

# New hints of dark matter?

*PASCOS 2018*

- Introduction
- Primordial black holes
- EDGES and DM-baryon interactions
- Intensity mapping and DM decay

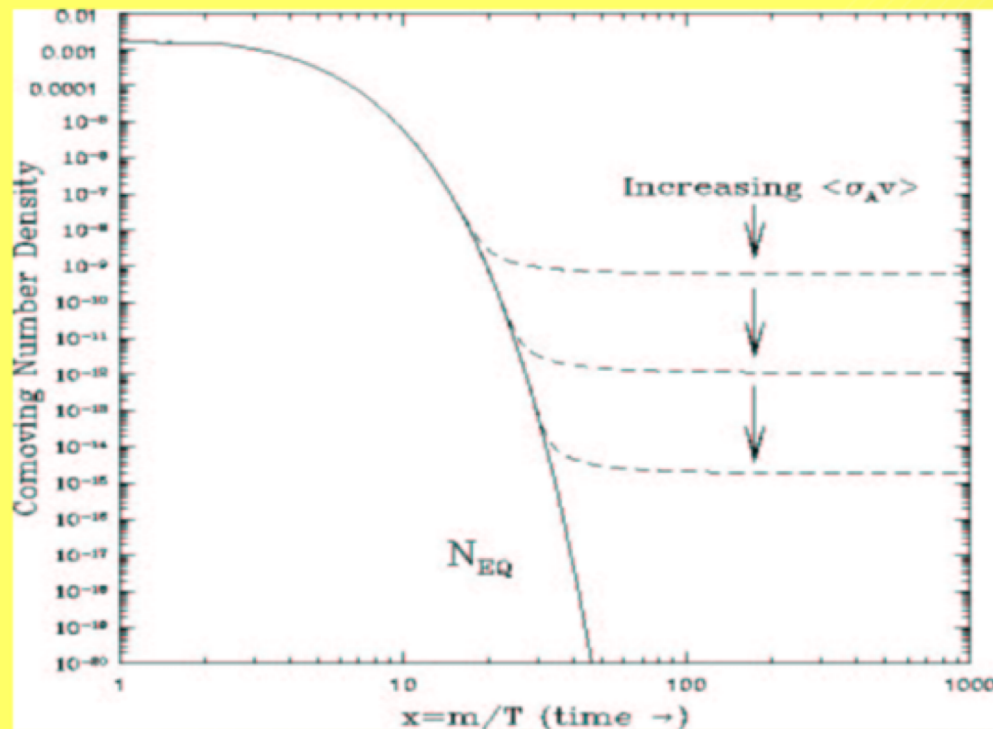


# Dark matter: A Cosmic mystery

- We know how much and its distribution in galaxies and throughout the Universe
- Does not emit/absorb light---cannot be ordinary atomic matter!
- What is it?

# The Party line (~1985—2015)

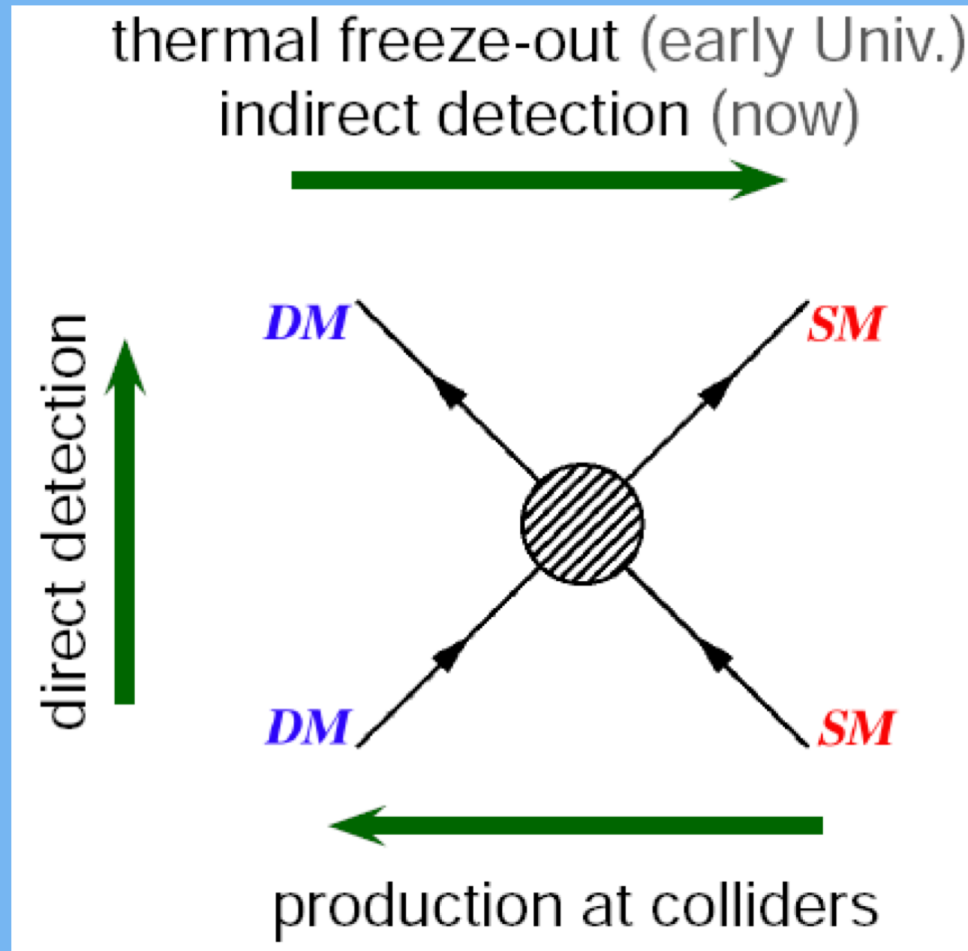
- Weakly Interacting Massive Particles (WIMPS).  
e.g., neutralinos



$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \text{ cm}^3 / \text{sec}}{\langle \sigma v \rangle}$$

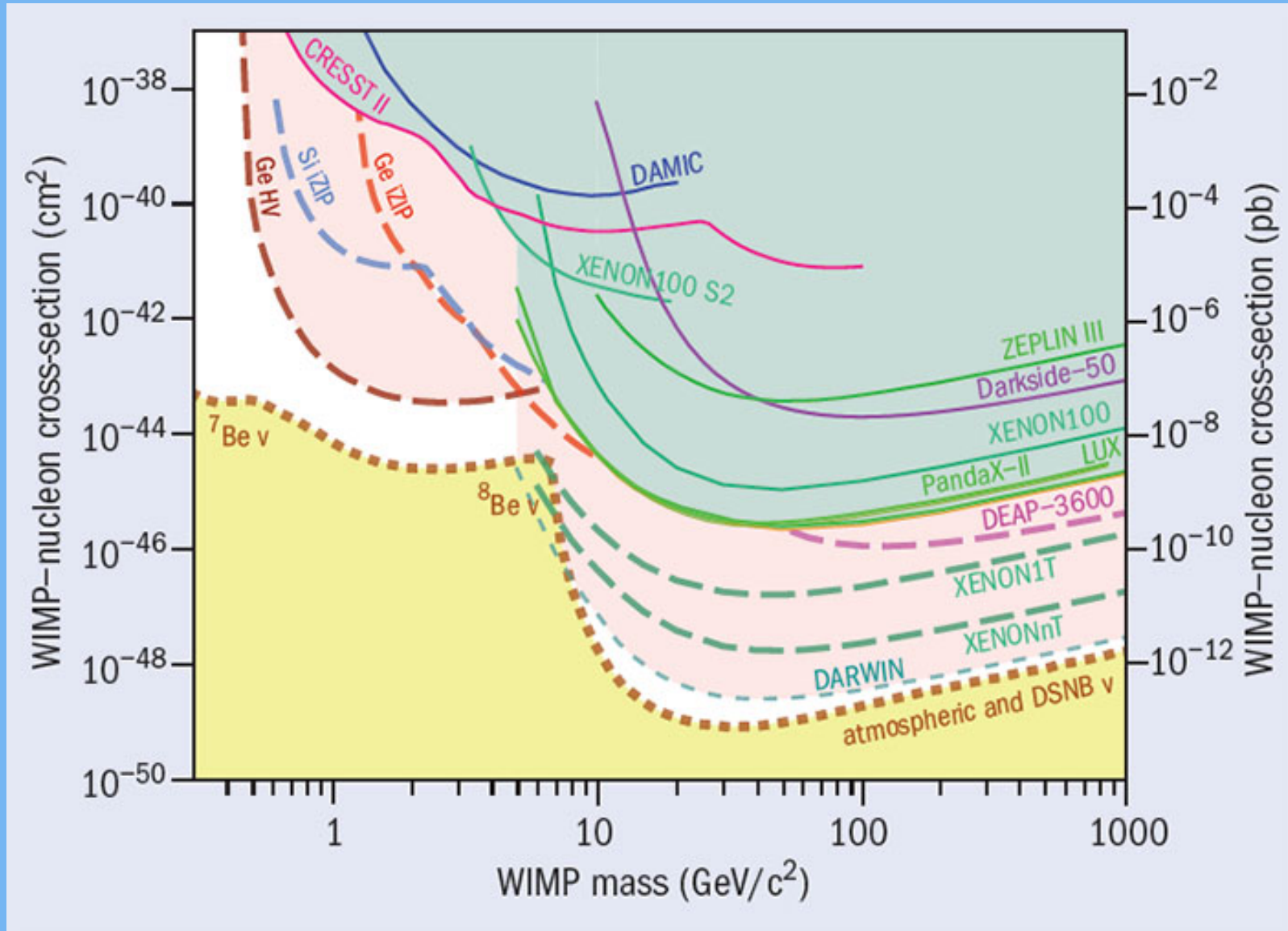
(e)

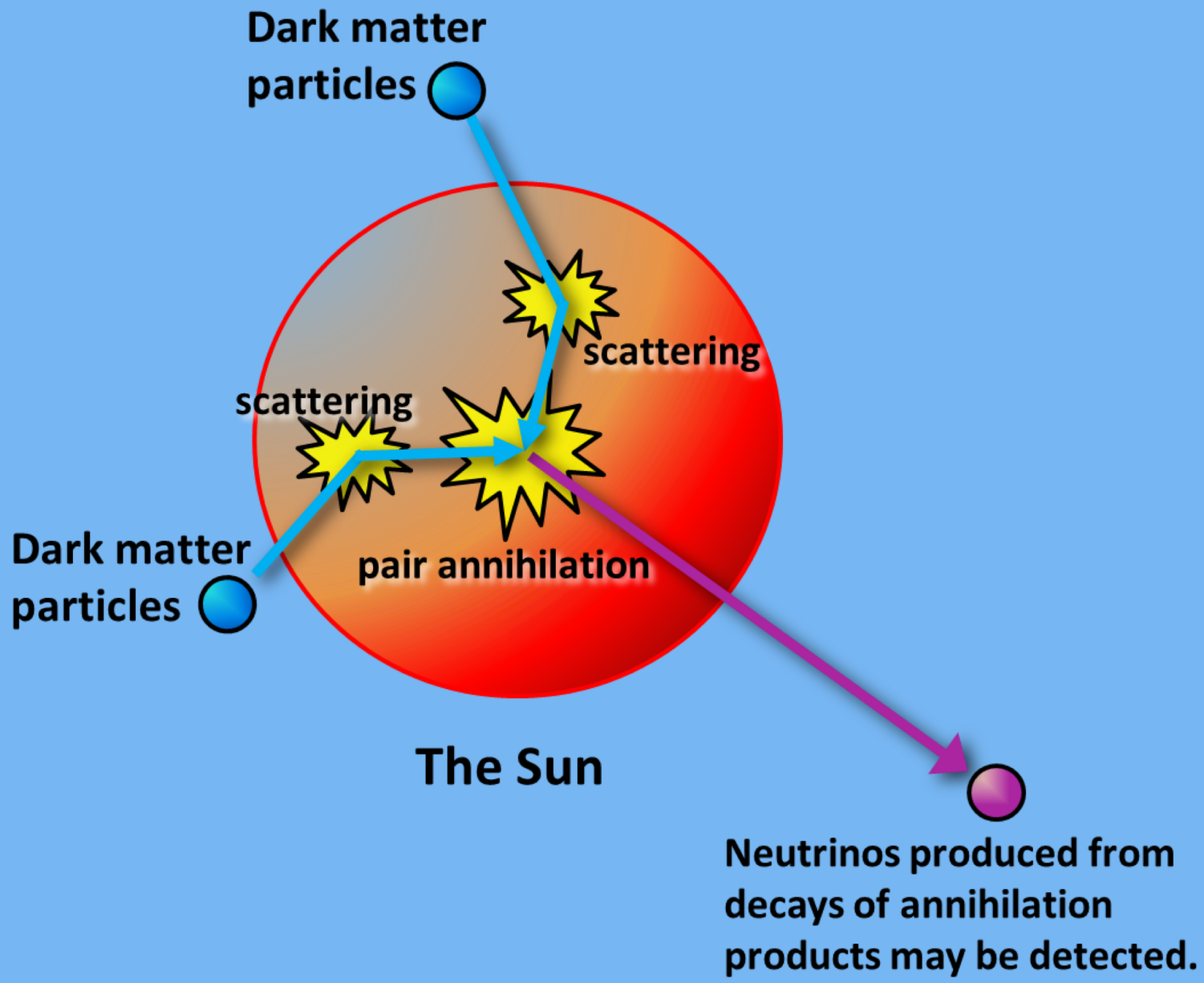




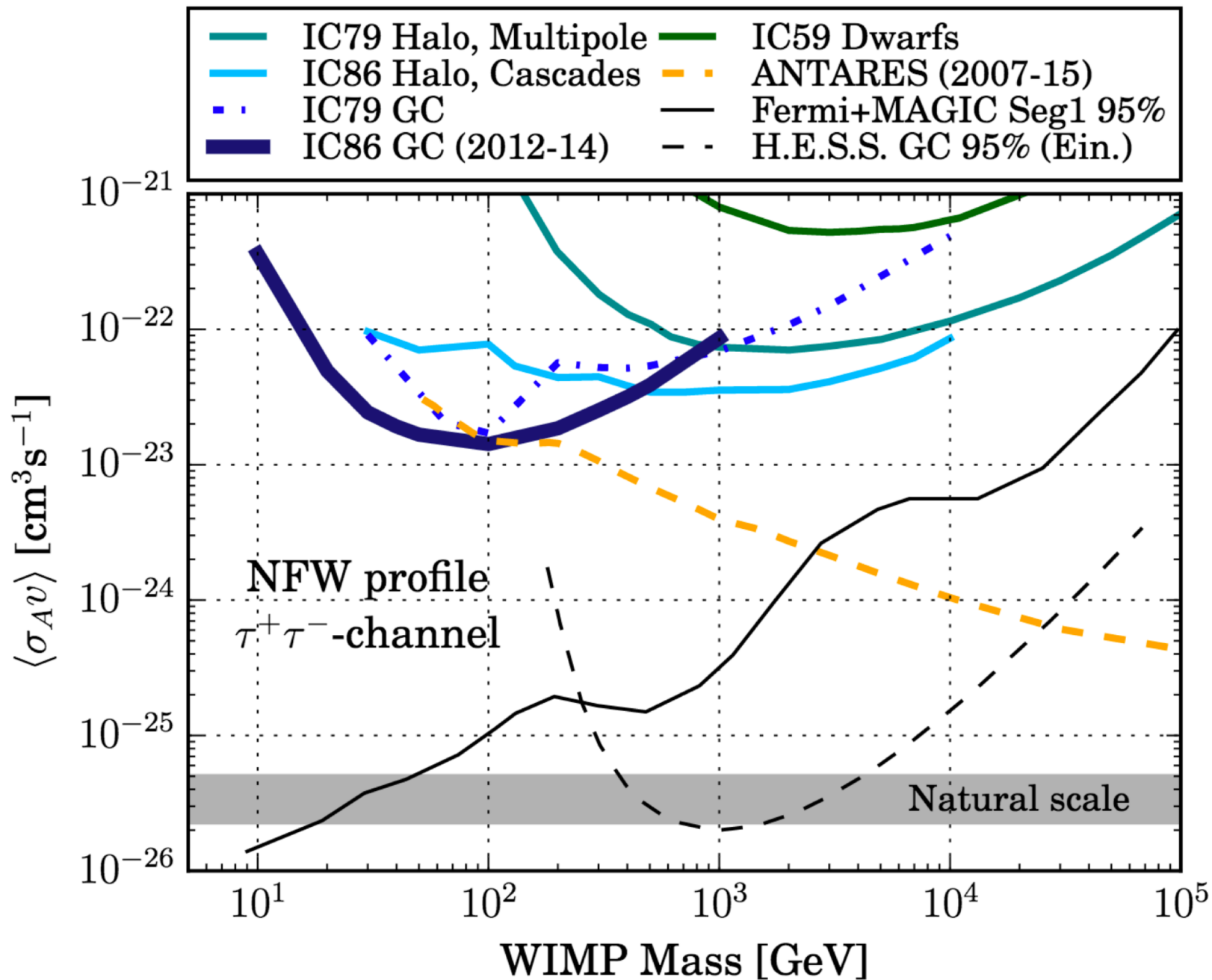
Simplicity/Elegance

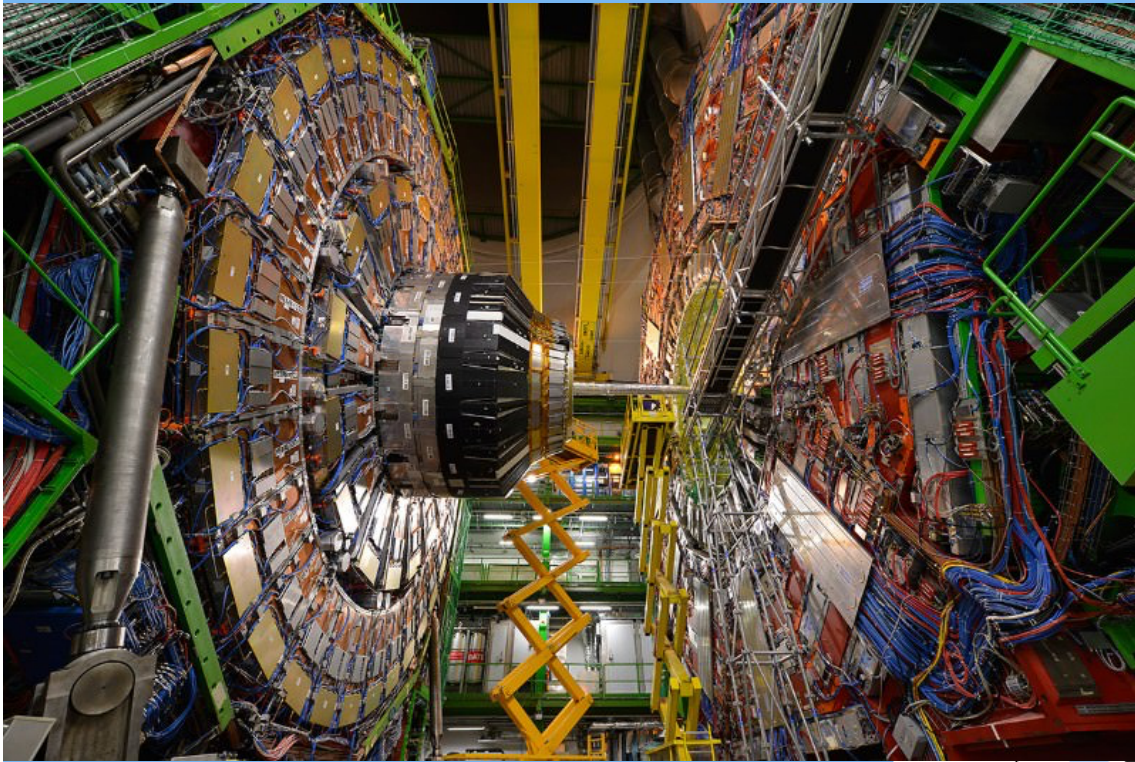
# Direct searches











on,  $\tilde{t}_1 \rightarrow b f f \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$  Status: May 2017

AS Preliminary

$\sqrt{s}=13$  TeV

$\rightarrow t \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$

0L 36.1 fb<sup>-1</sup> [CONF-2017-020]

$\rightarrow t \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow b f f \tilde{\chi}_1^0$

1L 36.1 fb<sup>-1</sup> [CONF-2017-037]

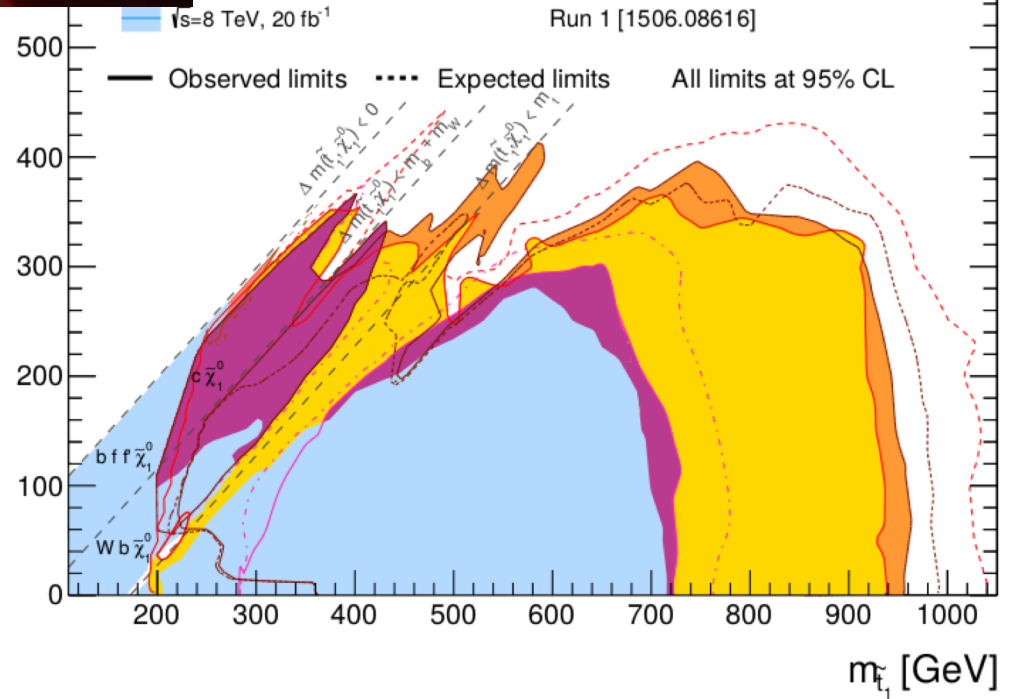
$\rightarrow t \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow b f f \tilde{\chi}_1^0$

2L 36.1 fb<sup>-1</sup> [CONF-2017-034]

$\rightarrow c \tilde{\chi}_1^0$

Monojet 3.2 fb<sup>-1</sup> [1604.07773]

Run 1 [1506.08616]



# Desperation?

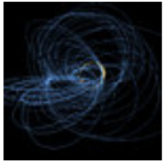
Inelastic, Sommerfeld-enhanced,  
momentum-dependent,  
leptophilic, co-annihilating, dipolar,  
millicharged, resonant, superheavy,  
sub-GeV, self-interacting, atomic,  
dark-sector, Higgs portal,.....



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~~Simplicity/Elegance~~

Time to look elsewhere?



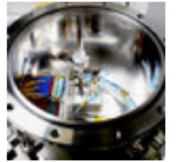
TRILOBITES  
How Cassini Will Begin Its Date With Death on Saturn



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





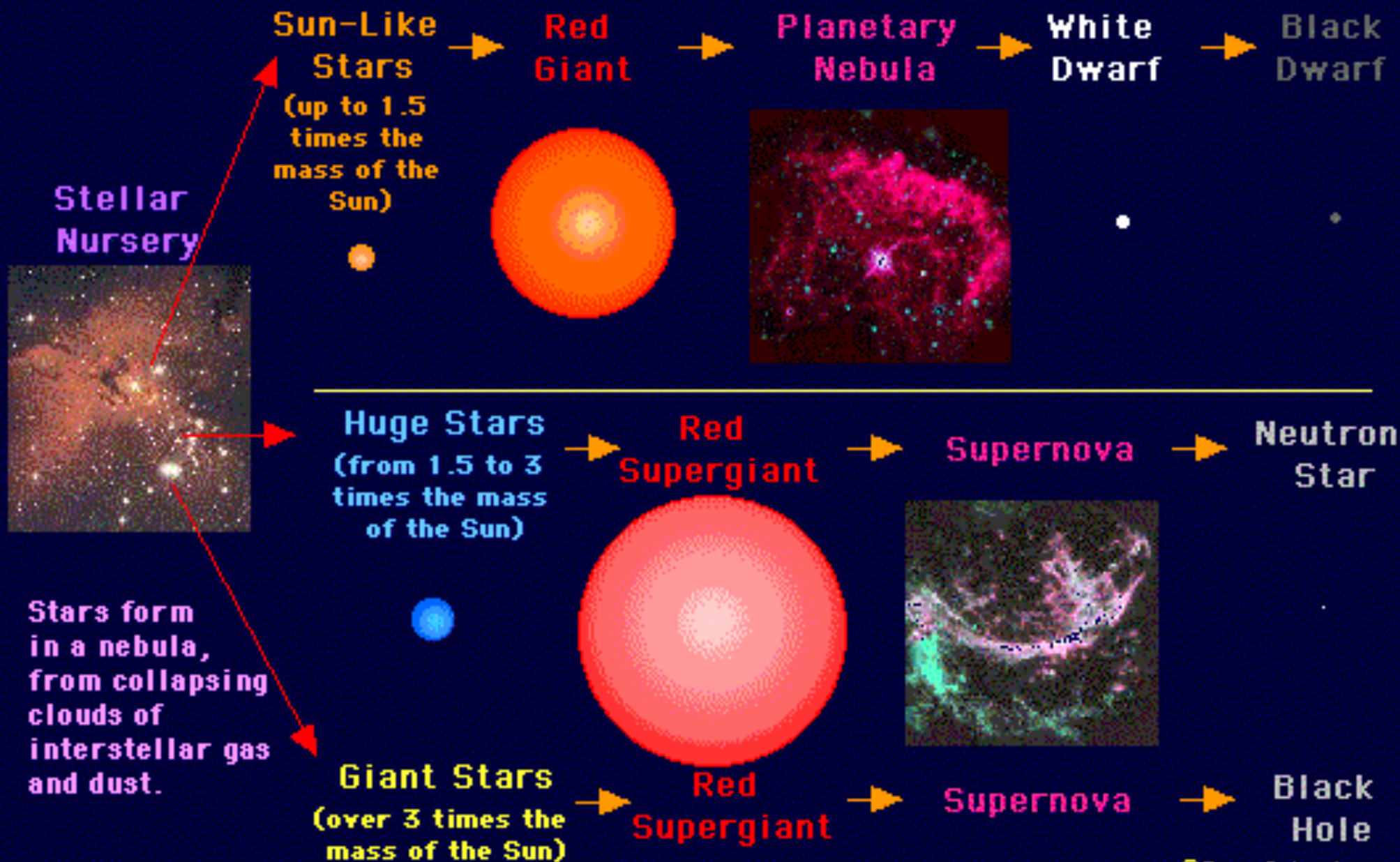
# Binary black hole

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

Where do these black holes come from?

Probably stellar remnants (binaries?  
globular clusters?)

# The Lifecycle of Stars



# 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)

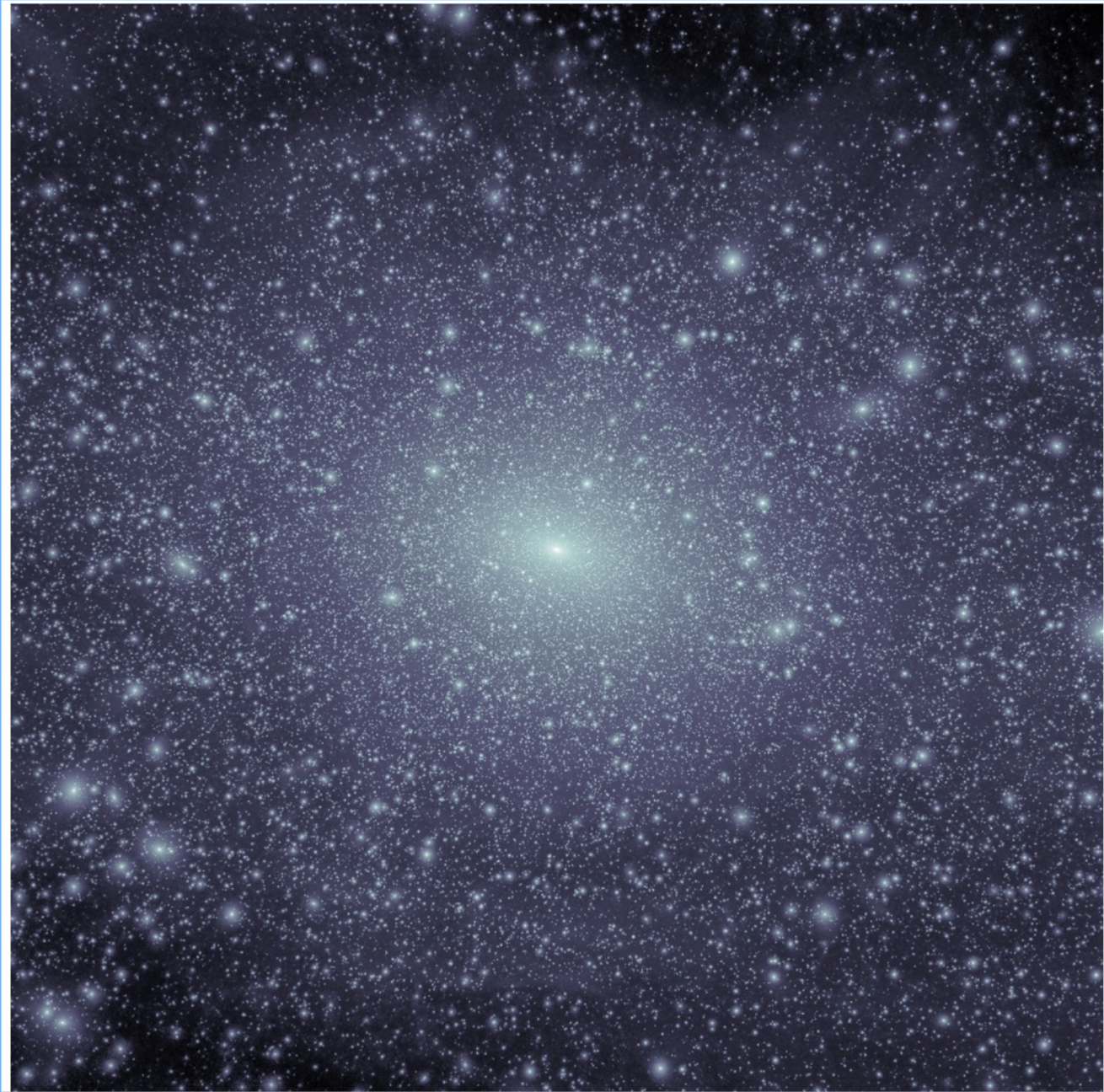
- highly speculative, but not crazy
- Surprising coincidence: If black holes of 30 solar masses make up the dark matter, they merge with rate comparable to that inferred from the initial LIGO event! (Bird et al. 2016)

Suppose DM = 30-Msun BHs

Gravitational radiative recombination

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





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

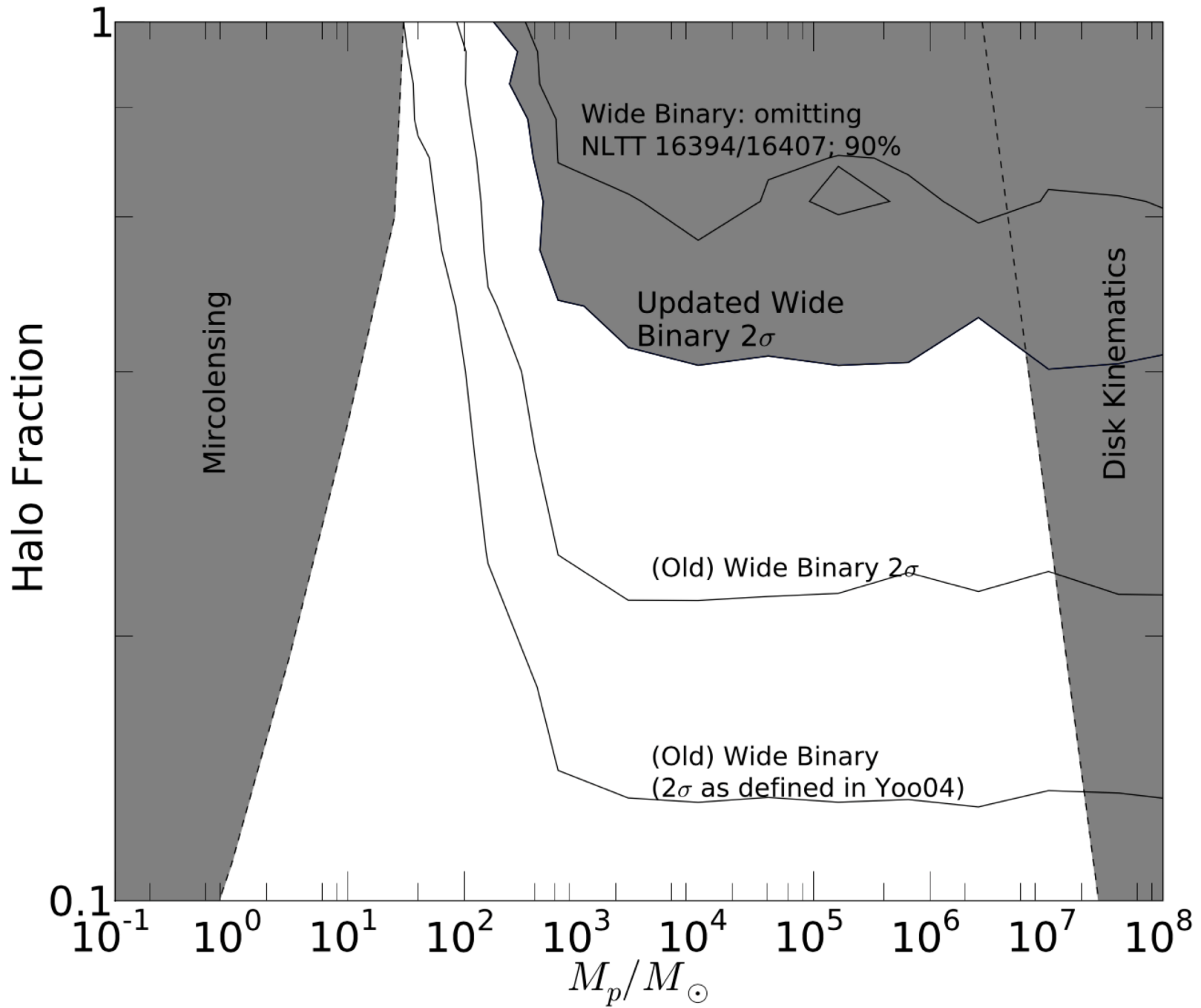
$$\mathcal{V} = 5 f(M_c/500 M_\odot)^{-11/21} \text{Gpc}^{-3} \text{yr}^{-1}$$

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

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!!!!!!!



Since then....

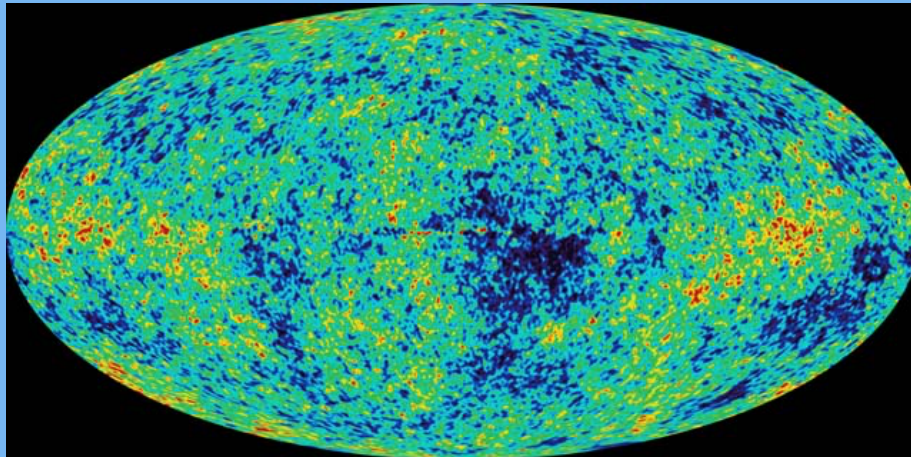


# Scenario ruled out (??) by:

- CMB (Ricotti, Ostriker, Mack 2007)
- Dwarf-galaxy dynamics (Brandt; 2016)
- 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  $\sim 3-4$  OoMs!!)



# Underlying physics for CMB bounds

Carr 1981, Ricotti et al. 2008, Ali – Haimoud & MK 2017

1. PBHs accrete baryons
2. a fraction of the accreted mass is re-radiated
3. a fraction of this luminosity is deposited into the plasma
4. some is deposited as heat => CMB spectral distortions
5. some leads to extra ionizations
  - => change the recombination history and visibility function
  - => affects CMB temperature and polarization anisotropies

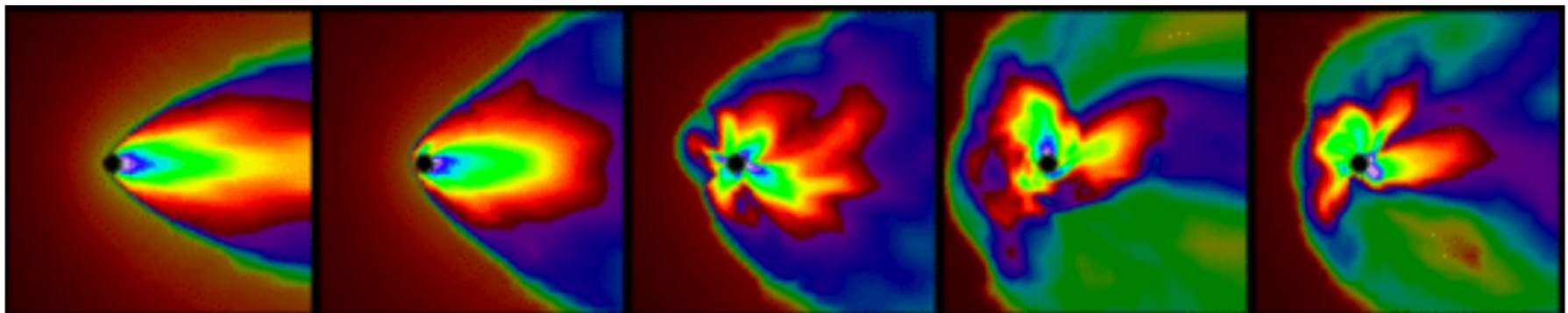
Our philosophy: (i) first-principles, low-fudge-number calculation (ii) estimate the minimal physically plausible effect in order to set **conservative upper limits**

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

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



Ruffert's website

# Baryon-dark matter relative velocity

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

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

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

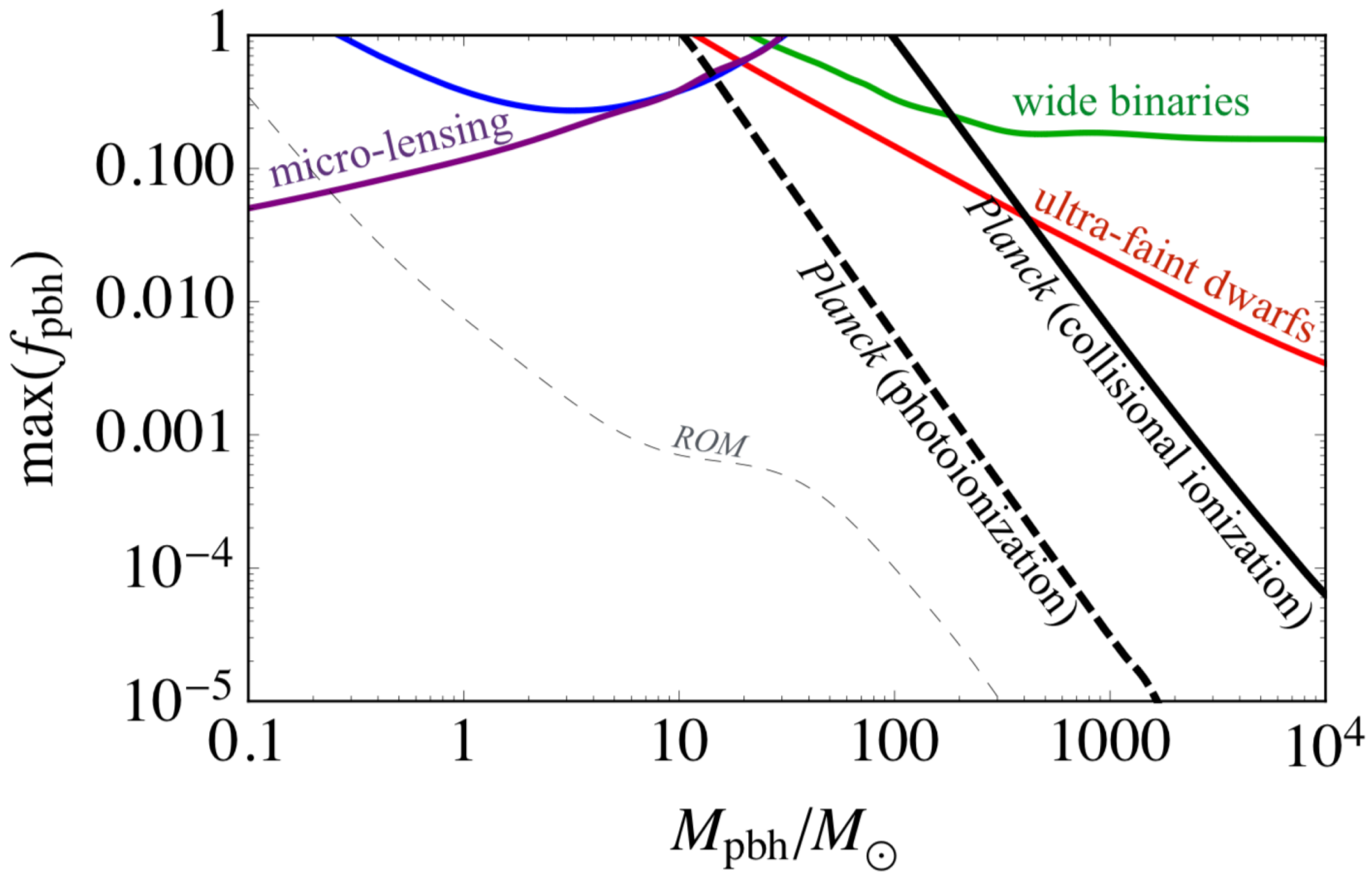
$$\frac{\langle L \rangle}{L(v_{\text{rel}} = 0)} \sim 10^{-2}$$

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.

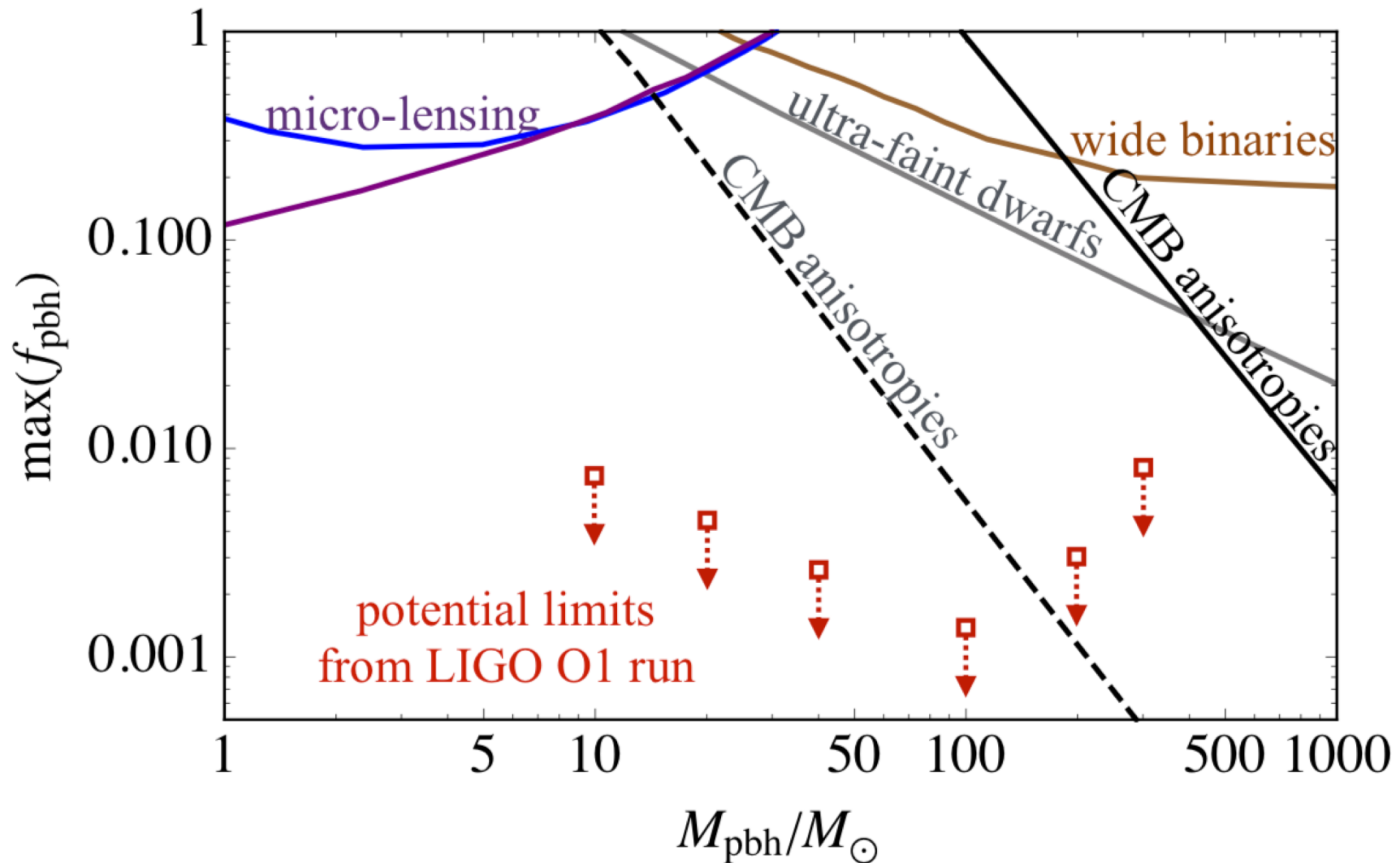
*We do not account for those.*



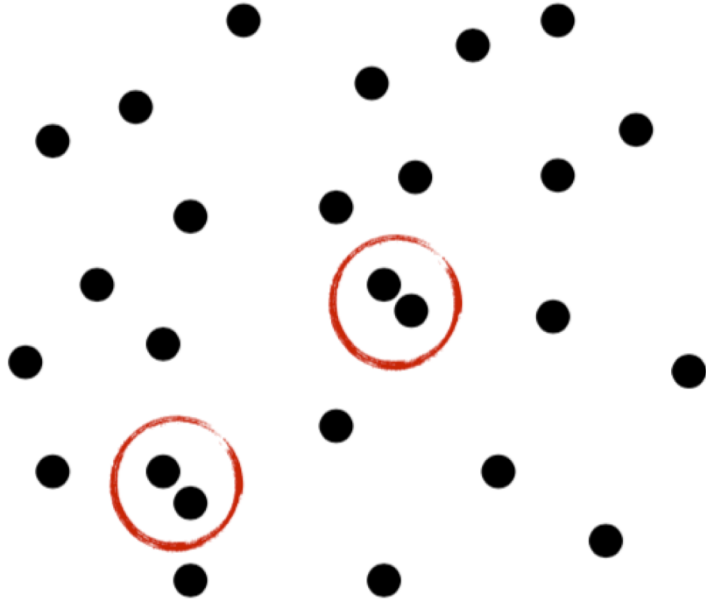


# Does LIGO rule out PBH-dark matter?

Ali-Haïmoud, Kovetz & Kamionkowski [1709.06576]



## 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

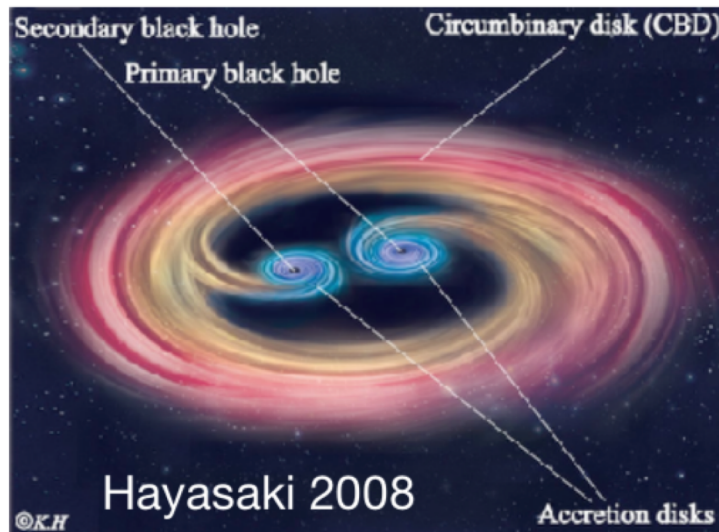
Inspiral through GW radiation, some merge at the present time.

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

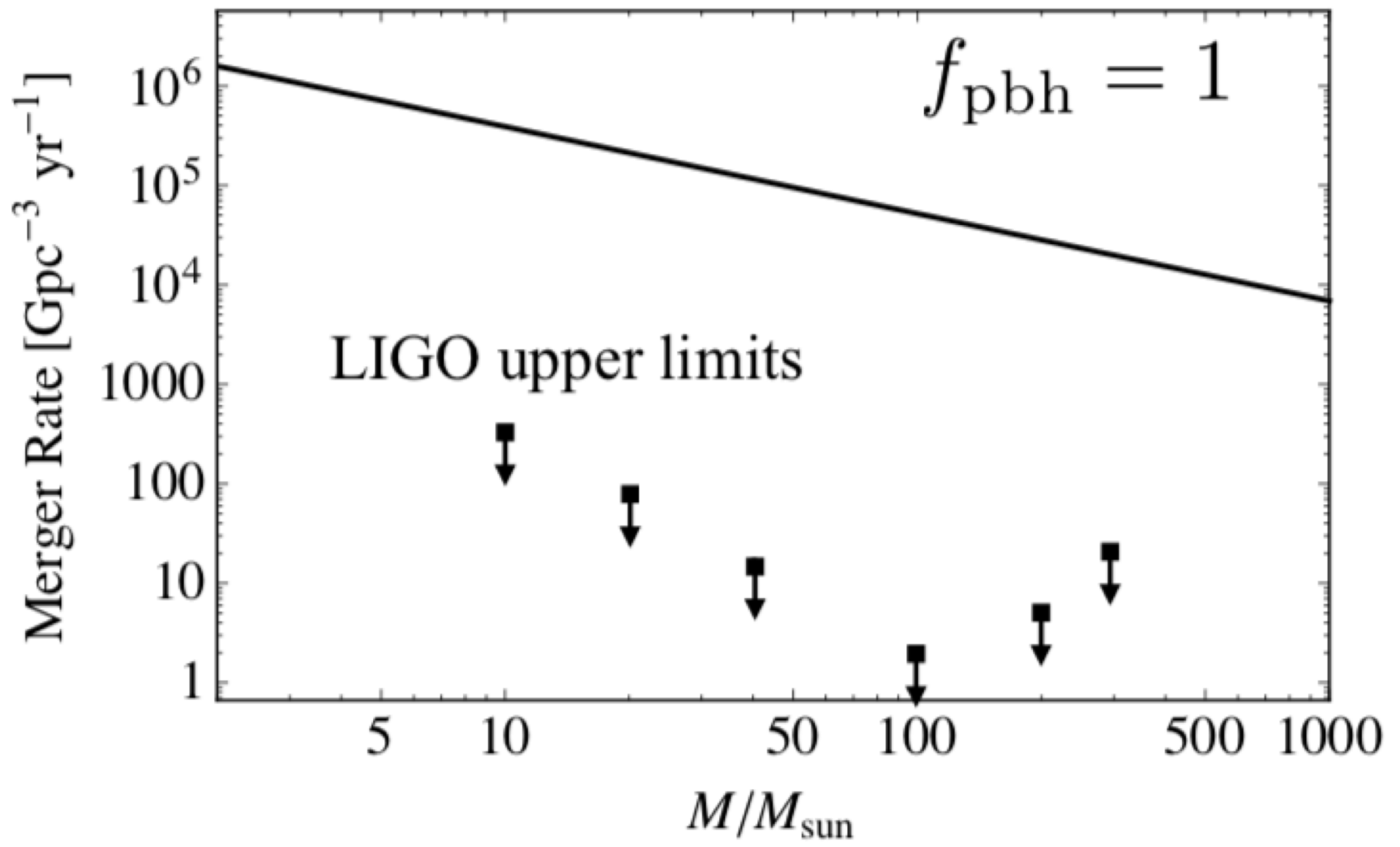
- Gravitational interactions with other PBHs and rest of dark matter

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

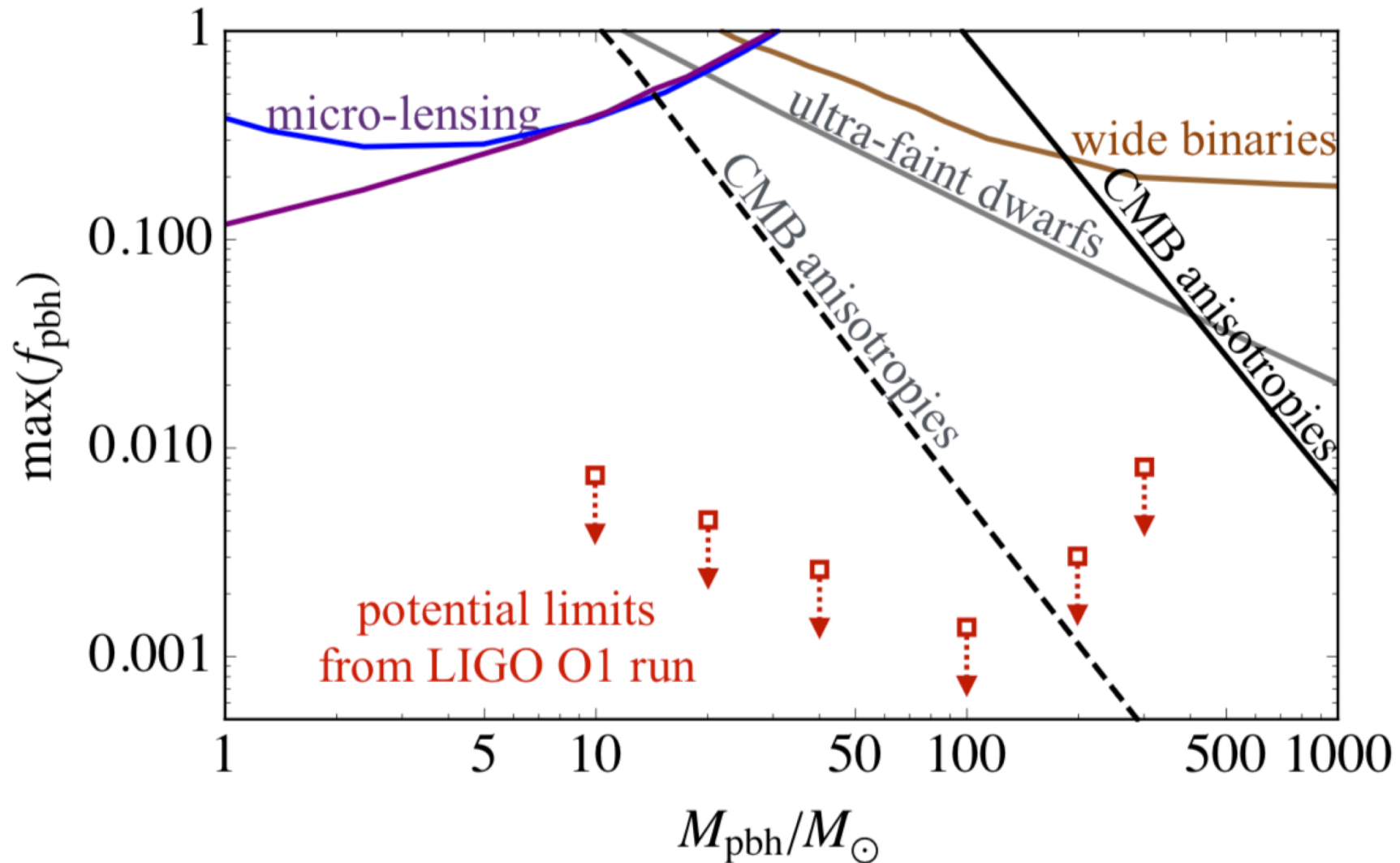


Most uncertain piece. Estimated that torques could be marginally relevant. Subject of active research (e.g. Tang, Haiman & MacFadyen 2018).



# Does LIGO rule out PBH-dark matter?

*Probably* but more checks are needed



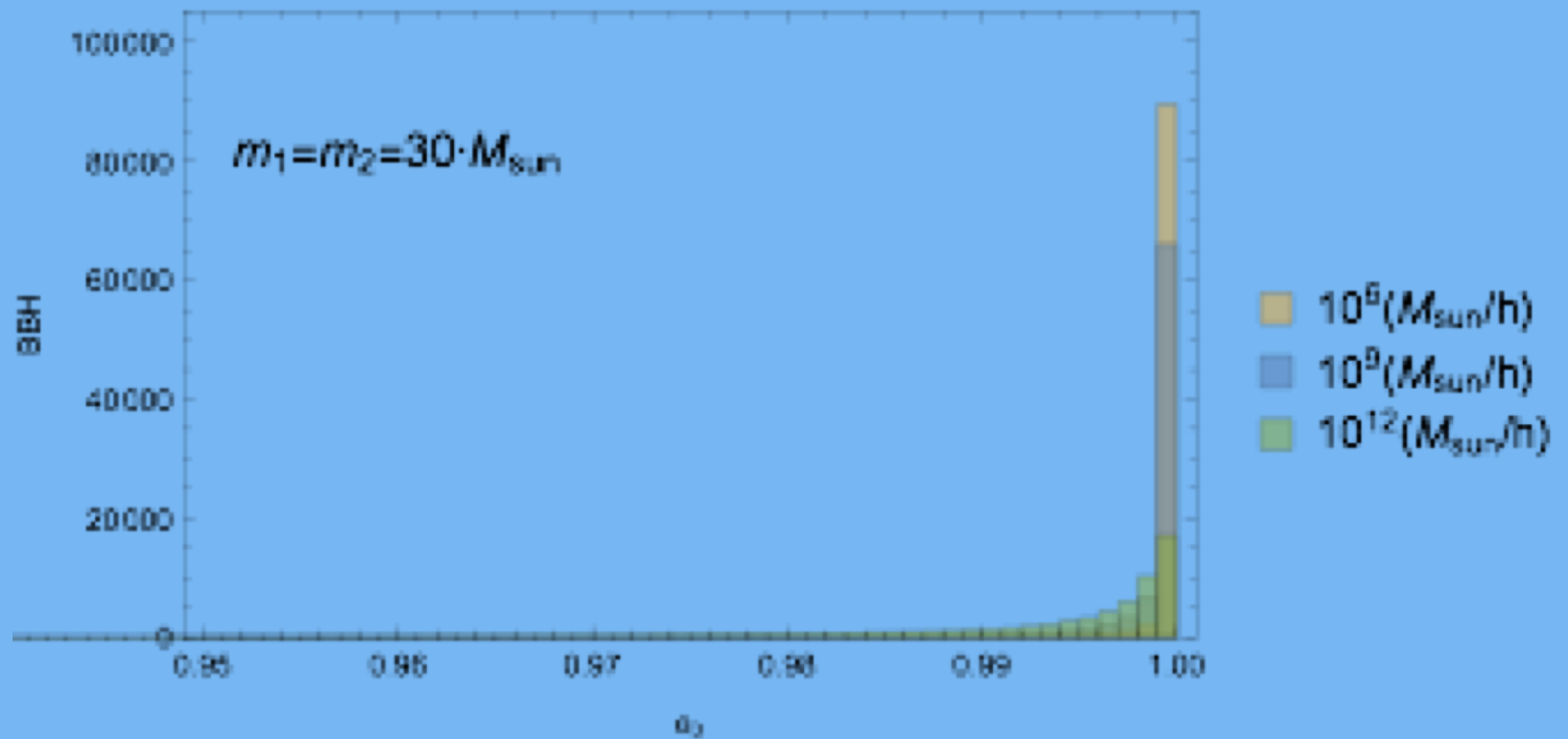
# How to test the hypothesis?

- 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  $\sim 20,000$  more BBH  
mergers in next decade!!

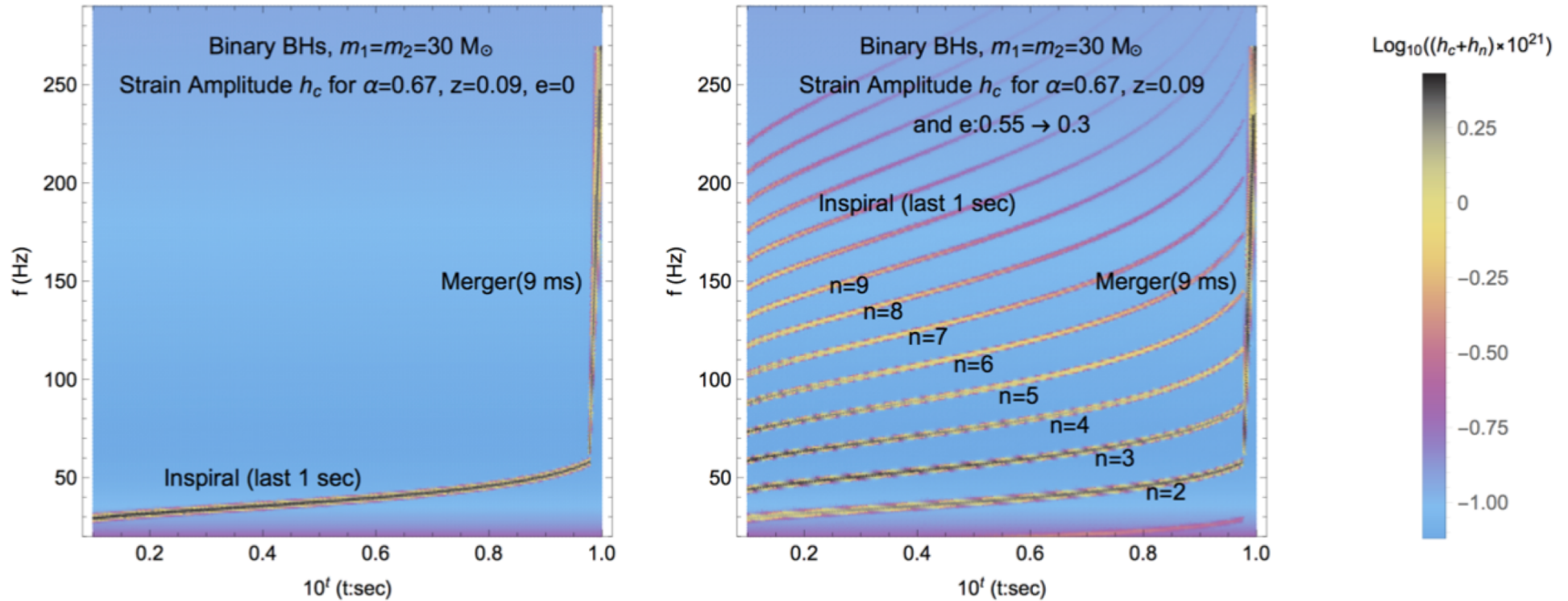


PBH binaries have high initial eccentricities:



see many more modes of grav. waves

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

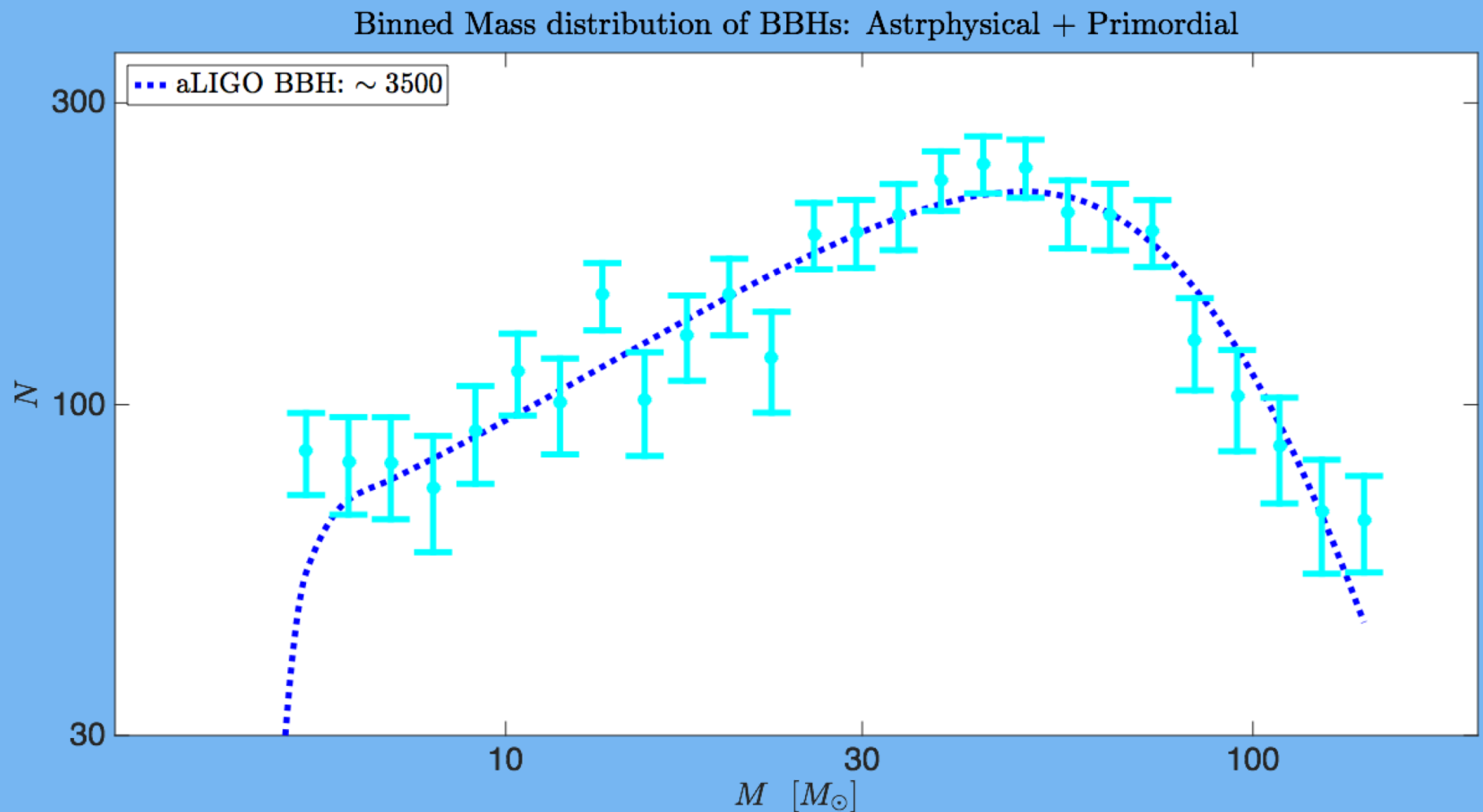


Cholis, Ali-Haimoud, Bird, Munoz, MK,  
Kovetz, and Raccanelli (2016)

# The BH binary mass distribution

# The Black-Hole Mass Function from GWs

with 5 years of aLIGO:

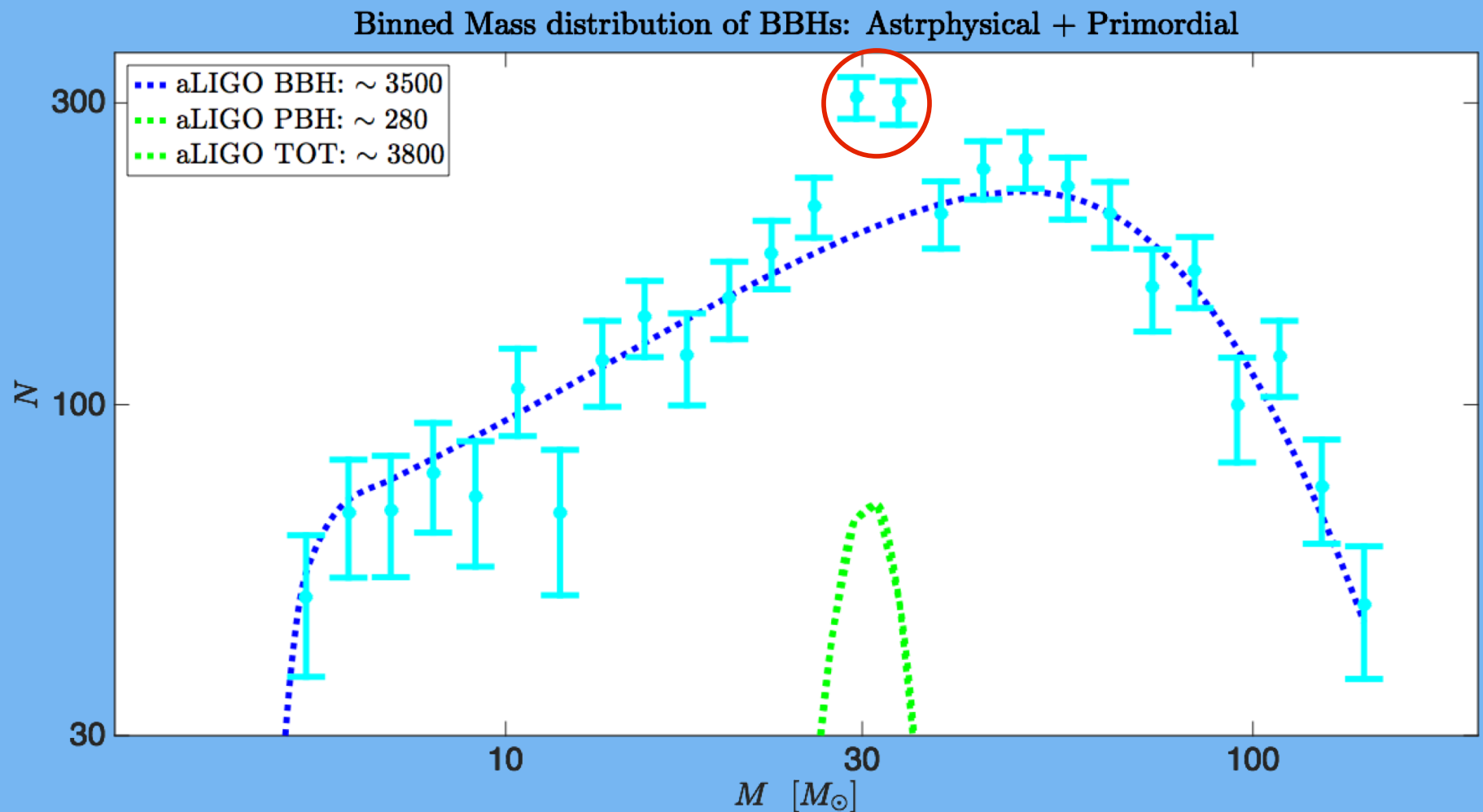


# The Black-Hole Mass Function from GWs

with 5 years of aLIGO data:

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

With Dark Matter PBHs:

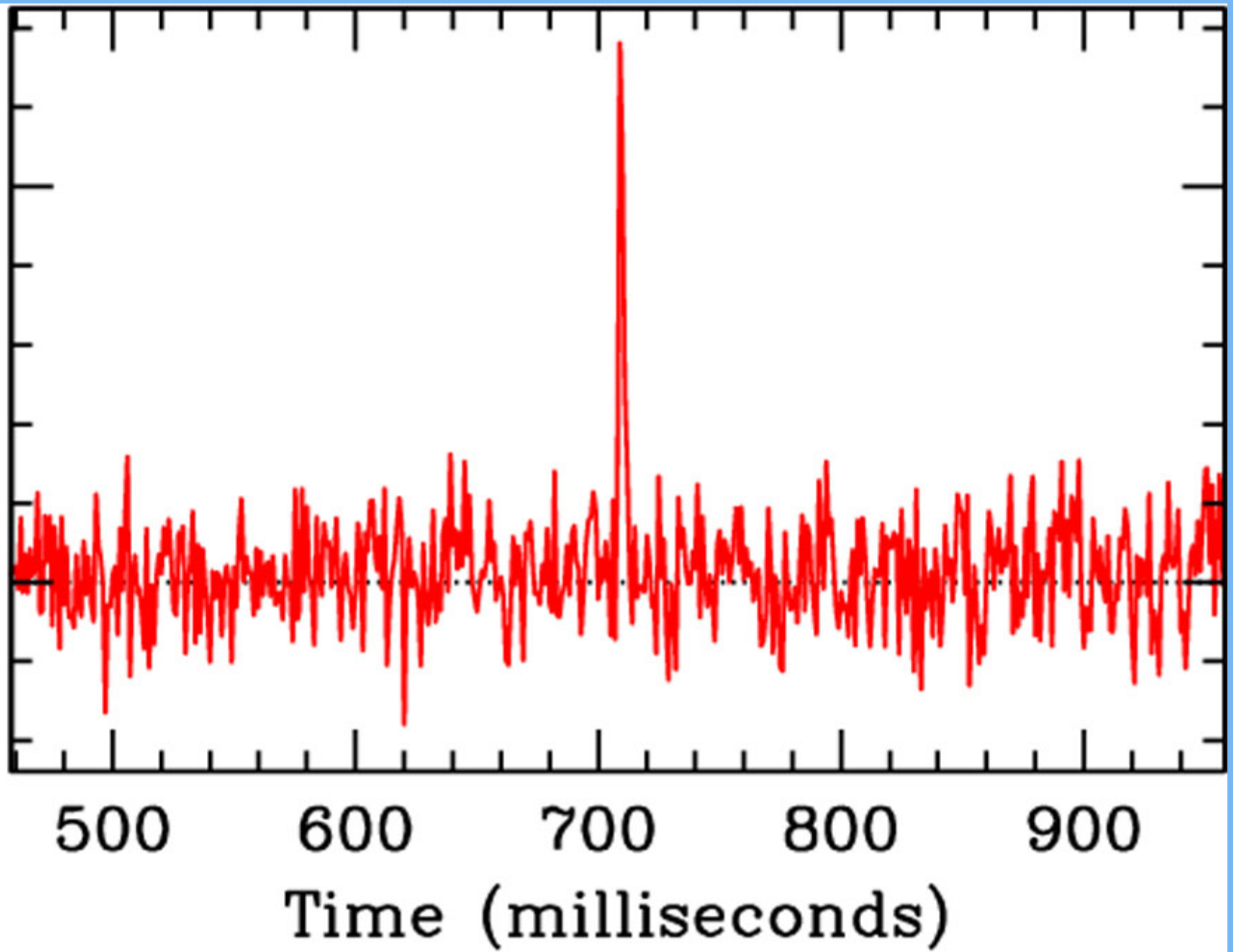


# Lensing of Fast Radio Bursts by Compact Objects

Munoz, Kovetz, Dai, MK, 1605.00008

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

Intensity

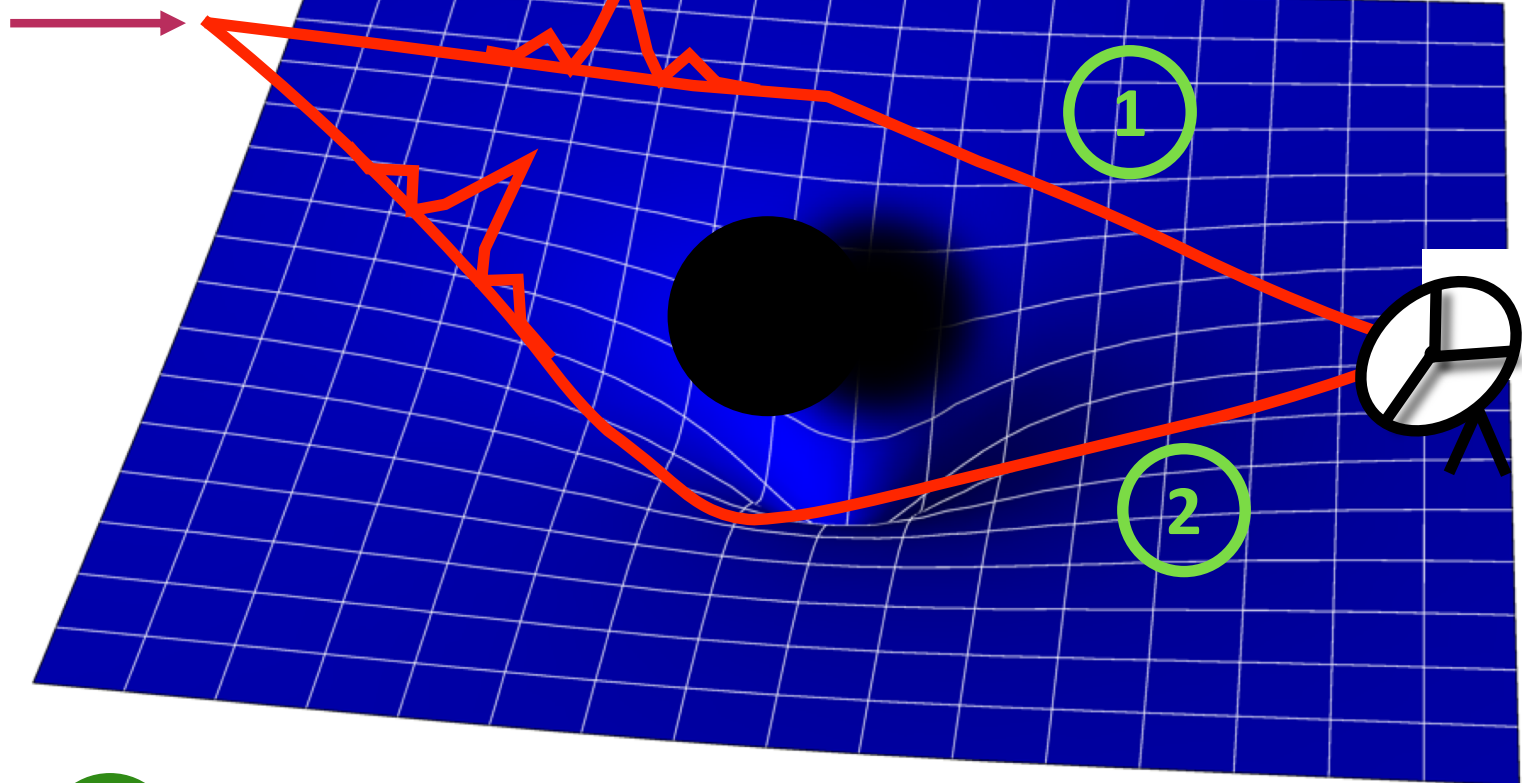




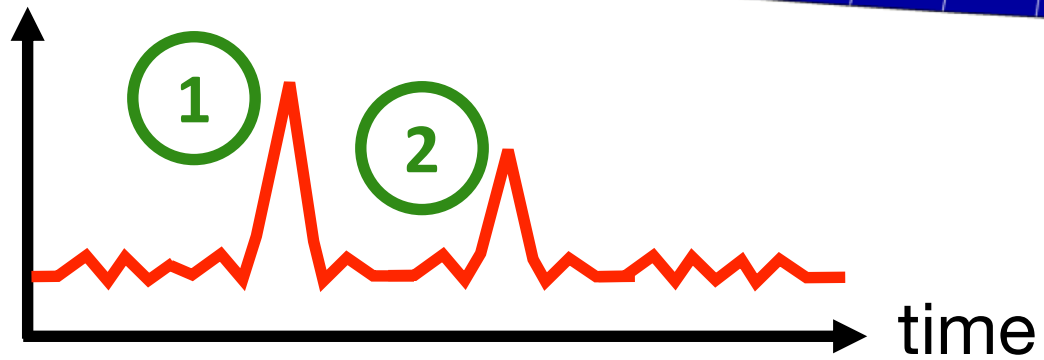
# FRB Lensing

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

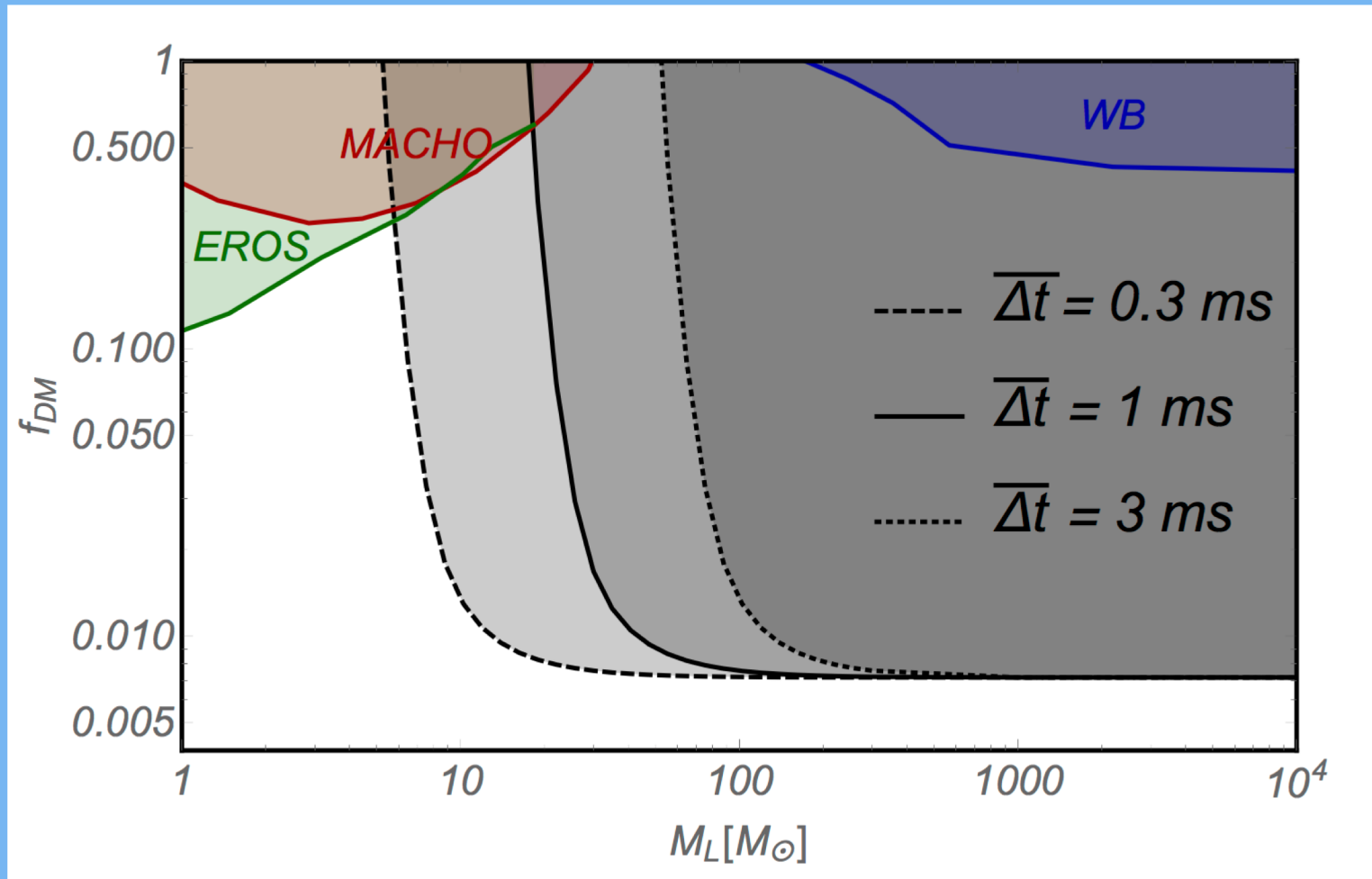
Source FRB



flux



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



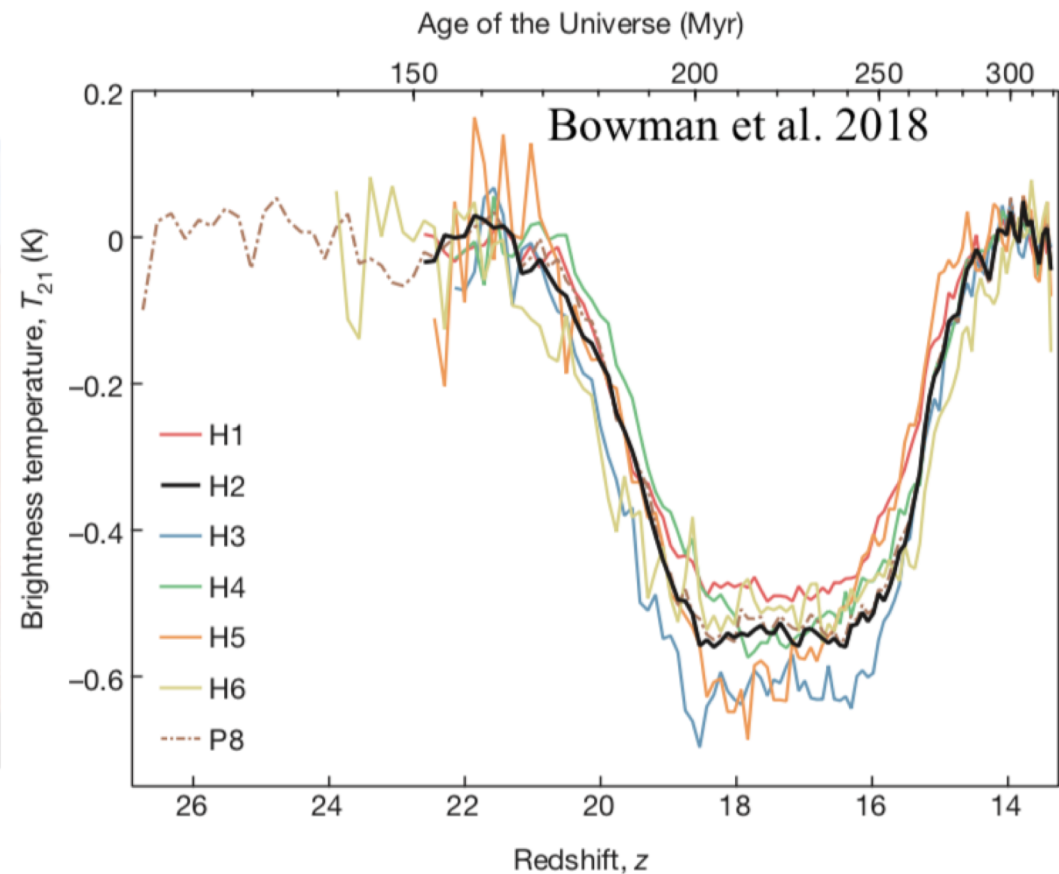
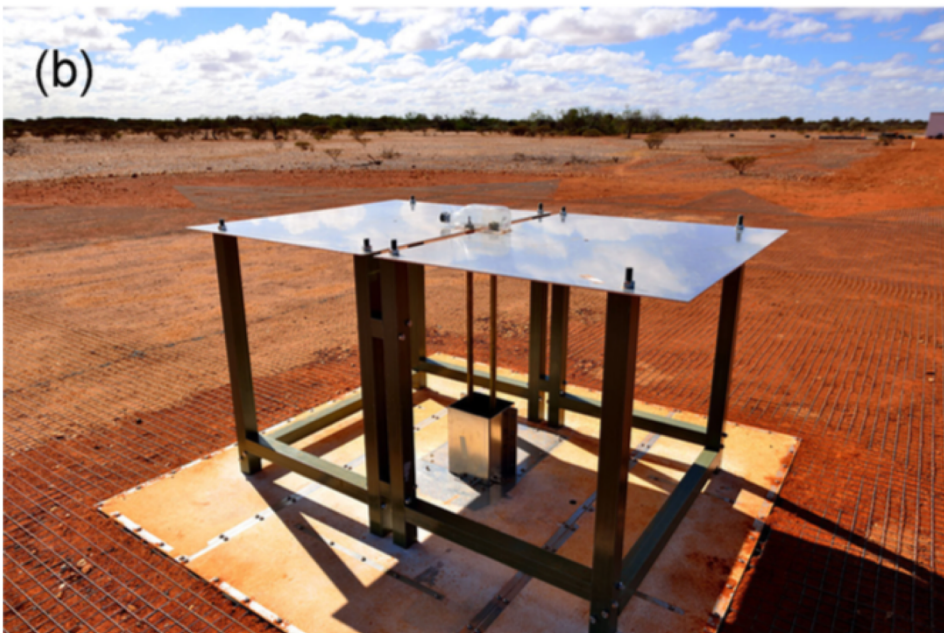
# In progress

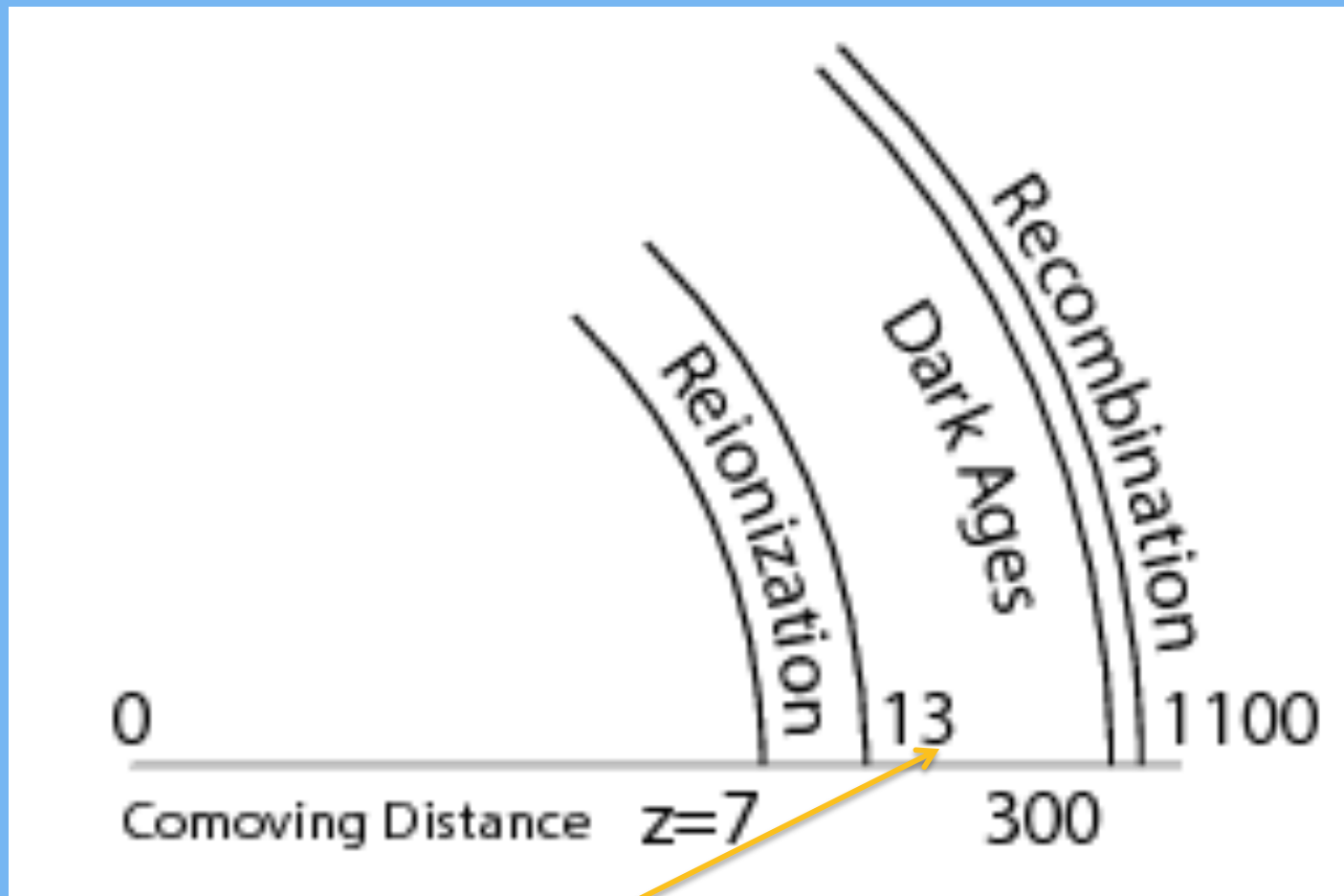
Can also seek echoes in gamma-ray-burst light curves  
(Ji, Kovetz, MK)

# Baryon—DM interactions from cosmic dawn?

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

February 2018





Lots of neutral hydrogen

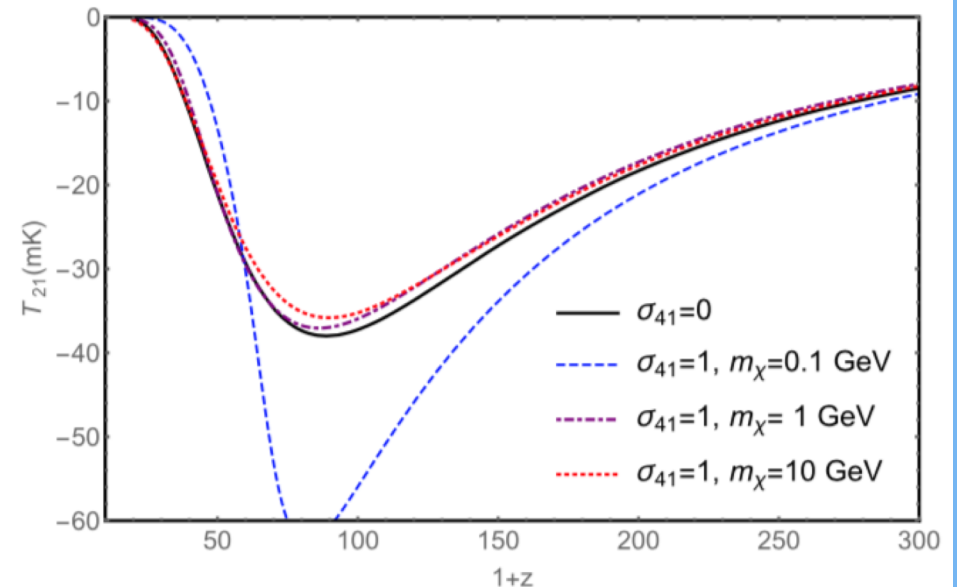
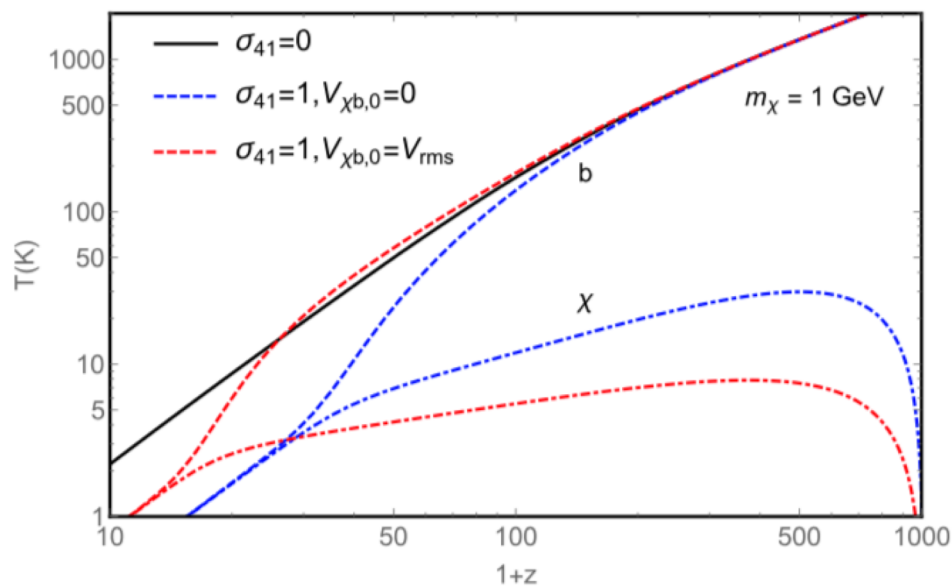
If DM-baryon interactions exist, they can mediate heat exchange between baryons and DM (Dvorkin, Blum, MK 2014)

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

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

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



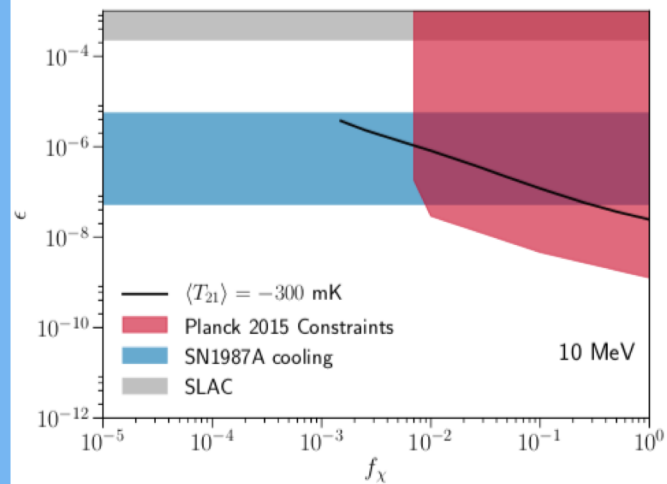
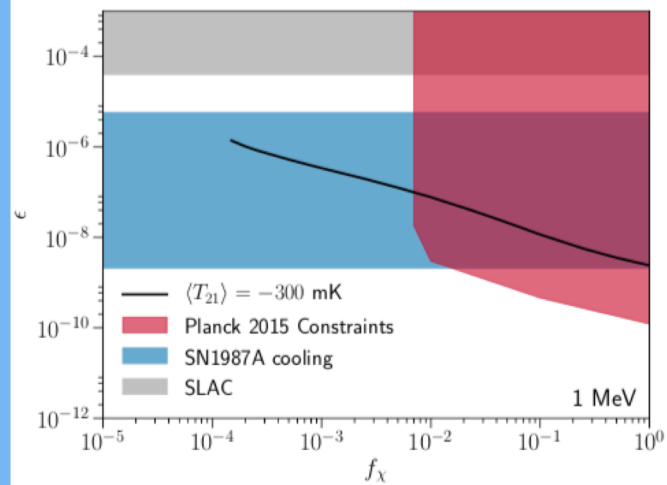
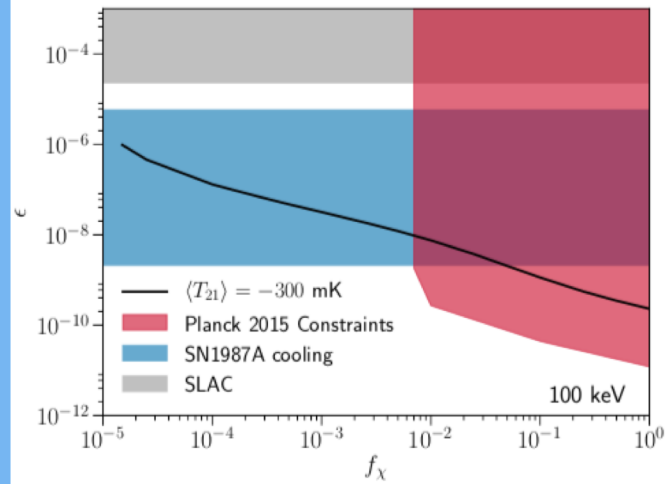


# Issues/concerns/question:

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



E.g., parameter constraints for millicharged DM  
 (Kovetz, Poulin, Gluscevic, Boddy, Barkana, MK, in prep)

# Dark-matter decay and line-intensity mapping

(Creque-Sarbinowski & MK, in prep)

# 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

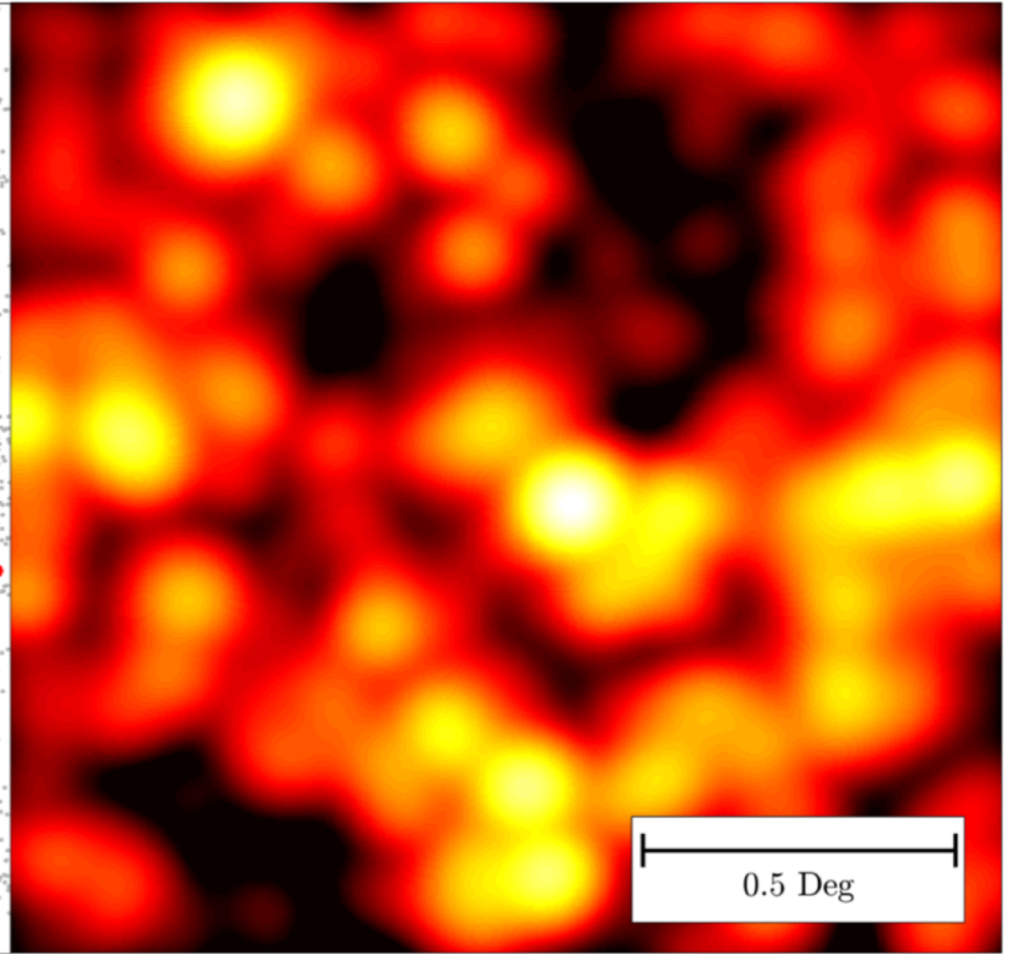
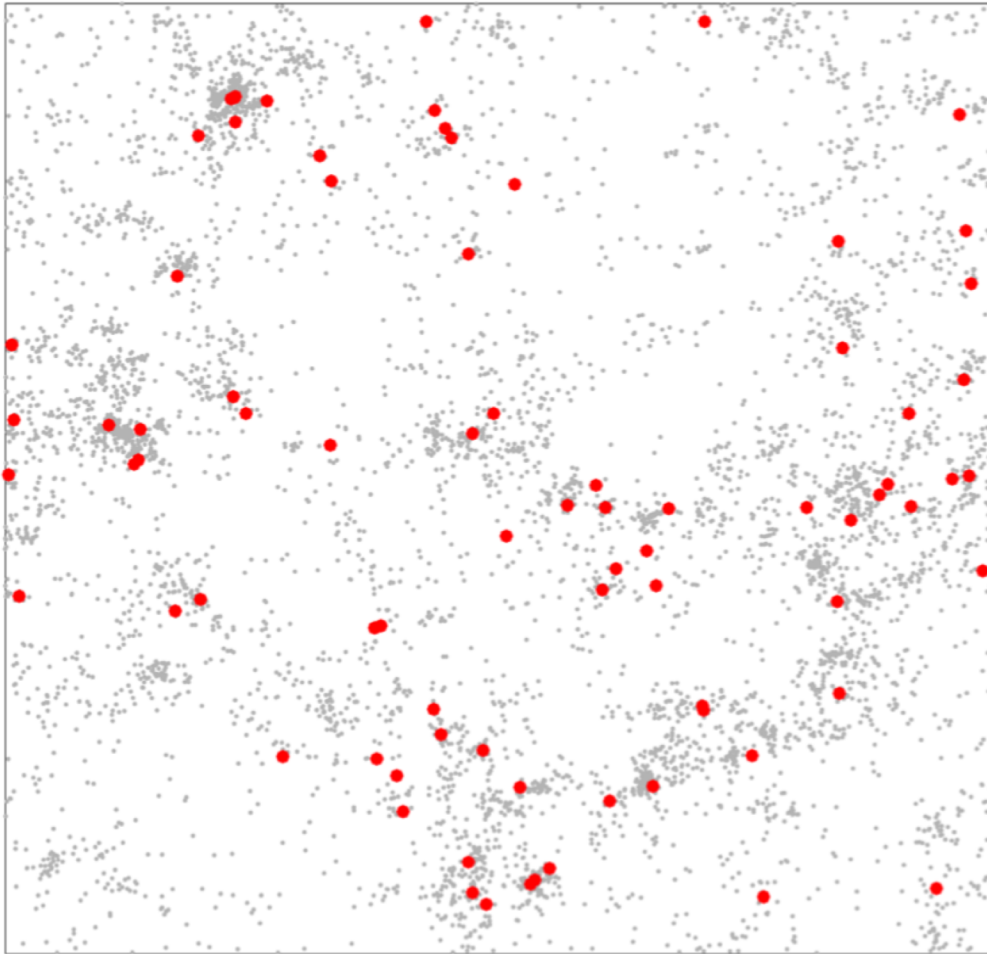


Fig credit: Patrick Breysse

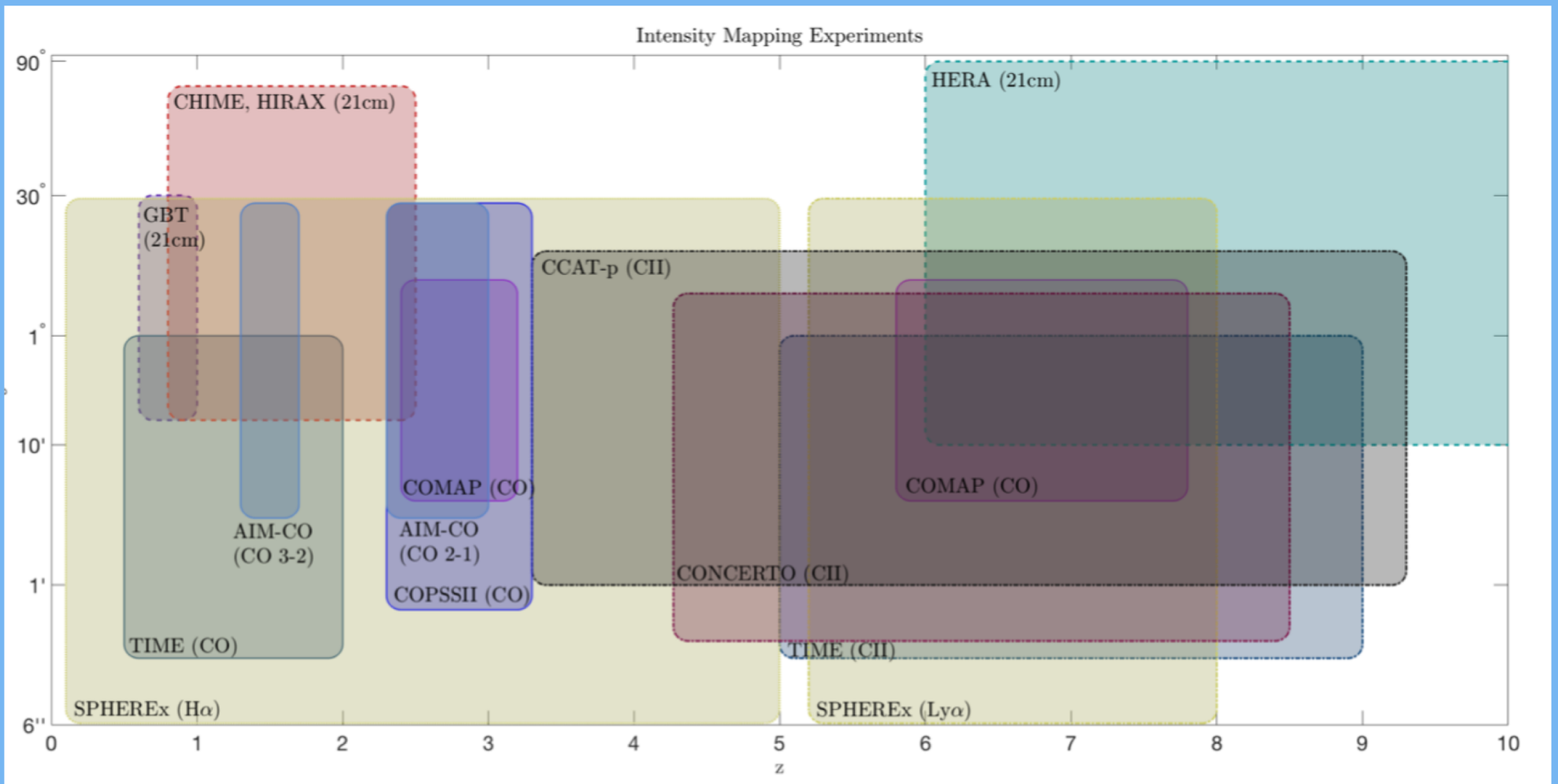
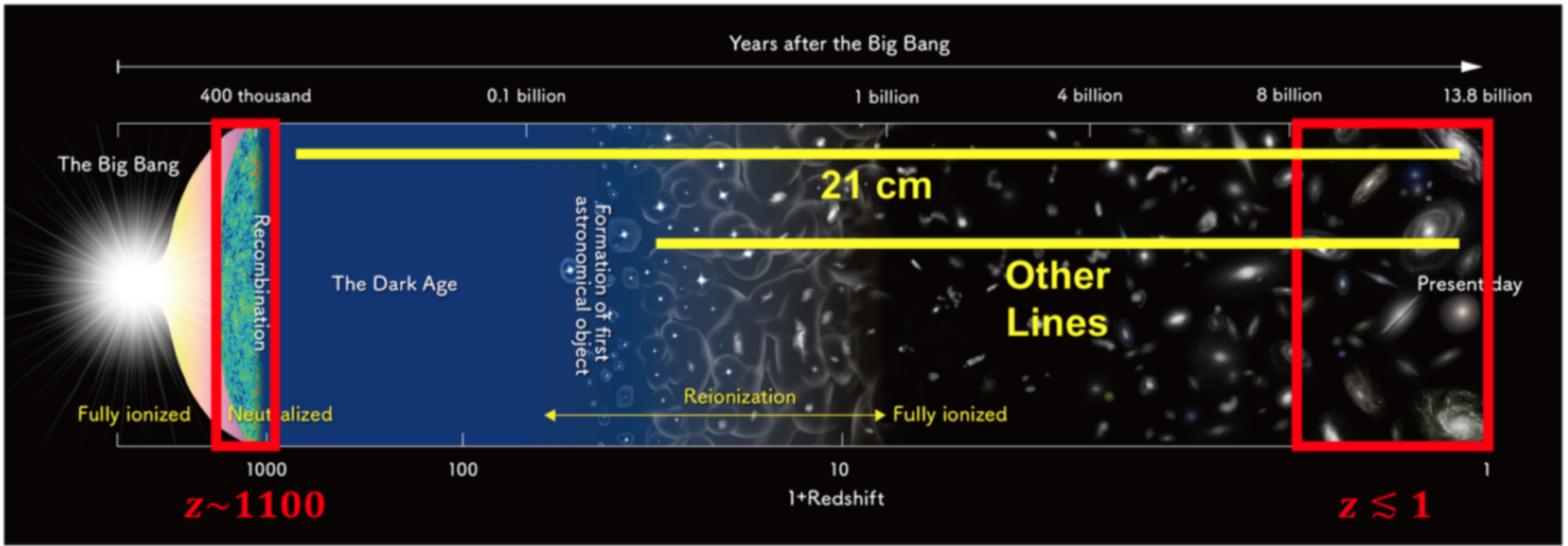


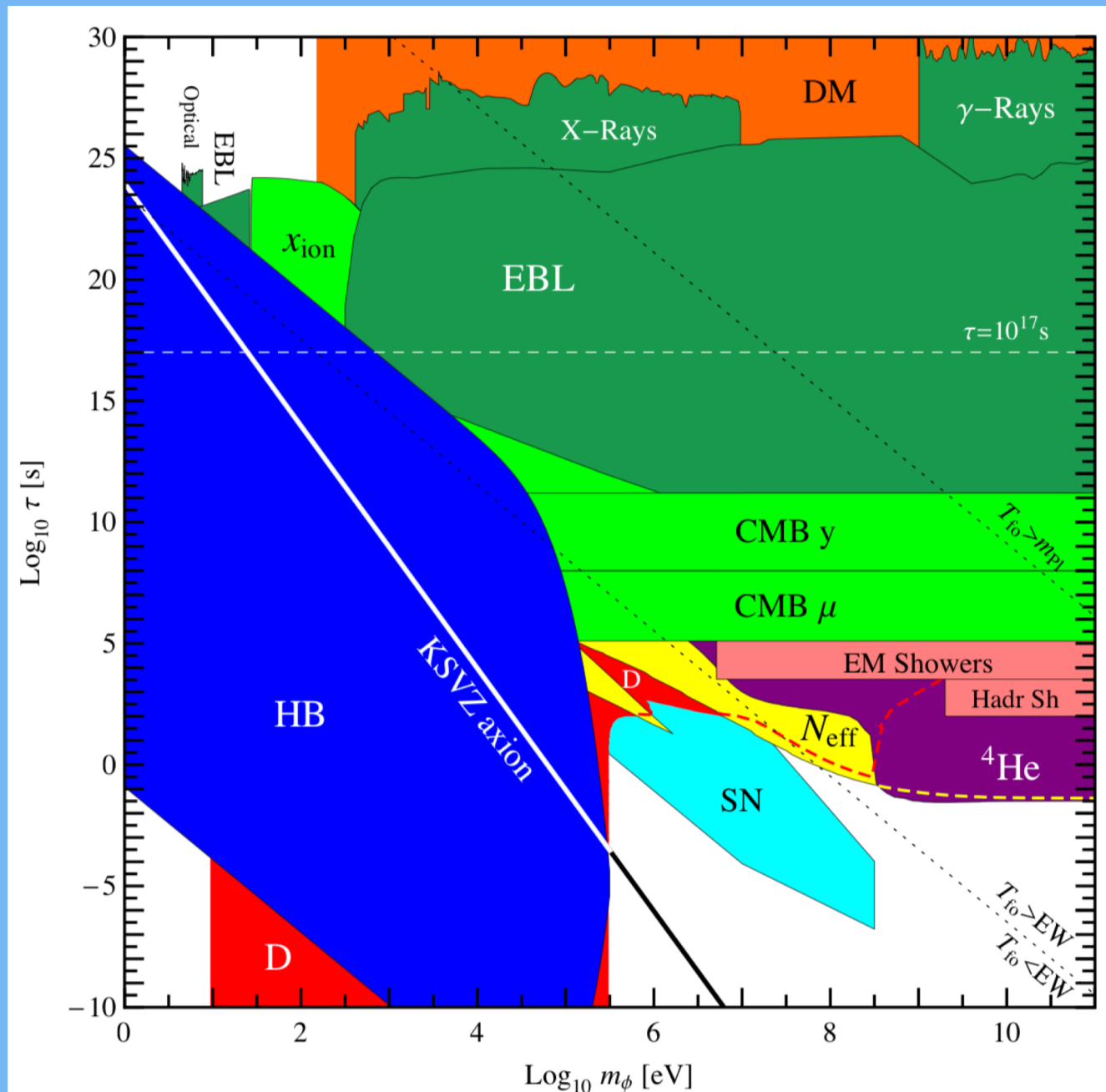
Fig. from Patrick Breysse and Ely Kovetz



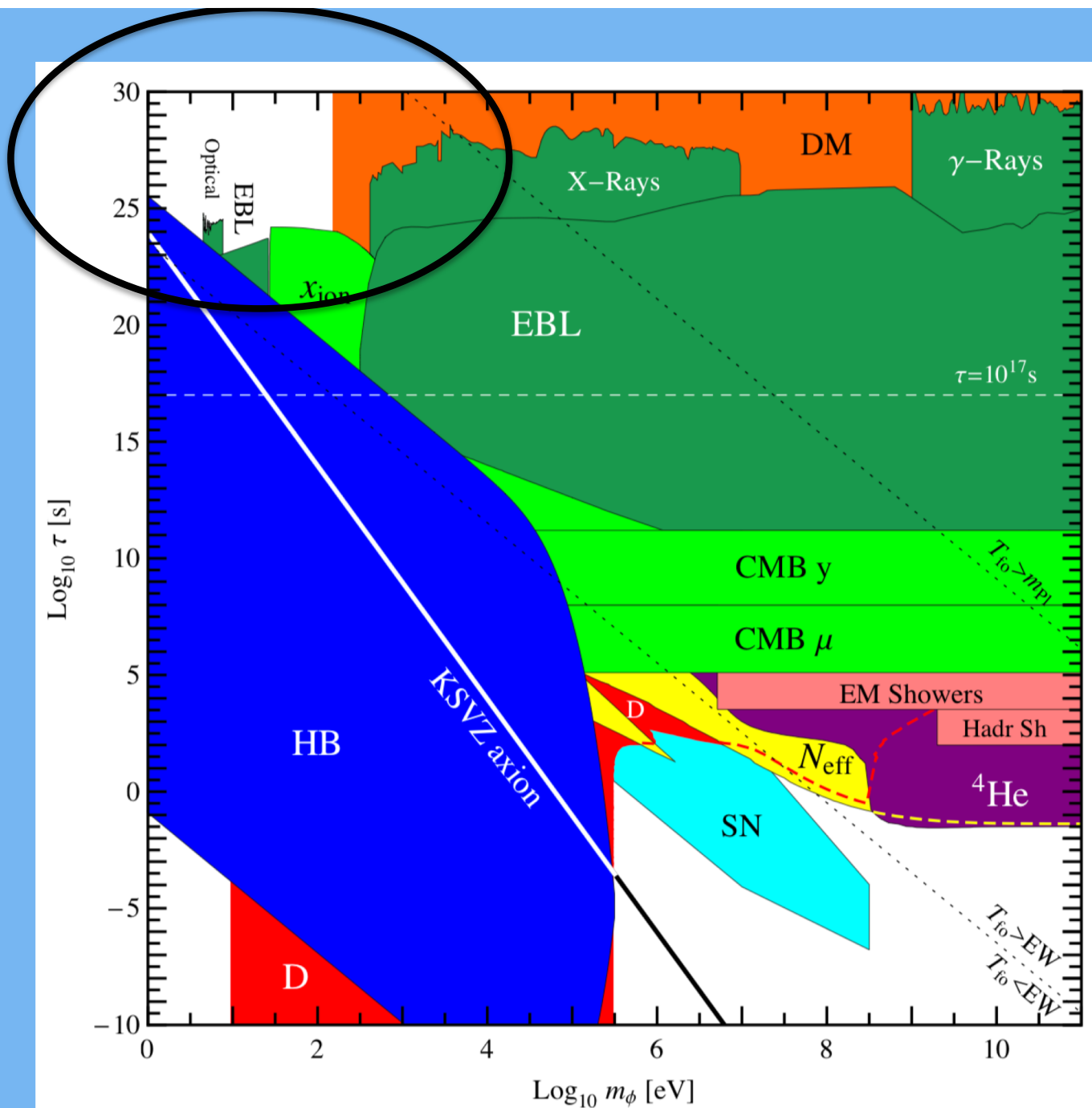


# DM decay

- If DM decays to photon line (e.g.,  $a \rightarrow \gamma\gamma$ ), decay line will be correlated with large-scale structure

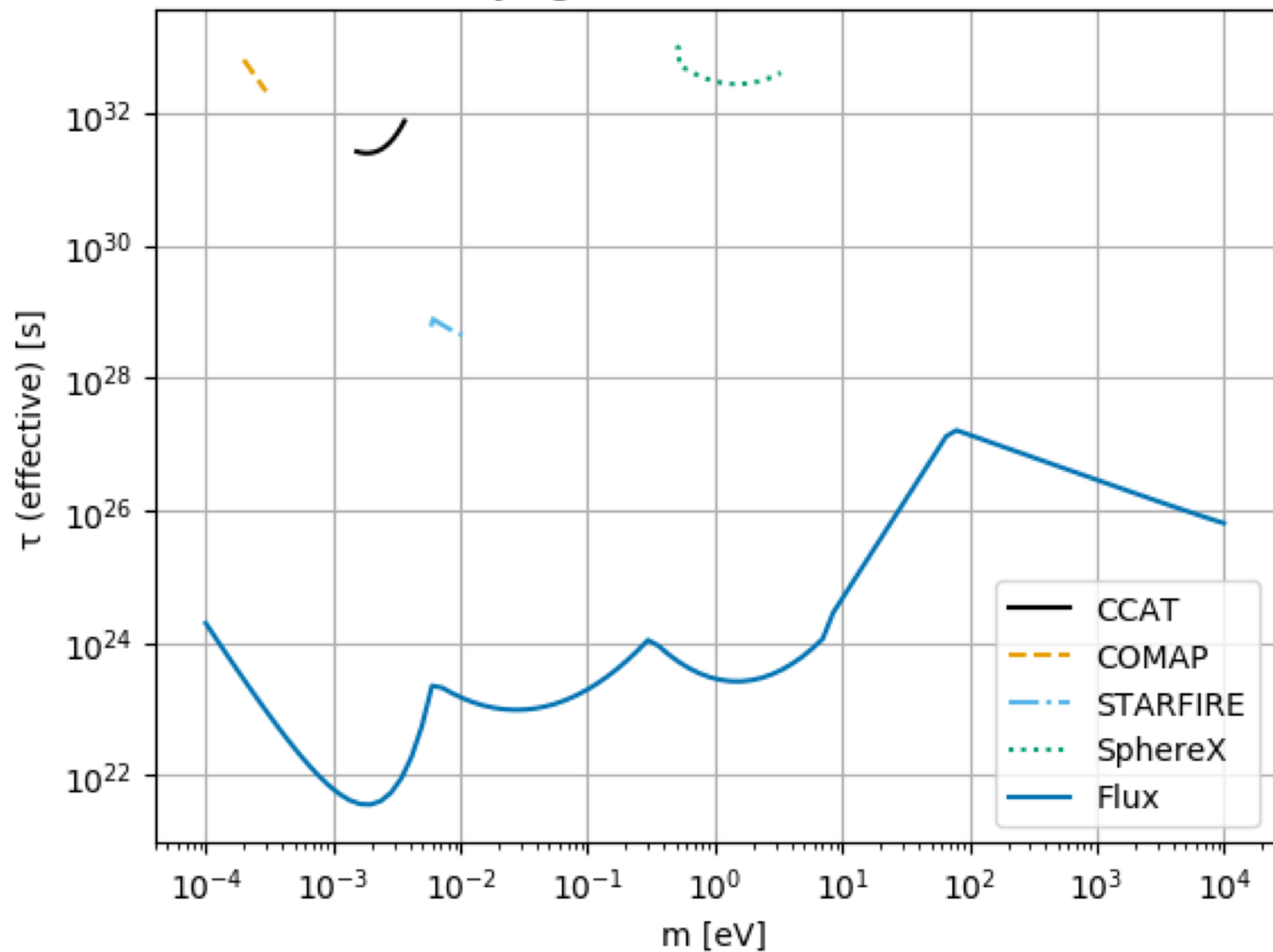


(Cadamuro & Redondo 2011)



(Cadamuro & Redondo 2011)

# Decaying Dark Matter Constraints



# Conclusions:

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- Parameter space for canonical WIMP shrinking --- time to think anew?
- $\sim 30$ - $M_{\text{sun}}$  PBHs face challenges---are now guilty until proven 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