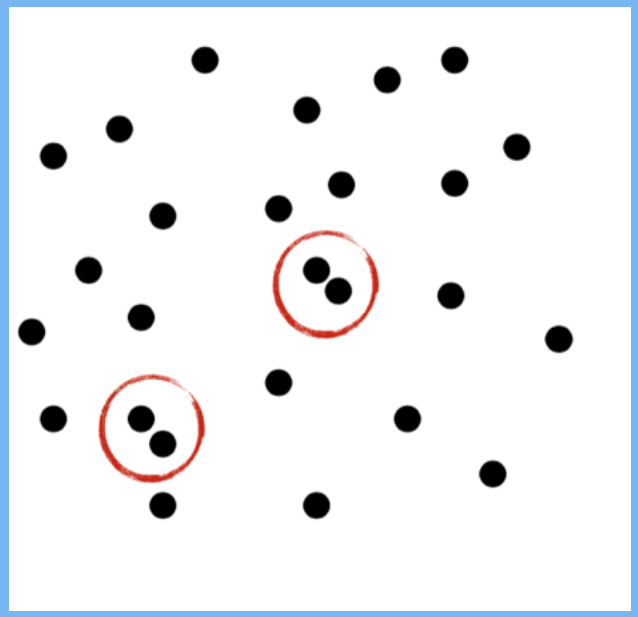
Scenario faces many (??) challenges:

- CMB (Ricotti, Ostriker, Mack 2007); **but see Ali-Haimoud & MK 2017**
- 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)....]]

The biggest challenge:

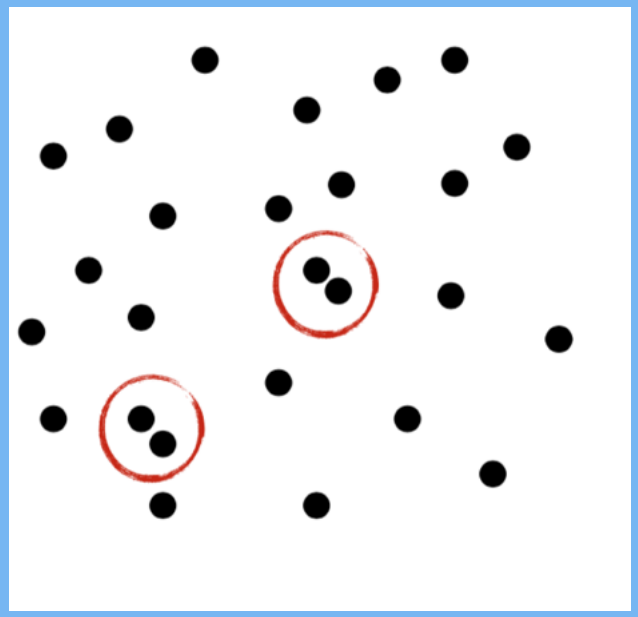
Primordial binaries

(Ali-Haimoud, Kovetz, MK 2017)



Some randomly distributed PBHs will fall near each other and form binaries in early U (Nakamura, Sasaki, Tanaka, Thorne, 1997)

But do these survive 13.8 billion years of galactic mergers/etc?



Some randomly distributed PBHs will fall near each other and form binaries in early U (Nakamura, Sasaki, Tanaka, Thorne, 1997)

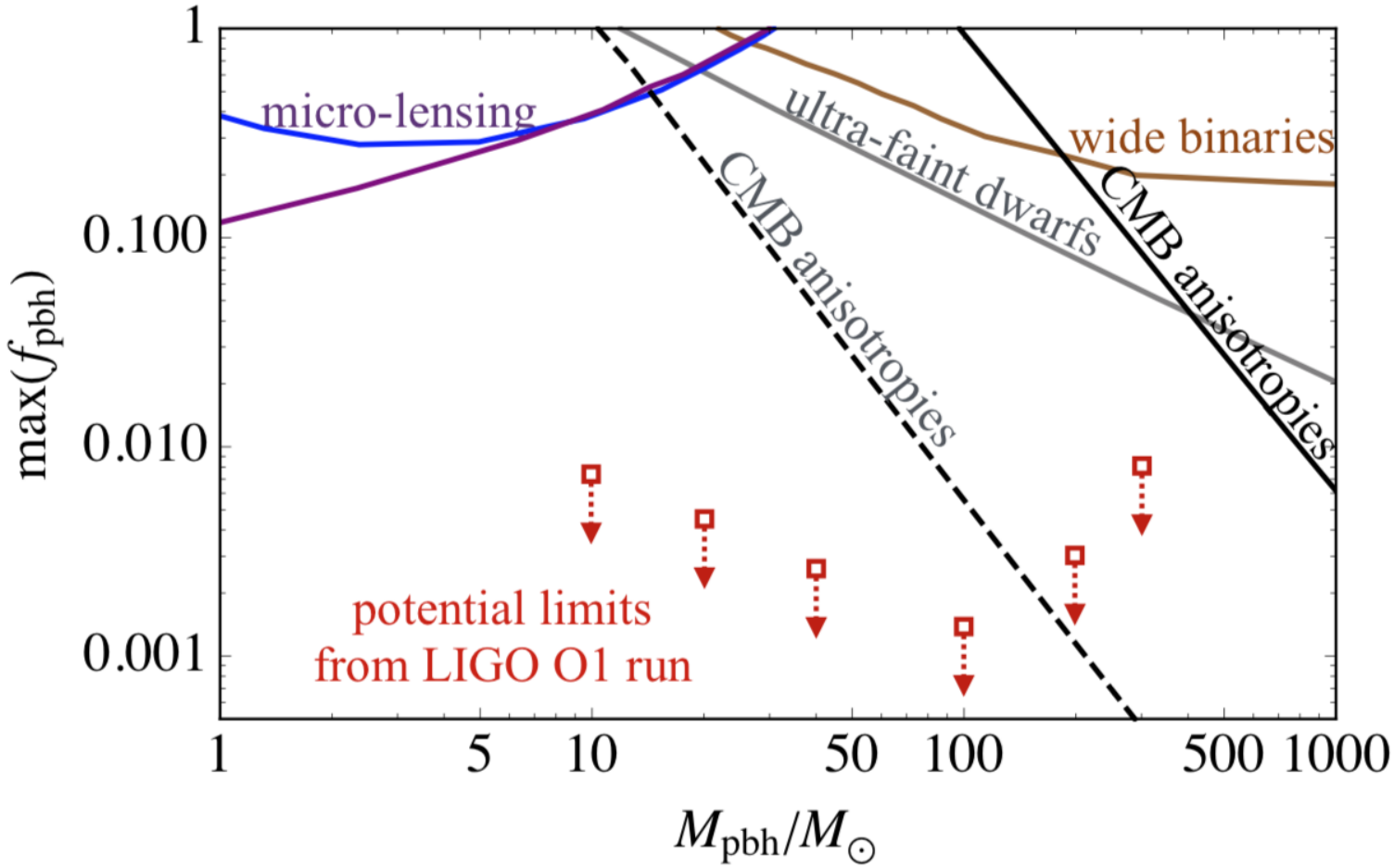
But do these survive 13.8 billion years of galactic mergers/etc?

We find many are disrupted,
but enough survive to exceed LIGO rates

Verdict still out: May still be other disruption mechanisms

Does LIGO rule out PBH-dark matter?

Probably but more checks are needed



Maybe scenario saved by primordial clustering (cf, JGB's talk)?

But we can use observation/experiment to figure it out!

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

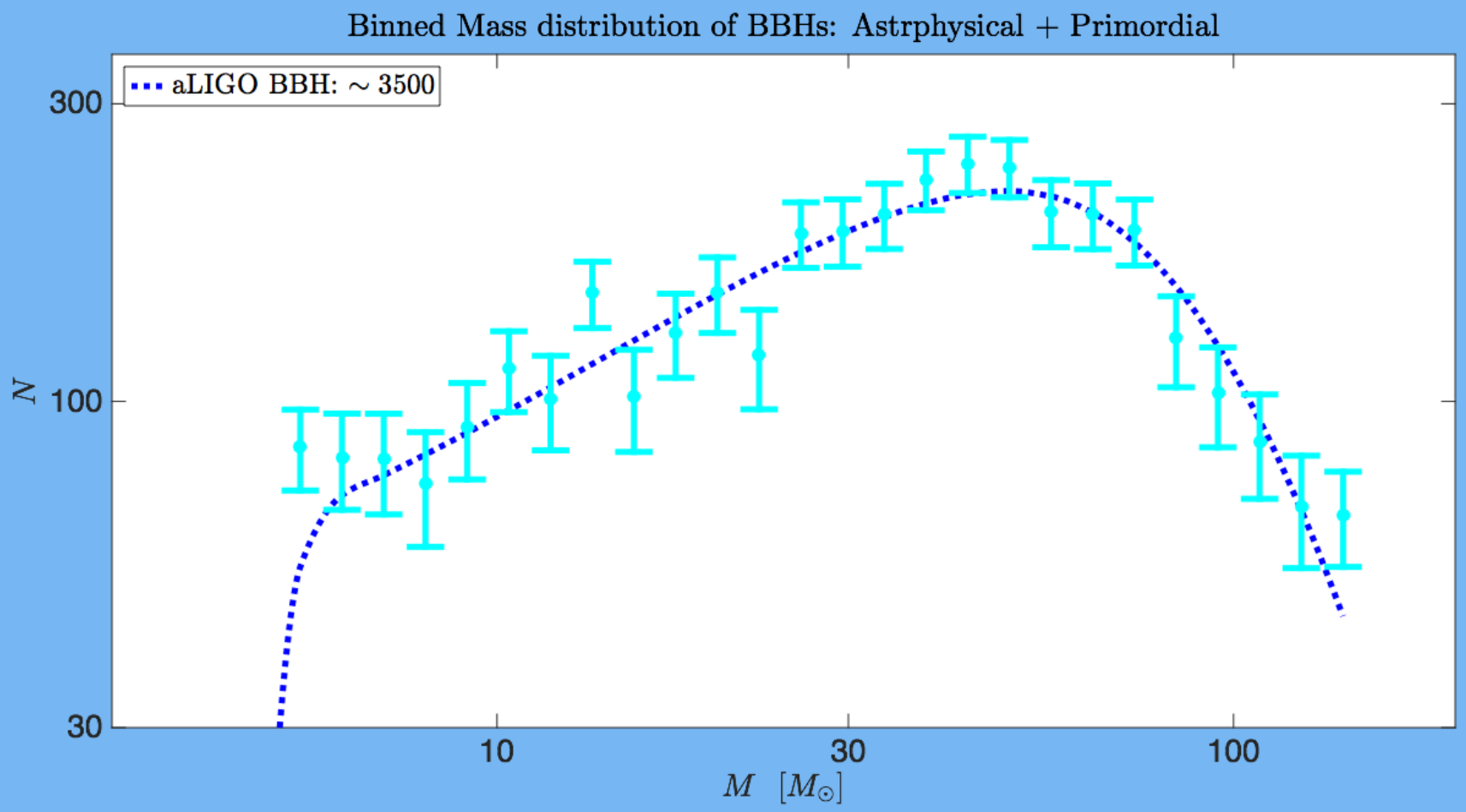
~1 such event in LIGO; ~10 in Einstein Telescope

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:

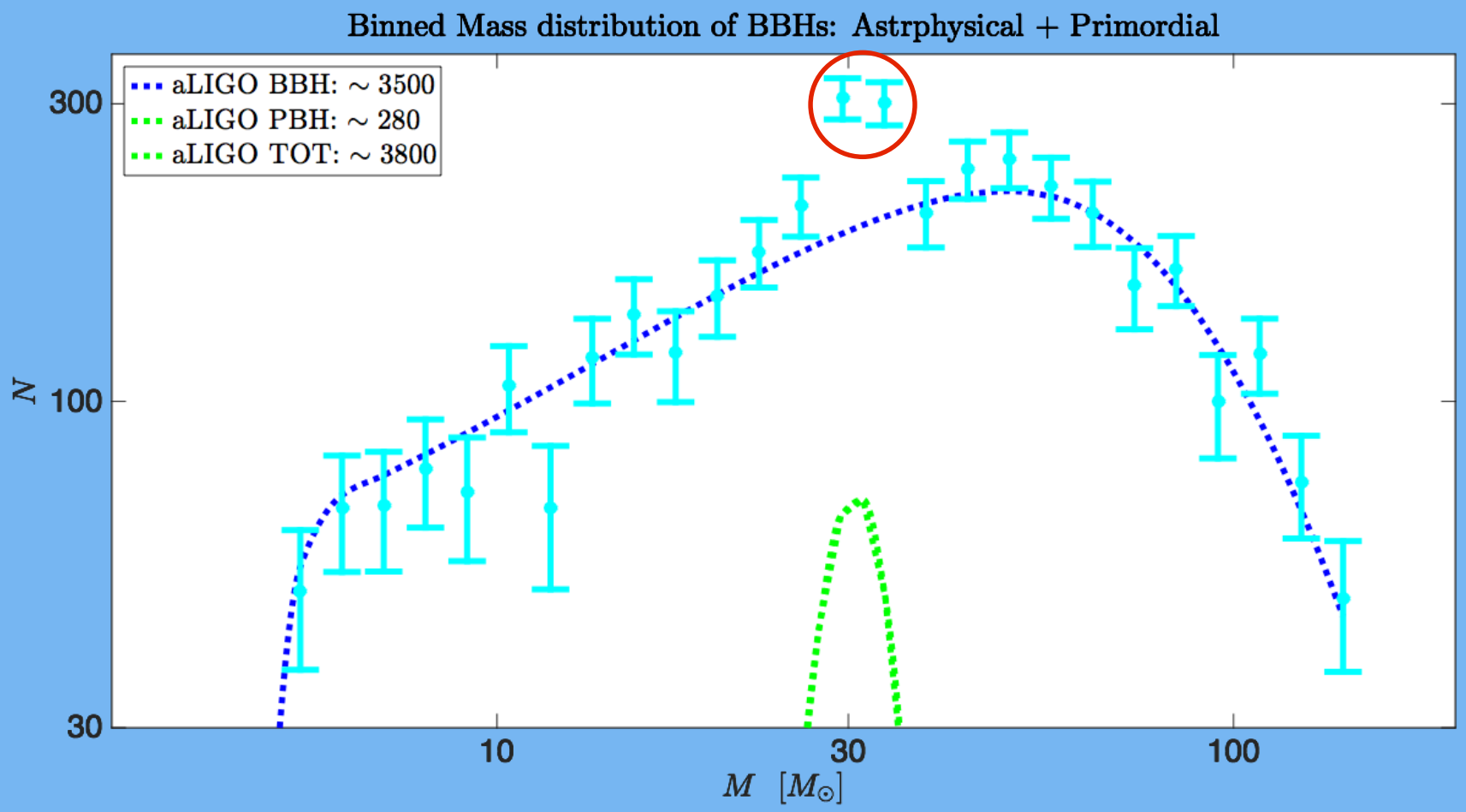


The Black-Hole Mass Function from GWs

with 5 years of aLIGO data:

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

With Dark Matter PBHs:



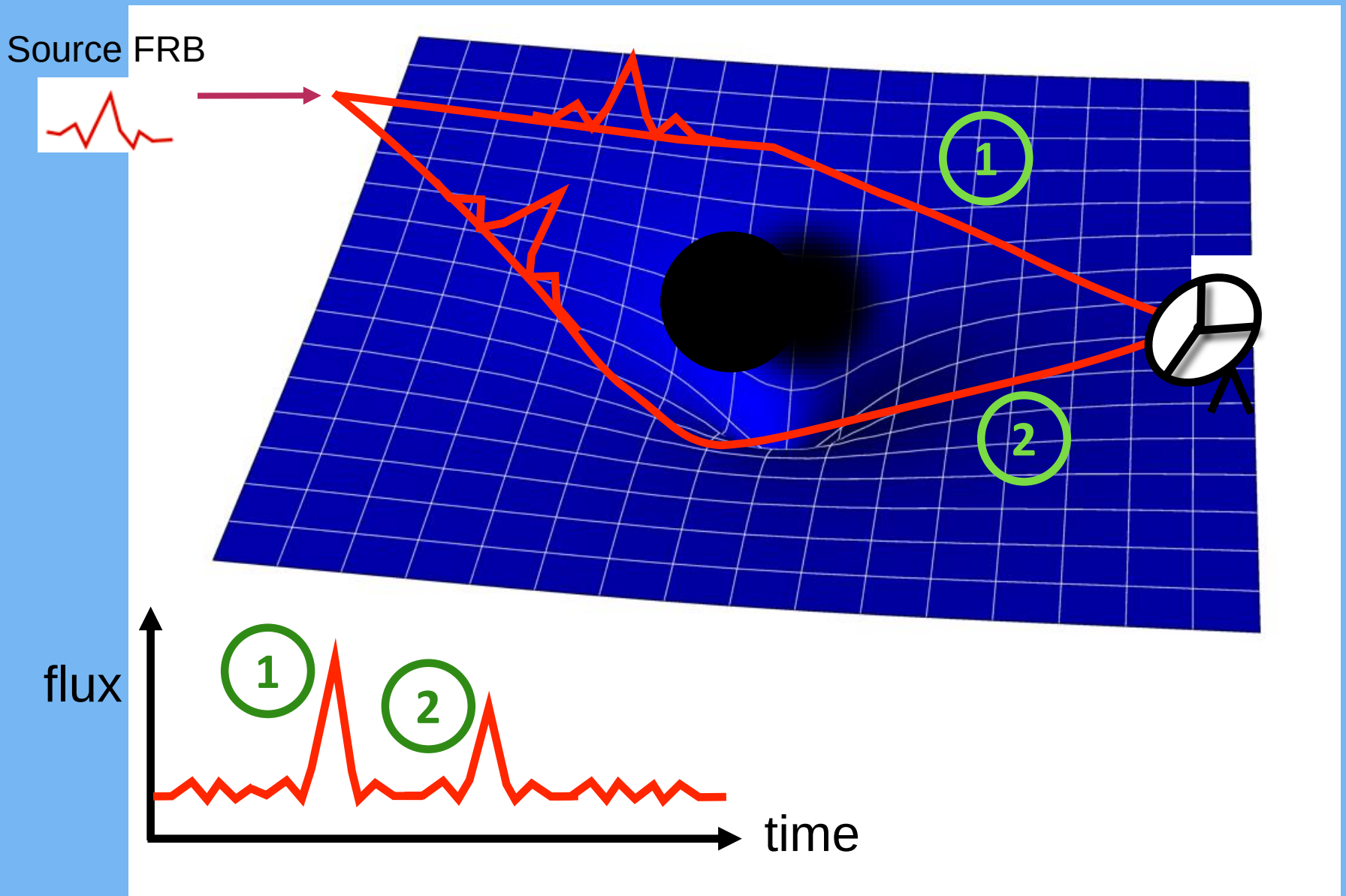
Lensing of Fast Radio Bursts by Compact Objects

Munoz, Kovetz, Dai, MK, 1605.00008

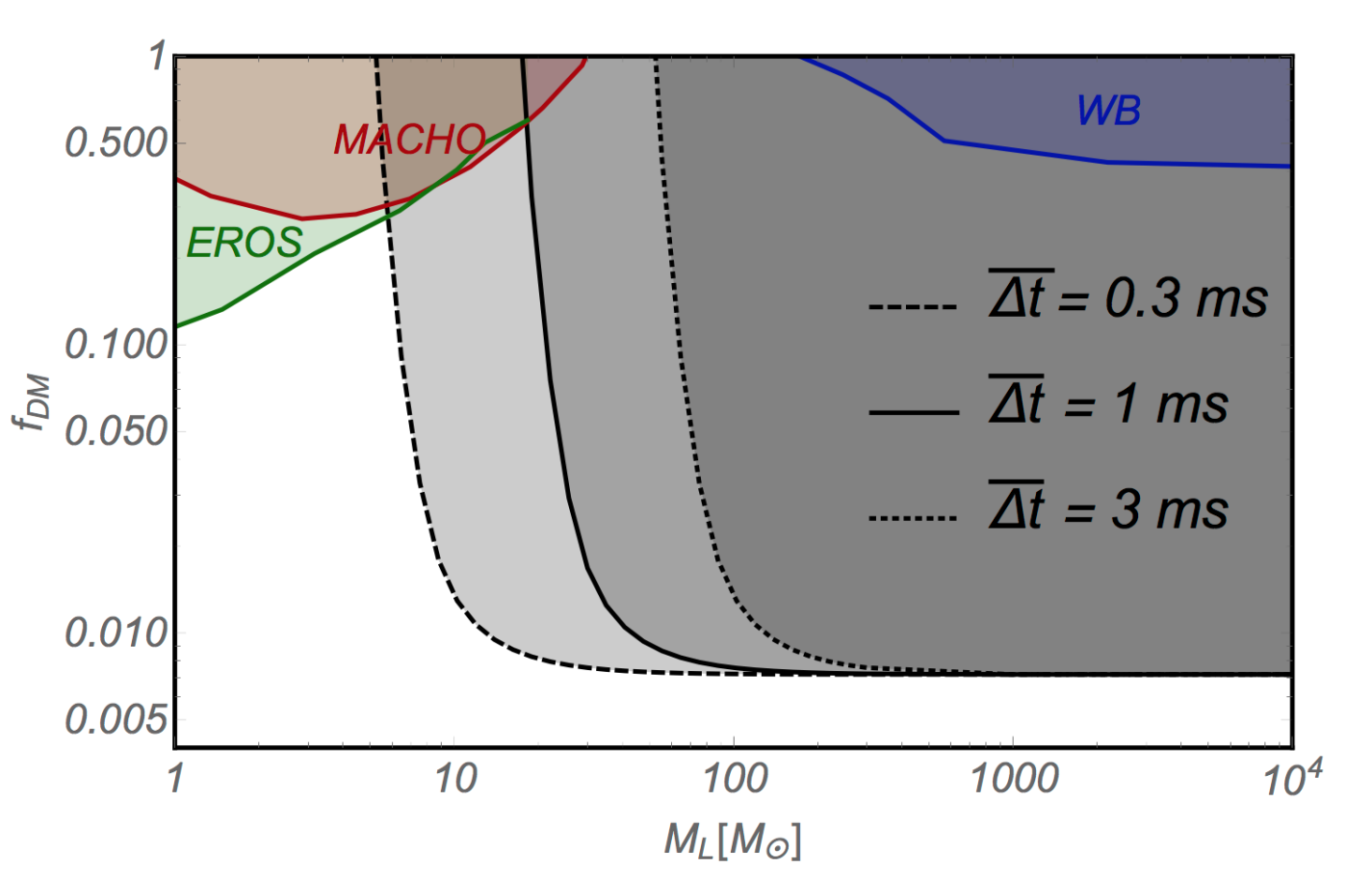
- FRBs : <msec ~GHz radio bursts
- ~10,000 on sky per day
- Large dispersion measures imply cosmological distances
- Forthcoming experiments (e.g., CHIME) should detect thousands

FRB Lensing

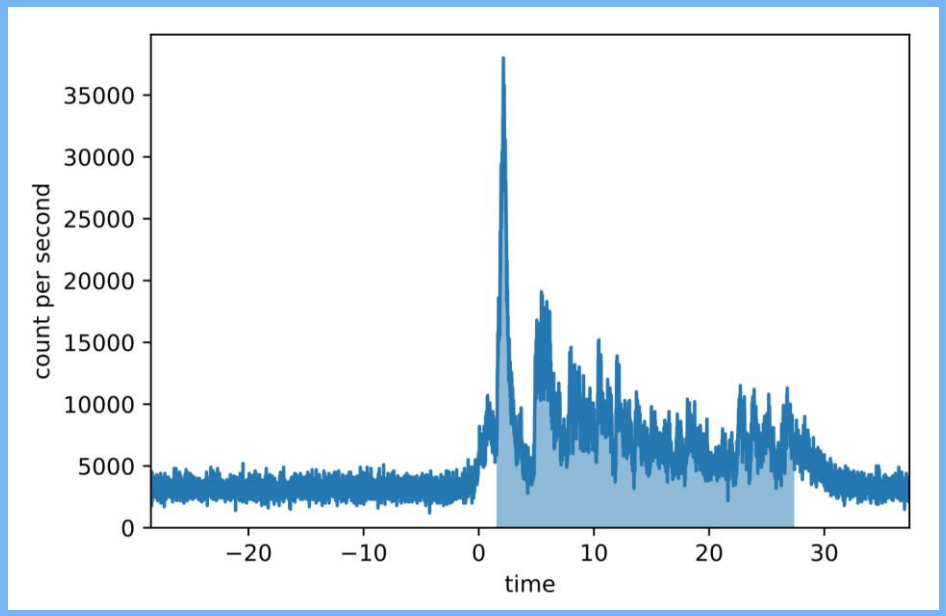
(Muñoz, Kovetz, Dai, Kamionkowski, PRL 117 (2016))

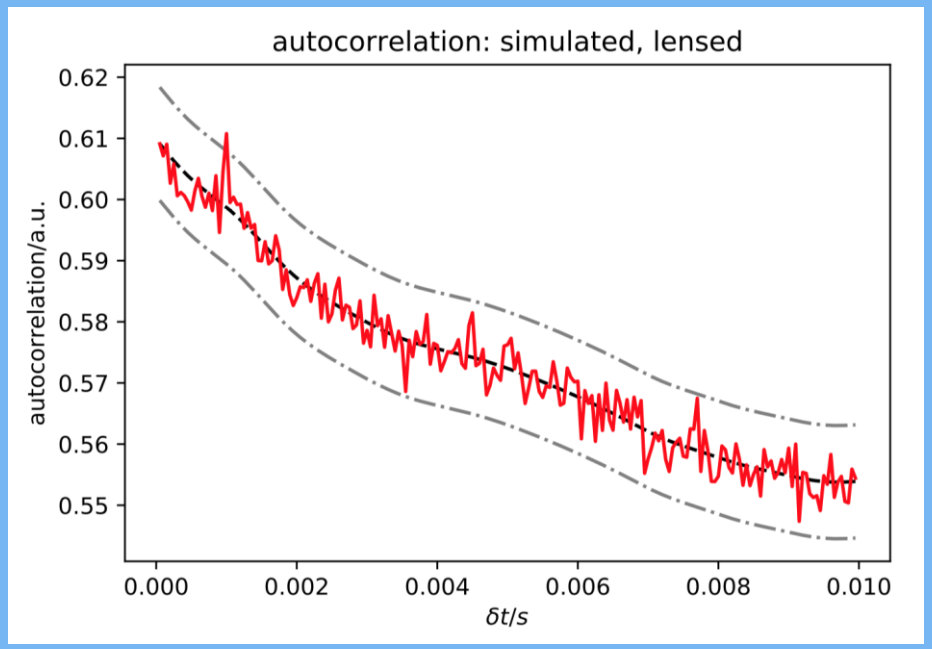


Images separation (~nano-arcsec) too small to be detected, but there can be a >ms time delay



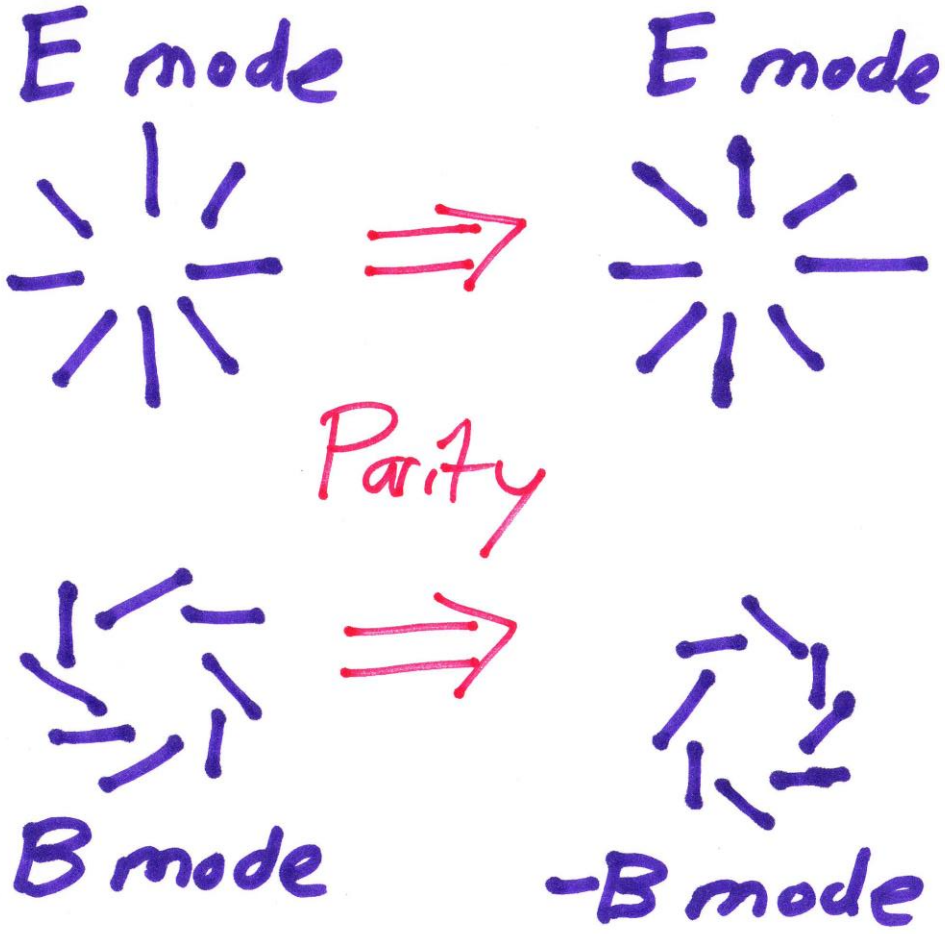
Can also seek echoes in gamma-ray-burst light curves
(Ji, Kovetz, MK 2019)





GWs, parity breaking, the CMB, and galaxy surveys

CMB Polarization



Parity-breaking CMB power spectra

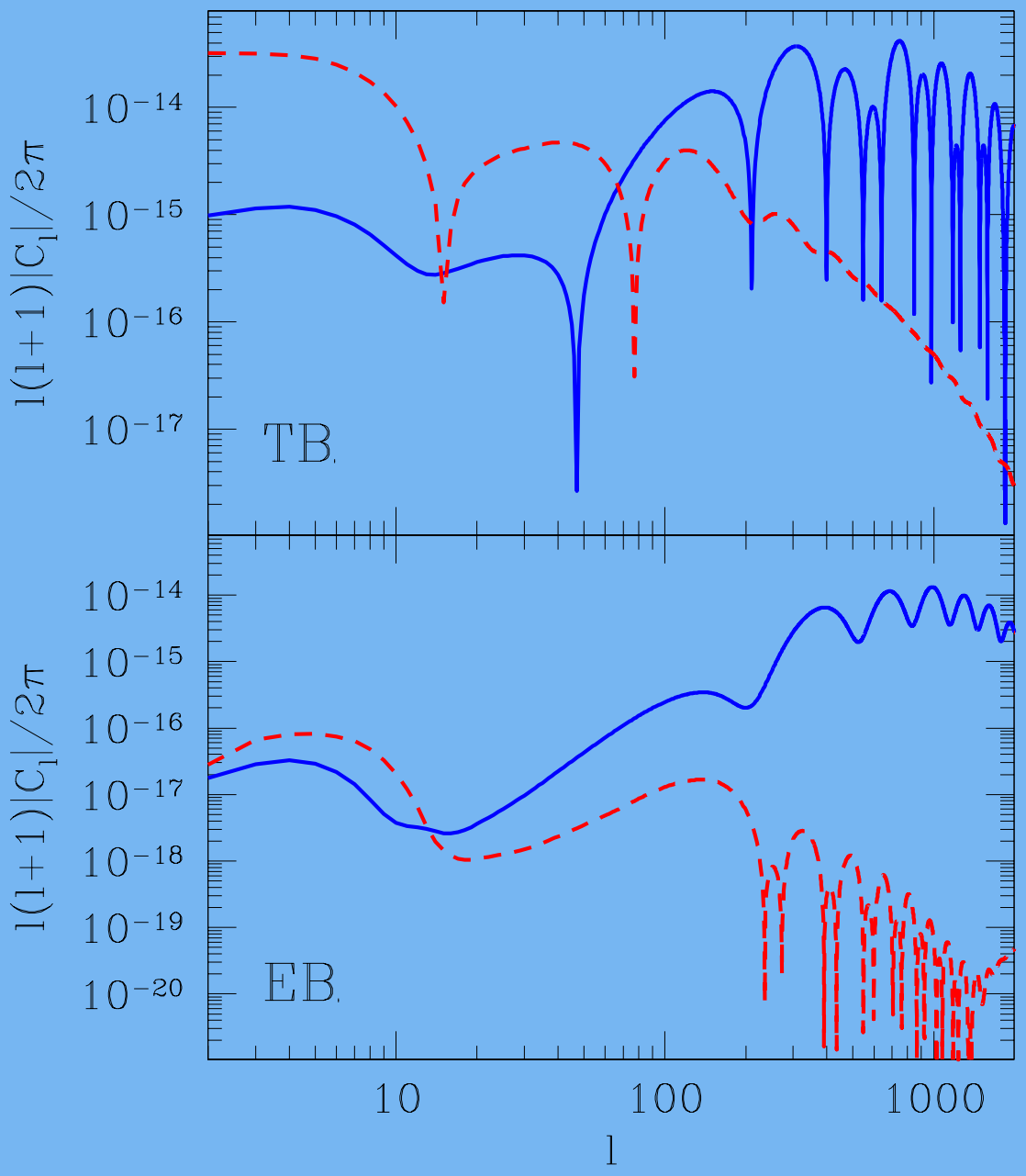
$$C_\ell^{\mathrm{TB}} \qquad C_\ell^{\mathrm{EB}}$$

Chiral gravitational waves
(Lue, Wang, MK, 1999)

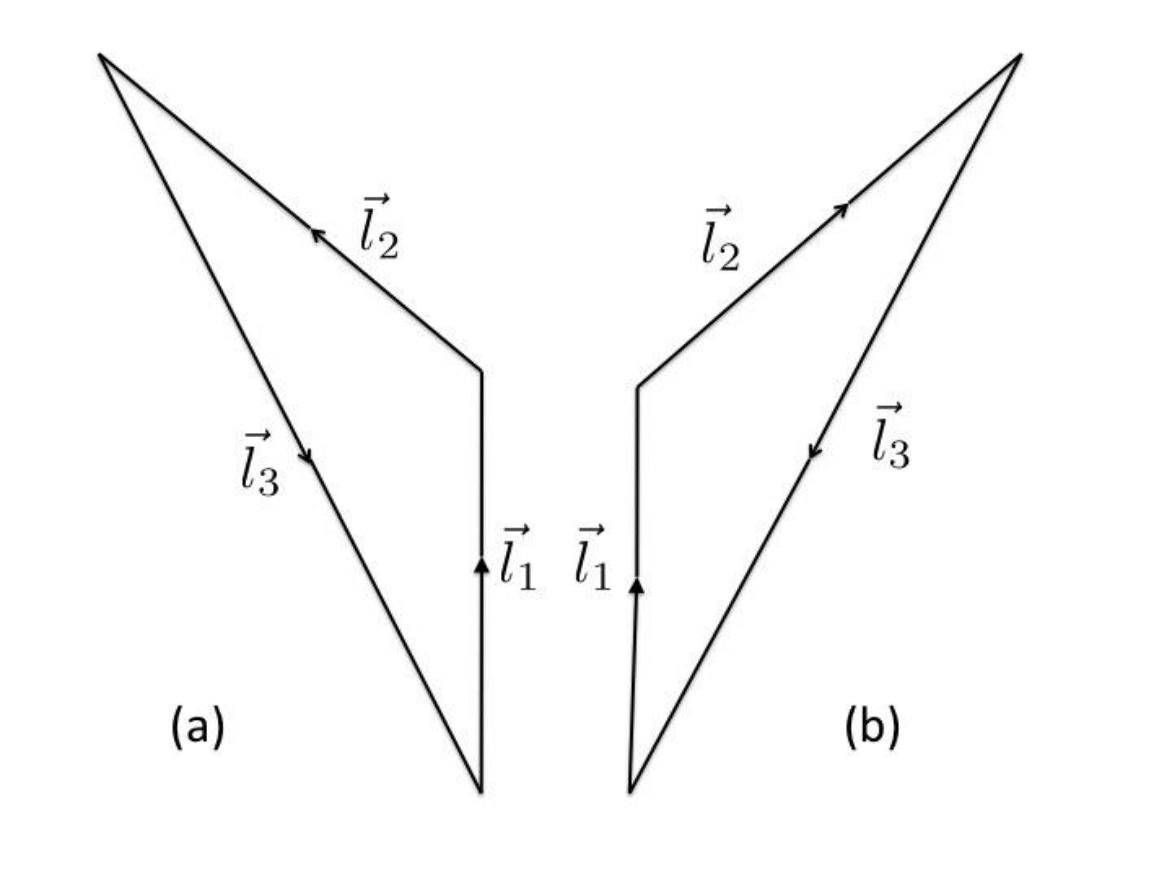
- Chern-Simons gravity during inflation

$$\phi R \tilde{R}$$

- May lead to right/left asymmetry and thus to EB/TB cross-correlation


10^{-14}
10^{-15}
10^{-16}
10^{-17}
$l(l+1)|C_l|/2\pi$
TB
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
$l(l+1)|C_l|/2\pi$
EB
10
100
1000
l

- Parity-breaking 3-pt correlations (Book, MK, Souradeep 2011)

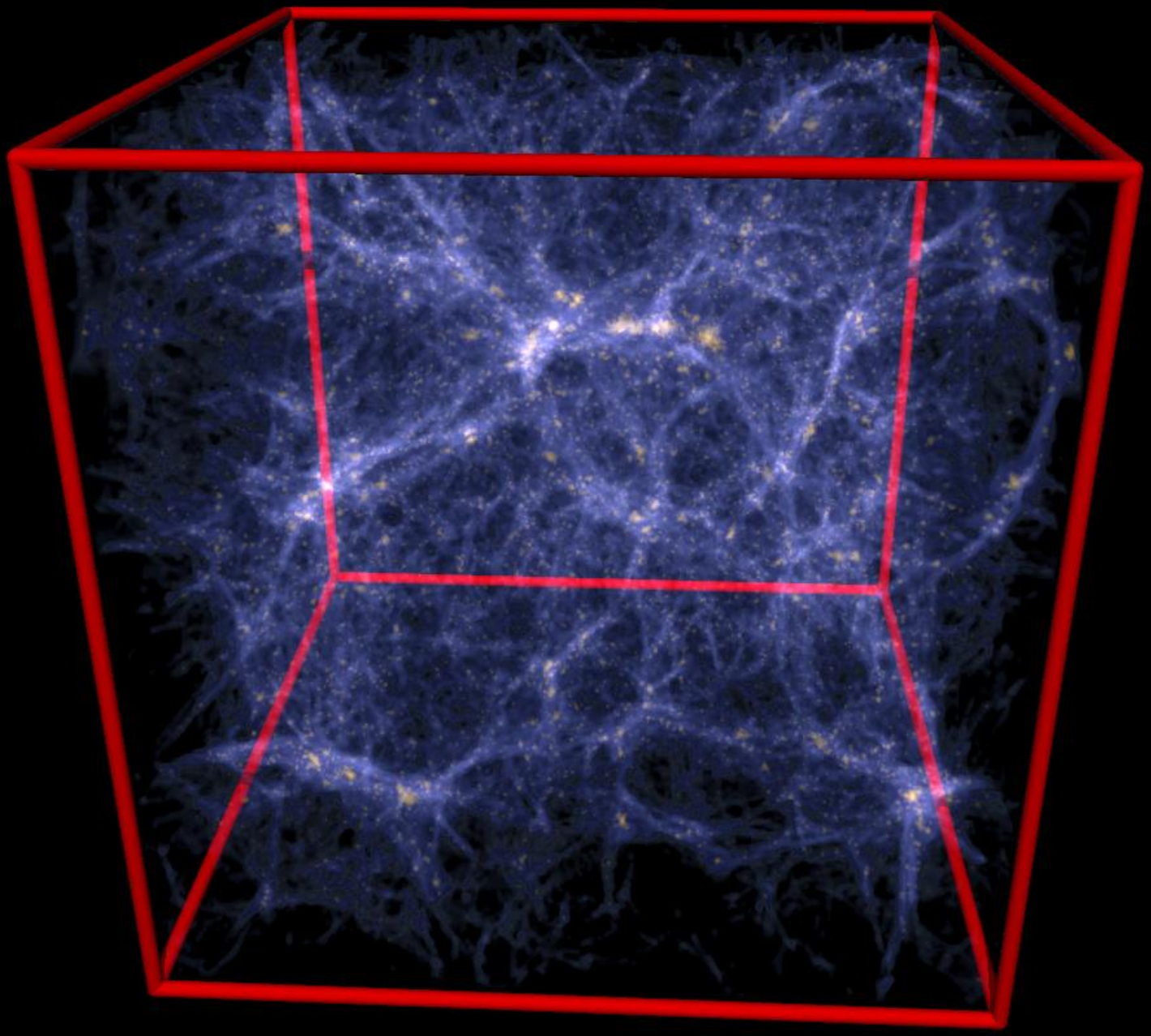


e.g., from chiral GWs

B modes and parity tests for galaxy surveys

Jeong & MK 2012

Dai, Jeong, MK 2013



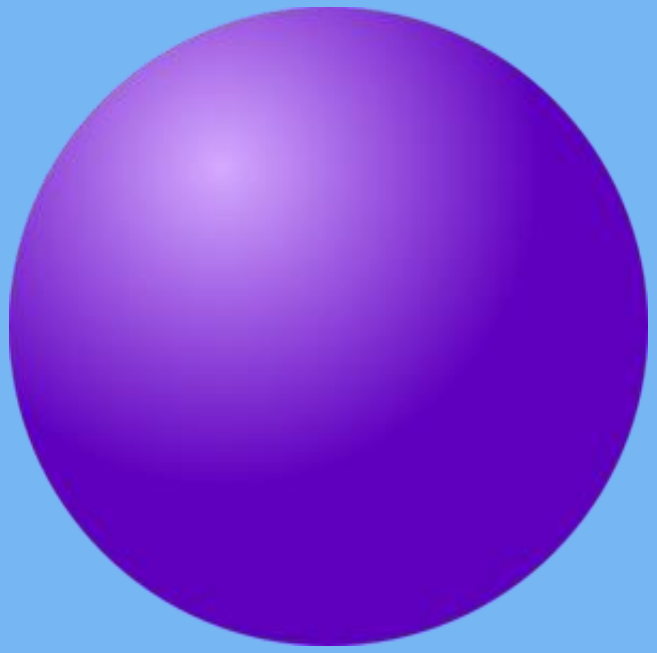
$$\rho(\vec{x})$$

$$\langle \rho(\vec{x})\rho(\vec{x}+\vec{r})\rangle = \xi(r)$$

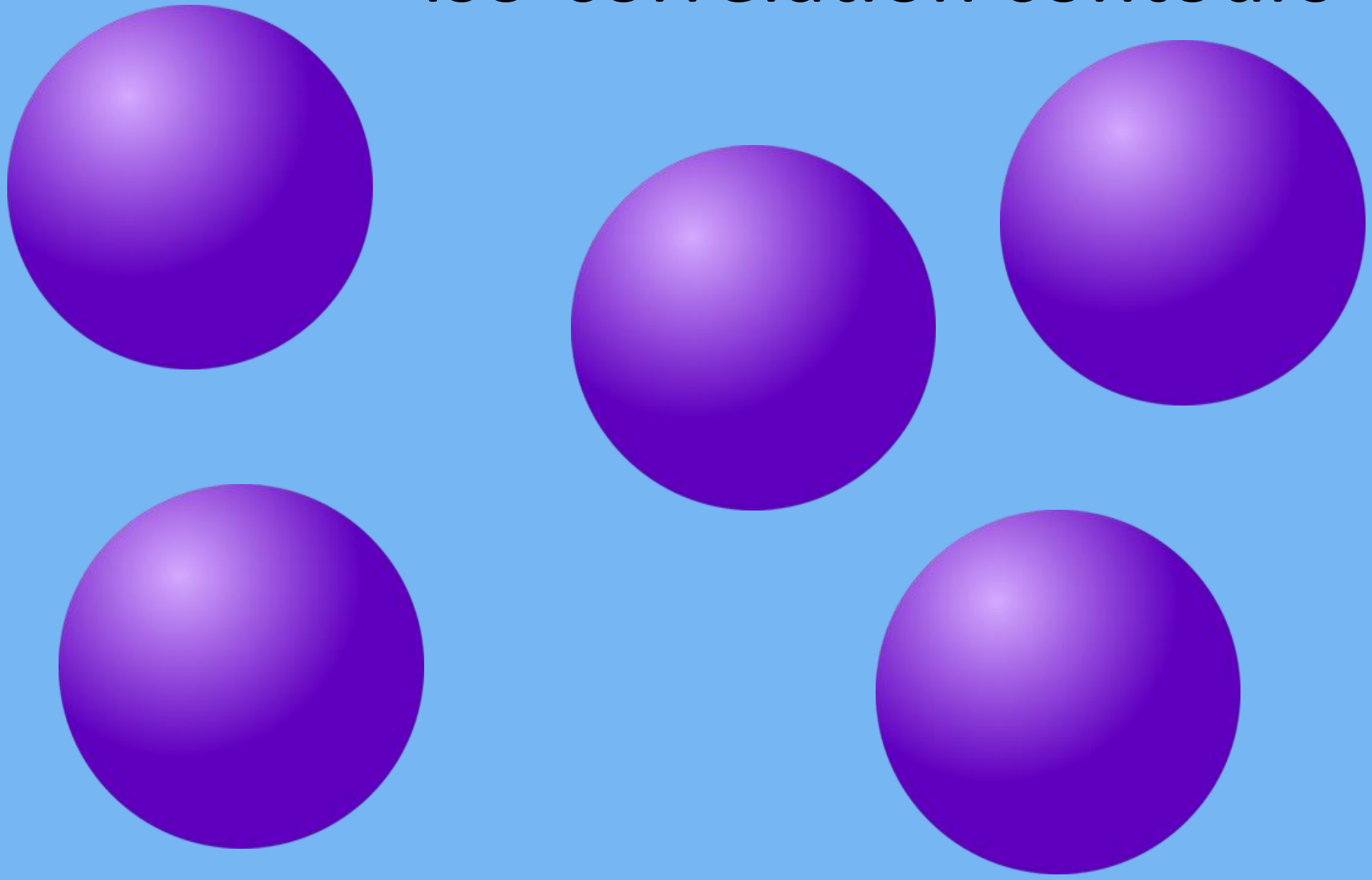
Two-point autocorrelation function

Statistically isotropy and homogeneity (translational/rotational invariance)

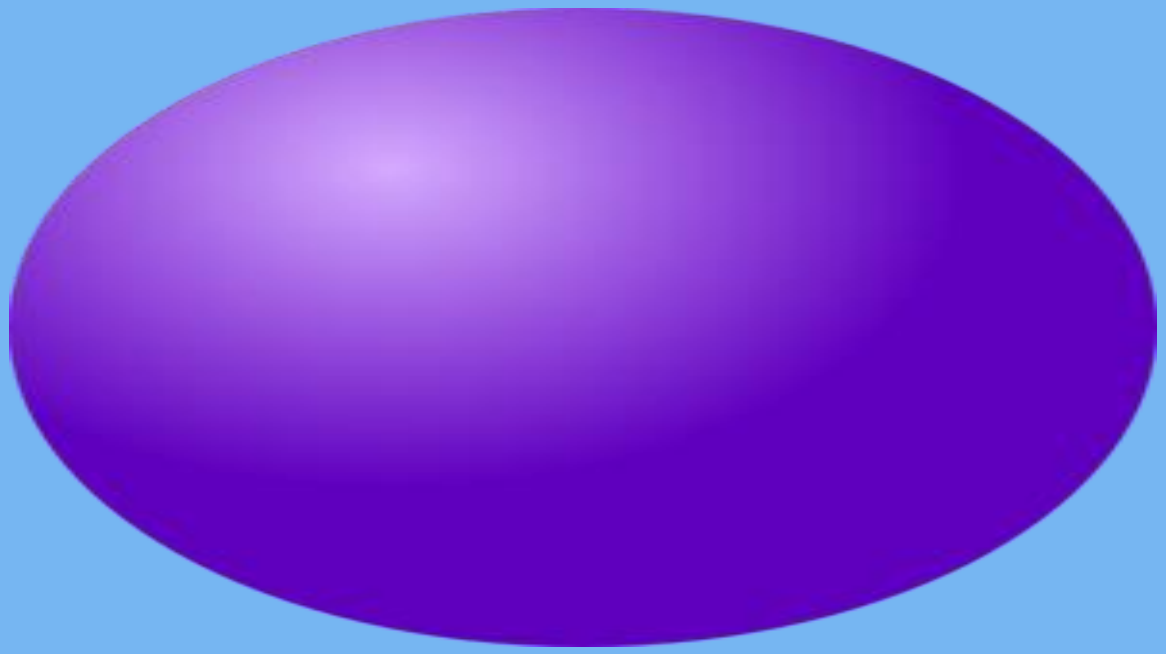
Iso-correlation contours



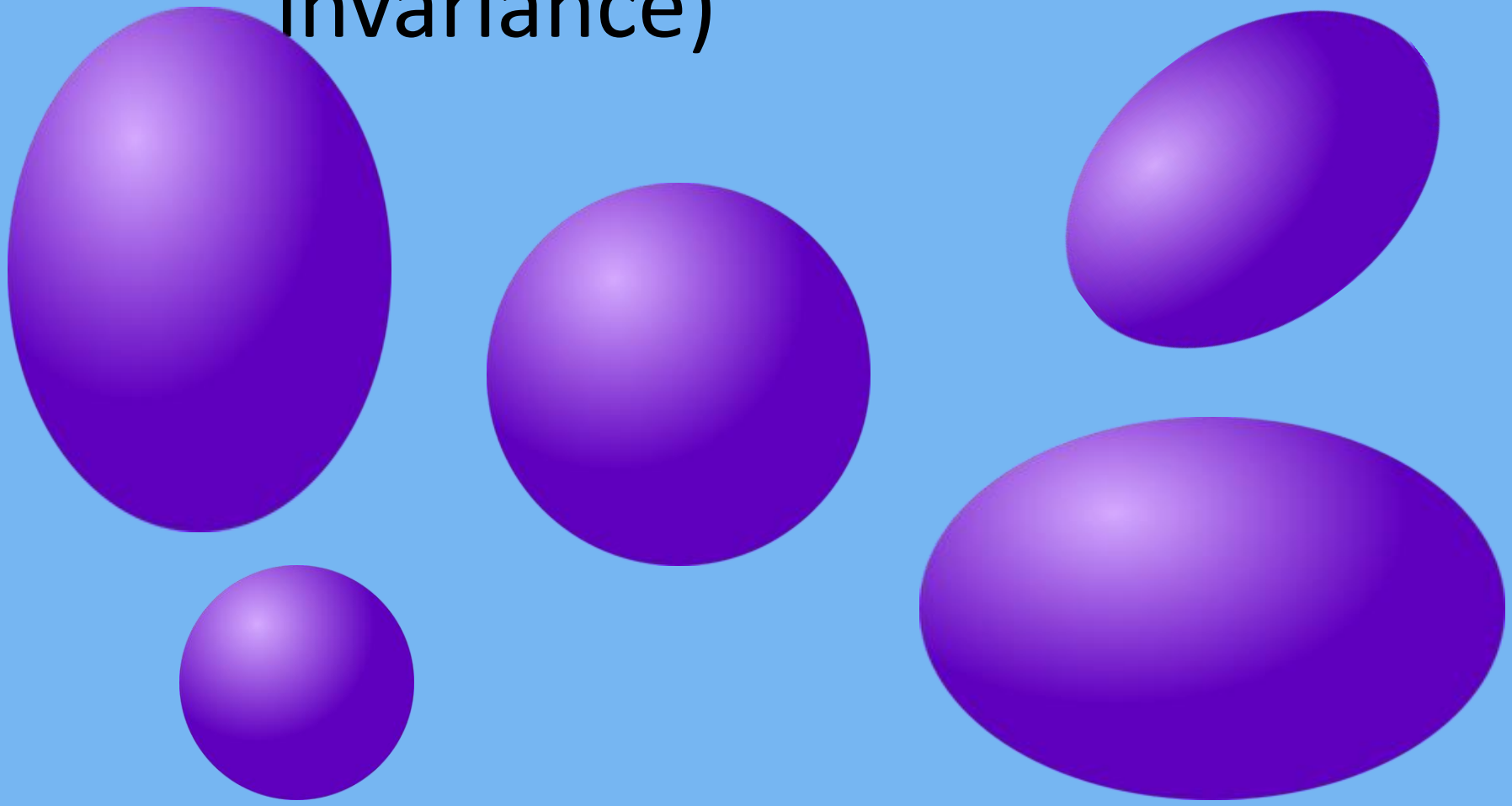
Iso-correlation contours



But departure from statistical isotropy (rotational invariance) is conceivable



As is departure from statistical homogeneity (translational invariance)



Elongations of iso-correlation contours

$\sim$

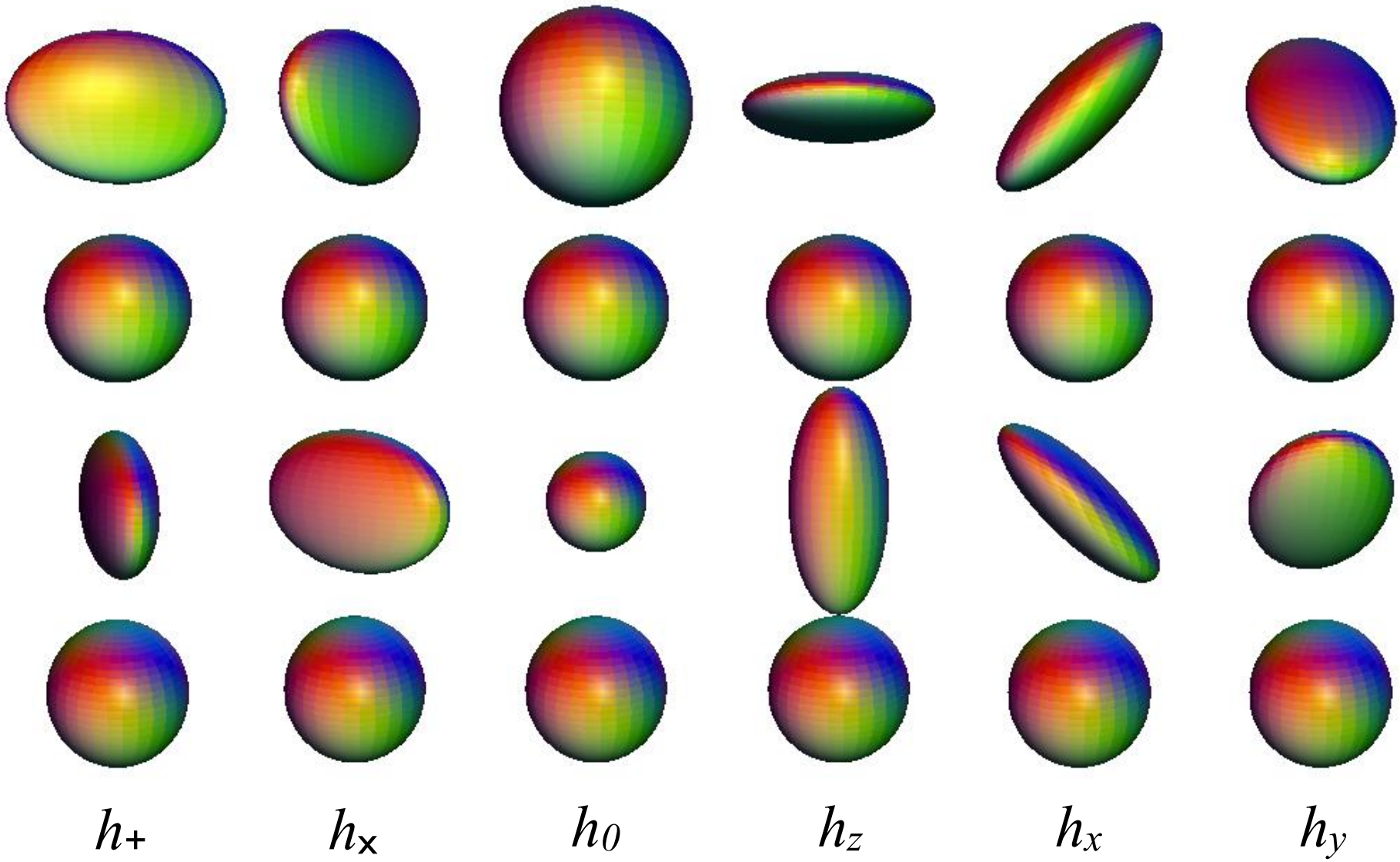
CMB polarization

Ellipticity in 3d

5 degrees of freedom

Elongation in 2d

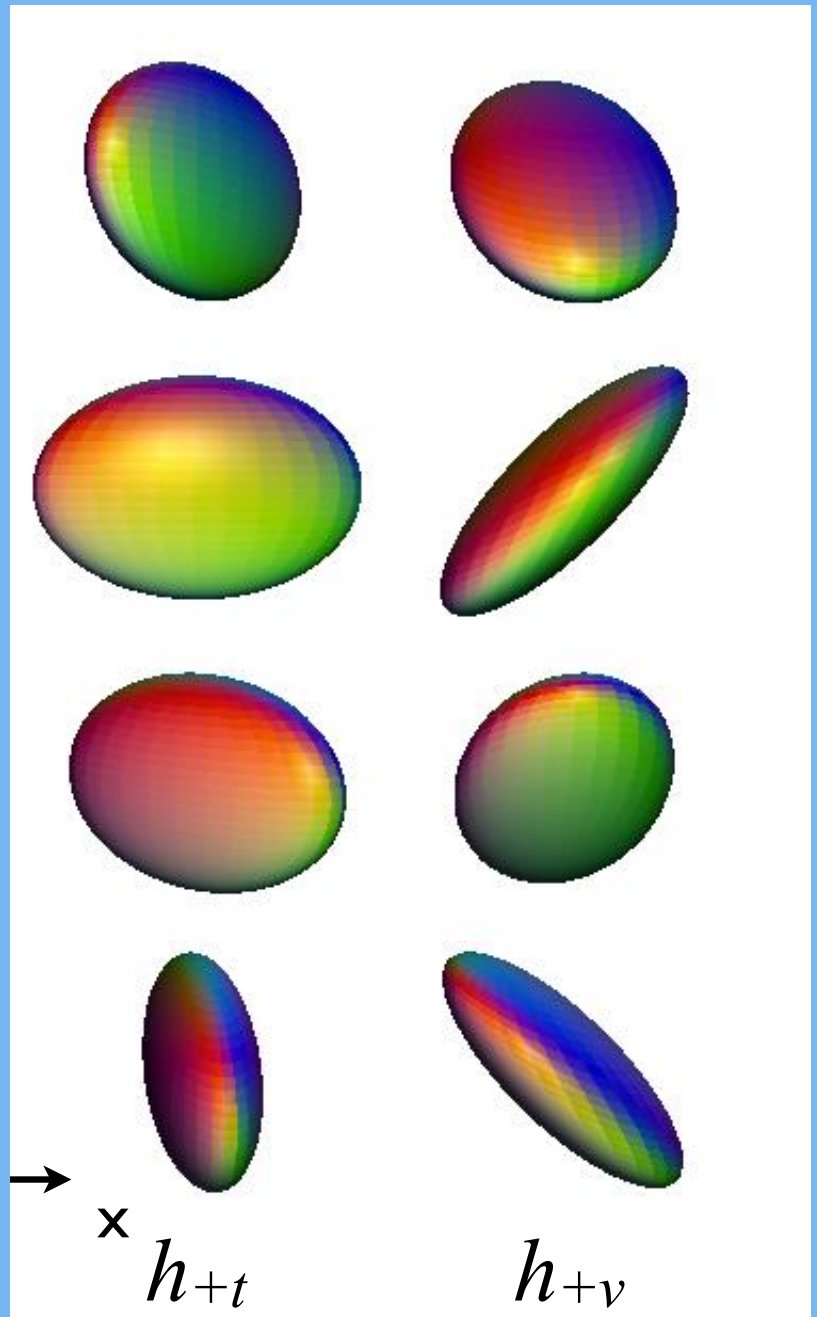
2 degrees of freedom

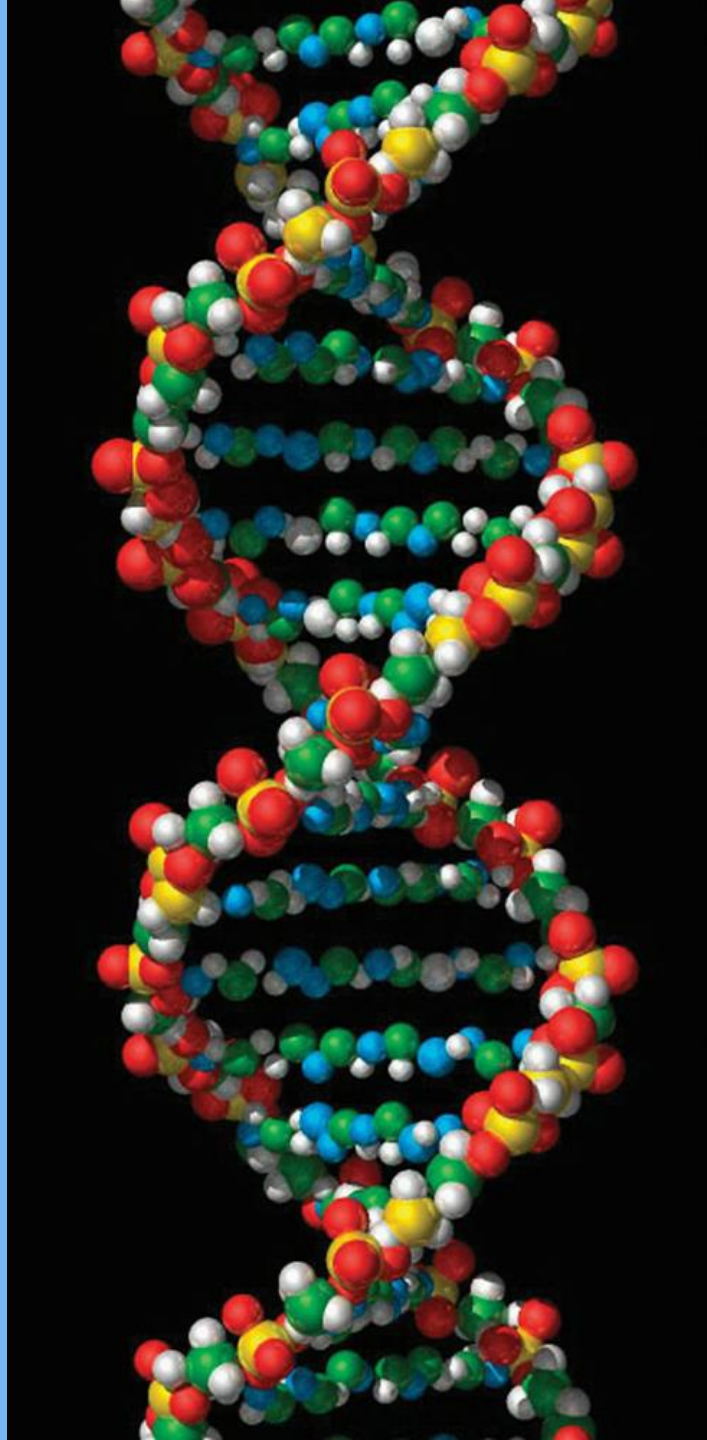

h_+
$h_\times$
h_0
h_z
h_x
h_y

parity

$$h^t_{R,L} = (h_+ \pm i h_\times)/\sqrt{2}$$

$$h^v_{R,L} = (h_x \pm i h_y)/\sqrt{2}$$


→
×
h_{+t}
h_{+v}



Chirals GWs → Chiral CMB photons

Interaction of CMB photons with anisotropic CMB bkgrd → circular polarization (Sawyer 2012, Montero-Camacho & Hirata 2018)

CMB anisotropies may be from primordial GWs (Inomata & MK, arXiv:1811.04957)

Preferred handedness in chiral GW bkgrd imprinted on CMB photons (Inomata&MK 1811.04959)

Conclusions:

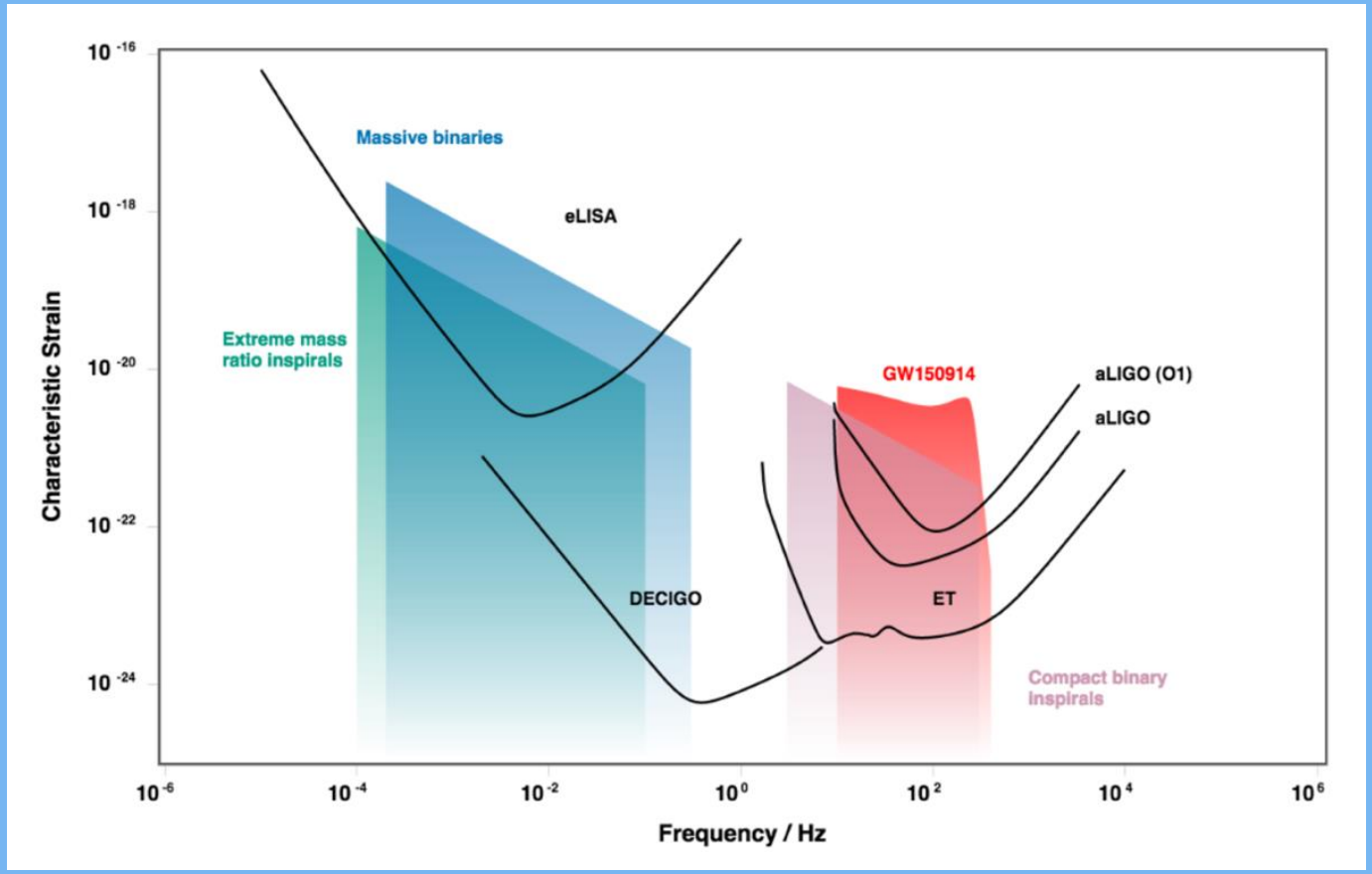
- ~30-Msun PBHs face challenges:
  now “guilty until proven innocent”;
  observations can shed more light

- CMB/LSS provide opportunities to seek parity-breaking effects that may arise from effects related to Hubble-scale GWs

- Need to keep thinking and searching!

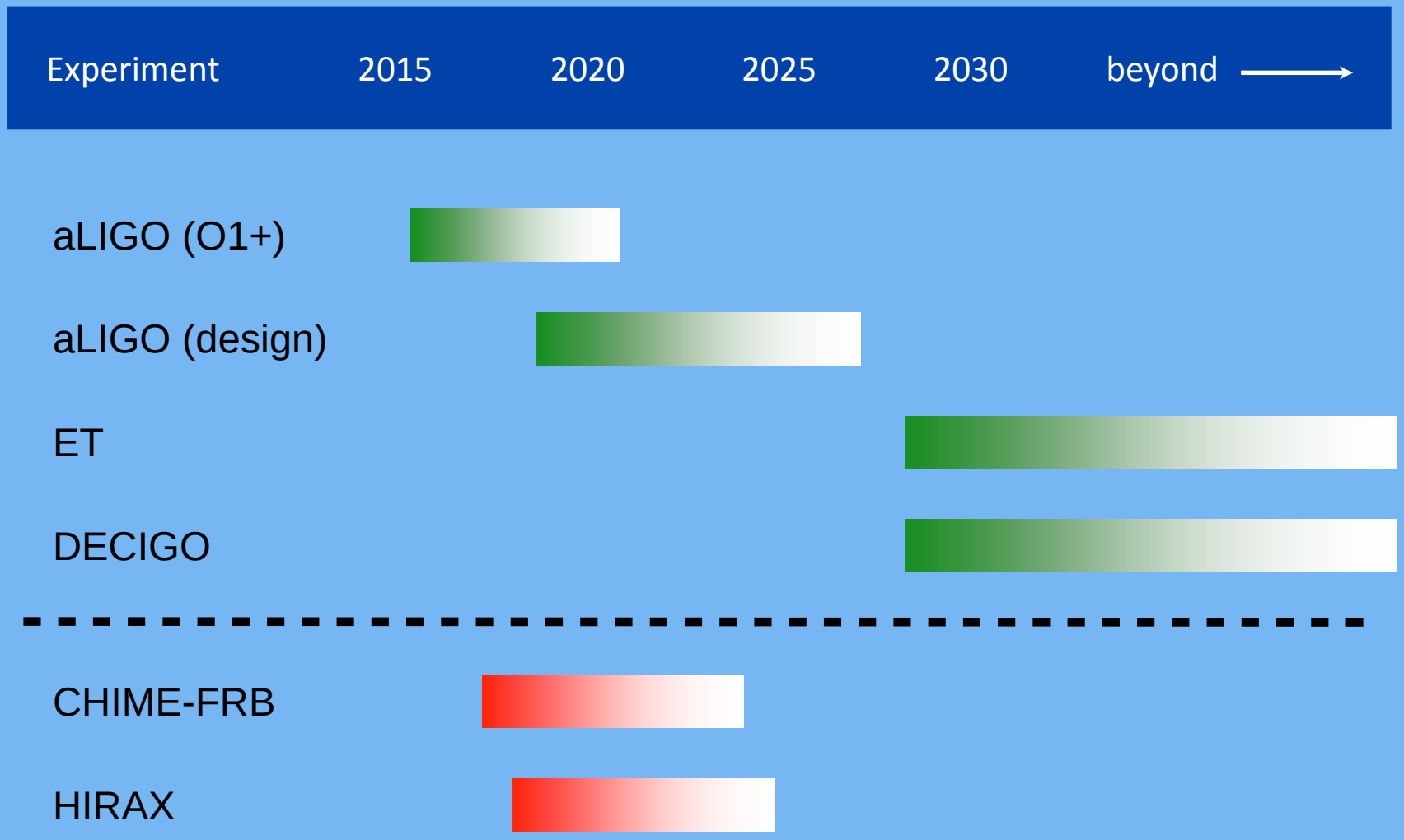
Observational Outlook

Gravitational waves:



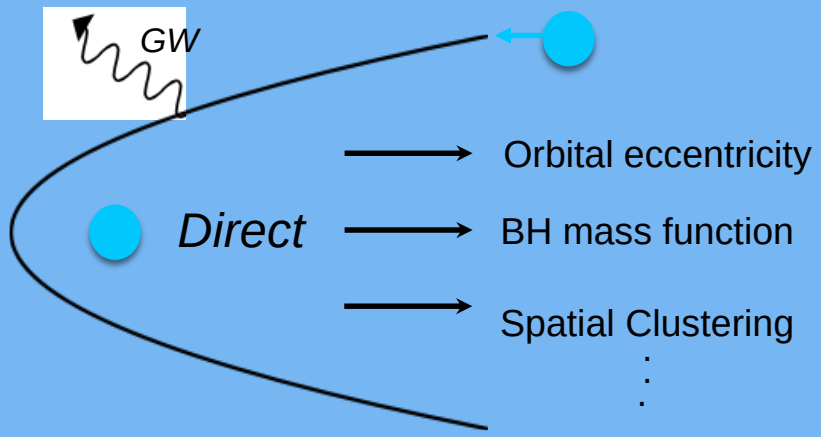
Fast Radio Bursts: **Lots of instruments, including CHIME, HIRAX...**

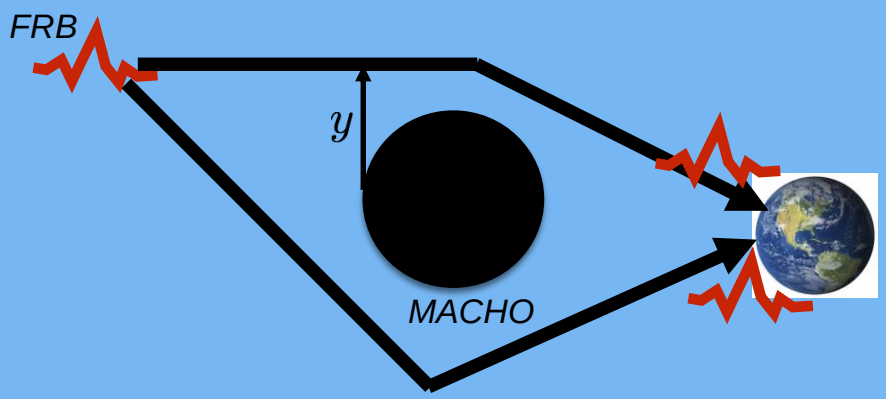
Observational Outlook: Experiment Timeline



Conclusion:

Theory



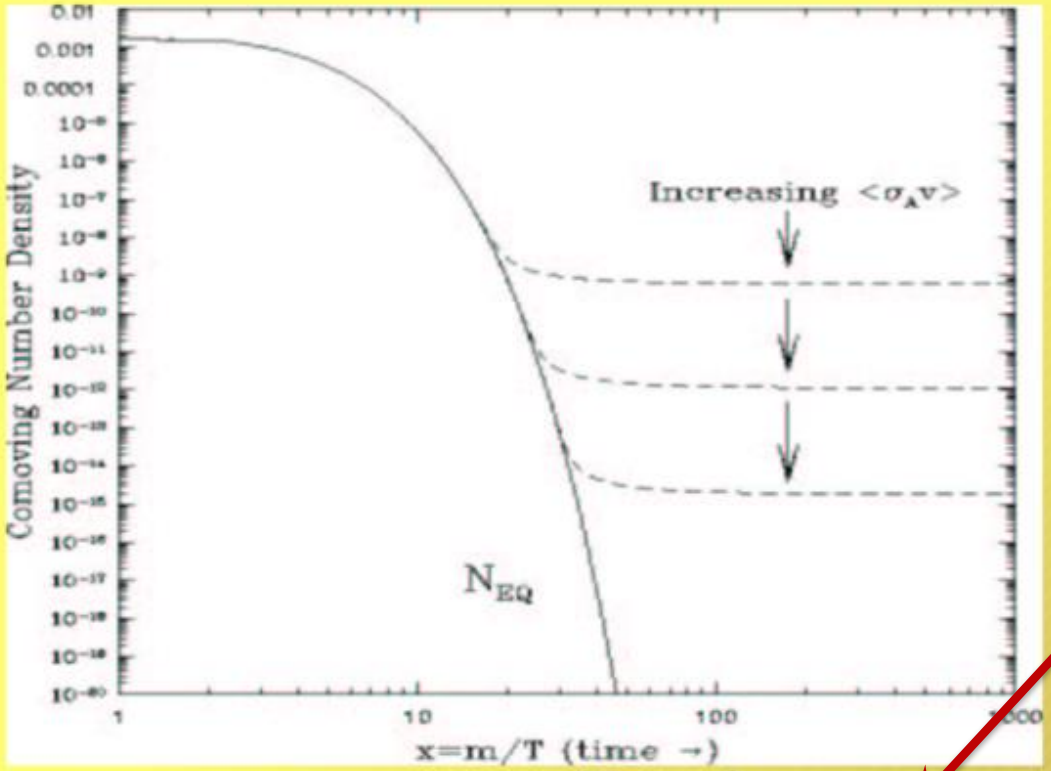


Indirect → FRB lensing time-delay + . . .

Experiment

Next Decade is promising!

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



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

$$\sim \frac{\alpha^2}{m_W^2}$$

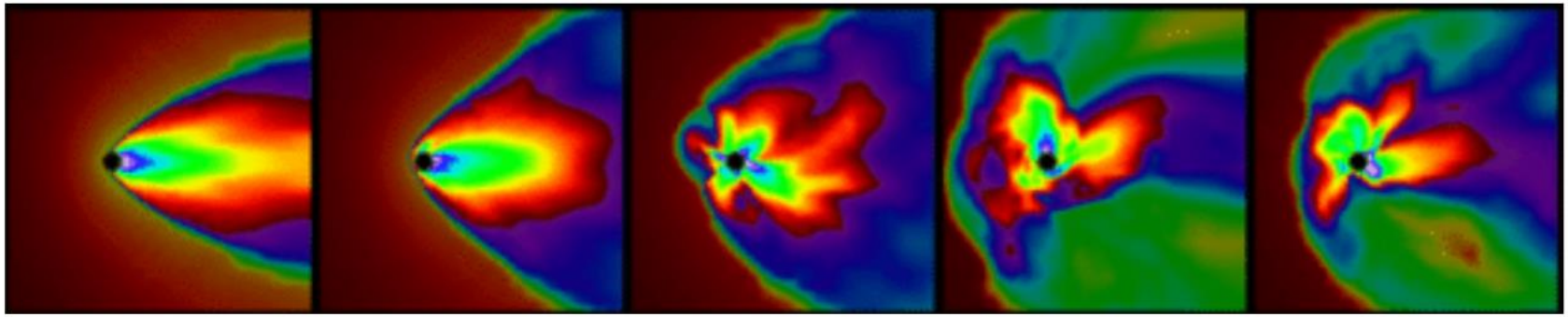
(e

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): $c_s \rightarrow (c_s^2 + v_{rel}^2)^{1/2}$

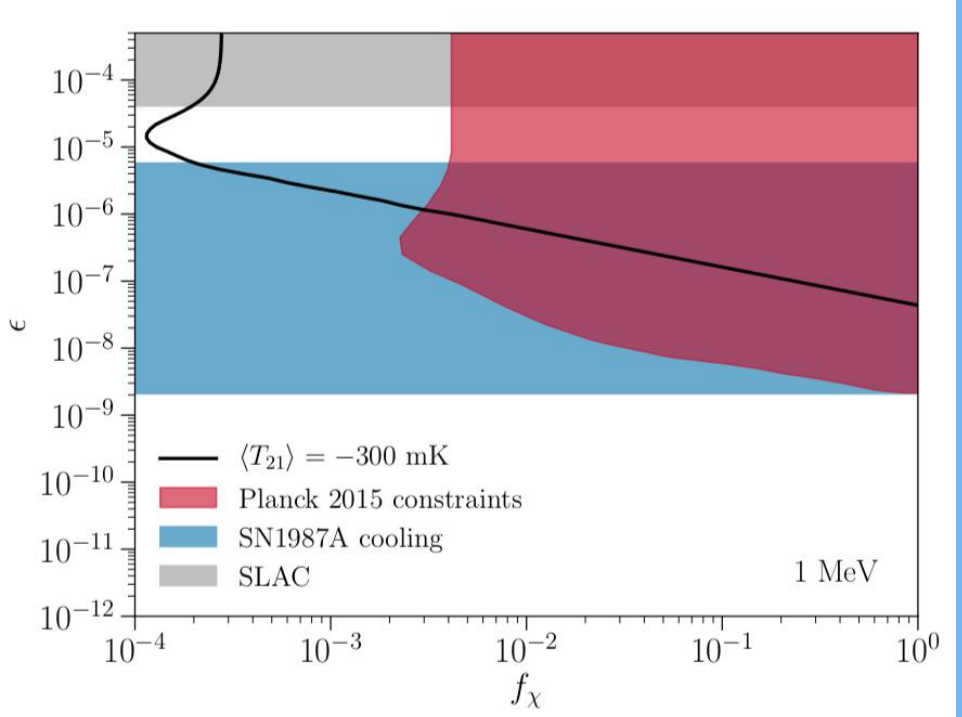
in the simple Bondi case: $$L \propto \dot{M}^2 \propto \frac{1}{(c_s^2 + v_{\rm rel}^2)^3}$$

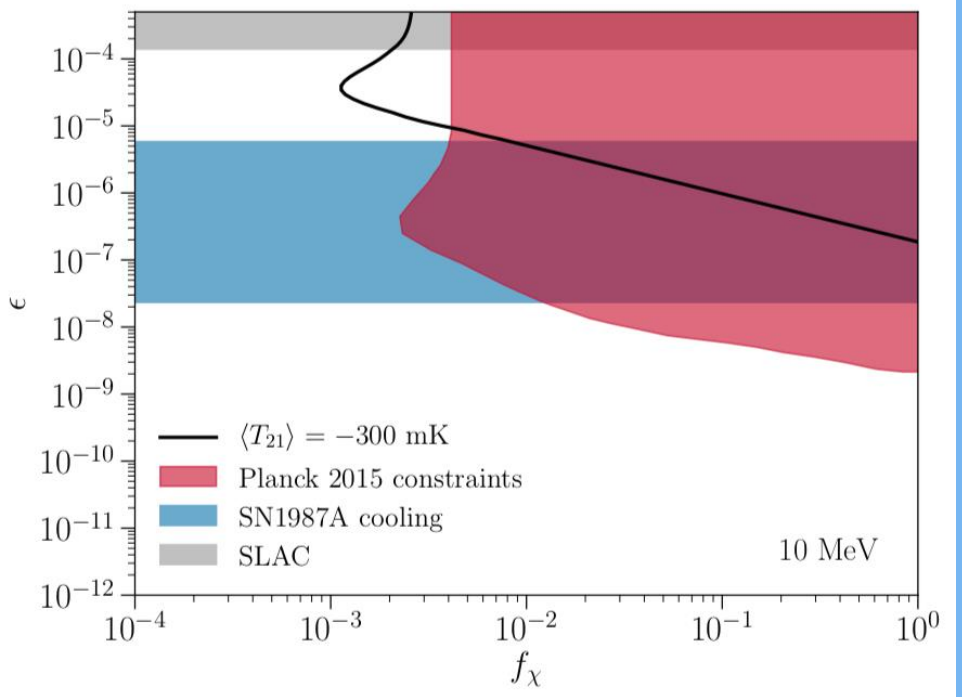
$$\langle L \rangle \propto \left\langle \frac{1}{(c_s^2 + v_{\rm rel}^2)^3} \right\rangle \approx \frac{1}{c_s^3 \langle v_{\rm rel}^2 \rangle^{3/2}}, \quad \langle v_{\rm rel}^2 \rangle \gg c_s^2$$

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

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.





New constraints for millicharged DM!

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

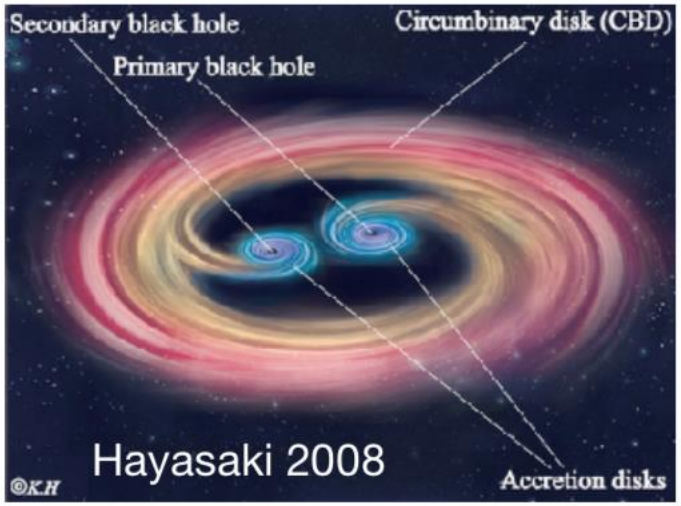
Kovetz, Poulin, Gluscevic, Boddy, Barkana, MK, any day now)

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.

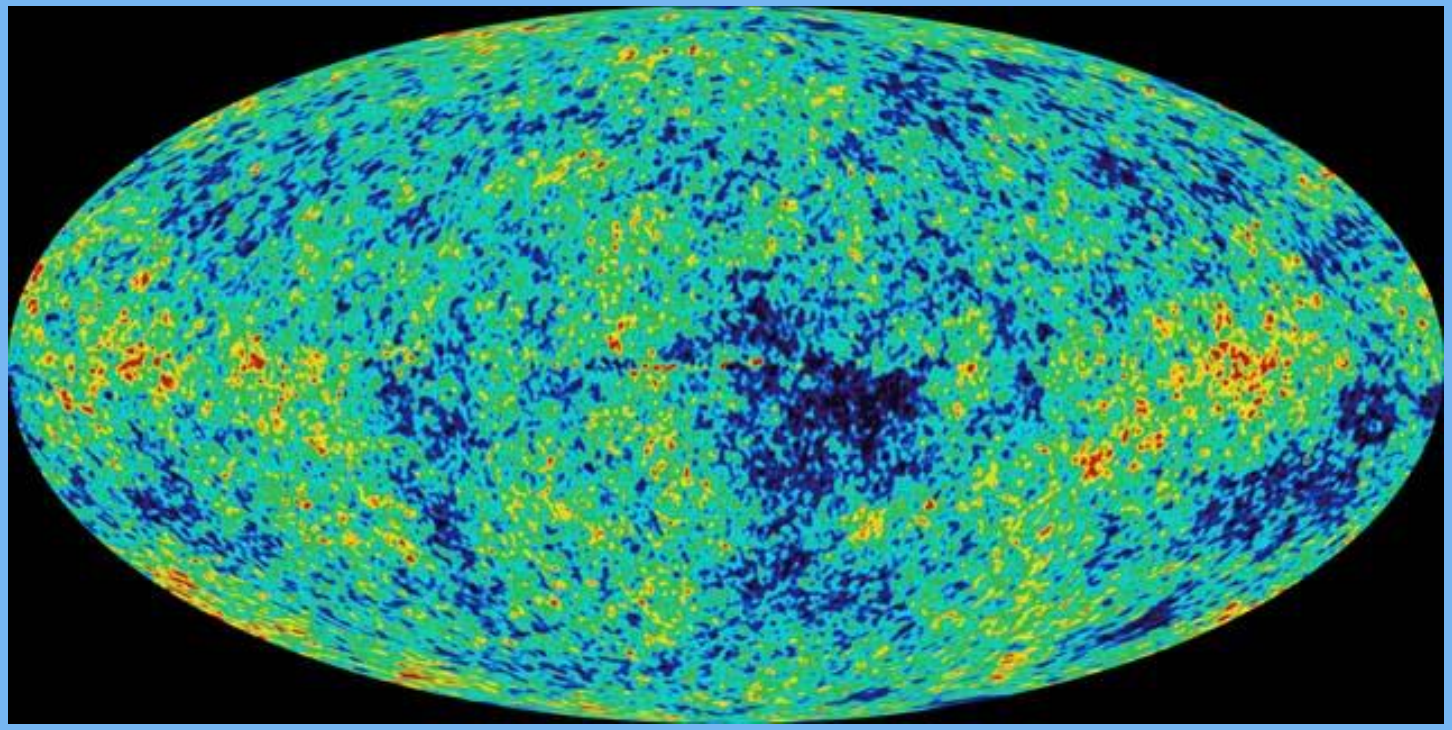
- Exchange of energy and angular momentum with accreting baryons



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

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!!)

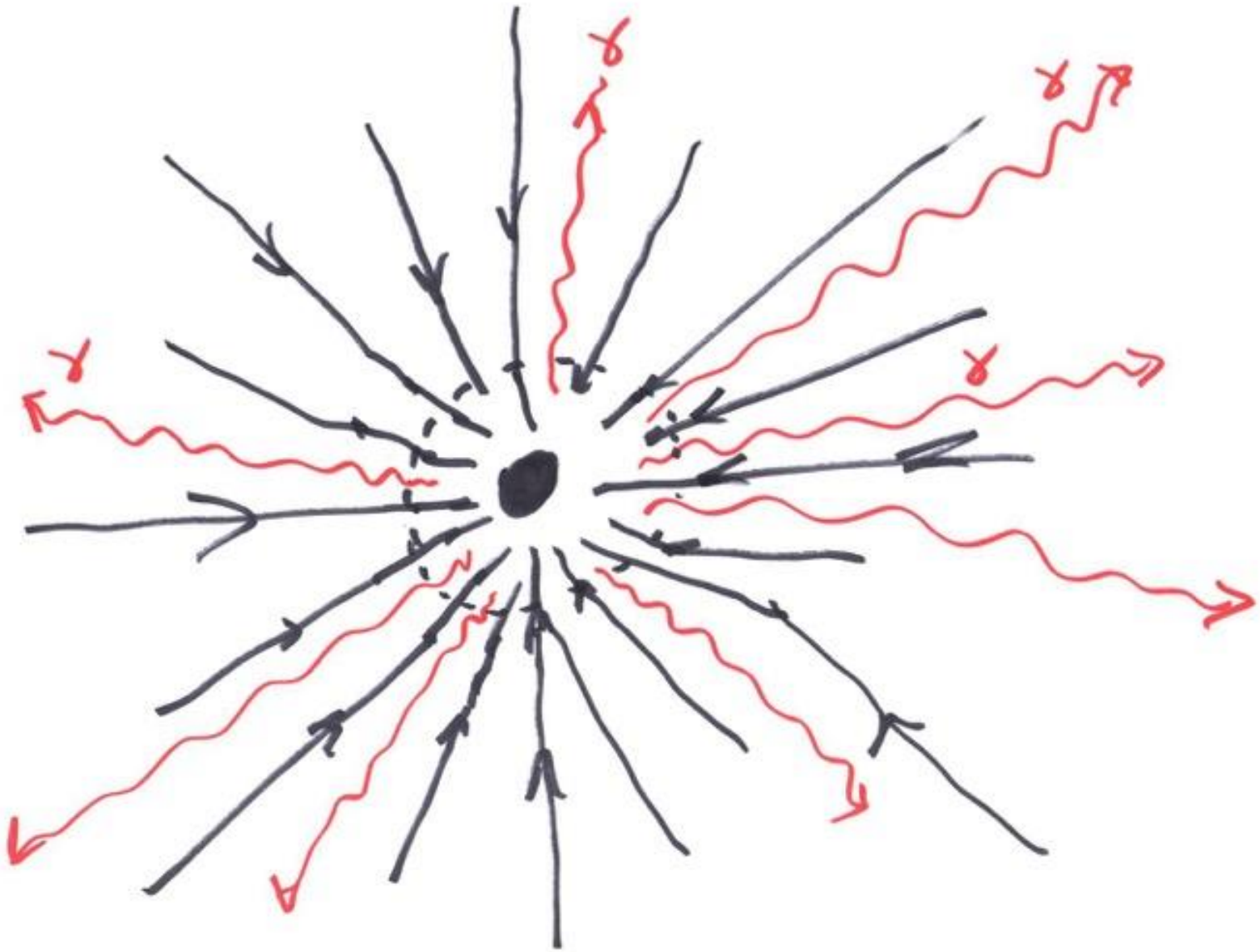


How does the CMB probe PBHs?

- PBHs accrete primordial plasma
- Accreted gas gets heated
- Heated gas radiates
- heats plasma → distortions to blackbody
- affects ionization balance

  → changes how $e^+ + p$ → H

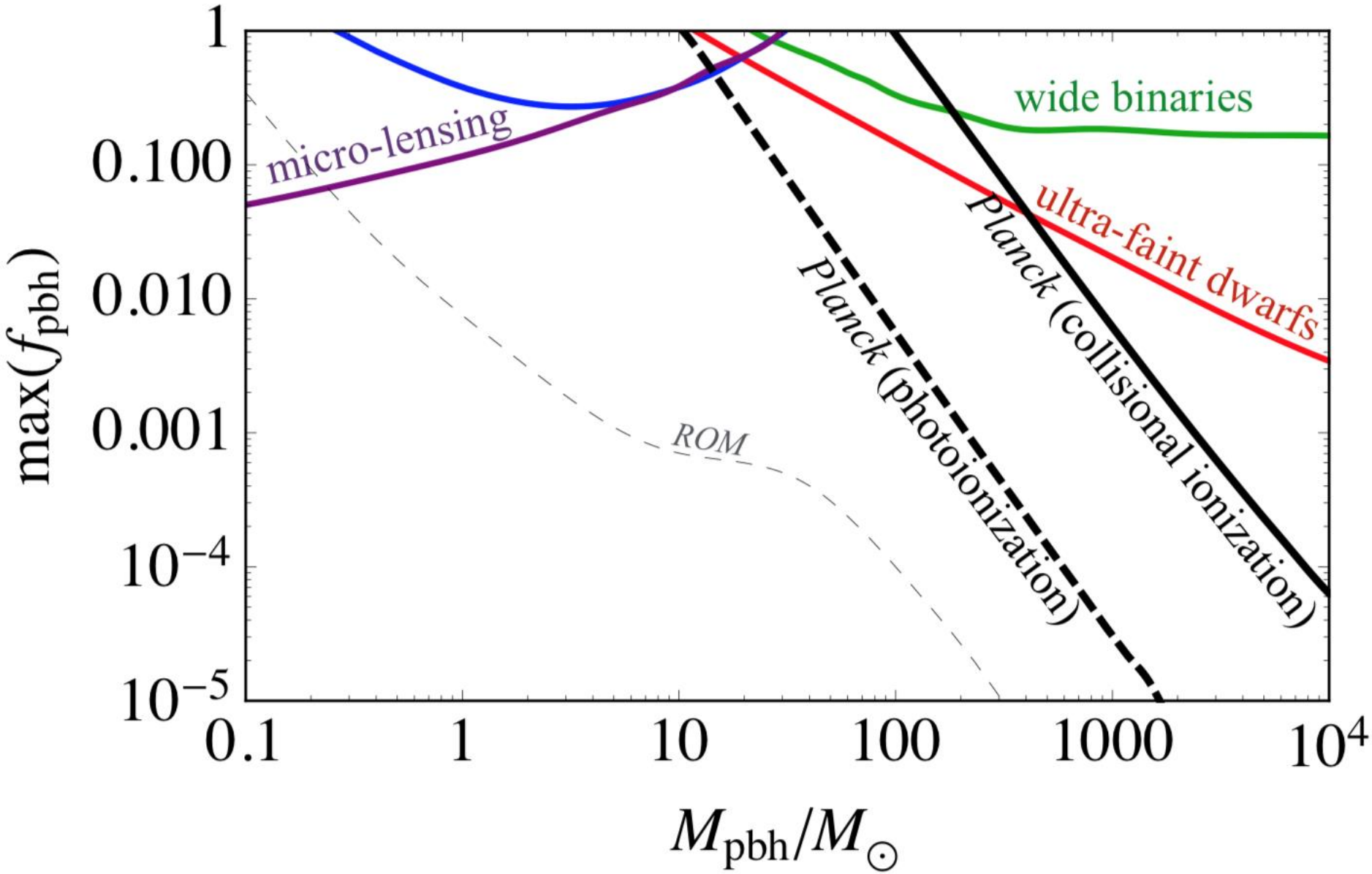
  → affects angular CMB pattern

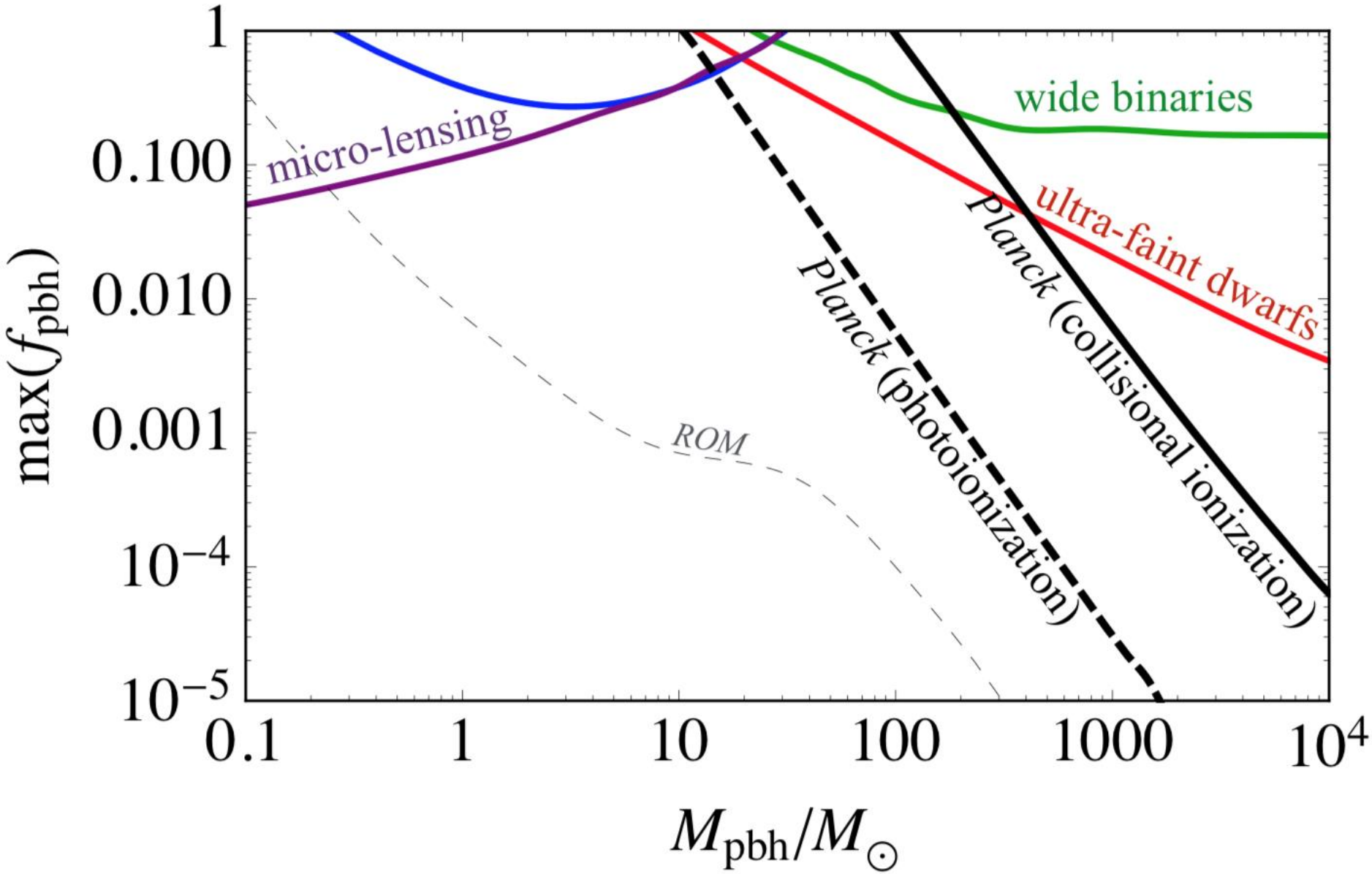

γ
γ
γ
γ

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


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



Horowitz (2017) and Aloni-Blum-Flauger (2017) concur

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~~

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

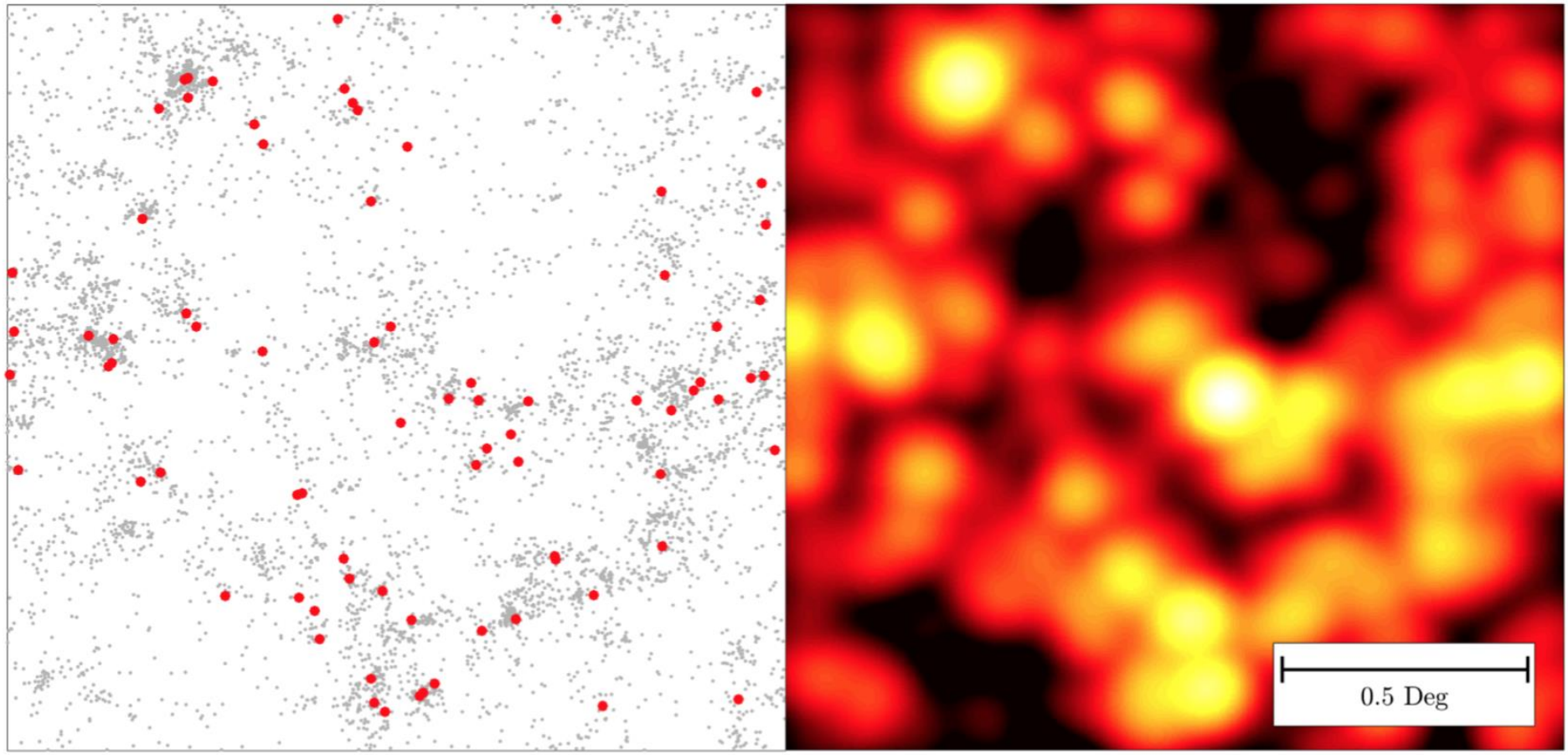


Fig credit: Patrick Breysse

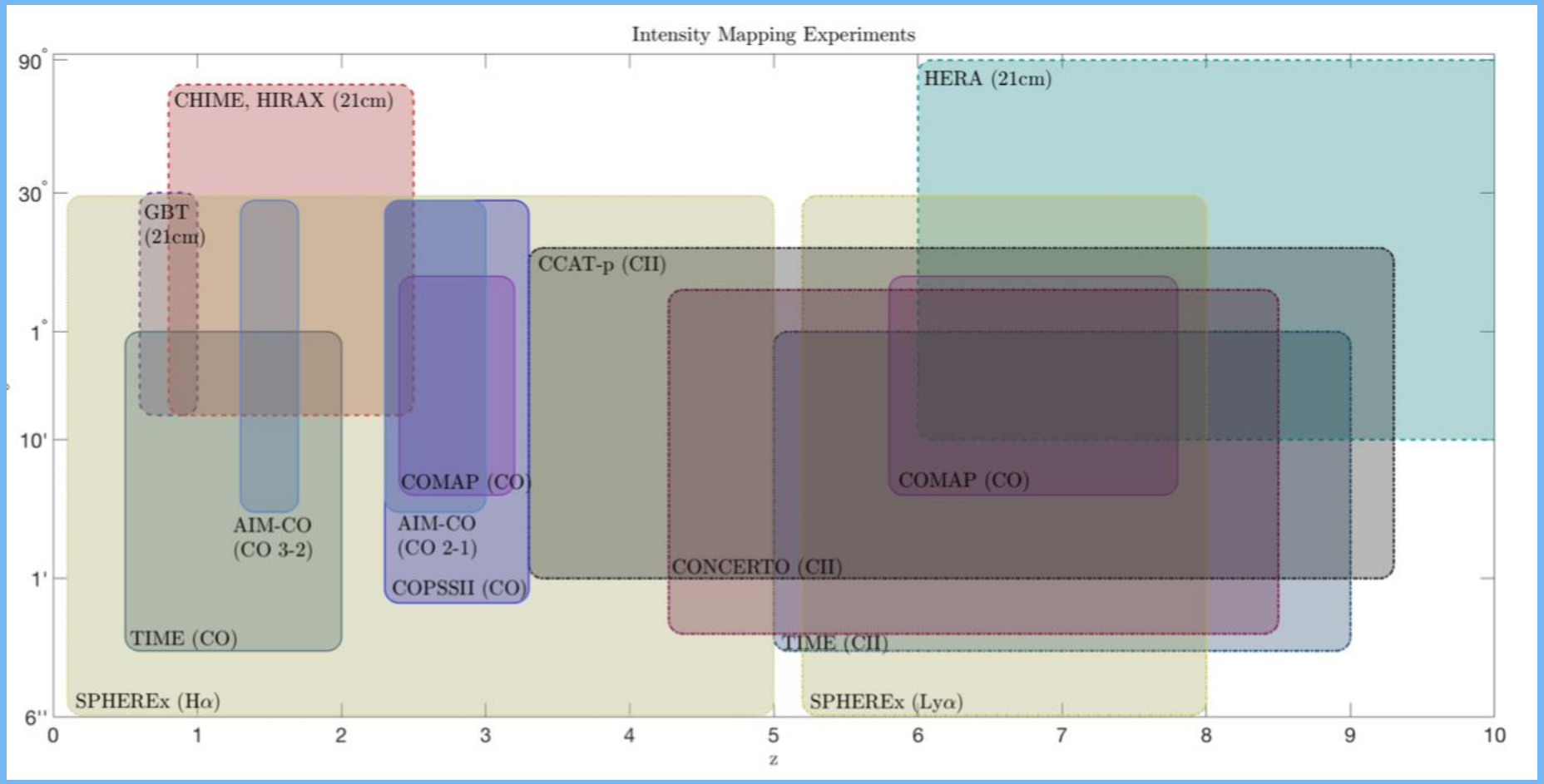
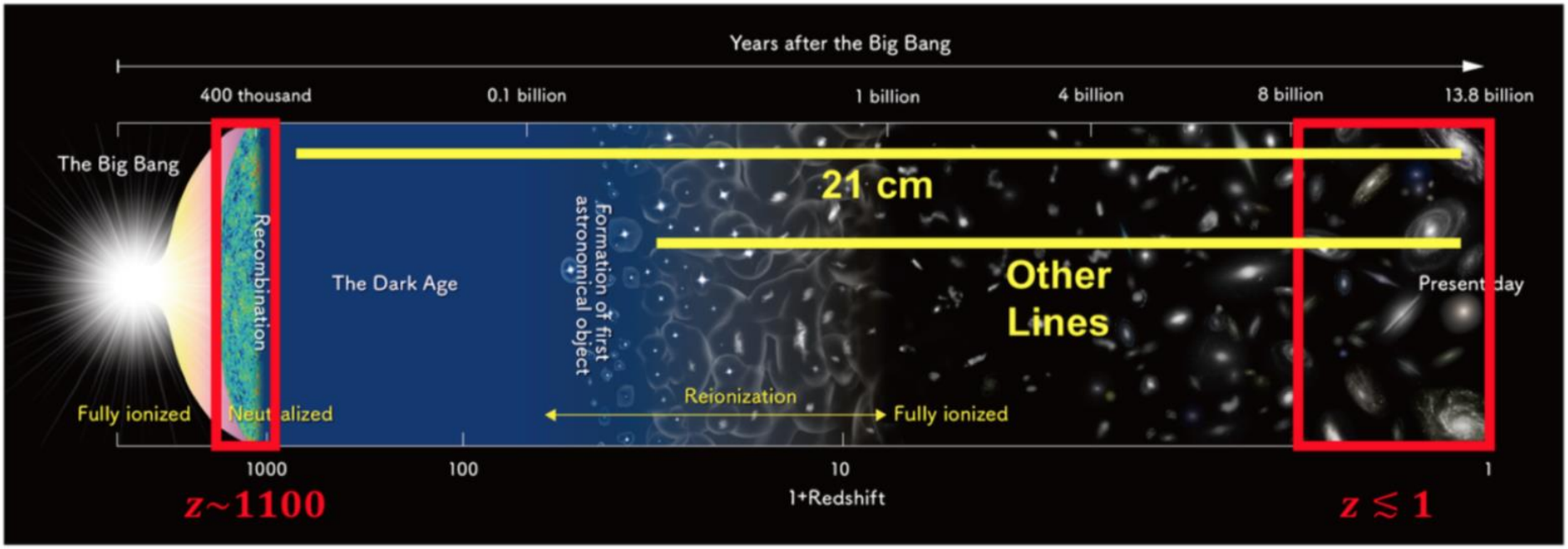
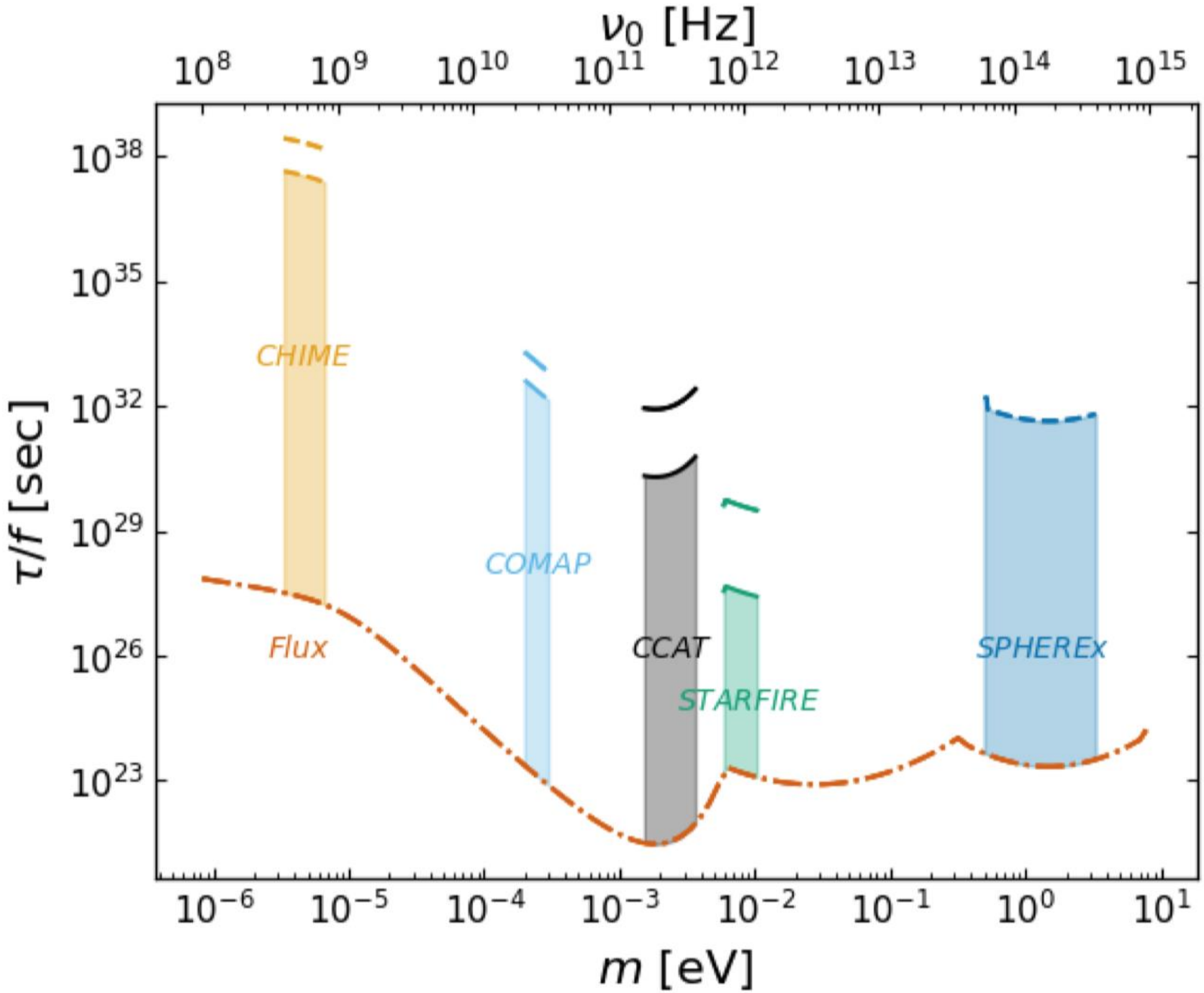


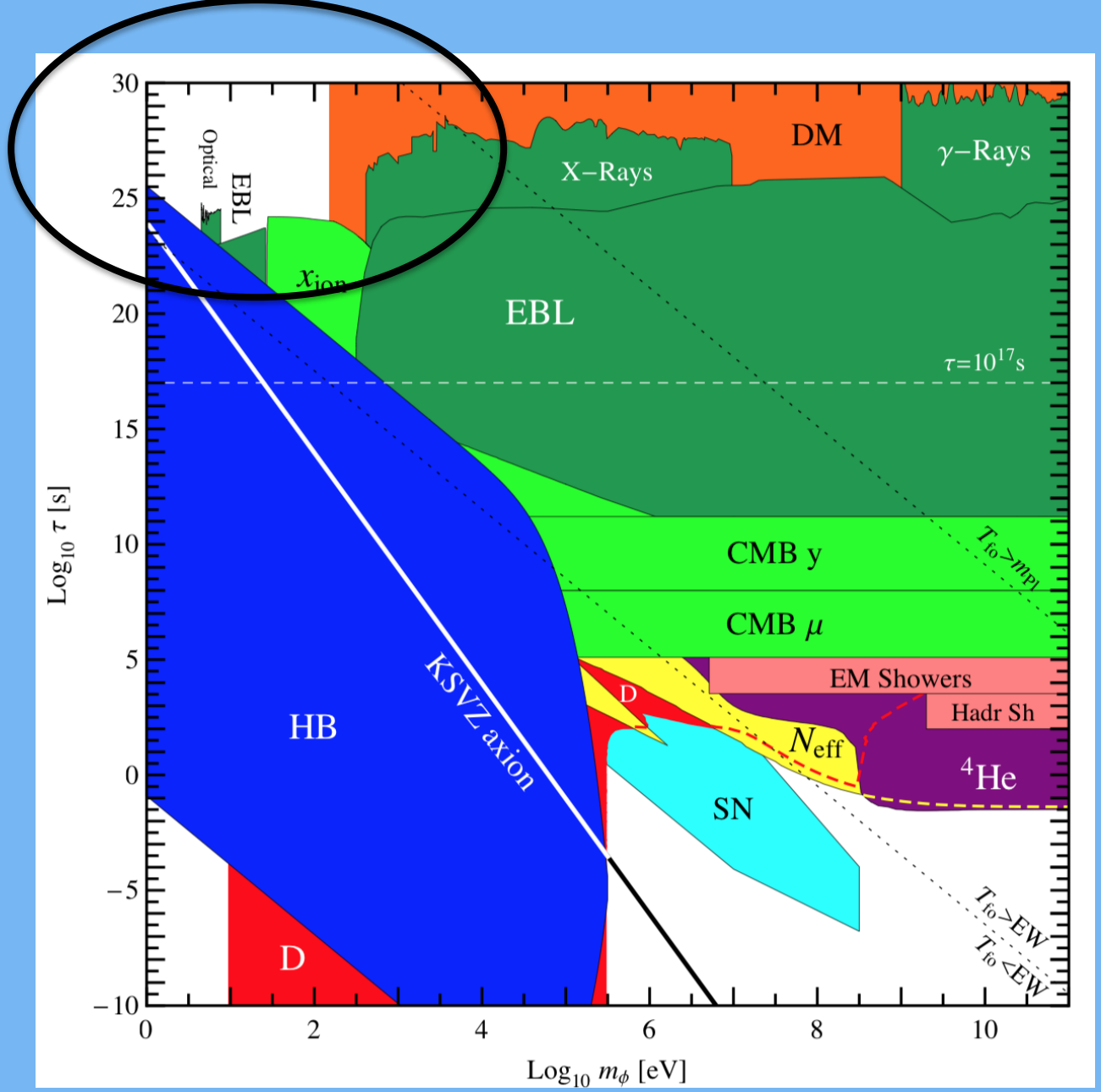
Fig. from Patrick Breysse and Ely Kovetz


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
Neut alized
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

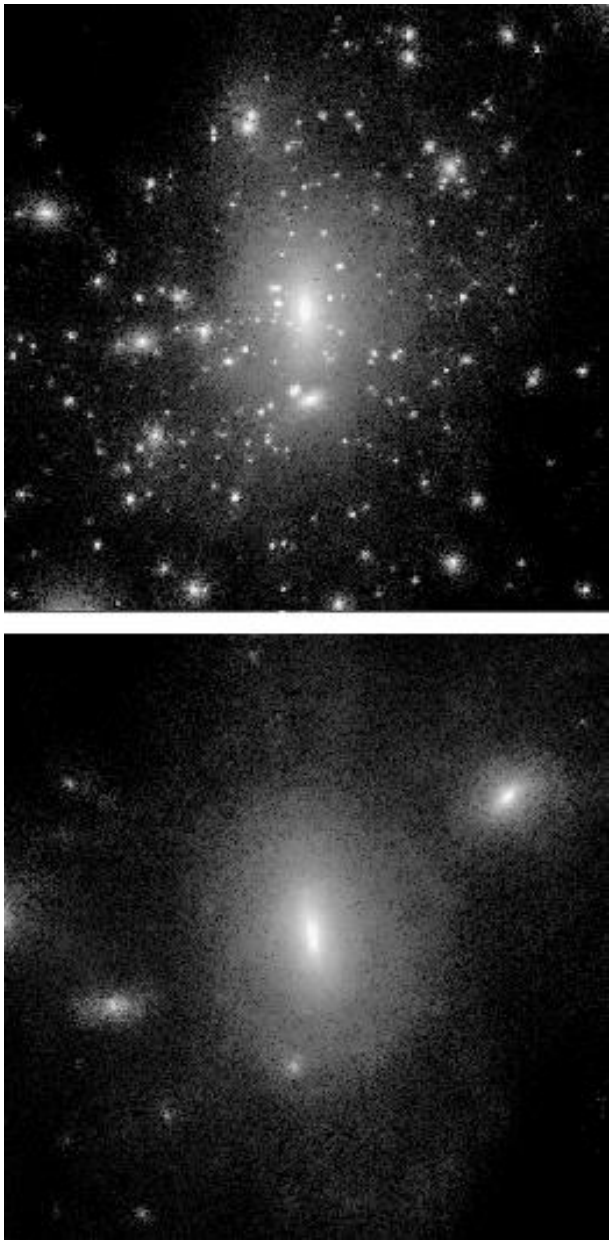

ν_0 [Hz]
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{38}
10^{35}
10^{32}
10^{29}
10^{26}
10^{23}
τ/f [sec]
CHIME
COMAP
CCAT
STARFIRE
SPHEREx
Flux
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
m [eV]

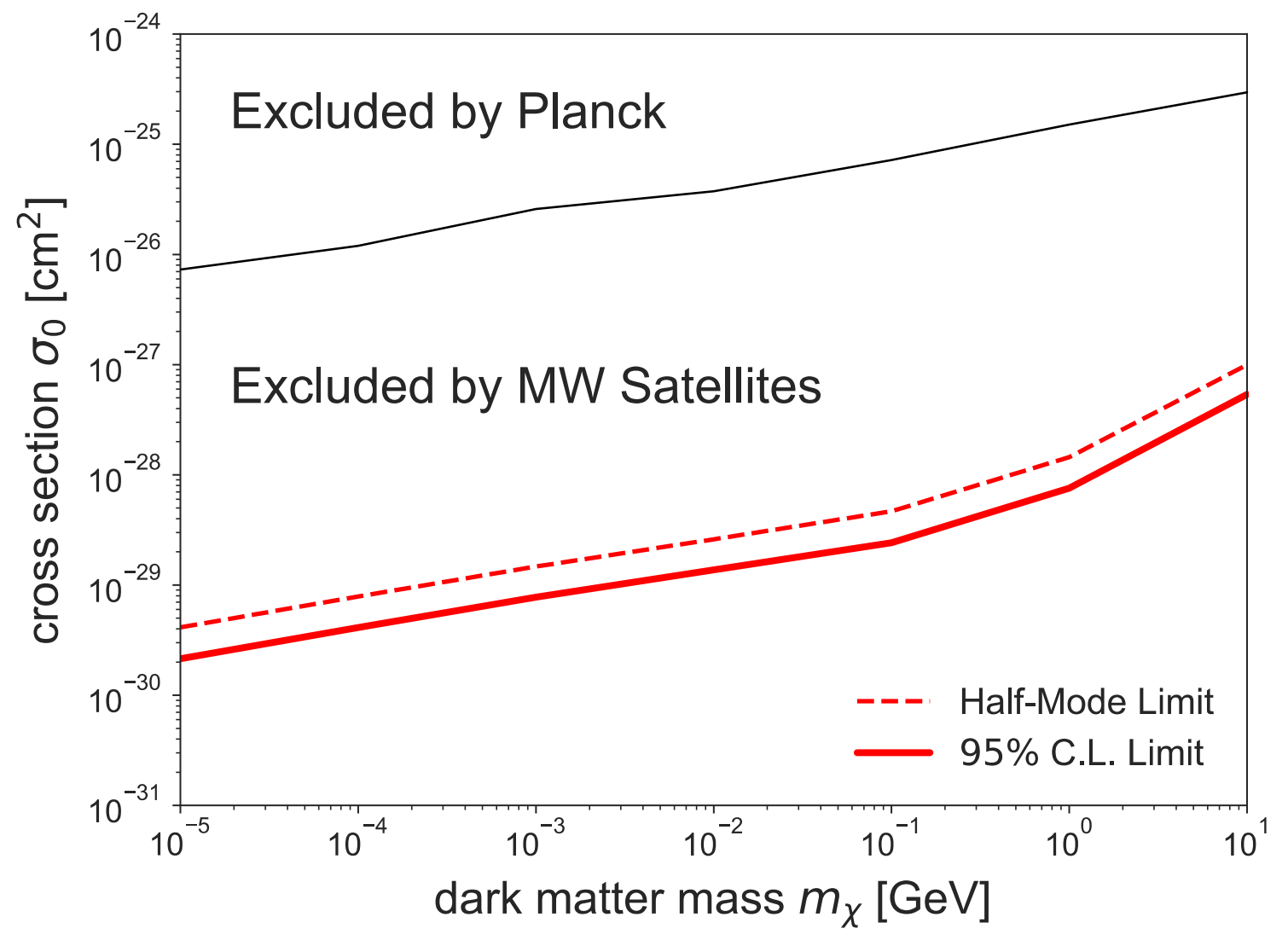


(Cadamuro & Redondo 2011)

More new related work: Strong new constraints to velocity-independent baryon-DM scattering!!
(Nadler, Gluscevic, Boddy, in prep)

Baryon-DM interactions in early Universe smooth density fluctuations leading to smoother galactic halos





Nadler, Gluscevic, Boddy, in prep