Dark matter, black holes, and gravitational waves

Gianfranco Bertone
GRAPPA center of excellence, U. of Amsterdam

DIFA Colloquium, U. of Bologna, 4/5/2023

GRAPPA
GRavitation AstroParticle Physics Amsterdam

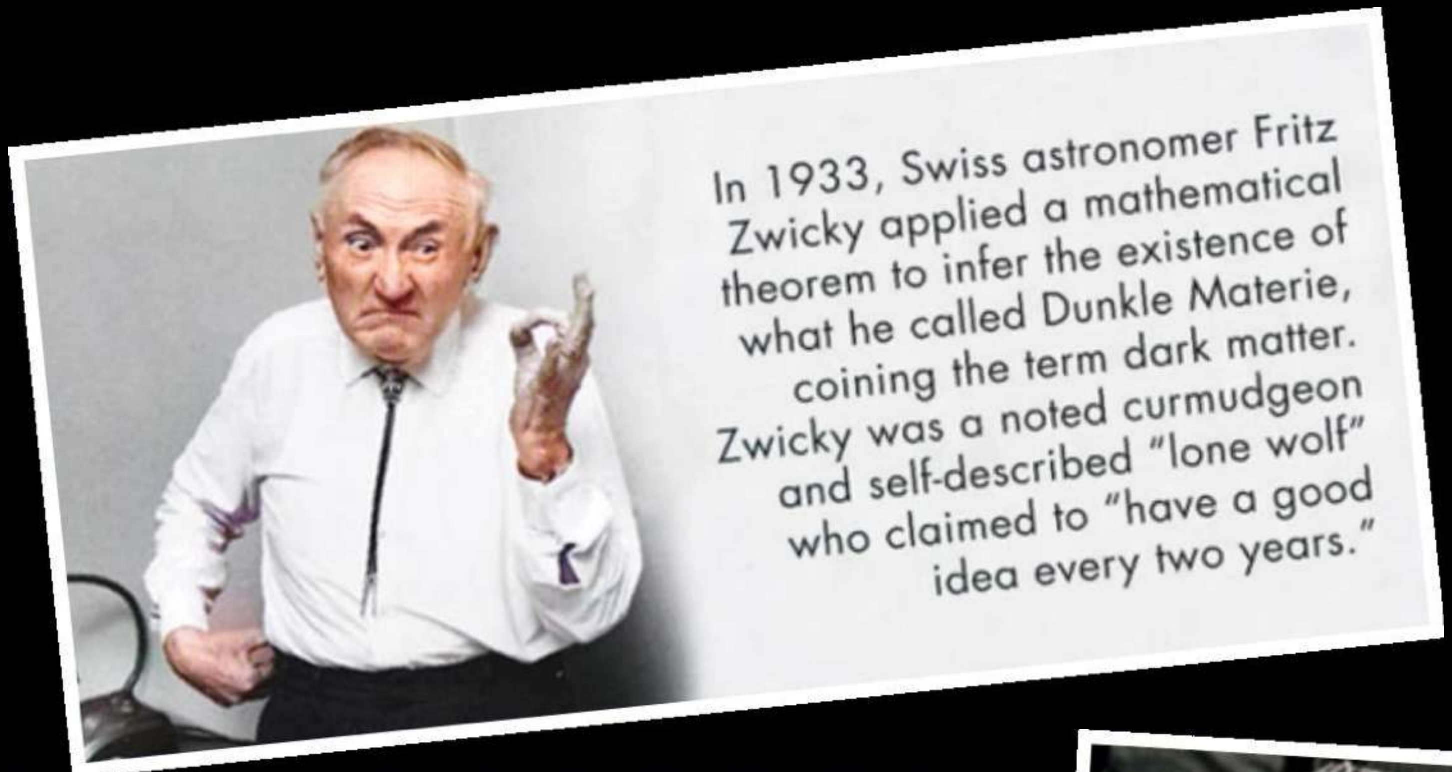
Plan of the talk:

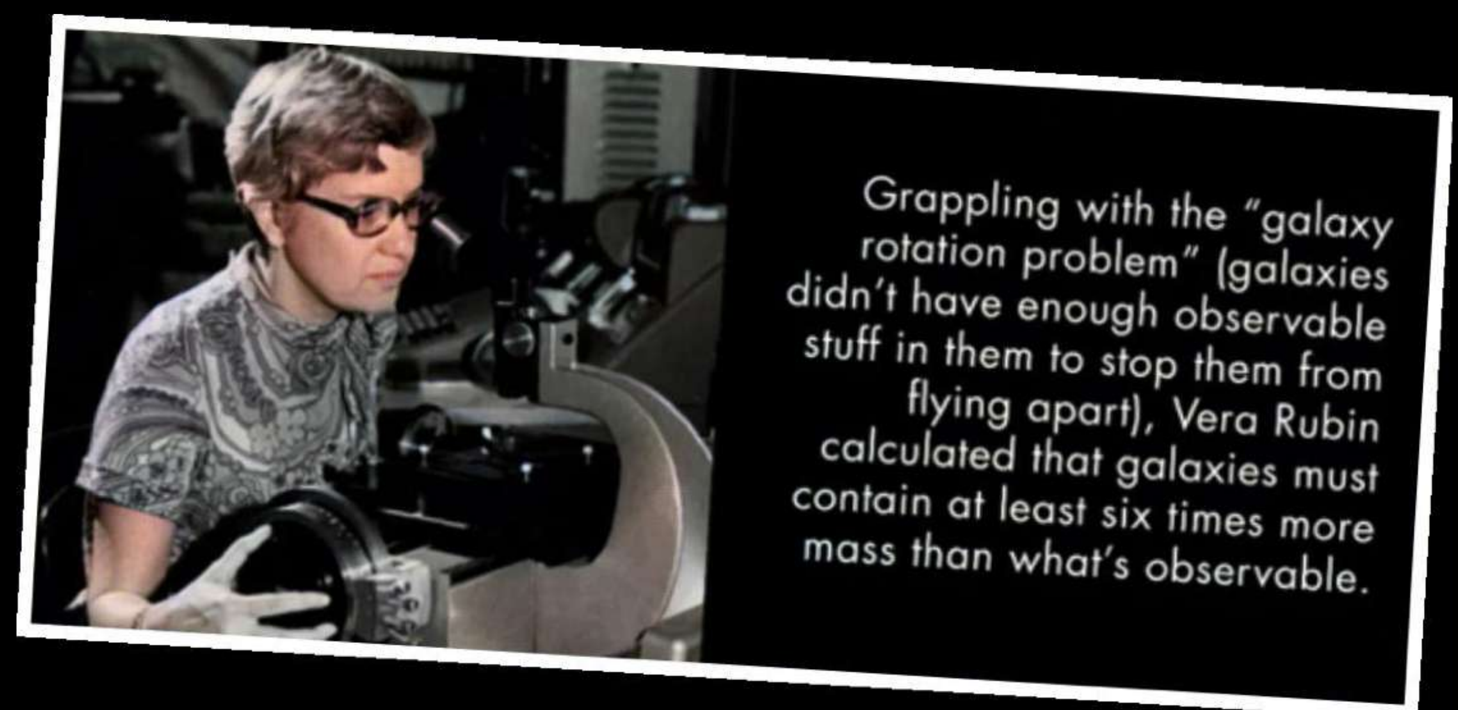
Prologue: the dark universe *narrative*

Part I: What have we learnt?

Part II: DM / BH / GWs

Dark Matter "Mythology"





Figures: Perimeter Institute

Did Zwicky coin the term *dark matter*?

How Far Do Cosmic Rays Travel?

Two entirely different suggestions have been advanced in the literature as to *where* the cosmic rays originate. The first suggestion is that cosmic rays are of local origin (upper earth atmosphere, our own planetary system, etc.). The other suggestion is that cosmic rays are produced or have been produced throughout the universe, or even more specifically, throughout interstellar or intergalactic spaces. This latter view has especially been advanced by R. A. Millikan.

The purpose of this paper is to examine these hypotheses somewhat more closely and to establish a relation between them and the red shift of extragalactic-nebulae.

Suppose that on the basis of the second suggestion mentioned above, the generation of cosmic rays is given as ϵ erg/cm^3 sec., where $\epsilon=\epsilon(r)$ is only a function of the distance r from the observer. Then the radiation intensity σ from a half sphere of radius R is given by

$$\sigma=\frac{1}{4}\int_0^R \epsilon(r)dr \text{ in ergs/cm}^2\text{ sec.} \qquad (1)$$

Provided that $\epsilon(r)=\epsilon_0=$ constant, this gives

$$\sigma=\epsilon_0 R/4. \qquad (2)$$

We know, however, that, because of the red shift

$$\epsilon(r)=\epsilon_0(1-r/D) \qquad (3)$$

where $D\sim 2000\times 10^6$ light years. This gives

$$\sigma=(\epsilon_0 R/4)(1-R/2D) \qquad (4)$$

or if the red shift is proportional to r all the way up to $r=D$ the total intensity from the universe

$$\sigma_t=\epsilon_0 D/8. \qquad (5)$$

In these cases no light signal could ever reach us from distances $r>D$. In spite of an infinite number of luminous stars, σ_t would be finite and one of the old arguments for the necessity of a finite space would have to be discarded.

The difficulty which arises in relation to the suggestion that cosmic rays are created throughout intergalactic space now is this. According to the observational data the ratios of the intensity due to the galaxy σ_g and the intensity due to the rest of the universe σ_u are

$$a=\sigma_g/\sigma_u\gg 1 \text{ for visible light} \qquad (6)$$

$$b=\sigma_g/\sigma_u\ll 1 \text{ for the cosmic rays.} \qquad (7)$$

The ratio a/b is equal at the very least to a hundred. It is therefore impossible that the cosmic rays, if photons, come from luminous matter. Now according to the present estimates the average density of dark matter in our galaxy (ρ_g) and throughout the rest of the universe (ρ_u) are in the ratio

$$\rho_g/\rho_u>100{,}000. \qquad (8)$$

If we assume that the cosmic rays are produced at a rate proportional to the density, then it follows that the above ratio b for the cosmic rays according to (2) can only be explained if these rays are collected from all distances up to $10^7\times d$ light years where $d>10{,}000$ light years is the radius of our galaxy. This would correspond to a distance greater than 10^{11} light years. Now if the red shift were linear with distance all the time, no cosmic-ray photon could reach us from distances greater than 2×10^9 light years. The discrepancy becomes still worse, as Dr. Tolman kindly informs me, if the cosmic rays consist of any particles of matter such as electrons or neutrons.

The following suggestions might be advanced in order to remove the above discrepancy.

(1) The extragalactic red shift may increase less than proportional to the distance for very great distances. The corresponding Doppler velocity at great distances however must then relatively soon approach quite closely the velocity of light in order to prevent a too great amount of visible light reaching us from distant hot stars (O, B-stars, etc.). It is also to be remembered that the simple Einstein-de Sitter theory requires the red shift to increase faster than the distance.

(2) The ratio (8) may be much smaller than assumed above. Difficulties however may arise contradicting the so far observed emptiness of extragalactic space. It is also to be remembered that cosmic rays at any rate are probably more strongly absorbed by any kind of interstellar matter than visible light.

(3) The "chemical reaction" producing the cosmic rays may be of a negative order, that is, it might be *proportional to some inverse power of the density*. One might picture, for instance, a set of quantum states of space which according to the exclusion principle is entirely filled up at higher densities. Free states might exist at very low densities and facilitate processes which are not possible at higher pressures.

(4) Cosmic rays may have been produced at a time when the universe was in an entirely different state than it is

How far do cosmic rays travel? January 9, 1933

No..

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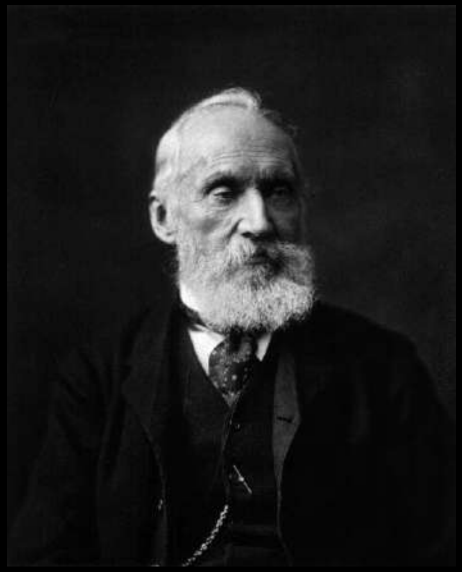
January 9, 1933

Dark matter: a problem with a long history..



Lord Kelvin (1904)

"Many of our stars, perhaps a great majority of them, may be dark bodies."

The term dark matter has been in use since early 1900s

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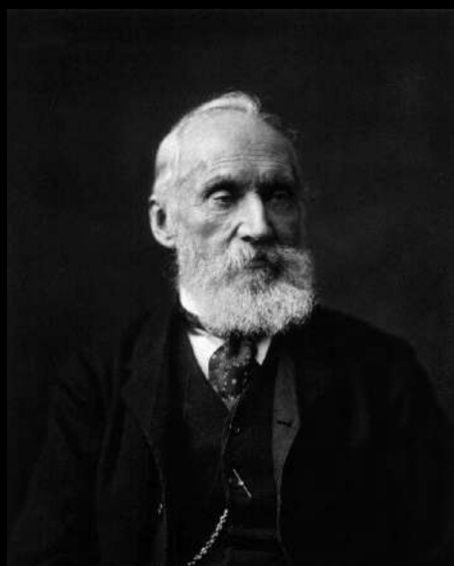

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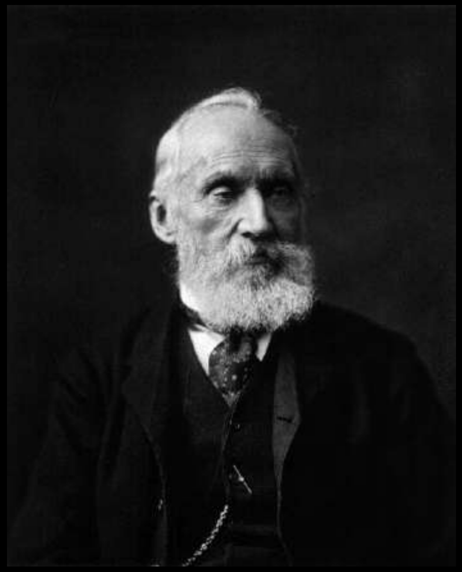

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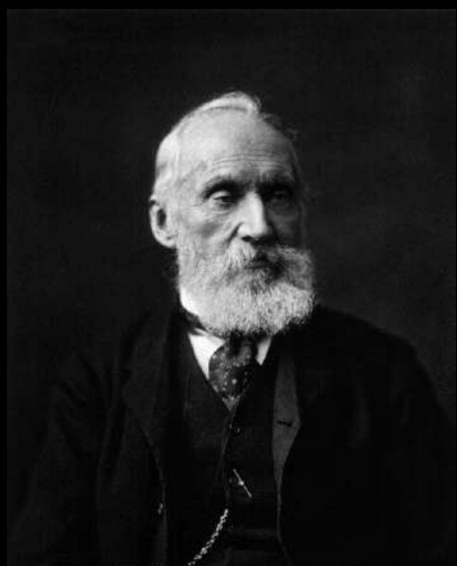
Albert Einstein (1921)

Applies virial theorem to star cluster: *"the non luminous masses contribute no higher order of magnitude to the total mass than the luminous masses"*

Virial theorem had been applied to (stellar) clusters way before Zwicky…

Dark matter: a problem with a long history..



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Fritz Zwicky (1933)

"According to present estimates the average density of dark matter in our galaxy and throughout the rest of the universe are in the ratio 10^5"

"Dark matter" used by Zwicky before his Coma cluster paper…

Dark matter: a problem with a long history..

FERMILAB-PUB-16-157-A

A History of Dark Matter

Gianfranco Bertone[1] and Dan Hooper[2,3]
[1] *GRAPPA, University of Amsterdam, Netherlands*
[2] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, USA and*
[3] *Department of Astronomy and Astrophysics, The University of Chicago, USA*

(Dated: May 26, 2016)

Although dark matter is a central element of modern cosmology, the history of how it became accepted as part of the dominant paradigm is often ignored or condensed into a brief anecdotical account focused around the work of a few pioneering scientists. The aim of this review is to provide the reader with a broader historical perspective on the observational discoveries and the theoretical arguments that led the scientific community to adopt dark matter as an essential part of the standard cosmological model.

arXiv:1605.04909v2 [astro-ph.CO] 24 May 2016

"A history of Dark Matter" GB & Hooper - RMP *1605.04909*

HOW DARK MATTER CAME TO MATTER

JACO DE SWART
Institute of Physics
University of Amsterdam

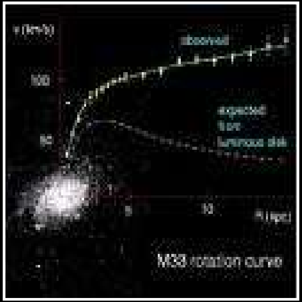
Ph.D. Thesis

October 2021 – version 2.0

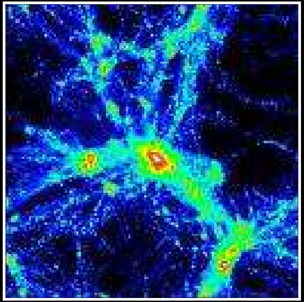
"How dark matter came to matter" de Swart, GB, van Dongen - Nature Astronomy; *1703.00013*

What is the Universe made of?

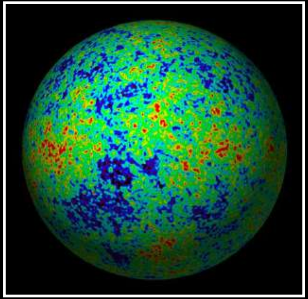
OBSERVATIONS



- Rotation Curves



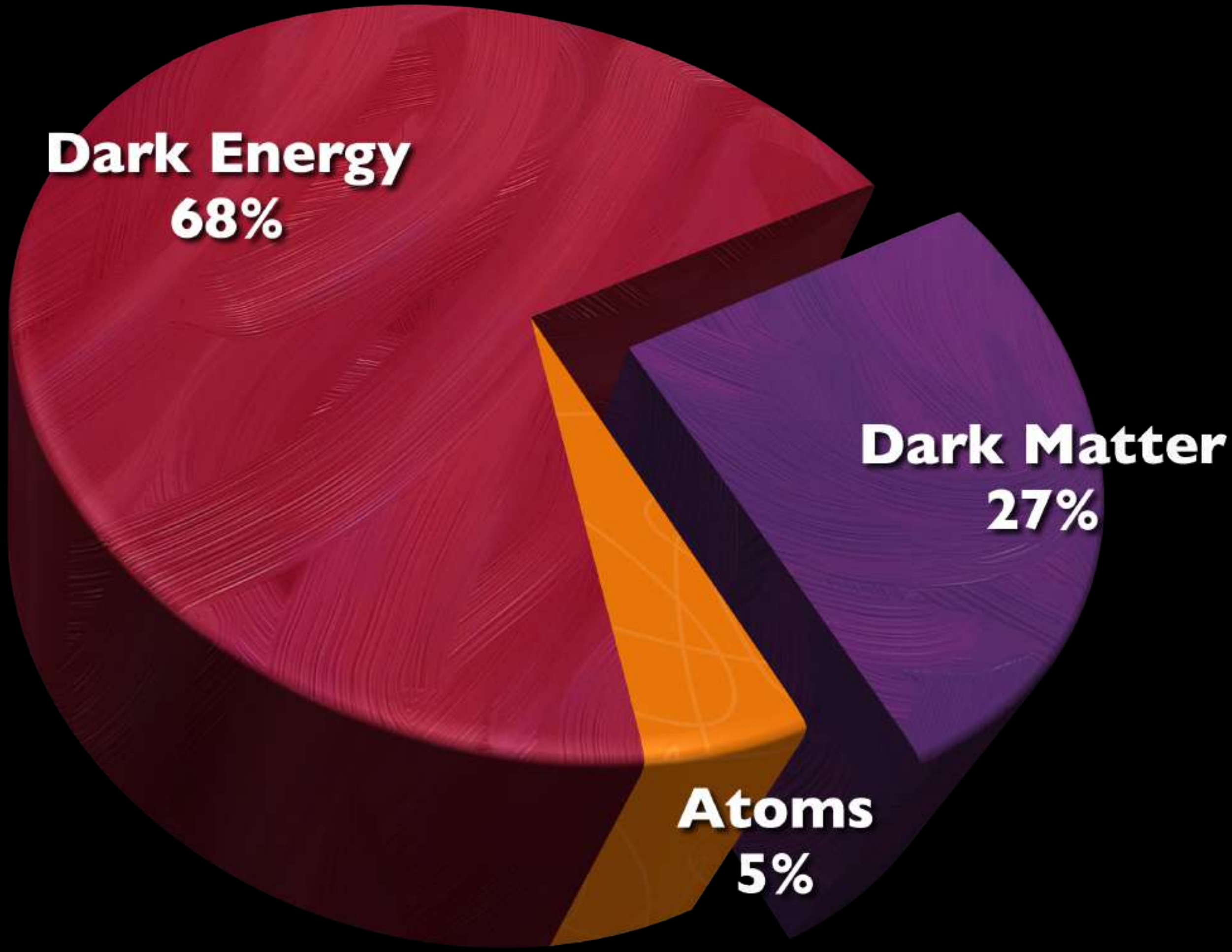
- Clusters of galaxies



- CMB

- Type Ia Supernovae

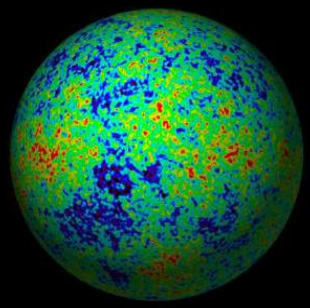
...

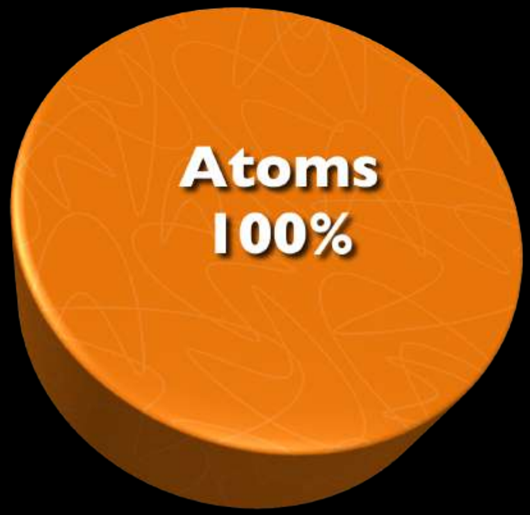


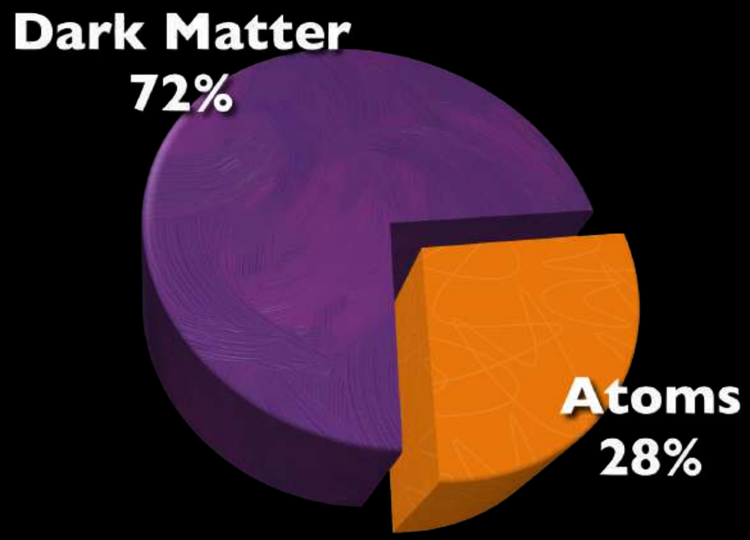
[statement valid _now_, and on _very large scales_]

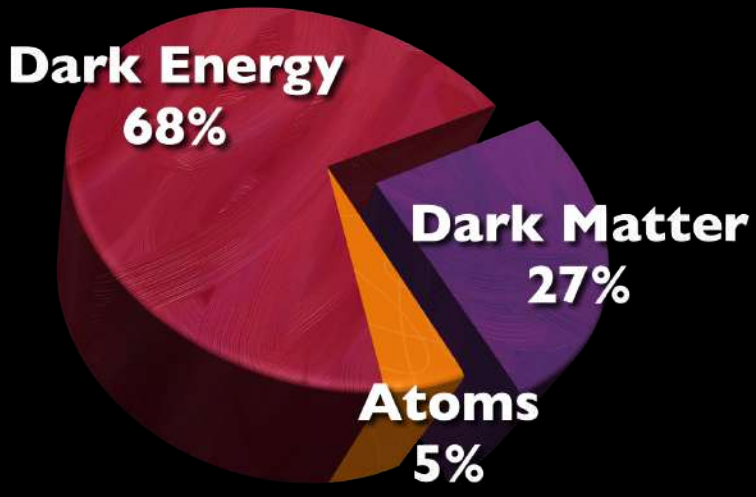
What is the Universe made of?

Posti & Helmi, A&A 621, A56 (2019)



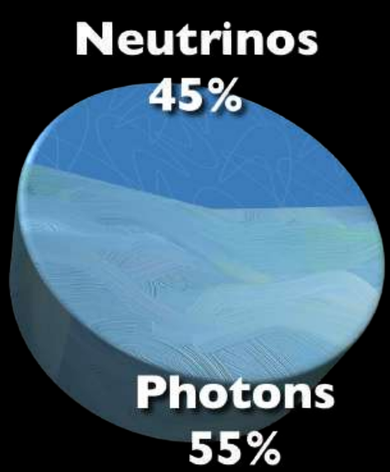




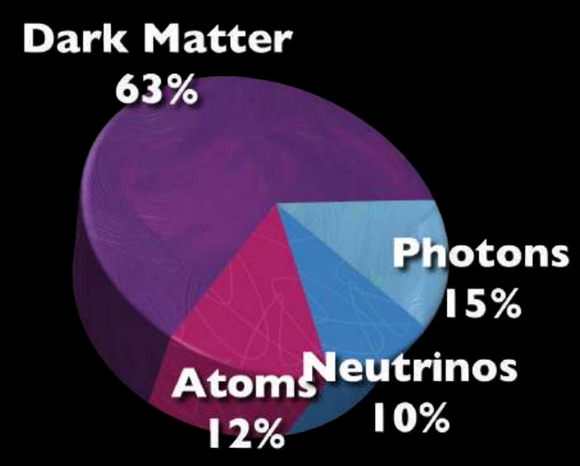


What <u>was</u> the Universe made of?

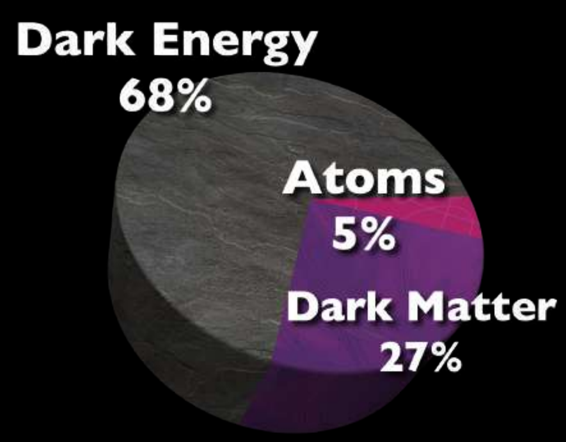
At BBN



At recombination

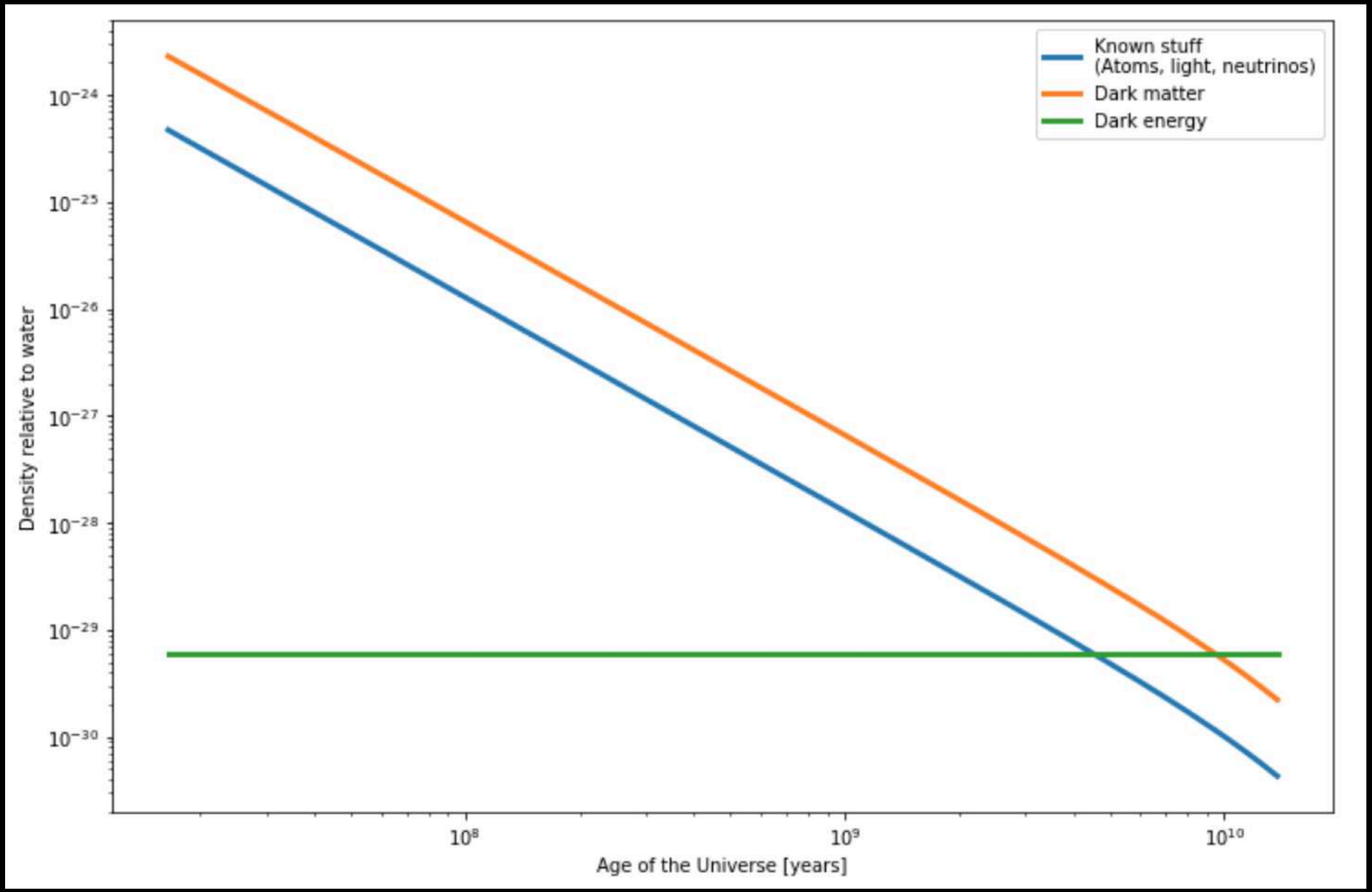


Today



…eventually

Evolution of matter/energy density



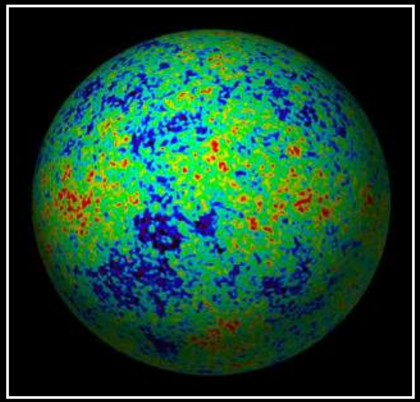
Created with #astropy https://astropy.org, astropy.cosmology package https://docs.astropy.org/en/stable/cosmology/

Simulating Galaxy Formation

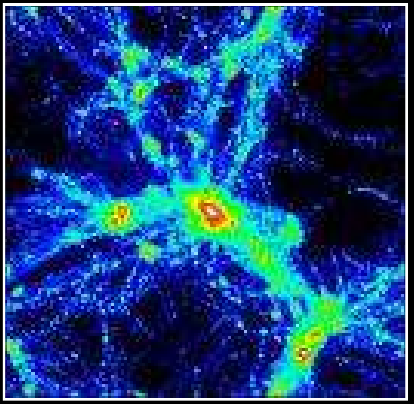
http://www.illustris-project.org/media/

Can ‘x’ be the DM in the Universe?

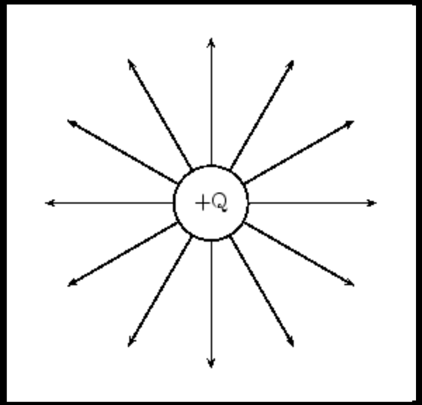
1) Abundance ok?



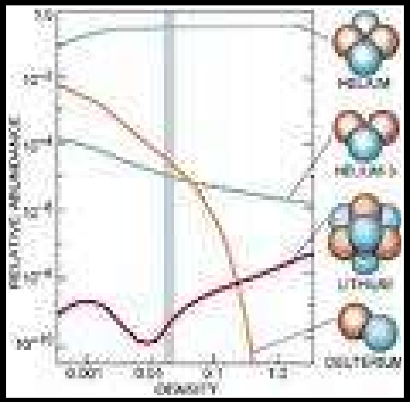
2) Cold?



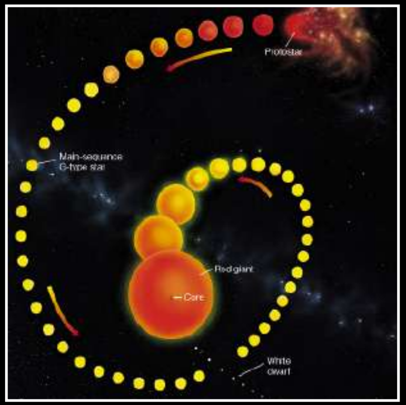
3) Neutral?



4) BBN ok?



5) Stars OK?



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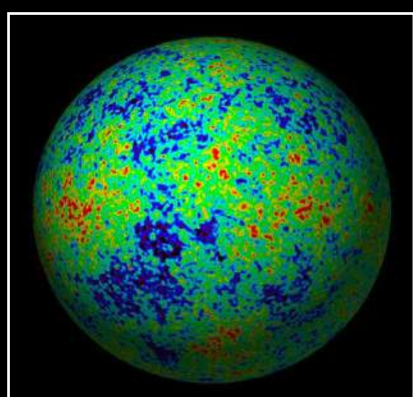

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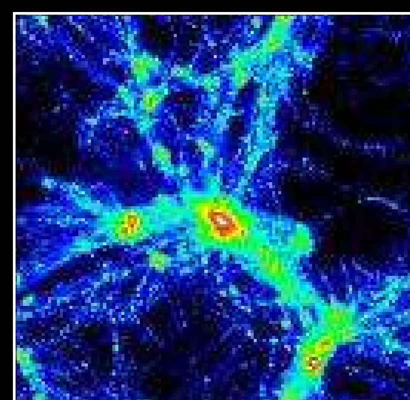

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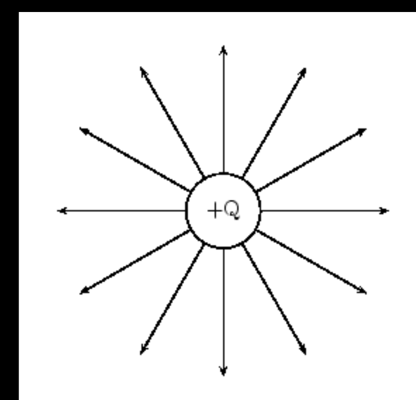

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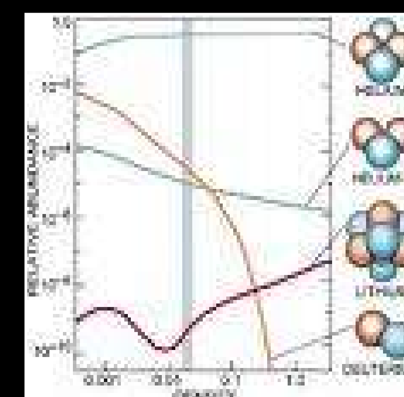

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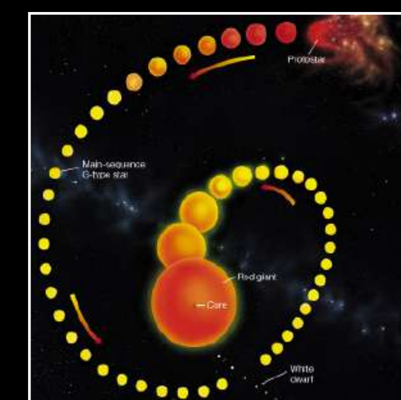
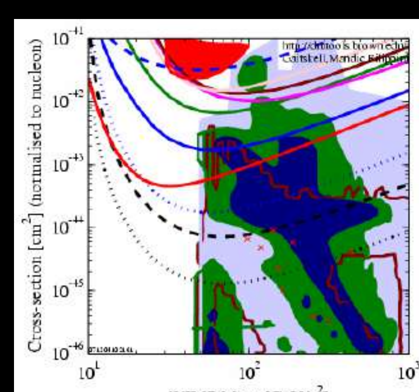
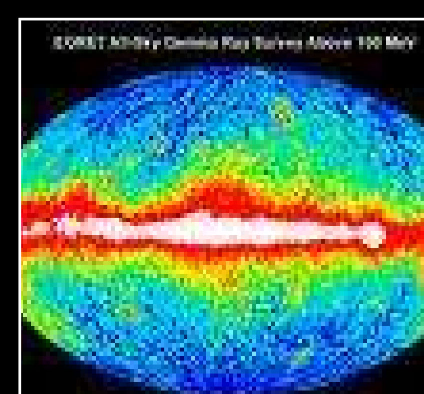


6) Collisionless?

7) Couplings OK?

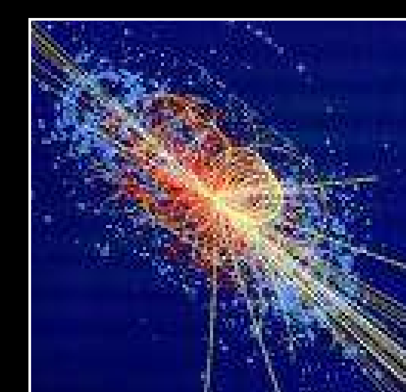


8) γ-rays OK?



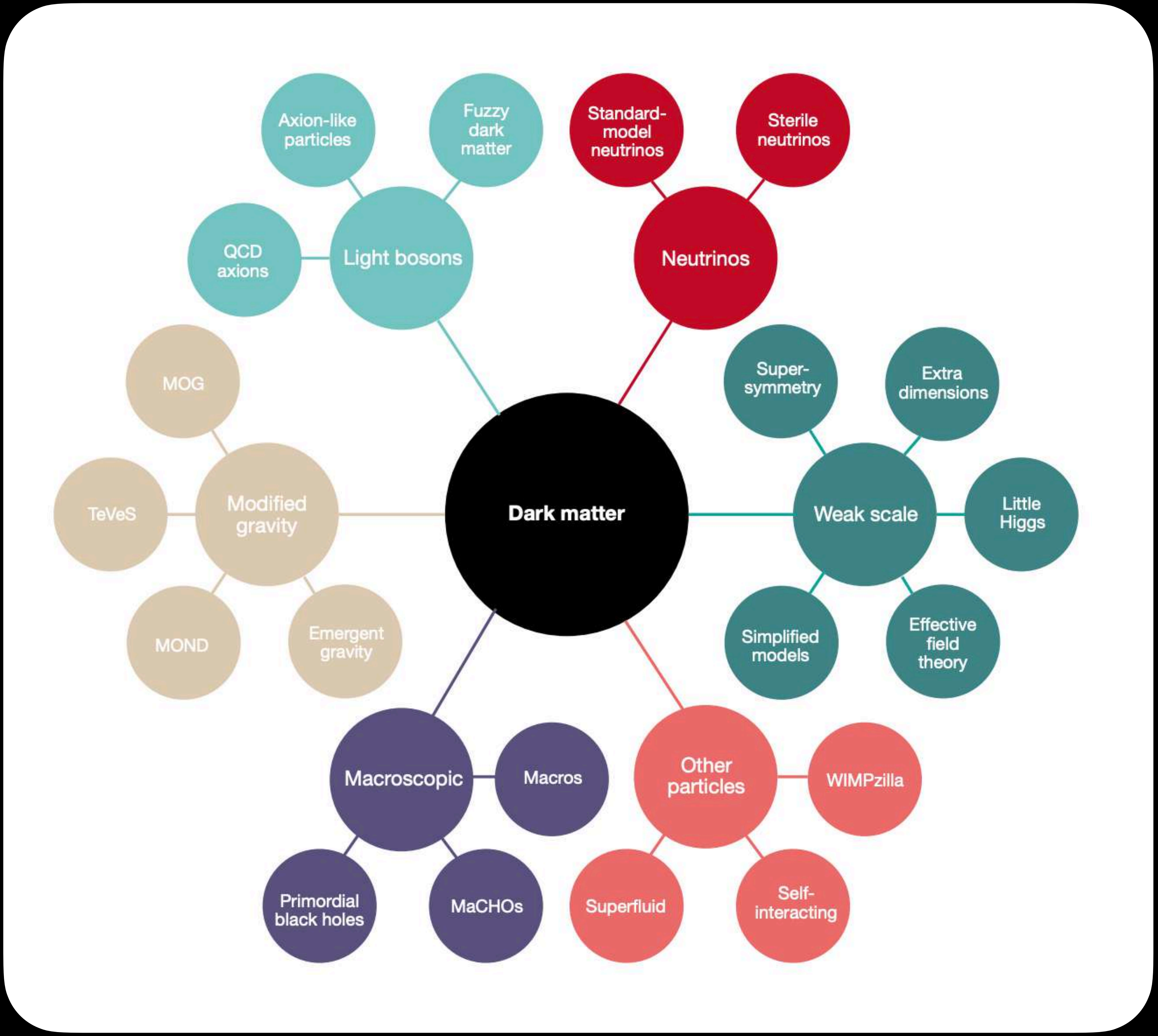
9) Astro bounds?

10) Can probe it?



Taoso, GB, Masiero 0711.4996

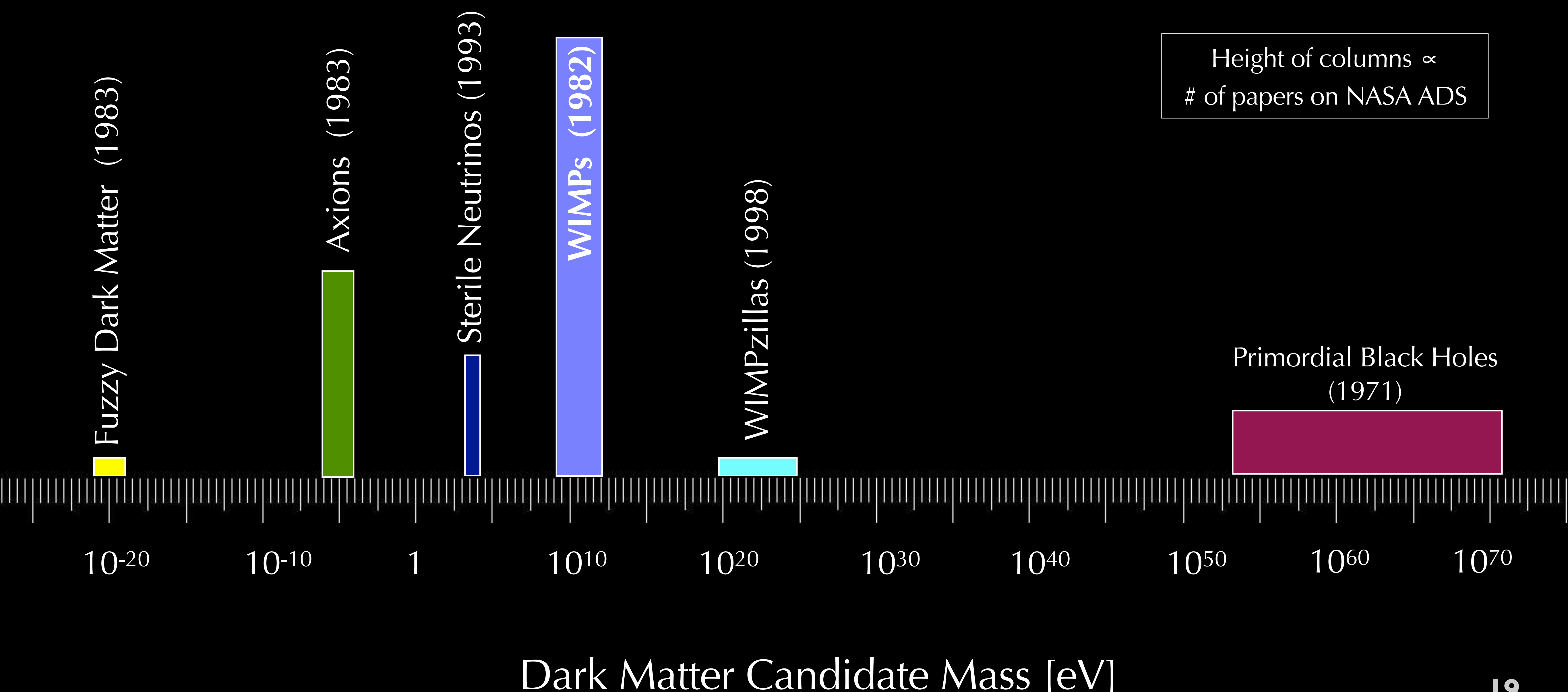
Candidates



GB, Tait, *Nature (2018) 1810.01668*

Candidates

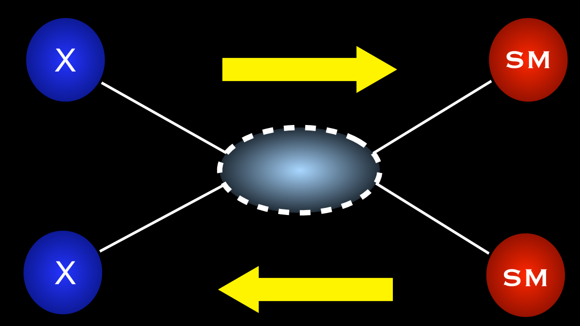
- No shortage of ideas..
- Tens of dark matter models, each with its own phenomenology
- Models span 90 orders of magnitude in DM candidate mass!



WIMPs

By far the most studied class of dark matter candidates.

The WIMP paradigm is based on a simple yet powerful idea:



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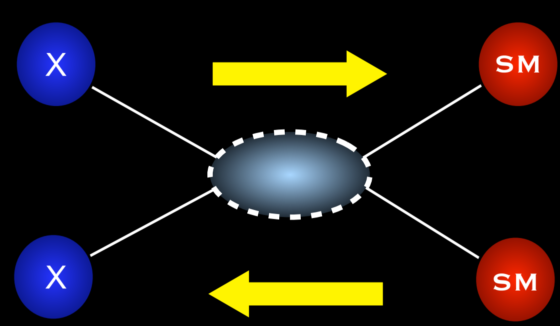


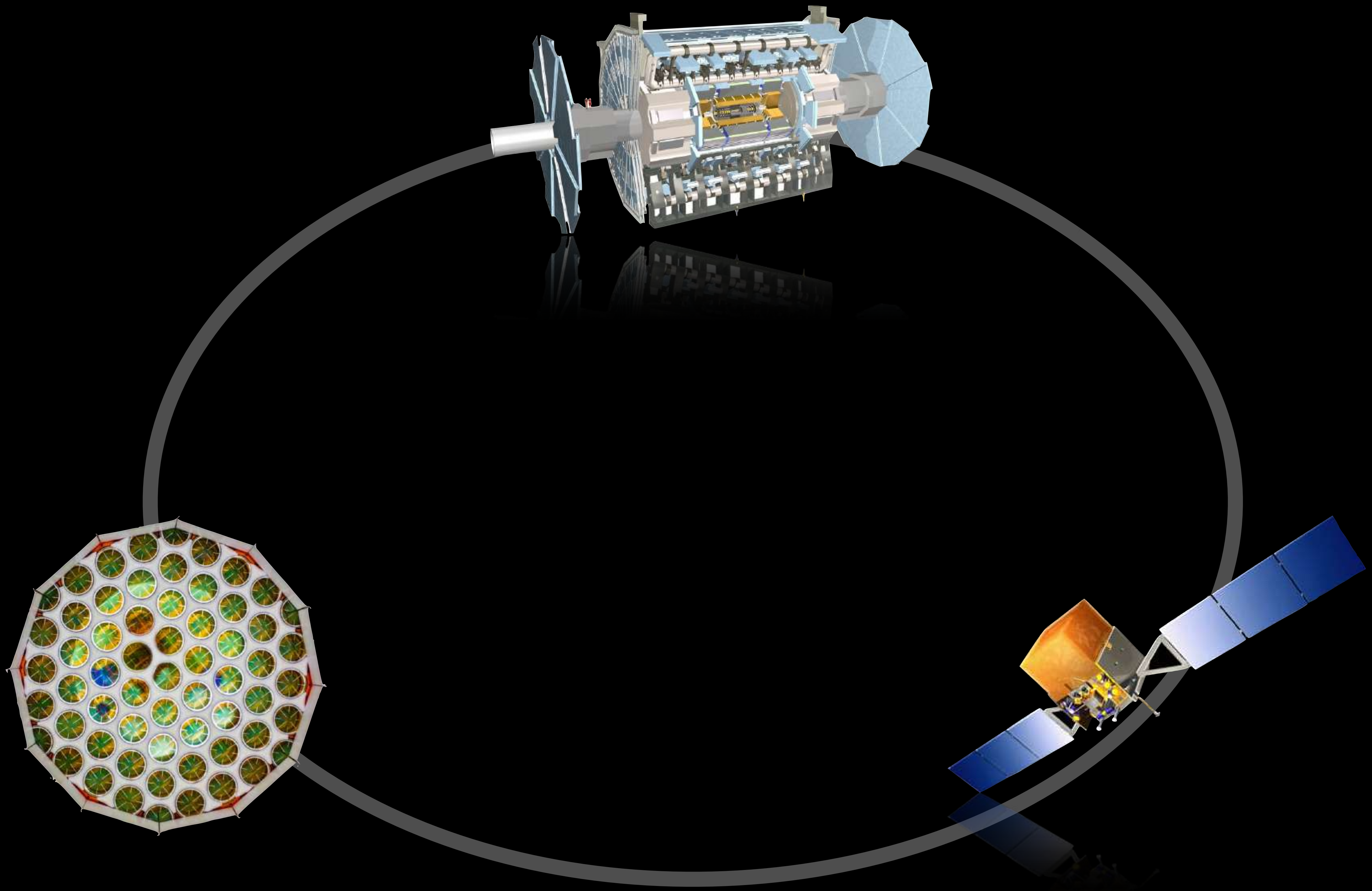
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Weak-scale cross sections can reproduce observed relic density

$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

'WIMP miracle': new physics at ~1TeV solves at same time fundamental problems of particle physics (*hierarchy problem*) AND DM

WIMPs searches



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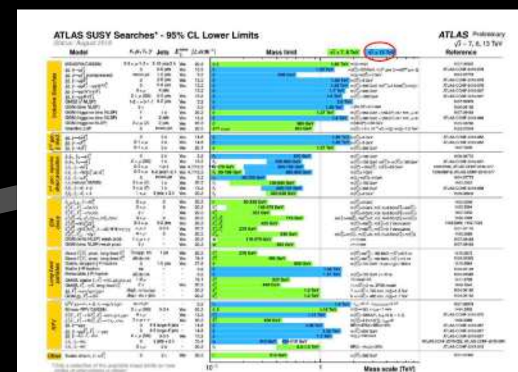
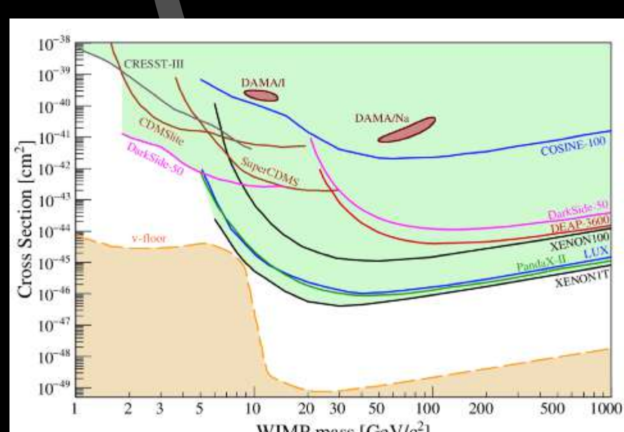
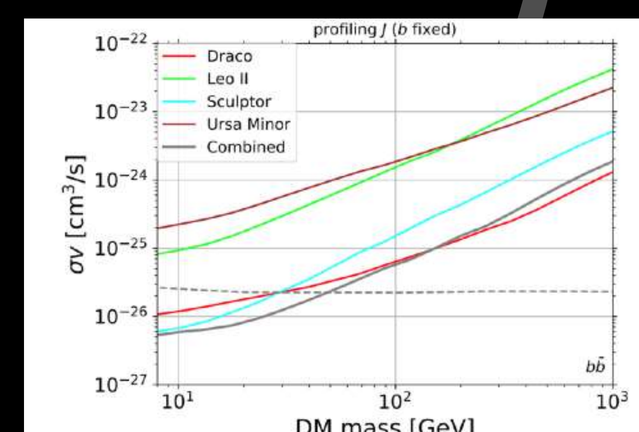


Where are the WIMPs?





Are WIMPs ruled out?

NO

absence of evidence ≠ evidence of absence

Are WIMPs ruled out?

ATLAS/CMS searches do put pressure on SUSY, and in general on "naturalness" arguments (e.g. Giudice 1710.07663).

However:

I. Non-fine tuned SUSY DM scenarios still exist (Beekveld+ 1906.10706)

II. WIMP paradigm ≠ WIMP miracle: particles at ~ EW scale may exist irrespectively of naturalness + achieve right relic density, thus be = DM

III. Clear way forward: 15 years of LHC data + DD experiments all the way to "neutrino floor"

Plan of the talk:

Preamble: the dark universe *narrative*

Part I: DM - what have we learnt?

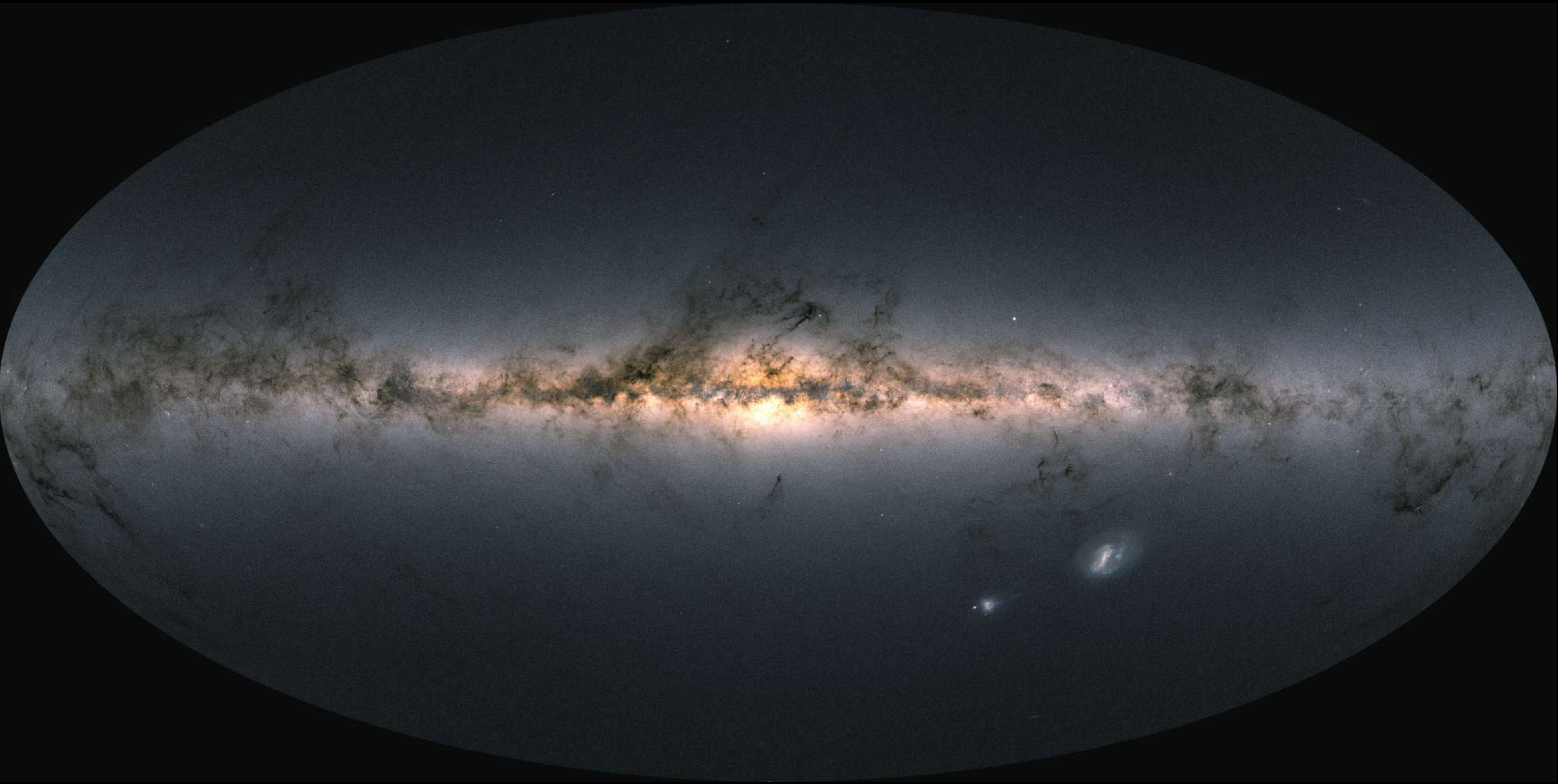
Part II: A new era in the quest for DM

A new era in the search for DM

GB, Tait, *Nature (2018)1810.01668*

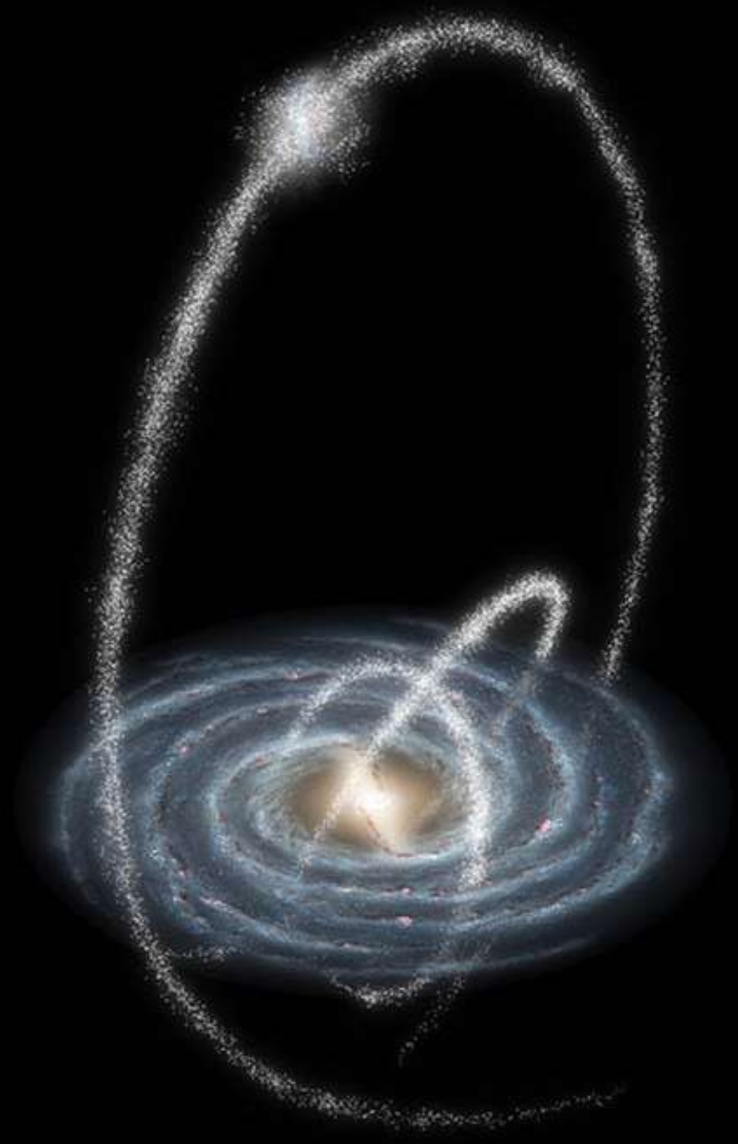
I. Broaden/improve/diversify searches
II. Exploit astro/cosmo observations
III. Exploit Gravitational Waves

GAIA'S SKY

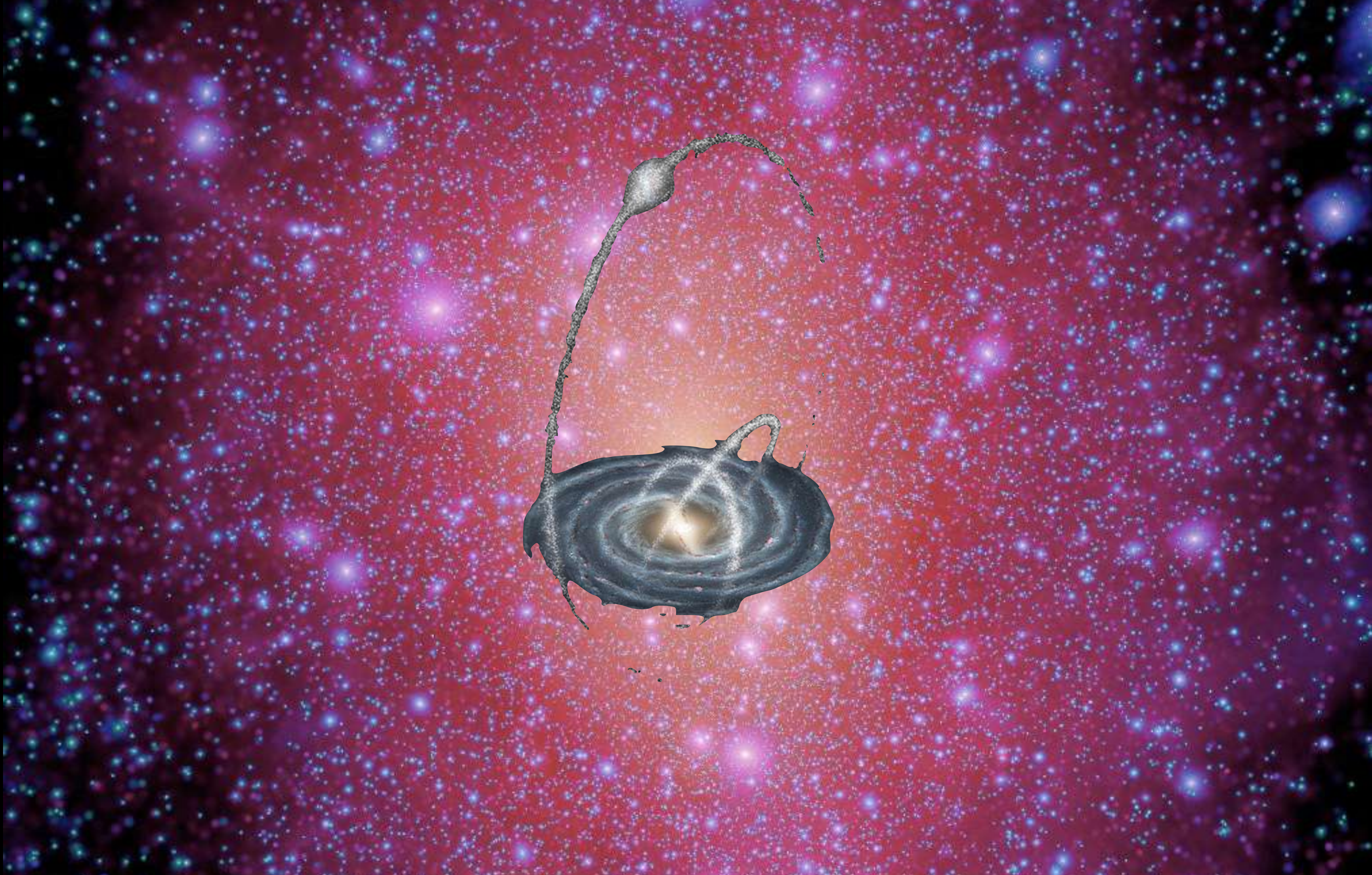


Total brightness and colour of stars observed by ESA's Gaia satellite and released as part of Gaia's Early Data Release 3

Stellar streams



Searching for dark matter substructures in the MW



The future of dark matter searches

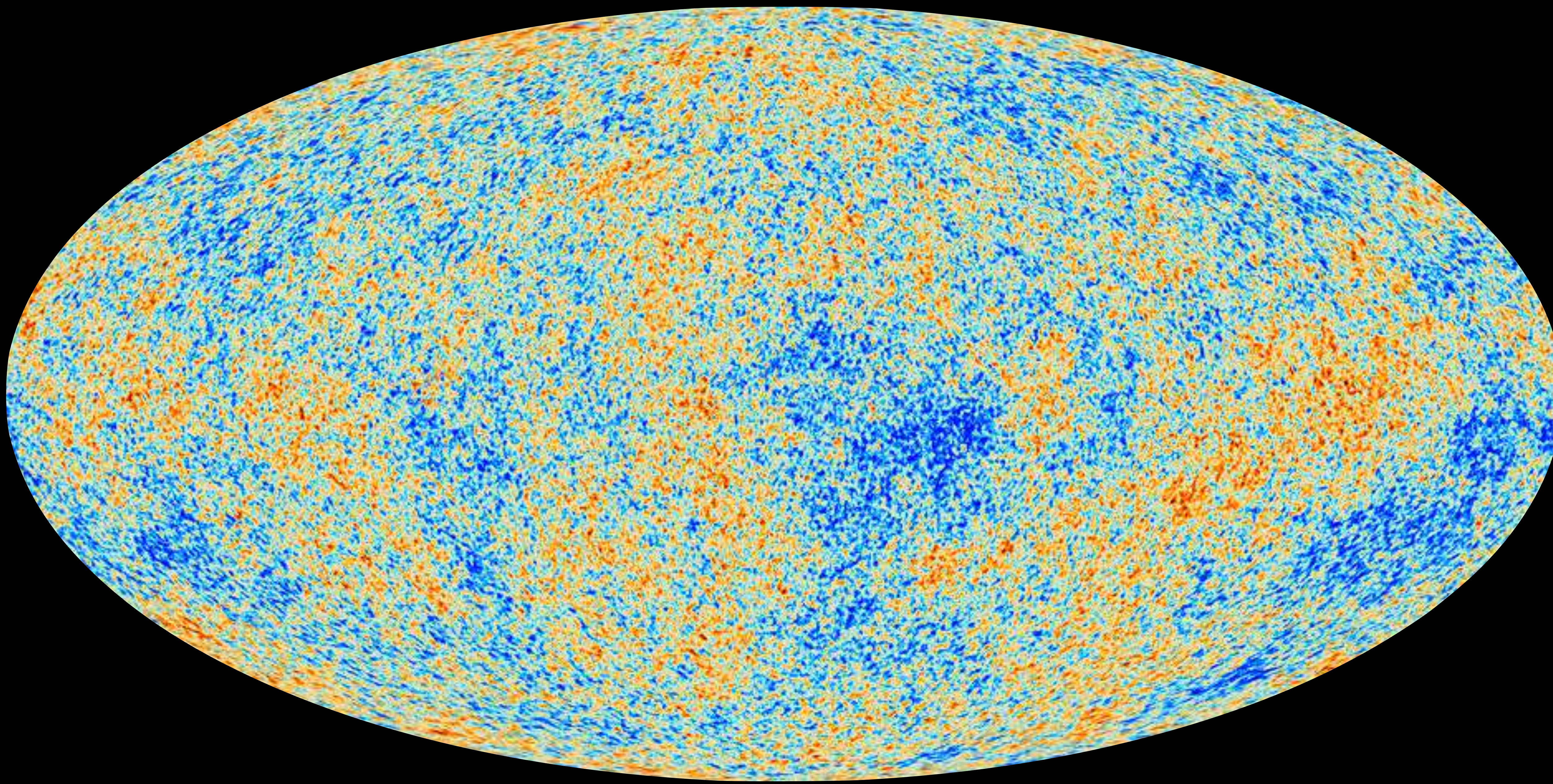
I. Broaden/improve/diversify searches

II. Exploit astro/cosmo observations

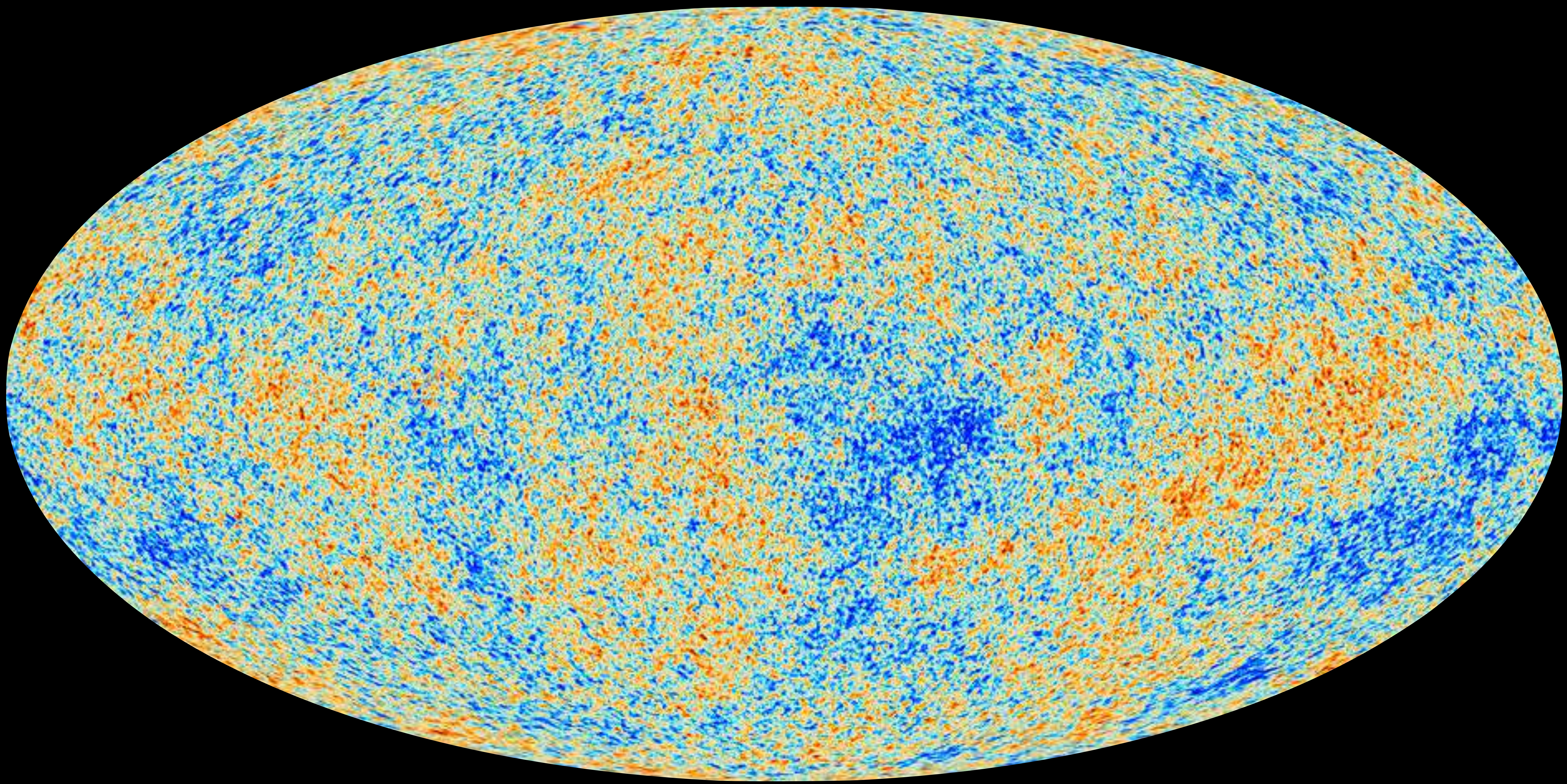
III. Exploit Gravitational Waves

$$DM \stackrel{?}{=} BHs$$

Dark matter was present already in the early universe



Dark matter was present already in the early universe..



..DM could be made of BHs, as long as they are *primordial* (not “astrophysical”)

Primordial Black Holes

Mon. Not. R. astr. Soc. (1971) **152,** 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

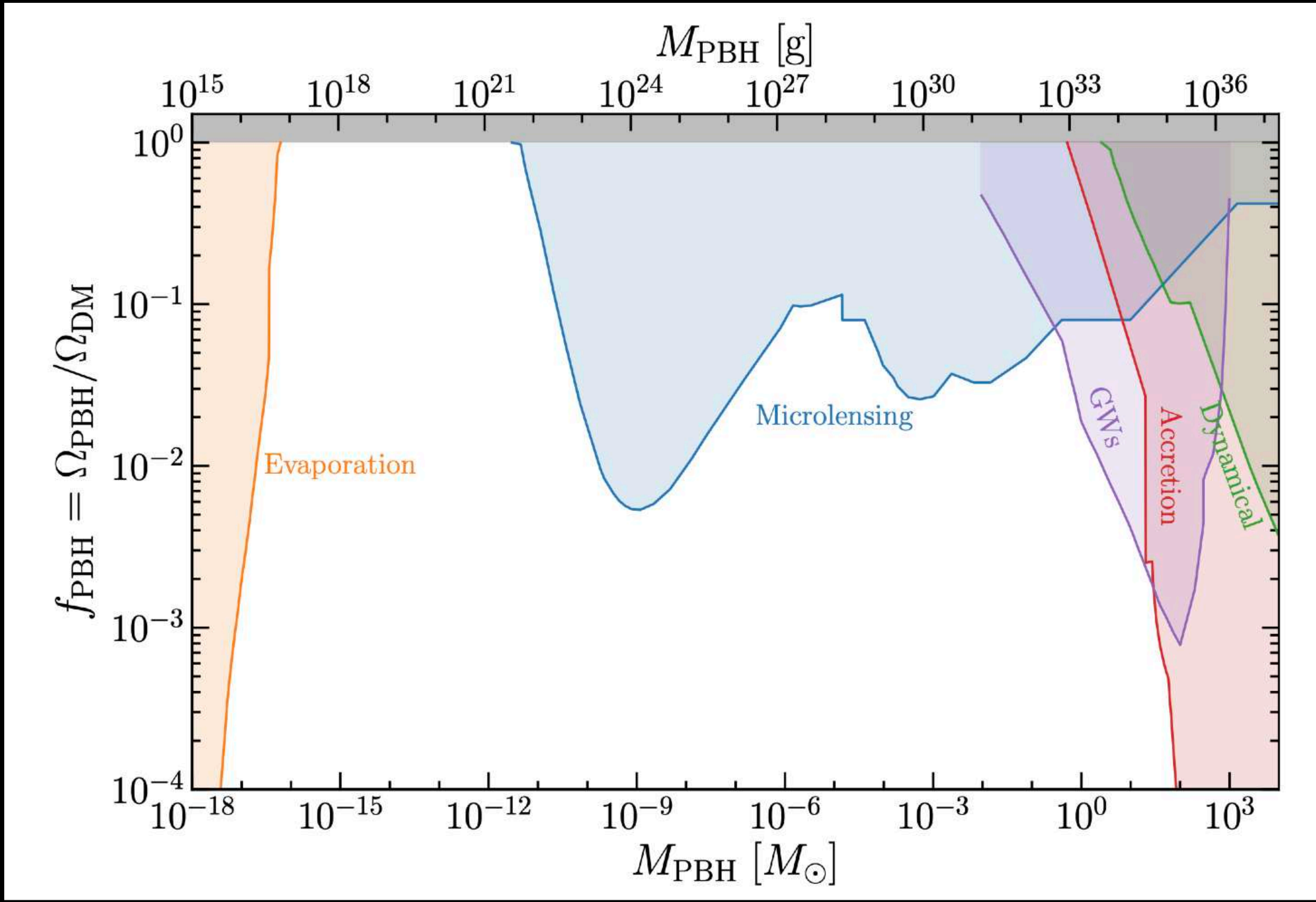
Stephen Hawking

(Communicated by M. J. Rees)

(Received 1970 November 9)

An upper bound on the number of these objects can be set from the measurements by Sandage (**7**) of the deceleration of the expansion of the Universe. These measurements indicate that the average density of the Universe cannot be greater than about 10^{-28} g cm^{-2}. Since the average density of visible matter is only about 10^{-31} g cm^{-2}, it is tempting to suppose that the major part of the mass of the Universe is in the form of collapsed objects. This extra density could stabilize clusters of galaxies which, otherwise, appear mostly not to be gravitationally bound.

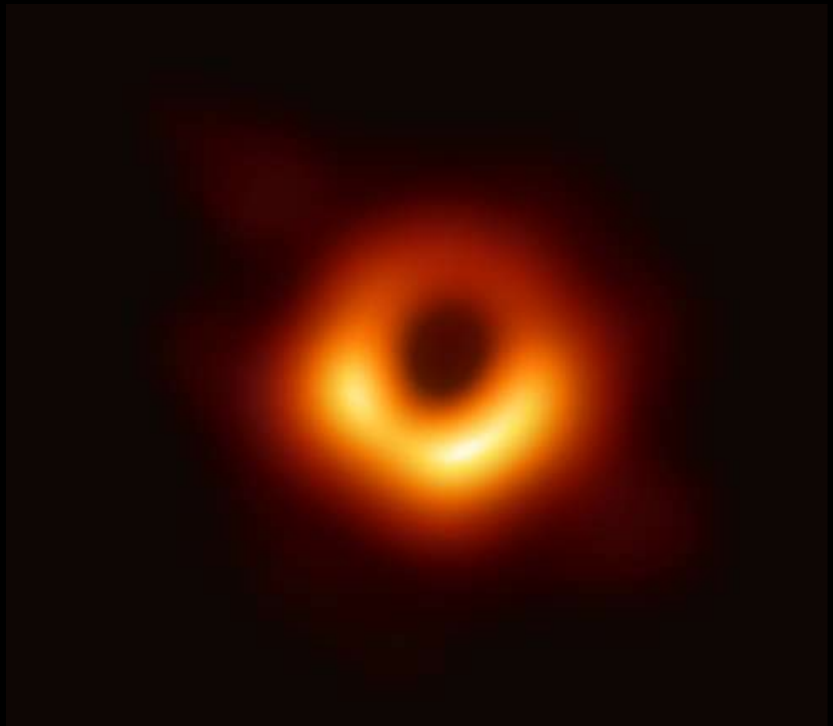
Constraints on BHs abundance



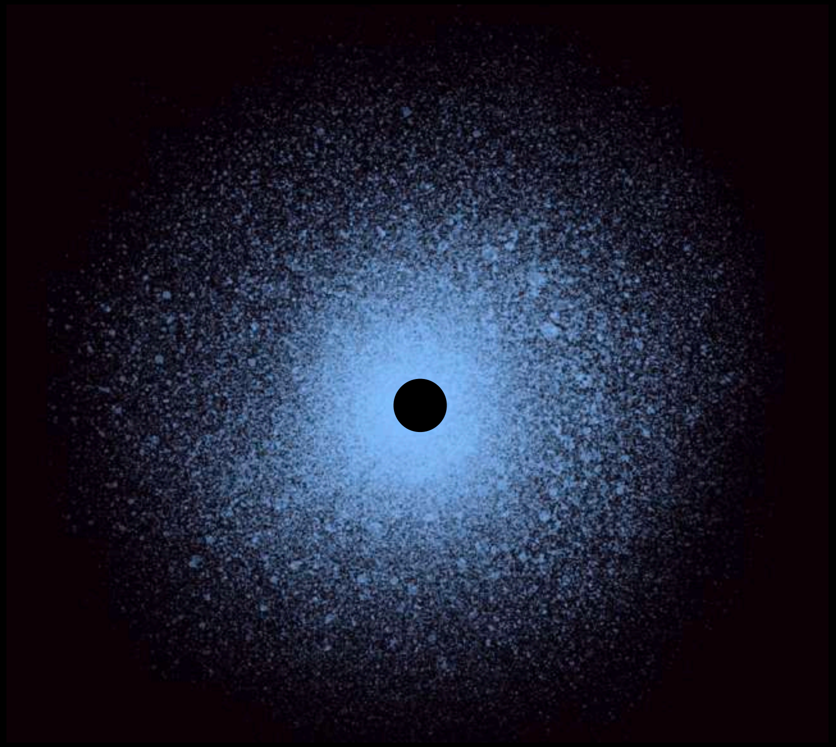
Green & Kavanagh 2007.10722

DM *around* BHs?

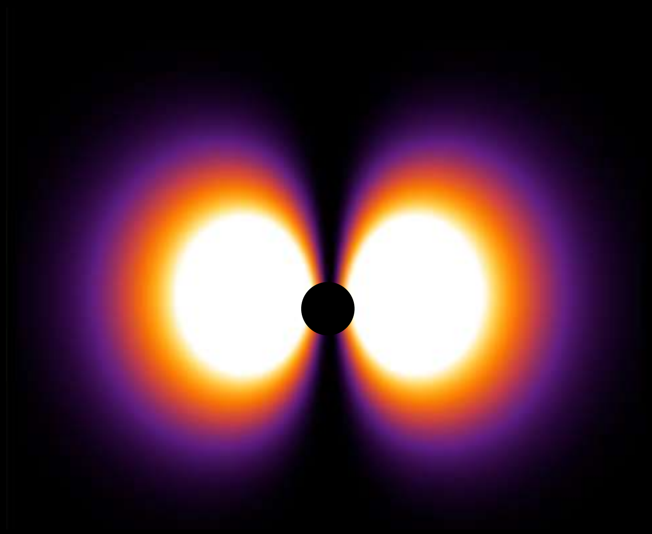
BH environments



Accretion discs

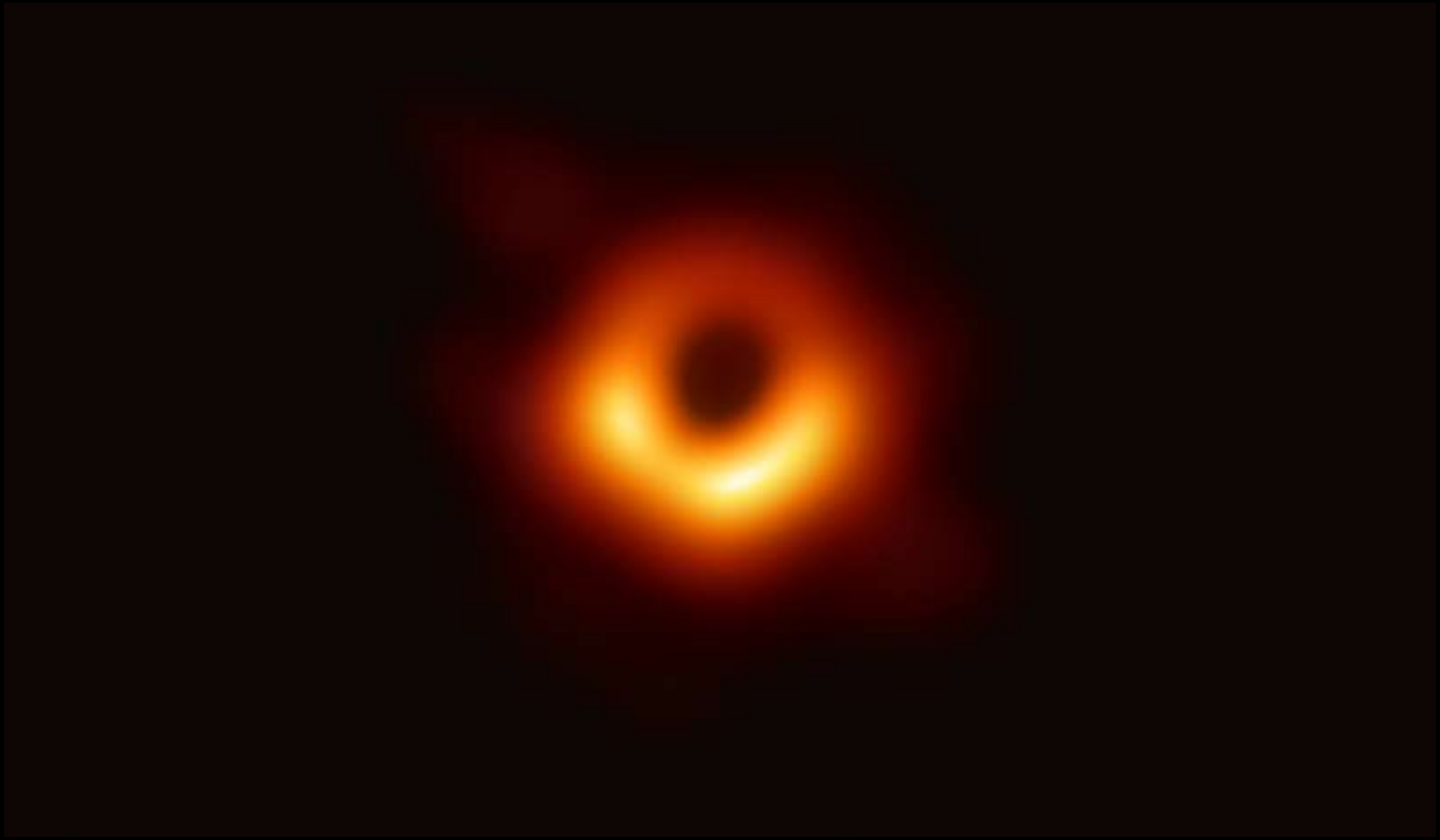


DM ‘spikes’



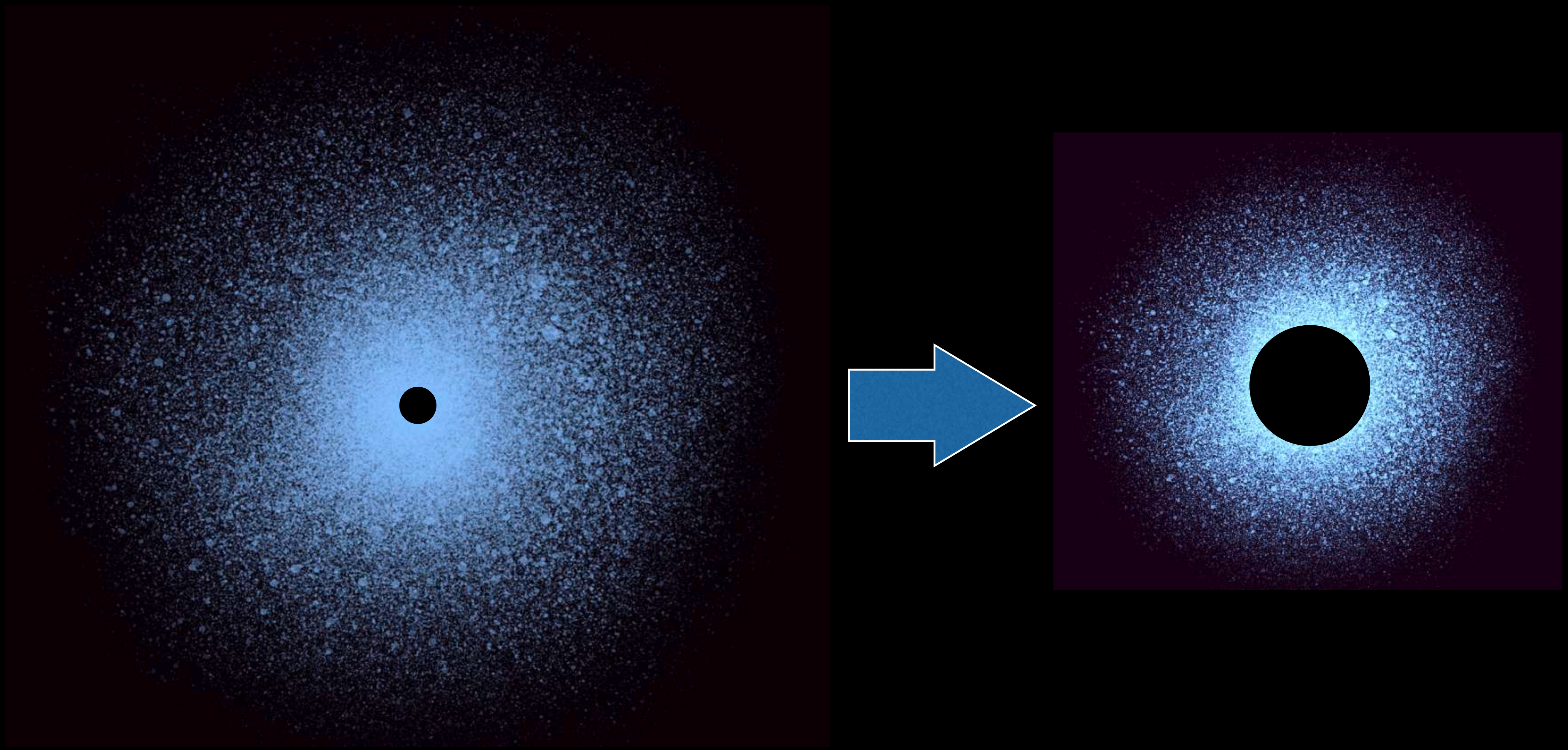
Gravitational atoms

Accretion discs

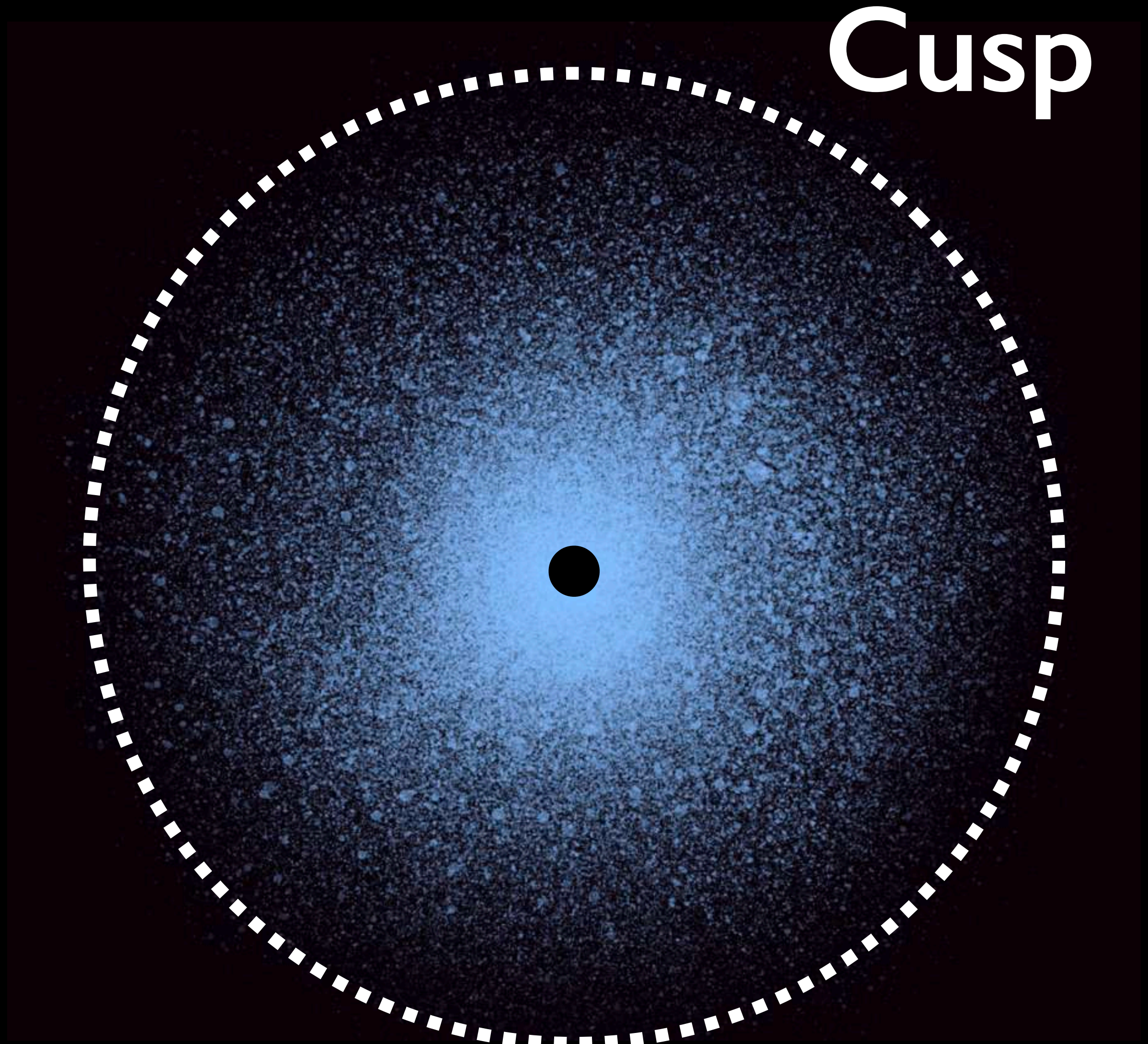


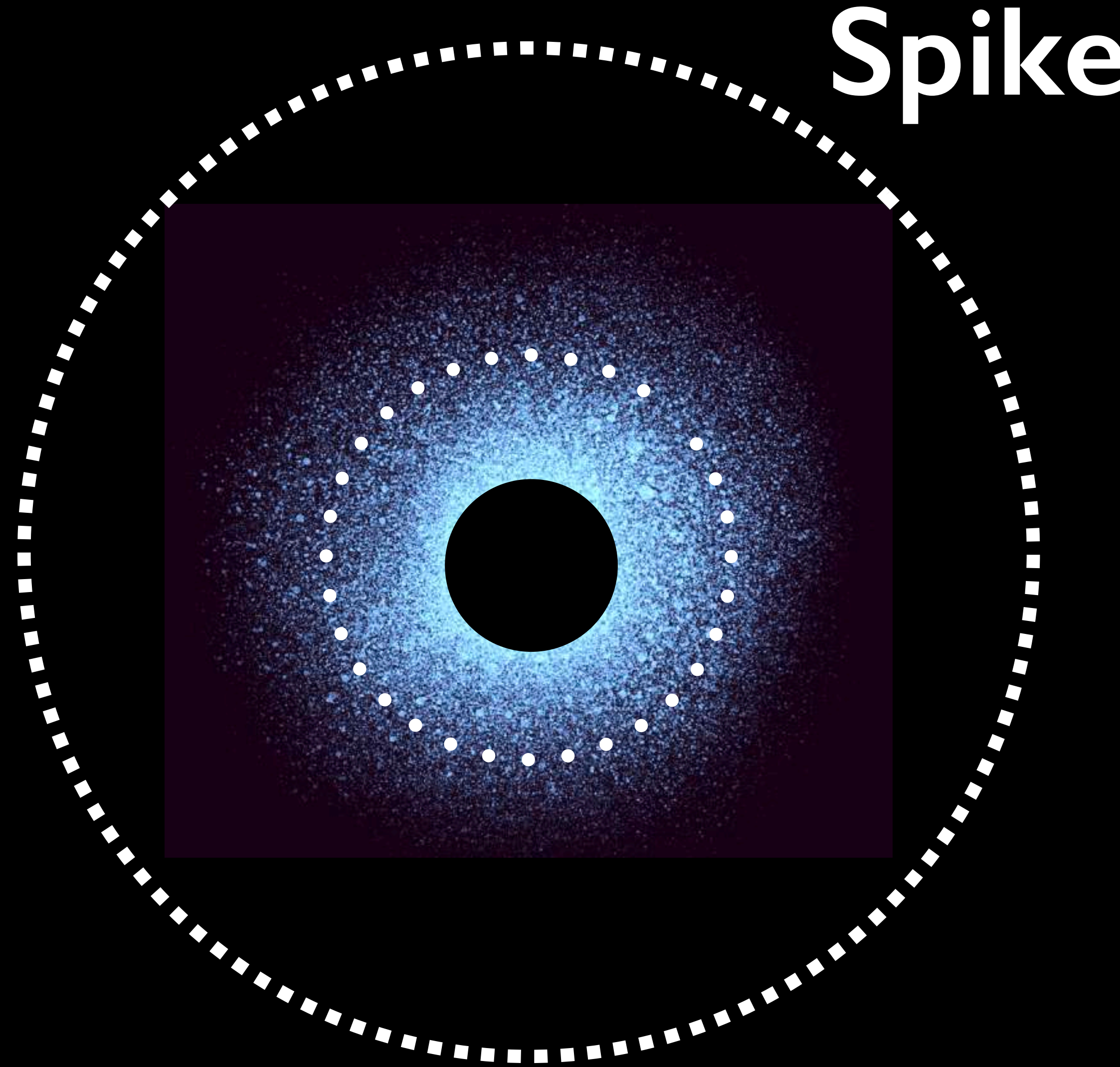
Event Horizon Telescope 2019

DM ‘spikes’ around Astrophysical BHs



DM ‘spikes’ around SMBH and IMBH

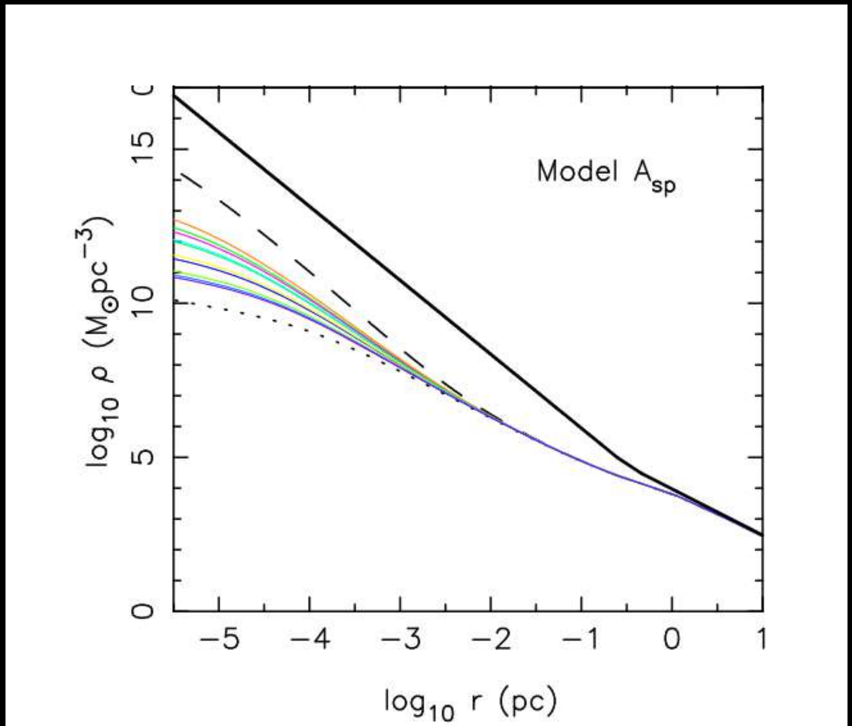




$$\rho_{\rm cusp}(r) \sim r^{-\gamma}$$

$$\rho_{\rm spike}(r) \sim r^{-\gamma_{\rm sp}}\ ,\ \gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma}$$

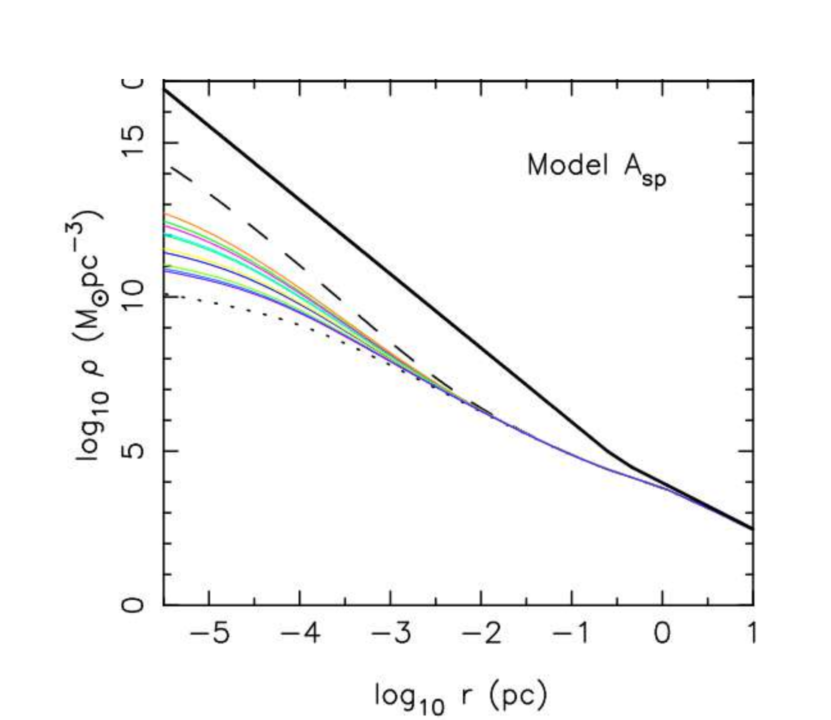
DM ‘spikes’



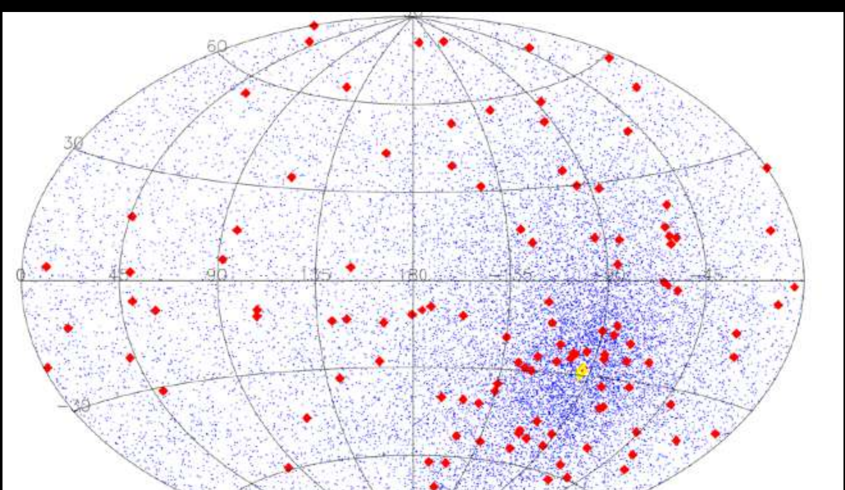
GB & Merritt 2005

- Initially proposed in the context of Sgr A* at the Galactic center *(Gondolo & Silk astro-ph/9906391)*
- High baryon density: major mergers + scattering off stars likely destroy any over density (GB & Merritt astro-ph/0504422)

DM 'spikes'

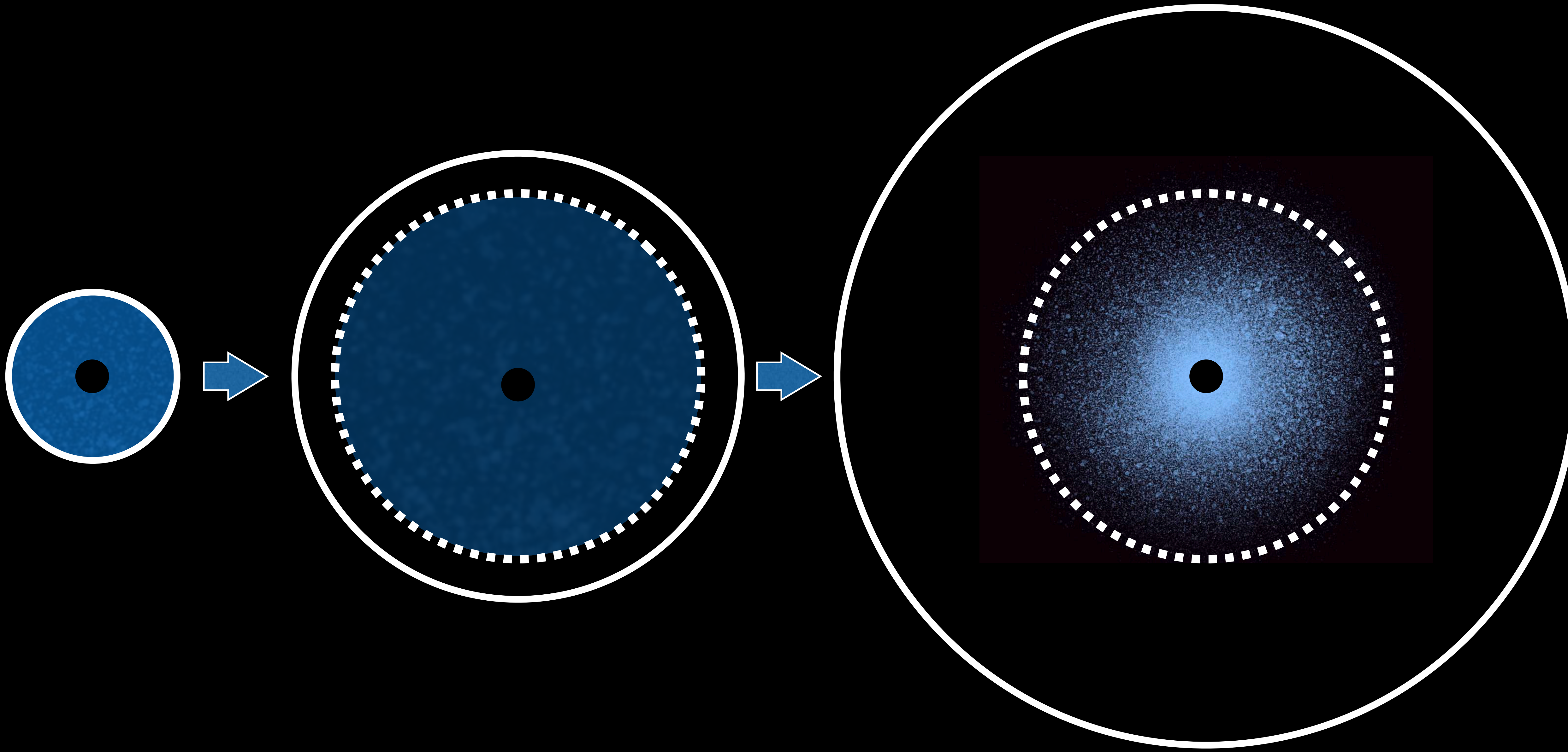


GB & Merritt 2005


GB 2006

- Initially proposed in the context of Sgr A* at the Galactic center *(Gondolo & Silk astro-ph/9906391)*
- High baryon density: major mergers + scattering off stars likely destroy any over density (GB & Merritt astro-ph/0504422)
- 'Mini-spikes' around IMBHs!
(GB, Zentner, Silk astro-ph/0509565)
- Targets for indirect detection (eg with neutrino telescopes GB astro-ph/0603148, Freese+ 2202.01126)

DM overdensities around PBHs



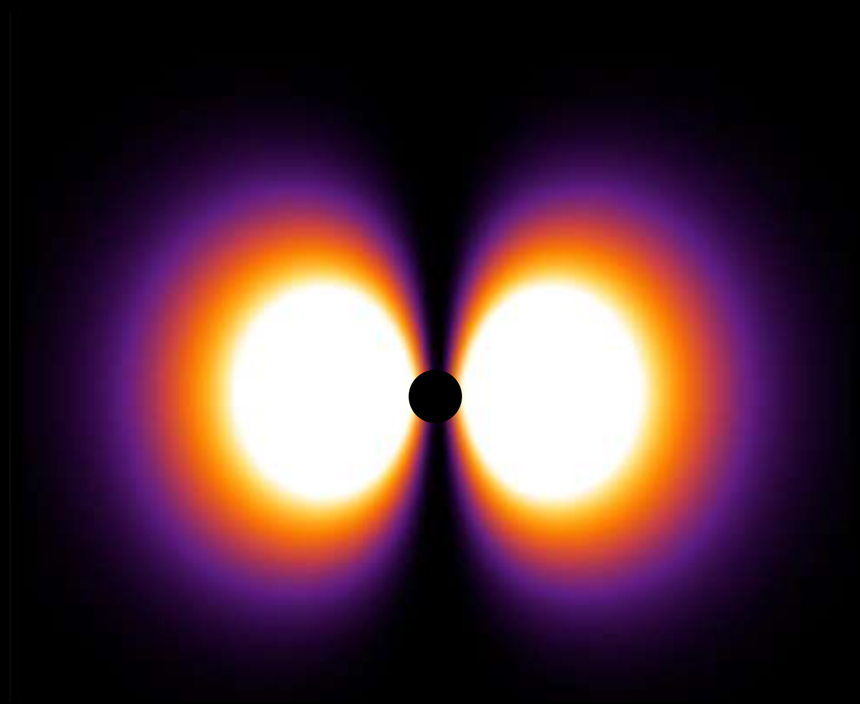
PBH

'Turnaround' point, when particles decouple from expansion

$$\rho_{\rm DM}(r) \sim r^{-9/4}$$

Adamek+ 1901.08528, Boudaud+ 2106.07480, ..

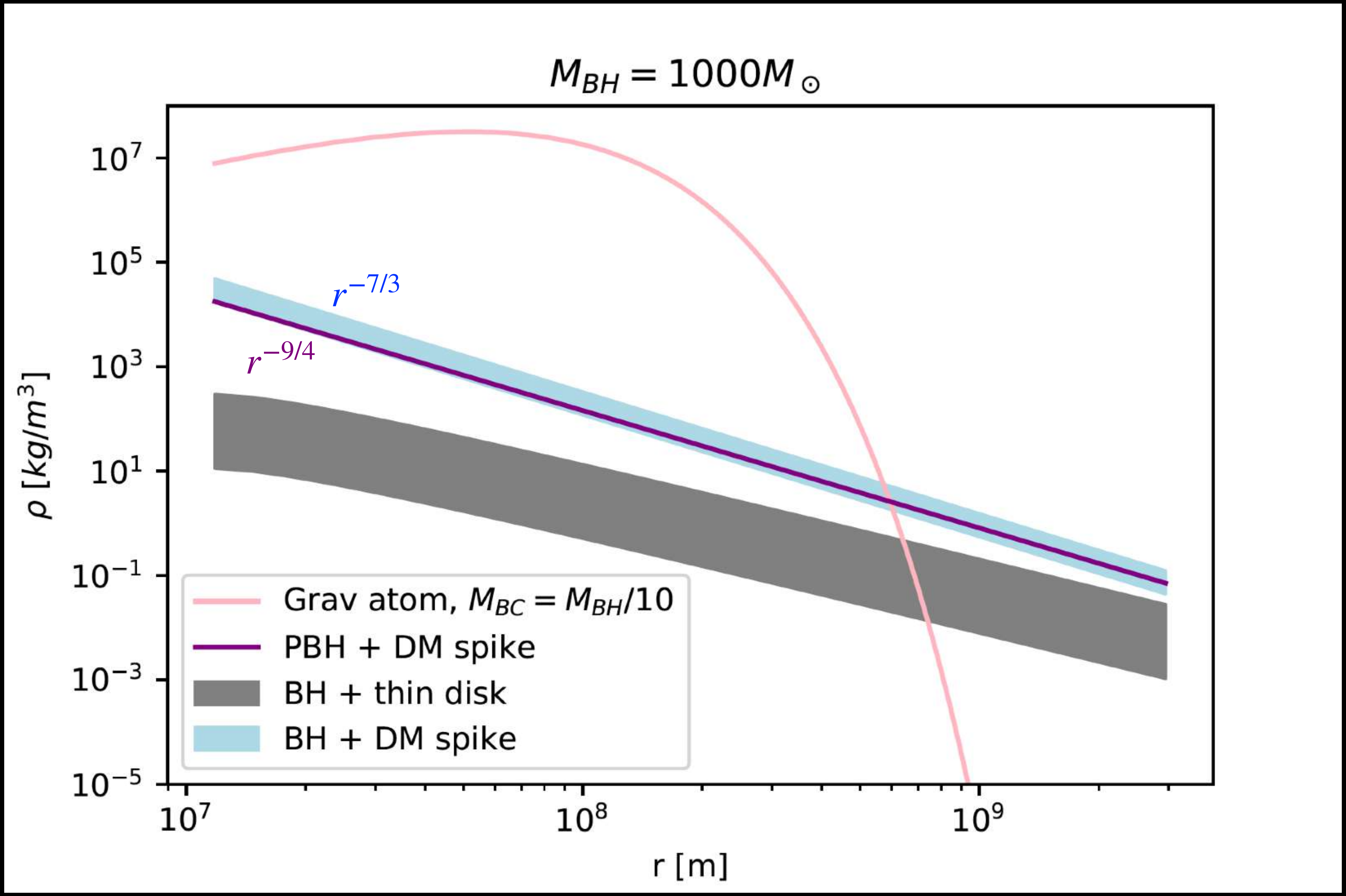
Gravitational atoms



Y. Zel'Dovich (1971,1972); C. Misner (1972); A. Starobinsky (1973); W. East and F. Pretorius (2017); R. Brito, V. Cardoso, and P. Pani (2015) …

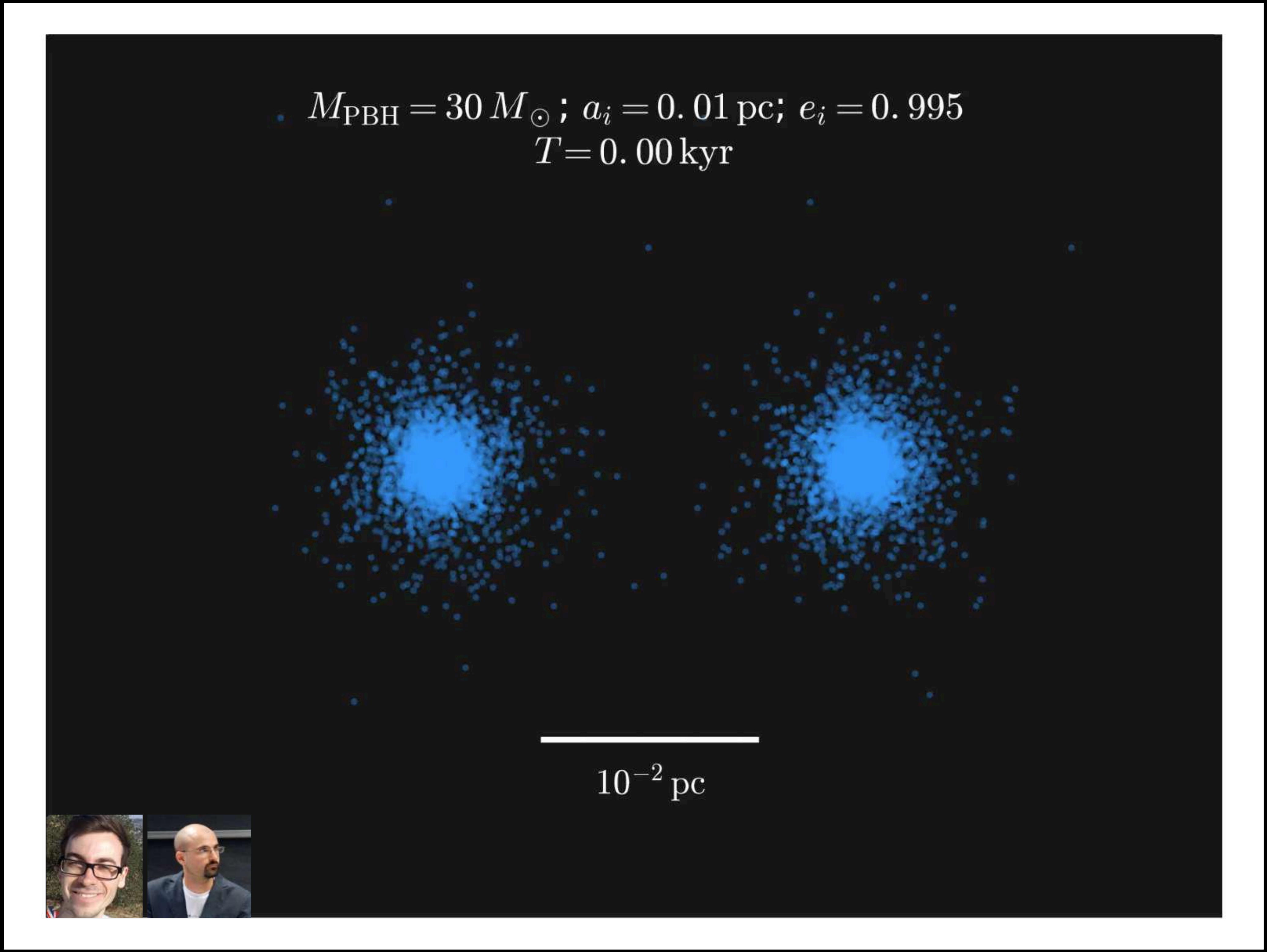
- If ultra-light bosons exist, they can be produced around rotating black holes through a process called **superradiance**
- This effect can extract enough mass and angular momentum to form large **cloud** of **condensate** of the bosonic field
- BH + boson cloud = **gravitational atom,** in analogy with proton-electron structure in H atom

BH environments



Pippa Cole, GB + 2302.03351

‘Dressed’ BH-BH merger



Kavanagh, Gaggero & GB, arXiv:1805.09034

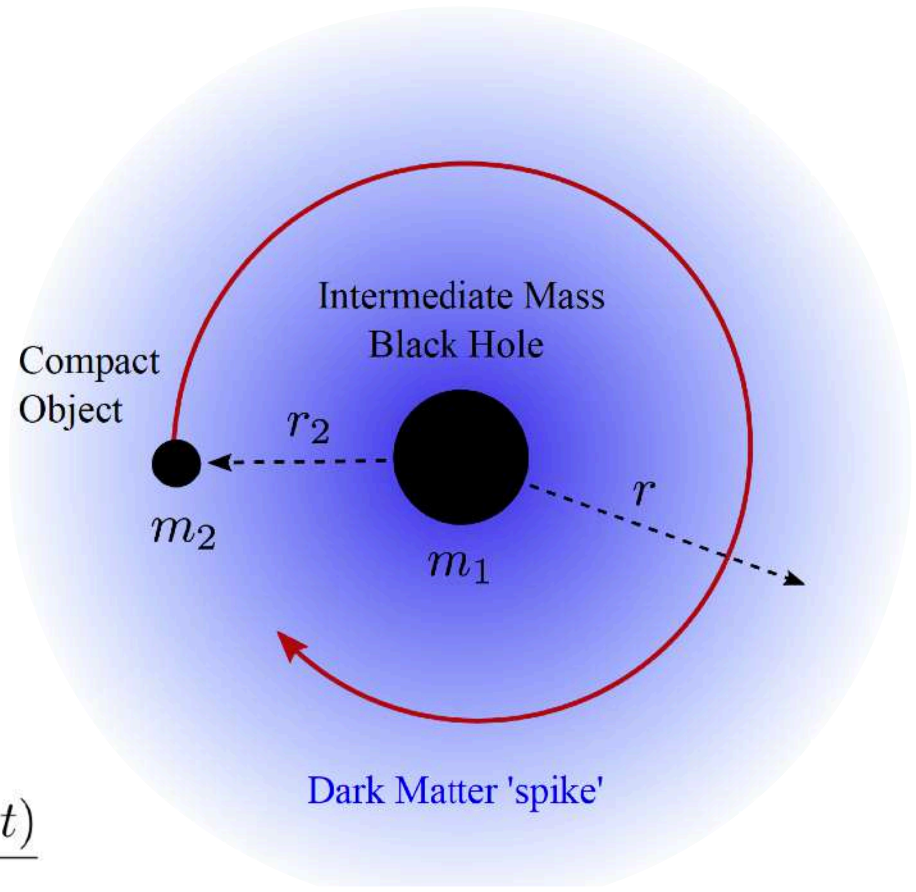
EMRIs in presence of spikes

Energy losses:

$$\dot{E}_{\rm orb} = -\dot{E}_{\rm GW} - \dot{E}_{\rm DF}$$

Separation:

$$\dot{r}_2 = -\frac{64\,G^3\,M\,m_1\,m_2}{5\,c^5\,(r_2)^3} - \frac{8\pi\,G^{1/2}\,m_2\,\log\Lambda r_2^{5/2}\,\rho_{\rm DM}(r_2,t)\,\xi(r_2,t)}{\sqrt{M}m_1}$$

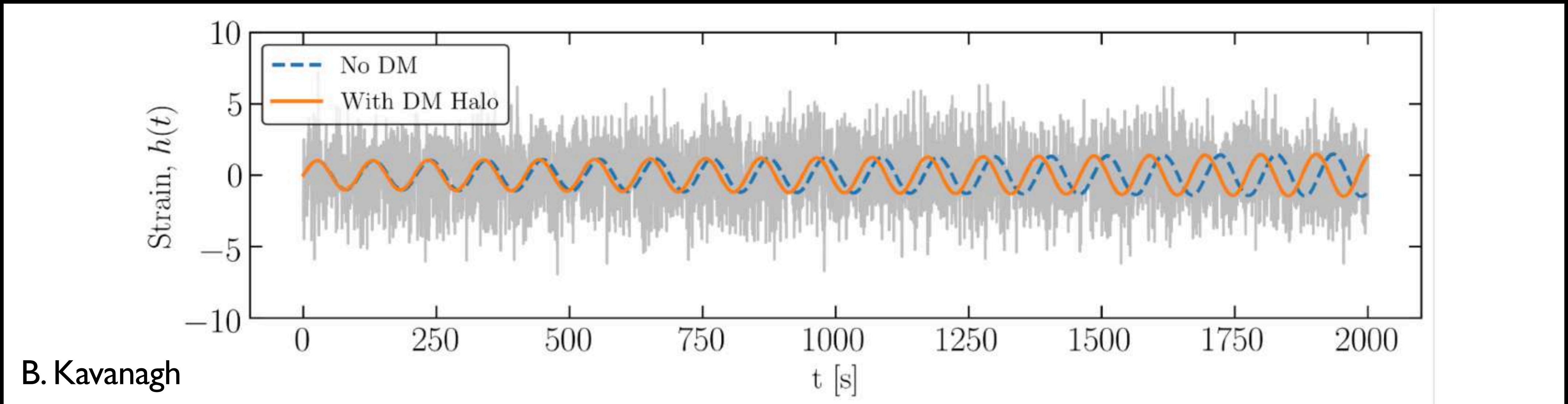


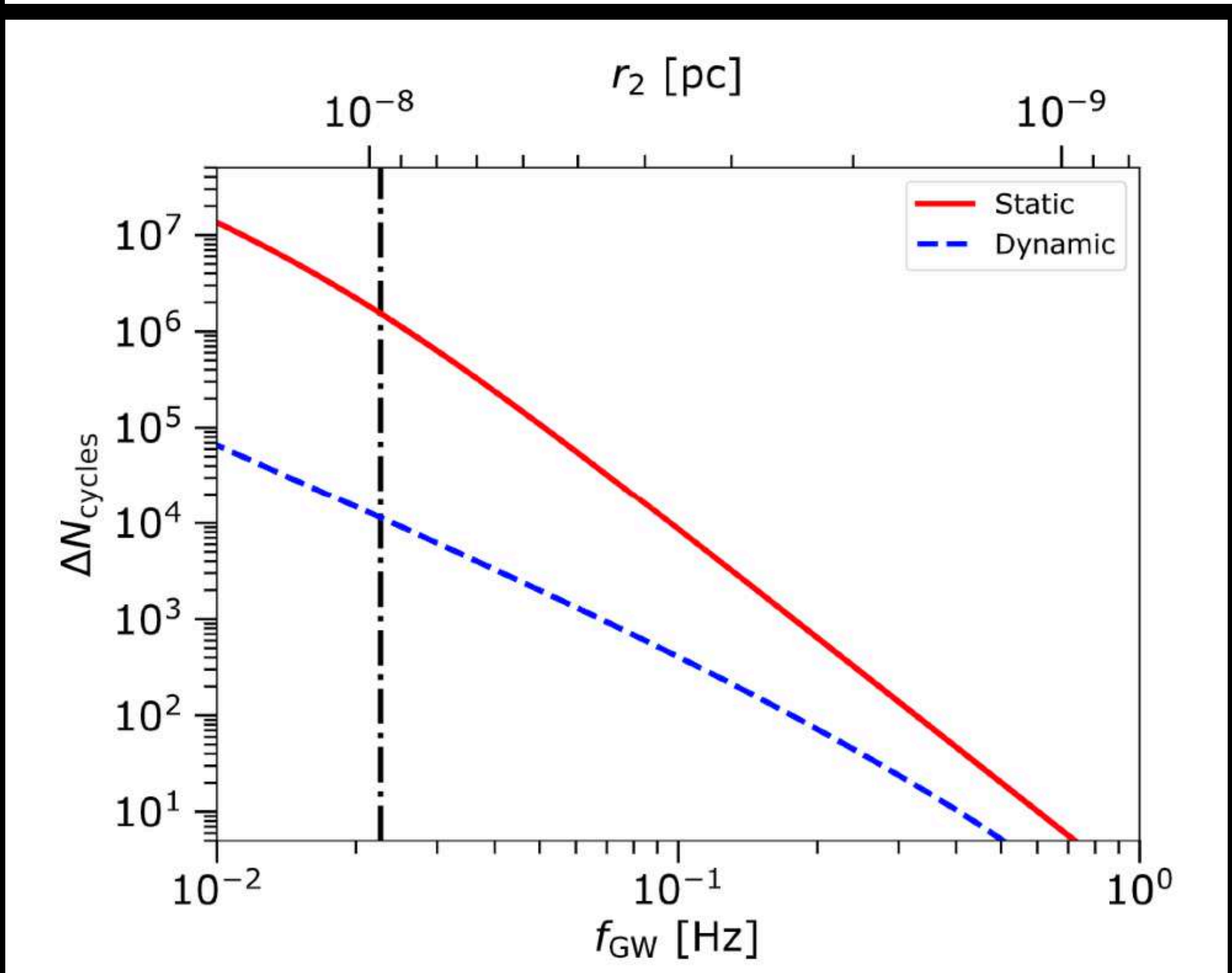
Time-dependent dark matter profile:

$$T_{\rm orb}\frac{\partial f(\mathcal{E},t)}{\partial t} = -p_{\mathcal{E}}f(\mathcal{E},t) + \int\left(\frac{\mathcal{E}}{\mathcal{E}-\Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E}-\Delta\mathcal{E},t)P_{\mathcal{E}-\Delta\mathcal{E}}(\Delta\mathcal{E})\,\mathrm{d}\Delta\mathcal{E}$$

Kavanagh, GB et al. 2002.12811

Gravitational Waveform dephasing



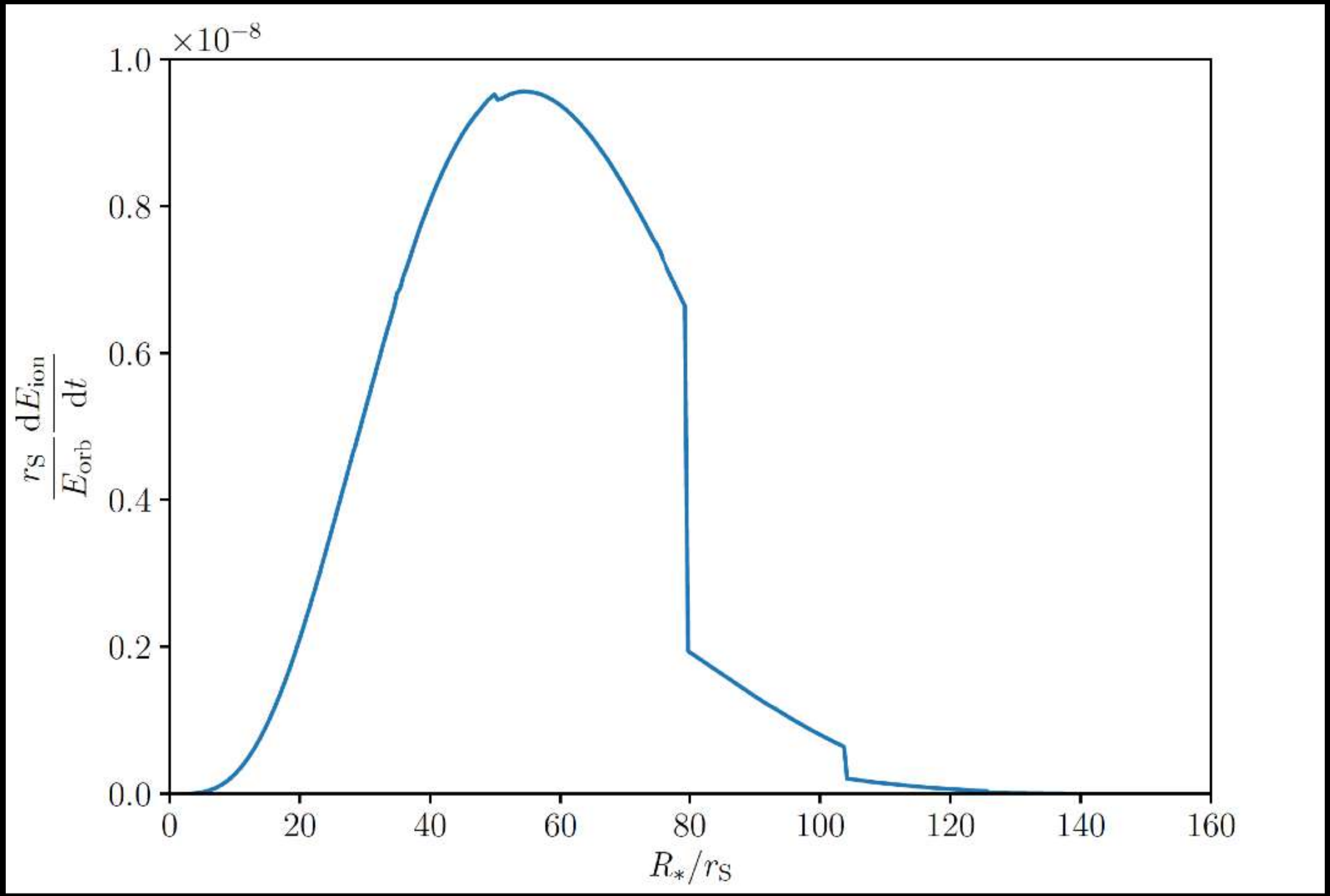


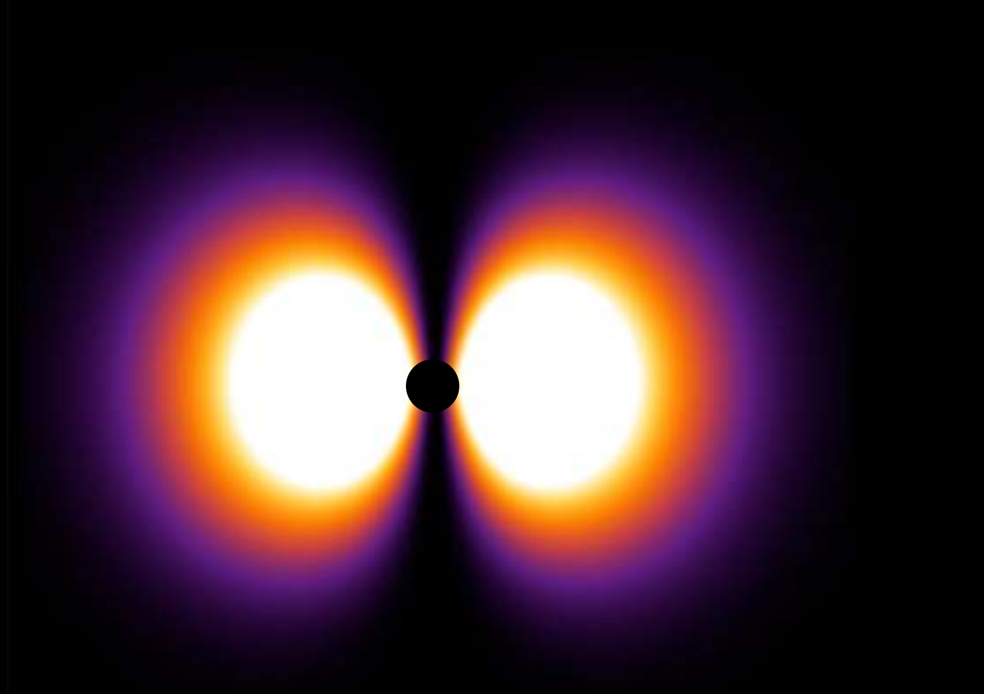
Kavanagh, GB et al. 2002.12811

- Dark matter modifies binary dynamics via dynamical friction (Eda+ 2013, 2014)
- Binary modifies DM phase space via dynamical friction (2002.12811)
- This induces a dephasing of the waveform, potentially detectable e.g. with LISA

EMRIs in presence of Gravitational Atoms

Energy lost by the binary due to 'ionisation'

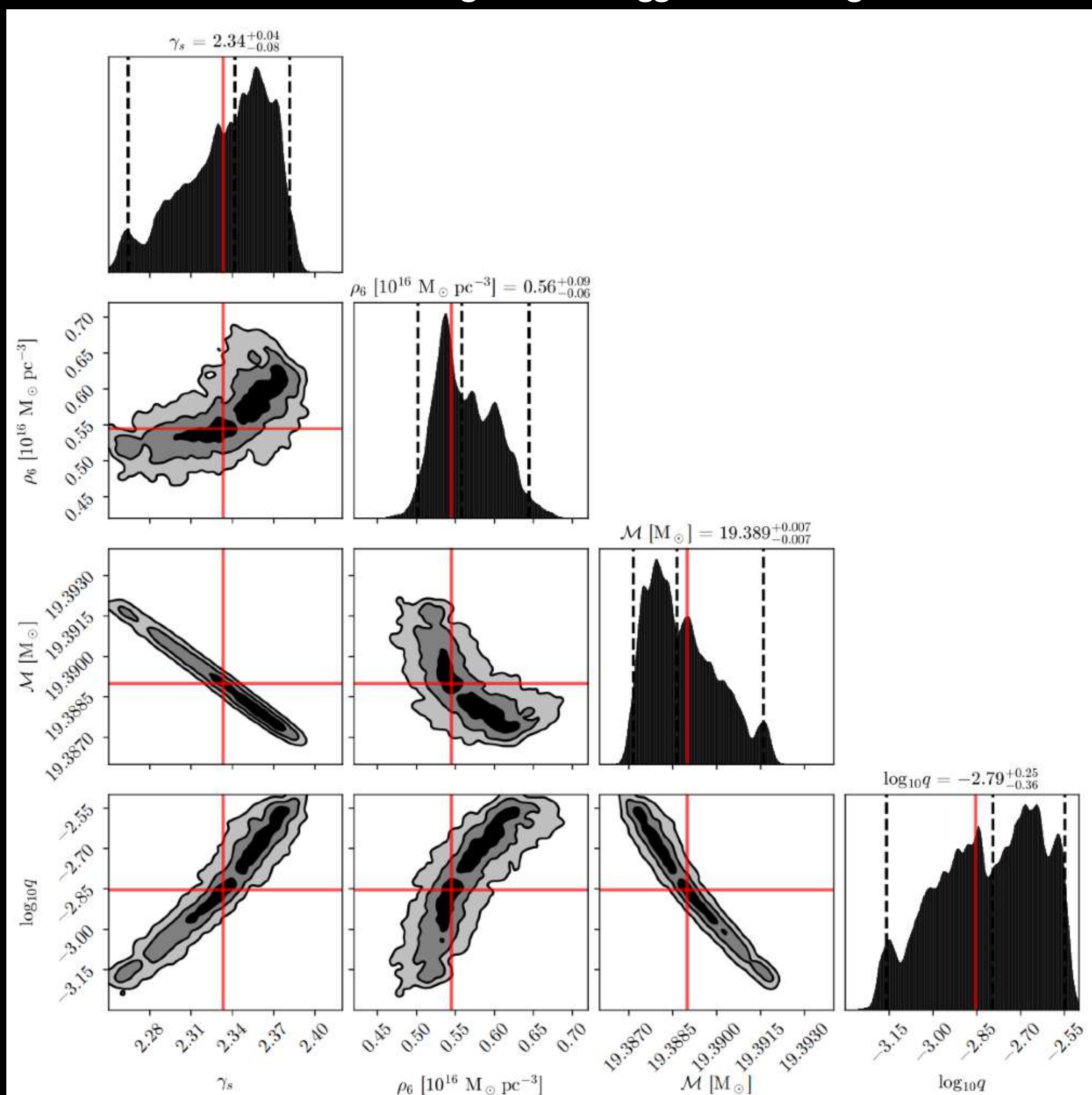




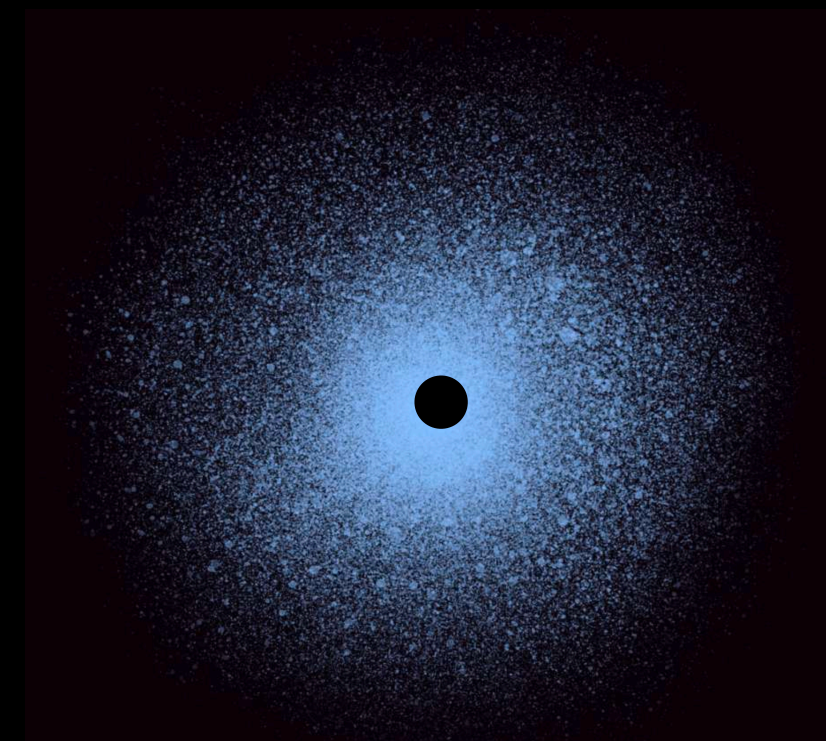
- 'Resonances' due to transitions between bound states $< a\,|\,V_*(t)\,|\,b >$
  Baumann, Chia, Porto, arXiv:1804.03208
- 'Ionization', i.e. transitions to continuum $< a\,|\,V_*(t)\,|\,klm >$
  Baumann, GB, Stout, Tomaselli Phys.Rev.Lett. 128 (2022) 22, 221102
- New: important role of accretion, leading to time dependent mass ratio q(t)
  Baumann, GB, Stout, Tomaselli 2112.14777 + PRL

Signature of DM in EMRI waveforms

Coogan, GB, Gaggero, Kavanagh Nichols 2021



Spike Slope Normalisation Chirp Mass Mass ratio



- Dark dresses within ~100 Mpc are detectable with Lisa
- Can discover that fiducial systems are not GR-in-vacuum (in terms of Bayes factor)
- Can measure DM density profile normalization, slope and even mass ratio

EMRIs in presence of Gravitational Atoms

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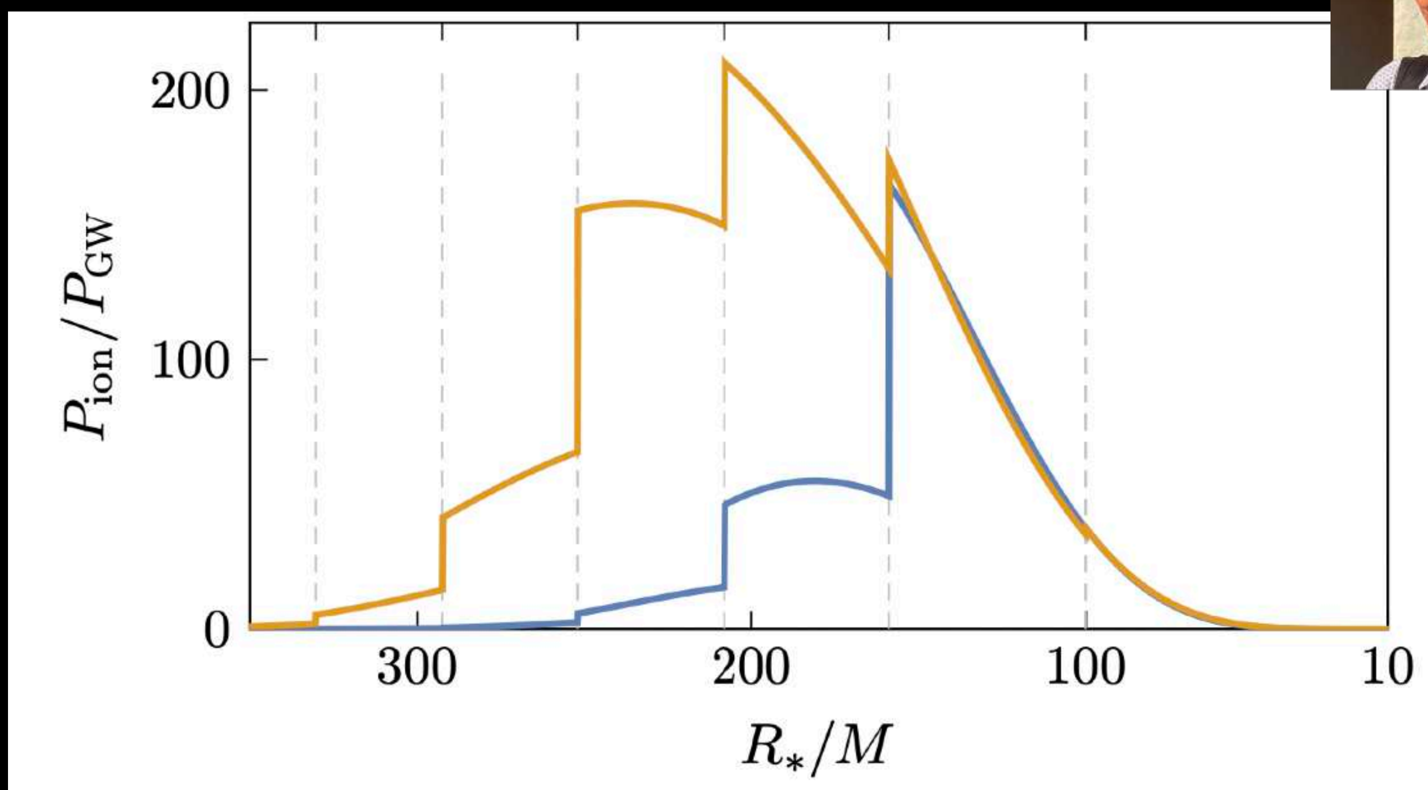

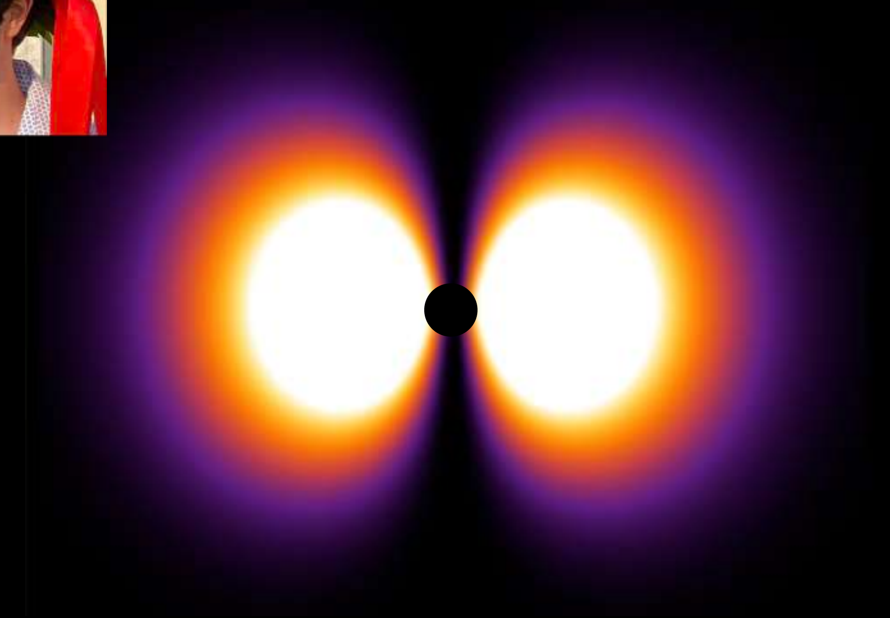

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- New: important role of accretion, leading to time dependent mass ratio q(t)
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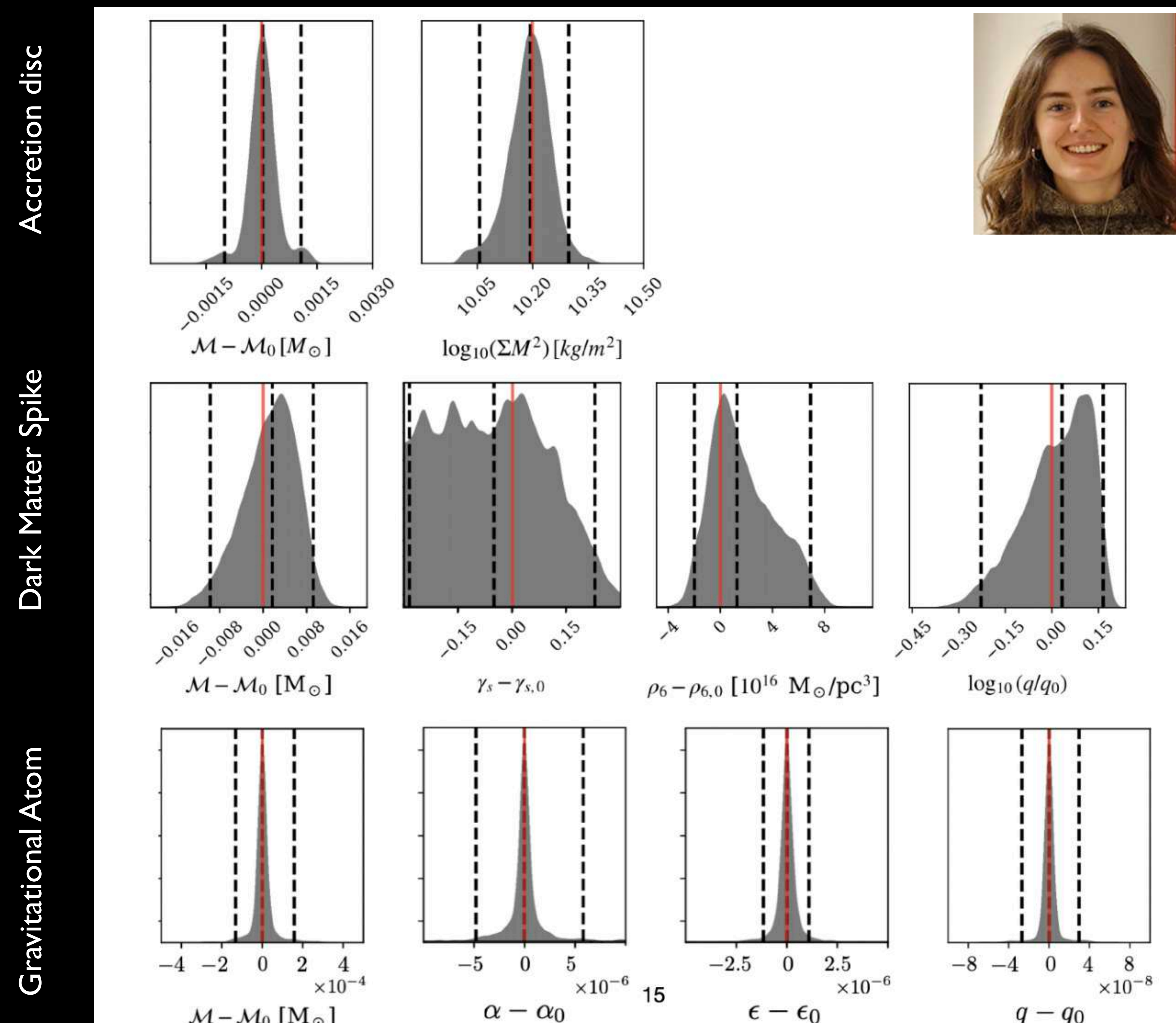
In case of detection, how well can we reconstruct parameters?



Cole, GB et al. Nature Astronomy 2023

In case of detection, can we identify the correct environment?

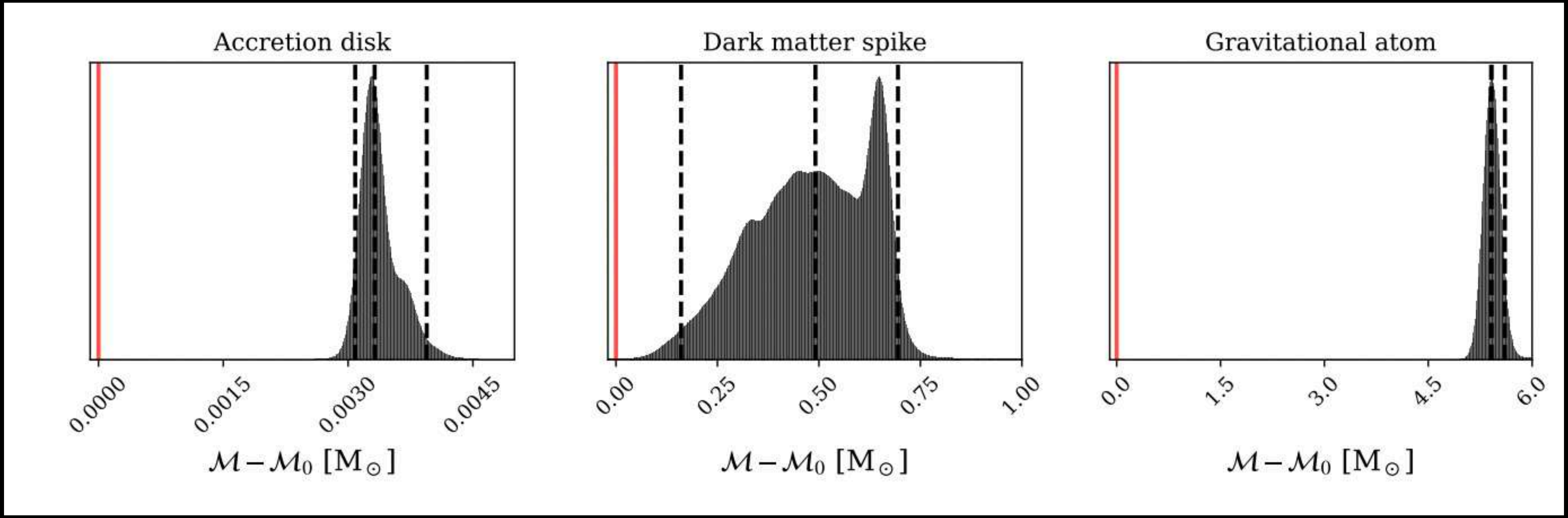
Generate mock Lisa data assuming:

Interpret with:

$\log_{10} \mathcal{B}$	Dark dress signal	Accretion disk signal	Gravitational atom signal
Vacuum template	34	6	39
Dark dress template	-	3	39
Accretion disk template	17	-	33
Gravitational atom template	24	6	-

Bayes factors always very strongly in favour of the correct environment.

Ignoring environments can strongly bias statistical inference on physical parameters
(and possibly lead to catastrophic SNR loss = miss events)



Cole, GB et al. Nature Astronomy 2023

Work in progress..

- How do we detect 'exotic' waveforms? (Machine Learning..)

- Realistic spike formation scenarios, via formation and collapse of **Supermassive Stars**

- Imprint of DM particle properties on the waveform

- Refined modeling of eccentricity, accretion, torques, etc

- Population studies, Merger rates, etc

Conclusions

- This is a time of profound transformation for dark matter studies, in view of the absence of evidence (though NOT evidence of absence) of popular candidates

- LHC, ID and DD experiments may still reserve surprises!

- At the same time, it is urgent to:
    - Diversify dark matter searches
    - Exploit astronomical observations
    - Exploit gravitational waves

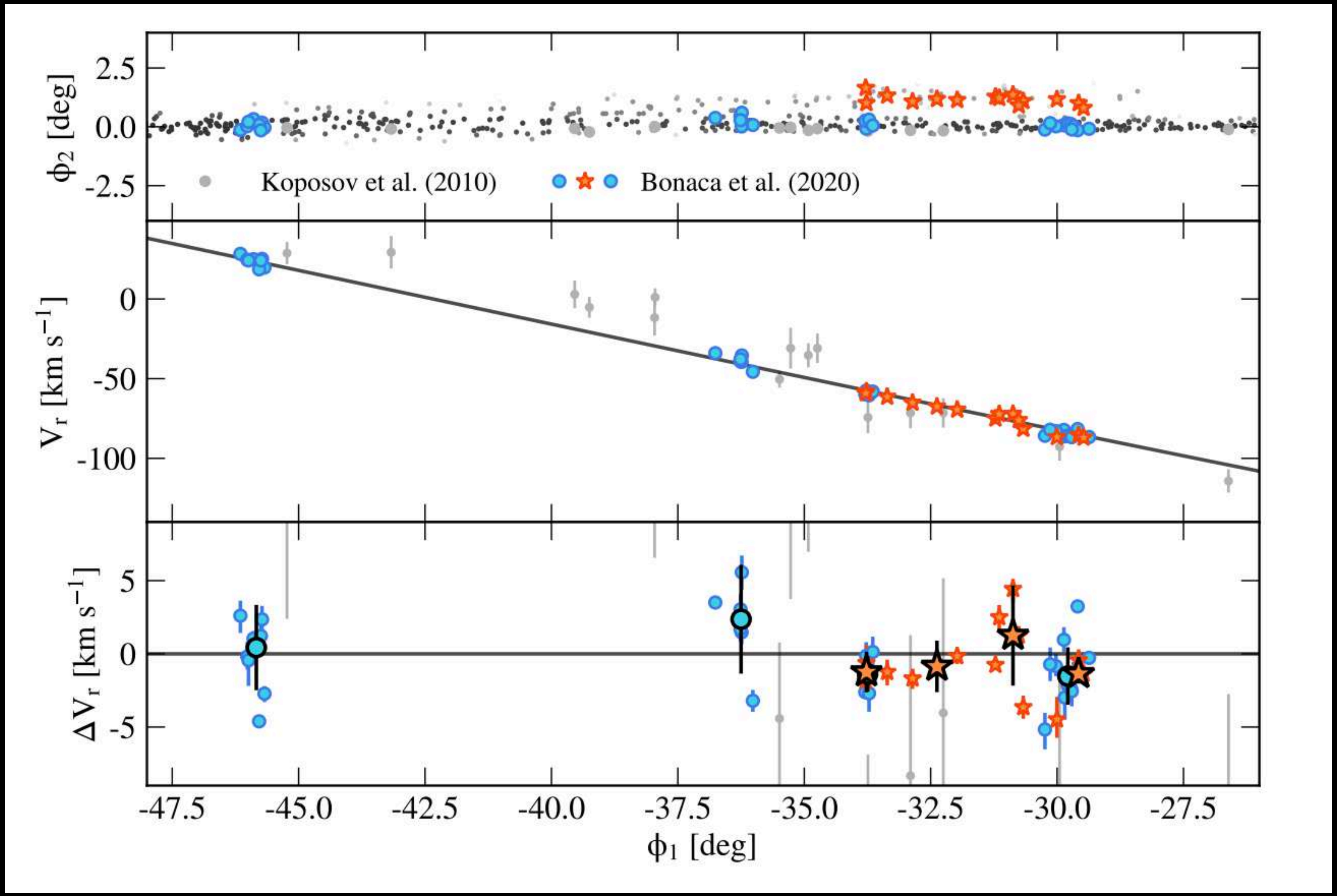
- The field is completely open: extraordinary opportunity for new generation to come up with new ideas and discoveries

Back up Slides

Gaia GD1 stream data!

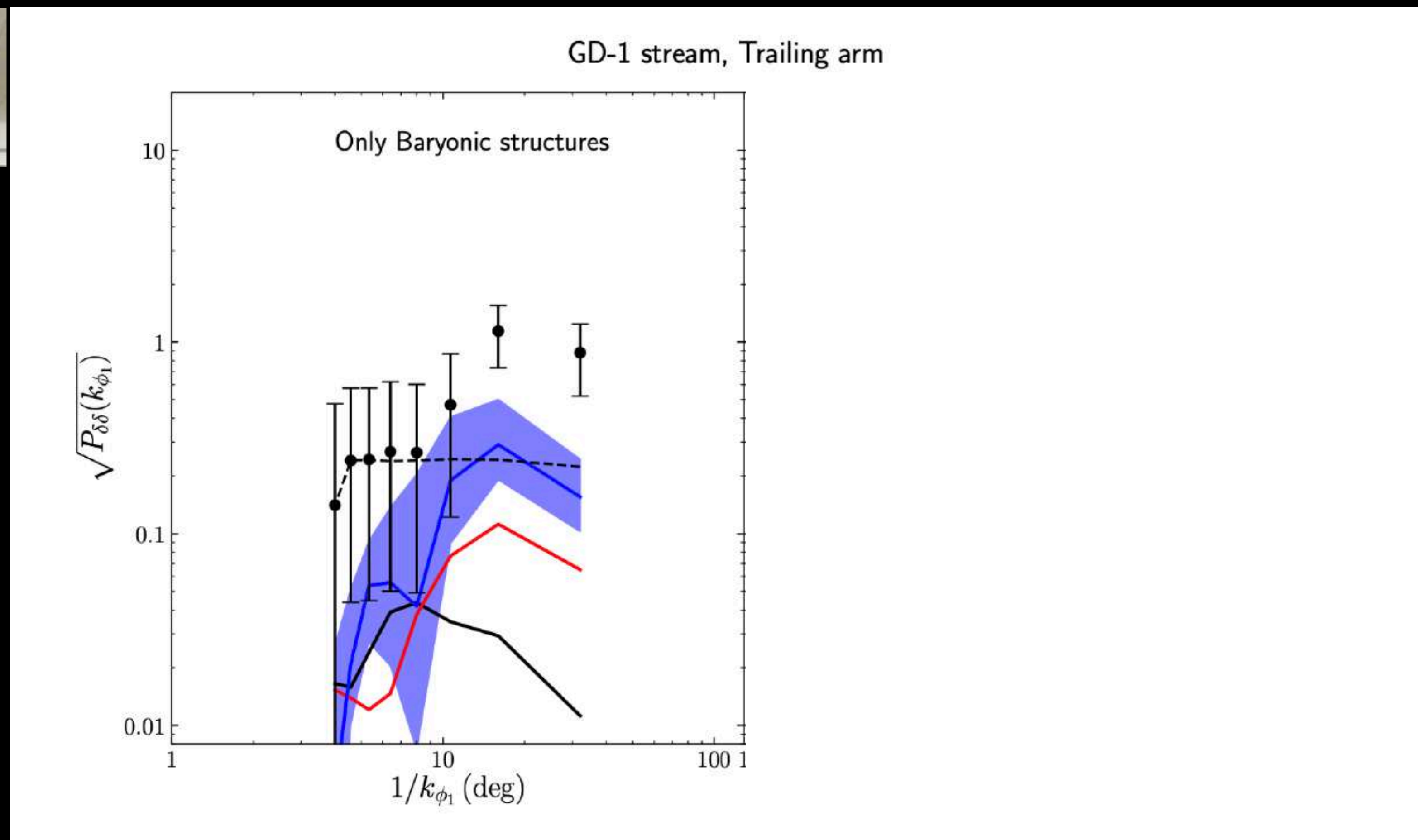
New map of stars in GD1 stream (longest cold stream in the MW) with *Gaia* second data release combined with *Pan-STARRS*.

Stream appears to be perturbed, with several 'gaps' and a 'spur'



Bonaca et al. 2001.07215

Statistical analysis of perturbations: Strong hints of dark substructures!

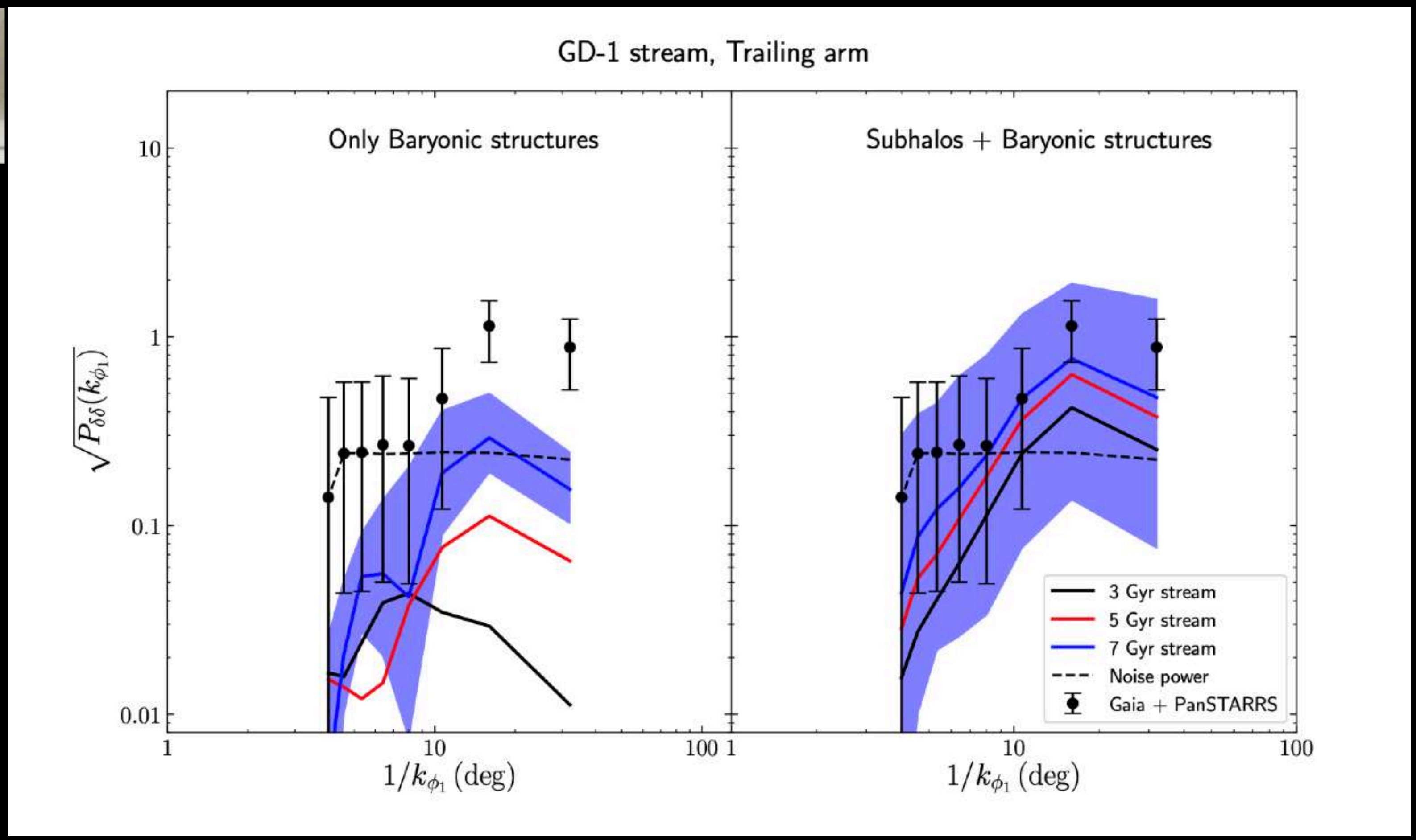


Banik, Bovy, GB, Erkal, de Boer, MNRAS 502, 2364 (2021)

- Gaia GD1 stream data exhibit substantial ‘structure’

- Density fluctuations cannot be explained by “baryonic” structures (GC, GMC, spiral arms etc)

Statistical analysis of perturbations: Strong hints of dark substructures!



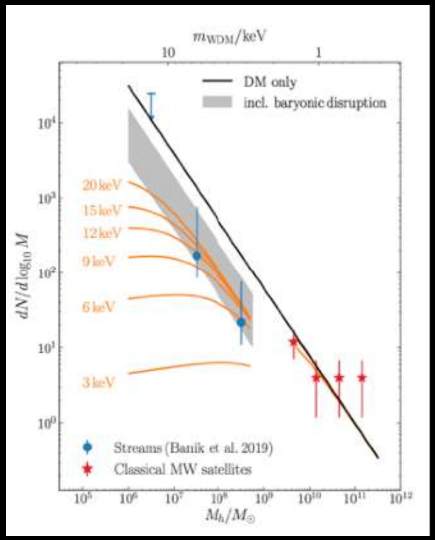
Banik, Bovy, GB, Erkal, de Boer, MNRAS 502, 2364 (2021)

- Gaia GD1 stream data exhibit substantial 'structure'

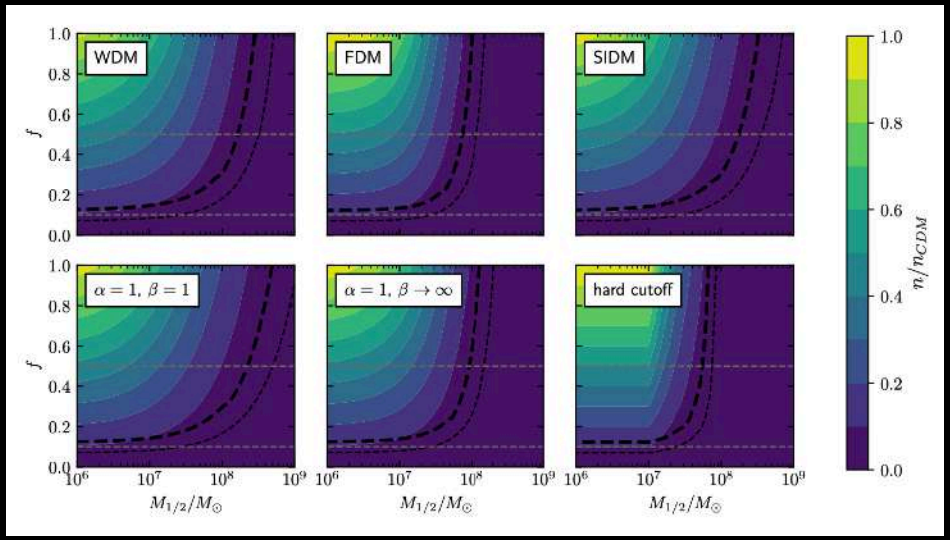
- Density fluctuations cannot be explained by "baryonic" structures (GC, GMC, spiral arms etc)

- Density fluctuations are consistent with CDM predictions (not a fit!)

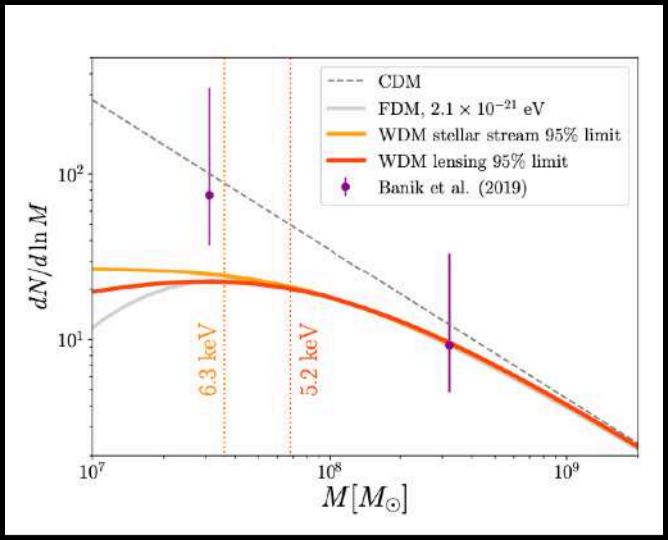
Statistical analysis of perturbations: Stringent constraints on the nature of DM



1911.02663



2001.11013

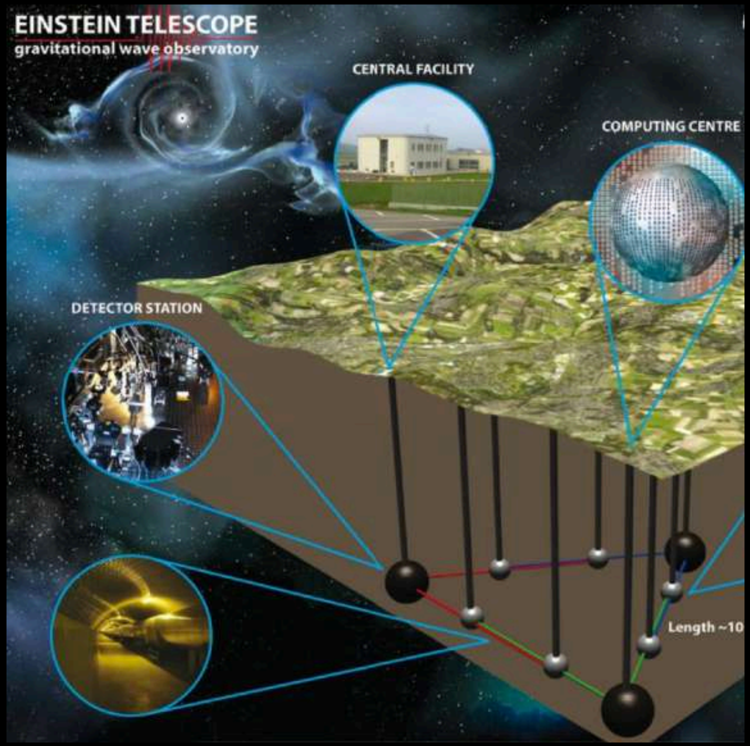


2001.05503

Constraints on the particle mass of dark matter candidates such as warm, fuzzy, and self-interacting dark matter.

Can we convincingly discover *primordial* BHs?

Yes, e.g. if we:



I. Detect sub-solar mass BHs with current interferometers

(e.g. 2109.12197)

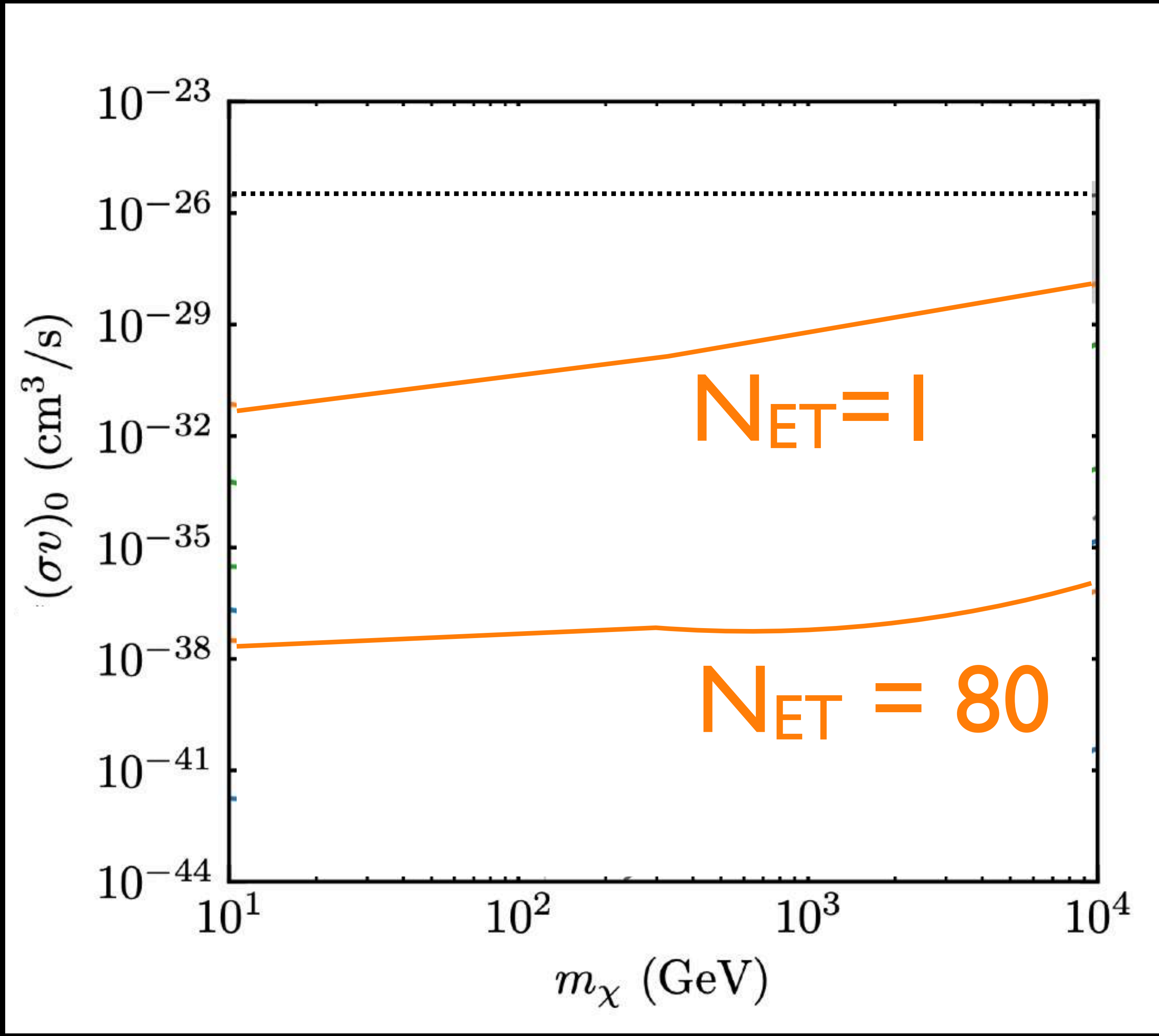
II. Detect O(100)$M_\odot$ BHs at $z > 40$ with Einstein Telescope

(e.g. 1708.07380)

III. Discover 'unique' radio signature with Square Kilometre Array

(e.g. 1810.02680)

If (subdominant) PBHs discovered: Extraordinarily stringent constraints on new physics at the weak scale!



GB, Coogan, Gaggero, Kavanagh, Weniger 1905.01238

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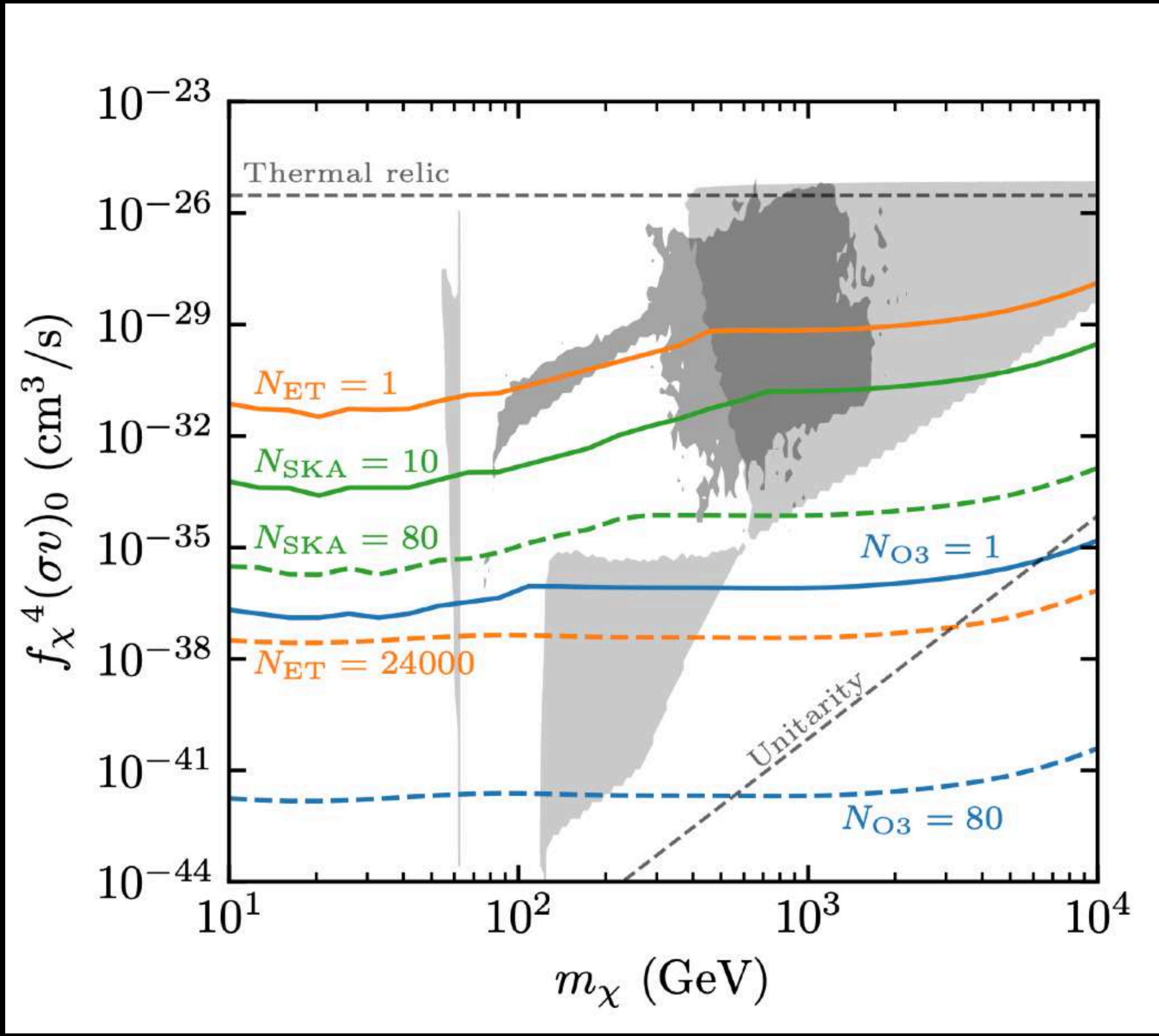
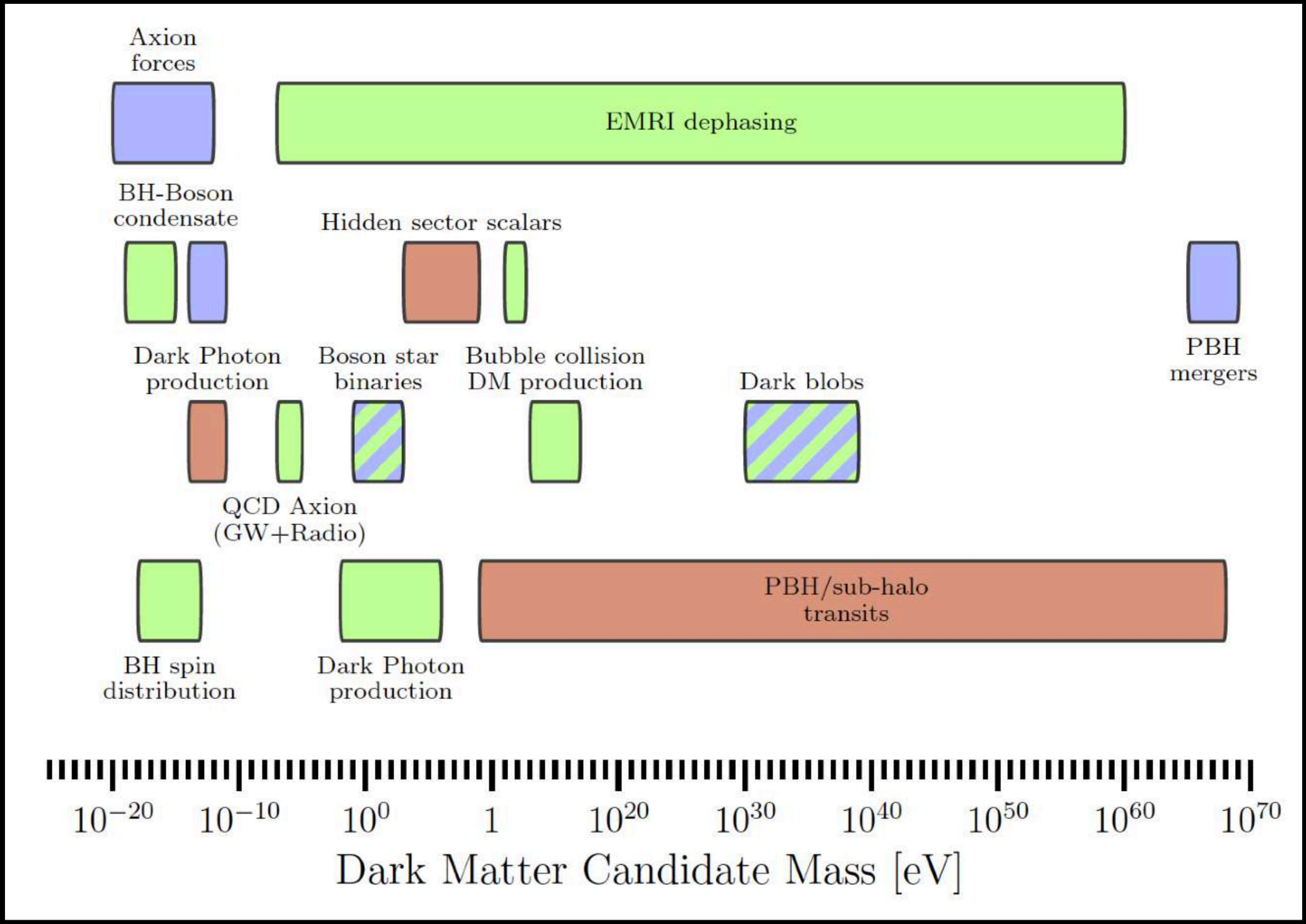


GB, Coogan, Gaggero, Kavanagh, Weniger 1905.01238

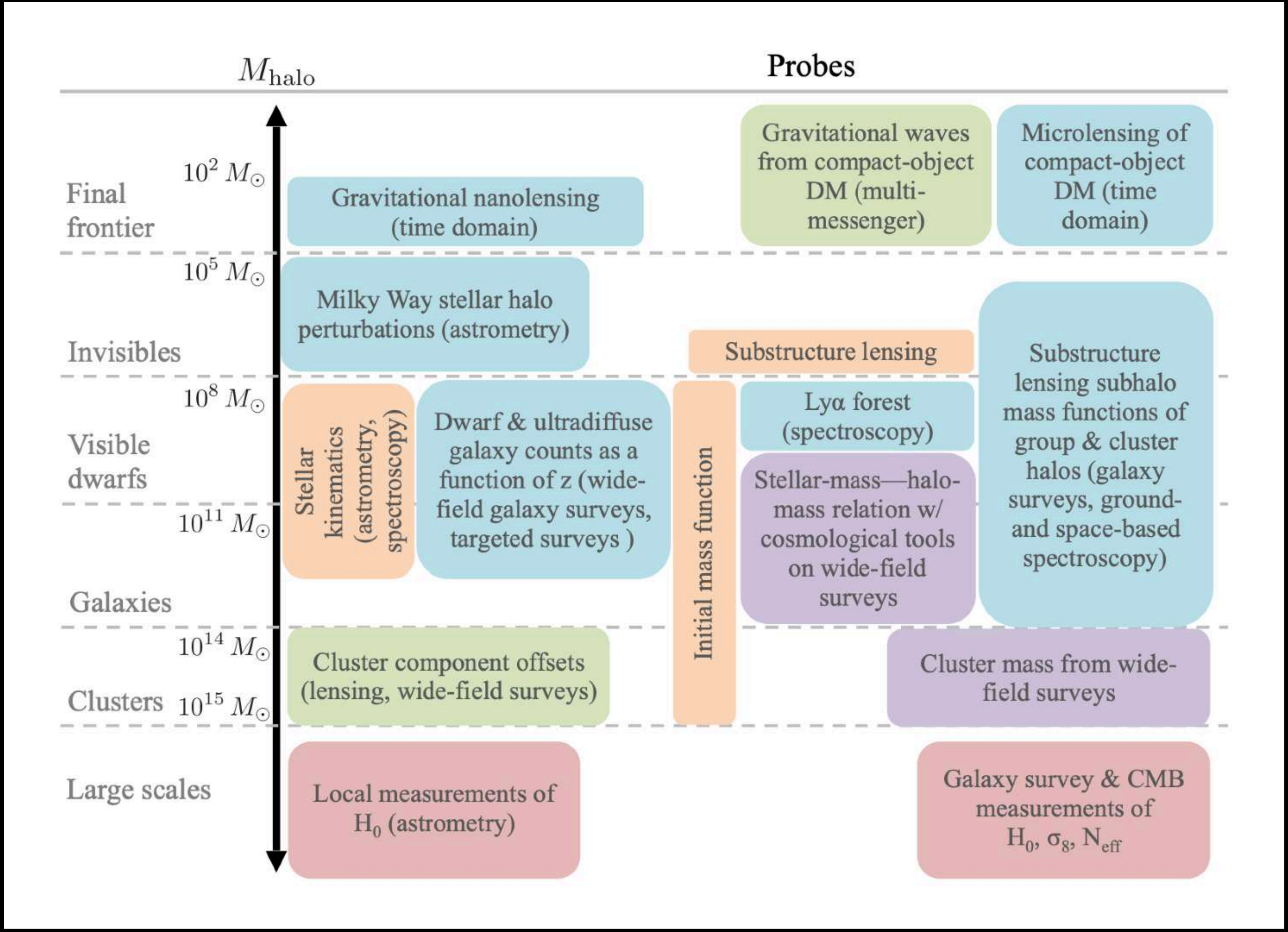
- Detecting a subdominant PBHs with the Einstein Telescope would essentially rule out not only WIMPs, but entire classes of BSM models (even those leading to subdominant DM!)

Further GW-DM connections:



"Gravitational wave probes of dark matter: challenges and opportunities"
GB, Croon, et al. 1907.10610

Gravitational probes of dark matter physics



M. Buckley and A. Peter, Physics Reports, 761, 1-60 (2018)