Searching for dark-matter black holes from LVK gravitational-wave detectors

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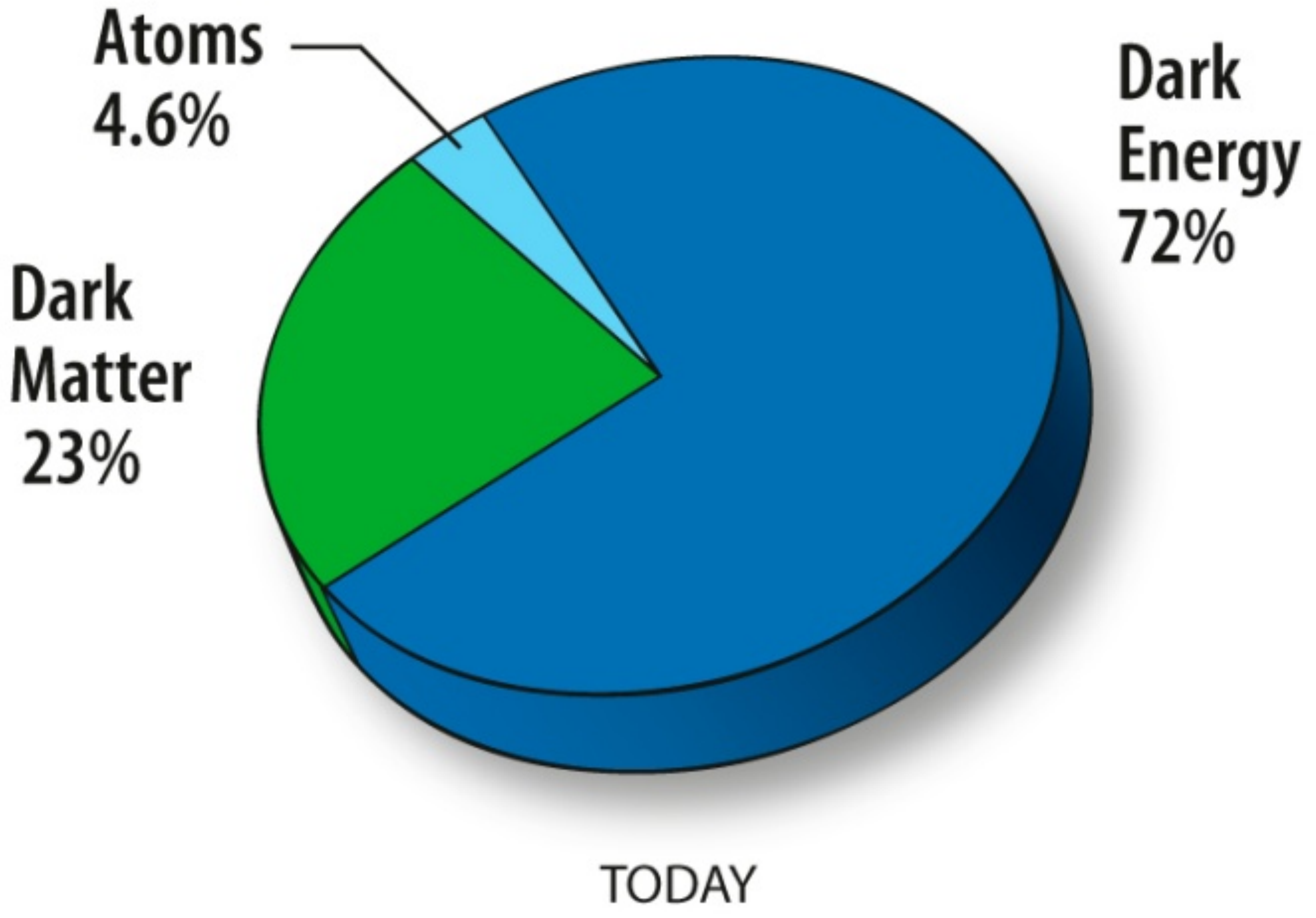
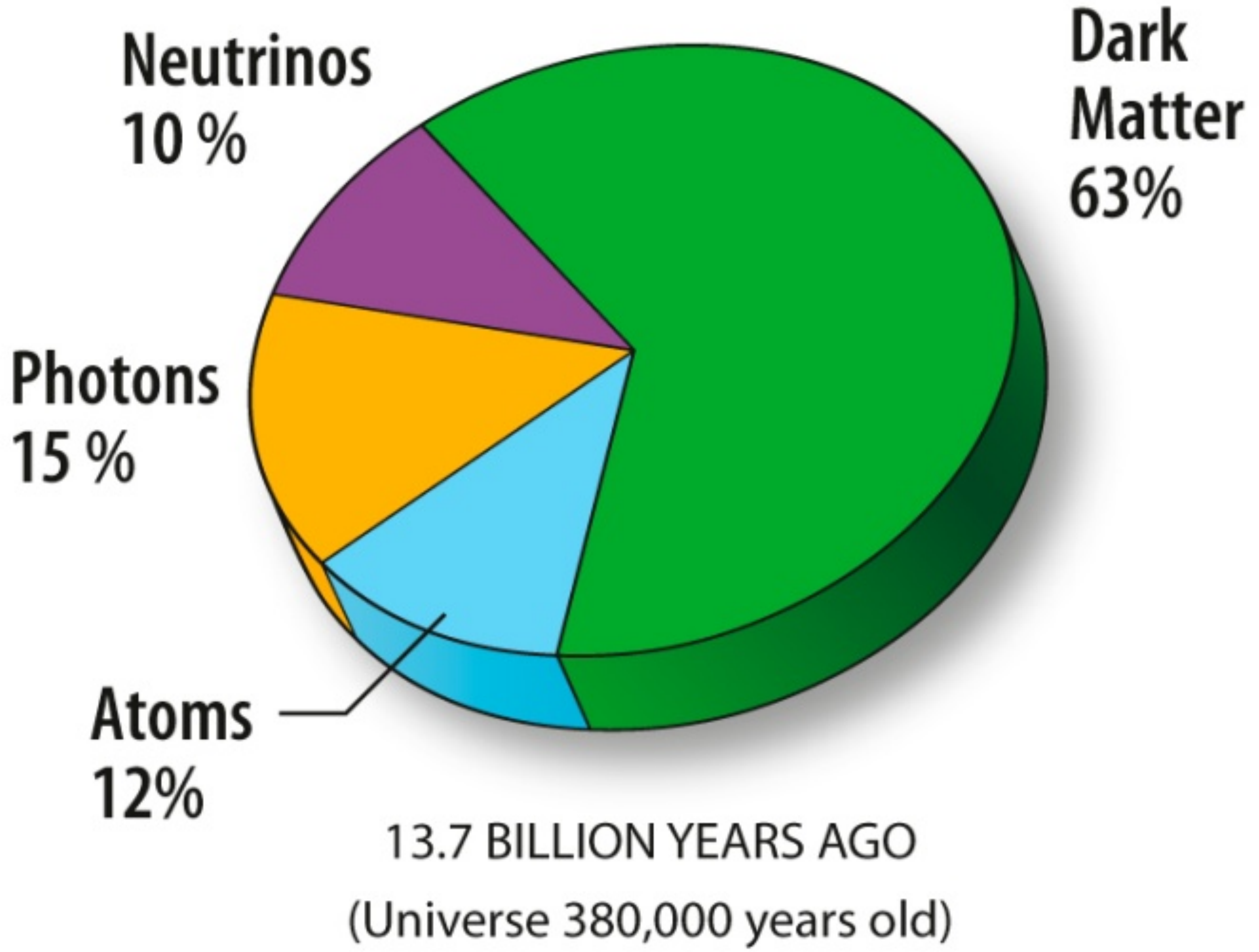
CAU BSM workshop
10 February 2022

Our Physical Cosmology

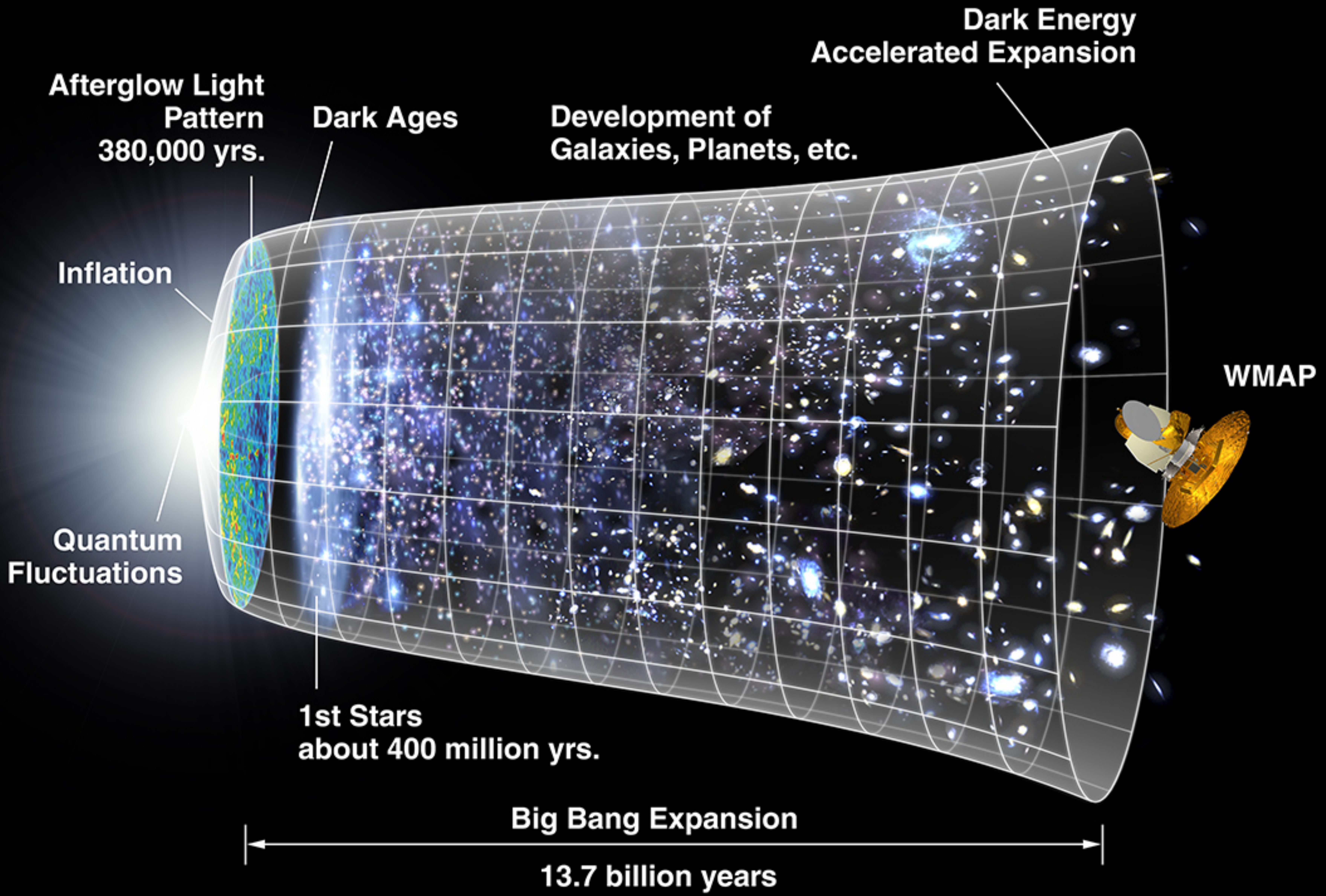
- The Universe is spatially flat, and the expansion is accelerating.



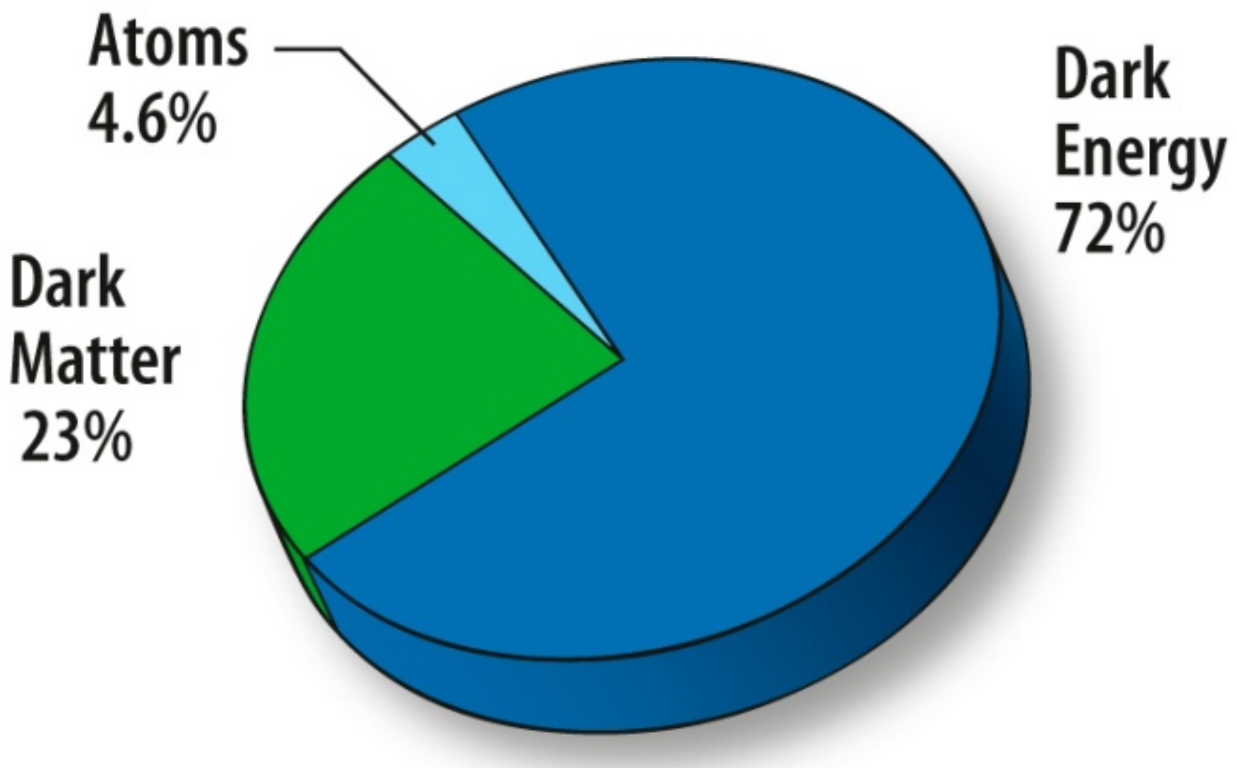


Source: NASA/WMAP science team

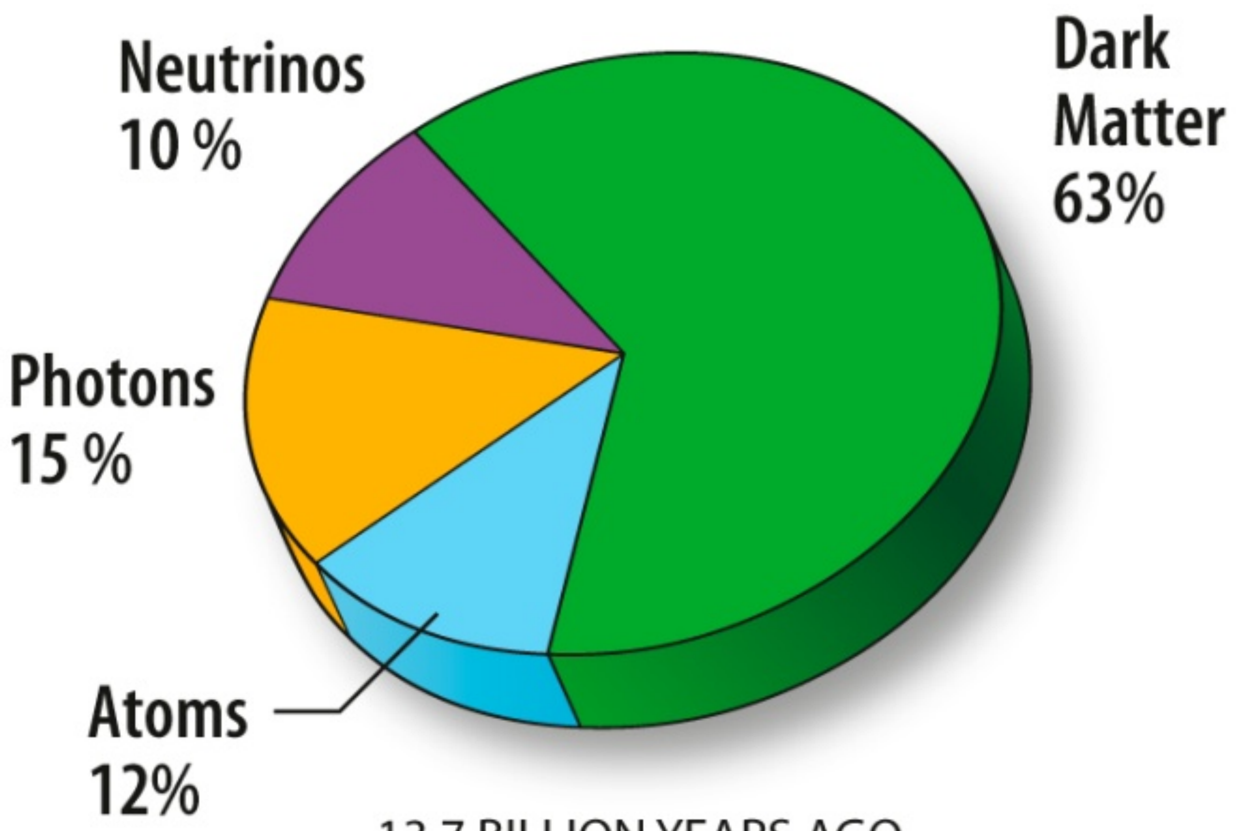
The concordance cosmology



Puzzles in the flat-ΛCDM model



TODAY

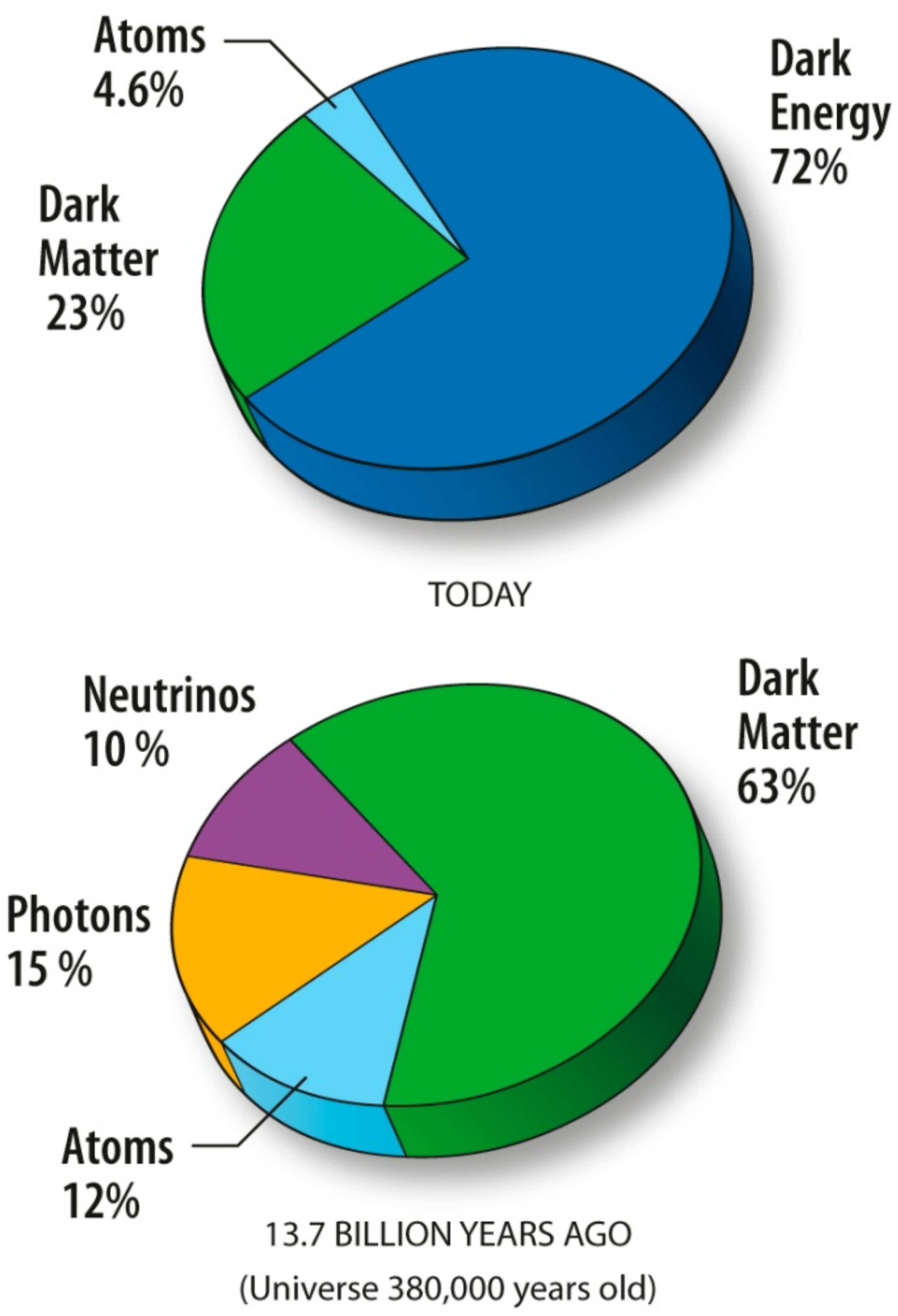


13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Unknown ***nature of the building blocks***:

- Dark matter: Excess gravity, not SM particles (Atoms)
- Dark energy: Current accelerating expansion
- Inflation: Accelerating expansion at the beginning
  Provides the seed for all cosmic structures
- Neutrinos: Radiation early on, matter later (mass!)

Puzzles in the flat-ΛCDM model



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Zwicky on Coma cluster, 1932

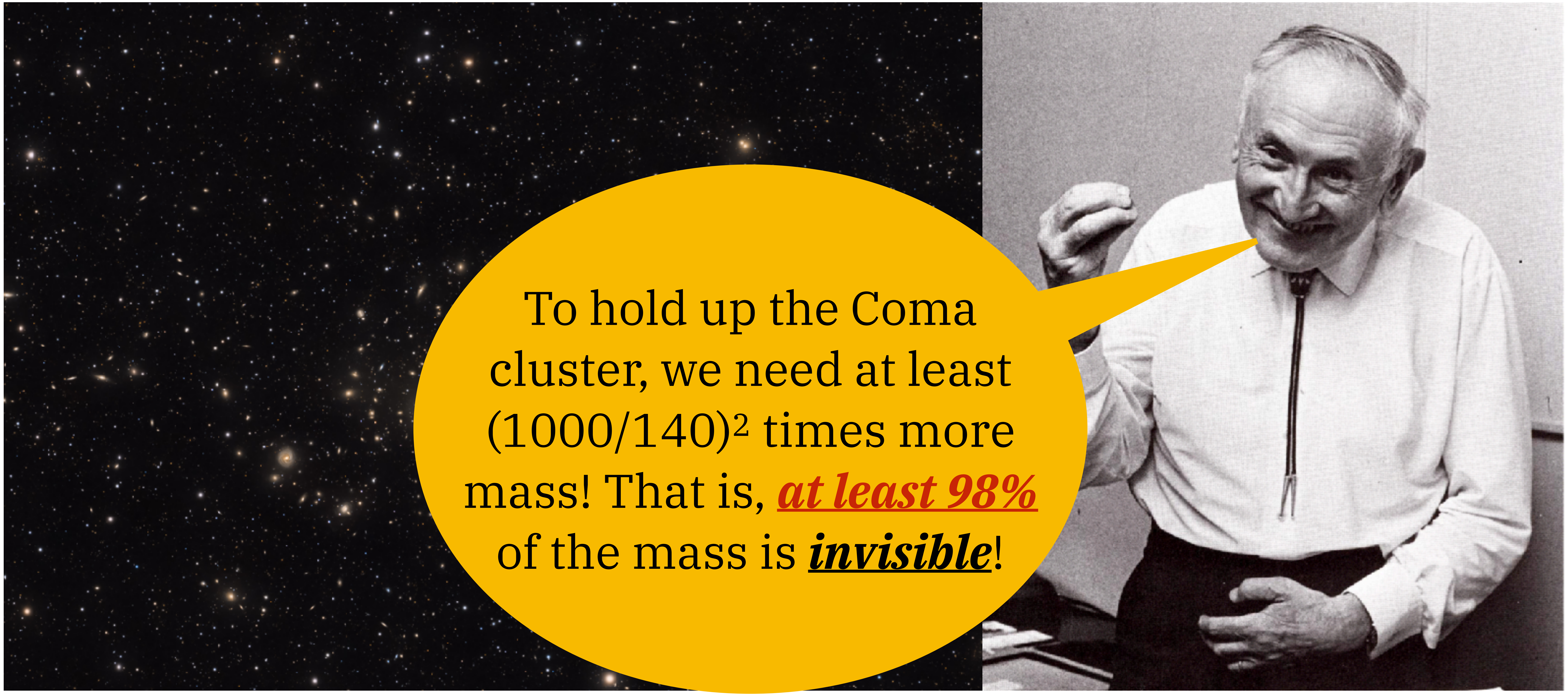
Large Scale Structure in the Local Universe

Coma cluster, ~100Mpc away

Zwicky on Coma cluster, 1932

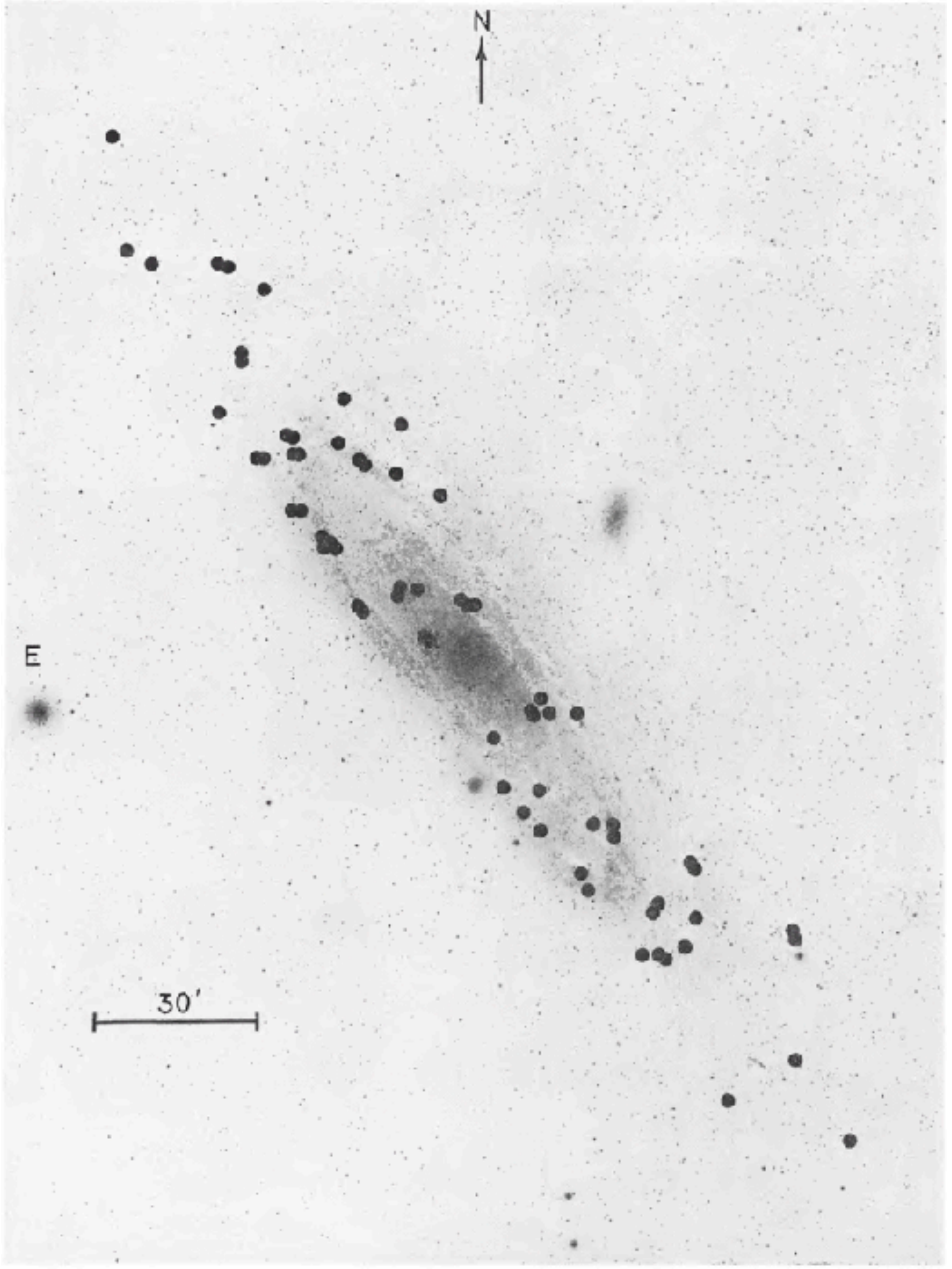
- Numbers for Coma
  - >10,000 galaxies!!
  - Size ~ 6 Mpc ~ $2x10^{25}$cm
  - σ_v ~ 1000 km/s
  - Crossing time ~ $6x10^9$ yrs!
  - Stellar mass ~ $3x10^{13}$ $M_\odot$
  - V_{esc} ~ 140 km/s!

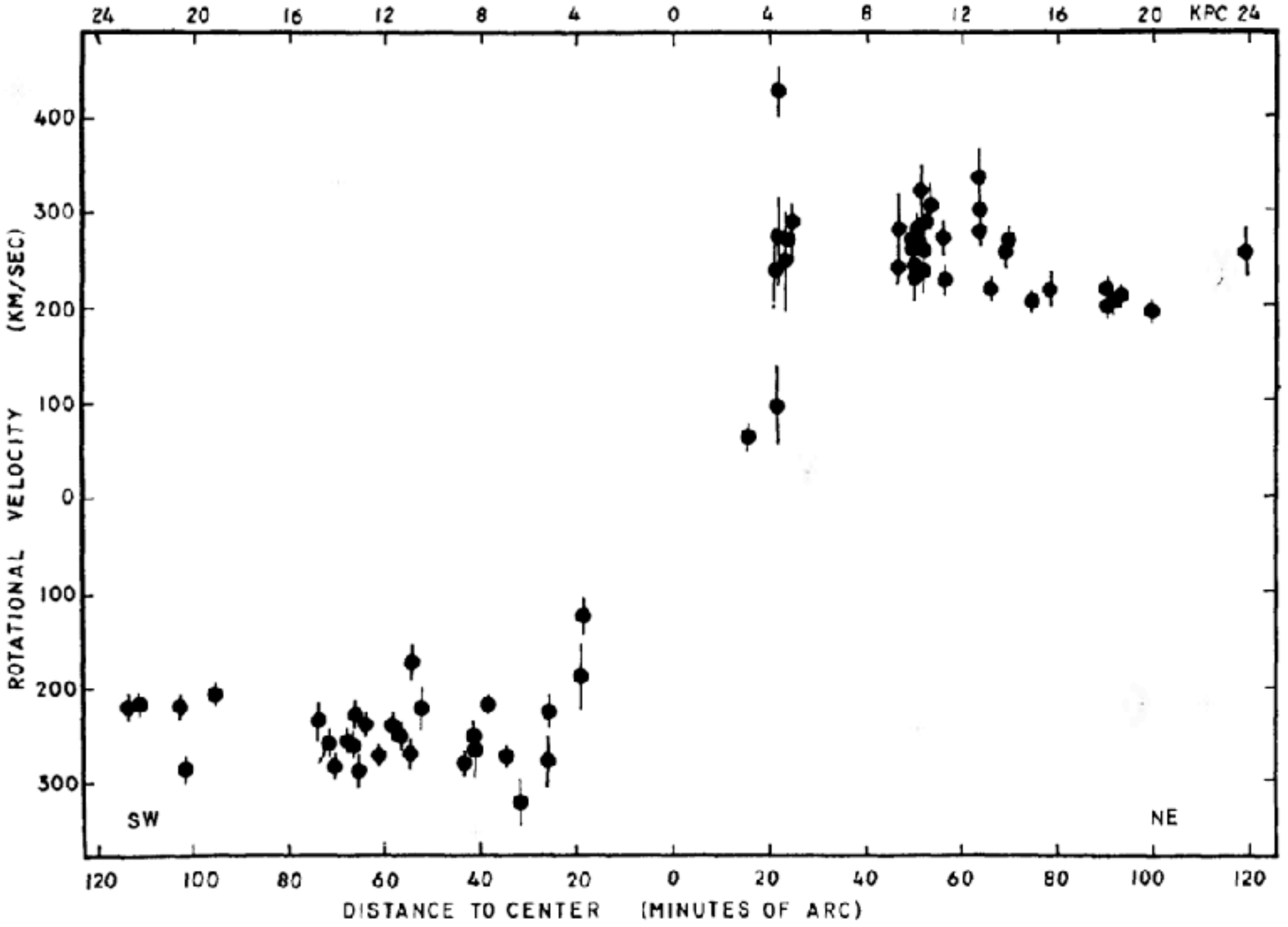
Zwicky on Coma cluster, 1932



Andromeda galaxy (M31), M32, M110

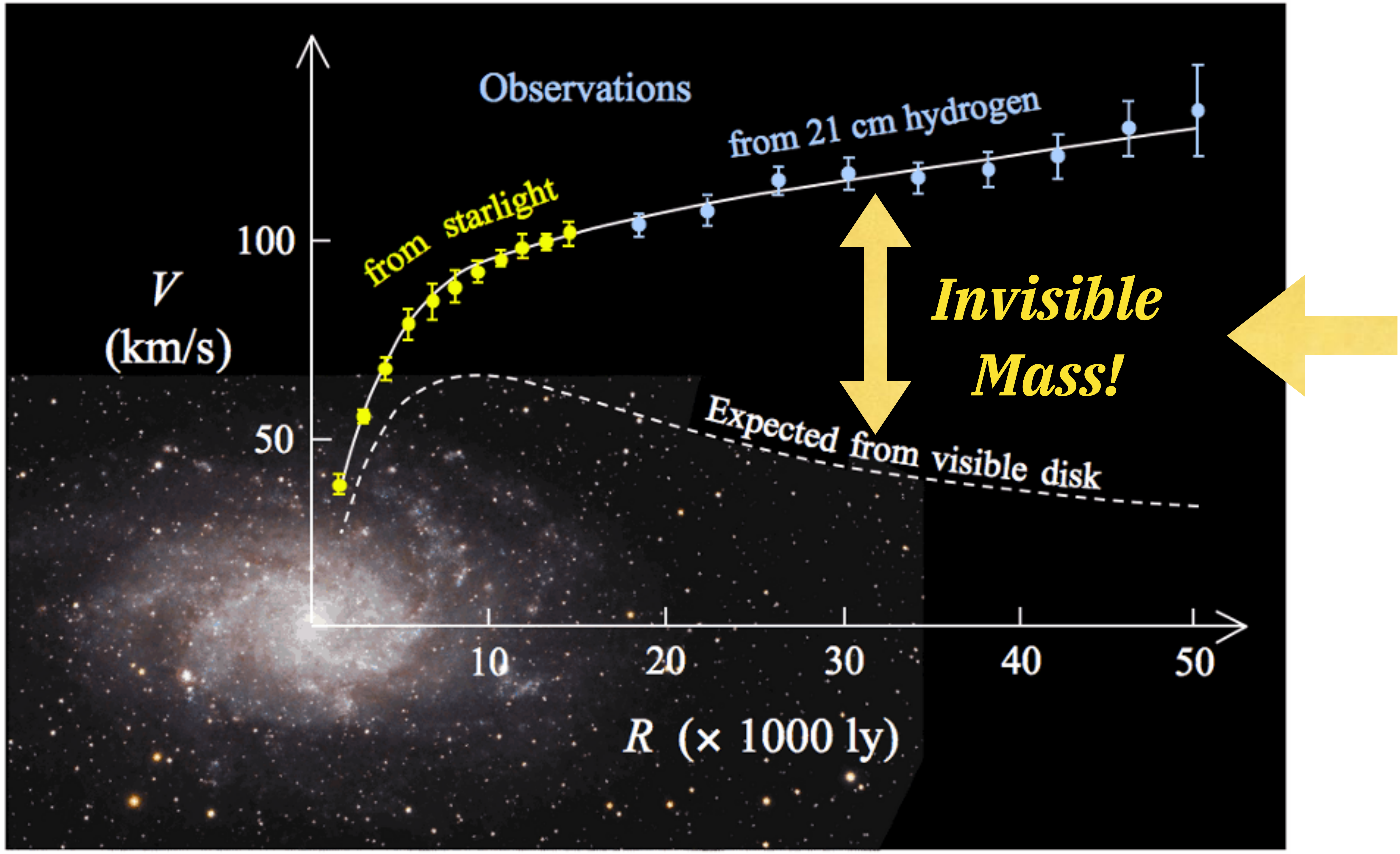
Vera Rubin on M31 (Andromeda), 1970





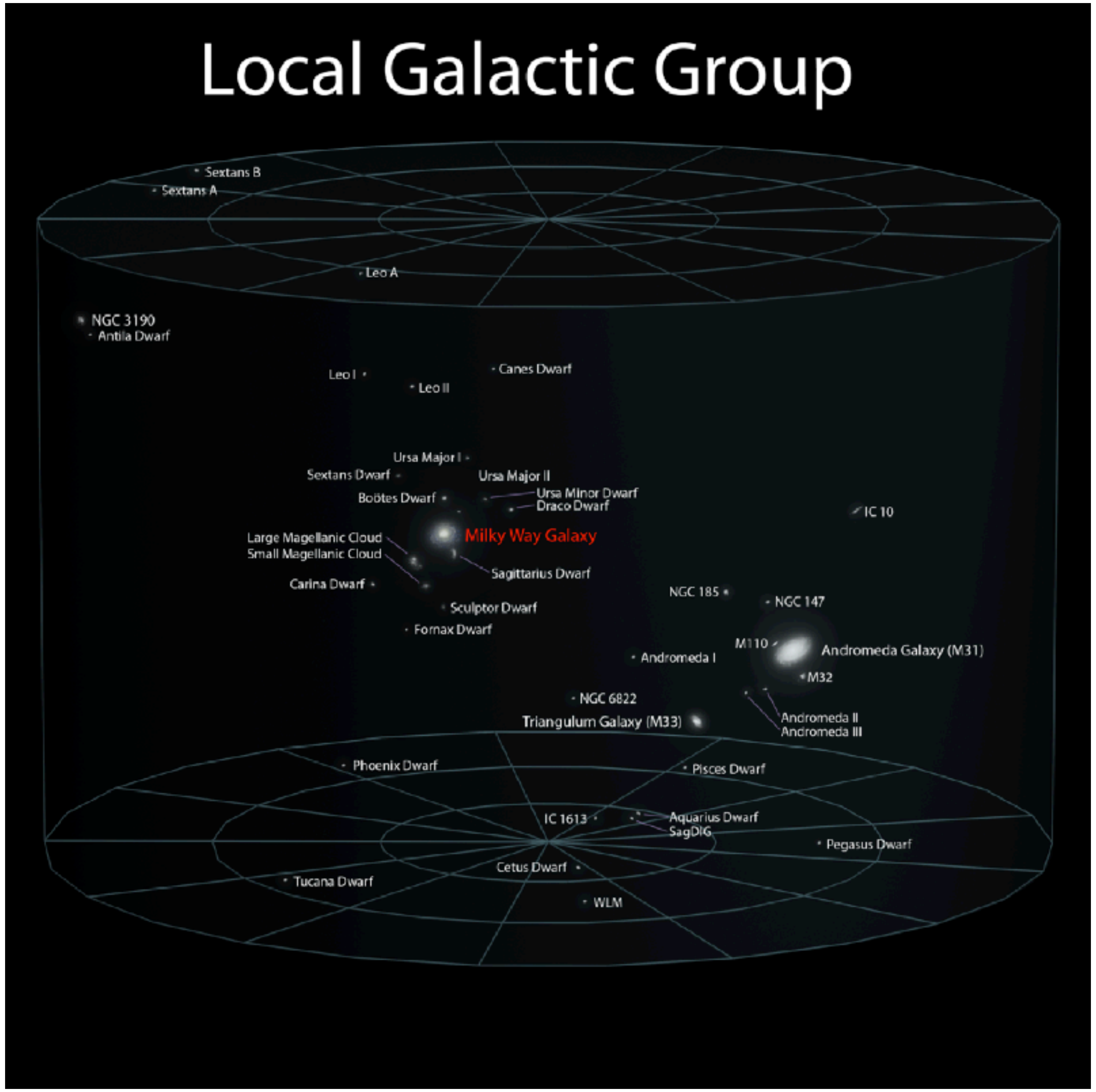
Triangulum galaxy (M33)

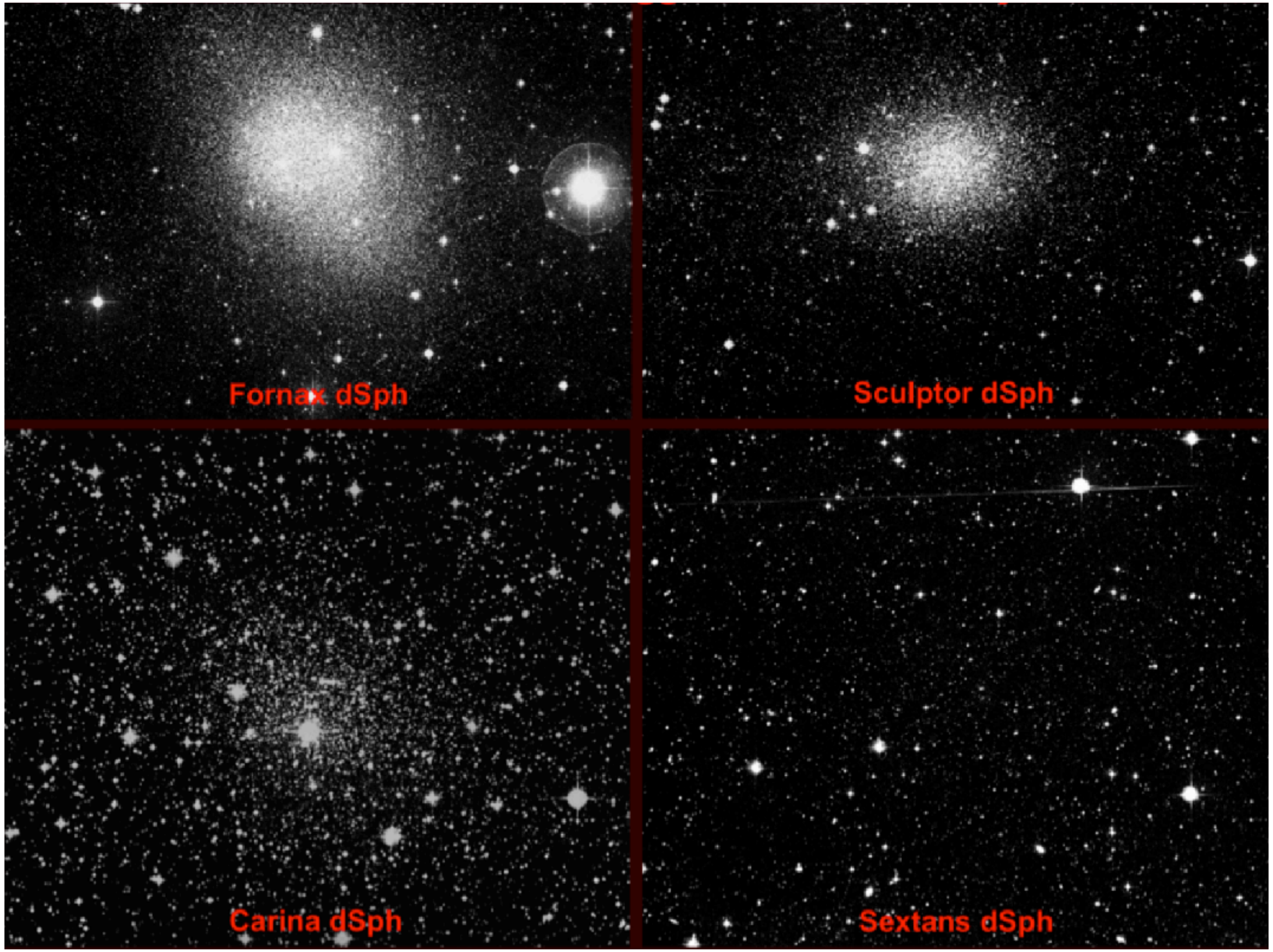
A modern rotation curve (for M33)



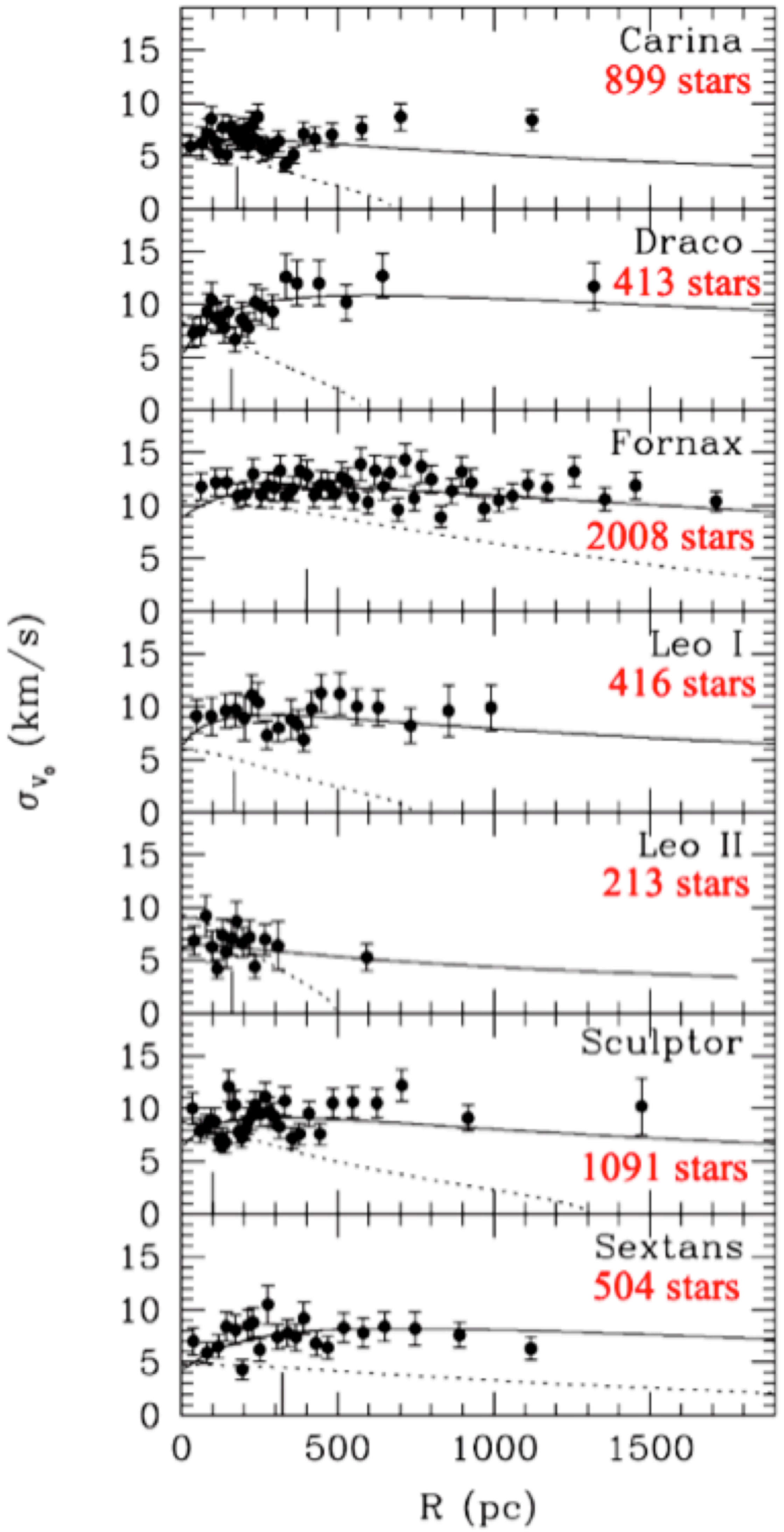
$$V(R) \propto \sqrt{\frac{GM(< R)}{R}}$$

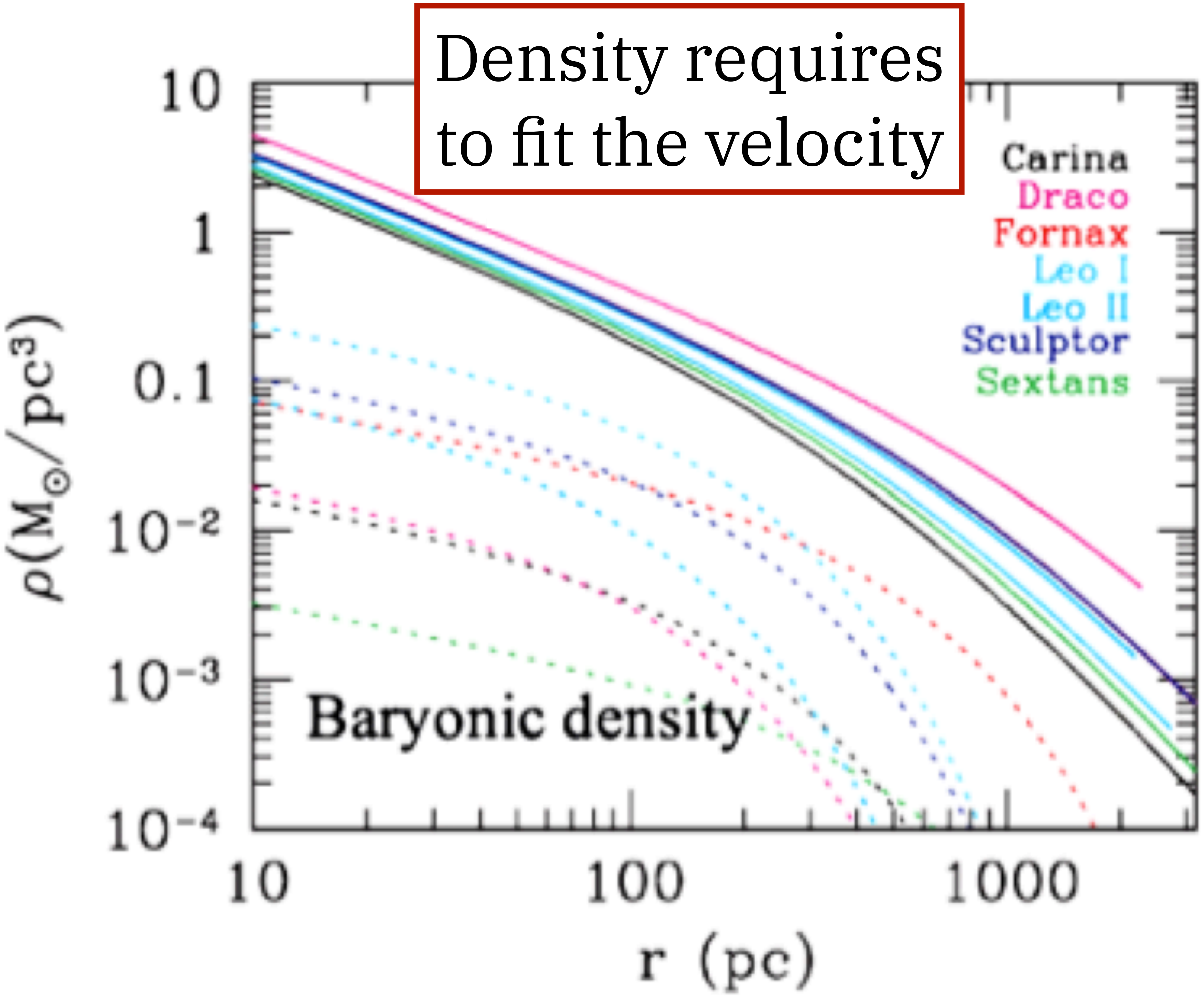
What about local dwarfs galaxies?



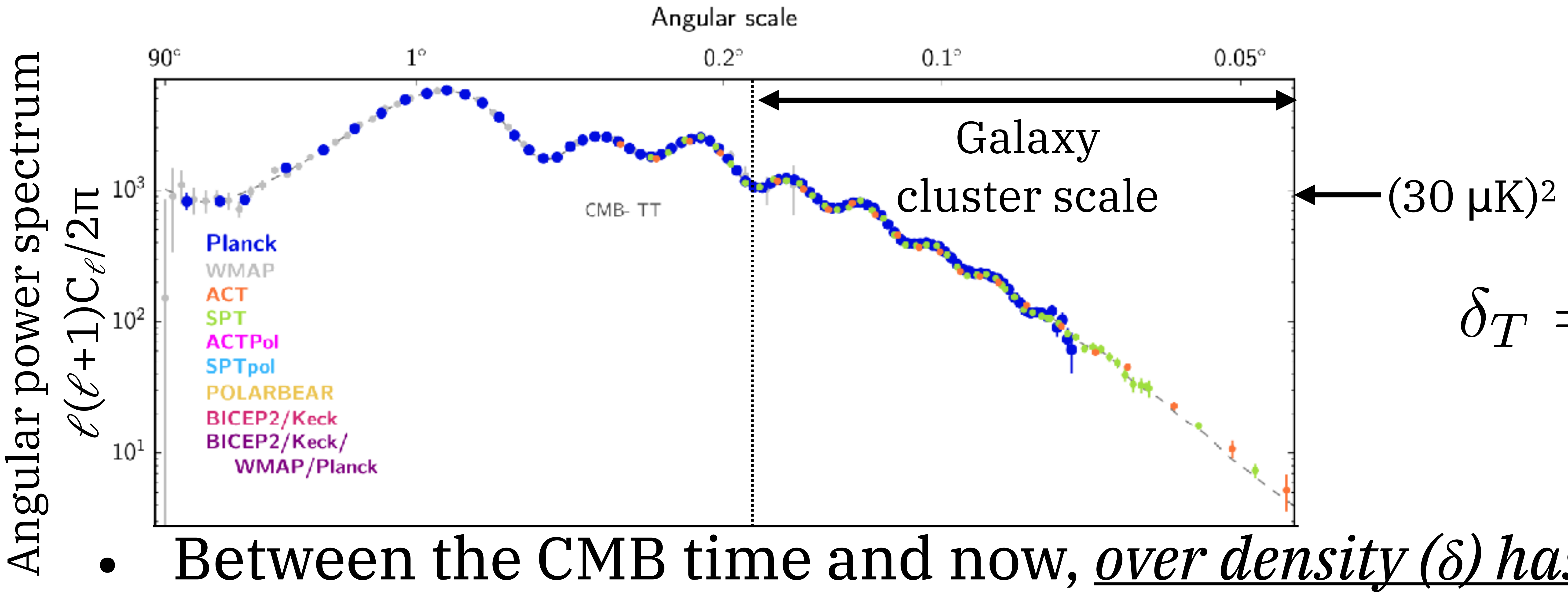


The same; we need invisible mass!





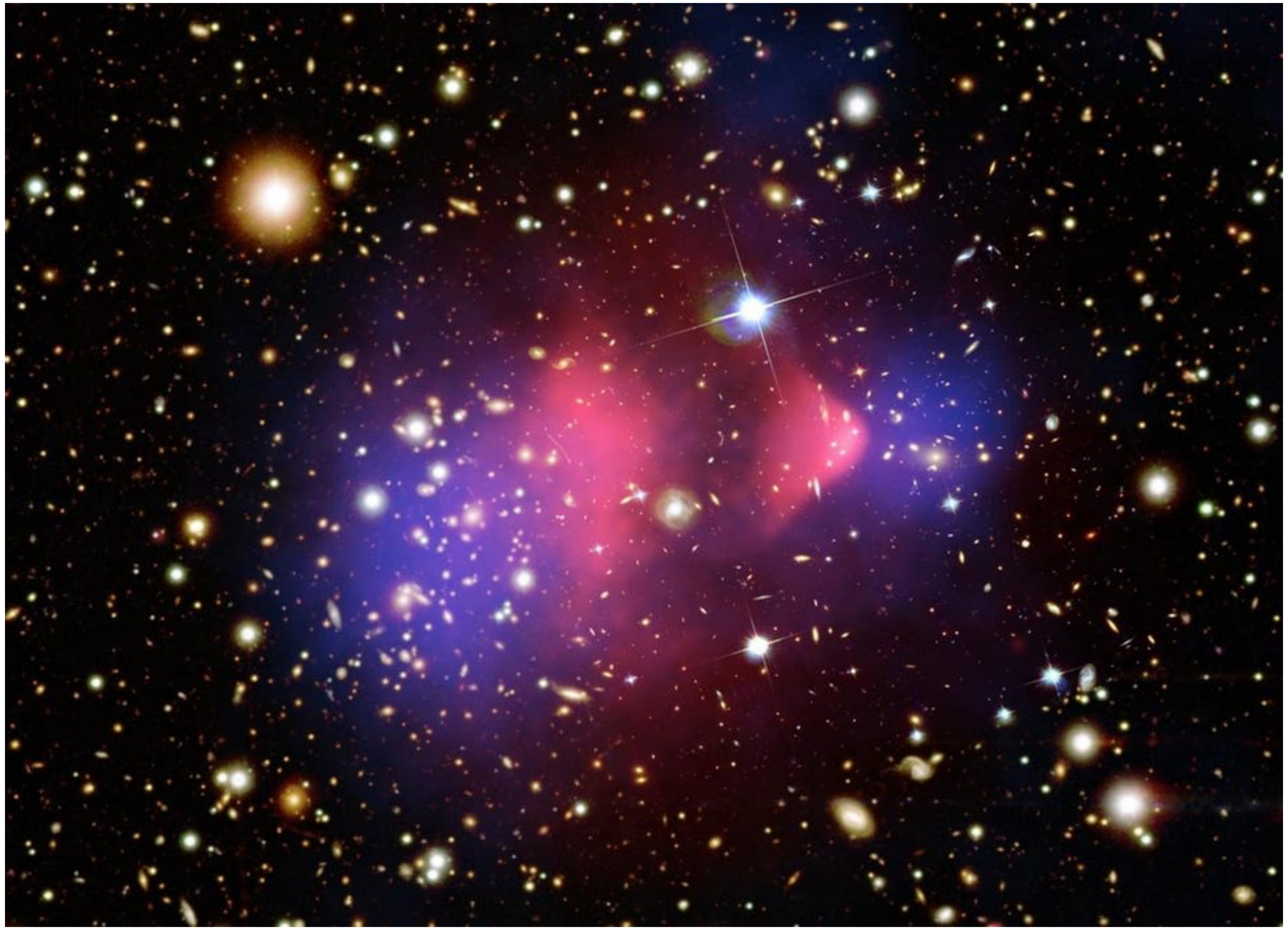
Invisible mass, but not "baryonic"



$$\delta_T = \frac{\delta T}{\bar{T}} \simeq \frac{30\,\mu\text{K}}{2.7K} \simeq 10^{-5}!$$

- Between the CMB time and now, *over density (δ) has grown by x1000*; If this were the only perturbations, no galaxy clusters (δ >> unity) would form.
- It is even worse for galaxies, which forms on smaller scales (~diffusion)!
- Therefore, we need some ***non-baryonic matter*** secluded from the baryon-photon plasma at early time; that excludes, for example, planets, us, etc.

Another evidence: the Bullet cluster

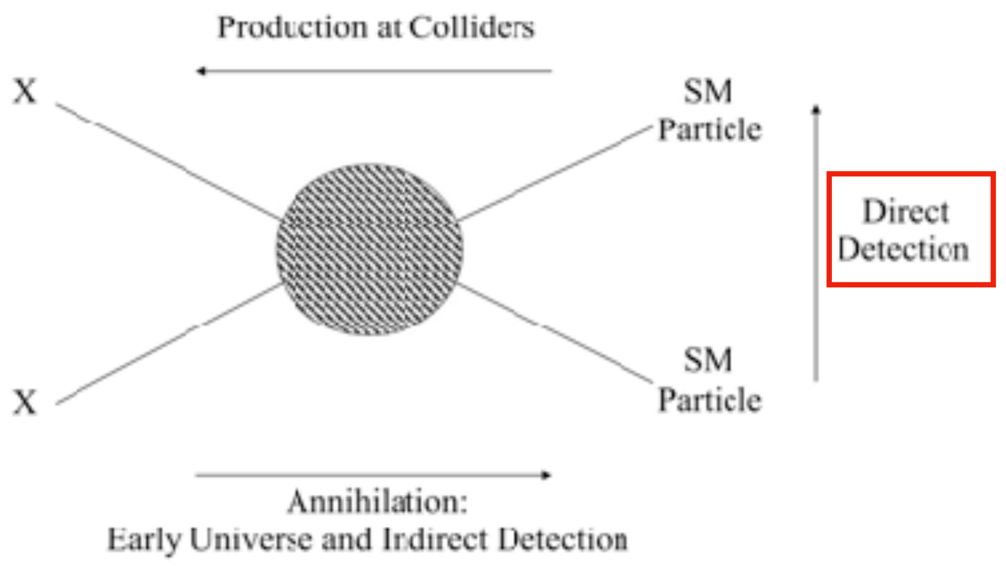


Gas distribution
(X-ray from Chandra)

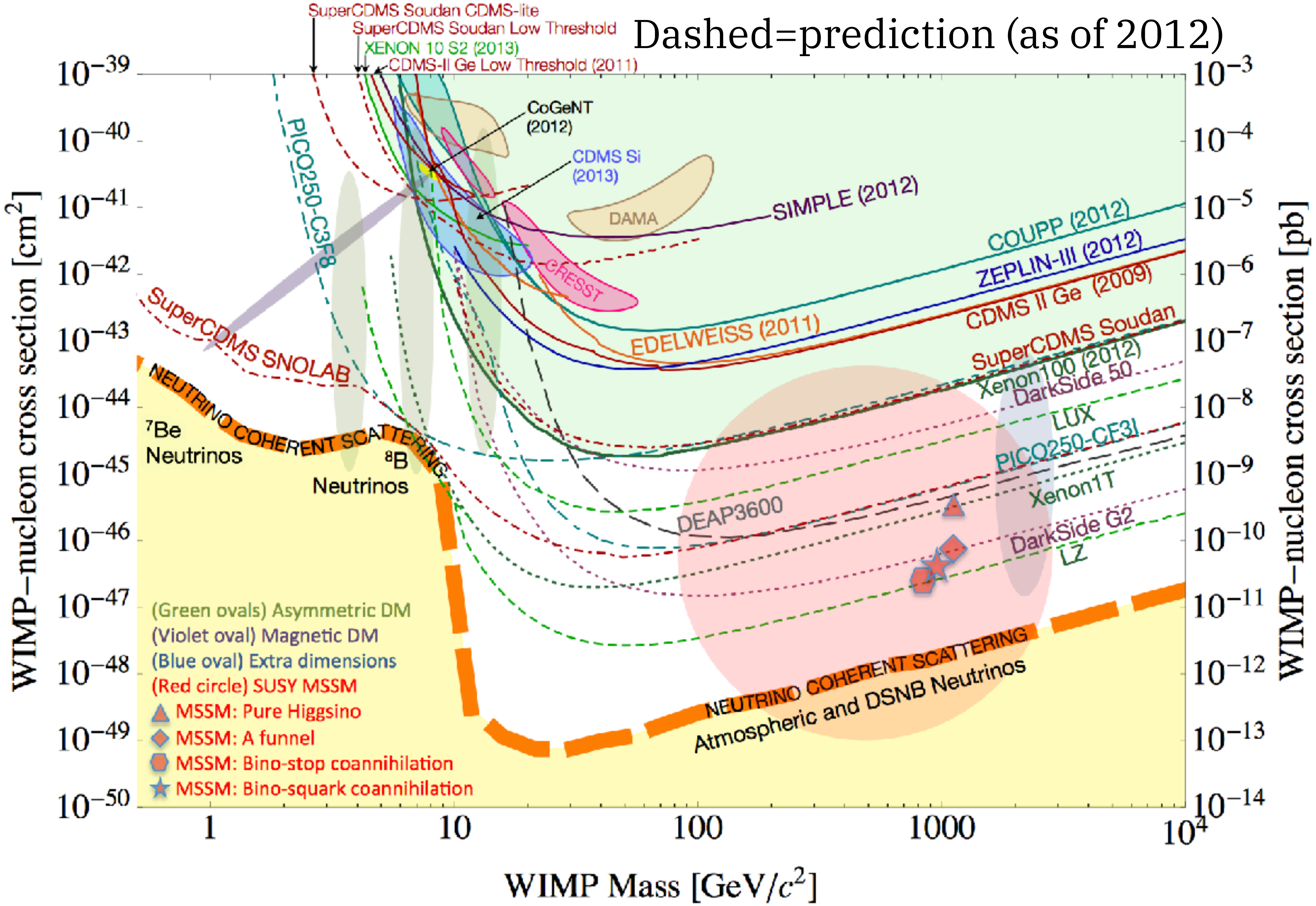
Mass distribution
(gravitational lensing)

Self interaction: $\sigma_{DM}/m < 1\ cm^2/g$

DM-nucleon scattering

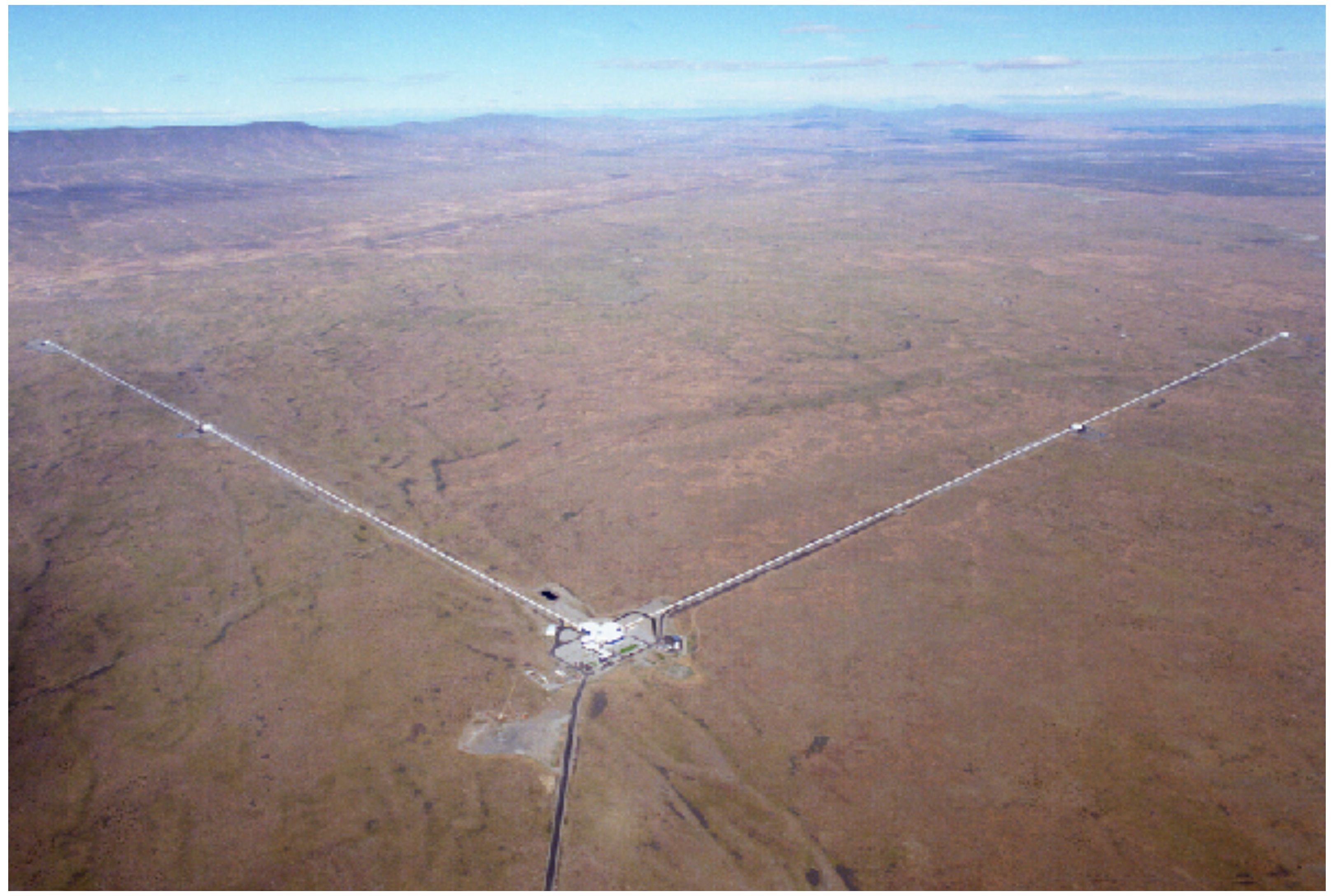


Solid= limit
Dashed=prediction (as of 2012)

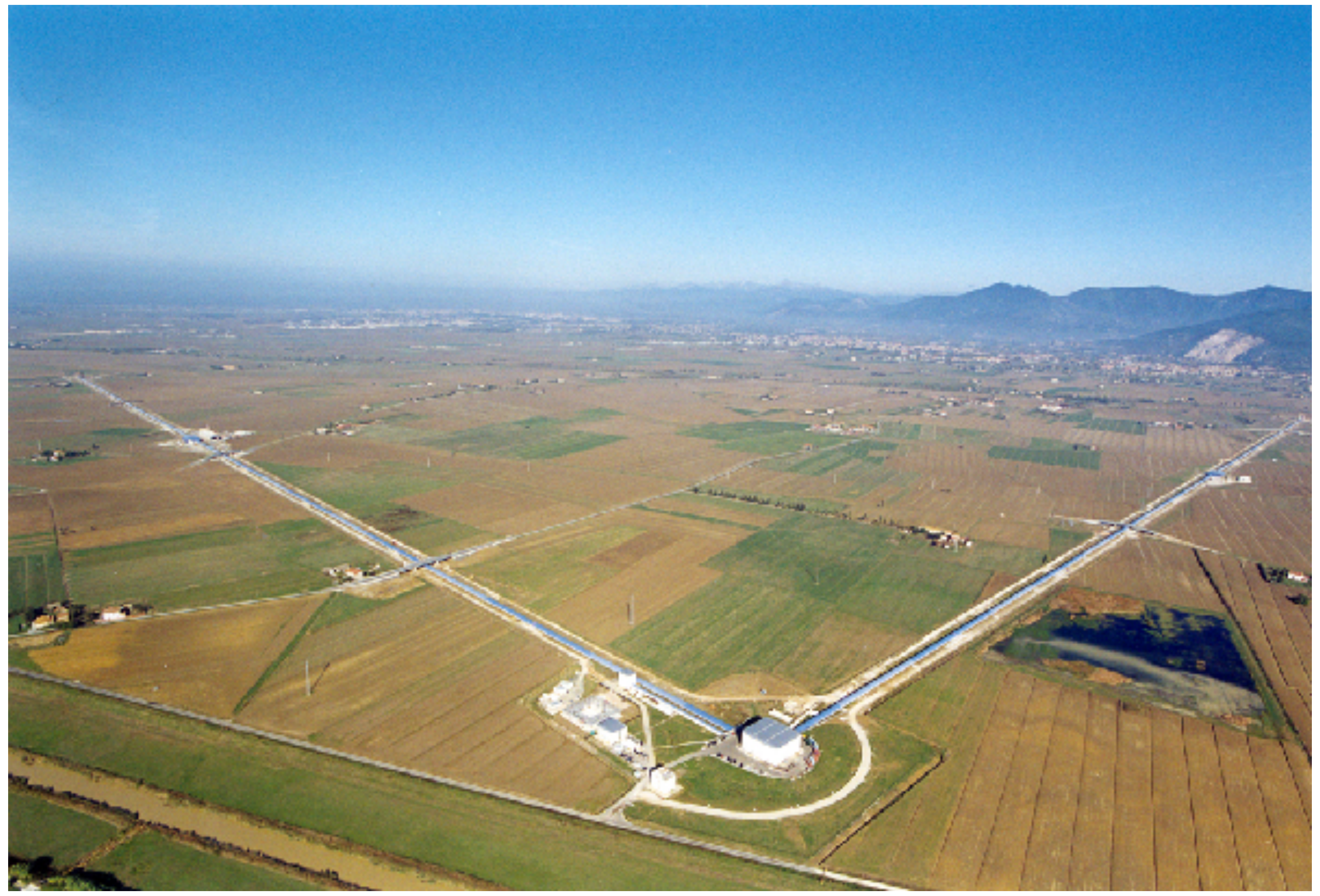


LVK Gravitational Wave observatories

LIGO Livingston (Louisiana)



LIGO Hanford (East Washington)



VIRGO, near Pisa, Italy

+ KAGRA (@ Kamioka mine in Japan, from O3b)

Masses in the Stellar Graveyard

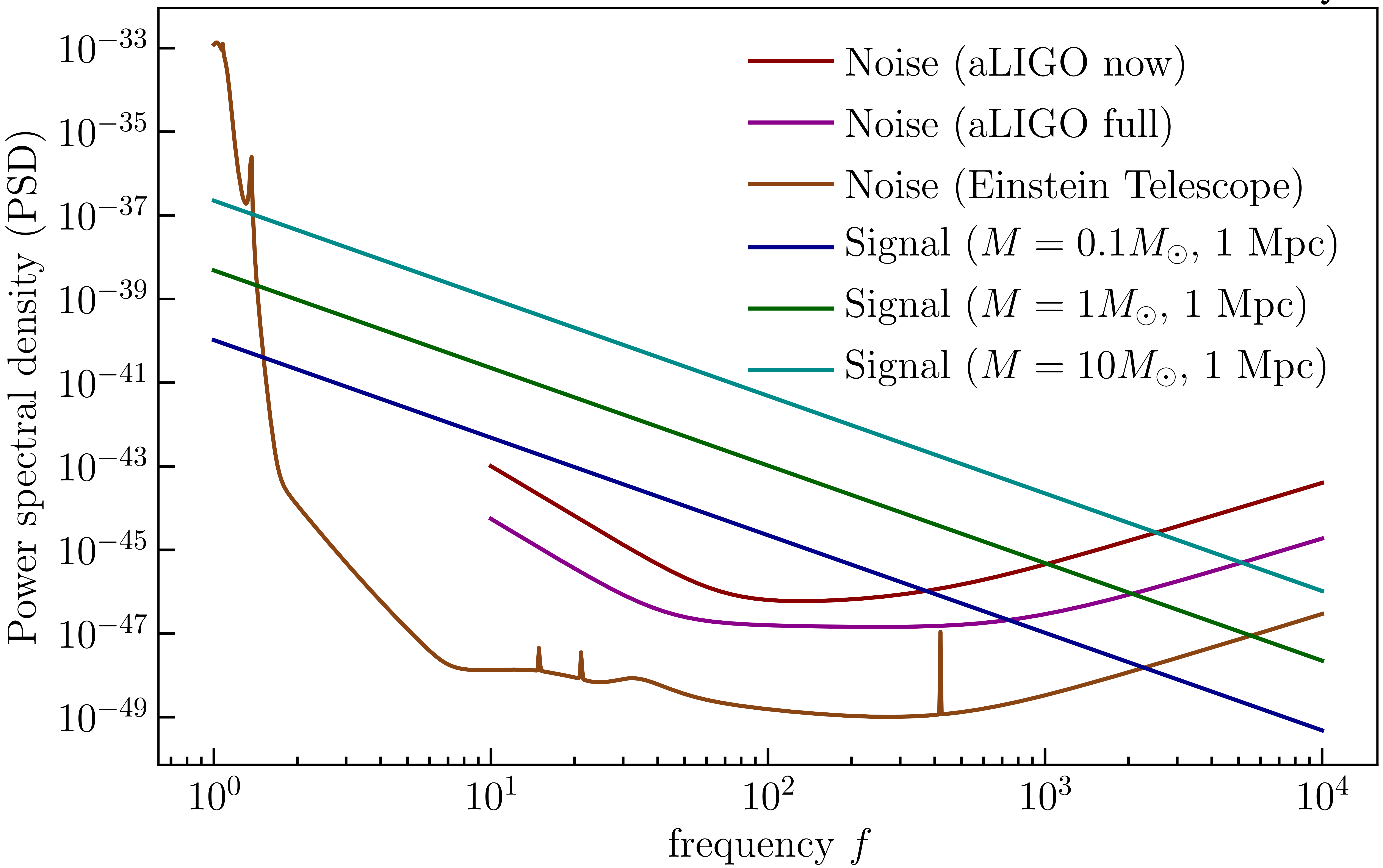
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses in the Stellar Graveyard

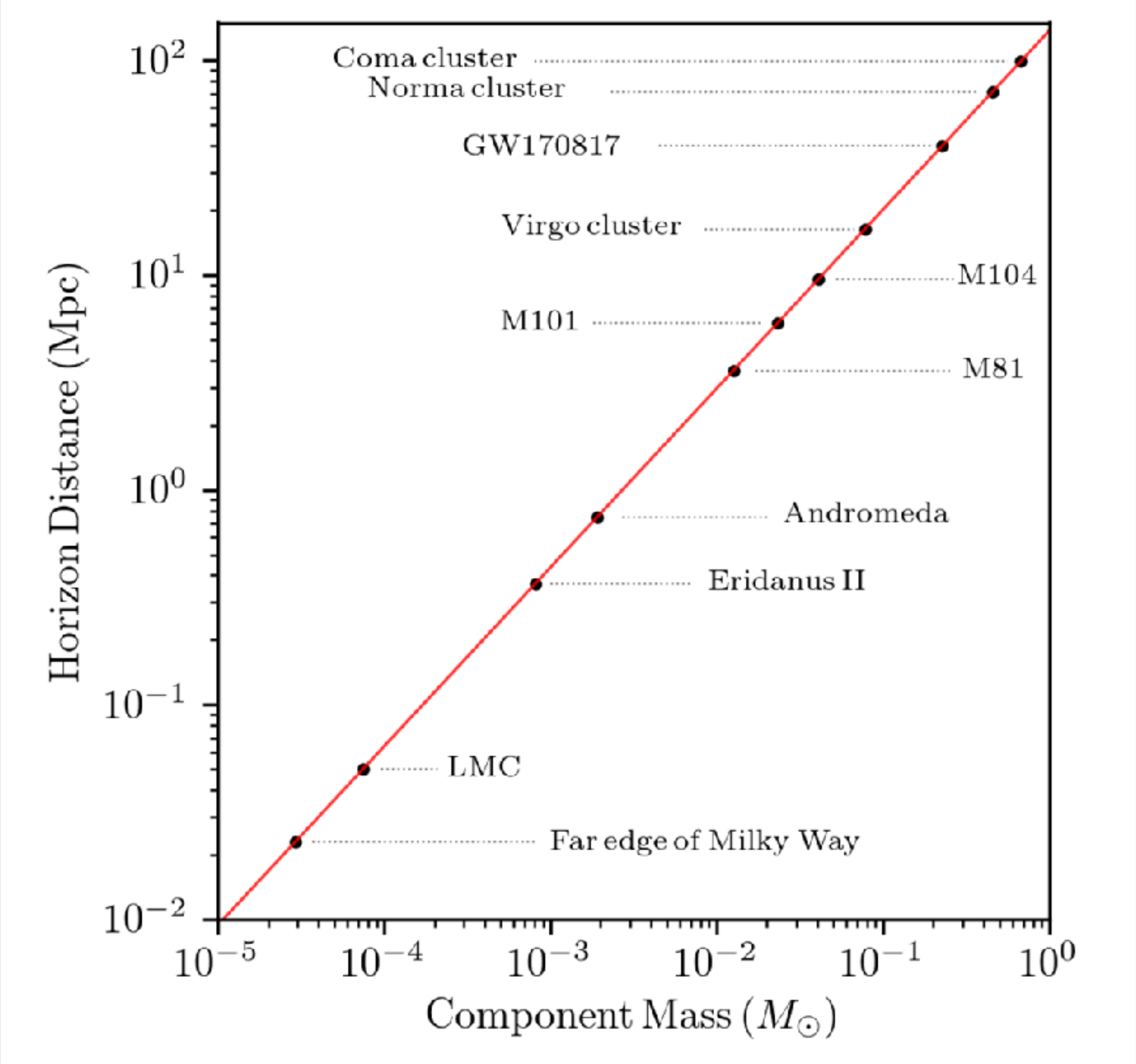
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

LVK is capability to *hear* BH binaries:

Noise curve from Sathya.



Caveat: smaller horizon volume



Sub-M⊙ compact binaries?

Surely, not from the usual stellar evolution!

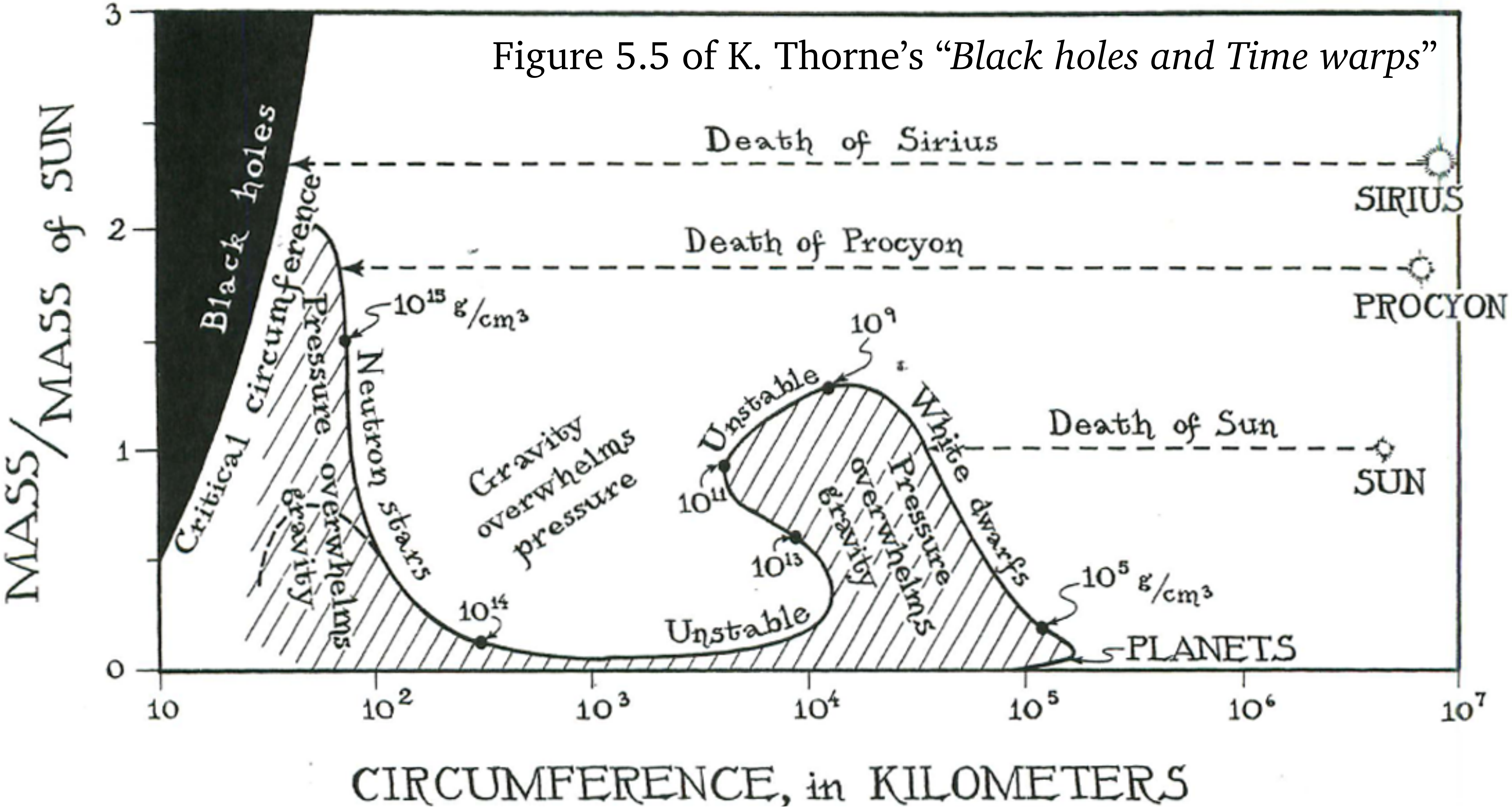


Figure 5.5 of K. Thorne's "*Black holes and Time warps*"

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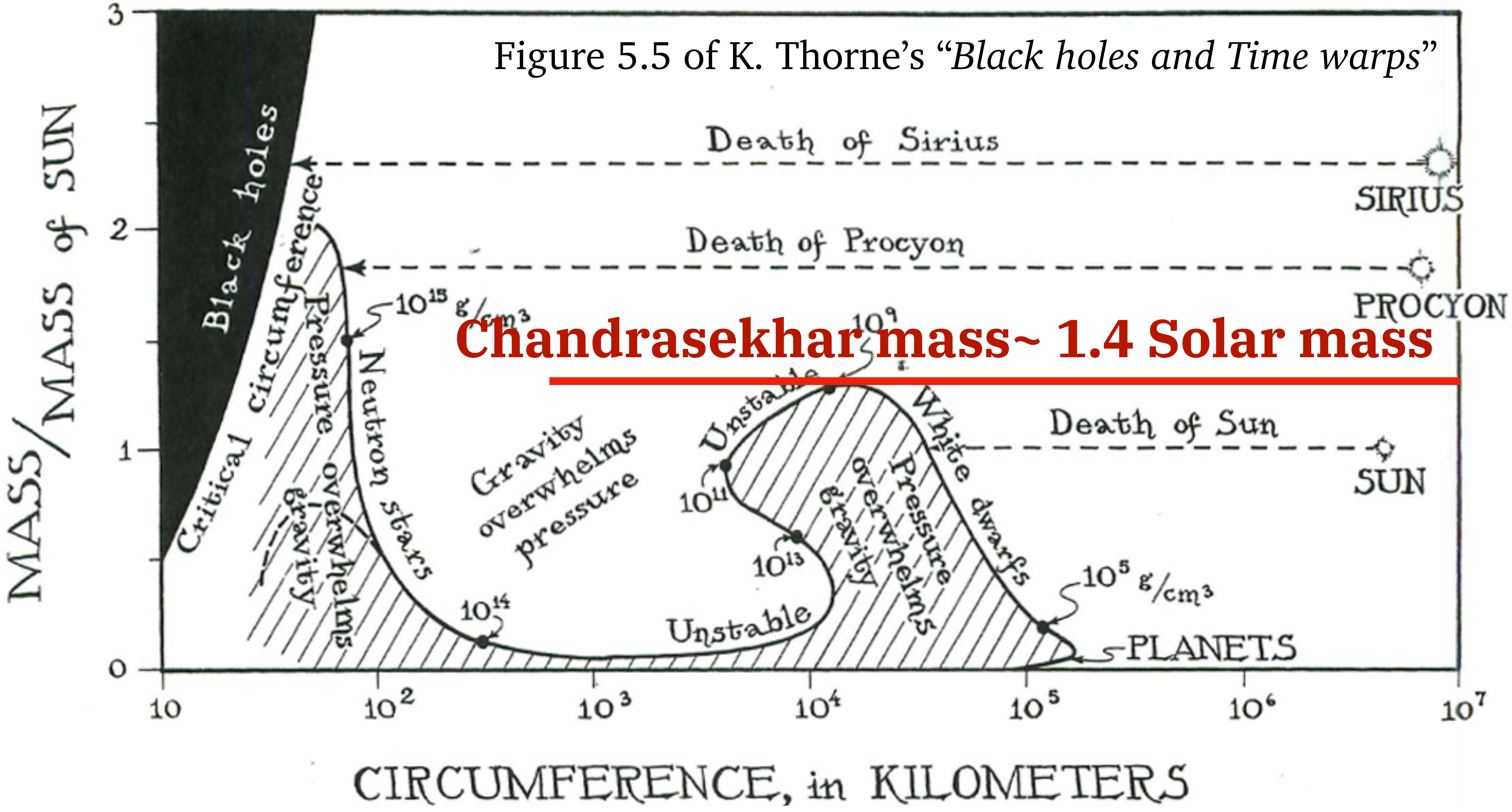


Chandrasekhar mass limit

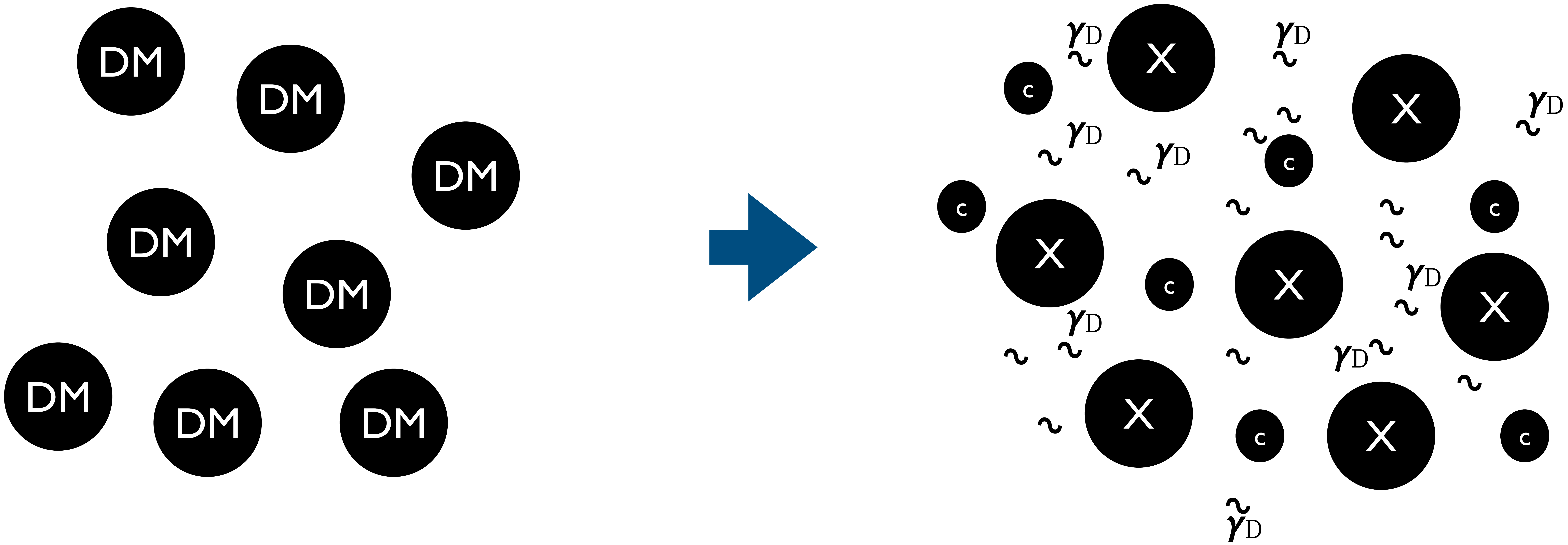
- There is a maximum mass that a star can be supported by degenerate pressure:

$$M_{\mathrm{Chandra}} \simeq \left(\frac{m_{\mathrm{Planck}}}{m_p}\right)^3 m_p \simeq M_{\odot}$$

- Key observation: $M_{\mathrm{Chandra}} \sim 1/m_p^2$!
  - For a given stellar mass, increasing the proton mass decreases the electron number density; that would decrease degenerate pressure & M_{Chandra}.

New possibility: *Dark* Black holes!

If dark matters can ***dissipate*** their kinetic energy!



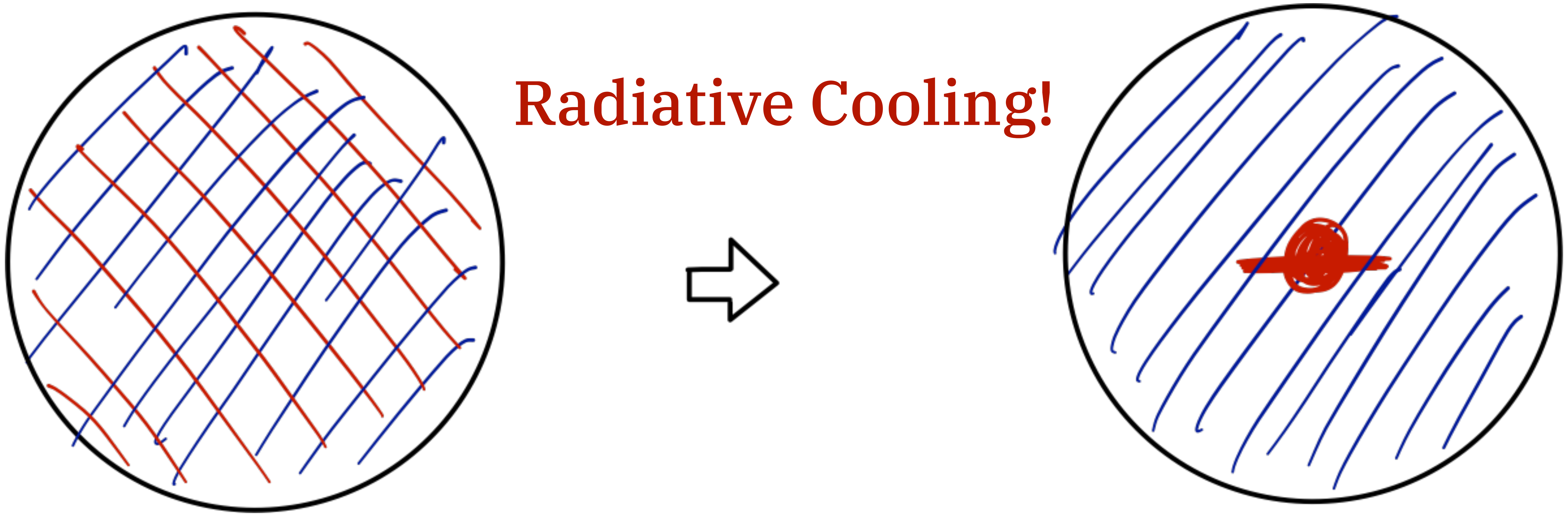
Boring single flavor

Three particle species

Simple set up: dark-sector particles

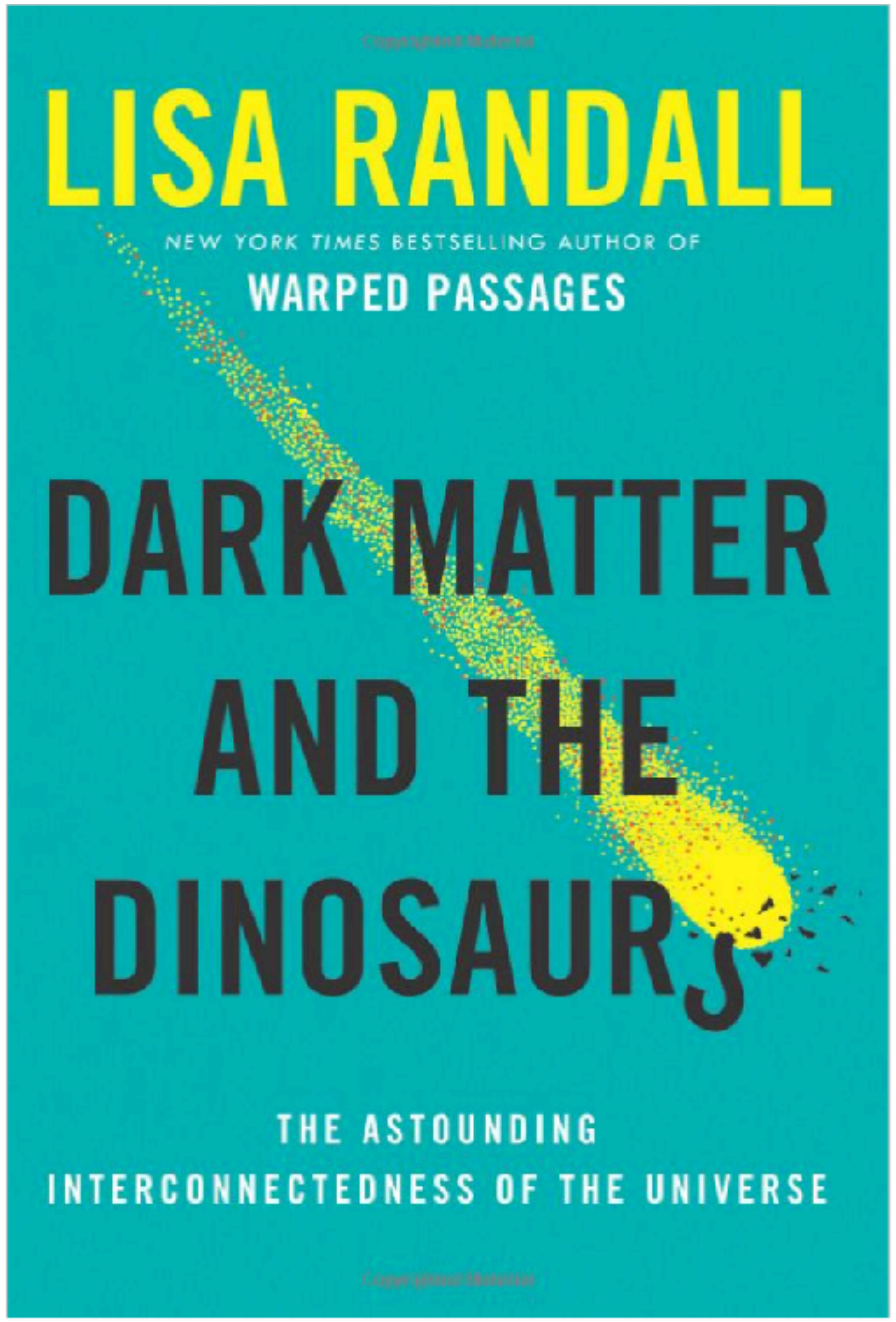
- In dark sector, we have
  - Dark proton (X) : Need to be heavier, + charge. No QCD required
  - Dark electron (c) : Need to be lighter, - charge.
  - Dark radiation (γ_D)
- Free parameters in the theory: m_X, m_c, α_D (~1/137), $\xi(=T_D/T_\gamma)$
- With dark radiation, we have a variety of ***dark structures*** by ***energy dissipation***, including dark black holes.

Dissipation and cosmic structures

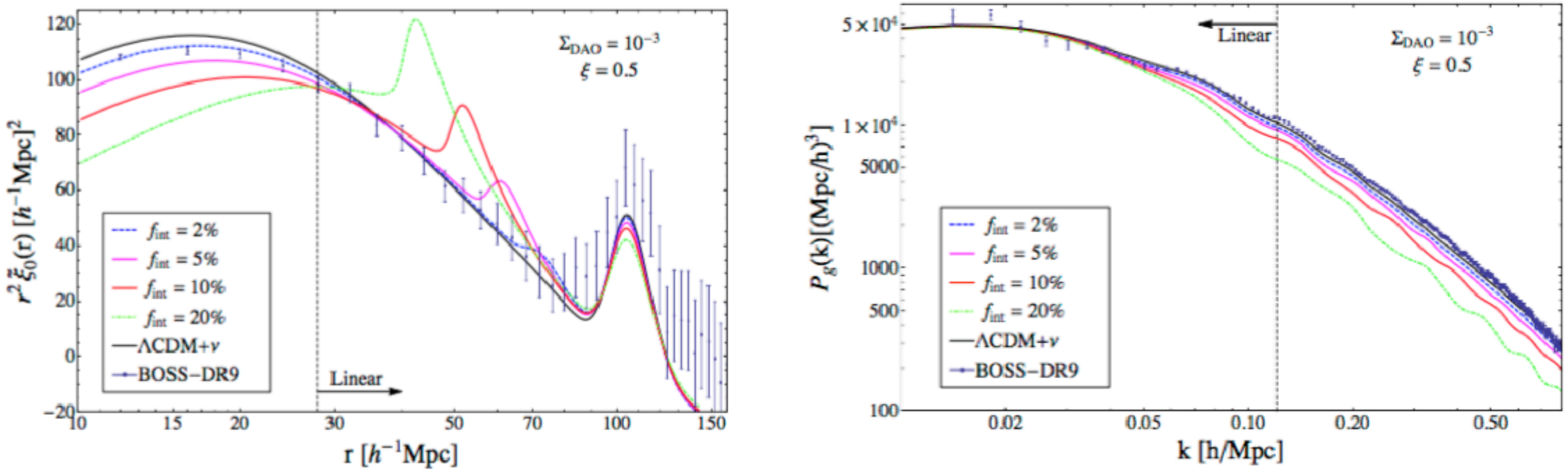


- CDM(~5/6): no interaction. responsible for growth of structure
- Baryons(~1/6): interaction with photon, can radiate, cool down
- **Atomic dark matter** also sink/form small structures.

Example: Double-Disk DM

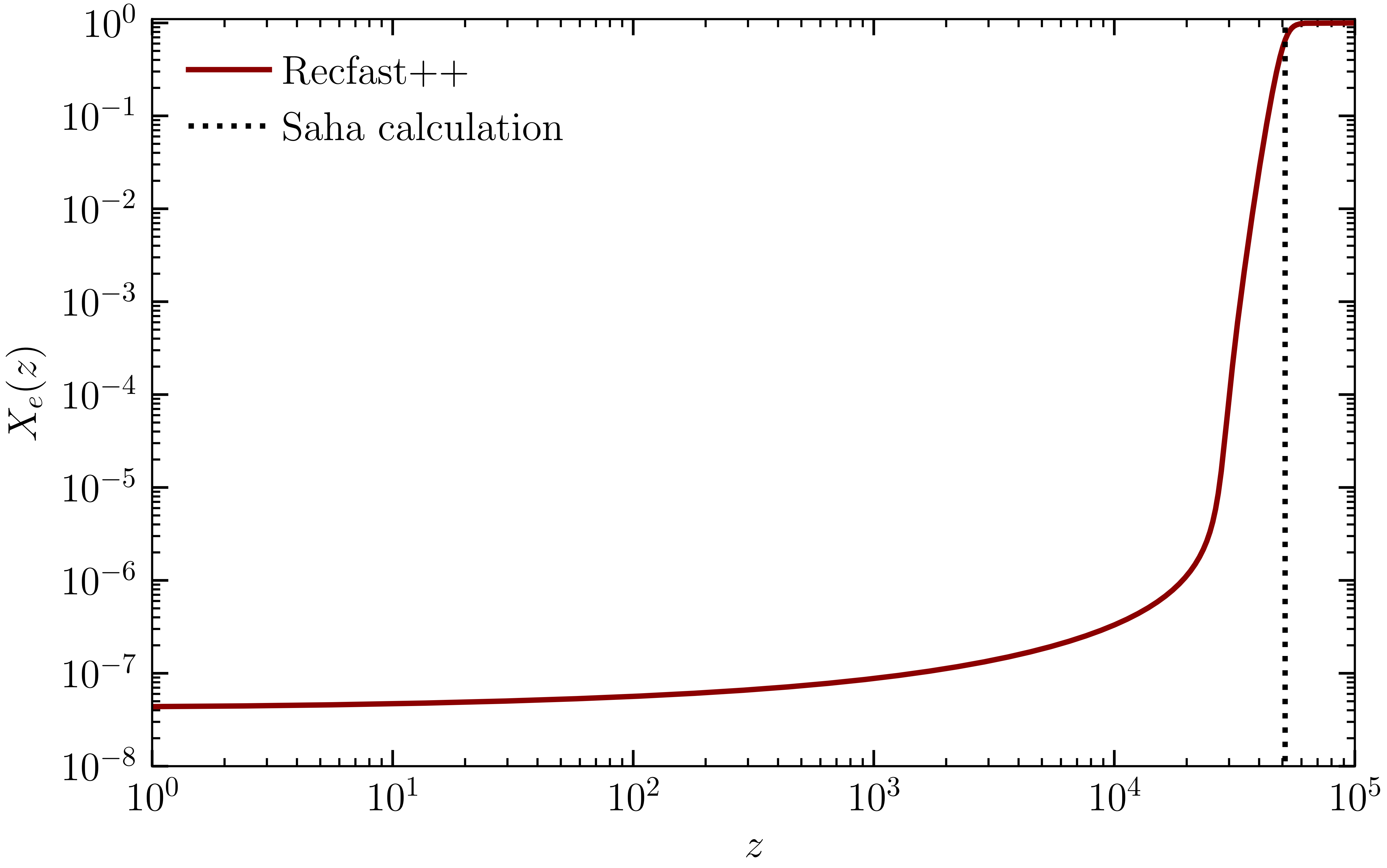


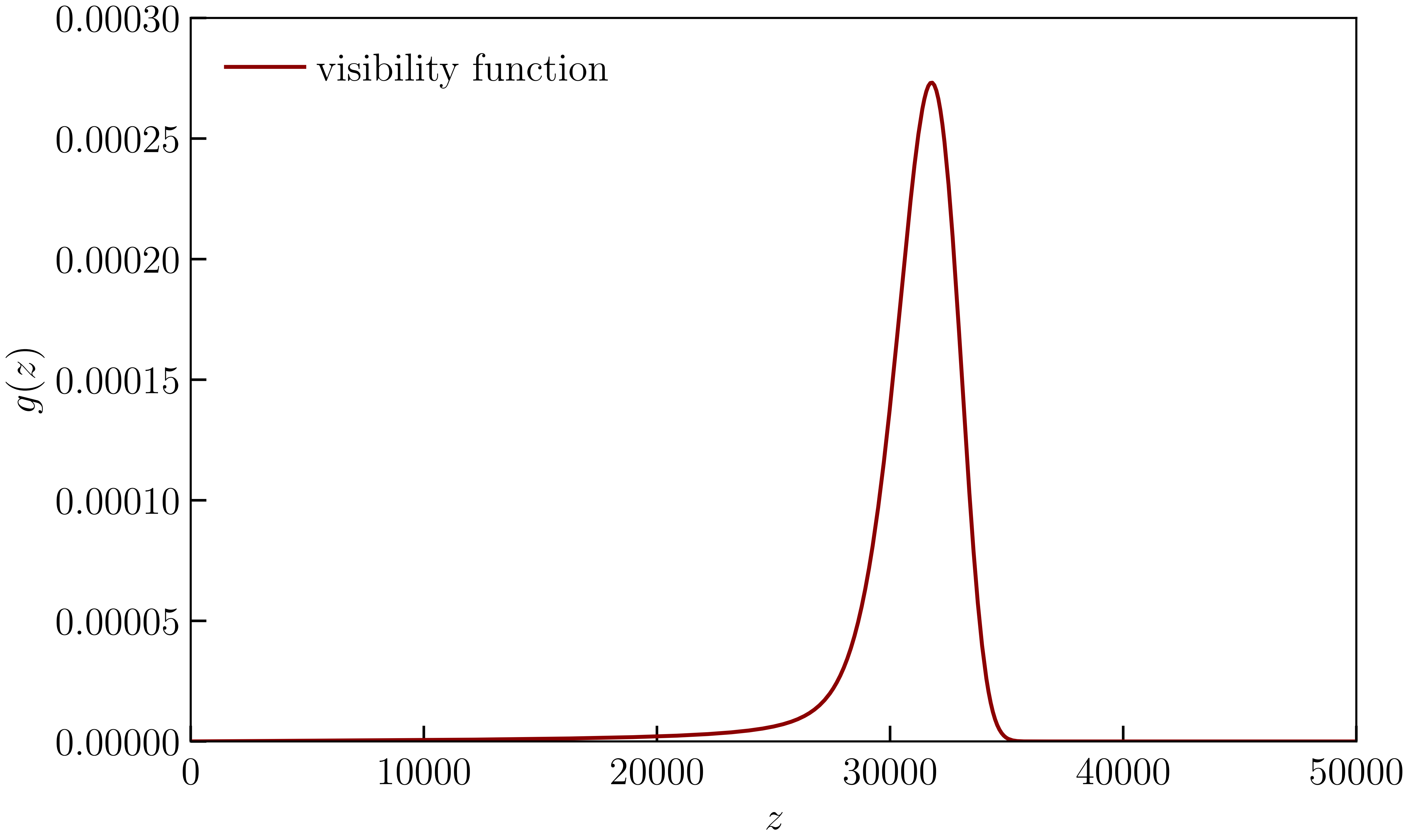
- Observable Effects:
  - Baryonic disk + Dark matter disk
  - Change the number of relativistic d.o.f.
  - Dark Acoustic Oscillations
  - Dark Silk damping (small-scale suppression)



Gurian, Jeong, Shandera, Ryan (2021)

Dark recombination & decoupling



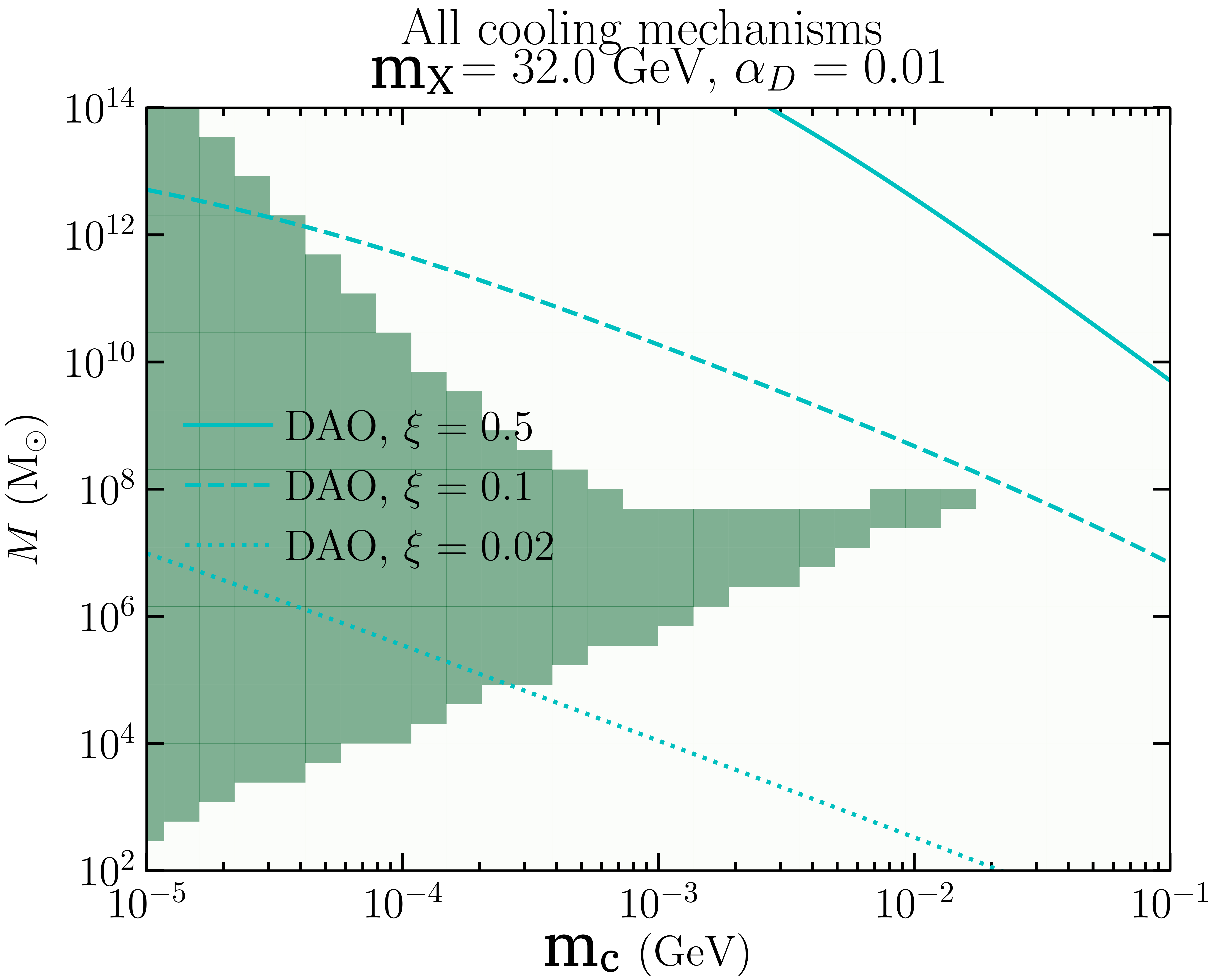


m_X=16 GeV, m_c=140 keV, T_D=0.02 T_{CMB} case

$z_{Recombination}$ ~ 51000, $z_{decoupling}$ ~ 32000, d_{DAO}~0.02Mpc, $1/k_D$~0.24 Mpc

Buckley & DiFranzo (2018)

DO NOT spoil large-scale structure



- With EM-like interaction, dark matter can cool as well!
- To explain observed large-scale structure, we invert the *Rees-Ostriker condition* to make cooling unimportant <u>for $M>10^{11} M_\odot$ halos,</u>

$t_{cool} > t_{age}$

Two mass scales

- Chandrasekhar mass

$$\boxed{M_{\mathrm{Chand.}}^{\mathrm{Dark}} = 1.457 M_{\odot} \left(\frac{m_p}{m_X}\right)^2}$$

Chandrasekhar (1931)

- Opacity limit (minimum Jeans mass of fragmentation)

$$\boxed{M_{\mathrm{DBH,min}} \sim \left(\frac{m_p}{m_X}\right)^{9/4} \left(\frac{T}{10^3 K}\right)^{1/4} 10^3 M_{\odot}}$$

Rees (1976), Low & Lynden-Bell (1976)

Dark star formation

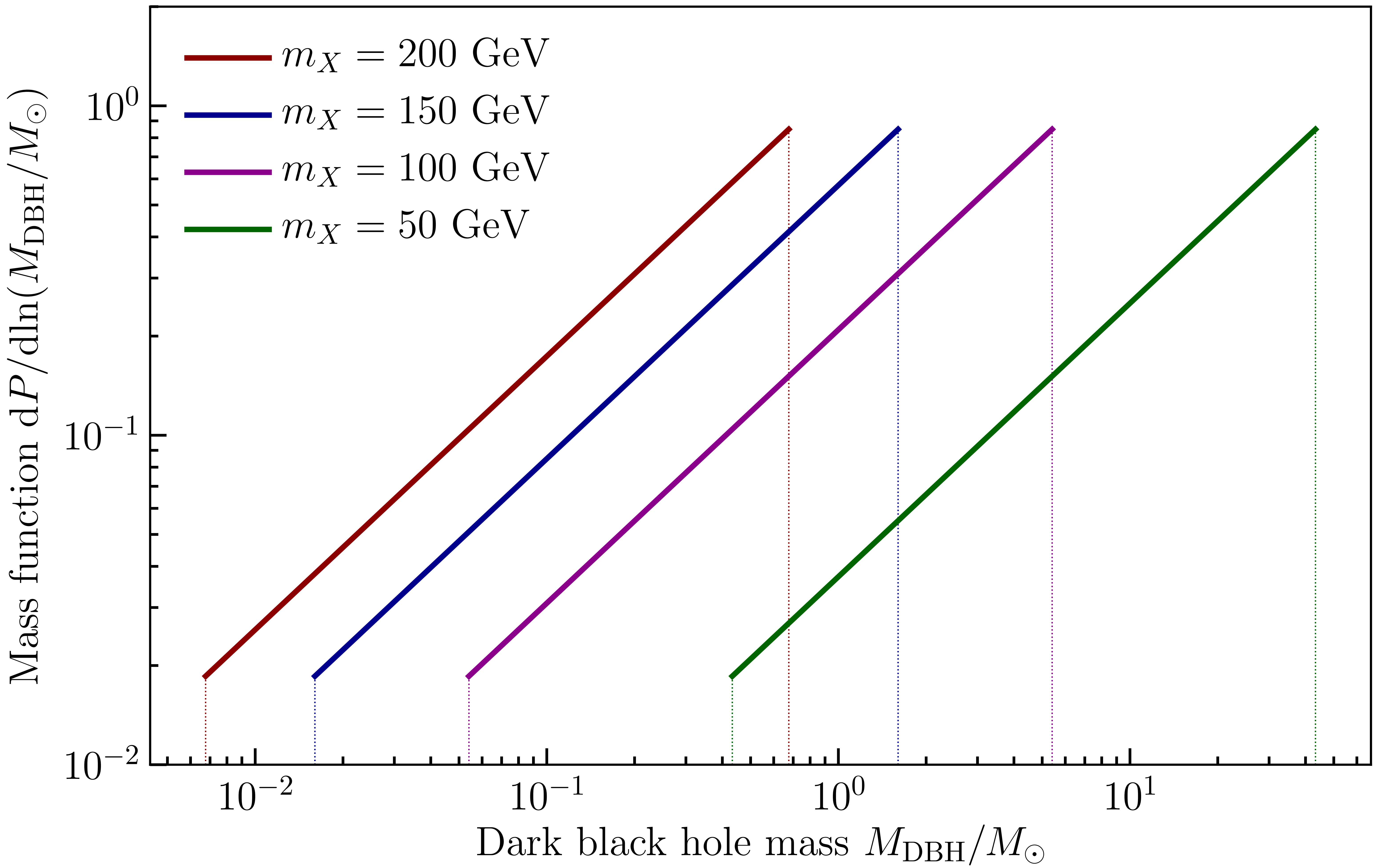
- is parallel to the formation of first stars.
- Residual dark electrons from dark recombination catalyze the formation of dark Hydrogen molecule. These molecules can *cool* dark matters with energy level

$$\Delta E = \left(\frac{m_p}{m_X}\right)\left(\frac{m_c}{511\,\mathrm{keV}}\right)^2\left(\frac{\alpha_D}{0.0073}\right)^2 \times 512\,K.$$

- DS formation is similar to Pop-III except for the energy gap.
- We, therefore, use the Pop-III binary literature extensively.

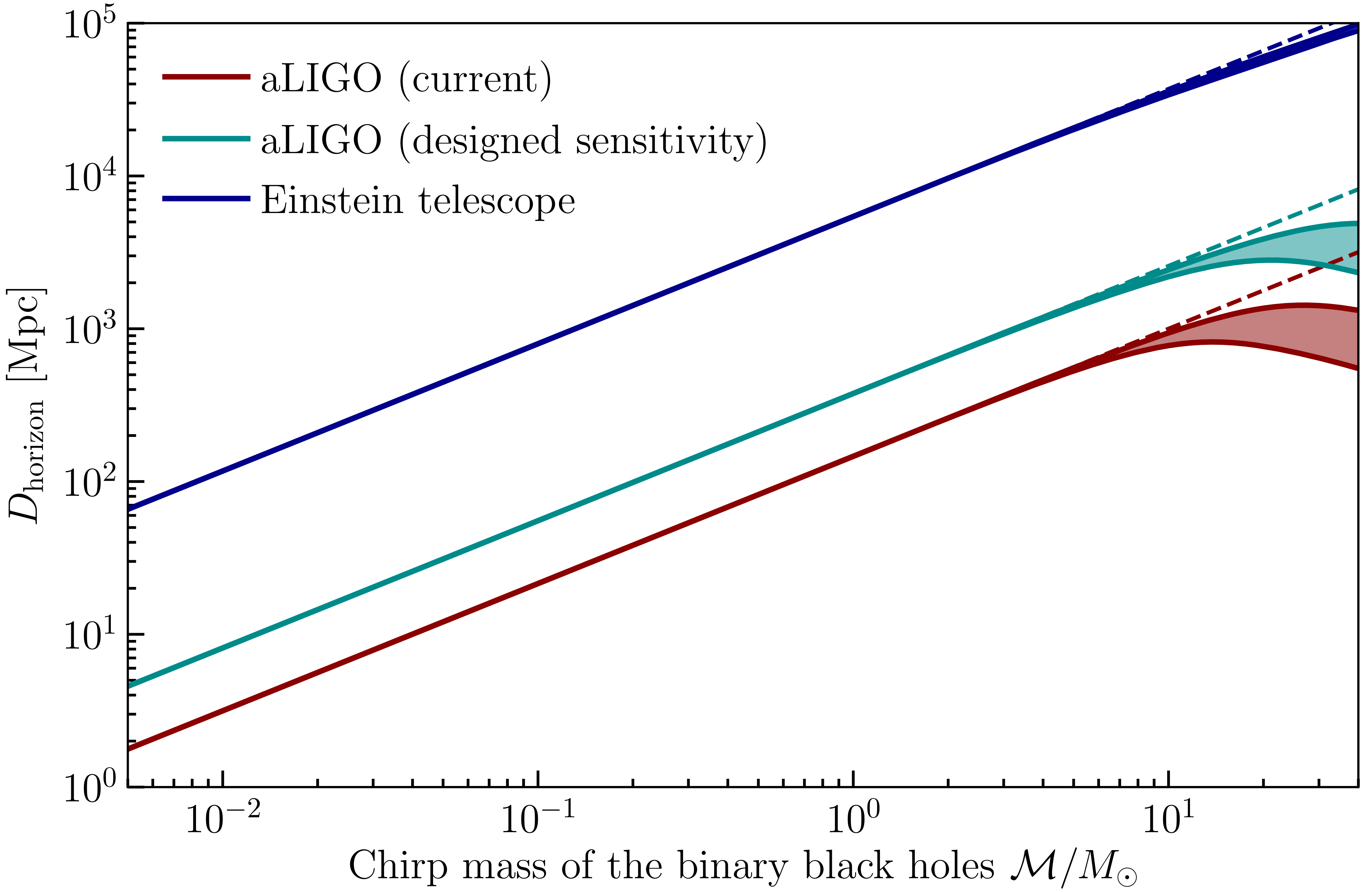
Shandera, Jeong, Gebhardt, (2018)

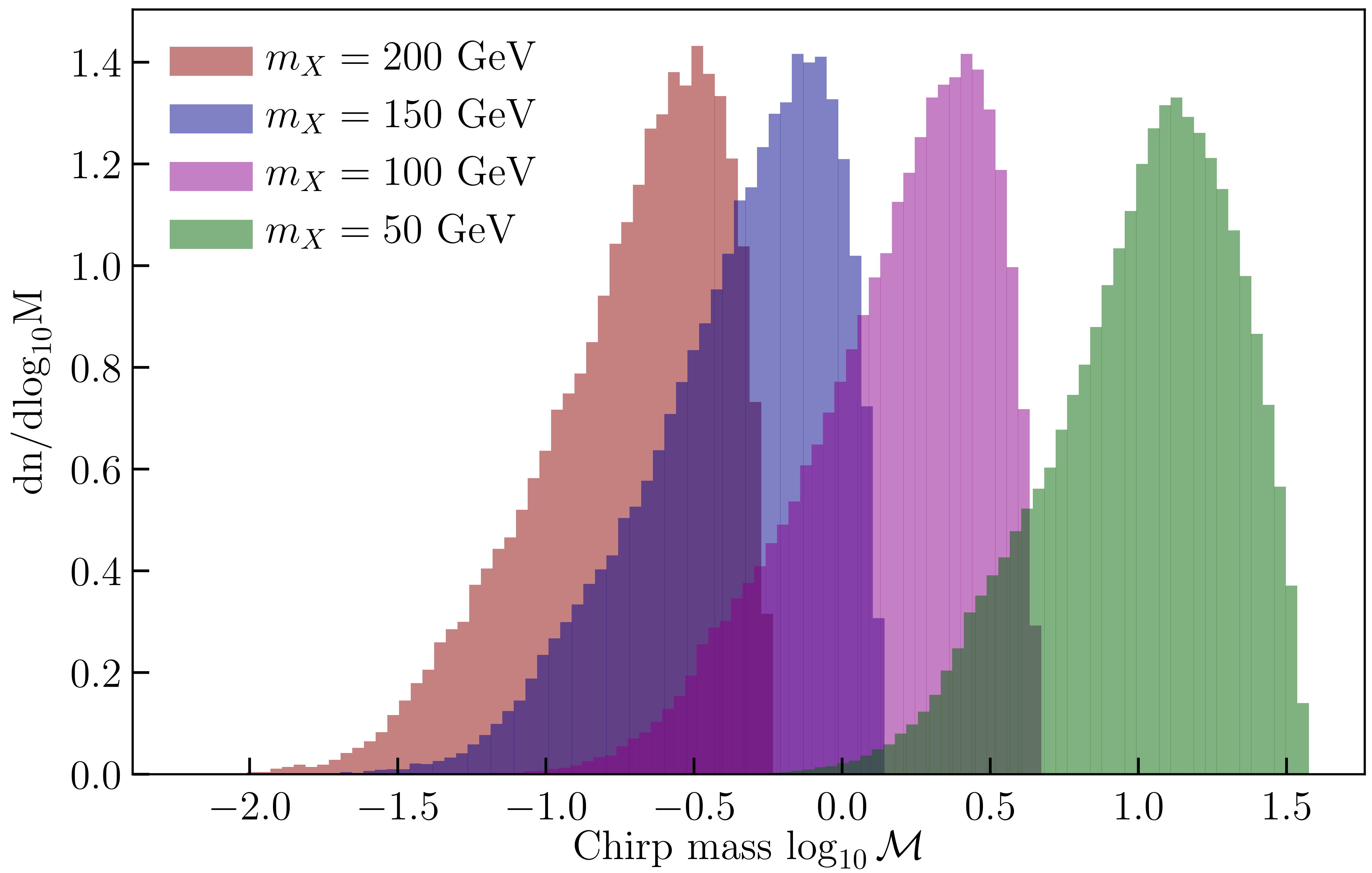
Dark BH mass function



Horizon radius (8σ-detection limit)

$$\mathcal{M} = \left[\frac{q^3}{1+q}\right]^{1/5} M$$





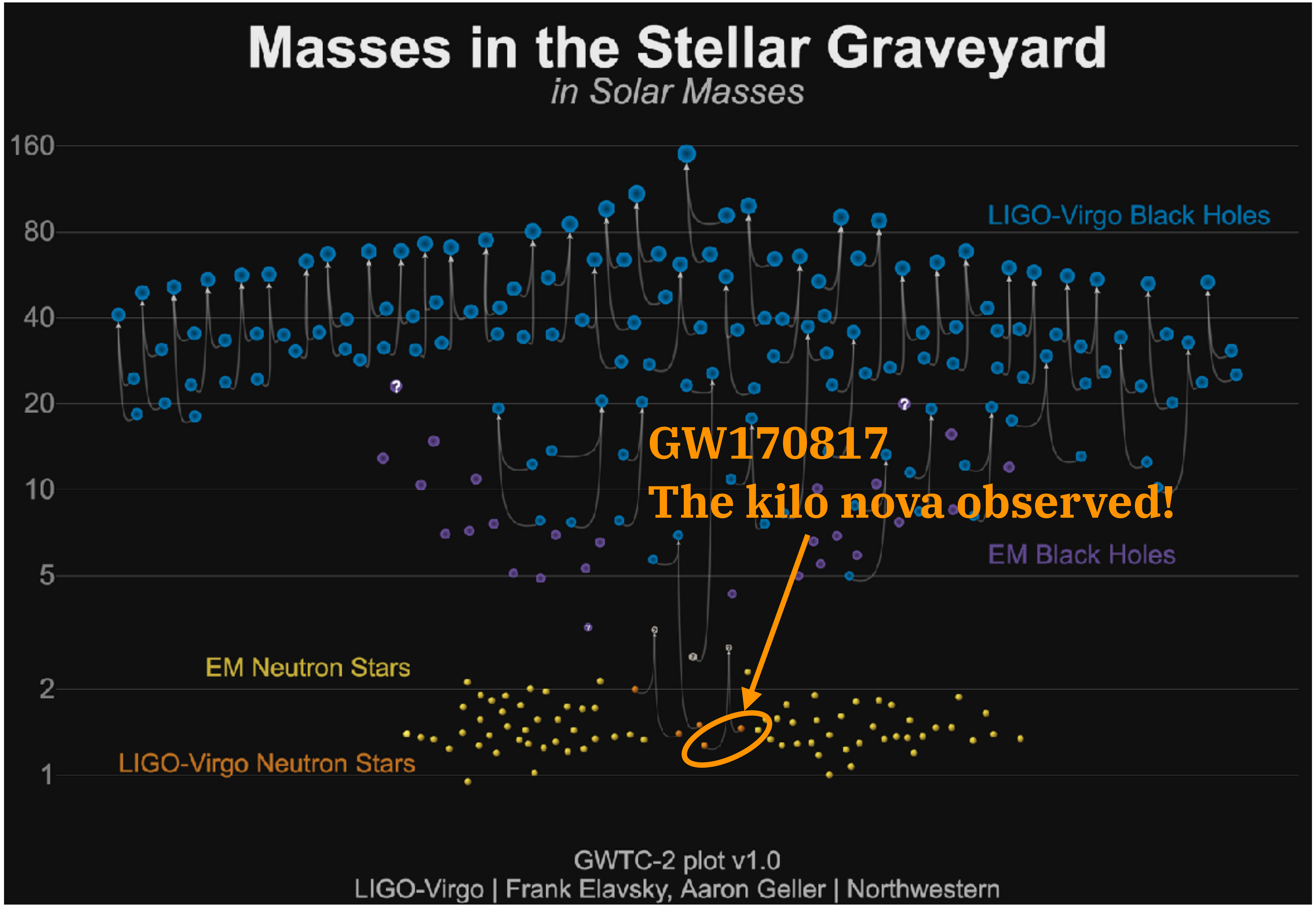
Shandera, Jeong, Gebhardt, (2018)

Yes, we *can* detect them!

m_X [GeV]	m_c [keV]	$M^{\rm dark}_{\rm Chand.}$ $[10^{-5} M_\odot]$	$M_{\rm DBH}$ $[M_\odot]$	Rates per year raw $({\rm MWEG}^{-1})$	aLIGO (current)	aLIGO (full)	Einstein T.	$m_1 < 1.4$ [%]	$m_1, m_2 < 1.4$ [%]
62	30	33	0.0068 – 0.68	$2.0\times10^{-6}(10^{-4})$	0.0012 (0.12)	0.020 (2.0)	60 (6000)	100%	100%
48	47	56	0.016 – 1.6	$1.3\times10^{-6}(10^{-4})$	0.0065 (0.65)	0.11 (11)	330 (33k)	99%	79%
32	70	125	0.054 – 5.4	$6.6\times10^{-7}(10^{-5})$	0.068 (6.8)	1.1 (110)	3500 (350k)	53%	9.3%
16	144	500	0.43 – 43	$1.9\times10^{-7}(10^{-5})$	0.89 (89)	22 (2200)	92k (9200k)	9.8%	0.14%

TABLE I. Dark black hole masses and binary merger rates today, estimated using the procedure in the text, for several choices of dark proton mass m_X and dark electron mass m_c. All black hole masses are given in solar masses. In all cases we have set the dark fine structure constant to $\alpha_D = 0.01$ and the ratio of present day temperature of the dark sector to photon temperature to $\xi = 0.02$. The conservative (optimistic) rates use $f_{\rm cool} \times f_{\rm form.\,eff.} = 10^{-5}(10^{-3})$. Note that the optimistic rate for $m_X = 50$ GeV is high enough that it would be worth a more careful analysis to see if current aLIGO already constrains this parameter space. The last two columns show the percent of binaries where one or both black holes in the binary has a mass less than the standard Chandrasekhar mass ($1.4\ M_\odot$).

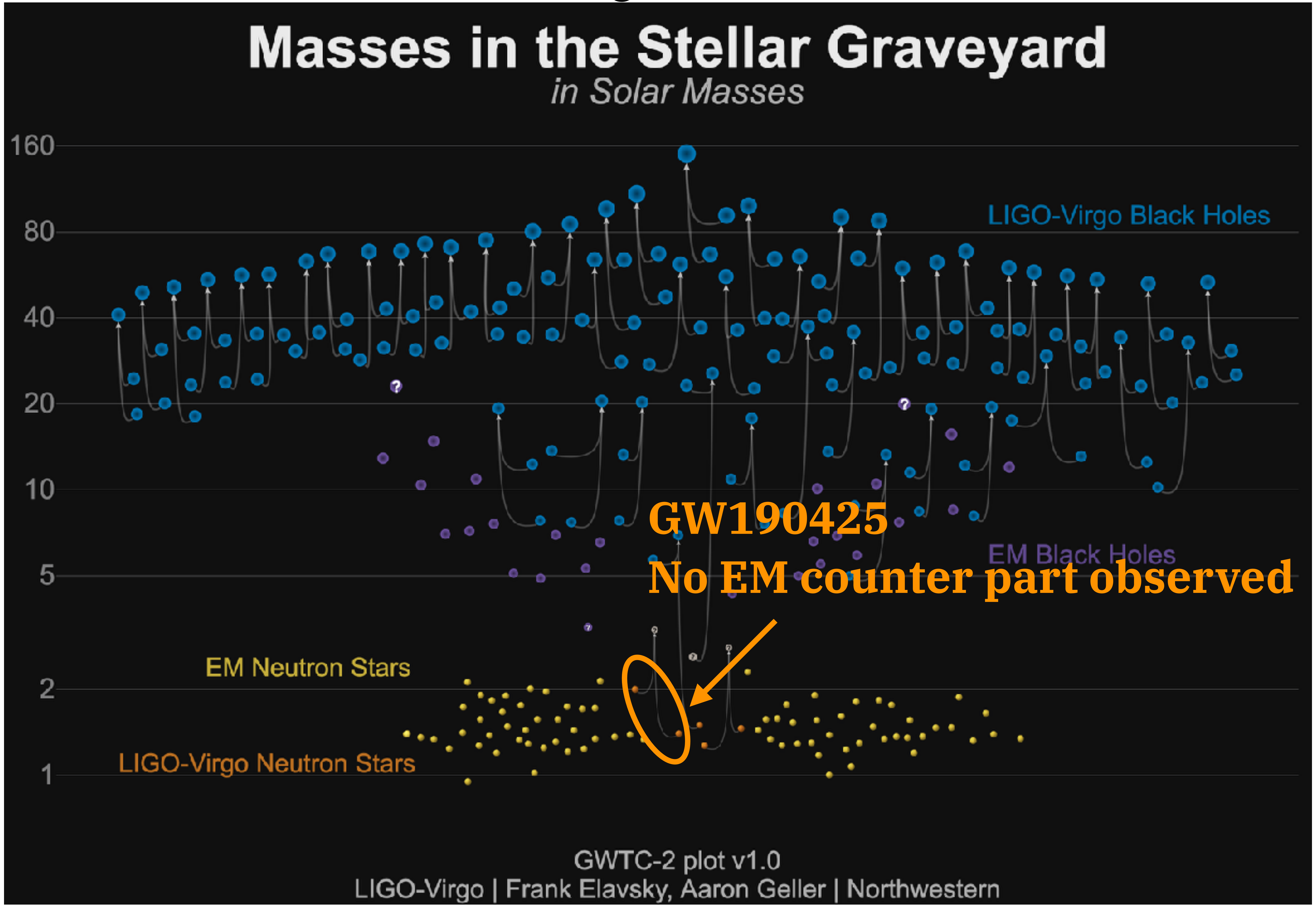
The famous GW170817



O1+O2+O3a
46 BBH
2 BNS
2 B+NS


Fermi
Reported 16 seconds after detection
LIGO-Virgo
Reported 27 minutes after detection
INTEGRAL
Reported 66 minutes after detection
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)
Gamma rays, 100 keV and higher
GRB 170817A
Counts per second
120,000
115,000
110,000

A case study: GW190425



O1+O2+O3a
46 BBH
2 BNS
2 B+NS

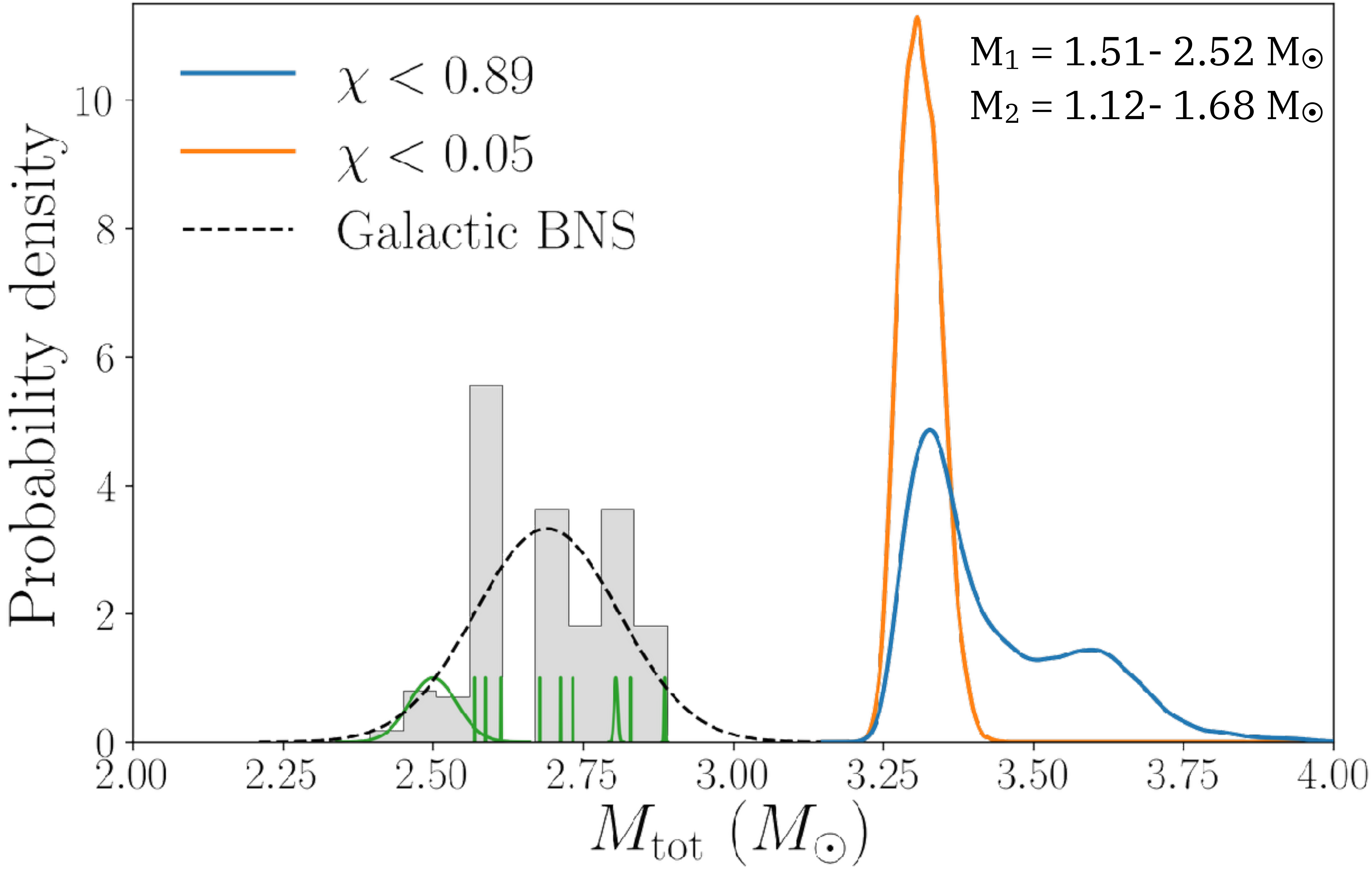
GW190425: what can that be?

$M_1 = 1.51 - 2.52\ M_\odot$

$M_2 = 1.12 - 1.68\ M_\odot$

- To emit GW, the event must be coalescence of compact objects:
  - Neutron star binary (BNS)
  - Neutron star + black hole binary (BH+NS)
  - Black hole + black hole binary (BBH)

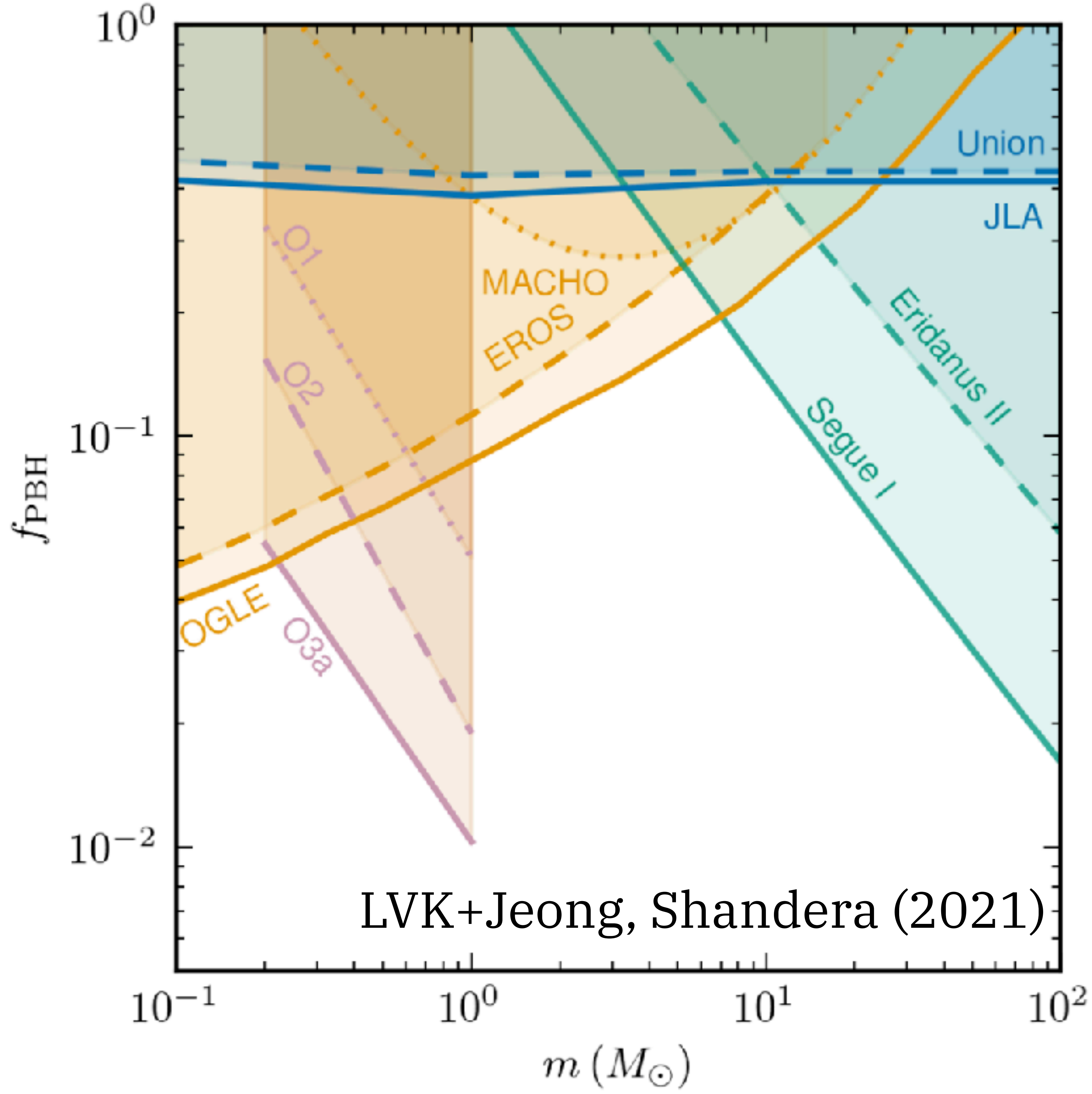
If BNS, GW190425 is an 5-σ outlier!



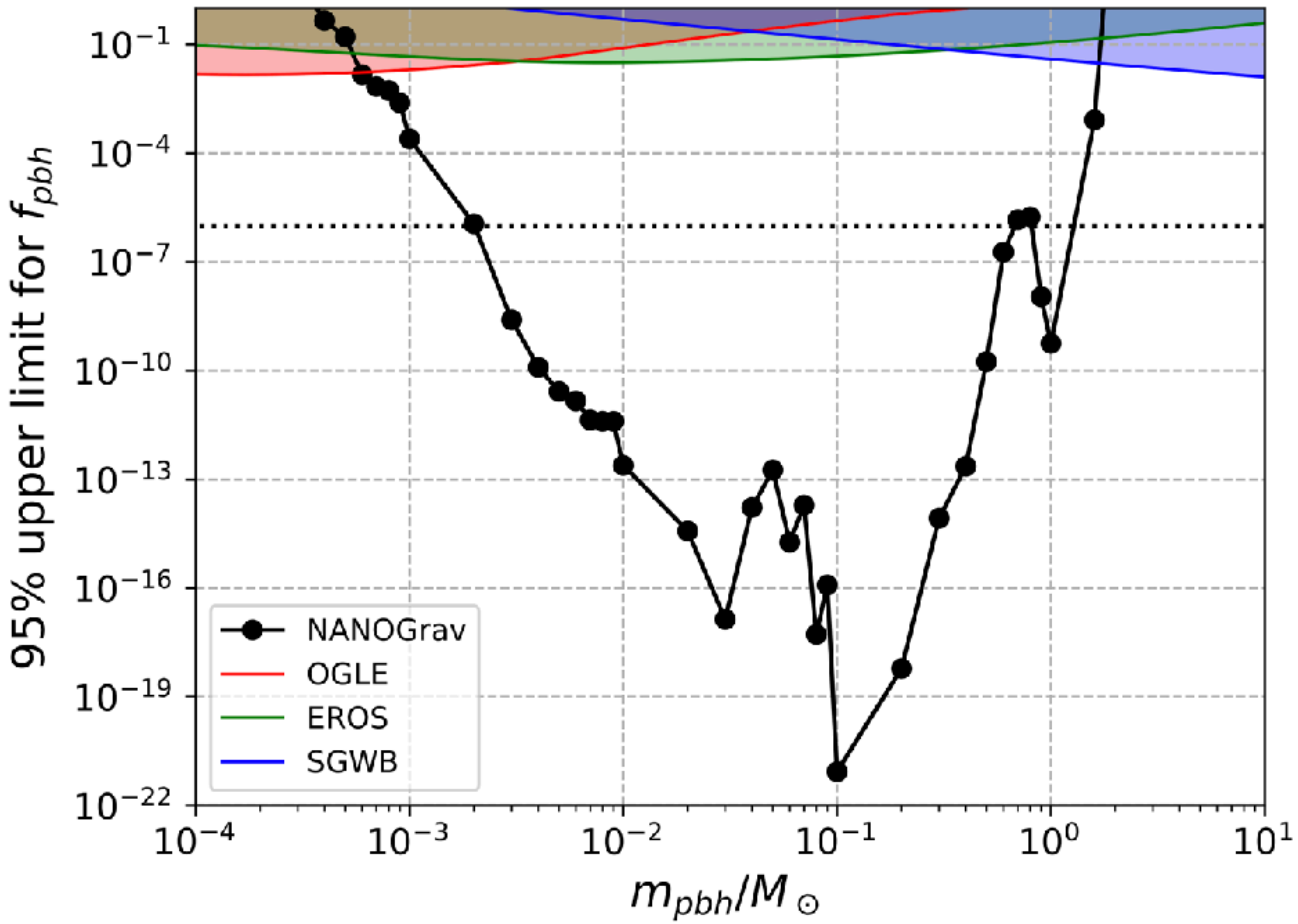
$M_1 = 1.51 - 2.52\ M_\odot$

$M_2 = 1.12 - 1.68\ M_\odot$

Can that be a PBH binary?

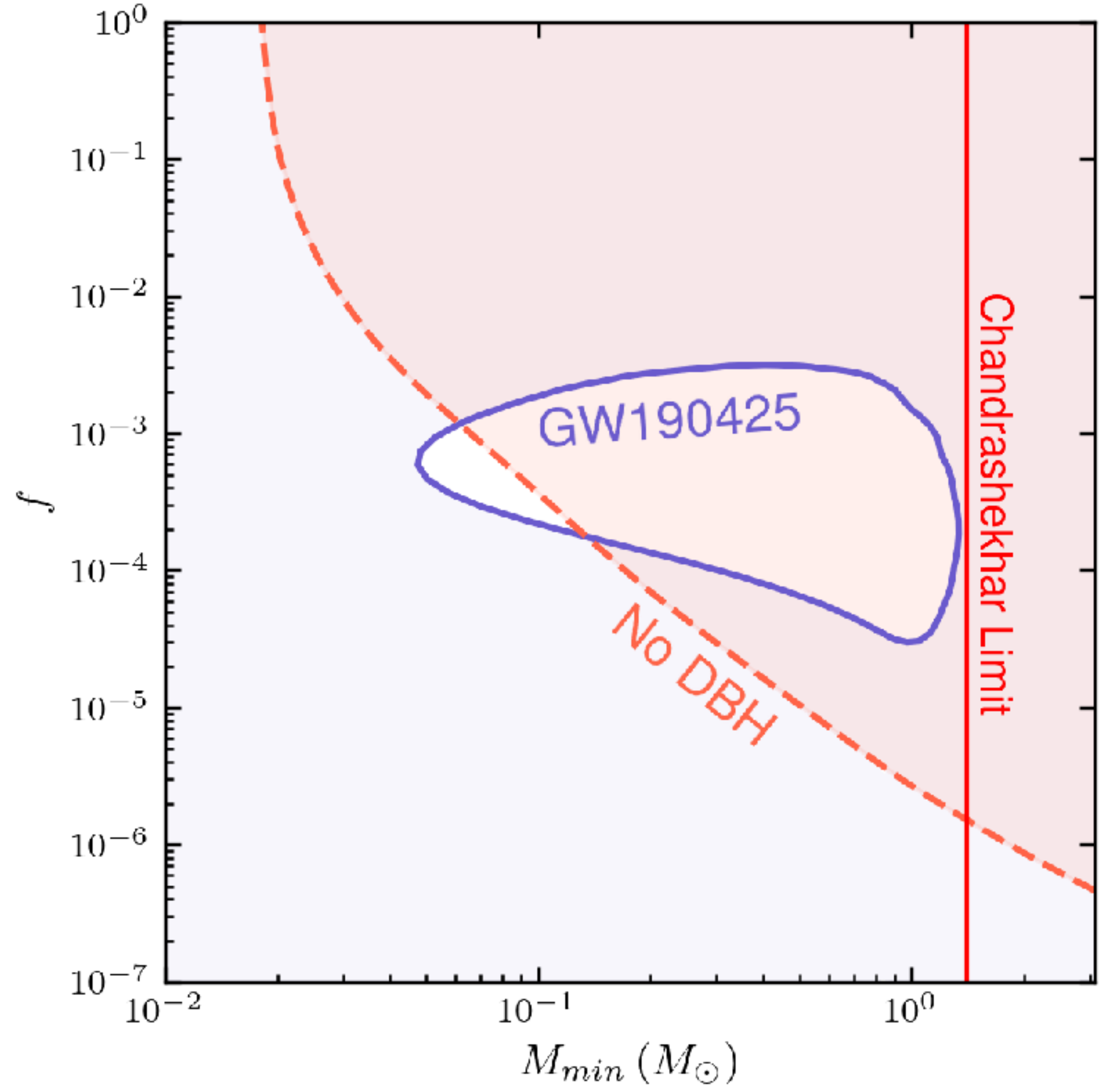


NANOGrav 11yr: Chen et al (2020)



Singh et al. (2021)

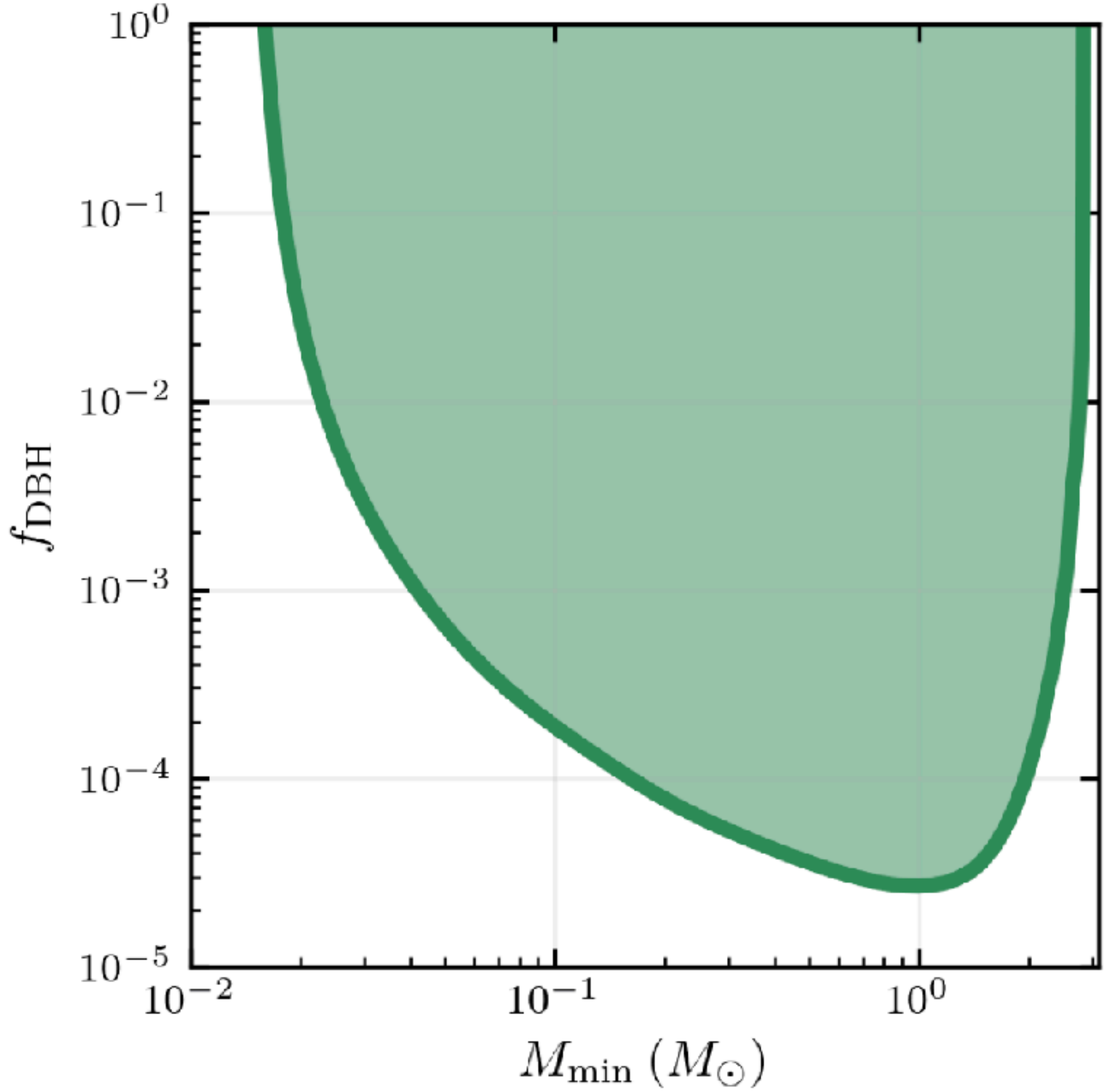
Implication of GW190425

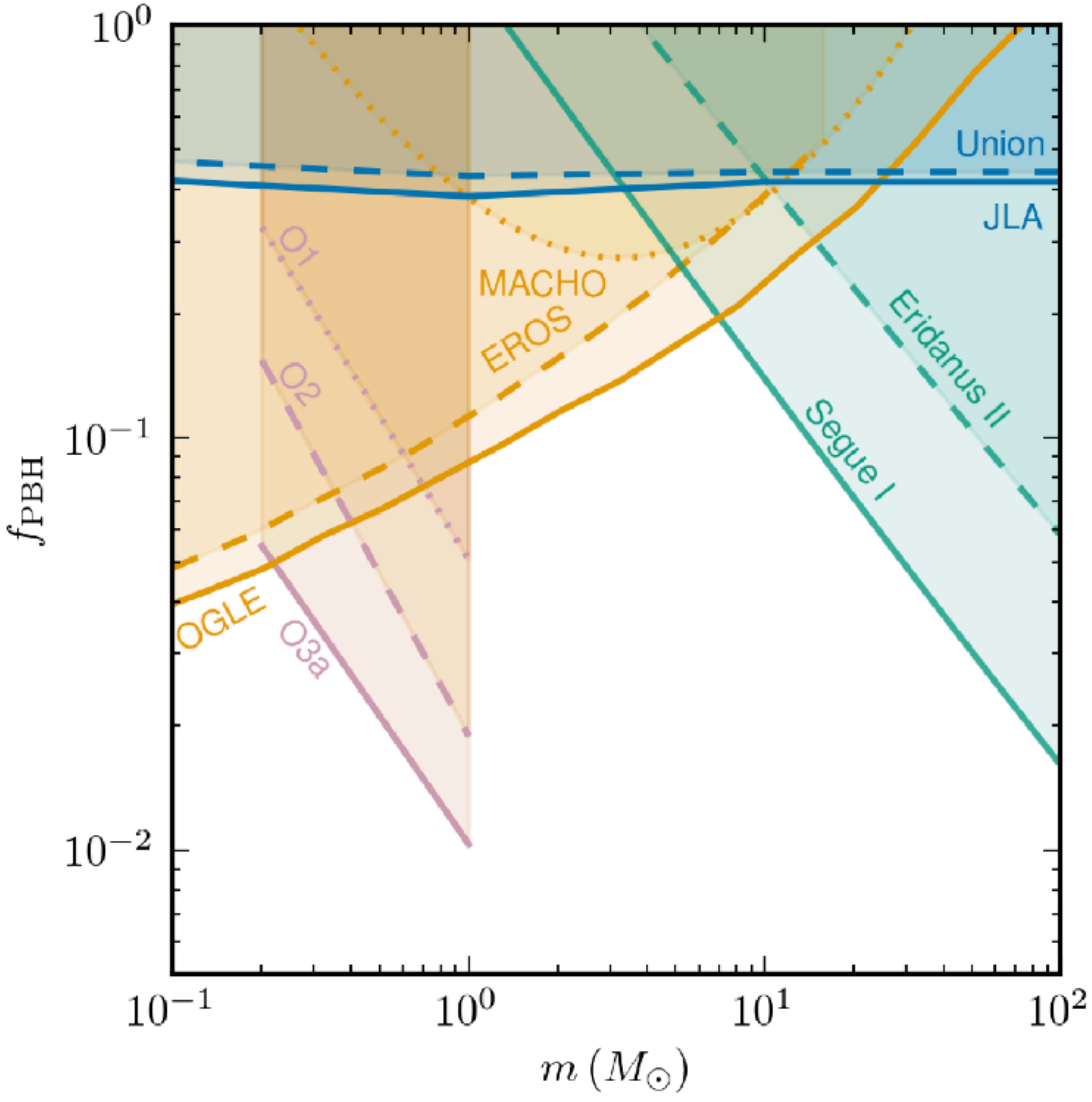


- If GW190425 is a Dark-BH binary, the dark Chandrasekhar mass is <u>less than 1.4 $M_\odot$ (99.9% C. L.)</u>; that is, *$m_X > 0.96$ GeV*.
- If GW190425 is not a Dark-BH (then we don't know what it is), we constrain large parameter space.

LVK+Jeong, Shandera (2021), arXiv:2109.12197

Up-to-date limit (for null detection)

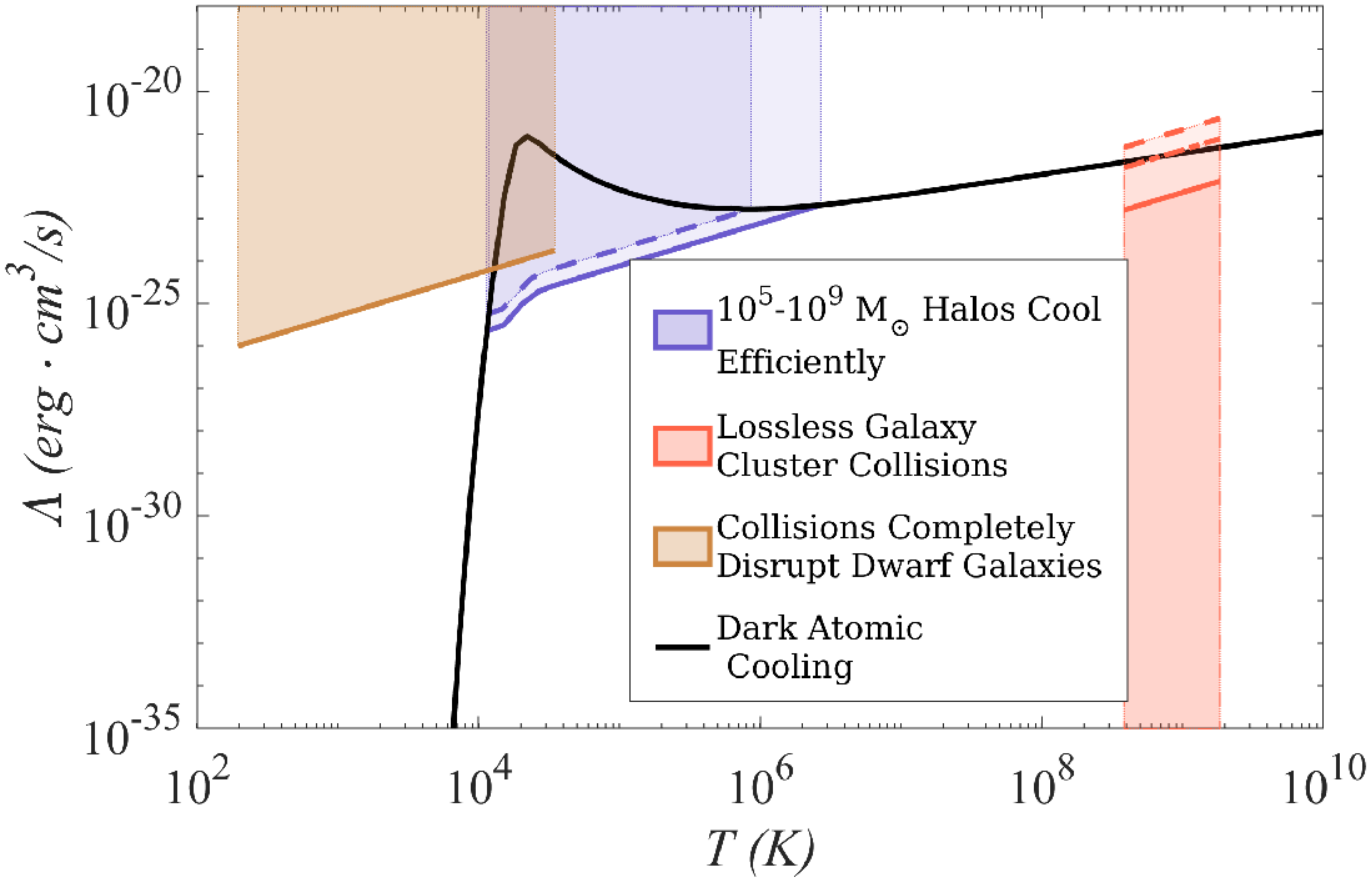




Singh et al. (2021)

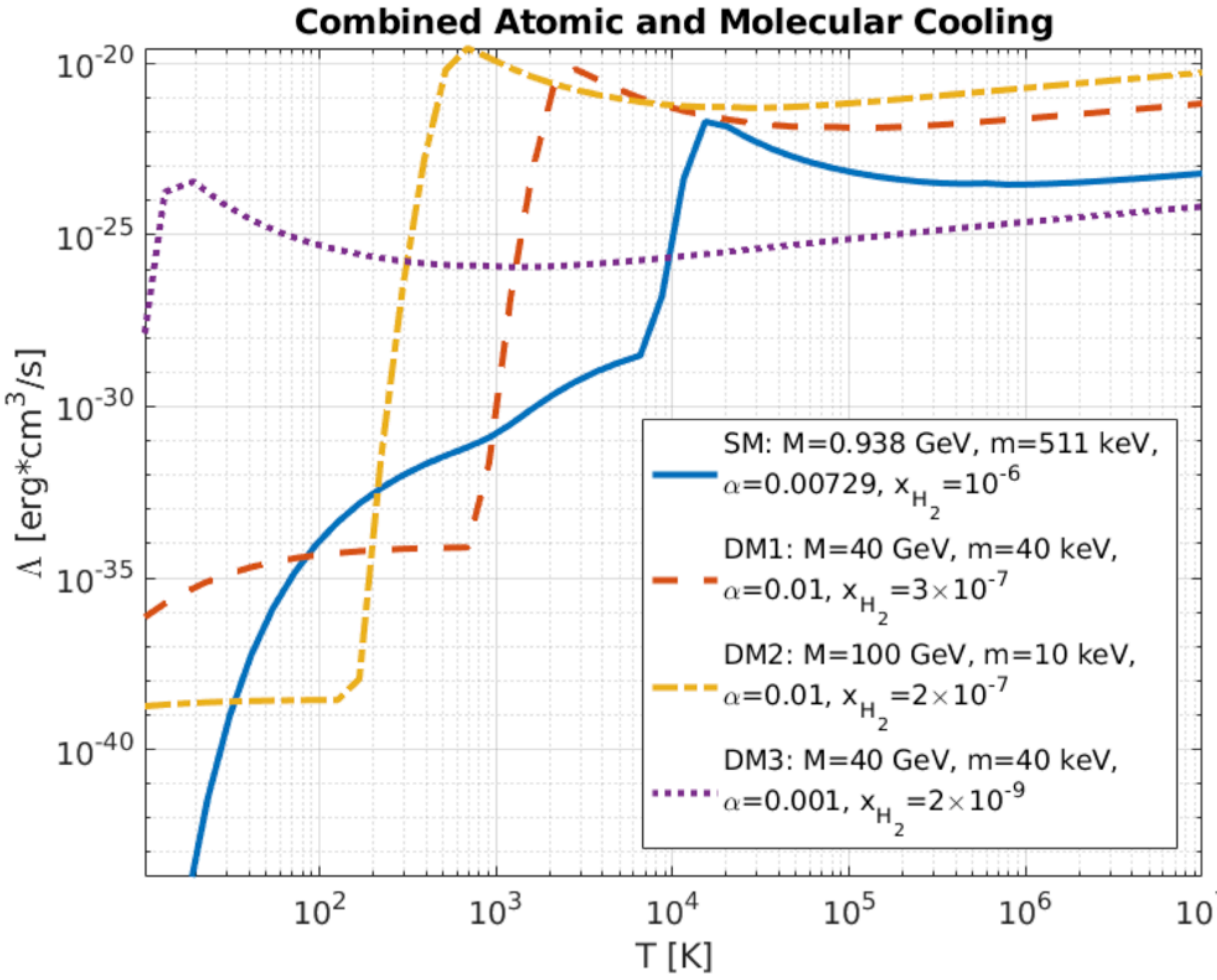
Constraints on *dark* cooling function

Energy dissipation rate as a function of particle temperature



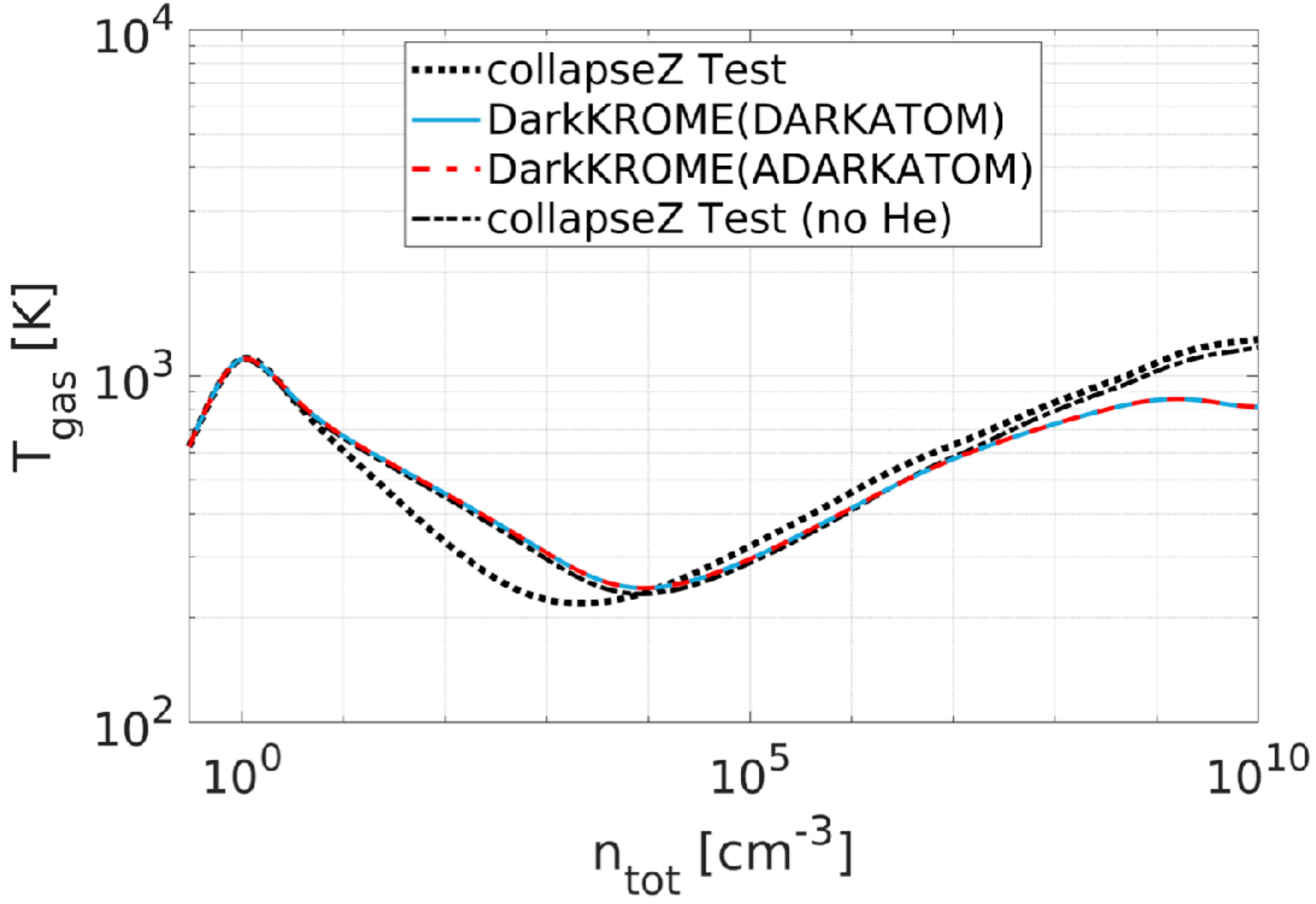
Gurian et a.l (2021)
Ryan et al. (2021a,b)

ADM cosmology: the cooling function



Gurian et a.l (2021)
Ryan et al. (2021a,b)

ADM cosmology: (n-T) phase space



Gurian et a.l (2021)
Ryan et al. (2021a,b)

ADM cosmology: initial condition

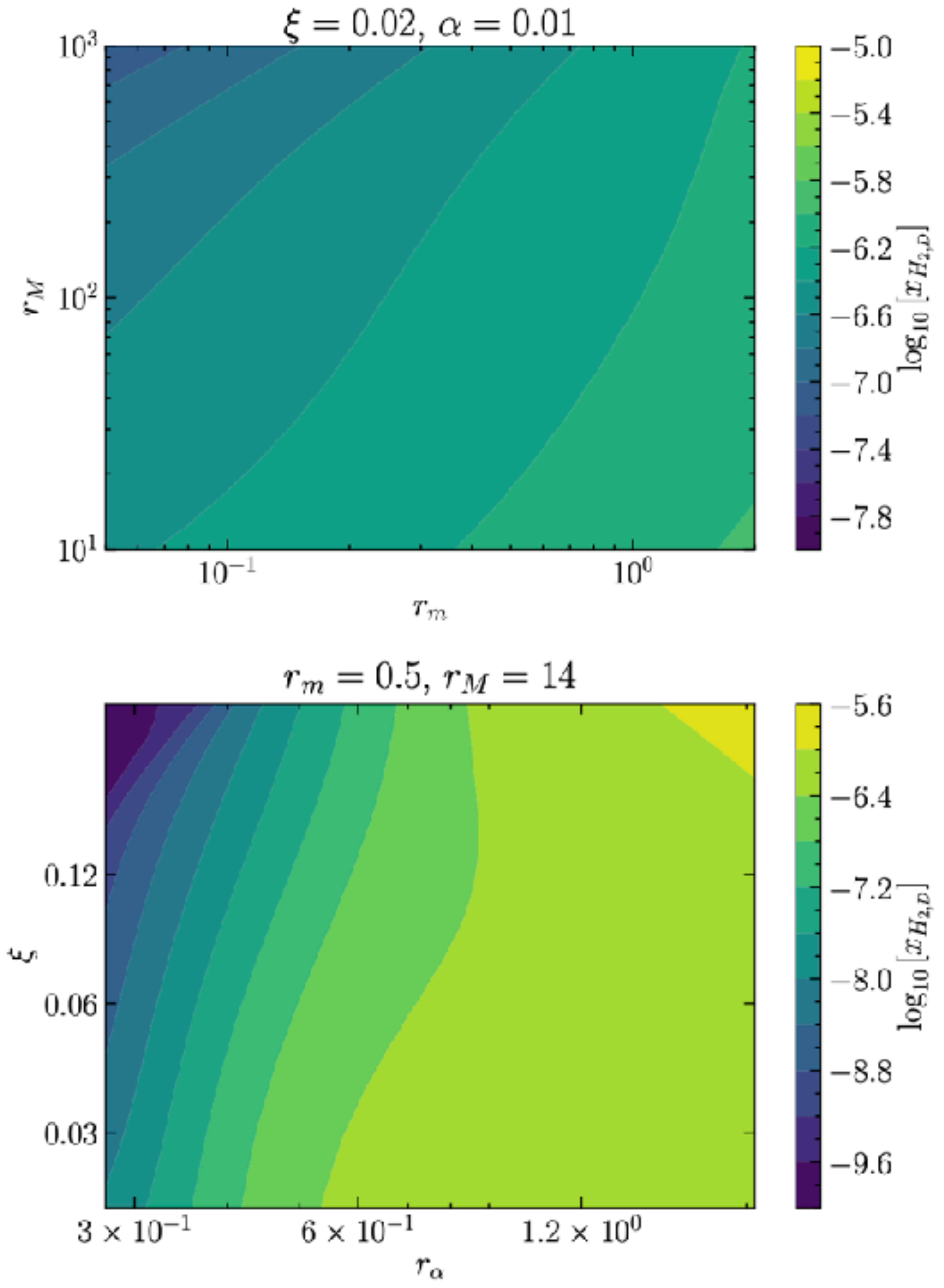


Figure 4. The dependence of the molecular hydrogen fraction $x_{H_{2,D}}$ at redshift 30 on the model parameters.

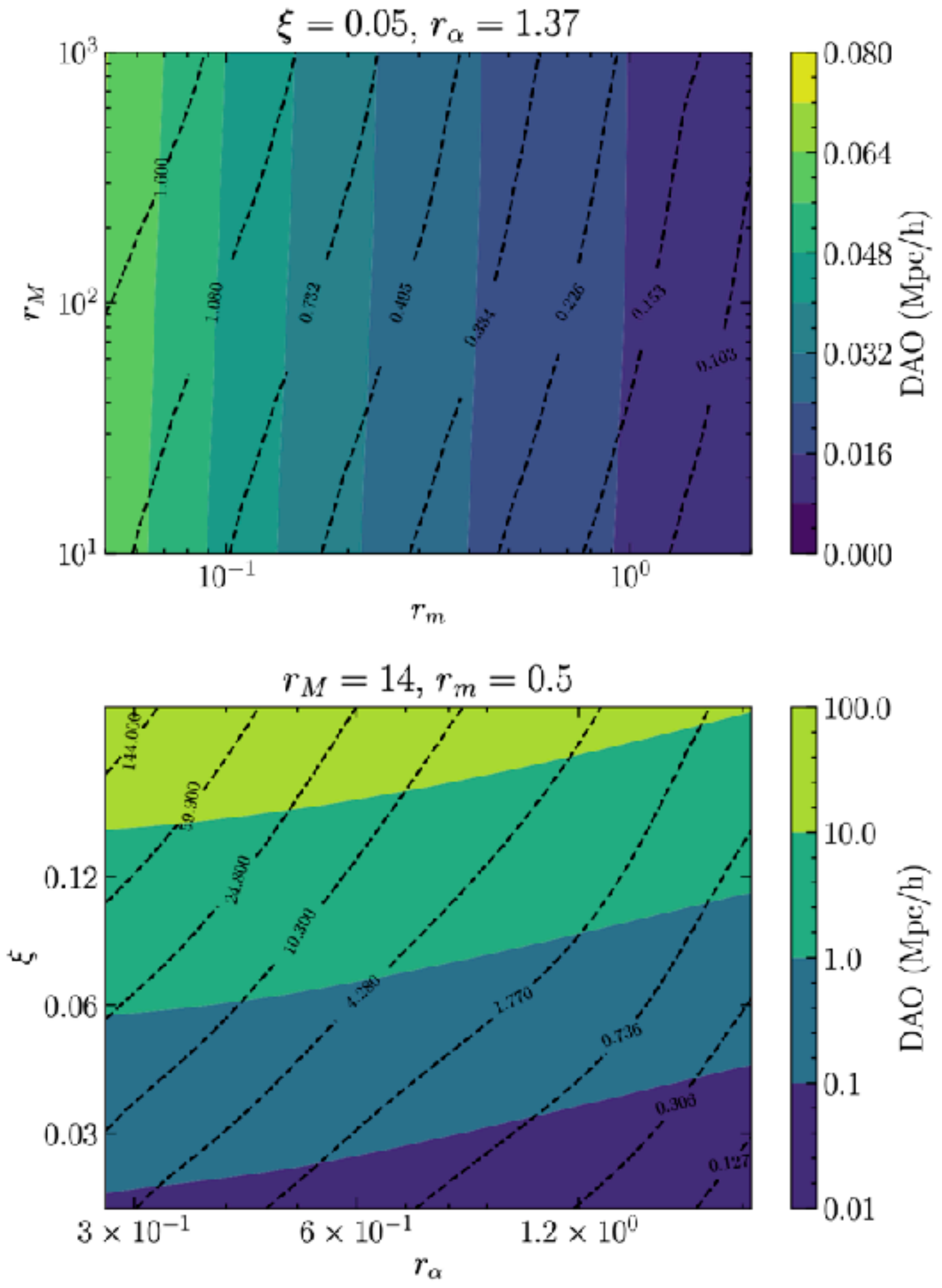
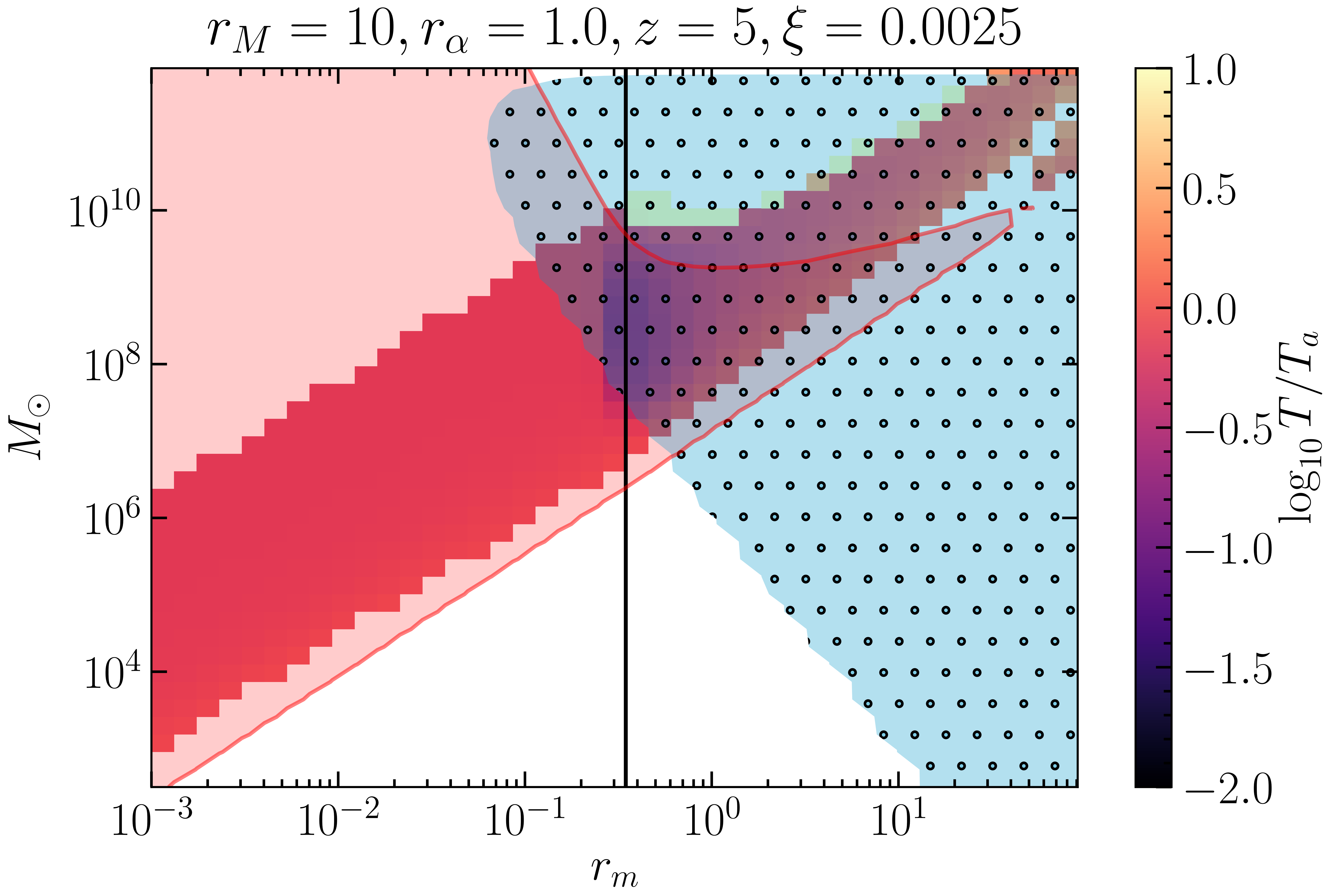


Figure 5. The dependence of the diffusion damping scale (black, dashed) and the acoustic scale (color bars) on the model parameters.

Gurian et a.l (2022), In preparation

ADM cosmology: halo cooling



Conclusion

- GW provides an exciting new avenue for studying dark matter using the only guaranteed property of dark matter: gravity!
- If GW190425 is a dark-BH binary, dark proton mass must be heavier than the proton mass.
- Combined with other astronomical constraints, we can also constrain the *dark* cooling function.
- Sub-solar mass (SSM) search ongoing in LVK collaboration with O3b dataset (+Shandera, myself).