Black holes, baryons, axions, the Sagittarius dwarf galaxy, and dark matter

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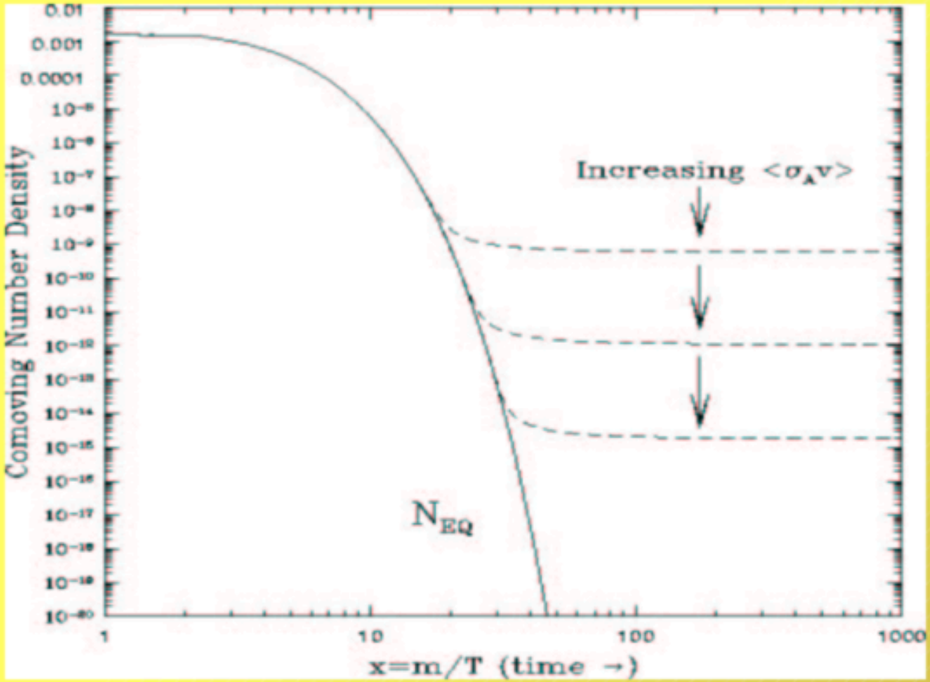
LSST DM Workshop, Chicago, 5 August 2019

Dark matter!!

What is it?

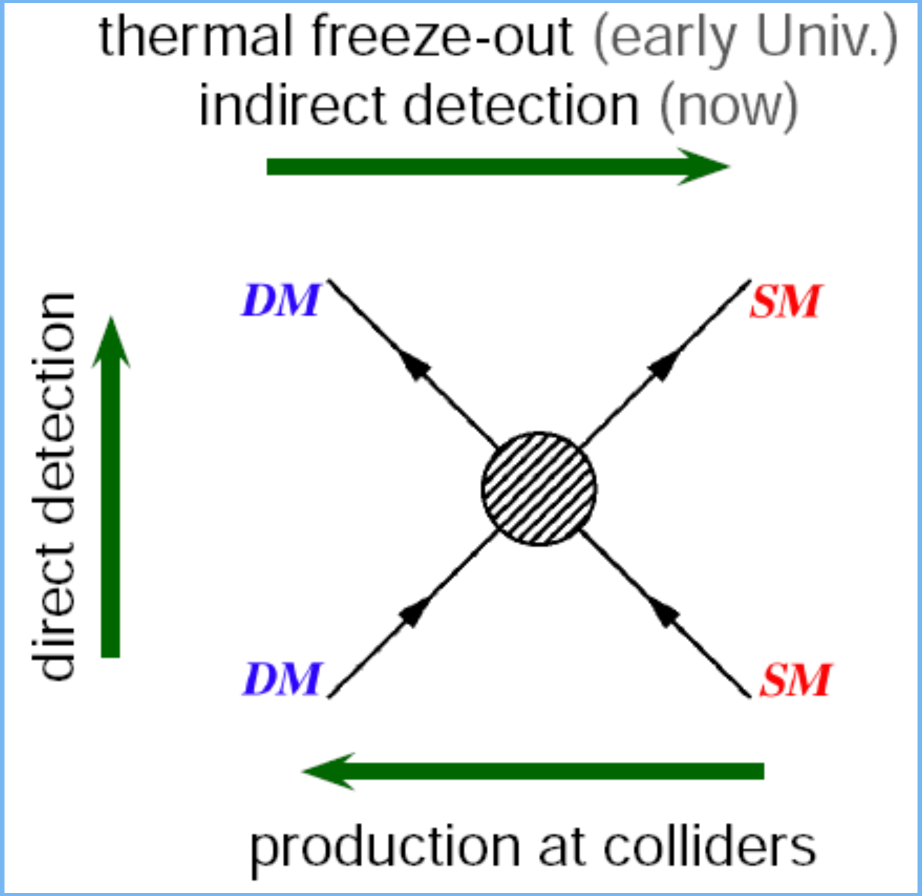
The Party line (~1985—2015)

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



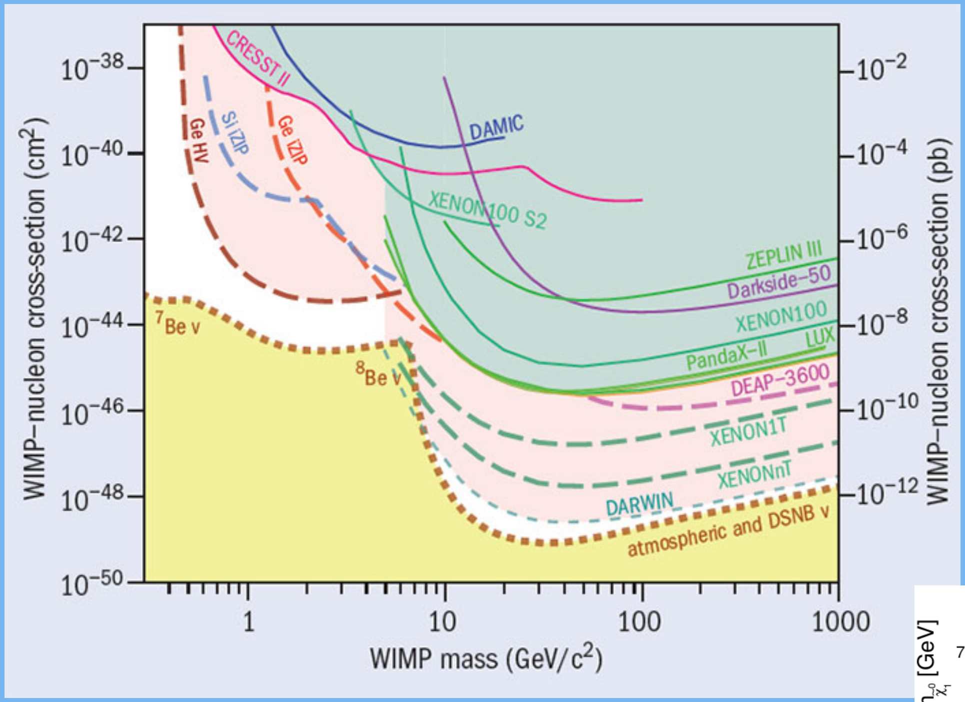
$$\Omega_\chi h^2 \approx \frac{3\times10^{-27}\,cm^3/\sec}{\langle\sigma v\rangle}$$

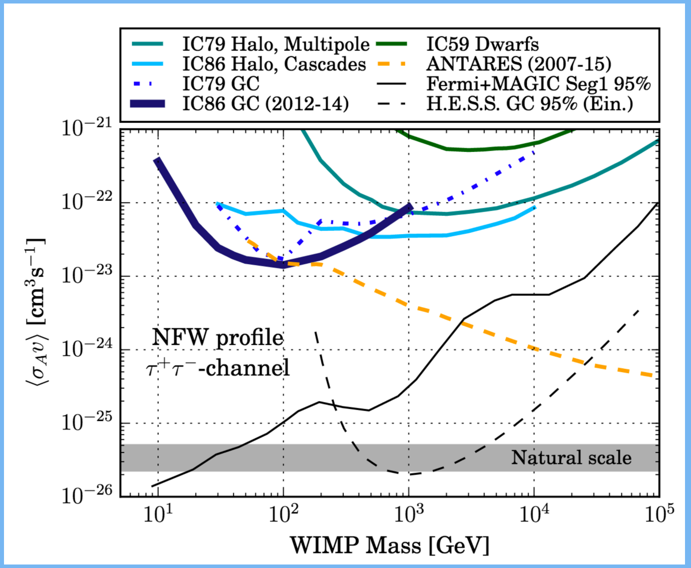
(e

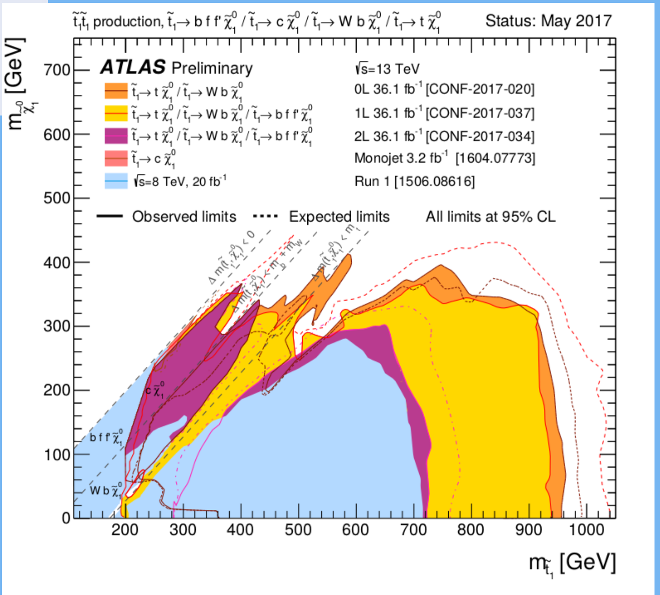


Simplicity/Elegance

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~~

The dark matter landscape now

Dark-matter candidates

How each 2020 ~~Democratic presidential~~ candidate could win

dark-matter

Literally all of them.

I. ~30-Msun black hole dark matter?
II. Millicharged DM and EDGES
III. Intensity mapping and decaying dark matter
IV. DM, the Sagittarius dwarf galaxy, and new long-range DM interactions

Did LIGO detect dark matter?

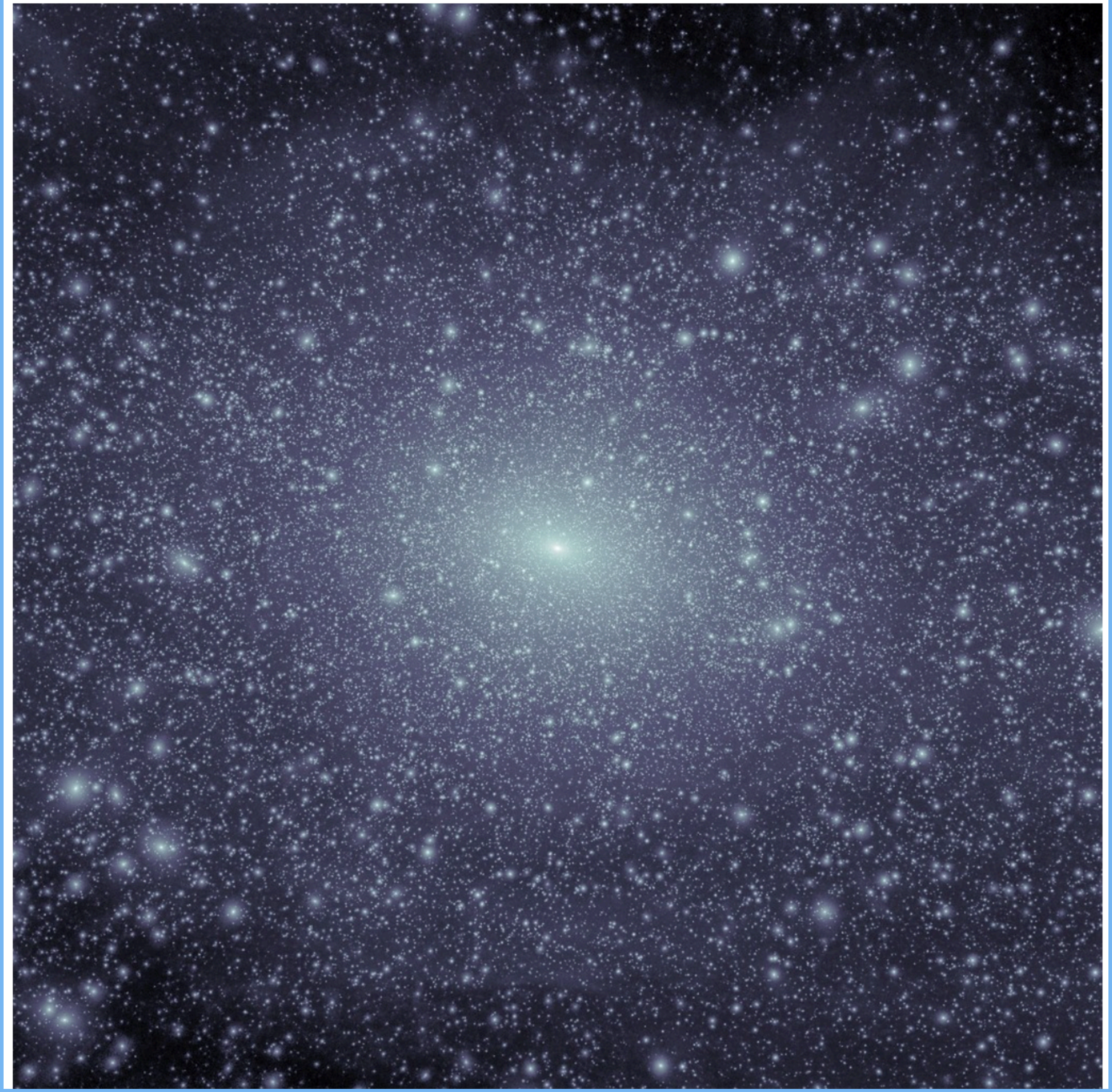
(Bird, Cholis, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli, Riess, 2016)

- 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

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



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

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

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!!!!!!!

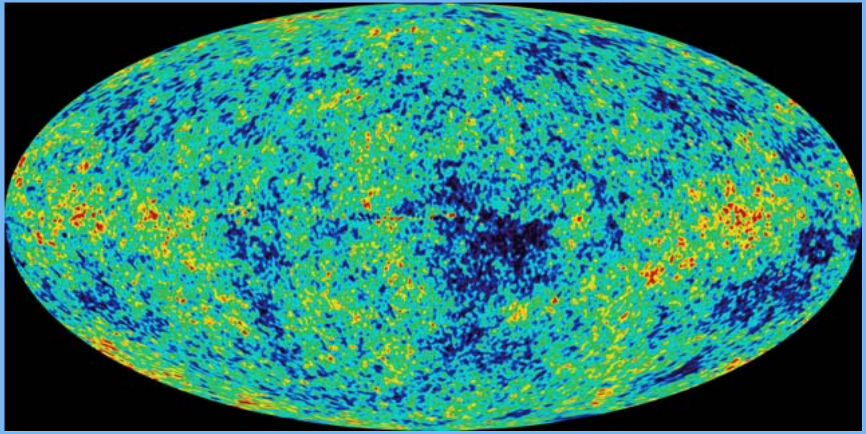
Since then....

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!!)



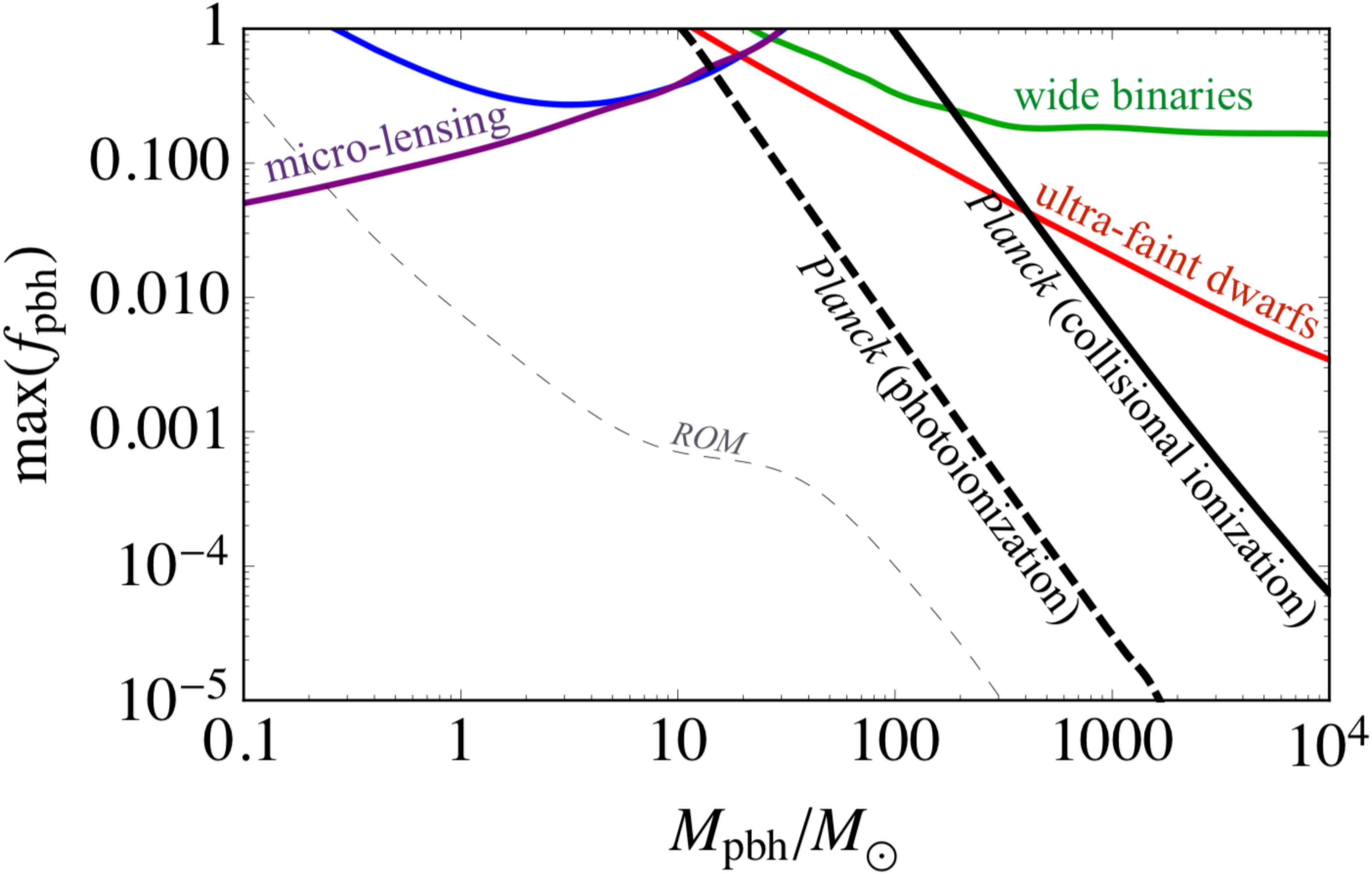
How does the CMB probe PBHs?

- 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

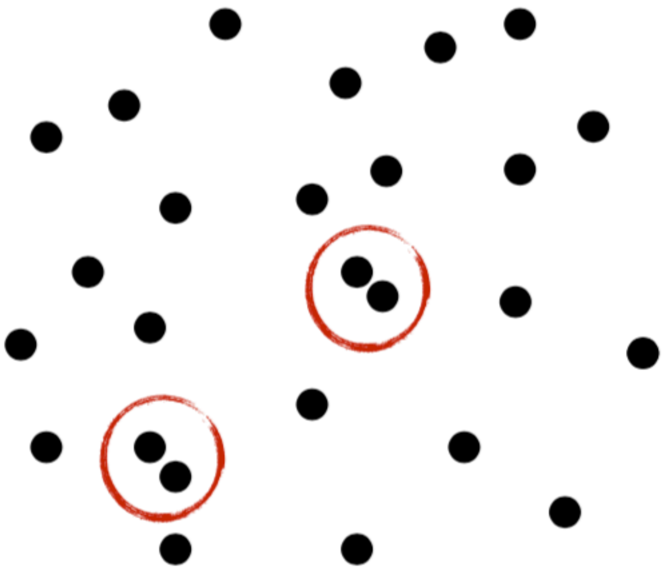


1
0.100
0.010
0.001
10^{-4}
10^{-5}
0.1
1
10
100
1000
10^4
$\max(f_{\rm pbh})$
$M_{\rm pbh}/M_\odot$
micro-lensing
wide binaries
ultra-faint dwarfs
Planck (collisional ionization)
Planck (photoionization)
ROM

Primordial PBH binaries

(Ali-Haimoud, Kovetz, MK 2017)

Basic idea: Nakamura, Sasaki, Tanaka & Thorne 1997



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

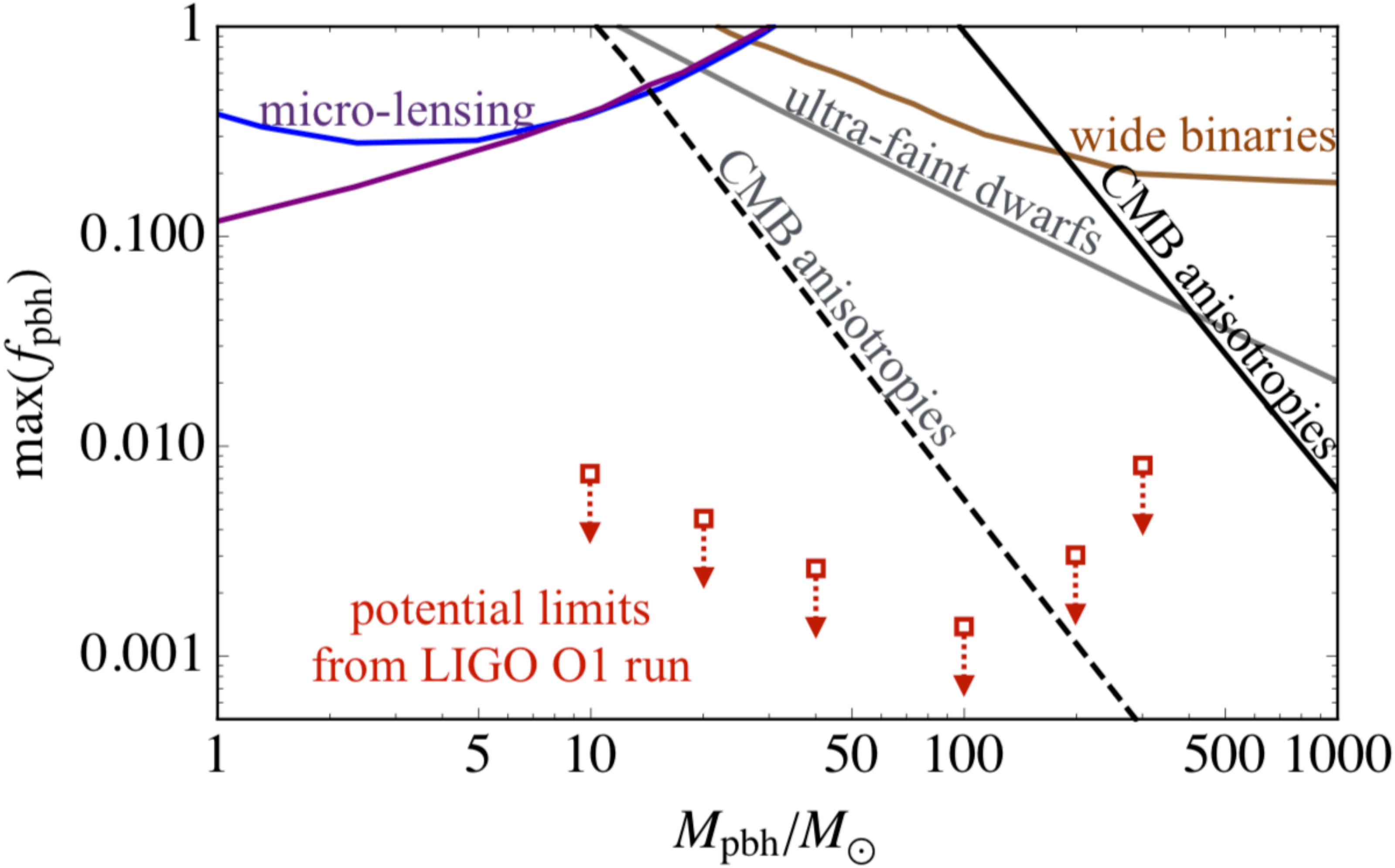
Some PBH pairs happen to be close enough that they decouple from the Hubble flow deep in the radiation era.

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.

Does LIGO rule out PBH-dark matter?

$Probably$ but more checks are needed

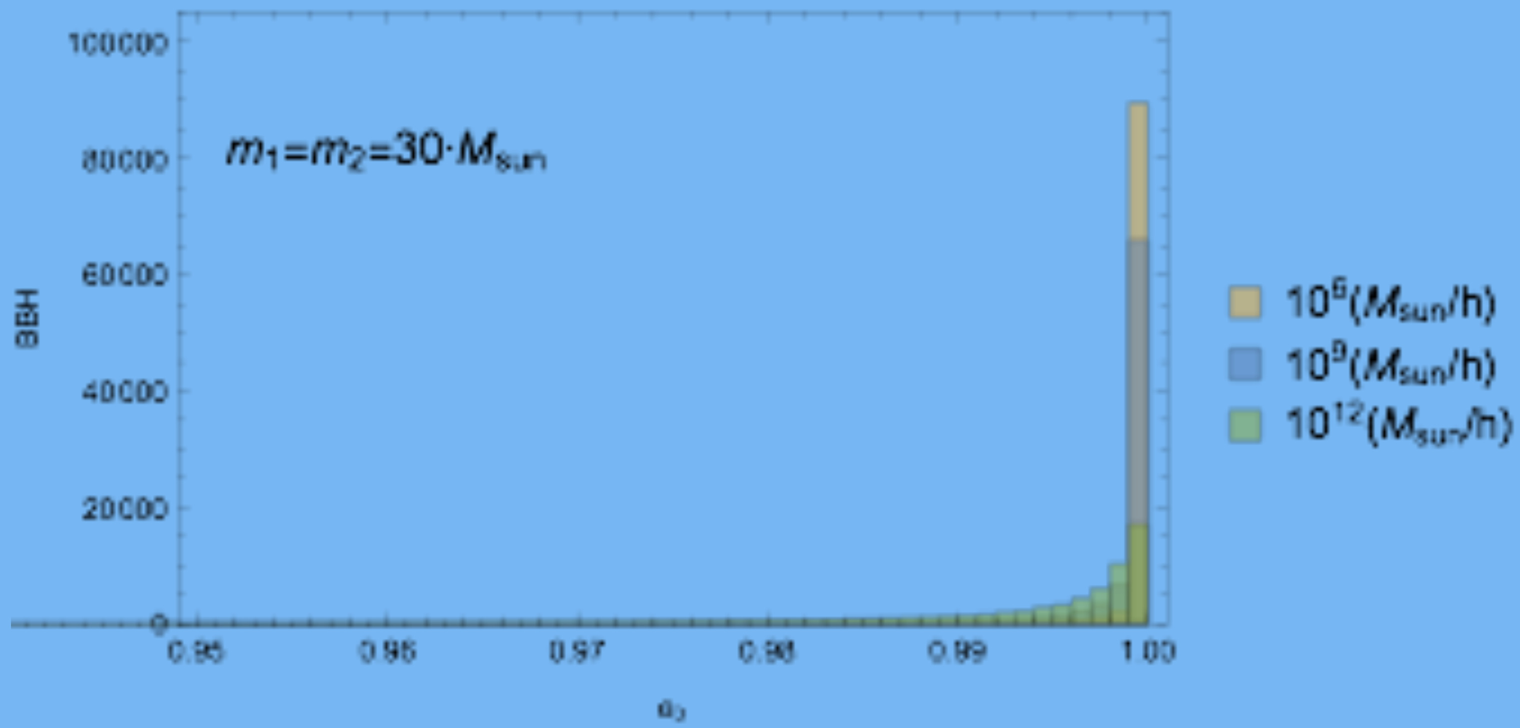


How to test PBH DM hypothesis?

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

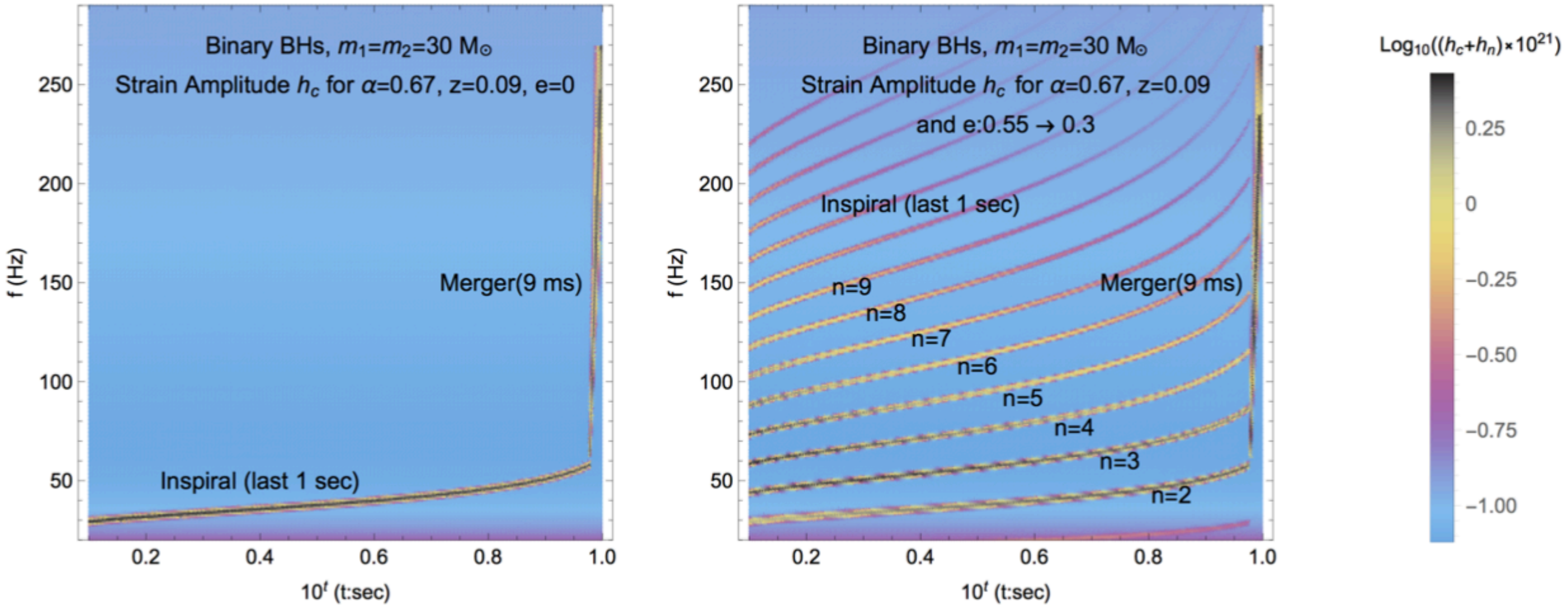
Given current LIGO rate, expect perhaps ~20,000 more BBH mergers in next decade!!

PBH binaries have high initial eccentricities:



see many more modes of grav. waves

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

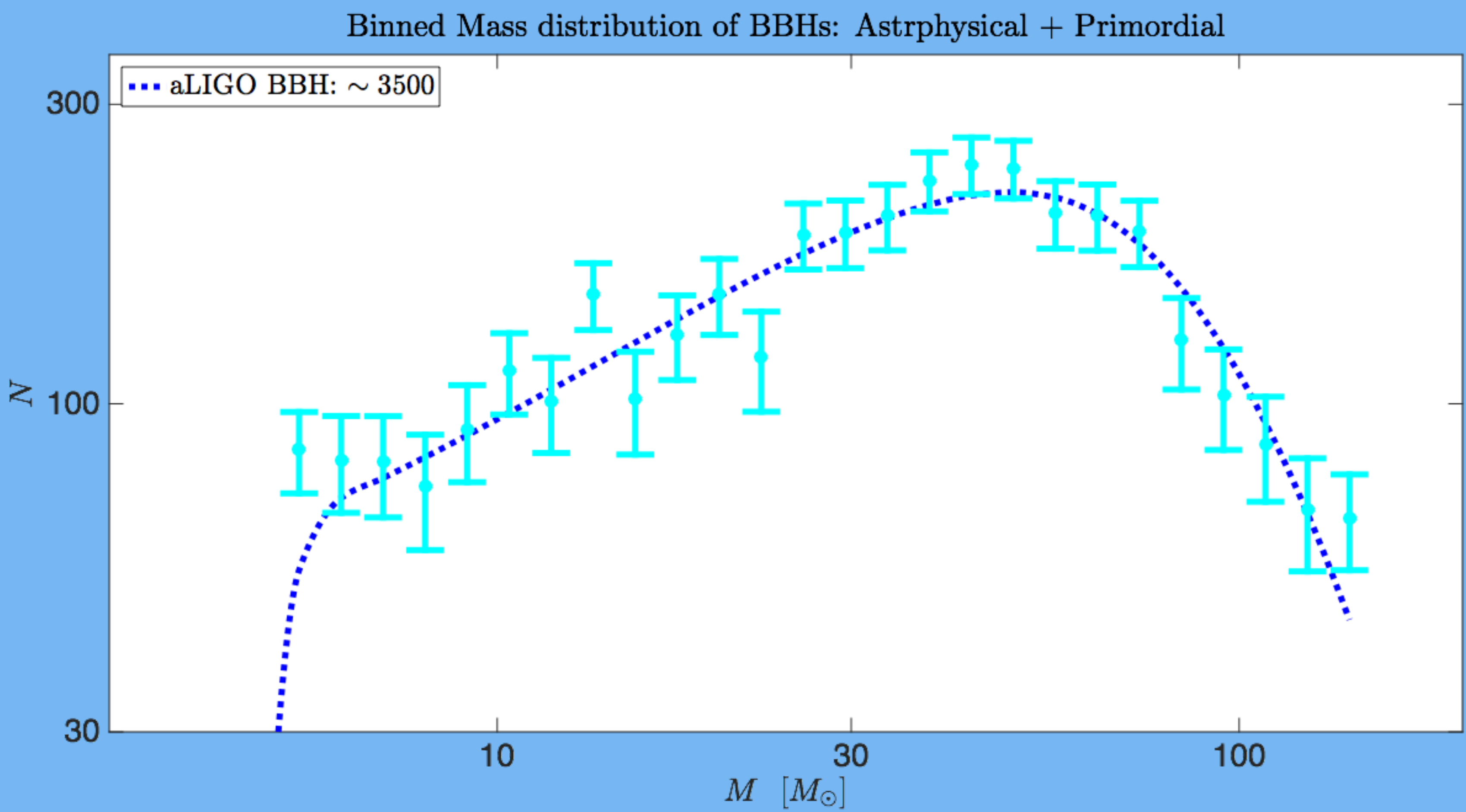


Cholis, Ali-Haimoud, Bird, Munoz,MK,
Kovetz, and Raccanelli (2016)

The BH binary mass distribution

The Black-Hole Mass Function from GWs

with 5 years of aLIGO:

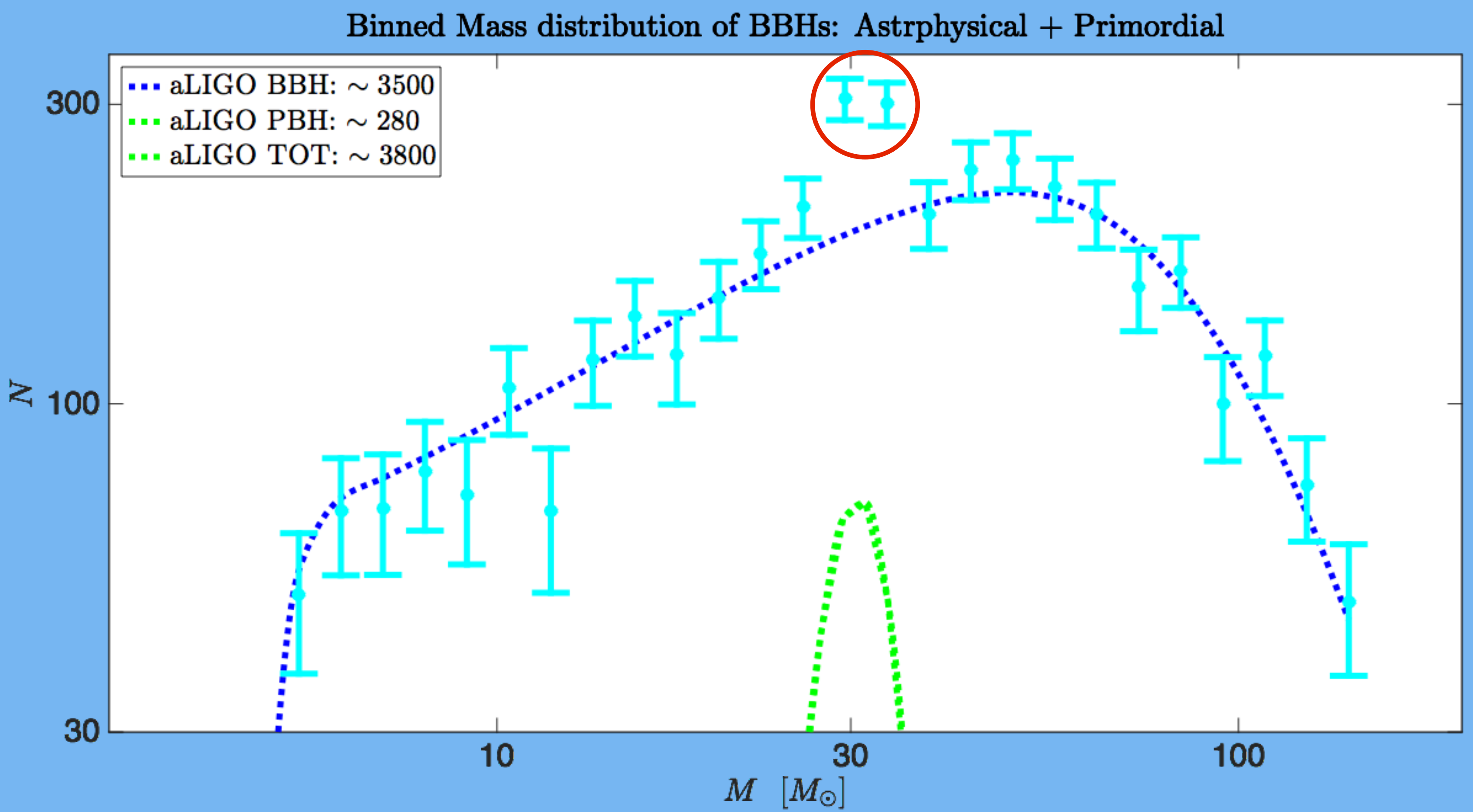


The Black-Hole Mass Function from GWs

with 5 years of aLIGO data:

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

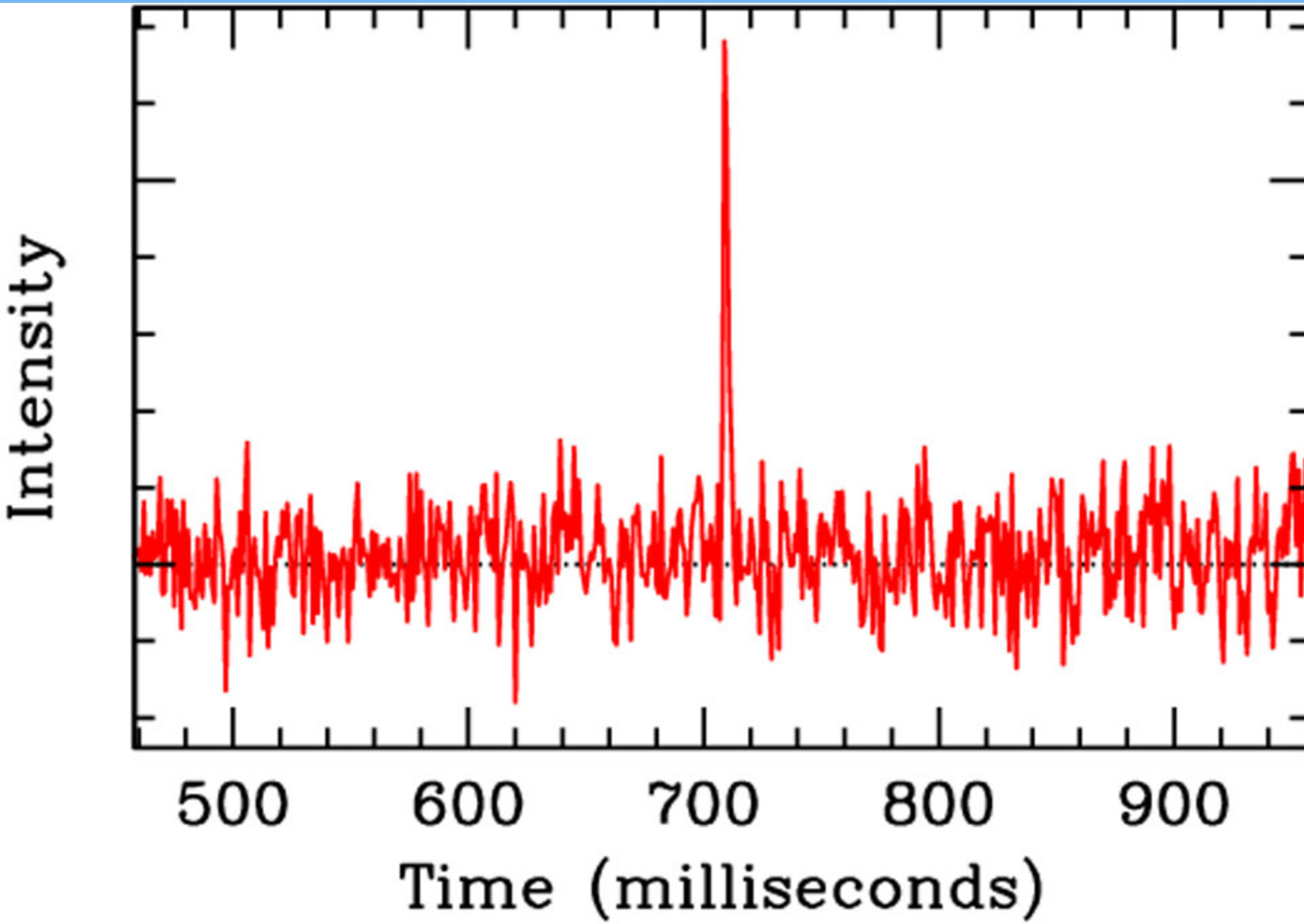
With Dark Matter PBHs:



Lensing of Fast Radio Bursts by Compact Objects

Munoz, Kovetz, Dai, MK, 1605.00008

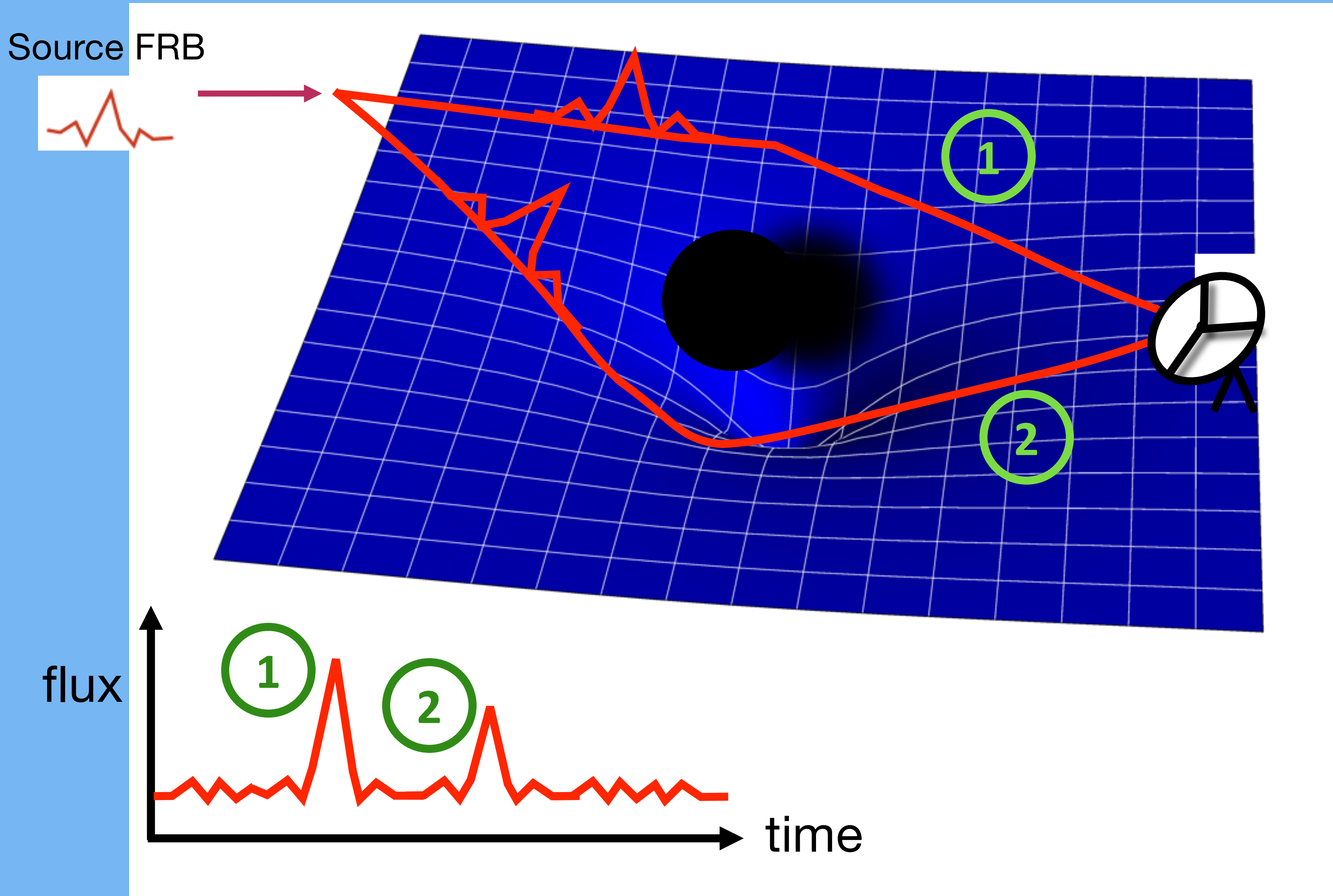
- FRBs = <millisecond ~GHz radio bursts
- ~10,000 on sky per day
- Large dispersion measures imply cosmological distances
- Forthcoming experiments (e.g., CHIME) should detect thousands



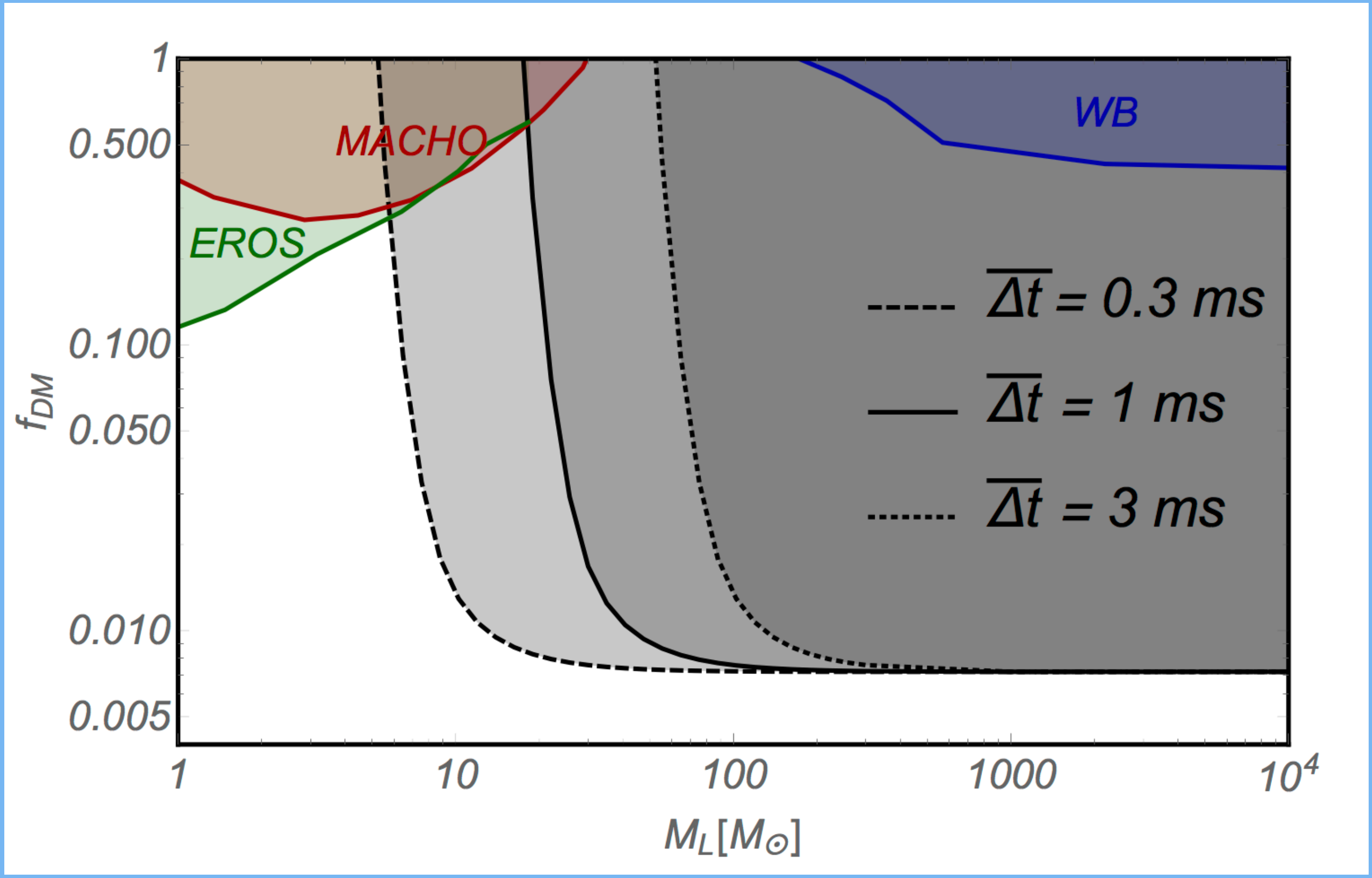
Intensity
500
600
700
800
900
Time (milliseconds)

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



Also tried echoes in gamma-ray-burst light curves, but not with current measurements

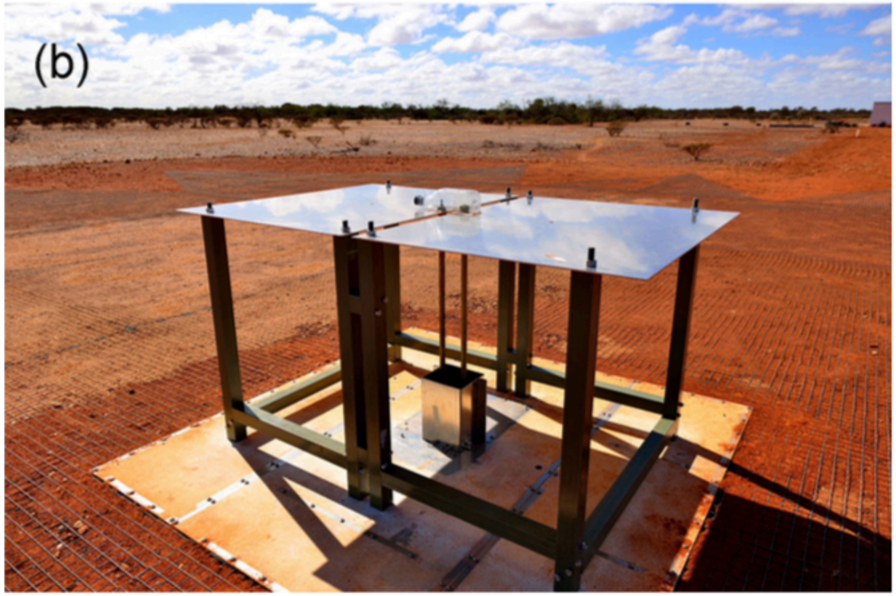
(Ji, Kovetz, MK, 2019)

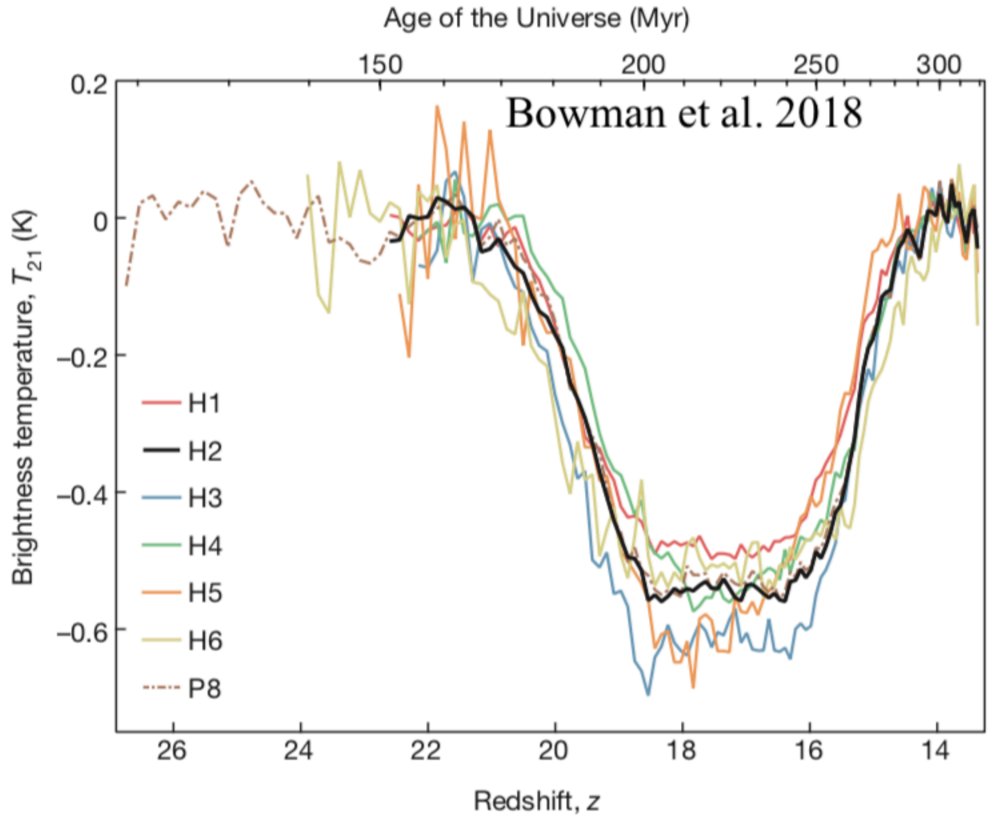
- Longer pathlengths → more lensing
- Seek GRB echo superimposed on original light curve

Baryon—DM interactions from cosmic dawn?

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

February 2018





Lots of neutral hydrogen

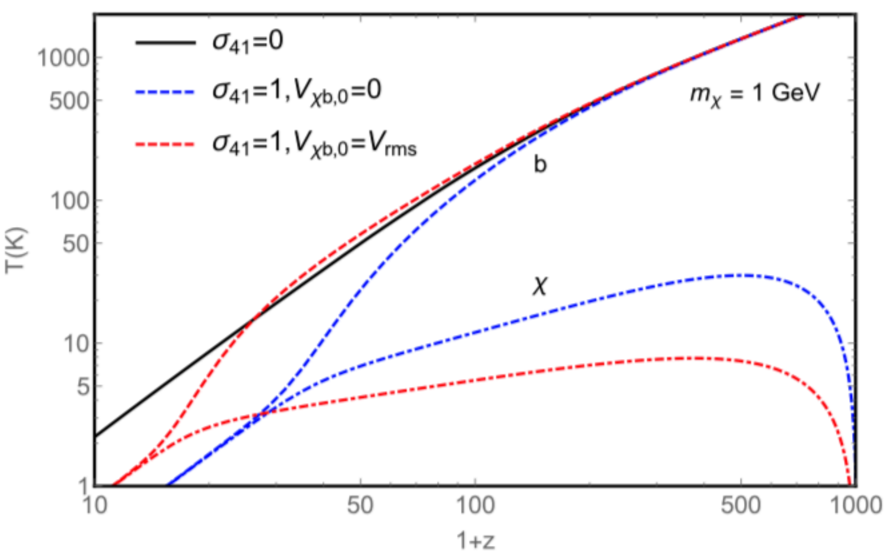
If DM-baryon interactions exist, they can mediate heat exchange between baryons and DM (Dvorkin, Blum, MK 2014)

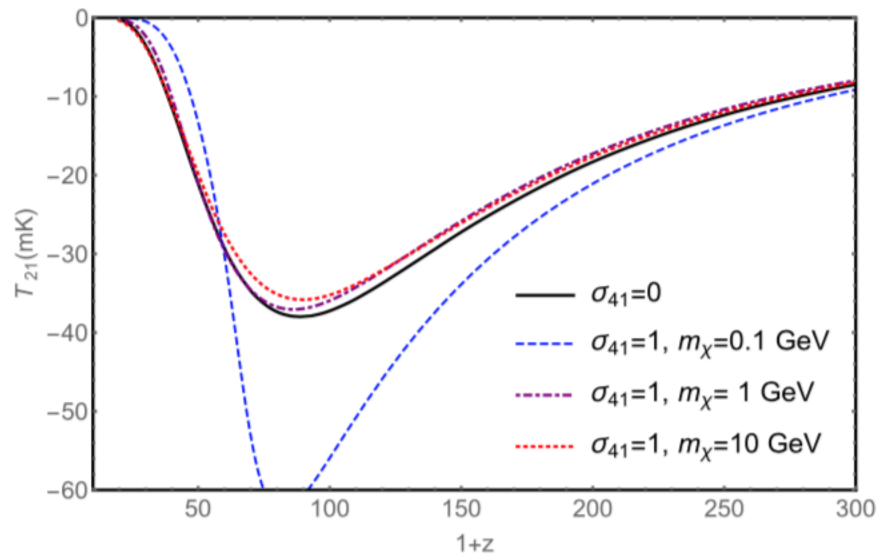
$$\frac{dT_\chi}{da} = -2\frac{T_\chi}{a} + \frac{2\dot{Q}_\chi}{3aH}, \qquad \frac{dT_b}{da} = -2\frac{T_b}{a} + \frac{\Gamma_C}{aH}(T_\gamma - T_b) + \frac{2\dot{Q}_b}{3aH}$$

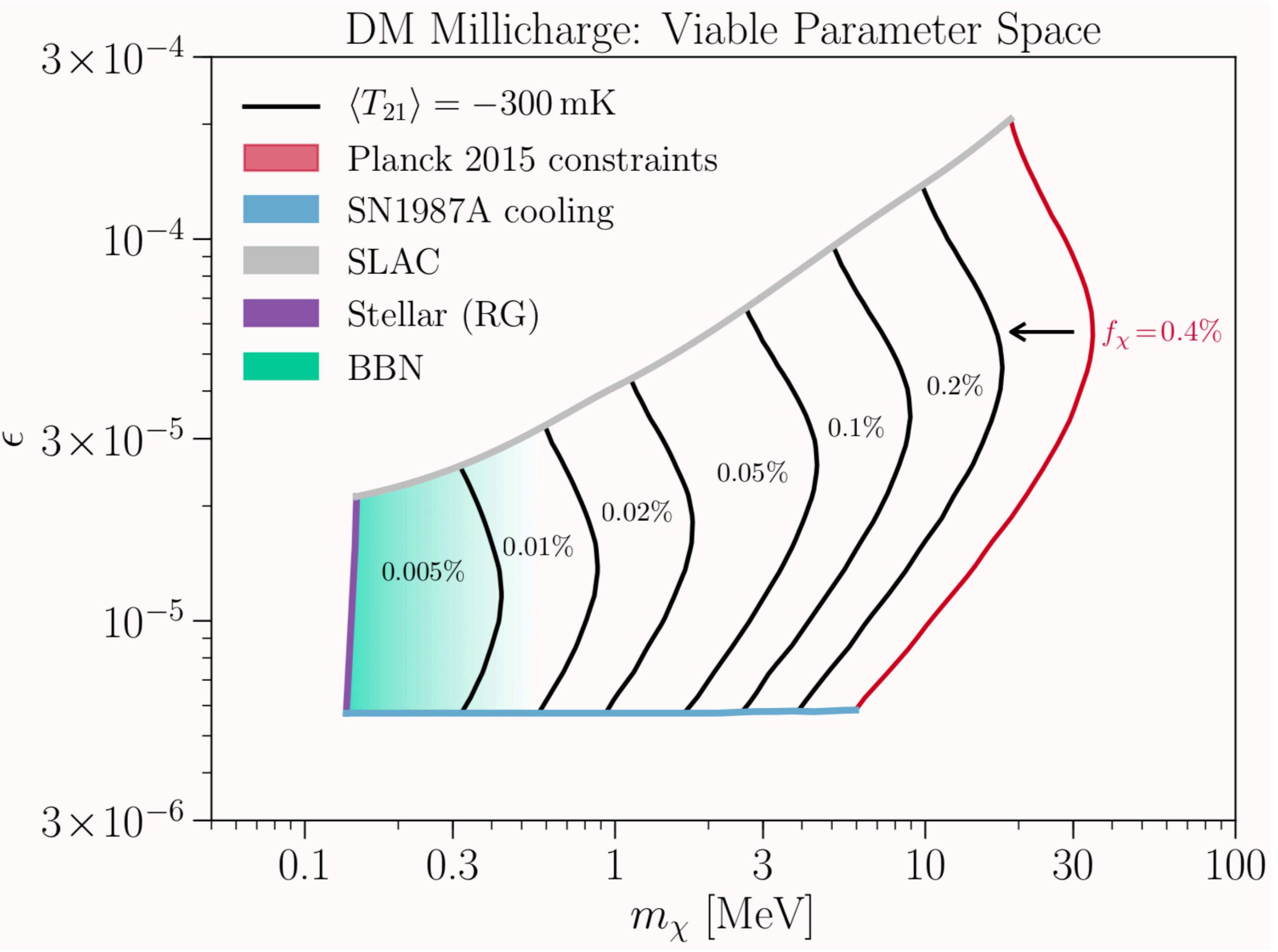
Tashiro, Kadota, Silk 2014: DM can act as heat sink and cool neutral hydrogen in dark ages

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

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







Mill-charged—DM explanation very tightly constrained (Boddy et al., 2018; Kovetz et al., 2018)

New results (Creque-Sarbinowski, Ji,Kovetz, MK 1903.09154)

Relic abundance fixed by charge&mass

→ rules out millicharged-DM parameter space for EDGES

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

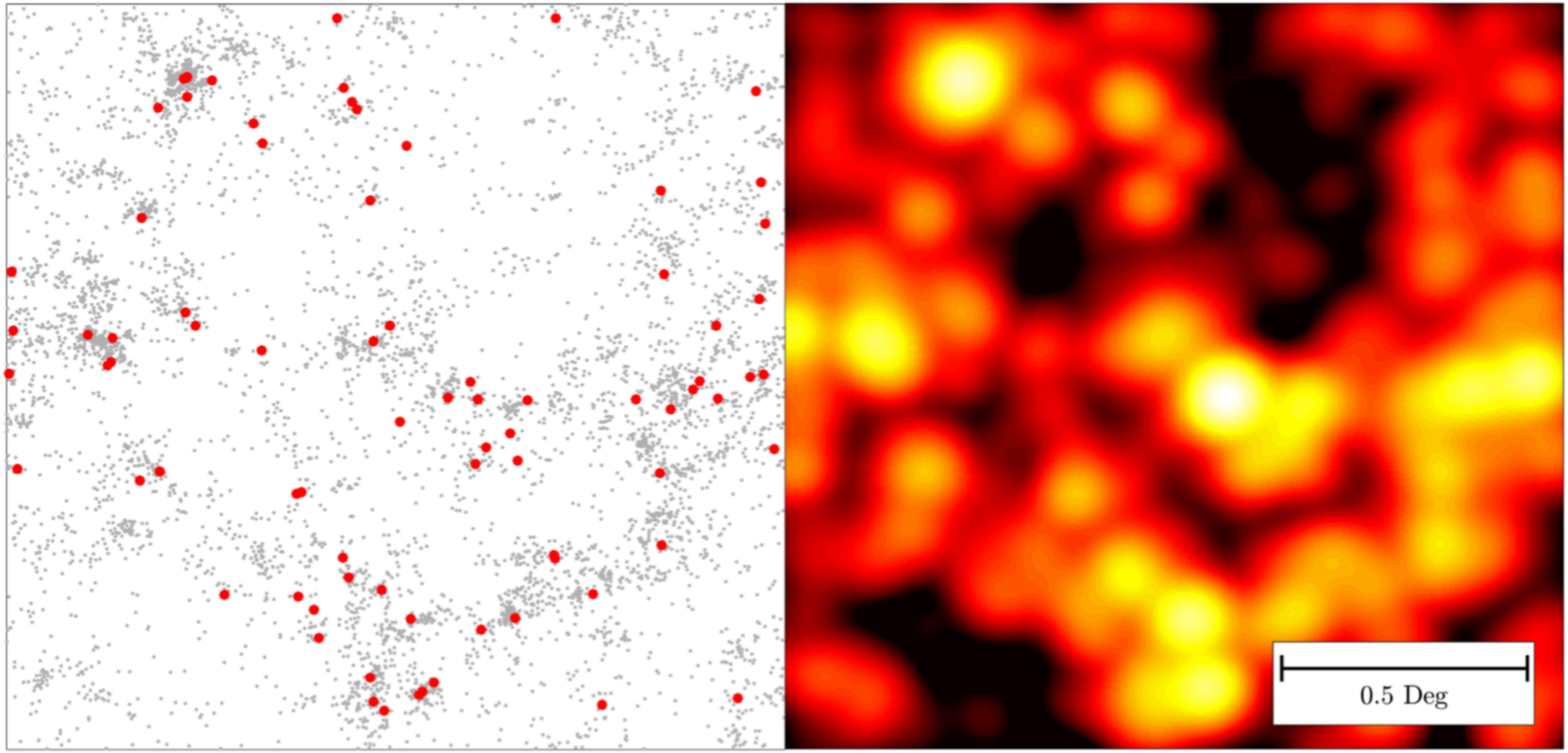


Fig credit: Patrick Breysse

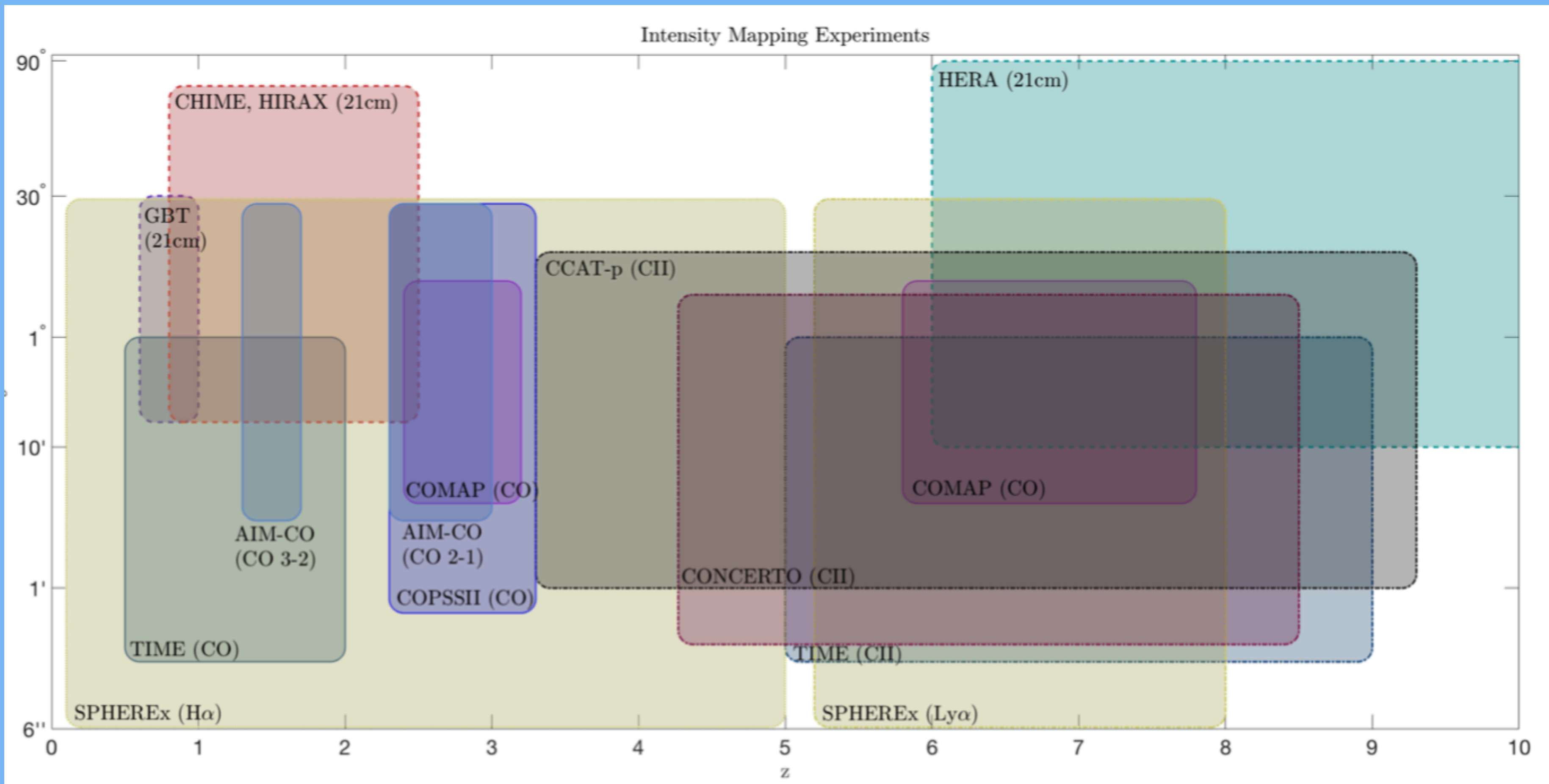
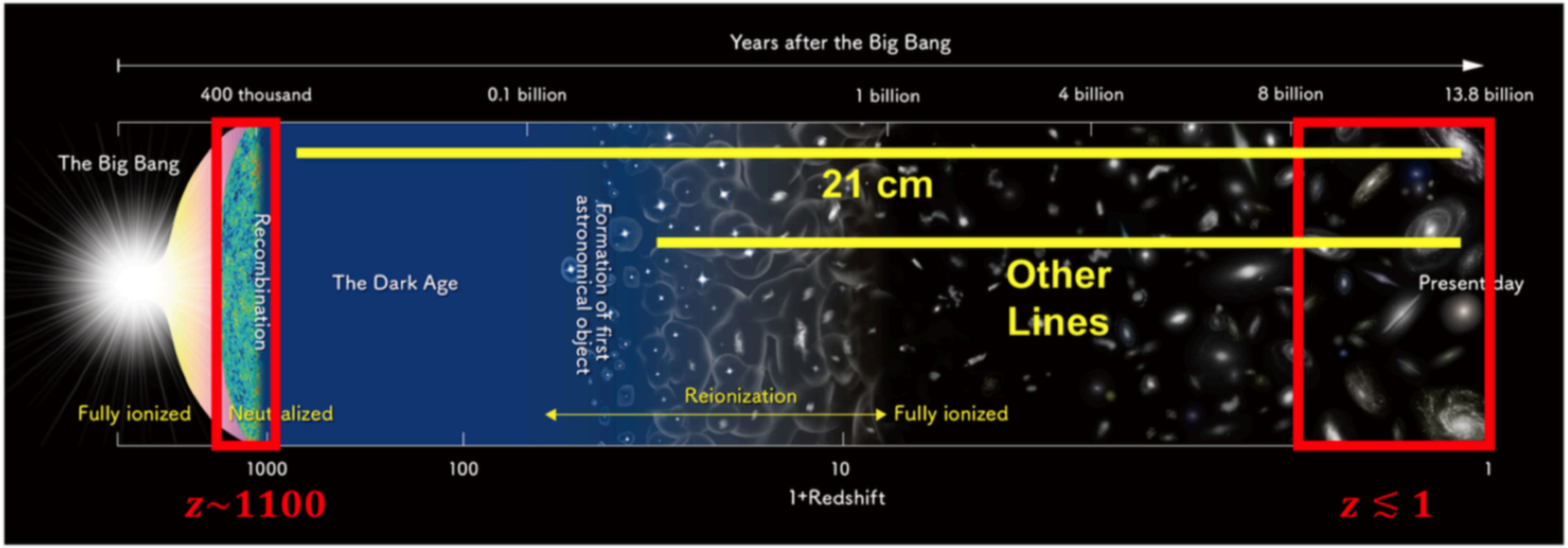


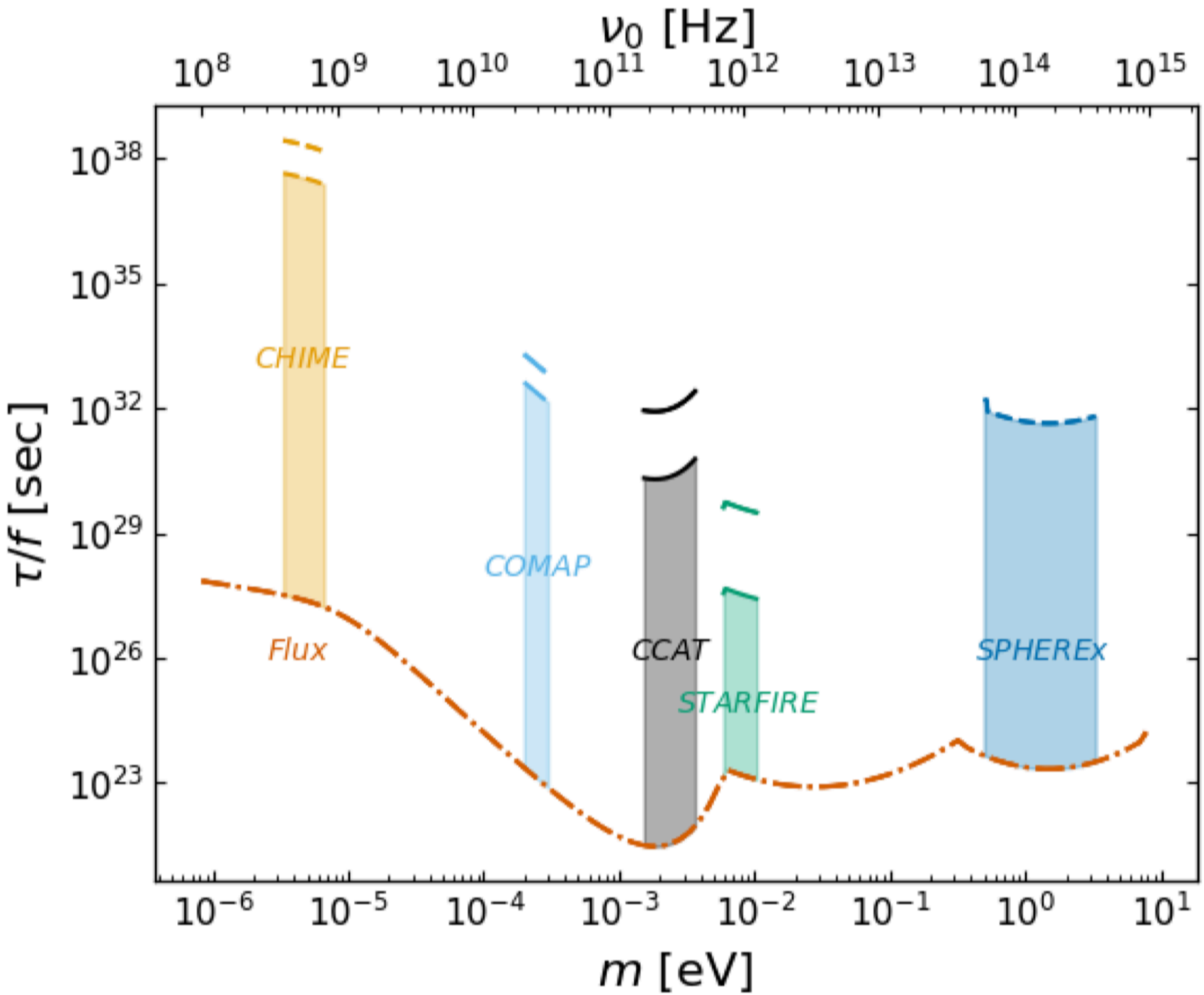
Fig. from Patrick Breysse and Ely Kovetz



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]

1. Dark Matter, the Equivalence Principle, and Dwarf Galaxies

Kesden & MK 2006

$$\vec{F} = m_i \vec{a}$$

Force

inertial mass

acceleration

Gravitational force

$$\vec{F} = m_g \vec{g}$$

Force

gravitational mass

gravitational field

Question: does dark matter fall same way in a gravitational field as ordinary matter?

Conclusions/Summary: We have shown that it does, even though we don’t even know what it is.

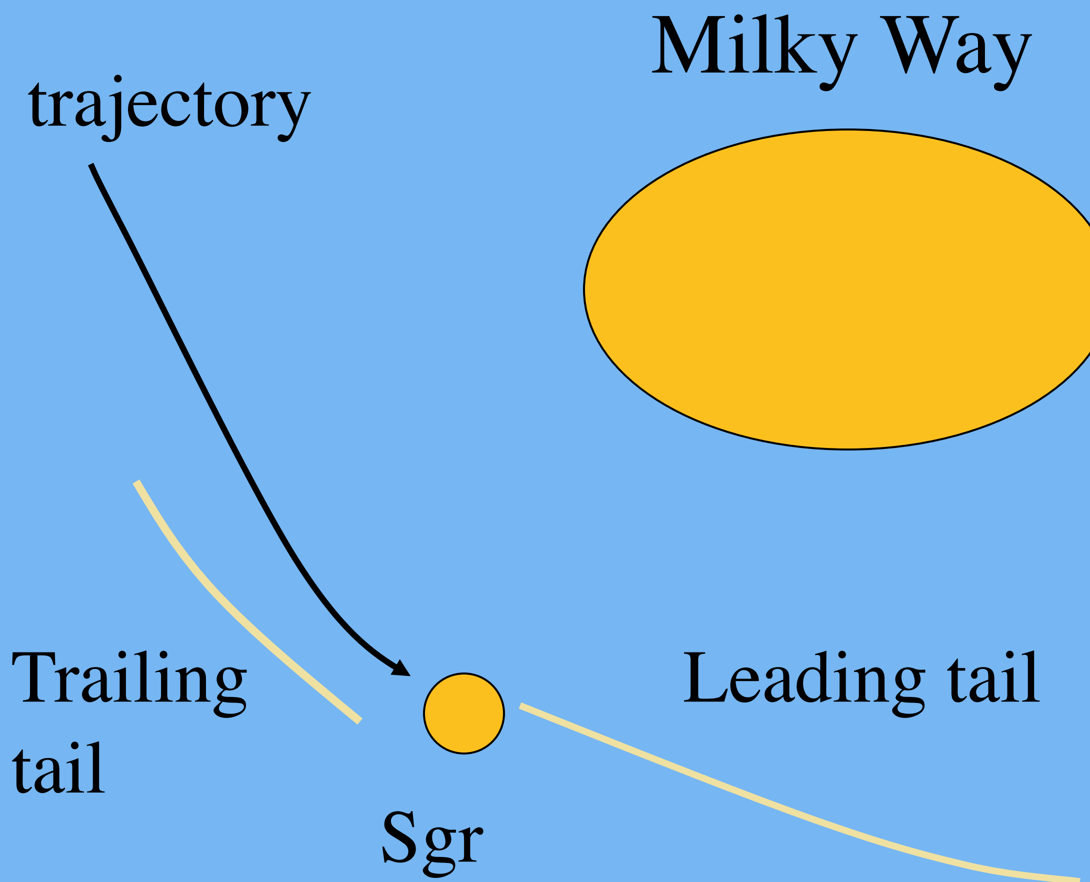
Here’s how:

Sagittarius dwarf galaxy

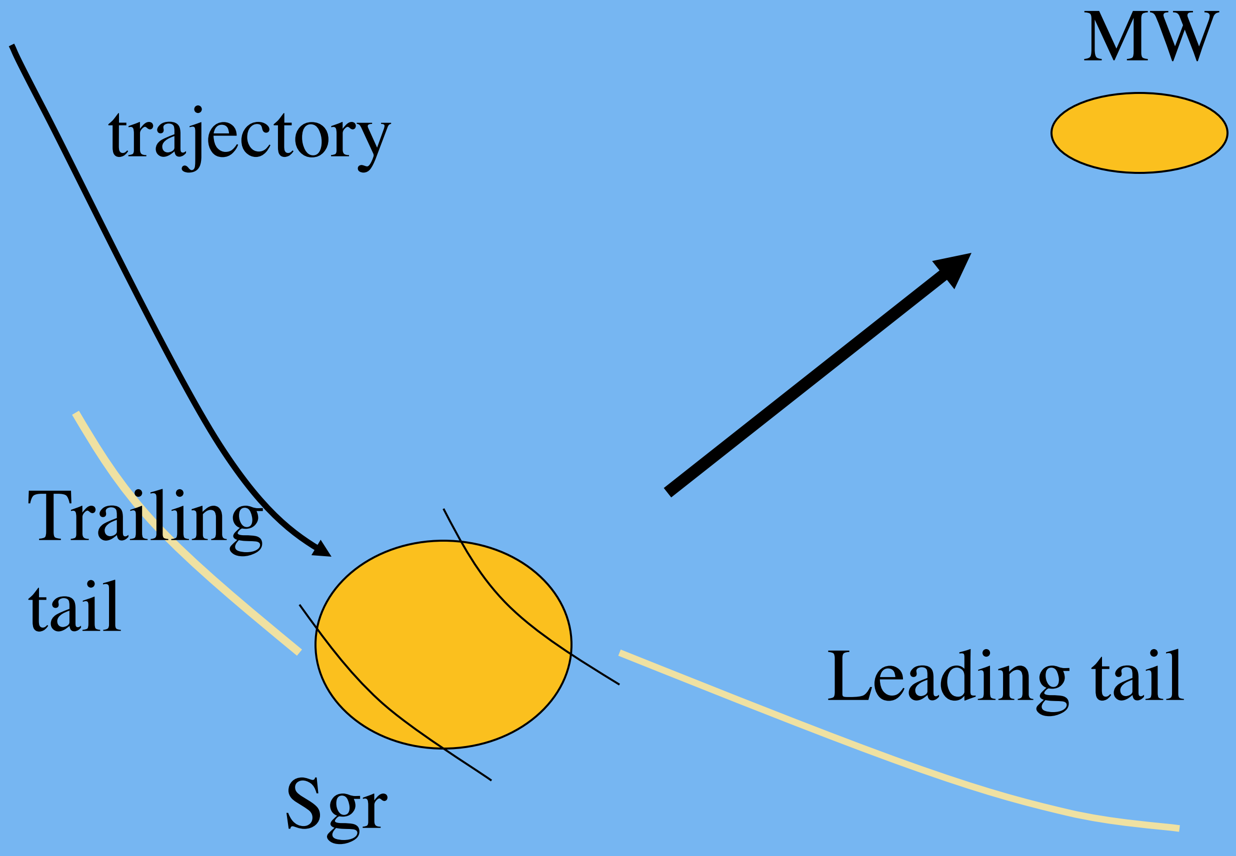
• small galaxy (~billion stars plus lots of dark matter held together by own self-gravity)

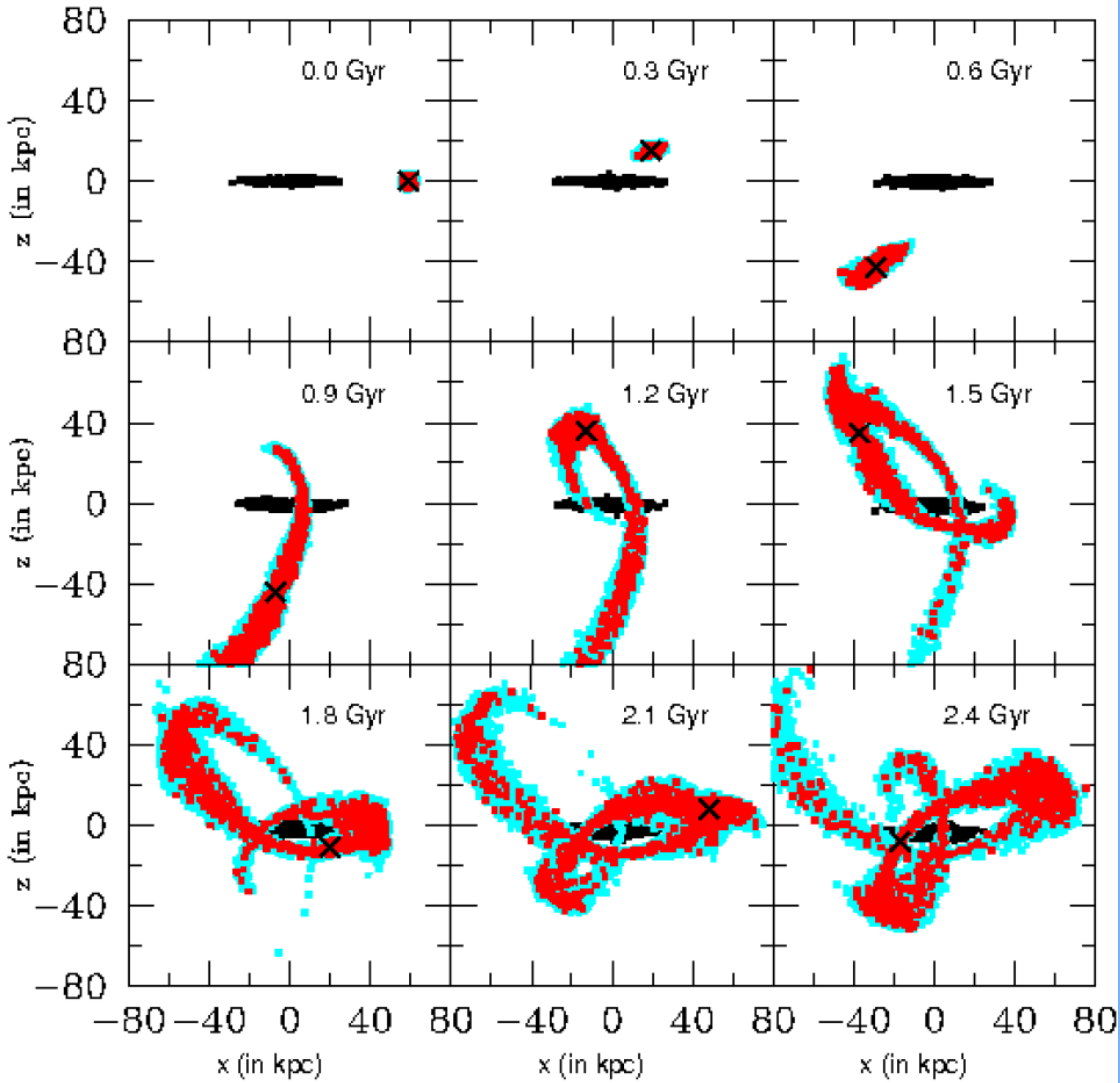
• A satellite of Milky Way (in orbit around Milky Way)

• Has “tidal tails” streams of stars, stripped from the galaxy, running ahead and behind the galaxy

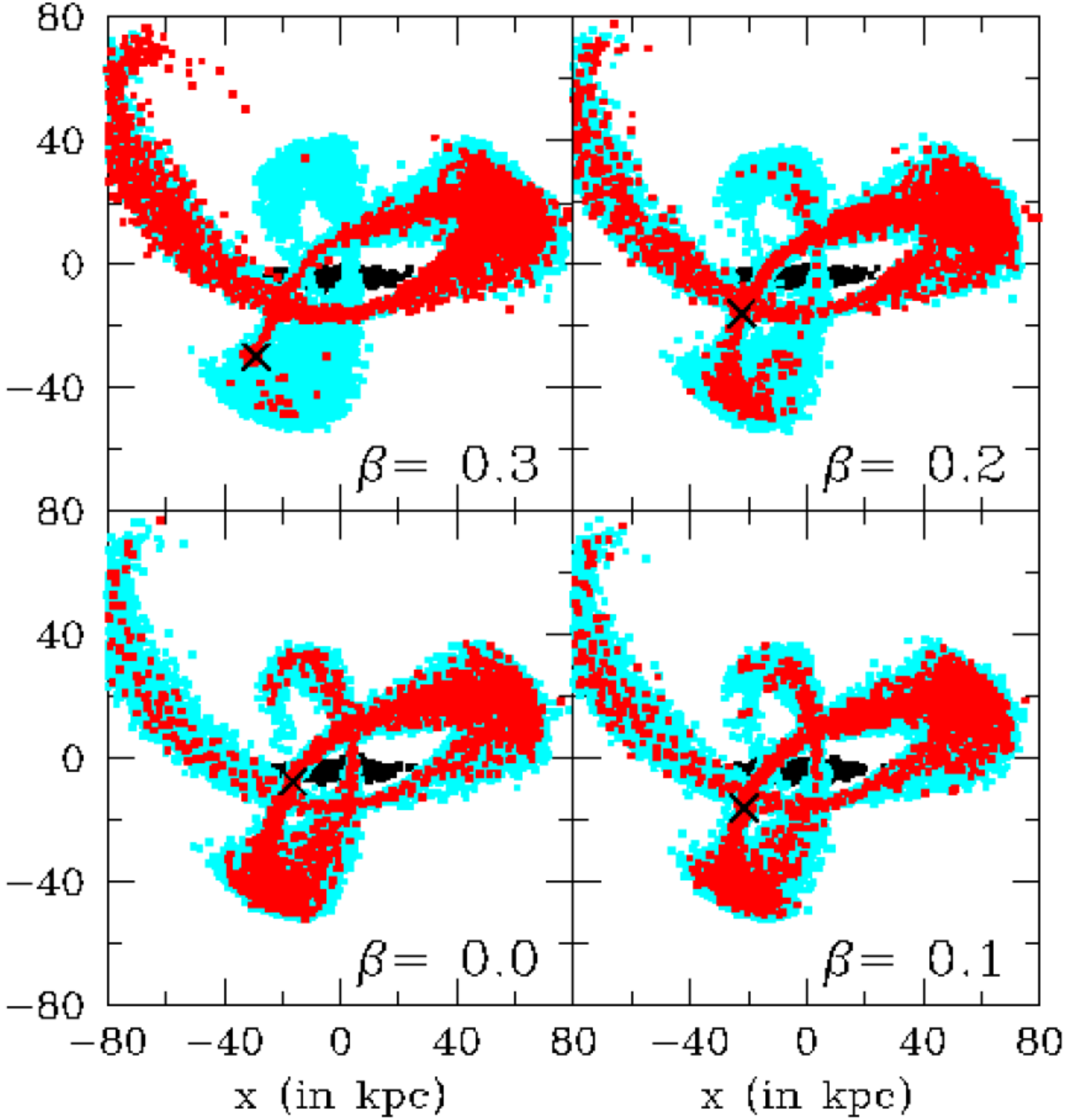

Milky Way
trajectory
Trailing tail
Sgr
Leading tail

Where do tidal streams come from?



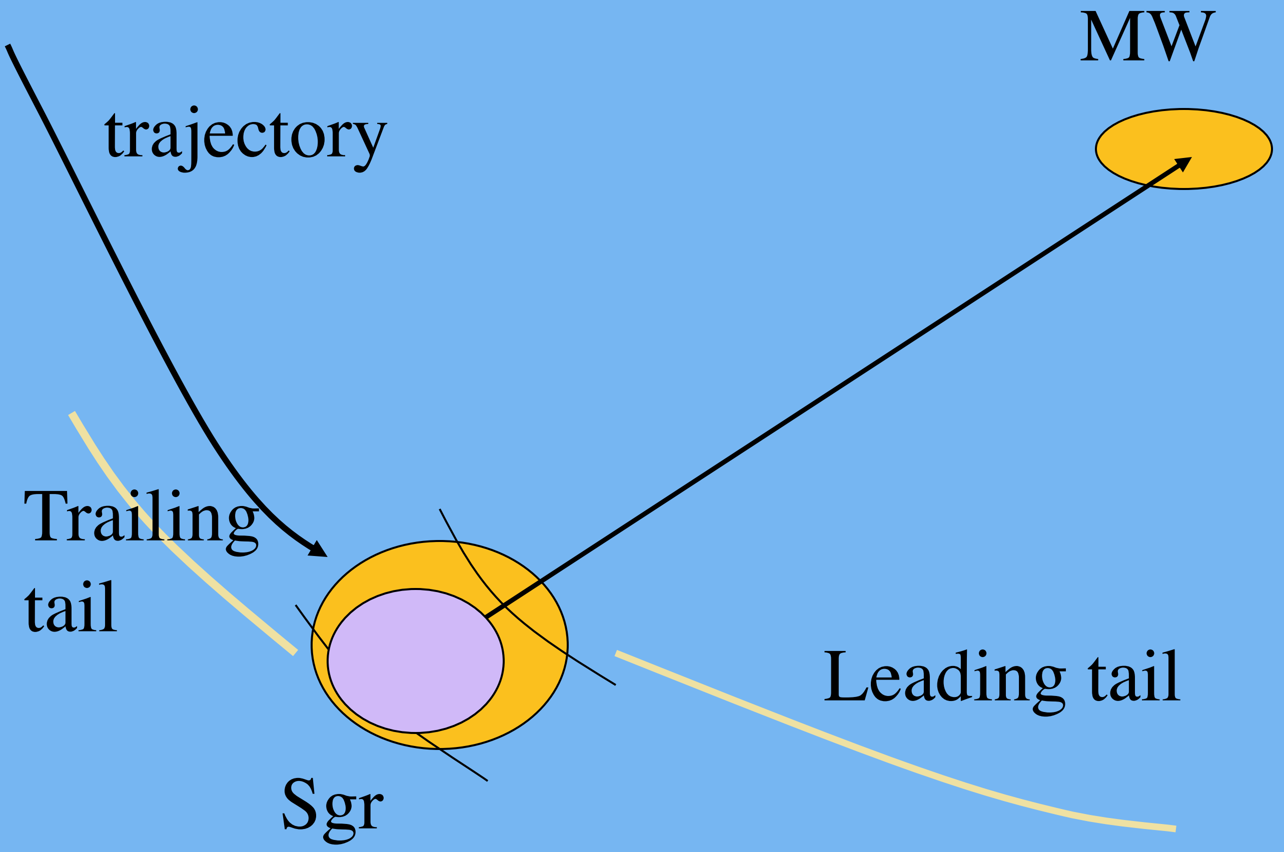


0.0 Gyr
0.3 Gyr
0.6 Gyr
0.9 Gyr
1.2 Gyr
1.5 Gyr
1.8 Gyr
2.1 Gyr
2.4 Gyr
z (in kpc)
x (in kpc)
80
40
0
−40
−80



80
40
0
−40
−80
z (in kpc)
x (in kpc)
−80
−40
0
40
80
β= 0.3
β= 0.2
β= 0.0
β= 0.1

What’s going on?


MW
trajectory
Trailing
tail
Leading tail
Sgr

By-eye analysis: Dark matter falls same way as ordinary matter to better than 10%

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
- Dark matter falls the same way as ordinary matter in g ravitational potential wells