A new era in the quest for
Dark Matter

Gianfranco Bertone
GRAPPA center of excellence, U. of Amsterdam

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GRAPPA

GRavitation AstroParticle Physics Amsterdam

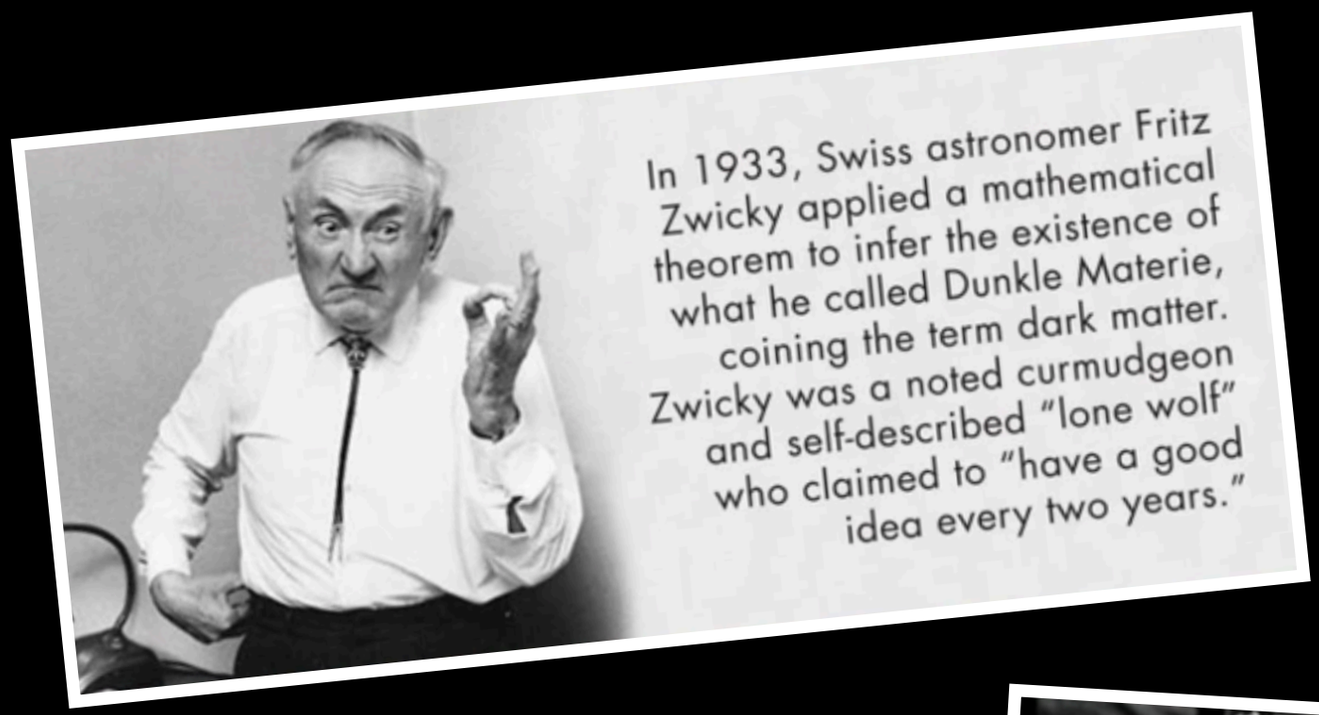
Plan of the talk:

Preamble: the dark universe *narrative*

Part I: What have we learnt?

Part II: A new era in the quest for DM

Dark Matter "Mythology"

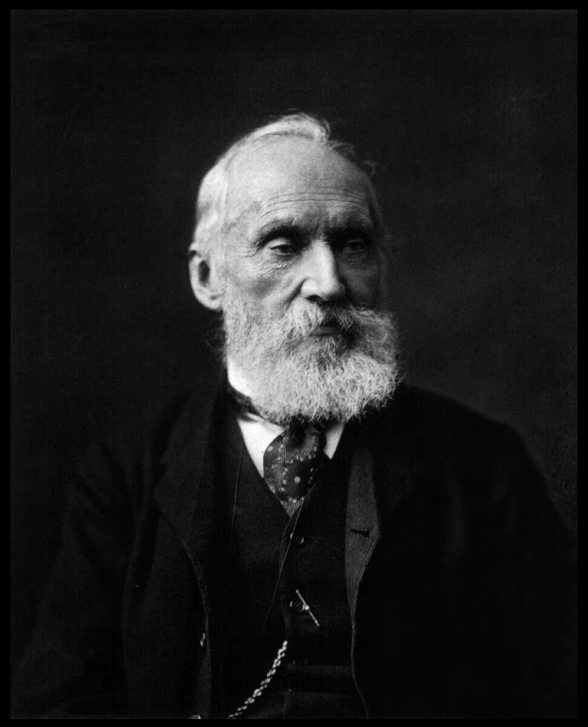


In 1933, Swiss astronomer Fritz Zwicky applied a mathematical theorem to infer the existence of what he called Dunkle Materie, coining the term dark matter. Zwicky was a noted curmudgeon and self-described "lone wolf" who claimed to "have a good idea every two years."

Grappling with the "galaxy rotation problem" (galaxies didn't have enough observable stuff in them to stop them from flying apart), Vera Rubin calculated that galaxies must contain at least six times more mass than what's observable.

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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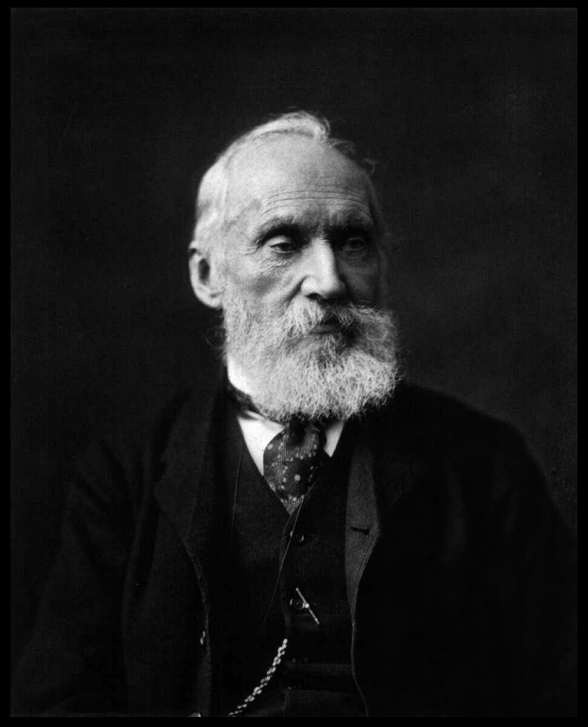

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Applies viral theorem to star cluster:"*the non luminous masses contribute no higher order of magnitude to the total mass than the luminous masses"*

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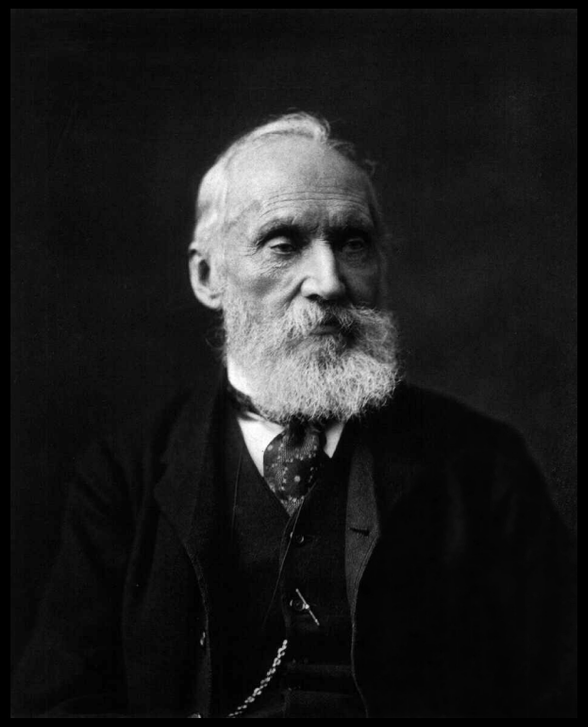

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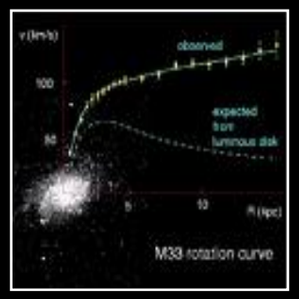
Fritz Zwicky (1933)

"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*"*

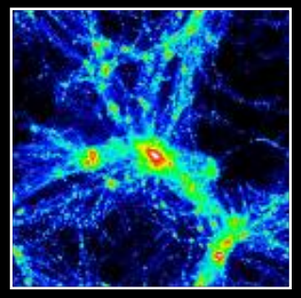
"A history of Dark Matter" GB & Hooper - RMP *1605.04909*
"How dark matter came to matter" de Swart, GB, van Dongen - Nature Astronomy; *1703.00013*

What is the Universe made of?

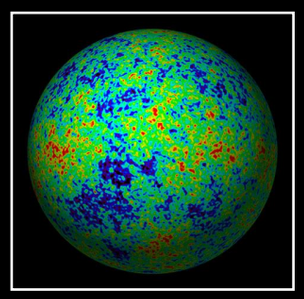
OBSERVATIONS



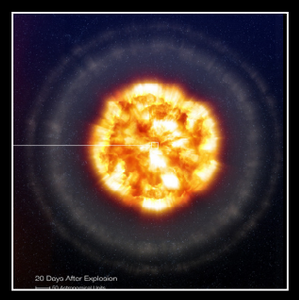
• Rotation Curves



• Clusters of galaxies

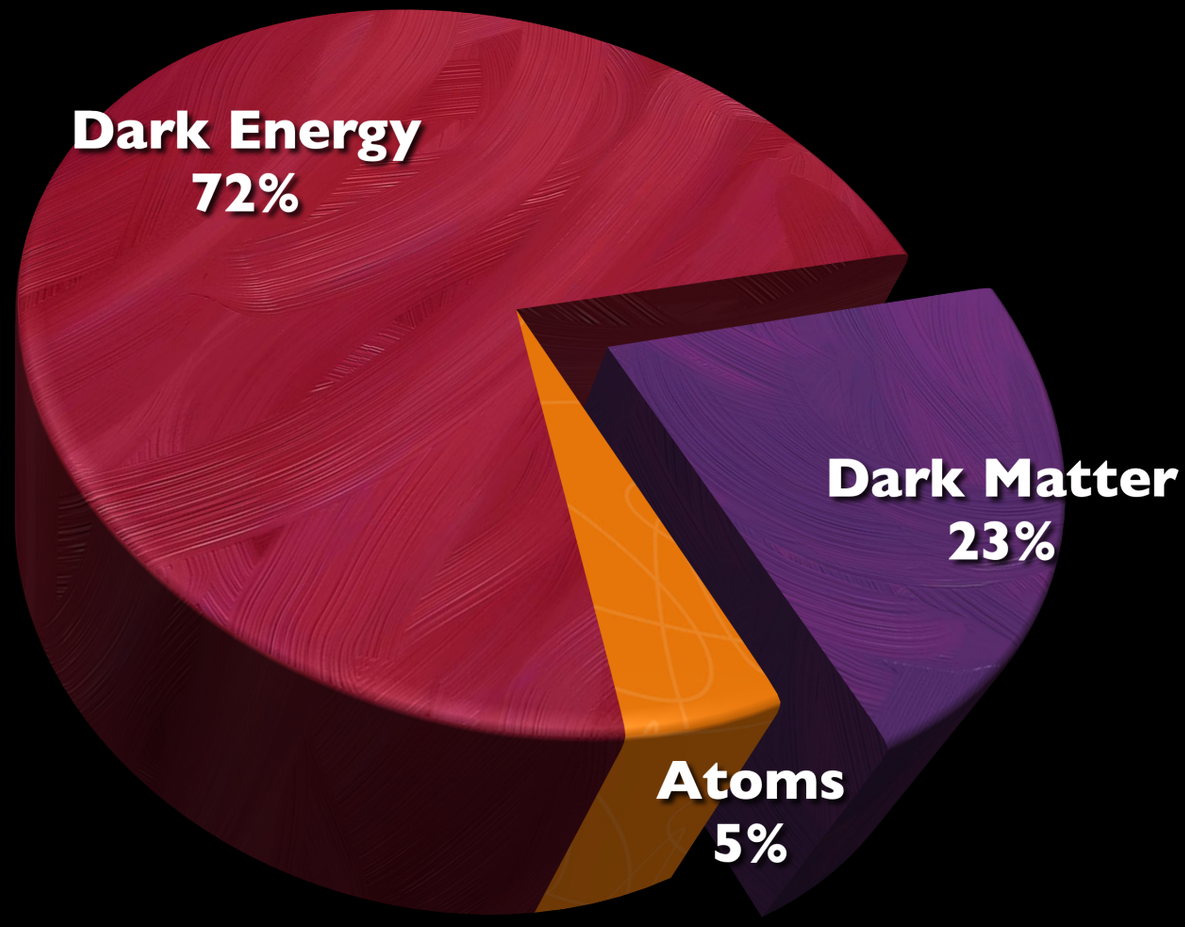


•CMB



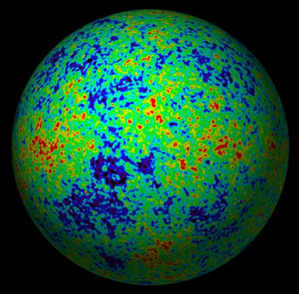
•Type Ia Supernovae

…

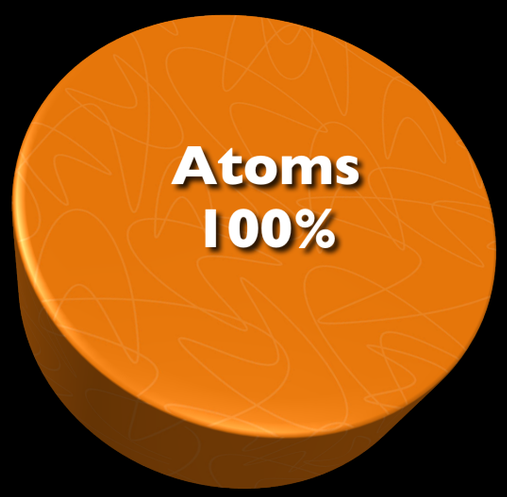


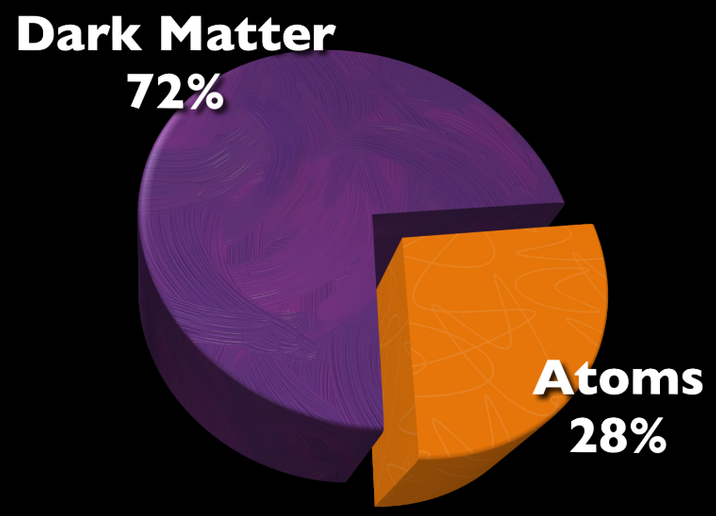
[statement valid *now*, and on *very large scales*]

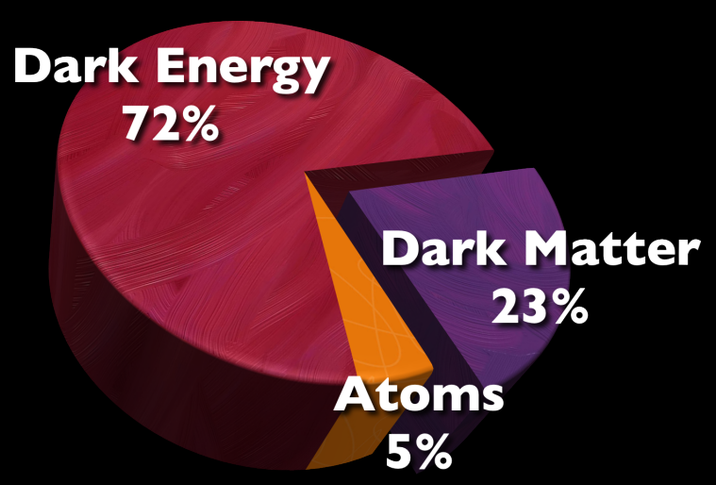
What is the Universe made of?



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

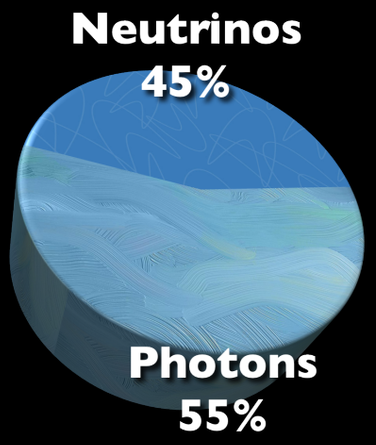




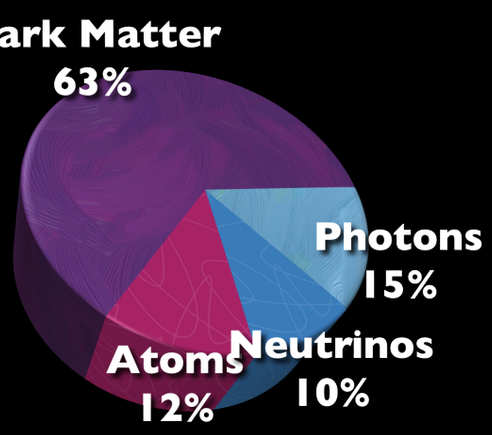


What was the Universe made of?

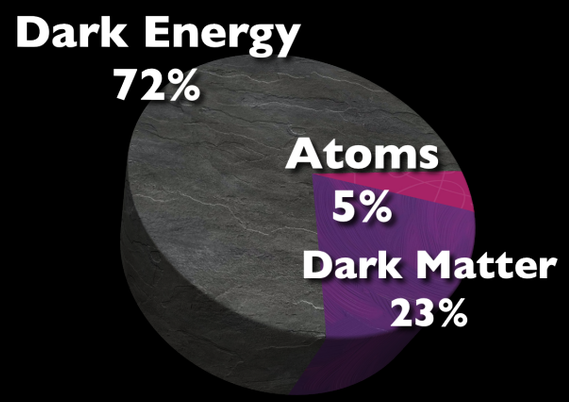
At BBN



At recombination

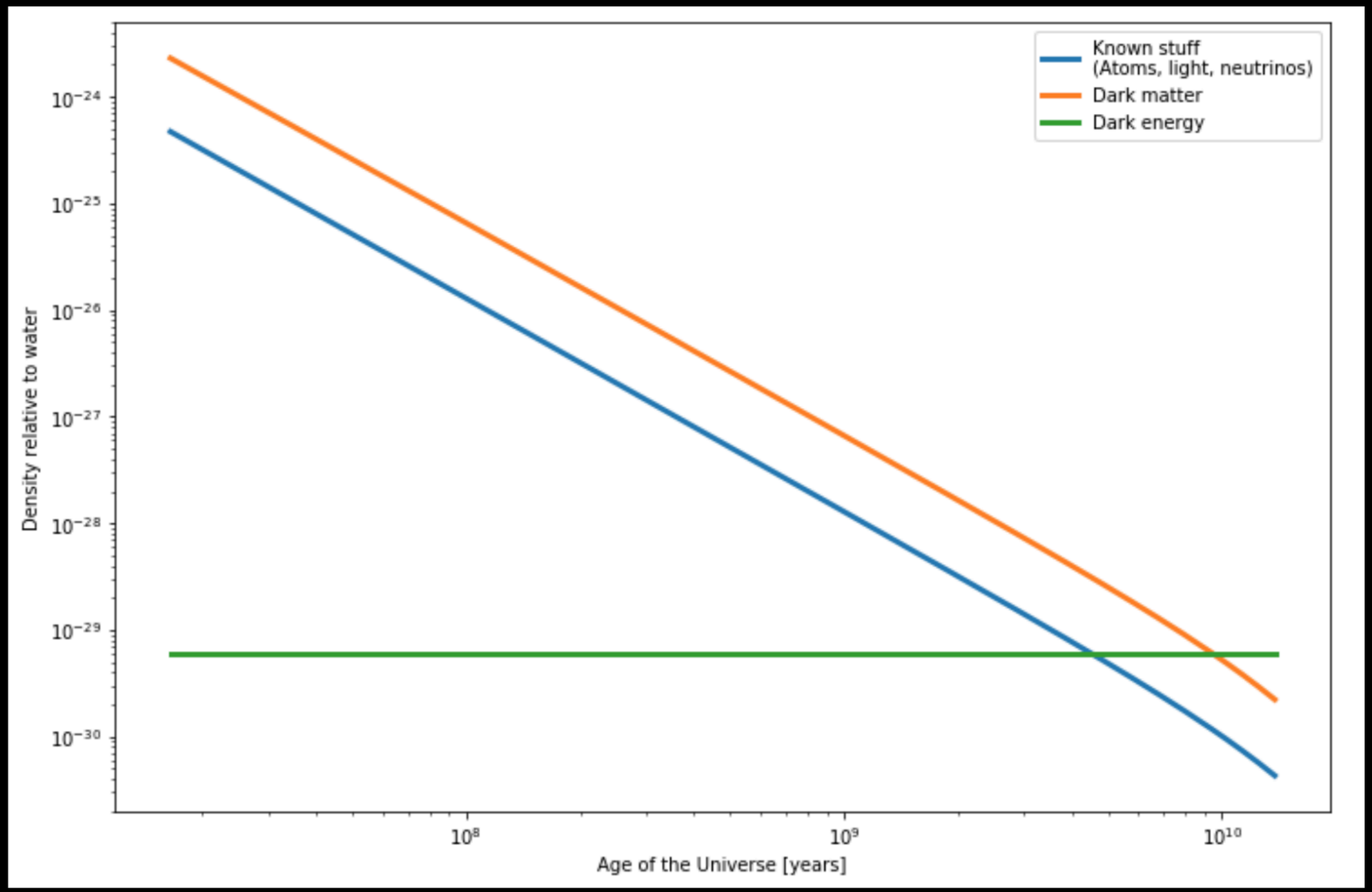


Today



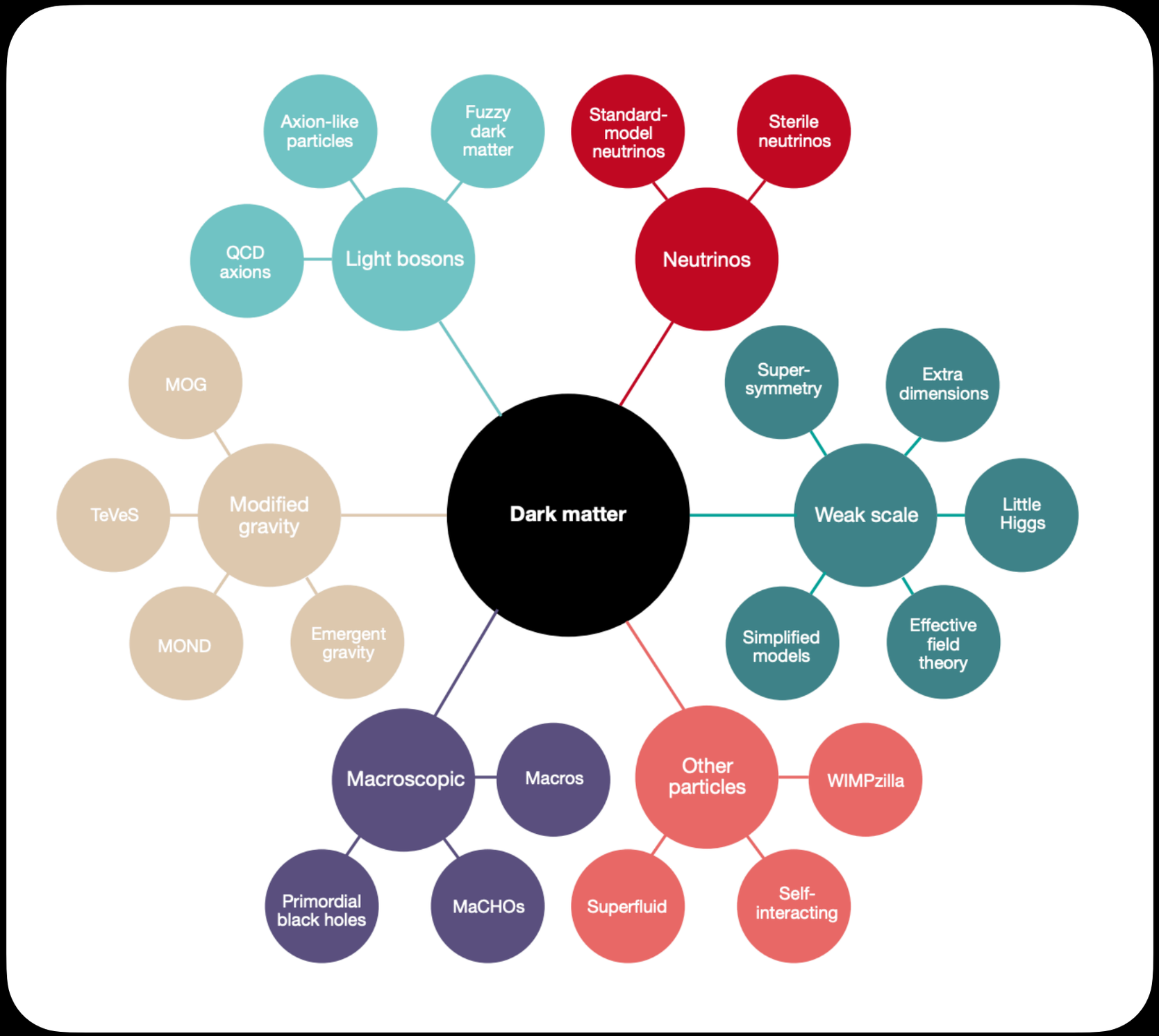
…eventually

Evolution of matter/energy density



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

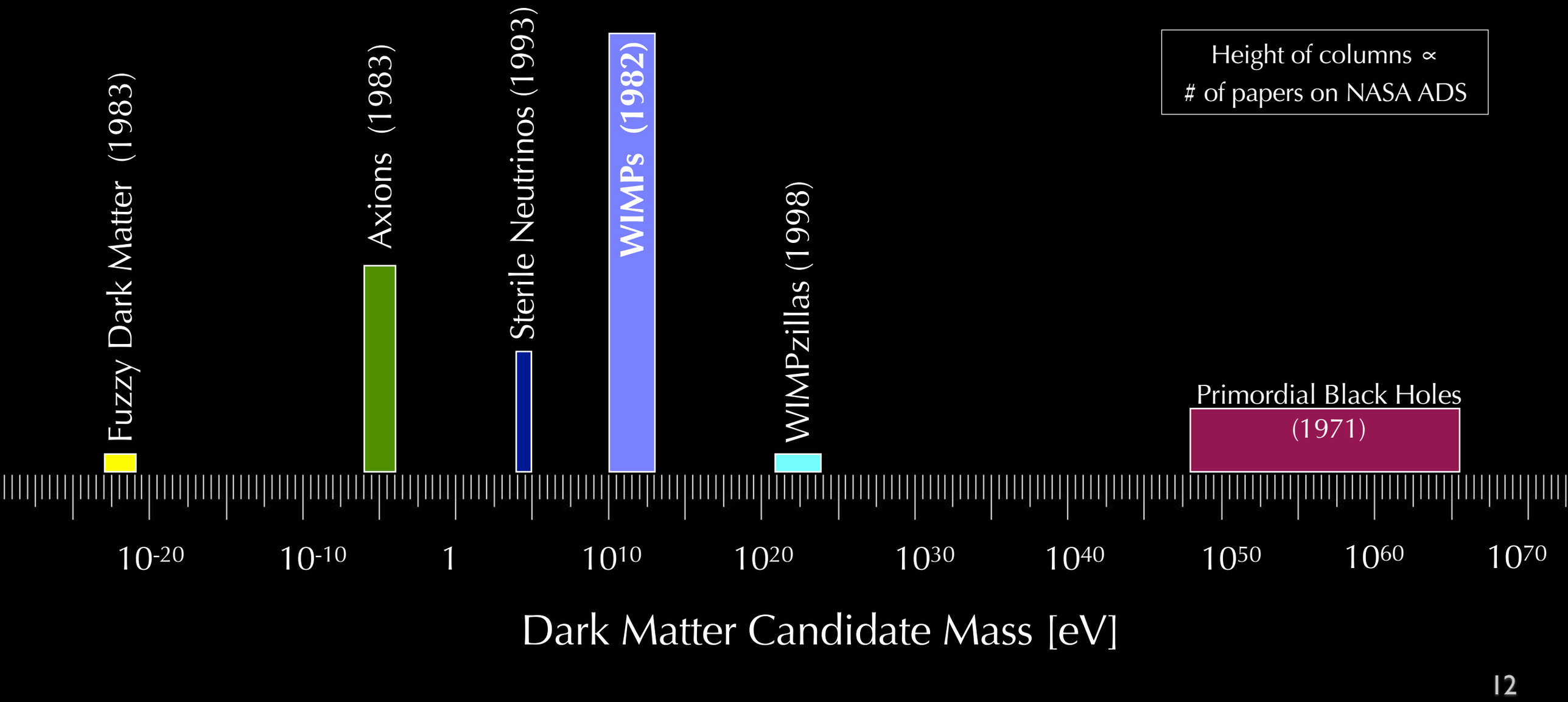
Candidates



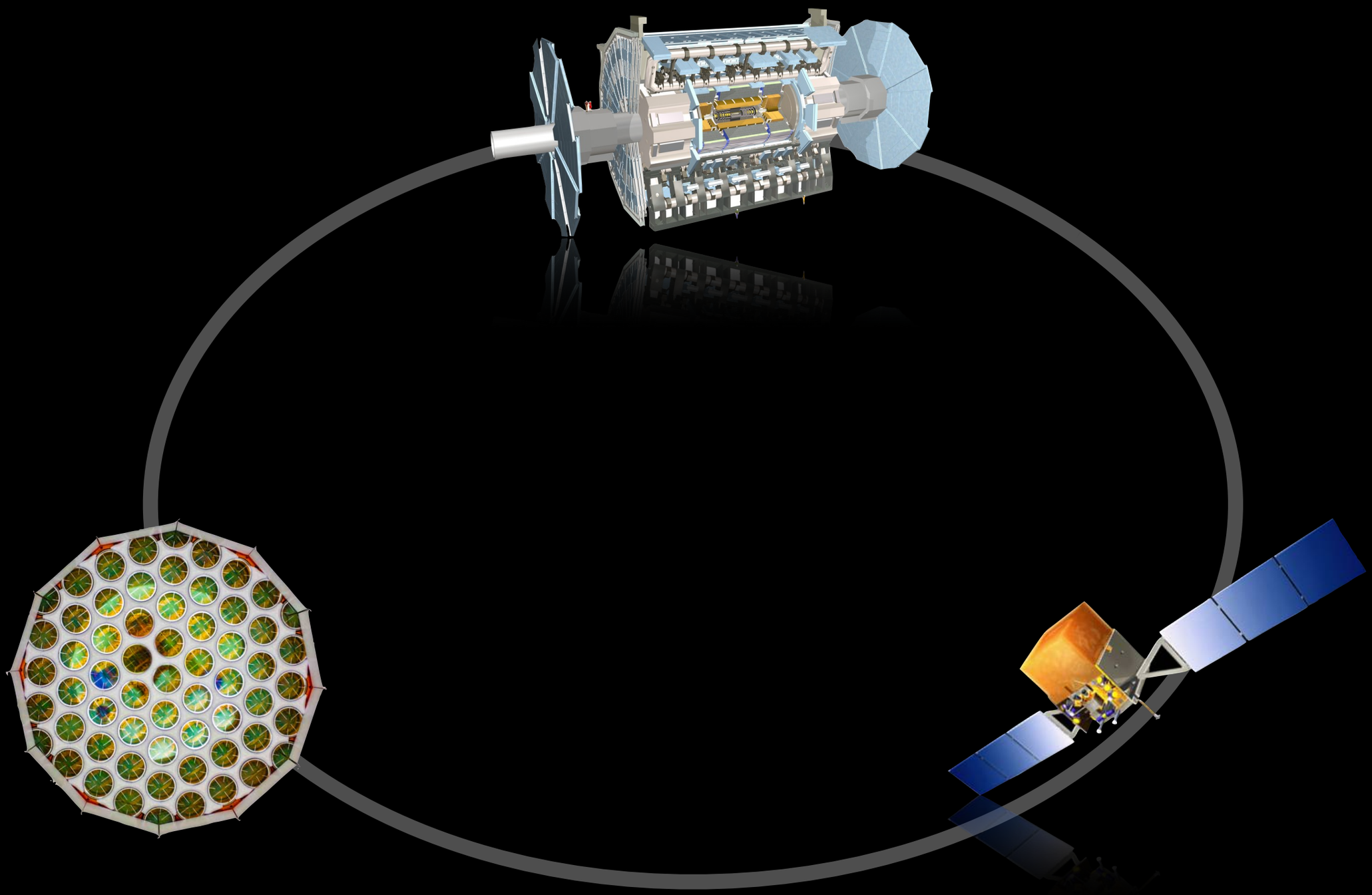
GB, Tait, *Nature (2018)1810.01668*

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 searches



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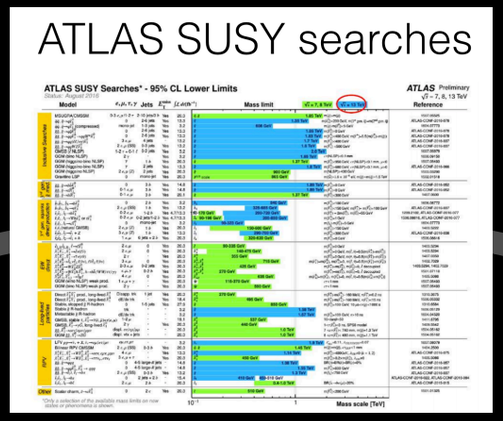
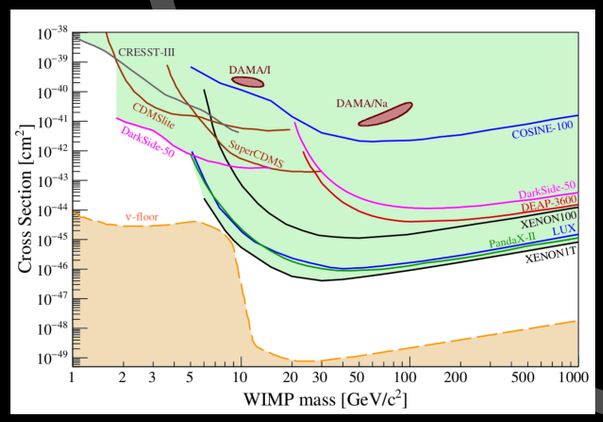
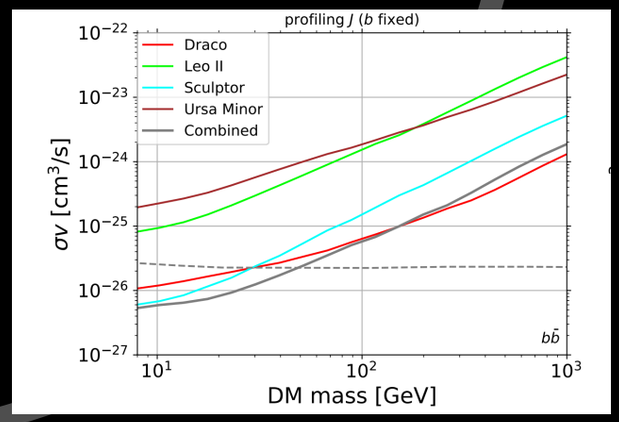


No WIMPs found yet, despite many efforts!





Are WIMPs ruled out?

NO

absence of evidence ≠ evidence of absence

A new era in the search for DM

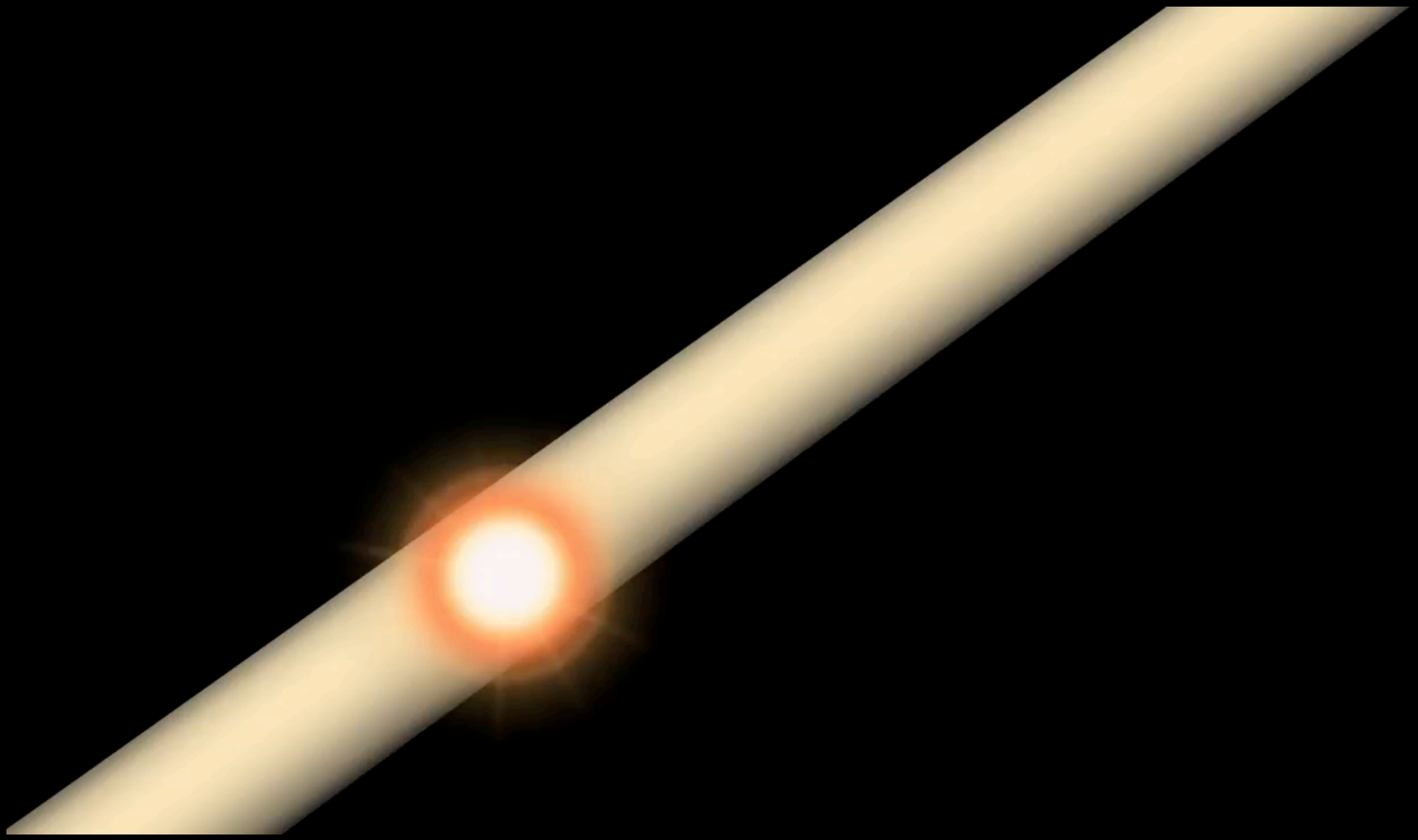
GB, Tait, *Nature (2018)1810.01668*

I. Broaden/improve/diversify searches

II. Exploit astro/cosmo observations

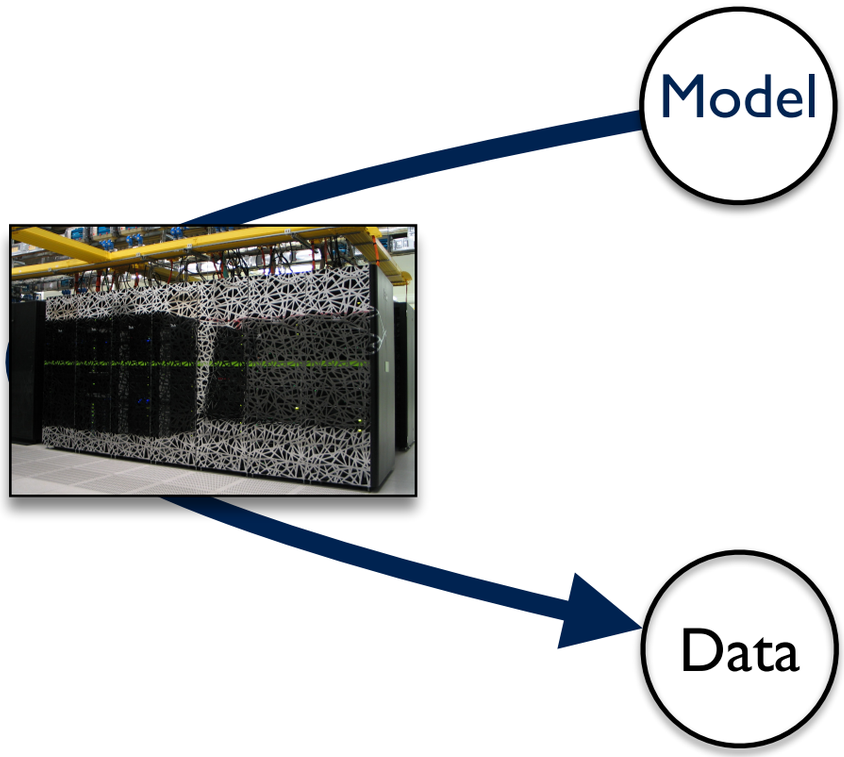
III. Exploit Gravitational Waves

Dark matter searches at the LHC



Improving existing strategies

Speeding up statistical inference with Machine Learning tools



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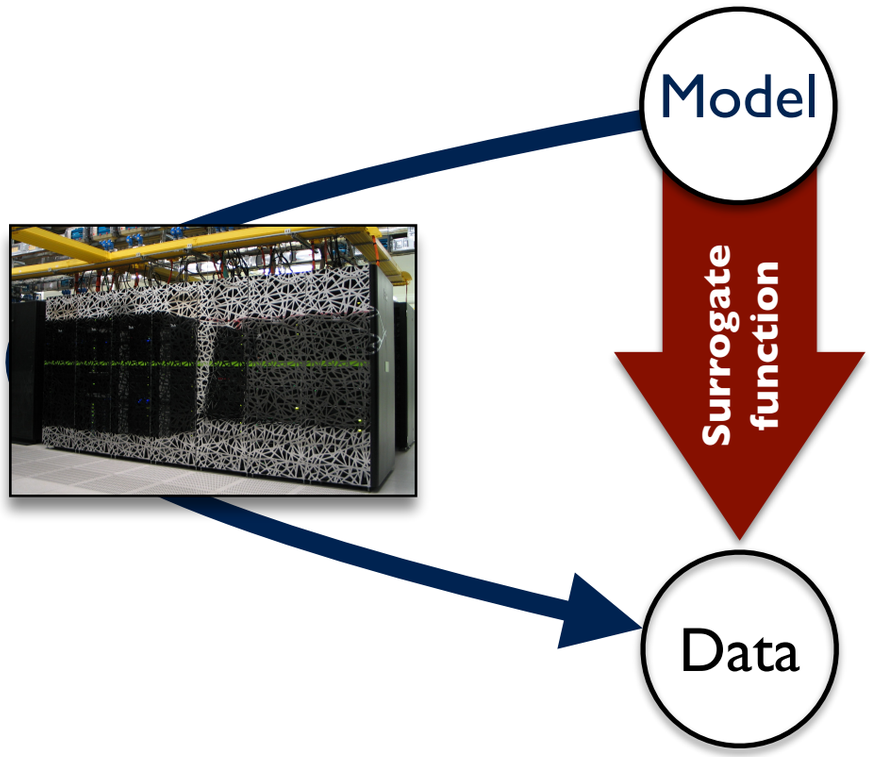
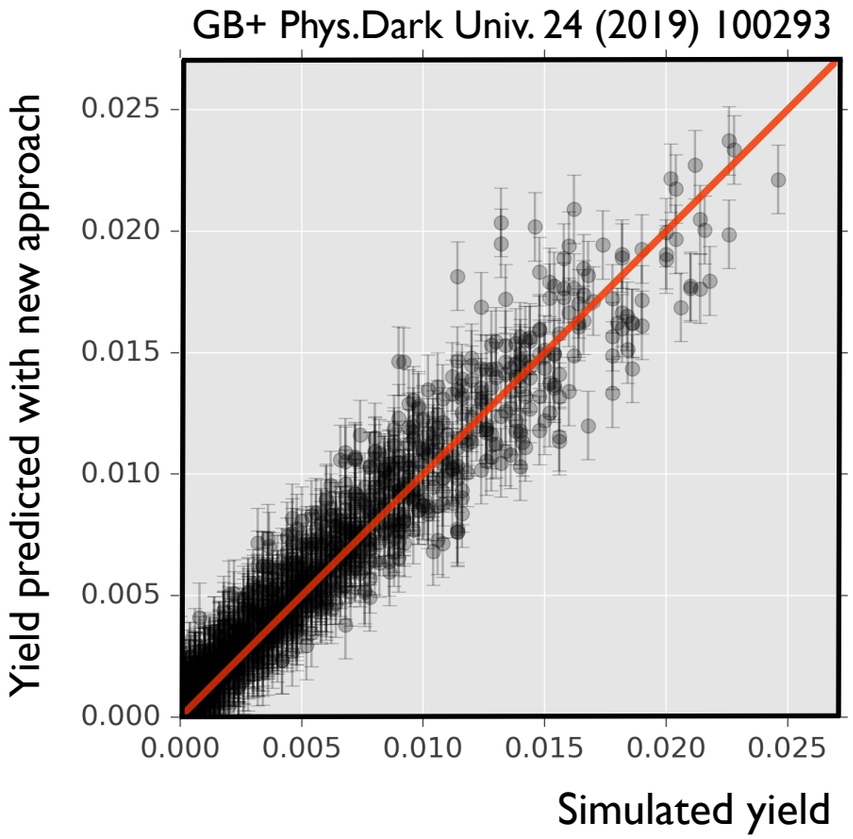




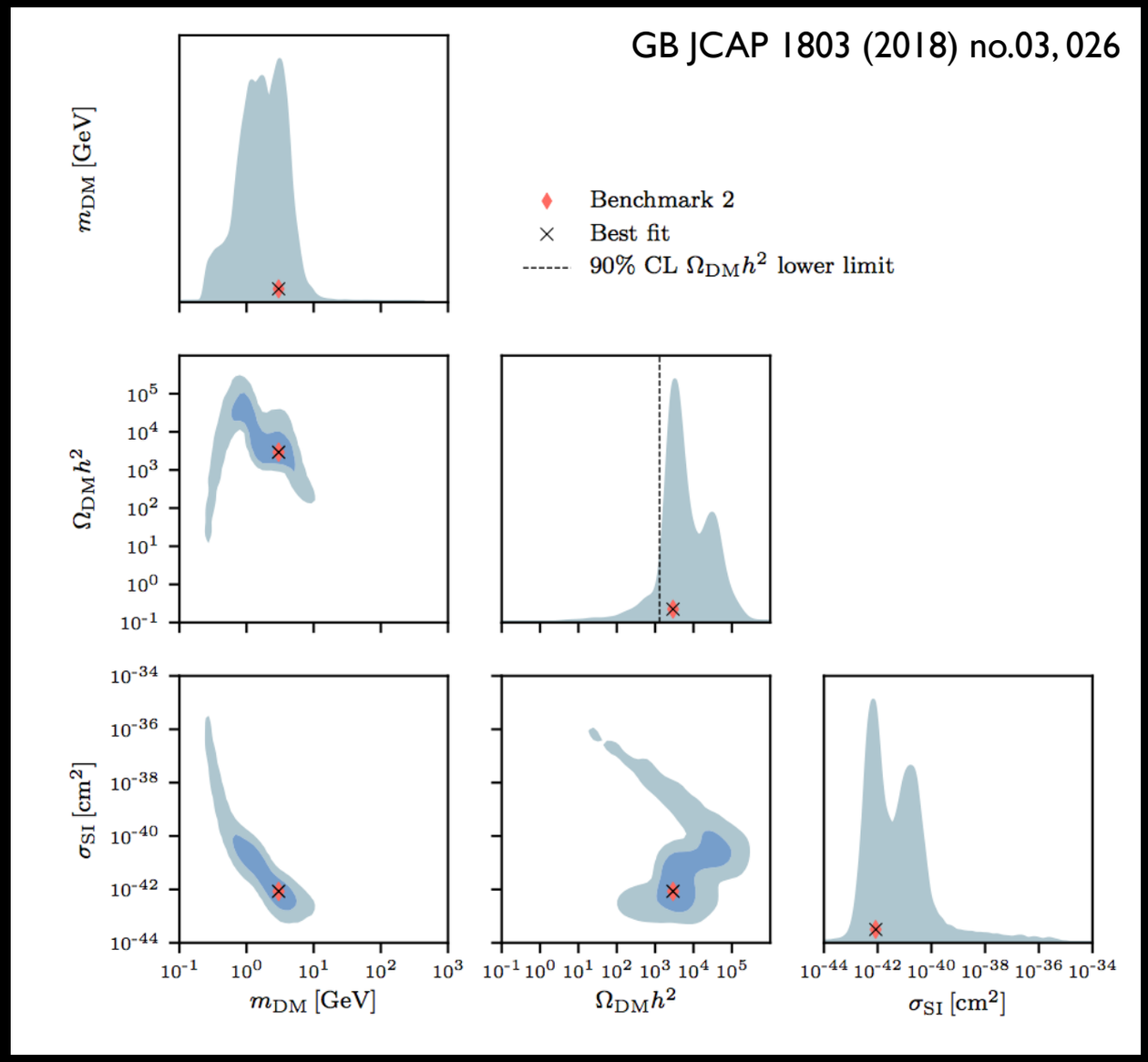
- Exploring parameter spaces of theoretical models computationally expensive
- Machine learning methods (*distributed gaussian processes*, *deep neural networks*) bring computation time from ~CPU *centuries* to ~CPU *weeks*!
- Can be run by a PhD student in 1 day on a desktop computer!

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

A new era in the search for DM

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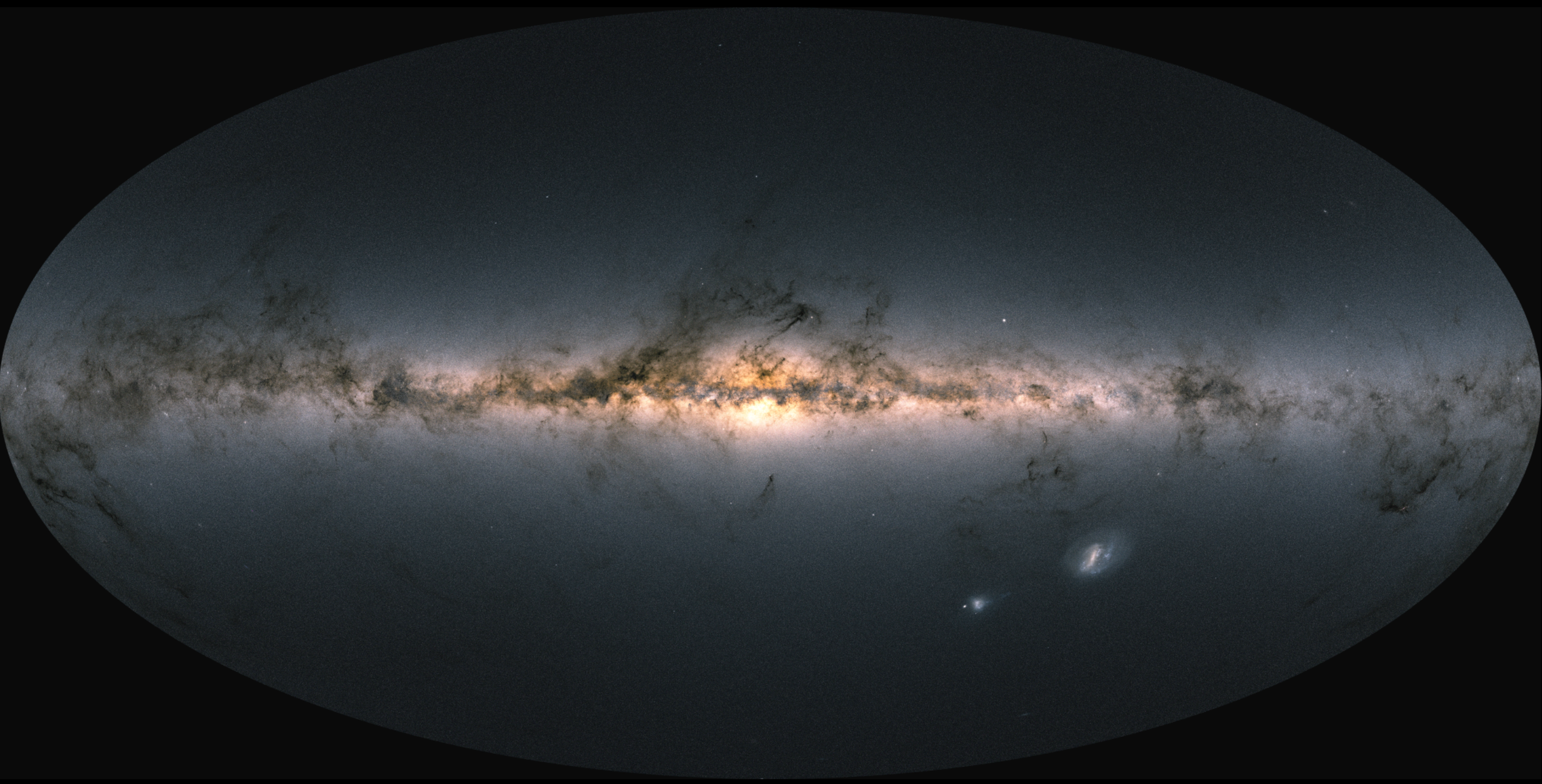
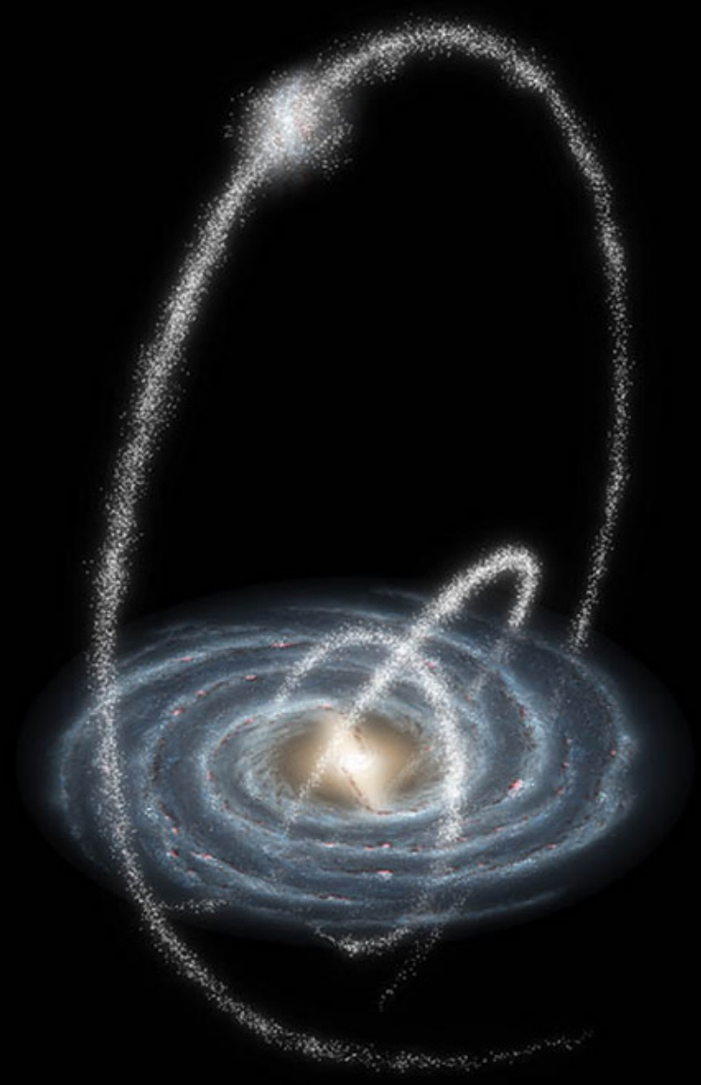
GAIA'S SKY



Total brightness and colour of stars observed by ESA's Gaia satellite and released as part of Gaia's Early Data Release 3

Stellar streams

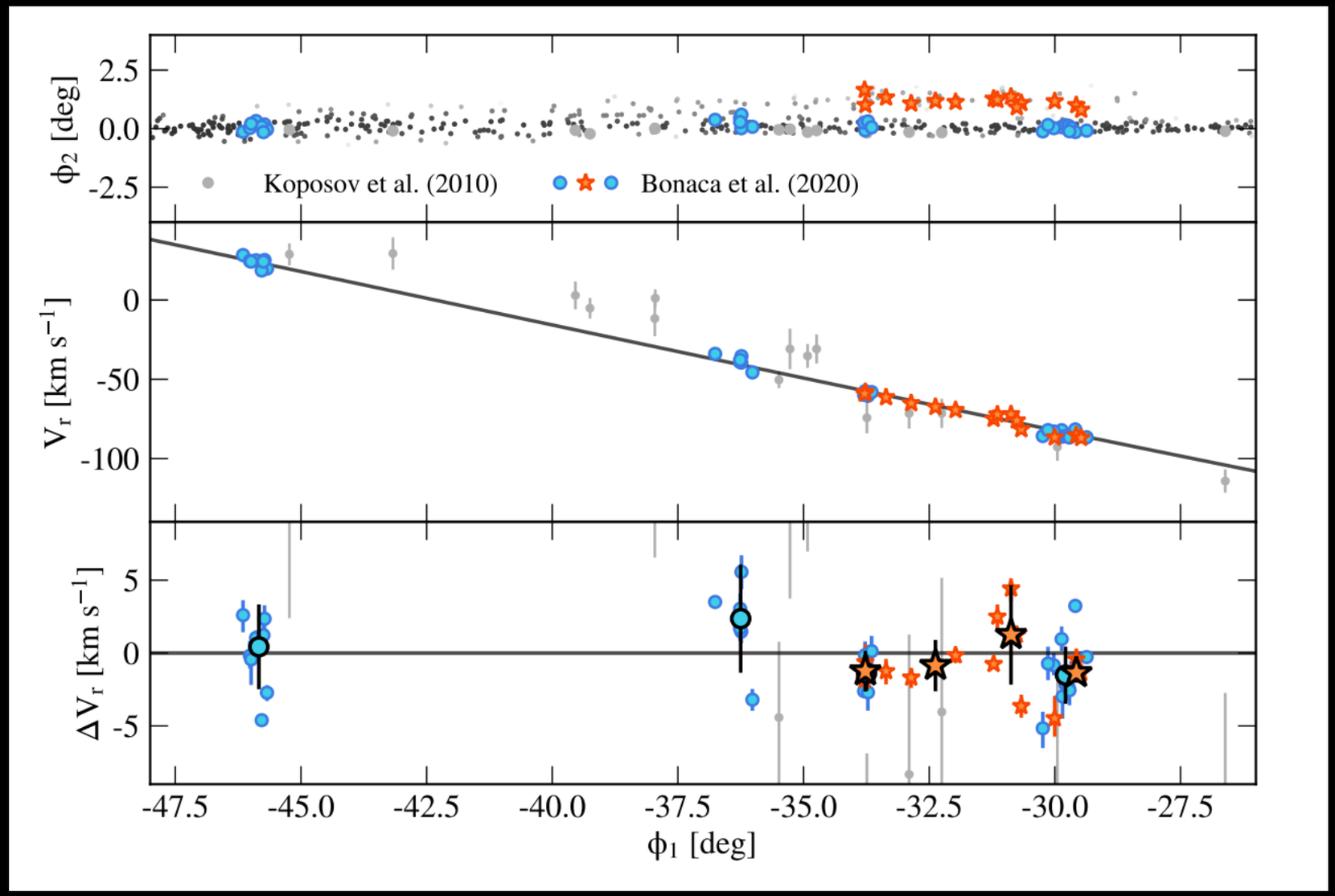


Searching for dark matter substructures in the MW

Gaia GD1 stream data!

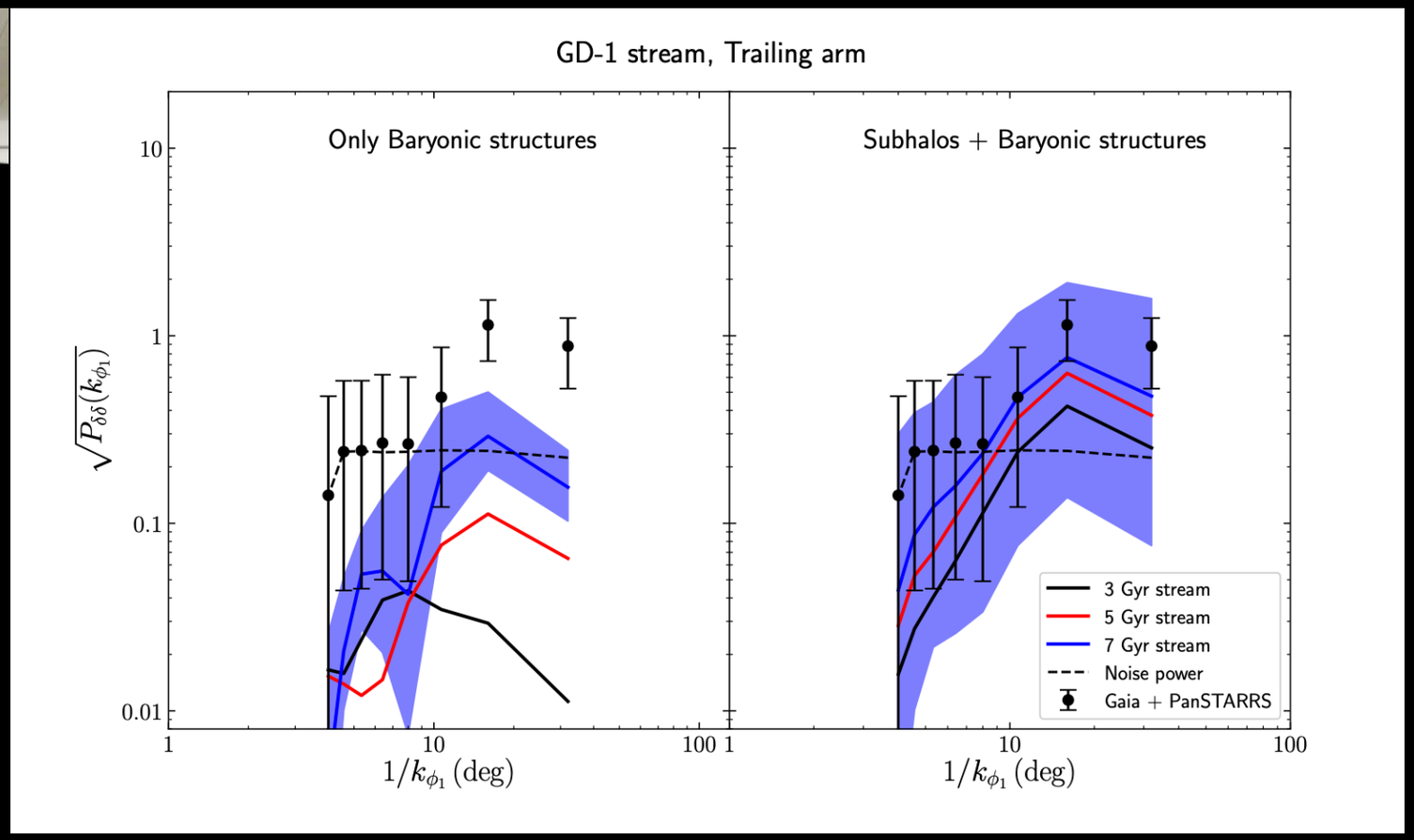
New map of stars in GD1 stream (longest cold stream in the MW) with *Gaia* second data release combined with *Pan-STARRS*.

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!



Banik, Bovy, GB, Erkal, de Boer, MNRAS 502, 2364 (2021)

- 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!)

The future of dark matter searches

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

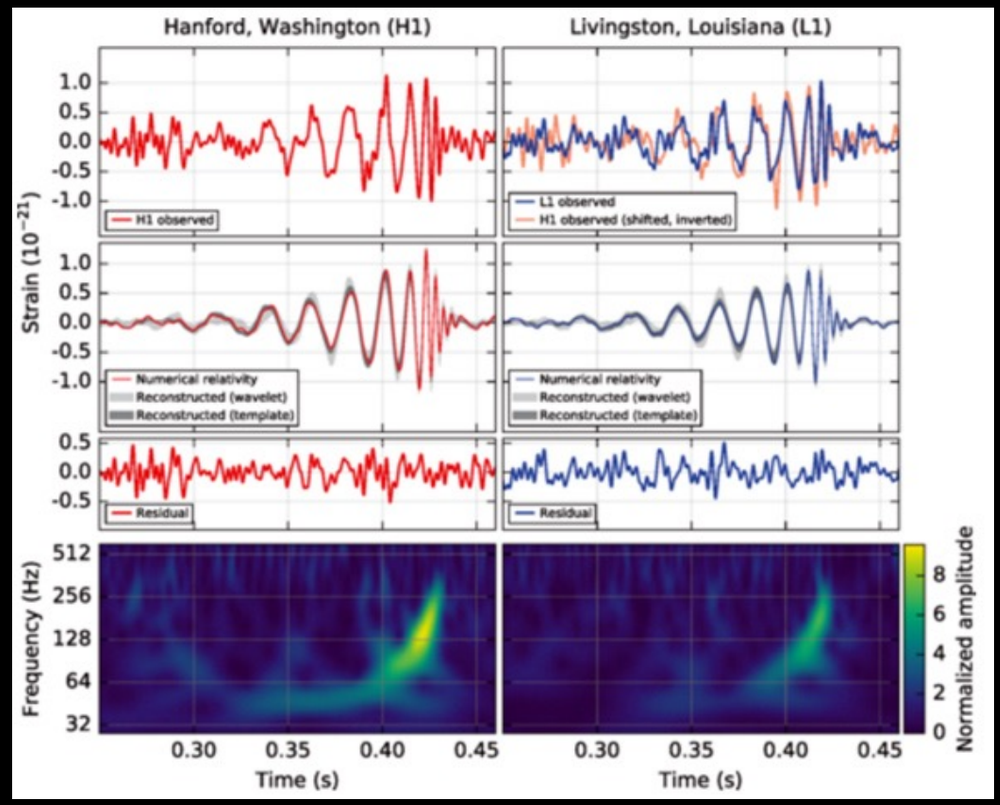
Gravitational Waves

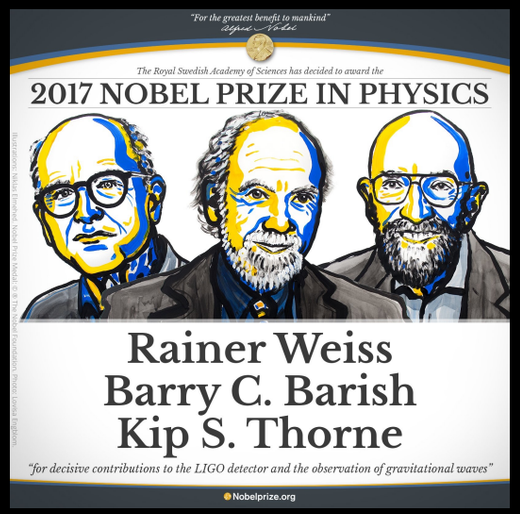
"The discovery that shook the world"

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

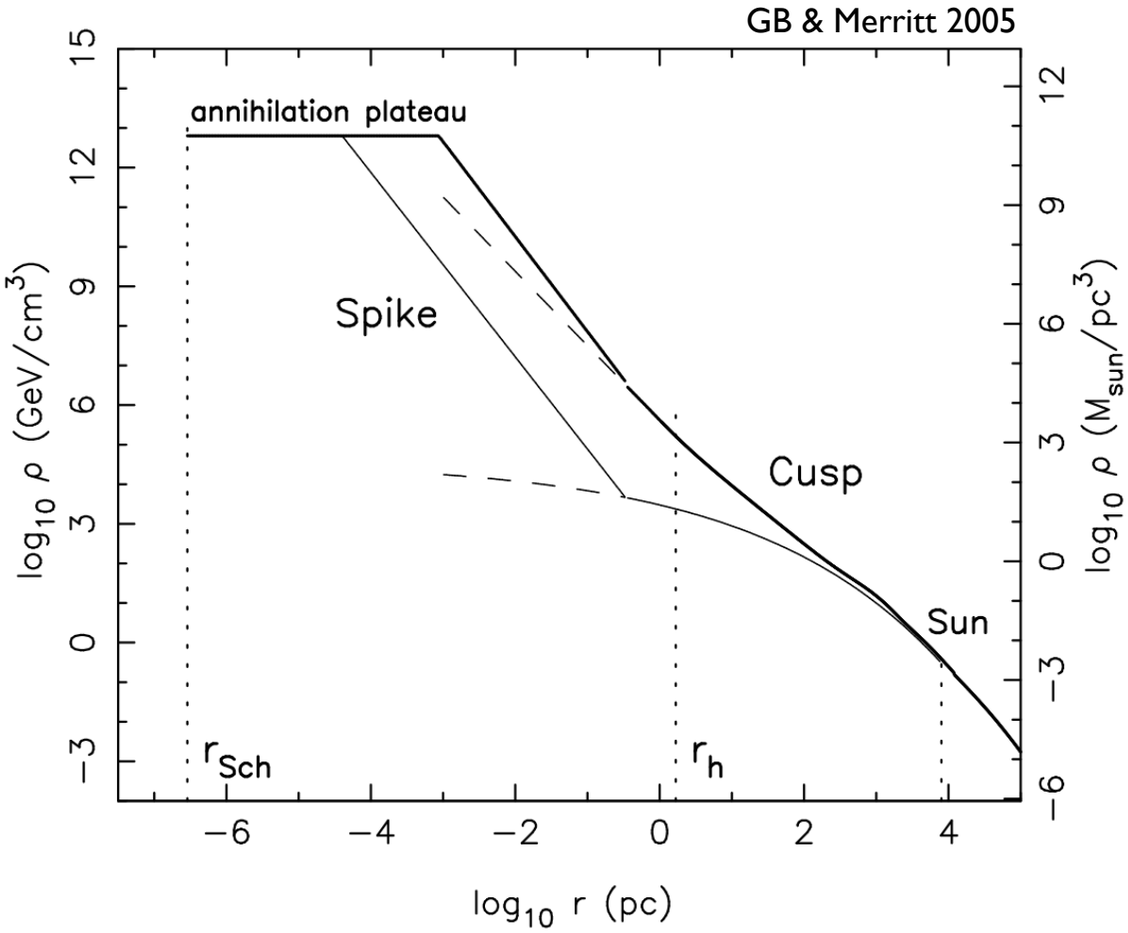
Secondary black hole mass $29^{+4}_{-4} M_\odot$

LIGO & Virgo coll, PRL 116, 061102





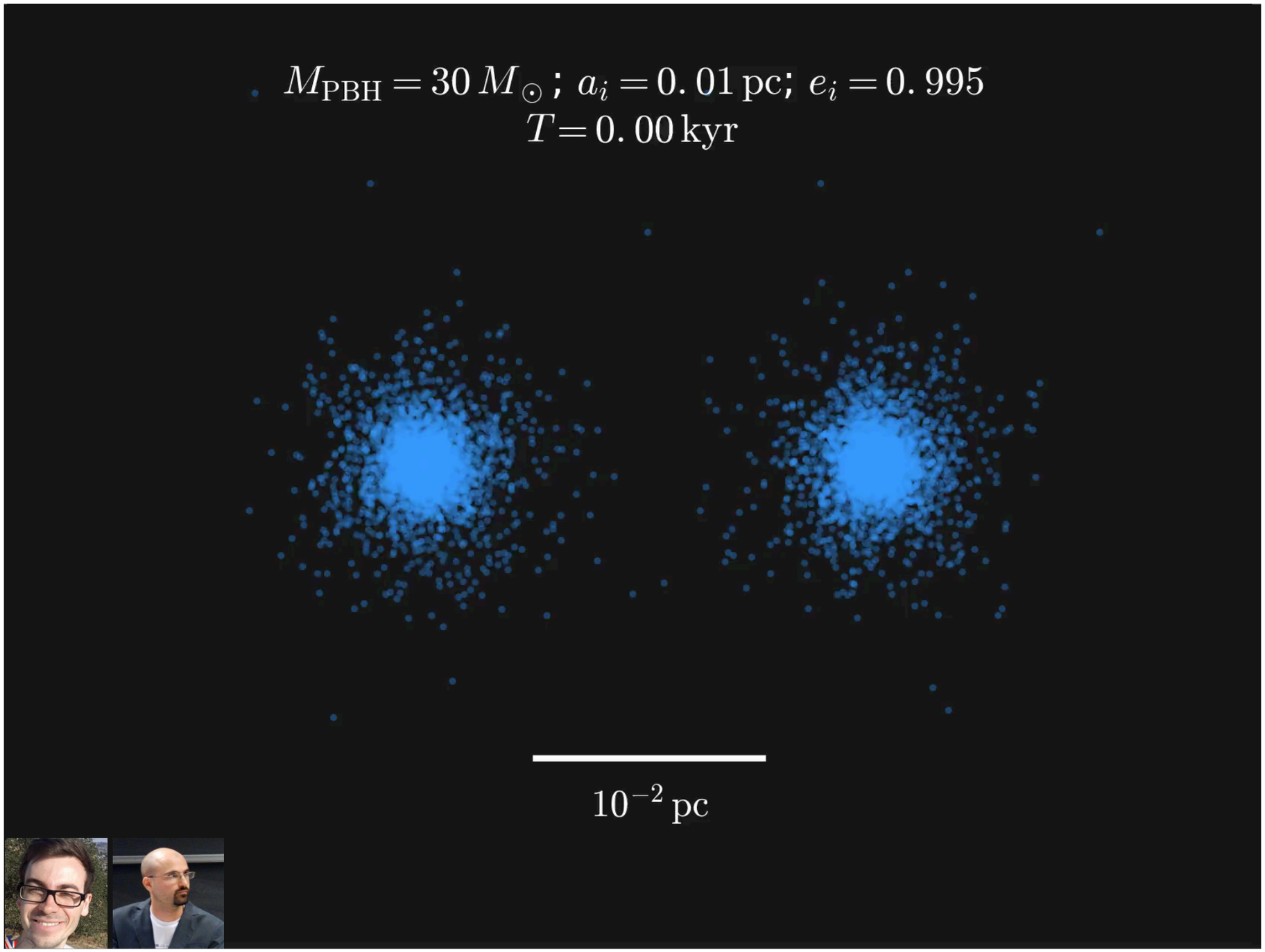
Dark Matter 'dress' around BHs



- **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)*

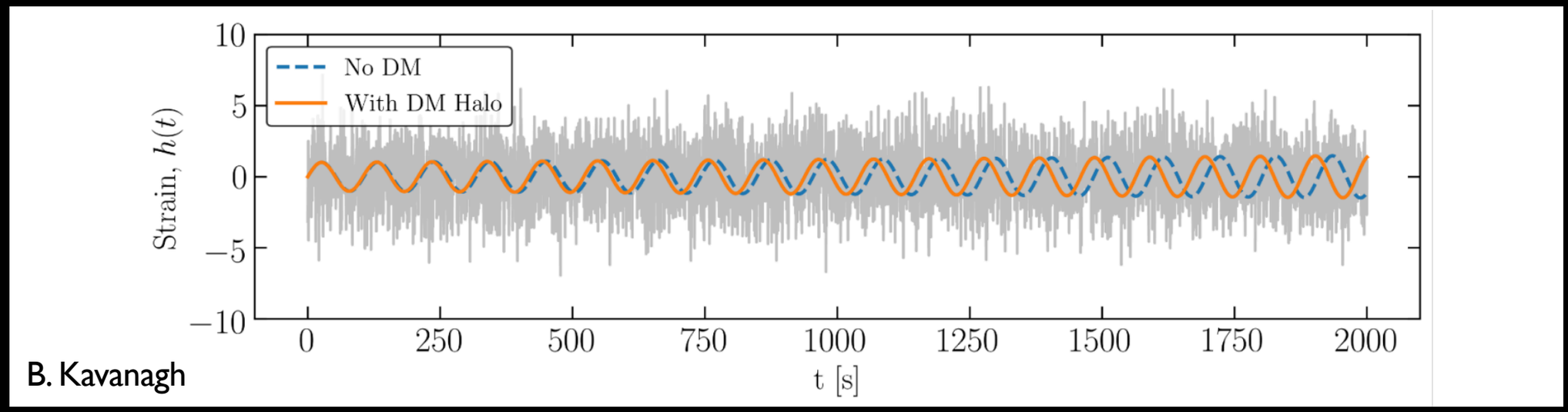
Open questions: astrophysical uncertainties, dependence on DM properties (self-interactions, annihilations)

‘Dressed’ BH-BH merger

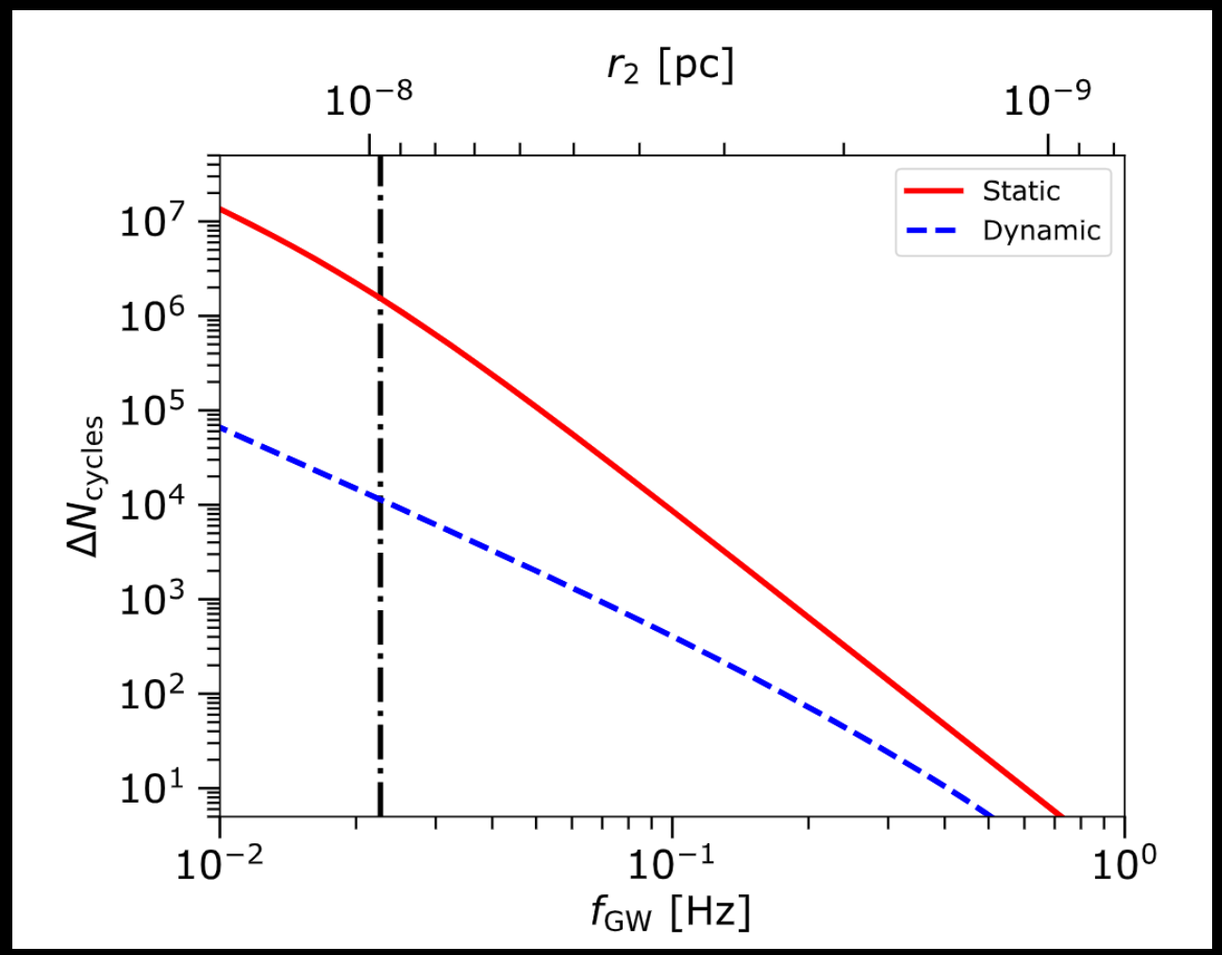


Kavanagh, Gaggero & GB, arXiv:1805.09034

Gravitational Waveform dephasing



B. Kavanagh



Kavanagh, GB et al. PRD 102 (2020) 8, 083006

- 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