A new era in the quest for
Dark Matter

Gianfranco Bertone
GRAPPA center of excellence, U. of Amsterdam

GSSI Colloquium, 25 March 2020

GRAPPA
GRavitation AstroParticle Physics Amsterdam

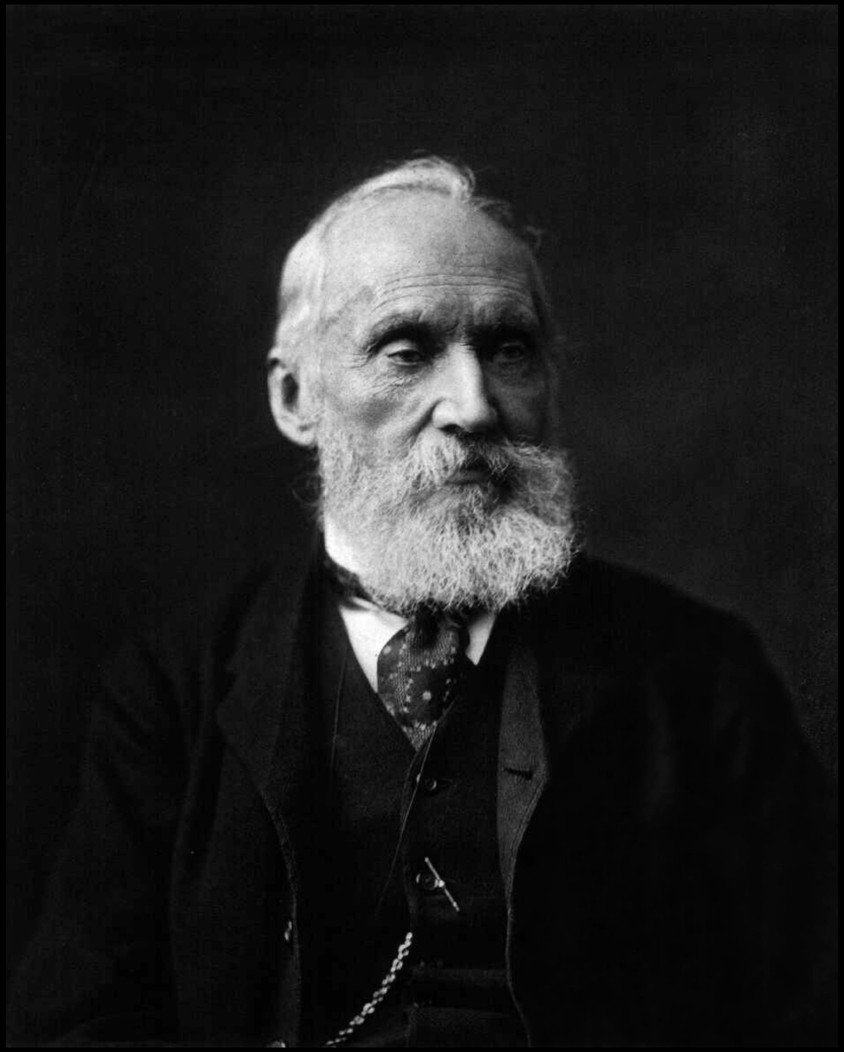
Plan of the talk:

Preamble: the dark universe *narrative*

Part I: DM - what have we learnt?

Part II: A new era in the quest for DM

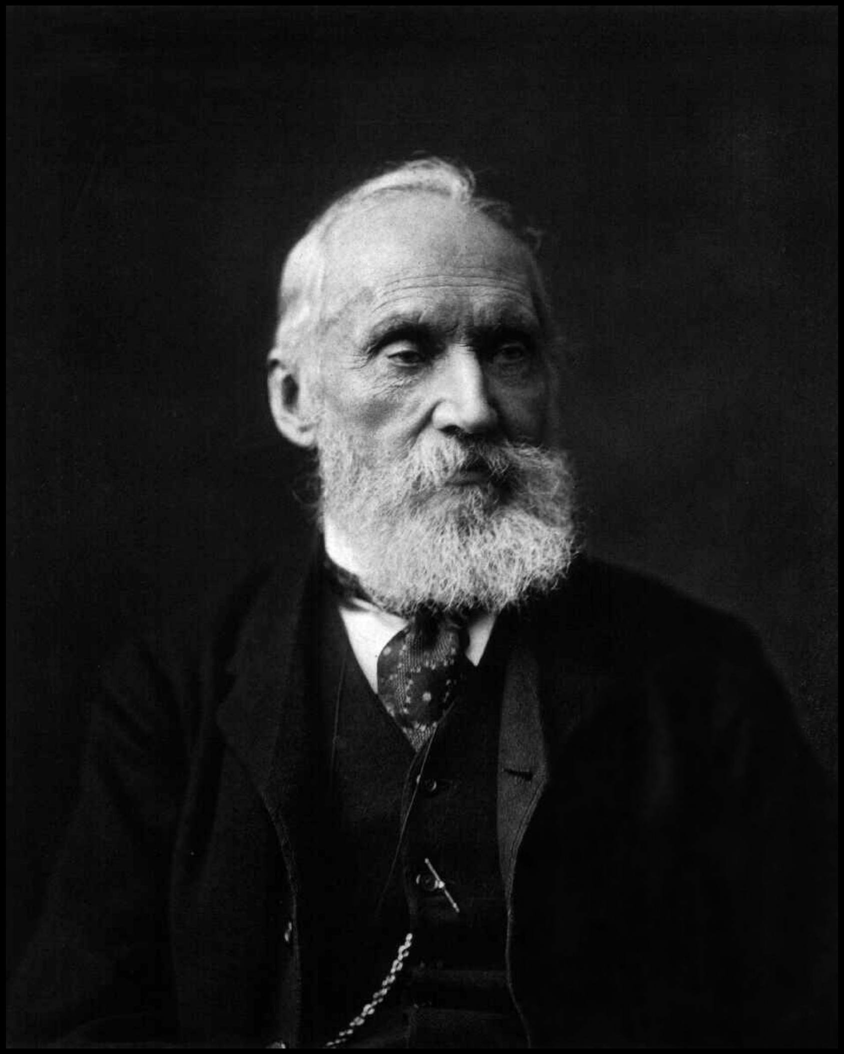
Dark matter: a problem with a long history..



Lord Kelvin (1904)

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

Dark matter: a problem with a long history..



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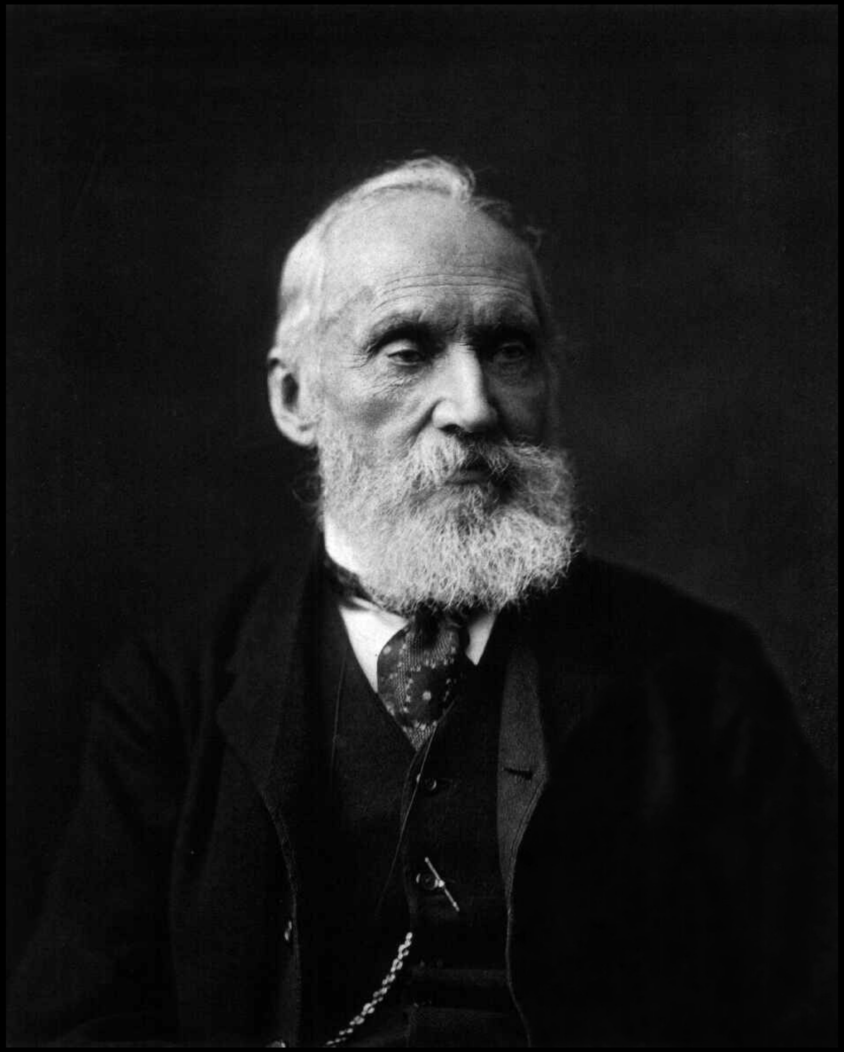

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"A history of Dark Matter" GB & Hooper - RMP *1605.04909*
"How dark matter came to matter" de Swart, GB, van Dongen - Nature Astronomy; *1703.00013*

2019: 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

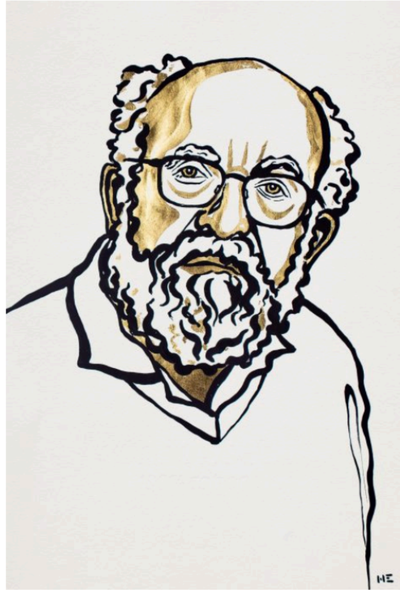
Didier Queloz
University of Geneva, Switzerland
University of Cambridge, UK

"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

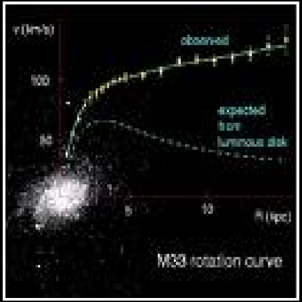
James Peebles' insights into physical cosmology have enriched the entire field of research and laid a foundation for the transformation of cosmology over the last fifty years, from speculation to science. His theoretical framework, developed since the mid-1960s, is the basis of our contemporary ideas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

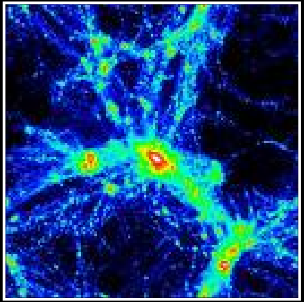
The results showed us a universe in which just five per cent of its content is known, the matter which constitutes stars, planets, trees – and us. The rest, 95 per cent, is unknown dark matter and dark energy. This is a mystery and a challenge to modern physics.

What is the Universe made of?

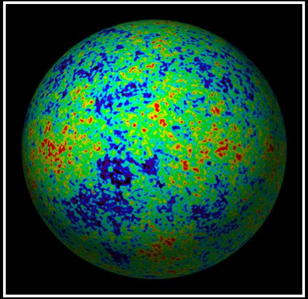
OBSERVATIONS



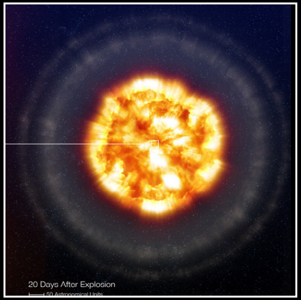
- Rotation Curves



- Clusters of galaxies



- CMB



- Type Ia Supernovae

…

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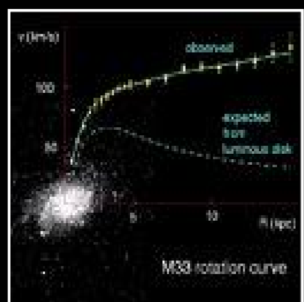

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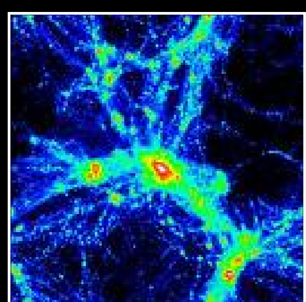

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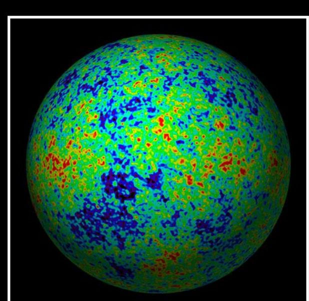

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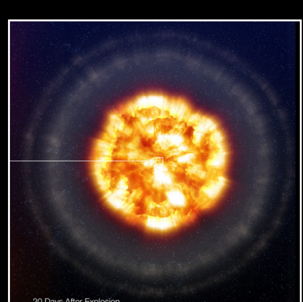

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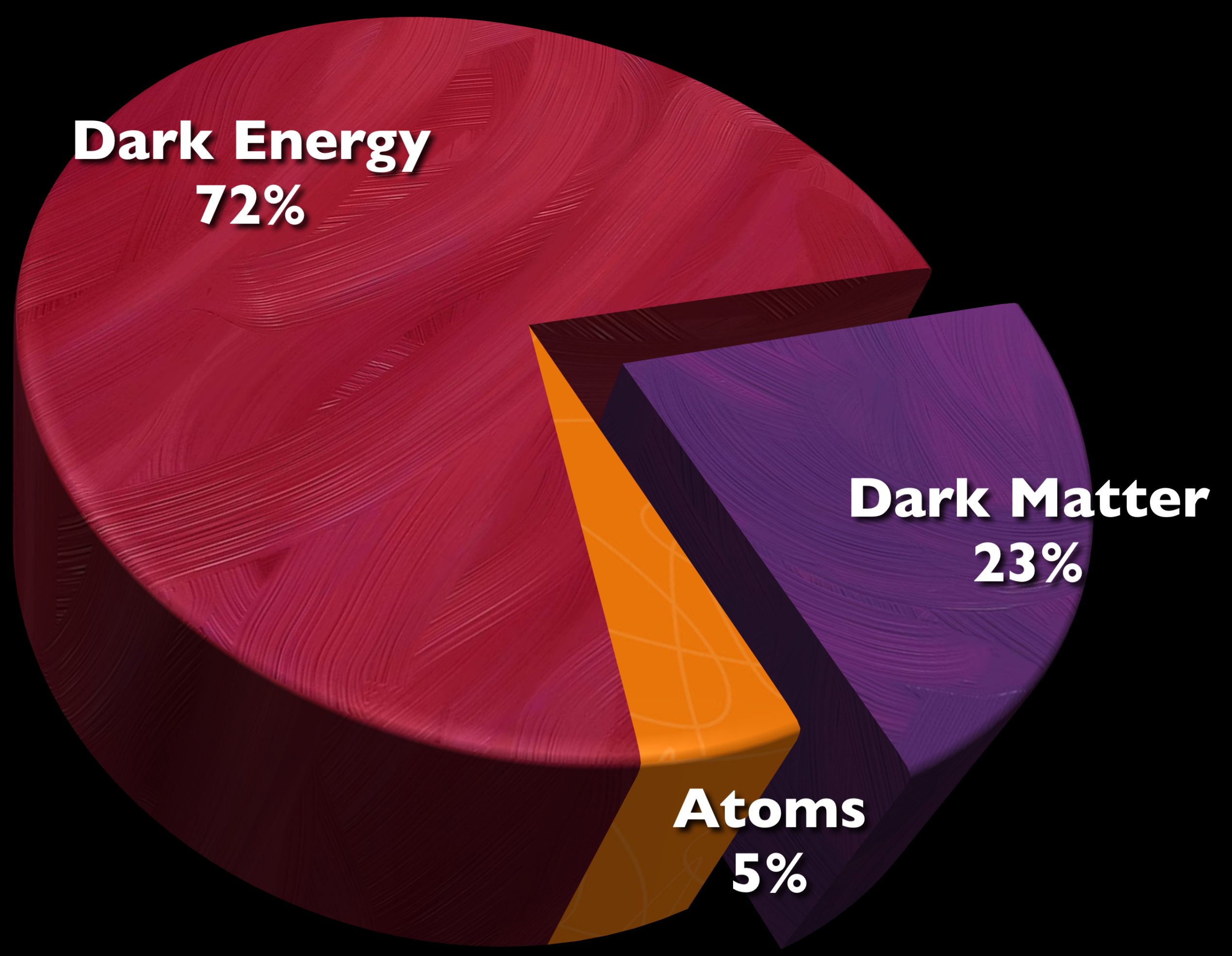
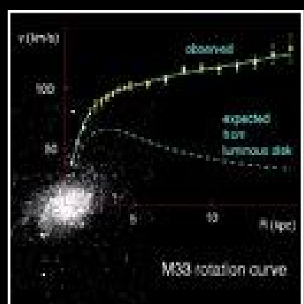


What is the Universe made of?

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

OBSERVATIONS



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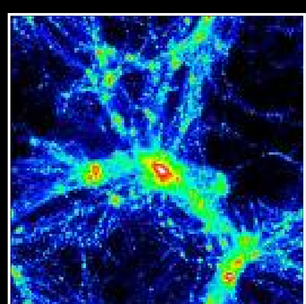

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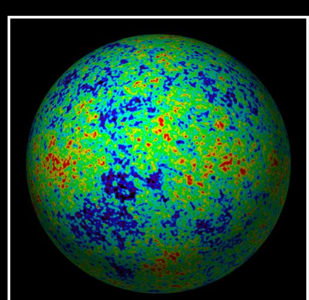

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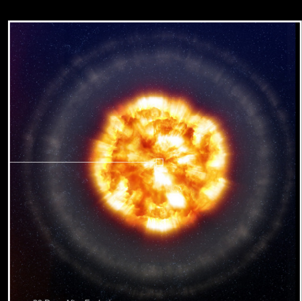

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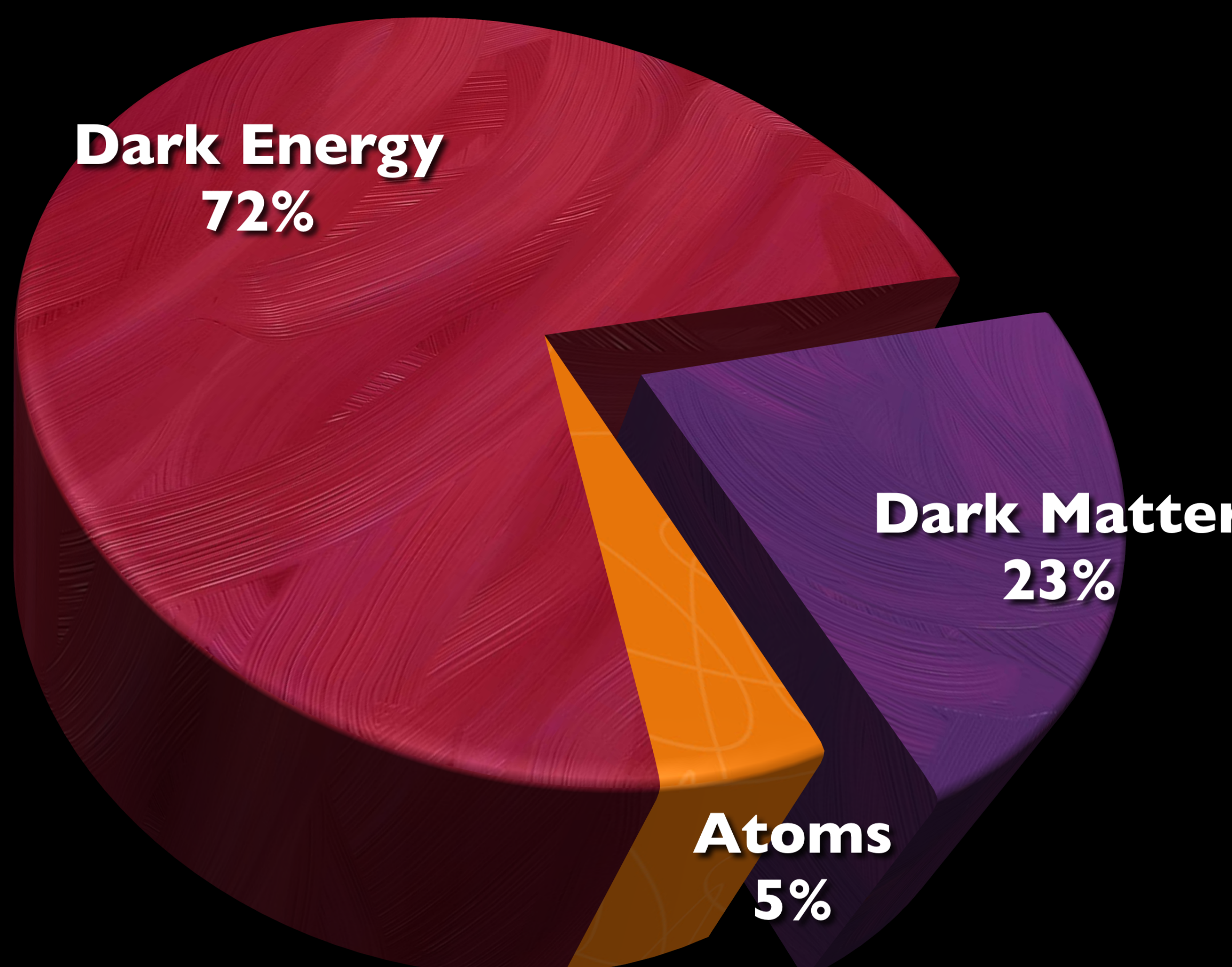
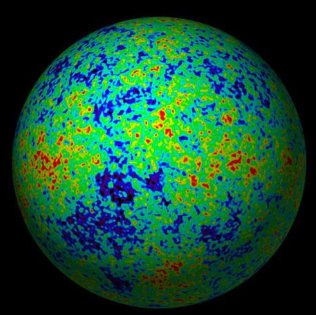
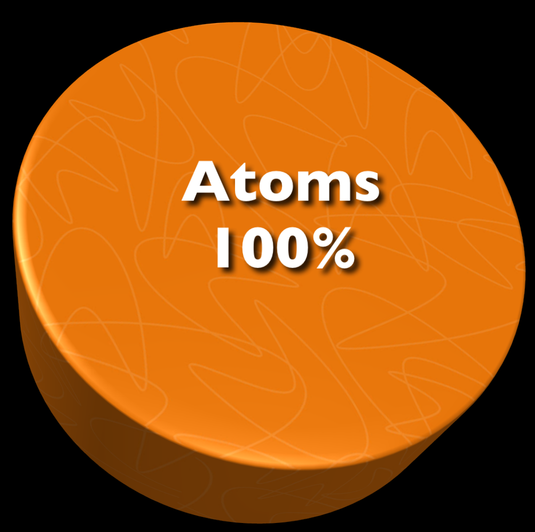
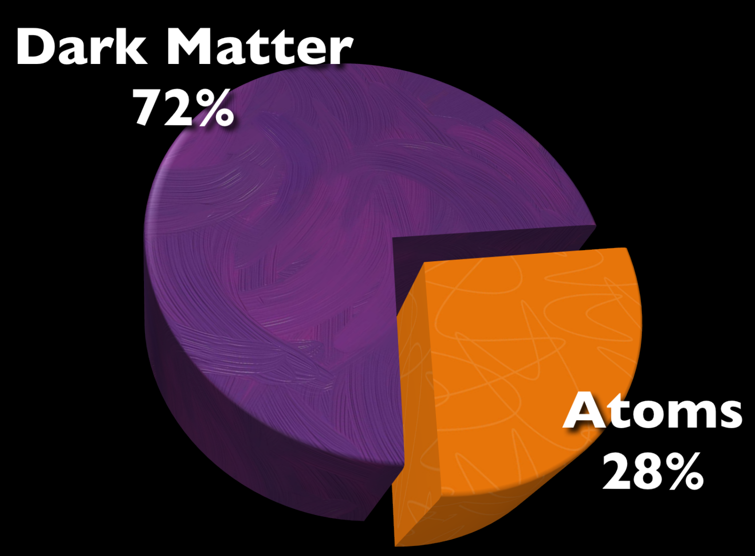


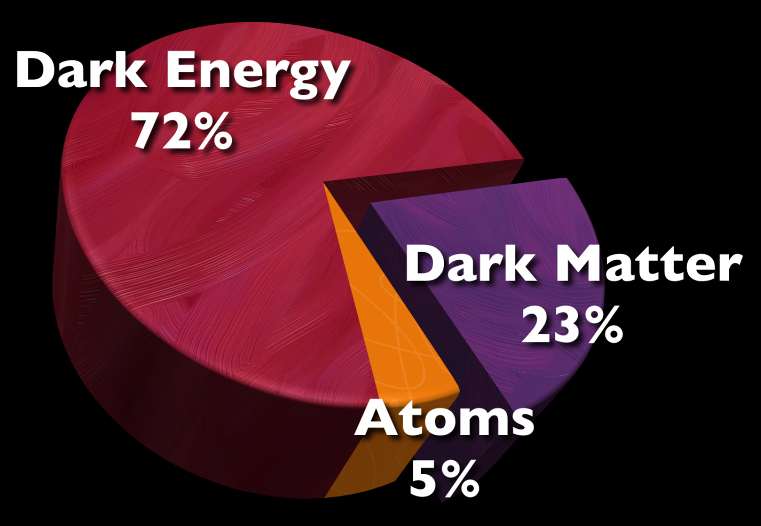
What is the Universe made of?

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



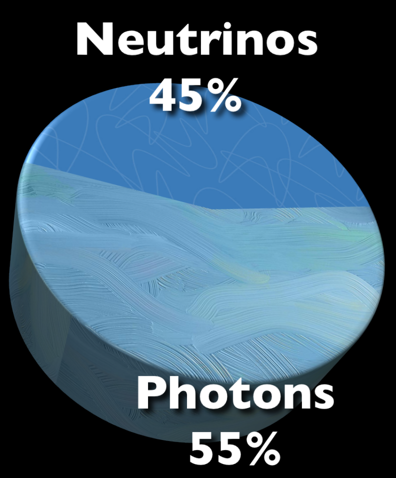






What <u>was</u> the Universe made of?

At BBN



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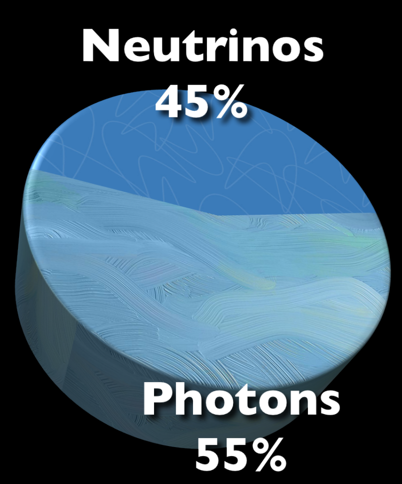
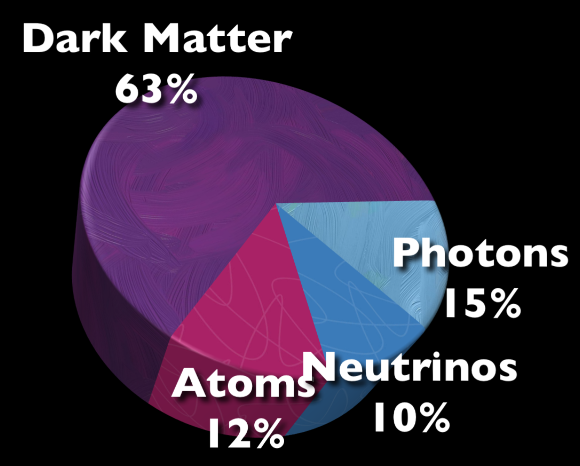


At recombination



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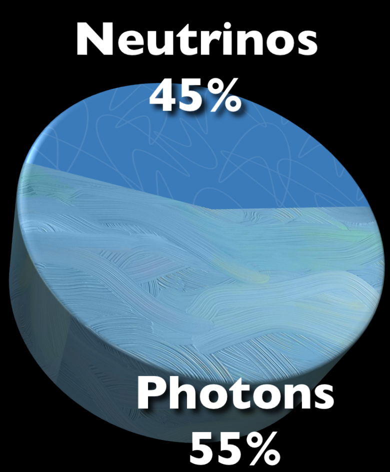

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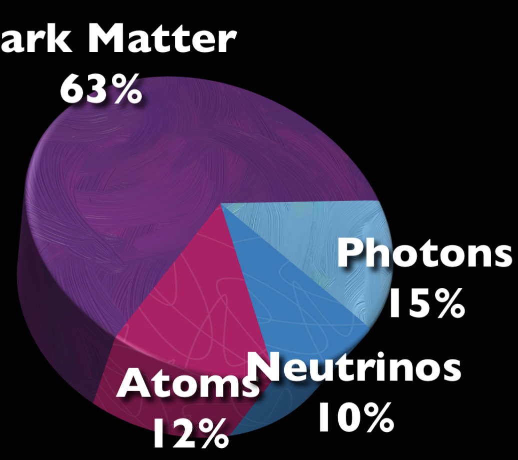
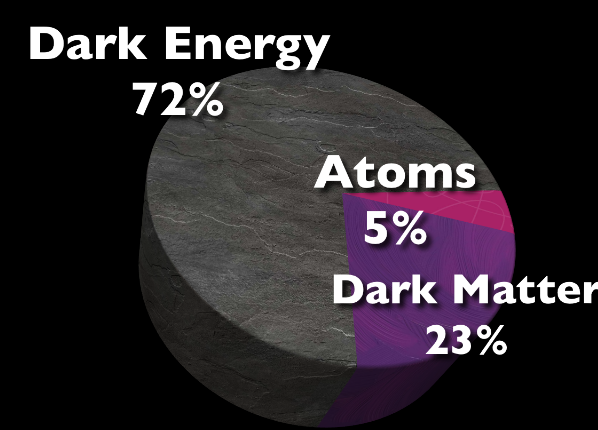


Today



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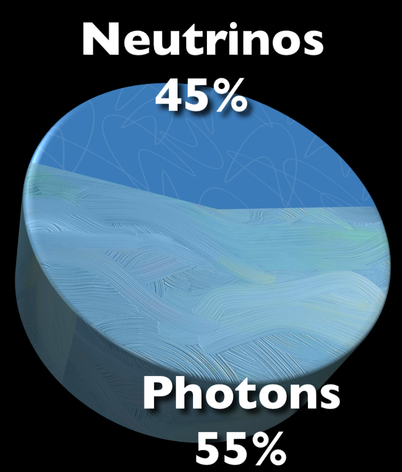

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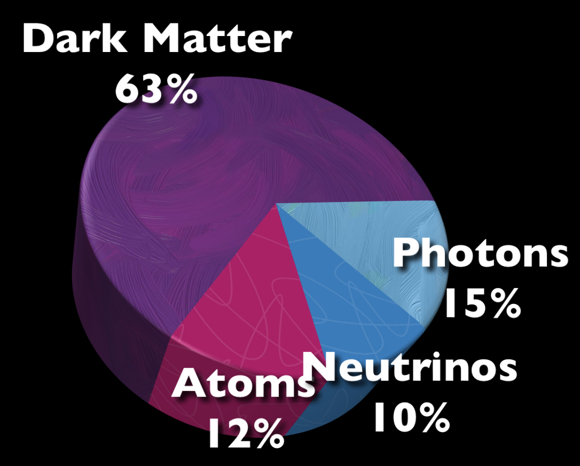

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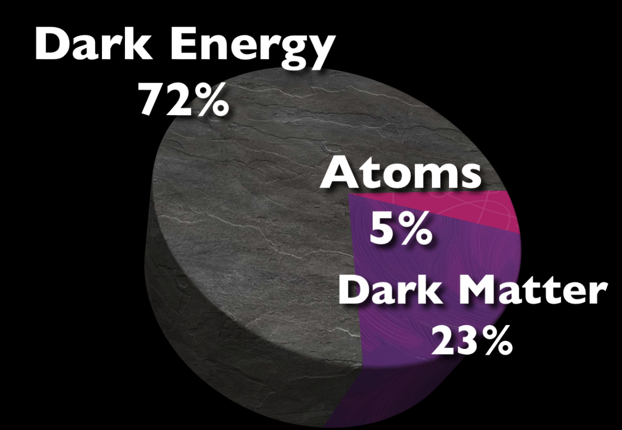
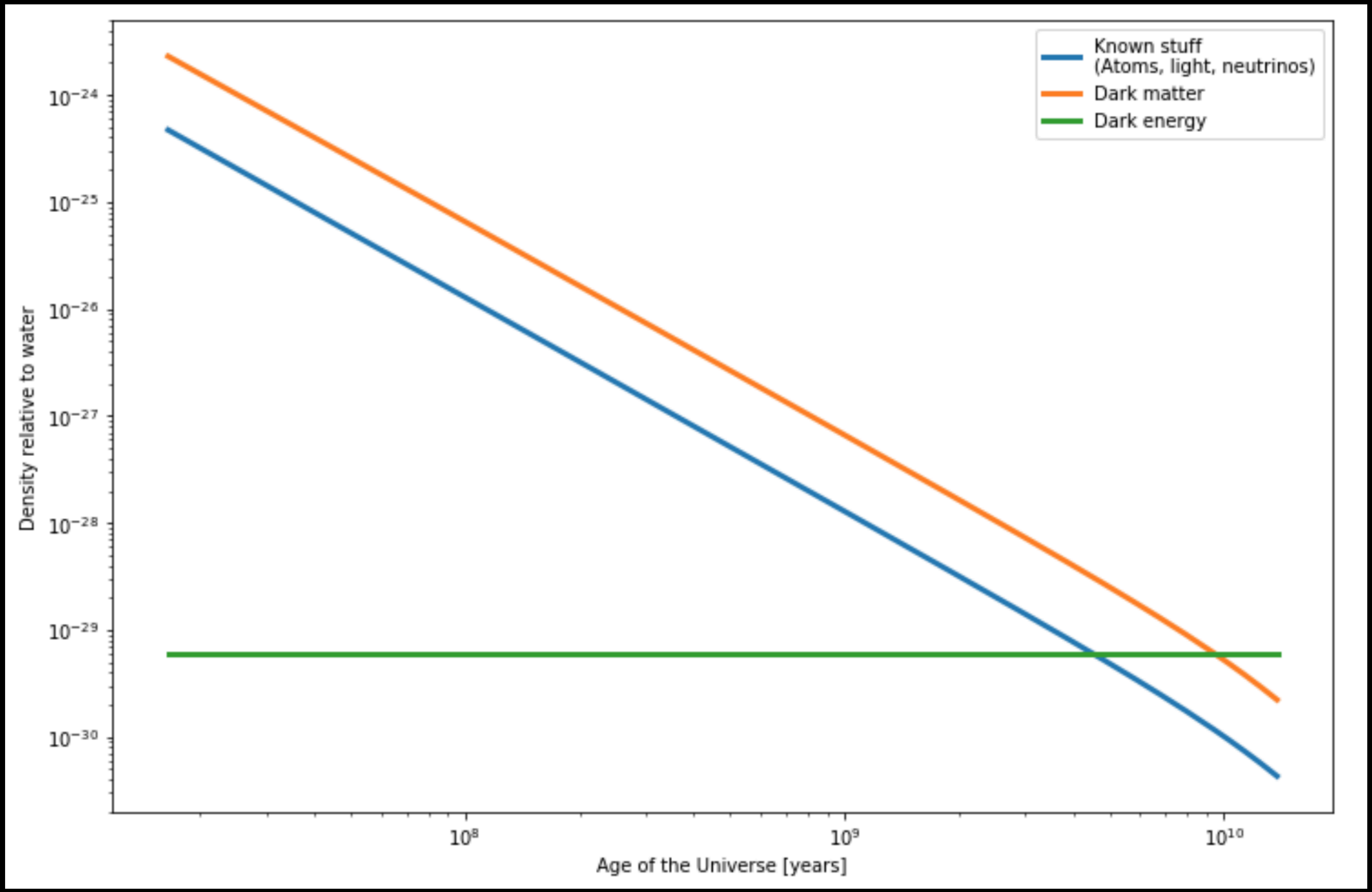


…eventually

Evolution of matter/energy density



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

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Simulating the Universe

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

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What do we know?

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

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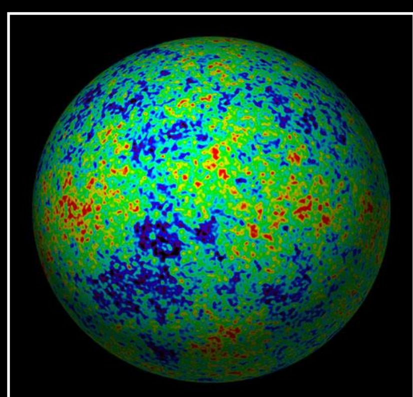
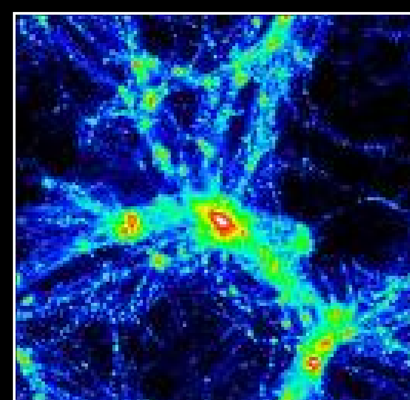
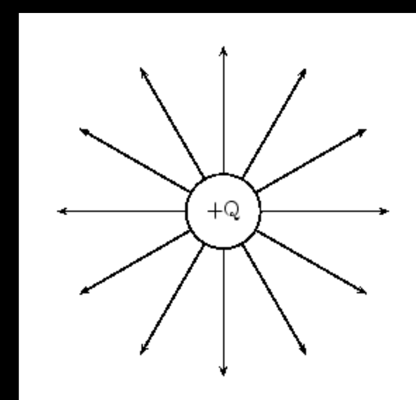


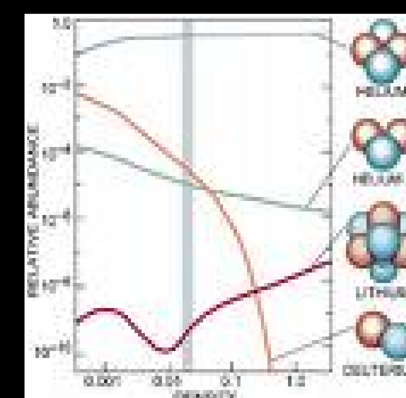
2) Cold?



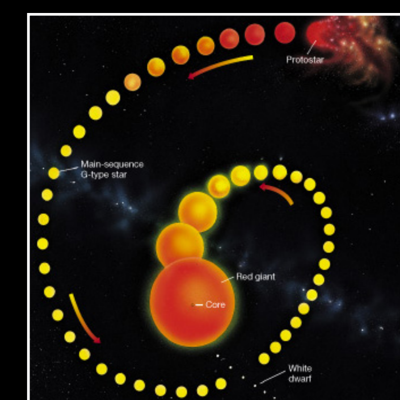
3) Neutral?



4) BBN ok?



5) Stars OK?



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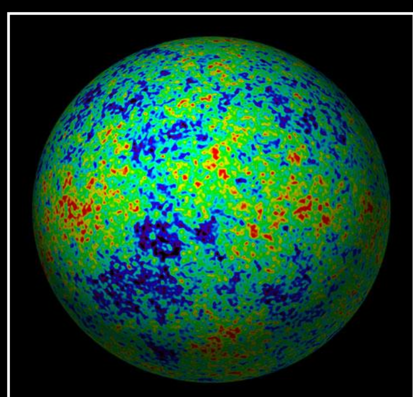

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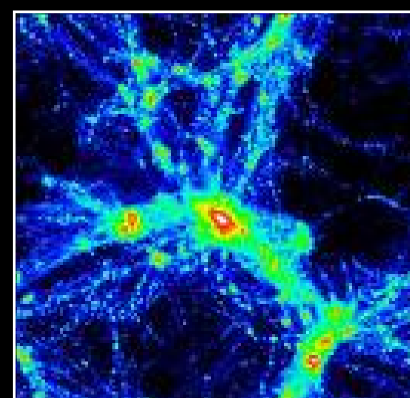

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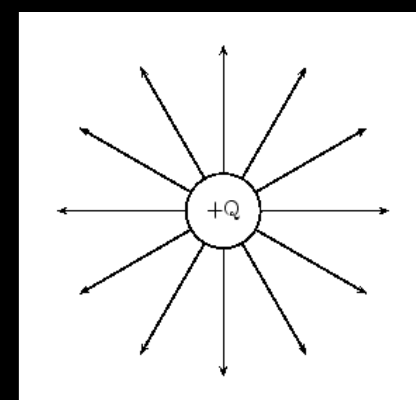

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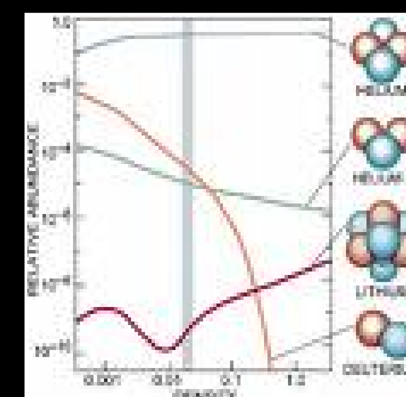

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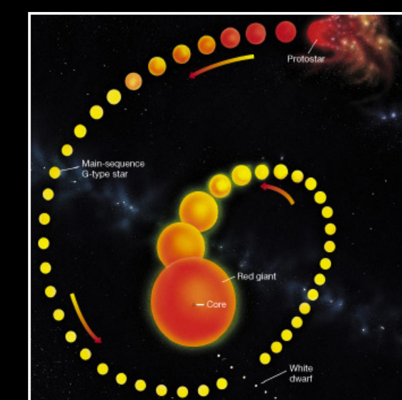
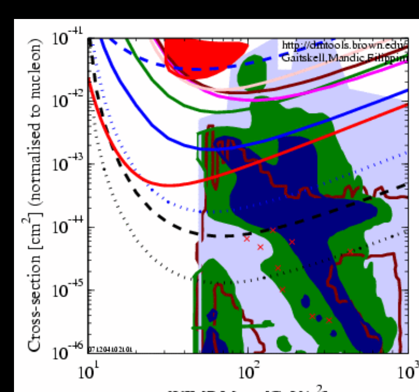
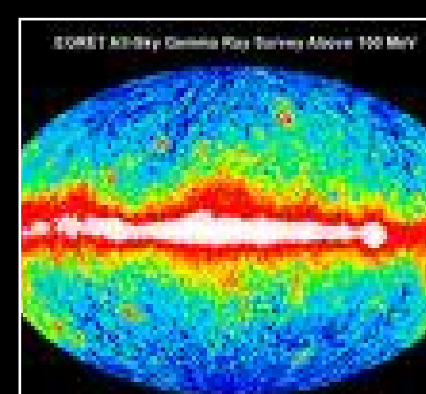


6) Collisionless?

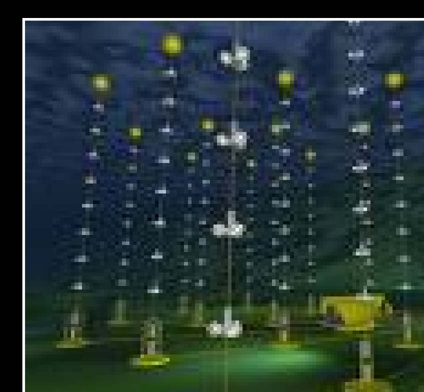
7) Couplings OK?



8) γ-rays OK?



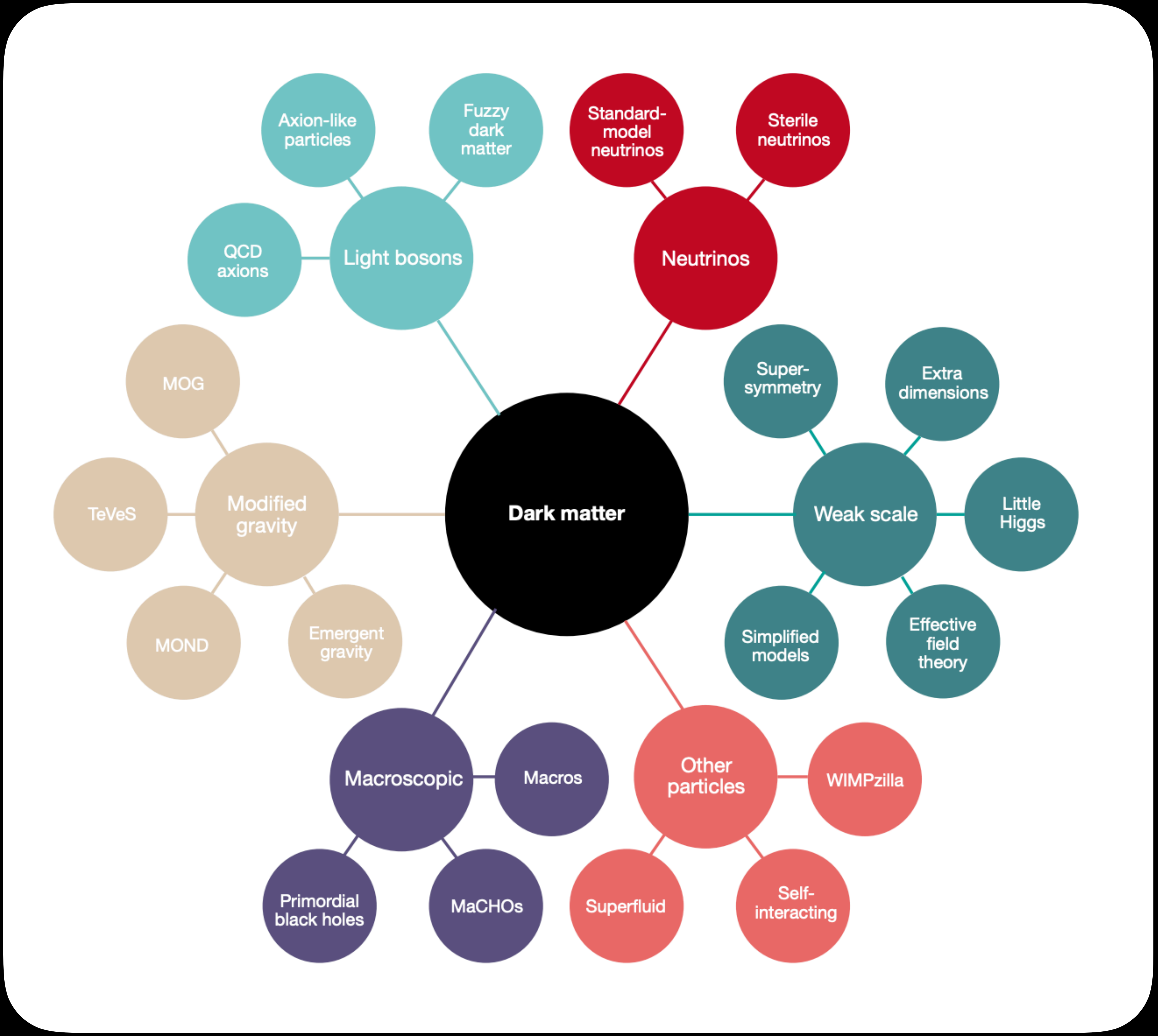
9) Astro bounds?



10) Can probe it?

Taoso, Bertone, Masiero 0711.4996

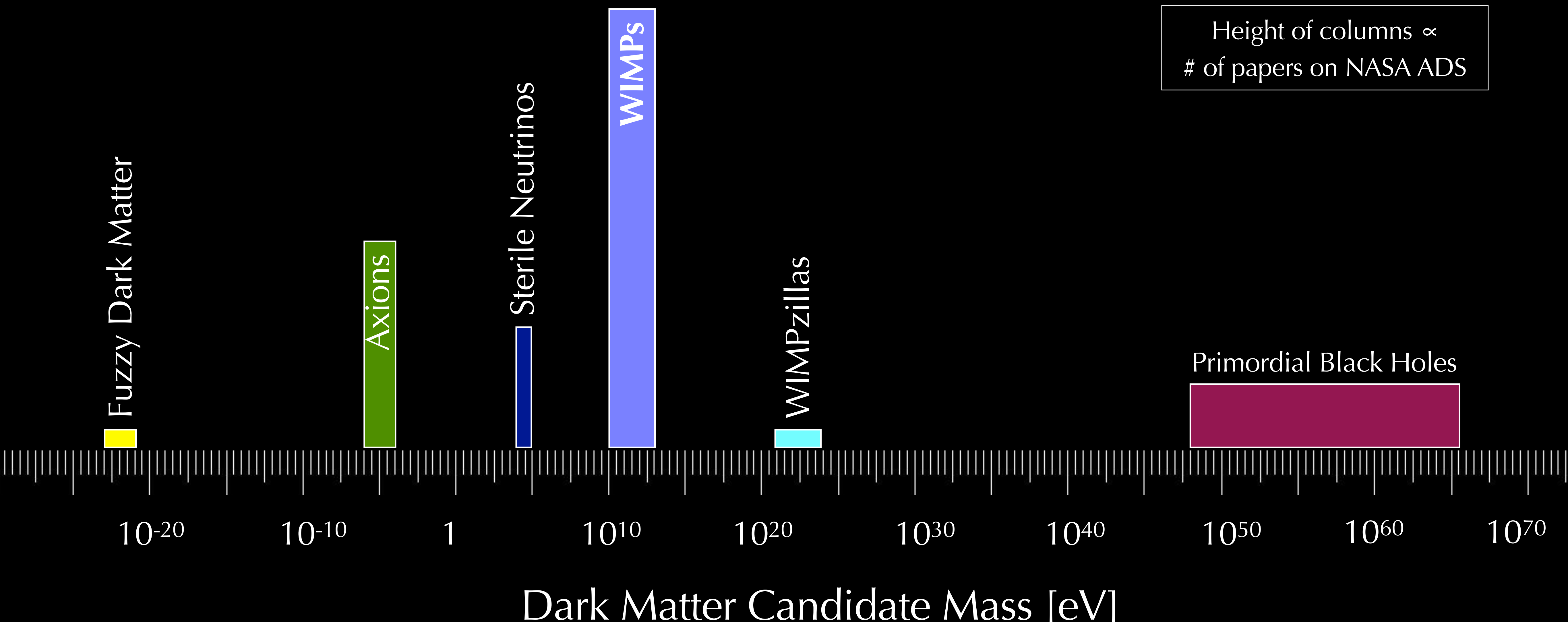
Candidates



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!



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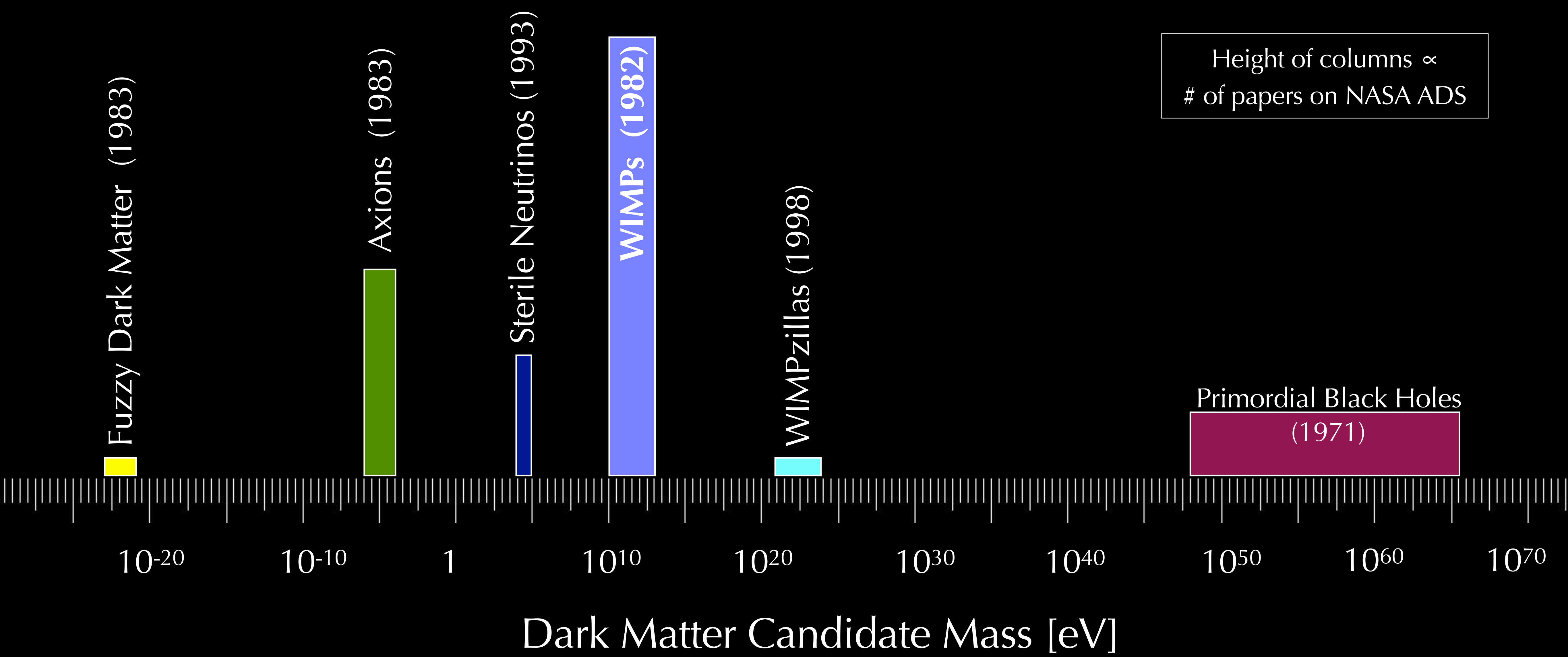
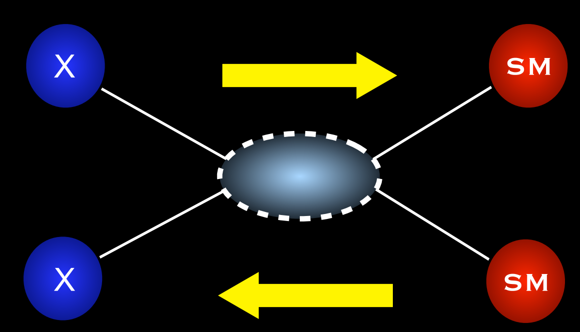


WIMPs

By far the most studied class of dark matter candidates.

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



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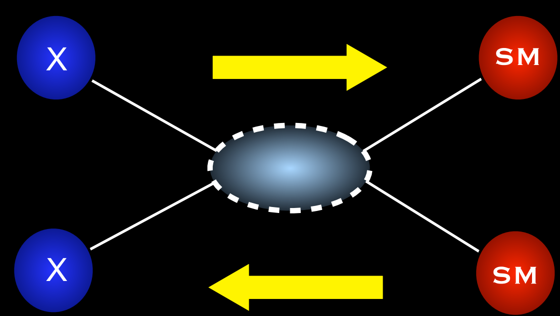


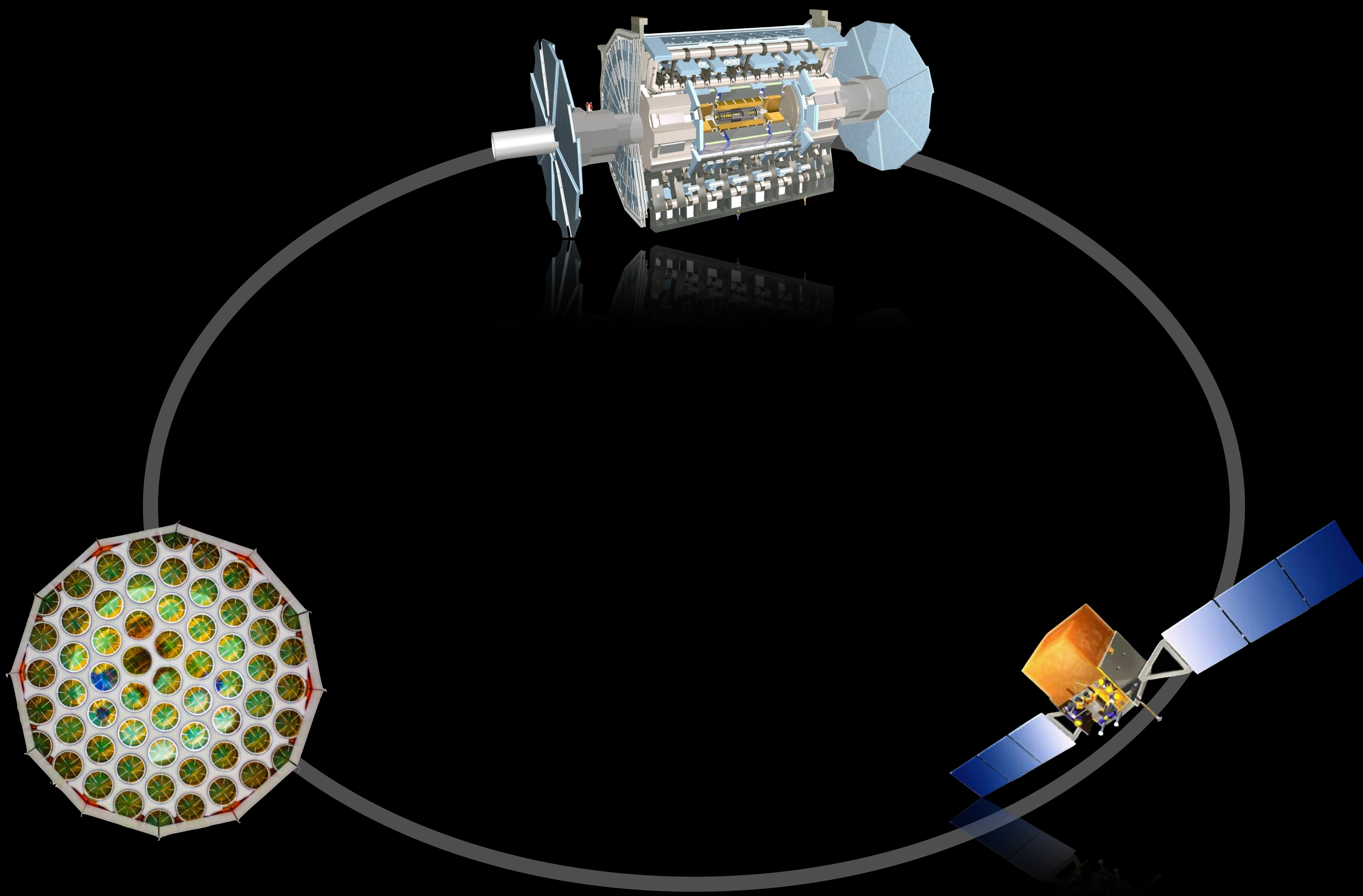
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Weak-scale cross sections can reproduce observed relic density

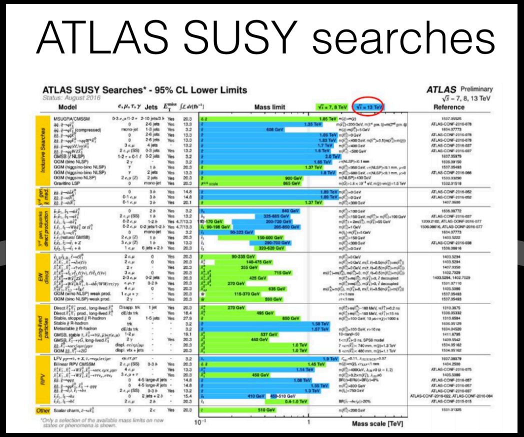
$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

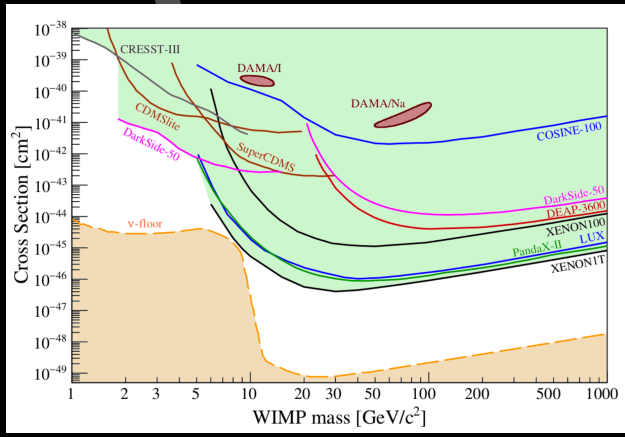
'WIMP miracle': new physics at ~1 TeV solves at same time fundamental problems of particle physics (*hierarchy problem*) AND DM

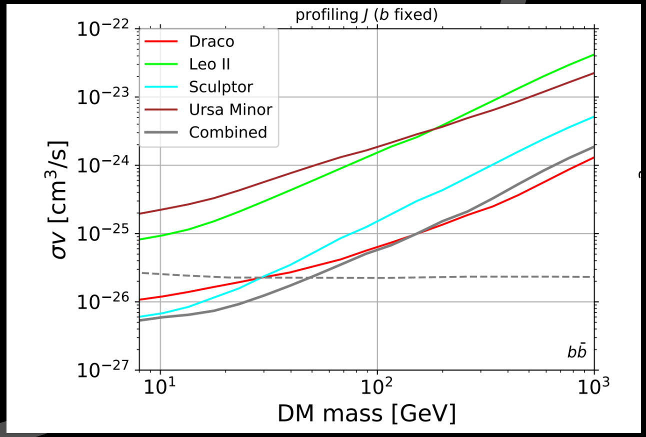
WIMPs searches



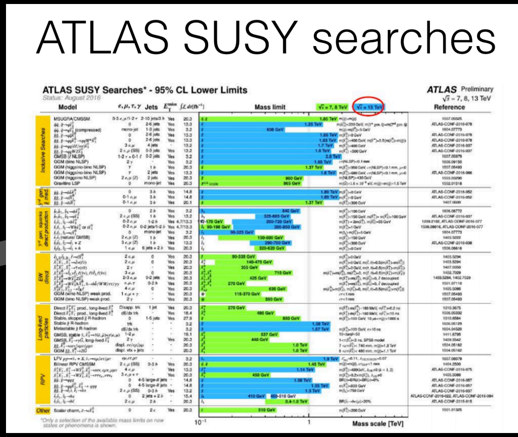
WIMPs searches



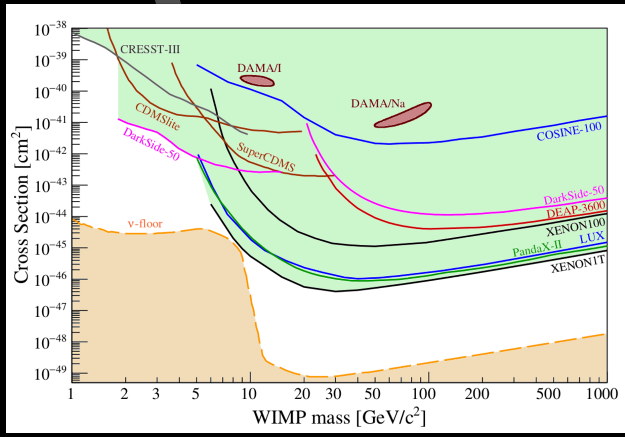


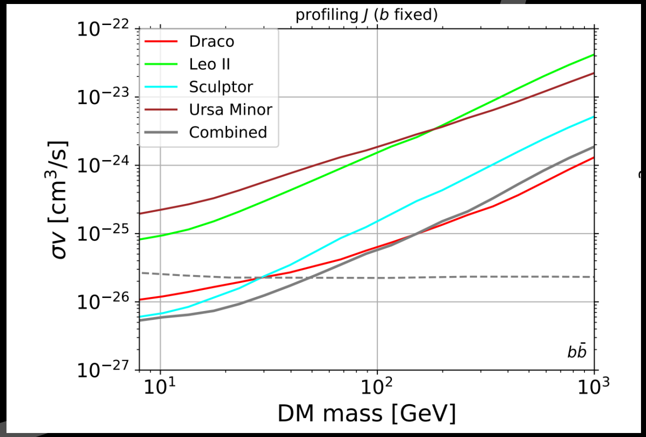


WIMPs searches



No WIMPs
found yet, despite many efforts!





Are WIMPs ruled out?

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NO

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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"

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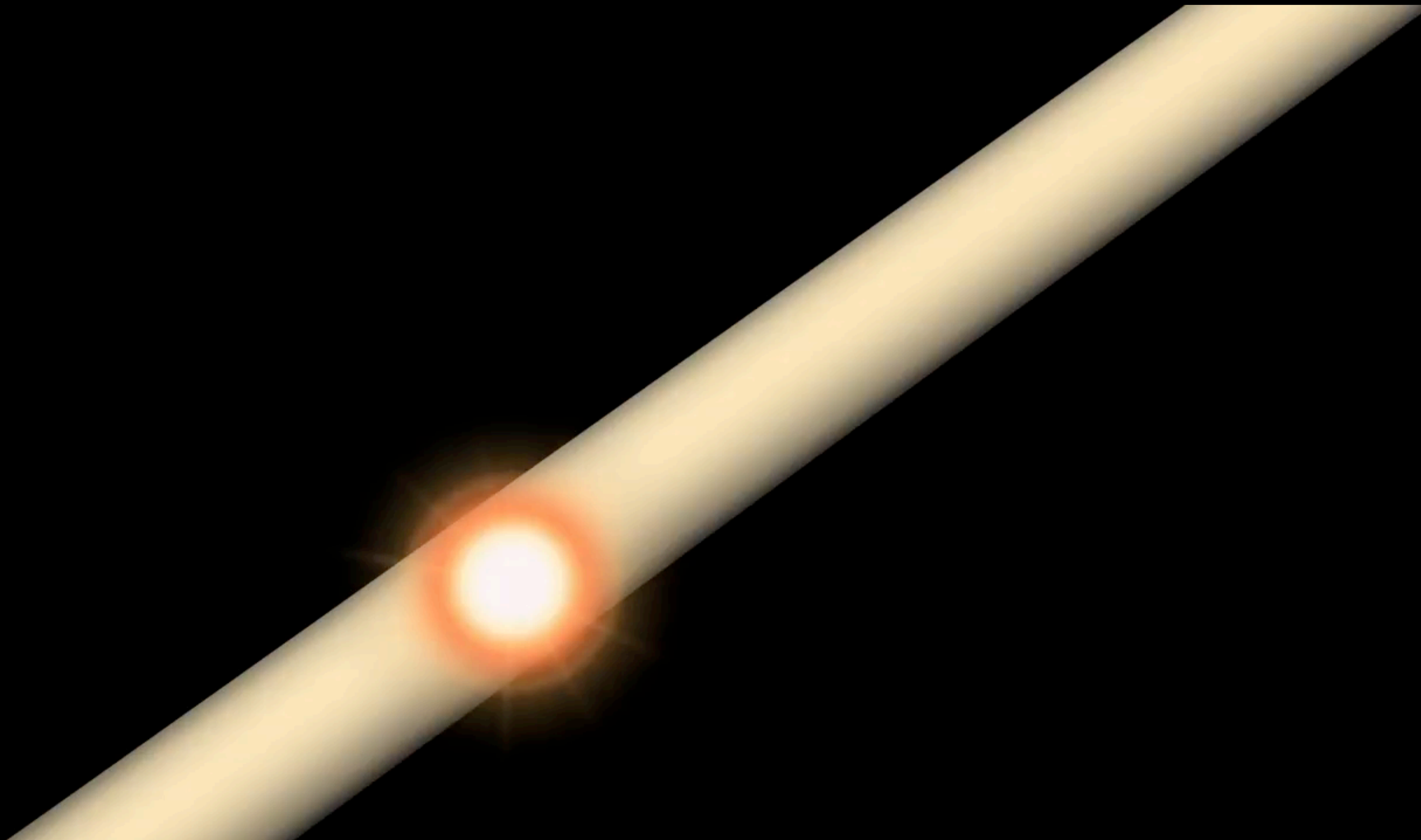
A new era in the search for DM

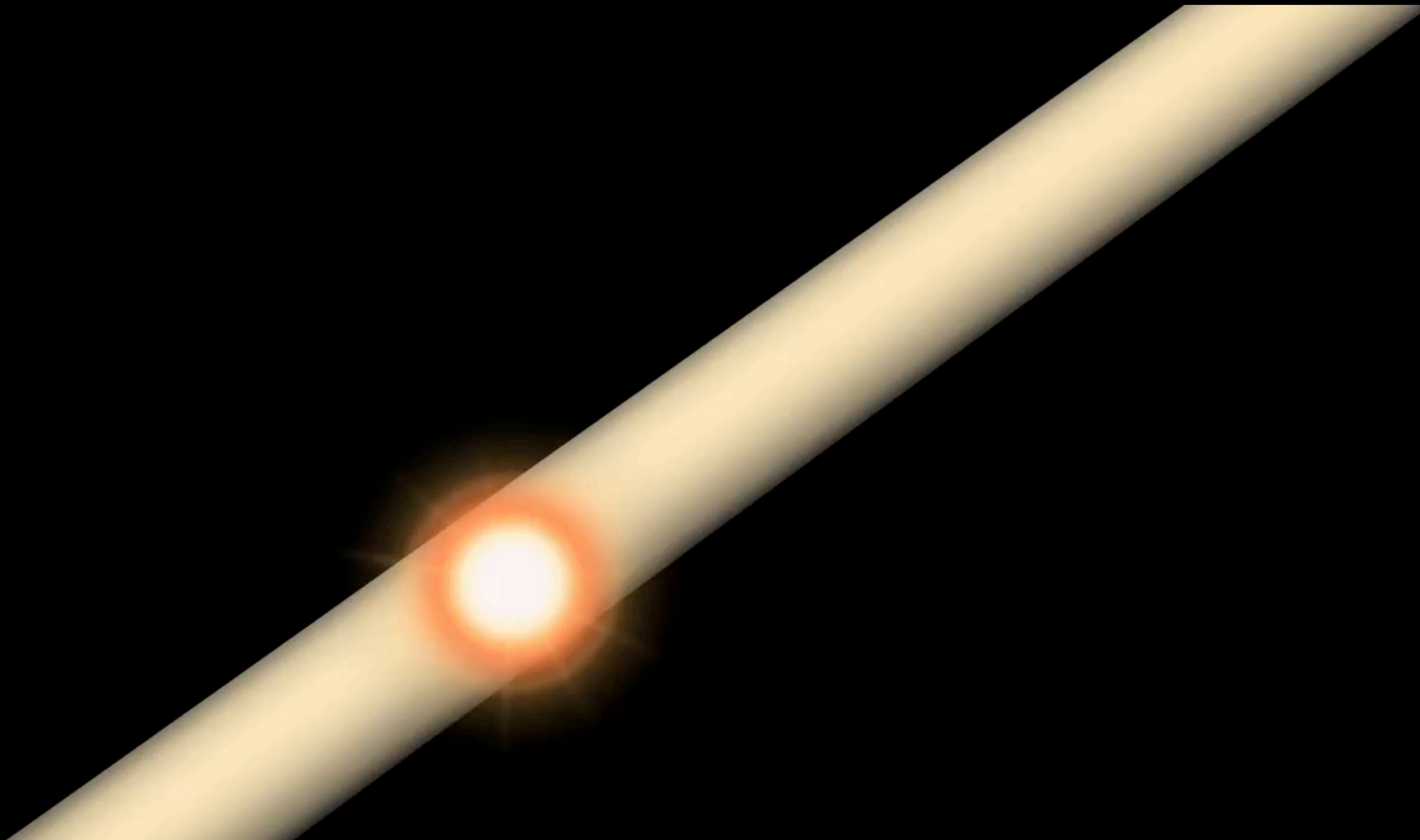
GB, Tait, *Nature (2018)1810.01668*

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

Dark matter searches at the LHC

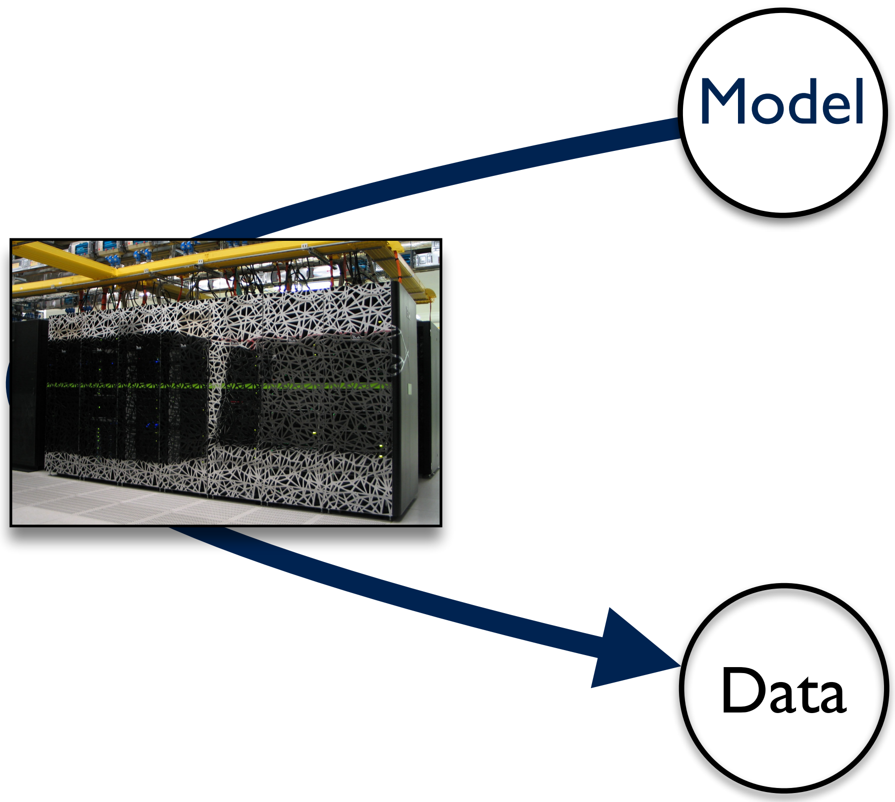


Dark matter searches at the LHC



Improving existing strategies

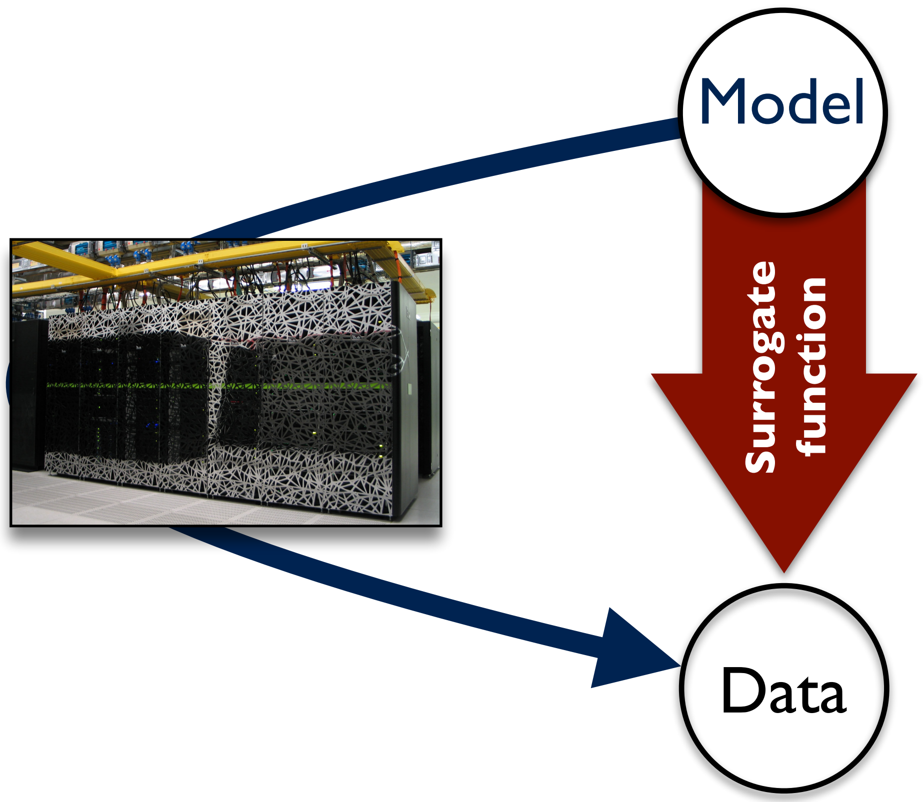
Speeding up statistical inference with Machine Learning tools



Improving existing strategies

Speeding up statistical inference with Machine Learning tools

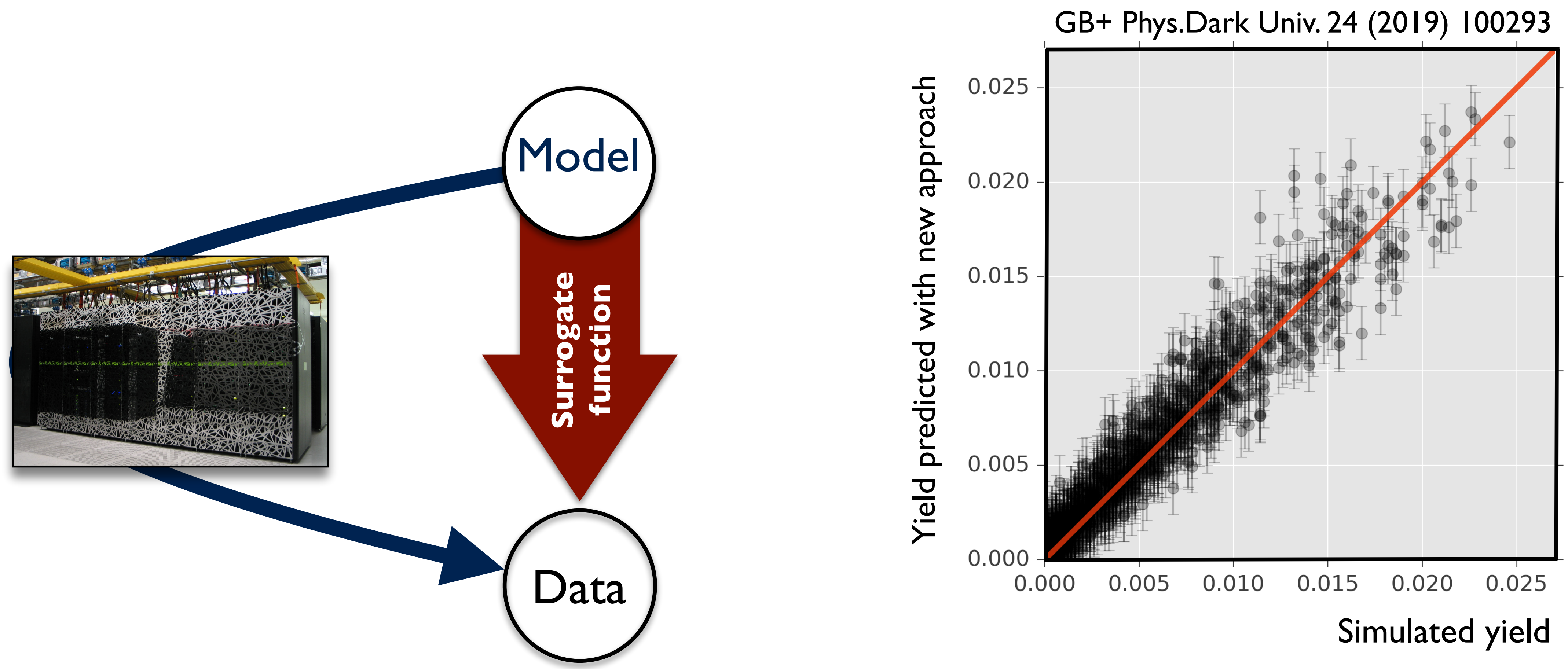
GB+ Phys.Dark Univ. 24 (2019) 100293



- 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

Speeding up statistical inference with Machine Learning tools



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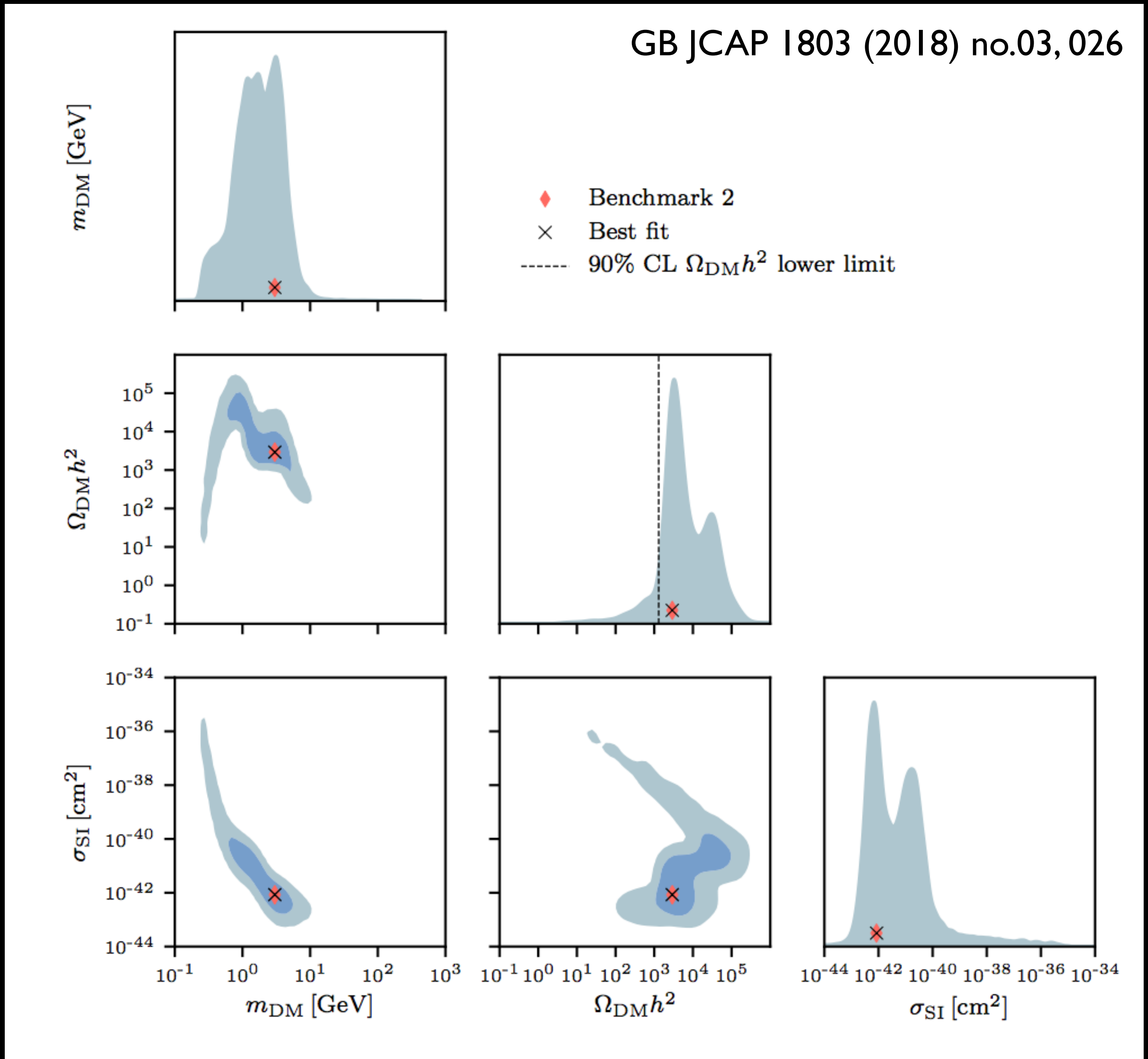
Improving existing strategies

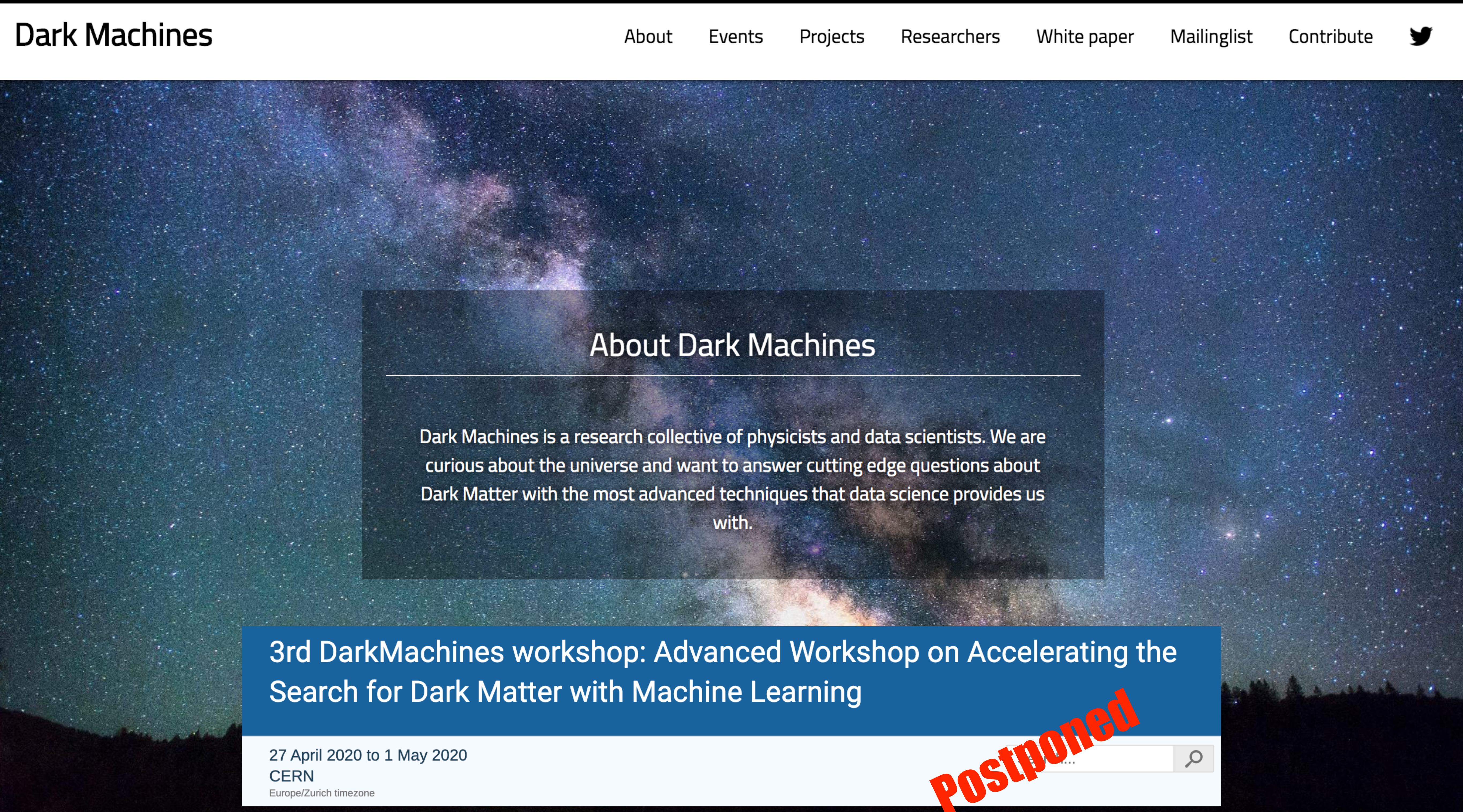
E.g. New Machine Learning tools applied to LHC searches:

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

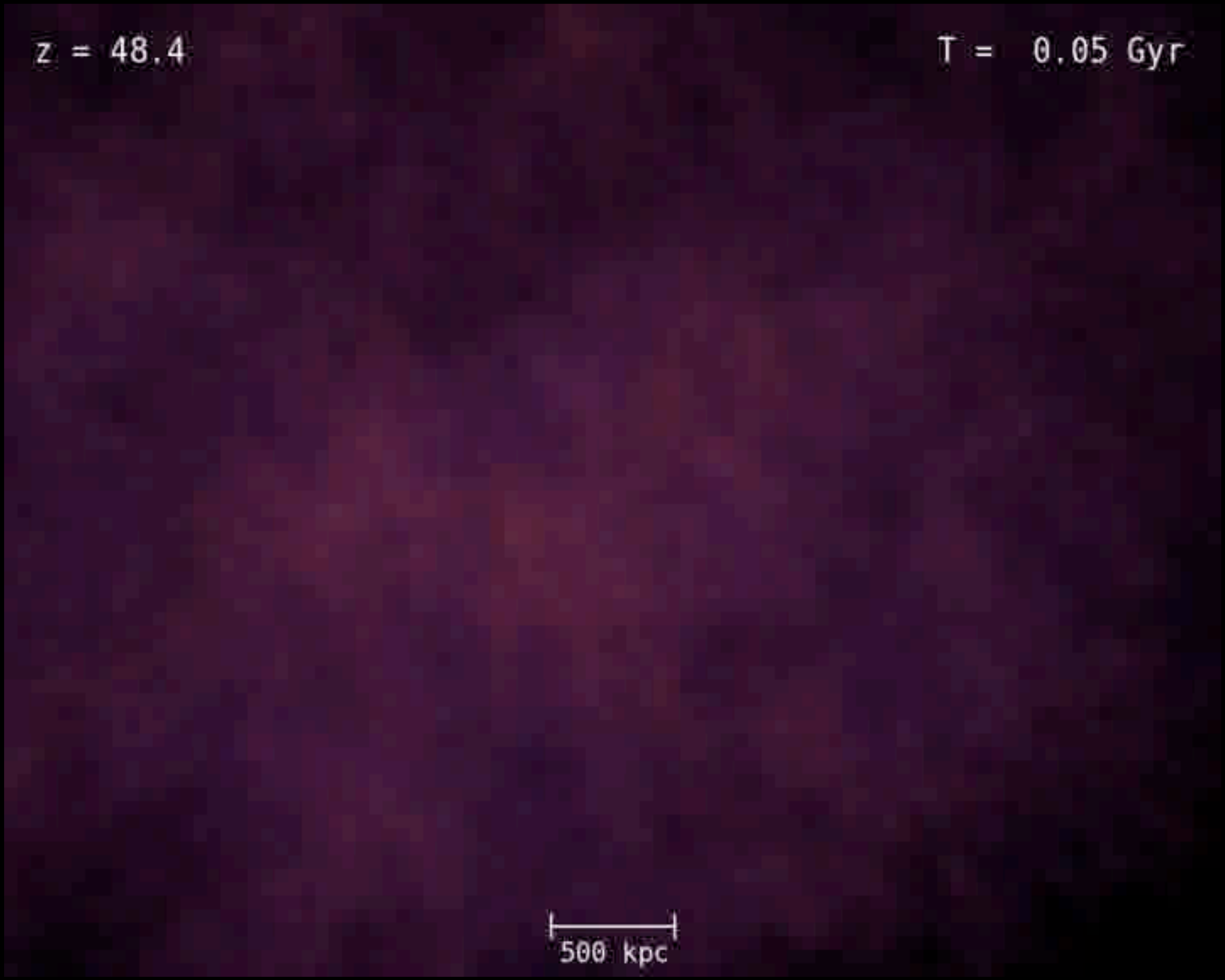


Website: darkmachines.org ; Twitter: dark_machines

The future of dark matter searches

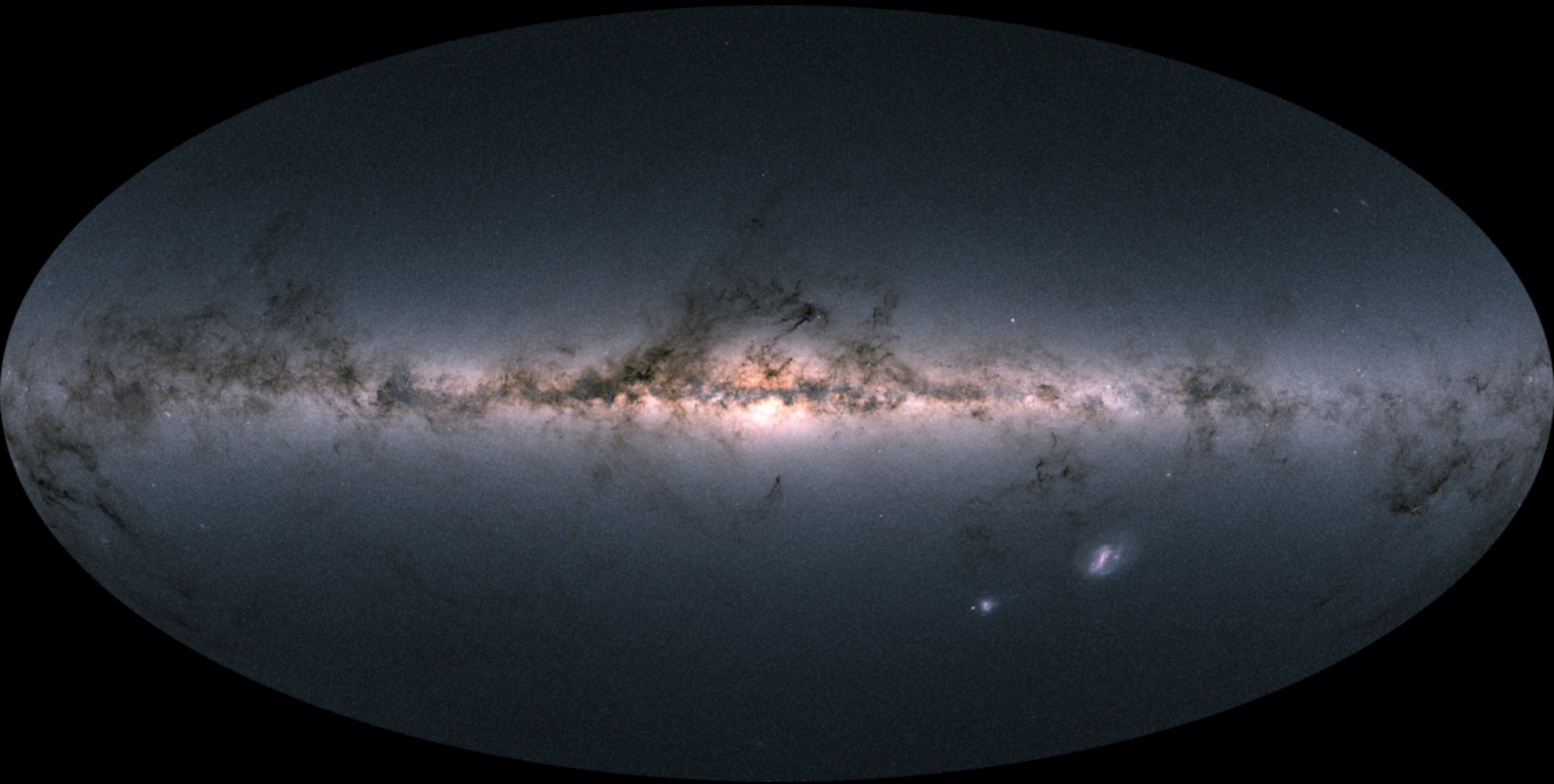
I. Broaden/improve/diversify searches
II. Exploit astro/cosmo observations
III. Exploit Gravitational Waves

Numerical Simulation: formation of a Milky Way-like galaxy



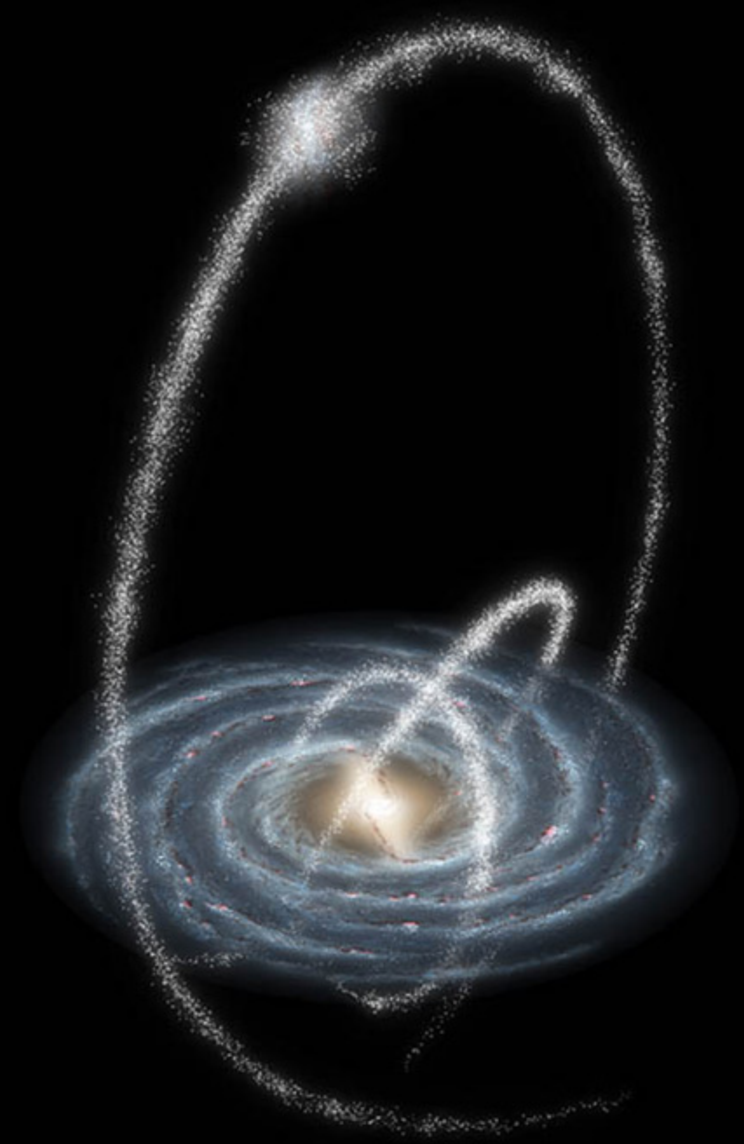
Numerical Simulation: formation of a Milky Way-like galaxy

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

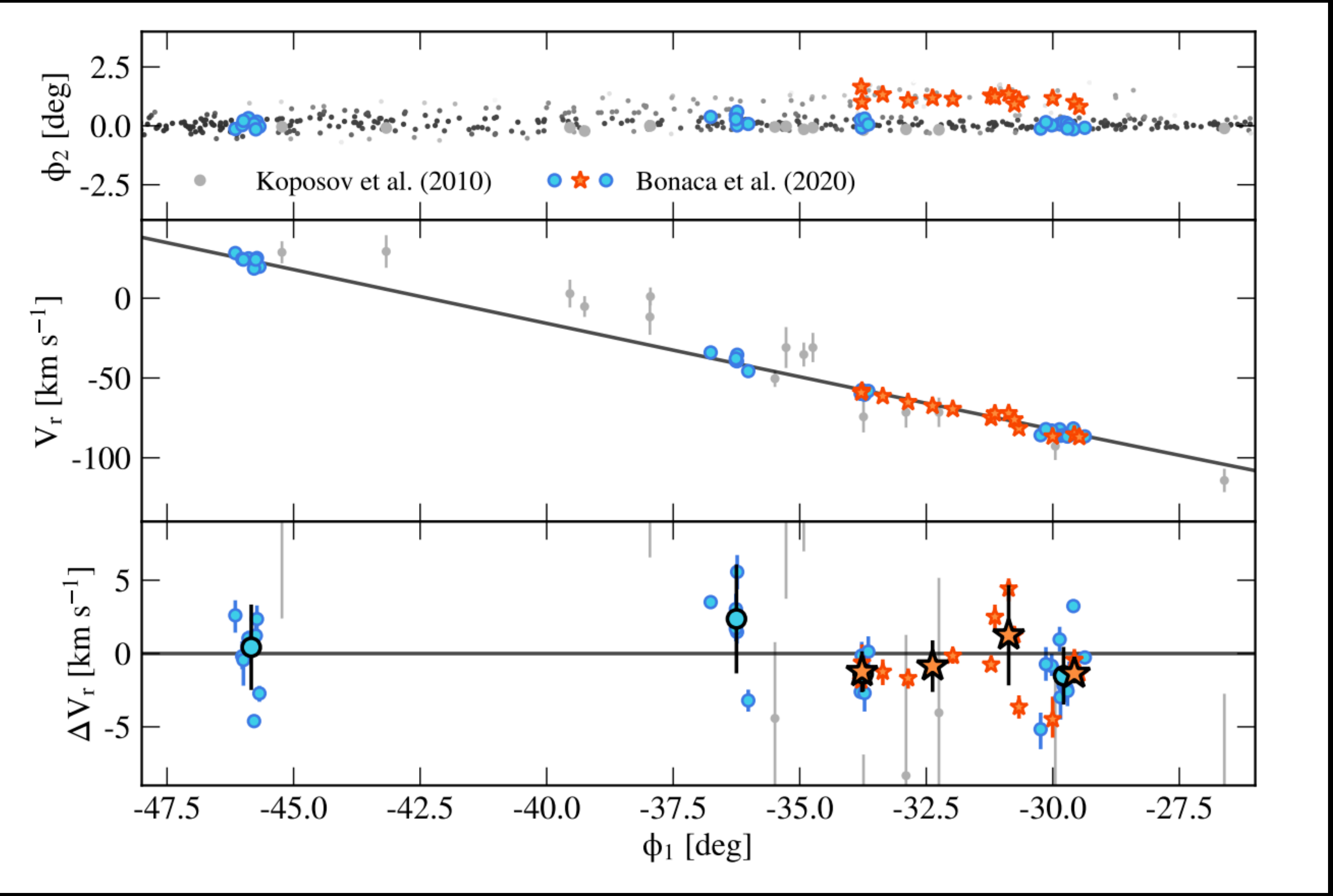


Searching for dark matter substructures in the MW

Gaia GD1 stream data!

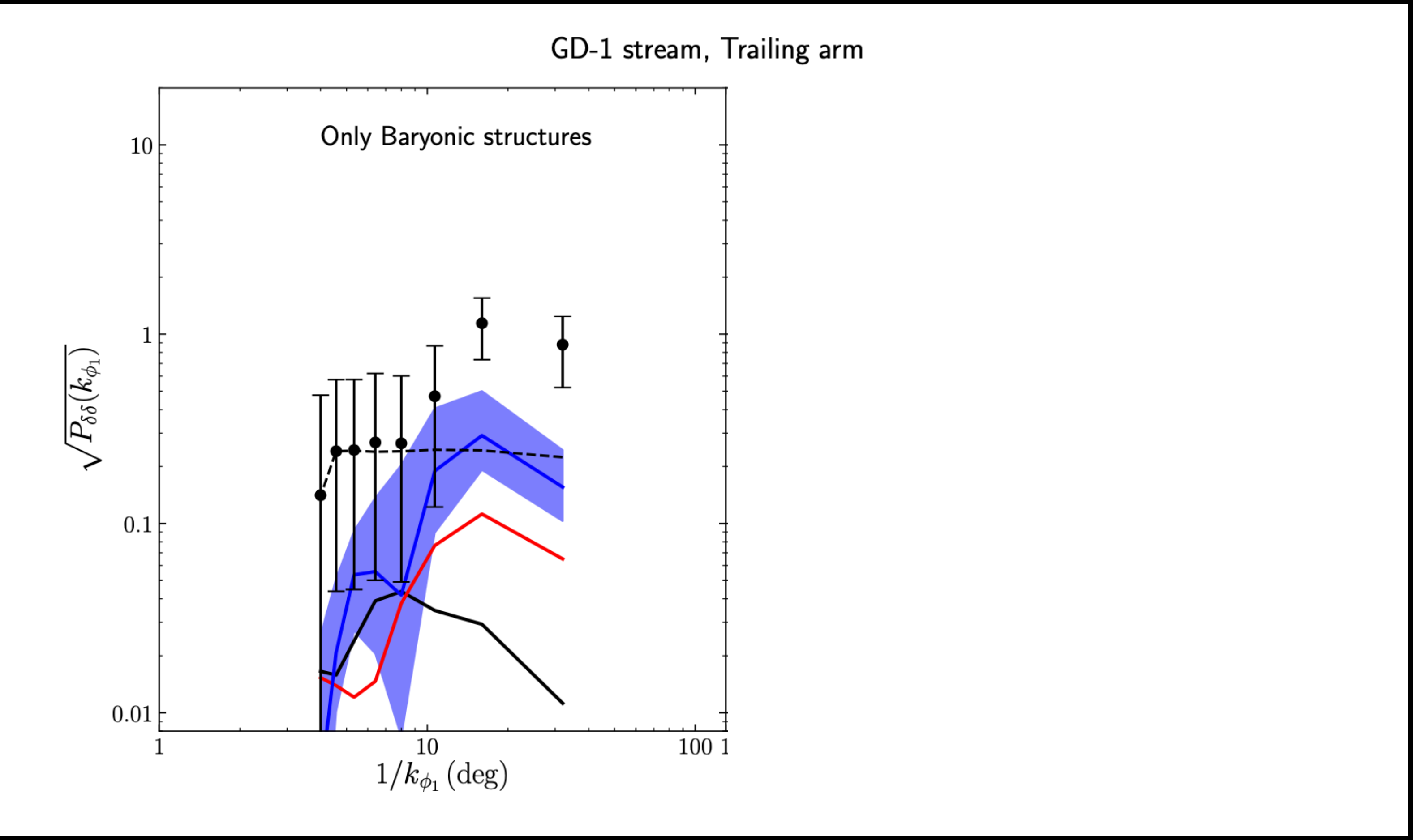
New map of stars in GD1 stream (longest cold stream in the MW) with *Gaia* second data release combined with *Pan-STARRS*.

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



Bonaca et al. 2001.07215

Statistical analysis of perturbations: Strong hints of dark substructures!



- Gaia GD1 stream data exhibit substantial 'structure'

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

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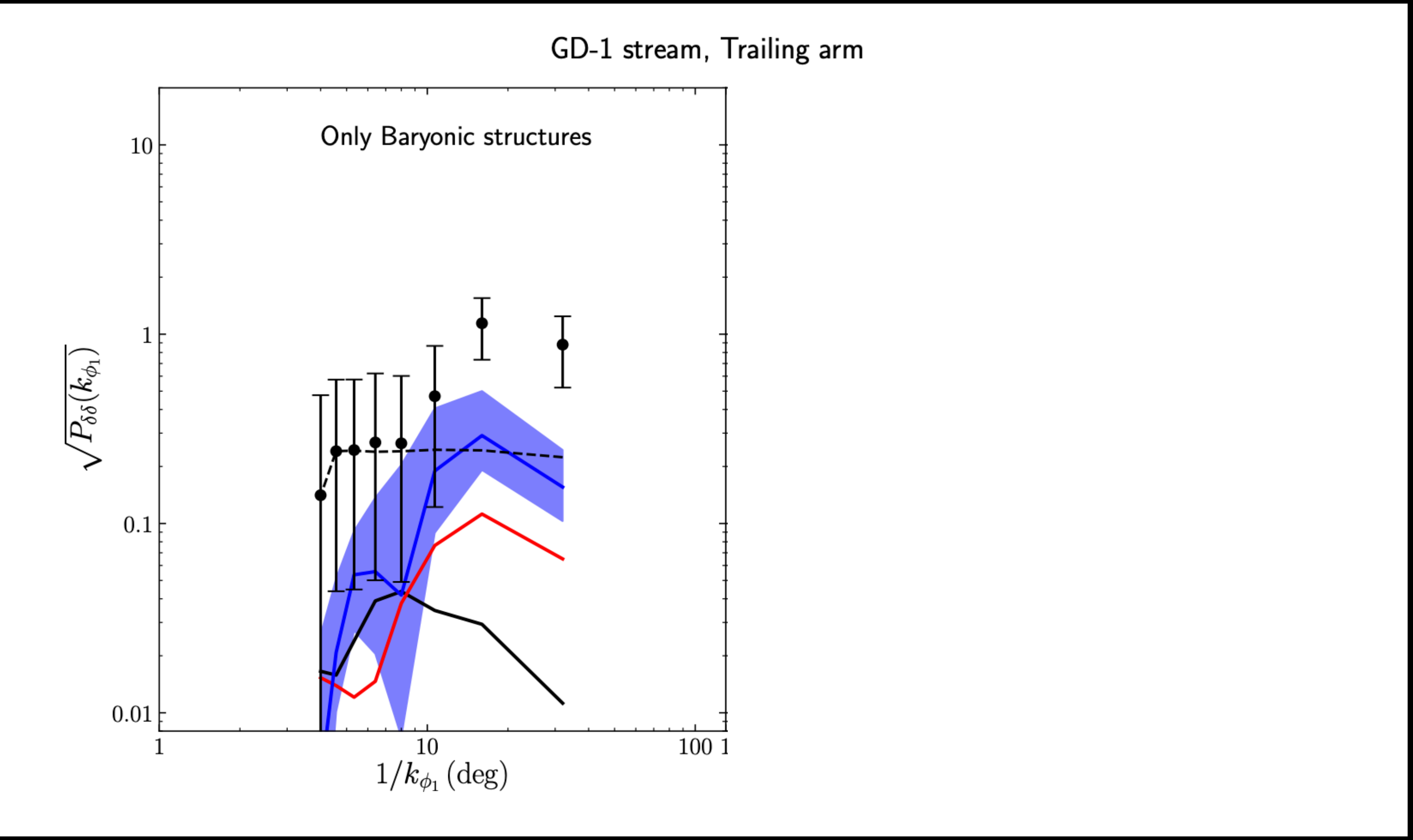

Banik, Bovy, GB, Erkal, de Boer, arXiv:1911.02663

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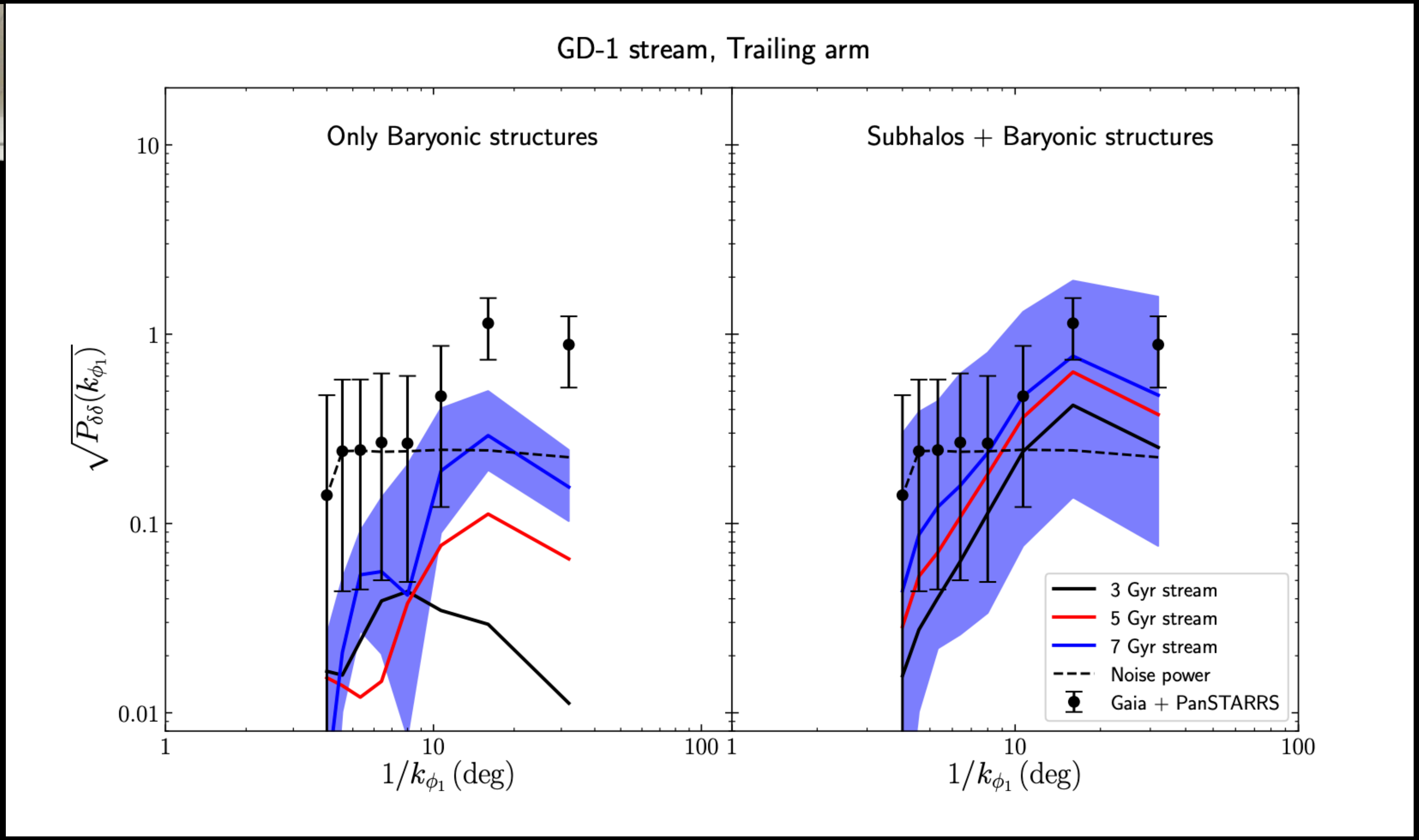

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- Density fluctuations cannot be explained by "baryonic" structures (GC, GMC, spiral arms etc)

- **Density fluctuations are consistent with CDM predictions (not a fit!)**

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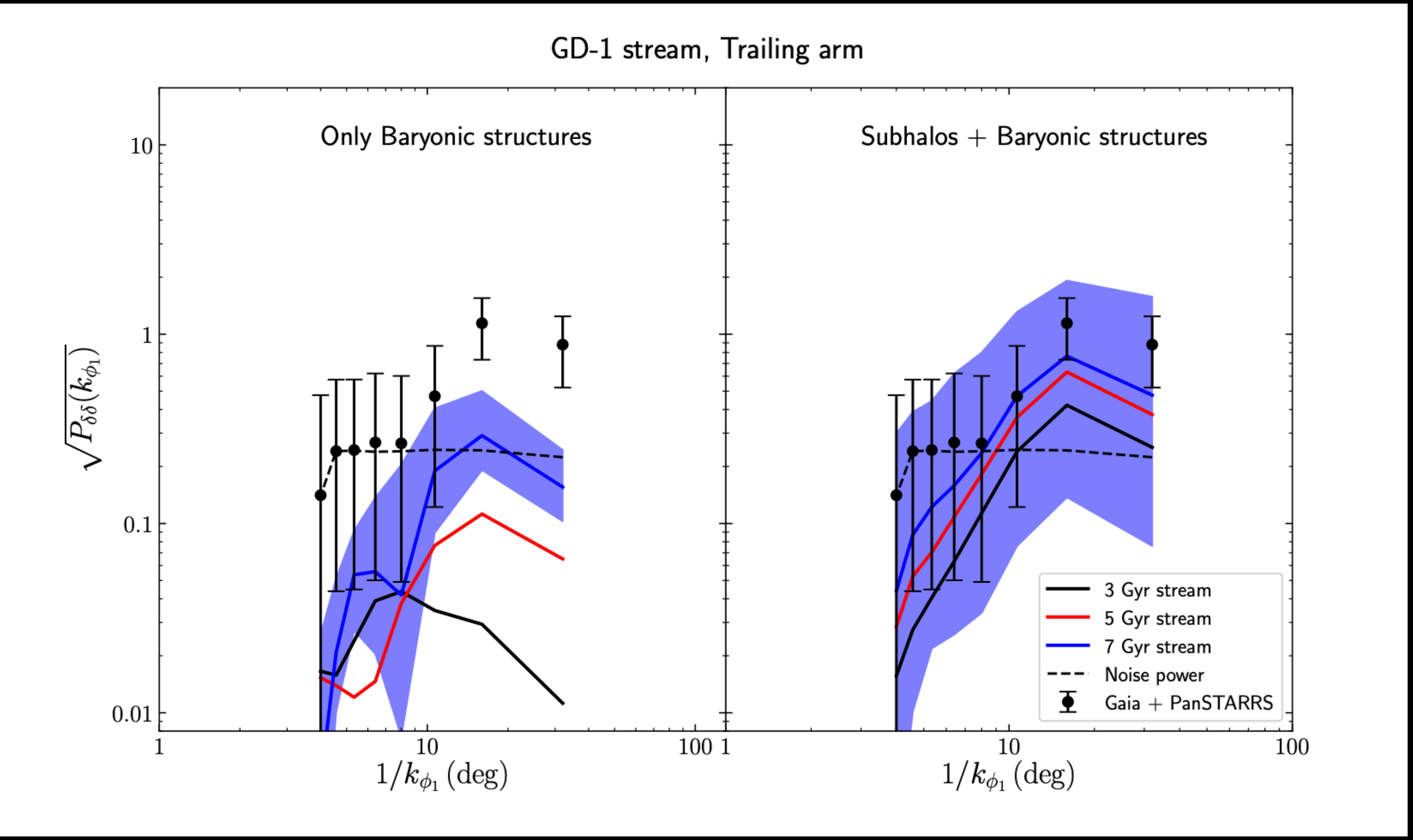

Banik, Bovy, GB, Erkal, de Boer, arXiv:1911.02663

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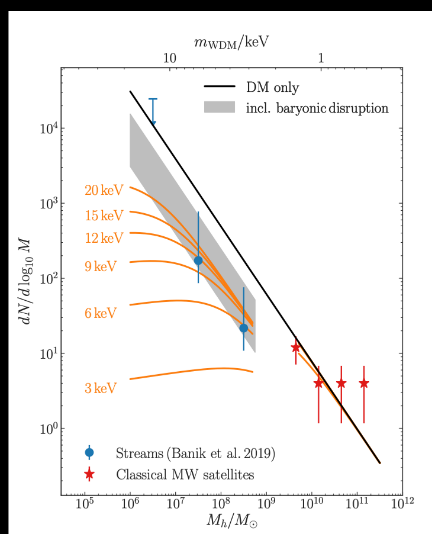
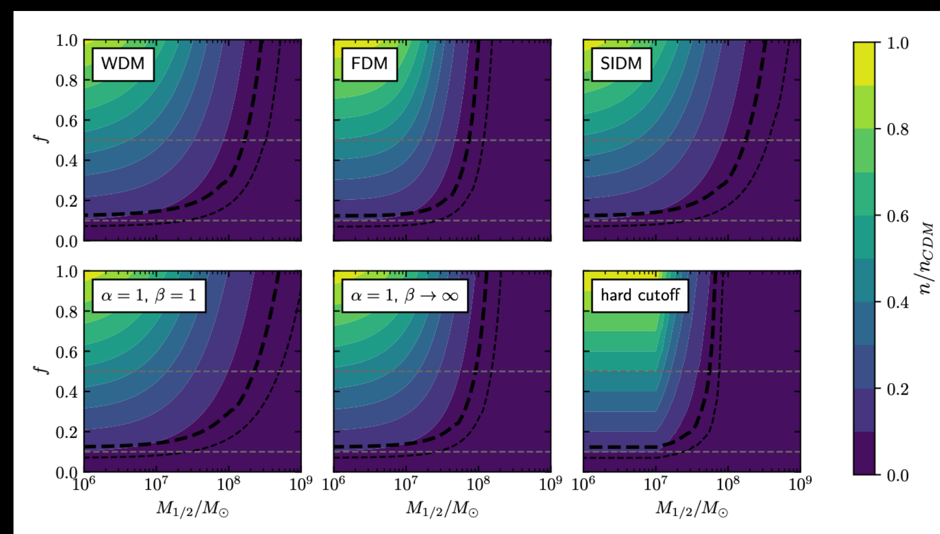
- Density fluctuations are consistent with CDM predictions (not a fit!)

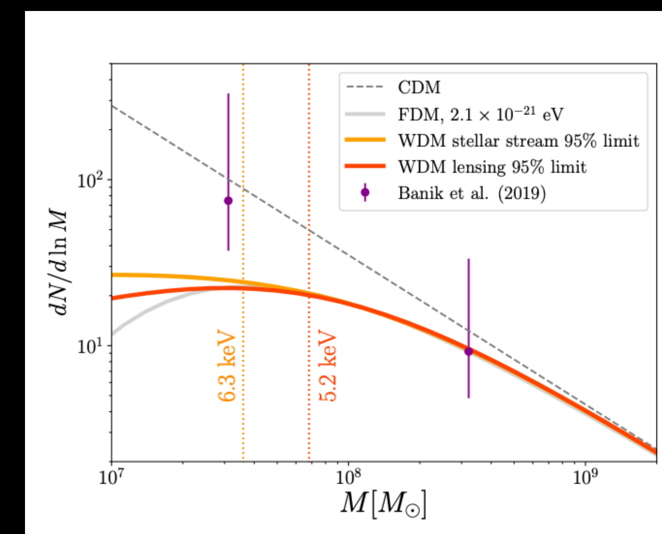
Statistical analysis of perturbations: Stringent constraints on the nature of DM



1911.02663



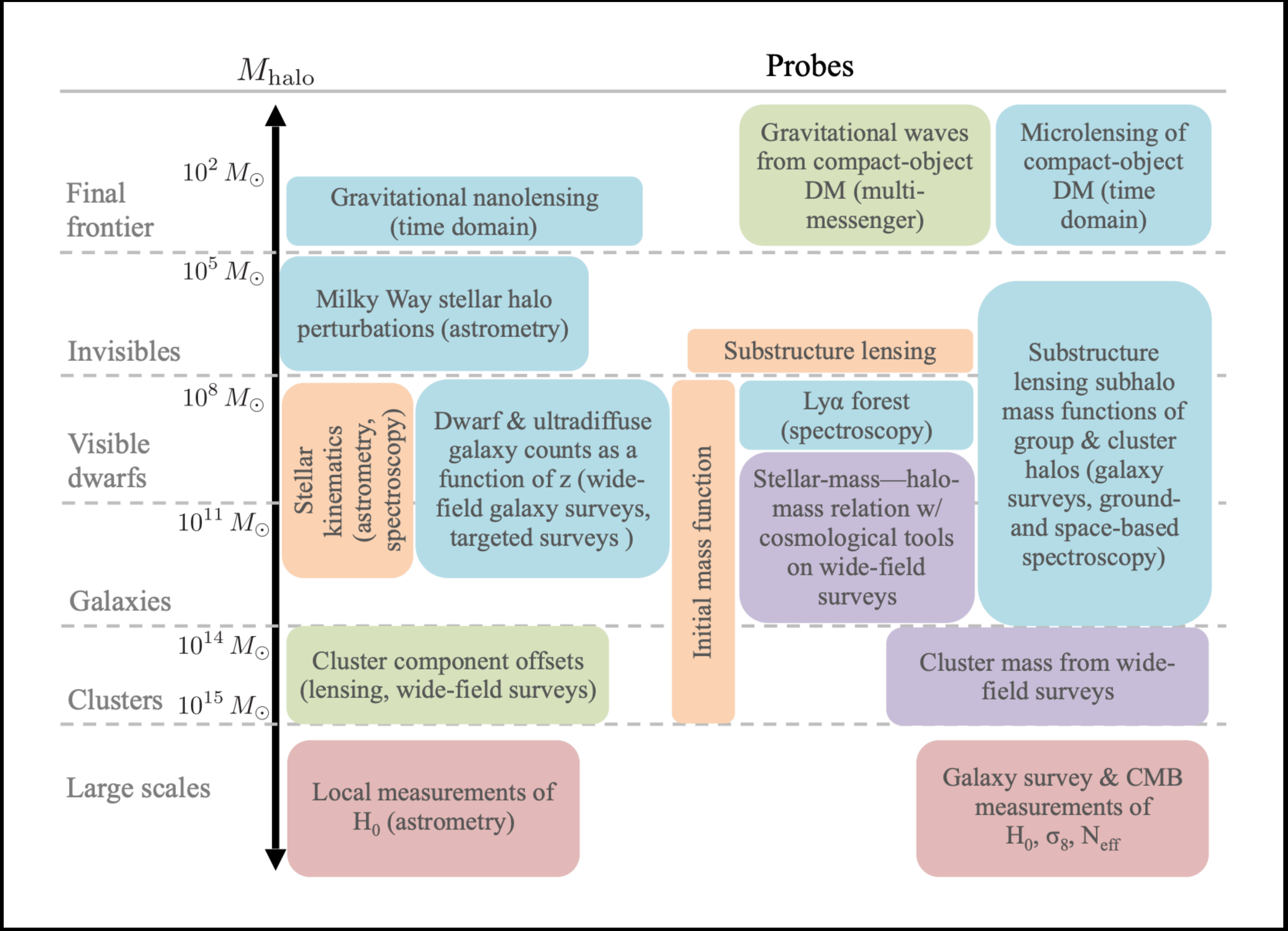
2001.11013



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

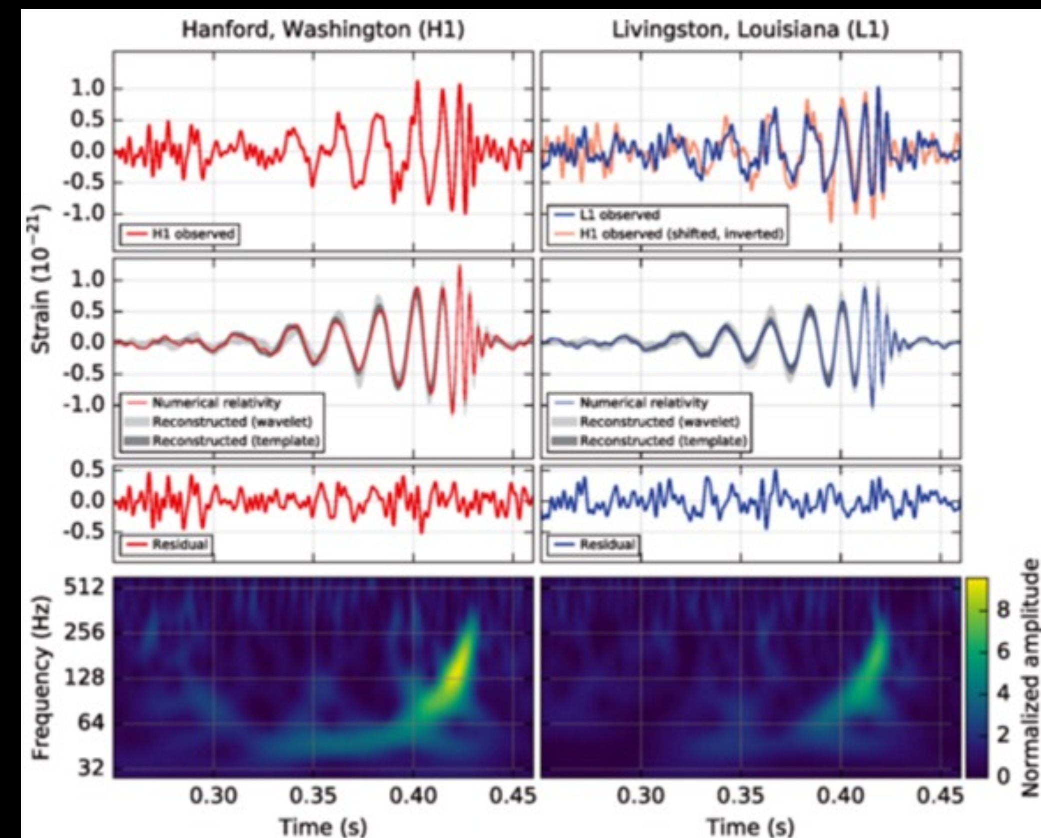
I. Broaden/improve/diversify searches
II. Exploit astro/cosmo observations
III. Exploit Gravitational Waves

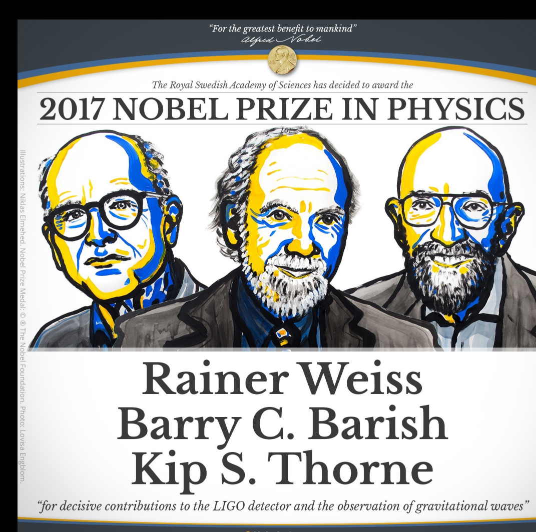
Gravitational Waves

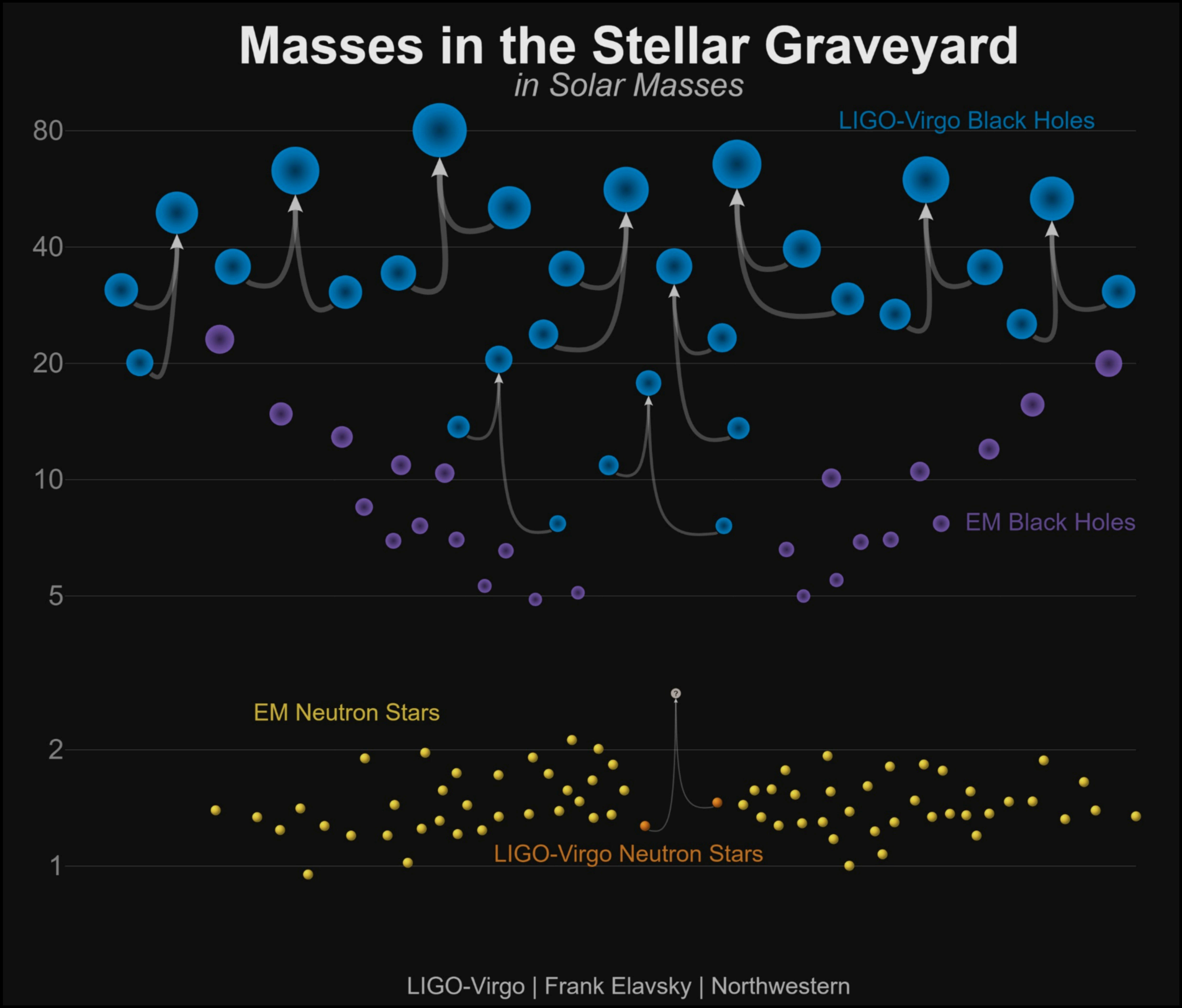
"The discovery that shook the world"

LIGO & Virgo coll, PRL 116, 061102

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



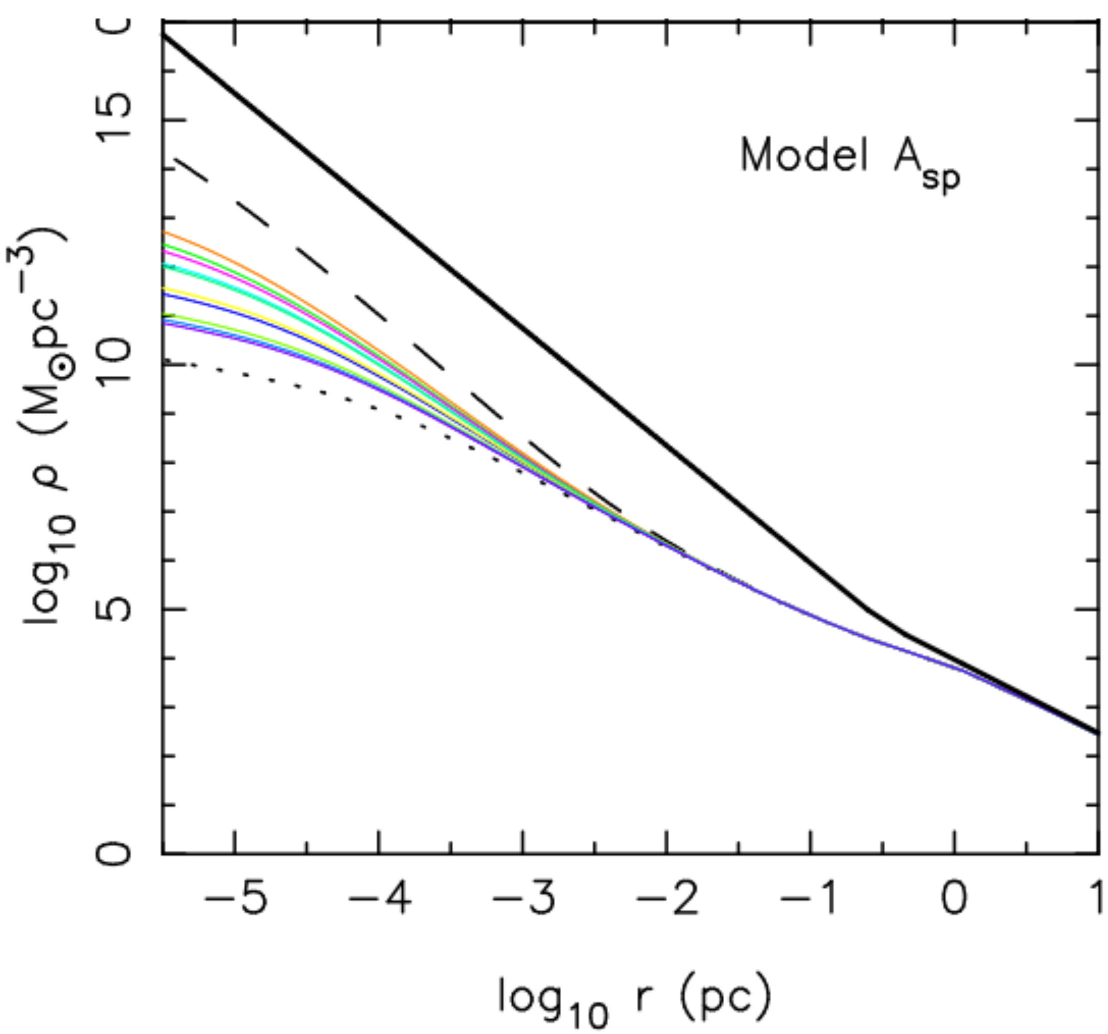




Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

Dark Matter 'dress' around BHs

GB & Merritt 2005



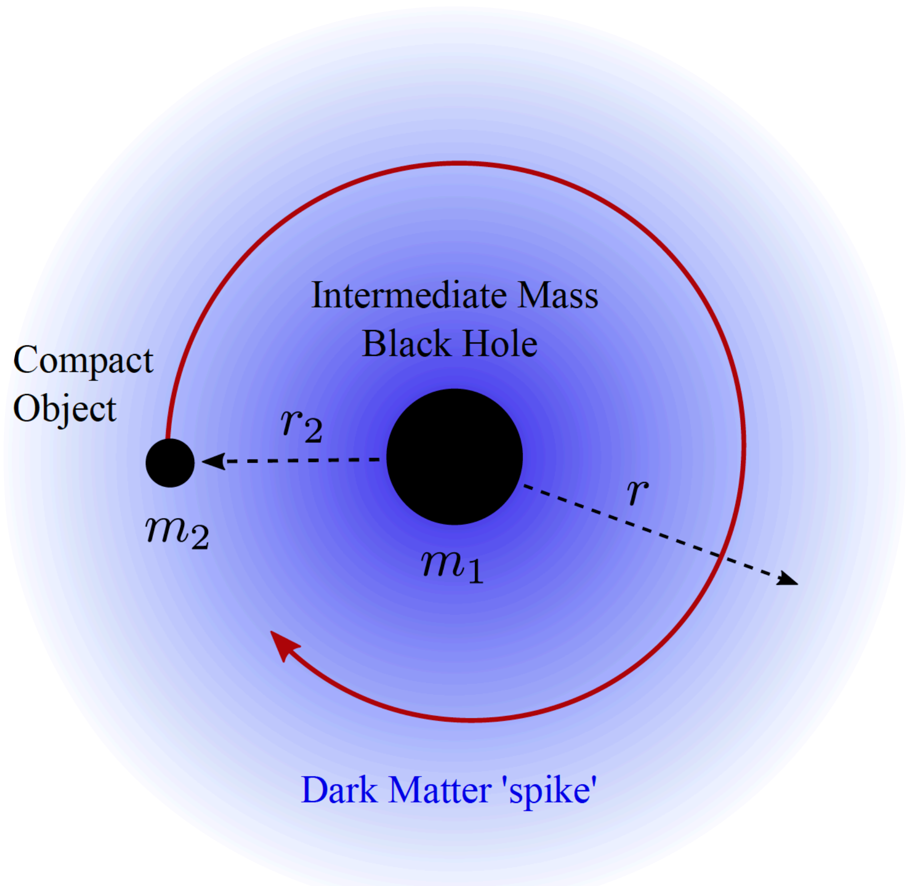
- **Adiabatic 'spikes' around SMBHs** *(Gondolo & Silk 2000)*
- **'Mini-spikes' around IMBHs** *(GB, Zentner, Silk 2005)*
- **Overdensities around primordial BHs** *(e.g. Adamek et al. 2019)*
- **Ultralight boson 'clouds'** *(e.g. Brito, Cardoso & Pani 2015)*

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)

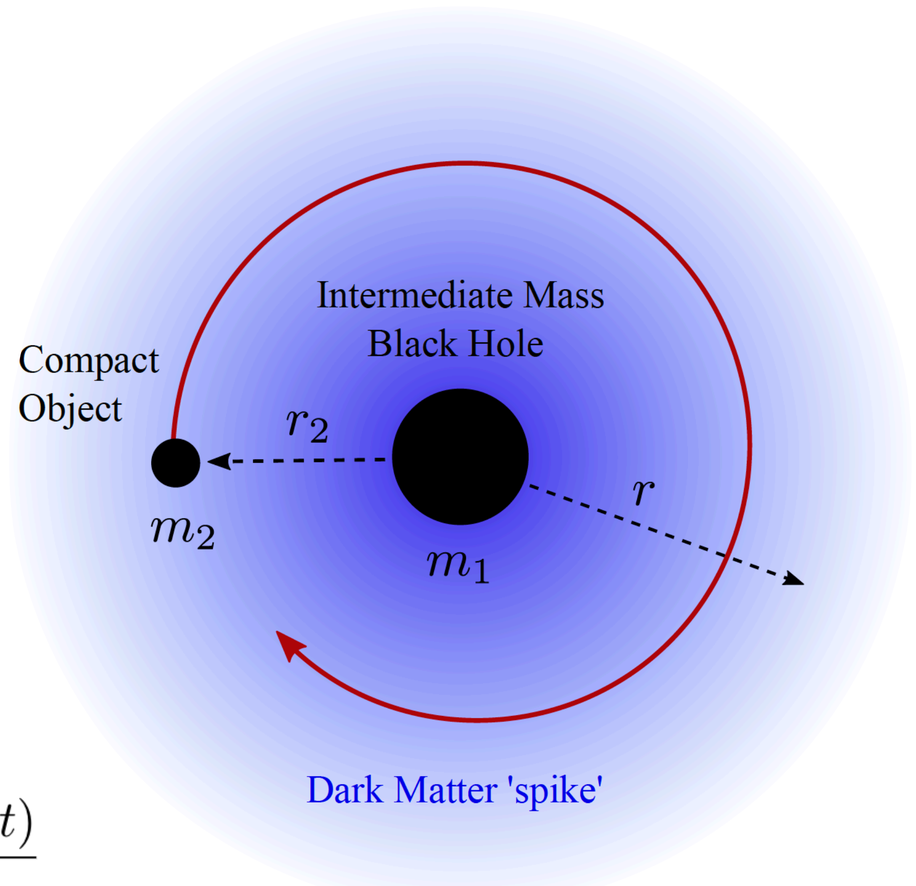
Dark Matter around BHs

Energy losses:

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

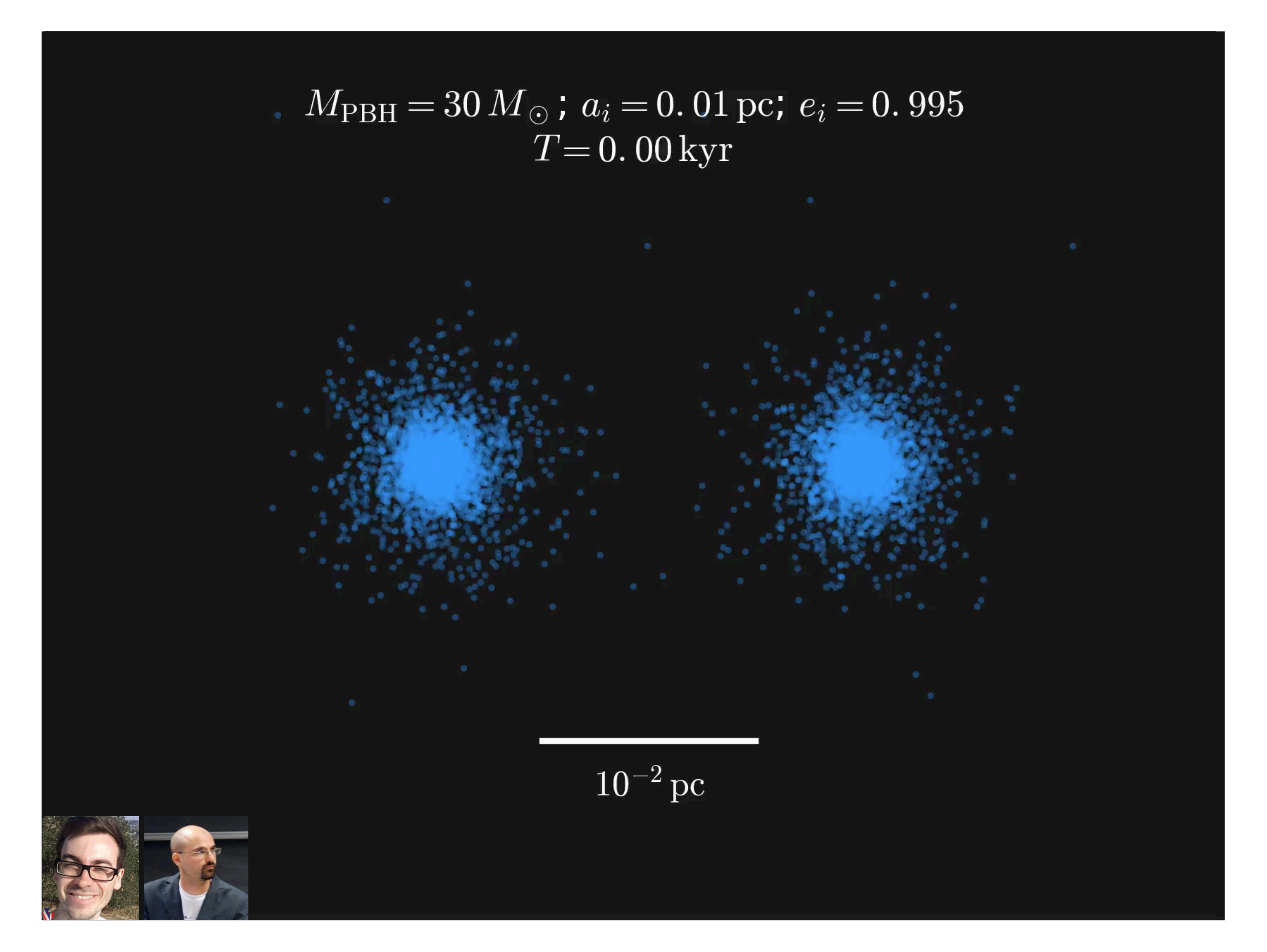
Separation:

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



Kavanagh, GB et al. 2002.12811

‘Dressed’ BH-BH merger



Kavanagh, Gaggero & GB, arXiv:1805.09034

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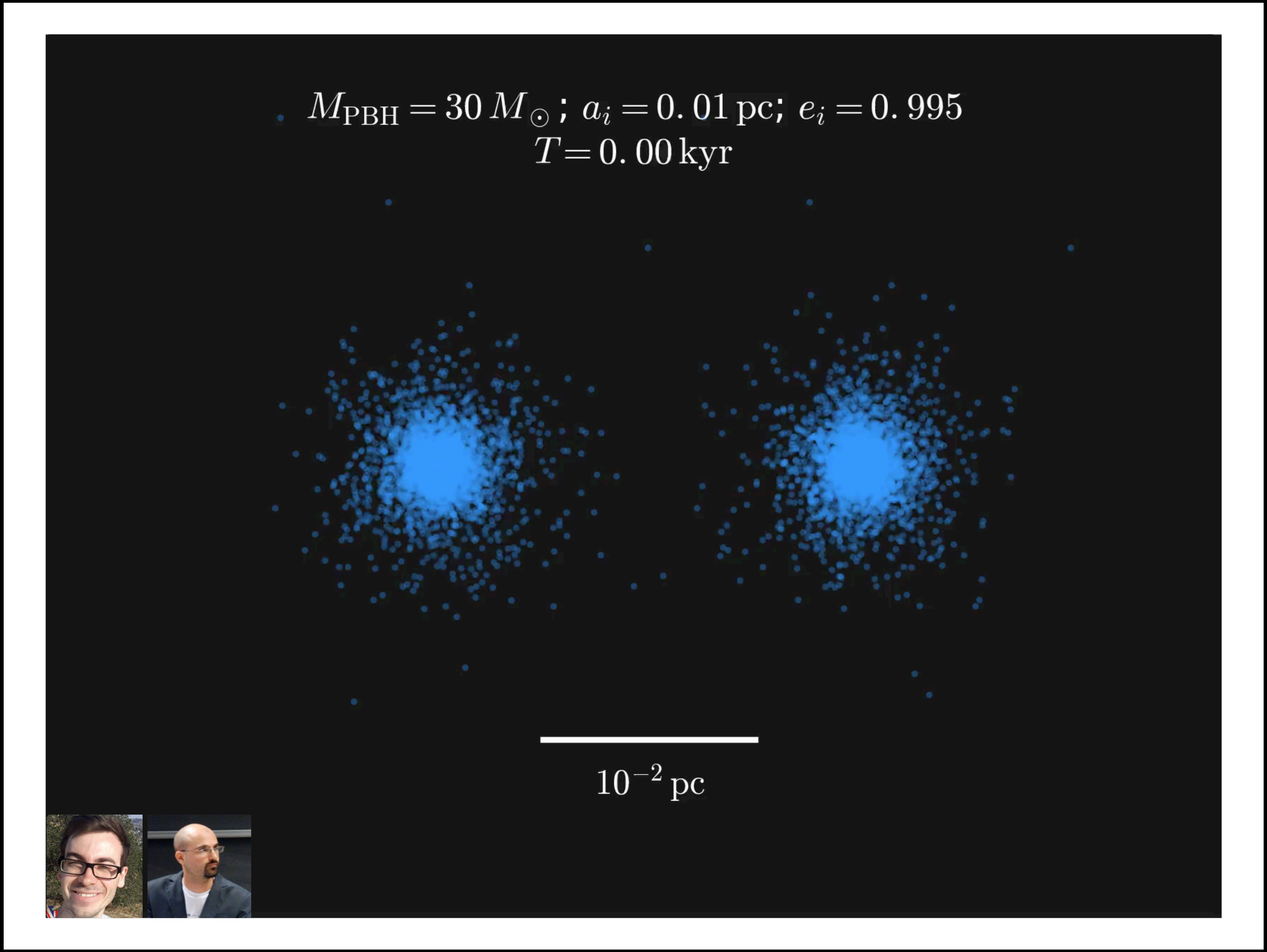

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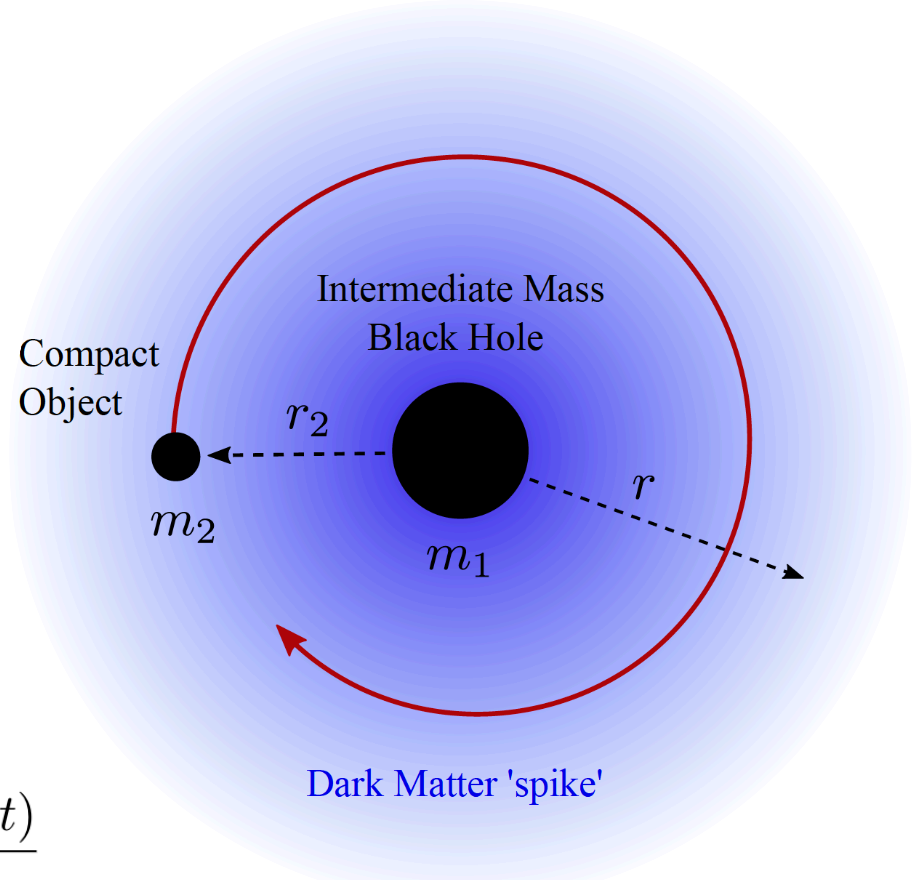

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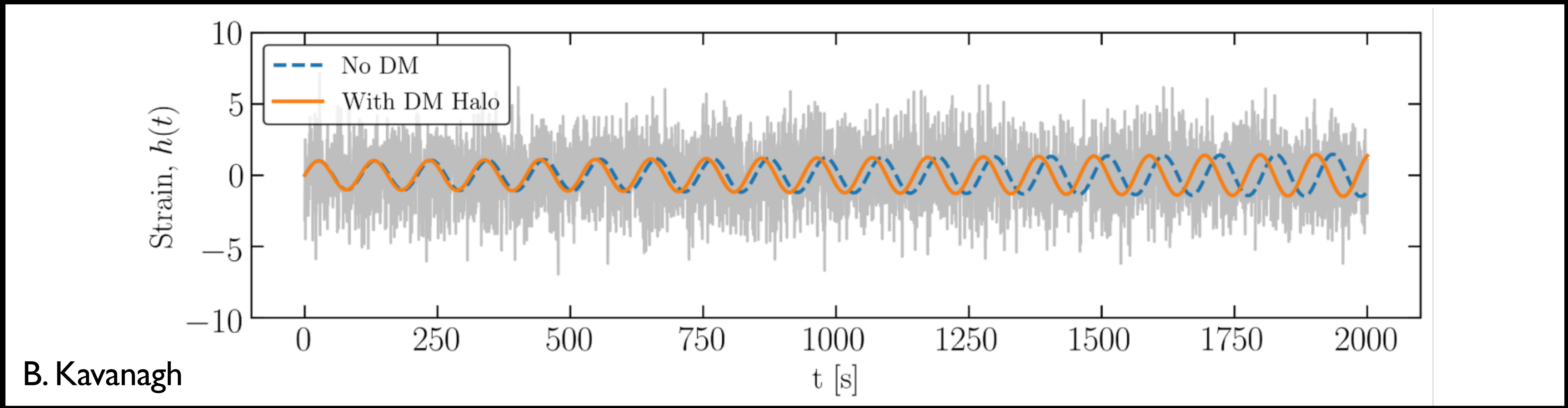
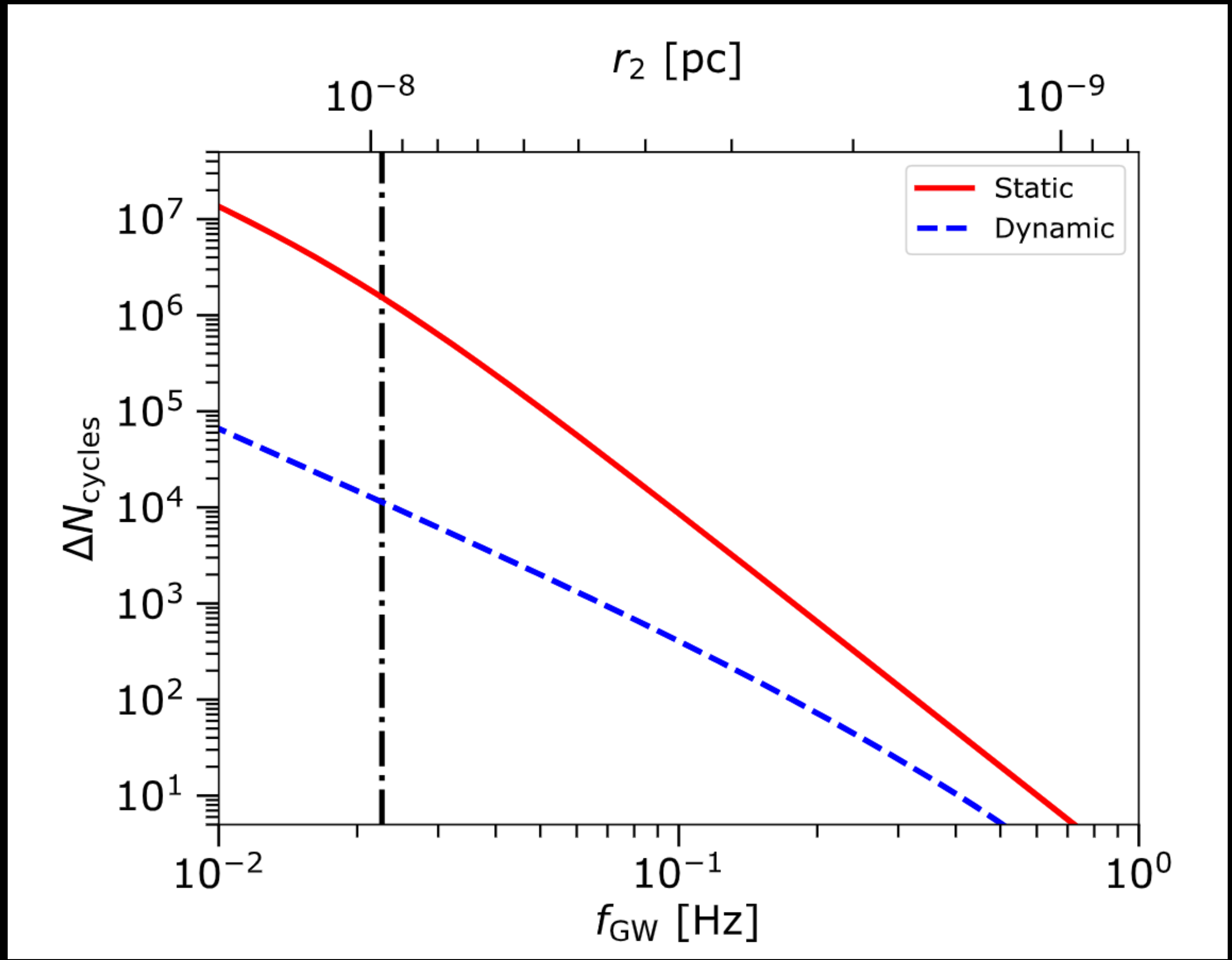
Time-dependent dark matter profile:

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

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

Primordial Black Holes

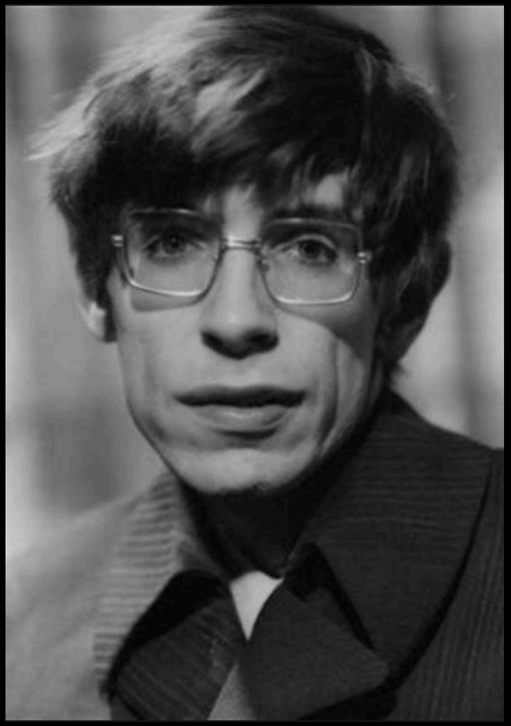
Mon. Not. R. astr. Soc. (1971) **152,** 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

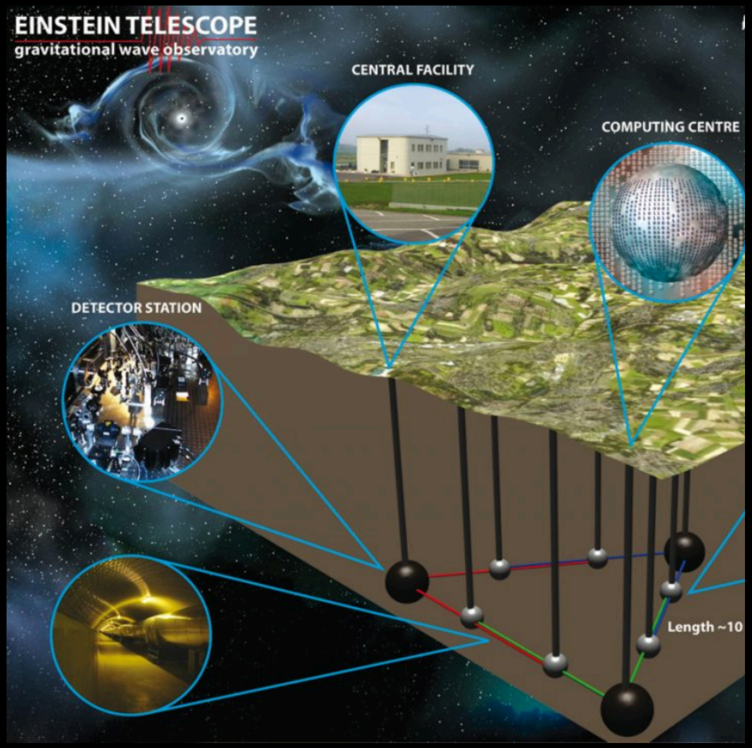
(Received 1970 November 9)



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.

Can we convincingly discover *primordial* BHs?

Yes, e.g. if we:

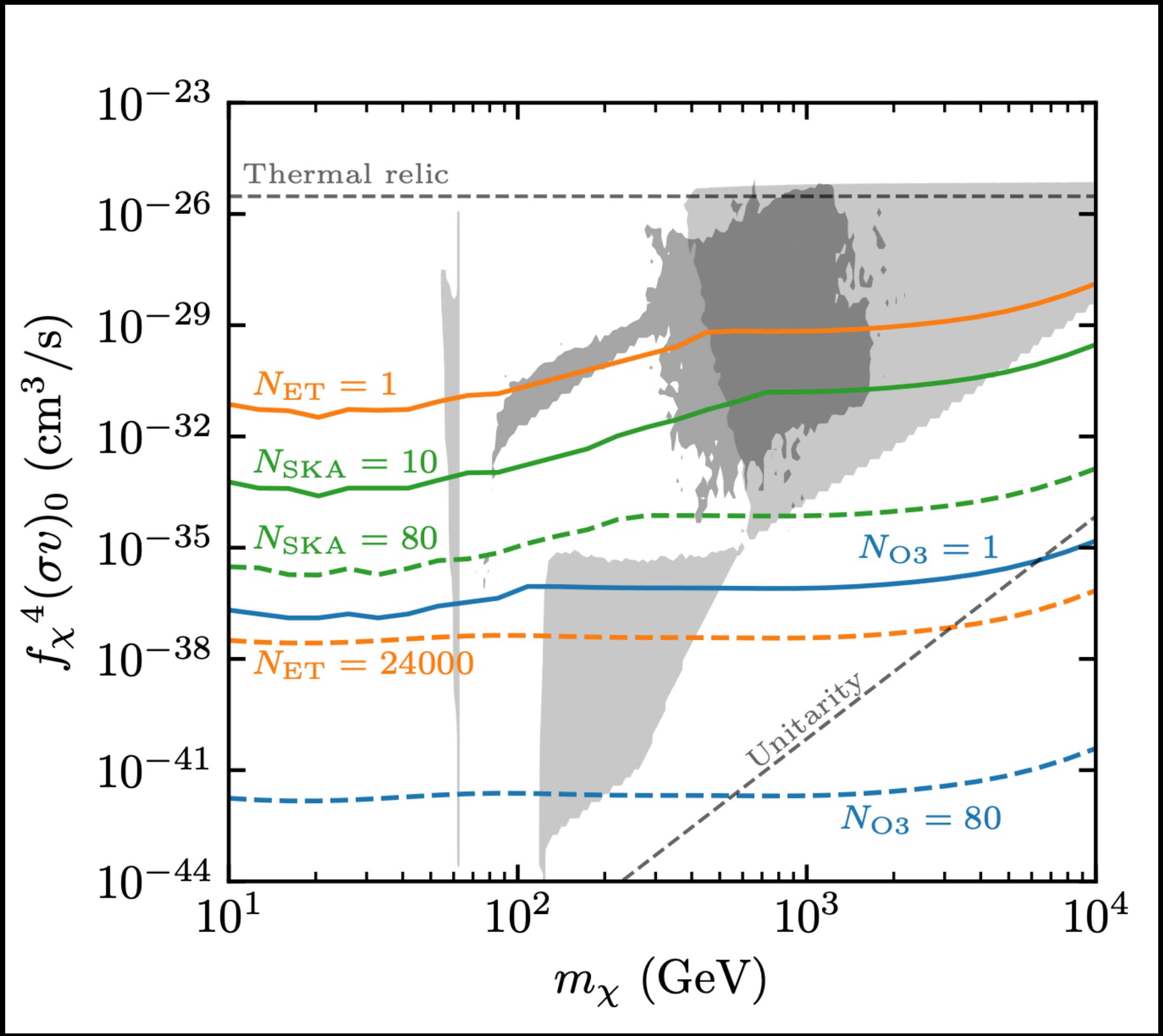


I. Detect sub-solar mass BHs with joint Ligo/Virgo observing run 3 (in progress)

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]

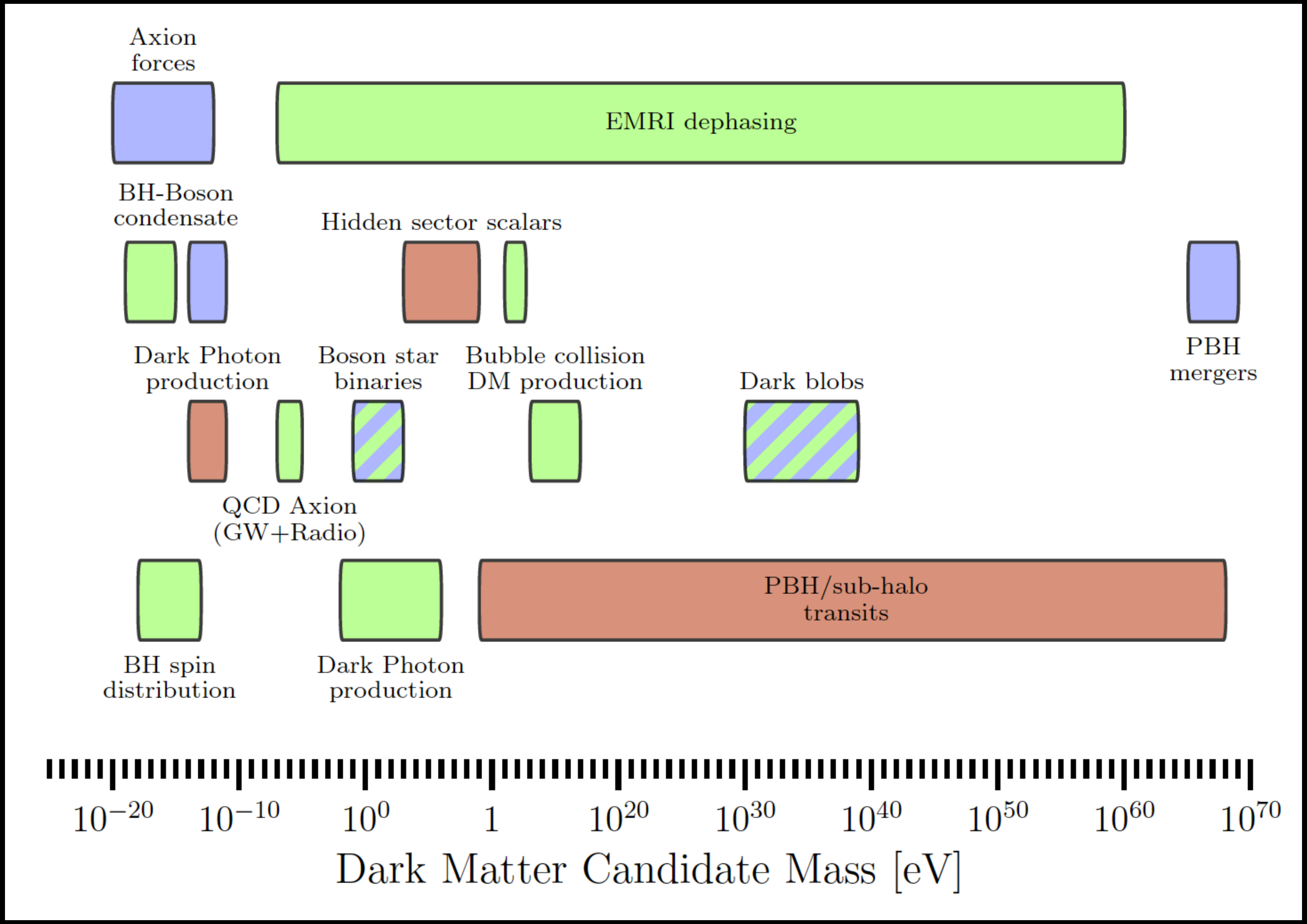
If PBHs discovered: Extraordinarily stringent constraints on new physics at the weak scale!



GB, Coogan, Gaggero, Kavanagh, Weniger 1905.01238

- 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