A new era in the quest for Dark Matter

Gianfranco Bertone

GRAPPA center of excellence, U. of Amsterdam

PANIC 2021, Lisbon 6/11/2021

GRAPPA

GRavitation AstroParticle Physics Amsterdam

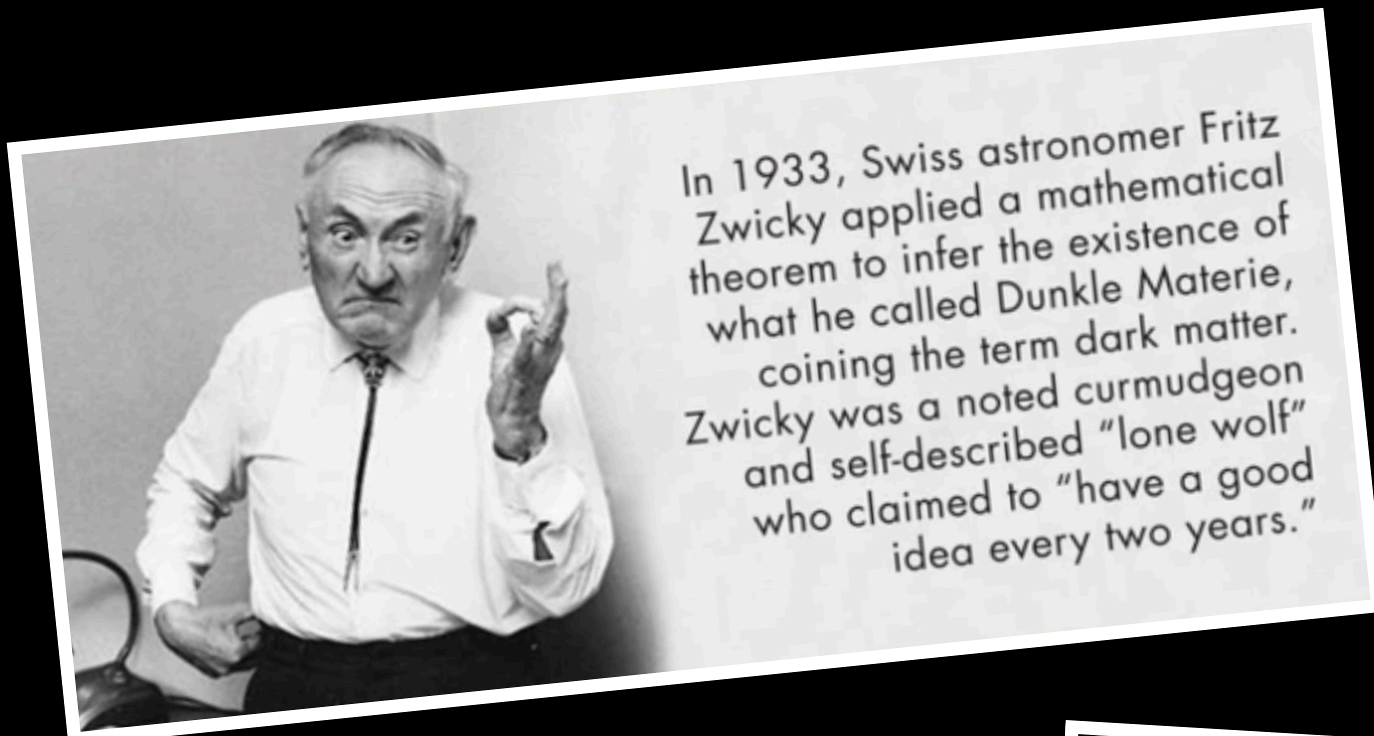
Plan of the talk:

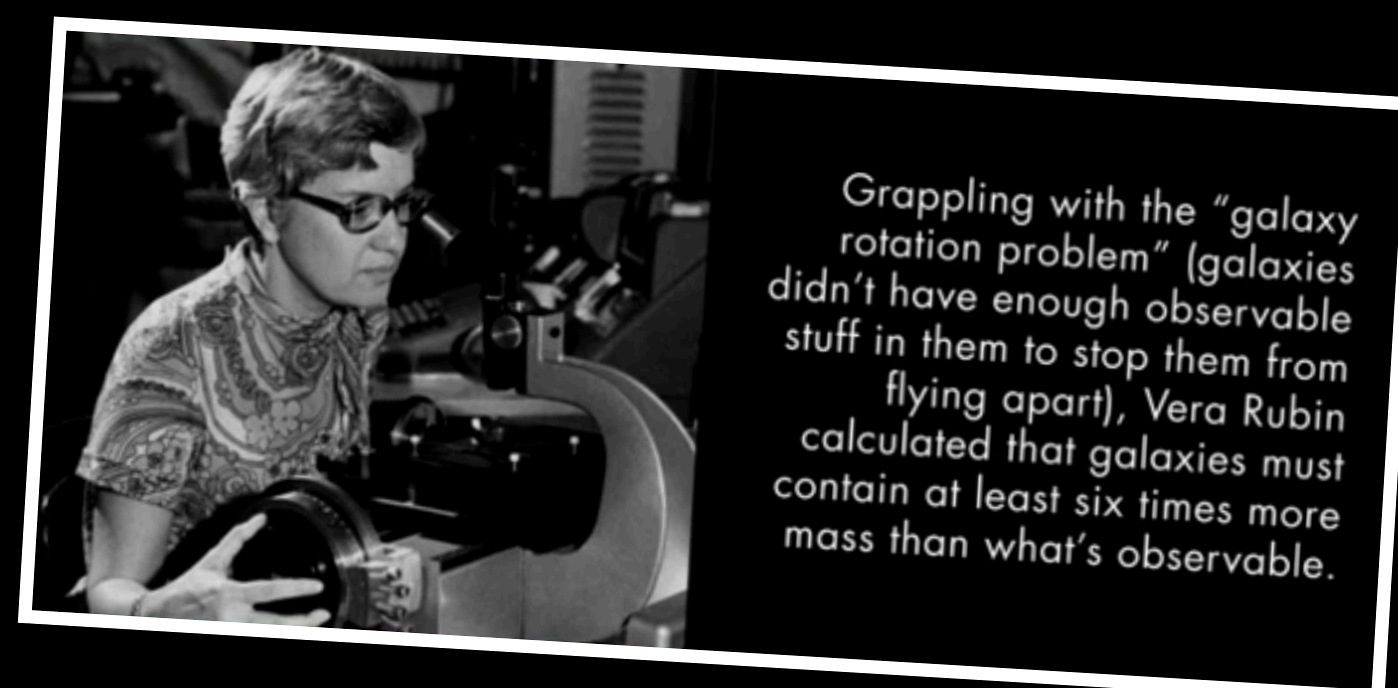
Preamble: the dark universe *narrative*

Part I: What have we learnt?

Part II: A new era in the quest for DM

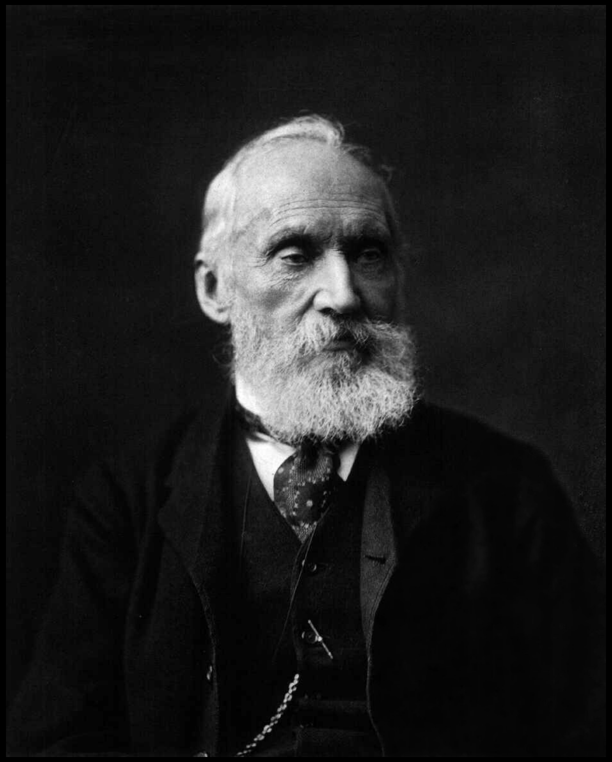
Dark Matter "Mythology"





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."*

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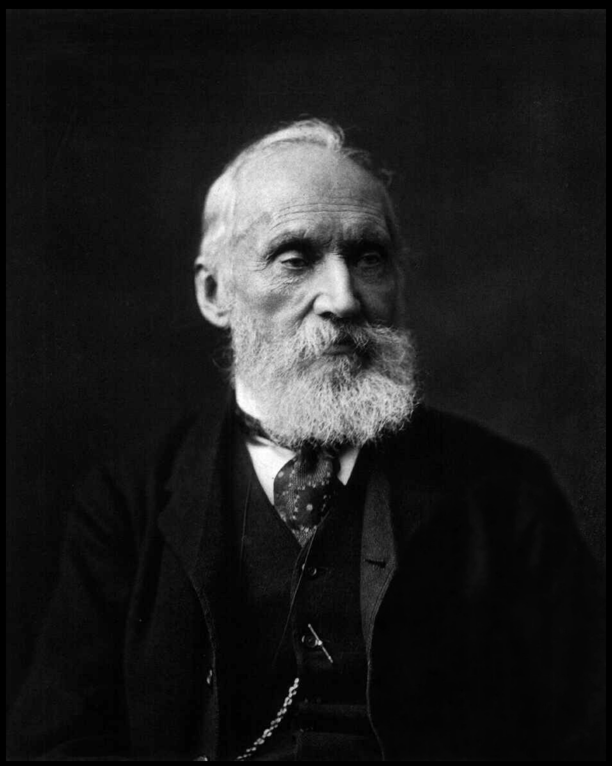

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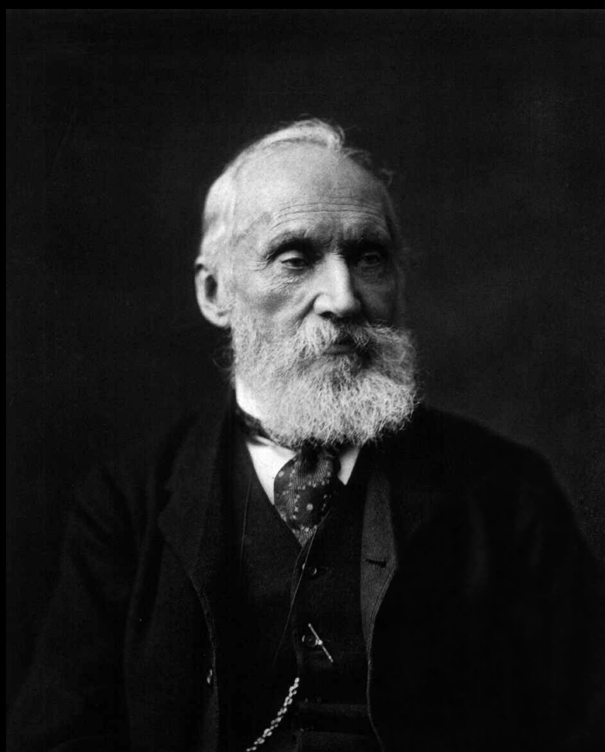

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Fritz Zwicky (1933)

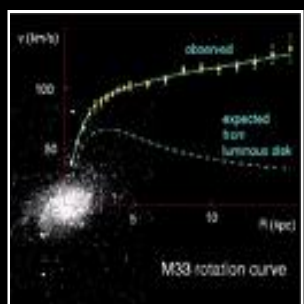
"According to present estimates the average density of dark matter in our galaxy and throughout the rest of the universe are in the ratio 10^5"

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

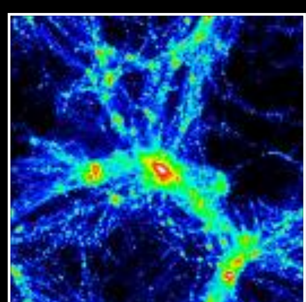
"How dark matter came to matter" de Swart, GB, van Dongen - Nature Astronomy; *1703.00013*

What is the Universe made of?

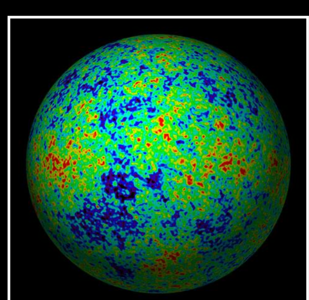
OBSERVATIONS



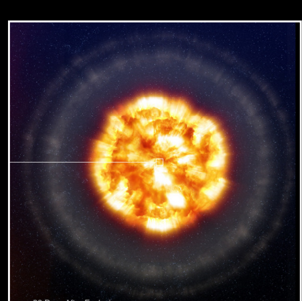
- Rotation Curves



- Clusters of galaxies

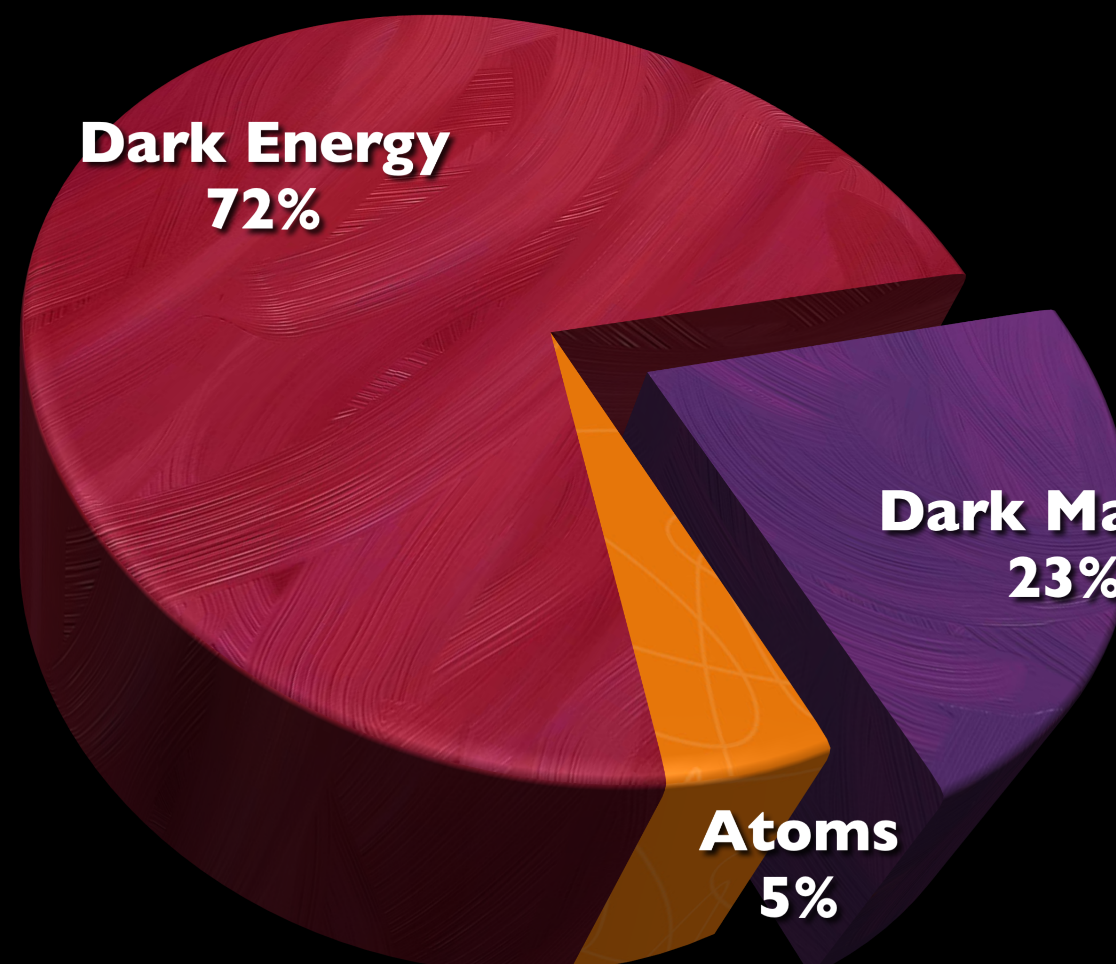


- CMB



- Type Ia Supernovae

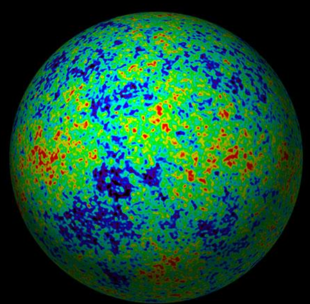
...

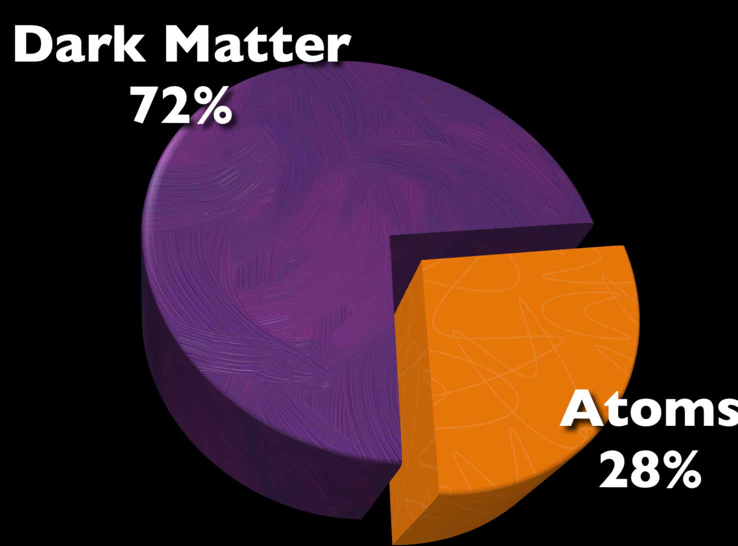


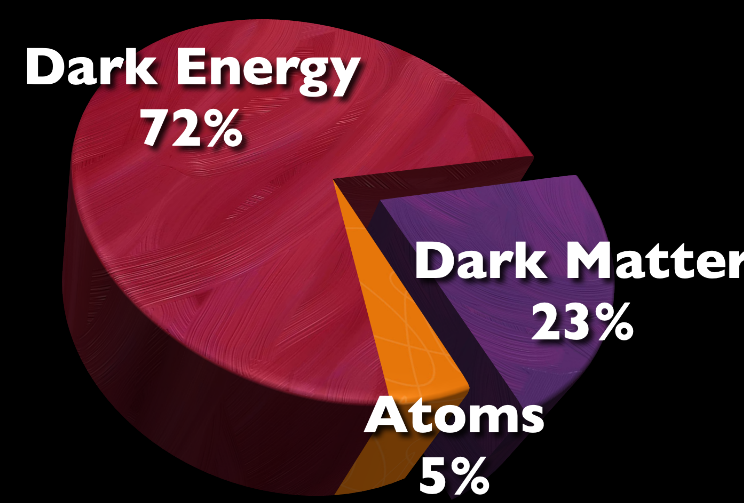
[statement valid _now_, and on _very large scales_]

What is the Universe made of?

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

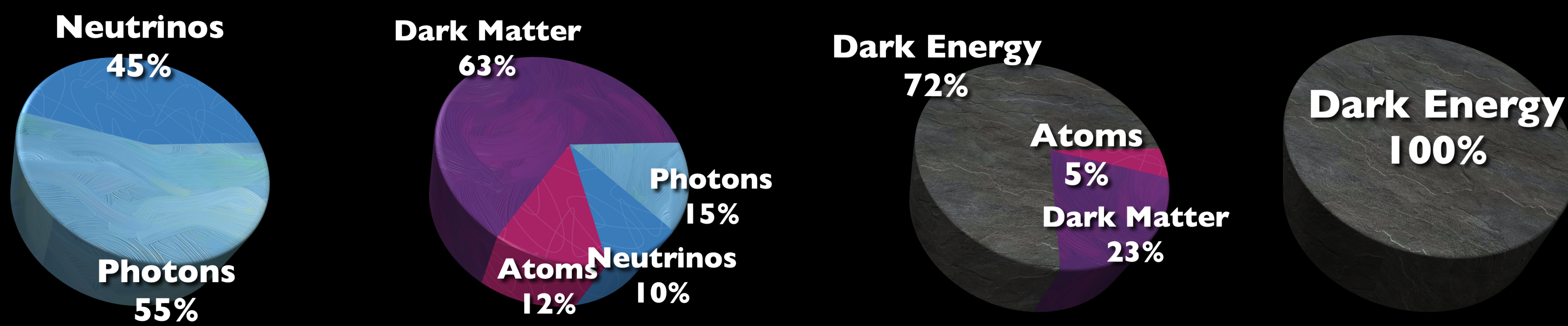




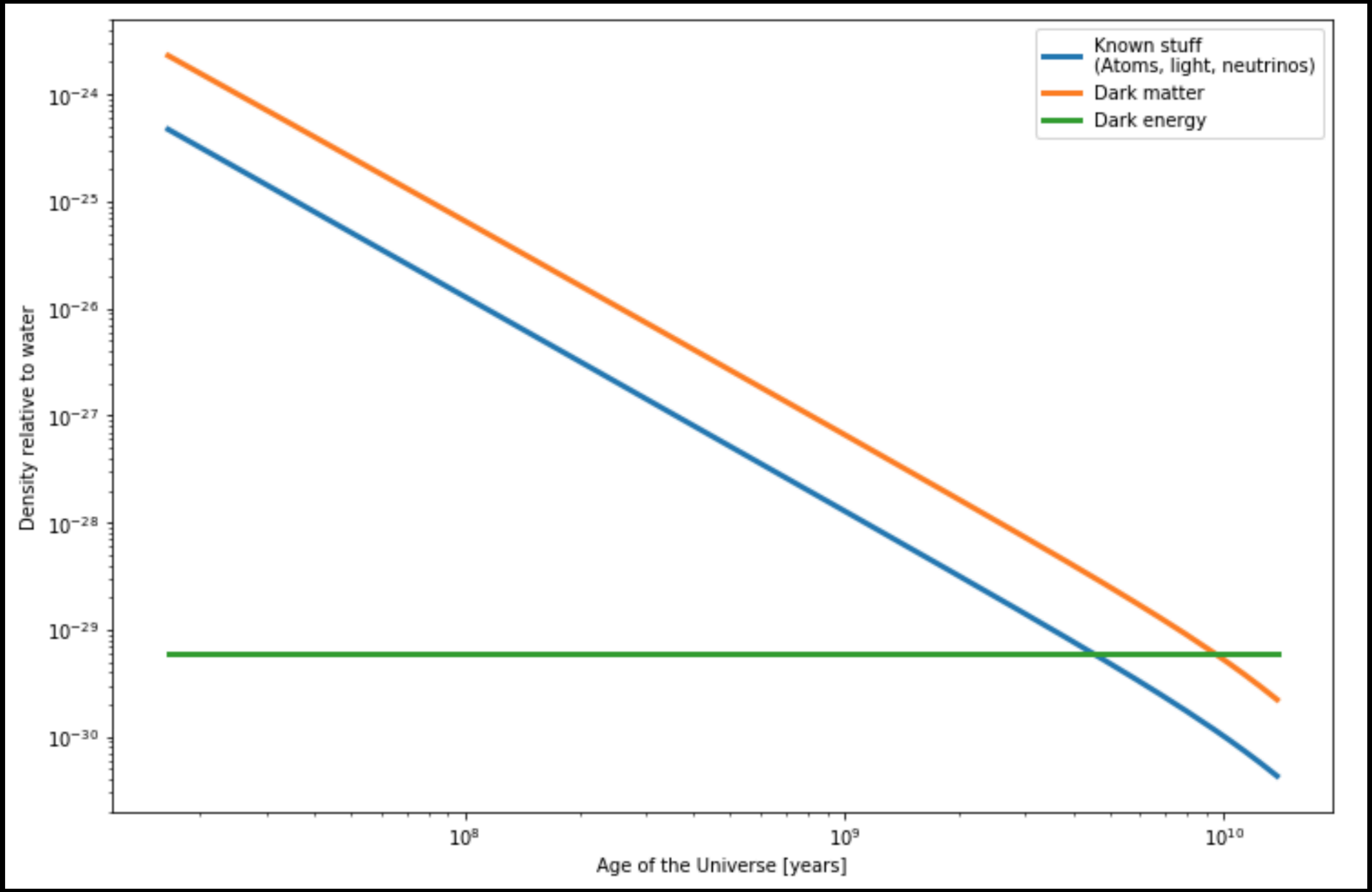


What was the Universe made of?

At BBN | At recombination | Today | …eventually



Evolution of matter/energy density

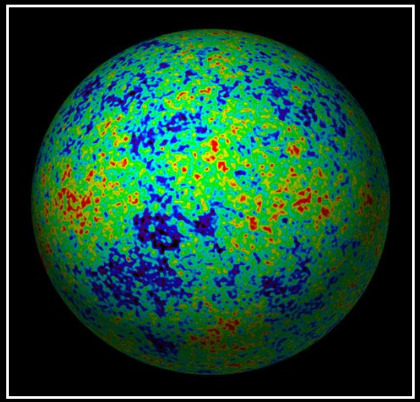


Created with #astropy https://astropy.org, astropy.cosmology package https://docs.astropy.org/en/stable/cosmology/

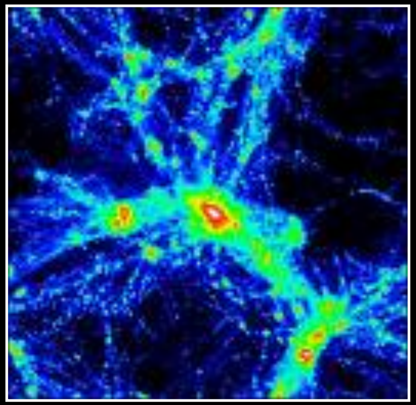
What do we know?

In order to be considered a viable DM candidate,
a new particle has to satisfy a number of conditions:

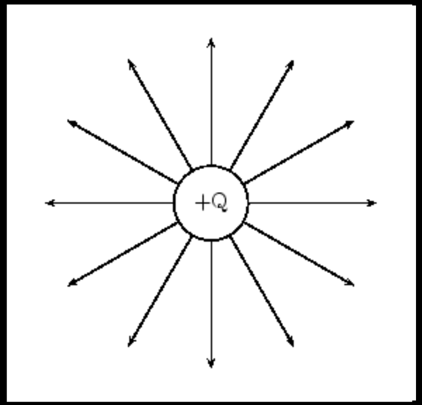
1) Abundance ok?



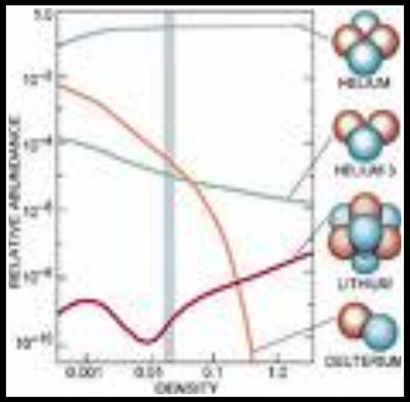
2) Cold?



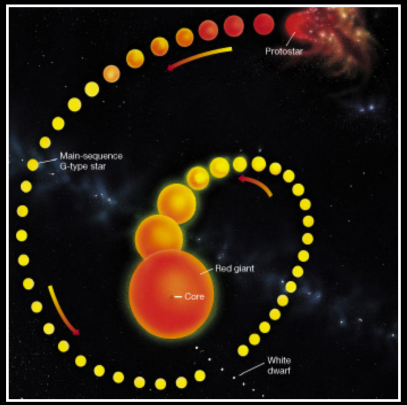
3) Neutral?



4) BBN ok?



5) Stars OK?



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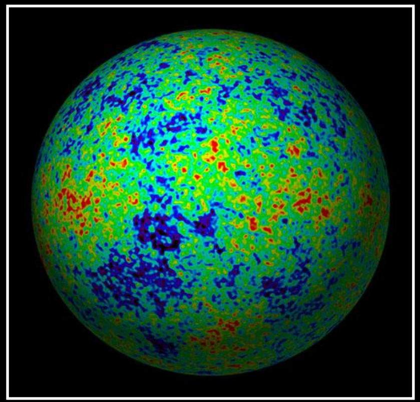

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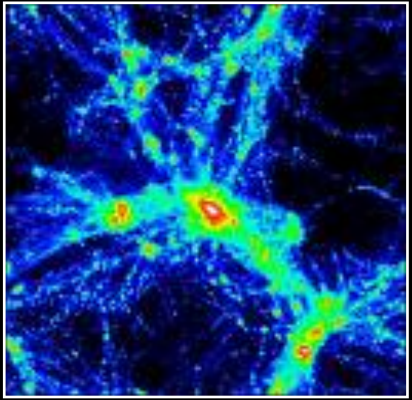

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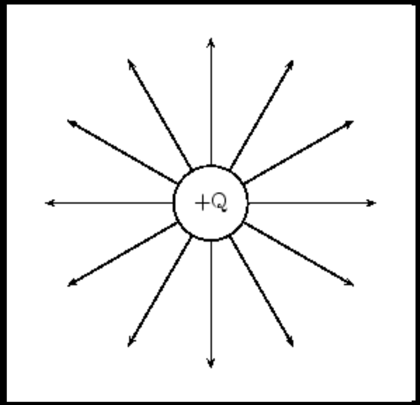

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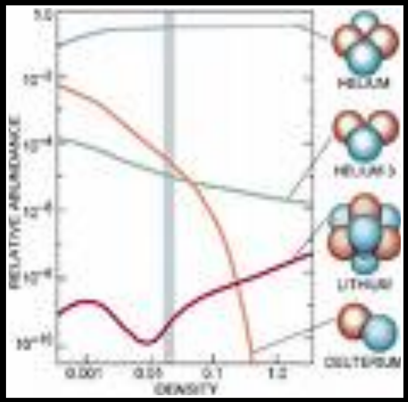

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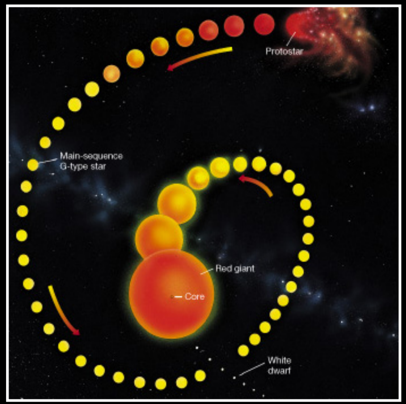
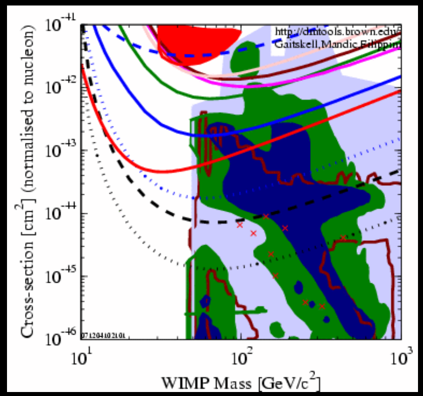
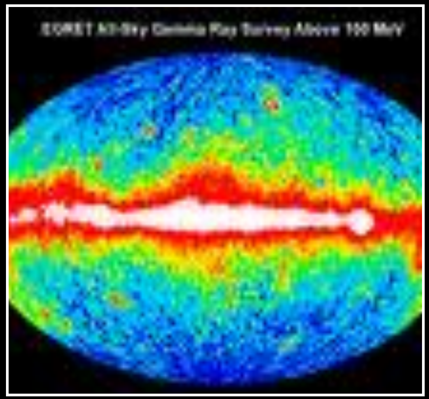


6) Collisionless?

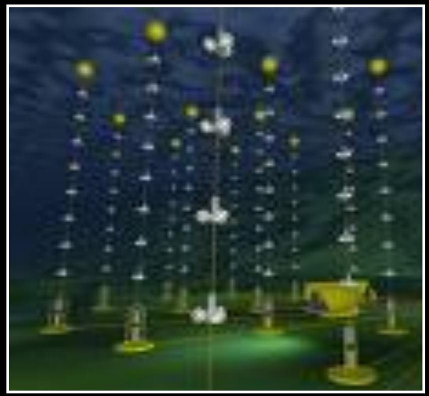
7) Couplings OK?



8) γ-rays OK?



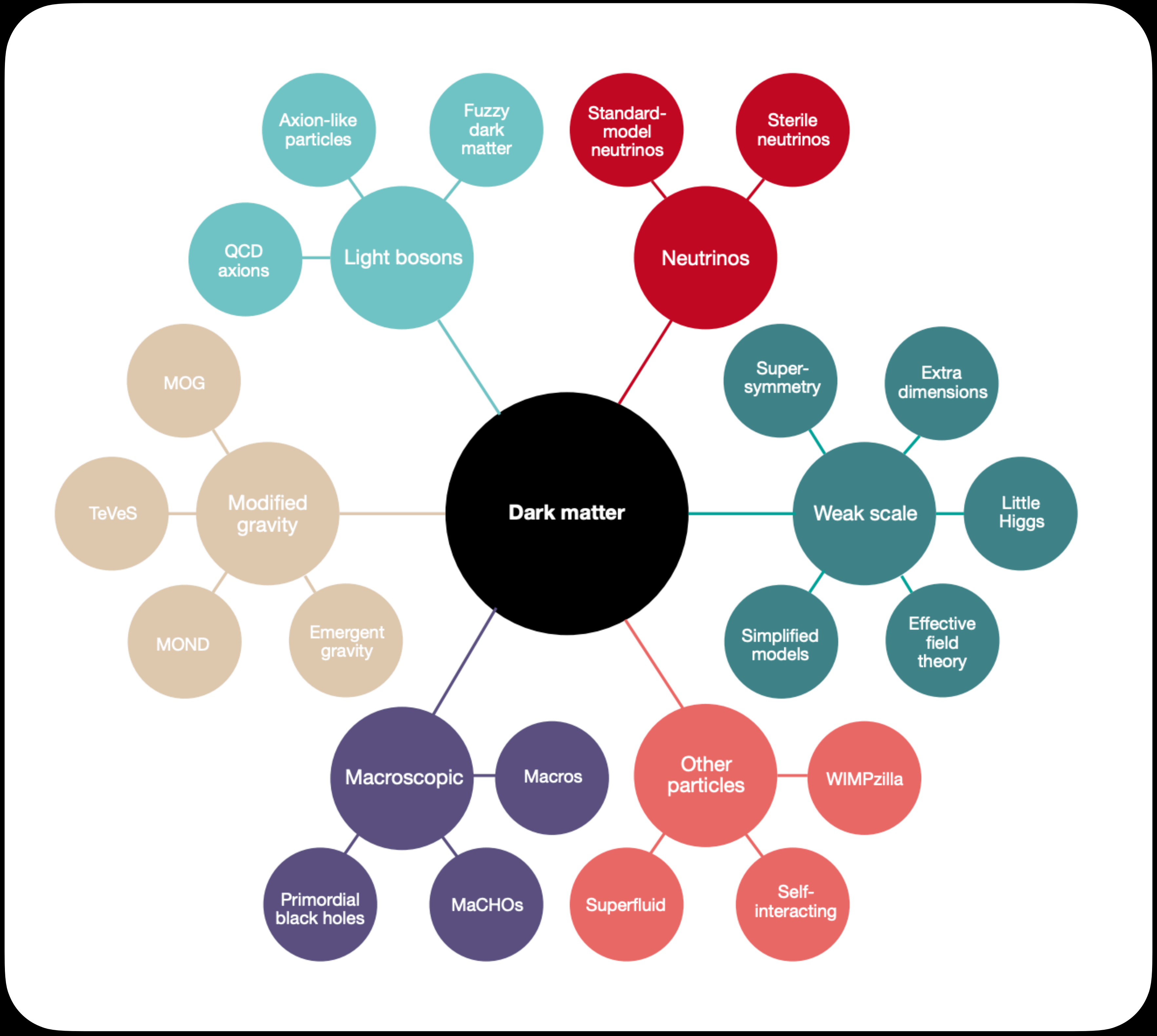
9) Astro bounds?



10) Can probe it?

Taoso, Bertone, Masiero 0711.4996

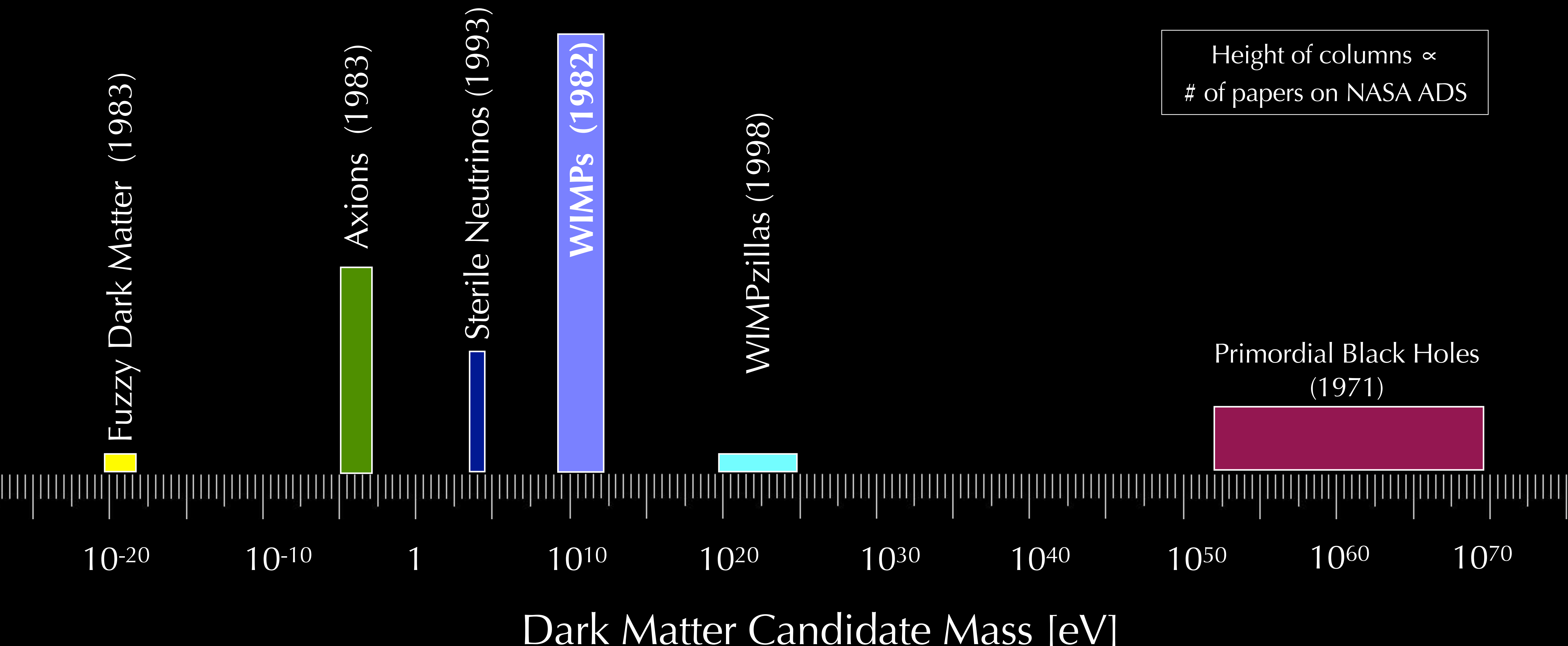
Candidates



GB, Tait, *Nature (2018) 1810.01668*

Candidates

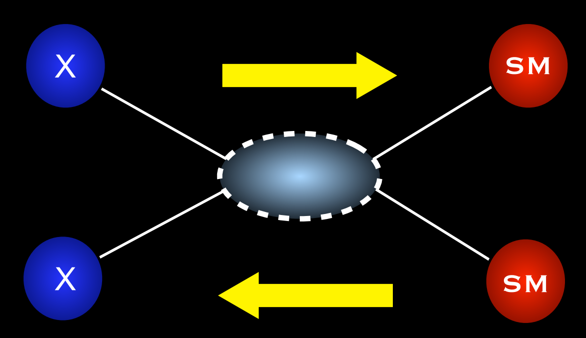
- No shortage of ideas..
- Tens of dark matter models, each with its own phenomenology
- Models span 90 orders of magnitude in DM candidate mass!



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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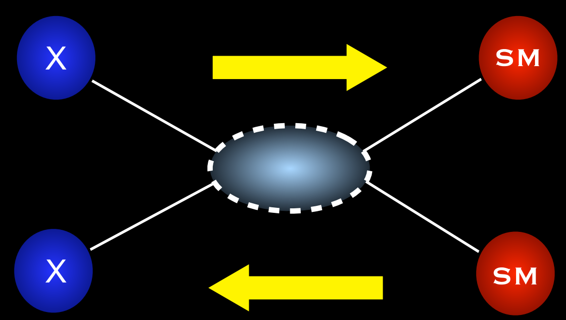


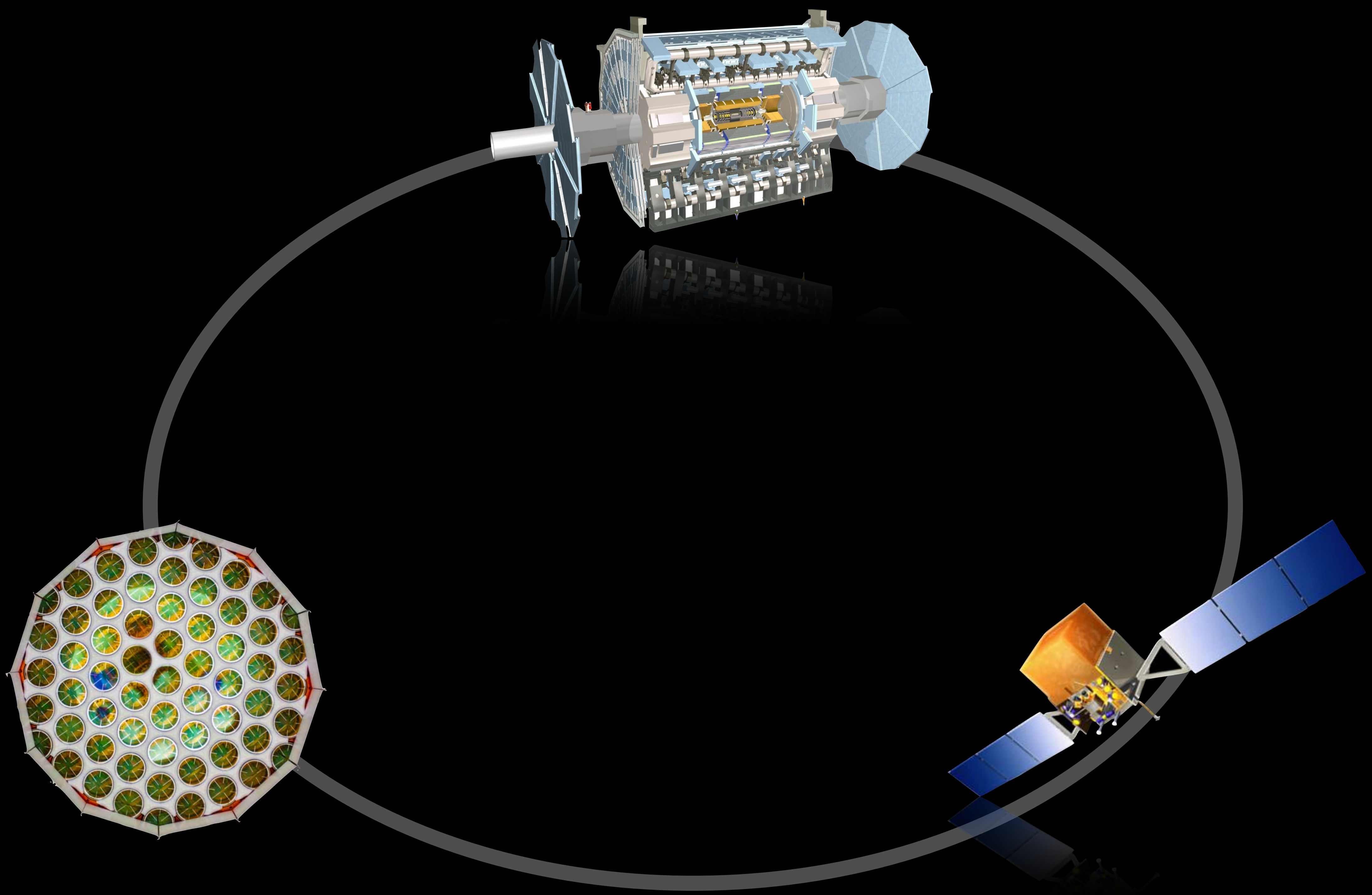
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Weak-scale cross sections can reproduce observed relic density

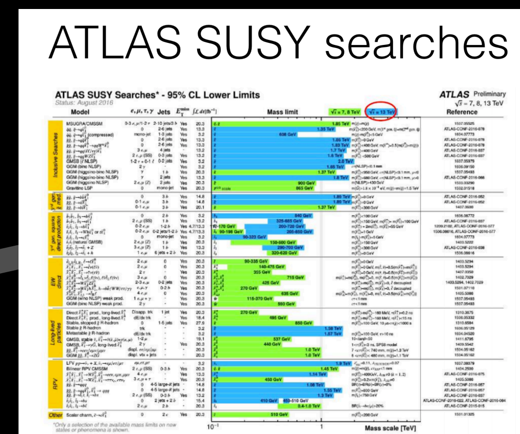
$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

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

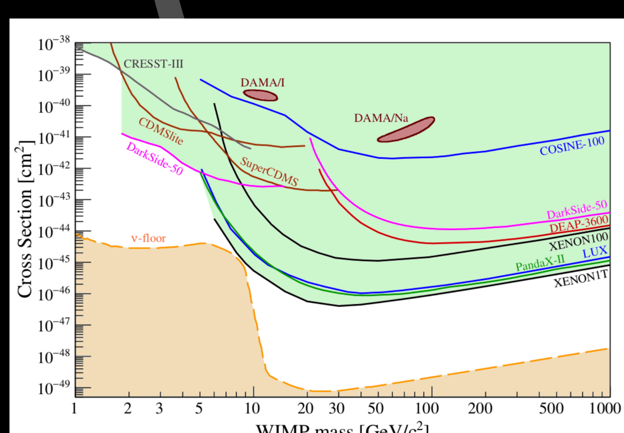
WIMPs searches



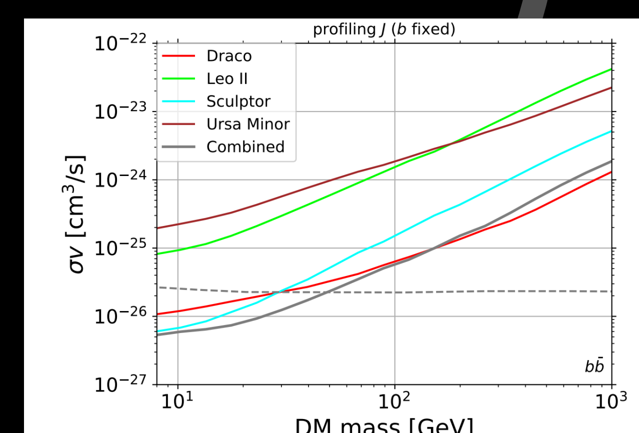
WIMPs searches



No WIMPs
found yet, despite many efforts!



See Rick Gaitskell's talk



Are WIMPs ruled out?

NO

absence of evidence $\neq$ 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) + The concept of naturalness evolves (Baer+ 2002.03013)

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?

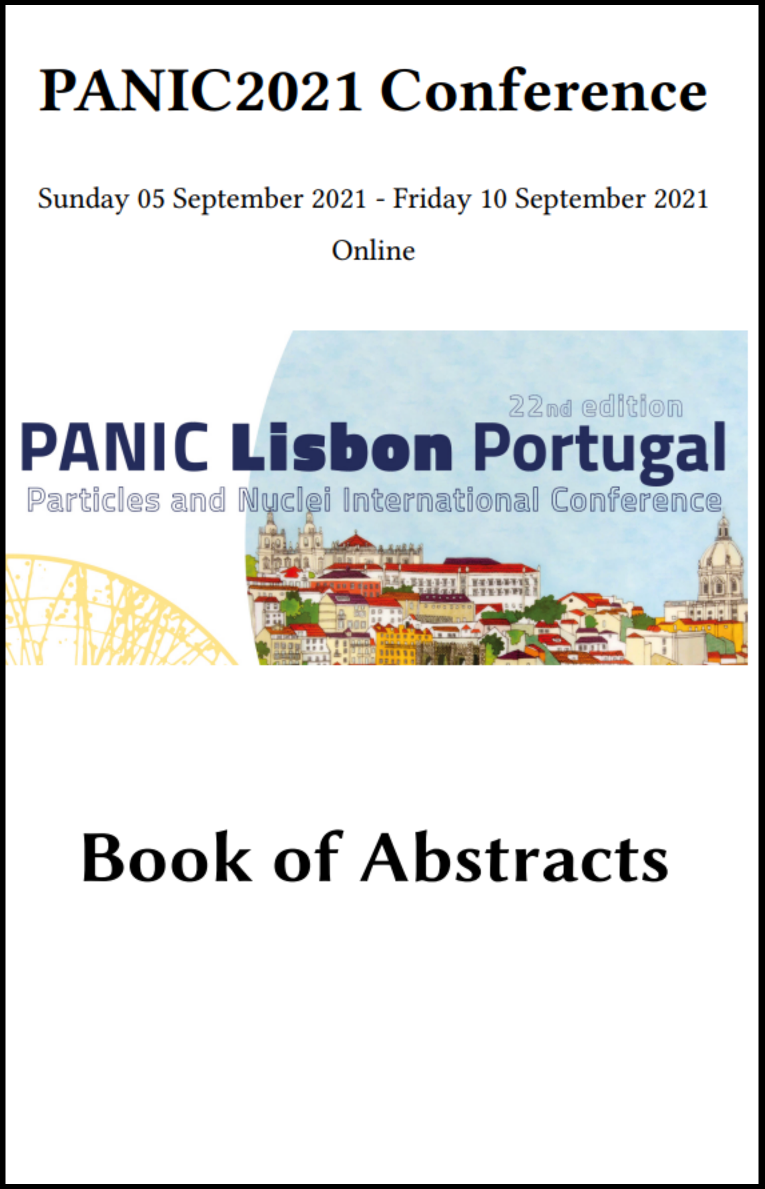
Part II: A new era in the quest for DM

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

Broaden/improve/diversify searches


PANIC2021 Conference

Sunday 05 September 2021 - Friday 10 September 2021

Online

Book of Abstracts

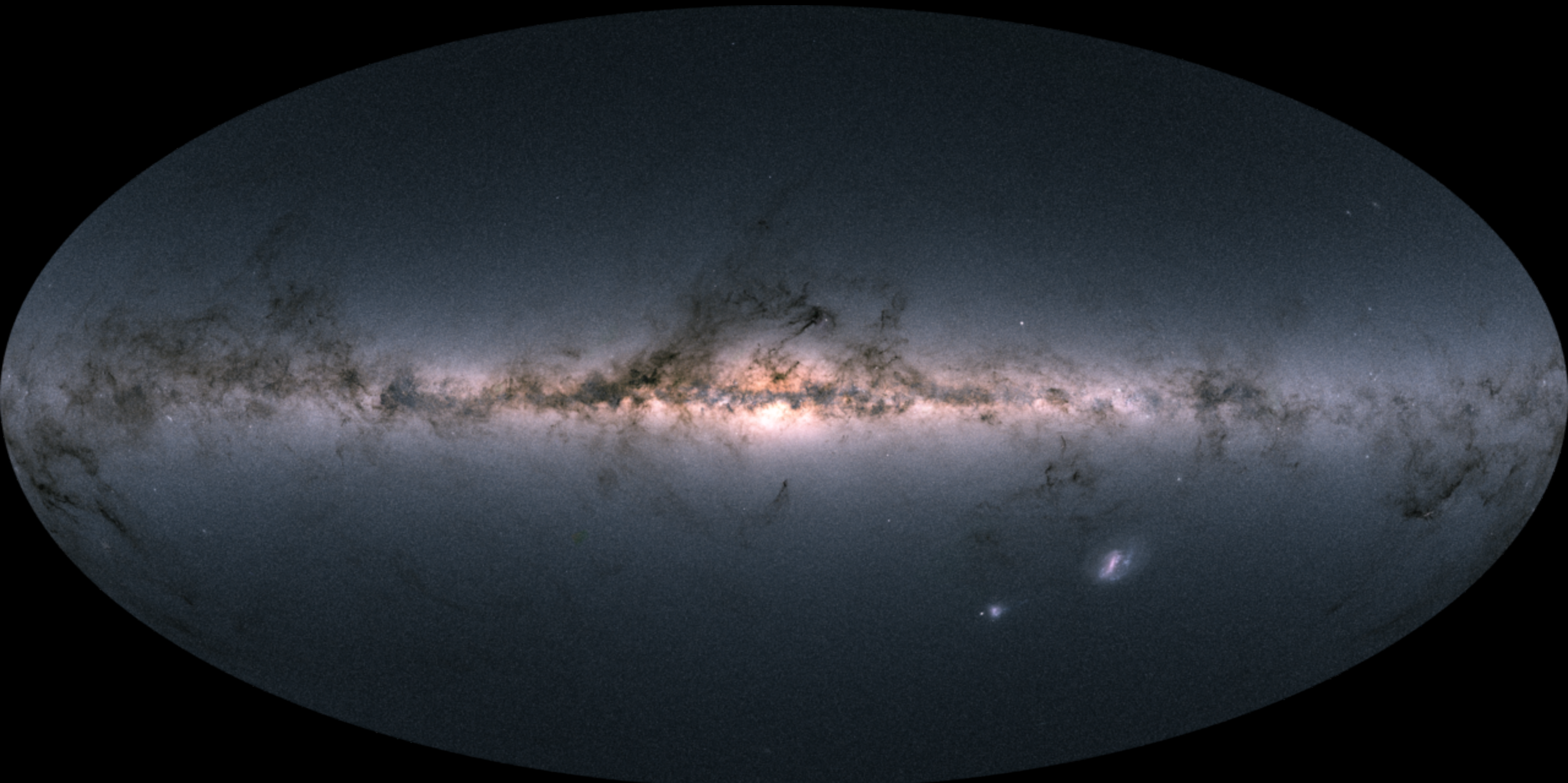
178 occurrences of “Dark Matter”…

The future of dark matter searches

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

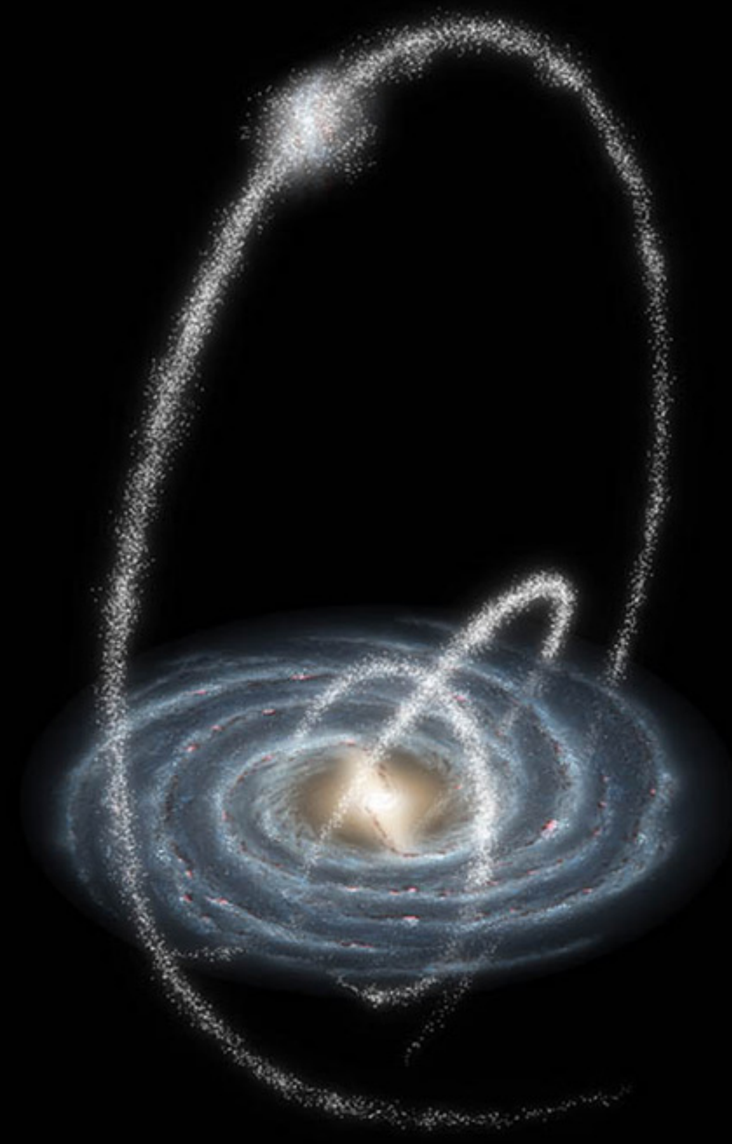
Numerical Simulation:
formation of a Milky Way-like galaxy

GAIA'S SKY

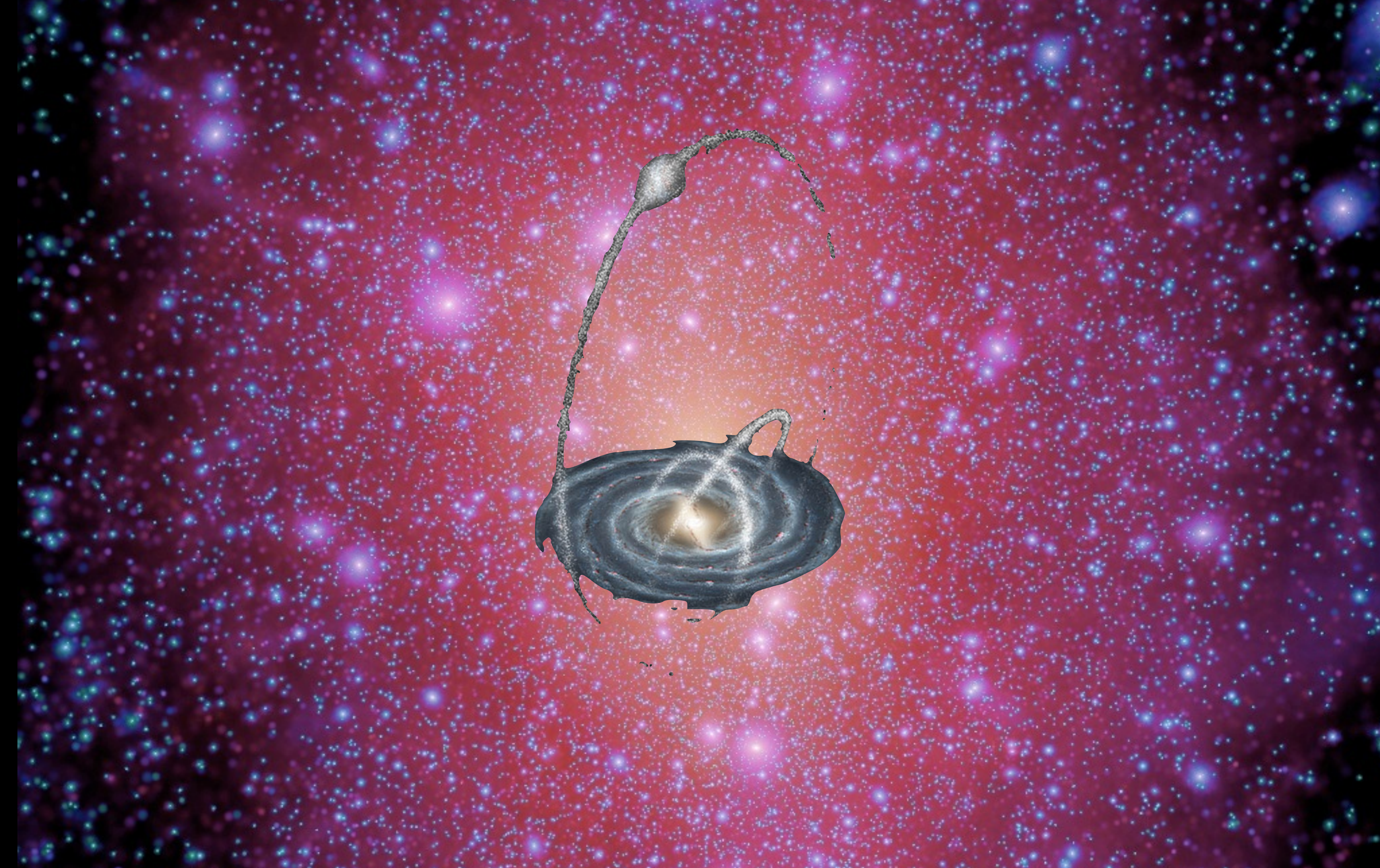


Gaia's all-sky view of our Milky Way Galaxy and neighbouring galaxies, based on brightness and colour of 1.7 billion stars (released April 2018).

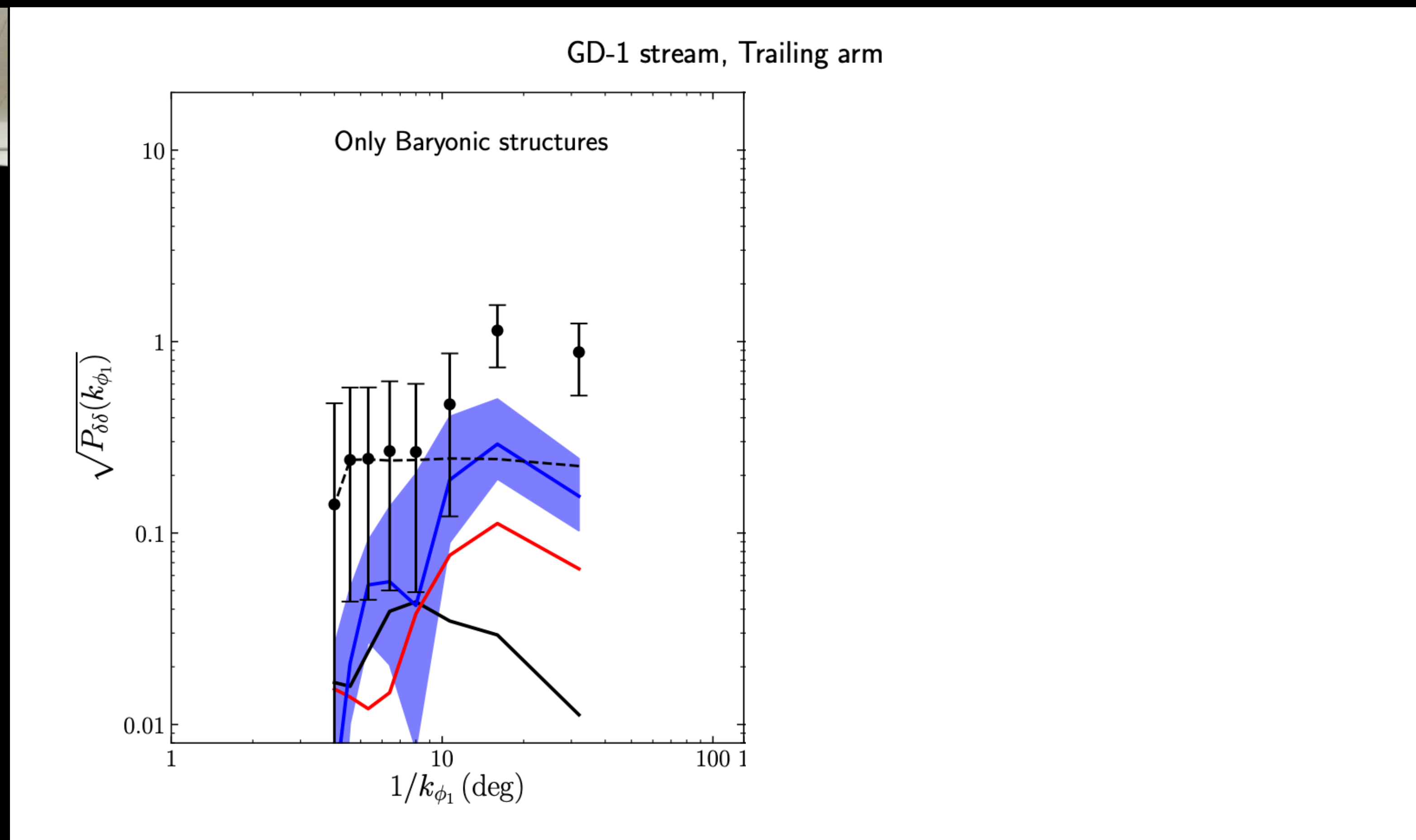
Stellar streams



Searching for dark matter substructures in the MW



Statistical analysis of perturbations: Strong hints of dark substructures!



Banik, Bovy, GB, Erkal, de Boer, arXiv:1911.02663

- Gaia GD1 stream data exhibit substantial ‘structure’

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

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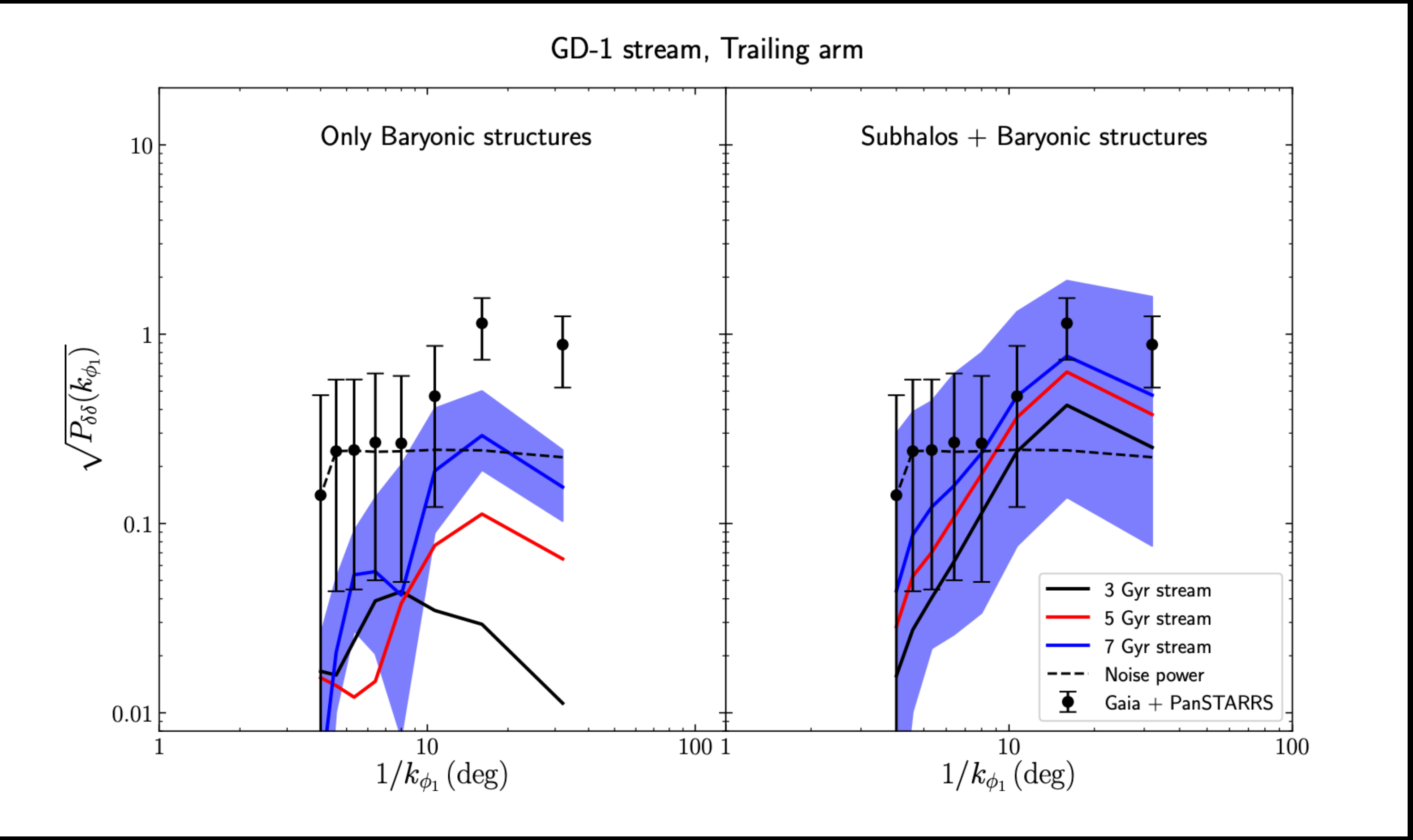


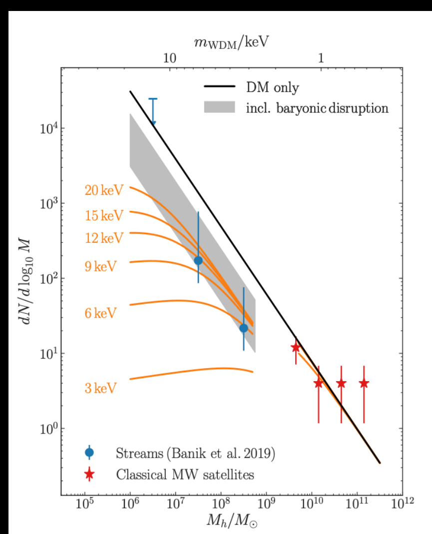
Banik, Bovy, GB, Erkal, de Boer, arXiv:1911.02663

- 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



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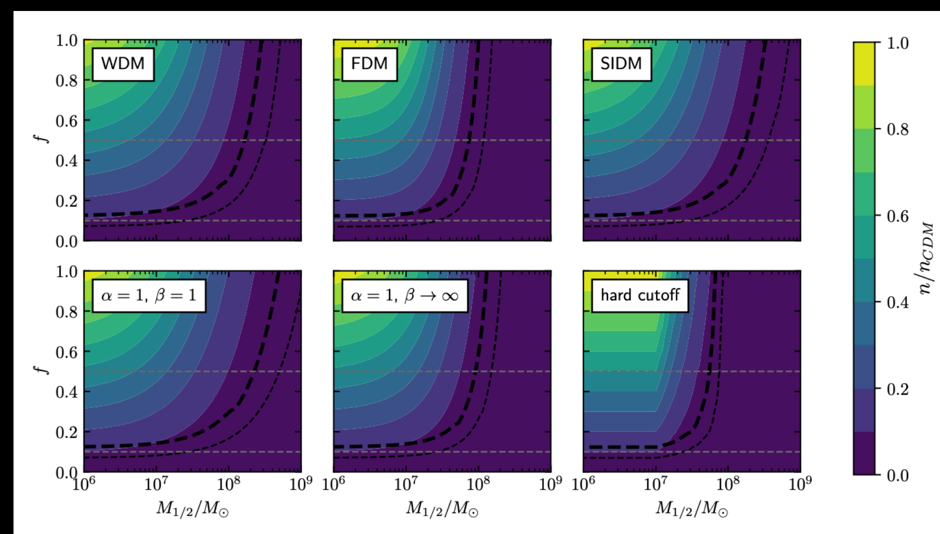
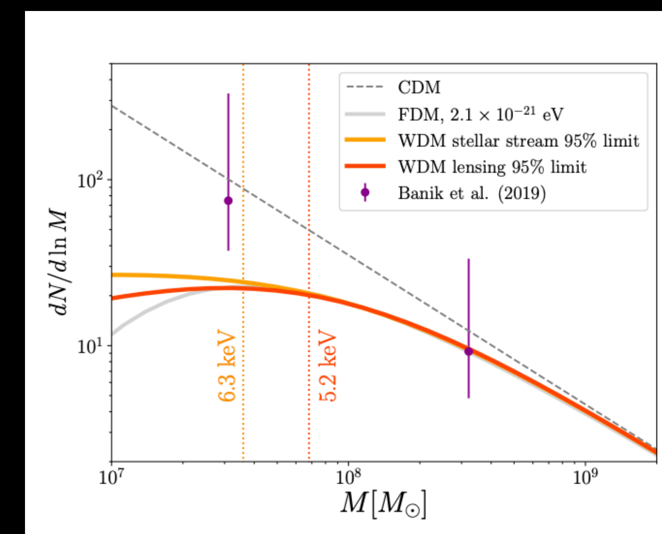


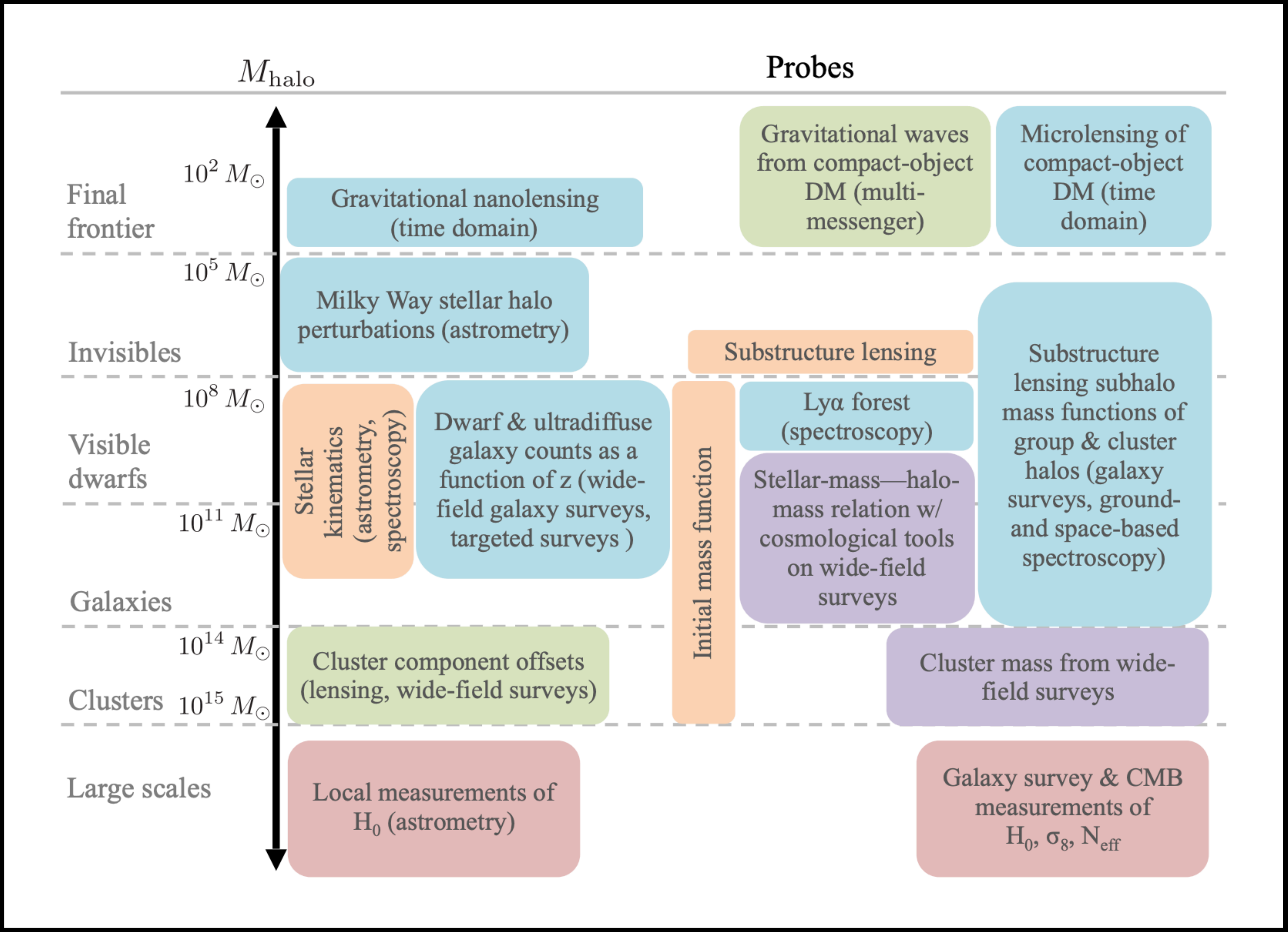
2001.11013



2001.05503

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

Gravitational probes of dark matter physics



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

The future of dark matter searches

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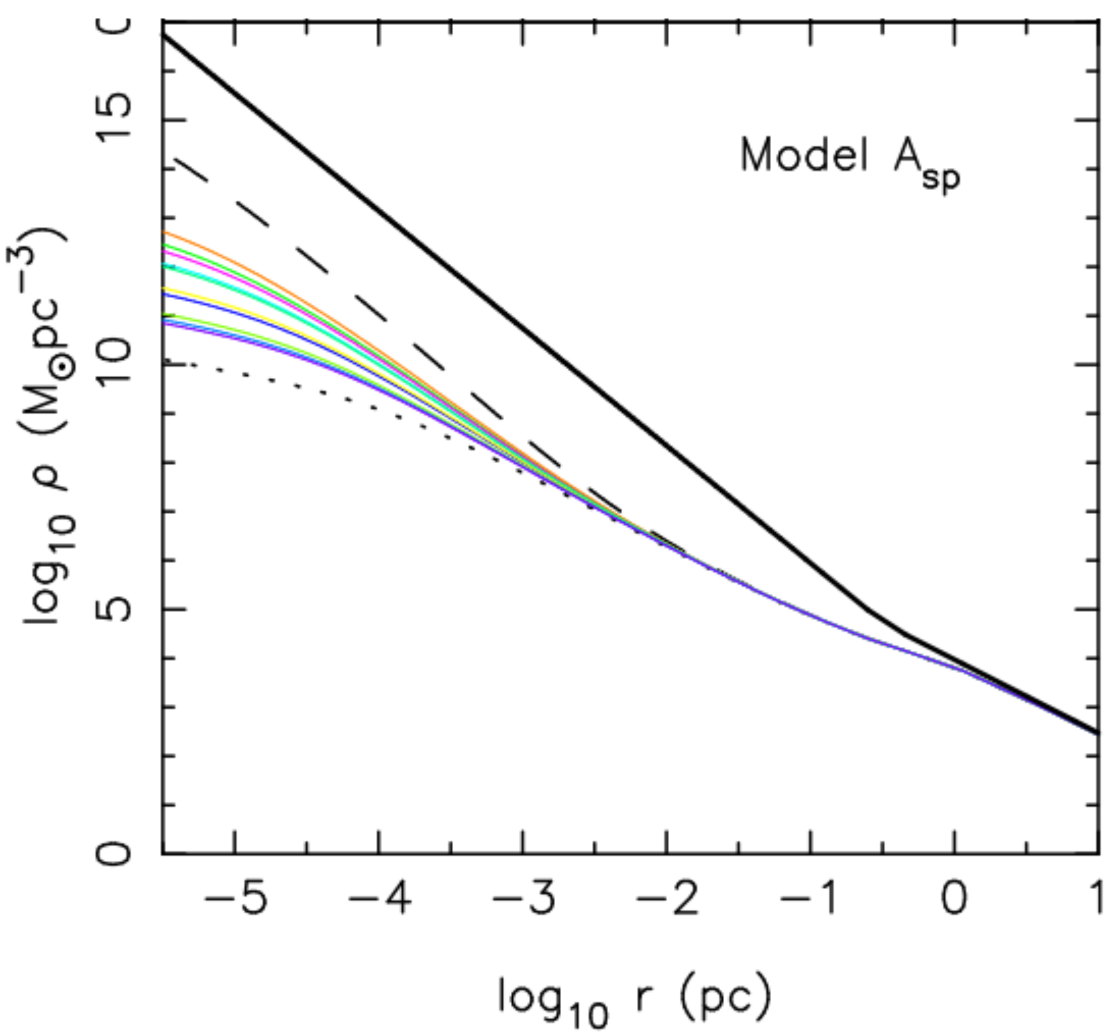
Dark Matter ‘dress’ around BHs

GB & Merritt 2005



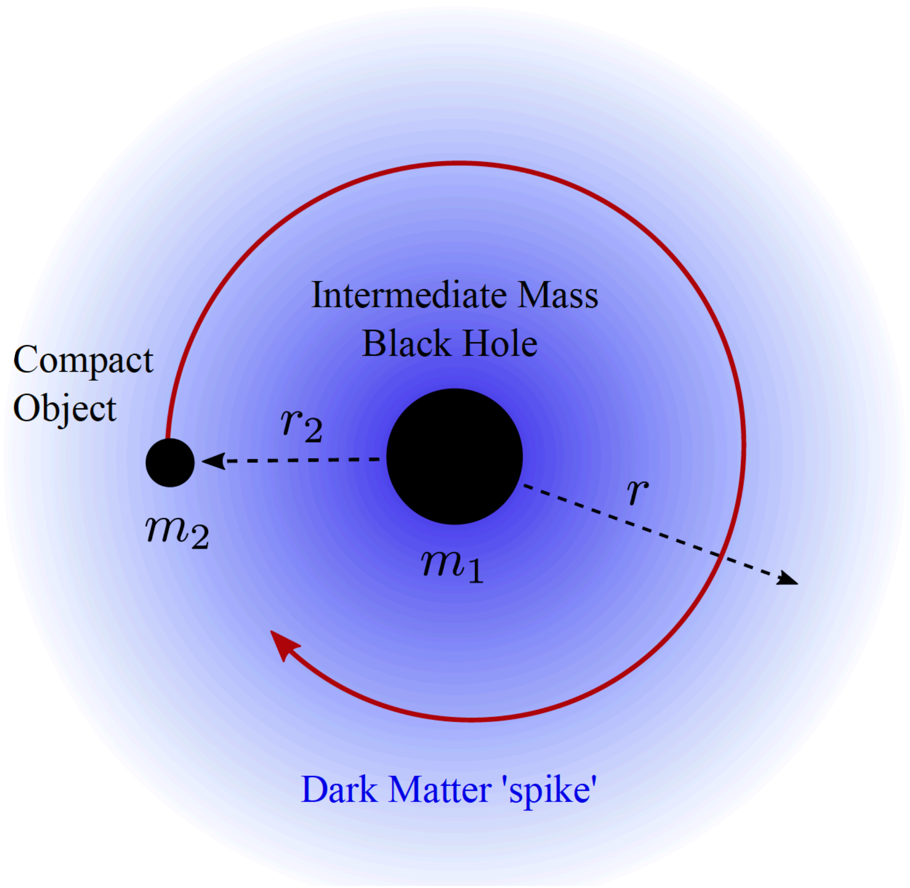
- **Adiabatic ‘spikes’ around SMBHs** *(Gondolo & Silk 2000)*
- **‘Mini-spikes’ around IMBHs** *(GB, Zentner, Silk 2005)*
- **Overdensities around primordial BHs** *(e.g.Adamek et al. 2019)*
- **Ultralight boson ‘clouds’** *(e.g. Brito, Cardoso & Pani 2015)*

Open questions: astrophysical uncertainties, dependence on DM properties (self-interactions, annihilations)

Dark Matter around BHs

Energy losses:

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



Eda+ PRL 110, 221101 (2013)

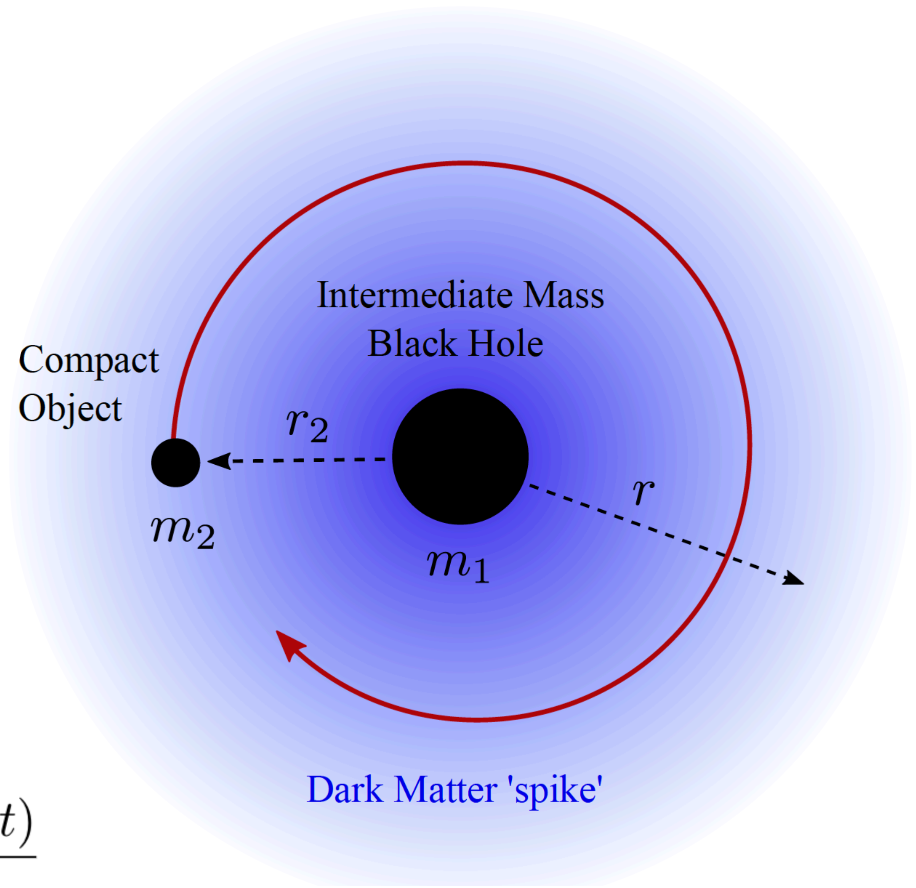
Dark Matter around BHs

Energy losses:

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

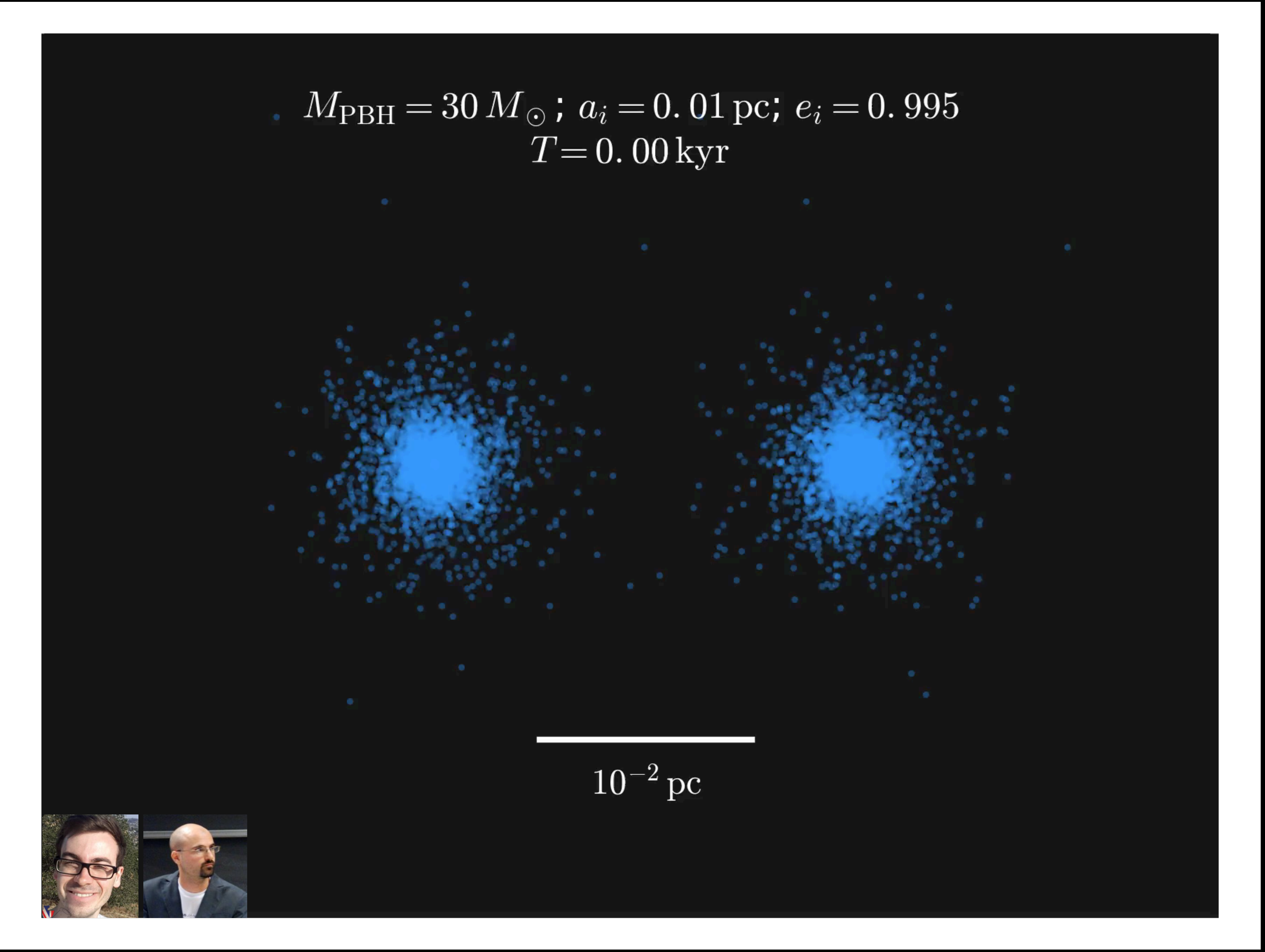
Separation:

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



Kavanagh, GB et al. 2002.12811

'Dressed' BH-BH merger



Kavanagh, Gaggero & GB, arXiv:1805.09034

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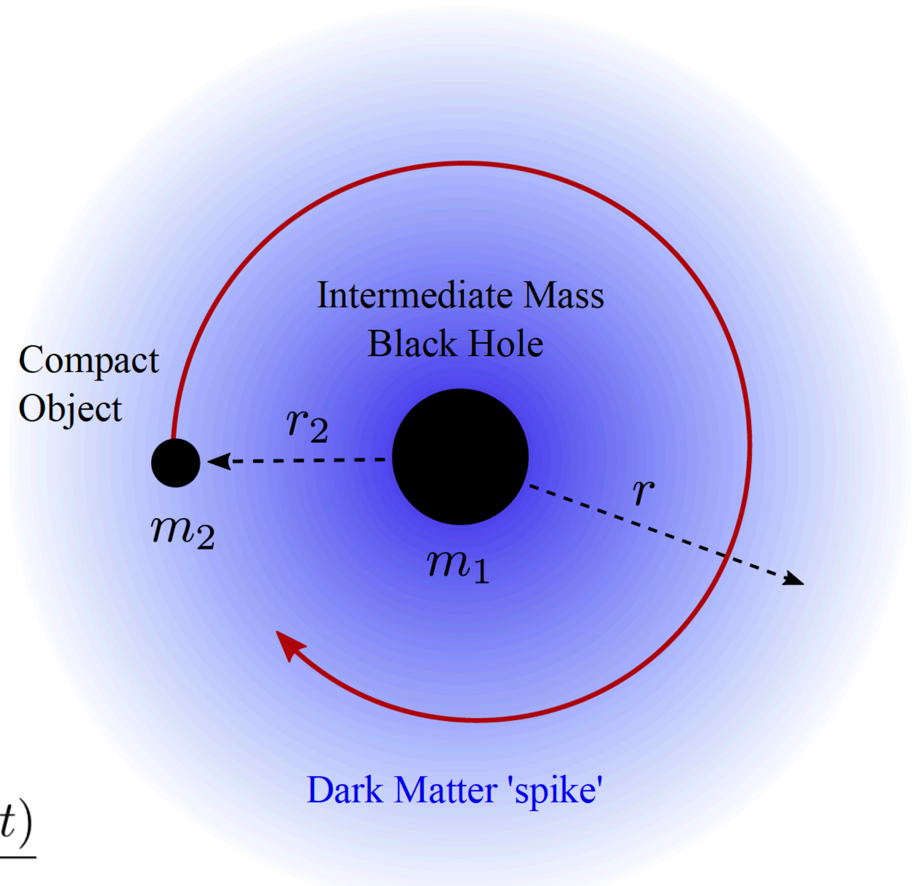

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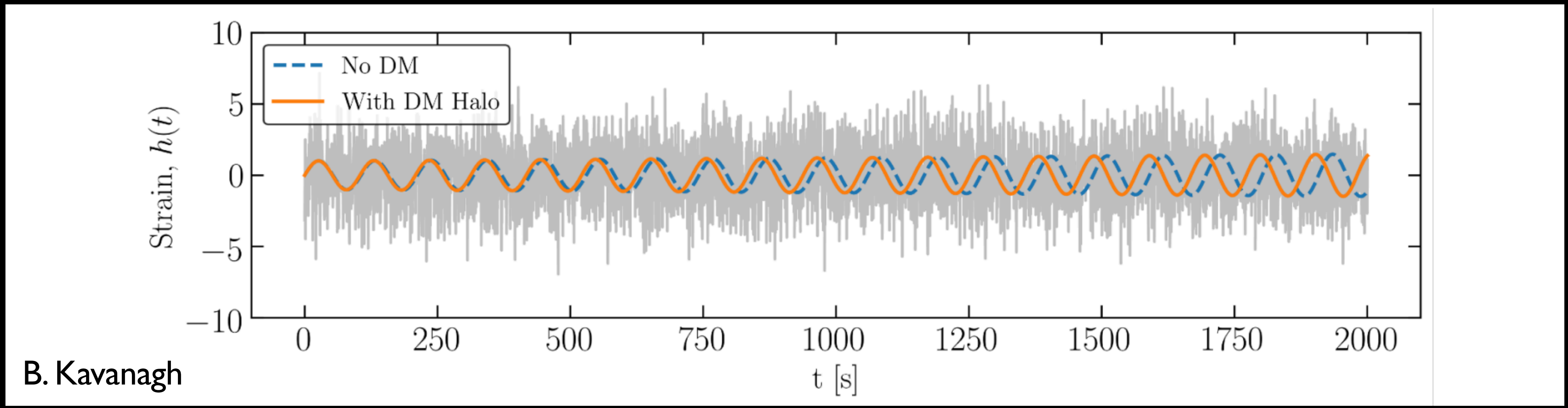
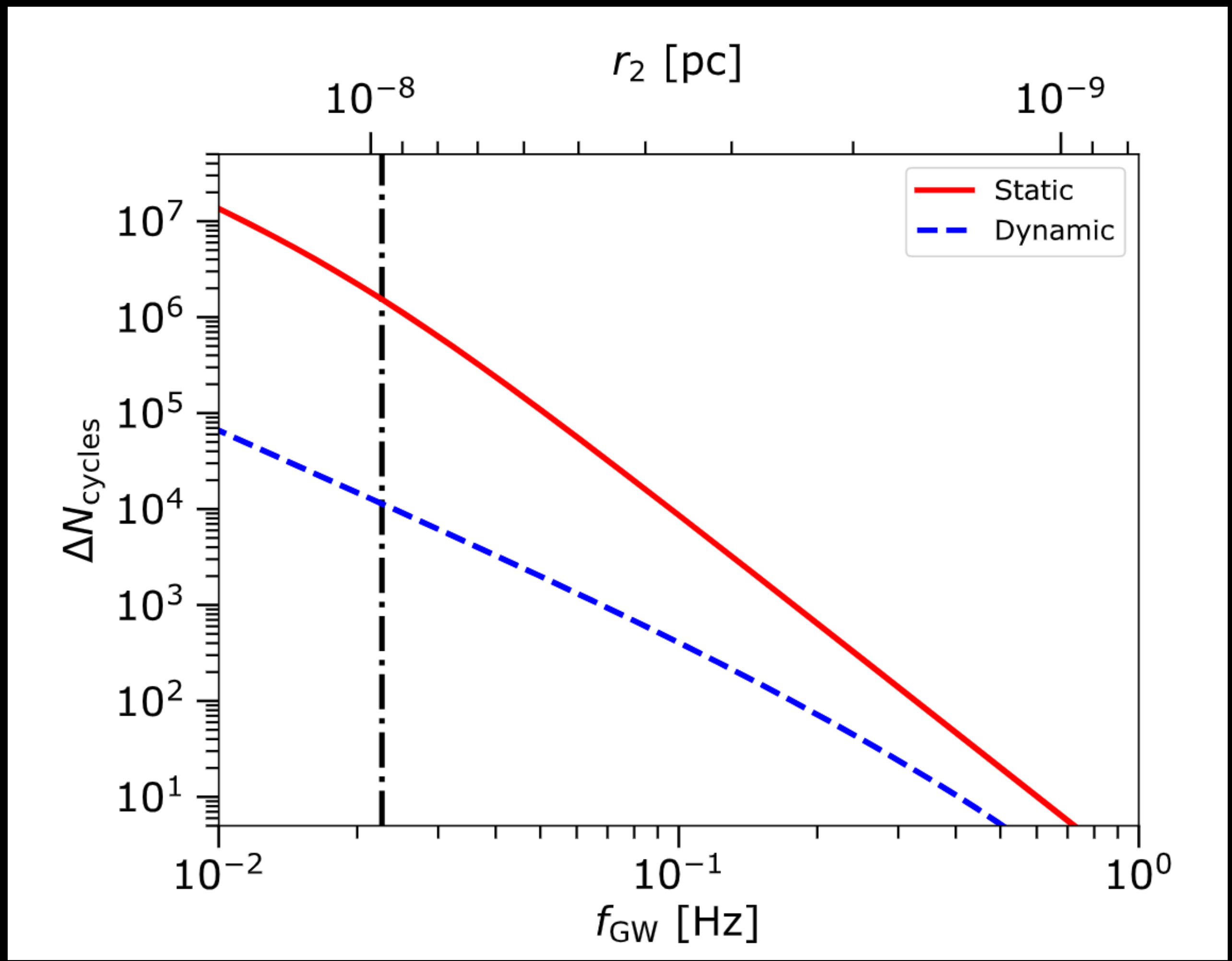
Time-dependent dark matter profile:

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

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)
- This induces a dephasing of the waveform, potentially detectable e.g. with LISA
- Dephasing is smaller than previously thought (i.e. wrt to case with fixed dark matter profile) but still potentially detectable

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