New strategies in the quest for Dark Matter

Gianfranco Bertone
GRAPPA center of excellence, U. of Amsterdam

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~ based on a review article (in preparation) with T.Tait

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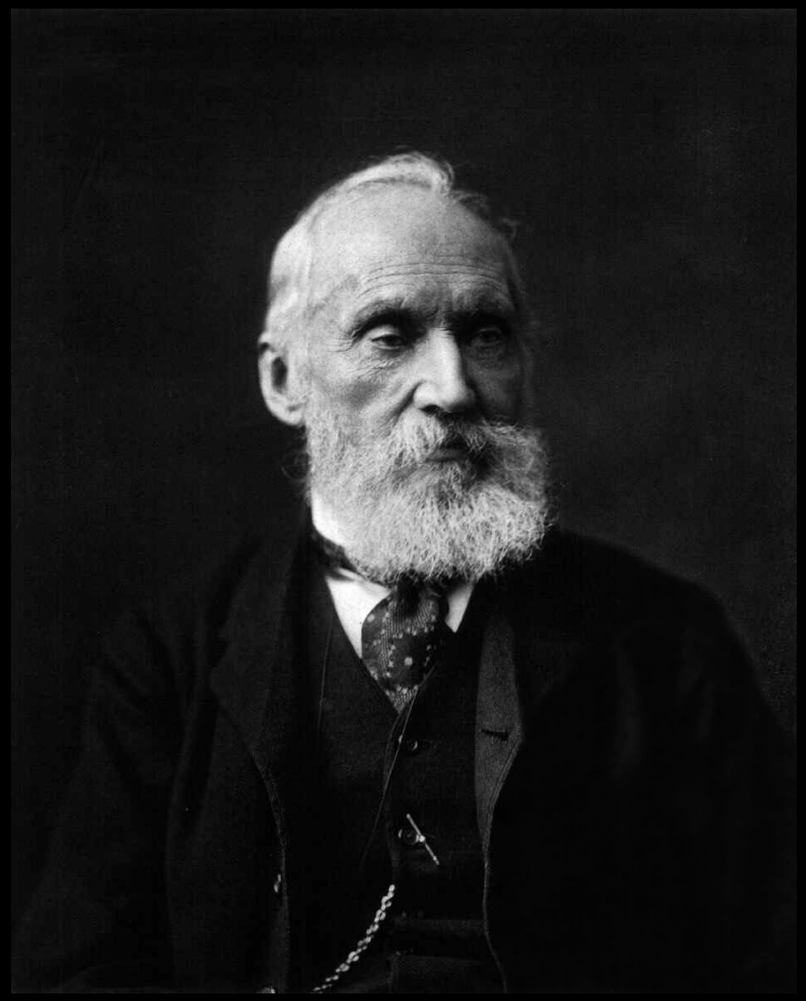
A problem with a long history



Lord Kelvin (1904)

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

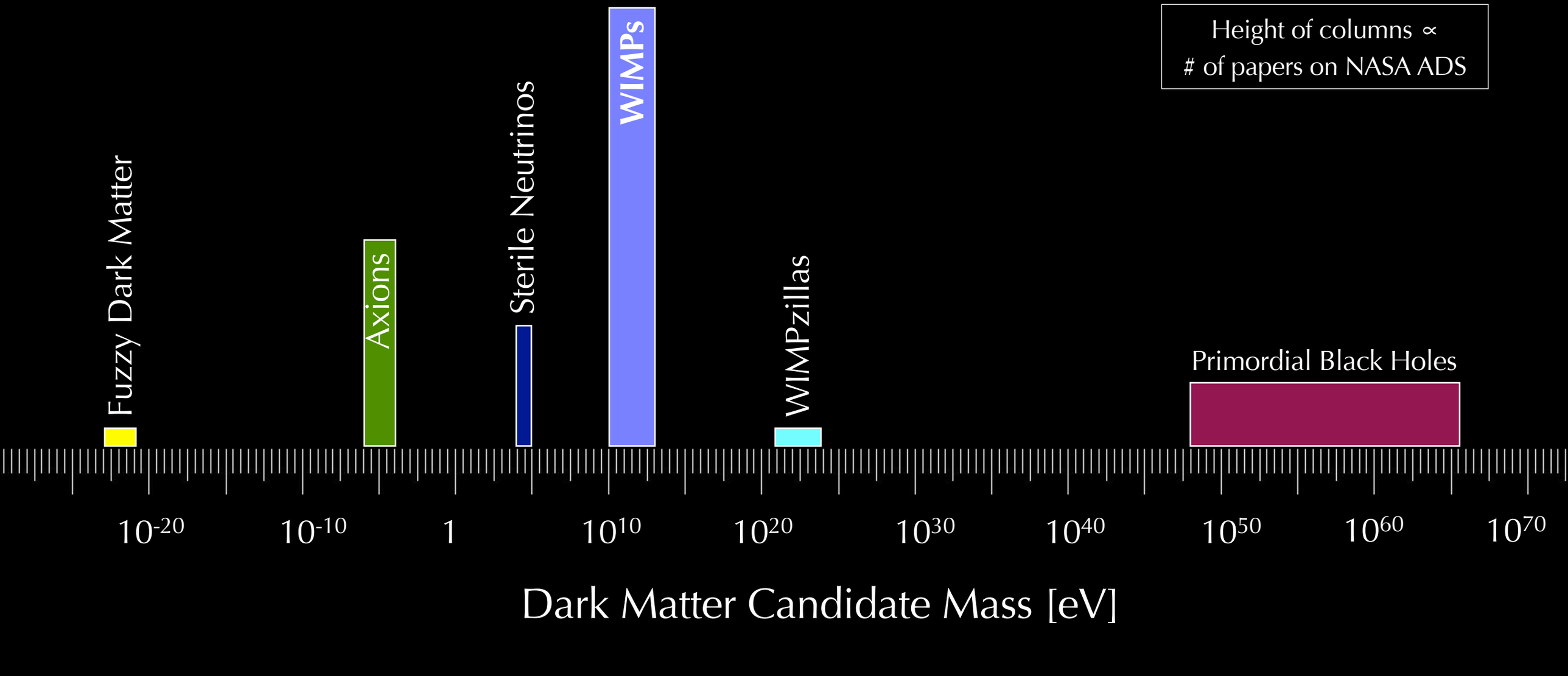
Henri Poincaré (1906)

"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."*

"A history of Dark Matter" GB & Hooper *1605.04909*
"How dark matter came to matter" de Swart, GB, van Dongen - Nature Astronomy; *1703.00013*

What is dark matter?

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



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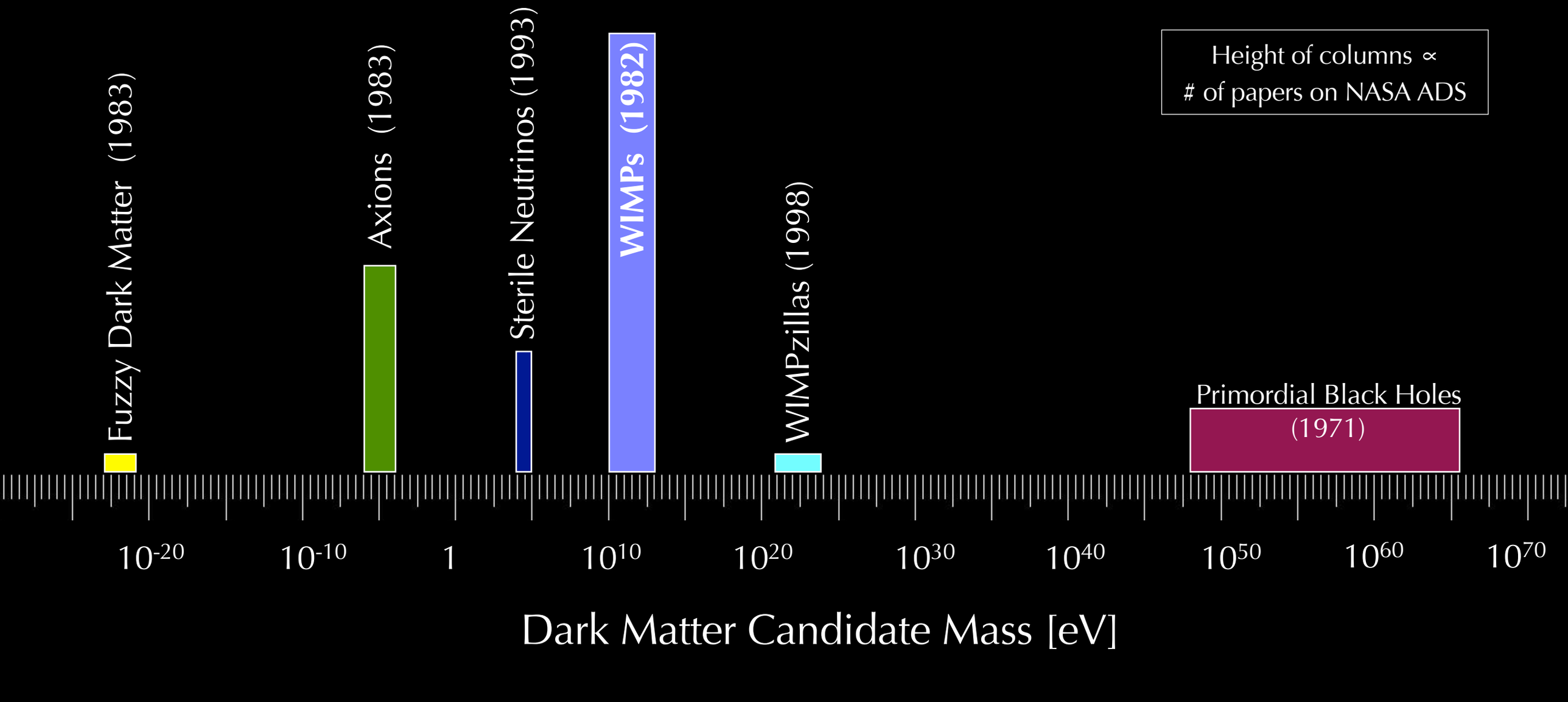
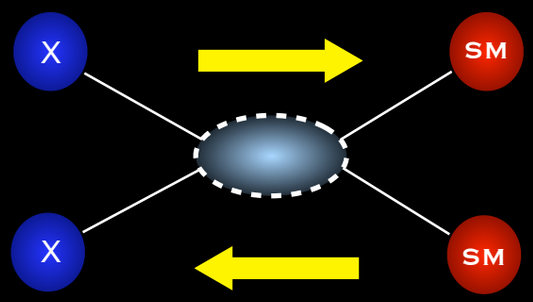


WIMPs

By far the most studied class of dark matter candidates.

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



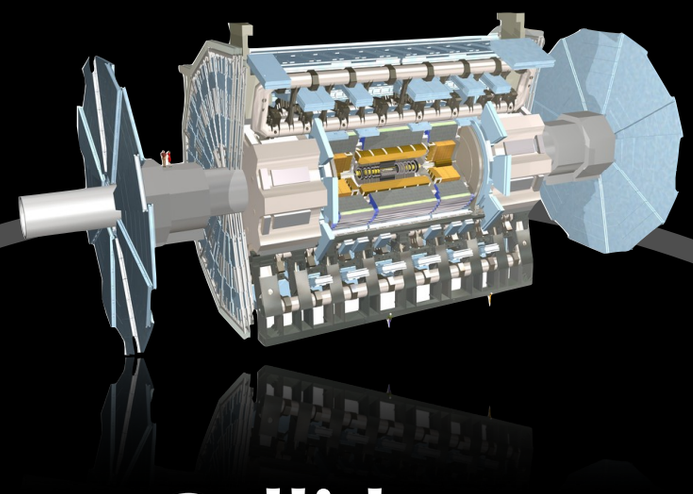
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle\left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

Weak-scale cross sections can reproduce observed relic density

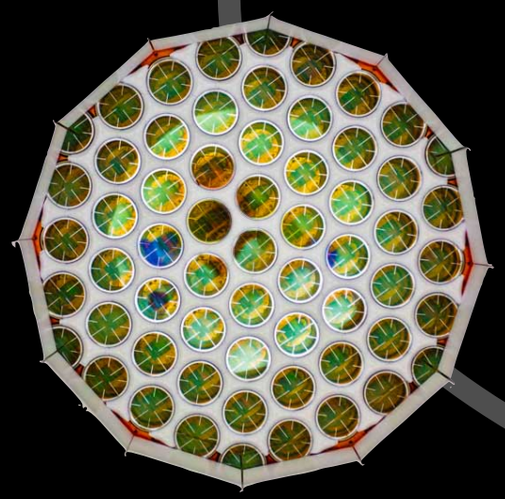
$$\Omega h^2 \approx \frac{3\times 10^{-27} cm^3 s^{-1}}{<\sigma v>}$$

'WIMP miracle'
(new physics at ~1 TeV solves at same time hierarchy problem AND DM)

WIMPs searches



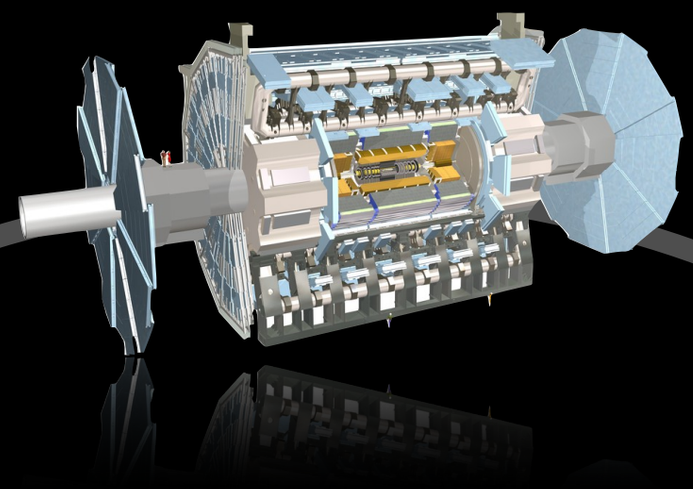
Colliders



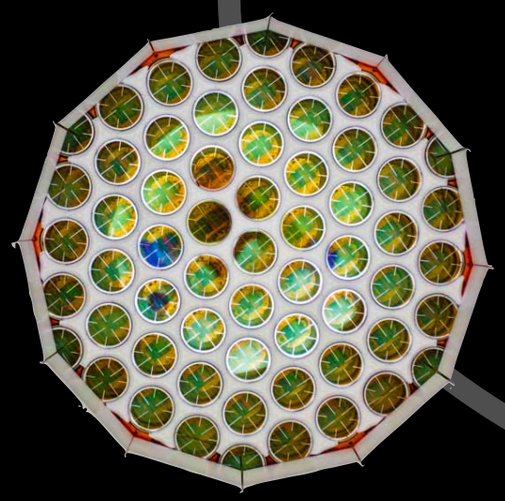
Direct Detection

Indirect Detection

WIMPs searches



No WIMPs (nor other DM)
found yet, despite many efforts!



Are WIMPs ruled out?

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NO

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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+ 1612.06333)

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

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

The future of dark matter searches

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

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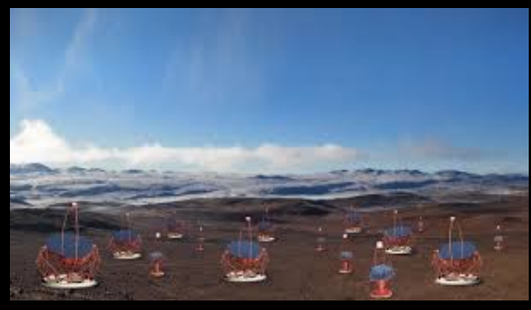
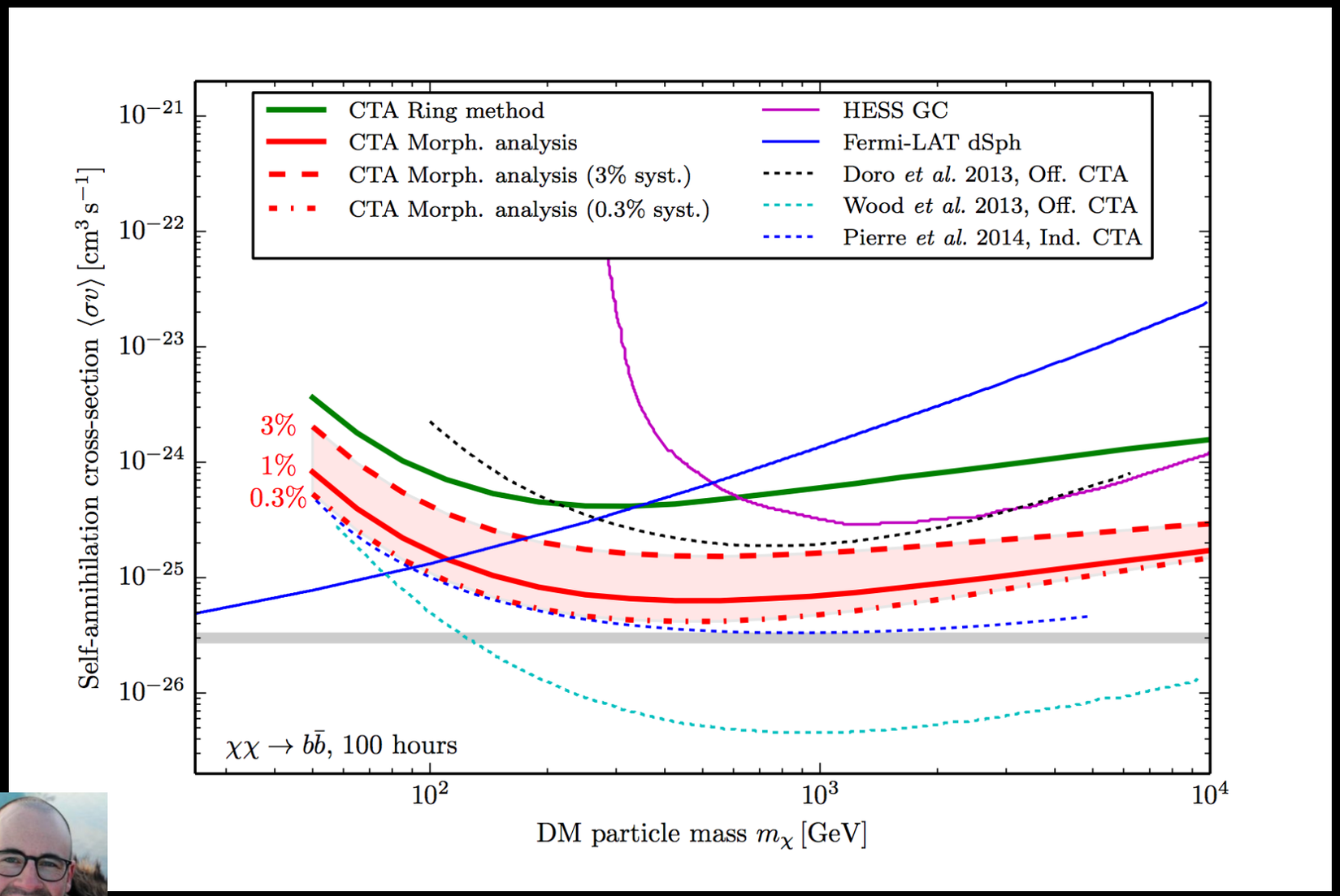
1A. Broaden searches

E.g. Massive WIMPs searches with CTA
(see talk A. Morselli)



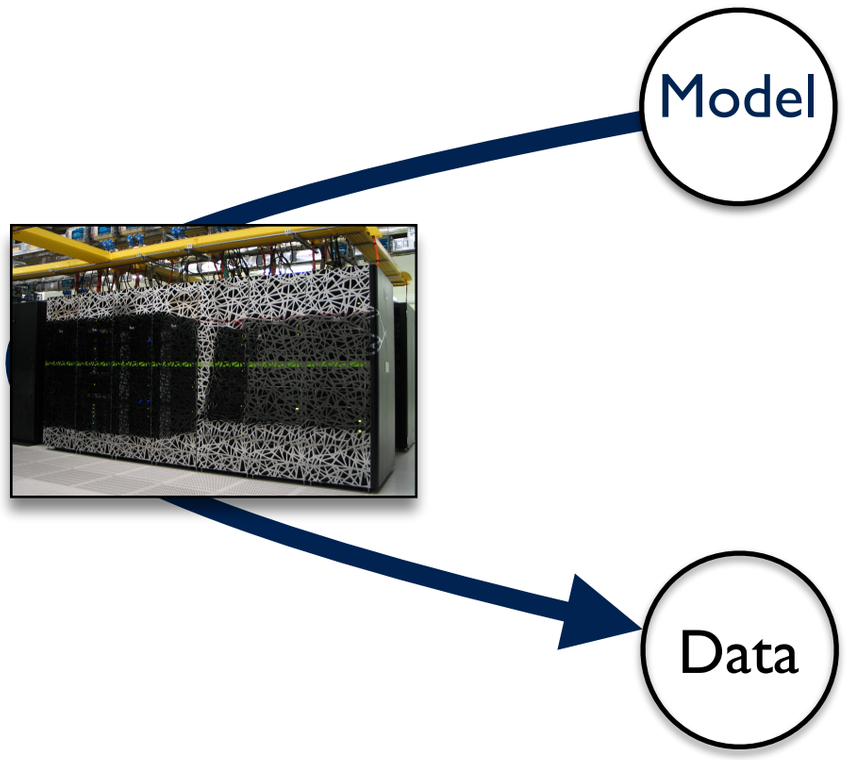
Generic WIMPs have masses 1 GeV — 100 TeV. We are far from probing the whole range



Silverwood, GB+ JCAP (2015)

1B. Improve existing strategies

Speeding up statistical inference with Machine Learning tools



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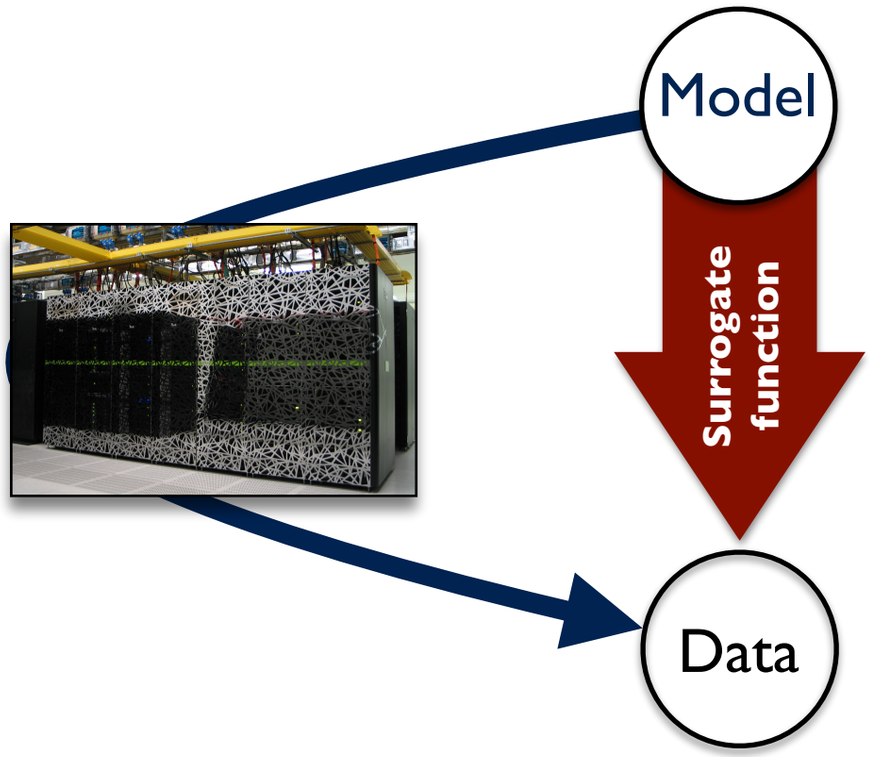
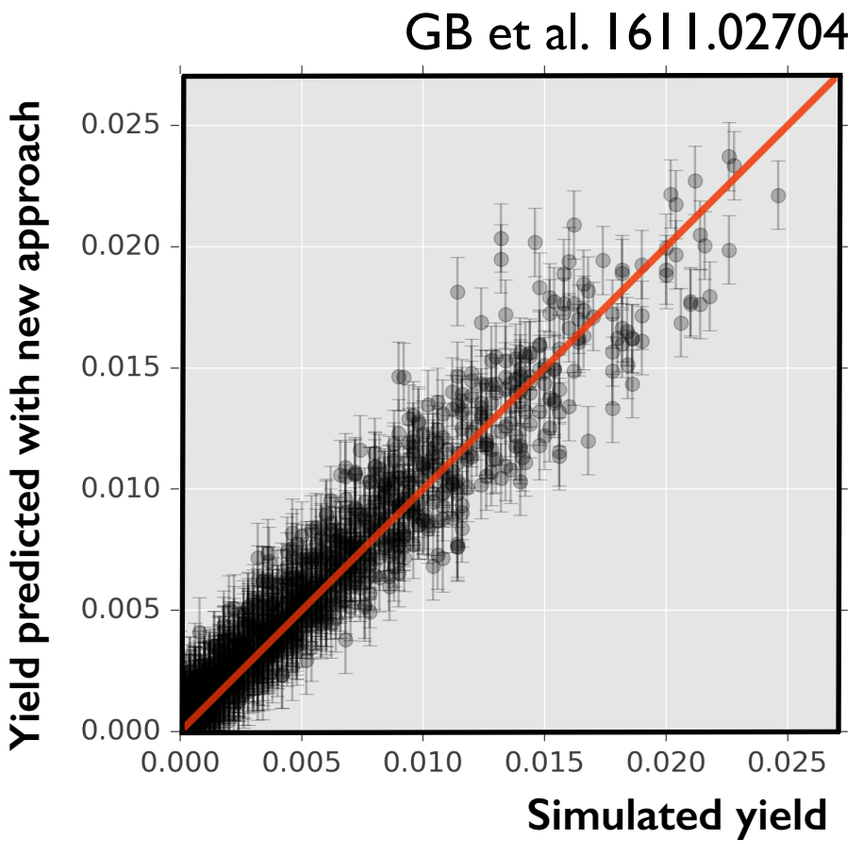


GB et al. 1611.02704



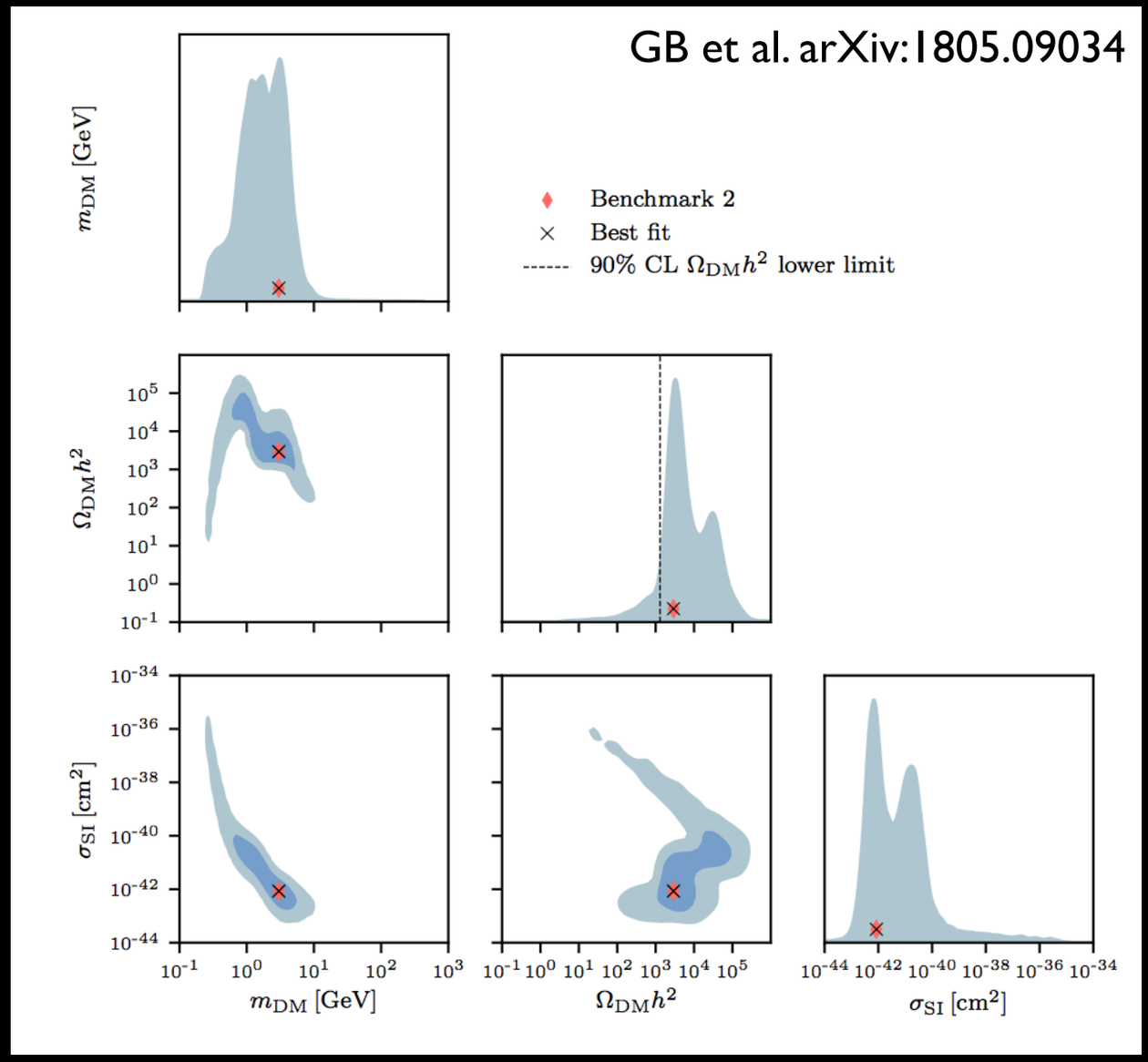
- Exploring parameter spaces of full theoretical models is very expensive.
- New machine learning methods (*distributed gaussian processes, deep neural networks*) bring computation time from ~CPU *centuries* to ~CPU *weeks*!
- Can be run by a PhD student in 1 day on a desktop computer!

1B. Improve existing strategies

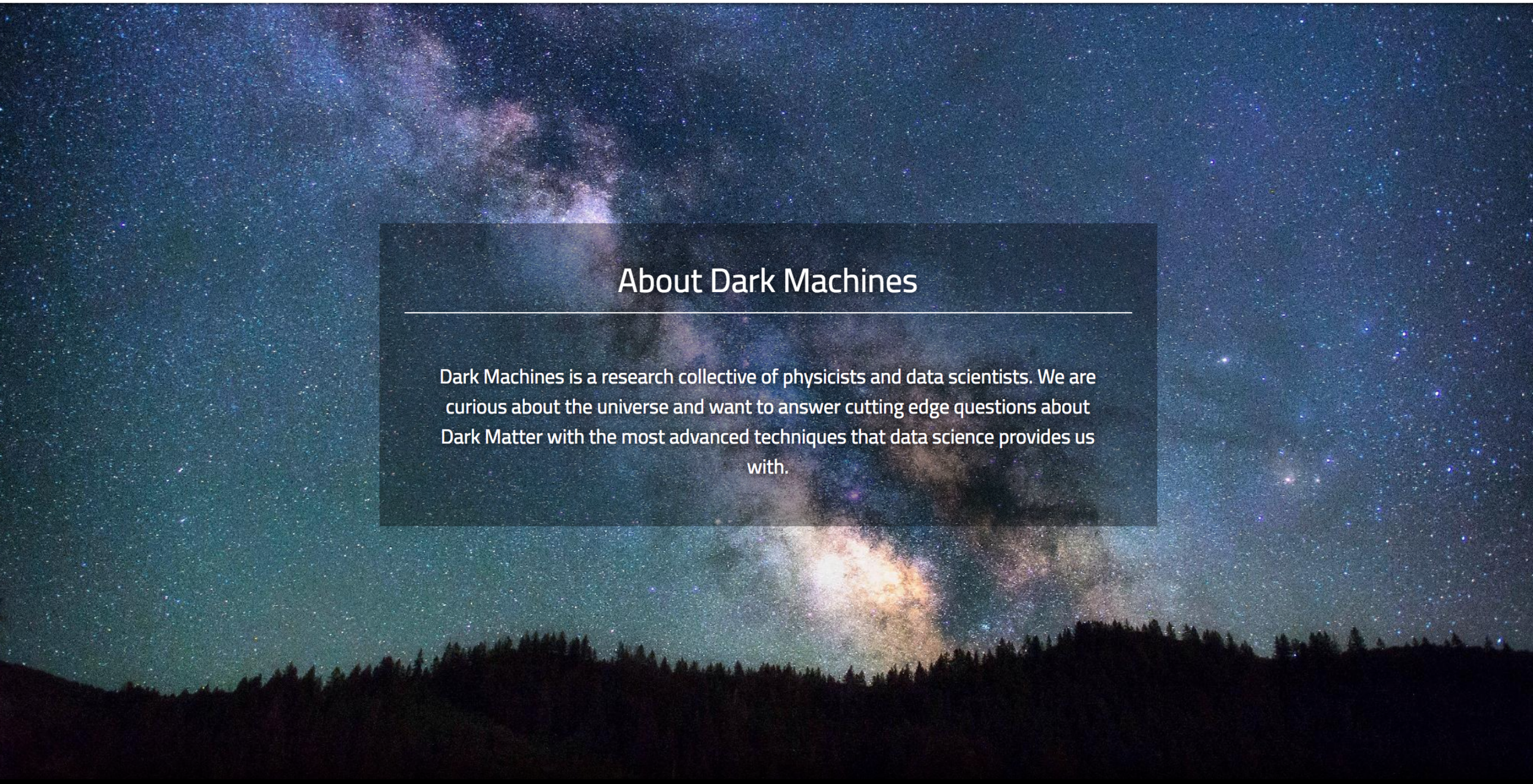
E.g. New Machine Learning tools applied to LHC searches:

i) Optimize search strategies, by e.g. identifying optimal signal and control regions in ATLAS/ CMS model by model

ii) Perform fast inference if new particles discovered



The *Dark Machines* initiative



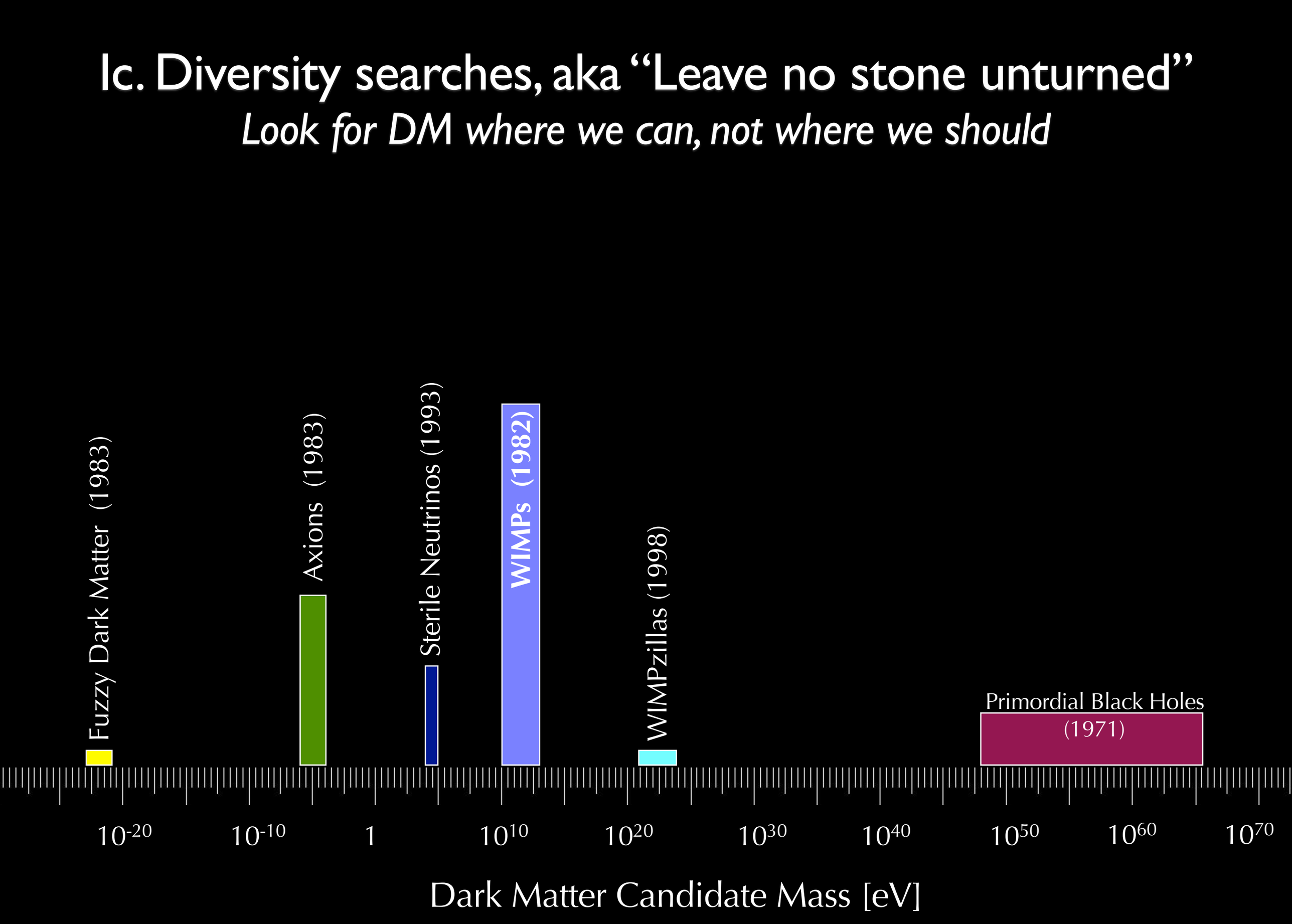
About Dark Machines

Dark Machines is a research collective of physicists and data scientists. We are curious about the universe and want to answer cutting edge questions about Dark Matter with the most advanced techniques that data science provides us with.

Website: darkmachines.org ; Twitter: dark_machines

Ic. Diversity searches, aka "Leave no stone unturned"

Look for DM where we can, not where we should



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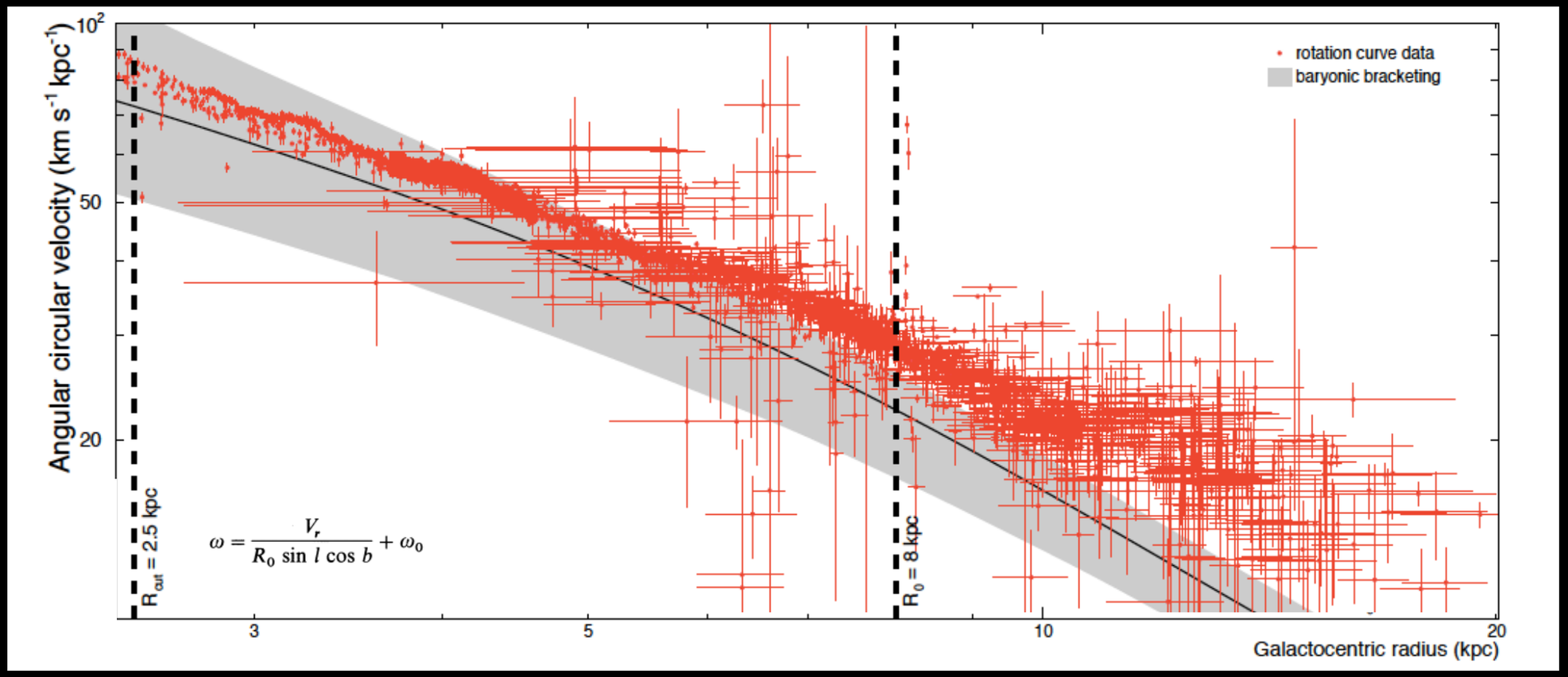
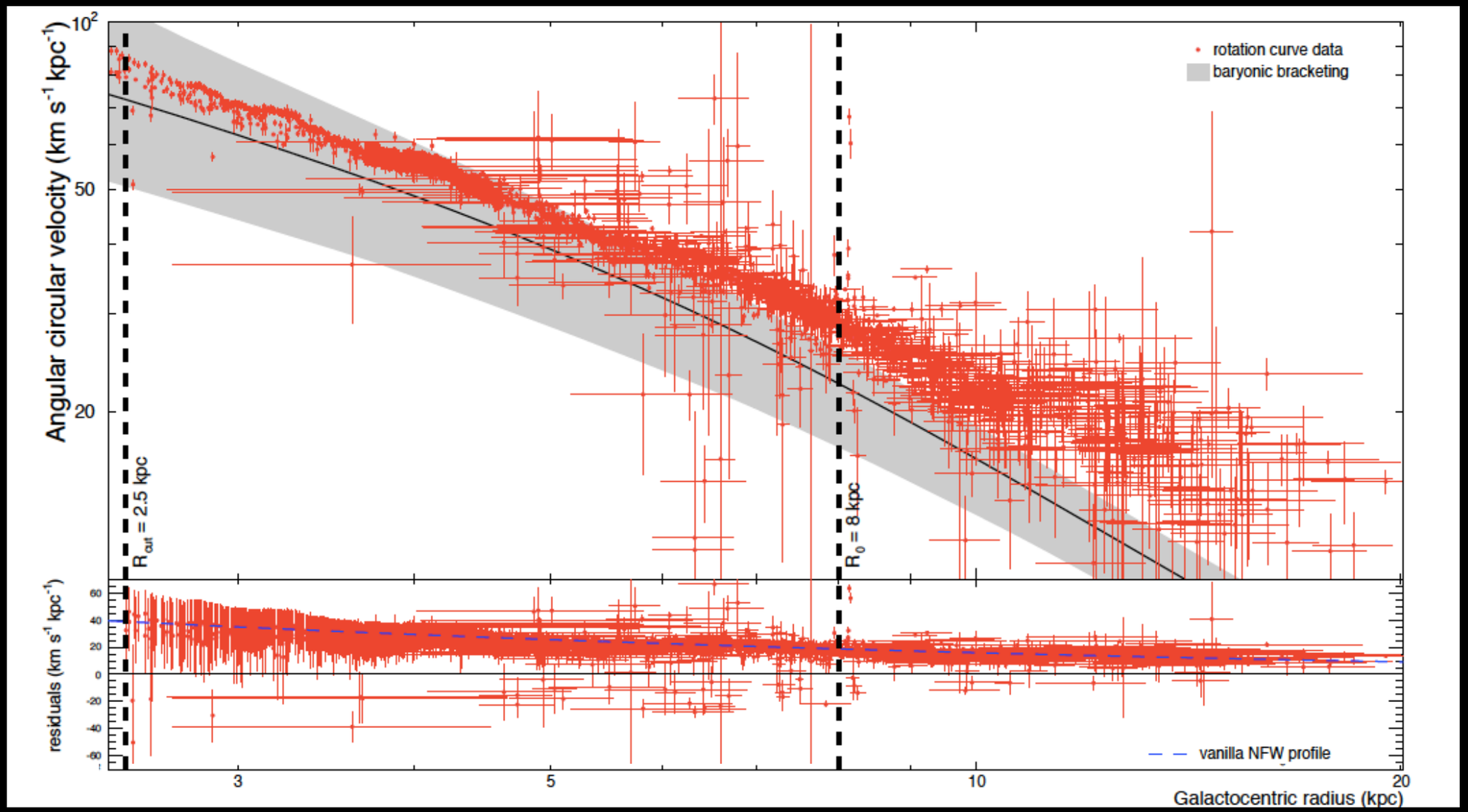
Example 1: Test dark matter distribution with rotation curve of the Milky Way

Rotation curve of the Milky Way



Iocco, Pato, GB, Nature Physics, arXiv:1502.03821

…compared with theoretical models



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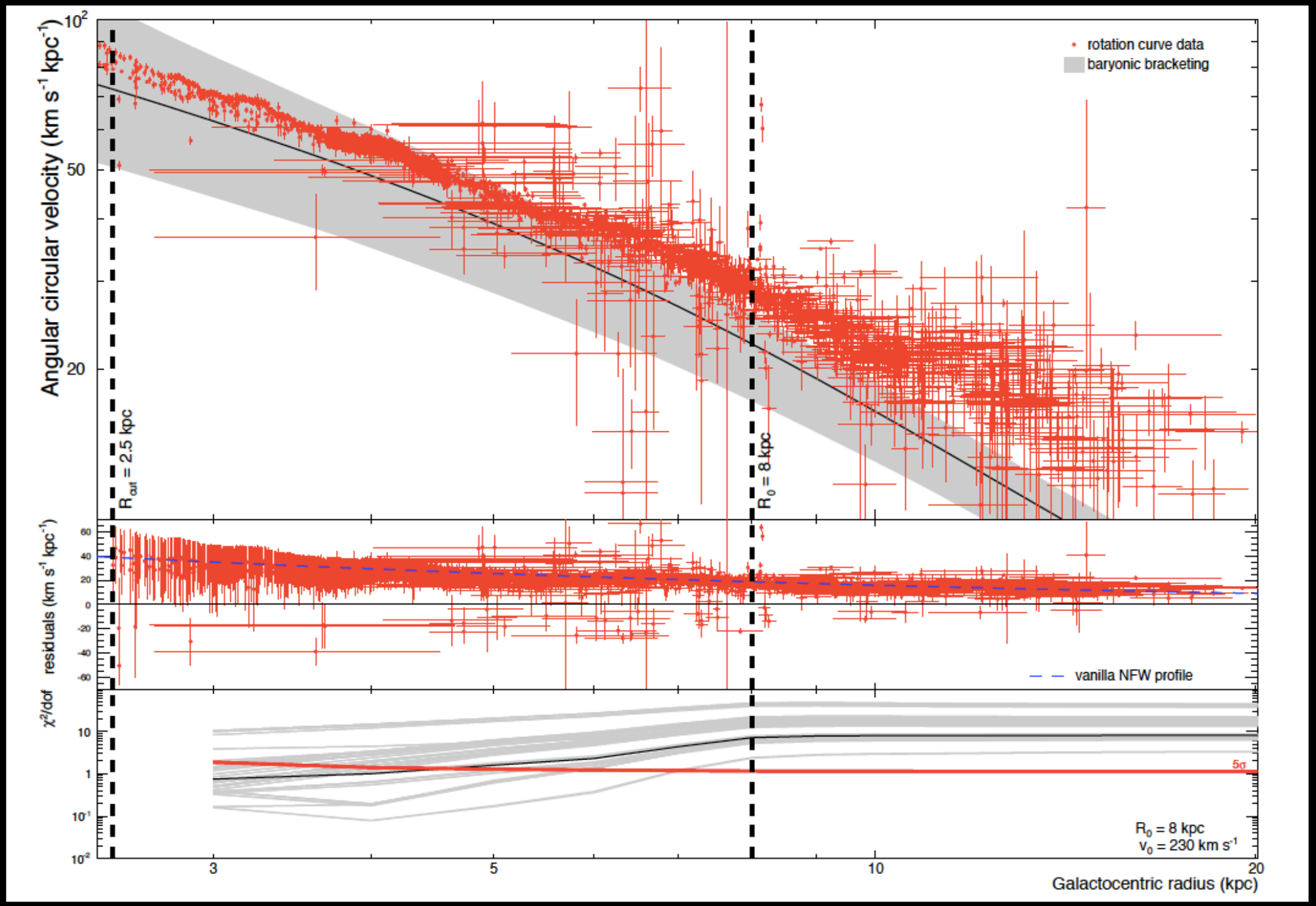
Analysis will be further improved with upcoming data e.g. from the Gaia satellite



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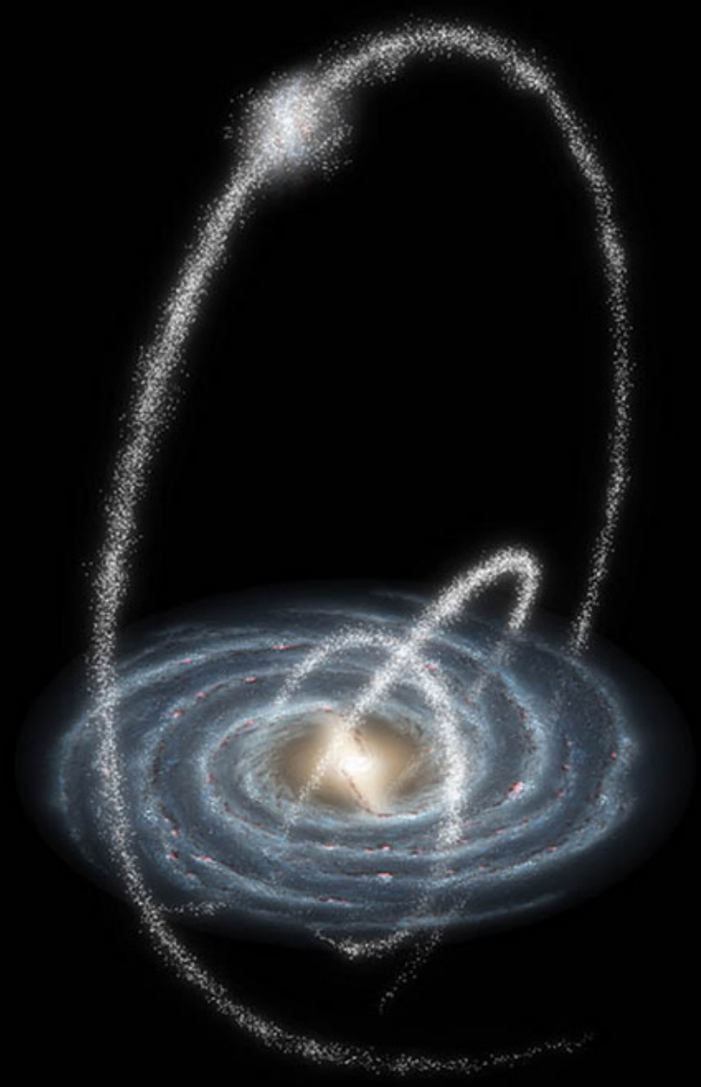
Example 2: Searching for dark matter substructures in the MW



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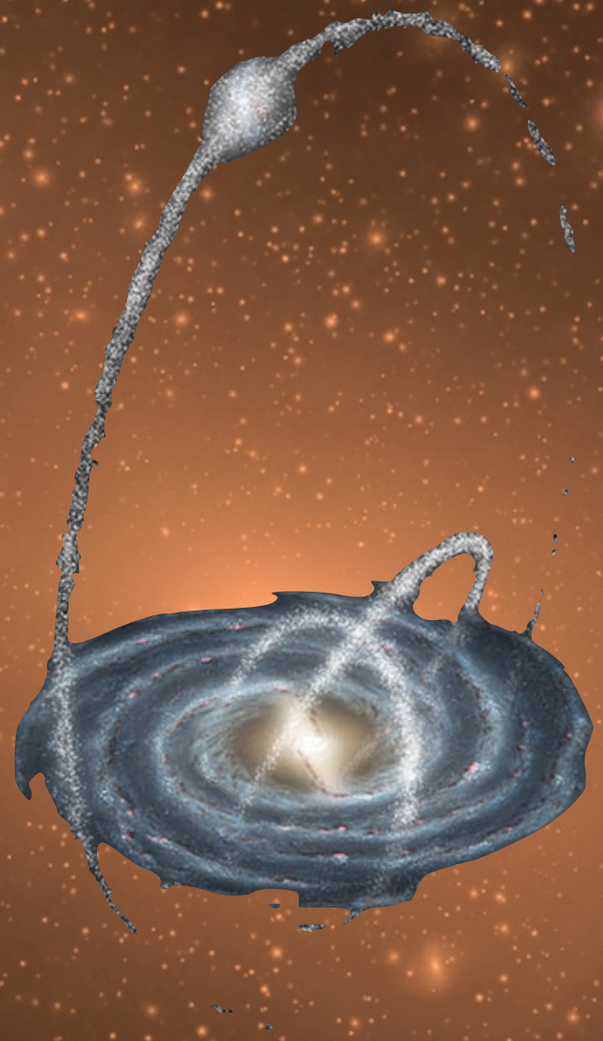
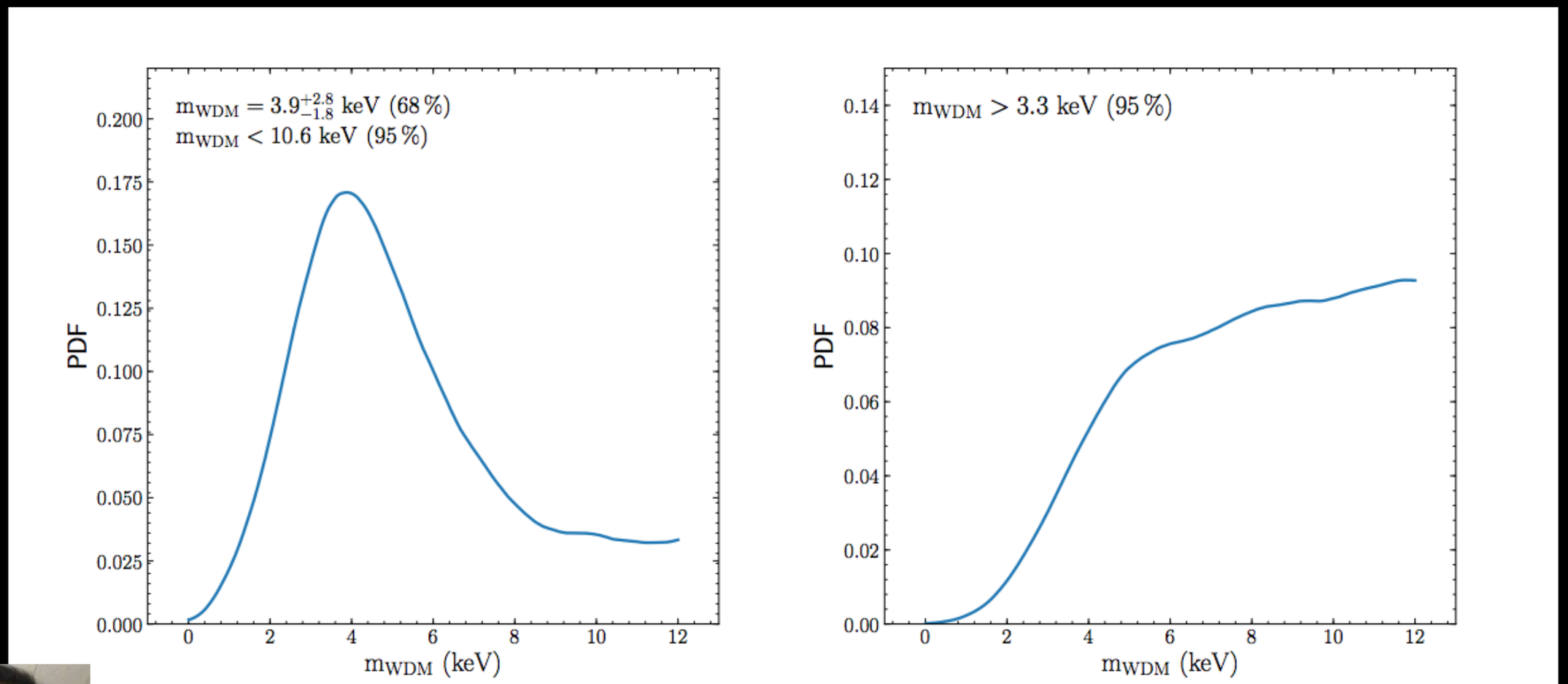


Example 2: searching for dark matter substructures in the MW

Example of reconstruction of DM particle properties from mock stream data, assuming noise level achievable by upcoming surveys like LSST



Banik, GB, Bozorgnia, Bovy arXiv:1804.04384

Other astro/cosmo tests of LCDM include:

- Discrepancy between ‘local’ (Riess+ 2018) and 'cosmological' (Planck 2015) measurements of the Hubble constant

- Alignment of satellite galaxies around Centaurus A that may hint to new dark matter physics (Mueller+ Science 2018)

- 21 cm measurements of the reionization era at z~20. New dark matter physics (Bowman+ Nature 2018)

- Tests of self-interactions etc. (review Buckley & Peter 2017)

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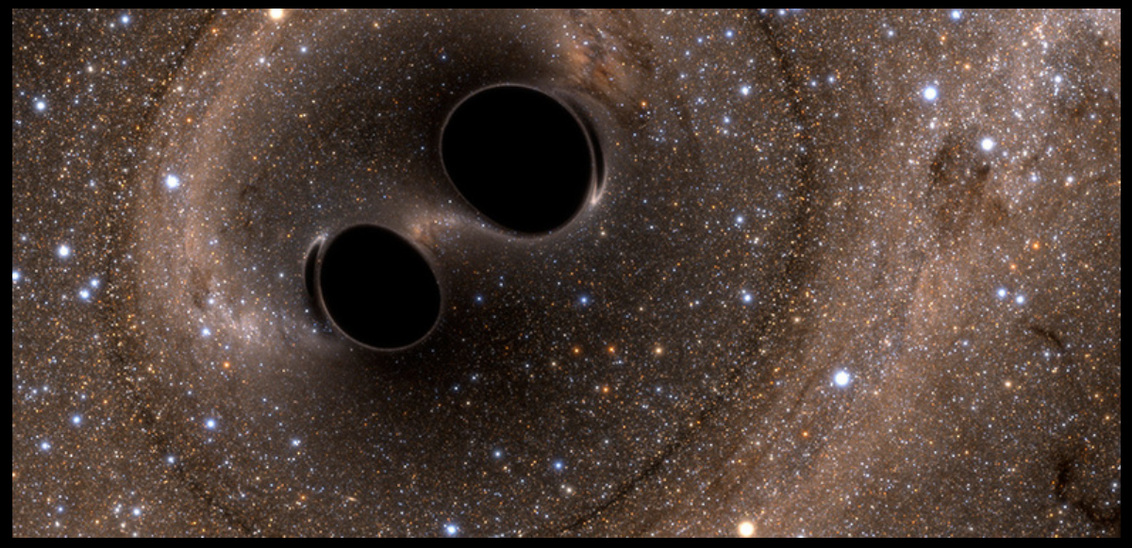
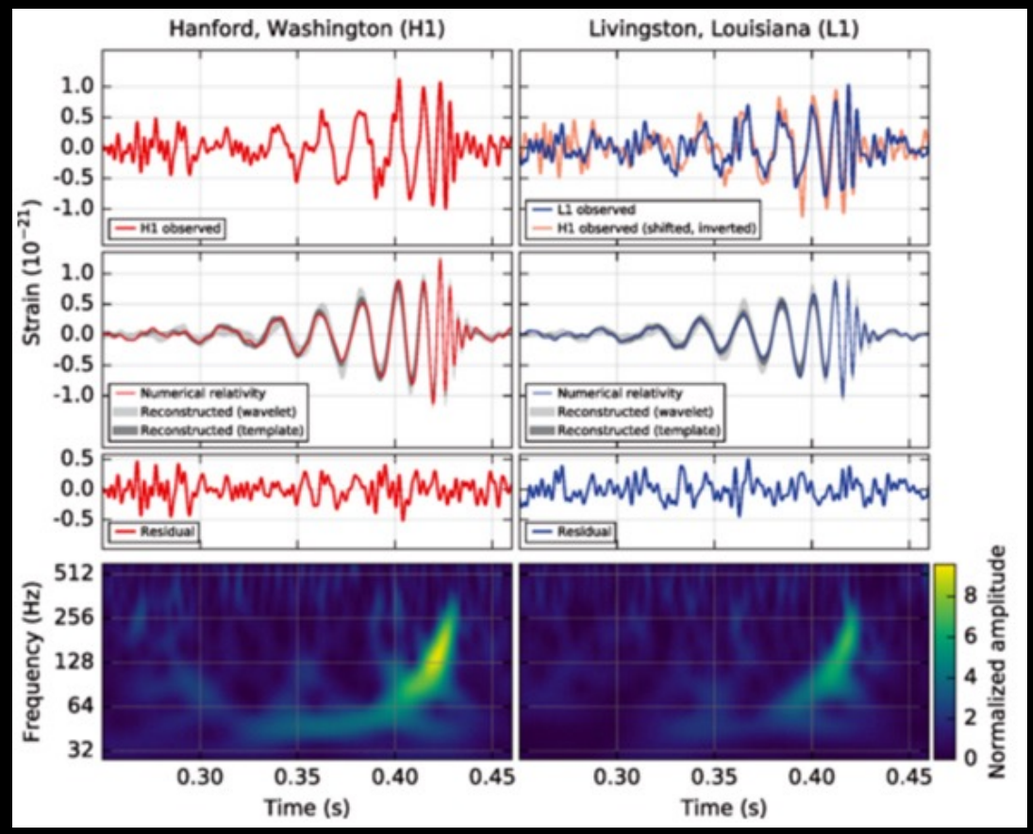
Gravitational Waves

"The discovery that shook the world"



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$

LIGO collaboration, PRL 116, 061102

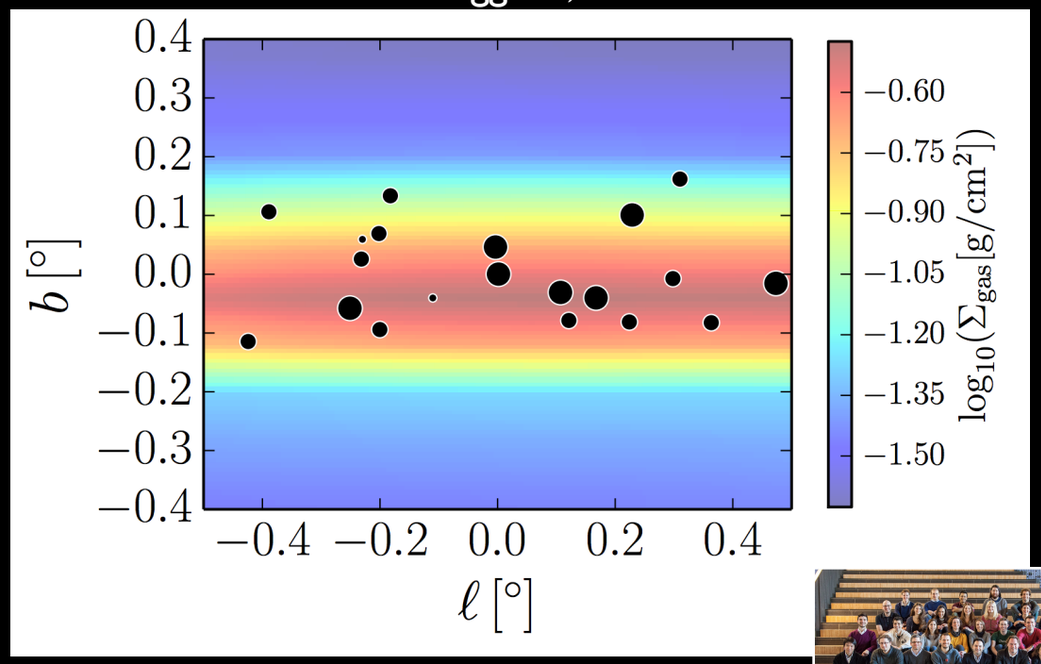


IIIa. Could such BHs be 'the' DM?

(e.g. Bird et al. 1603.00464, Clesse & Garcia Bellido 1603.05234)

IIIa. Primordial Black Holes

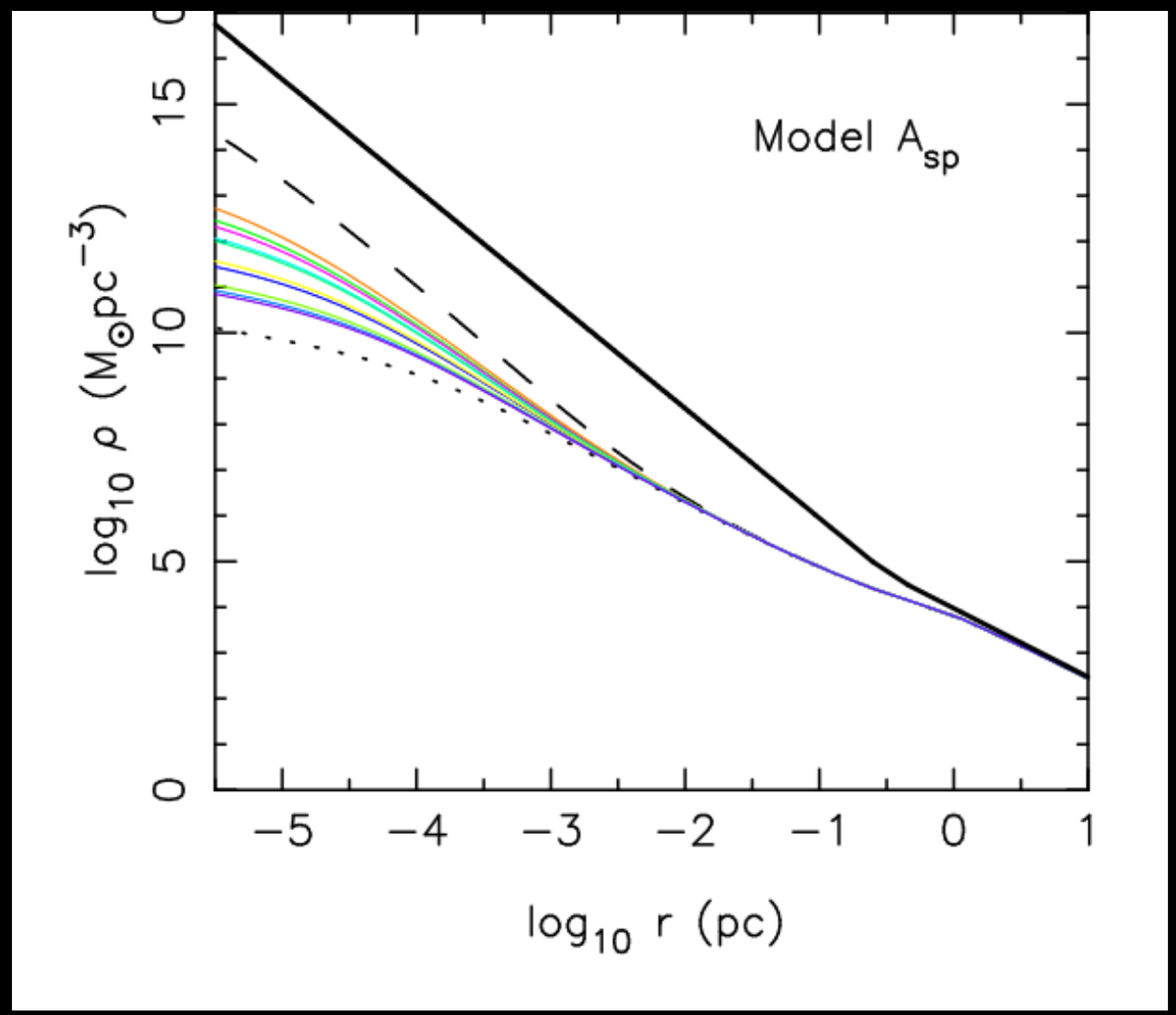
Gaggero, GB et al. PRL 1612.00457



- If PBHs are out there (10^{10} objects in the Galactic bulge if PBHs = DM) they would accrete gas from the dense central molecular zone at the GC
- We should be able to directly observe them in radio and X-ray (Gaggero, GB et al. 1612.00457 - PRL)
- Already strong constraints from VLA and Chandra. Interesting prospects for SKA.

Dark Matter around BHs

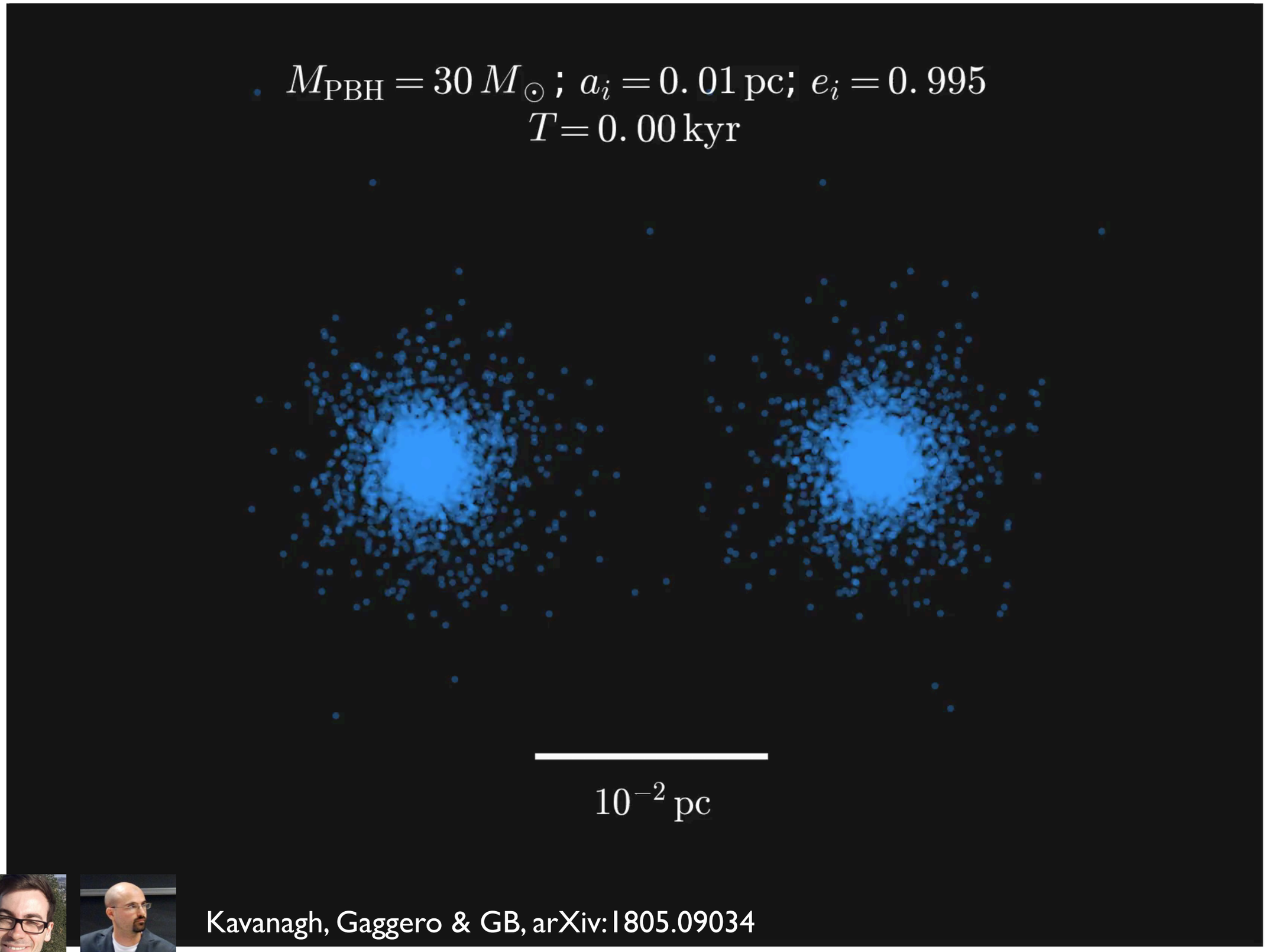
GB & Merritt 2005



- Formation of an adiabatic 'spike' at the GC (Gondolo and Silk 2000)
- 'Mini-spikes' around IMBHs (GB, Zentner, Silk 2015)
- What about PBHs?

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

Dark Matter around BHs



Kavanagh, Gaggero & GB, arXiv:1805.09034

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 and DD experiments may still reserve surprises!

- However 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