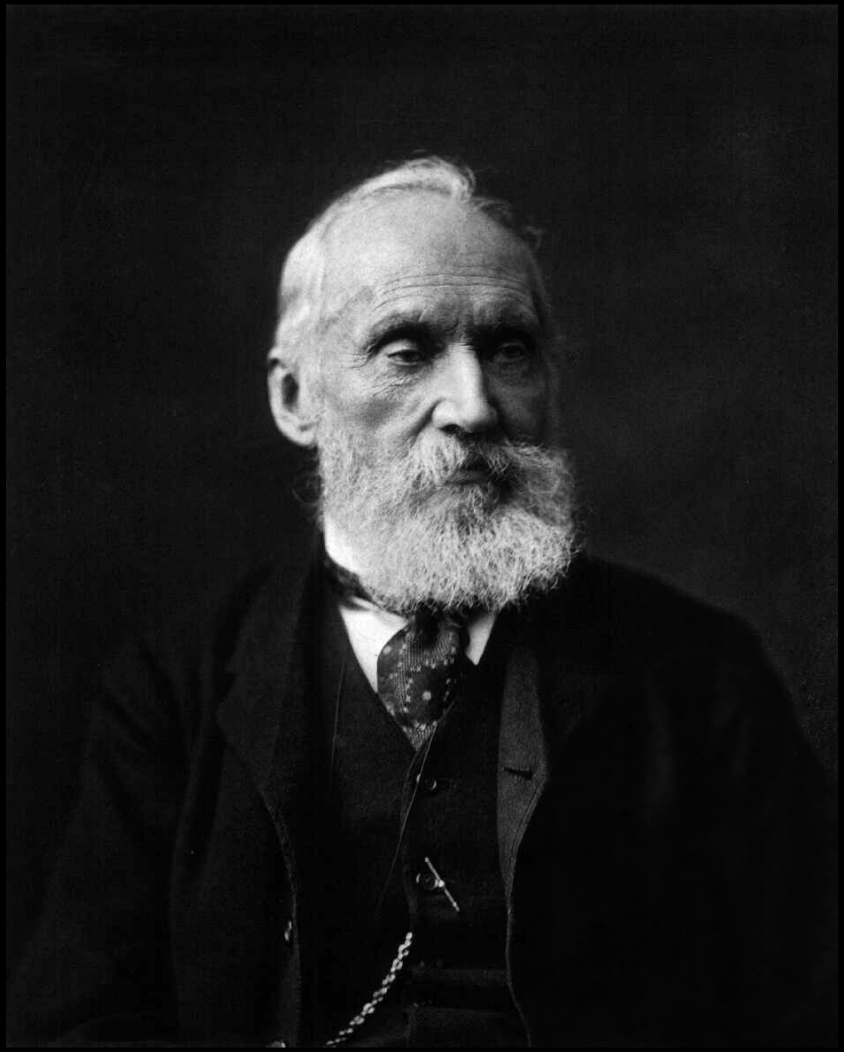
A new era in the quest for **Dark Matter**

Gianfranco Bertone
GRAPPA center of excellence, U. of Amsterdam

Lorentz Center Workshop
"Light Anti-Nuclei as a Probe for New Physics"
Leiden, 14 Oct 2019

GRAPPA
GRavitation AstroParticle Physics Amsterdam

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."*

"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*

The first Nobel prize for dark matter

PRESS RELEASE

8 October 2019

The Nobel Prize in Physics 2019

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2019

"for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos"

with one half to

James Peebles
Princeton University, USA

"for theoretical discoveries in physical cosmology"

and the other half jointly to

Michel Mayor
University of Geneva, Switzerland

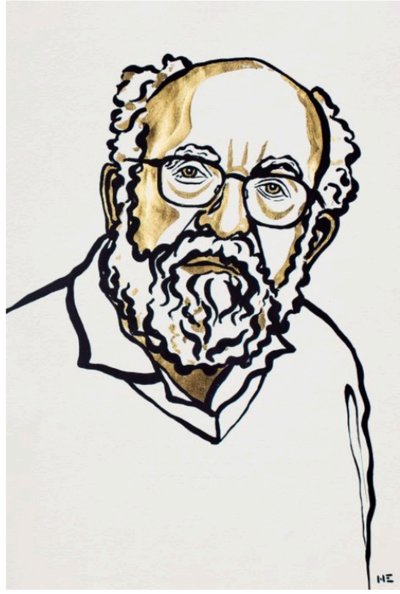
Didier Queloz
University of Geneva, Switzerland
University of Cambridge, UK

"for the discovery of an exoplanet orbiting a solar-type star"

Ill. Niklas Elmehed. © Nobel Media.

James Peebles

Prize share: 1/2



Ill. Niklas Elmehed. © Nobel Media.

Michel Mayor

Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media.

Didier Queloz

Prize share: 1/4

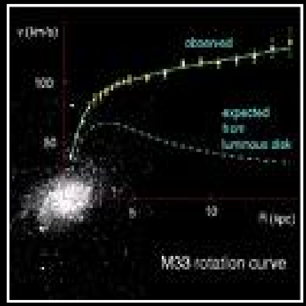
James Peebles' insights into physical cosmology have enriched the entire field of research and laid a foundation for the transformation of cosmology over the last fifty years, from speculation to science. His theoretical framework, developed since the mid-1960s, is the basis of our contemporary ideas about the universe.

The Big Bang model describes the universe from its very first moments, almost 14 billion years ago, when it was extremely hot and dense. Since then, the universe has been expanding, becoming larger and colder. Barely 400,000 years after the Big Bang, the universe became transparent and light rays were able to travel through space. Even today, this ancient radiation is all around us and, coded into it, many of the universe's secrets are hiding. Using his theoretical tools and calculations, James Peebles was able to interpret these traces from the infancy of the universe and discover new physical processes.

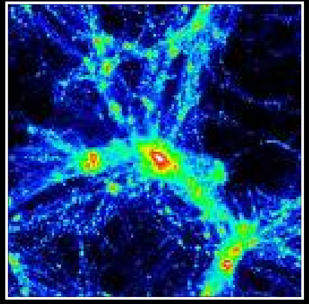
The results showed us a universe in which just five per cent of its content is known, the matter which constitutes stars, planets, trees – and us. The rest, 95 per cent, is unknown dark matter and dark energy. This is a mystery and a challenge to modern physics.

What is the Universe made of?

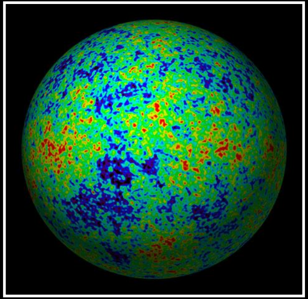
OBSERVATIONS



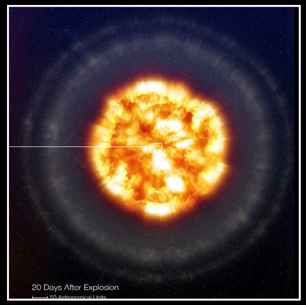
• Rotation Curves



• Clusters of galaxies

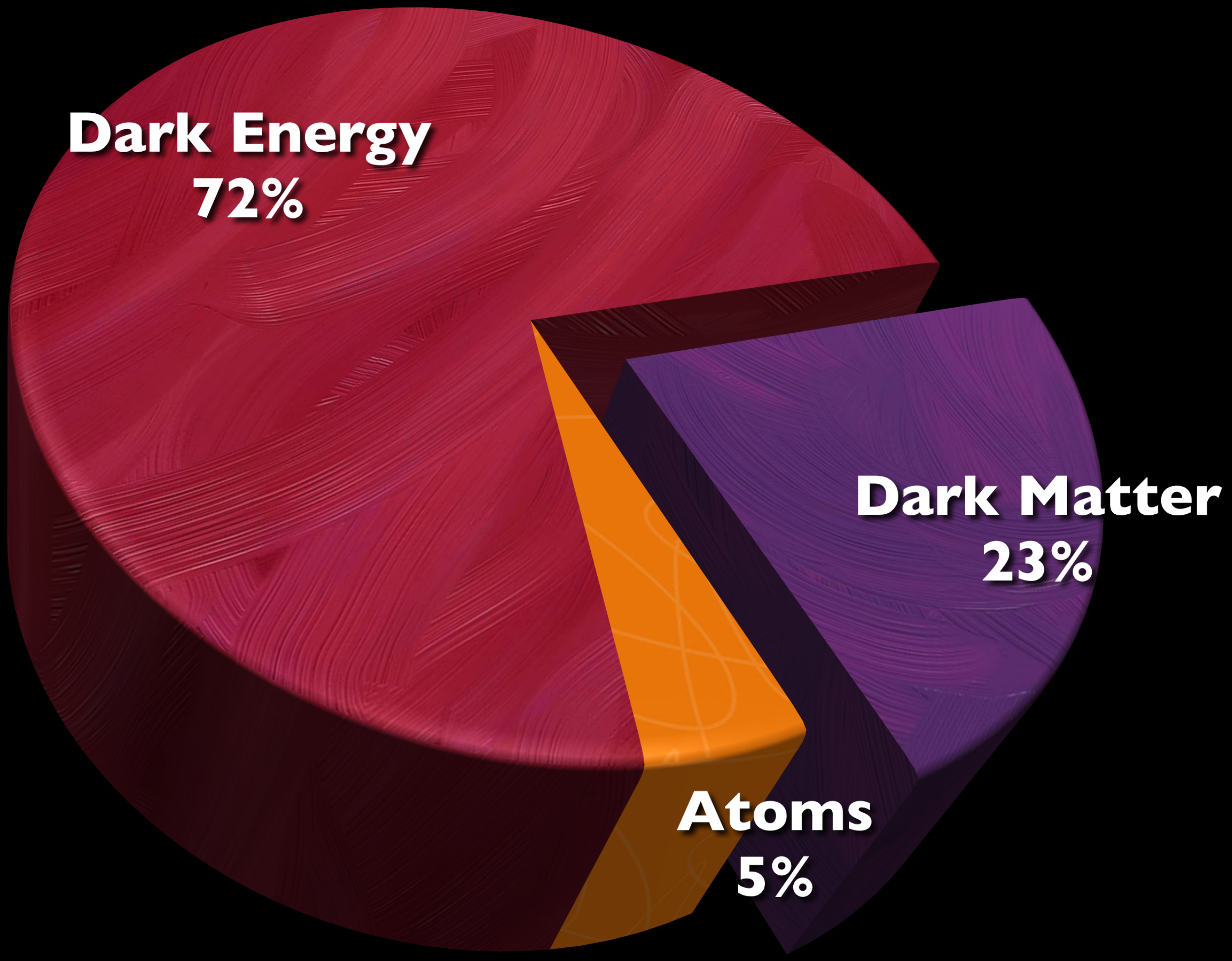


•CMB



•Type Ia Supernovae

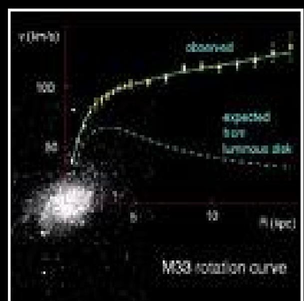
...



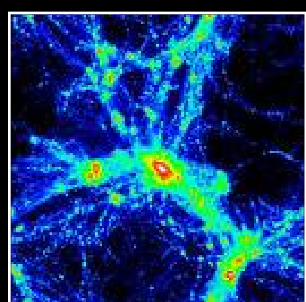
But…

the relative amount of dark matter, dark energy and relativistic particles changed with time

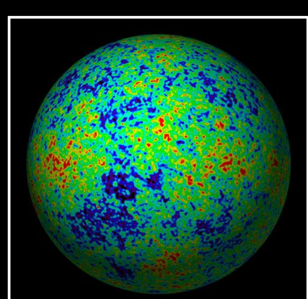
COSMOLOGICAL OBSERVATIONS



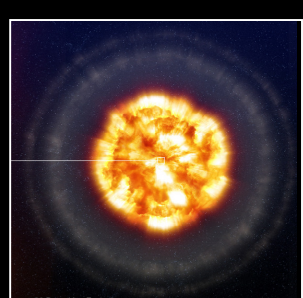
- Rotation Curves



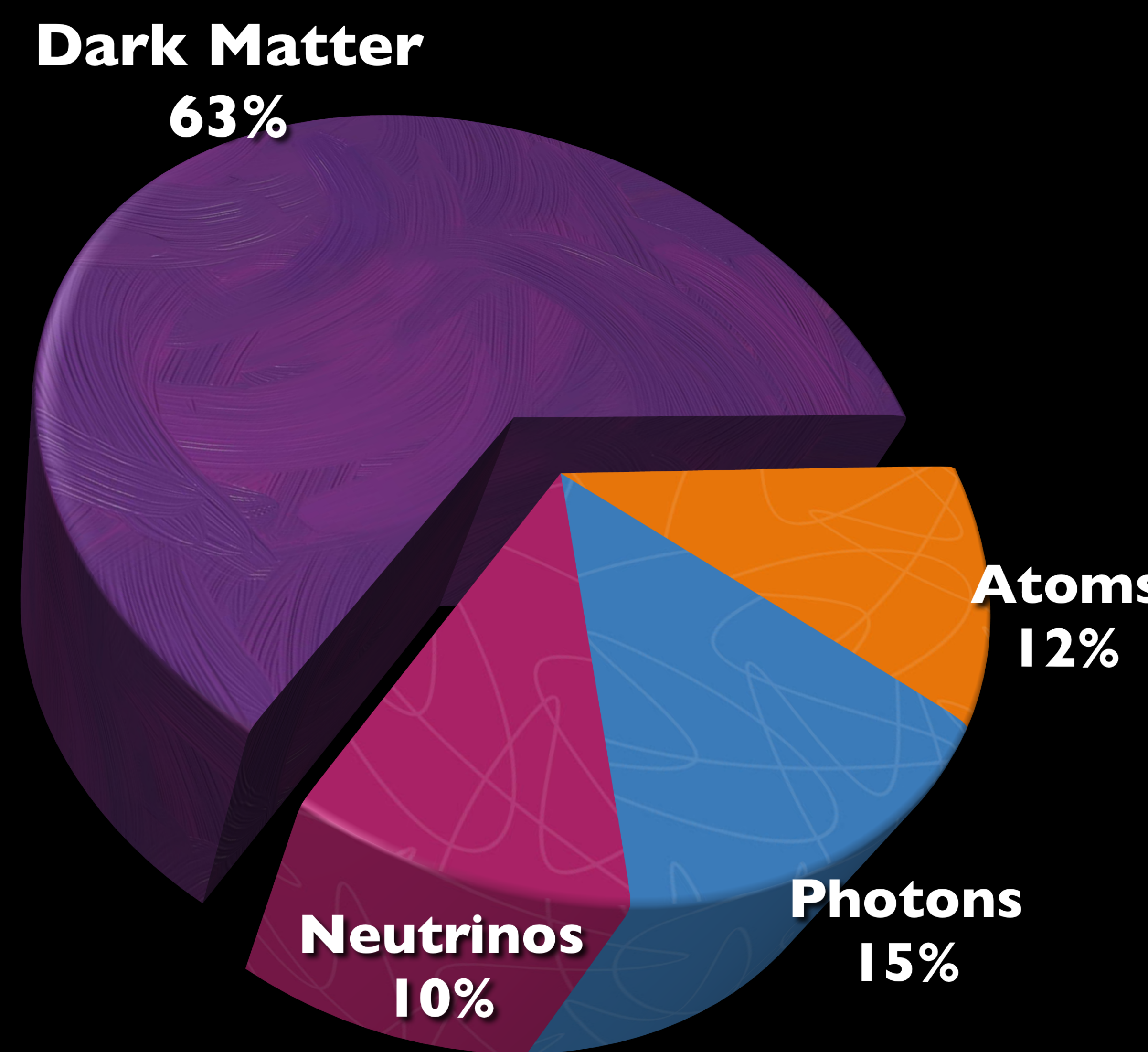
- Clusters of galaxies



- CMB

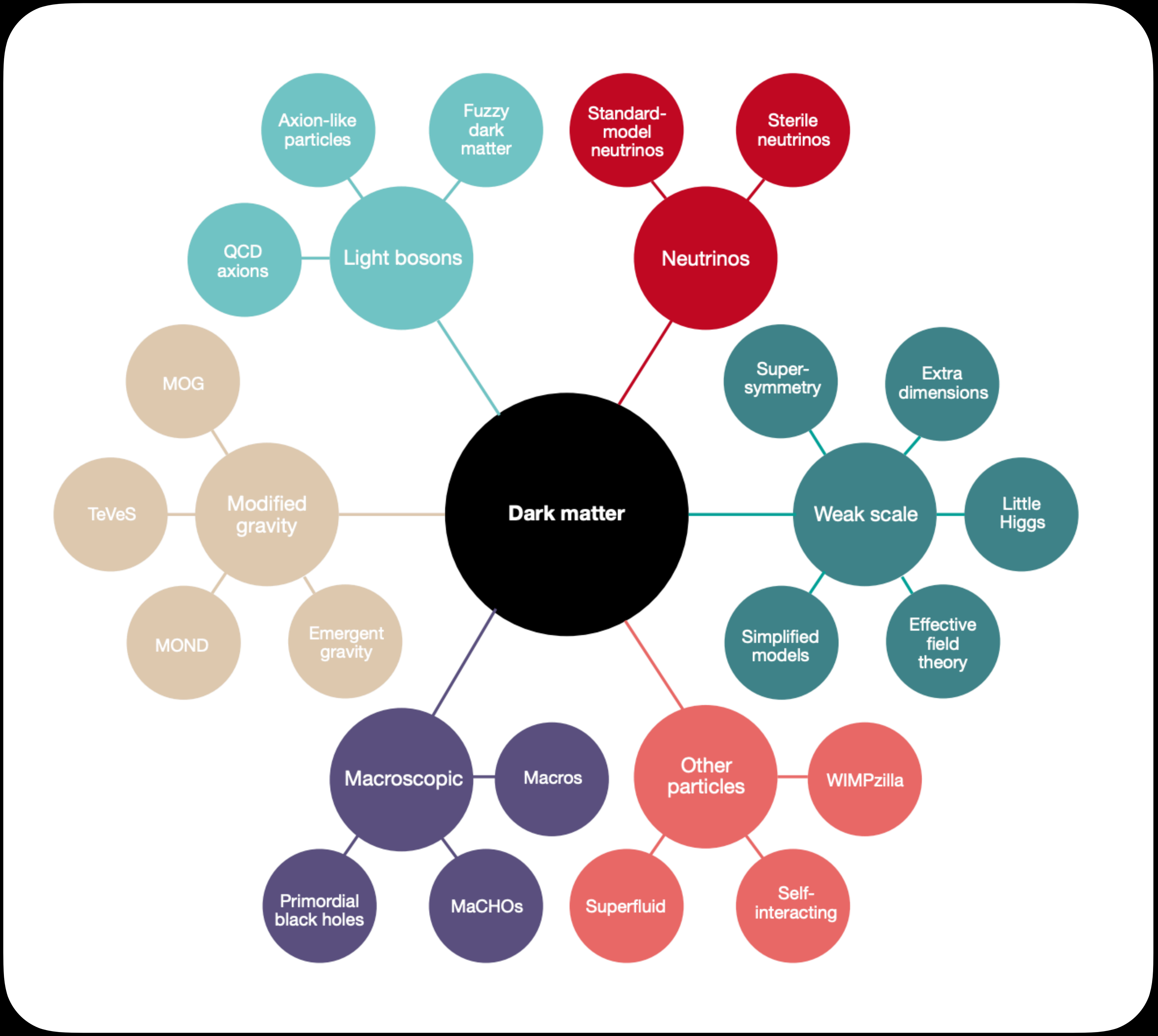


- Type Ia Supernovae



At recombination, when structures started to form, dark matter dominated the universe.

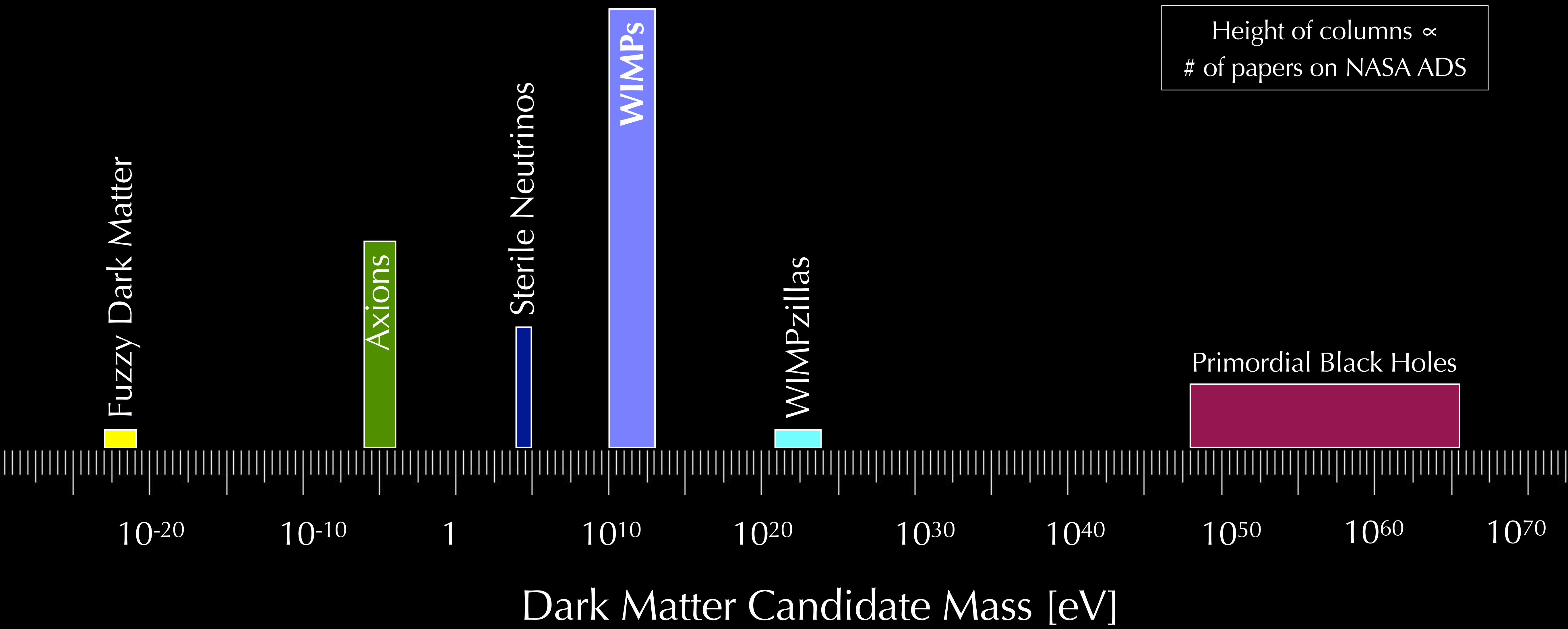
What is dark matter?



GB, Tait, *Nature* (2018) 1810.01668

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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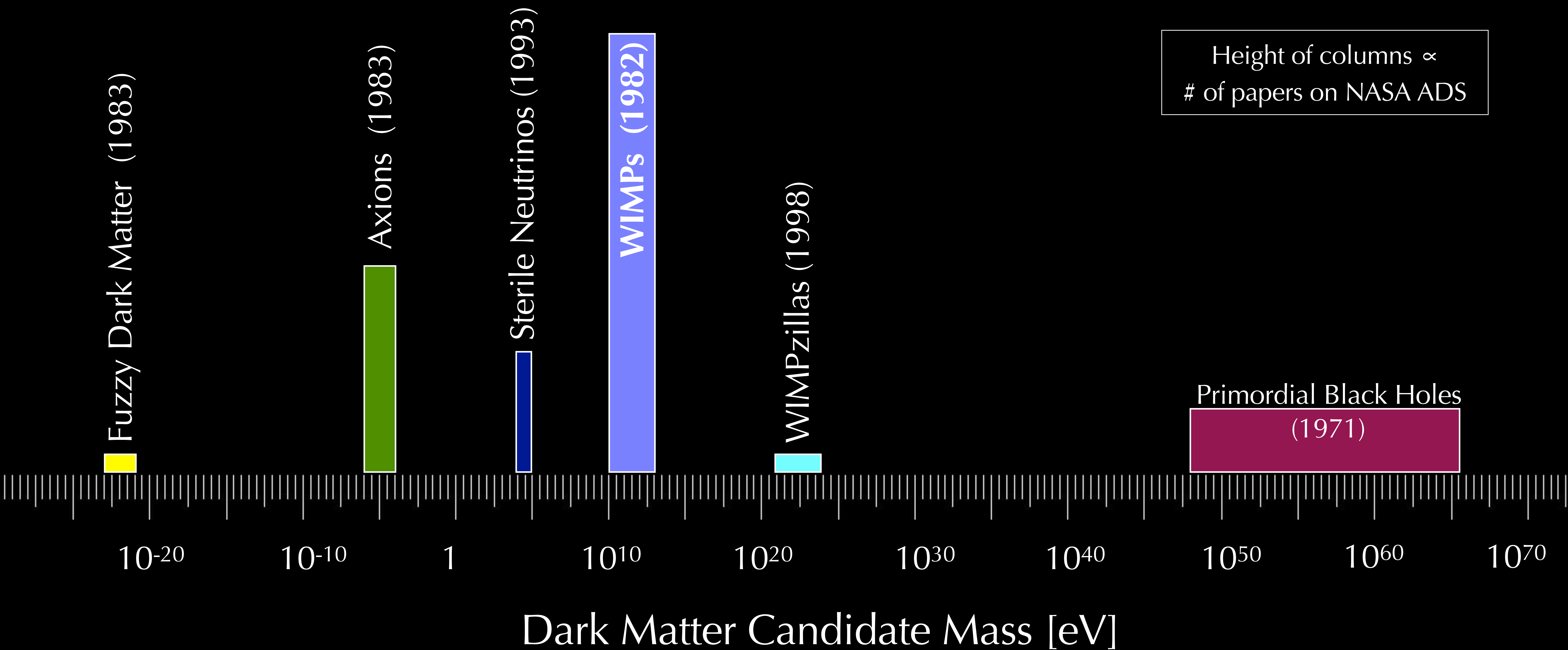
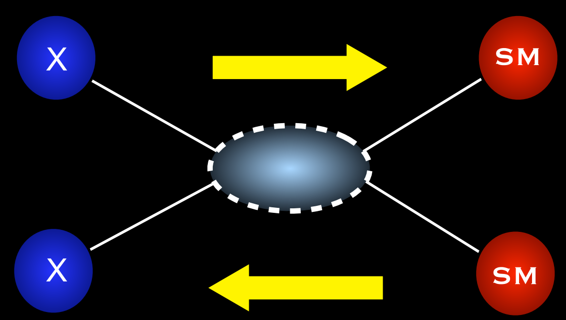


WIMPs

By far the most studied class of dark matter candidates.

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



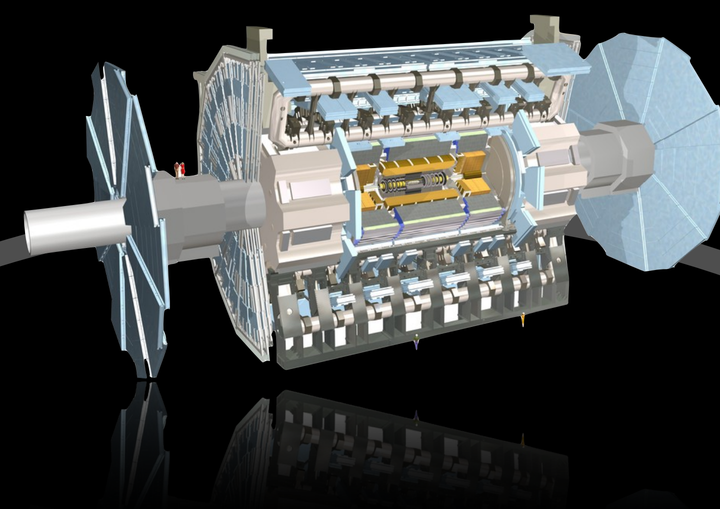
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Weak-scale cross sections can reproduce observed relic density

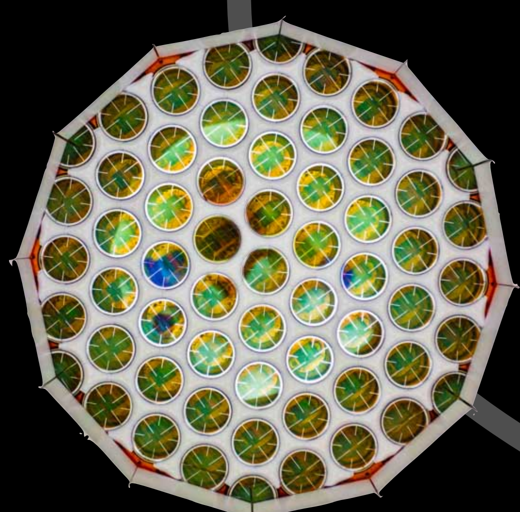
$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

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

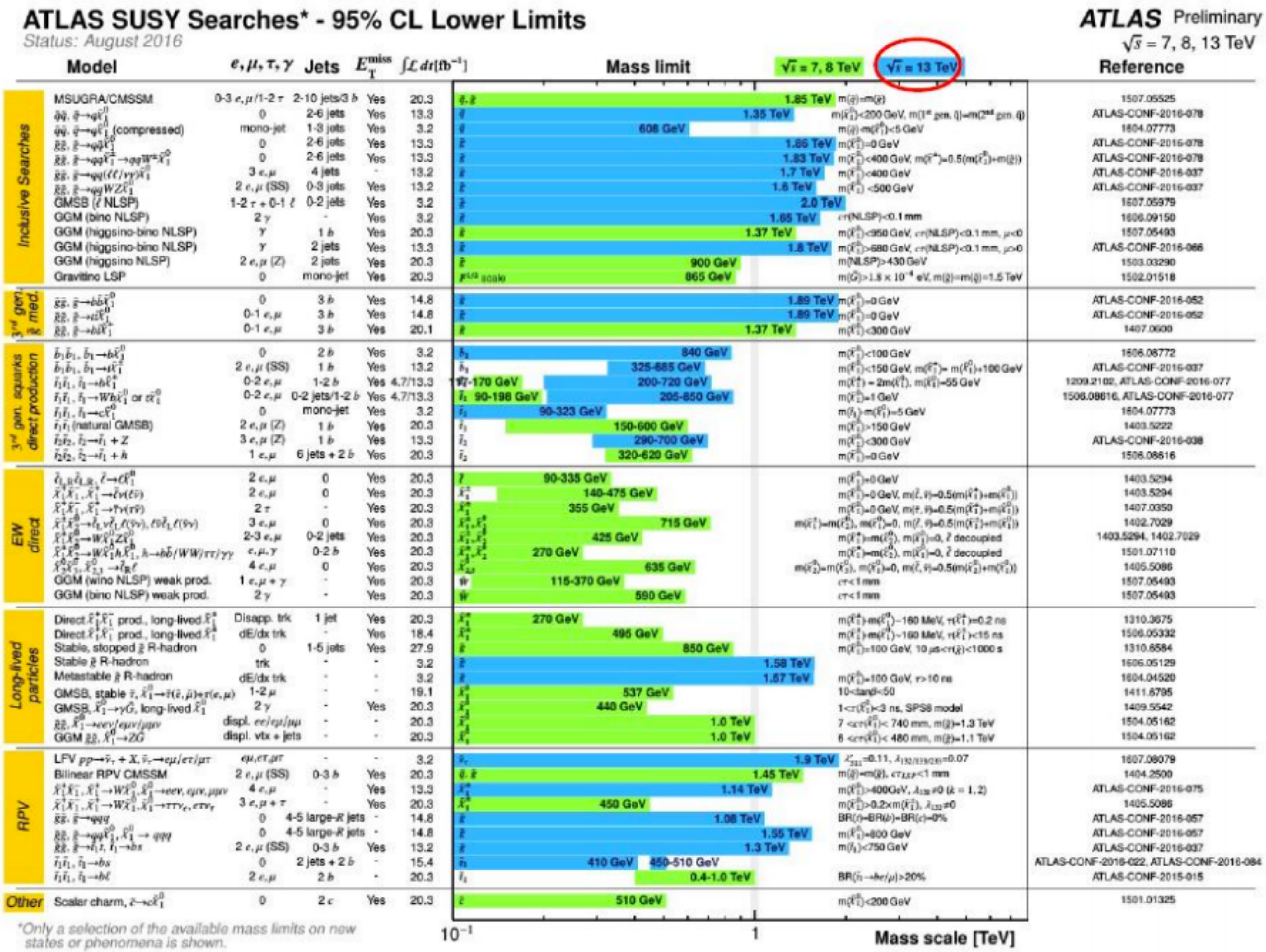
WIMPs searches



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



ATLAS SUSY searches



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 viable (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"

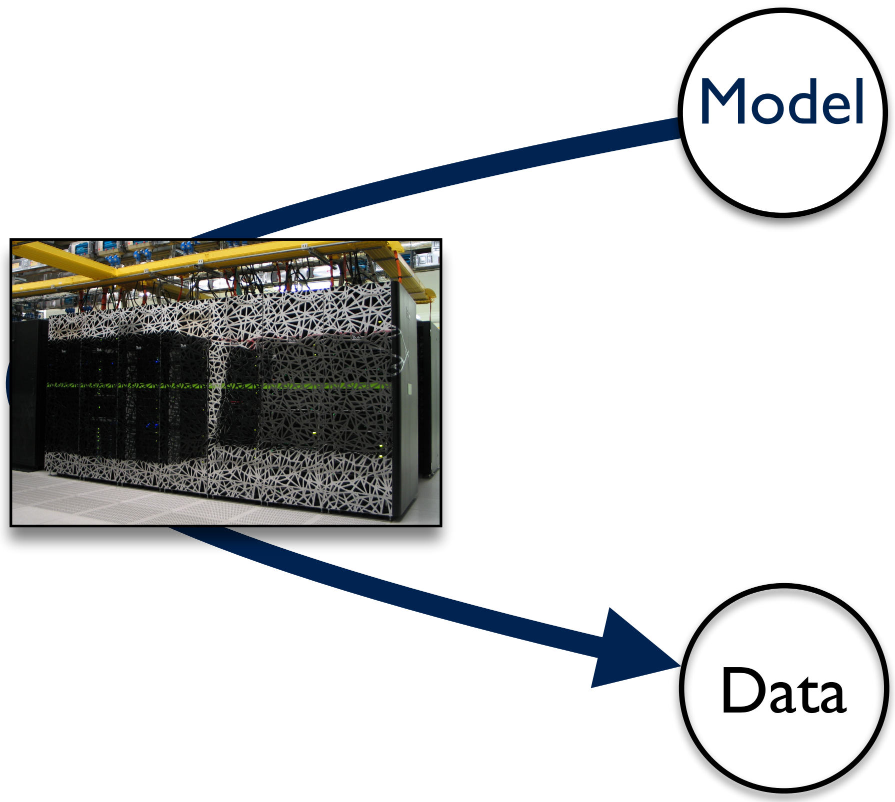
A new era in the search for DM

GB, Tait, *Nature (2018)1810.01668*

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

Improving existing strategies

Speeding up statistical inference with Machine Learning tools



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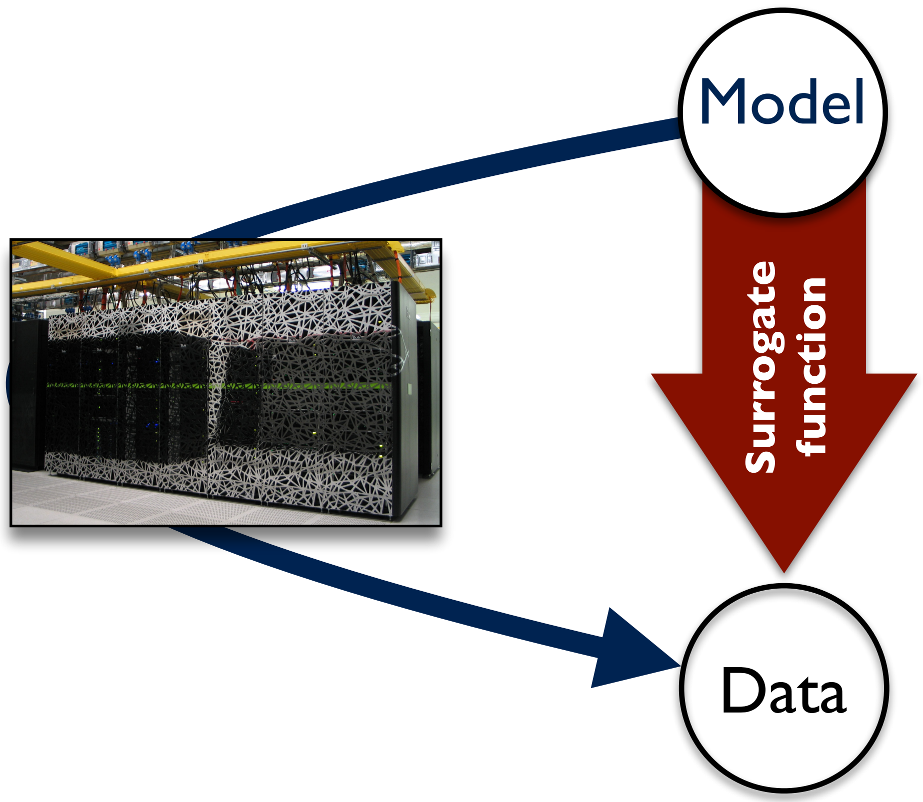
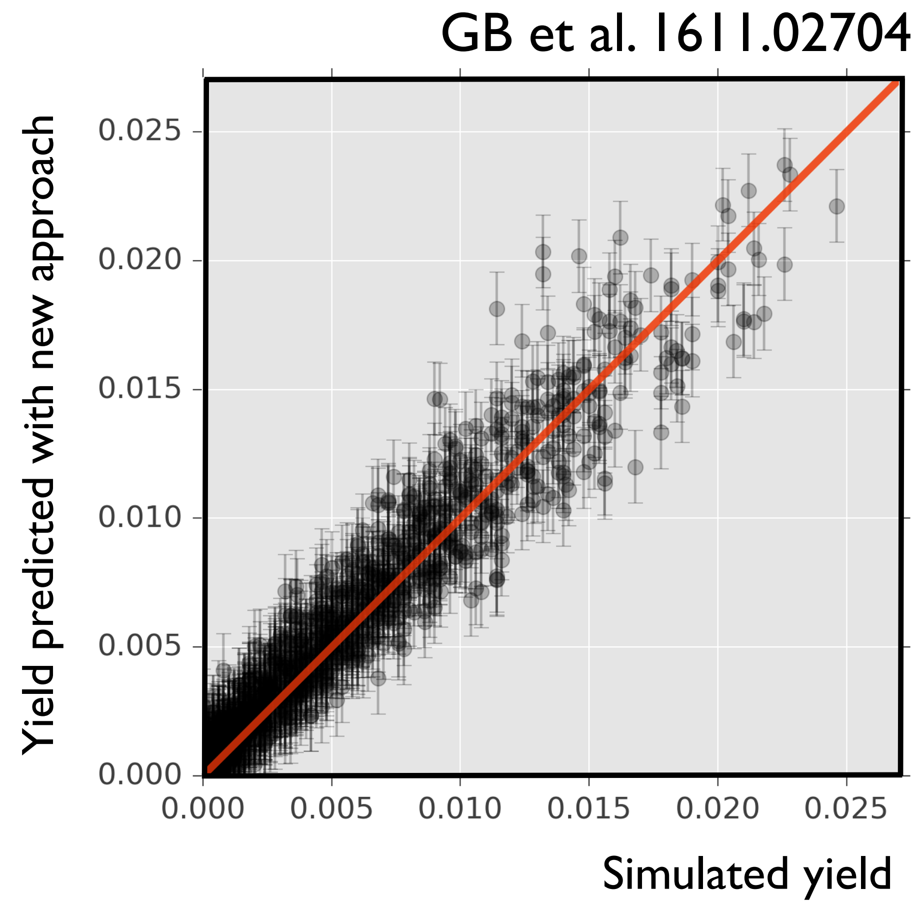




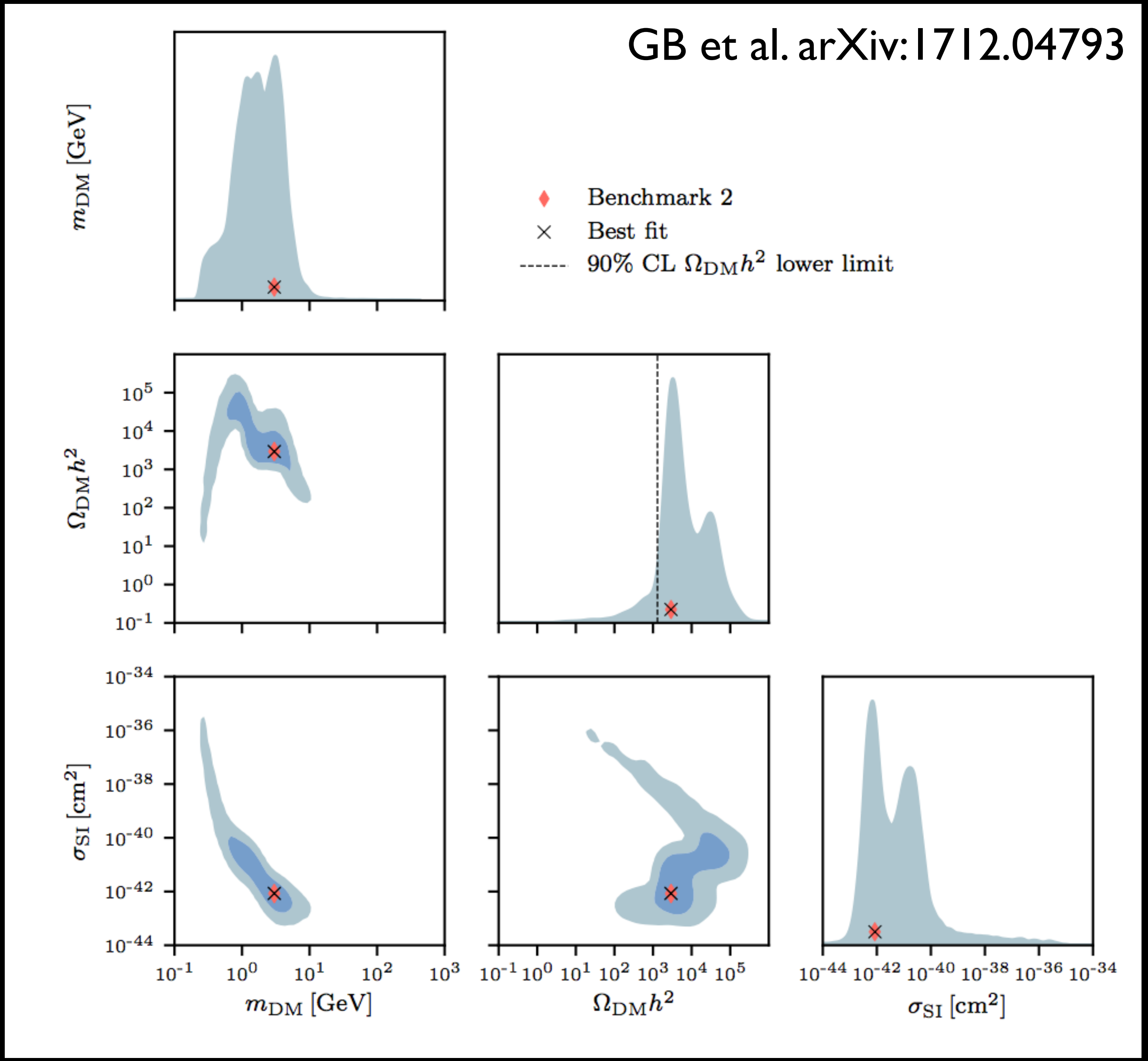
- Exploring parameter spaces of theoretical models computationally expensive
- Machine learning methods (*distributed gaussian processes*, *deep neural networks*) bring computation time from ~CPU *centuries* to ~CPU *weeks*!
- Can be run by a PhD student in 1 day on a desktop computer!

Improving existing strategies

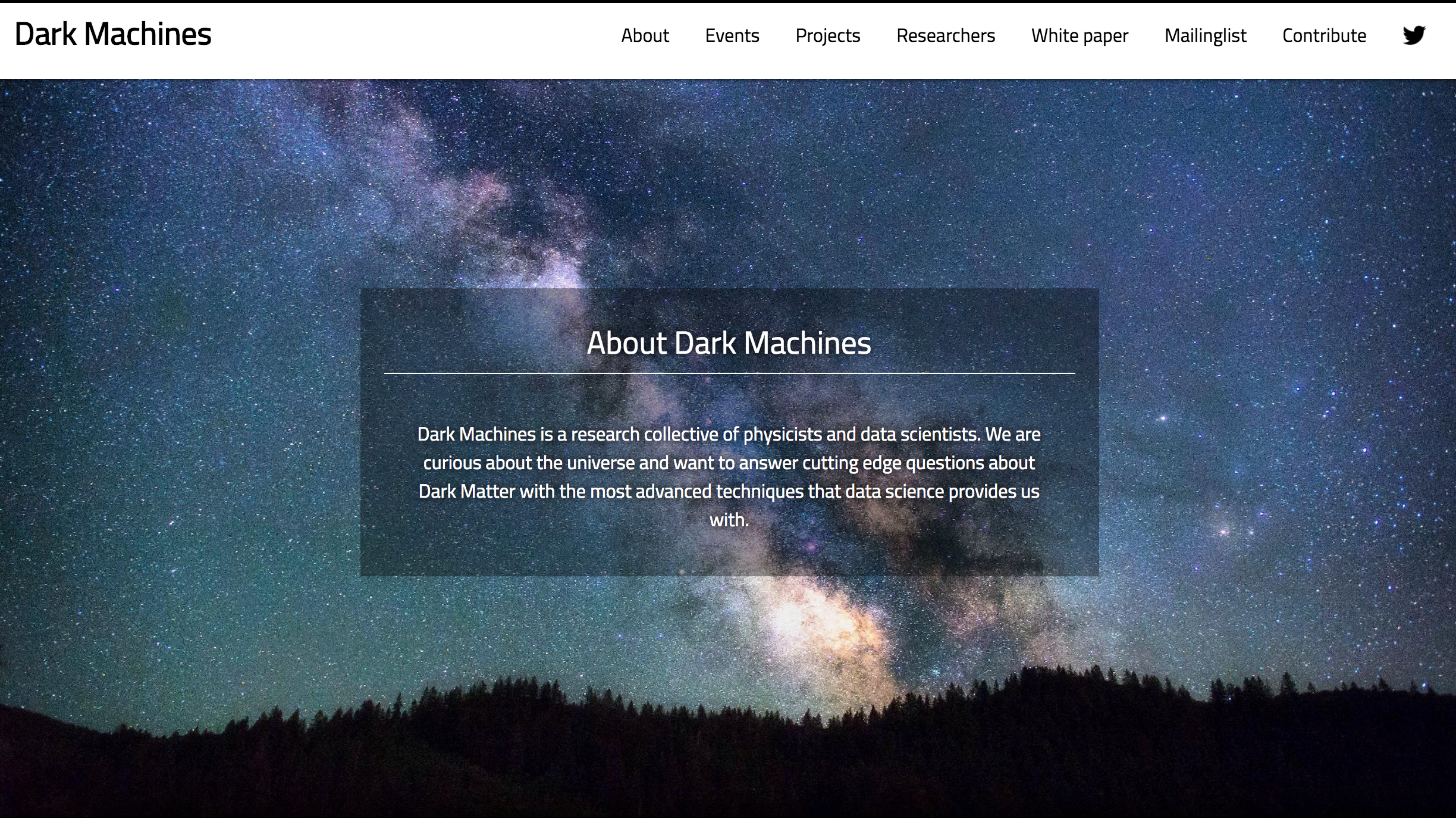
E.g. New Machine Learning tools applied to LHC searches:

i) Fast exploration of phenomenology in high-dimensional parameter spaces

ii) Perform fast inference if new particles discovered, that allows us to recover theory parameters compatible with data



The *Dark Machines* initiative

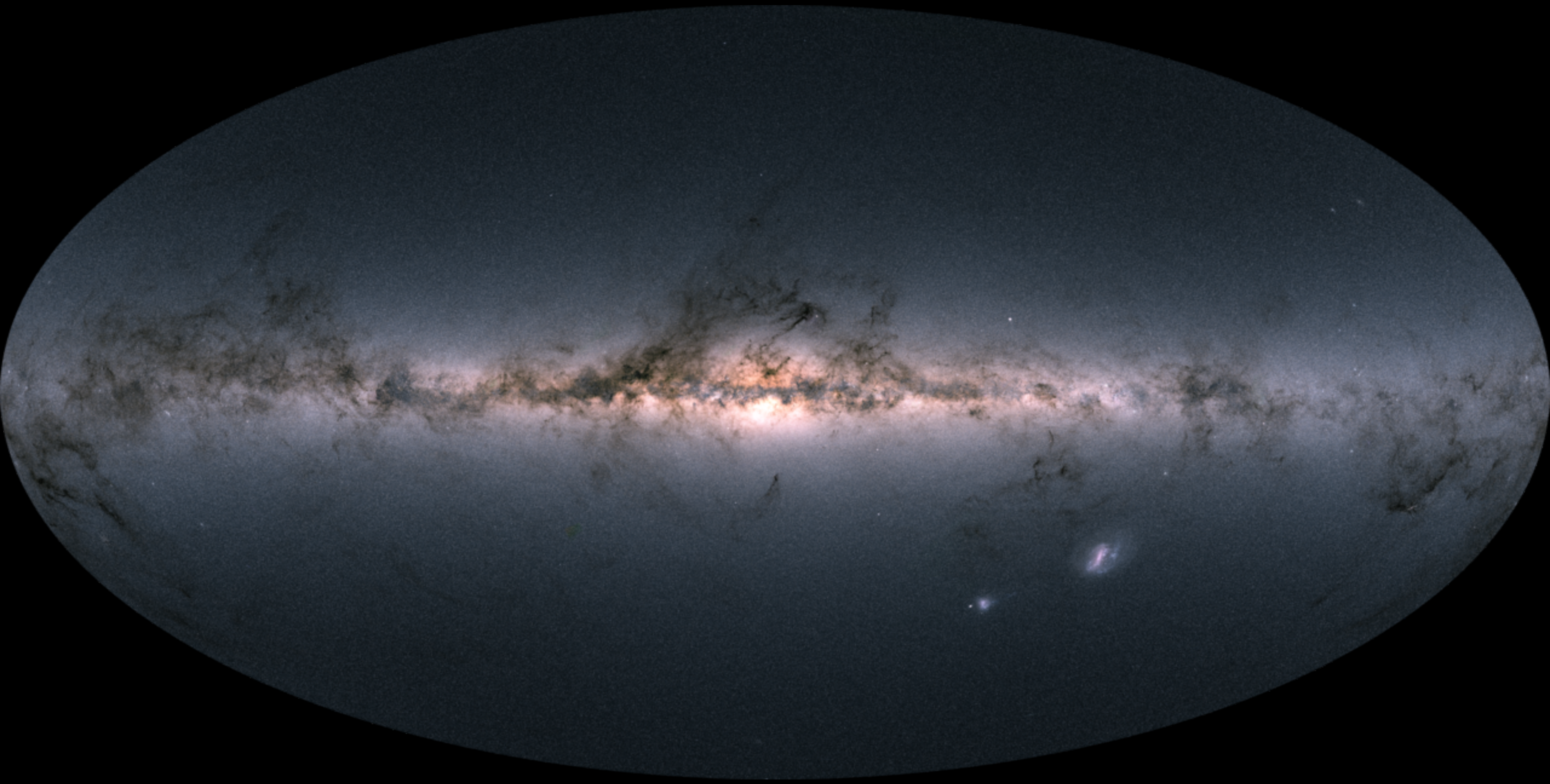


Website: darkmachines.org ; Twitter: dark_machines

The future of dark matter searches

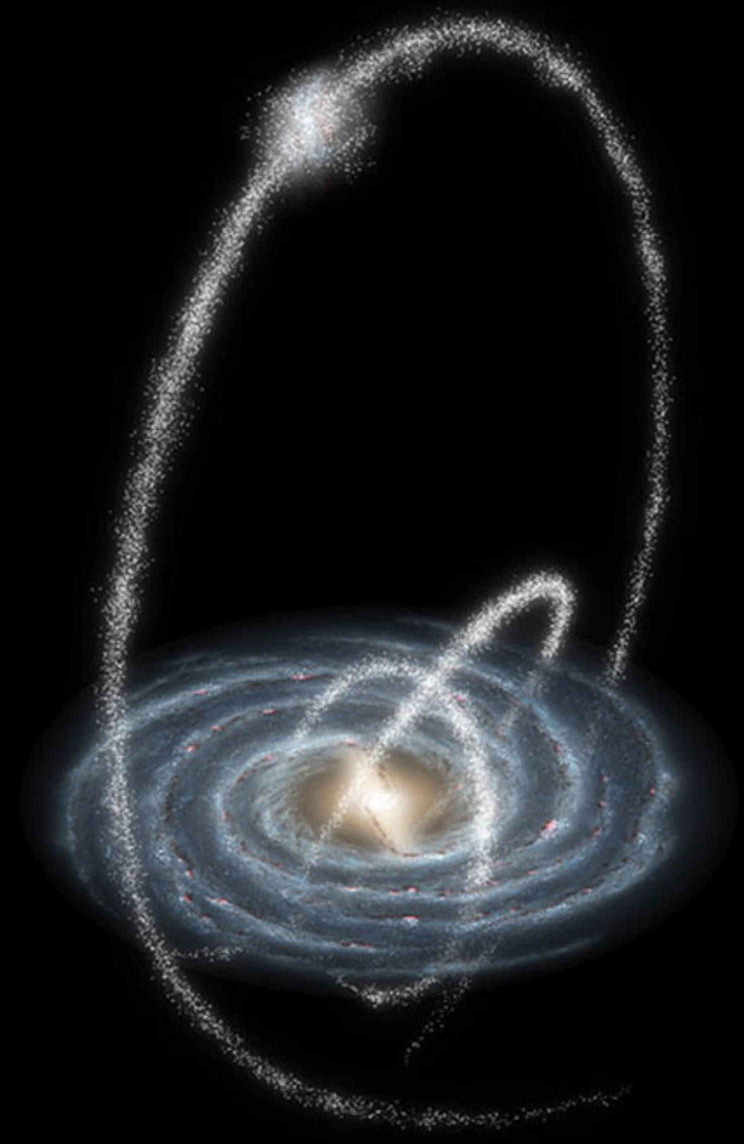
I. Broaden/improve/diversify searches
II. Exploit astro/cosmo observations
III. Exploit Gravitational Waves

GAIA'S SKY

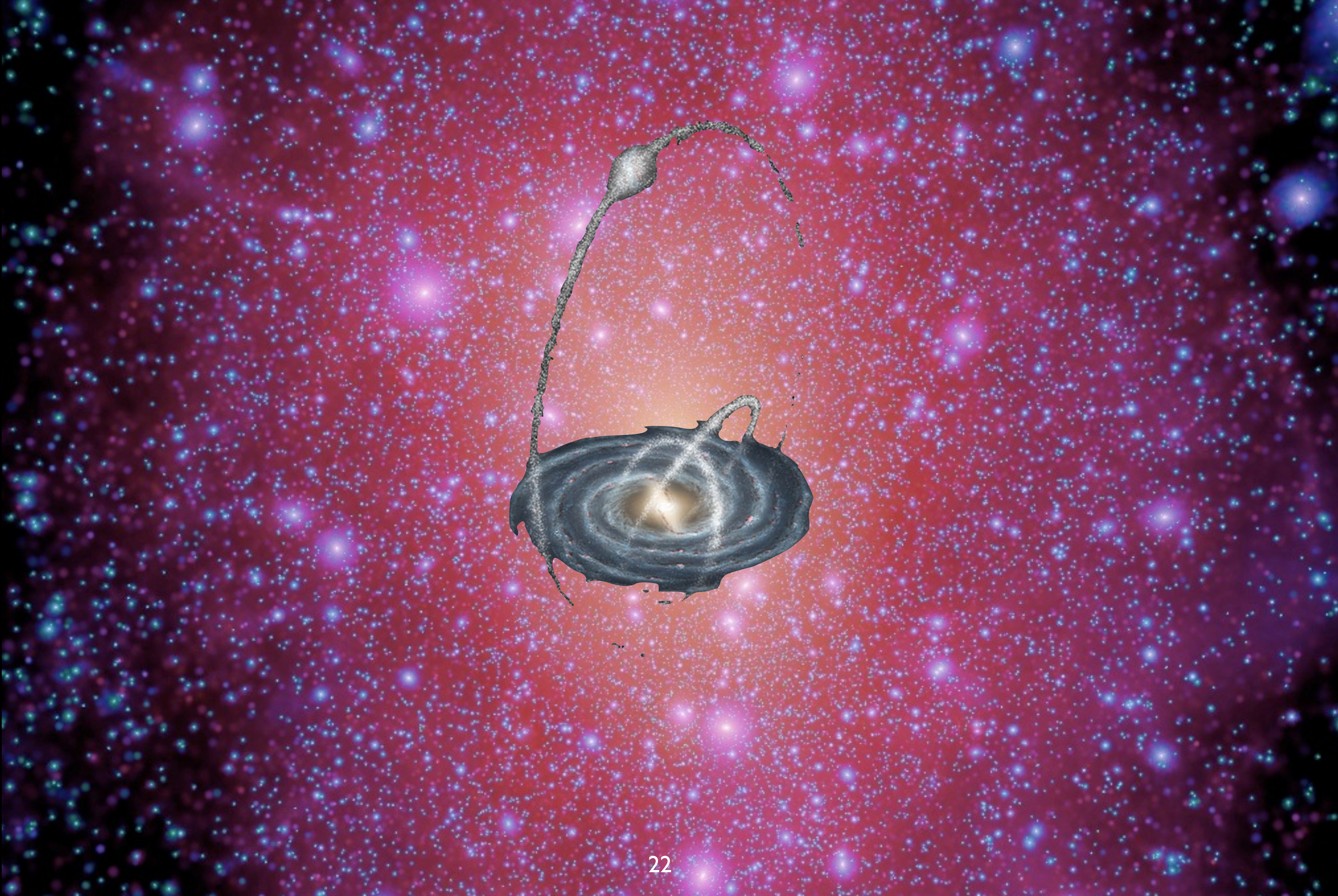


Gaia's all-sky view of our Milky Way Galaxy and neighbouring galaxies, based on brightness and colour of 1.7 billion stars (released April 2018).

Stellar streams



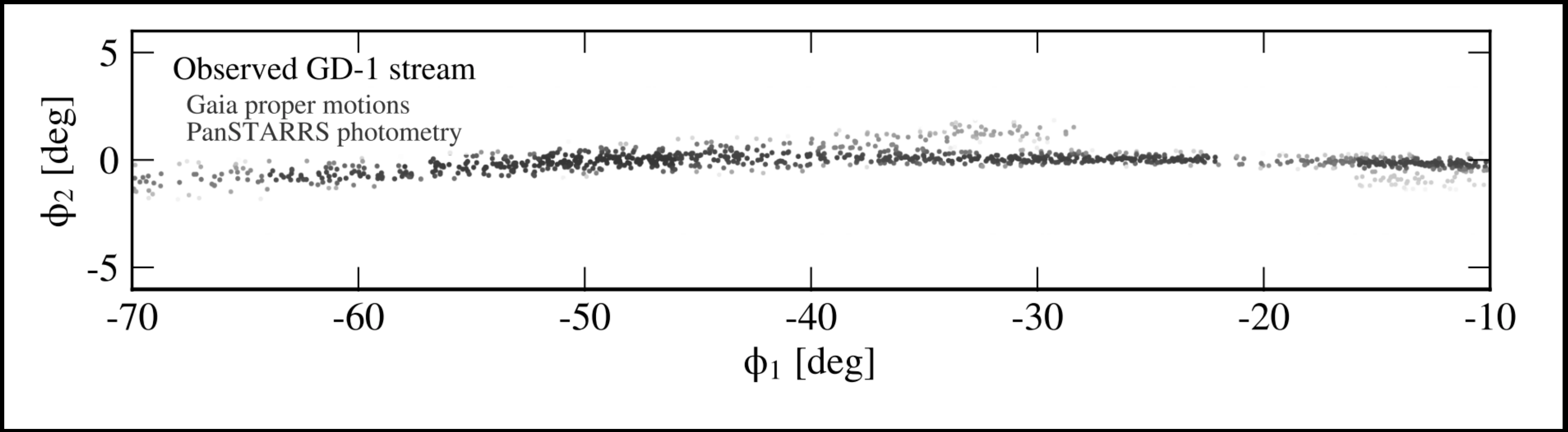
Searching for dark matter substructures in the MW



Gaia GD1 stream data!

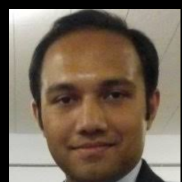
New map of stars in GD1 stream (longest cold stream in the MW) with *Gaia* second data release combined with *Pan-STARRS*.

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

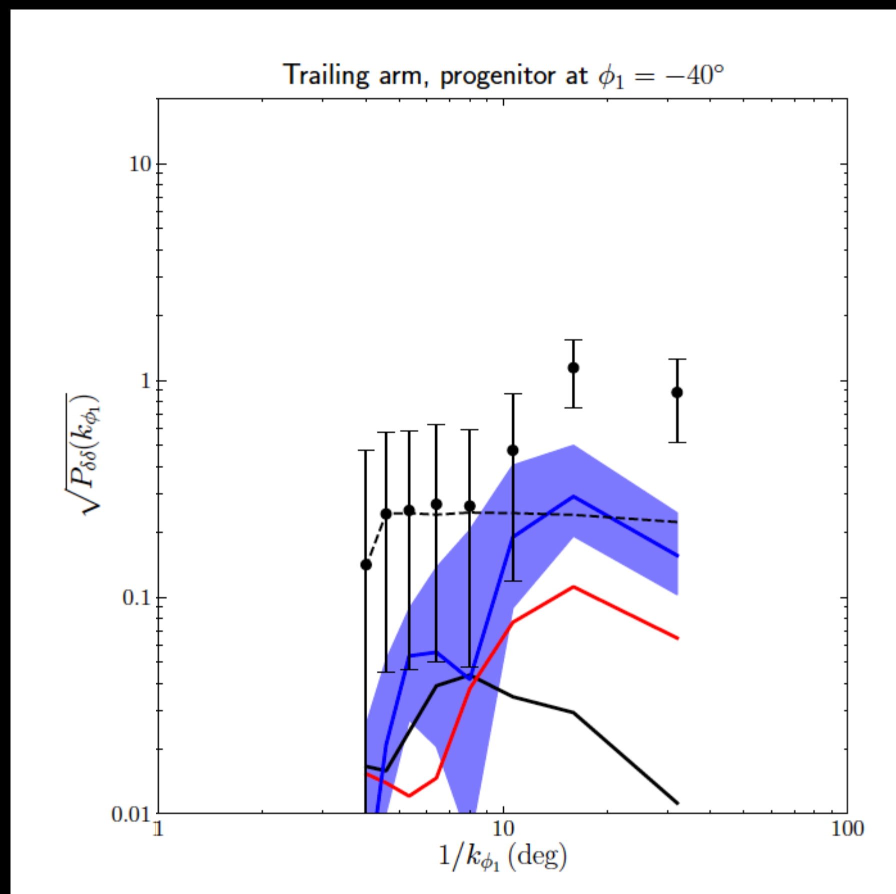


Bonaca et al. 1811.03631

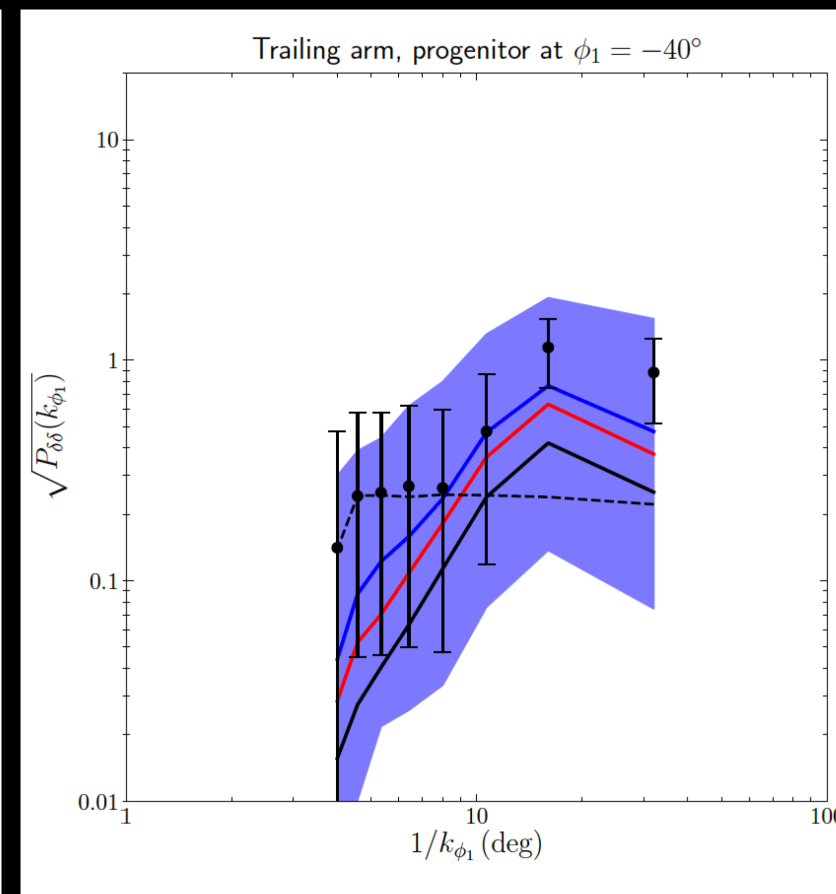
Preliminary: strong hints of dark substructures!



Baryonic substructures



Baryonic + CDM substructures



Banik, Bovy, Erkal, GB, de Boer, arXiv:1909.xxxxx

- 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!)**

- [constraints on shape and slope of subhalo mass function, m_{WDM}, etc.]

The future of dark matter searches

I. Broaden/improve/diversify searches
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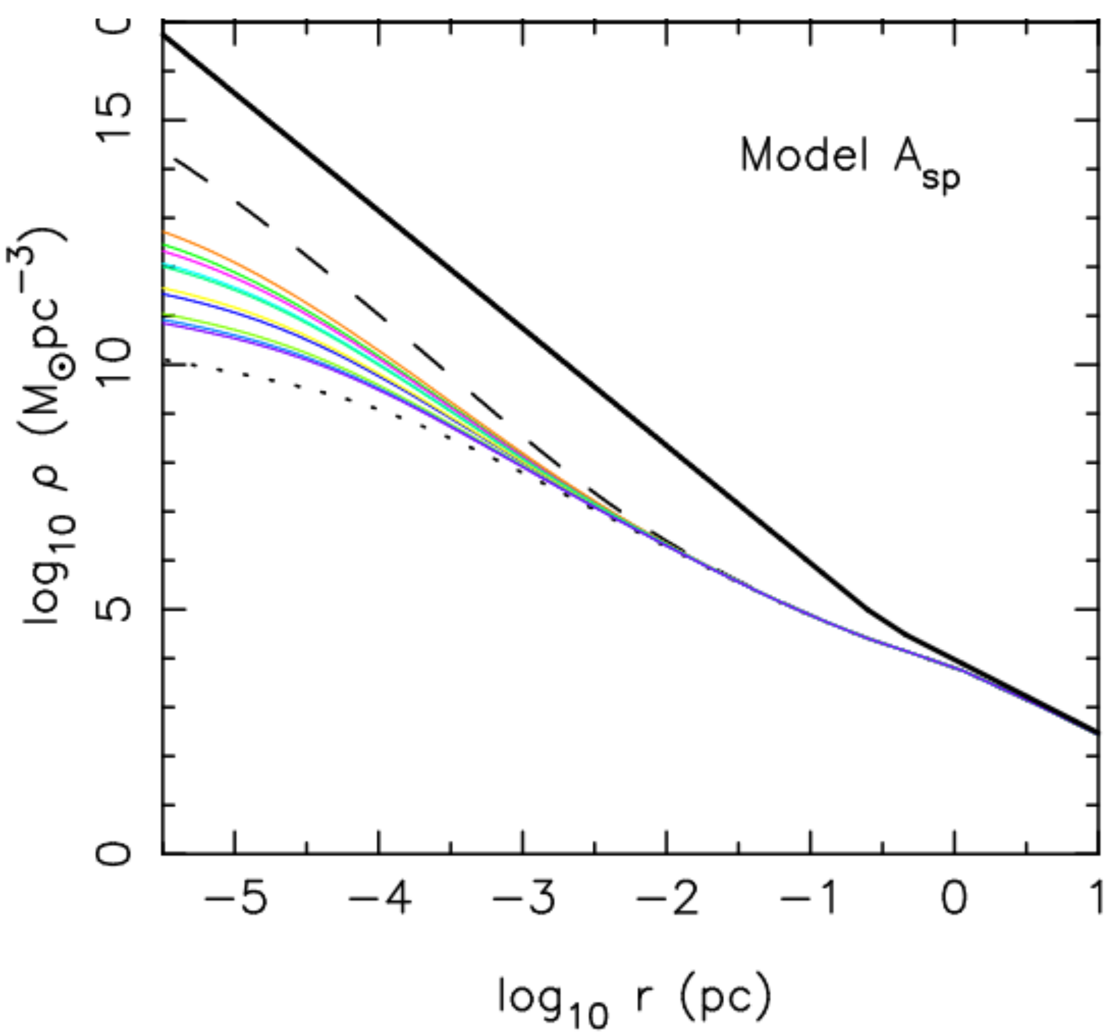
III. Exploit Gravitational Waves

Dark Matter 'dress' around BHs

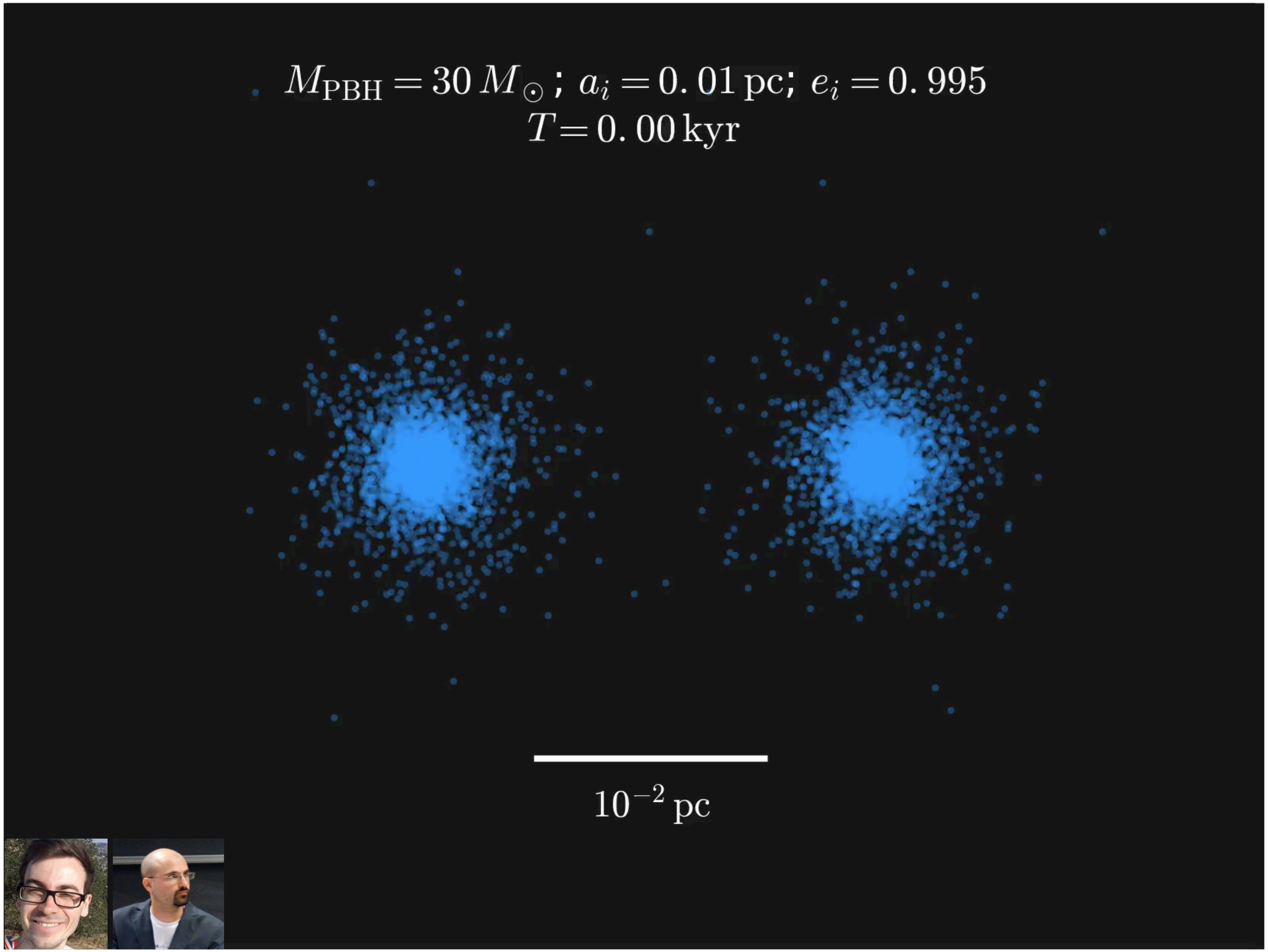
GB & Merritt 2005



- **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)*

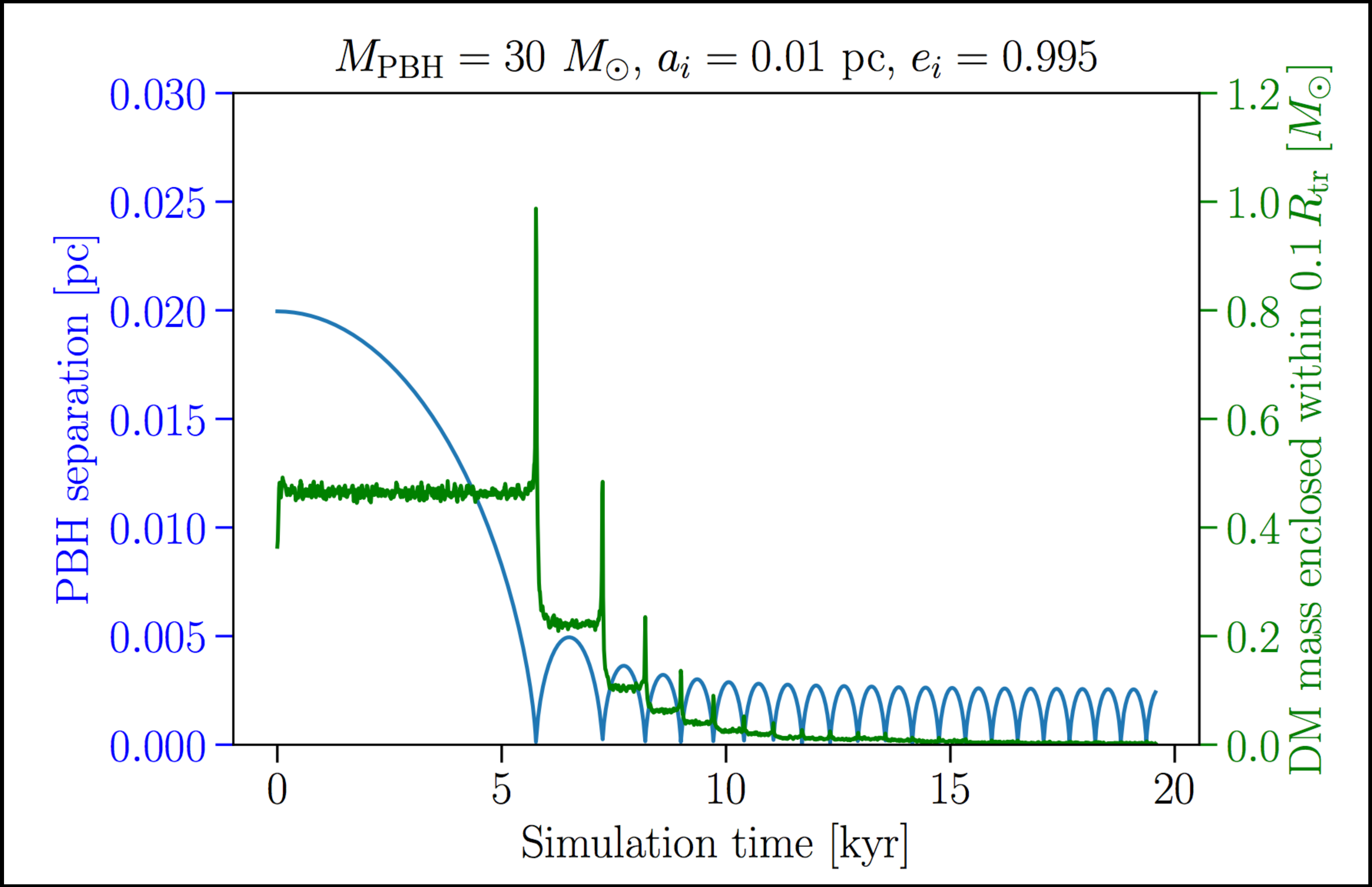
Open questions: astrophysical uncertainties, dependence on DM properties (self-interactions, annihilations)

'Dressed' BH-BH merger



Kavanagh, Gaggero & GB, arXiv:1805.09034

Dark Matter around BHs



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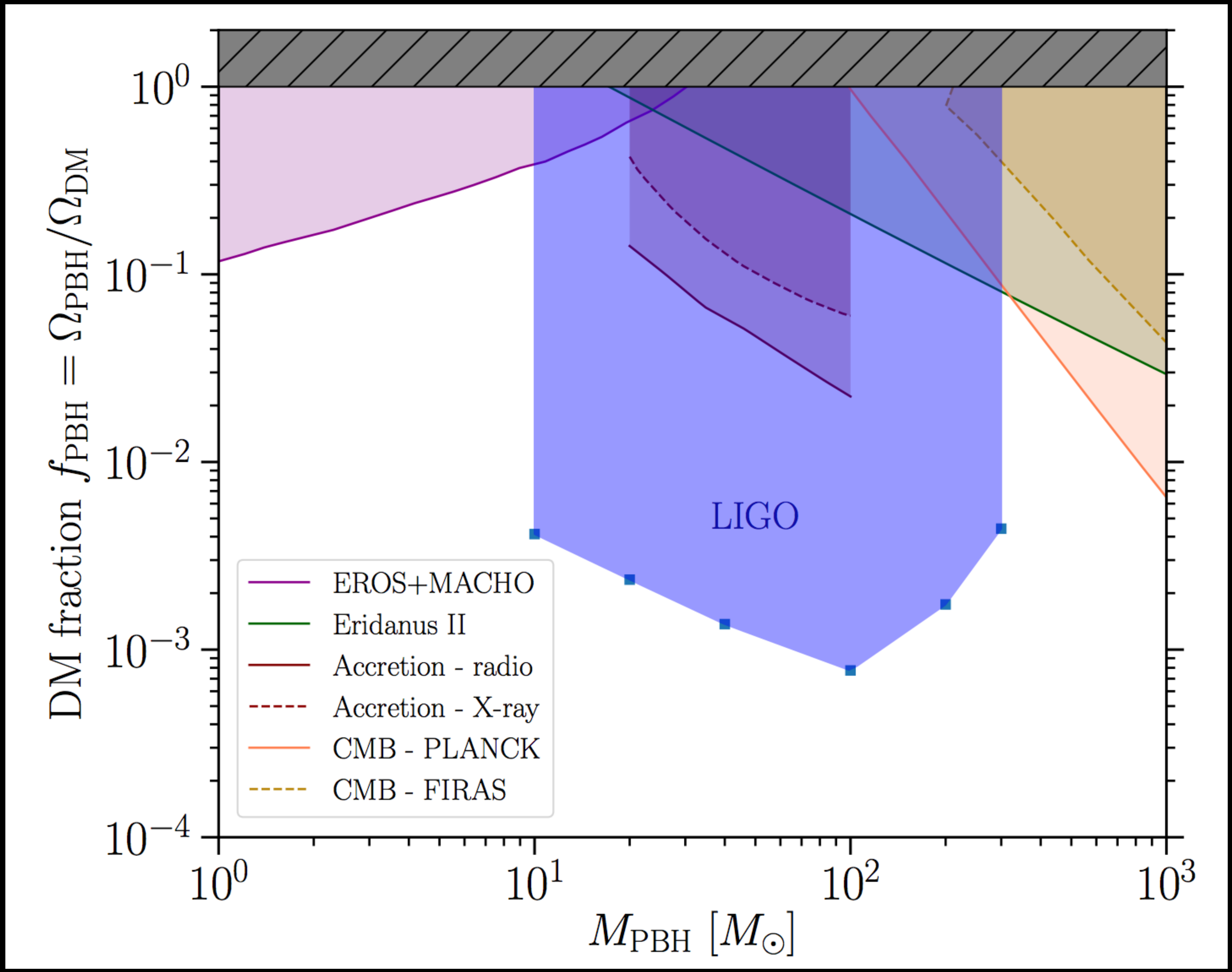
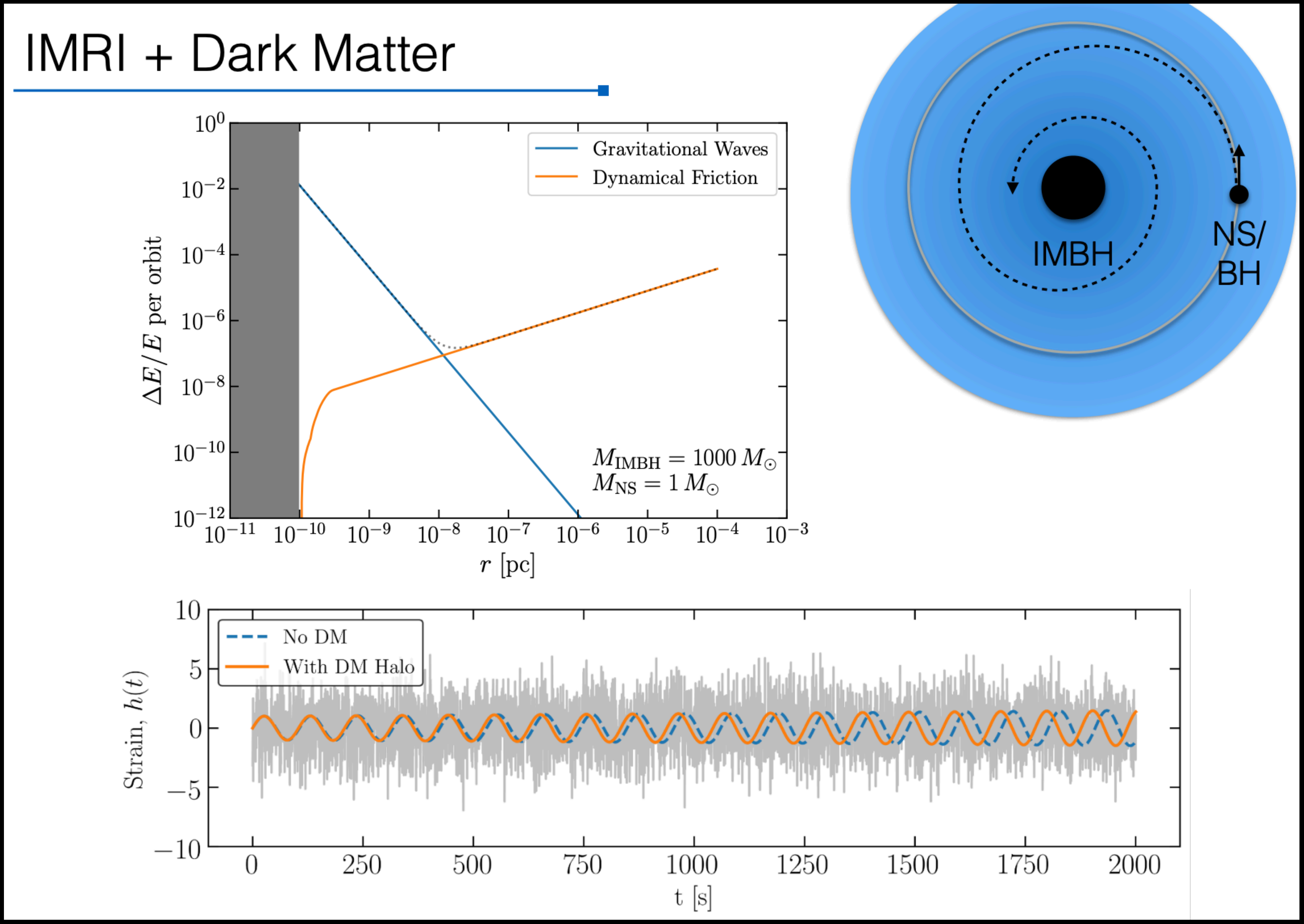


Kavanagh, Gaggero & GB, arXiv:1805.09034

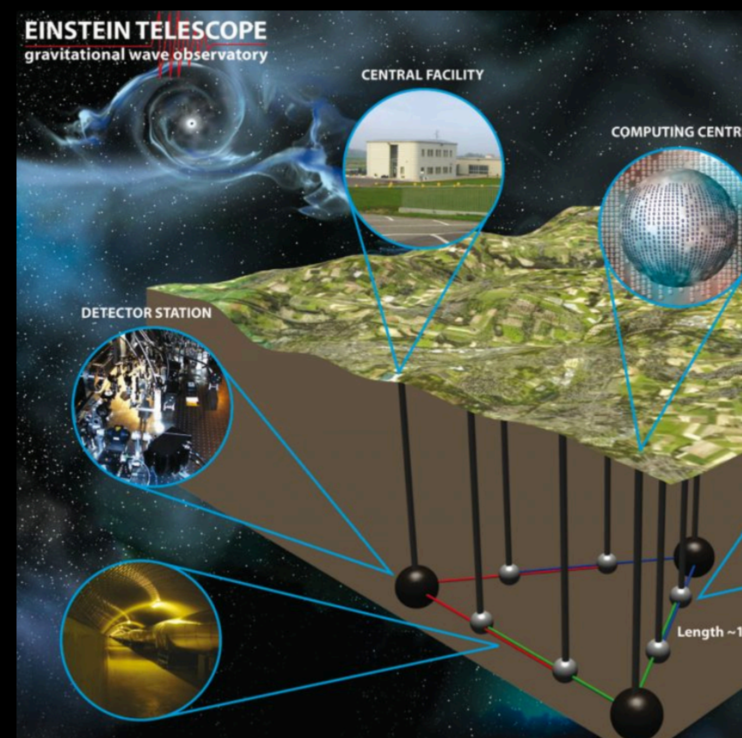
Dark Matter around BHs



Slide courtesy of B. Kavanagh (Based on Kavanagh, GB et al. 2019)

Can we convincingly discover primordial BHs?

Yes, e.g. if we:

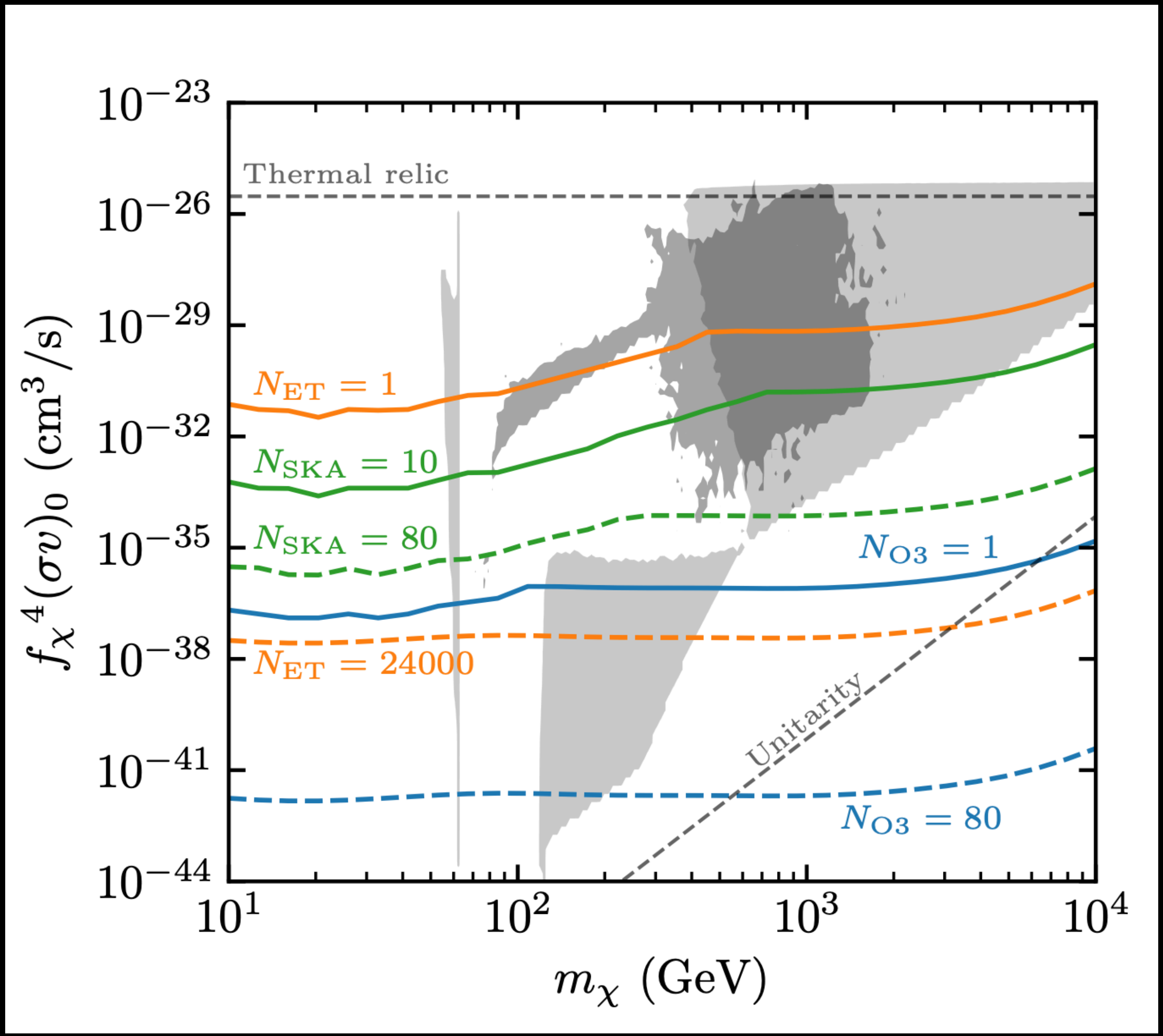


1. Detect sub-solar mass BHs with joint Ligo/Virgo observing run 3 (in progress)

II. Detect O(100) Msun BHs at very high-z ($z > 40$) with Einstein Telescope (e.g. 1708.07380)

III. Discover 'unique' radio signature with Square Kilometre Array [tricky]

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

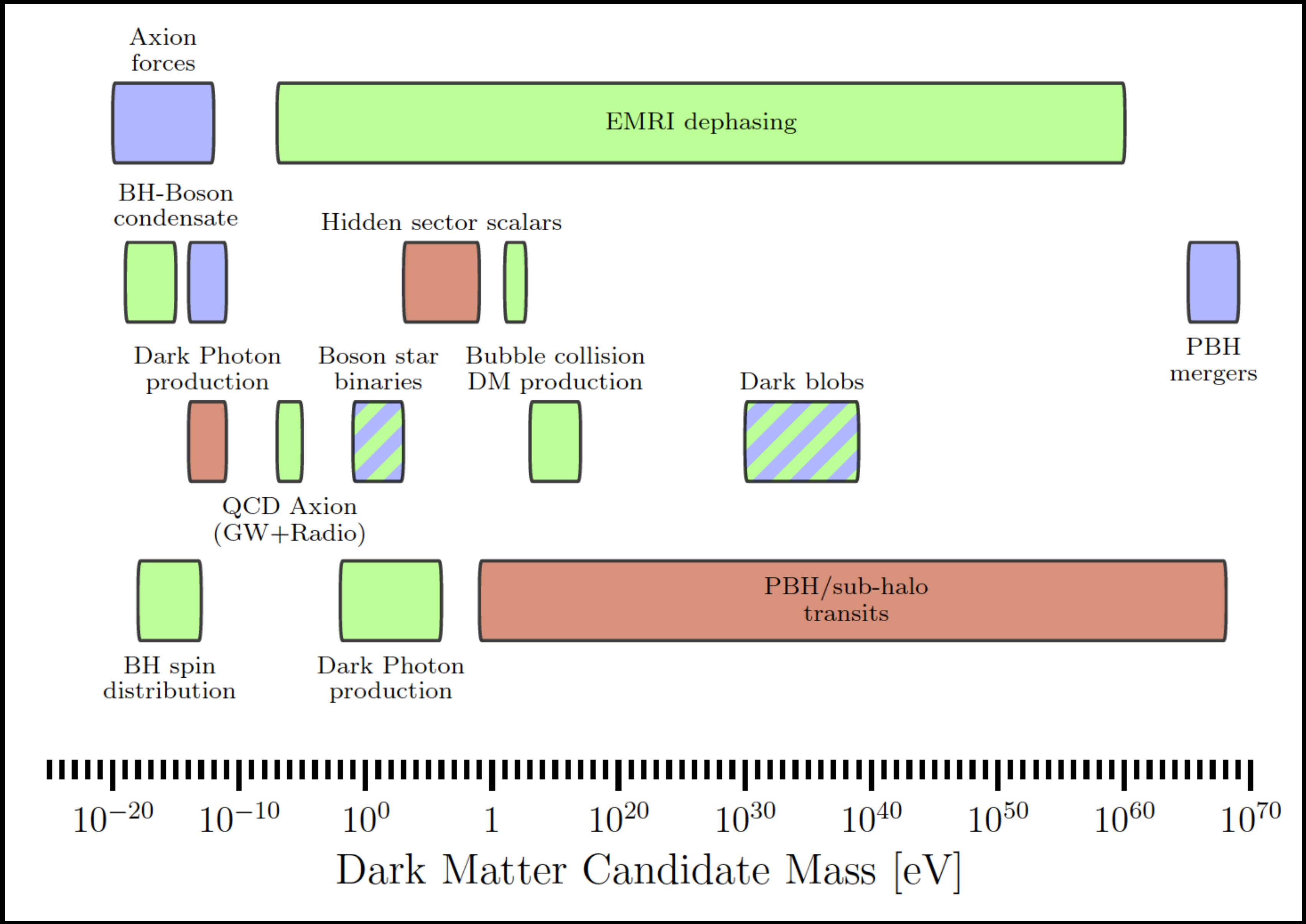


GB, Coogan, Gaggero, Kavanagh, Weniger 1905.01238

See Adam Coogan's talk on Friday!

- 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!

- 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

APPEC

Ceremonial launch of the European Center for Astro Particle Theory – EuCAPT

On the 10th of July the European Center for Astro Particle Theory, EuCAPT was officially launched at CERN, which is also the first central hub for the next 5 years.

The first director is Gianfranco Bertone who is chairing a steering committee of 12 partners. The aim of EuCAPT is to coordinate and favour the already existing activities in several European centers and institutions active in astroparticle theory. The main activities organised by EuCAPT will include:
a. An annual general meeting of the European theoretical astroparticle physics community at the central hub;
b. Thematic workshops to be organised by other participating institutions;
c. The central hub will host dedicated meetings for small groups of scientists to consolidate/finalize collaborative projects and common proposals;
d. Coordination of existing/planned activities of the participating institutions to prevent overlaps and enrich the overall portfolio. Activities that are part of the coordinated portfolio will be labelled as EuCAPT activities;
e. Contacts/coordination with ApP theorists from all over the world favouring collaboration/visits and bolstering common actions also with institutions not belonging to the EuCAPT;
f. Advice, referee support, training concerning funding proposals;
g. Create and operate an EuCAPT website, including an activity calendar.

Along with the official launch the first meeting of the steering committee took place. We are looking forward to a fi theoretical Astroparticle Physics.

Gian Francesco Giudice, Teresa Montaruli, Eckhard Elsen and Job de Kleuver signing the official agreement for EuCAPT. Credits: CERN

Francesca Moglia, Antoine Kouchner, Antonio Masiero, Gian Francesco Giudice, Teresa Montaruli, Gianfranco Bertone, Eckhard Elsen, Job de Kleuver, Tony Riotto and Silvia Pascoli. Credits: CERN