The multimessenger fingerprint of Dark Matter

Gianfranco Bertone
GRAPPA center of excellence, U. of Amsterdam

19/2/2021, XIX International Workshop on Neutrino Telescopes

GRAPPA
GRavitation AstroParticle Physics Amsterdam

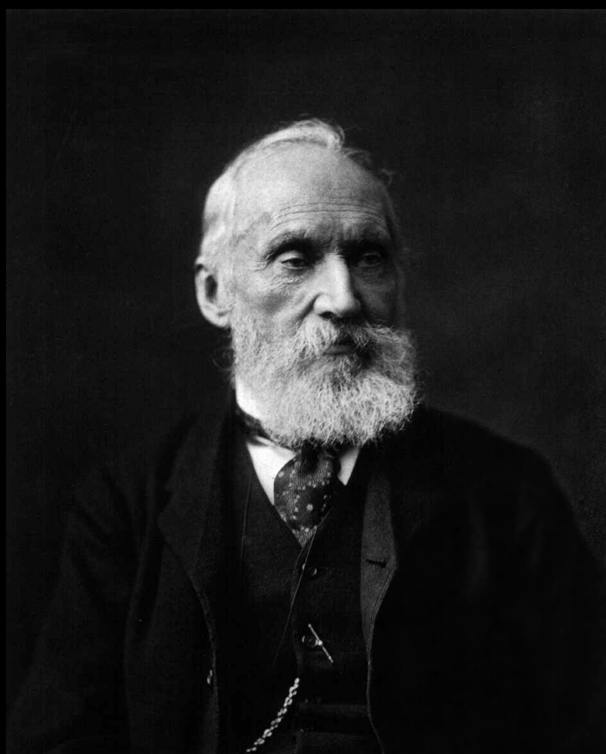
Plan of the talk:

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..



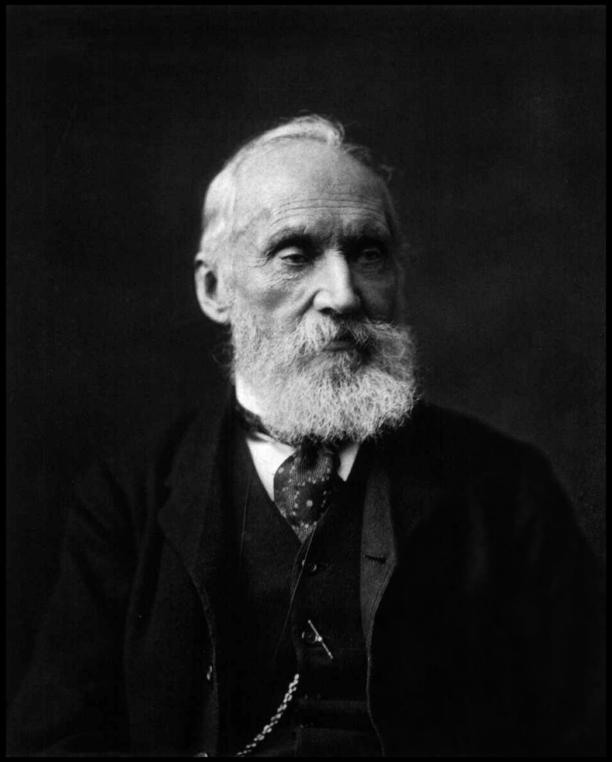
Lord Kelvin (1904)

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

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."*

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."

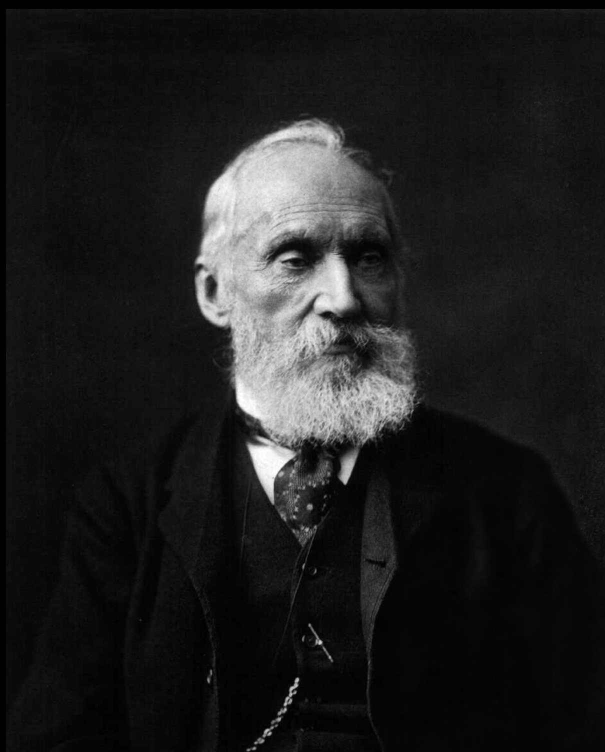
Henri Poincaré (1906)

"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."*

Albert Einstein (1921)

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

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."*

Albert Einstein (1921)

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

Fritz Zwicky (1933)

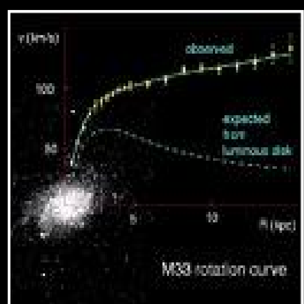
"According to present estimates the average density of dark matter in our galaxy and throughout the rest of the universe are in the ratio 10^5"

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

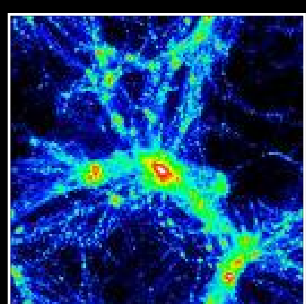
"How dark matter came to matter" de Swart, GB, van Dongen - Nature Astronomy; *1703.00013*

What is the Universe made of?

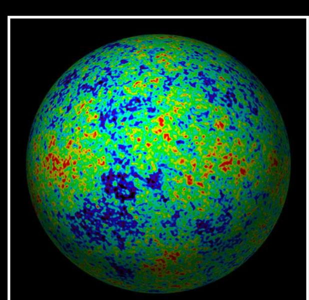
OBSERVATIONS



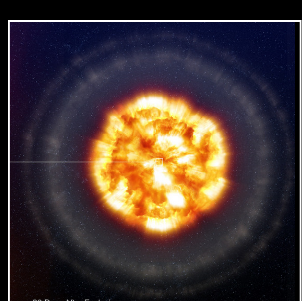
- Rotation Curves



- Clusters of galaxies

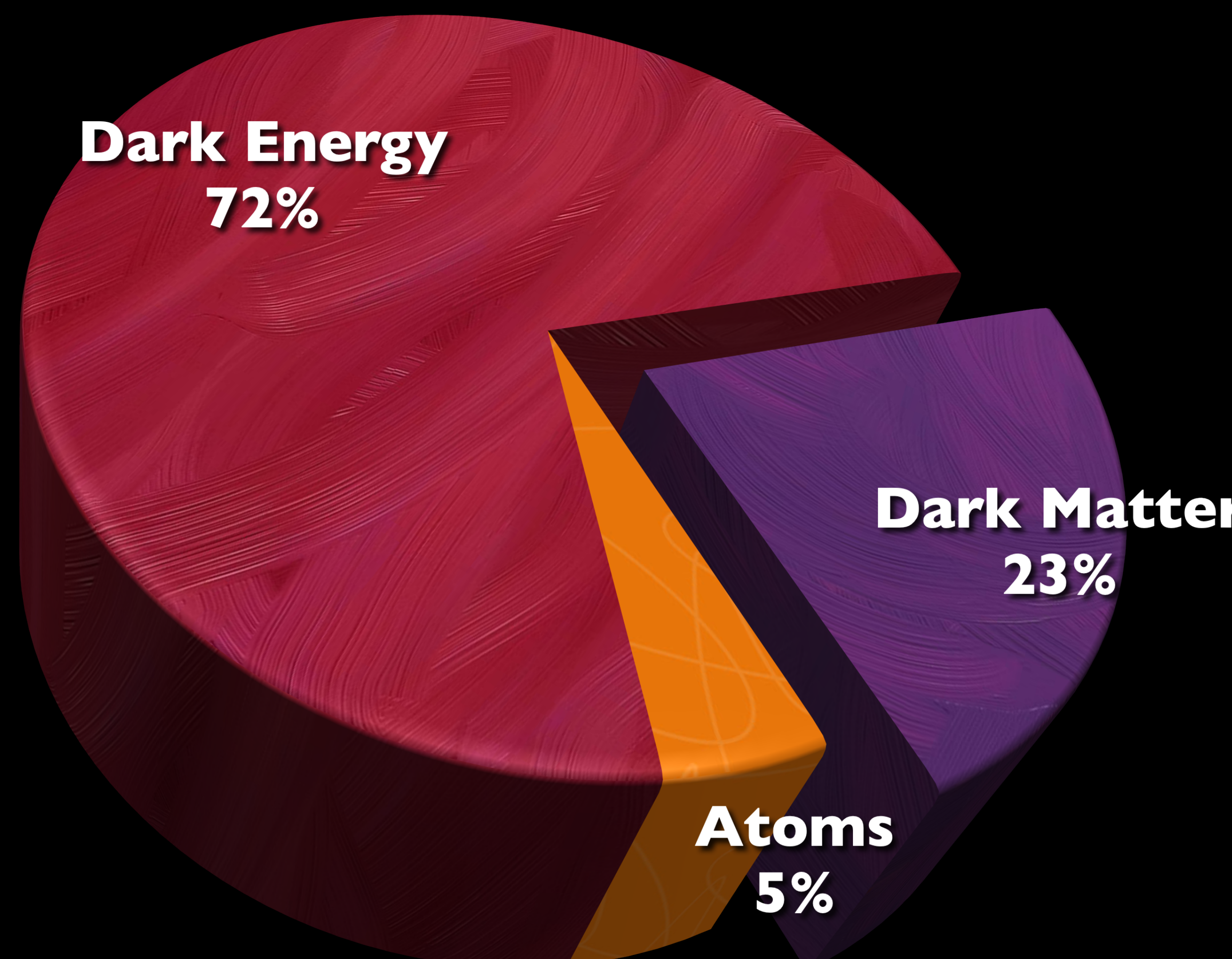


- CMB



- Type Ia Supernovae

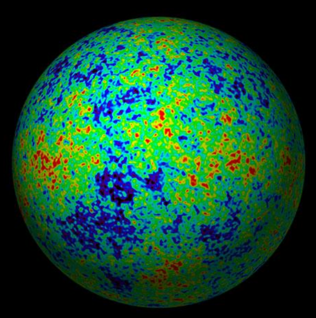
...

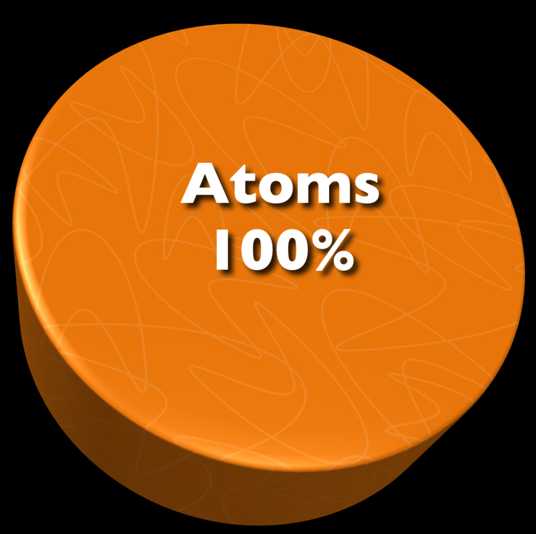


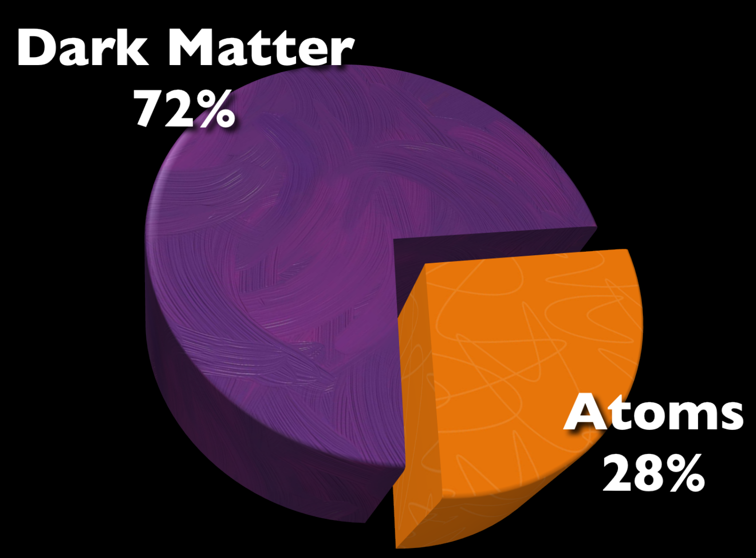
[statement valid *now*, and on *very large scales*]

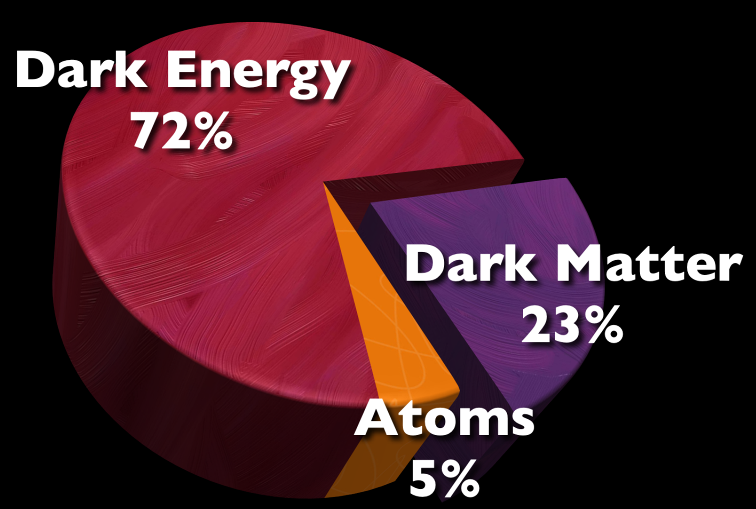
What is the Universe made of?

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



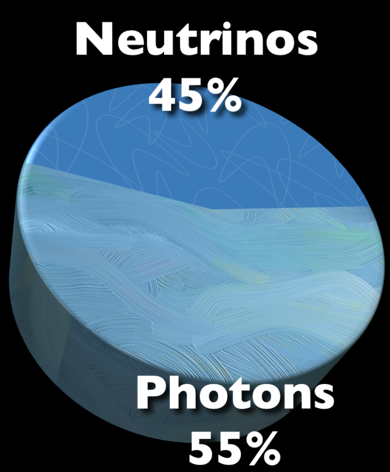




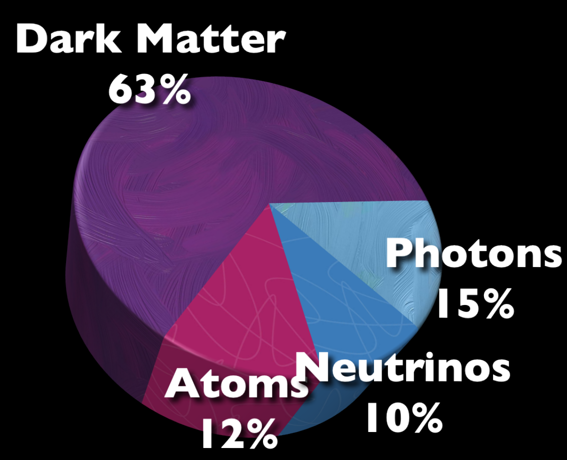


What <u>was</u> the Universe made of?

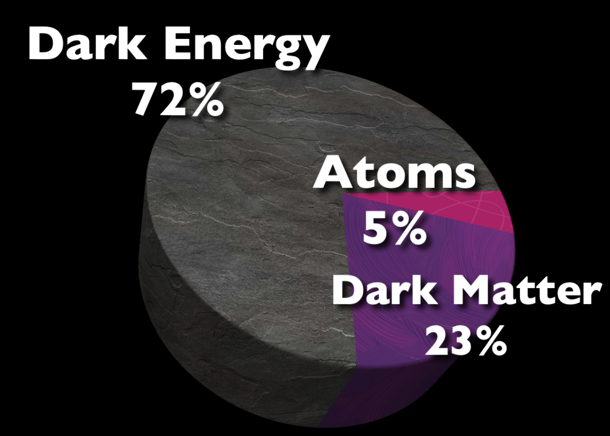
At BBN



At recombination

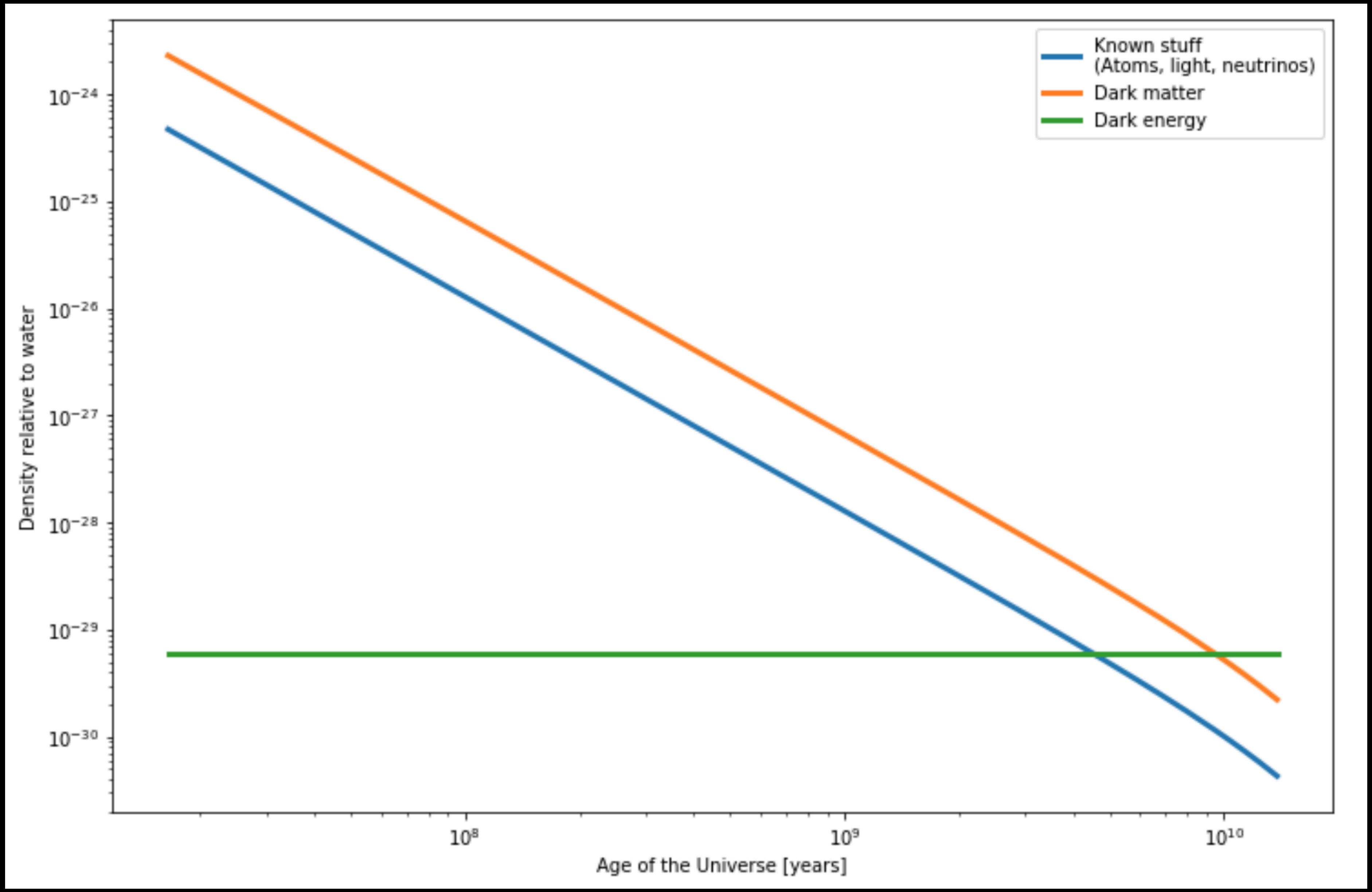


Today



…eventually

Evolution of matter/energy density



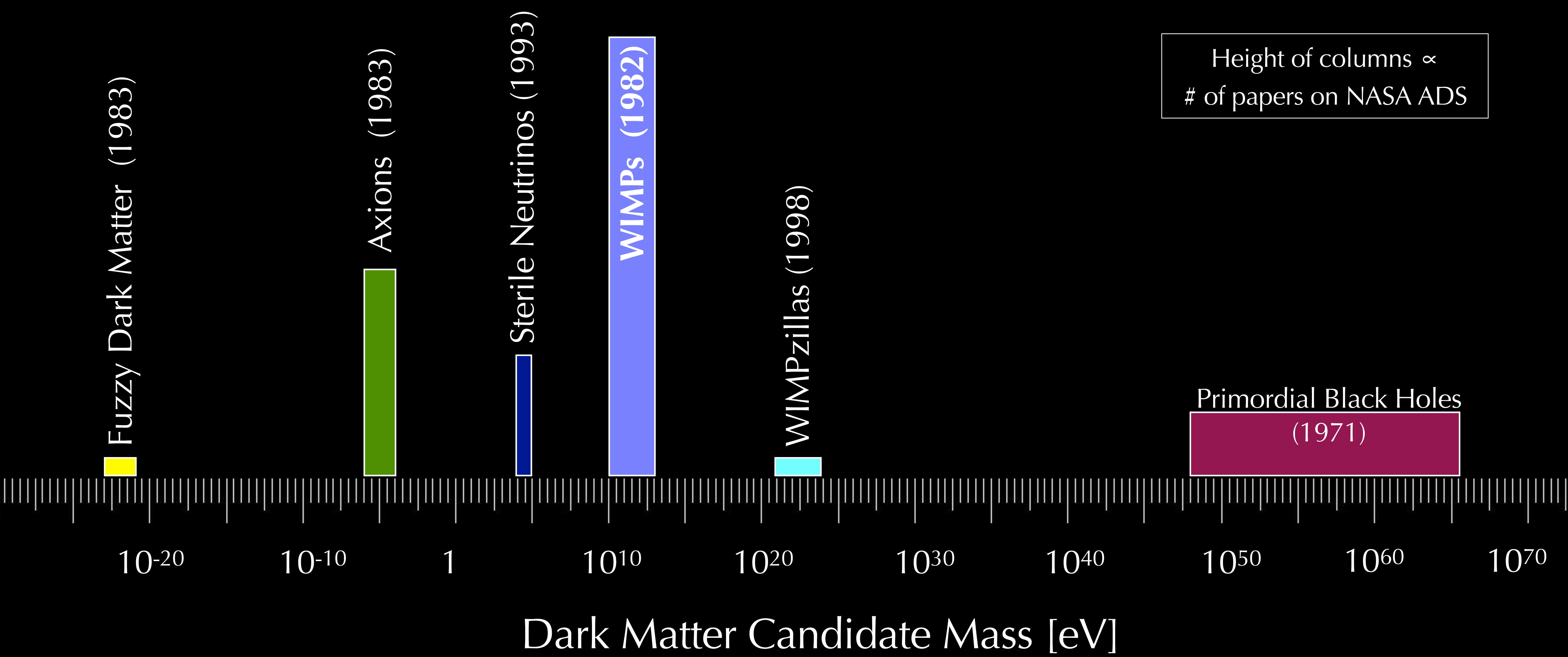
Created with #astropy https://astropy.org, astropy.cosmology package https://docs.astropy.org/en/stable/cosmology/

Candidates

GB, Tait, *Nature (2018) 1810.01668*

Candidates

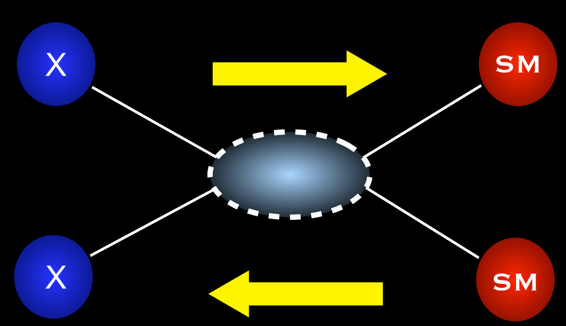
- No shortage of ideas..
- Tens of dark matter models, each with its own phenomenology
- Models span 90 orders of magnitude in DM candidate mass!



WIMPs

By far the most studied class of dark matter candidates.

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



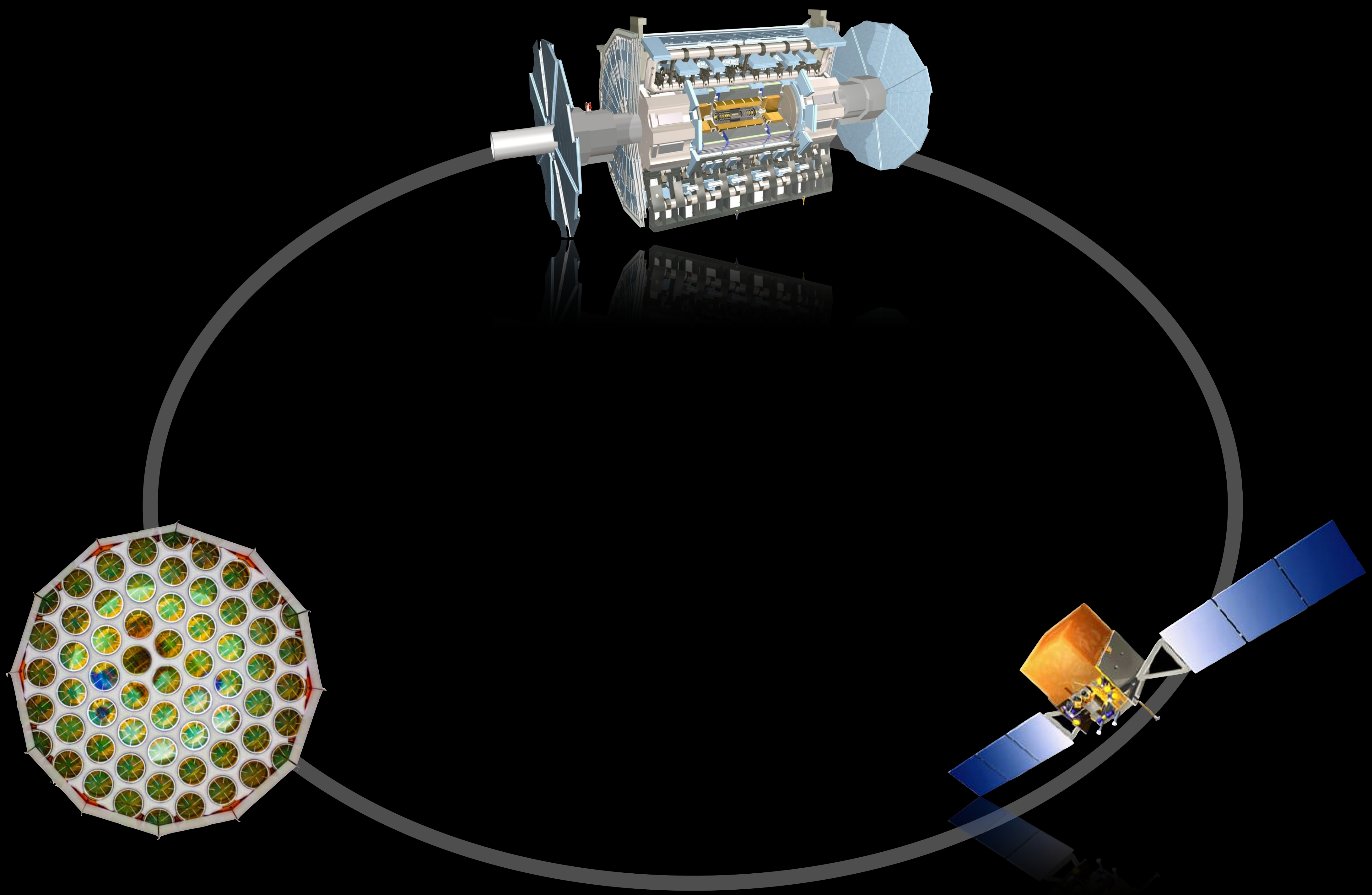
$$\frac{dn_\chi}{dt} - 3Hn_\chi = -\langle\sigma v\rangle \left[n_\chi^2 - (n_\chi^{eq})^2\right]$$

Weak-scale cross sections can reproduce observed relic density

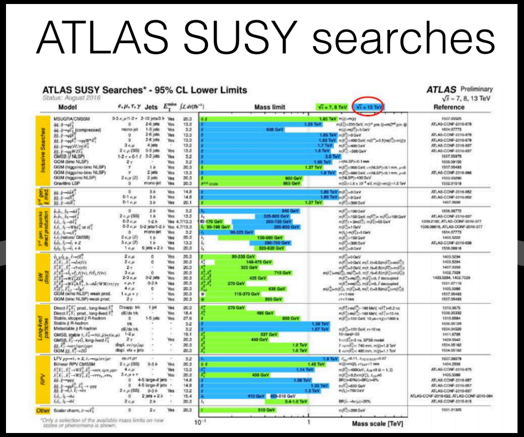
$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{< \sigma v >}$$

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

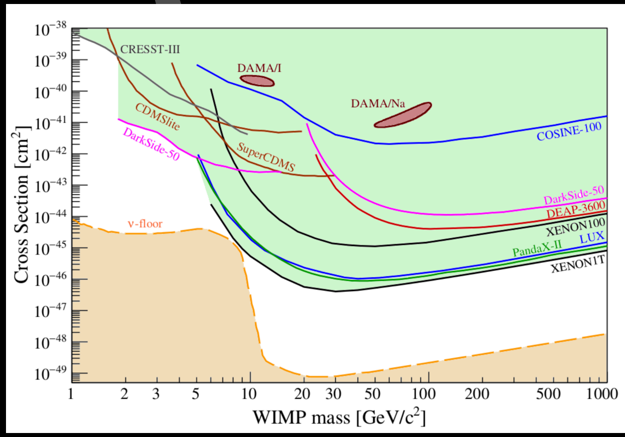
WIMPs searches

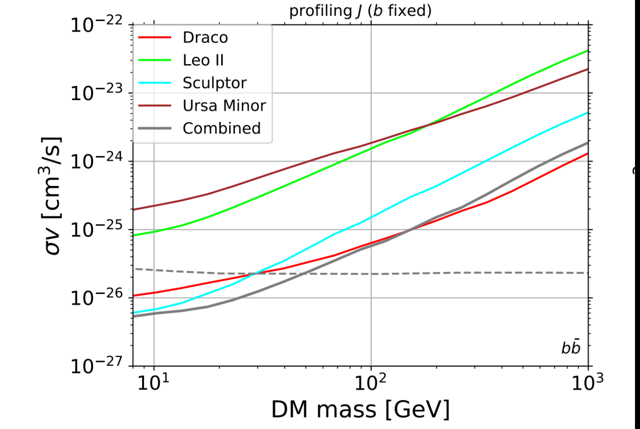


WIMPs searches



No WIMPs
found yet, despite many efforts!





Are WIMPs ruled out?

NO

absence of evidence ≠ evidence of absence

Are WIMPs ruled out?

Absence of evidence has dampened the enthusiasm for WIMPs, but:

- Large portions of the parameter space of specific WIMP candidates remain viable *[Leane+ 1805.10305, Beekveld+ 1906.10706, Blanco+ 1907.05893,…]*
- WIMP paradigm ≠ WIMP miracle *[Arakawa and Tait 2101.11031,…]*
- Clear way forward:
  - 15 years of LHC & HL-LHC data
  - Direct detection experiments all the way to "neutrino floor"
  - Non-dedicated Indirect Detection experiments

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

Broaden/improve/diversify searches

15. Dark Matter through the Neutrino Portal
Bowen Fu (University of Southa...)
19/02/2021, 17:10
Neutrino Theory and Cos... | Parallel Contributed Talk | Non Standard Interactions

We study the connection between the two indications of physics beyond the Standard Model (SM): the masses and mixing of neutrinos and the existence of dark matter (DM). The most attractive proposal for the origin of neutrino mass

18. Minimal scoto-seesaw mechanism for neutrino masses with spontaneous CP violation
D. Barreiros (CFTP/IST, U.Lisboa)
19/02/2021, 17:30
Neutrino Theory and Cos... | Parallel Contributed Talk | Non Standard Interactions

I will discuss our recent work on a simple scoto-seesaw model that accounts for dark matter and neutrino masses with spontaneous CP violation. This is achieved with a single horizontal $\mathcal{Z}_8$ discrete symmetry, broken to a residual $\mathcal{Z}_2$

285. Directional Dark Matter Search with NEWSdm
Valeri Tioukov (NA)
22/02/2021, 10:40
Neutrino Masses and Mi... | Parallel Contributed Talk | Data Science and Detect...

In spite of the extensive search for the detection of the dark matter (DM), experiments have so far yielded null results: they are probing lower and lower cross-section values and are touching the so-called neutrino floor. A way to possibly

160. Probing Dark Matter with IceCube
Atri Bhattacharya
25/02/2021, 10:40
Neutrino Telescopes and ... | Parallel Contributed Talk | Multimessenger Investig...

In view of the IceCube's 6-year high-energy starting events (HESE) sample, we revisit the possibility that the updated data may be better explained

207. Dark Matter Neutrino Scattering in the Galactic Centre
Adam McMullen (Queen's University)
25/02/2021, 11:50
Neutrino Telescopes and ... | Parallel Flash talk | Astrophysical Models

While there is evidence for the existence of dark matter, its properties have yet to be discovered. Similarly, the nature of high-energy astrophysical neutrinos detected at the IceCube Neutrino Observatory remains unresolved. If dark matter and

163. Neutrinos as signal and background in the search for dark matter with INO
Deepak Tiwari (PICO, University of M...)
26/02/2021, 10:20
Neutrino Telescopes and ... | Parallel Contributed Talk | New Facilities

Annihilation of Weakly Interacting Massive Particles (WIMPs) in the center of the sun(⊙), earth(⊕) and the galaxy can give rise to neutrino-antineutrino pairs as their final products. We look at the prospects of detecting such neutrinos at the

248. Searching for Dark Matter from the Sun with Ten Years of IceCube Data
Jeff Lazar (University of Wiscon...)
23/02/2021, 12:05
Neutrino Telescopes and ... | Parallel Flash talk | Multimessenger Investig...

Dark matter's existence (DM) has been well-established by repeated experiments over many length scales. Even though DM is expected to make up 85% of the current matter content of the Universe, its nature remains unknown. One broad

252. A New Window into Neutrino Astronomy with Dark Matter Experiments: Supernova Forecast and the Origin of Supermassive Black Holes
Volodymyr Takhistov
24/02/2021, 11:00
Neutrino Telescopes and ... | Parallel Contributed Talk | Low Energy Neutrinos

Advances in dark matter detection call for even more massive underground experiments than state-of-the-art. I will illustrate how such experiments can act as unique telescopes for exploring neutrino astronomy. As I will show, using

66. Dark Matter at Neutrino Telescopes: Searching for the Heaviest Particle in the Universe
Nicholas Rodd
24/02/2021, 16:45
Neutrino Telescopes and ...

183. Dark Matter search with neutrino telescopes through Angular Power Spectrum
Ariane Dekker
25/02/2021, 11:40
Neutrino Telescopes and ... | Parallel Flash talk | Astrophysical Models

Dark matter can produce a high-energy neutrino flux through decay or annihilation, that can be observed by current and future neutrino telescopes. The neutrino flux from astrophysical, atmospheric and dark matter origin can be

147. Potential of neutrino physics with DARWIN
Andrii Terliuk (Heidelberg University)
25/02/2021, 17:30
Neutrino Masses and Mi... | Parallel Contributed Talk | New Facilities

The DARWIN observatory is a future dark matter detector containing 40 tons of liquid xenon in an active volume of a dual-phase time projection chamber. An ultra low intrinsic radioactivity, large mass, low threshold and good energy

191. keV Sterile Neutrino Dark Matter Terrestrial Searches: Alive and Well
Cristina Benso (Max Planck Institute ...)
26/02/2021, 11:35
Neutrino Masses and Mi... | Parallel Flash talk | Sterile Neutrinos and Ne...

What if the dark matter content of the universe was made up of sterile neutrinos with a mass of the order of keV? Currently, constraints from the measured relic abundance of dark matter and from observations in the X-ray band

253. Recent results from XENON1T and multi-messenger future of XENONnT
Ricardo Peres (University of Zürich)
19/02/2021, 10:40
Neutrino Telescopes and ... | Parallel Contributed Talk | Low Energy Neutrinos

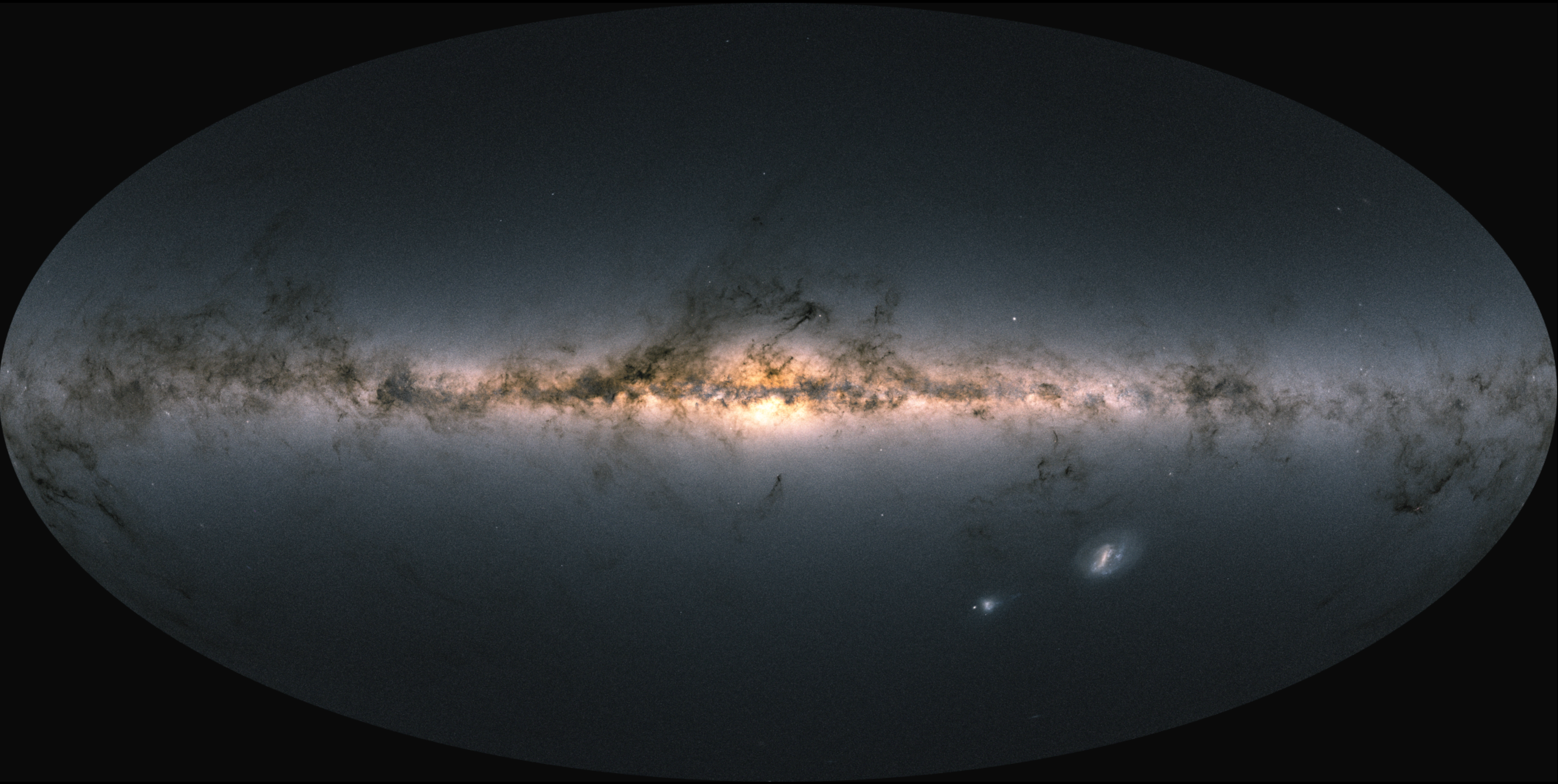
The XENONnT detector recently started its commissioning phase at Laboratori Nazionali del Gran Sasso. Utilizing 5.9 tonnes of liquid xenon (LXe) as active target and designed for a high level of background reduction, it will greatly improve

A new era in the search for DM

GB, Tait, *Nature (2018)1810.01668*

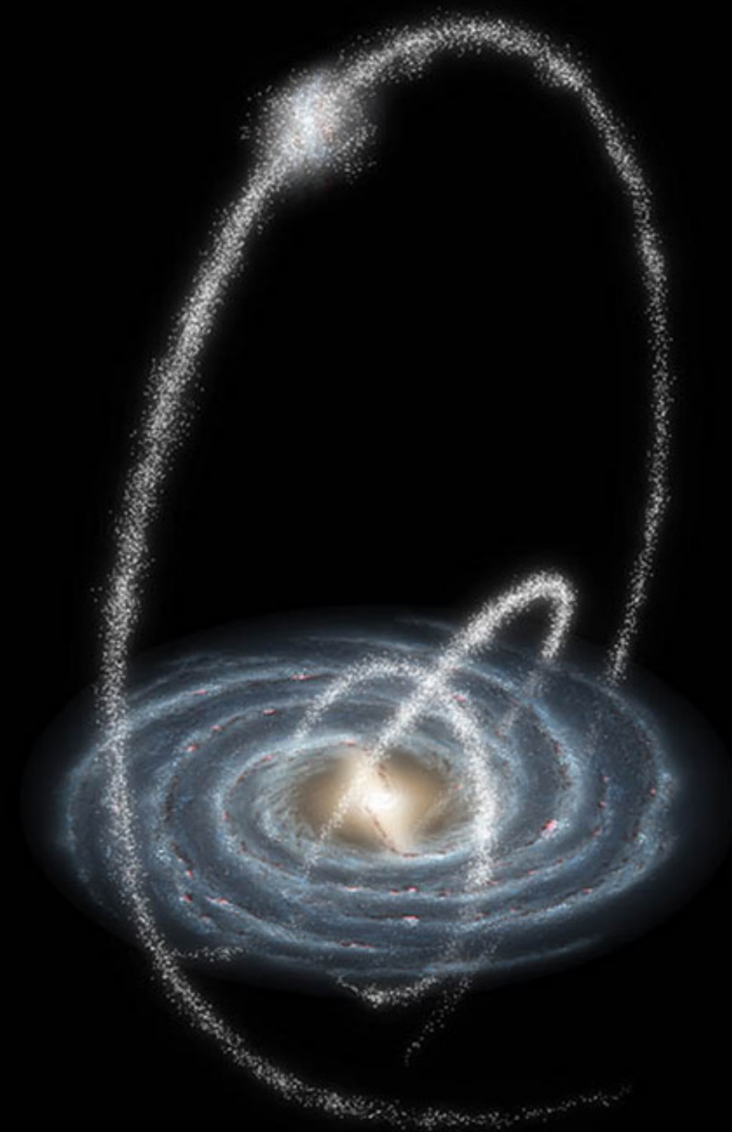
I. Broaden/improve/diversify searches
II. Exploit astro/cosmo observations
III. Exploit Gravitational Waves

GAIA'S SKY

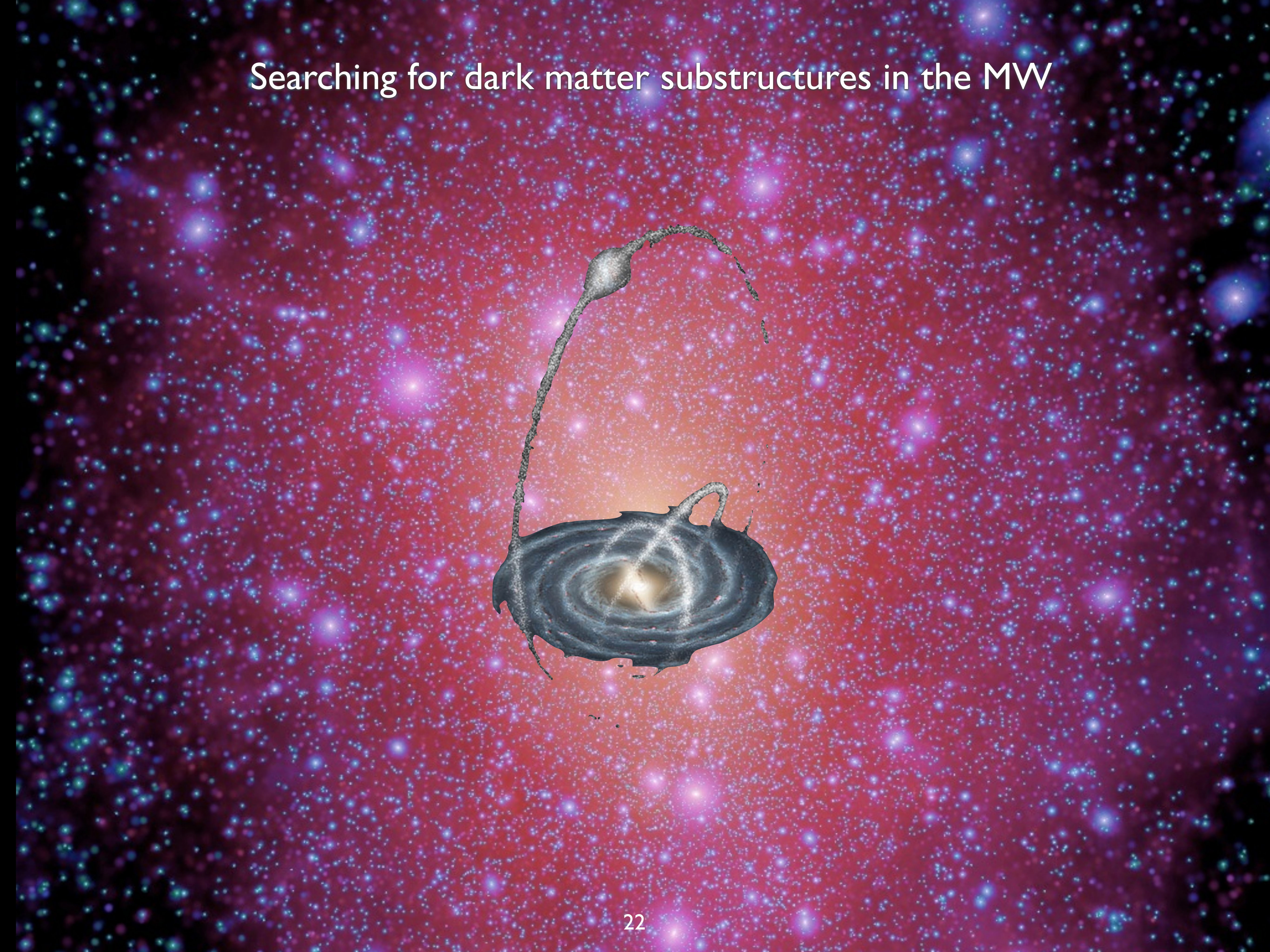


Total brightness and colour of stars observed by ESA's Gaia satellite and released as part of Gaia's Early Data Release 3

Stellar streams



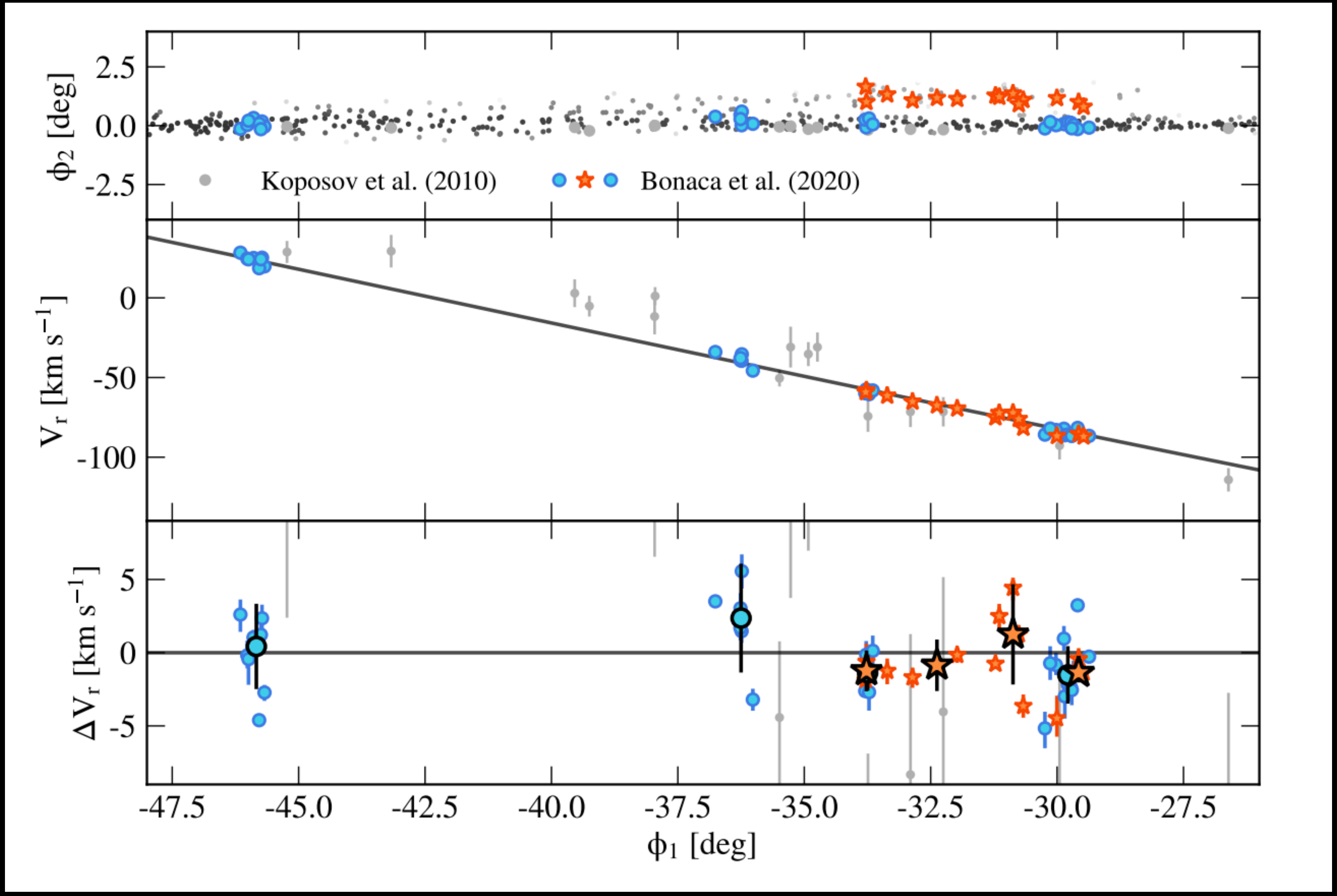
Searching for dark matter substructures in the MW



Gaia GD1 stream data!

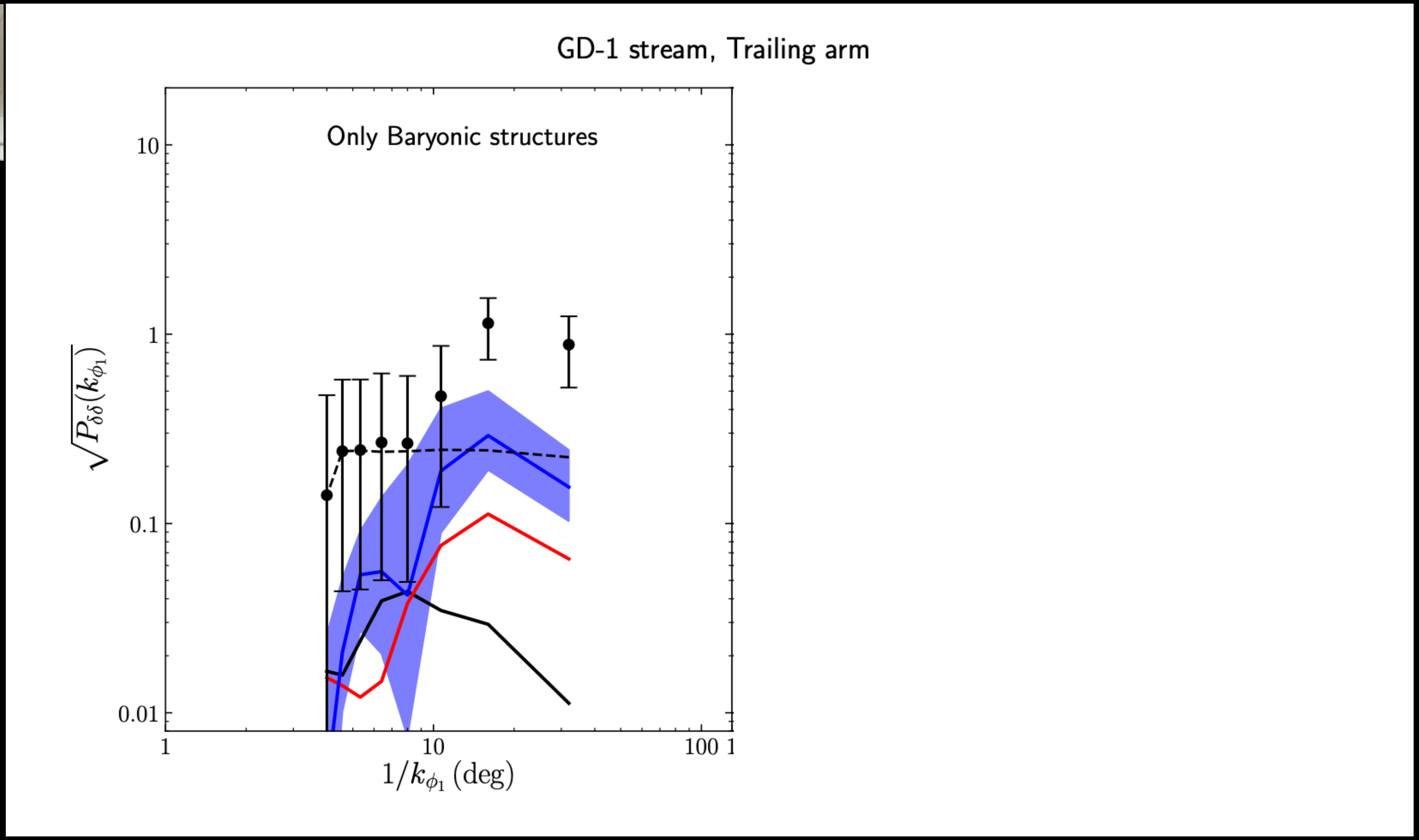
New map of stars in GD1 stream (longest cold stream in the MW) with *Gaia* second data release combined with *Pan-STARRS*.

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!

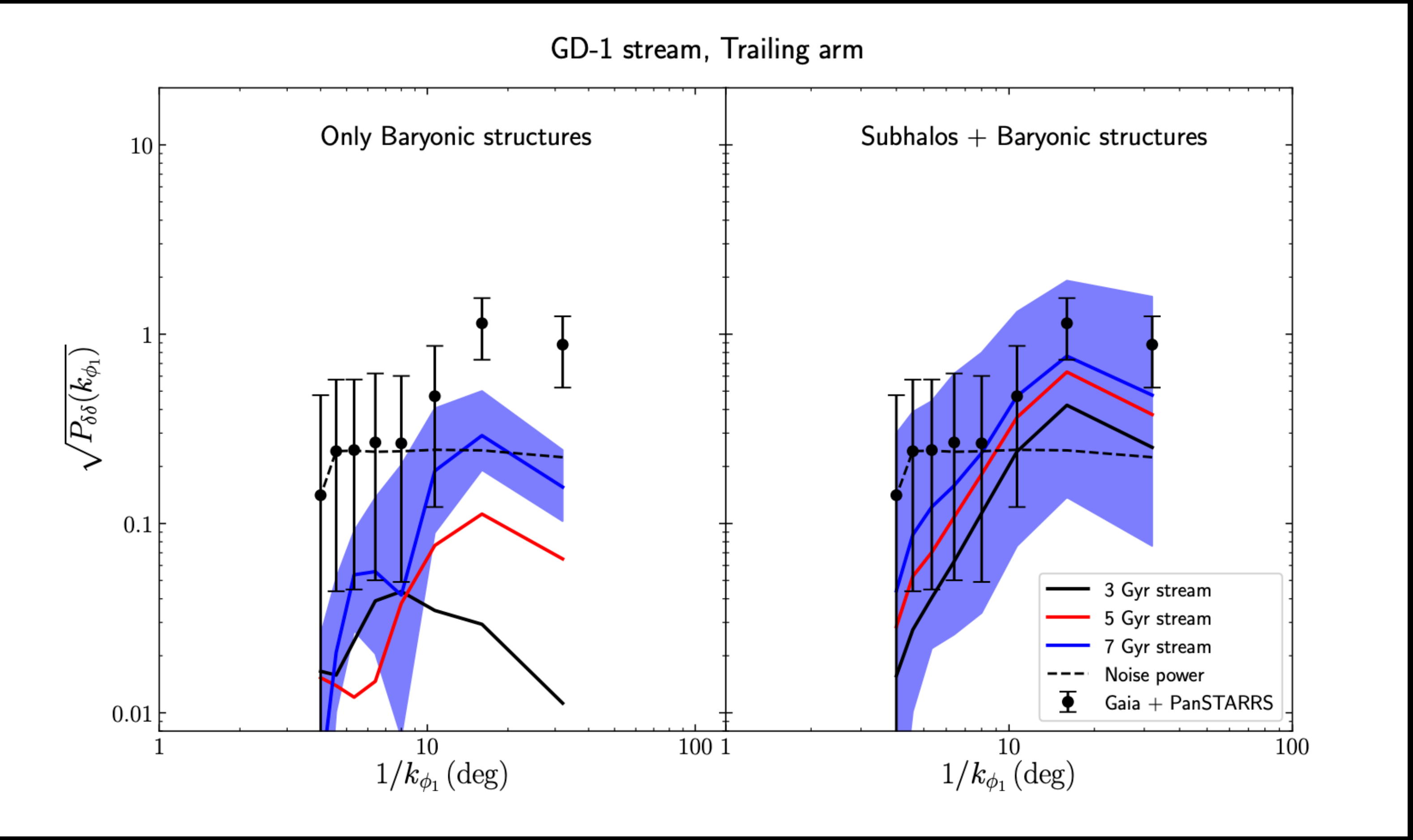


Banik, Bovy, GB, Erkal, de Boer, MNRAS 502, 2364 (2021)

- Gaia GD1 stream data exhibit substantial 'structure'

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

Statistical analysis of perturbations: Strong hints of dark substructures!



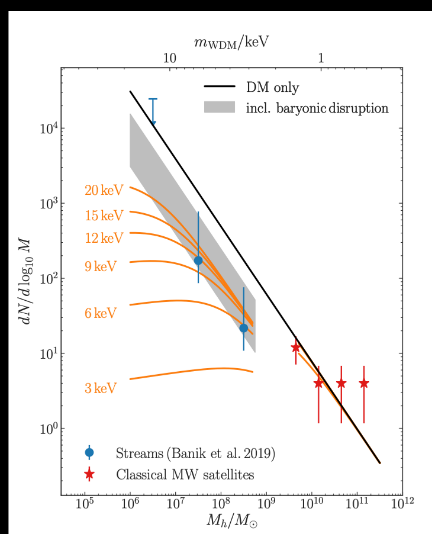
Banik, Bovy, GB, Erkal, de Boer, MNRAS 502, 2364 (2021)

- Gaia GD1 stream data exhibit substantial 'structure'

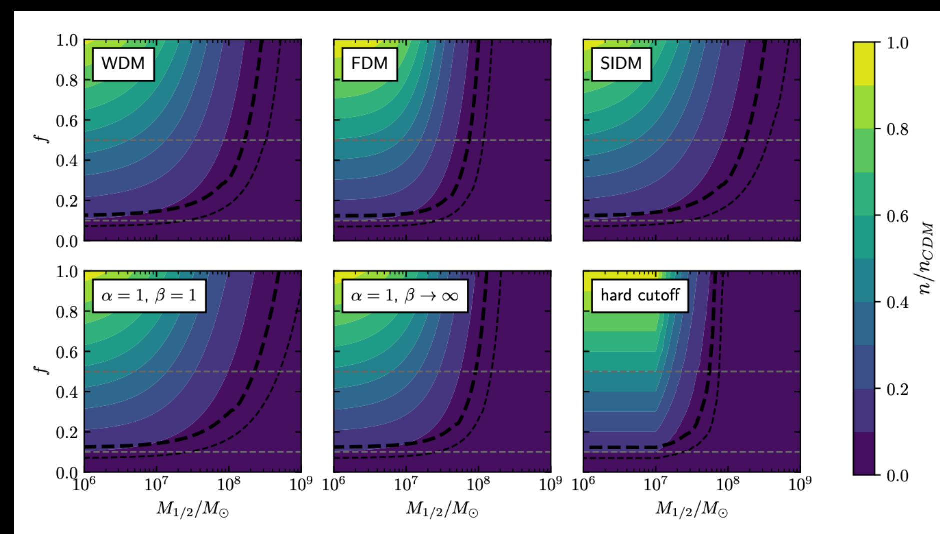
- Density fluctuations cannot be explained by "baryonic" structures (GC, GMC, spiral arms etc)

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

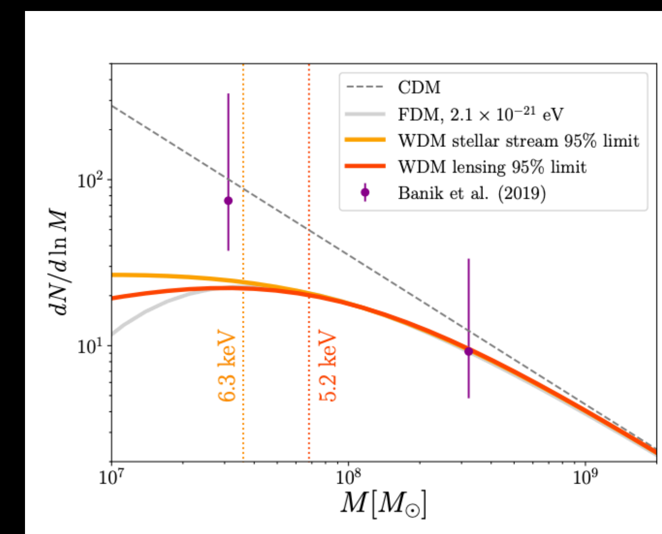
Statistical analysis of perturbations: Stringent constraints on the nature of DM



1911.02663



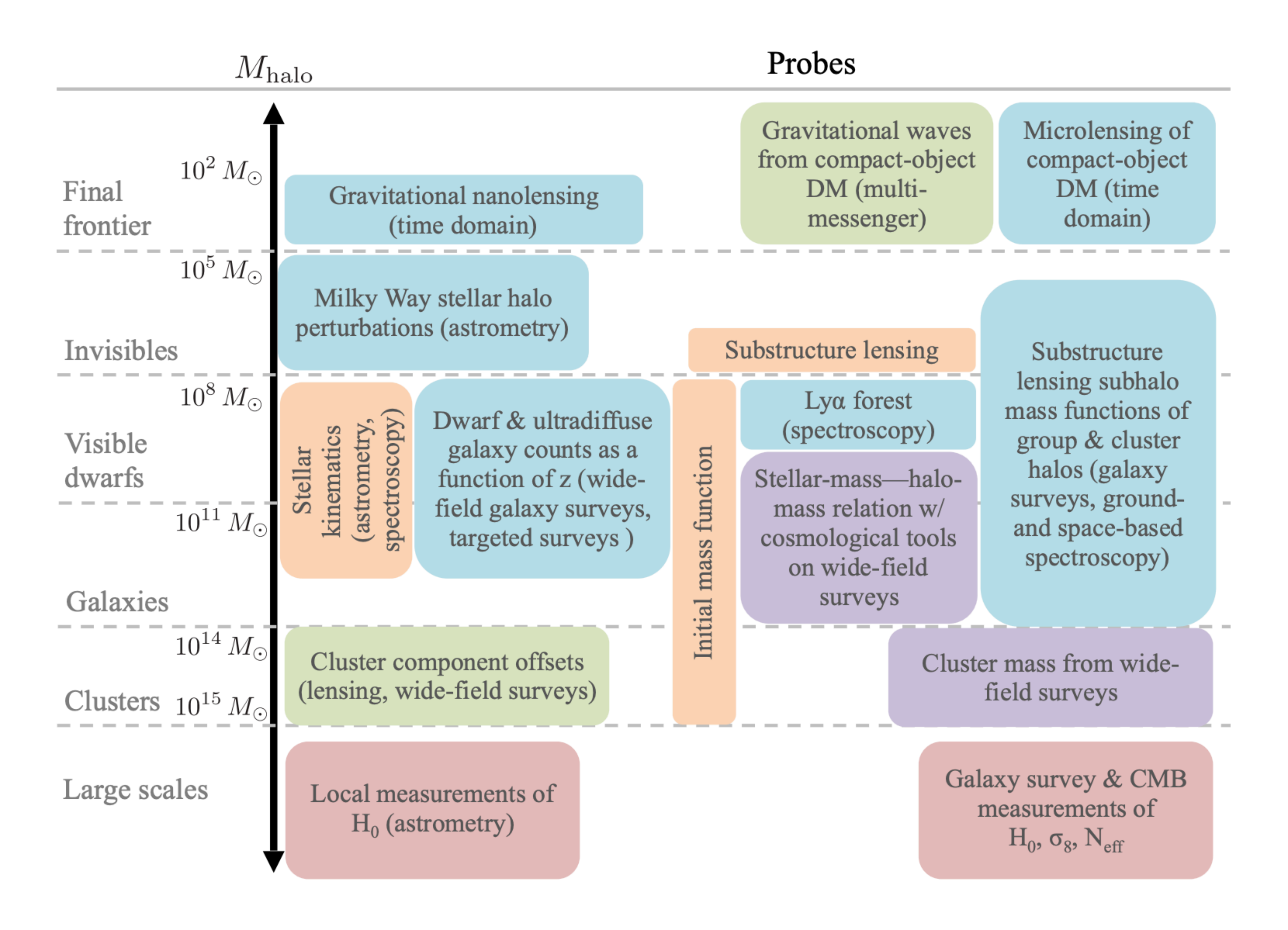
2001.11013



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

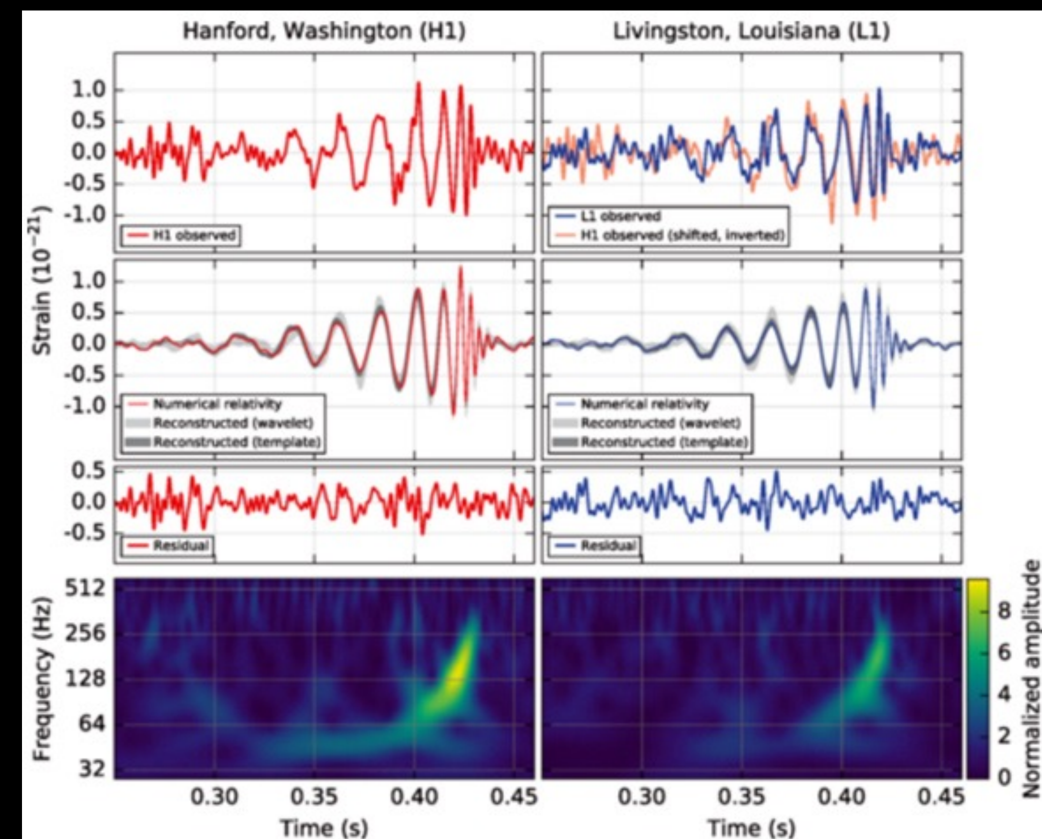
III. Exploit Gravitational Waves

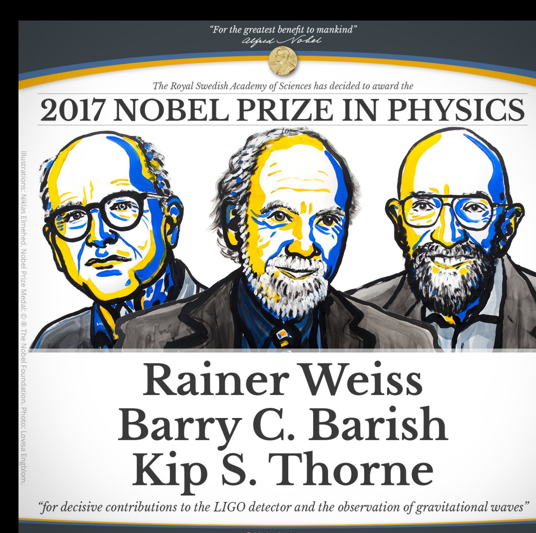
Gravitational Waves

"The discovery that shook the world"

LIGO & Virgo coll, PRL 116, 061102

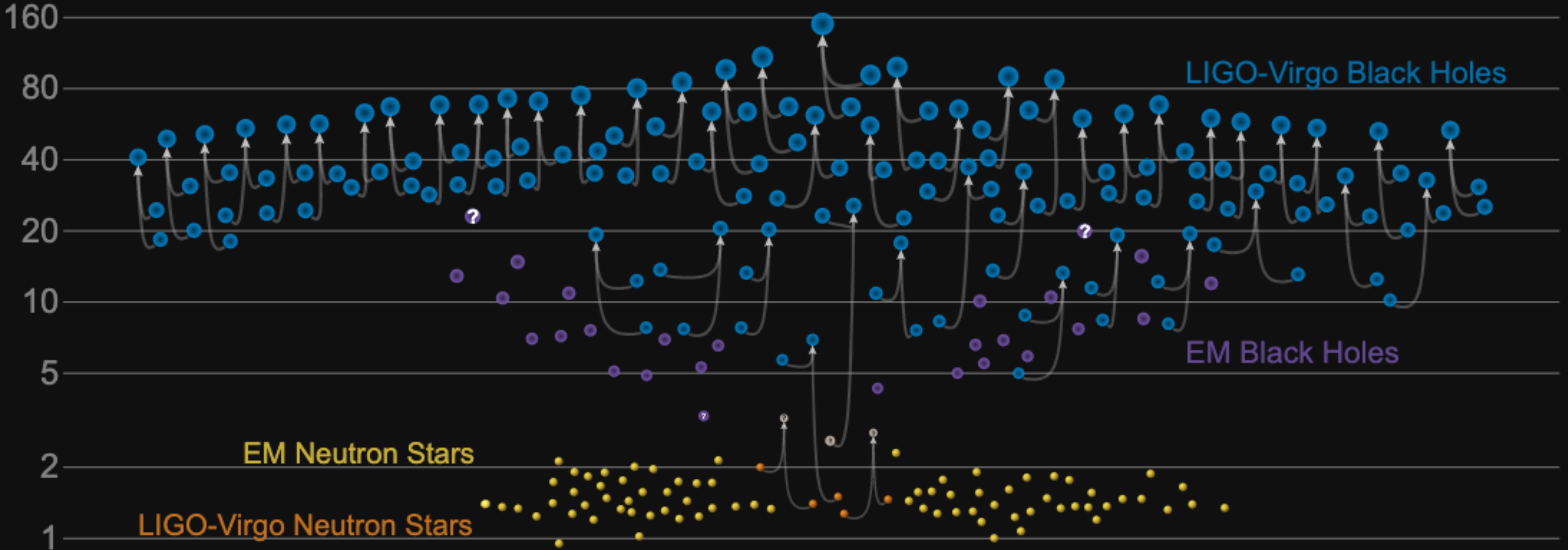
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$





Masses in the Stellar Graveyard

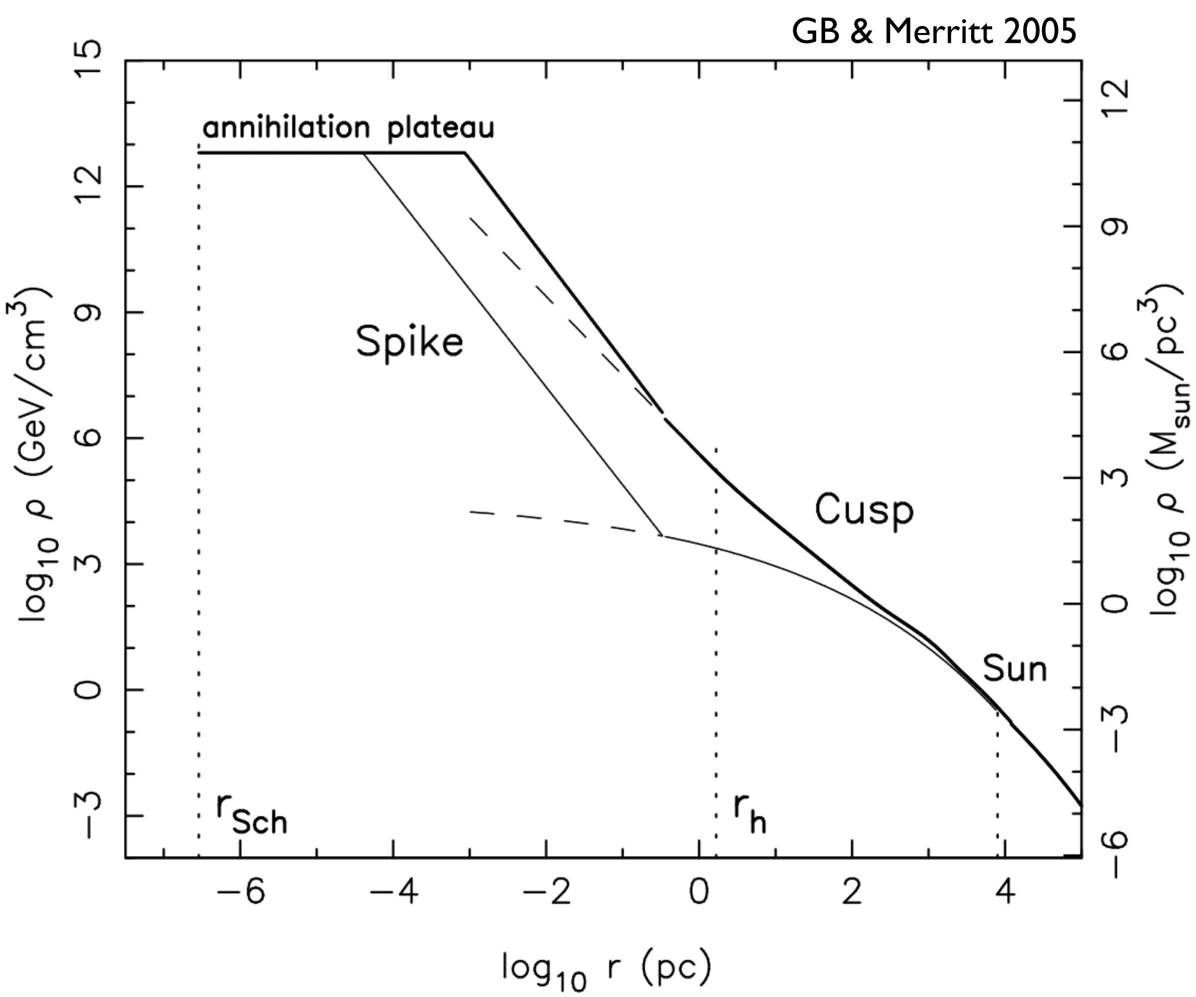
in Solar Masses



GWTC-2 plot v1.0

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Dark Matter 'dress' around BHs



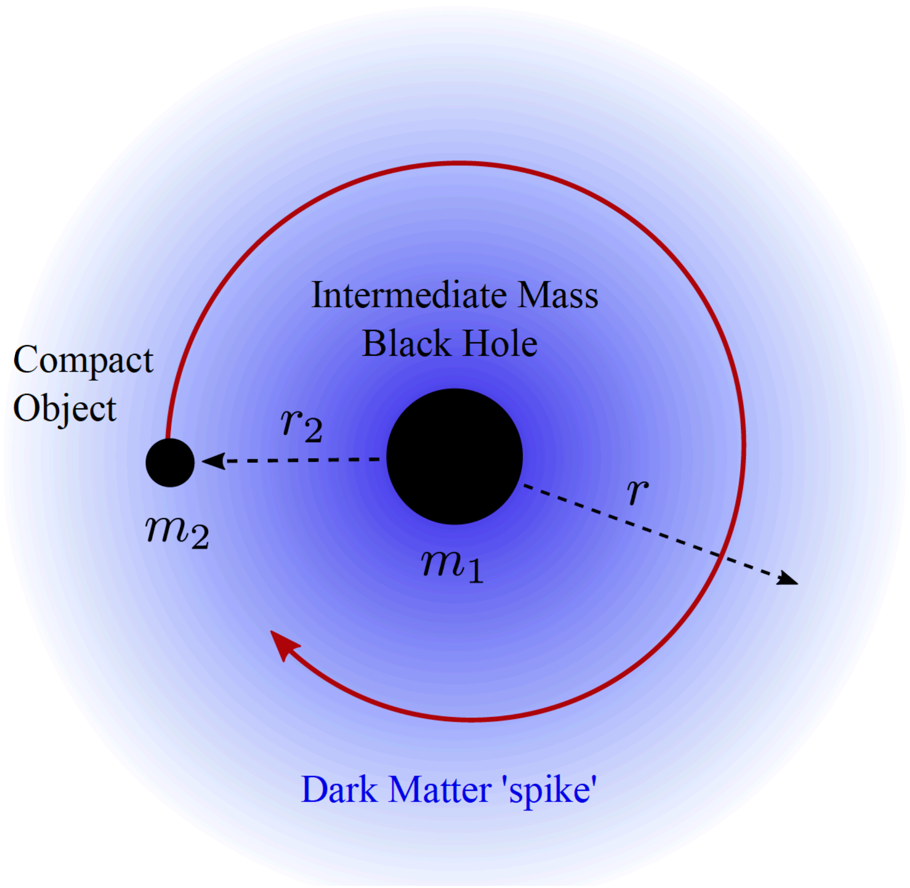
- **Adiabatic 'spikes' around SMBHs**
  (Gondolo & Silk 2000)
- **'Mini-spikes' around IMBHs**
  (GB, Zentner, Silk 2005)
- **Overdensities around primordial BHs**
  (e.g. Adamek et al. 2019)
- **Ultralight boson 'clouds'**
  (e.g. Brito, Cardoso & Pani 2015)

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

Dark Matter around BHs

Energy losses:

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



Eda+ PRL 110, 221101 (2013)

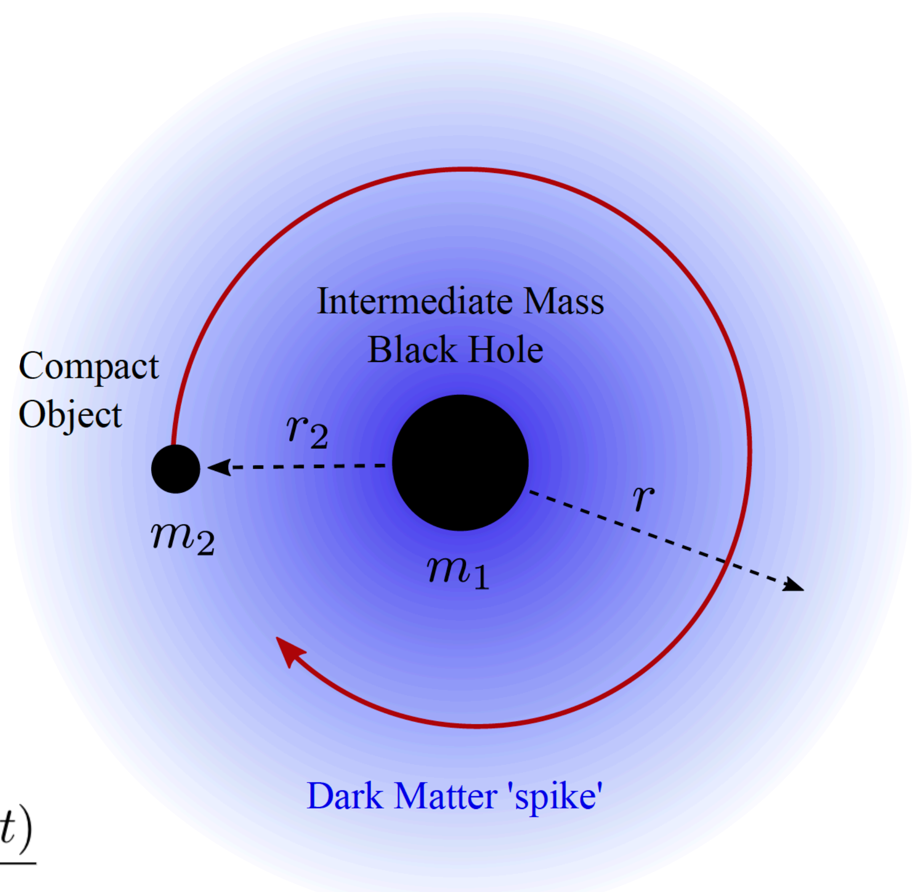
Dark Matter around BHs

Energy losses:

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

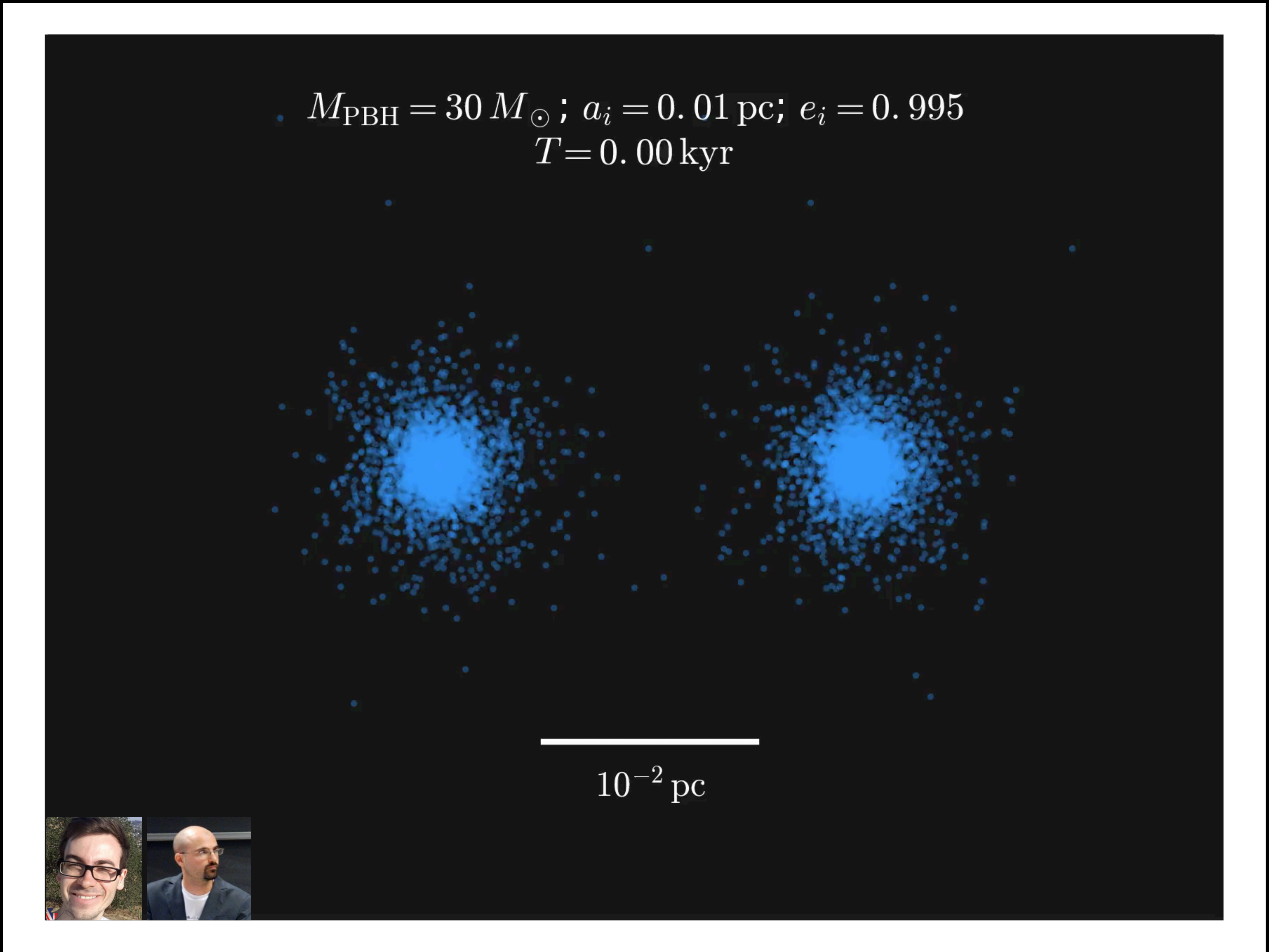
Separation:

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



Kavanagh, GB et al. 2002.12811

‘Dressed’ BH-BH merger



Kavanagh, Gaggero & GB, arXiv:1805.09034

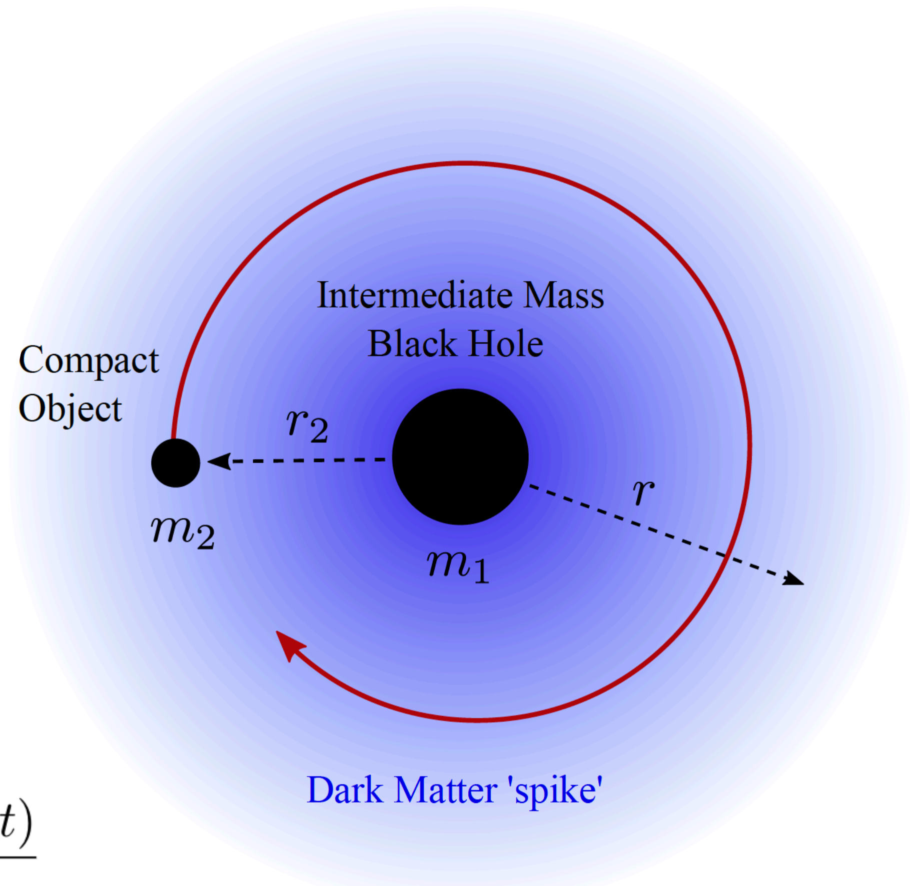
Dark Matter around BHs

Energy losses:

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

Separation:

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

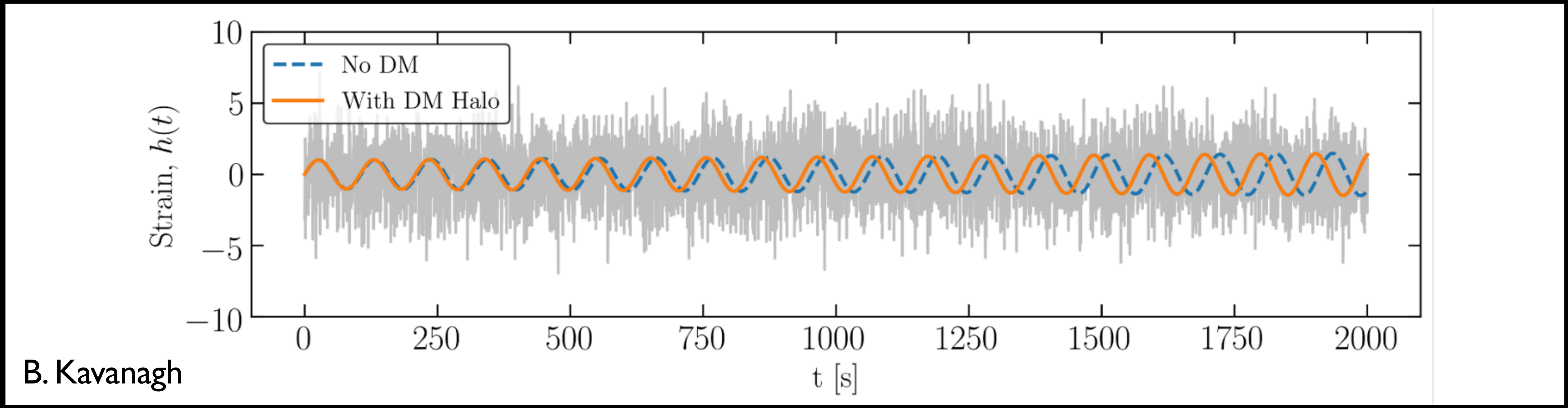


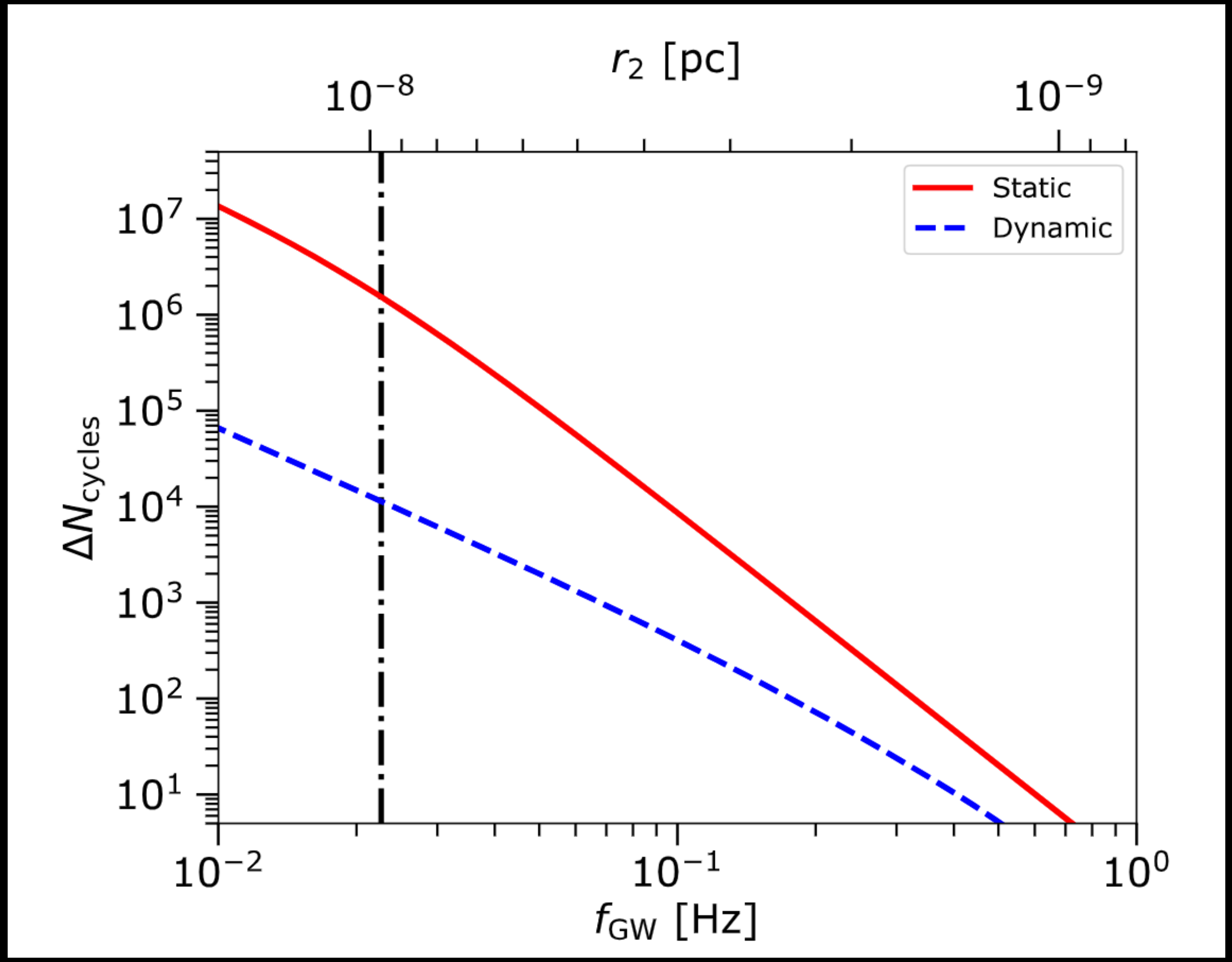
Time-dependent dark matter profile:

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

Kavanagh, GB et al. 2002.12811

Gravitational Waveform dephasing





Kavanagh, GB et al. 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

Primordial Black Holes

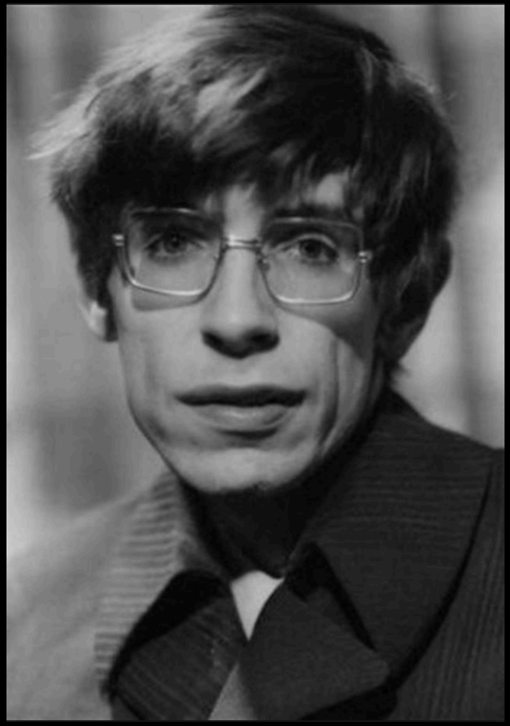
Mon. Not. R. astr. Soc. (1971) **152**, 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

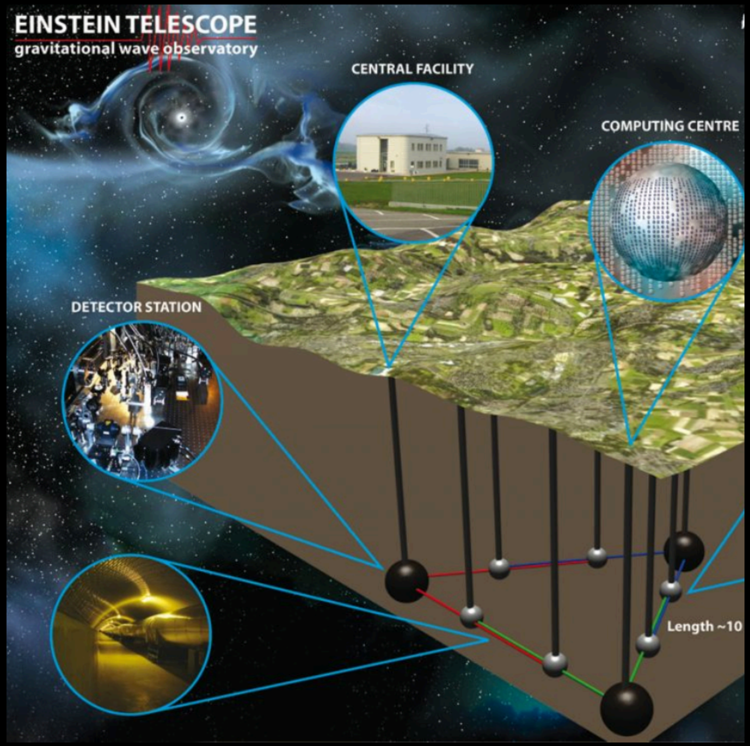
(Received 1970 November 9)



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:

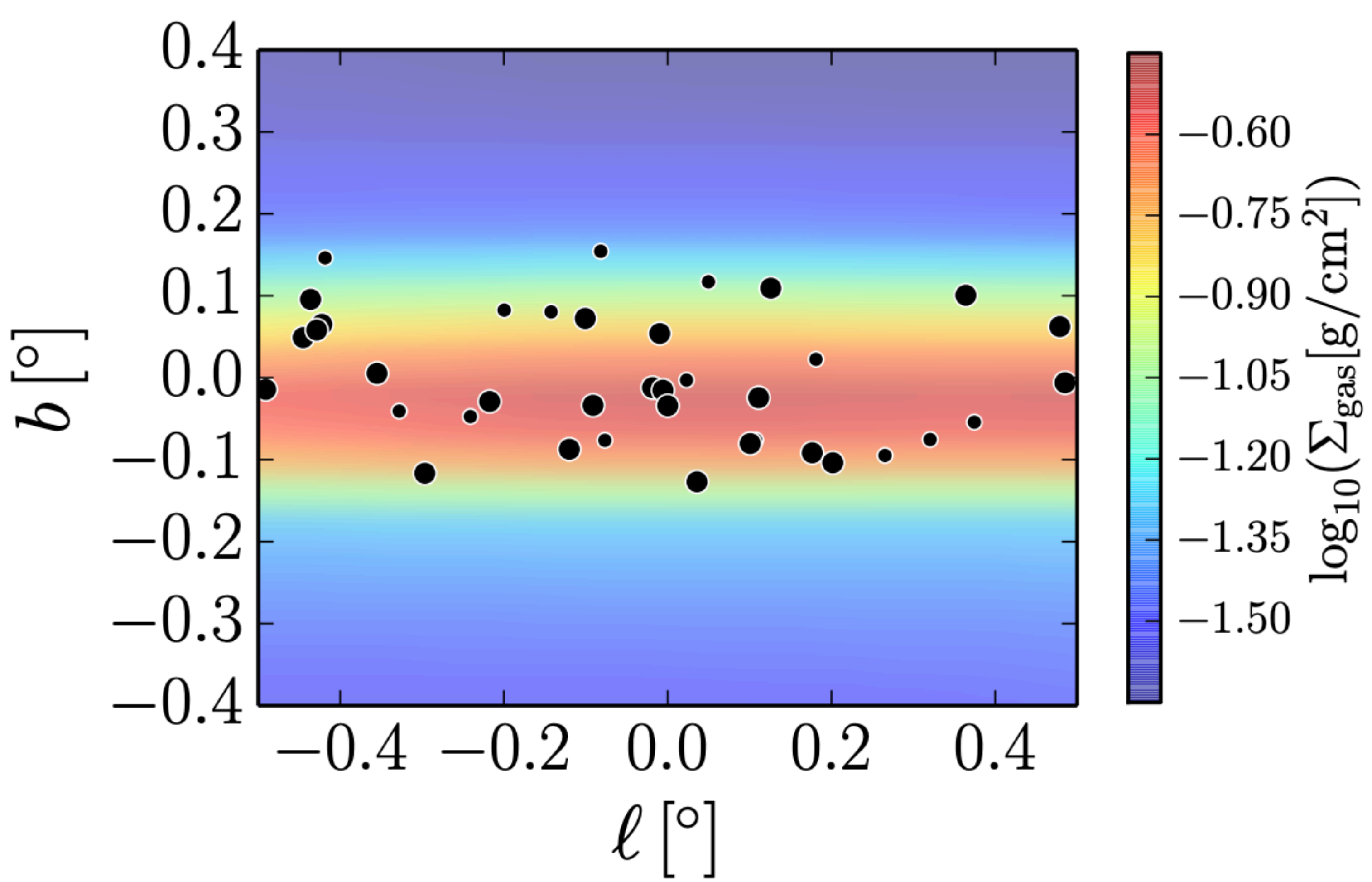


I. Detect sub-solar mass BHs with joint Ligo/Virgo observing run 3 (in progress)

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]

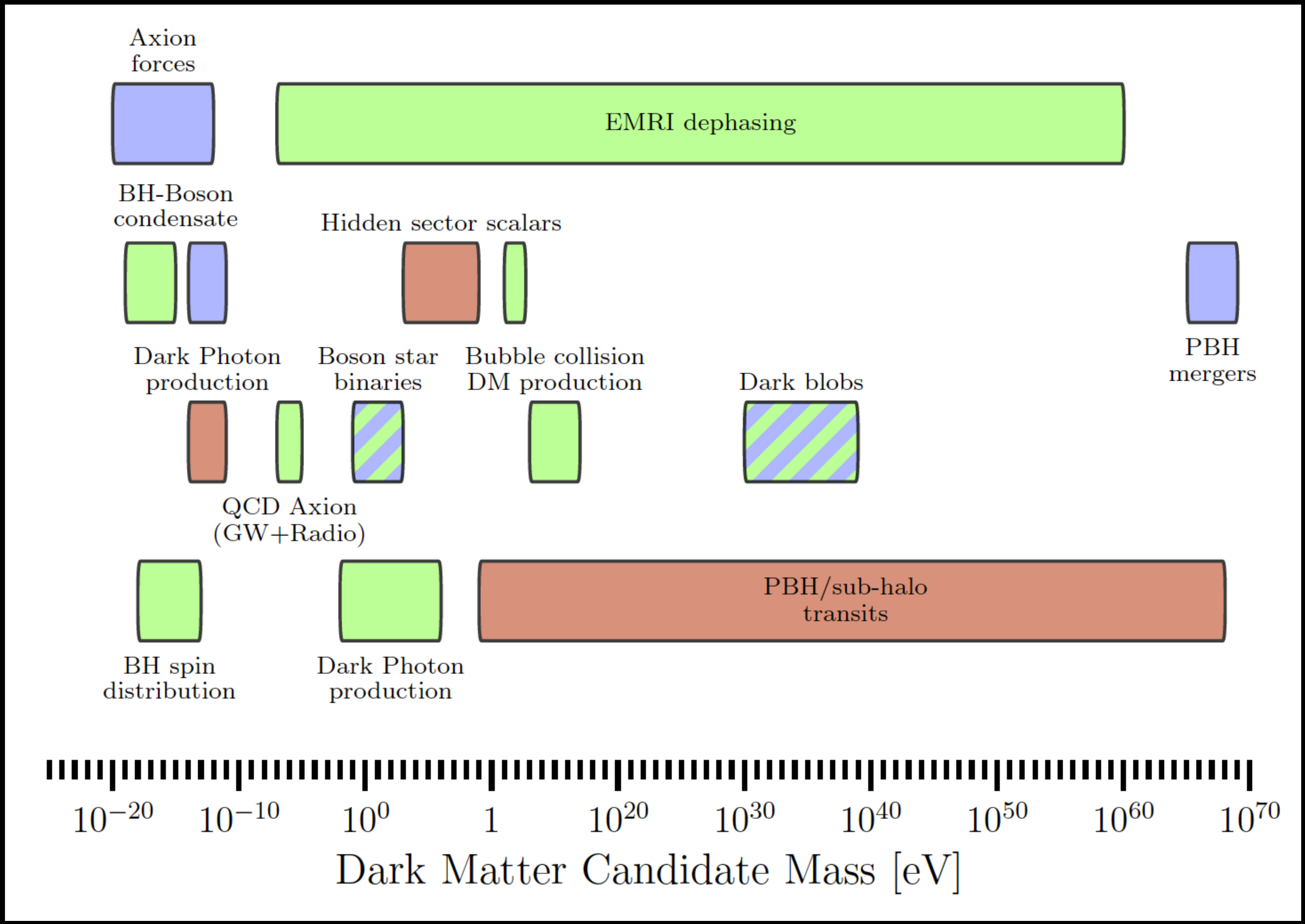
Multiwavelength observations of PBHs (and astrophysical BHs) in the MW



Gaggero, GB et al. PRL 118, 241101 (2017)

- Isolated BH moving at supersonic speed in ISM produce radio and X-ray emission. Exciting prospects for detecting primordial and astrophysical BHs with SKA *[Manshanden, Gaggero+ JCAP 06 (2019) 02, Scarcella, Gaggero+, 2012.10421]*

Further GW-DM connections:



"Gravitational wave probes of dark matter: challenges and opportunities"
GB, Croon, et al. SciPostPhysCore 3, 007 (2020)

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

First EuCAPT Annual Symposium

5-7 May 2021
CERN
Europe/Zurich timezone

Search...

*** 09/02/2021: the Symposium will be held in **fully remote mode**. Registration is now open ***

21/12/2020: invited speakers and area conveners announced.

The European Consortium for Astroparticle Theory (EuCAPT, https://www.eucapt.org) is a new initiative, with central hub at CERN, that aims to bring together the European community of theoretical astroparticle physicists and cosmologists. Our goals are to increase the exchange of ideas and knowledge; to coordinate scientific and training activities; to help scientists attract adequate resources for their projects; and to promote a stimulating, fair and open environment in which young scientists can thrive. More than 660 scientists completed the 1st EuCAPT census in January 2020, and expressed an interest in EuCAPT activities.

We are delighted to announce the first edition of the EuCAPT annual symposium, the flagship event of our consortium, that aims to provide an interdisciplinary Europe-wide forum to discuss opportunities and challenges in Theoretical Astroparticle Physics and Cosmology. We invite all scientists (PhD students, postdocs, and staff) active in these fields of research to join us remotely from May 5 to May 7, 2021. The symposium will feature invited presentations, and young scientists will have the opportunity to present their work with lightning talks. Beside scientific presentations, the programme also includes: thematic parallel discussions; a plenary session dedicated to the planning of a community-wide white paper; an award ceremony for the best talks from young scientists.