

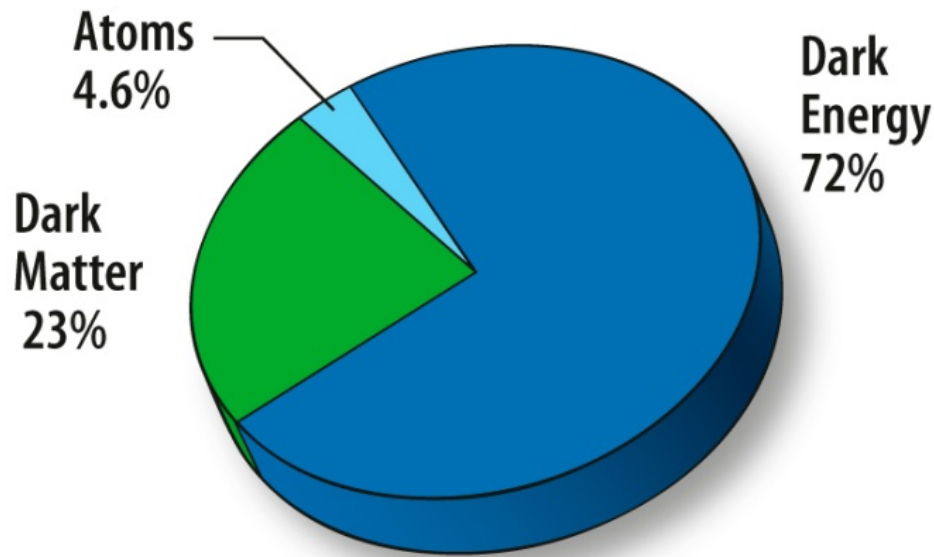
Searching for dark-matter black holes from LVK gravitational-wave detectors

Donghui Jeong
(Penn State / KIAS)

ASIAA Colloquium, 6 December 2023

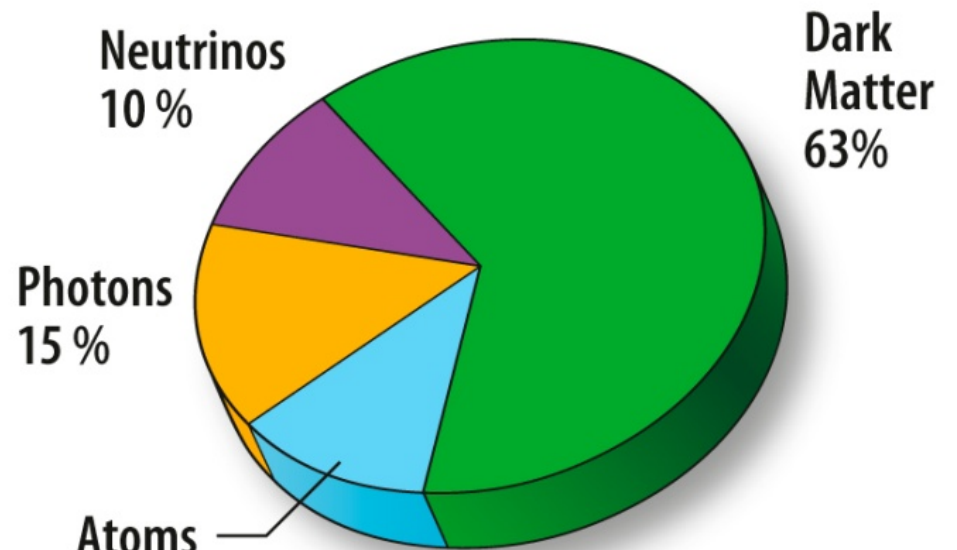
Our Physical Cosmology

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



TODAY

Source: NASA/WMAP science team



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

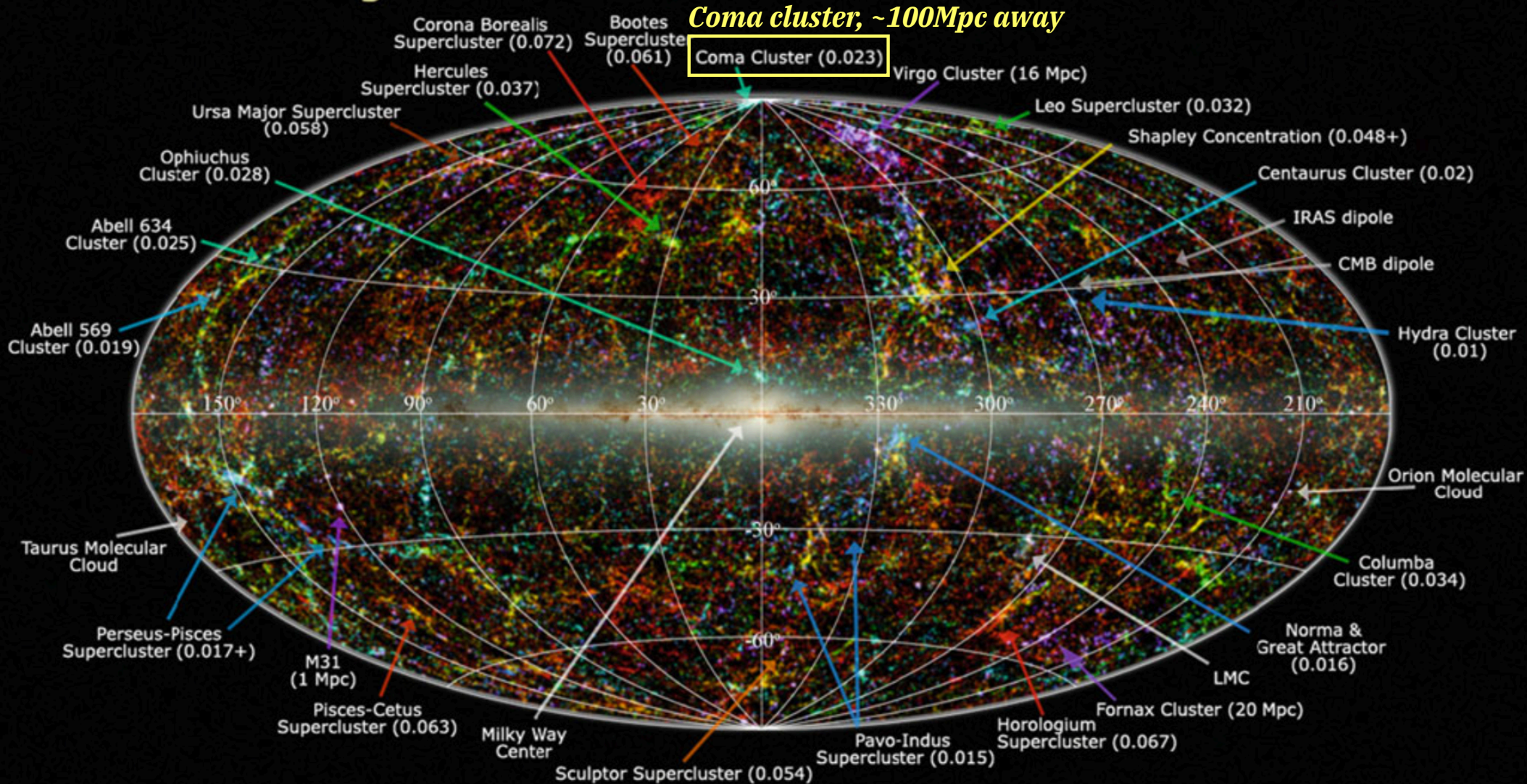
Zwicky on Coma cluster, 1932



Large Scale Structure in the Local Universe

Coma cluster, ~100Mpc away

Coma Cluster (0.023)



Zwicky on Coma cluster, 1932



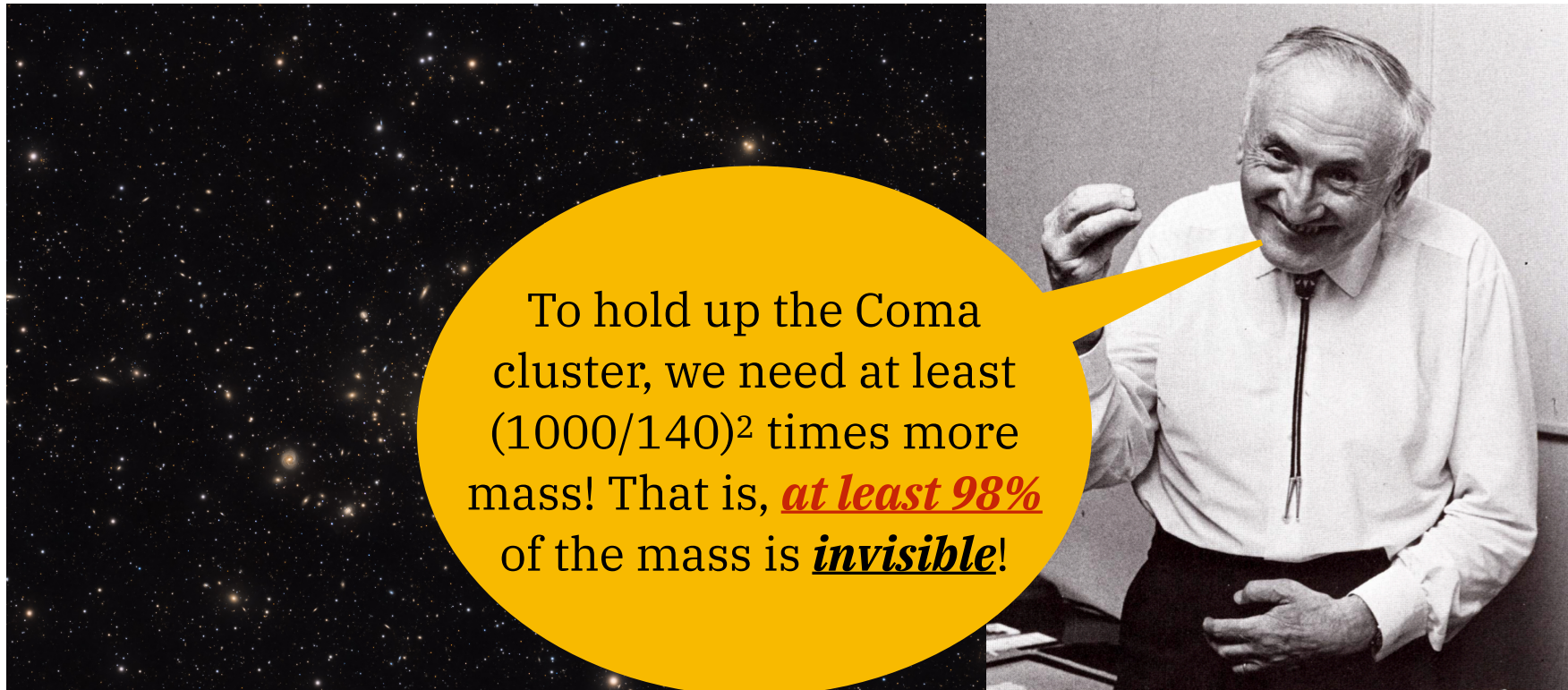
- Numbers for Coma
 - >10,000 galaxies!!
 - Size ~ 6 Mpc $\sim 2 \times 10^{25}$ cm
 - $\sigma_v \sim 1000$ km/s
 - Crossing time $\sim 6 \times 10^9$ yrs!
 - Stellar mass $\sim 3 \times 10^{13} M_{\odot}$

Zwicky on Coma cluster, 1932



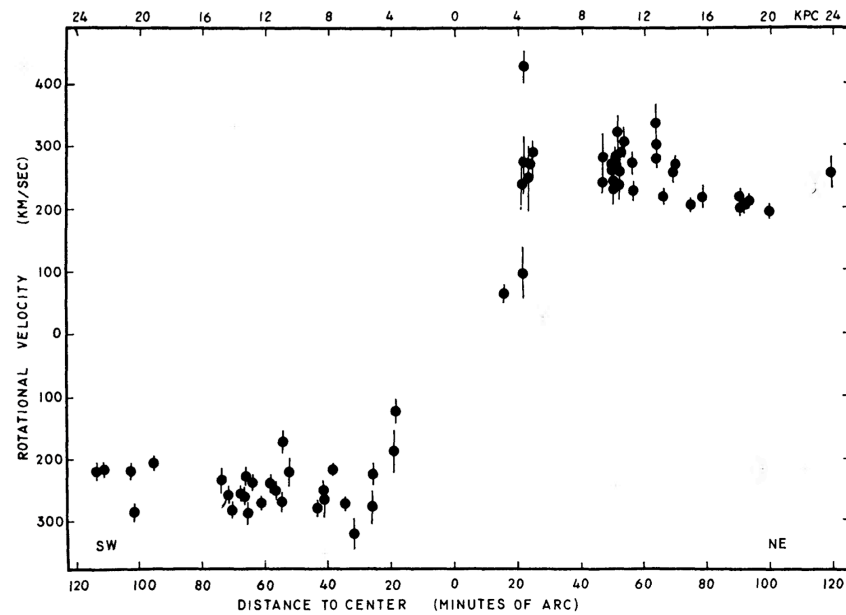
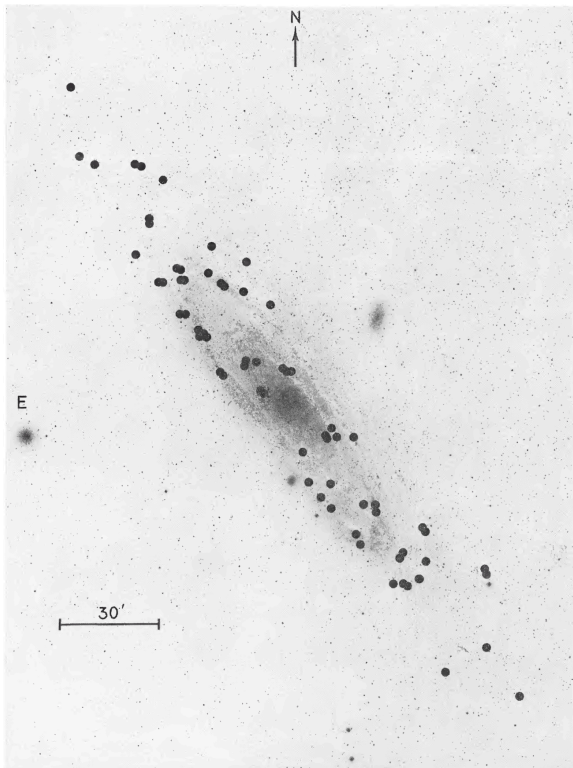
- Numbers for Coma
 - >10,000 galaxies!!
 - Size ~ 6 Mpc ~ 2×10^{25} cm
 - $\sigma_v \sim 1000$ km/s
 - Crossing time ~ 6×10^9 yrs!
 - Stellar mass ~ $3 \times 10^{13} M_{\odot}$
 - $V_{\text{esc}} \sim 140$ km/s!

Zwicky on Coma cluster, 1932

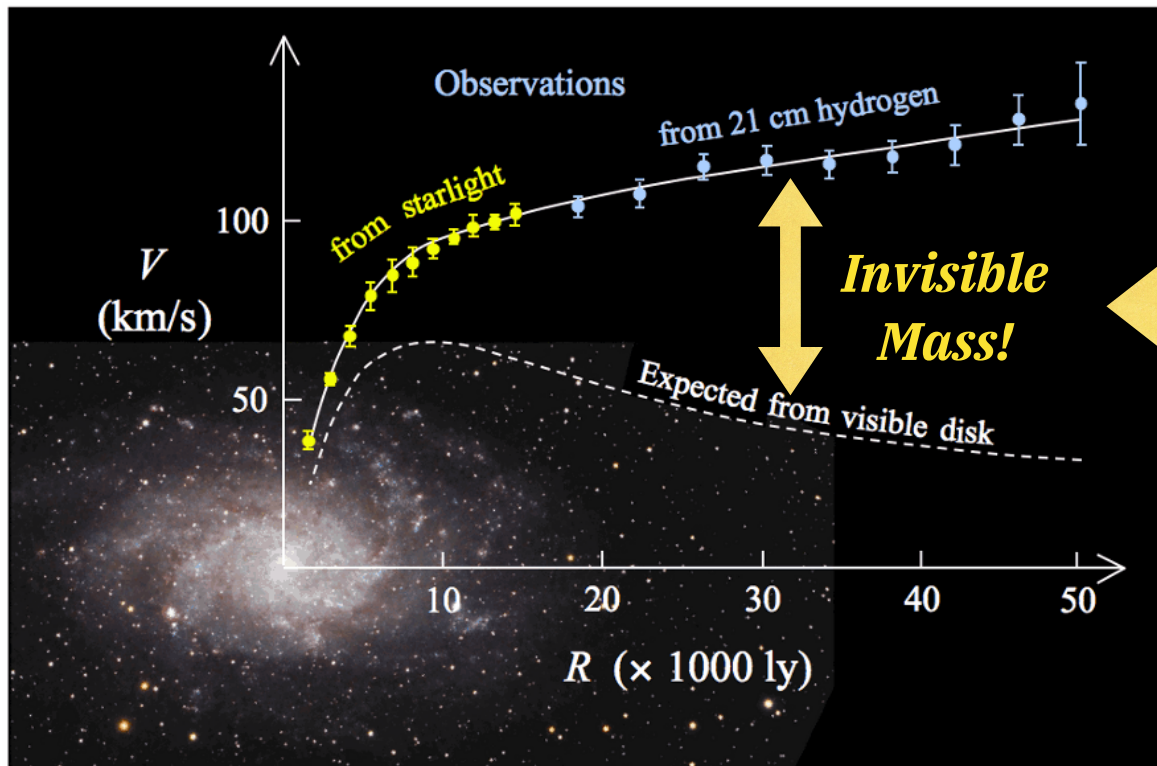


To hold up the Coma cluster, we need at least $(1000/140)^2$ times more mass! That is, *at least 98%* of the mass is *invisible!*

Vera Rubin on M31 (Andromeda), 1970



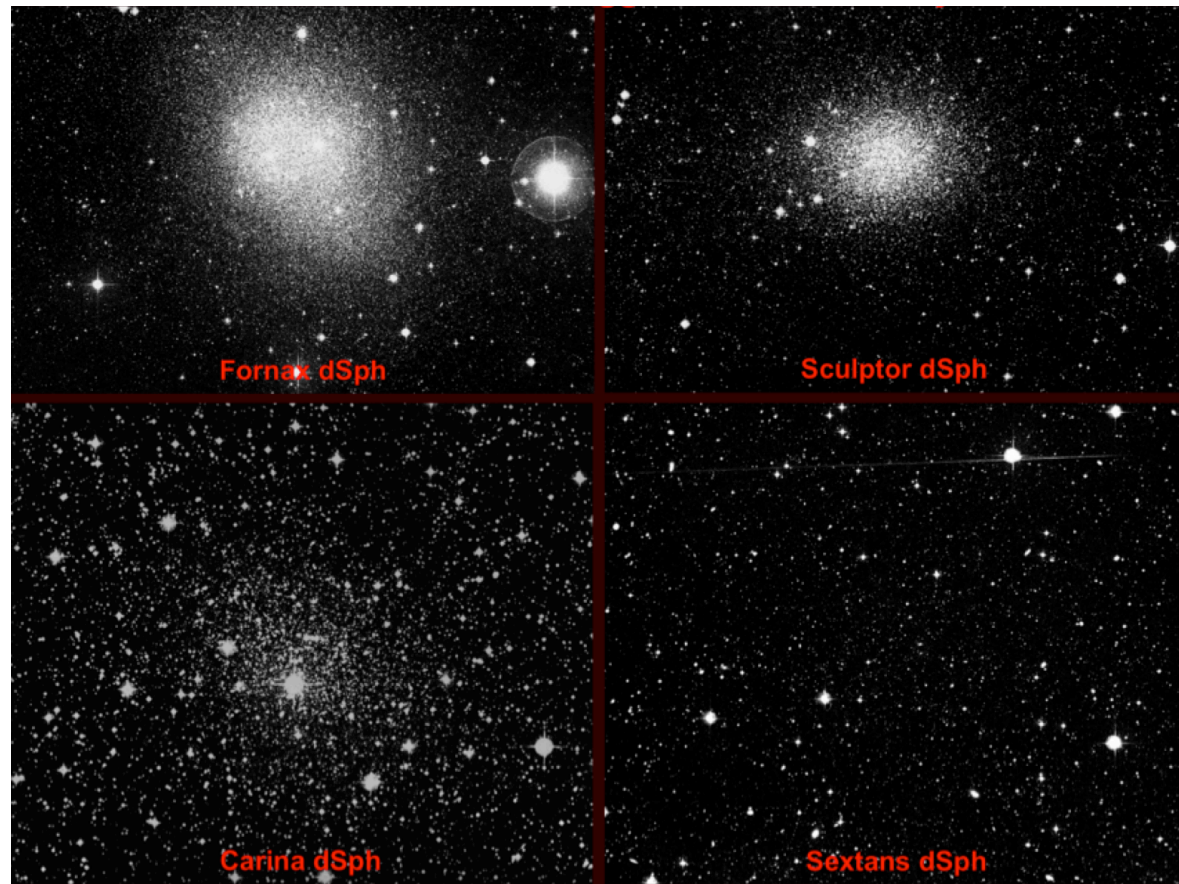
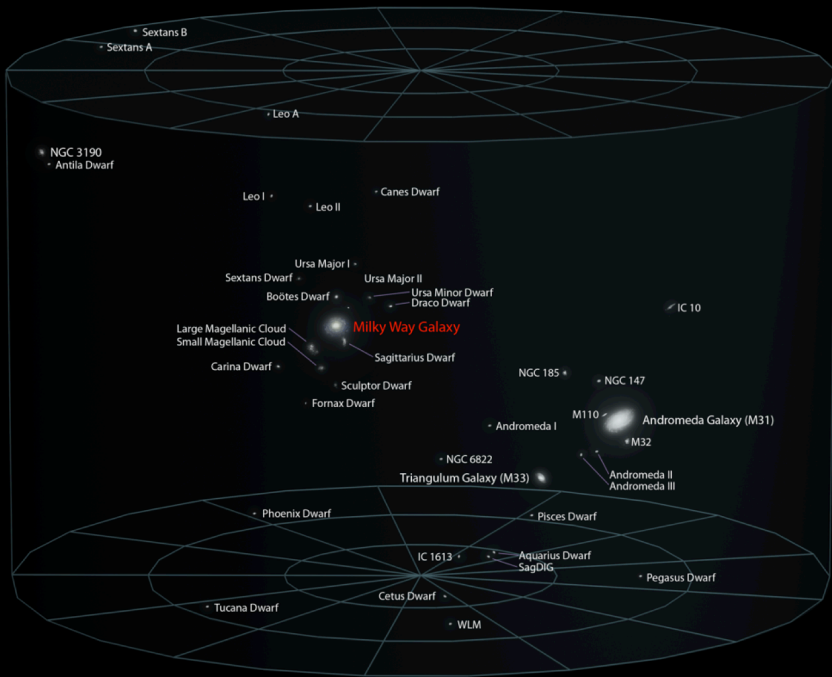
A modern rotation curve (for M33)



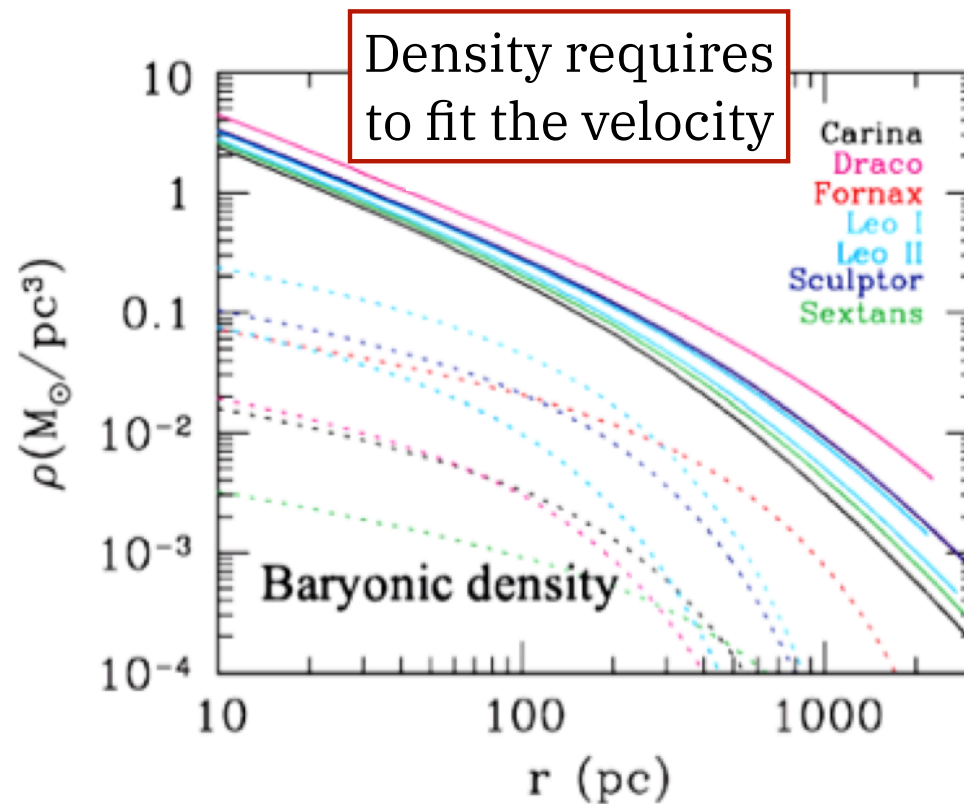
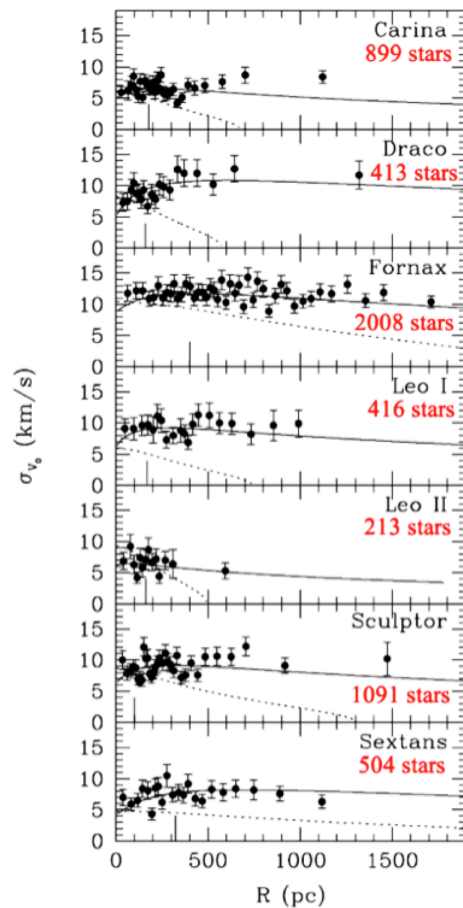
$$V(R) \propto \sqrt{\frac{GM(< R)}{R}}$$

What about local dwarfs galaxies?

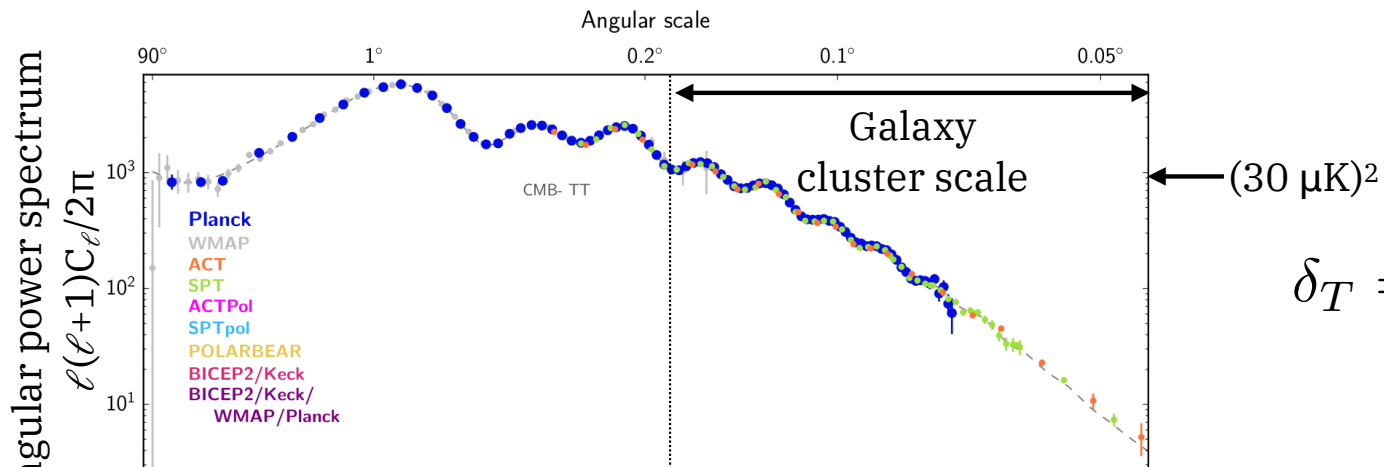
Local Galactic Group



The same; we need invisible mass!



Invisible mass, but not “baryonic”



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

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

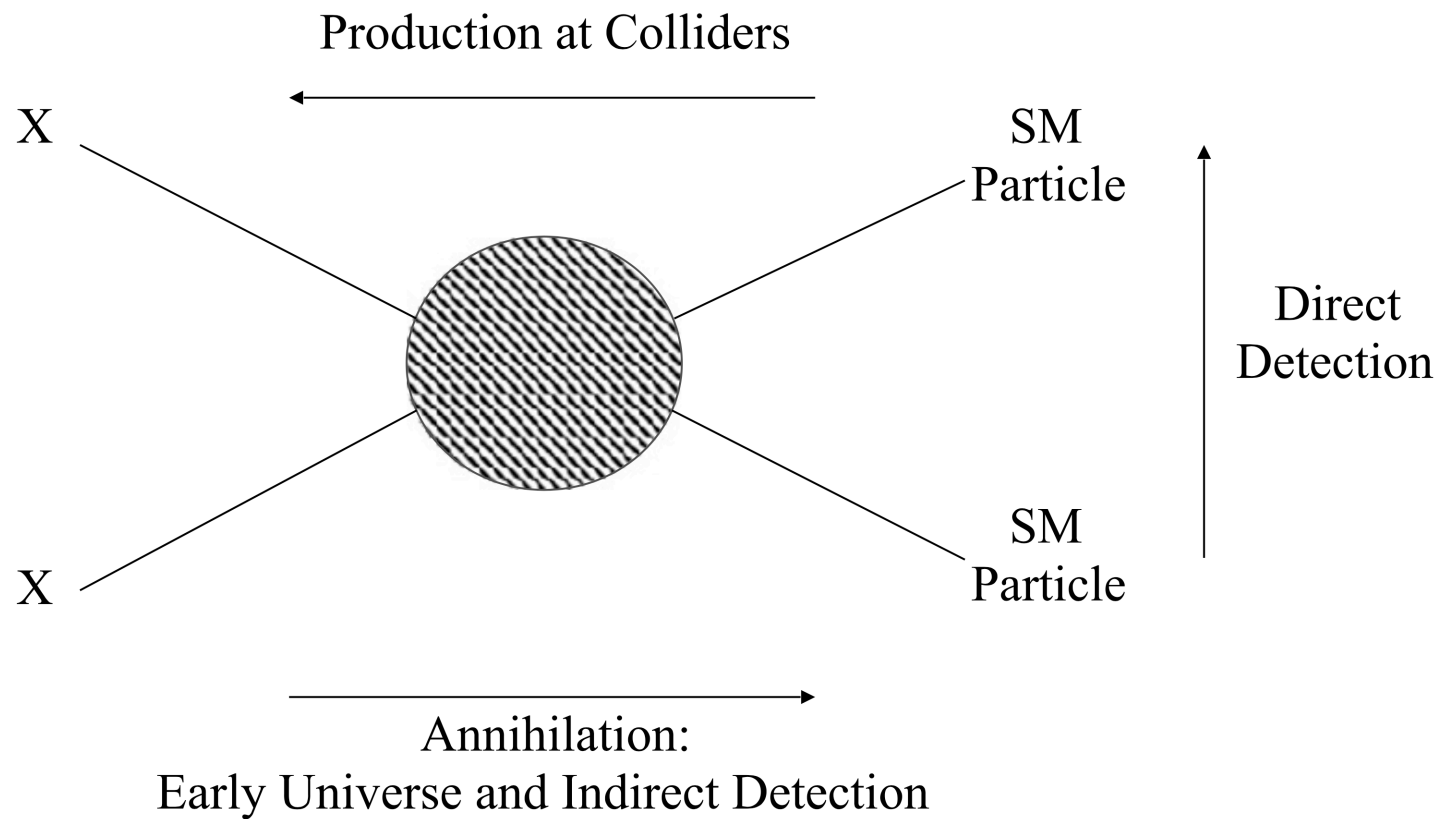
Another evidence: the Bullet cluster



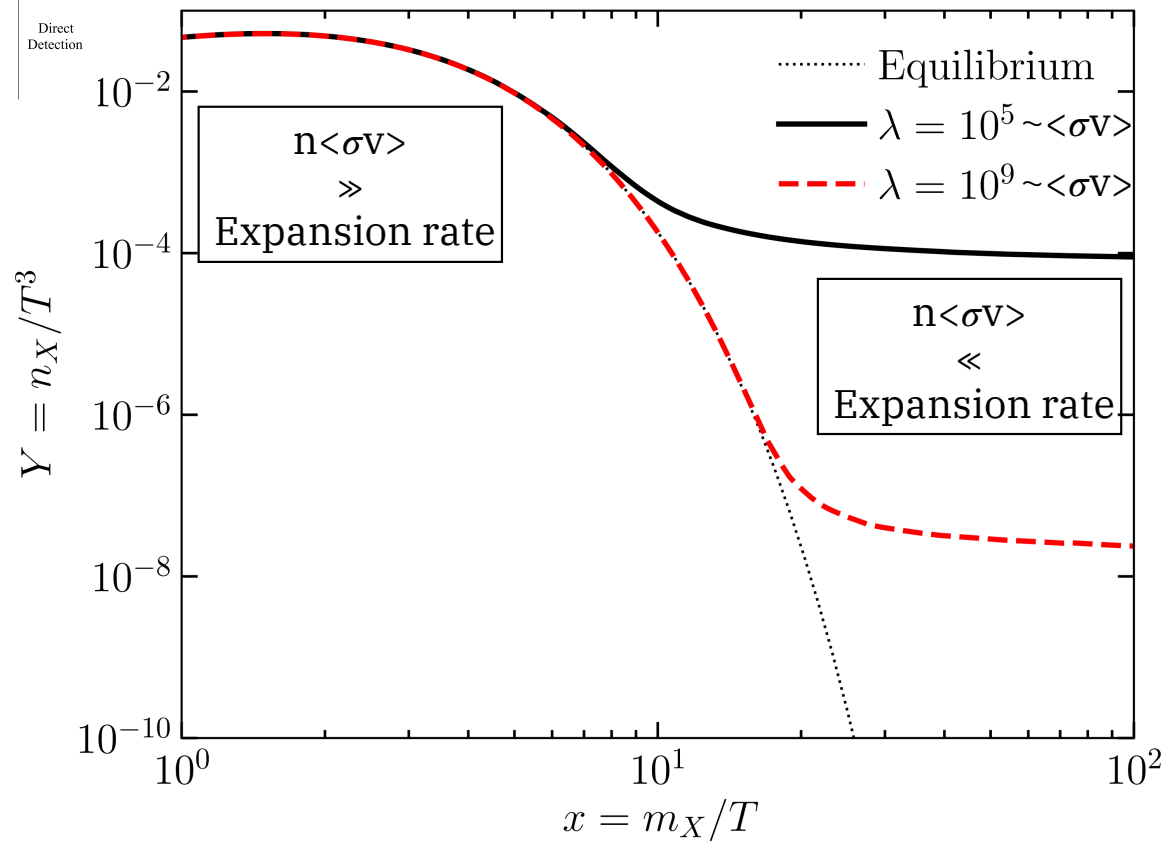
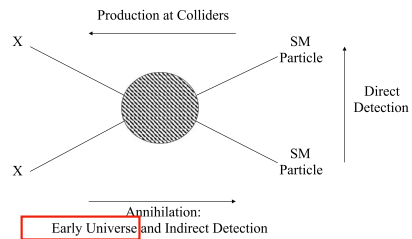
- Gas distribution
(X-ray from Chandra)
- Mass distribution
(gravitational lensing)

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

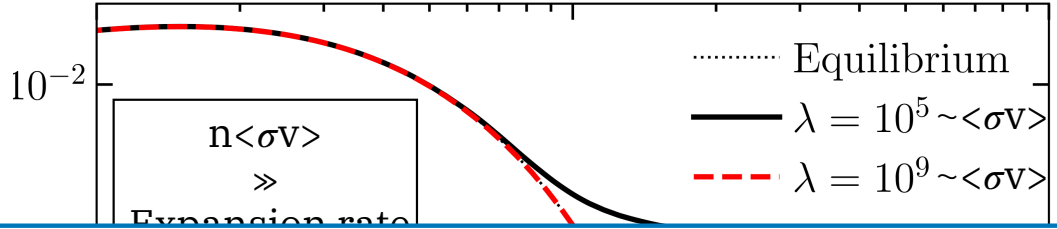
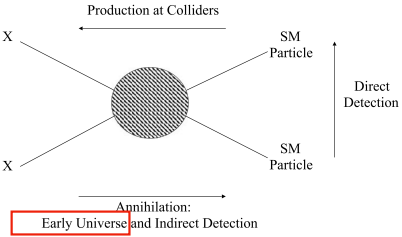
Can dark matter interact with SM?



Annihilation @ Early Universe



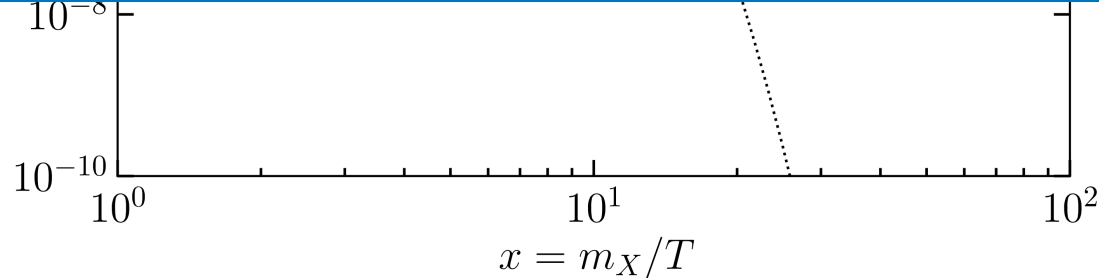
WIMP miracle!



$$\Omega_X h^2 = 0.1 \left(\frac{x_f}{20}\right) \left(\frac{g_*(m_X)}{100}\right)^{1/2} \frac{2 \times 10^{-26} \text{cm}^3 \text{sec}^{-1}}{\langle\sigma v\rangle}$$

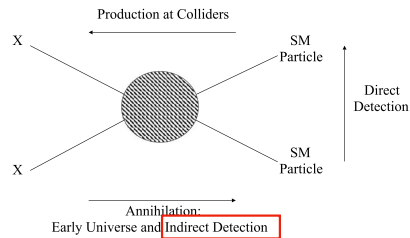
Cosmology

Particle physics

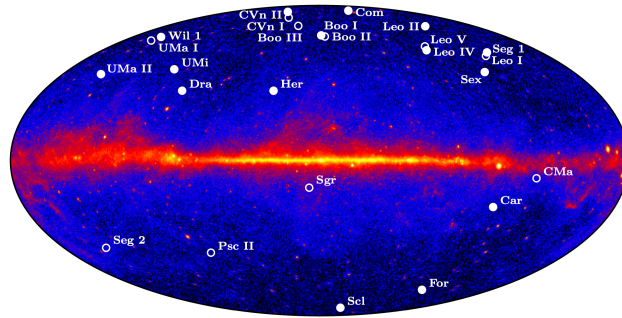


Annihilation signal now?

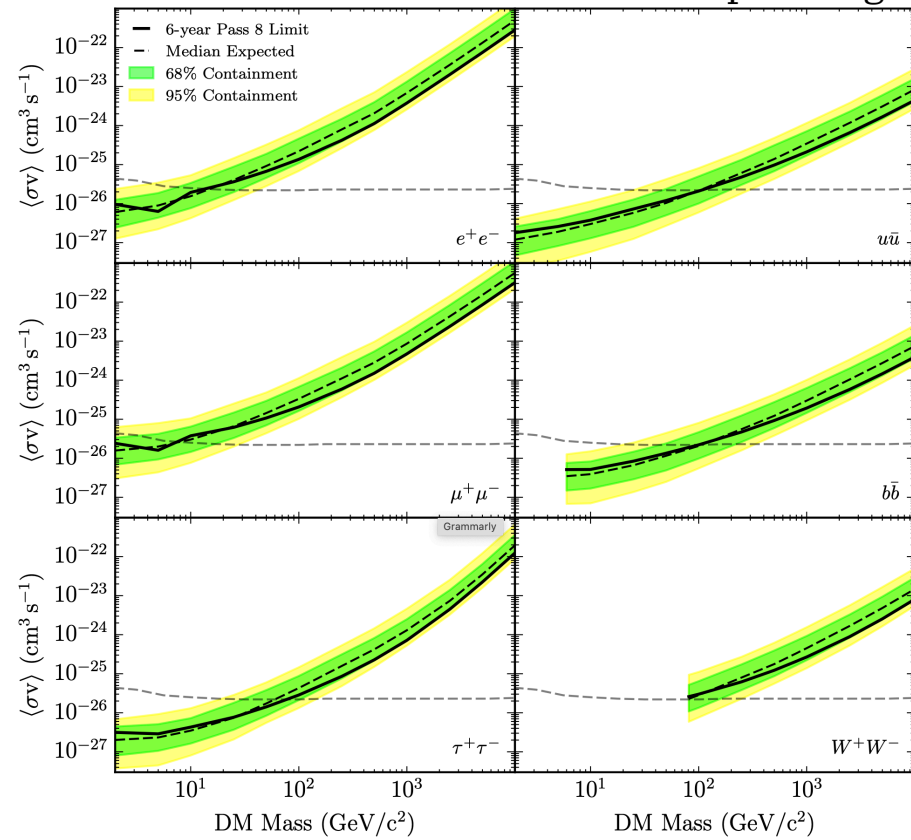
Solid = 15 dwarf galaxy stacked
Dashed = 300 random pointings



Fermi γ -ray telescope



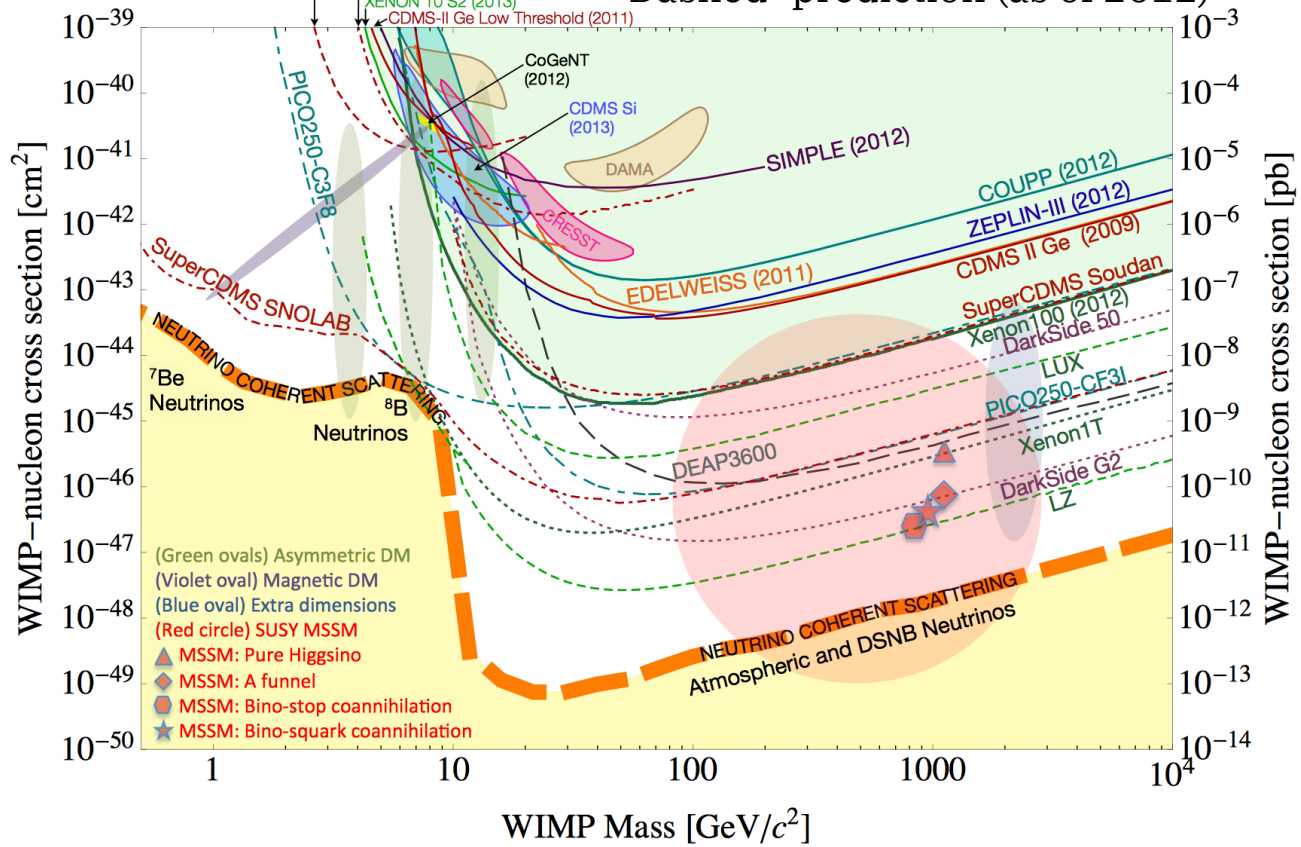
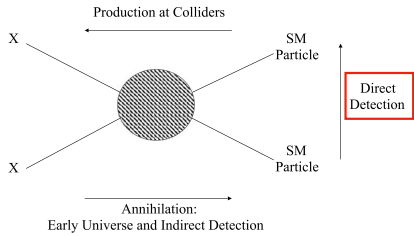
15 Milky-way satellite dwarf galaxies



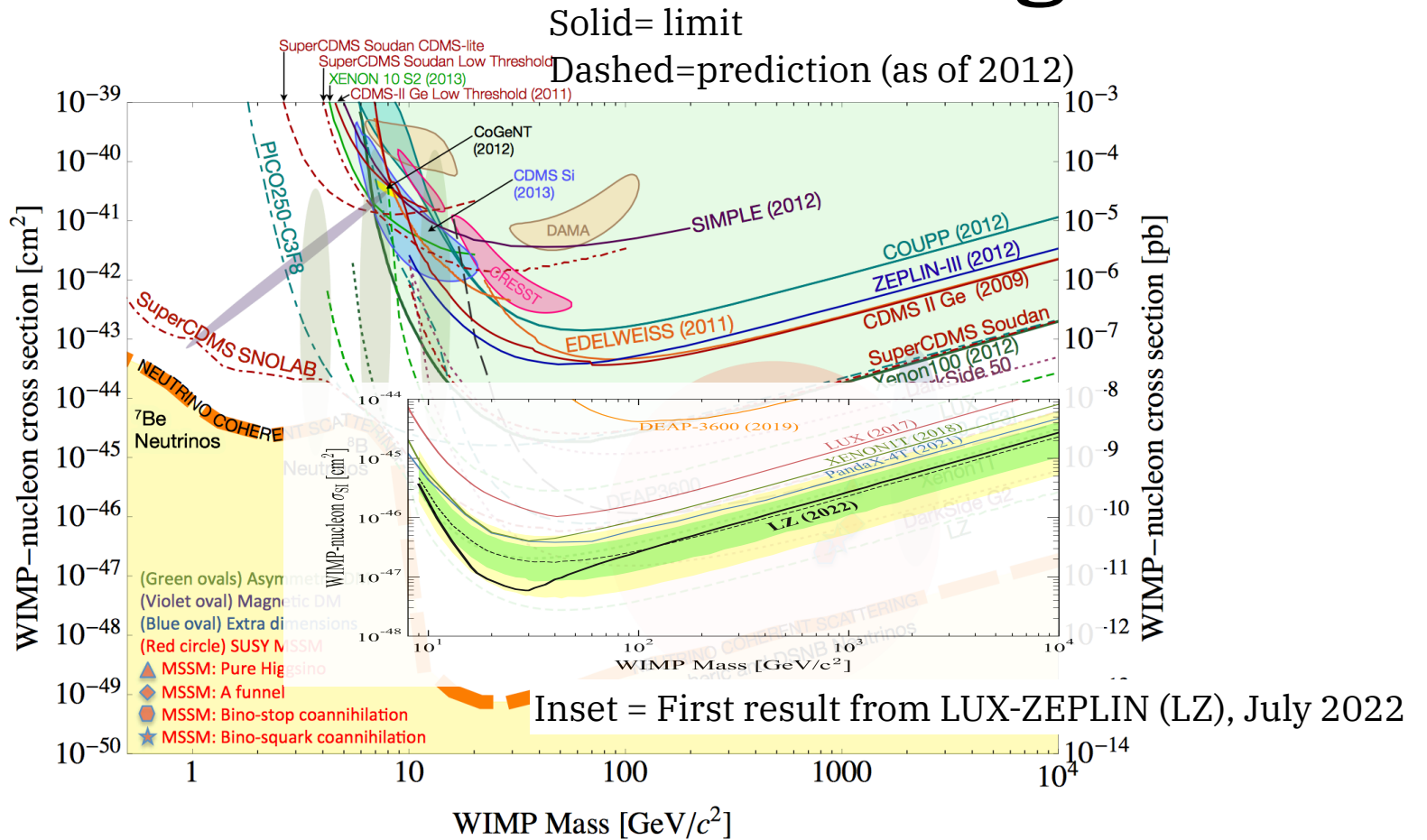
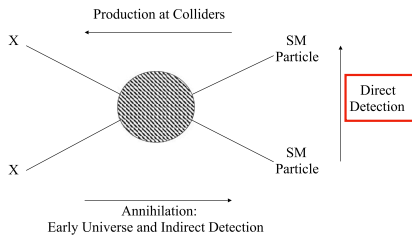
DM-nucleon scattering

Solid= limit

Dashed=prediction (as of 2012)



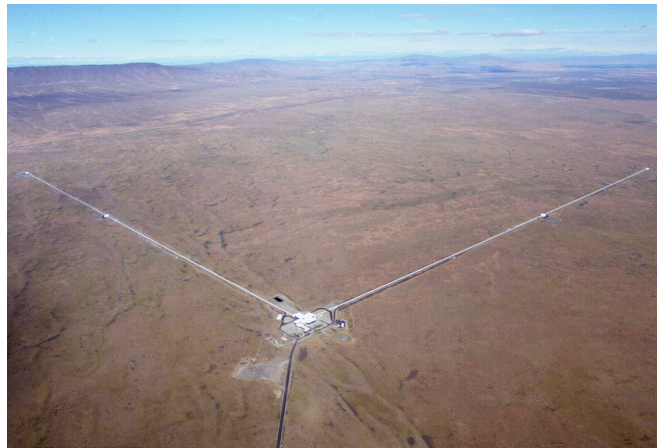
DM-nucleon scattering



LVK Gravitational Wave observatories



LIGO Livingston (Louisiana)



LIGO Hanford (East Washington)

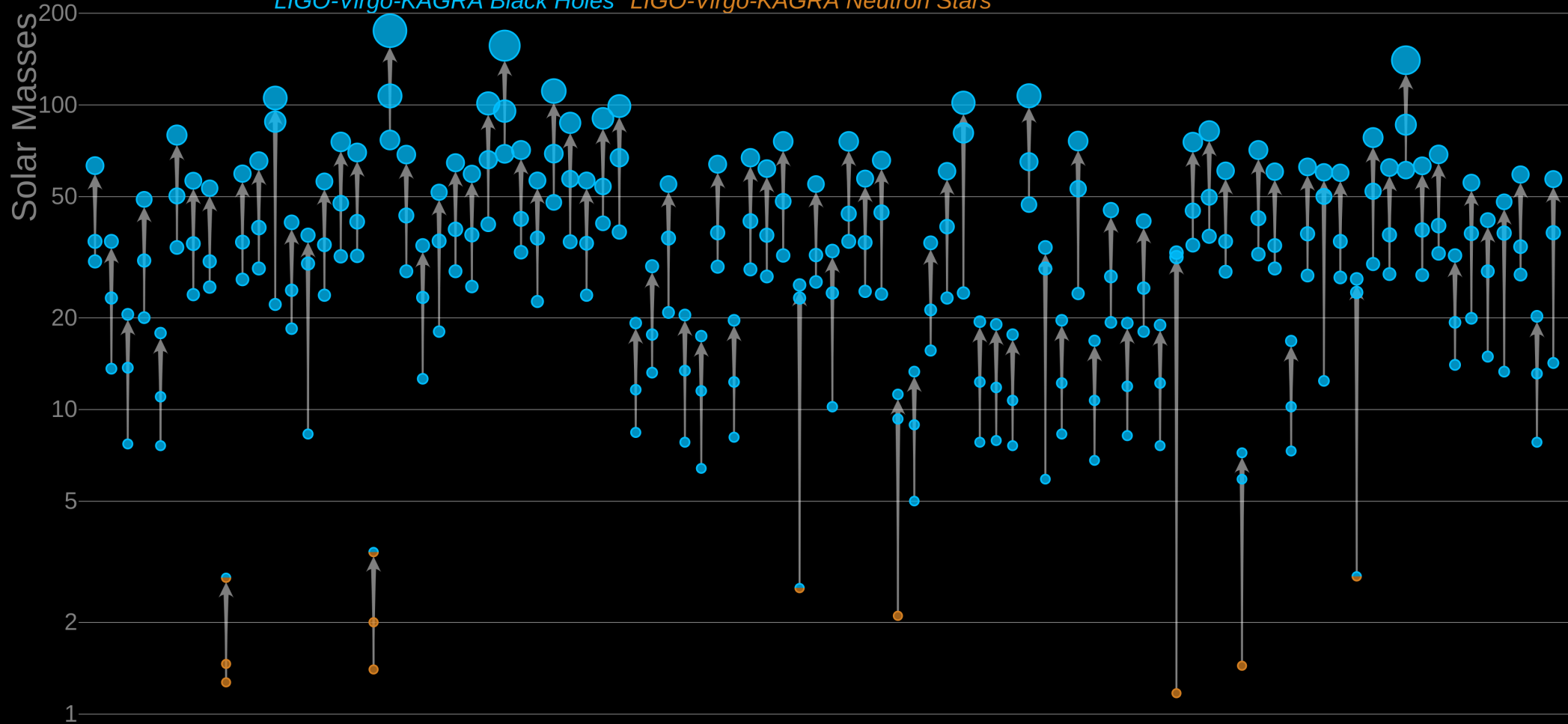


VIRGO, near Pisa, Italy

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

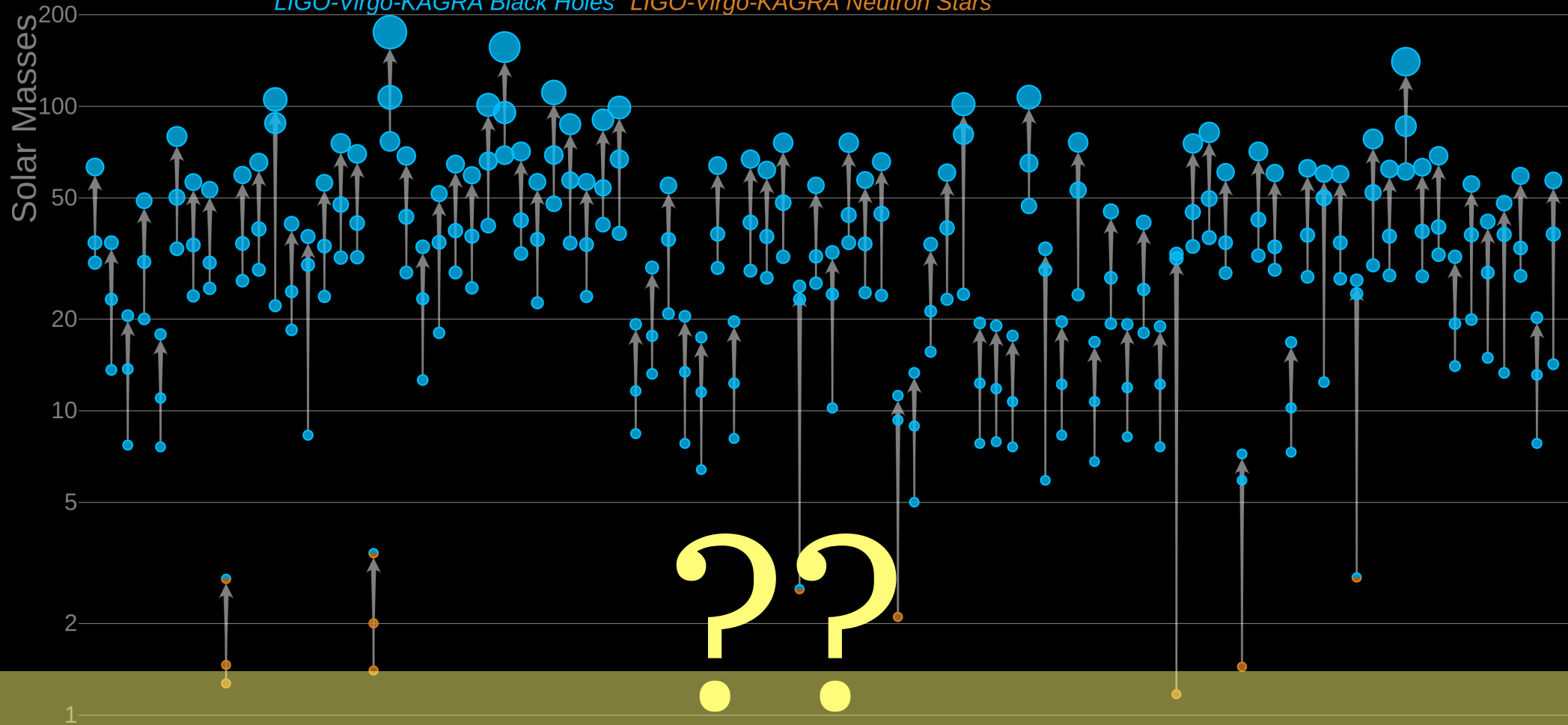
Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars*

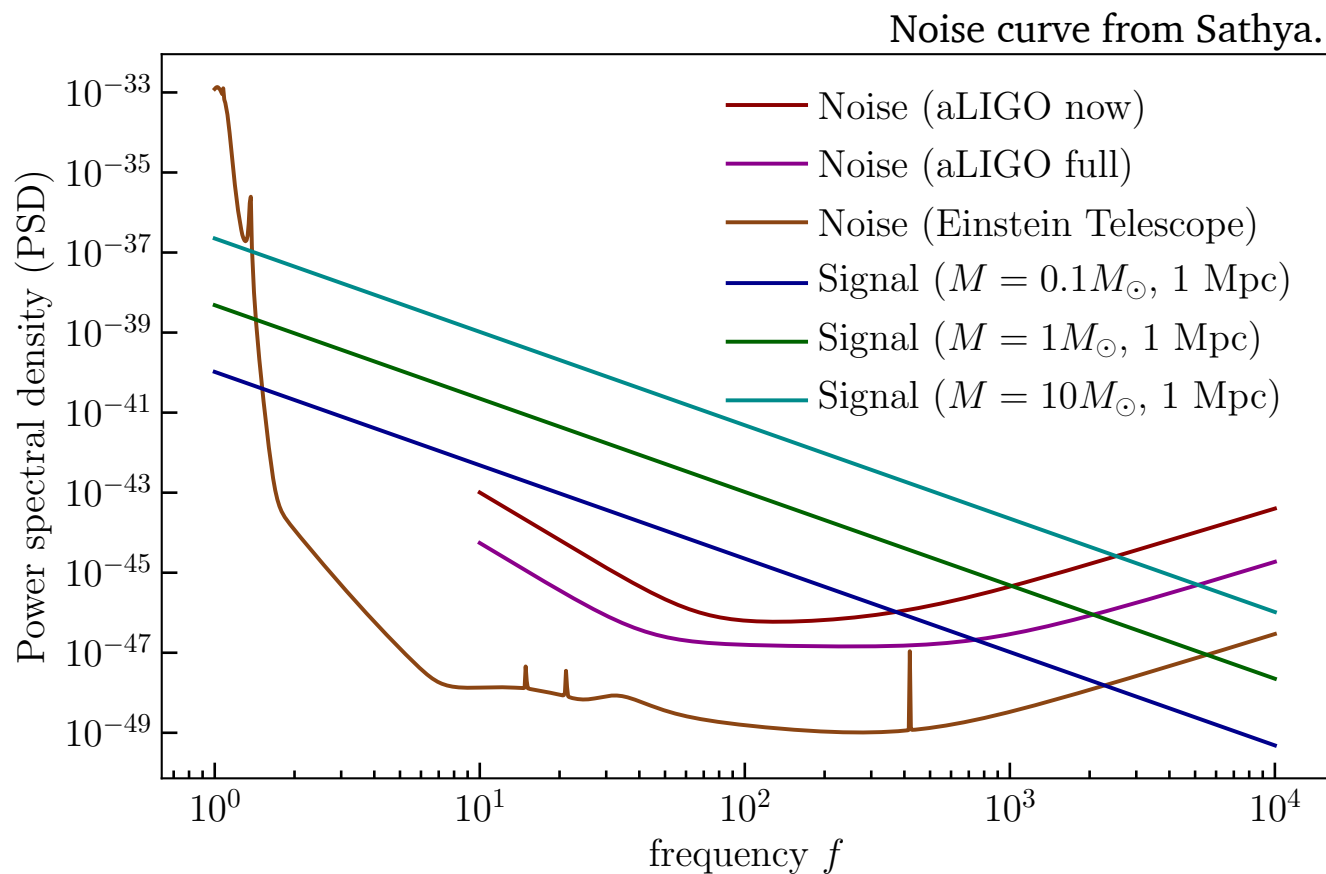


Masses in the Stellar Graveyard

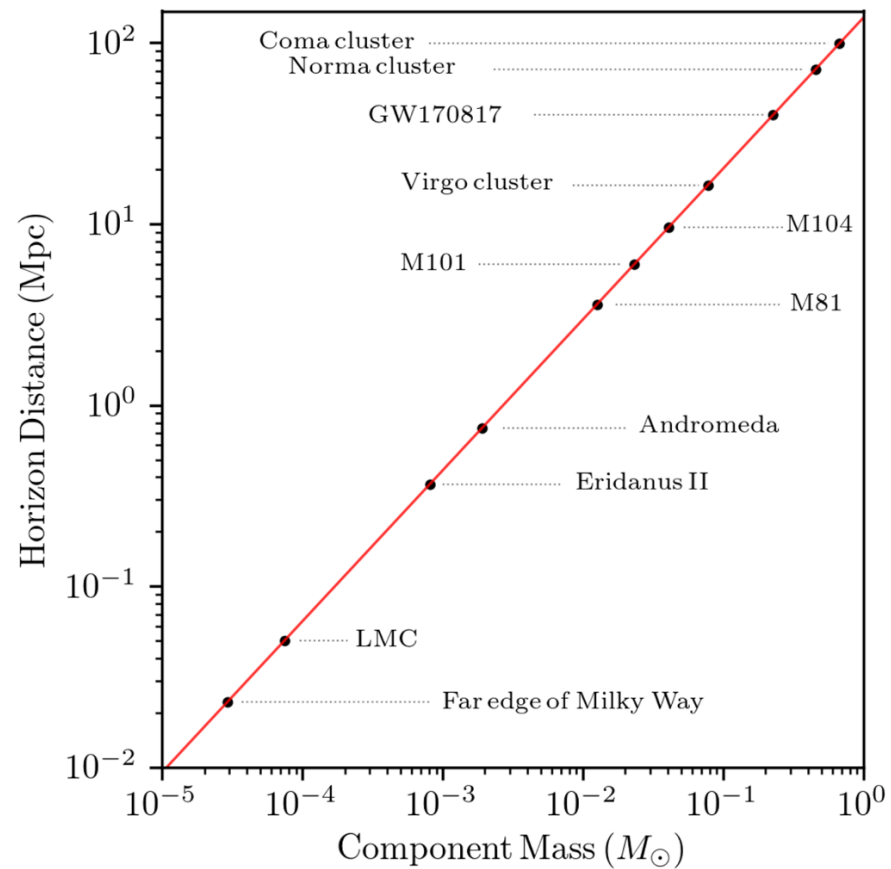
LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars



LVK is capability to *hear* BH binaries:

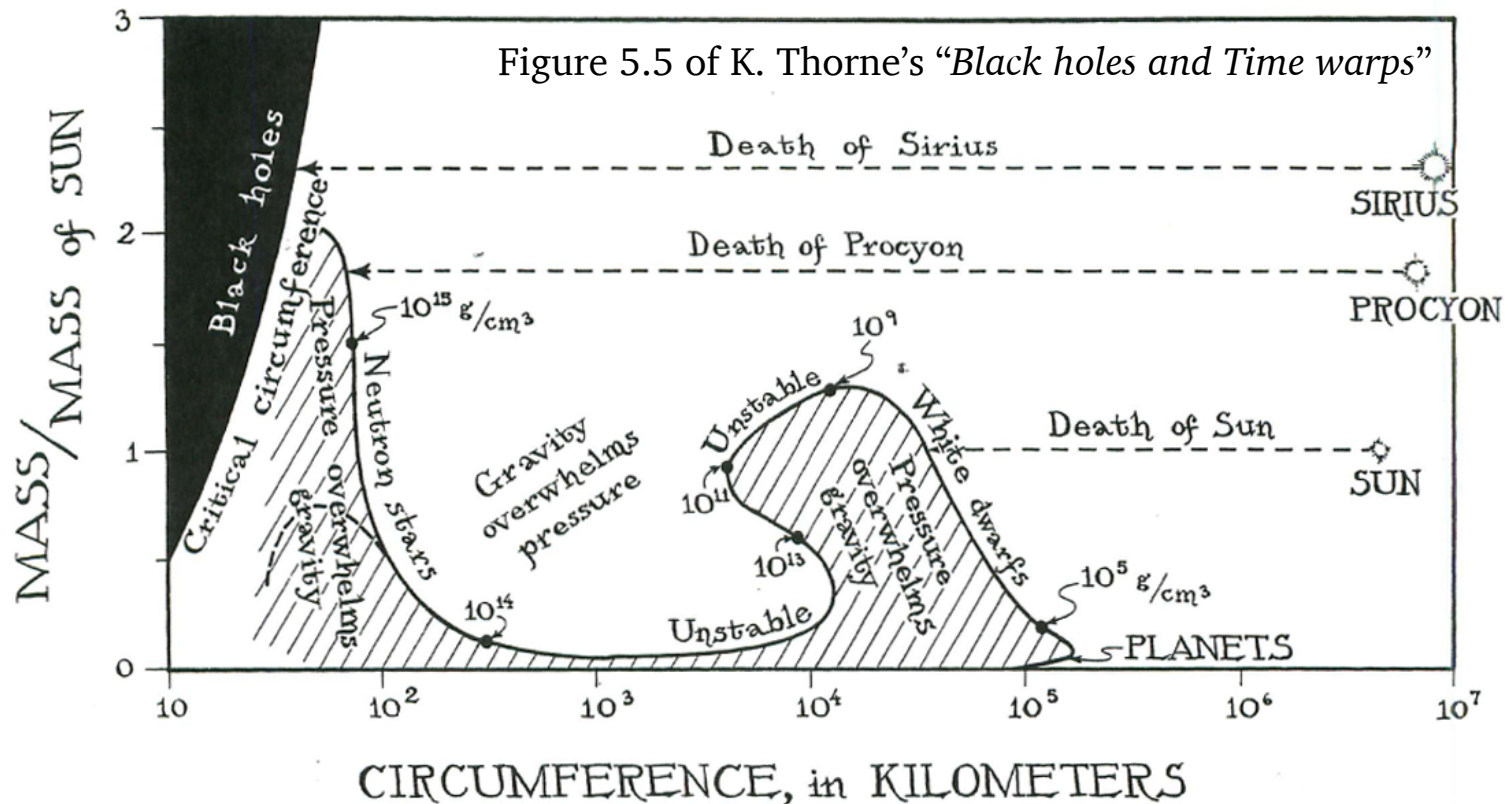


Caveat: smaller horizon volume



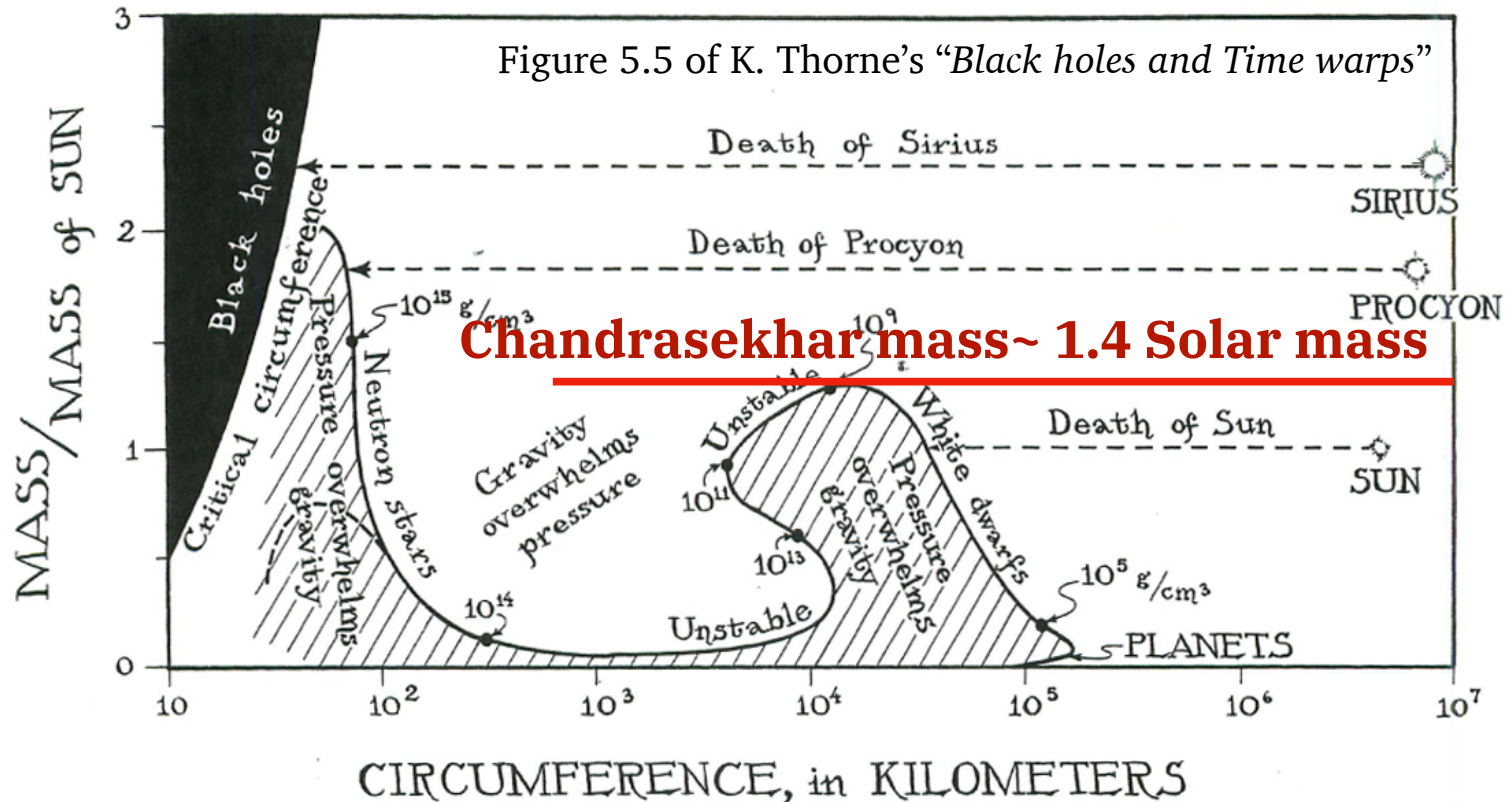
Sub- M_{\odot} compact binaries?

Surely, not from the usual stellar evolution!



Sub- M_{\odot} compact binaries?

Surely, not from the usual stellar evolution!



Chandrasekhar mass limit



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

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

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

Chandrasekhar mass limit



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

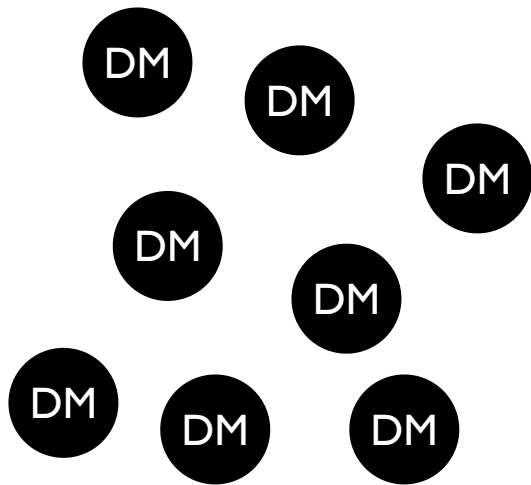
$$M_{\text{Chandra}} \simeq \left(\frac{m_{\text{Planck}}}{m_p} \right)^3 m_p \simeq M_{\odot}$$

- Key idea:

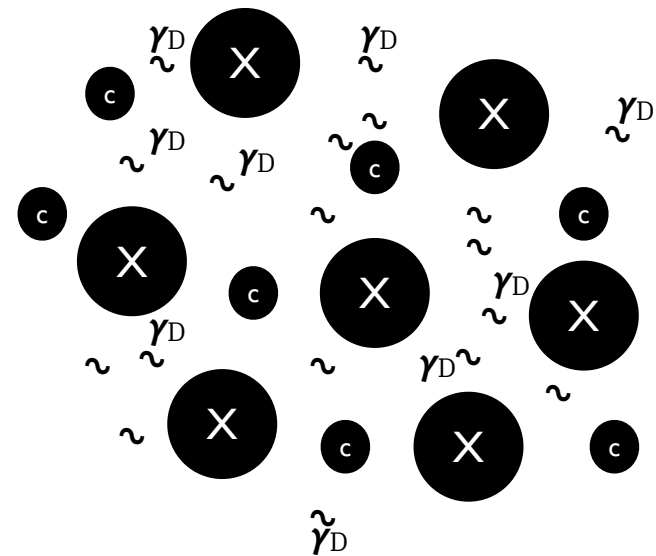
The same limit must be applied to the *dark world*, but the proton mass can be heavier!!

New possibility: *Dark* Black holes!

If dark matters can dissipate their kinetic energy!



Boring single flavor

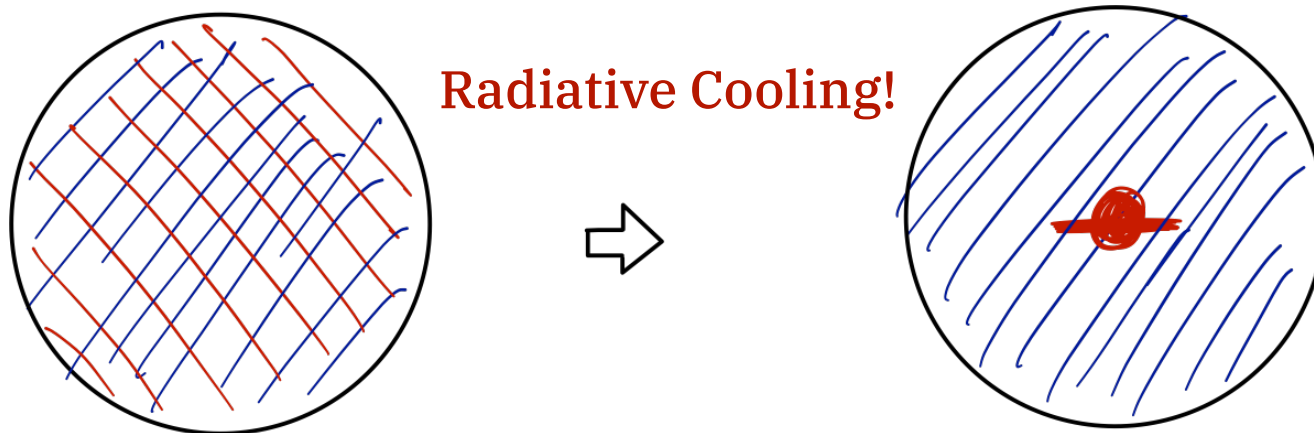


Three particle species

Simple set up: dark-sector particles

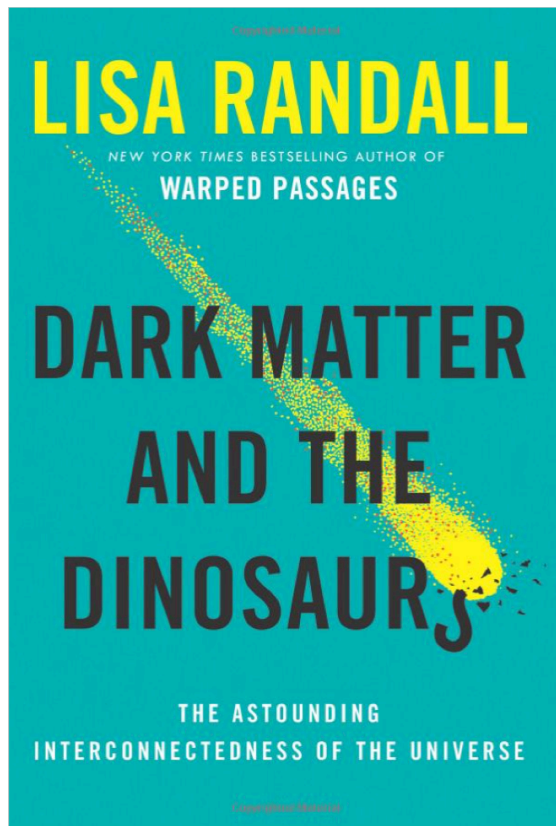
- In dark sector, we have
 - Dark **proton (X)** : Need to be heavier, + charge. No QCD required
 - Dark **electron (c)** : Need to be lighter, - charge.
 - Dark **radiation (γ_D)**
- Free parameters in the theory: m_X , m_c , α_D ($\sim 1/137$), $\xi(=T_D/T_\gamma)$
- With dark radiation, we have a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

Dissipation and cosmic structures

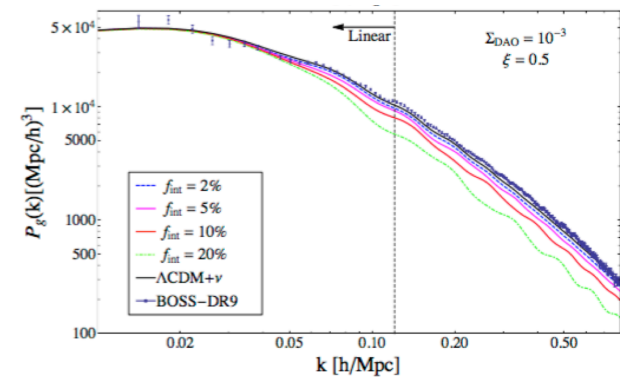
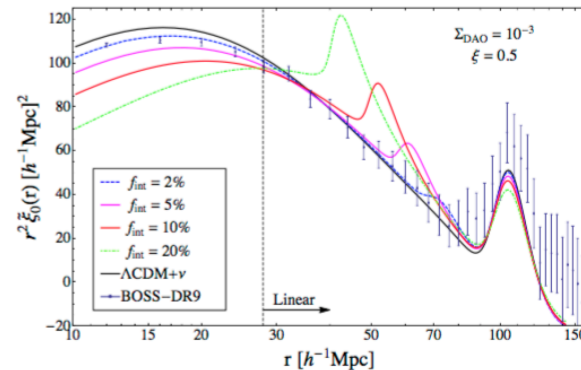


- **CDM**($\sim 5/6$): no interaction. responsible for growth of structure
- **Baryons**($\sim 1/6$): interaction with photon, can **radiate, cool down**
- **Atomic dark matter** also sink/form small structures.

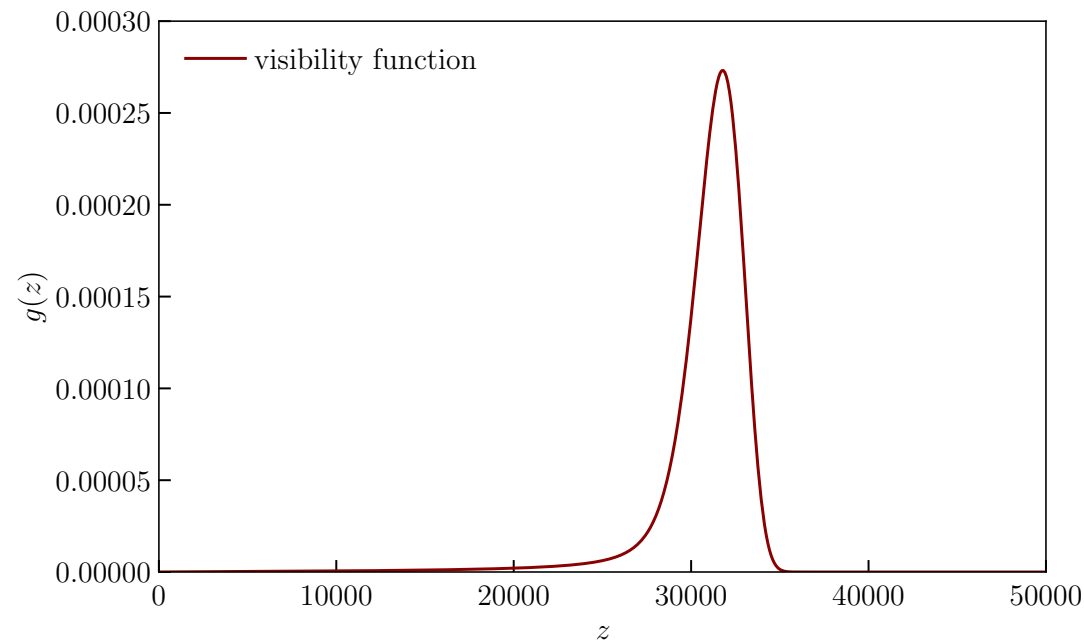
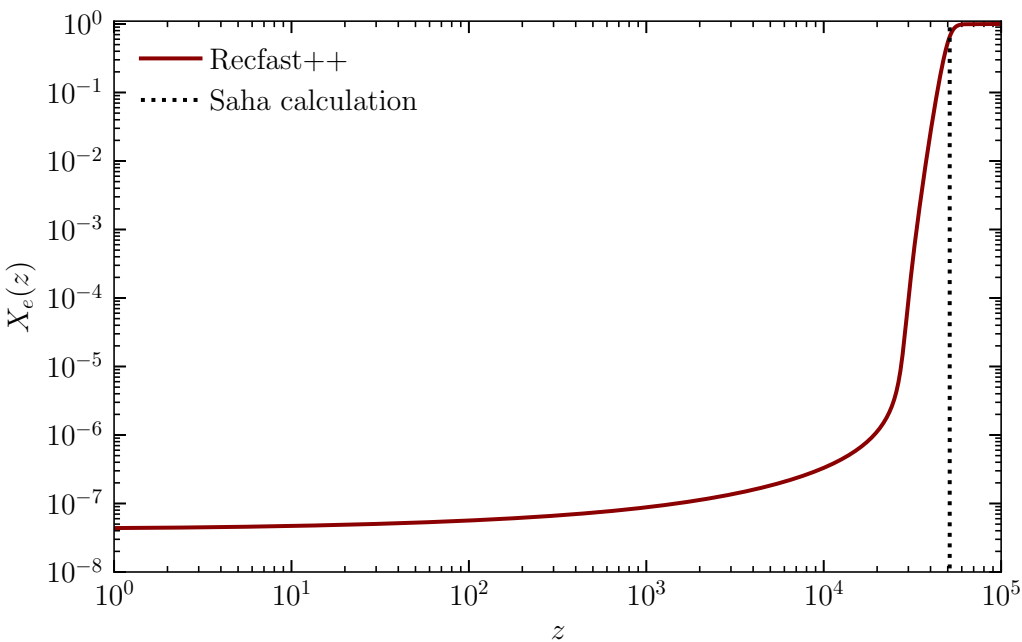
Example: Double-Disk DM



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



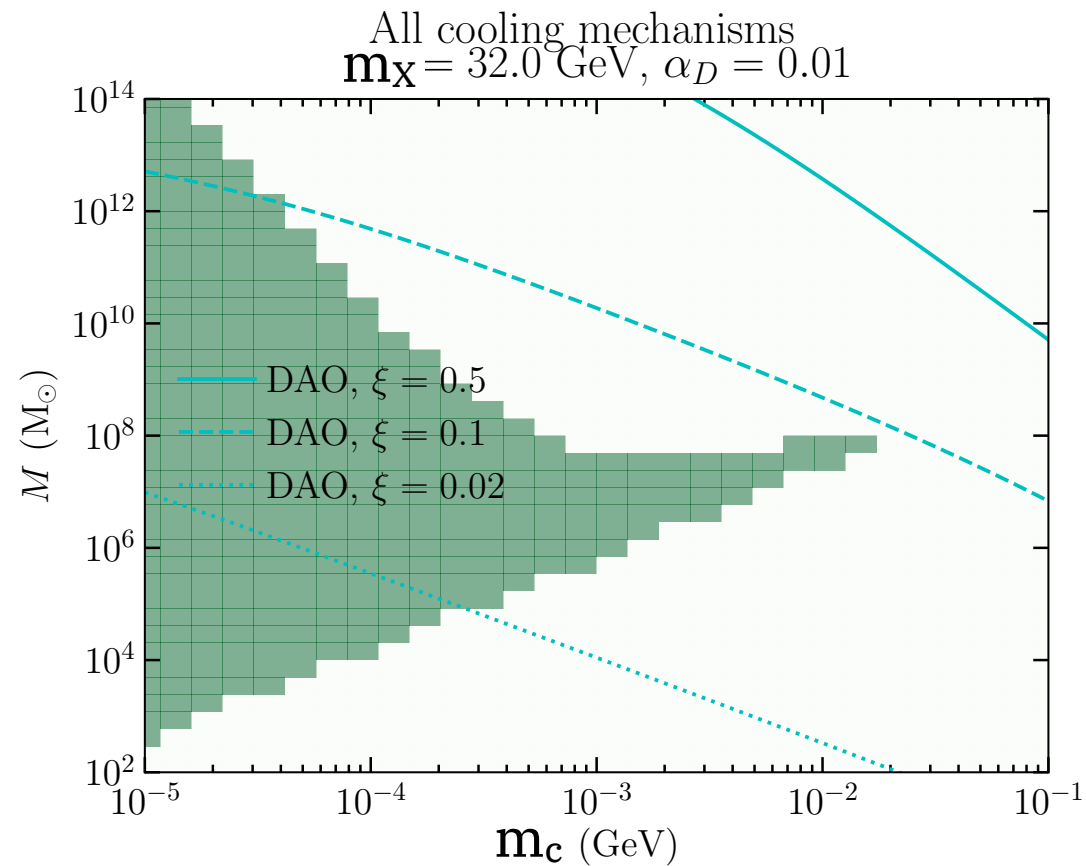
Dark recombination & decoupling



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

$z_{\text{Recombination}} \sim 51,000$, $z_{\text{decoupling}} \sim 32,000$, $d_{\text{DAO}} \sim 0.02 \text{ Mpc}$, $1/k_D \sim 0.24 \text{ Mpc}$

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 for $M > 10^{11} M_\odot$ halos,

$$t_{\text{cool}} > t_{\text{age}}$$

Two mass scales

- Chandrasekhar mass

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

Chandrasekhar (1931)

- Opacity limit (minimum Jeans mass of fragmentation)

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

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

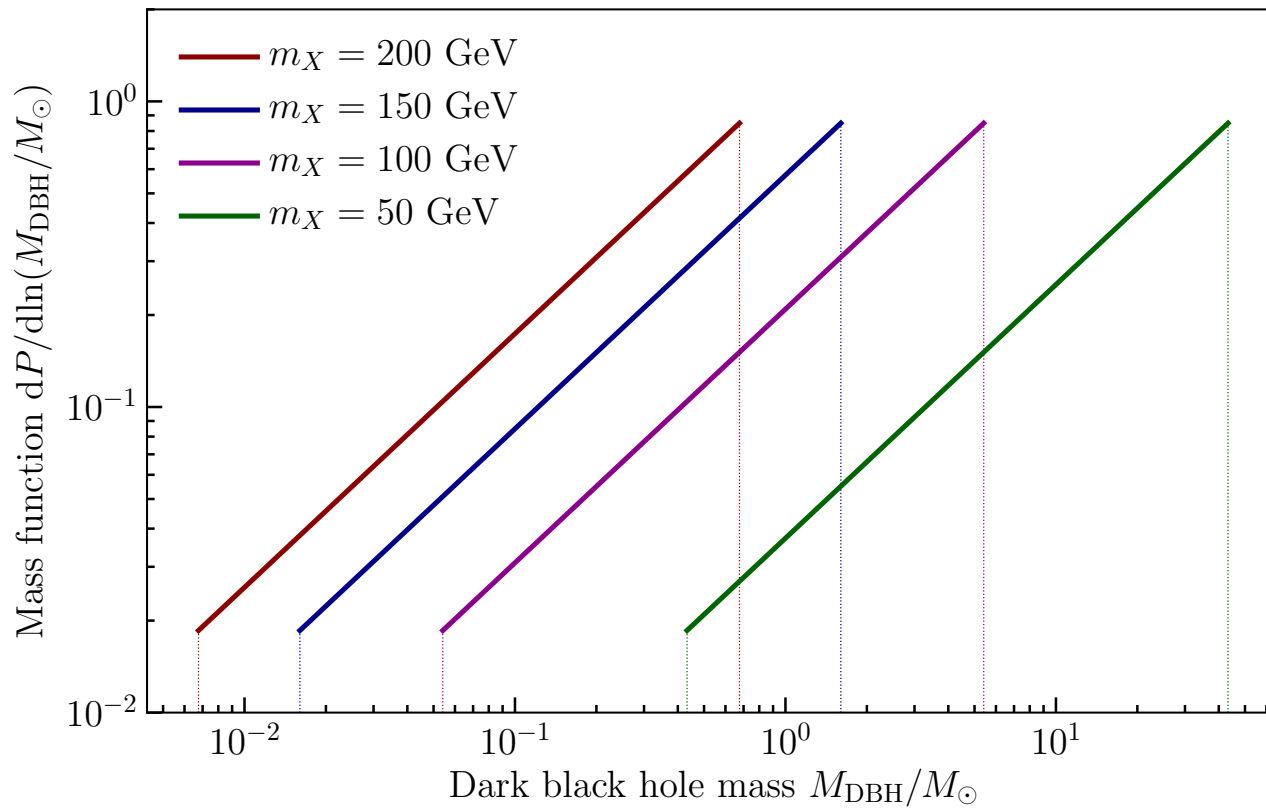
Dark Star (DS) formation

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

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

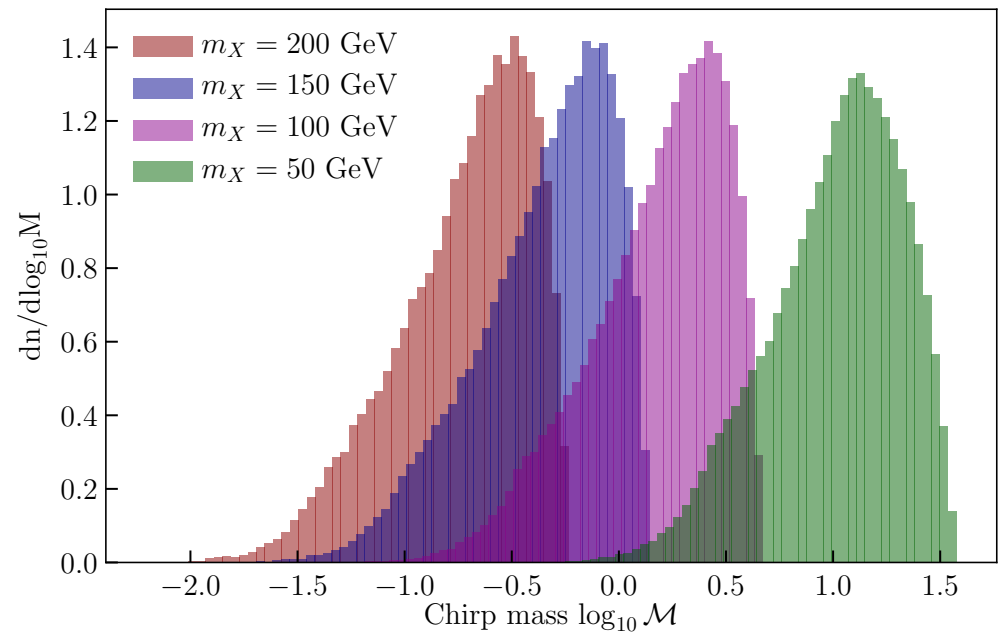
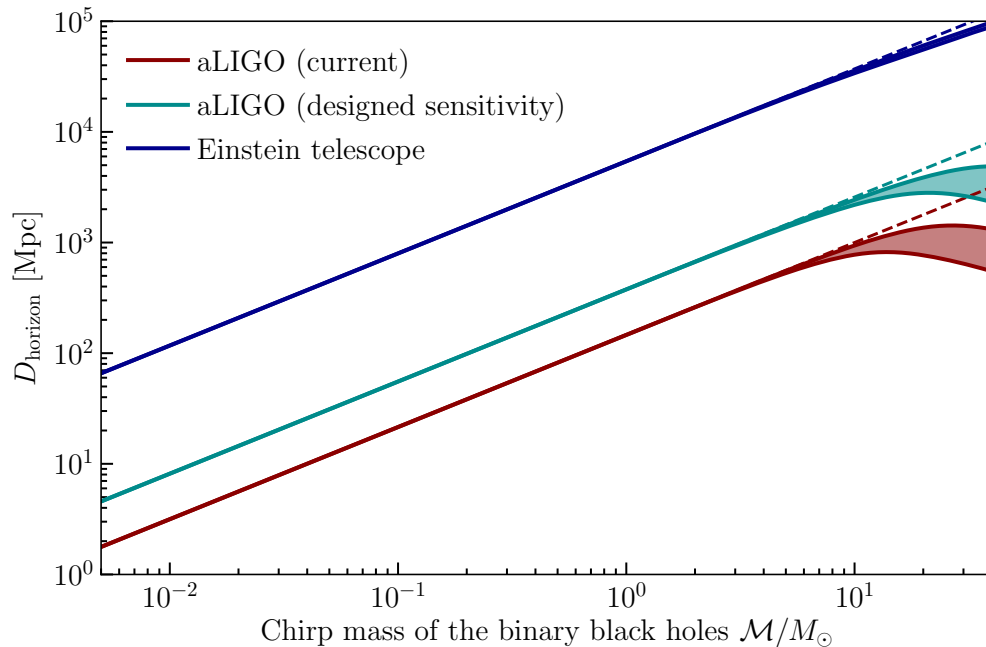
- DS formation is similar to Pop-III except for the energy gap.
- We, therefore, use the results in Pop-III binary literature.

Dark BH mass function



Horizon radius (8 σ -detection limit)

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

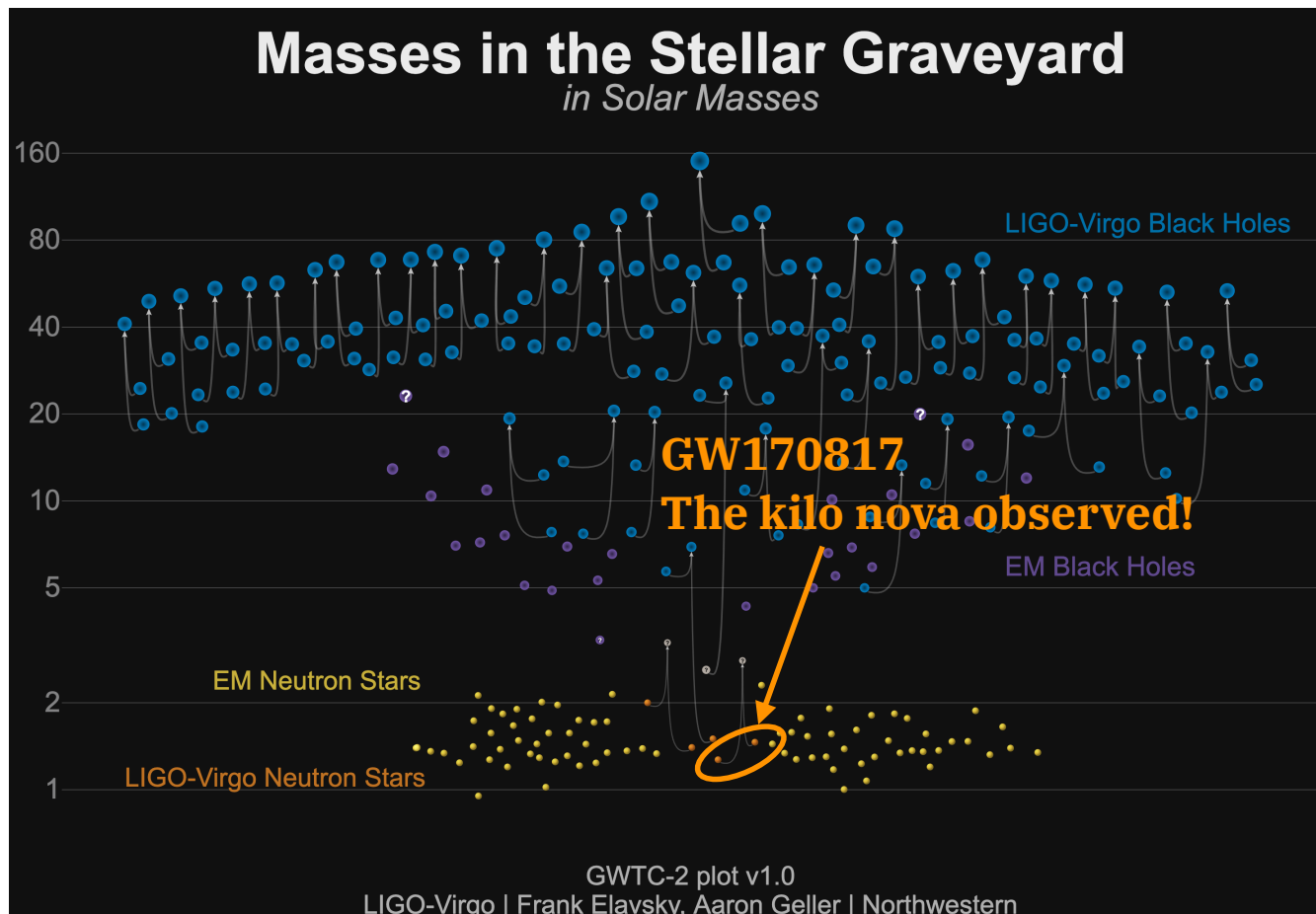


Yes, we *can* detect them!

m_X [GeV]	m_c [keV]	$M_{\text{Chand.}}^{\text{dark}}$ [$10^{-5} M_{\odot}$]	M_{DBH} [M_{\odot}]	Rates per year				$m_1 < 1.4$ [%]	$m_1, m_2 < 1.4$ [%]
				raw (MWEG ⁻¹)	aLIGO (current)	aLIGO (full)	Einstein T.		
62	30	33	0.0068 – 0.68	$2.0 \times 10^{-6} (10^{-4})$	0.0012 (0.12)	0.020 (2.0)	60 (6000)	100%	100%
48	47	56	0.016 – 1.6	$1.3 \times 10^{-6} (10^{-4})$	0.0065 (0.65)	0.11 (11)	330 (33k)	99%	79%
32	70	125	0.054 – 5.4	$6.6 \times 10^{-7} (10^{-5})$	0.068 (6.8)	1.1 (110)	3500 (350k)	53%	9.3%
16	144	500	0.43 – 43	$1.9 \times 10^{-7} (10^{-5})$	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 $f_{\text{cool}} \times f_{\text{form. eff.}} = 10^{-5} (10^{-3})$. 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 ($1.4 M_{\odot}$).

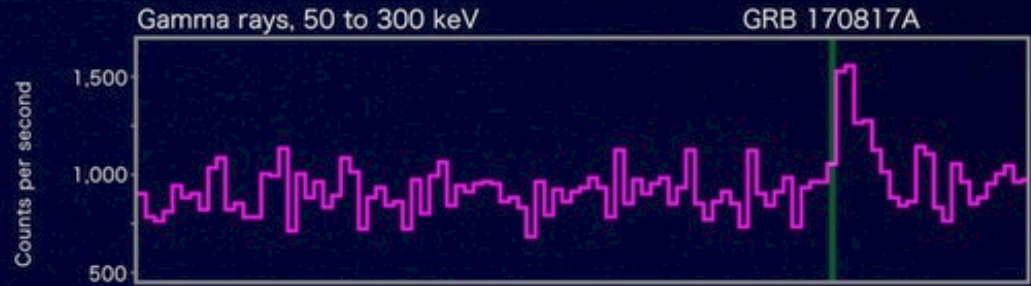
The famous GW170817



01+02+03a
46 BBH
2 BNS
2 B+NS

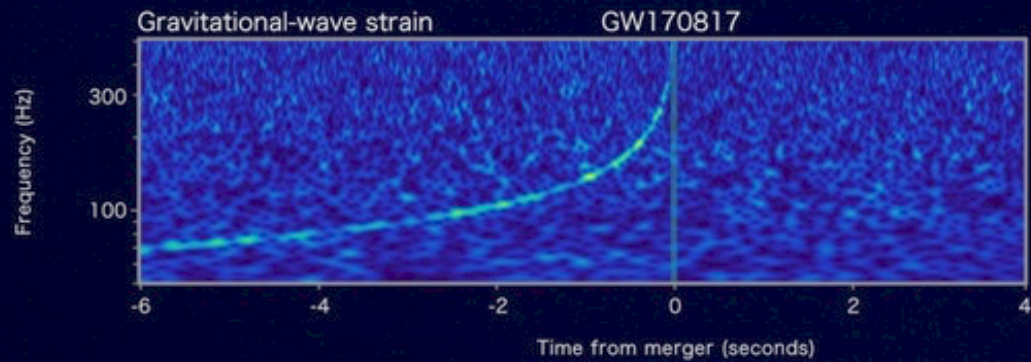
Fermi

Reported 16 seconds after detection



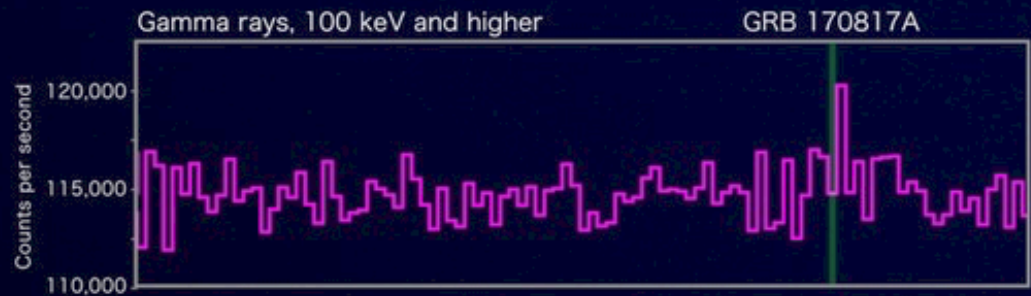
LIGO-Virgo

Reported 27 minutes after detection

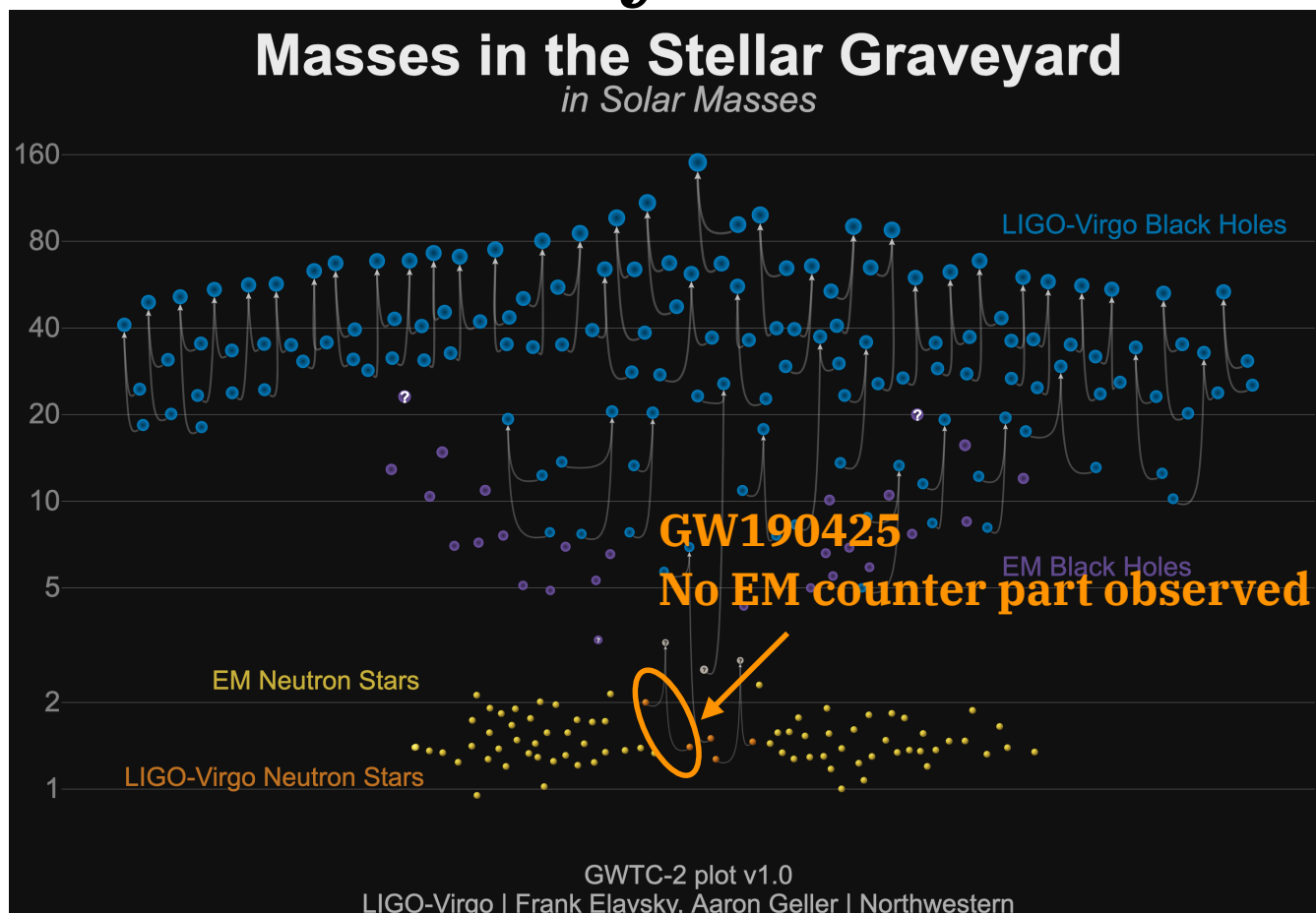


INTEGRAL

Reported 66 minutes after detection



A case study: GW190425



01+02+03a
46 BBH
2 BNS
2 B+NS

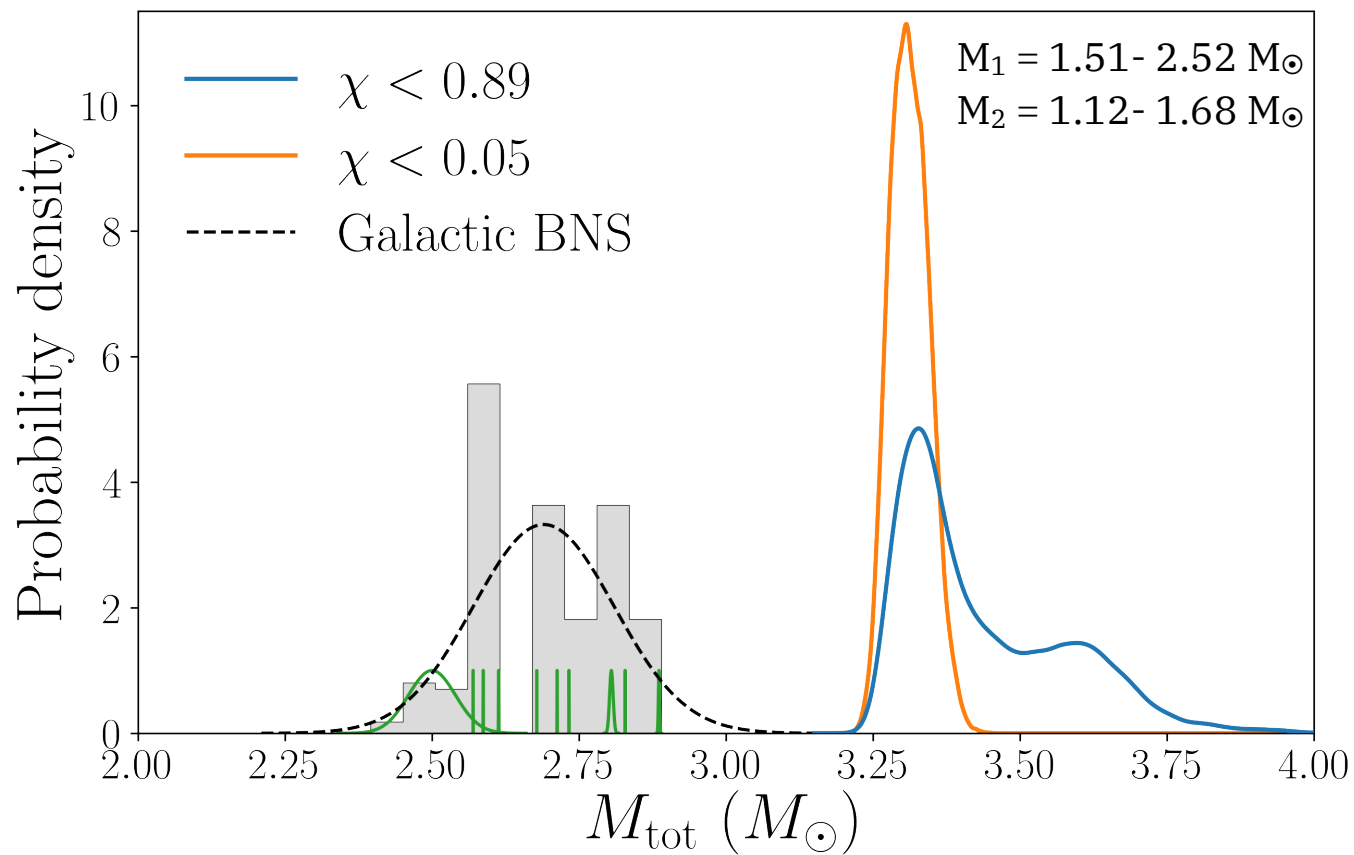
GW190425: what can that be?

$$M_1 = 1.51 - 2.52 M_{\odot}$$

$$M_2 = 1.12 - 1.68 M_{\odot}$$

- 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)

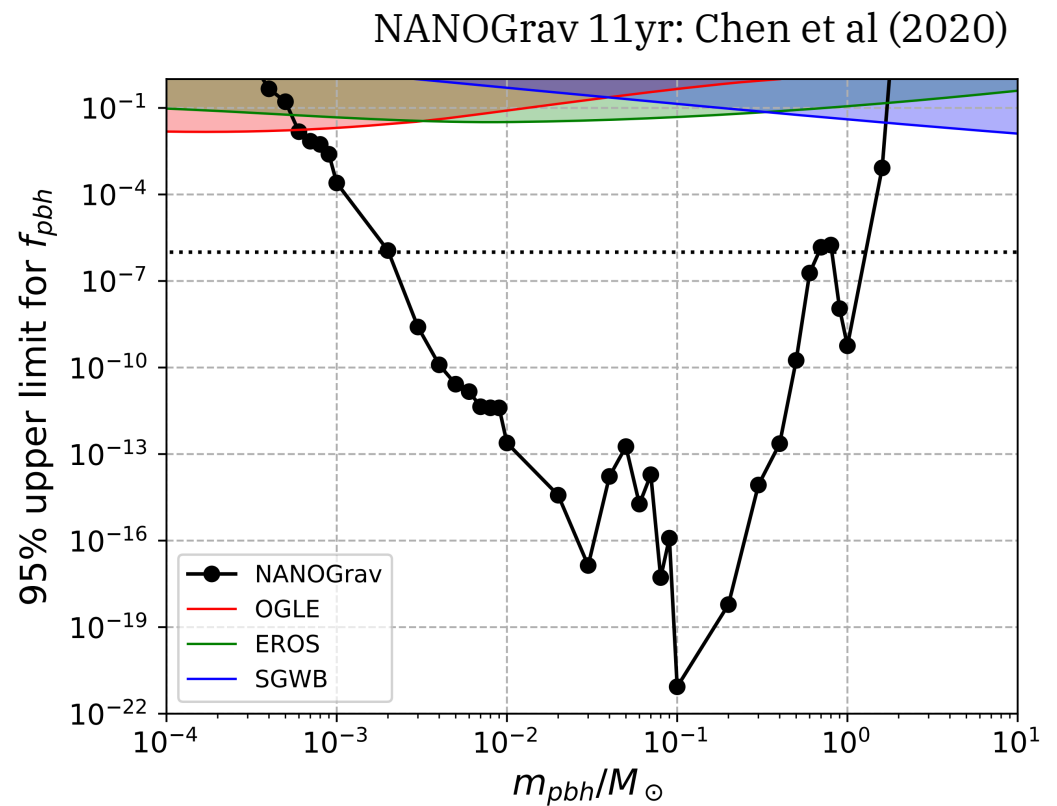
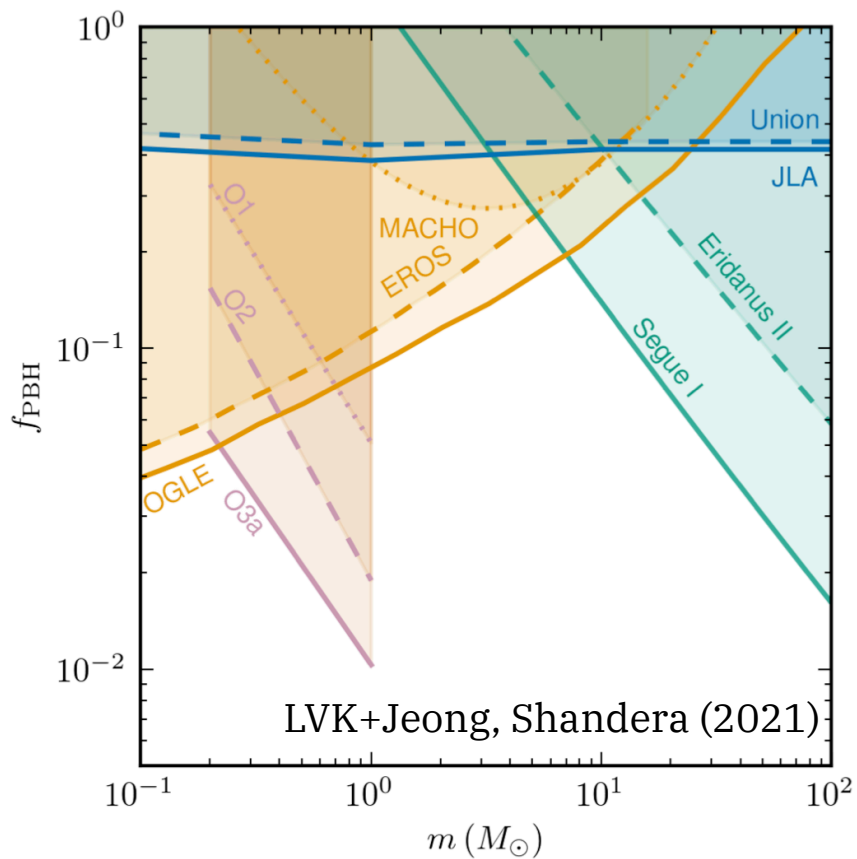
If BNS, GW190425 is an 5- σ outlier!



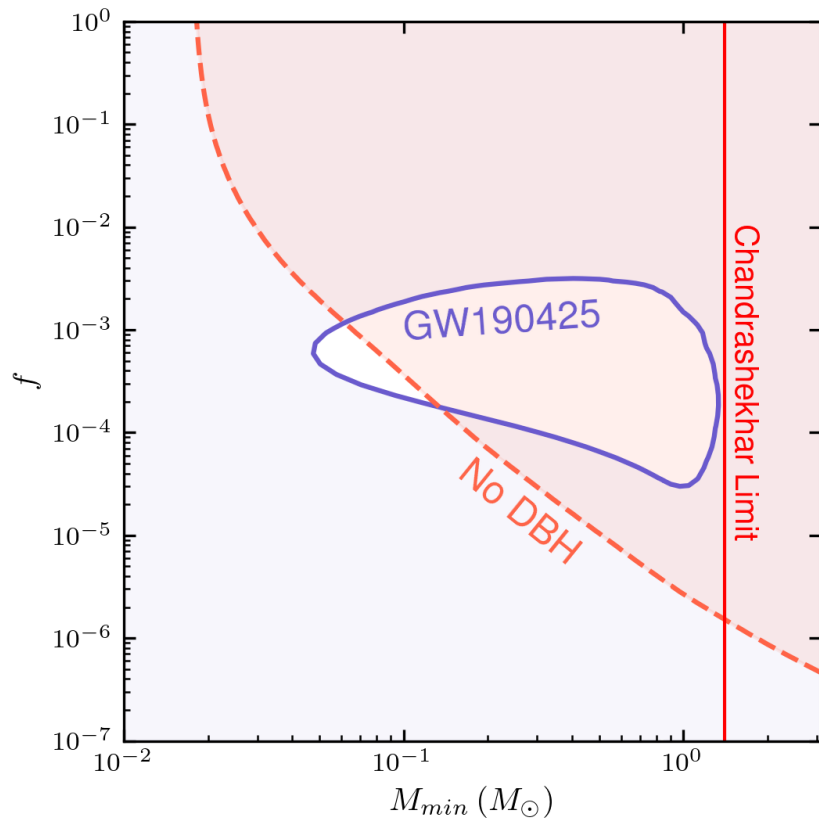
$$M_1 = 1.51 - 2.52 M_\odot$$

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Can that be a PBH binary?

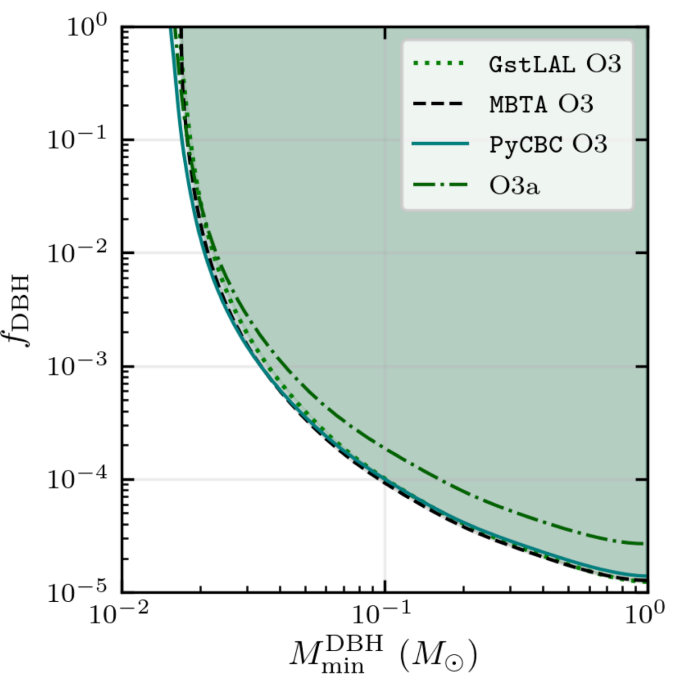
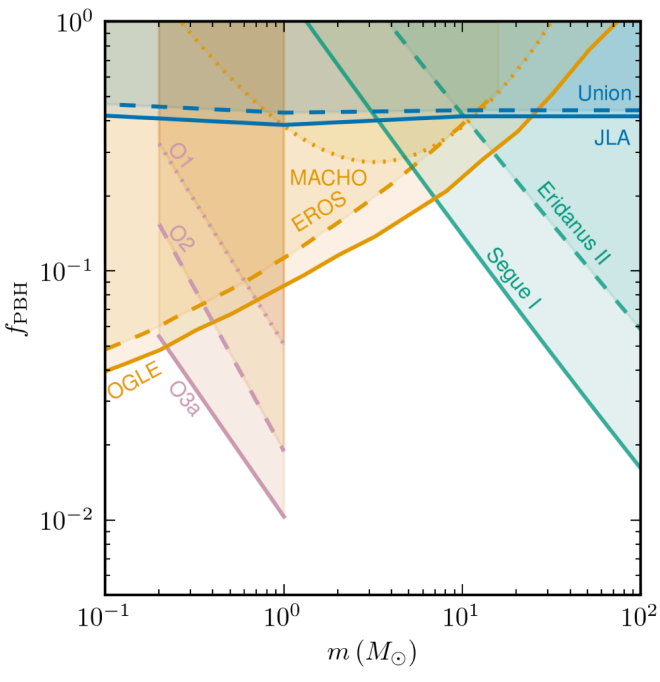
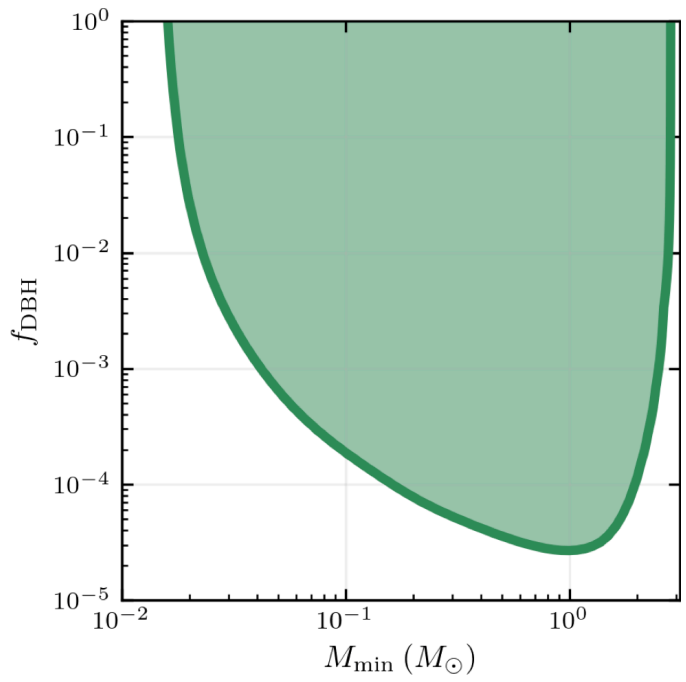


Implication of GW190425



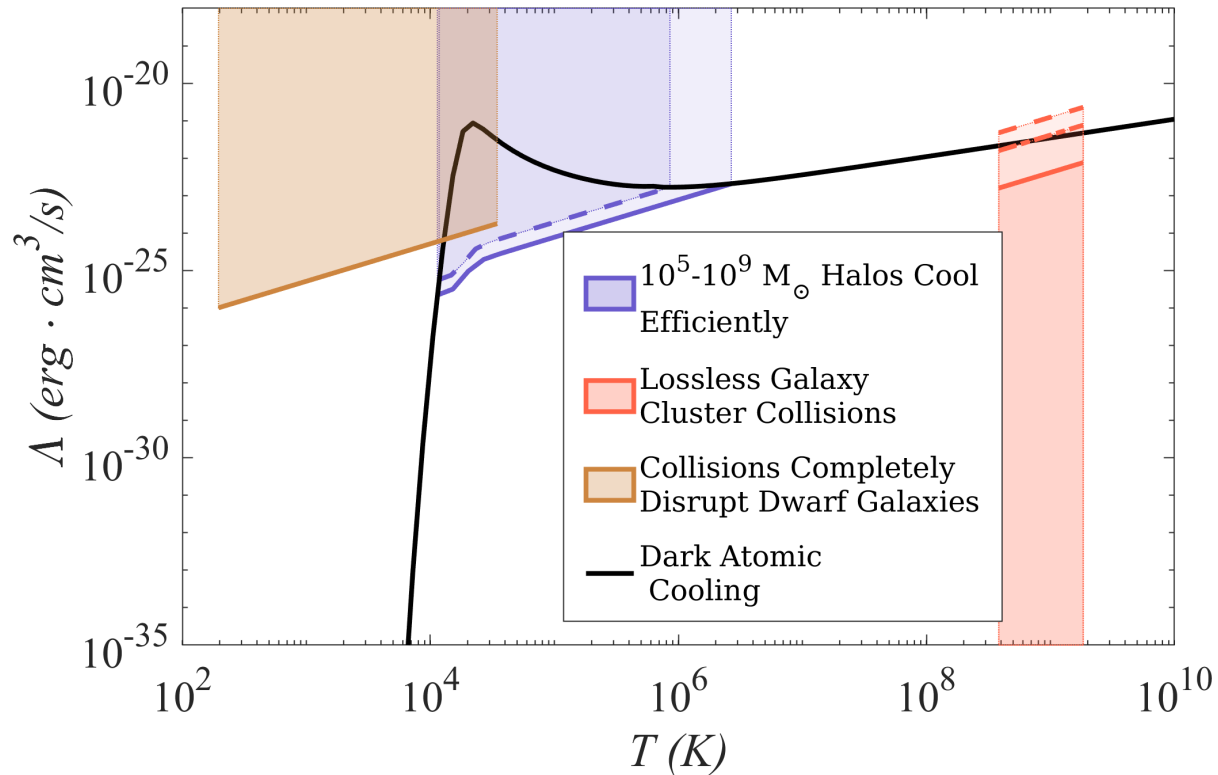
- If GW190425 is a Dark-BH binary, the dark Chandrasekhar mass is less than $1.4 M_{\odot}$ (99.9% C. L.); that is, $m_X > 0.96 \text{ GeV}$.
- If GW190425 is not a Dark-BH (then we don't know what it is), we constrain large parameter space.

Limit from O3a/b (for null detection)

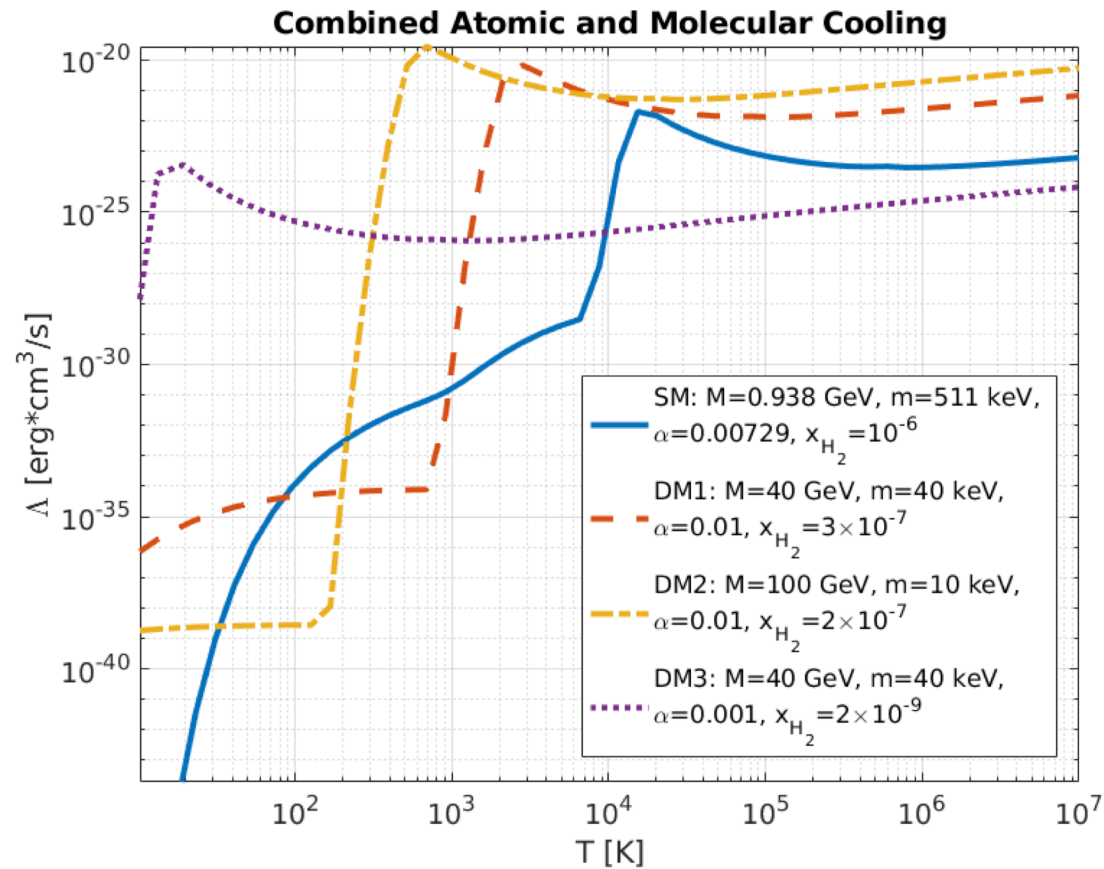


Constraints on *dark* cooling function

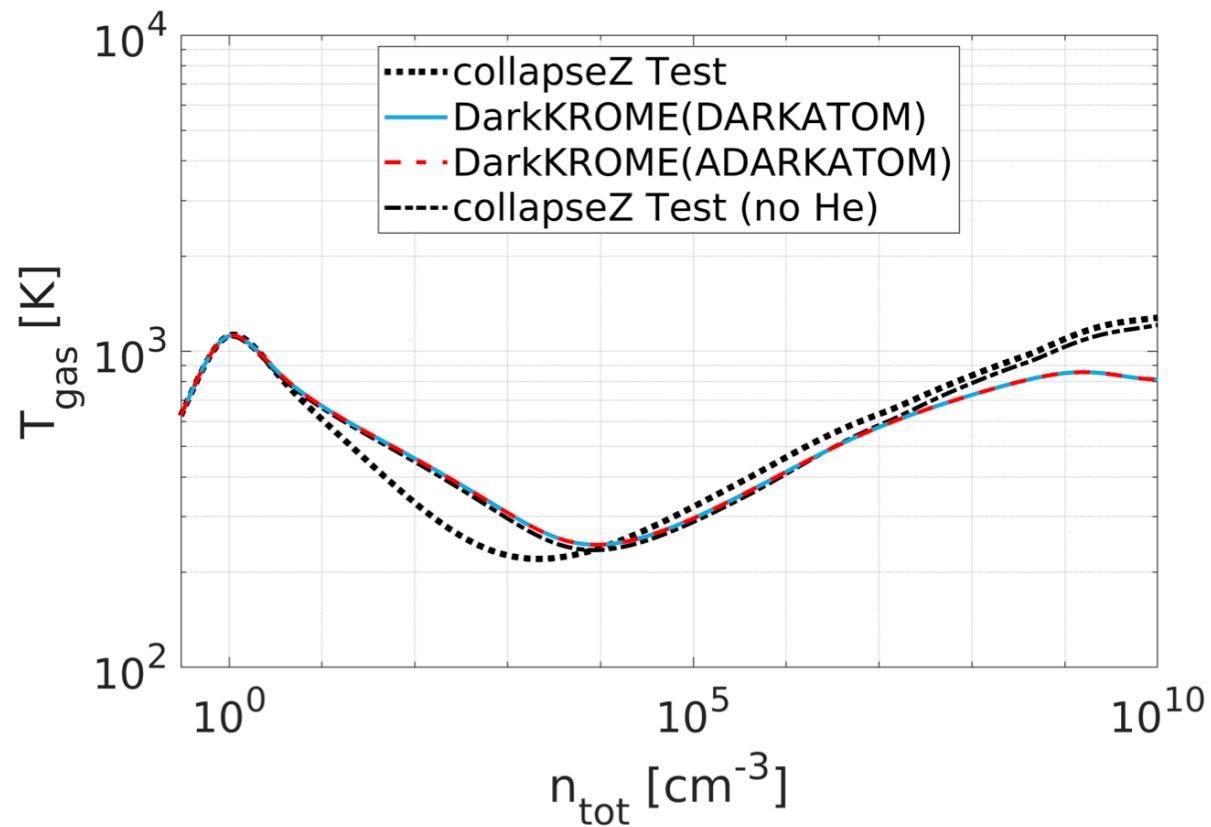
Energy dissipation rate as a function of particle temperature



ADM cosmology: the cooling function



ADM cosmology: (n-T) phase space



ADM cosmology: initial condition

We do form
 dark
 molecular
 hydrogen!

Dark
 Silk-damping
 suppress
 the small-scale
 matter power
 spectrum!

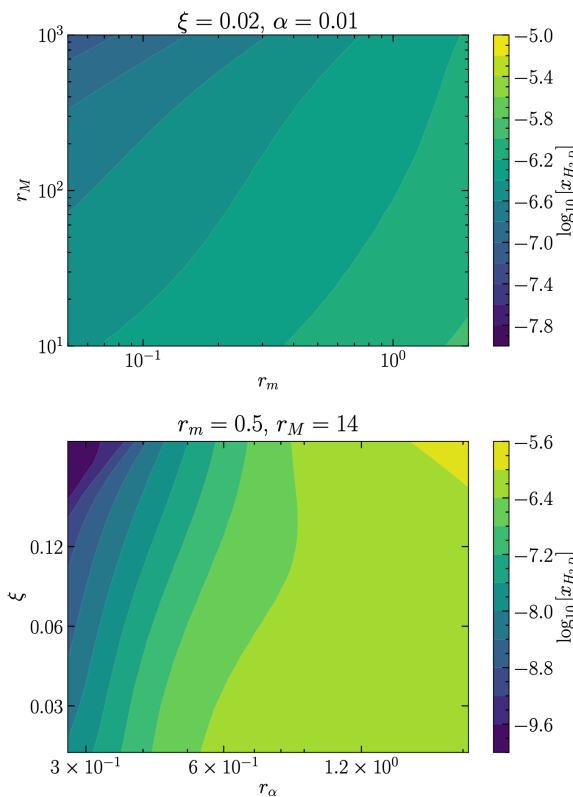


Figure 4. The dependence of the molecular hydrogen fraction $x_{H_2,D}$ at redshift 30 on the model parameters.

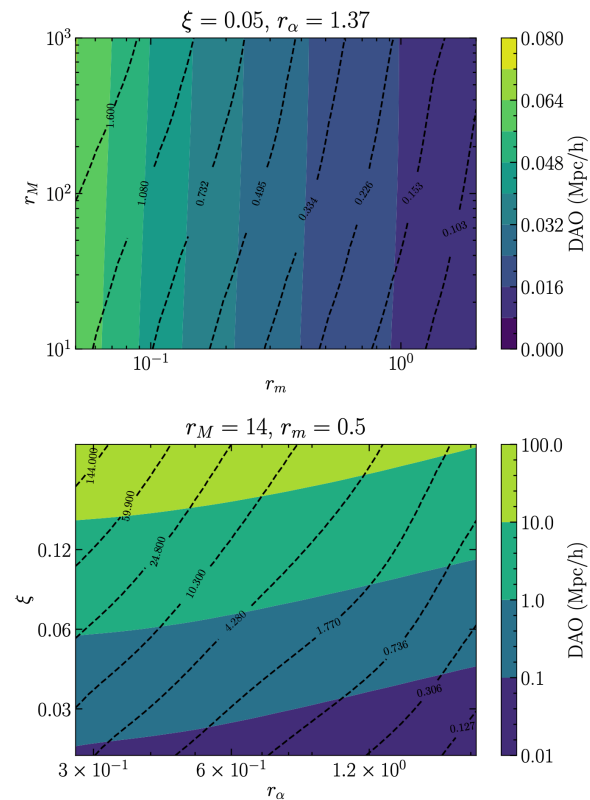
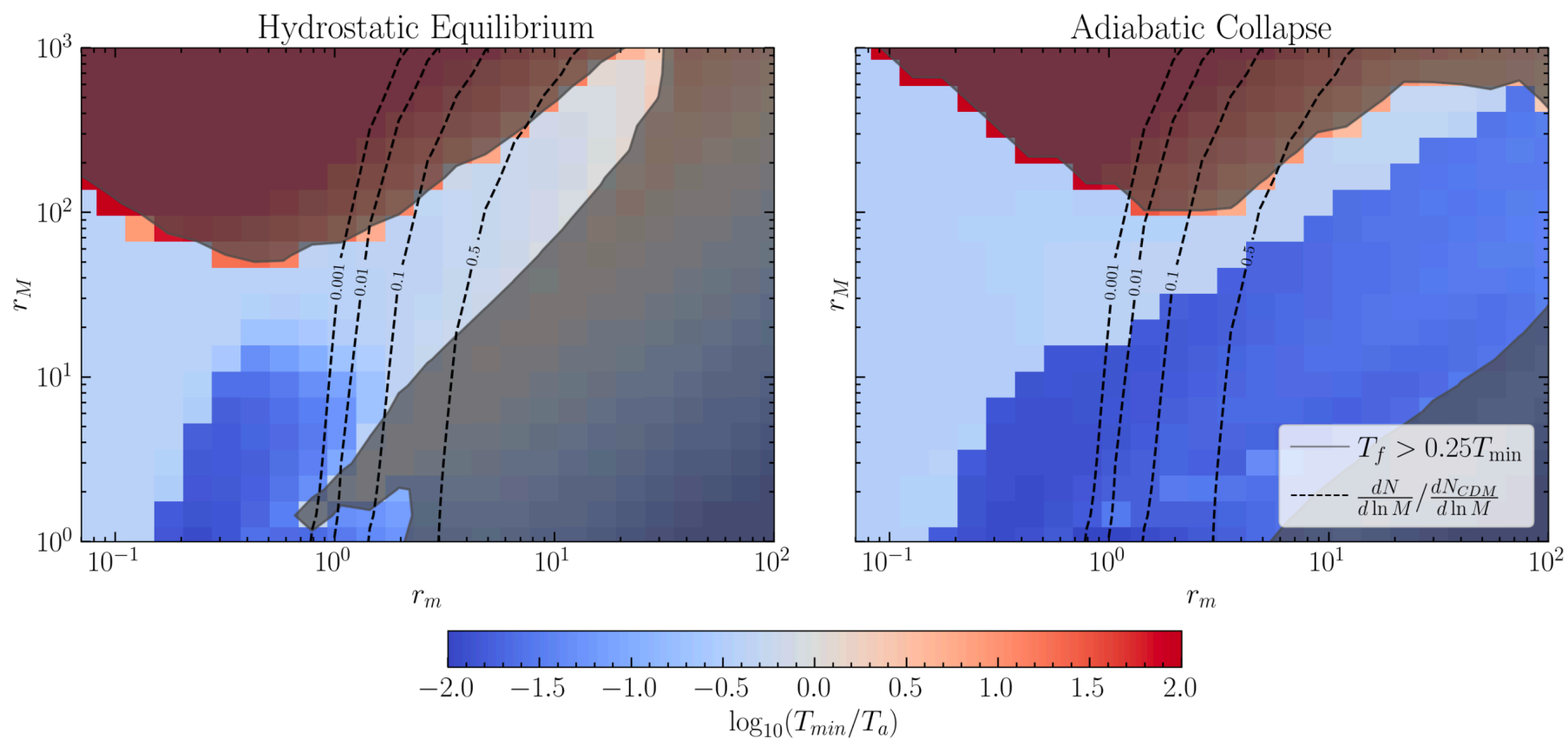


Figure 5. The dependence of the diffusion damping scale (black, dashed) and the acoustic scale (color bars) on the model parameters.

ADM cosmology: halo cooling

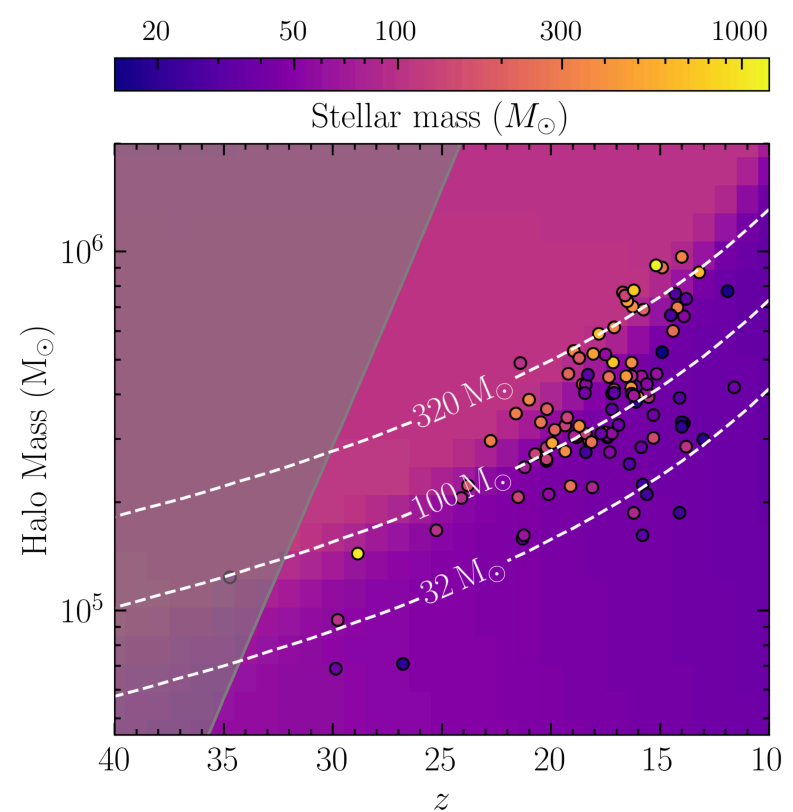
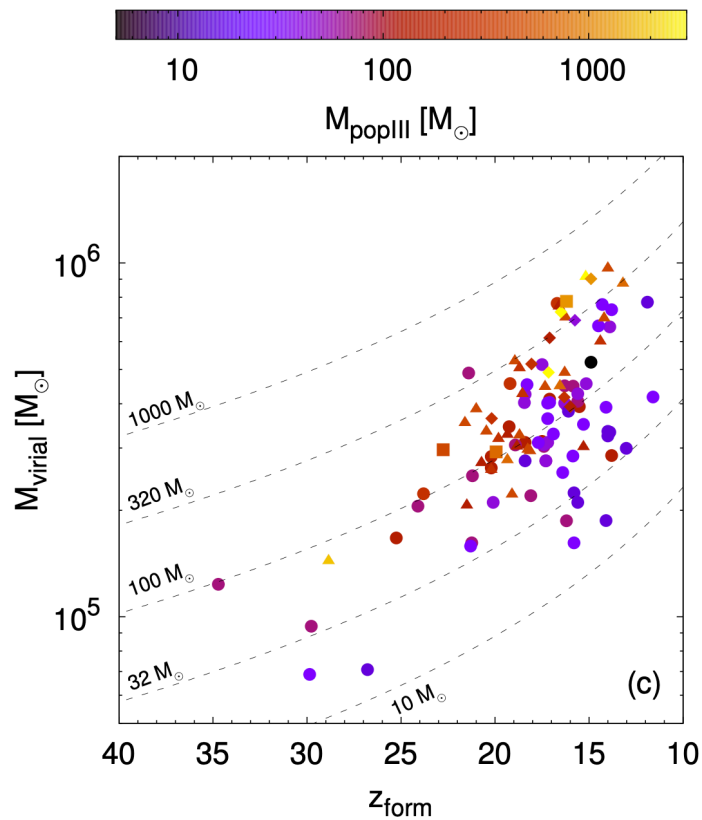
How much cooling do we expect for a $10^8 M_\odot$ halo at $z=10$ (T_a =atomic cooling limit)



“Zero metallicity with zero CPU hours”

Hirano et al. (2013):

Cosmological simulations + Radiative Hydrodynamic simulations with scaling relations and timescales



Conclusion

- GW provides an exciting new avenue for studying dark matter using the only guaranteed property of dark matter: gravity!
- Example: if GW190425 is a dark-BH binary, the 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 is ongoing in LVK collaboration with the O4a dataset, started on 24 May 2023!

Notice

Notice

Application Period: 2023-06-02 ~ 2024-06-02 | School/Center: -- All -- | Job Openings: Job Openings | Search

No	School/Center	Job Openings	Application Period	Posted By
1	Quantum Universe Center	[Quantum Information Science] 2023-02 KIAS Recruitment Announcement for QUC Research Fellow Positions	2023-10-05~2024-01-31	Admin
2	Quantum Universe Center	[Quantum Information Science] 2023-02 KIAS Recruitment Announcement for QUC Fellow (QUC Assistant professor) Positions	2023-10-05~2024-01-31	Admin
3	Quantum Universe Center	[Astrophysics] 2023-02 KIAS Recruitment Announcement for QUC Research Fellow Positions	2023-10-25~2023-12-31	Admin
4	Quantum Universe Center	[Astrophysics] 2023-02 KIAS Recruitment Announcement for QUC Fellow (QUC Assistant professor) Positions	2023-10-25~2023-12-31	Admin
5	School of Physics	[Astrophysics] 2023-03 KIAS Recruitment Announcement for Research Fellow Positions	2023-10-25~2023-12-31	Admin
6	School of Physics	[Statistical Physics] 2023-02 KIAS Recruitment Announcement for Research Fellow Positions	2023-10-05~2023-12-31	Admin
7	Quantum Universe Center	[Quantum Field Theory & String Theory] 2023-02 KIAS Recruitment Announcement for QUC Research Fellow Positions	2023-10-25~2023-12-15	Admin
8	School of Physics	[Quantum Field Theory & String Theory] 2023-02 KIAS Recruitment Announcement for Research Fellow Positions	2023-10-25~2023-12-15	Admin
9	School of Physics	[Particle Physics] 2023-02 KIAS Recruitment Announcement for Research Fellow Positions	2023-10-25~2023-12-15	Admin
10	June E Huh Center for Mathematical Challenges	2023-02 CMC Fellow Positions in Mathematics	2023-10-04~2023-12-01	Admin