Shandera+, arXiv:1802.08206
Singh+, arXiv: 2009.05209

A gravitational-wave limit on the Chandrasekhar mass of dark matter

An intriguing implication of GW190425

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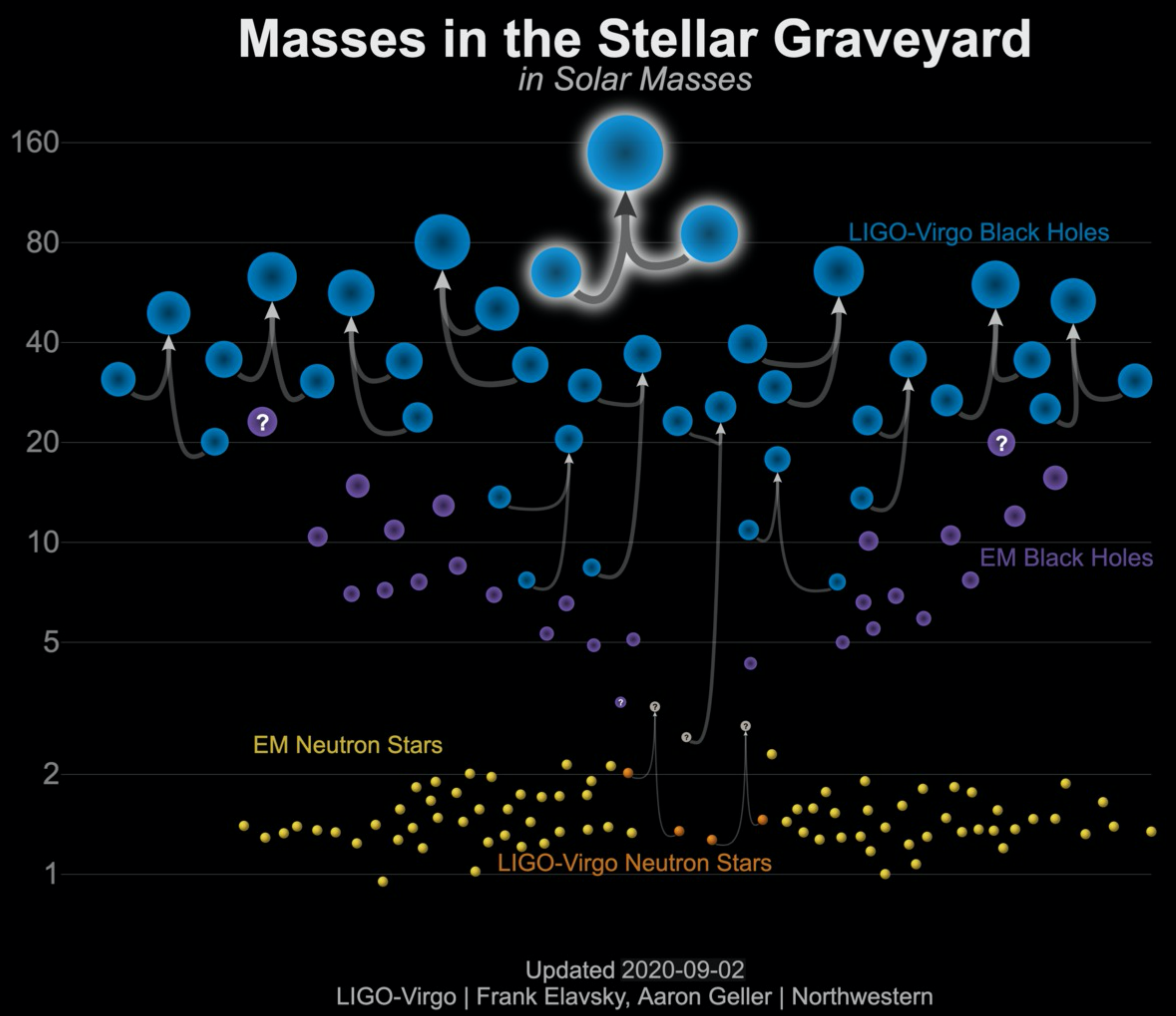
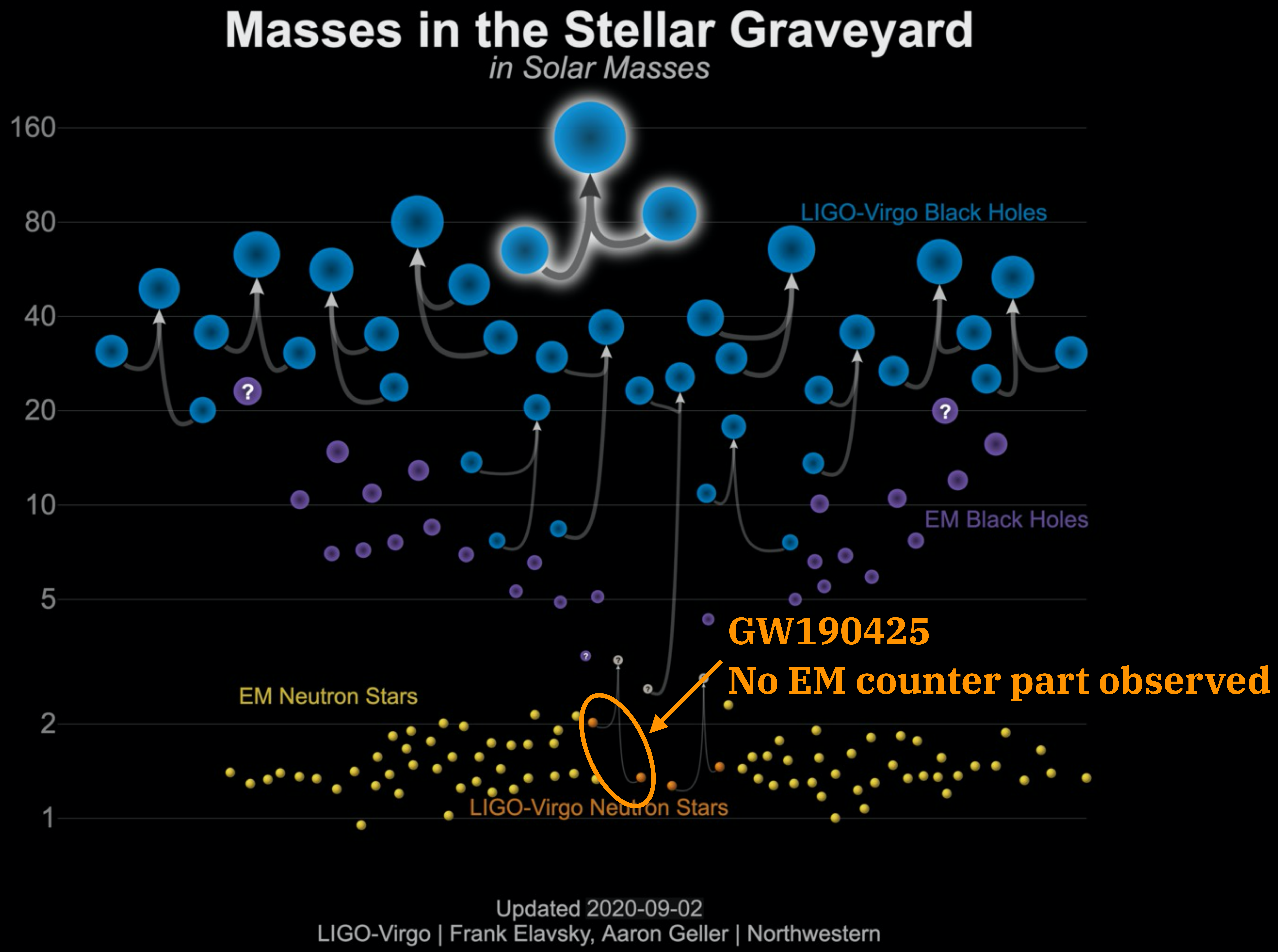
The 9th KIAS workshop, 2 November 2020


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern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LIGO-Virgo Black Holes
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GW190425
No EM counter part observed
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

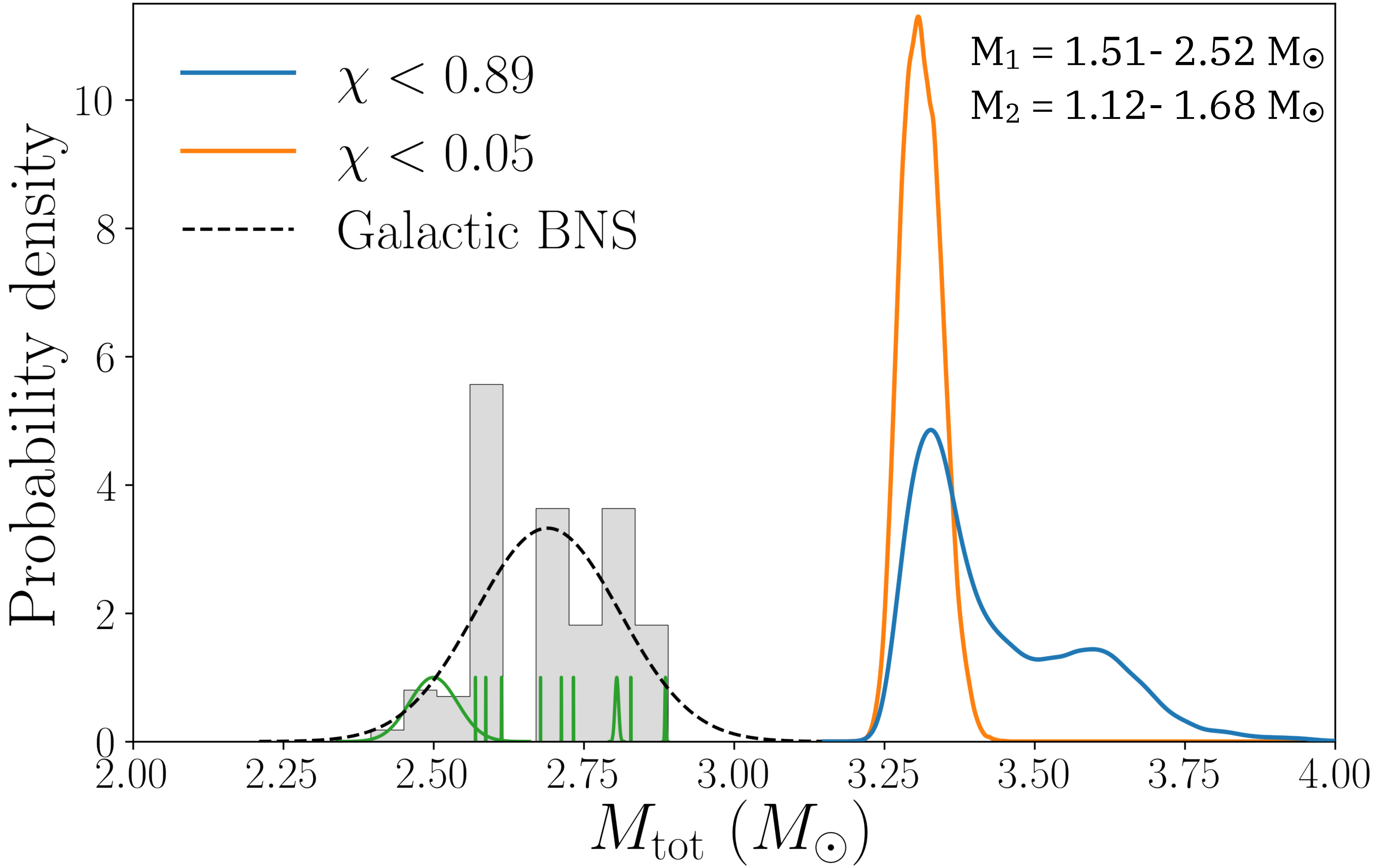
GW190425: what can this be?

$M_1 = 1.51- 2.52\ M_\odot$

$M_2 = 1.12- 1.68\ M_\odot$

- To emit GW, the event must be coalescence of compact objects:
    - Neutron star binary
    - Neutron star + black hole binary
    - Black hole + black hole binary

If BNS, GW190425 is an 5-σ outlier!

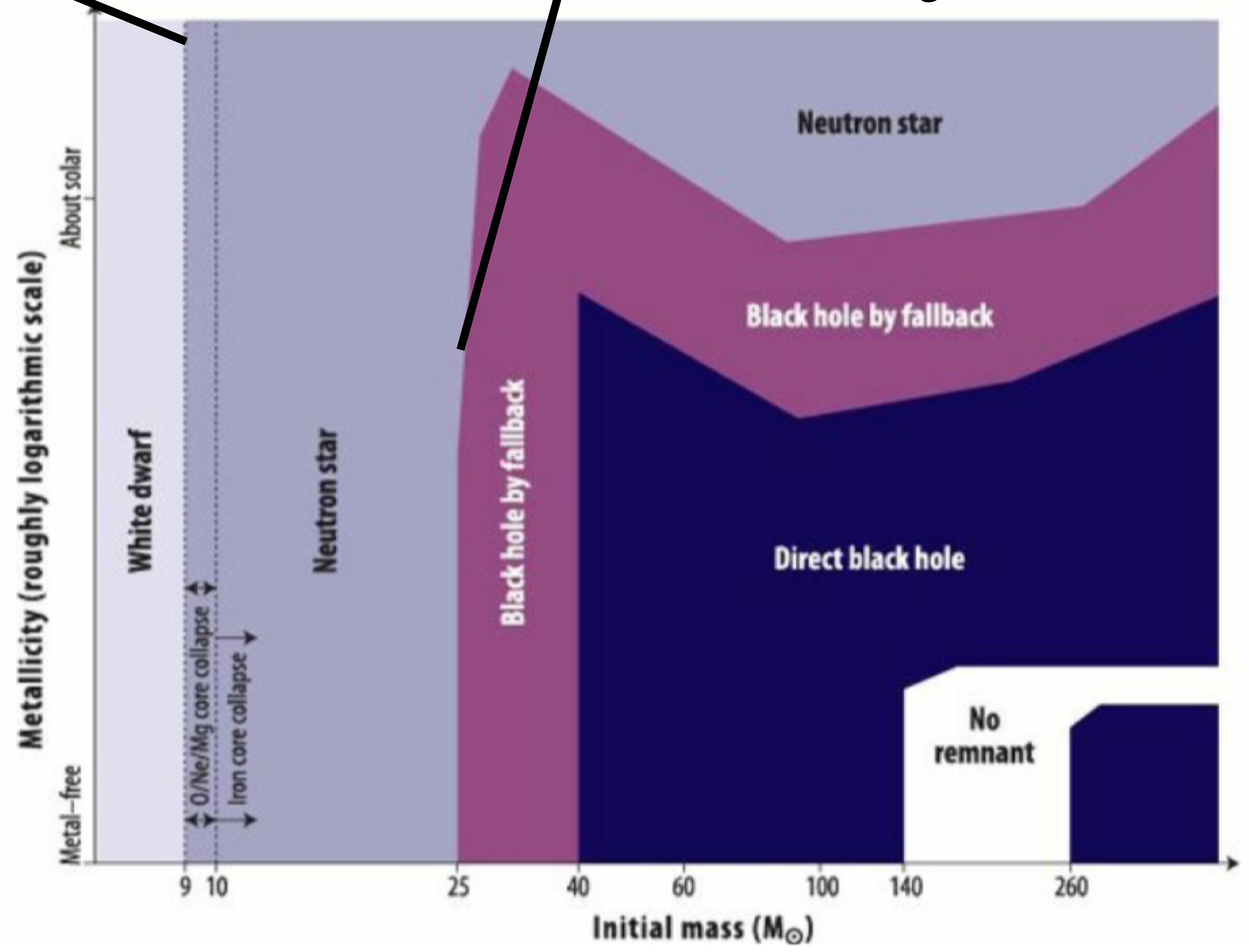


$M_1 = 1.51 - 2.52\ M_\odot$
$M_2 = 1.12 - 1.68\ M_\odot$

If BBH, stars cannot produce them.

1.4 $M_\odot$ (Chandrasekhar mass) 2~3 $M_\odot$ (Maximum mass of the NSs)

Final mass Heger et al. (2003)



$M_1 = 1.51 - 2.52\ M_\odot$

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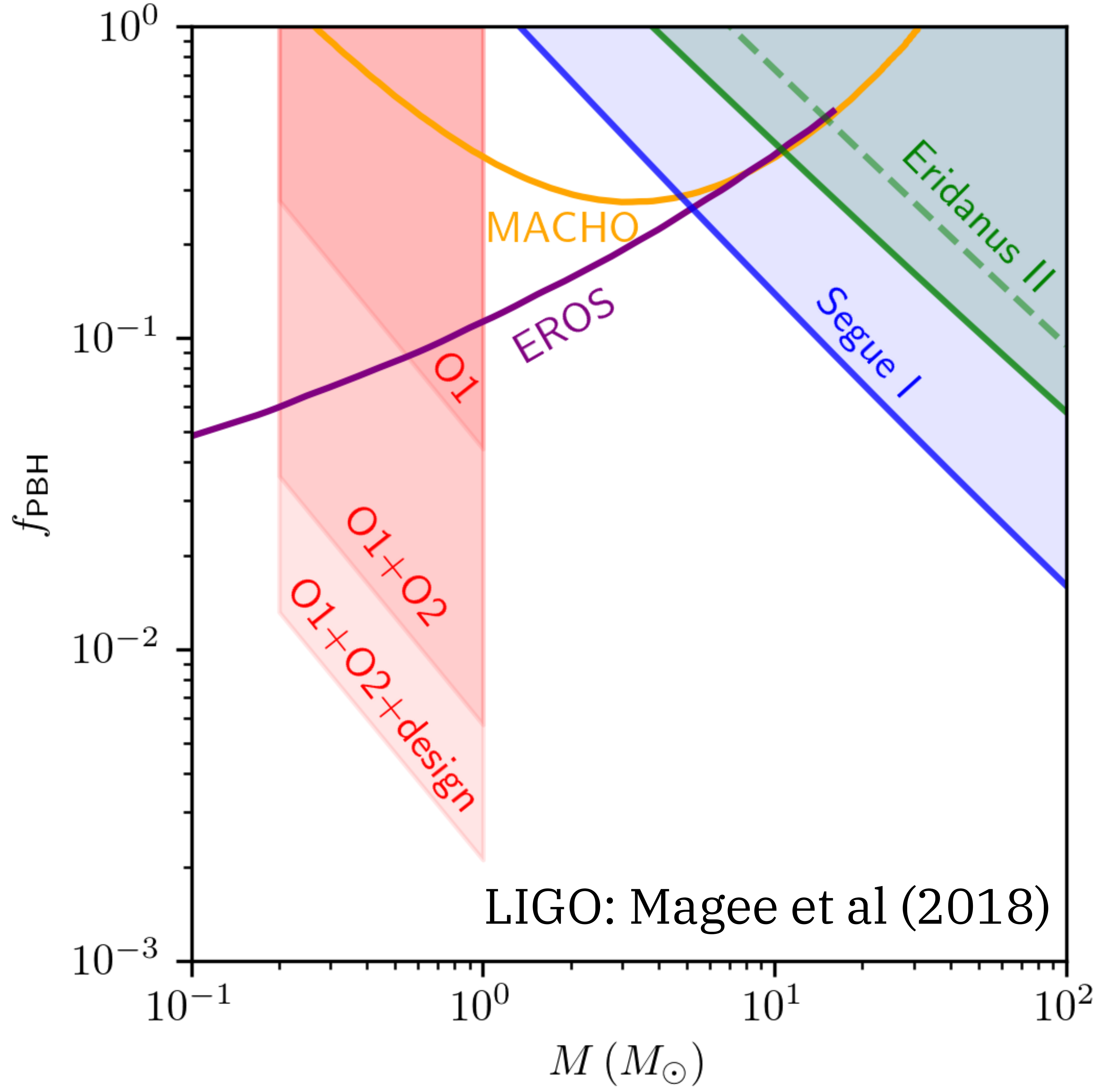
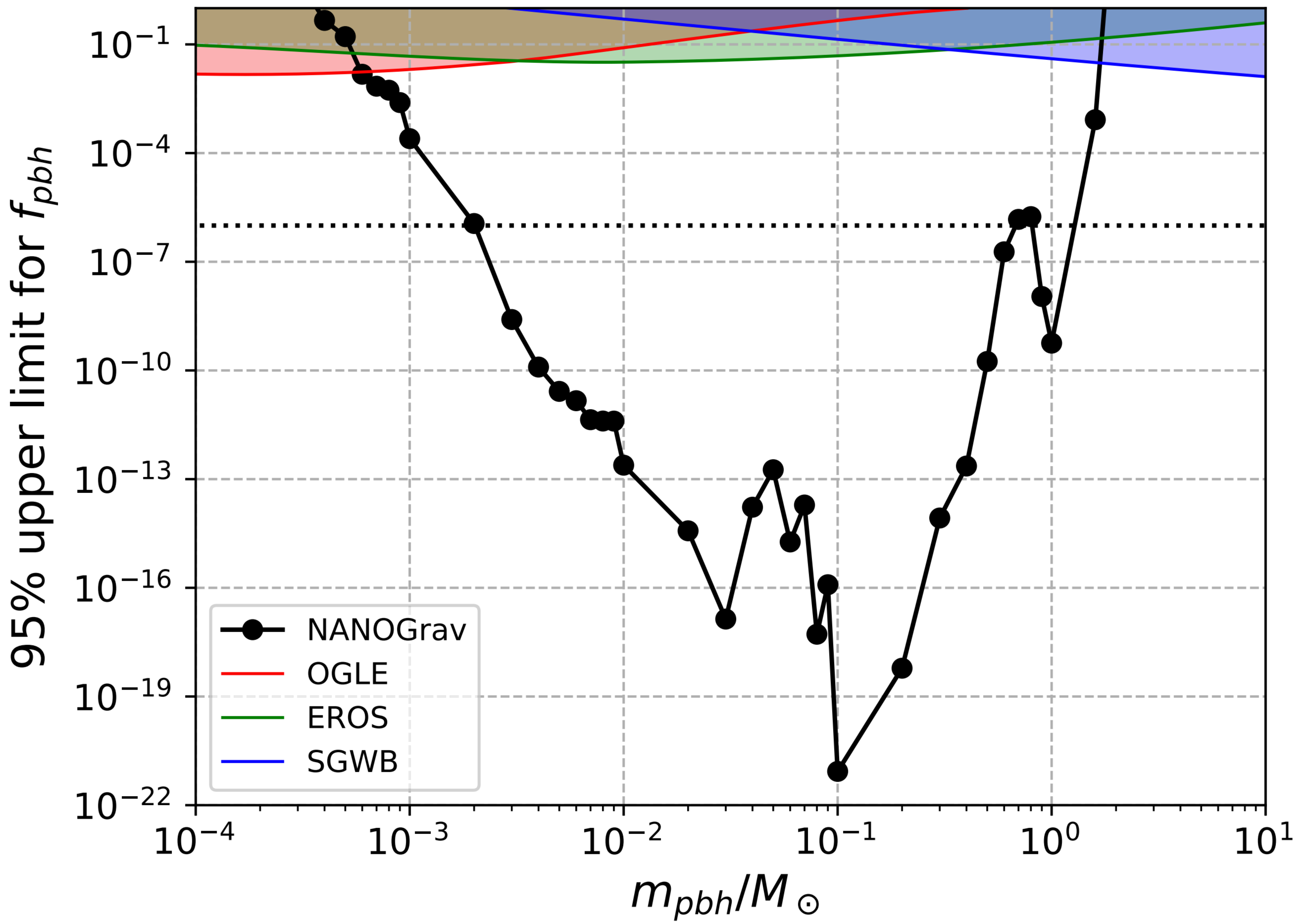
Can that be a PBH binary?

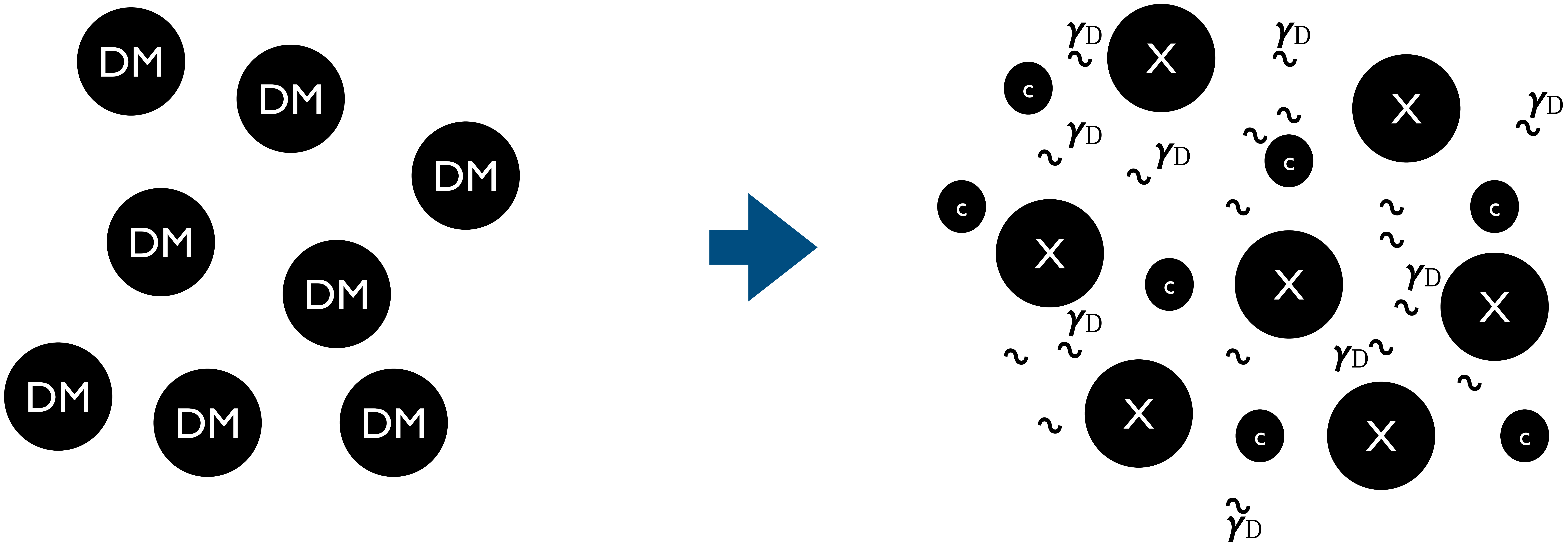


NANOGrav 11yr: Chen et al (2020)



New possibility: *Dark* Black holes!

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



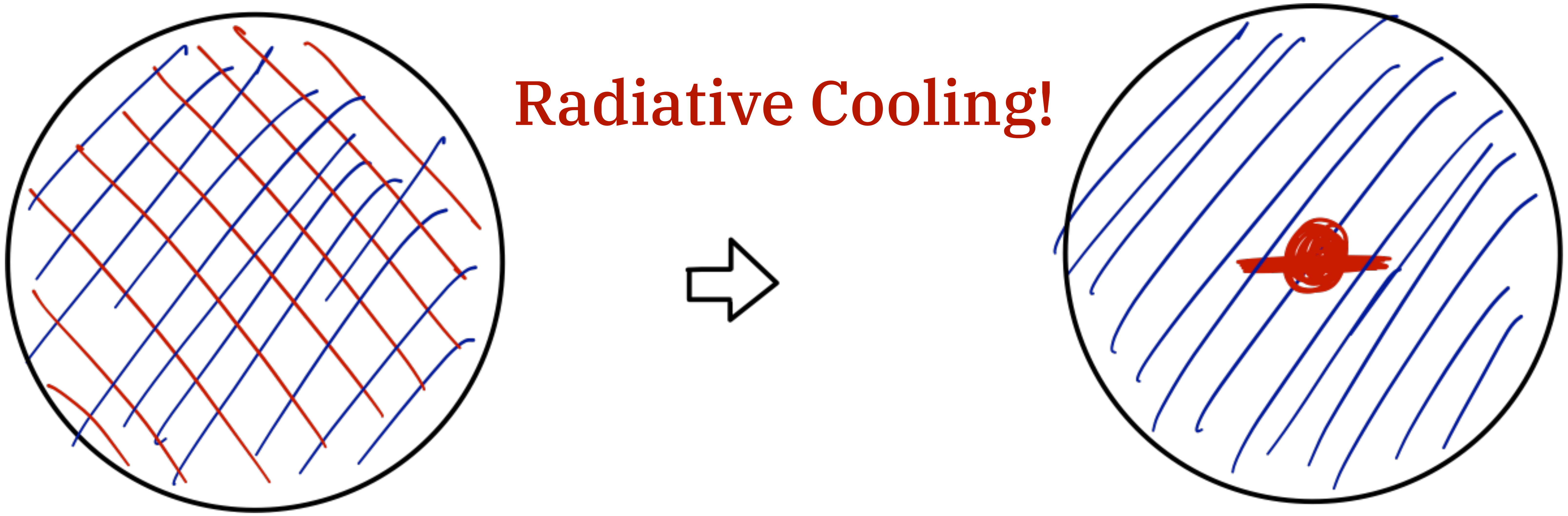
Boring single flavor

Three particle species

Simple set up: dark-sector particles

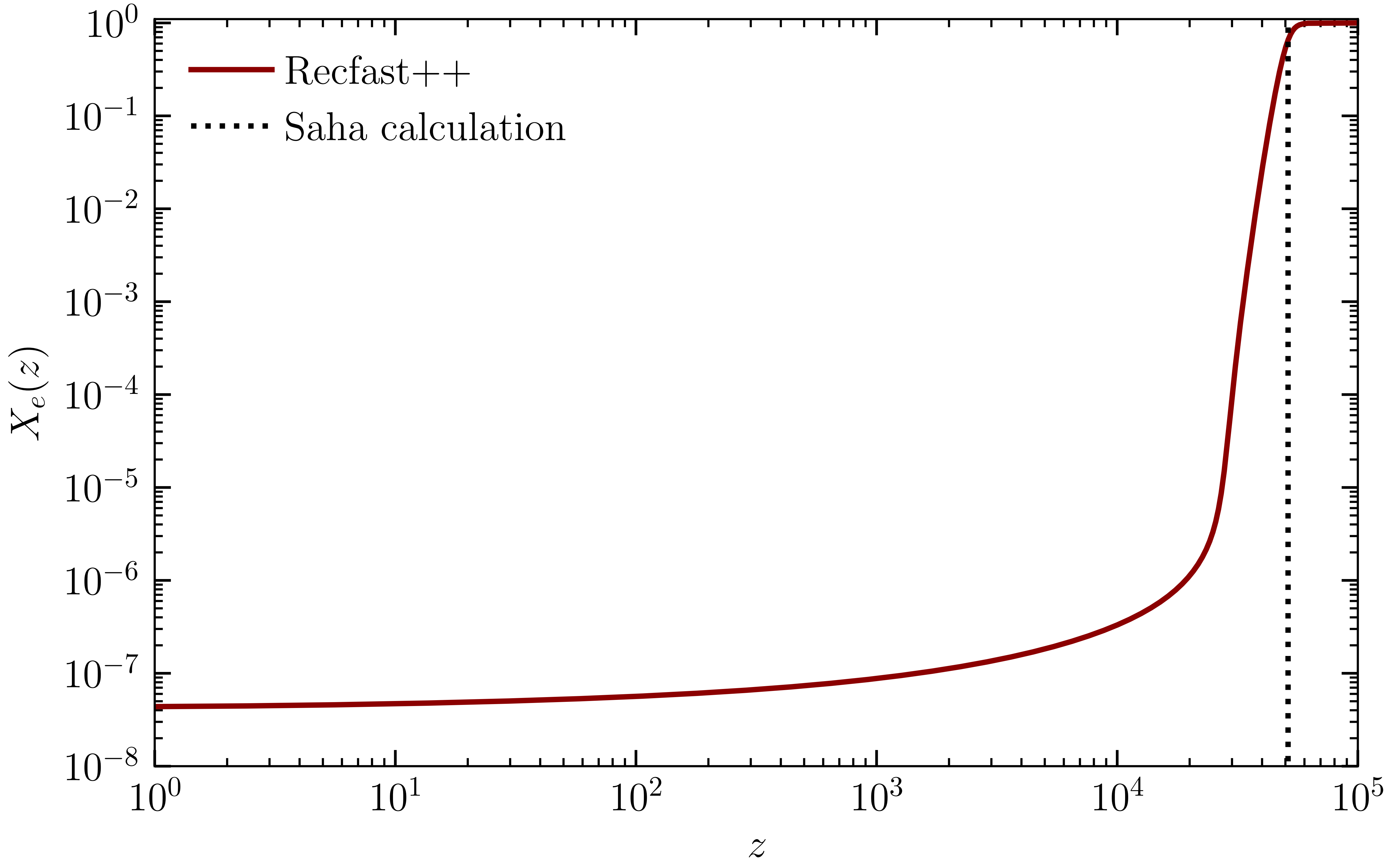
- In dark sector, we have
  - Dark proton (X)
  - Dark electron (c)
  - Dark radiation (γ_D)
- Free parameters in the theory: m_X, m_c, α_D (~1/137), $\xi (= T_D/T_\gamma)$
- With dark radiation, we have a variety of dark structures by ***energy dissipation***, including dark black holes.

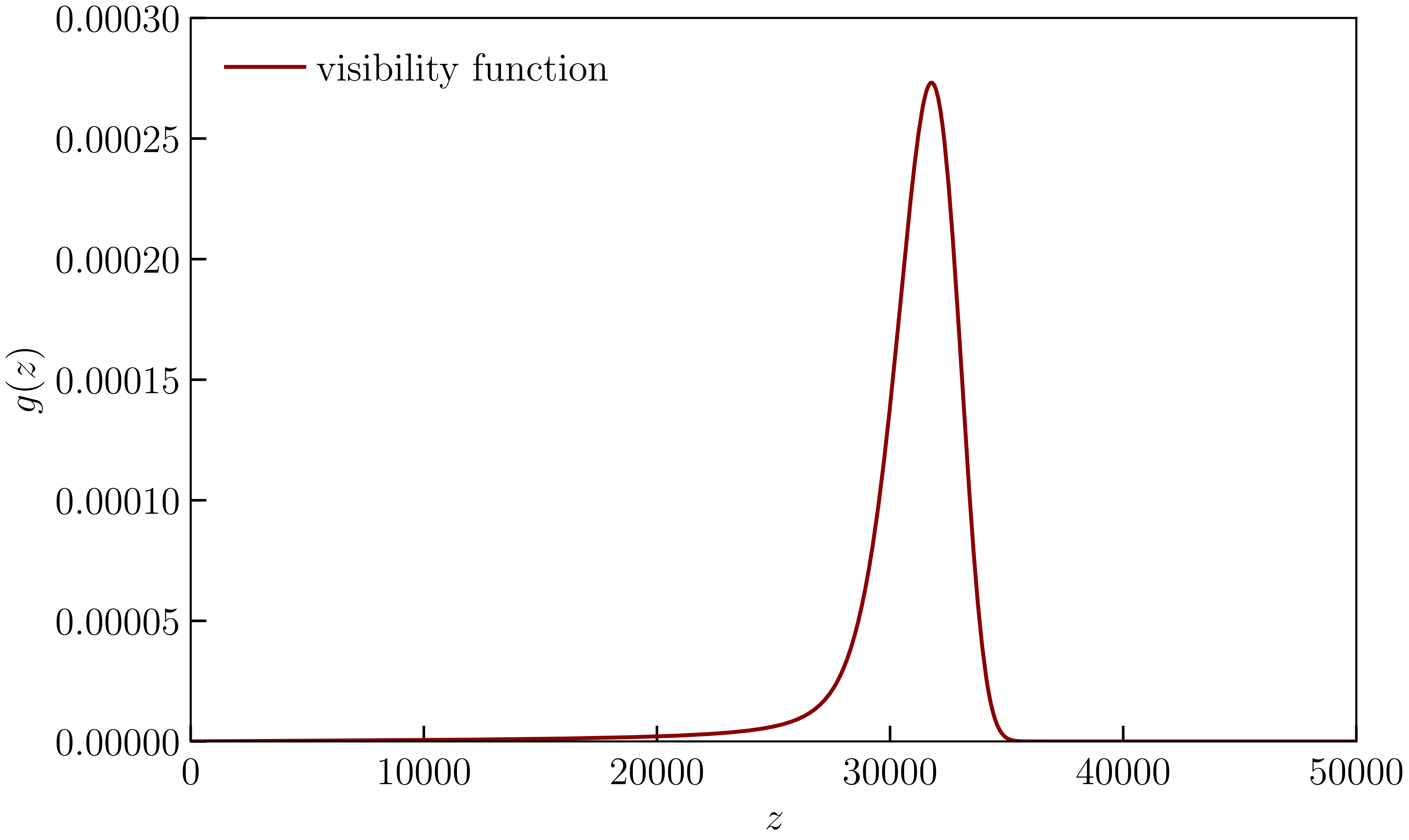
Dissipation and cosmic structures



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

Dark recombination & decoupling



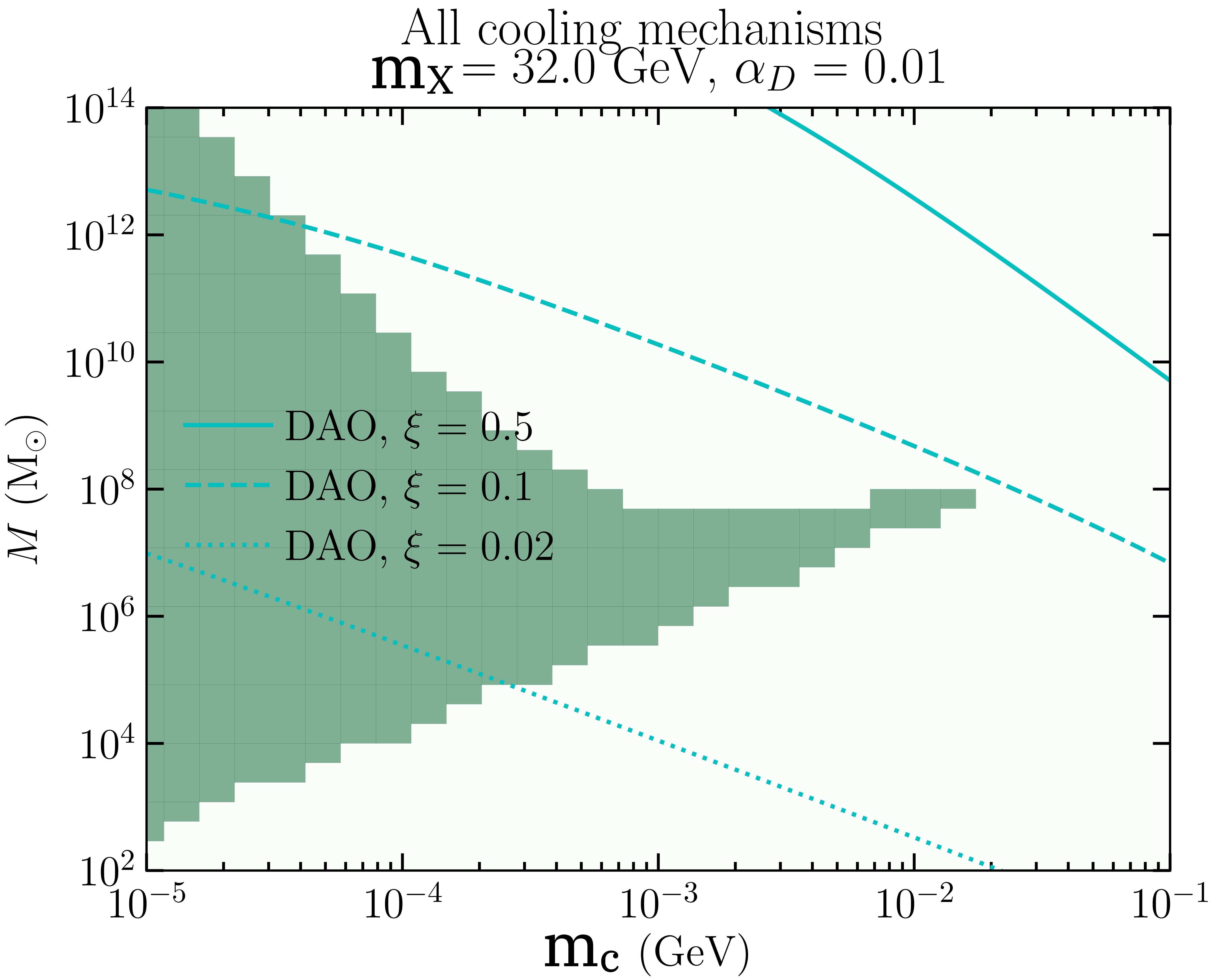


m_X=16 GeV, m_c=140 keV, T_D=0.02 T_{CMB} case

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

Buckley & DiFranzo (2018)

DO NOT spoil large-scale structure



- With U(1)-DM, dark matters can cool by usual processes
- 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

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

Chandrasekhar (1931)

- Opacity limit (minimum Jeans mass of fragmentation)

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

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

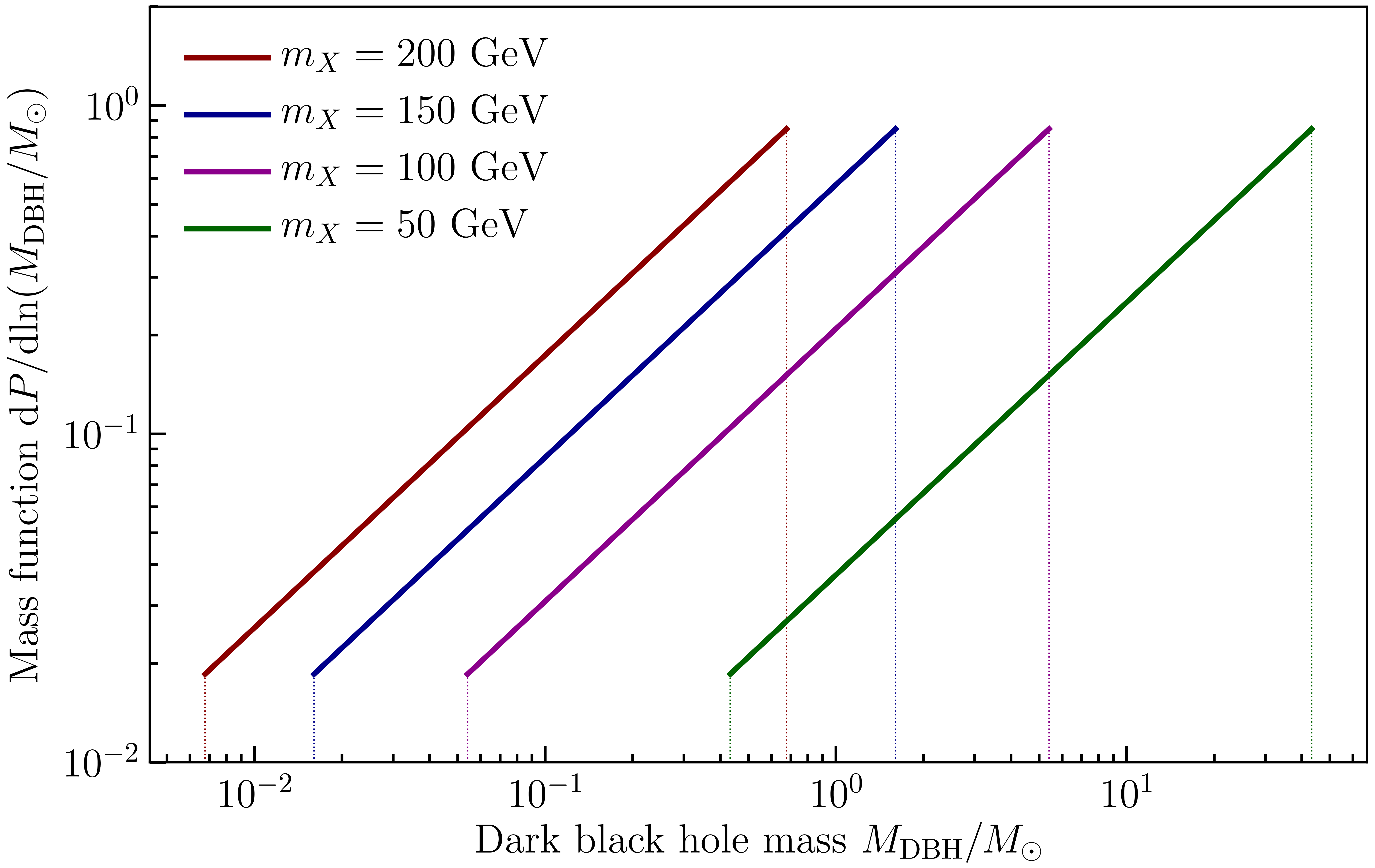
Dark star formation

- 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

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

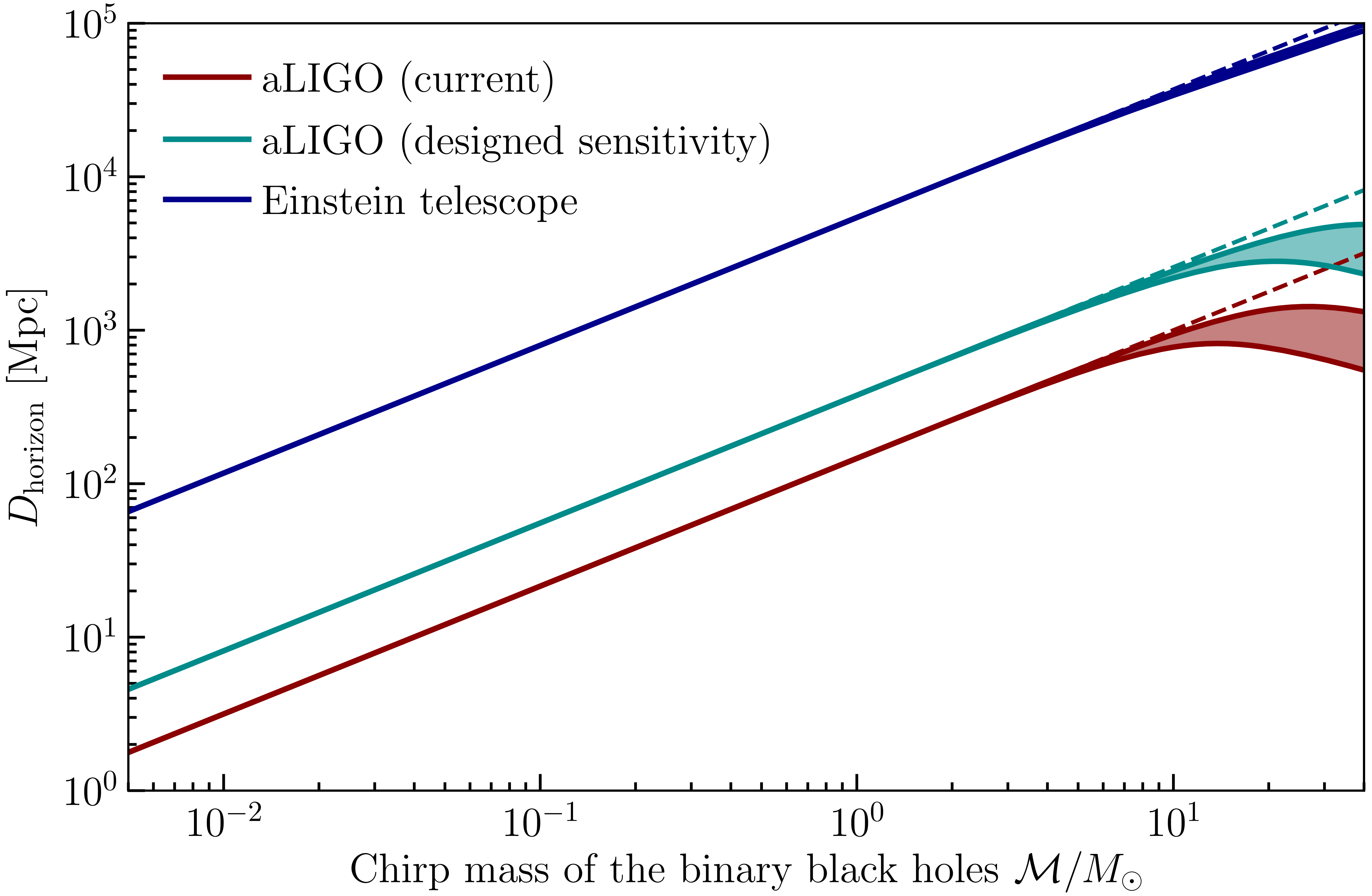
- DS formation is similar to Pop-III except for the energy gap.
- We, therefore, use the Pop-III binary literature extensively.

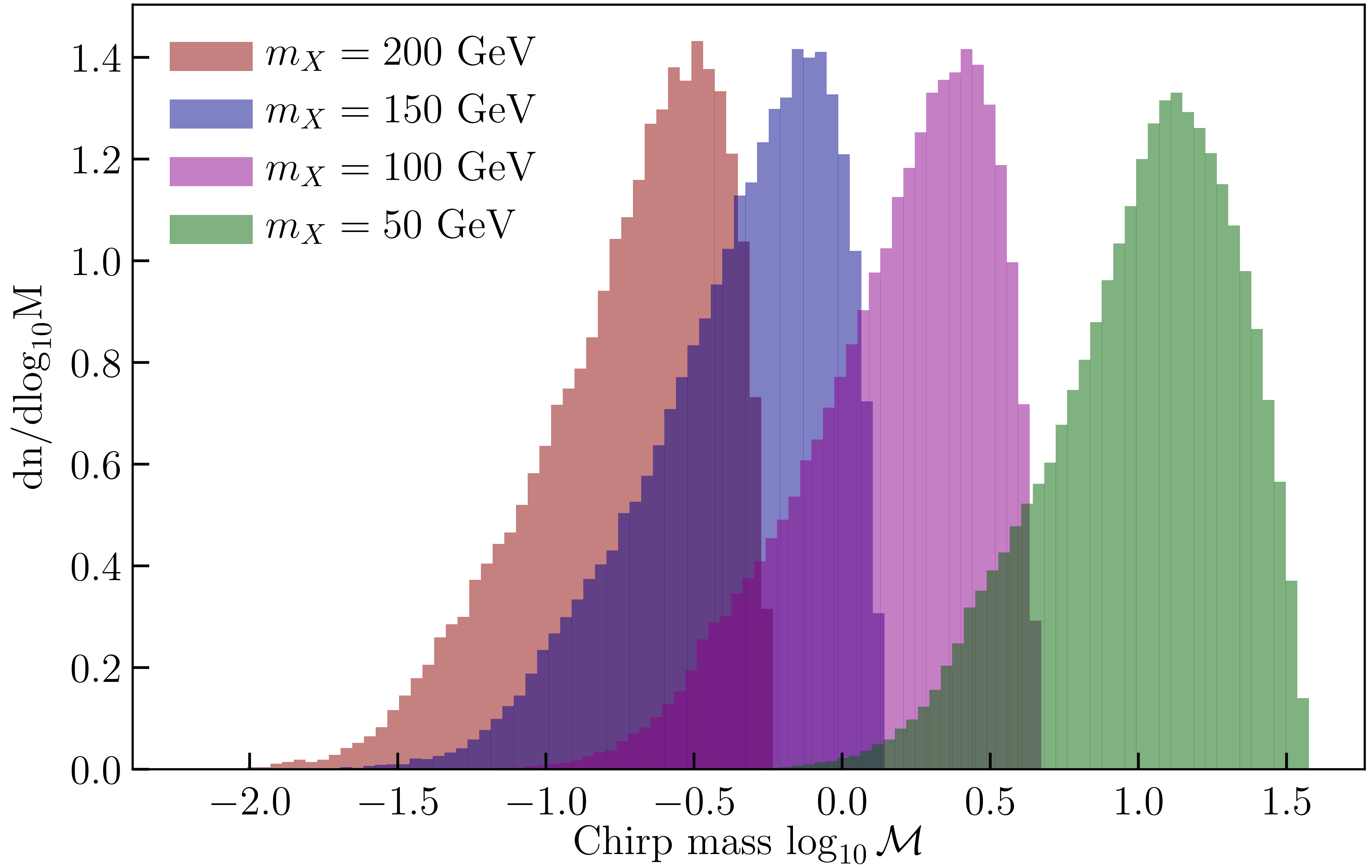
Dark BH mass function



Horizon radius (8σ-detection limit)

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





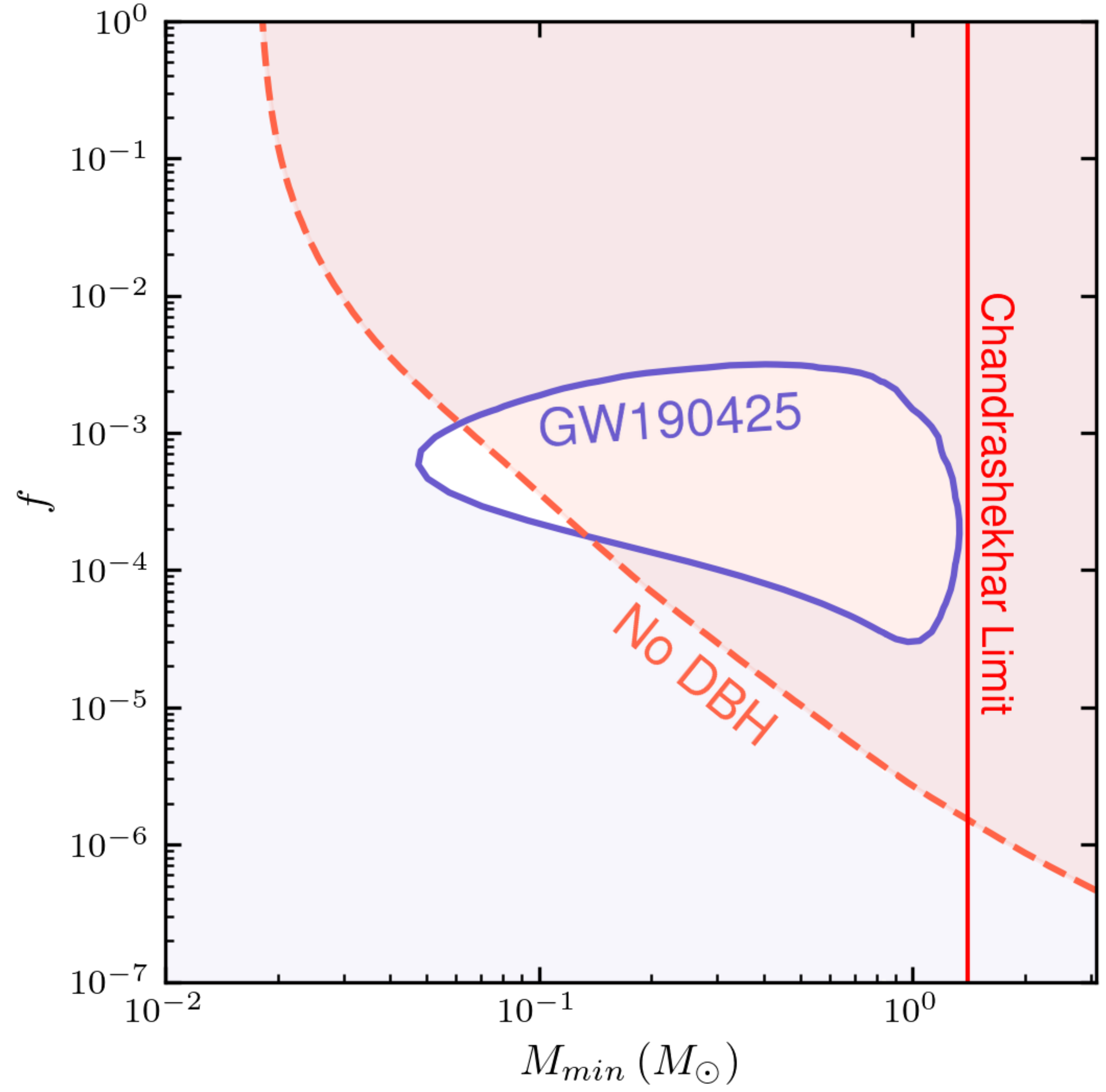
The rates are encouraging!

m_X [GeV]	m_c [keV]	$M^{\rm dark}_{\rm Chand.}$ $[10^{-5} M_\odot]$	$M_{\rm DBH}$ $[M_\odot]$	Rates per year				$m_1 < 1.4$	$m_1, m_2 < 1.4$
				raw ($\rm MWEG^{-1}$)	aLIGO (current)	aLIGO (full)	Einstein T.	[%]	[%]
200	10	3	$0.0068 - 0.68$	$2.0\times10^{-6}(10^{-4})$	0.0012 (0.12)	0.020 (2.0)	60 (6000)	100%	100%
150	14	5.7	$0.016 - 1.6$	$1.3\times10^{-6}(10^{-4})$	0.0065 (0.65)	0.11 (11)	330 (33k)	99%	79%
100	21	13	$0.054 - 5.4$	$6.6\times10^{-7}(10^{-5})$	0.068 (6.8)	1.1 (110)	3500 (350k)	53%	9.3%
50	42	500	$0.43 - 43$	$1.9\times10^{-7}(10^{-5})$	0.89 (89)	22 (2200)	92k (9200k)	9.8%	0.14%

$f_{\rm DBH}$ = fraction of DBHs in total DM

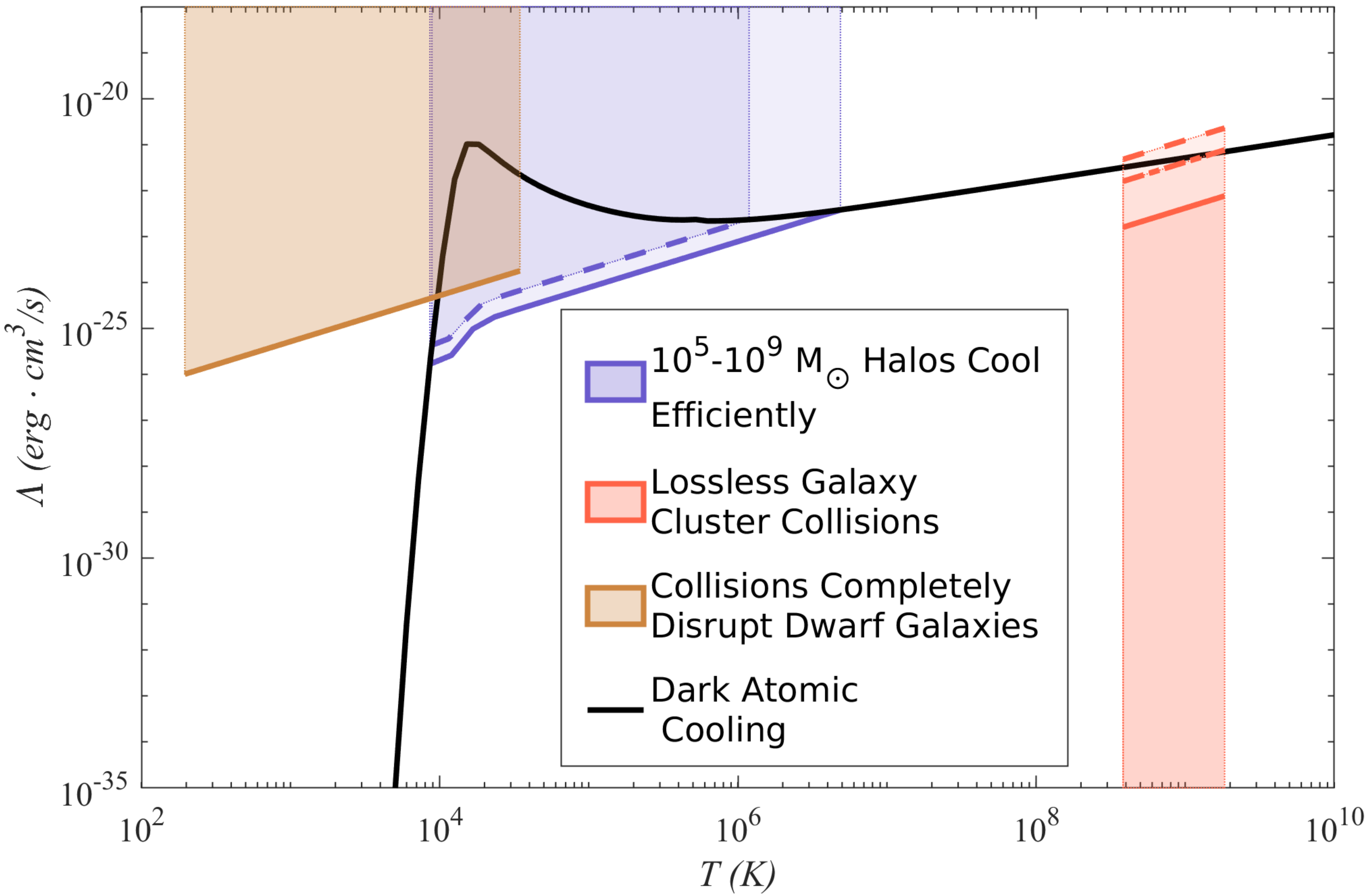
conservative (Optimistic) = 10^{-5} (10^{-3})

Implication of GW190425



- If GW190425 is a Dark-BH binary, the dark Chandrasekhar mass is less than 1.4 $M_{\odot}$ (99.9% C. L.); 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.

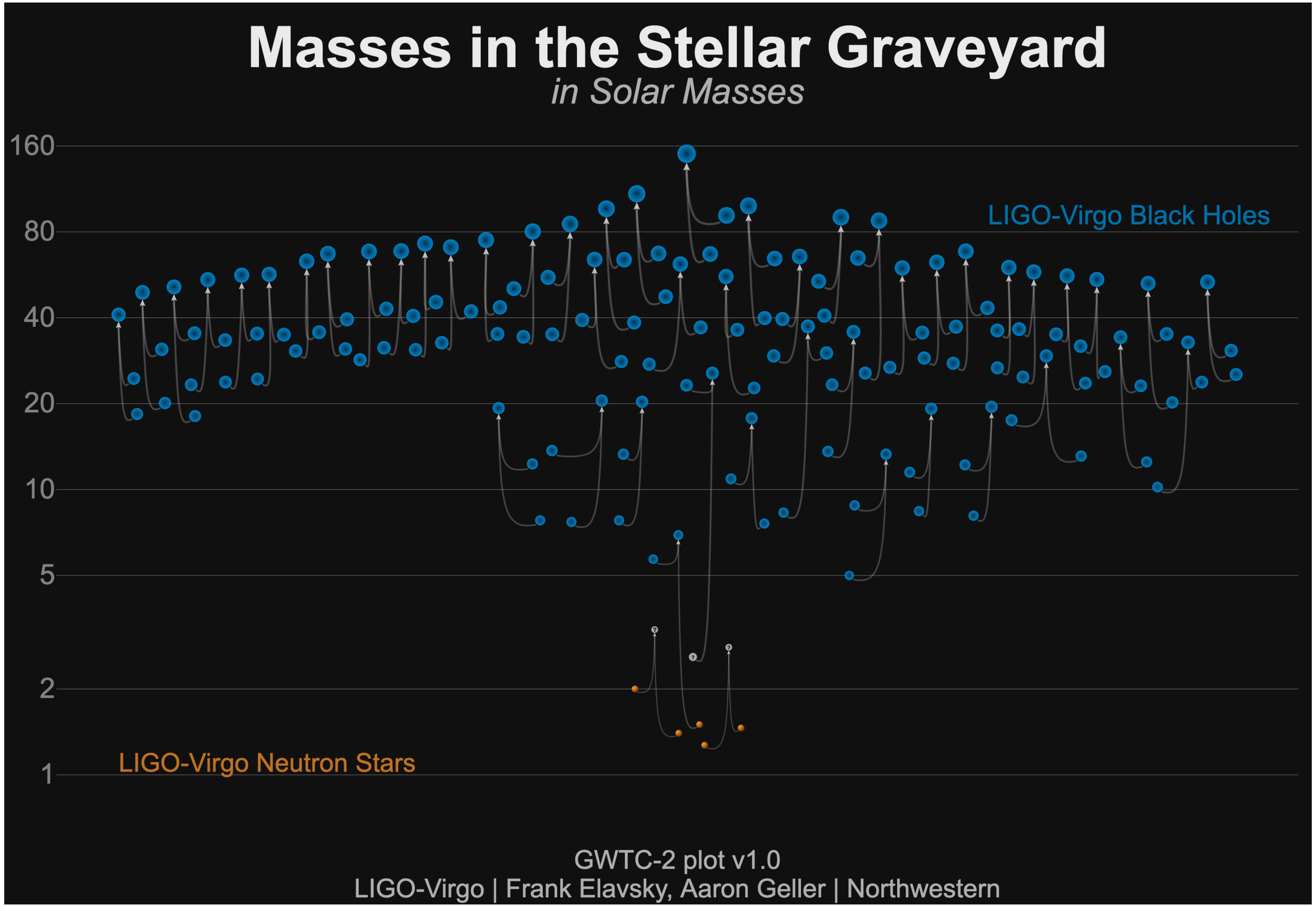
Constraints on *dark* cooling function



Conclusion

- GW provides an exciting new avenue for studying dark matter.
- This uses the only guaranteed property of dark matter: gravity!
- If GW190425 is a dark-BH binary, <u>dark proton mass must be heavier than the proton</u>.
- Combined with other astronomical constraints, we can also constrain the *dark* cooling function.
- Sub-solar mass search ongoing in LIGO/Virgo collaboration.

To do next: include all O3a events



O1+O2+O3a