The future of dark matter searches

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IIHE Seminar, 16 March 2018

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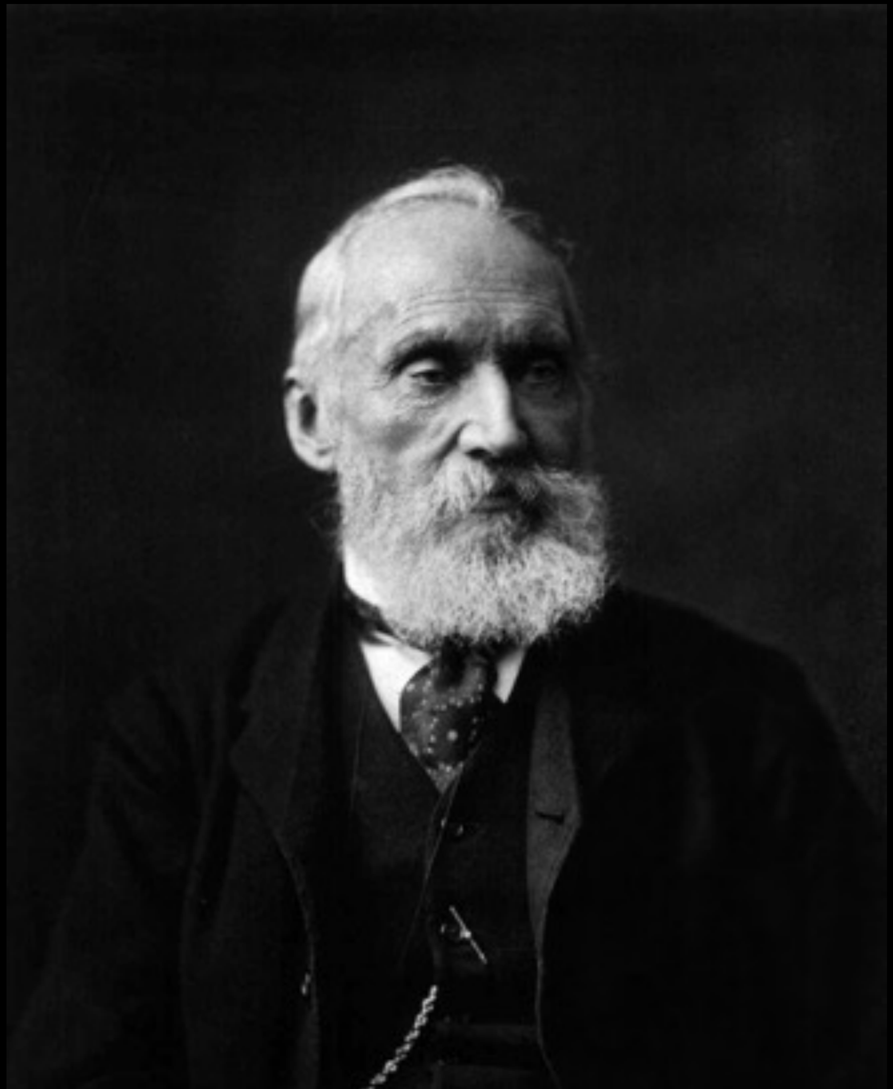
GRavitation AstroParticle Physics Amsterdam

A problem with a long history



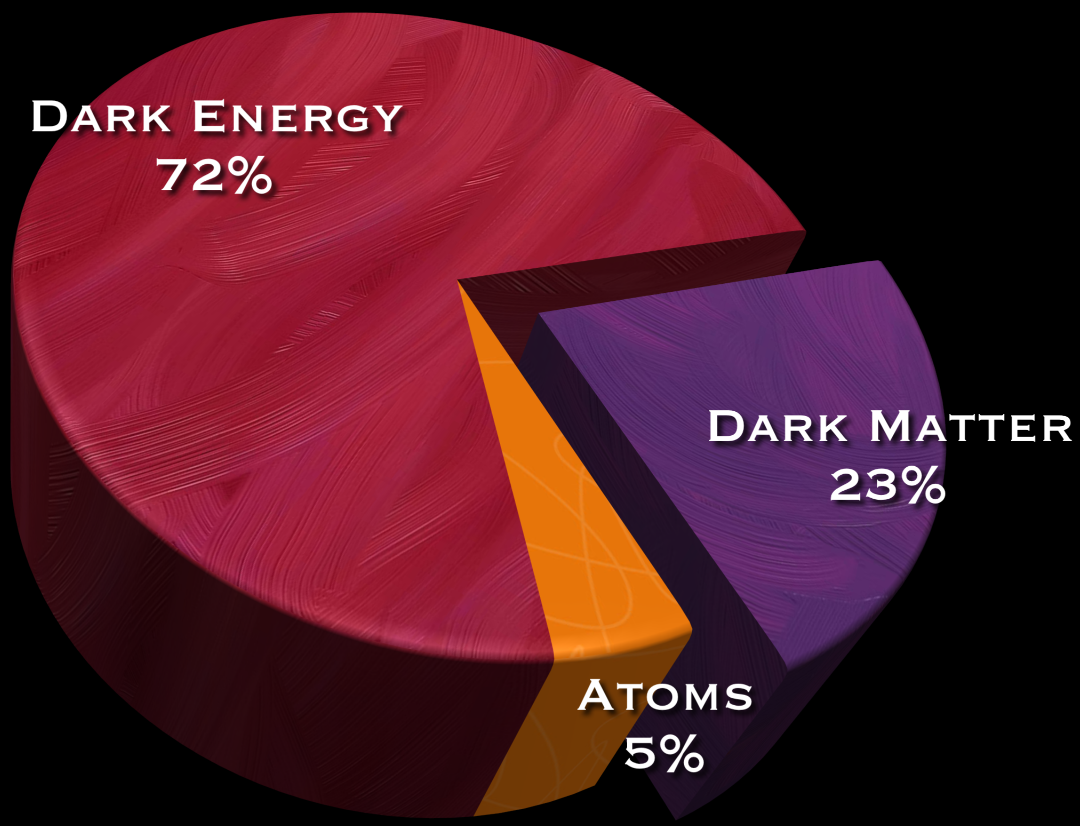
Lord Kelvin (1904) *"Many of our stars, perhaps a great majority of them, may be dark bodies."*

Henri Poincaré (1906) : *"Lord Kelvin's method gives us the total number of stars including the dark ones; since his number 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."*

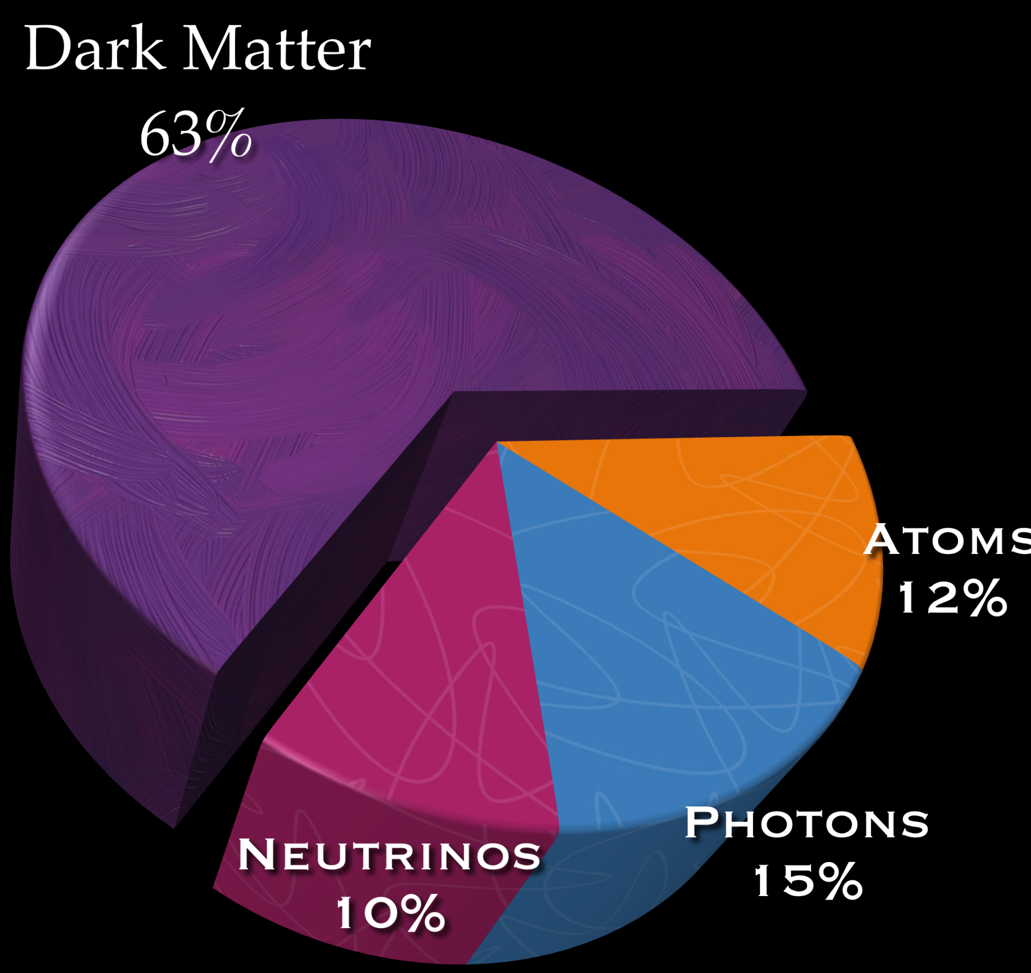
"A history of Dark Matter" GB & Hooper *1605.04909*

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

What is the Universe made of?



TODAY



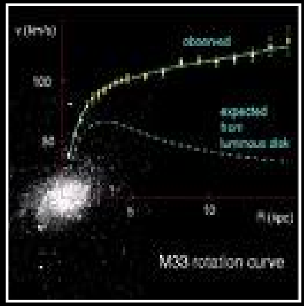
AT DECOUPLING

Evidence for Dark Matter

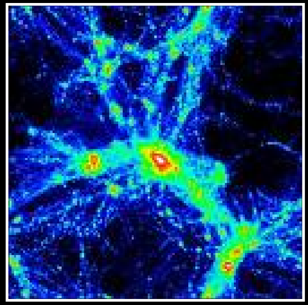
Assuming GR is correct, evidence for the existence of an unseen, “dark”, component in the energy density of the Universe comes from several independent observations at different length scales

COSMOLOGICAL OBSERVATIONS

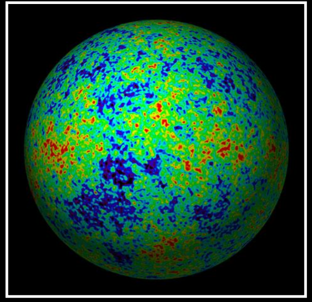
- **‘Local’ matter density**



- **Rotation Curves**



- **Clusters of galaxies**



- **CMB**

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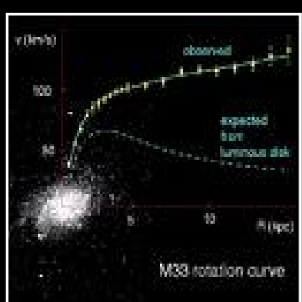

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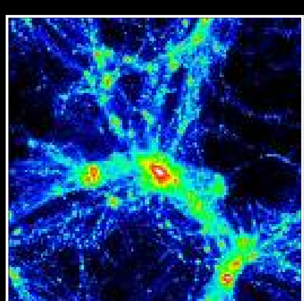

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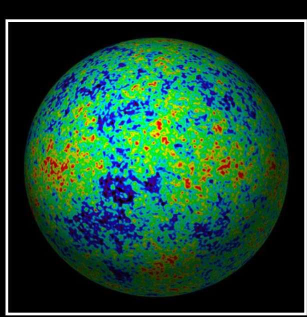

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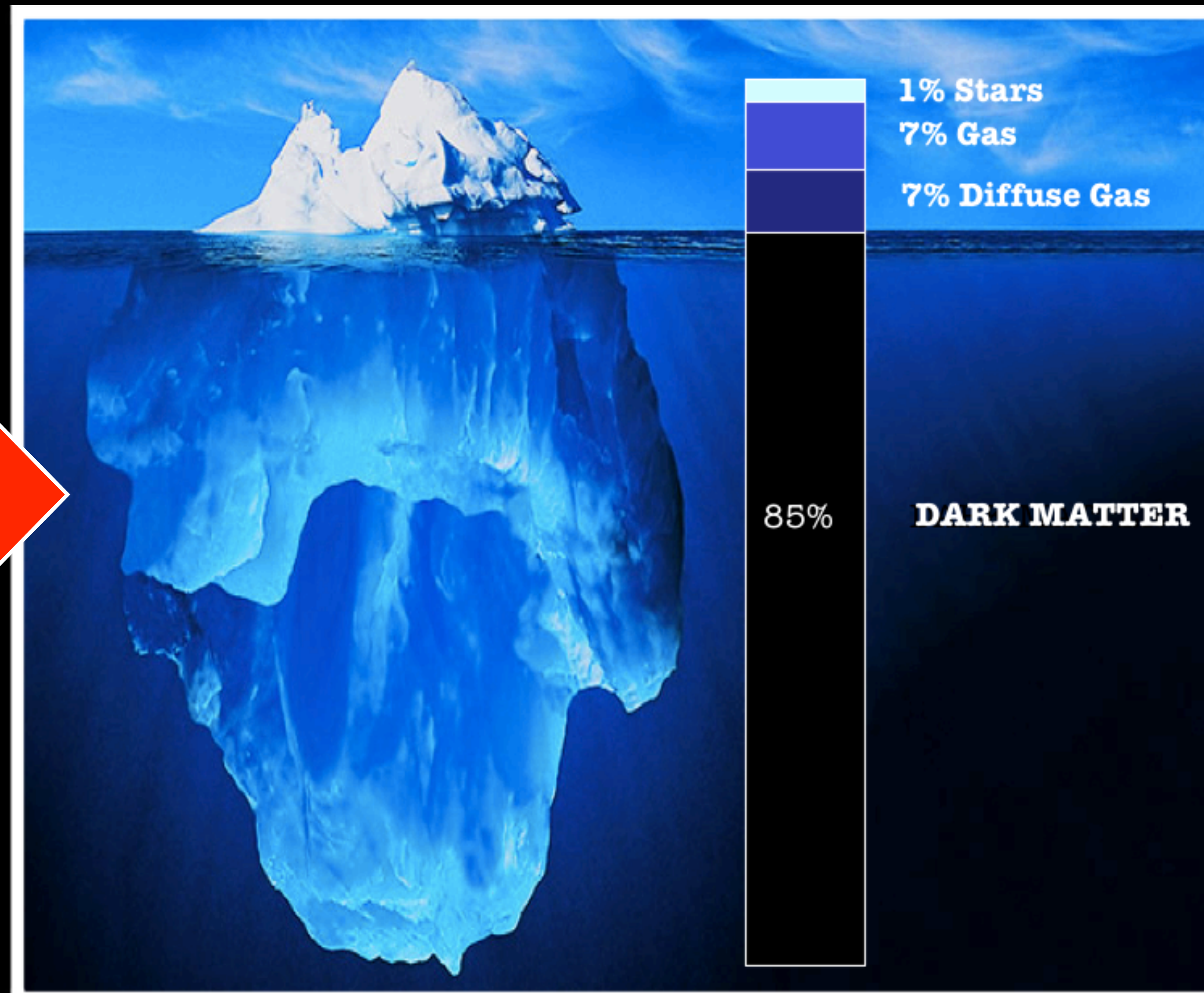
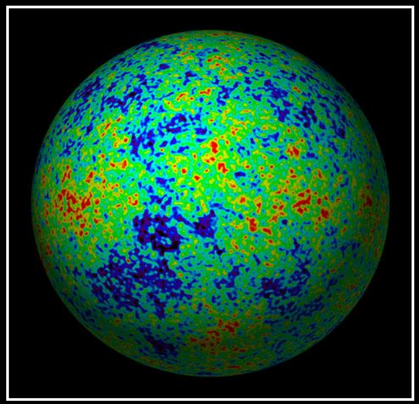


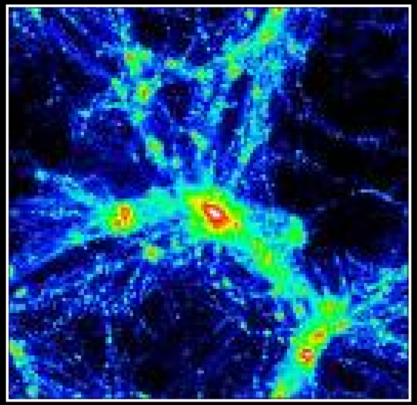
What do we know?

An extraordinarily rich zoo of non-baryonic Dark Matter candidates! In order to be considered a viable DM candidate, a new particle has to pass the following 10-point test

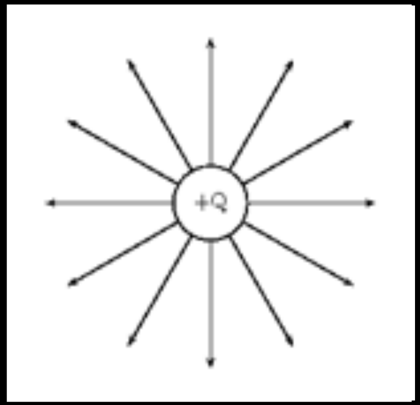
1) Ωh^2 OK?



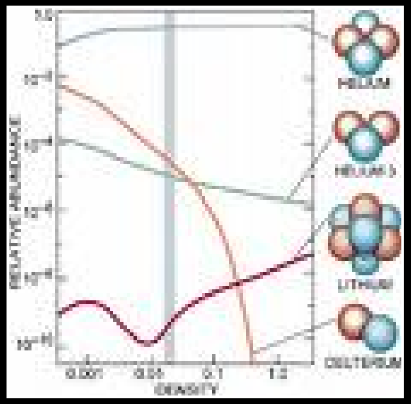
2) Is it cold?



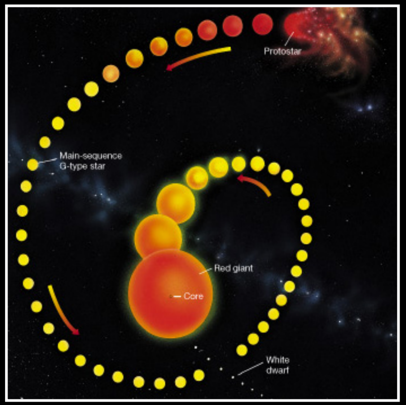
3) Is it neutral?



4) Is BBN ok?



5) Stars OK?



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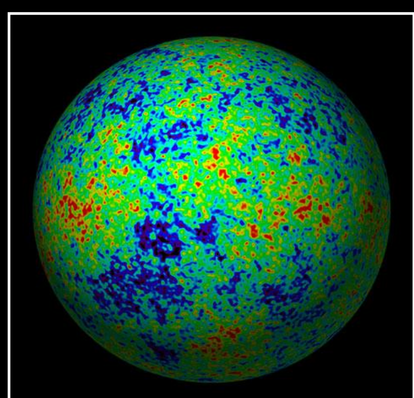

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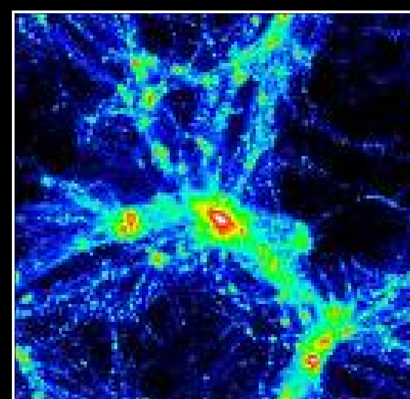

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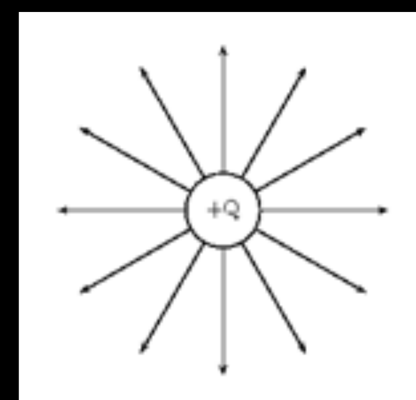

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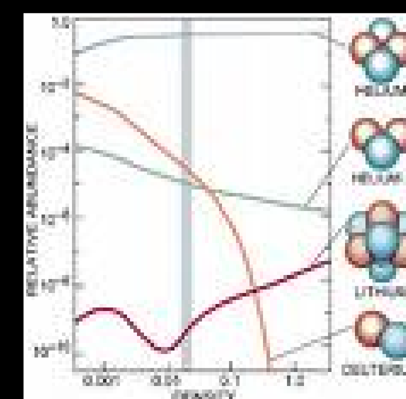

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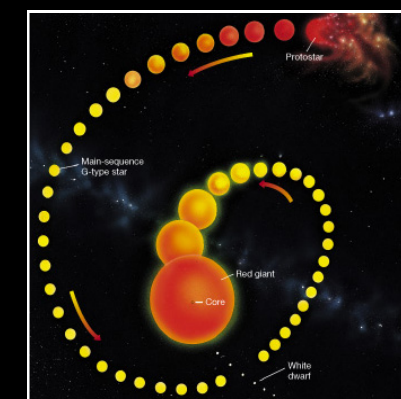
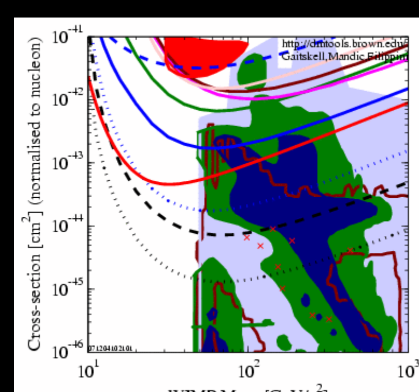
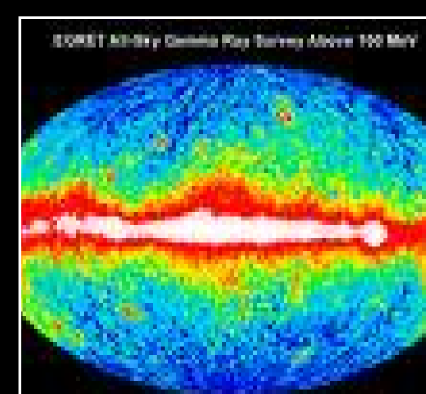


6) Collisionless?

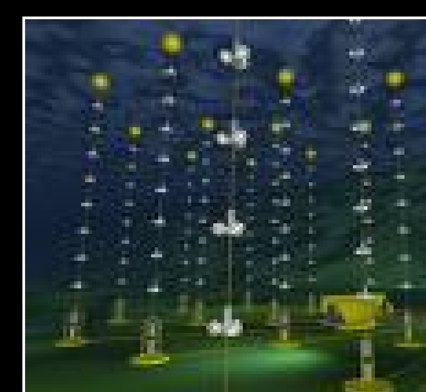
7) Couplings OK?



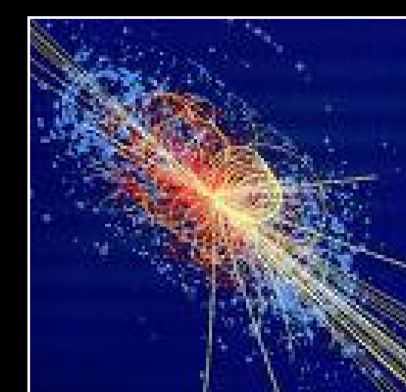
8) γ-rays OK?



9) Astro bounds?



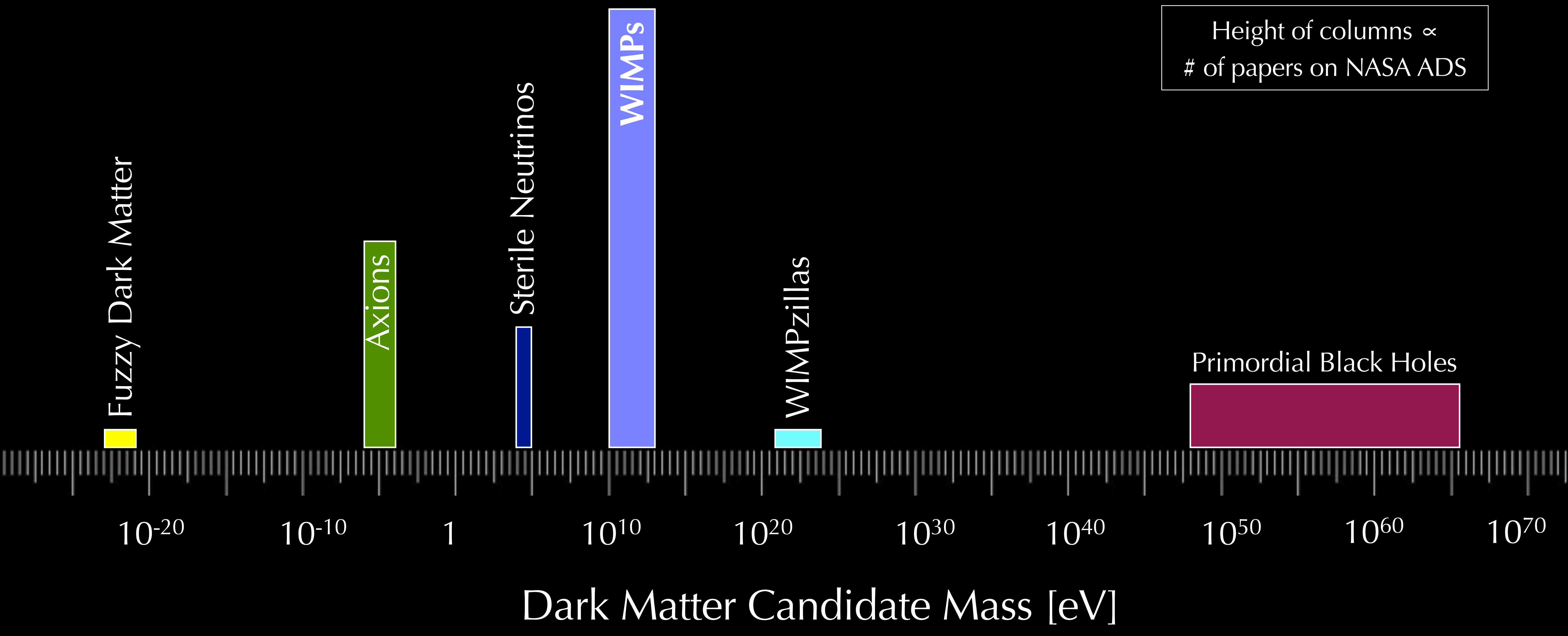
10) Can probe it?



Taoso, GB & Masiero 0711.4996

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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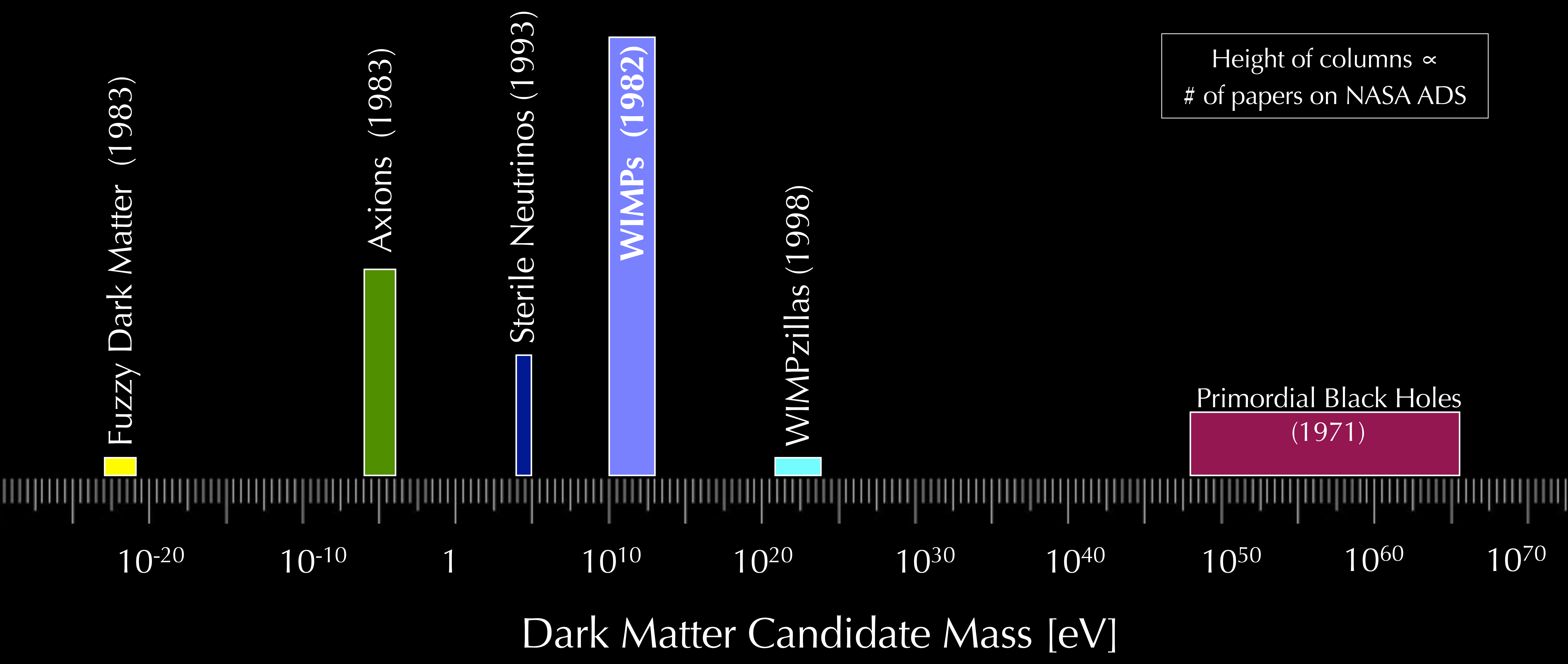
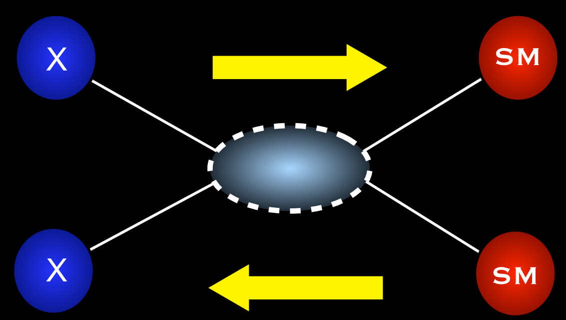


WIMPs

By far the most studied class of dark matter candidates.

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



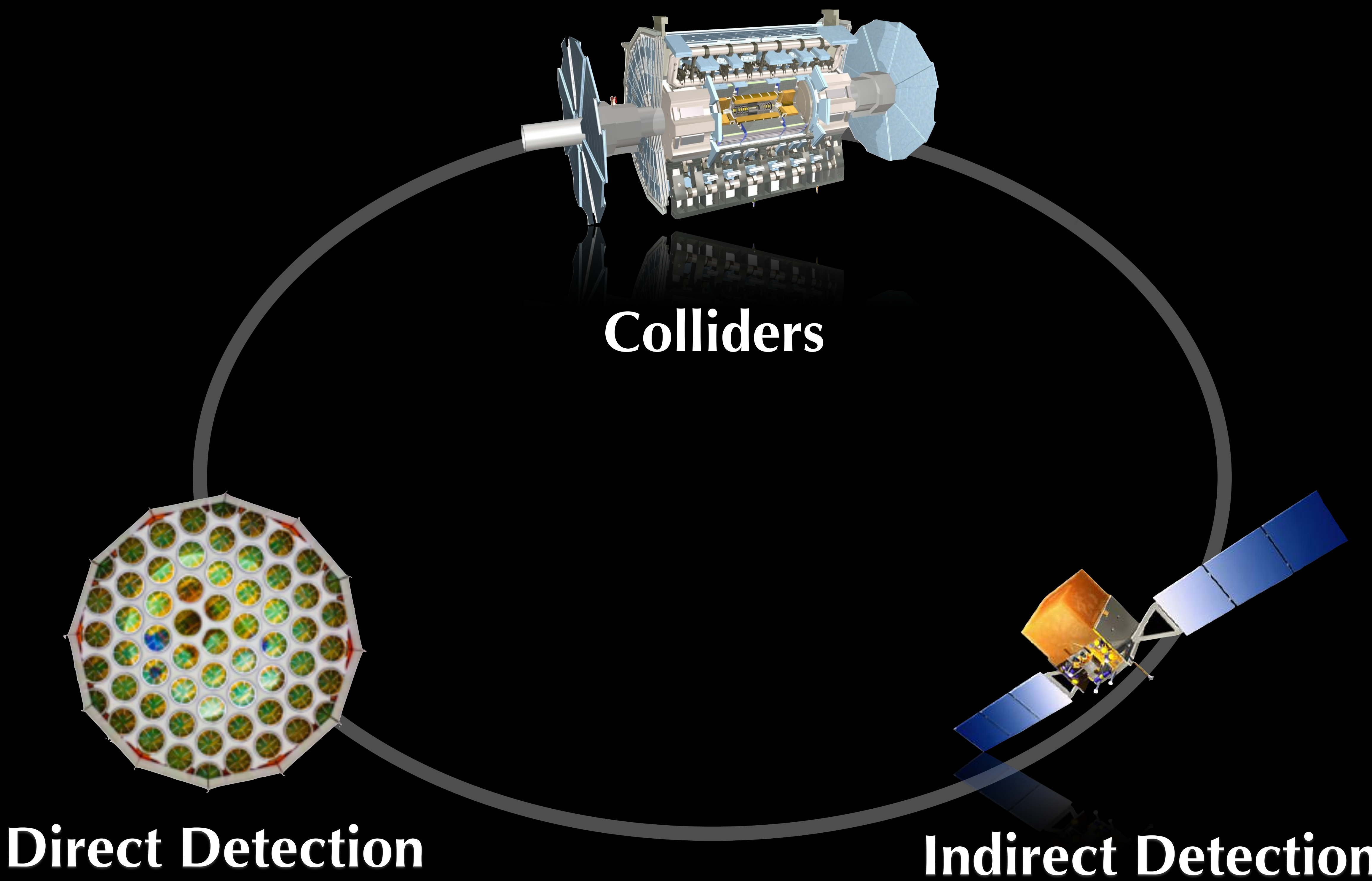
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Weak-scale cross sections can reproduce correct relic density.

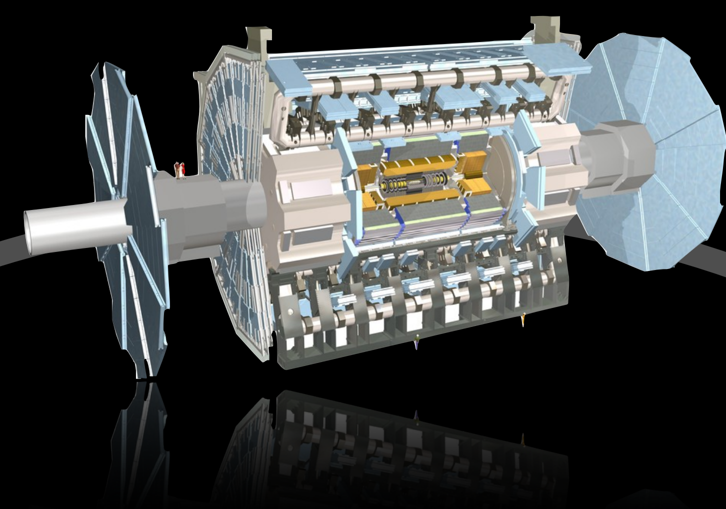
$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

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

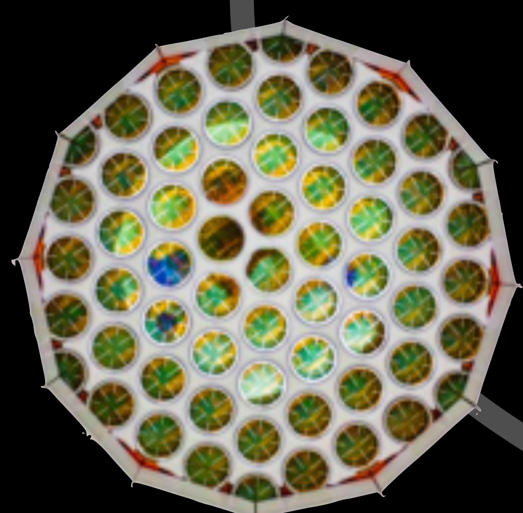
WIMPs searches



WIMPs searches



No WIMPs (nor other DM) found despite many efforts. Should we keep trying?



Are WIMPs ruled out?

ATLAS/CMS searches do put pressure on SUSY, and in general absence of evidence for new particles at EW scale puts pressure on "naturalness" arguments (e.g. Giudice 1710.07663).

However:

I. Non-fine tuned SUSY DM scenarios still exist (Beekveld+ 1612.06333)

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

The future of dark matter searches

I. Diversify searches
II. Exploit astro/cosmo observations
III. Exploit Gravitational Waves

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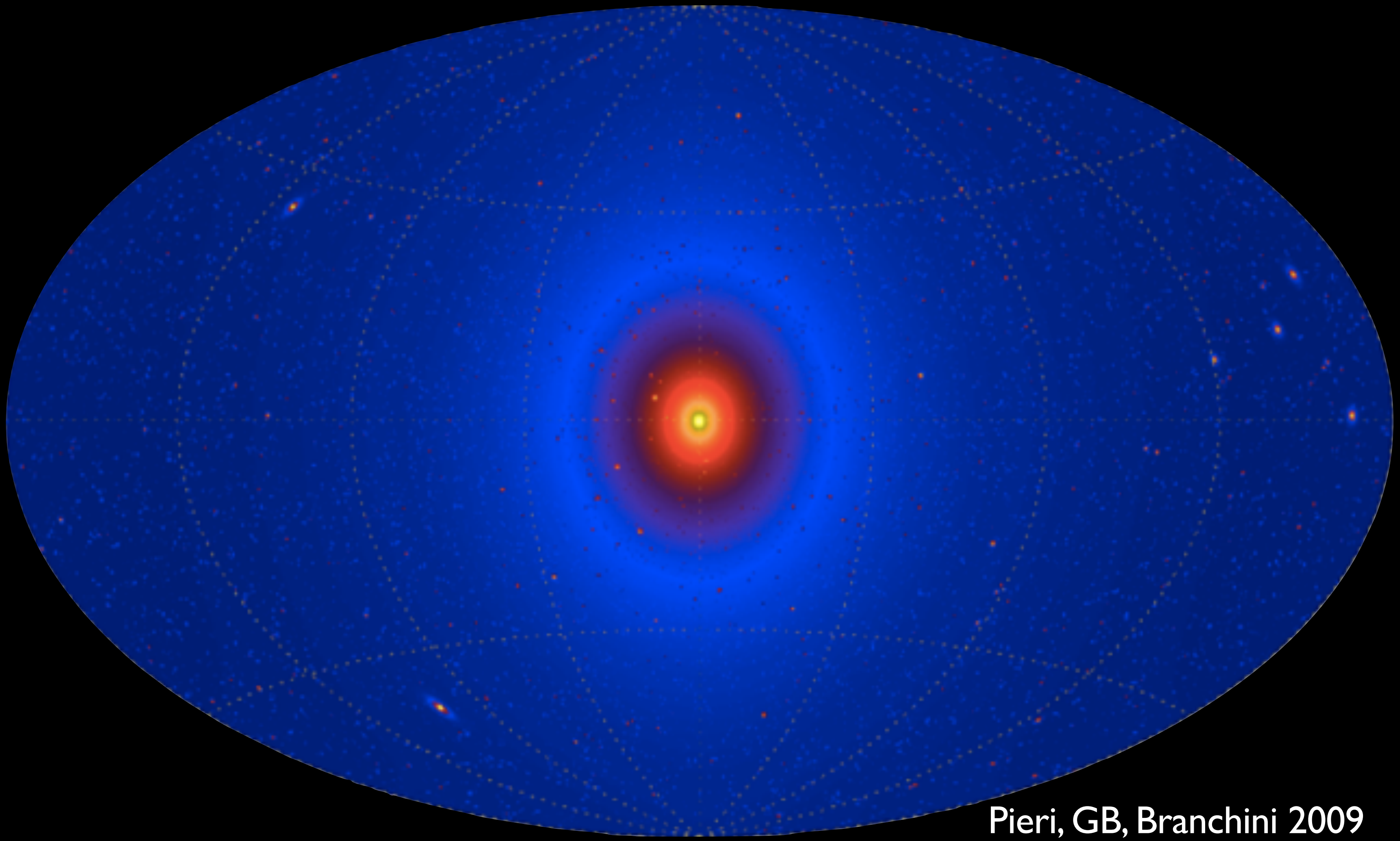
Example: Indirect detection with gamma-rays

Given: a particle physics model (particle mass **m_χ**, annihilation cross section **σv**, # of photons per annihilation **dN/dE**) and the dark matter density profile **$\rho(x)$**, it is possible to calculate the expected rate of events in a detector.

$$\Phi_i(\Omega, E_i) = \frac{dN}{dE_i}\frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\int_{los}\rho_\chi^2(\ell,\Omega)d\ell$$

Full-sky map of predicted gamma-ray flux

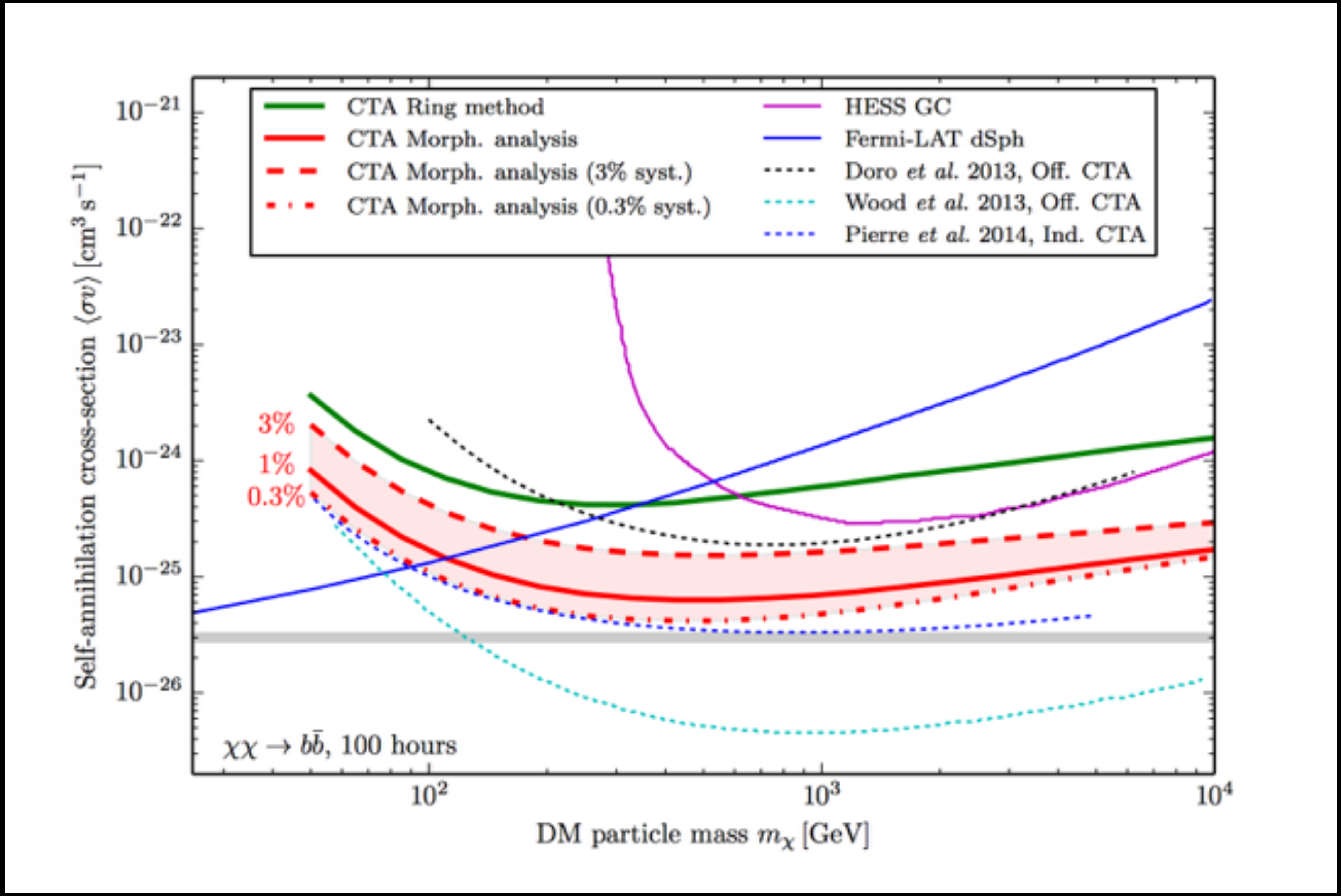


Pieri, GB, Branchini 2009

1A. Broaden searches

E.g. Massive WIMPs searches with CTA

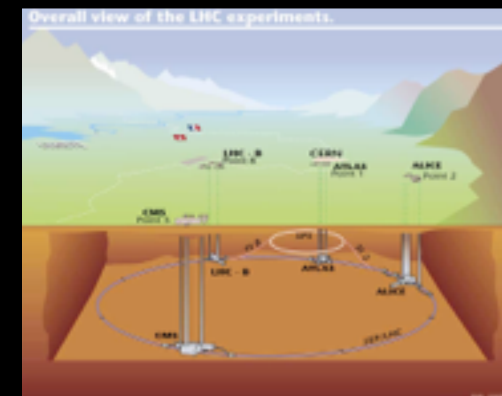
Generic WIMPs have masses 1 GeV — 100 TeV. We are far from probing the whole range

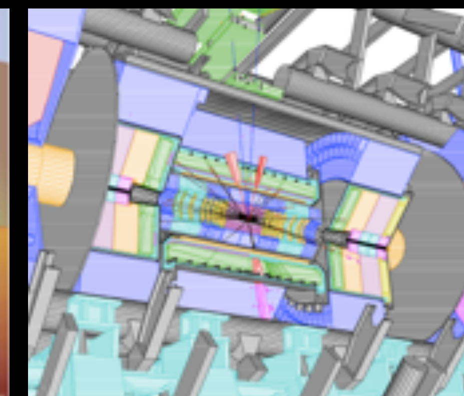


Silverwood, GB+ JCAP (2015)

1B. Improve existing strategies

E.g. Search for new physics at the LHC



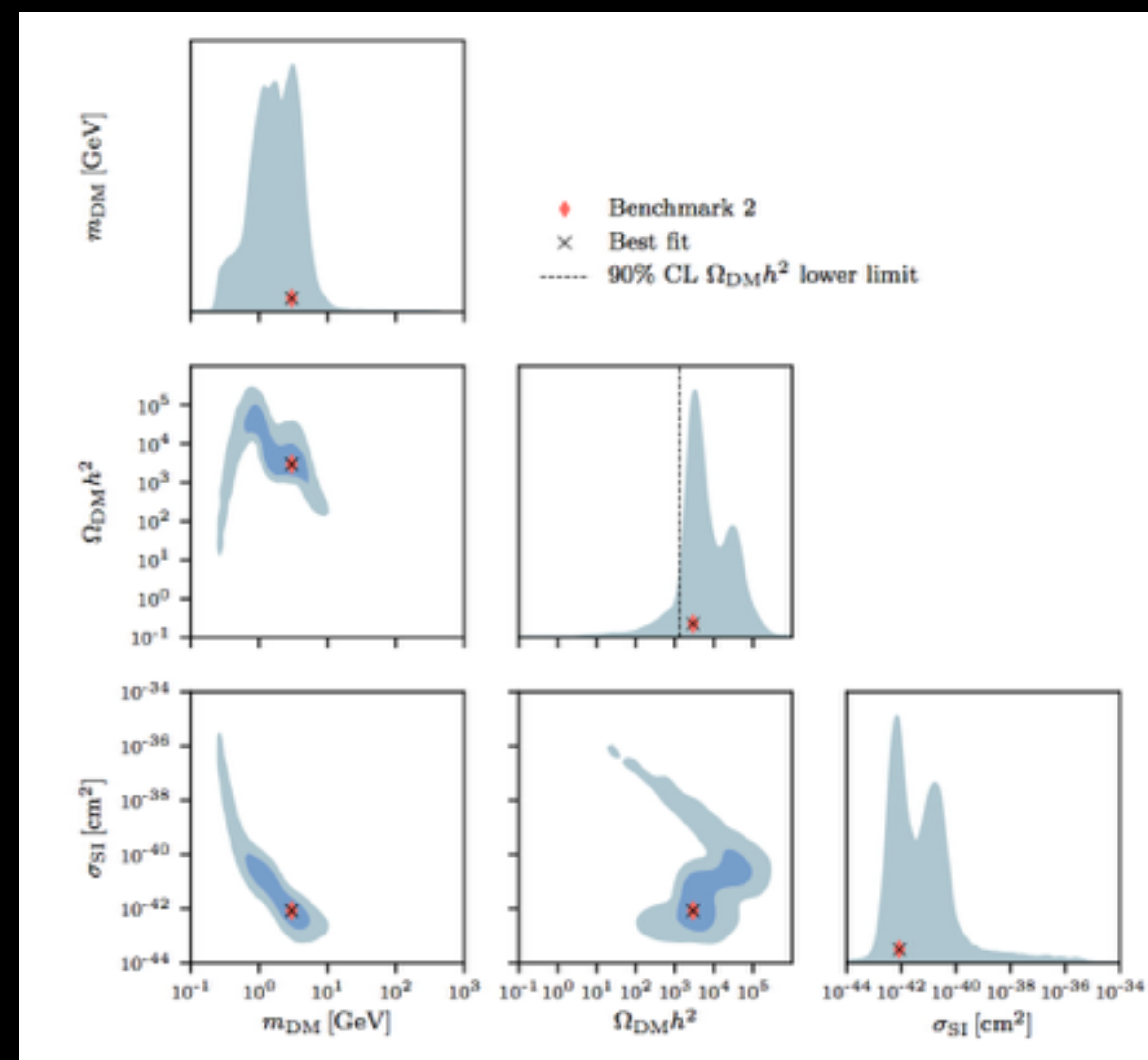


New Machine Learning tools allow to scan large-d theory parameter spaces.

This allows us to:

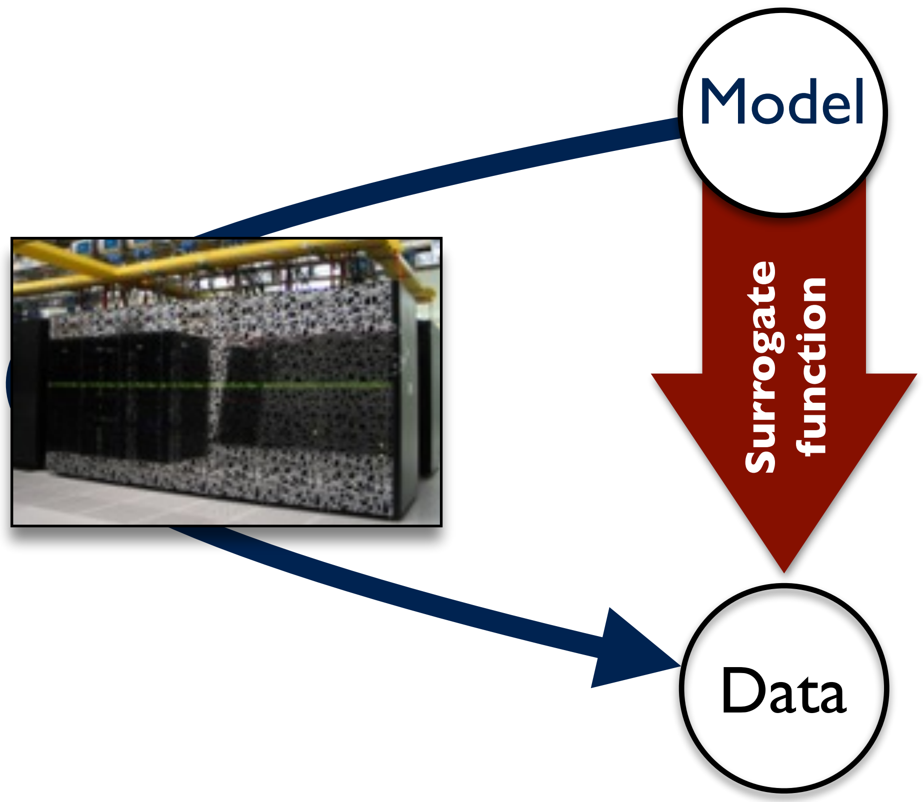
i) Perform fast inference if new particles discovered

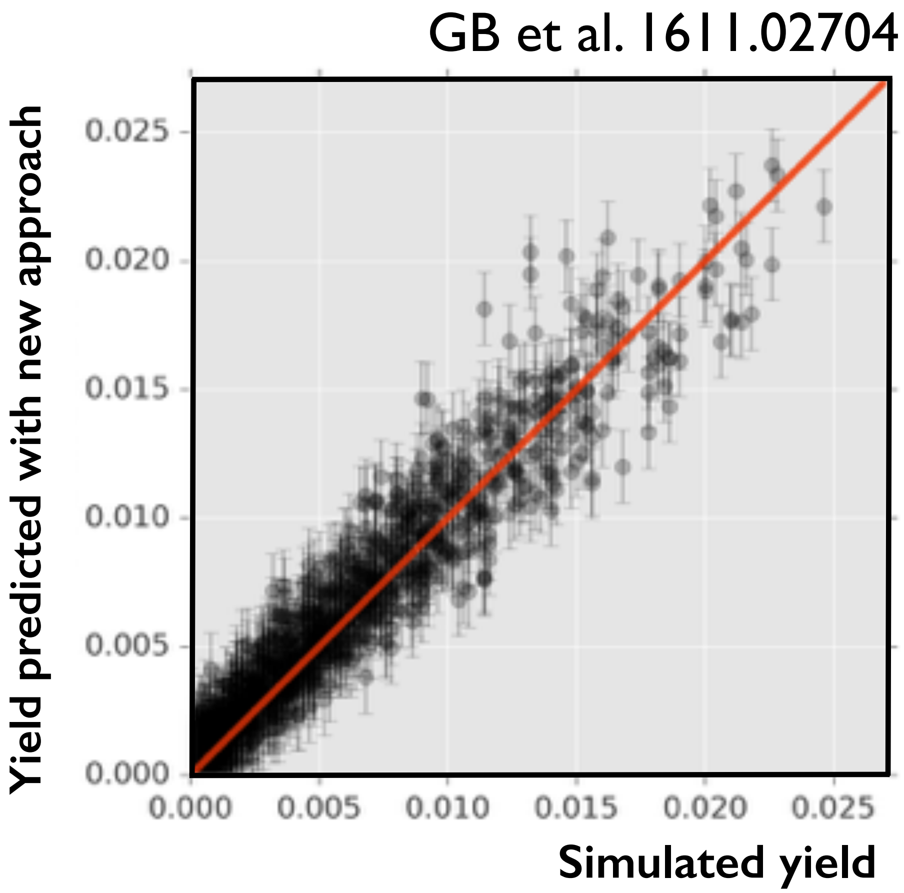
ii) Optimize search strategies, by e.g. identifying optimal signal and control regions in ATLAS/CMS searches for new particles for each individual point in the theory parameter space



GB+ JCAP (2018)

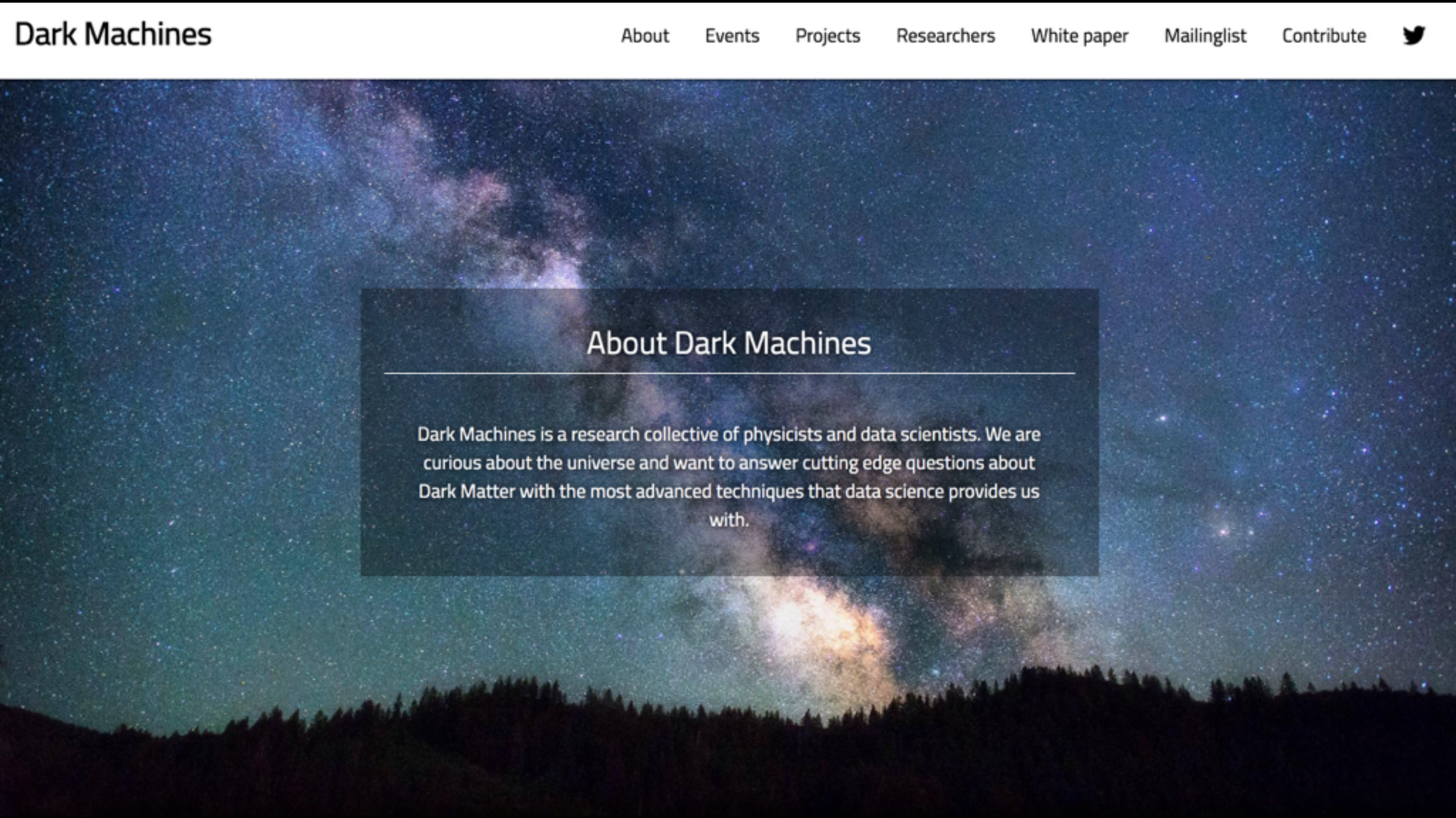
Speeding up statistical inference with Machine Learning tools





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

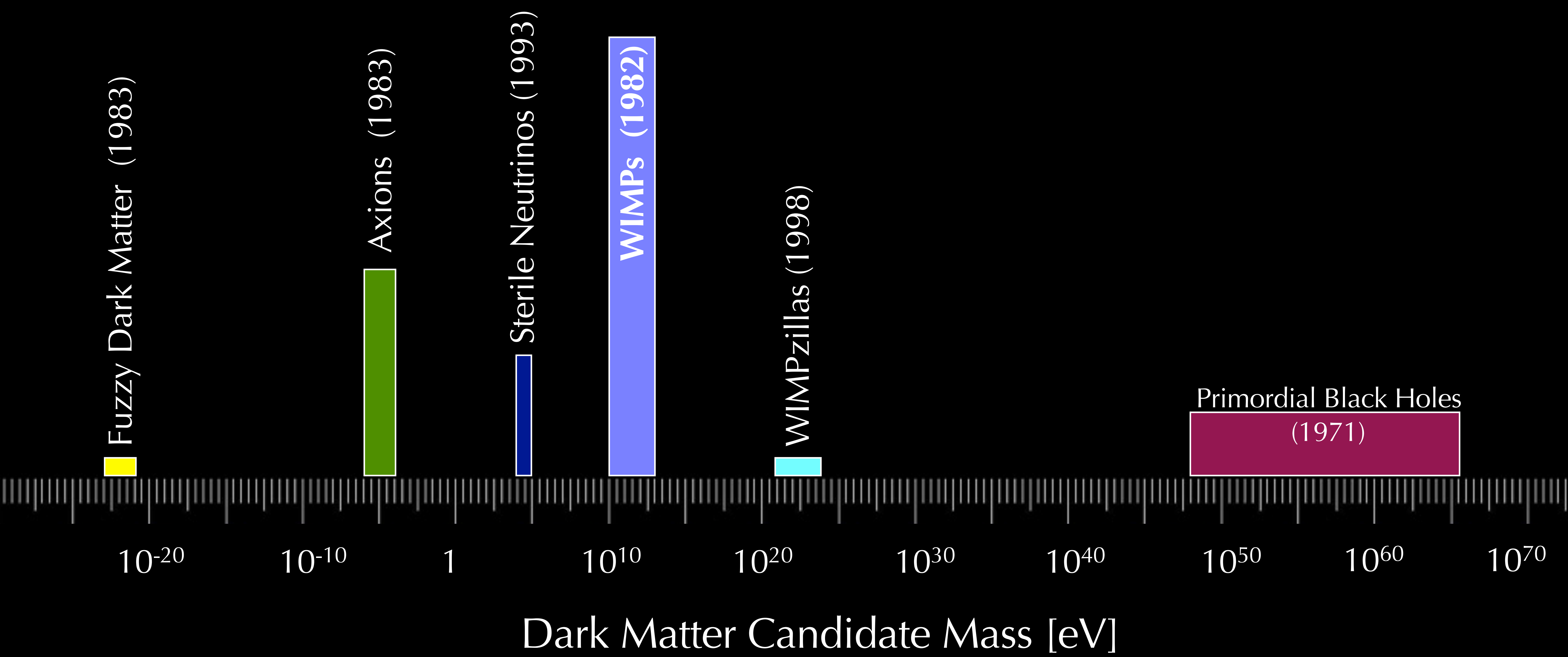
The *Dark Machines* initiative



Website: darkmachines.org ; Twitter: dark_machines

Ic. Leave no stone unturned

Look for DM where we can, not where we should



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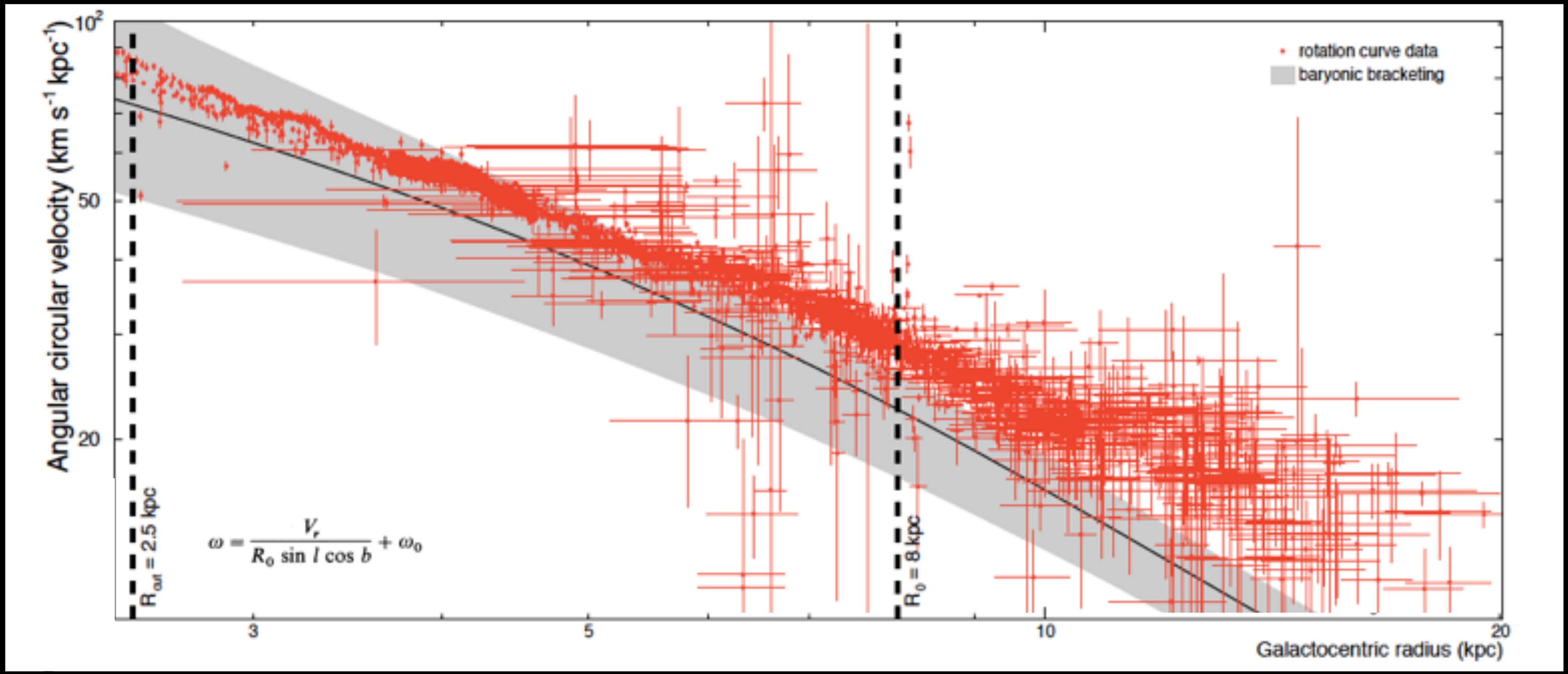
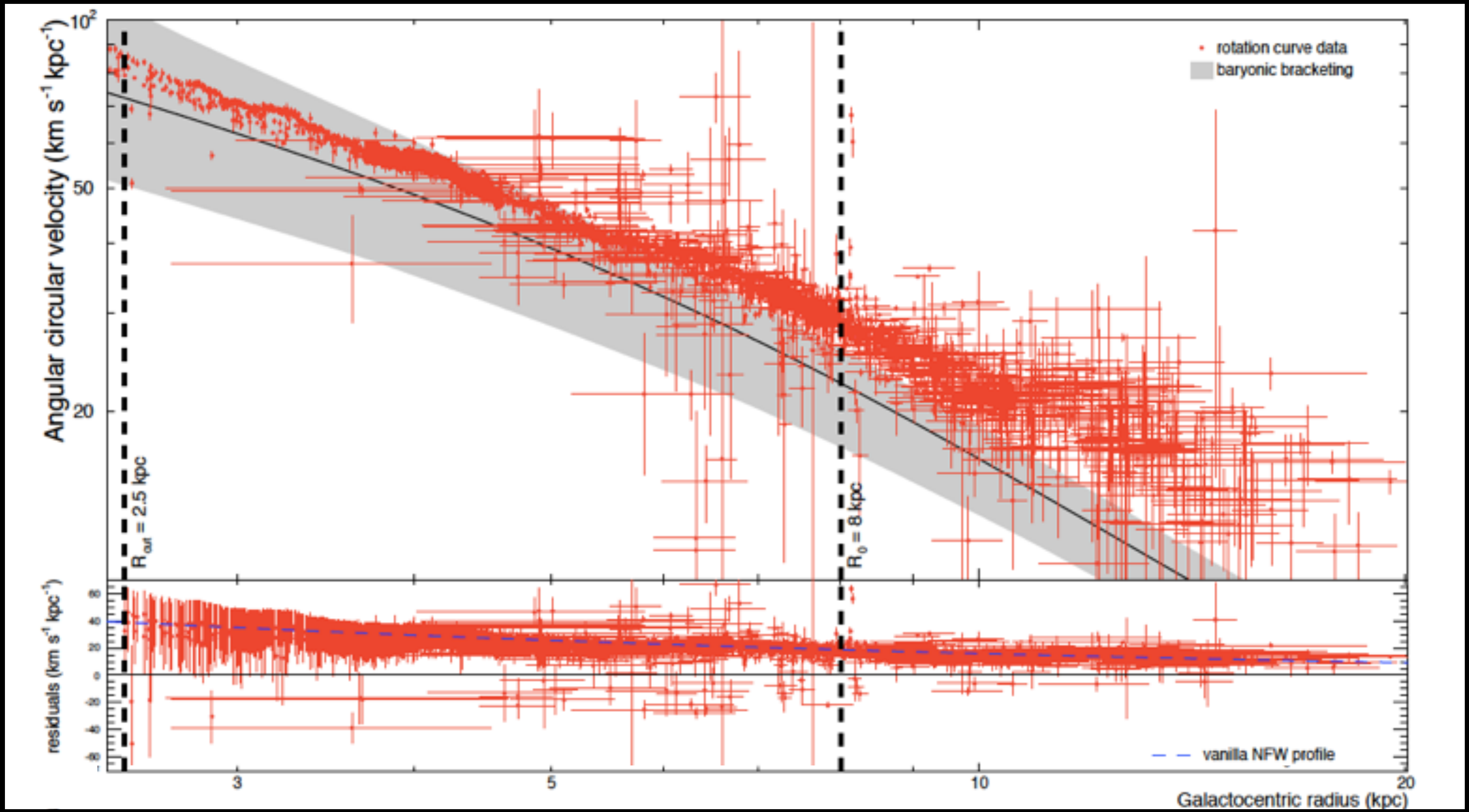
Example 1: Test dark matter distribution with rotation curve of the Milky Way

Rotation curve of the Milky Way



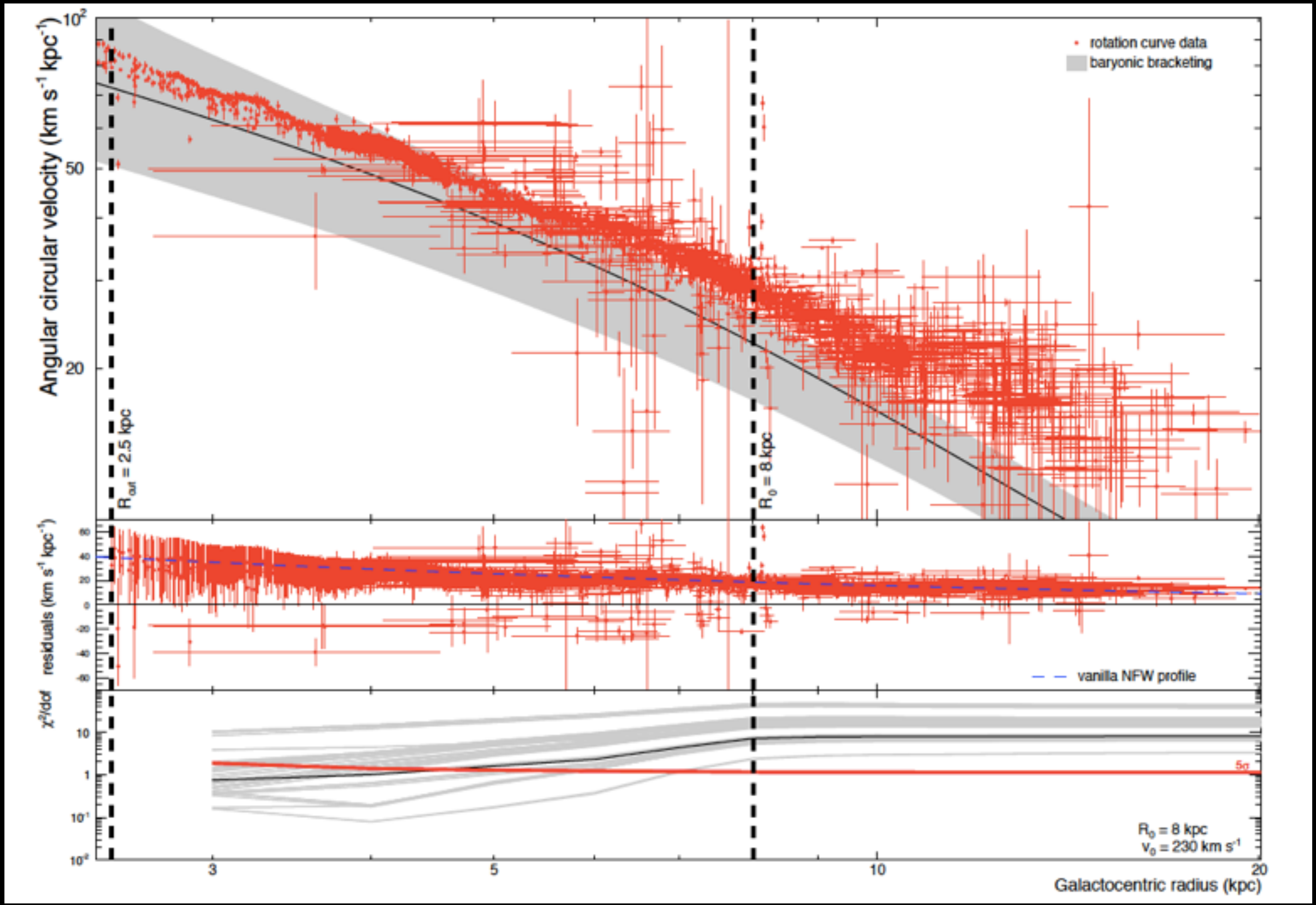
Iocco, Pato, GB, Nature Physics, arXiv:1502.03821

…compared with theoretical models



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

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



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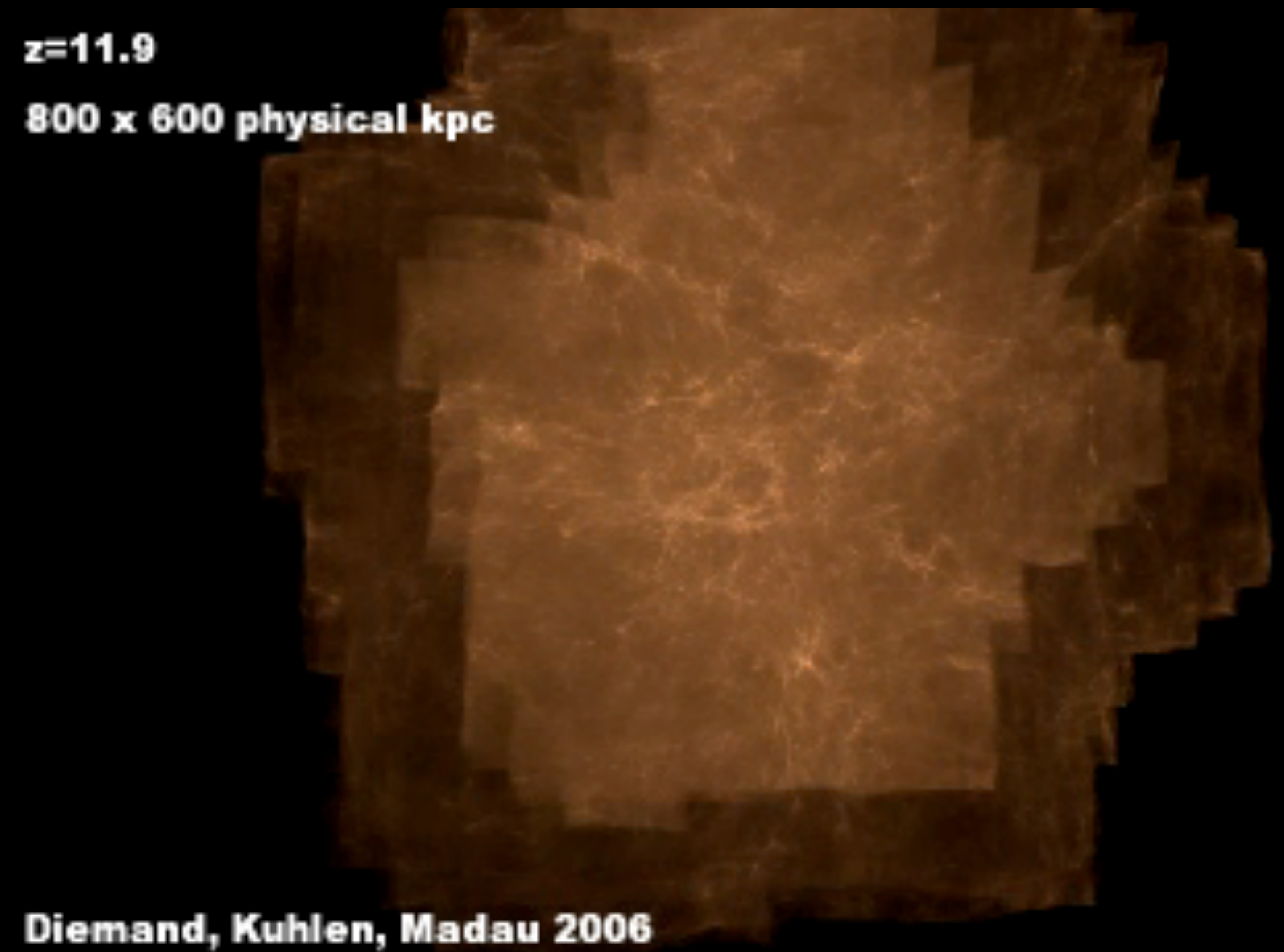
Example 2: searching for dark matter substructures in the MW



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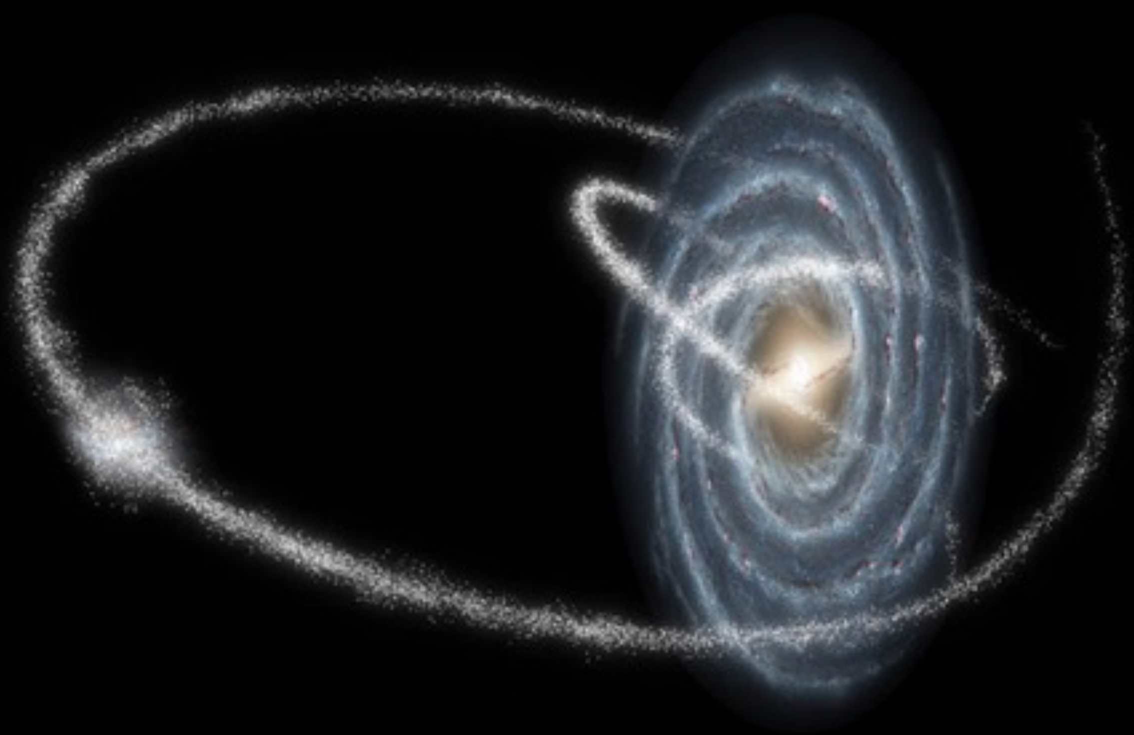
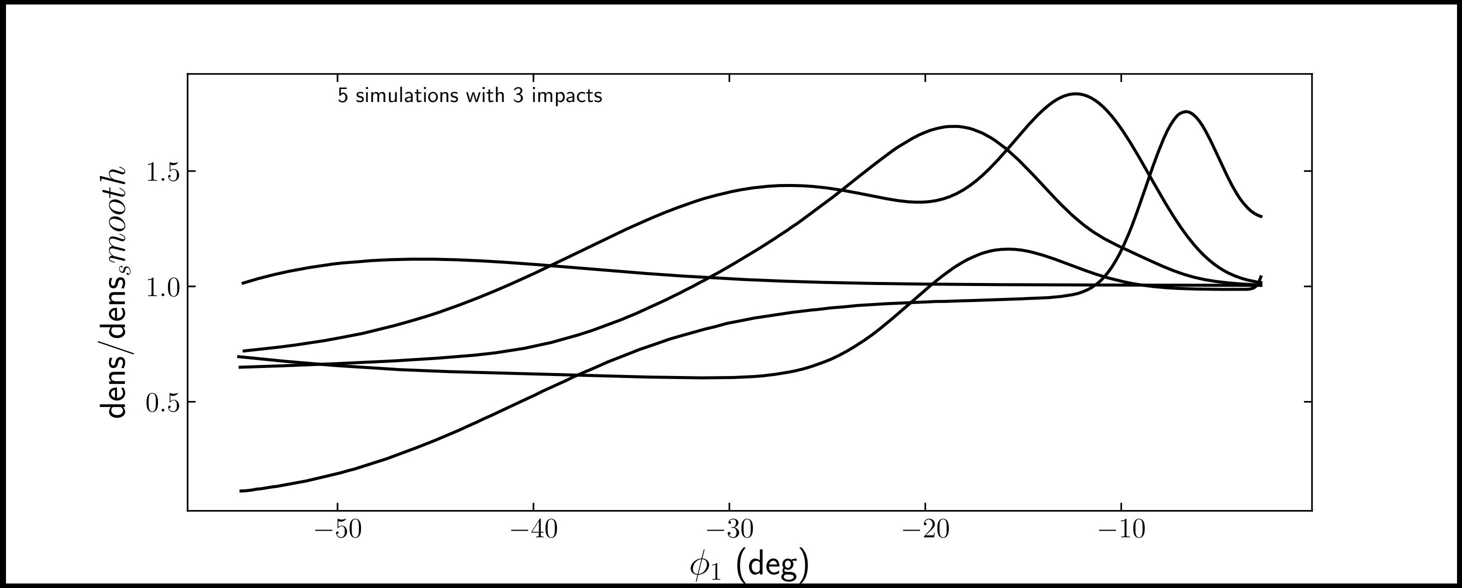


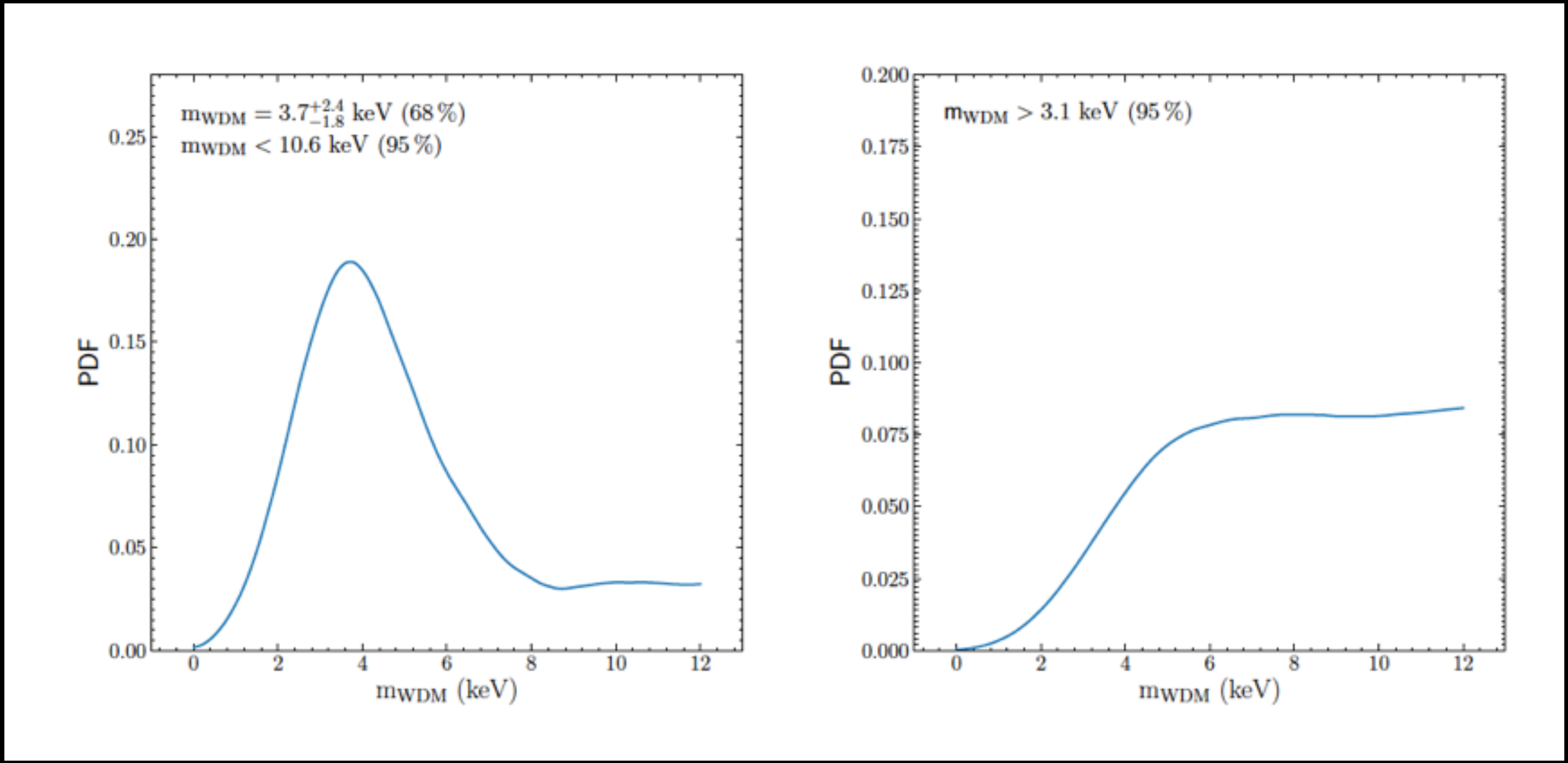
E.g. Erkal+ 2015, Bovy+ 2016



Banik, Bertone, Bozorgnia, Bovy (BBBB) in preparation

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, Bertone, Bozorgnia, Bovy (BBBB) in preparation

Booming field! Other recent LCDM tests 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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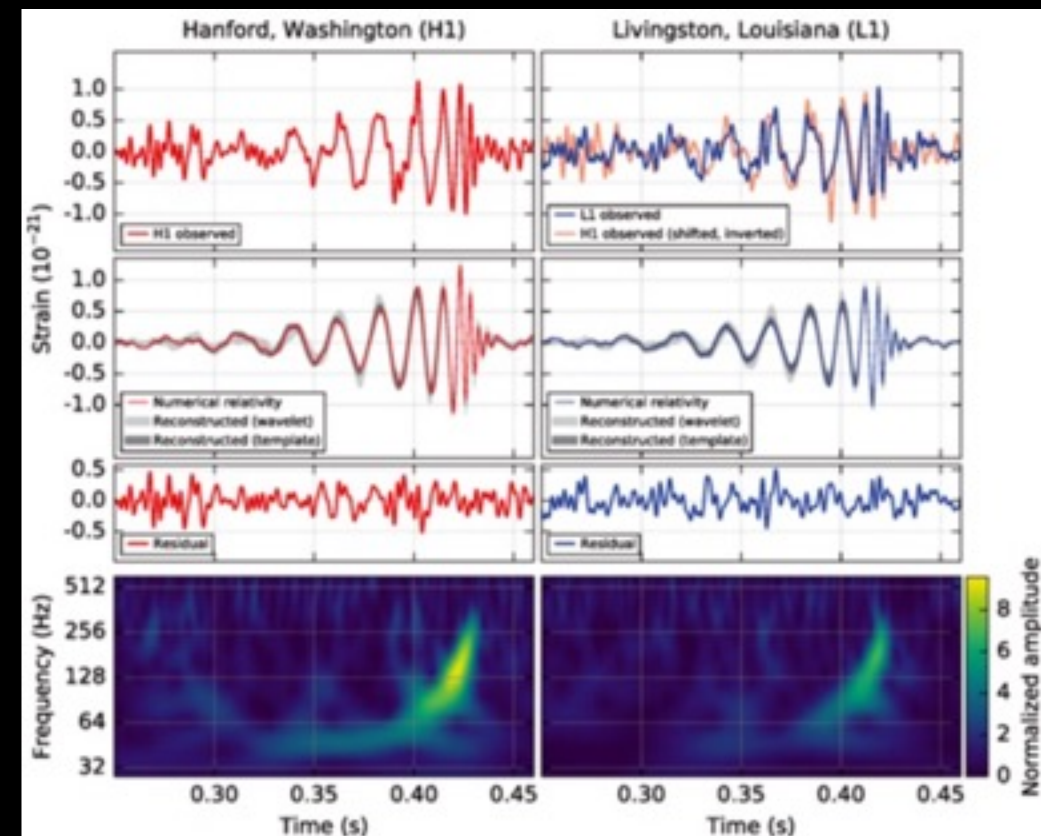
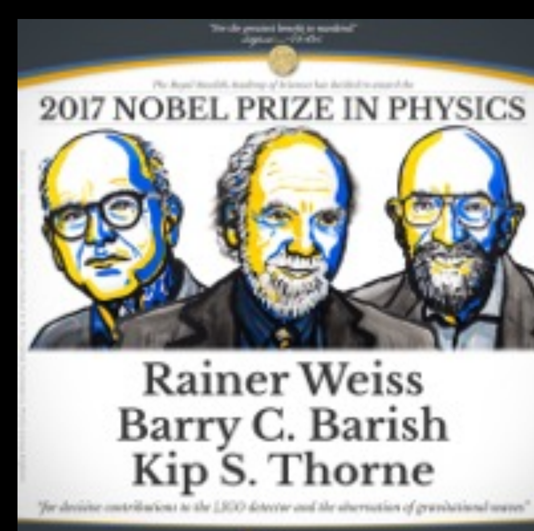
Gravitational Waves

“The discovery that shook the world”

LIGO collaboration, PRL 116, 061102

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





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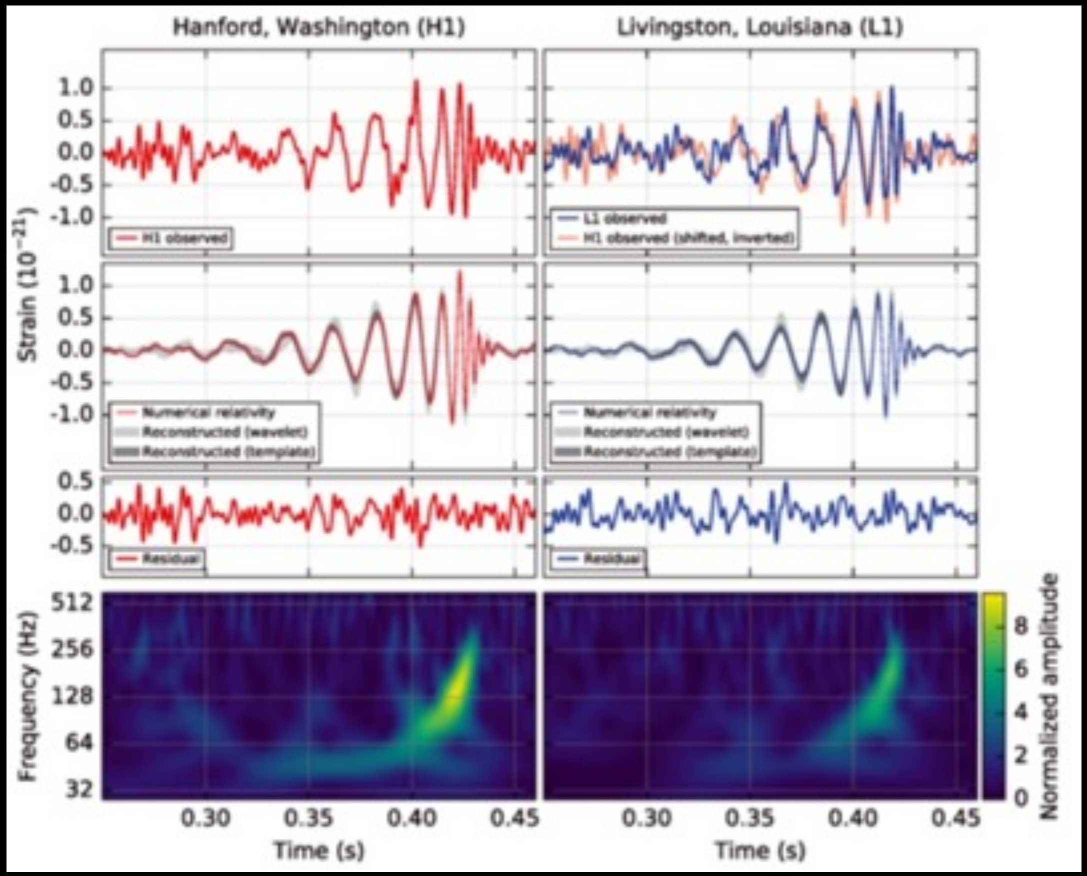
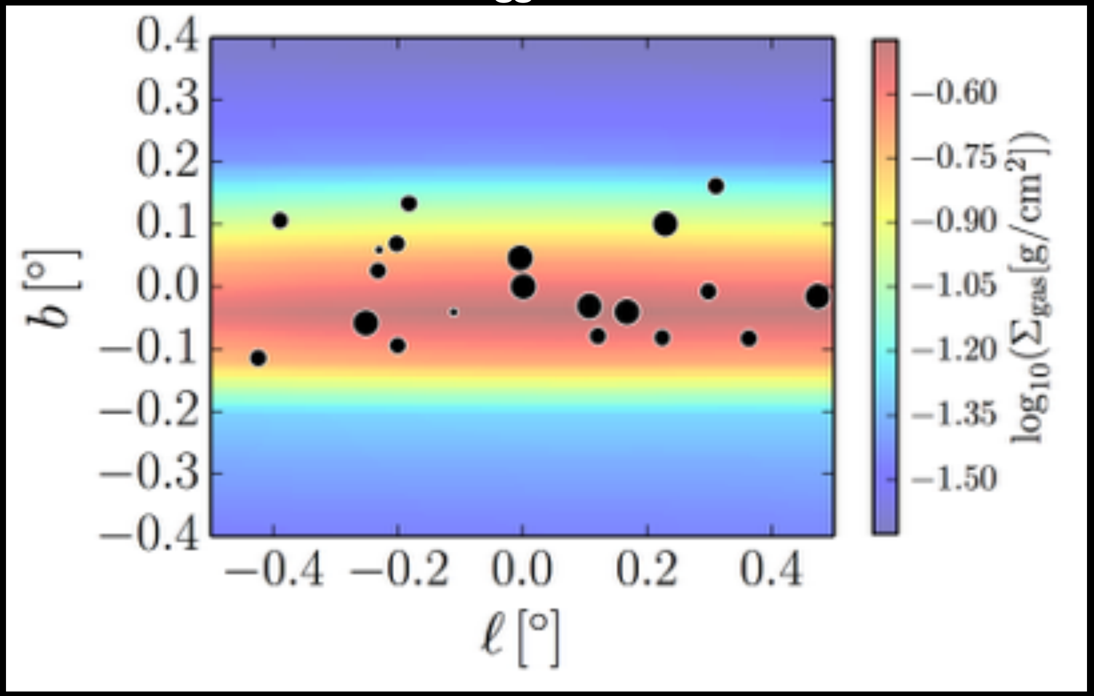


IIIa. Could such BHs be 'the' DM?

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

IIIa. Primordial Black Holes

Gaggero, GB et al. PRL 1612.00457

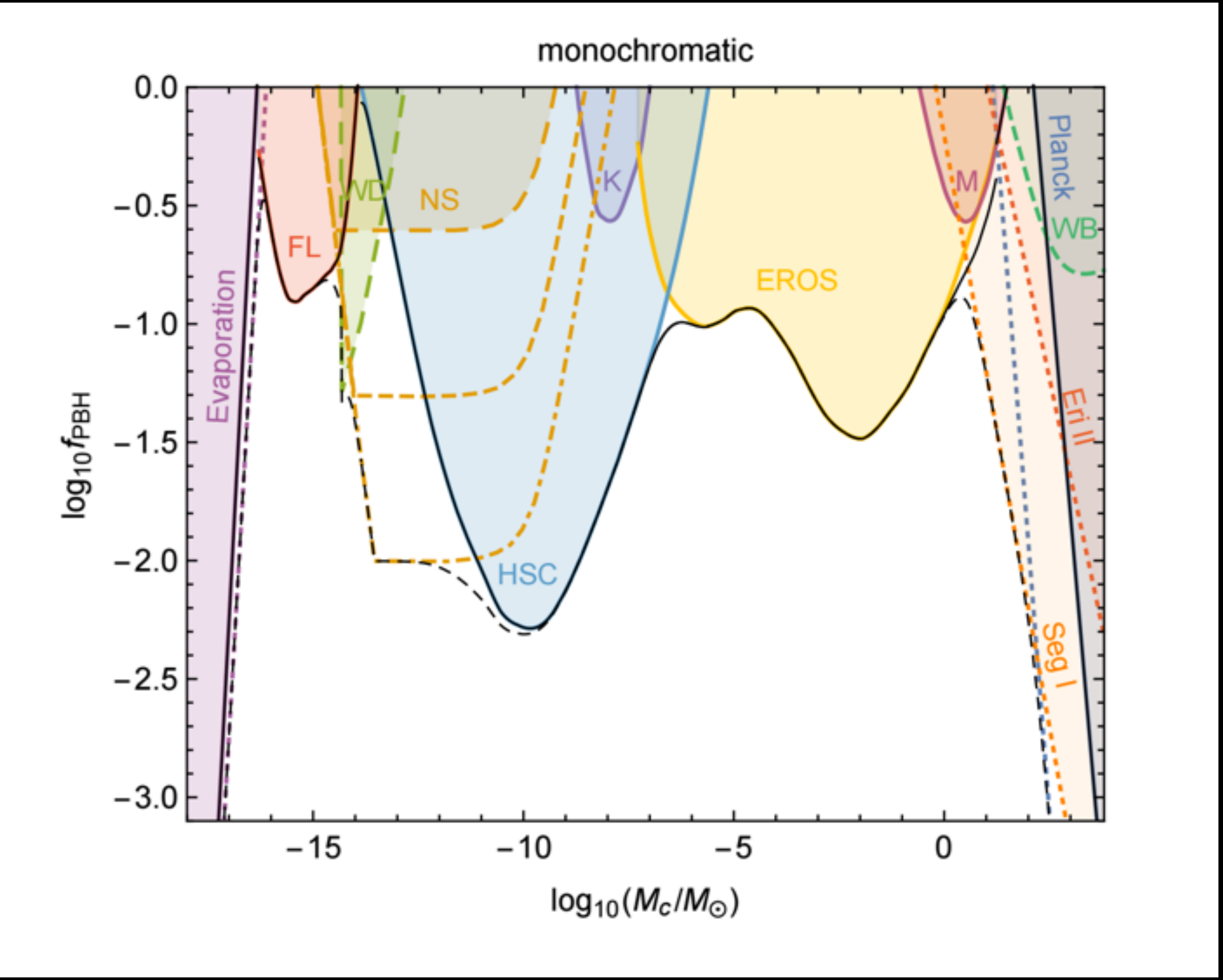


- If PBHs are out there (10^{10} objects in the Galactic bulge if PBHs = DM) they would accrete gas from the dense central molecular zone at the GC

- 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.

PBHs: overview of existing constraints



Carr et al. 1705.05567

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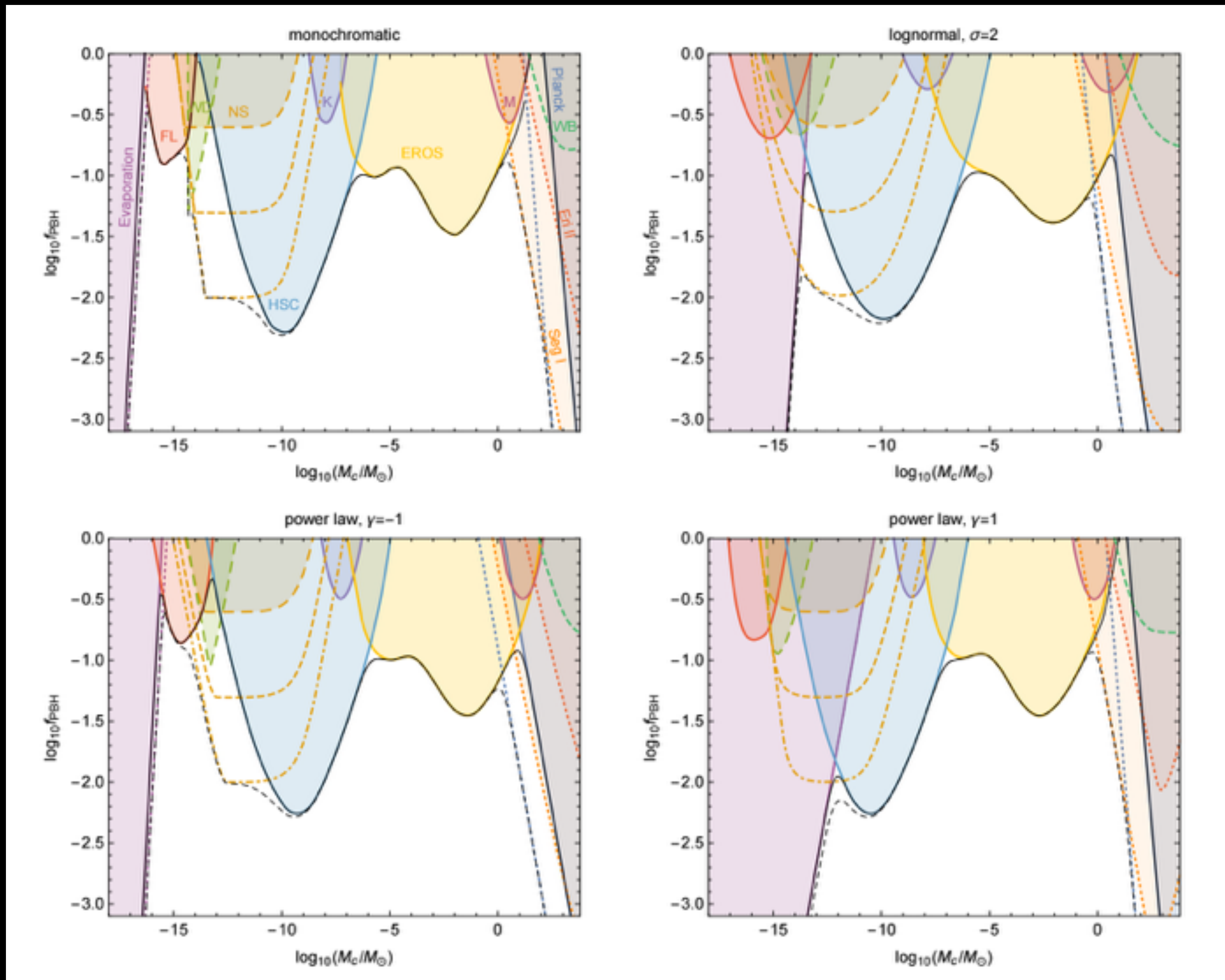
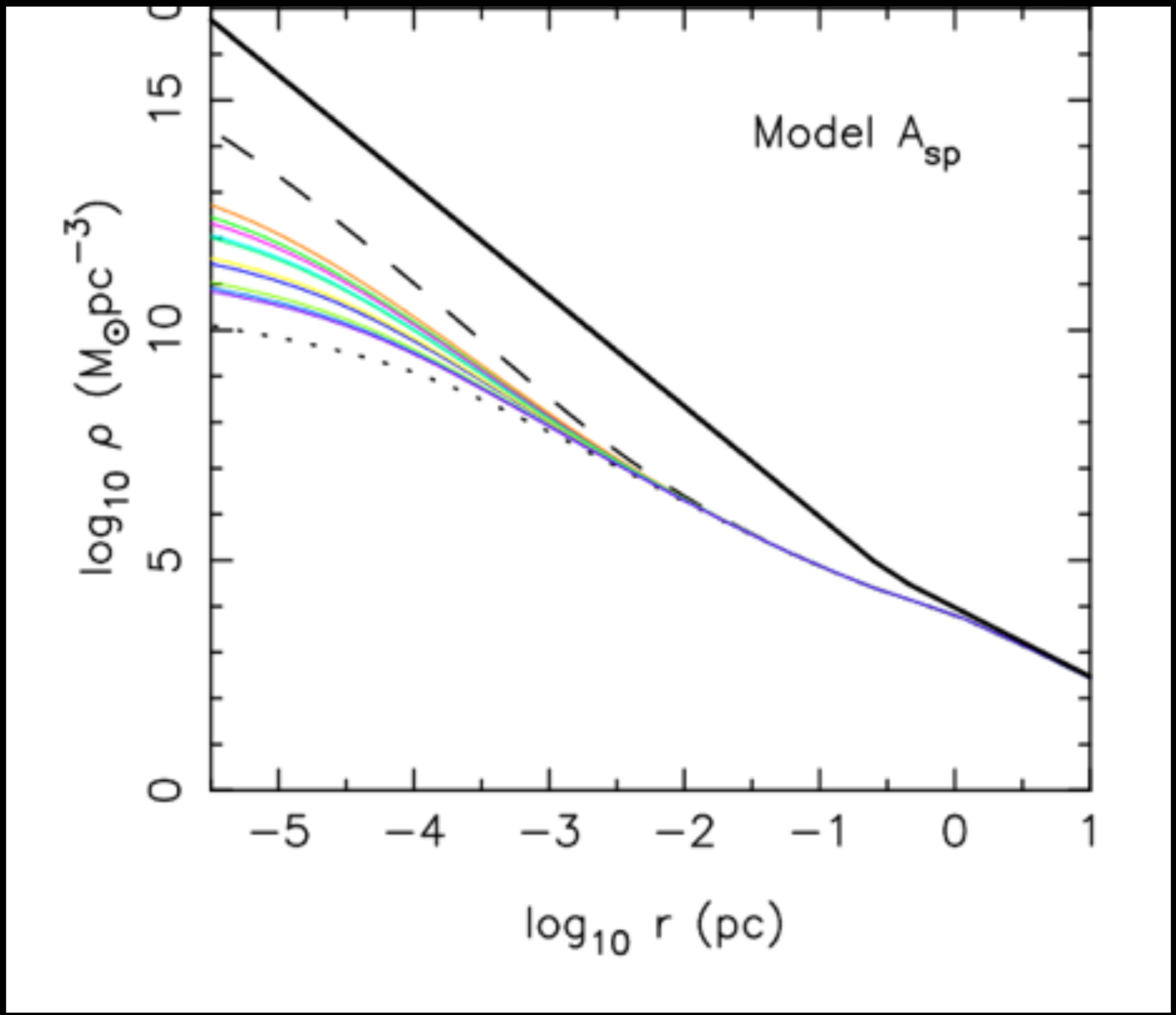


Carr et al. 1705.05567

Dark Matter around BHs

GB & Merritt 2005

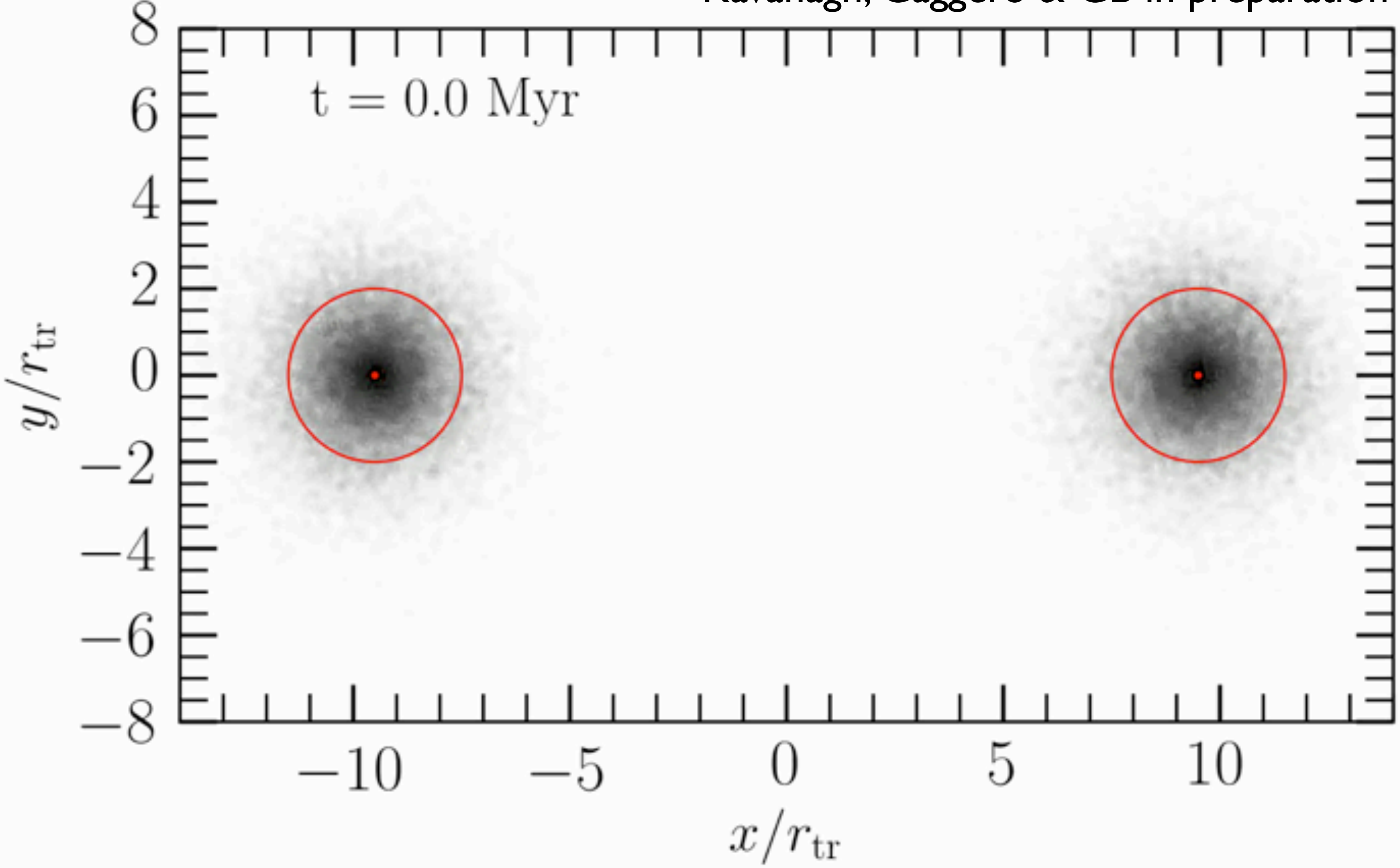


- Formation of an adiabatic 'spike' at the GC (Gondolo and Silk 2000)
- 'Mini-spikes' around IMBHs (GB, Zentner, Silk 2015)
- What about PBHs?

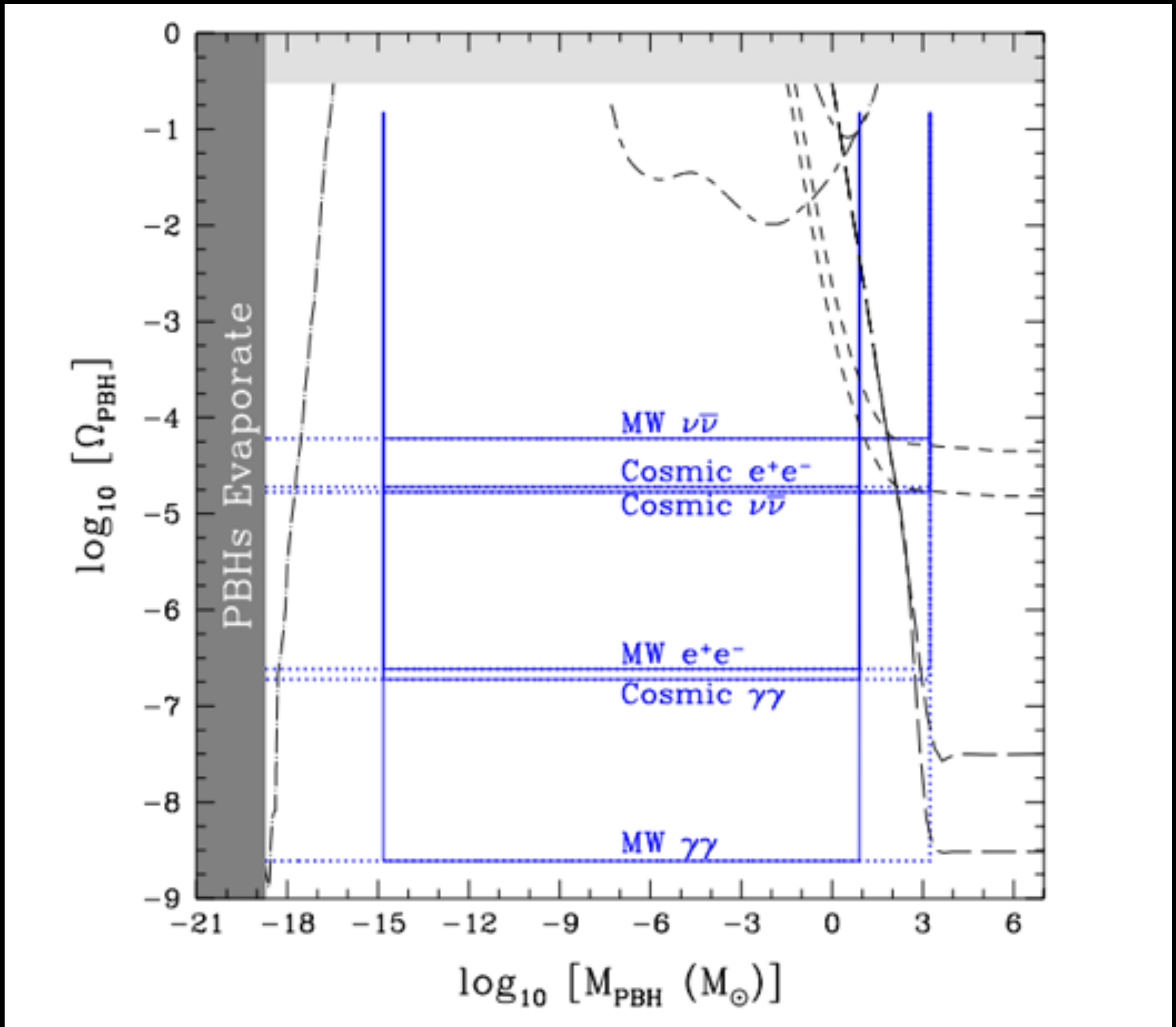
Many open questions: astrophysical uncertainties, dependence on DM properties (self-interactions, annihilations)

Dark Matter around BHs

Kavanagh, Gaggero & GB in preparation



PBH impact on WIMP searches



Identifying (even a subdominant population of) PBHs may provide interesting clues on the nature of dark matter

PBHs are in particular incompatible with WIMPs, e.g. Beacom and Macki 2010

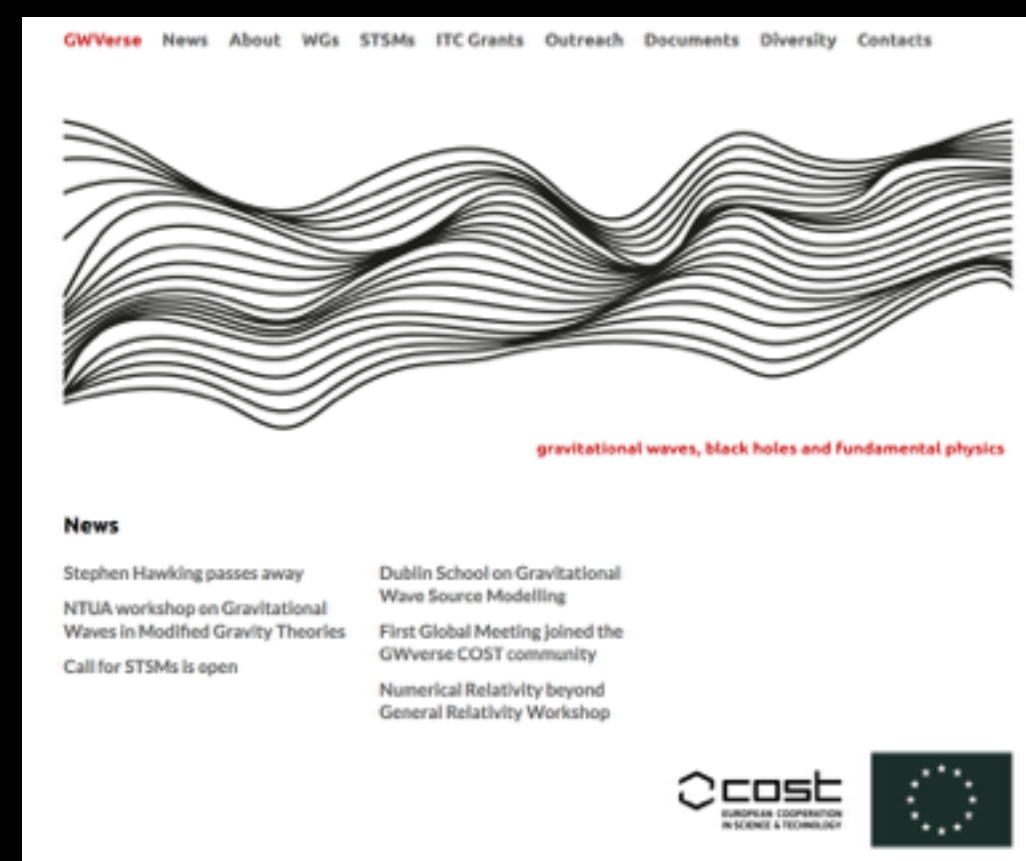
Further GW-DM connections:

- If DM = ultralight bosons (e.g. QCD axion/axion-like particles) with masses 10^{-21} — 10^{-11} eV, possible to extract energy from spinning BHs through "Super-radiance" (Brito+ 1501.06570, Pani+ 1209.0465)

- EM counterparts to GW events constrain GW propagation speed to be v~c. This rules entire classed of theories of modified gravity (e.g. Boran+ 1710.06168)

- Many other ideas currently being explored!

- Join the discussion @ GWVerse
  gwverse.tecnico.ulisboa.pt



Conclusions

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

- I have argued that in order to make progress we need 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