Dark matter, black holes, and gravitational waves

Gianfranco Bertone
GRAPPA center of excellence, U. of Amsterdam

Copernicus Webinar, 28/6/2022

GRAPPA

GRavitation AstroParticle Physics Amsterdam

Plan of the talk:

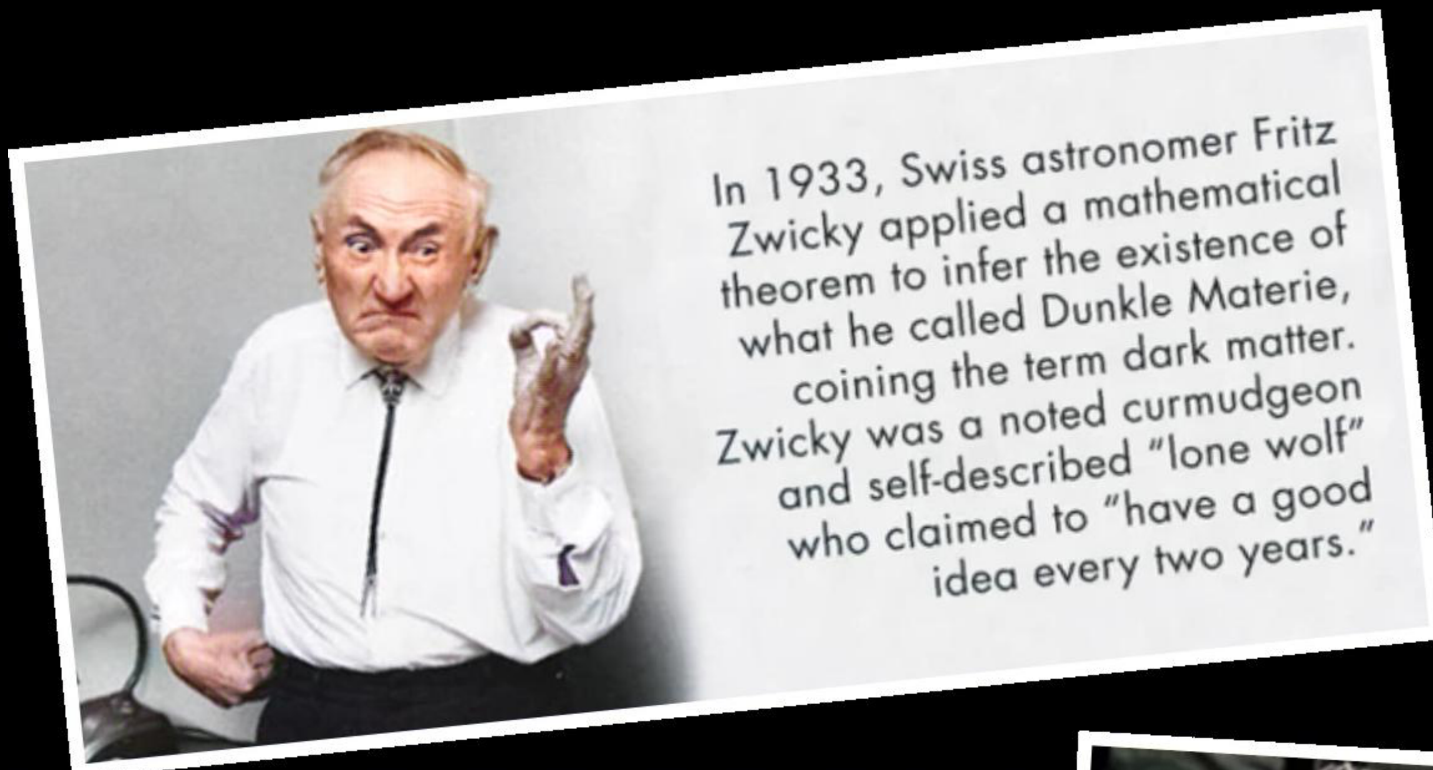
Prologue: the dark universe *narrative*

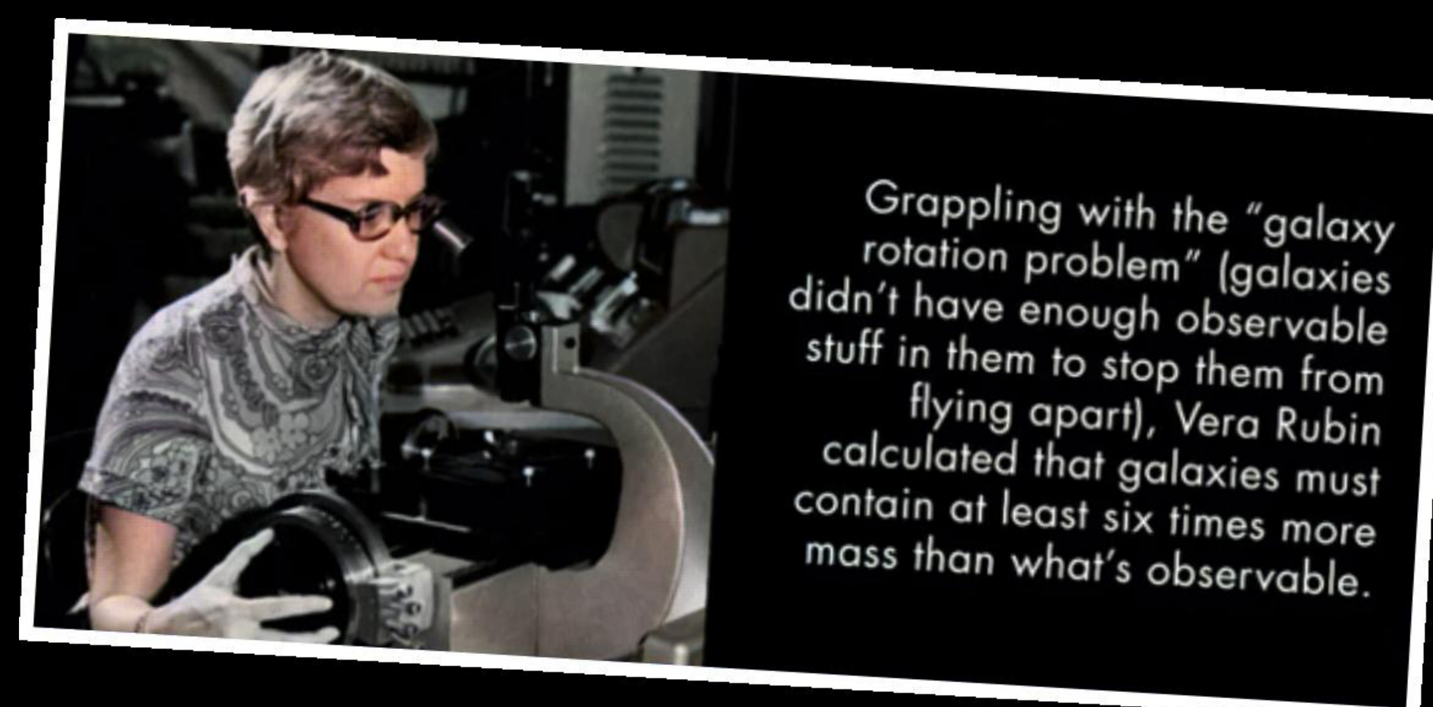
Part I: What have we learnt?

Part II: GW probes of DM

(Epilogue: EuCAPT!)

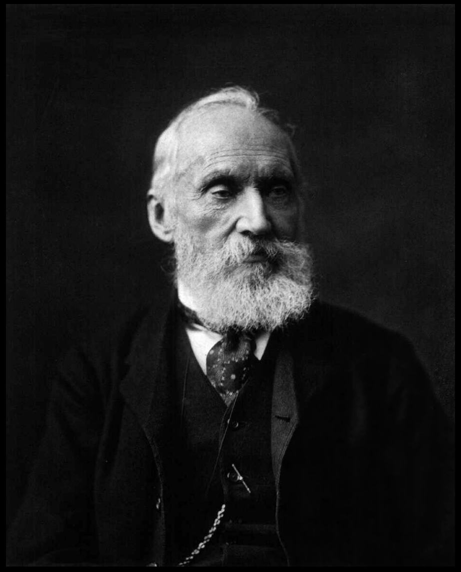
Dark Matter "Mythology"





Figures: Perimeter Institute

Dark matter: a problem with a long history..



Lord Kelvin (1904)

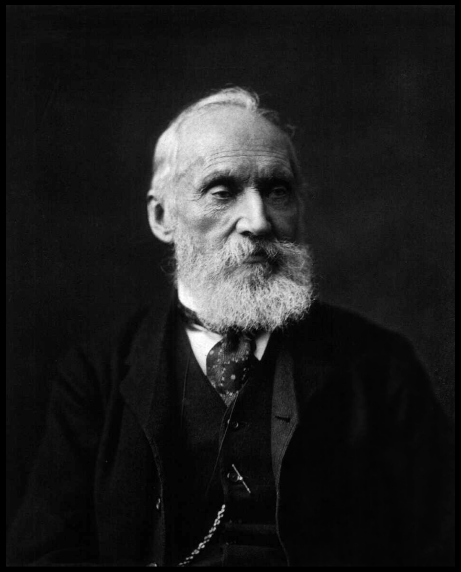
"Many of our stars, perhaps a great majority of them, may be dark bodies."

Henri Poincaré (1906)

"Since [the total number of stars] is comparable to that which the telescope gives, then there is no ***dark matter,*** *or at least not so much as there is of shining matter."*

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

Dark matter: a problem with a long history..



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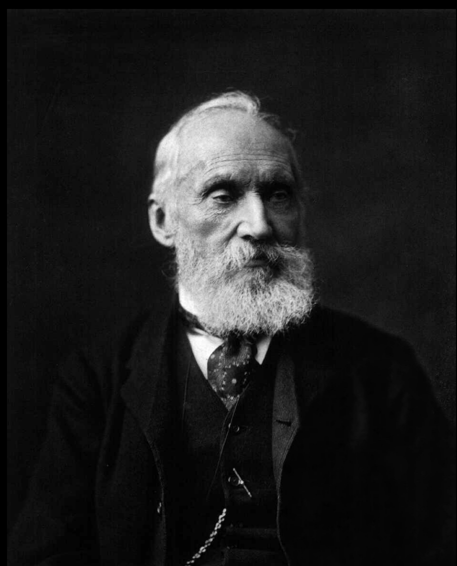
Albert Einstein (1921)

Applies viral 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

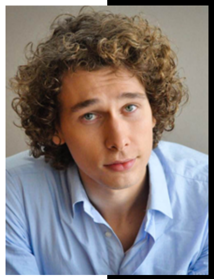
"A history of Dark Matter" GB & Hooper - RMP *1605.04909*

HOW DARK MATTER CAME TO MATTER

JACO DE SWART
Institute of Physics
University of Amsterdam

Ph.D. Thesis

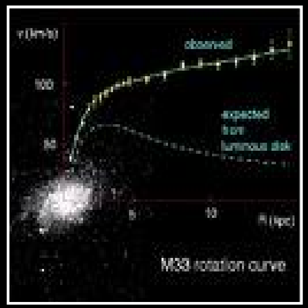
October 2021 – version 2.0



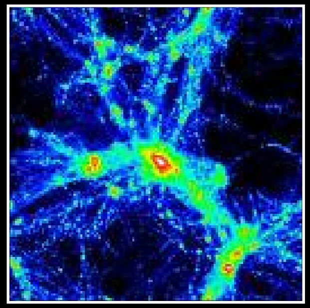
"How dark matter came to matter" de Swart, GB, van Dongen - Nature Astronomy; *1703.00013*

What is the Universe made of?

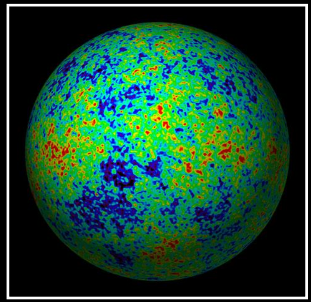
OBSERVATIONS



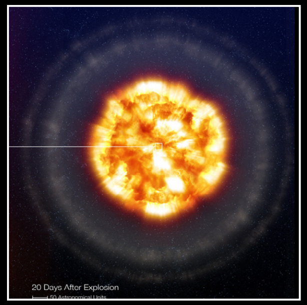
- Rotation Curves



- Clusters of galaxies

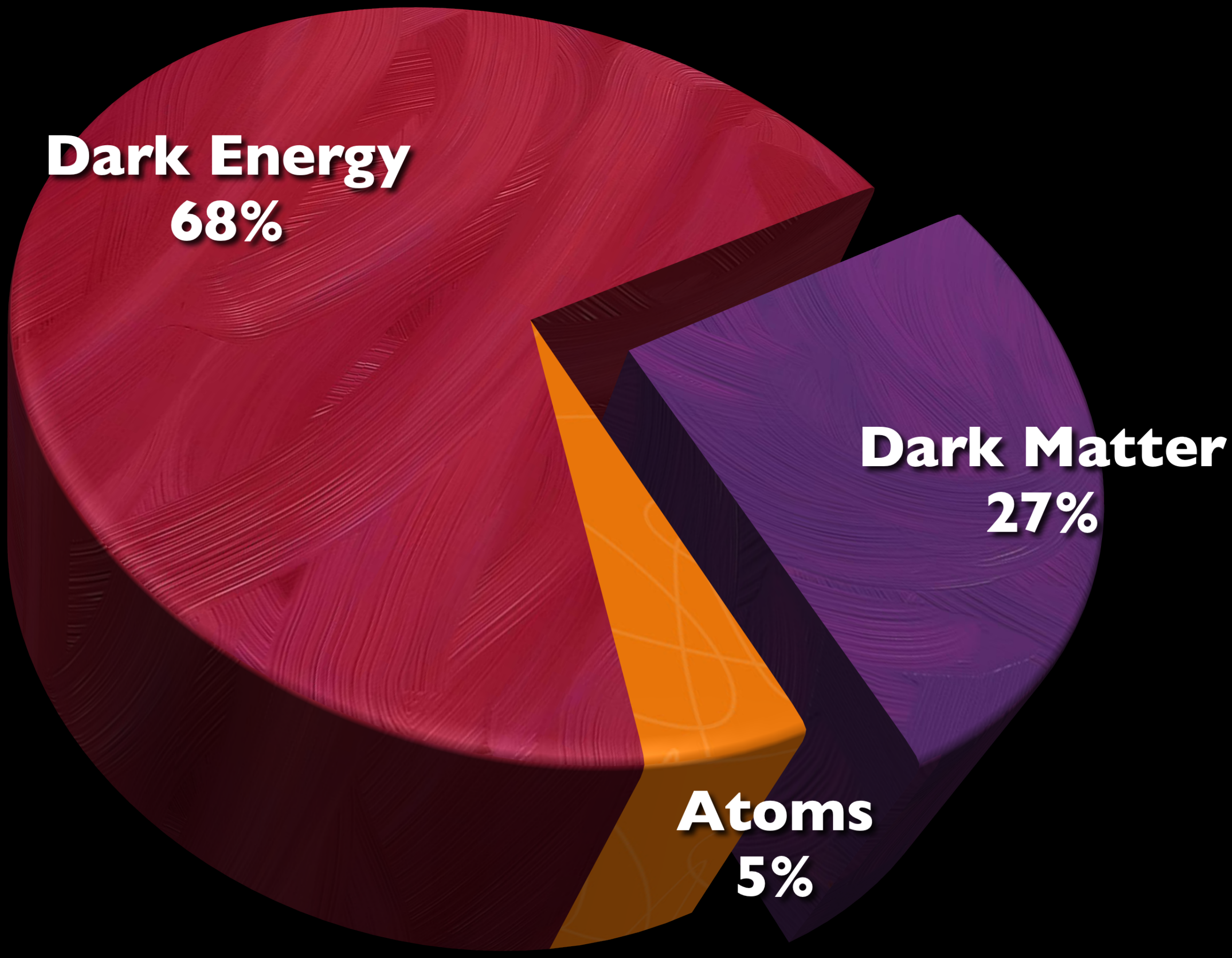


- CMB



- Type Ia Supernovae

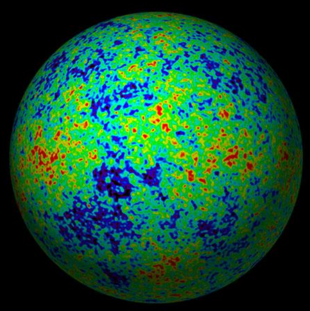
…

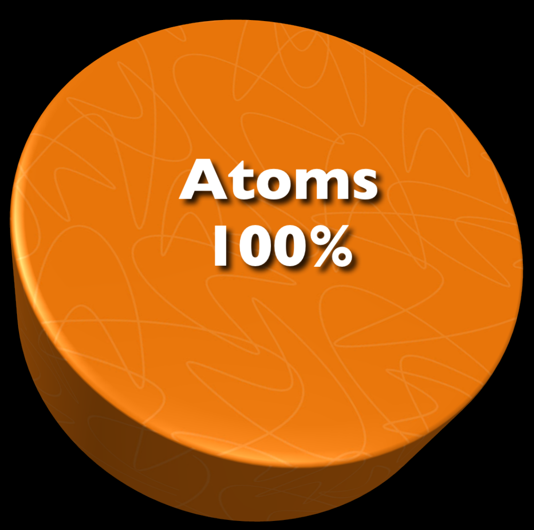


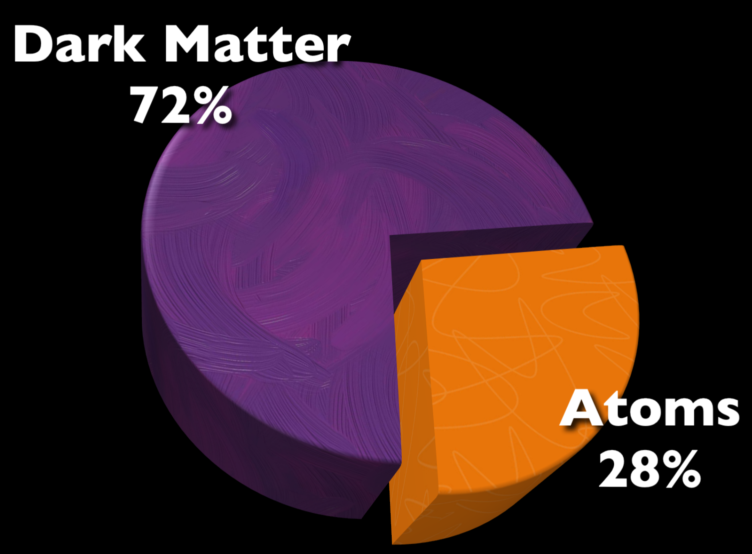
[statement valid *now*, and on *very large scales*]

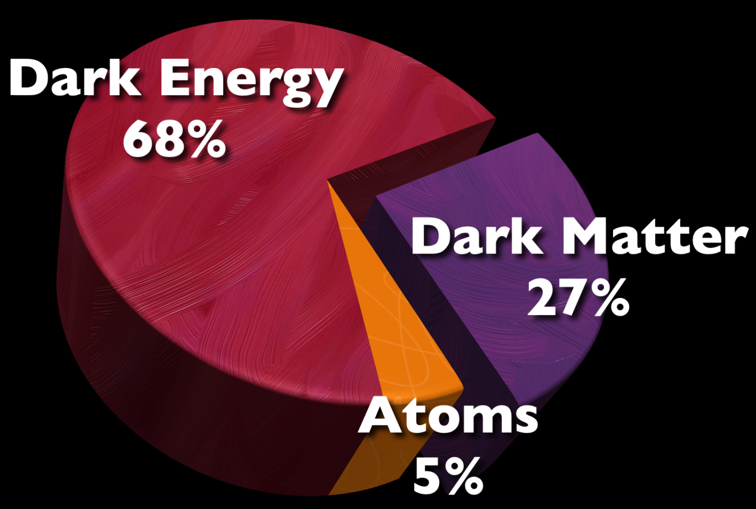
What is the Universe made of?

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



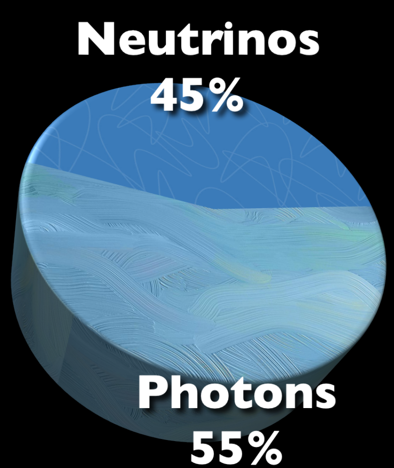




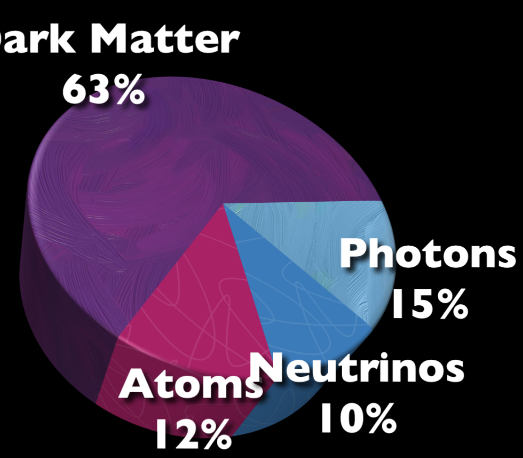


What was the Universe made of?

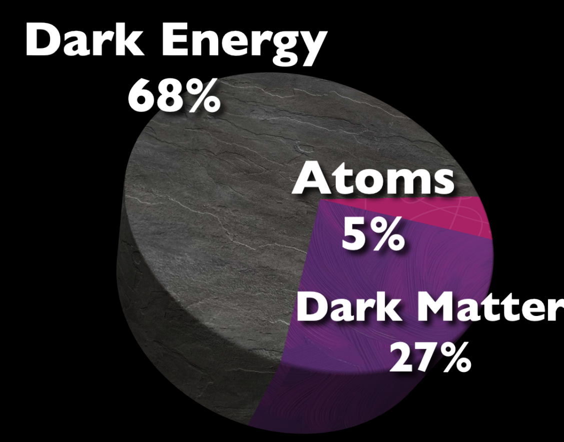
At BBN



At recombination

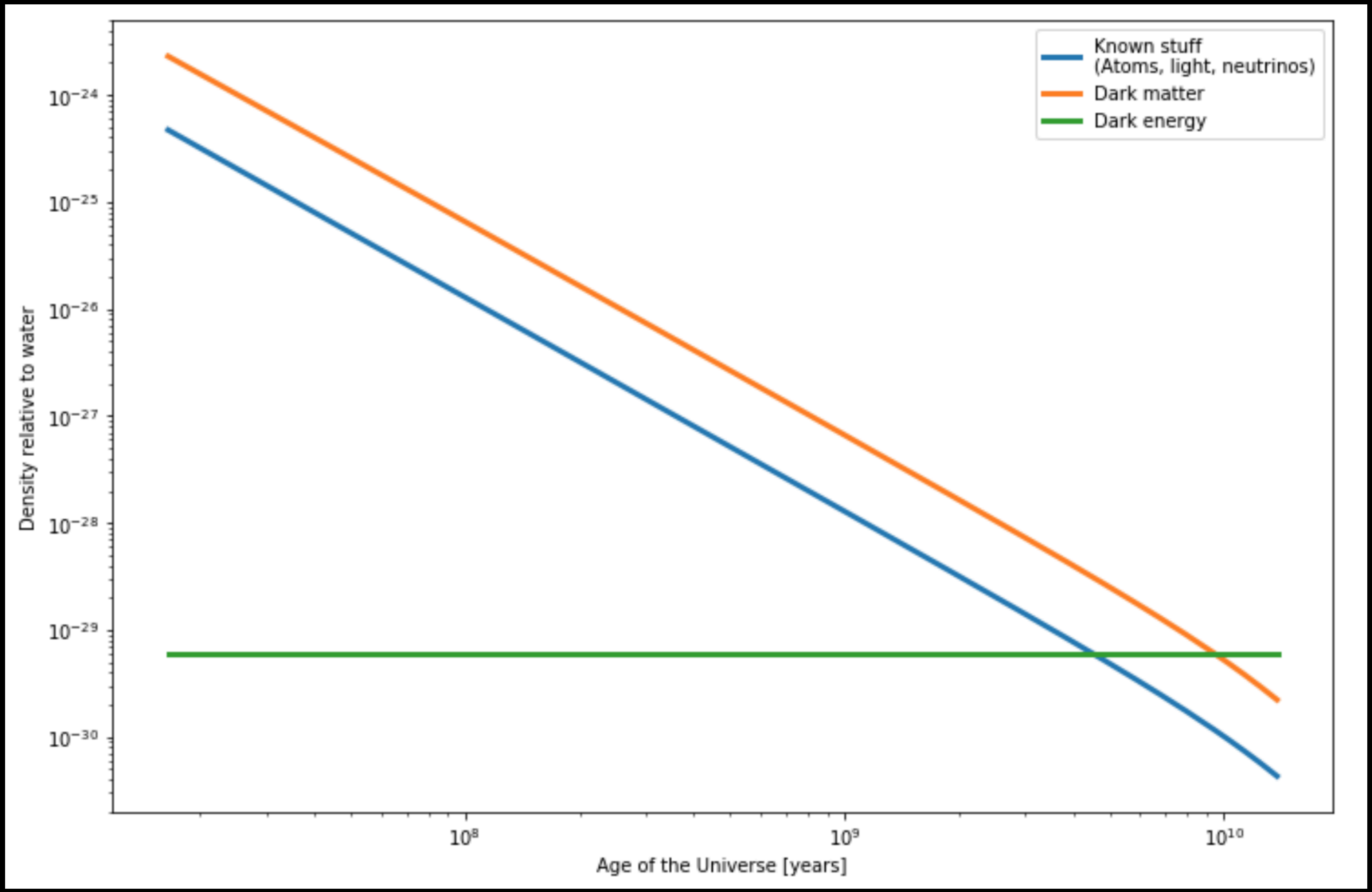


Today



…eventually

Evolution of matter/energy density



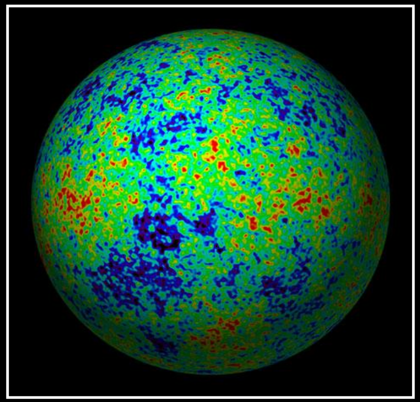
Created with #astropy https://astropy.org, astropy.cosmology package https://docs.astropy.org/en/stable/cosmology/

Simulating Galaxy Formation

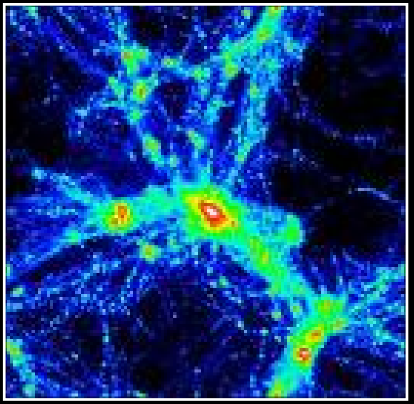
http://www.illustris-project.org/media/

Can ‘x’ be the DM in the Universe?

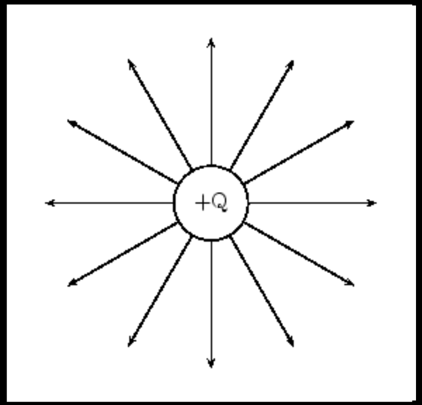
1) Abundance ok?



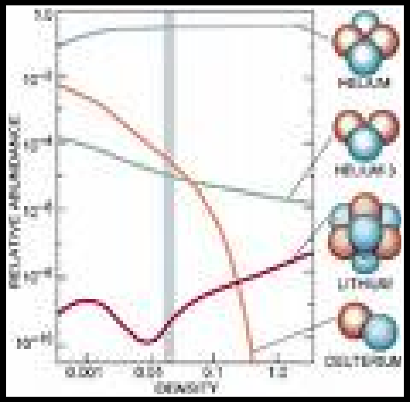
2) Cold?



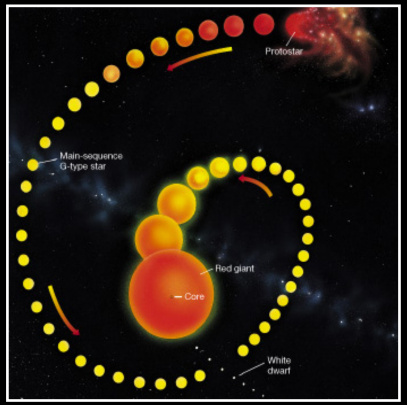
3) Neutral?



4) BBN ok?



5) Stars OK?



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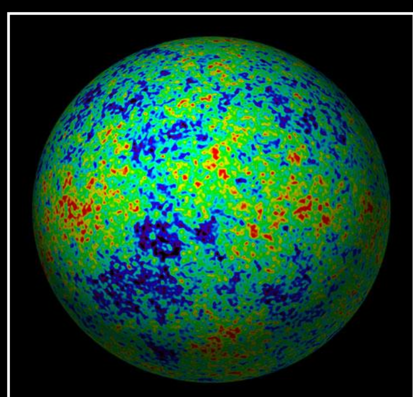

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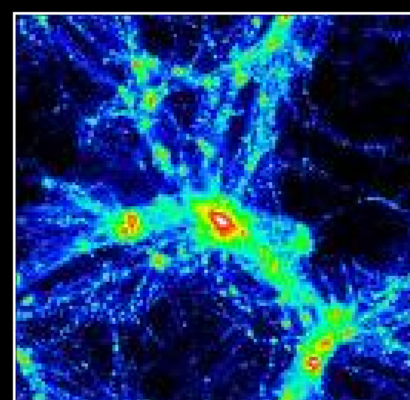

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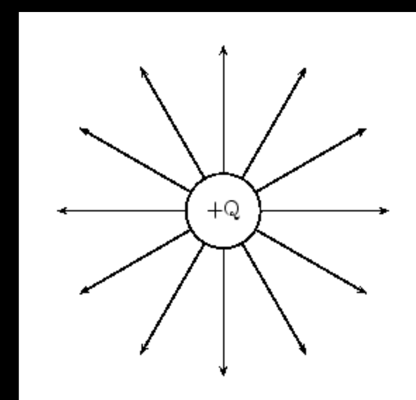

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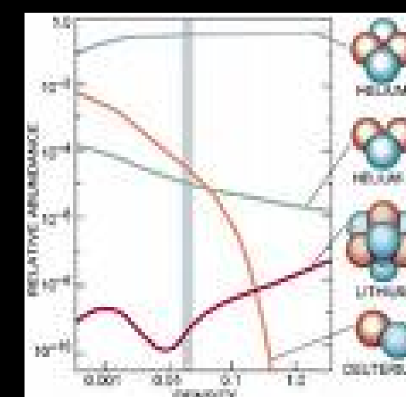

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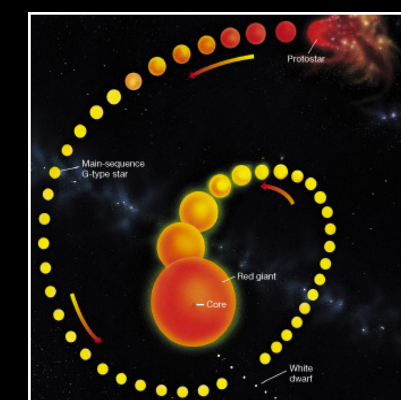
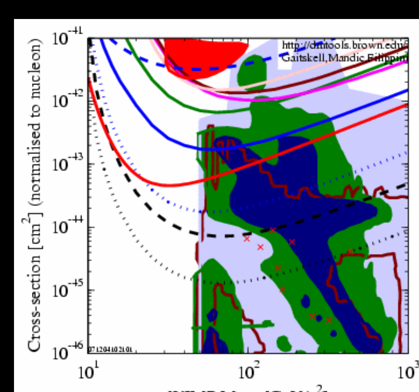
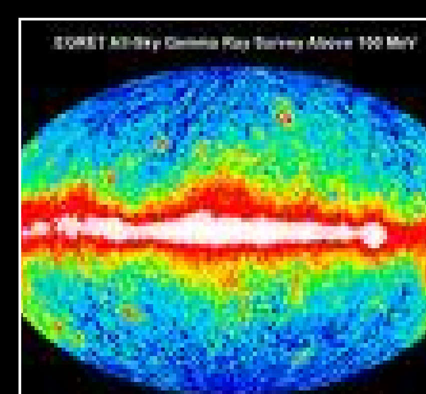


6) Collisionless?

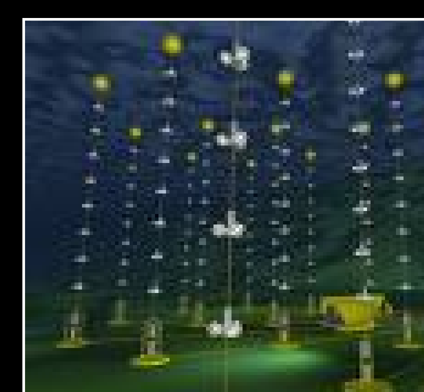
7) Couplings OK?



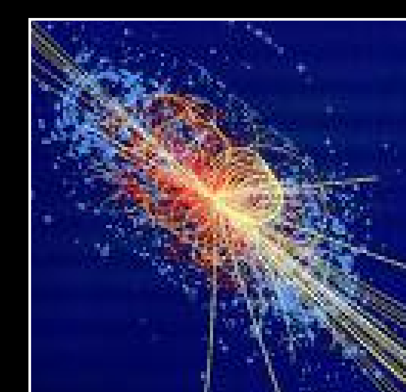
8) γ-rays OK?



9) Astro bounds?

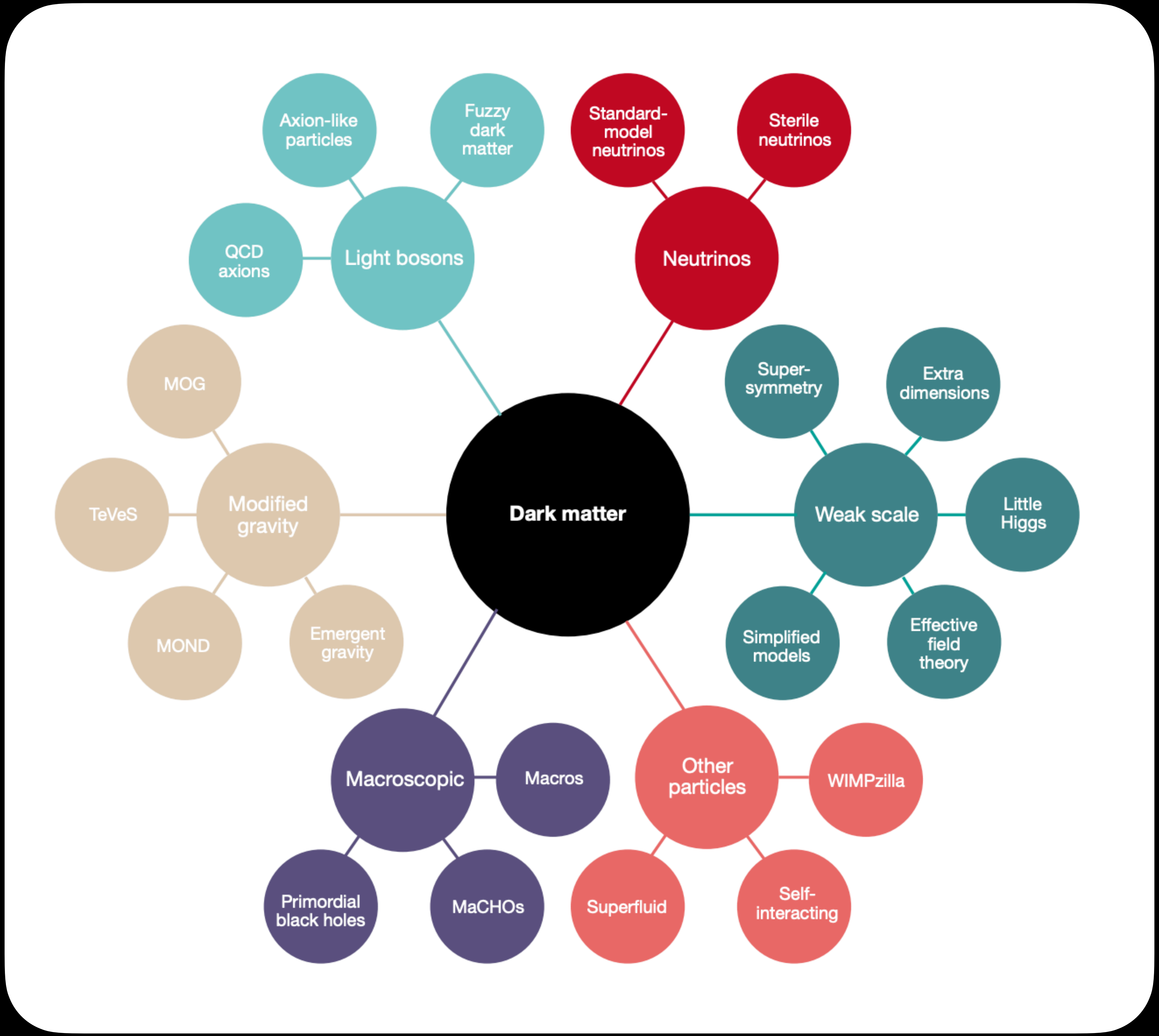


10) Can probe it?



Taoso, GB, Masiero 0711.4996

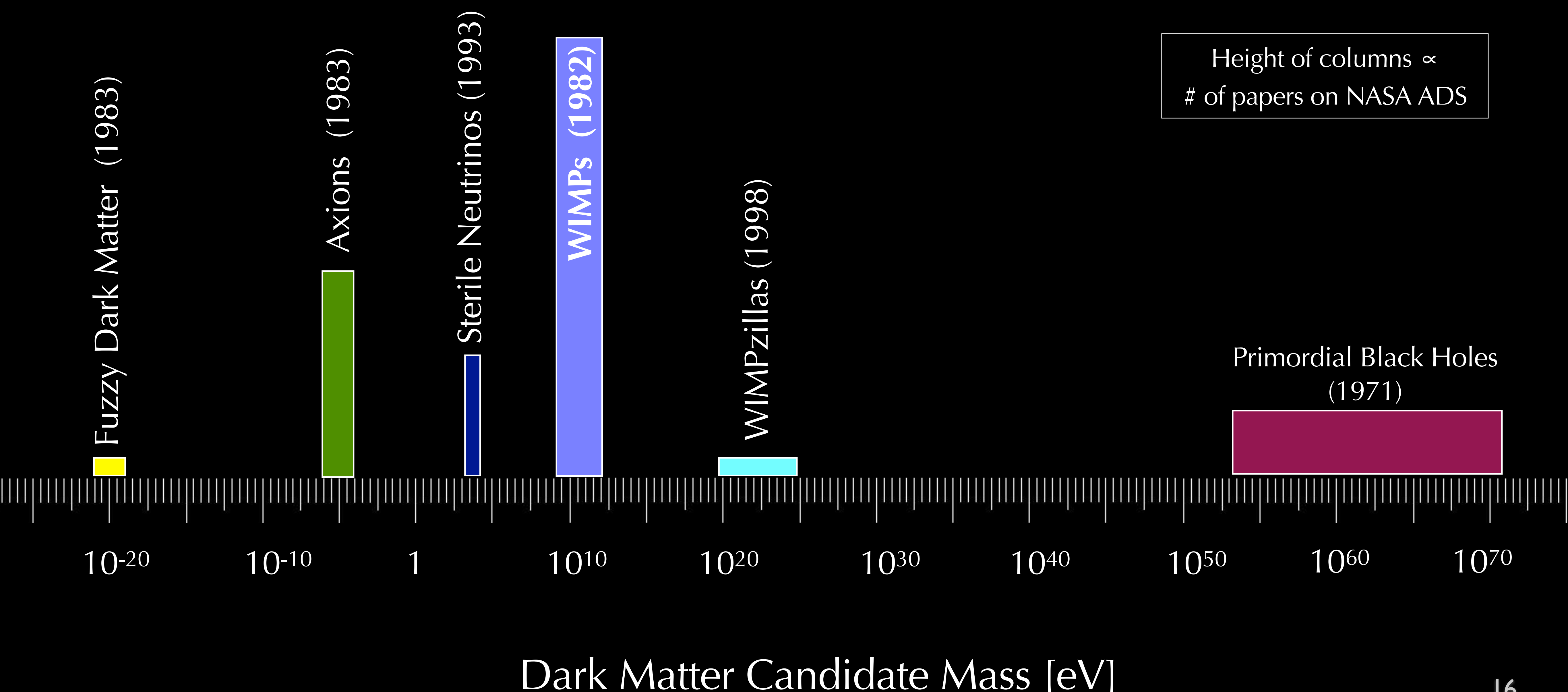
Candidates



GB, Tait, *Nature (2018) 1810.01668*

Candidates

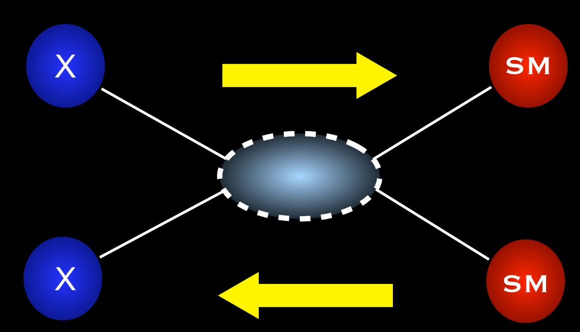
- No shortage of ideas..
- Tens of dark matter models, each with its own phenomenology
- Models span 90 orders of magnitude in DM candidate mass!



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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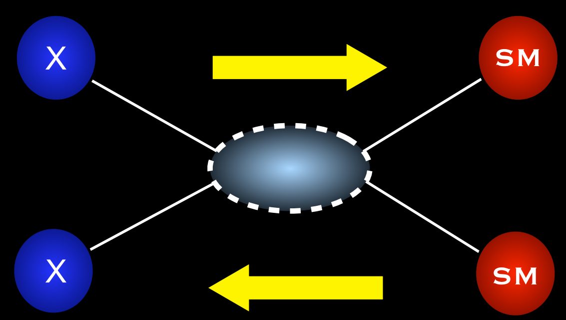


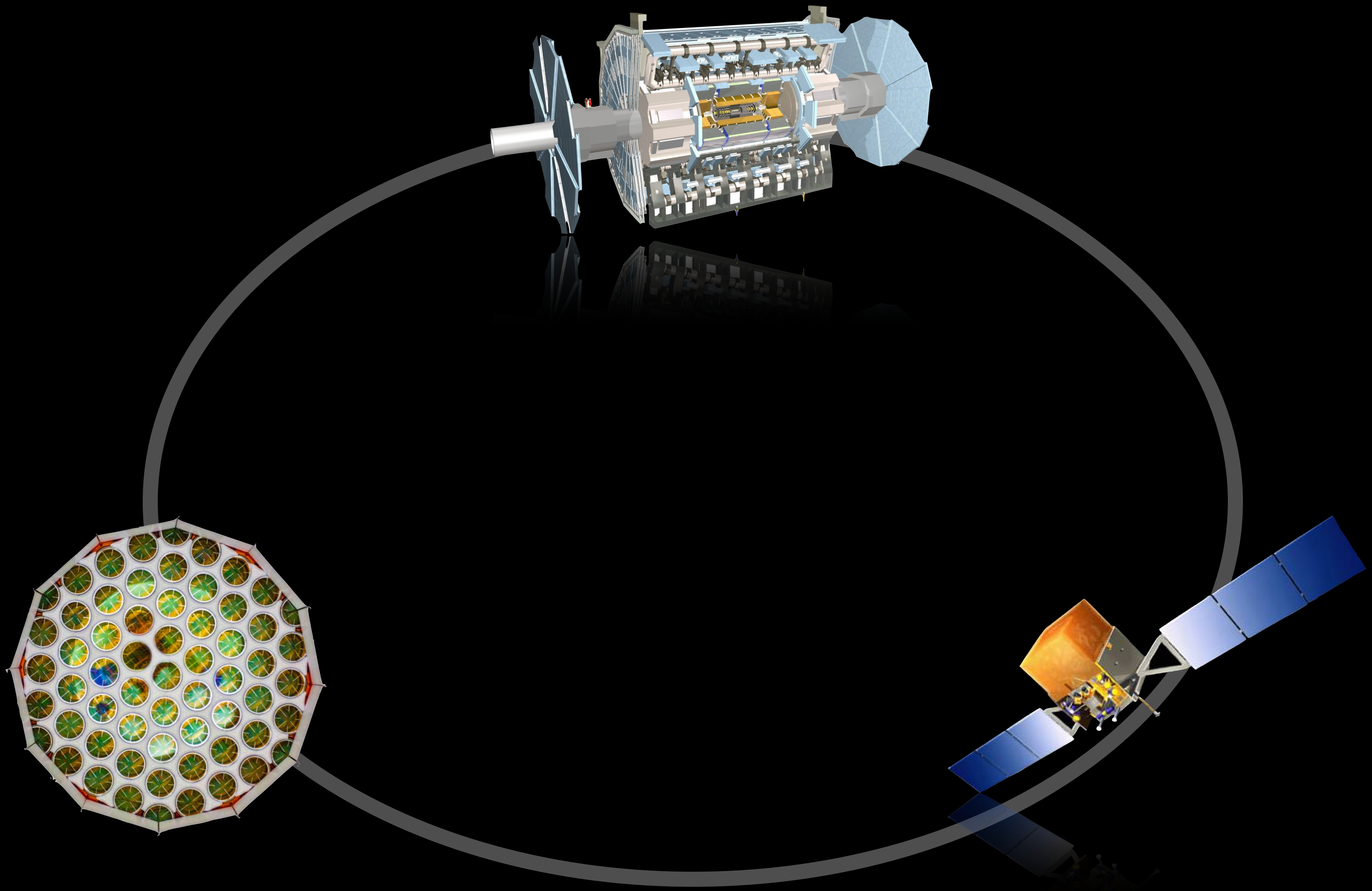
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

Weak-scale cross sections can reproduce observed relic density

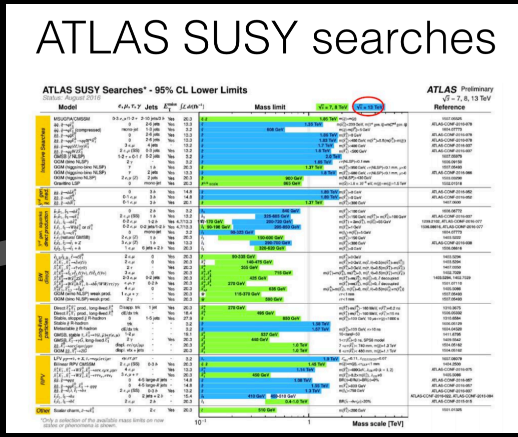
$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

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

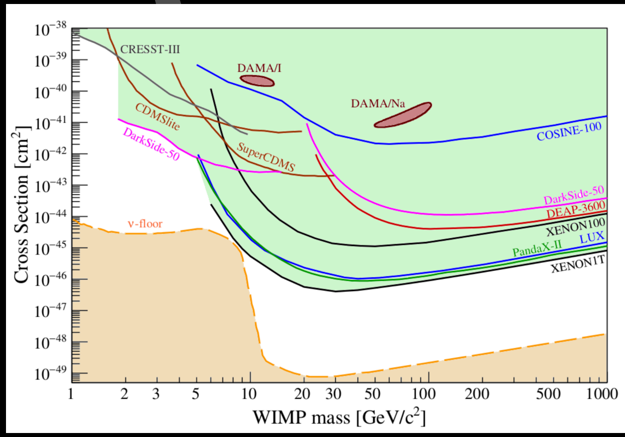
WIMPs searches

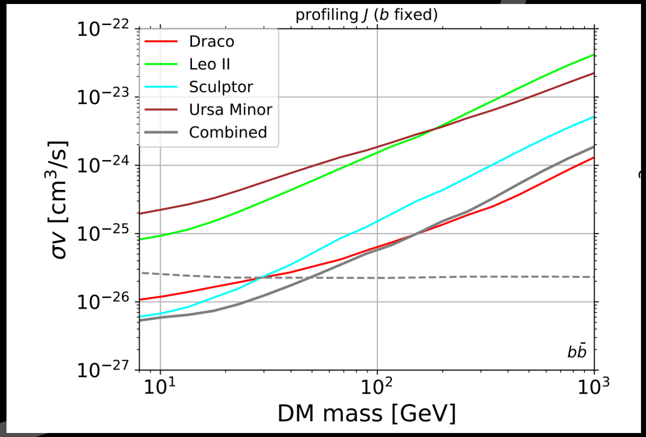


WIMPs searches



No WIMPs
found yet, despite many efforts!





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

The future of dark matter searches

I. Broaden/improve/diversify searches

II. Exploit astro/cosmo observations

III. Exploit Gravitational Waves

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

Primordial Black Holes

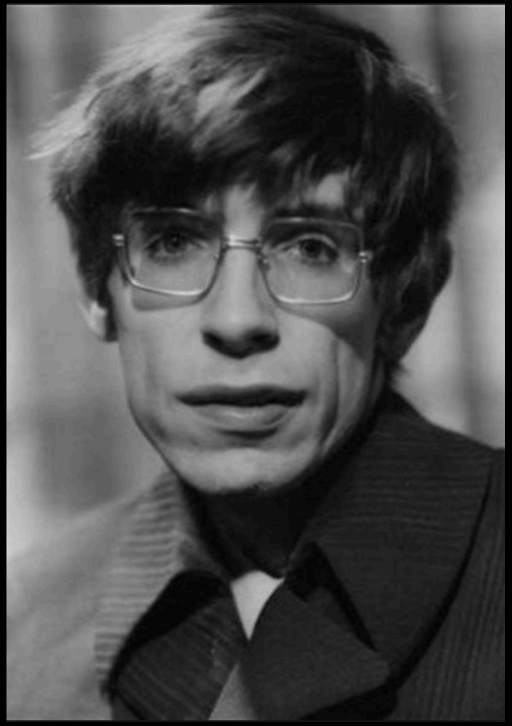
Mon. Not. R. astr. Soc. (1971) **152**, 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

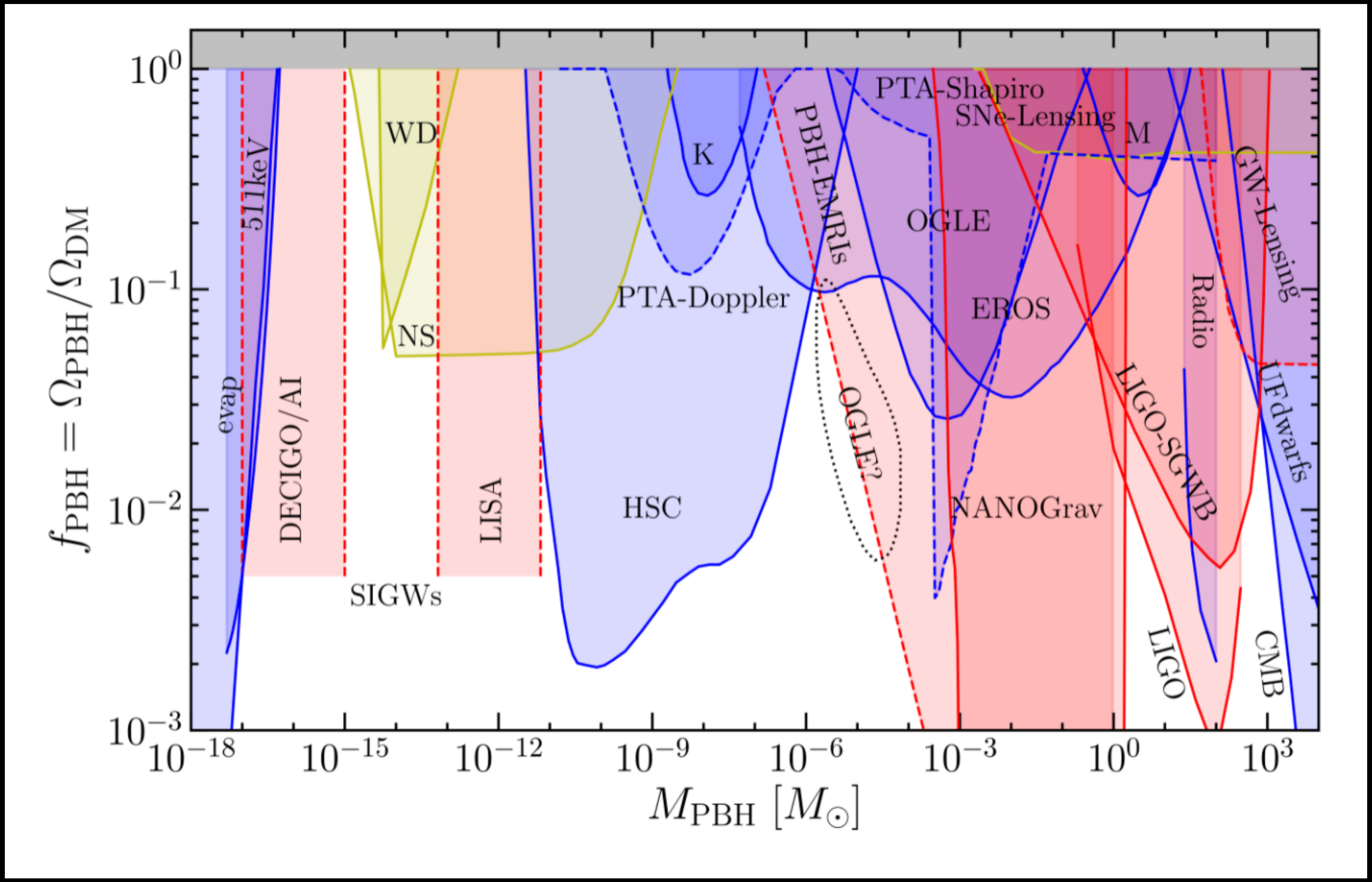
(Received 1970 November 9)



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.

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

In principle possible if BHs are *primordial*, in order to satisfy BBN constraints, but…

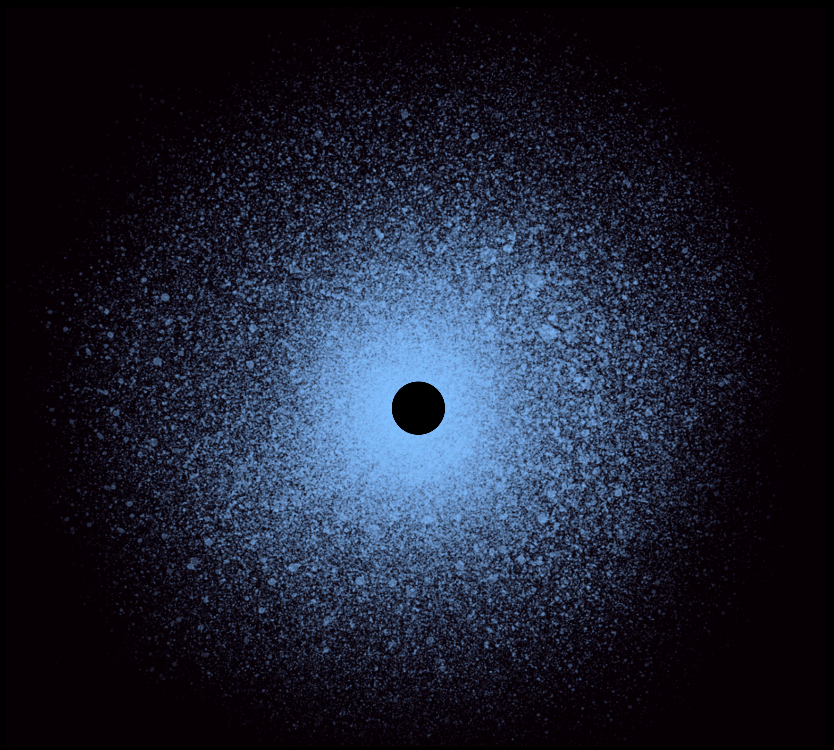


https://github.com/bradkav/PBHbounds

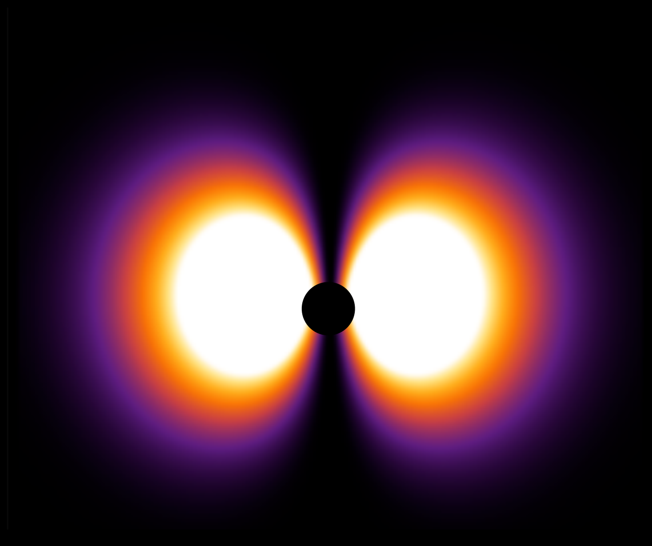
DM *around* BHs?

BH environments

Accretion discs



DM ‘spikes’

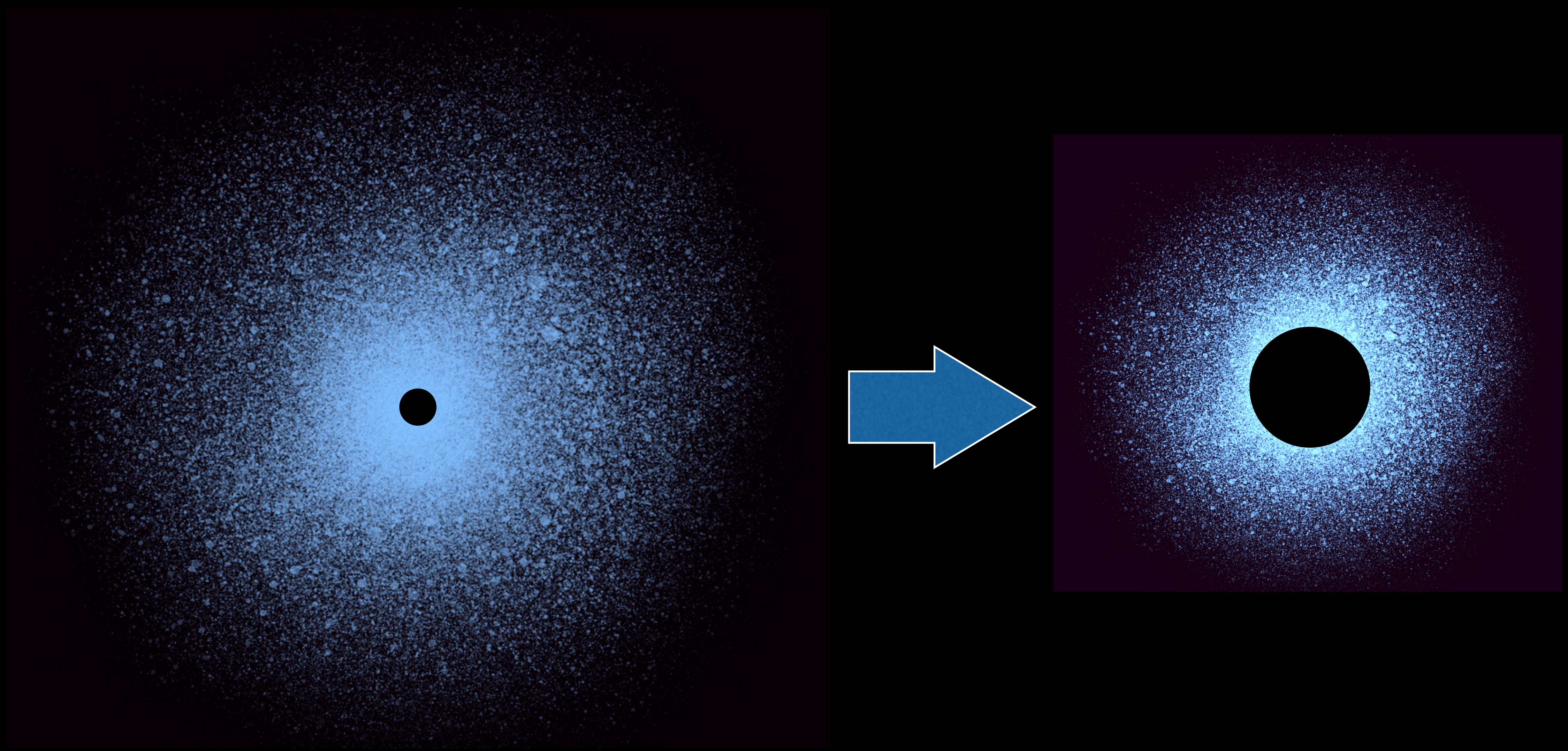


Gravitational atoms

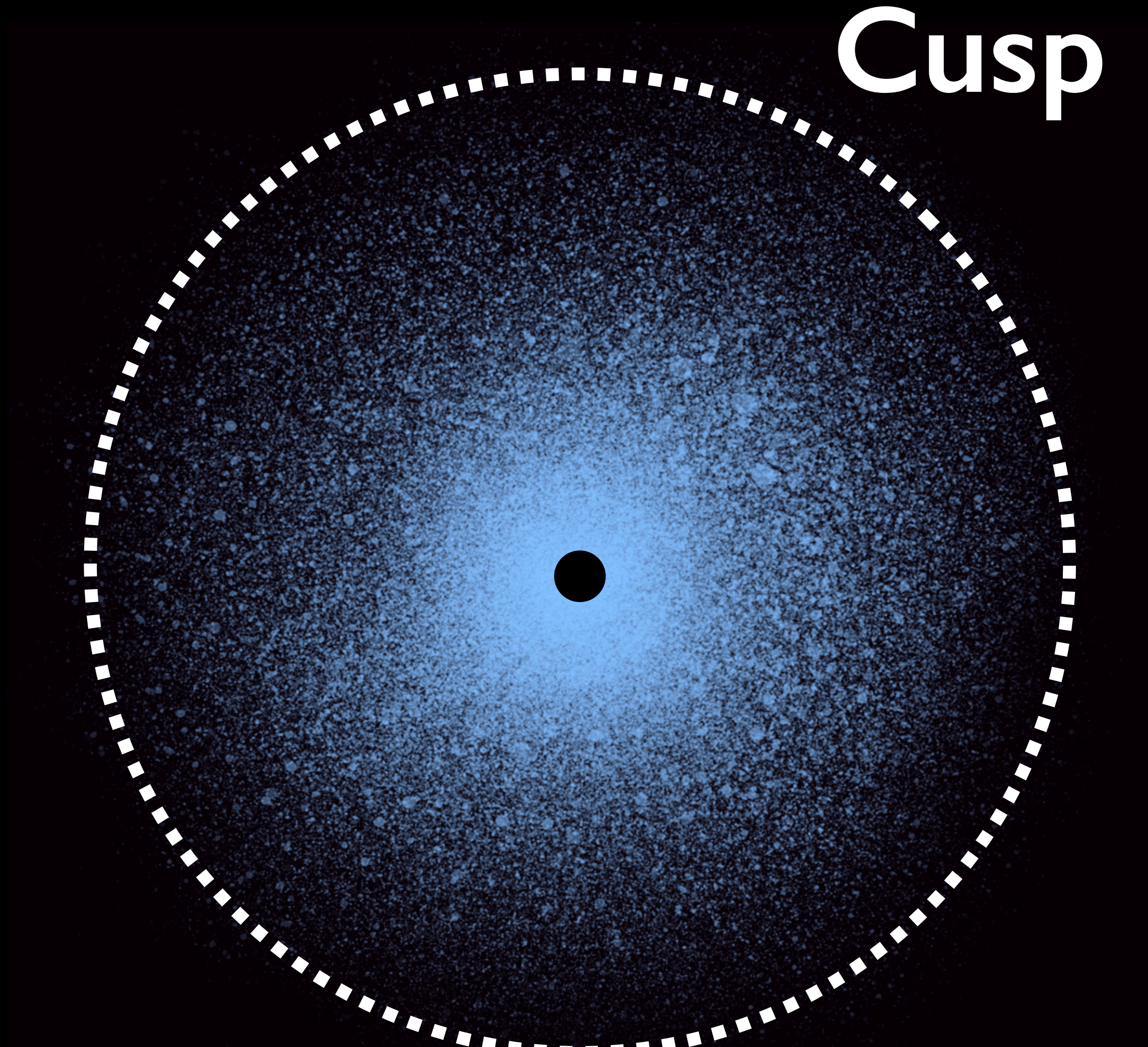
Accretion discs

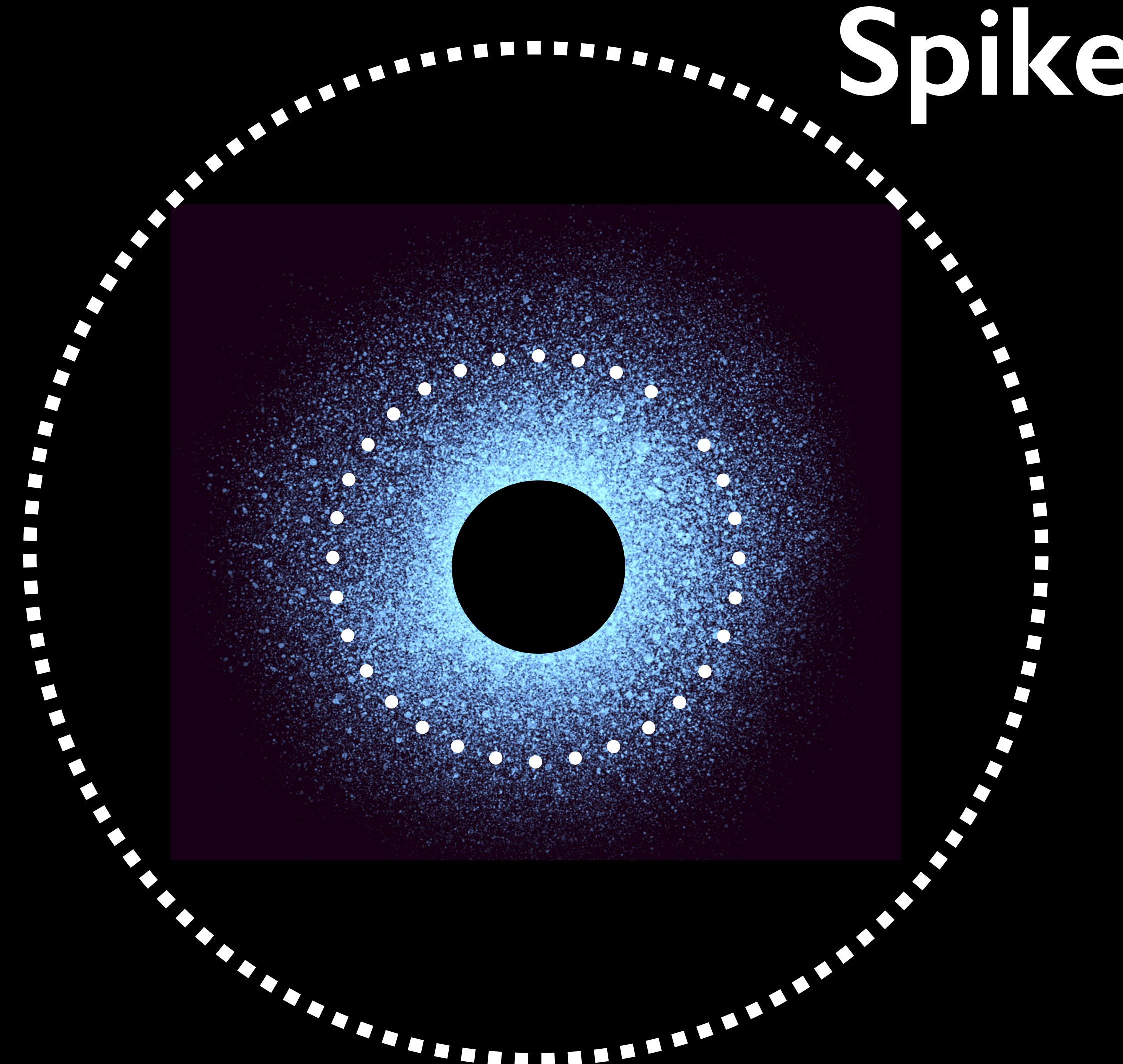
Event Horizon Telescope 2019

DM 'spikes' around Astrophysical BHs



DM 'spikes' around SMBH and IMBH

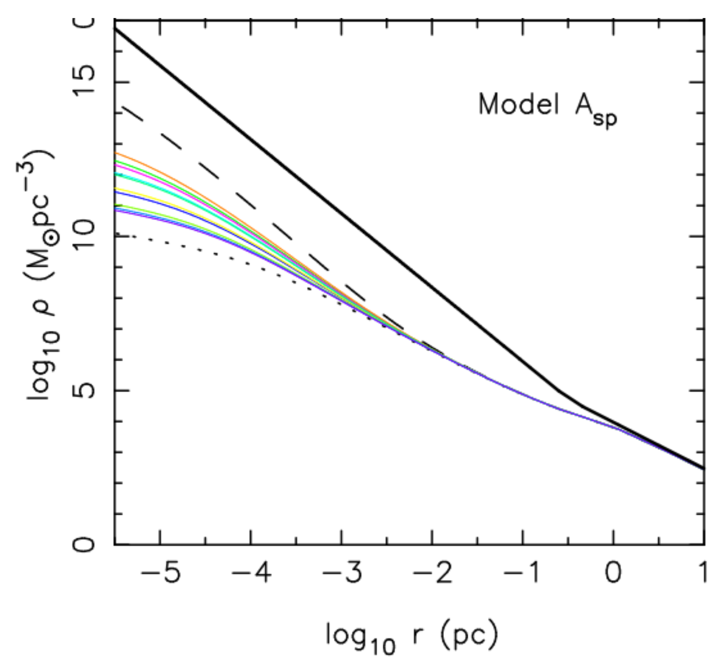




$$\rho_{\mathrm{cusp}}(r) \sim r^{-\gamma}$$

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

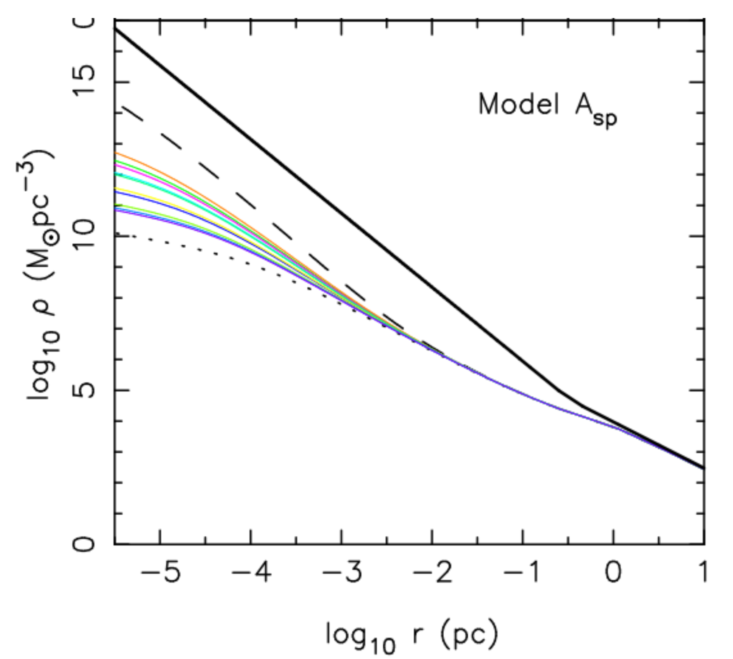
DM 'spikes'



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'



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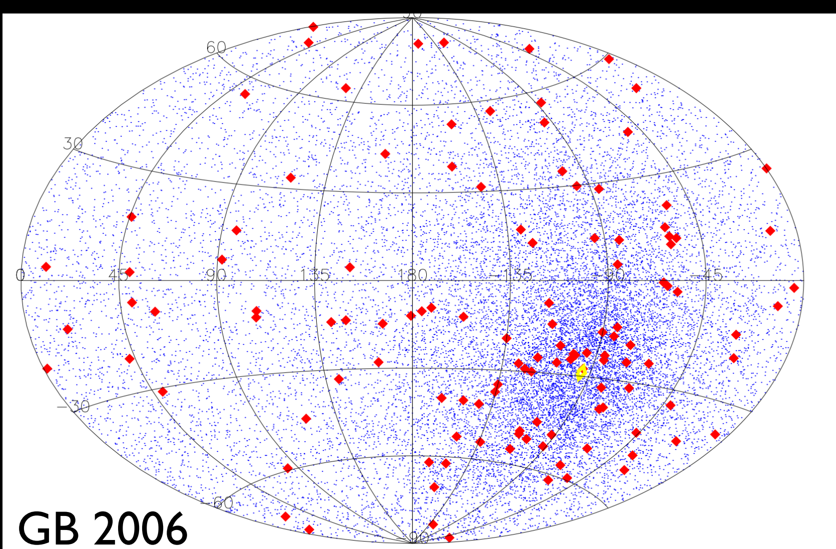
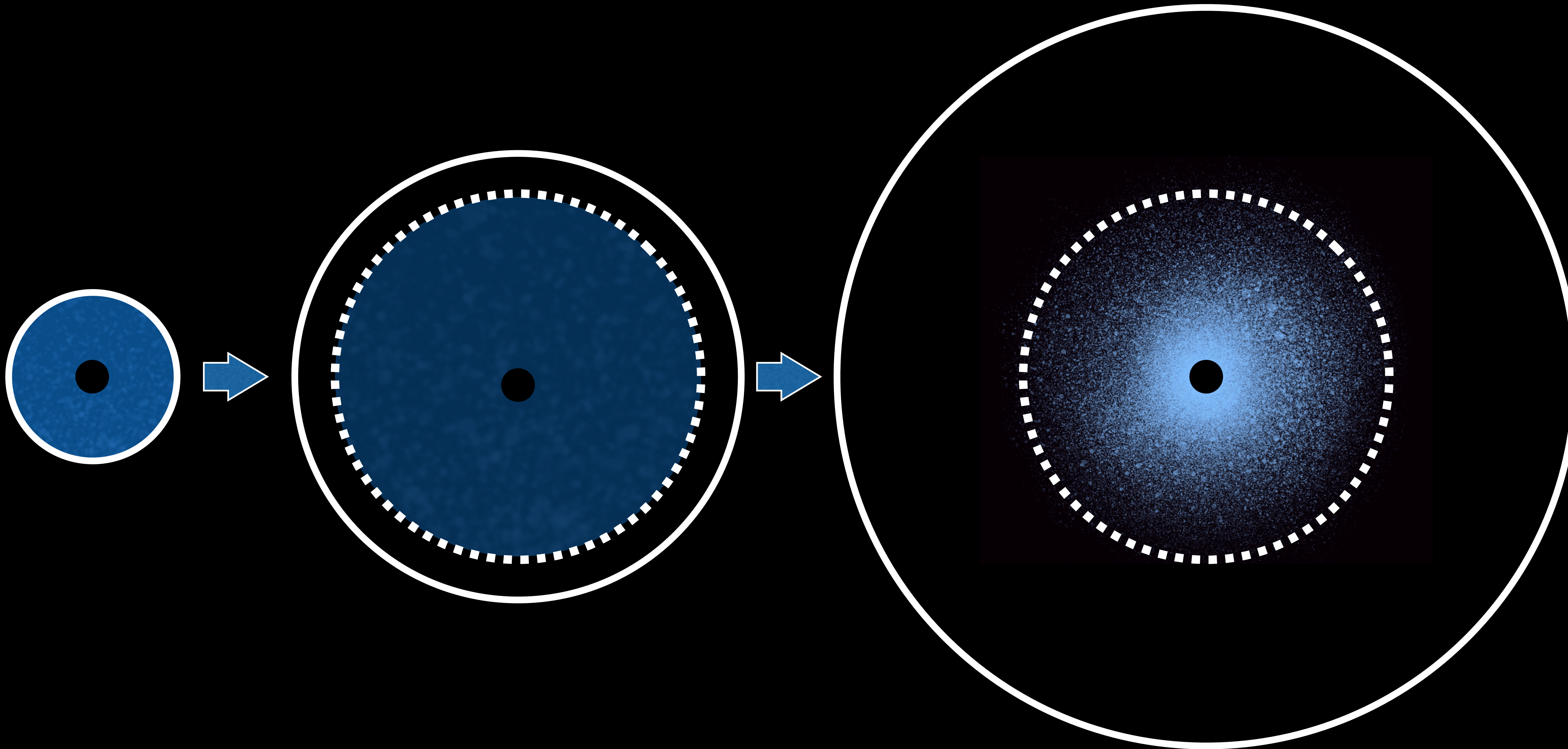

GB 2006

- 'Mini-spikes' around IMBHs! (GB, Zentner, Silk astro-ph/0509565)
- Targets for indirect detection (eg GB astro-ph/0603148)

DM overdensities around PBHs



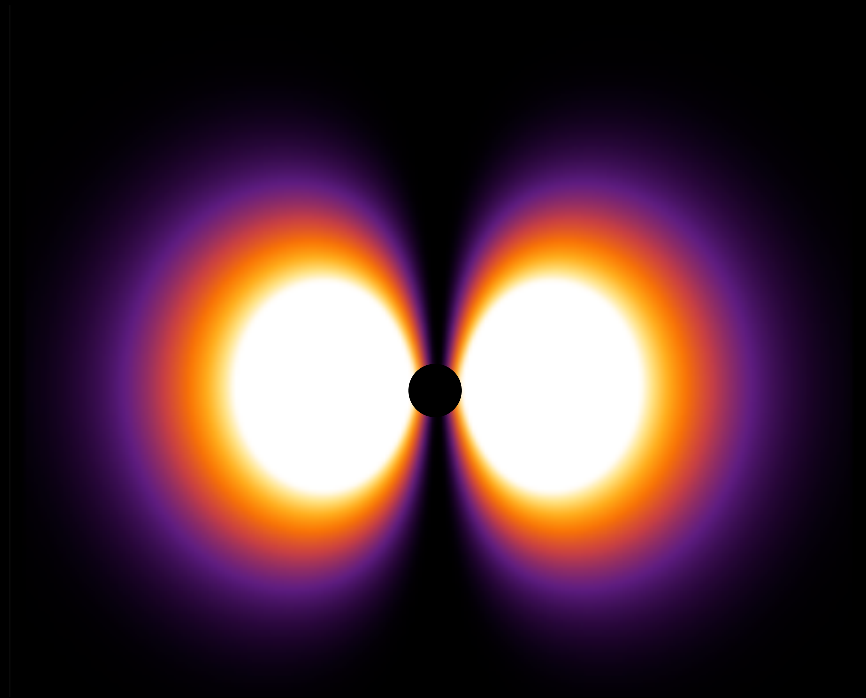
PBH

'Turnaround' point, when particles decouple from expansion

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

Adamek+ 1901.08528, Boudaud+ 2106.07480, ..

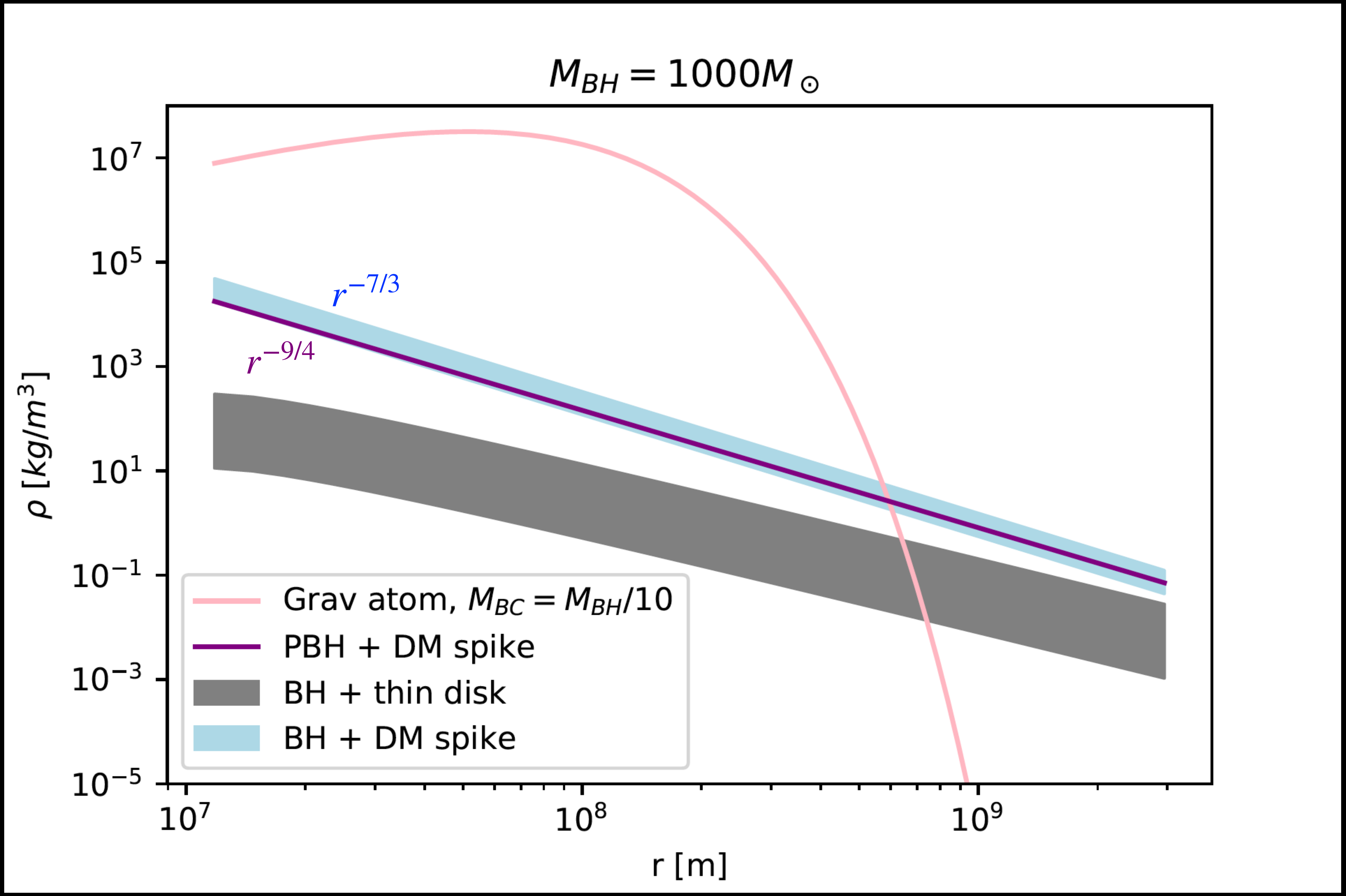
Gravitational atoms



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) …

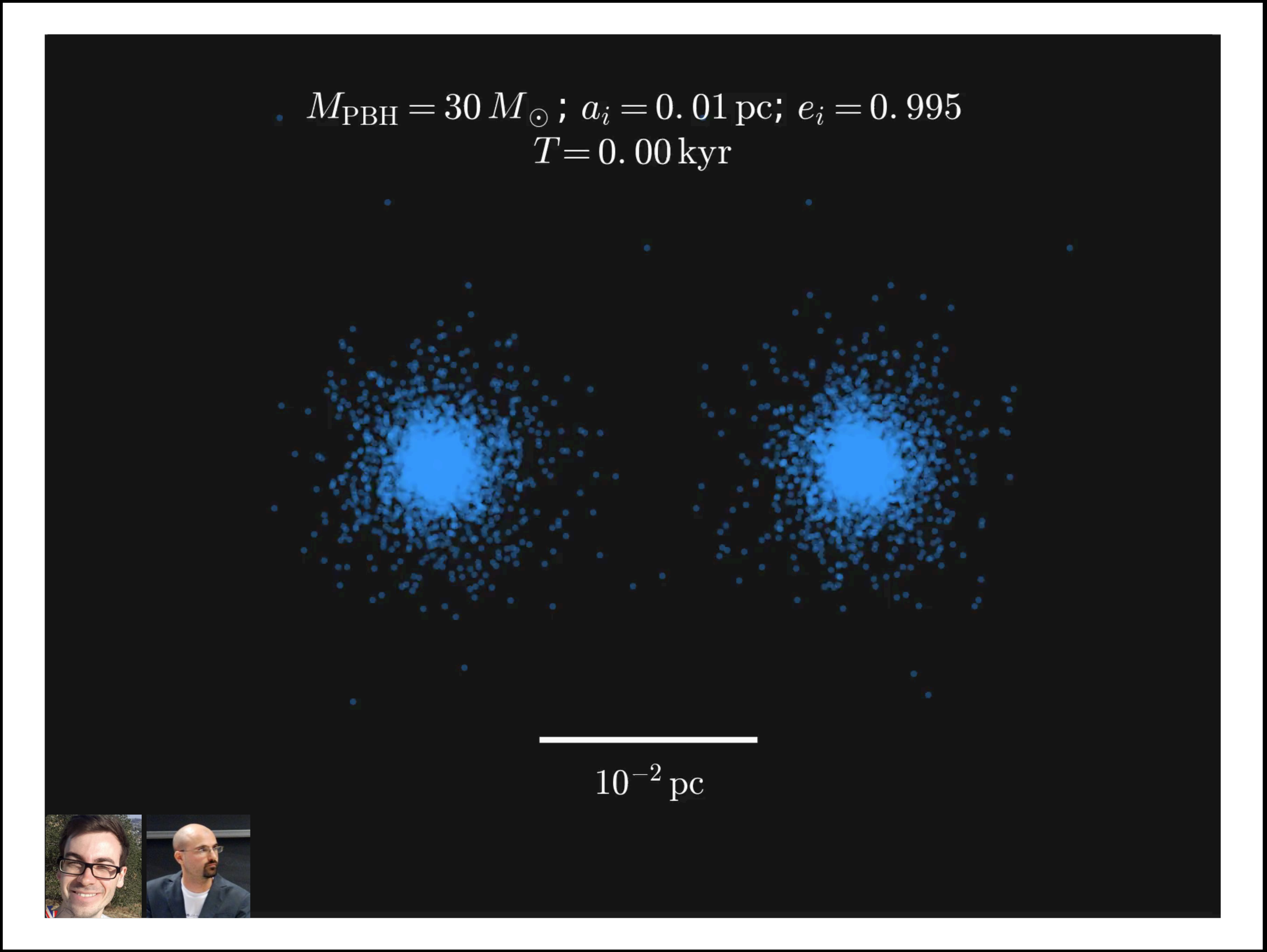
- If ultra-light bosons exist, they can be produced around rotating black holes through a process called **superradiance**
- This effect can extract enough mass and angular momentum to form large **cloud** of **condensate** of the bosonic field
- BH carrying boson cloud is called a **gravitational atom**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

BH environments



Pippa Cole, GB, + *in preparation*

‘Dressed’ BH-BH merger



Kavanagh, Gaggero & GB, arXiv:1805.09034

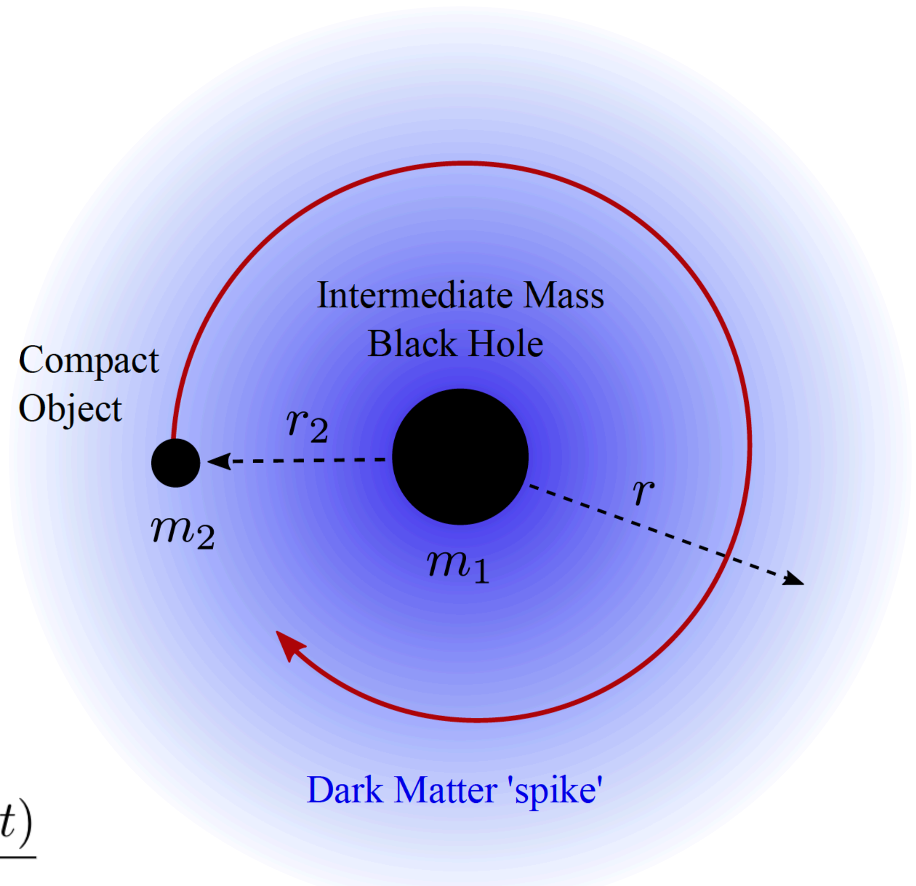
EMRIs in presence of spikes

Energy losses:

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

Separation:

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

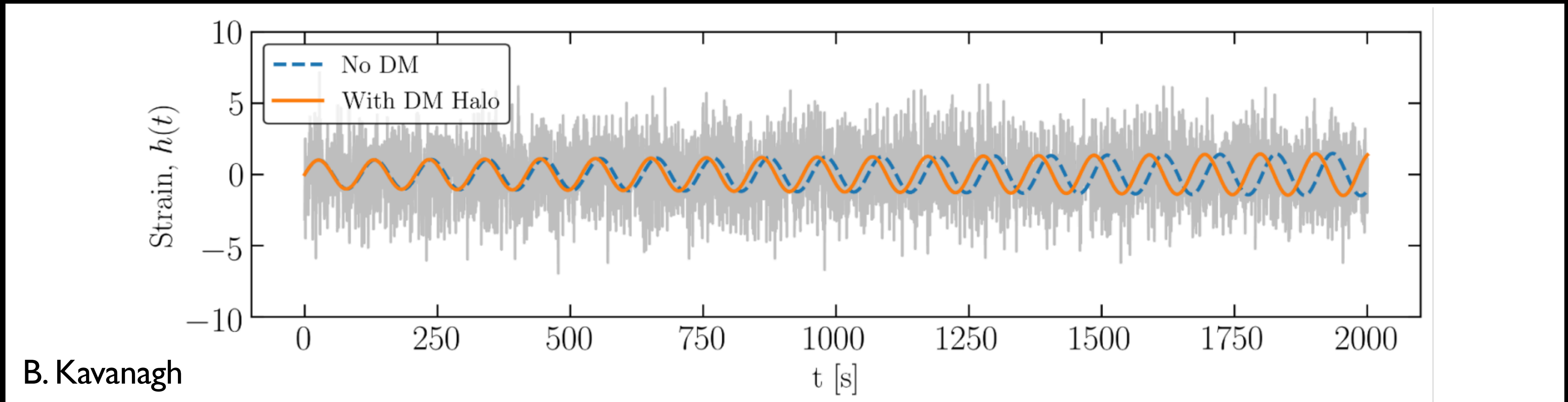


Time-dependent dark matter profile:

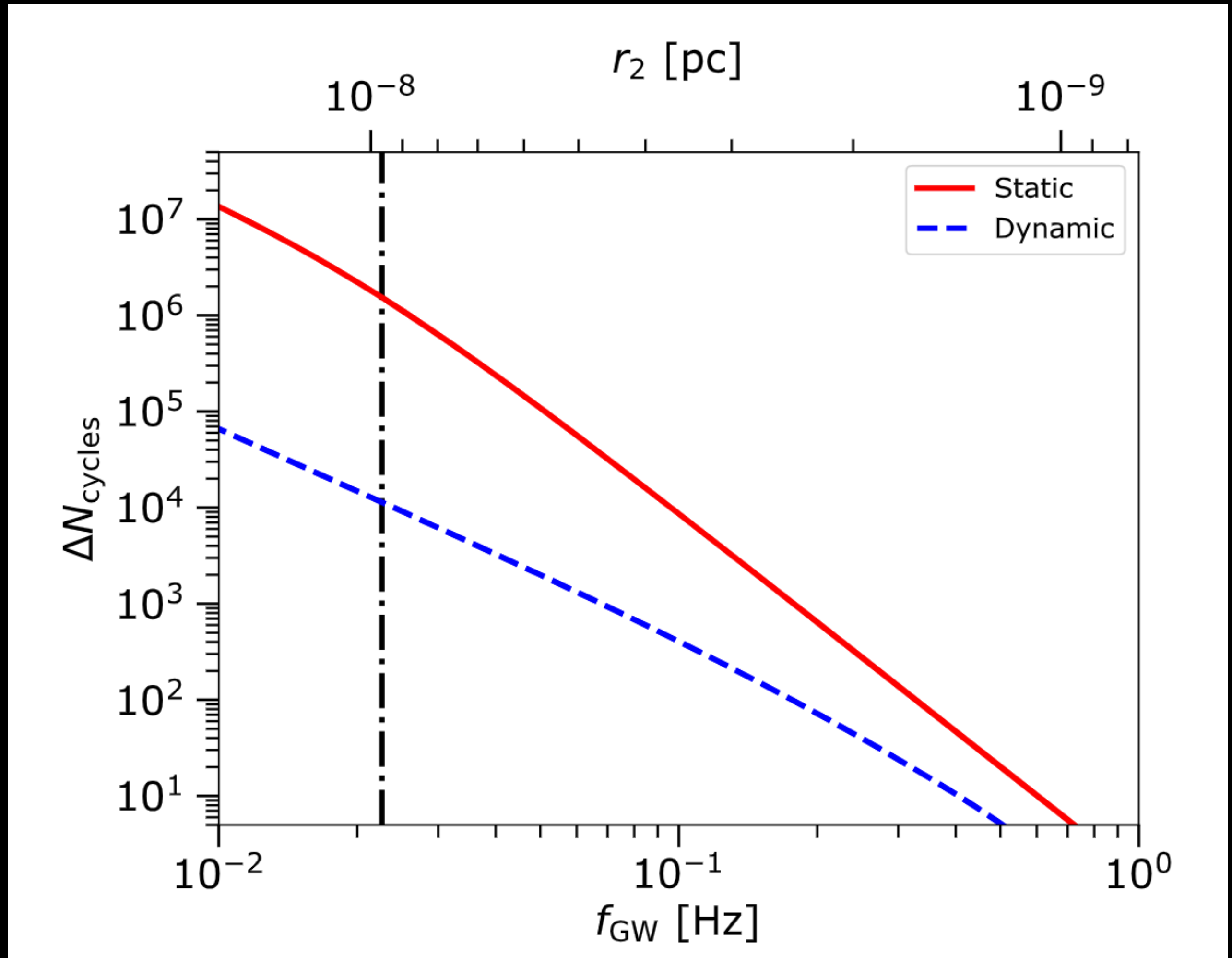
$$T_{\rm orb}\frac{\partial f(\mathcal{E},t)}{\partial t} = -p_{\mathcal{E}} f(\mathcal{E},t) + \int \left(\frac{\mathcal{E}}{\mathcal{E}-\Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E}-\Delta\mathcal{E},t) P_{\mathcal{E}-\Delta\mathcal{E}}(\Delta\mathcal{E})\, \mathrm{d}\Delta\mathcal{E}$$

Kavanagh, GB et al. 2002.12811

Gravitational Waveform dephasing



B. Kavanagh

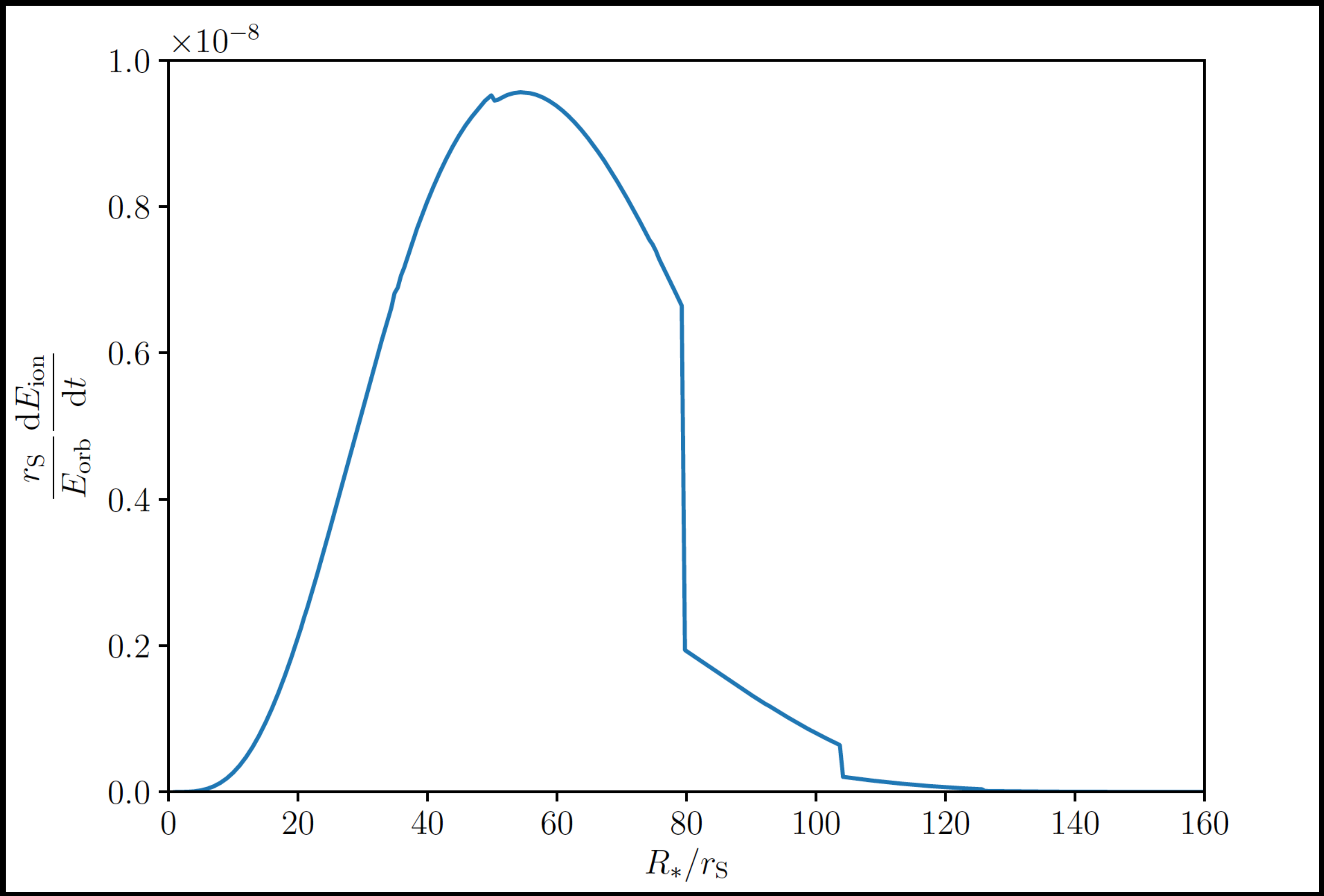


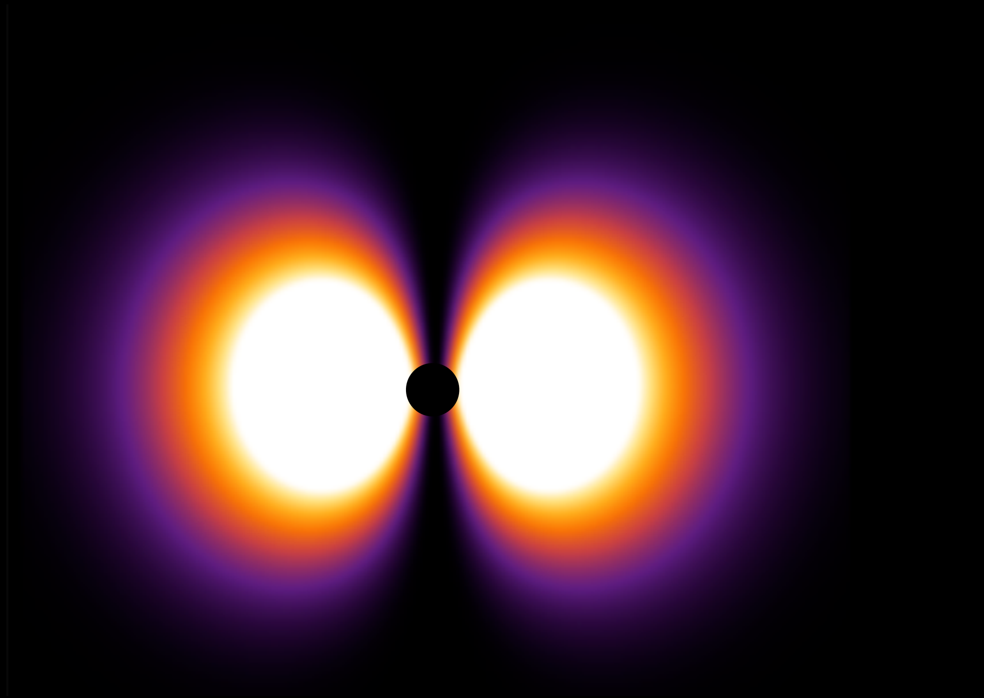
Kavanagh, GB et al. 2002.12811

- 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'

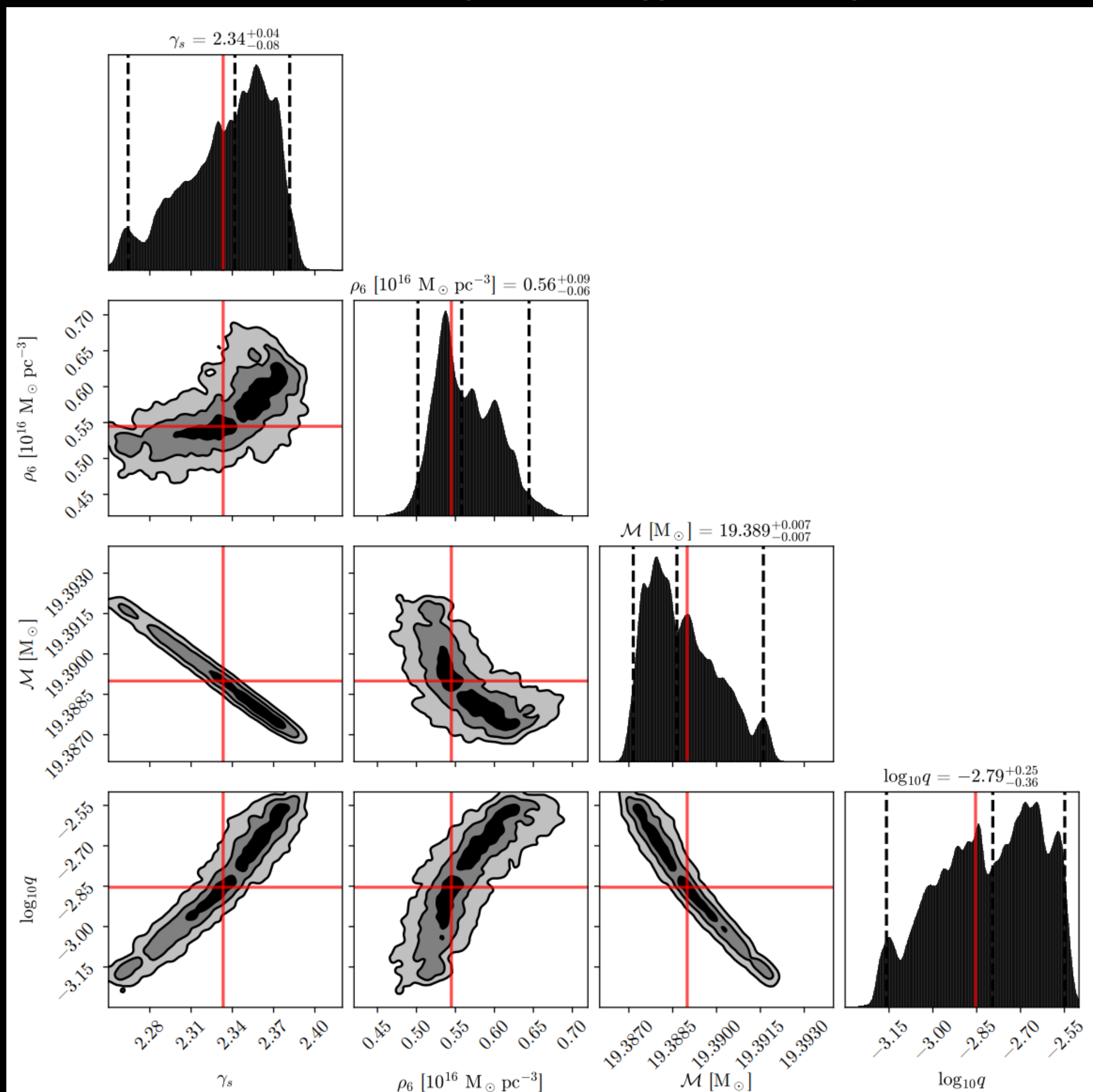




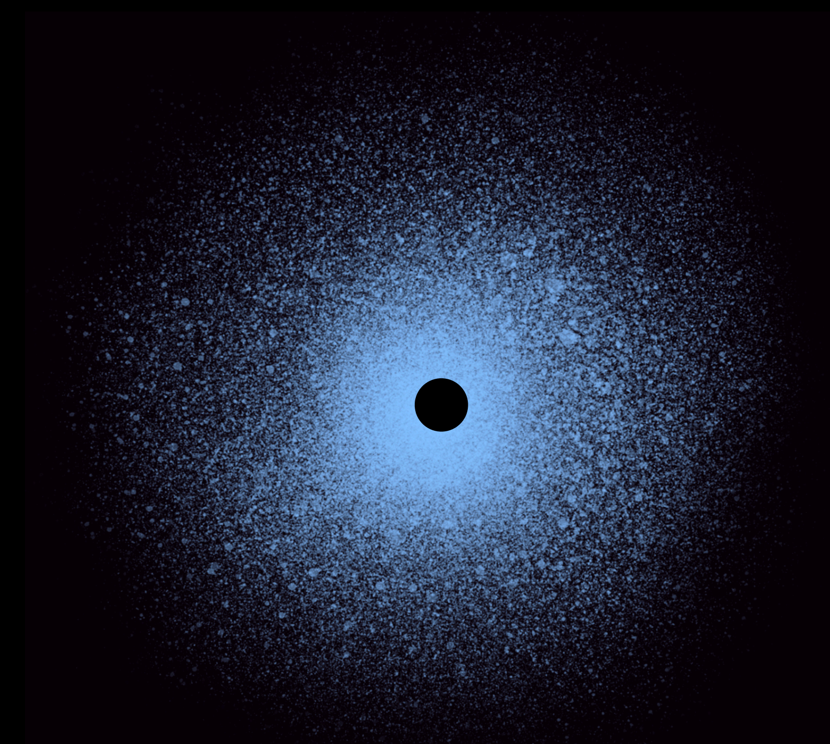
- 'Resonances' due to transitions between bound states $< a \,|\, V_*(t) \,|\, b >$
  Baumann, Chia, Porto, arXiv:1804.03208
- 'Ionization', i.e. transitions to continuum $< a \,|\, V_*(t) \,|\, klm >$
  Baumann, GB, Stout, Tomaselli Phys.Rev.Lett. 128 (2022) 22, 221102
- New: important role of accretion,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



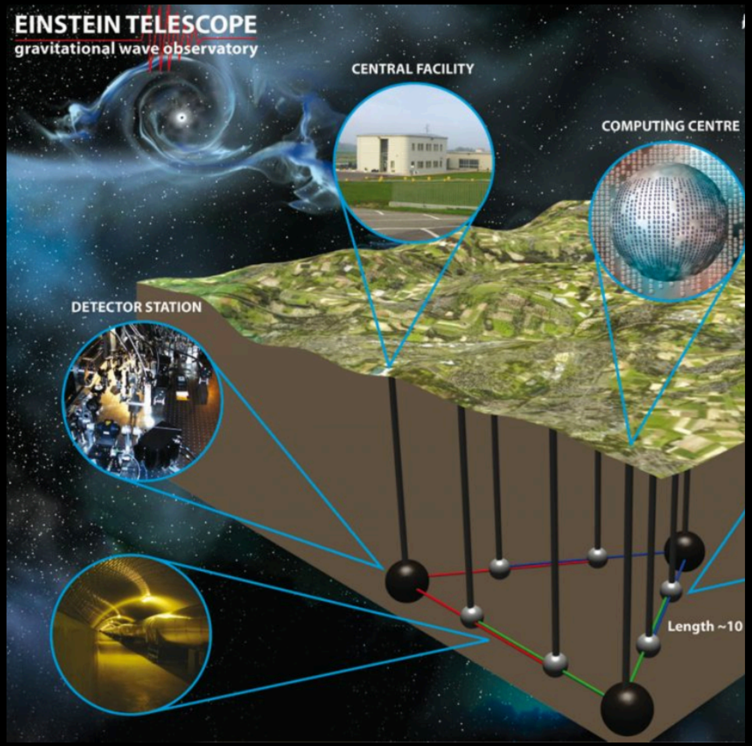
Spike Slope | Normalisation | Chirp Mass | Mass ratio



- 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

Can we convincingly discover *primordial* BHs?

Yes, e.g. if we:



I. Detect sub-solar mass BHs with current interferometers

(e.g. 2109.12197)

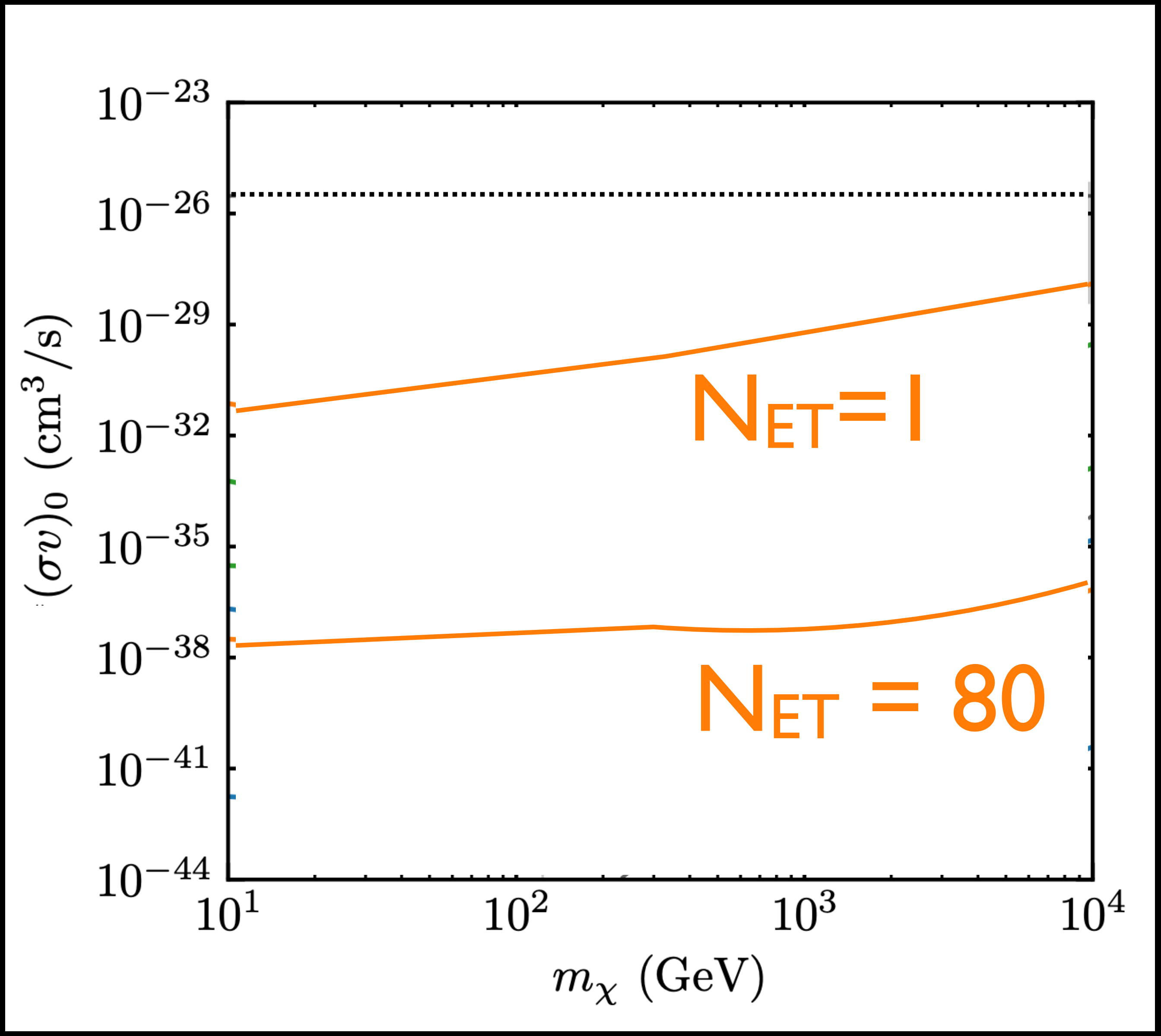
II. Detect O(100)$M_\odot$ BHs at $z > 40$ with Einstein Telescope

(e.g. 1708.07380)

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

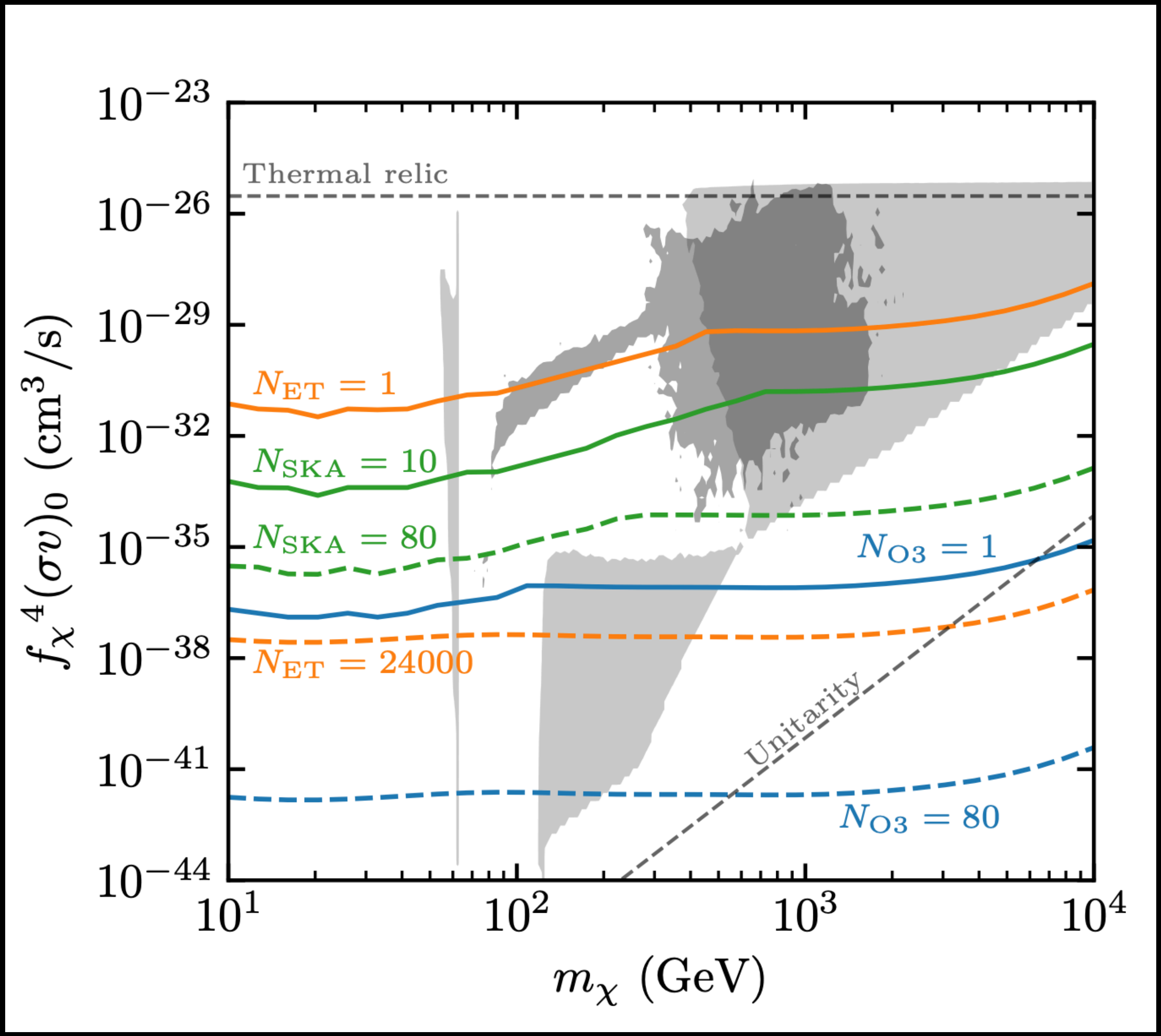
(e.g. 1810.02680)

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



GB, Coogan, Gaggero, Kavanagh, Weniger 1905.01238

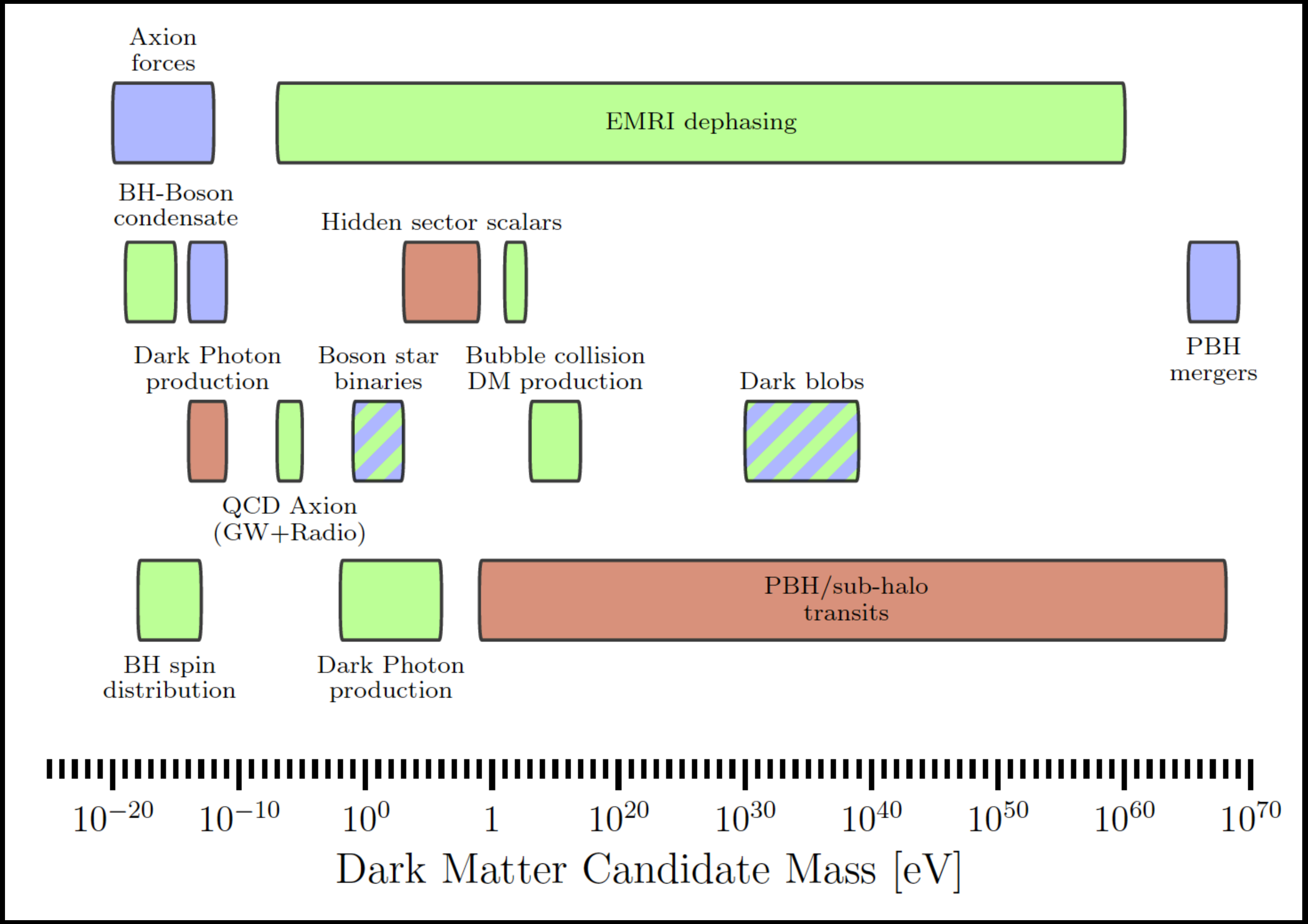
If (subdominant) PBHs discovered: Extraordinarily stringent constraints on new physics at the weak scale!



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

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