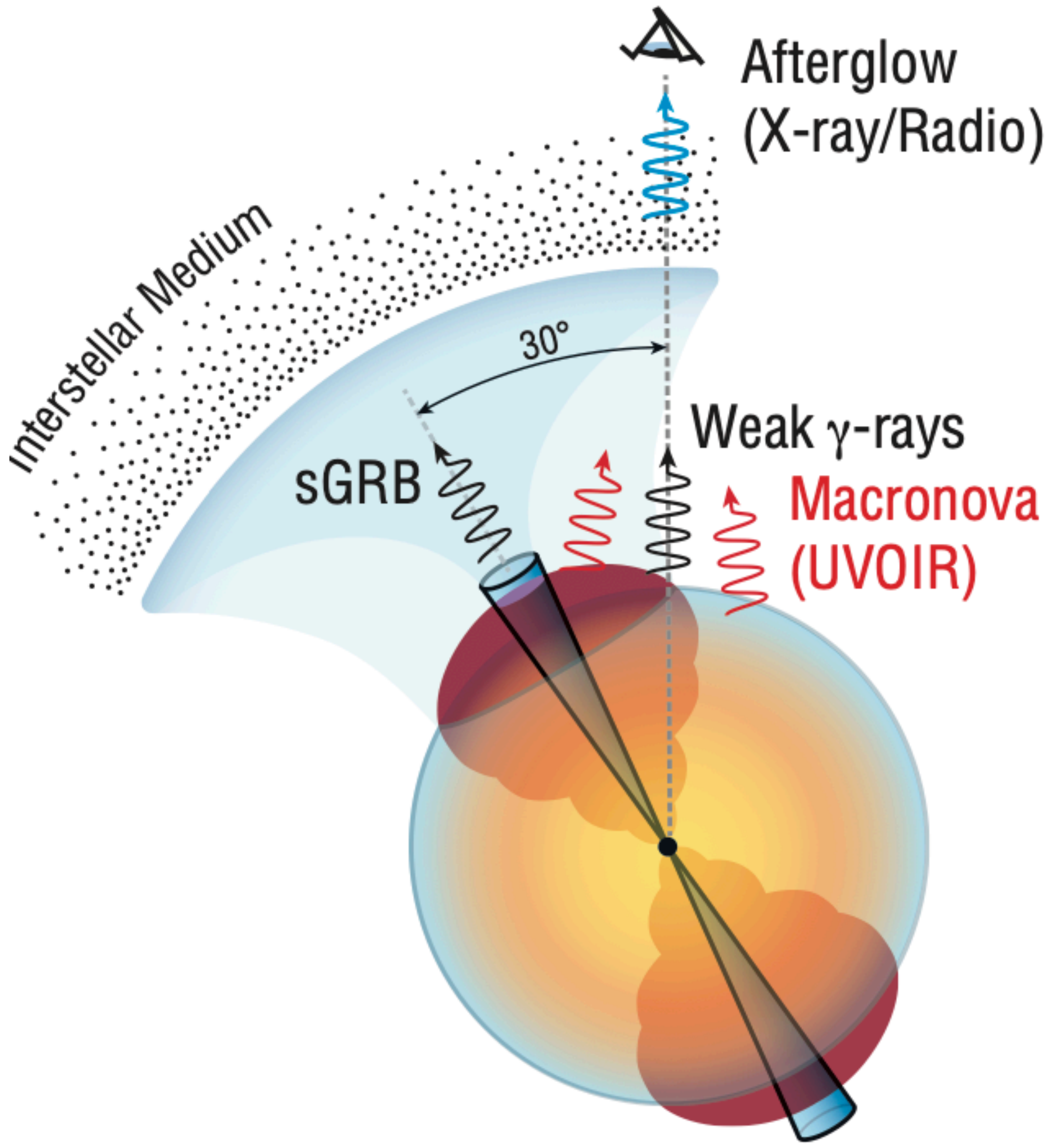
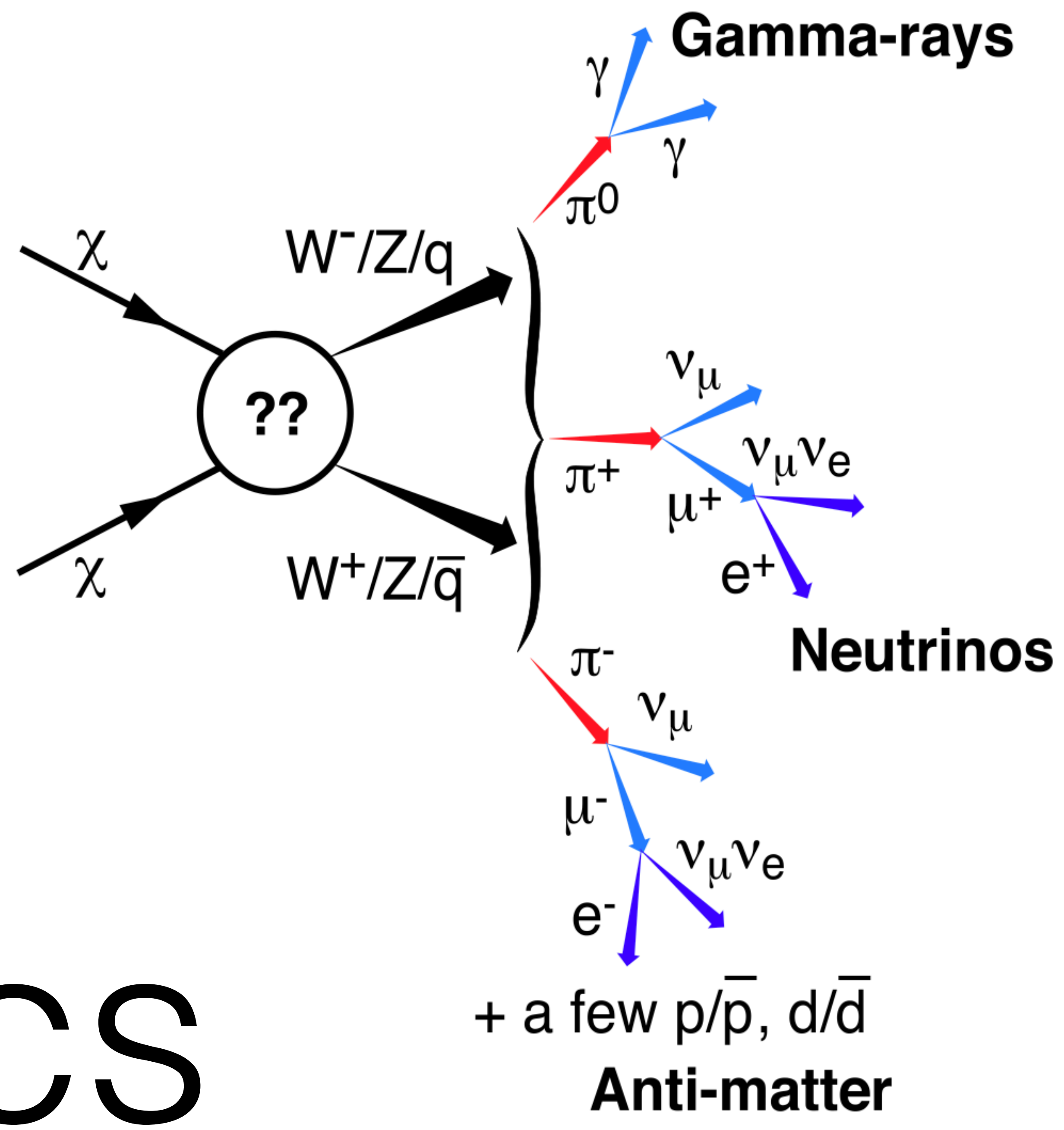




(An introduction to)

Astroparticle Physics

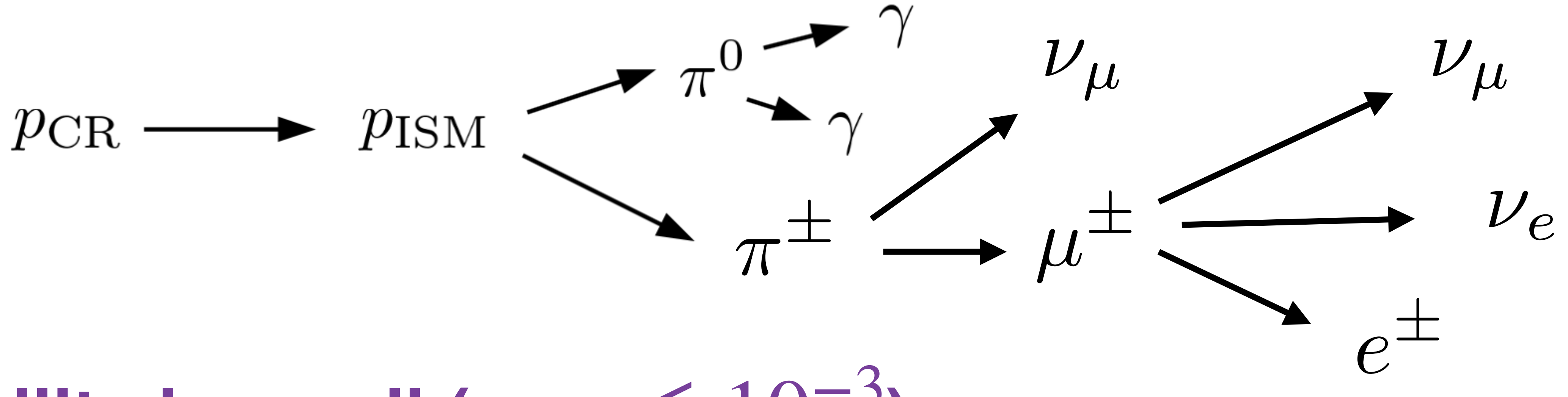
Lecture 2/2

Bradley J Kavanagh [he/him]
Instituto de Fisica de Cantabria (CSIC-UC)
kavanagh@ifca.unican.es

CERN Summer Student Lecture Programme:
Thursday 17th July 2025

Slides here: bradkav.net/talks

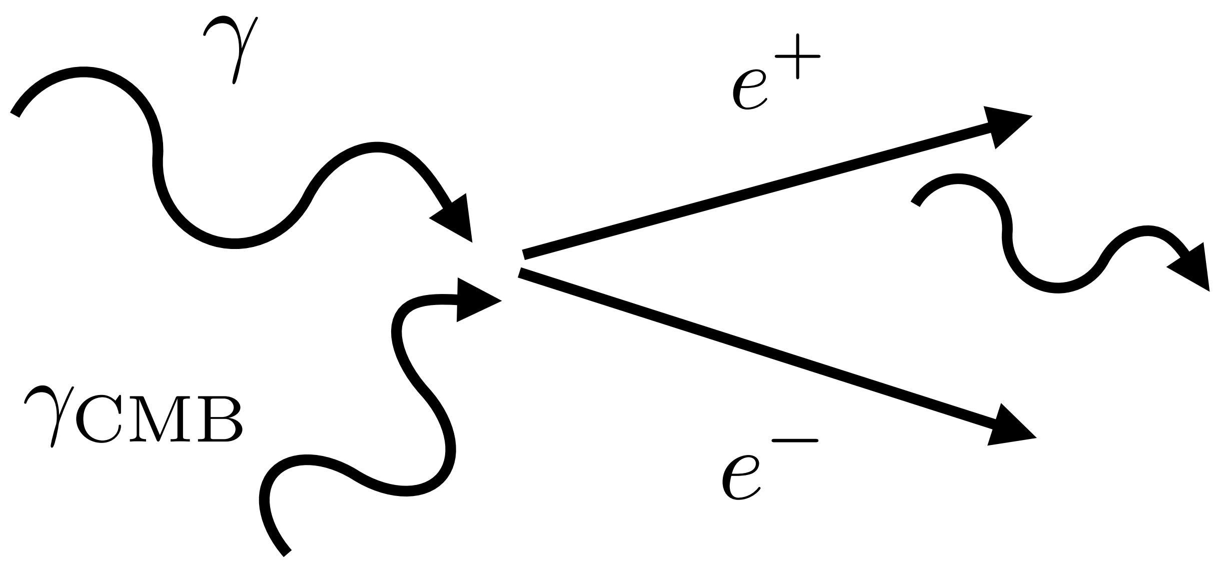
Q: CR, neutrino and γ-ray energies?

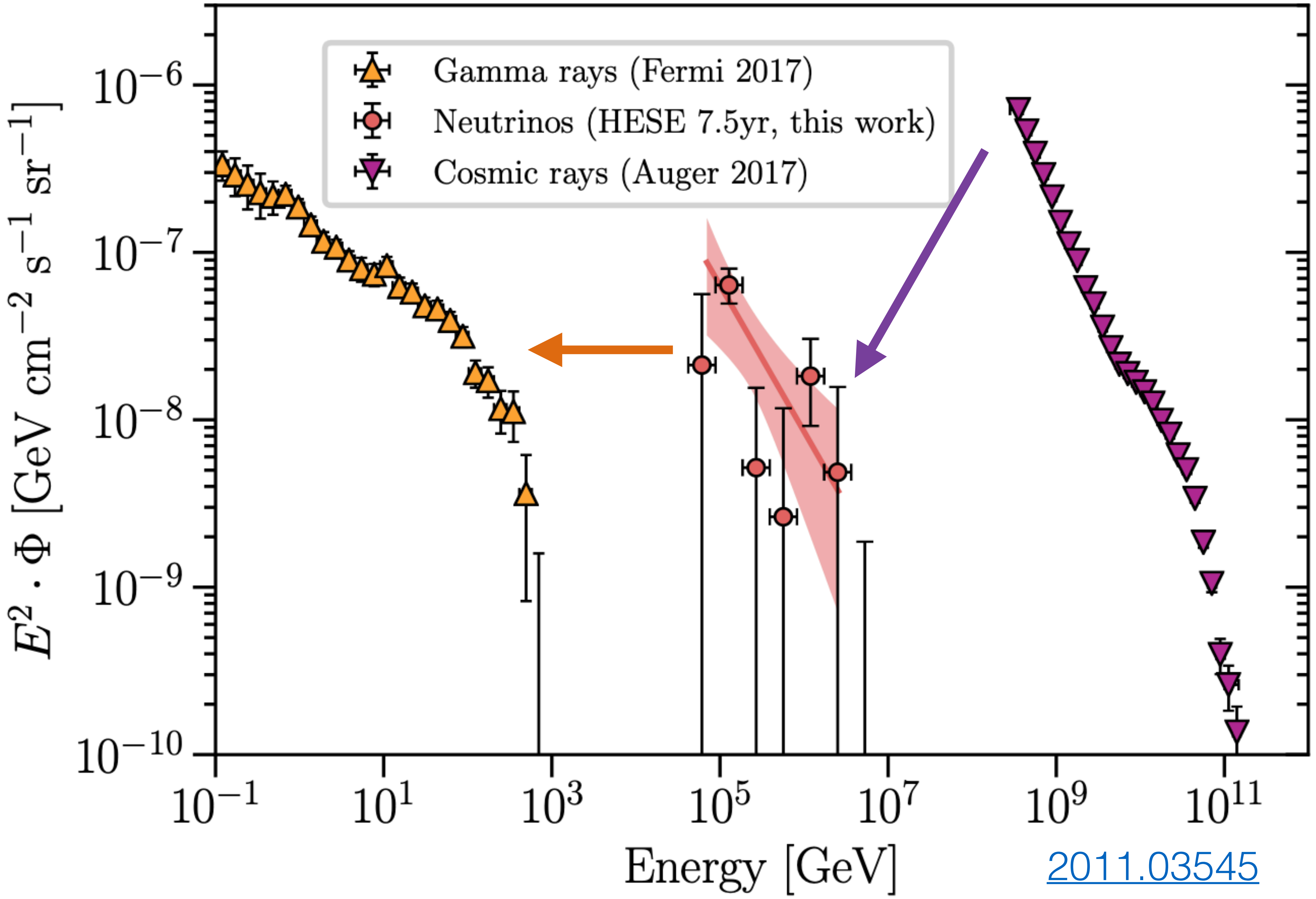


For CR interactions with interstellar medium, **interaction probability is small (say $\lesssim 10^{-3}$) and only some fraction of the initial CR energy** goes into any given pion

This pp process dumps comparable energy into gamma-rays and neutrinos. astro-ph/0606058

But, PeV gamma rays are above the threshold for pair-production, so they **cascade down** to the TeV energy scale



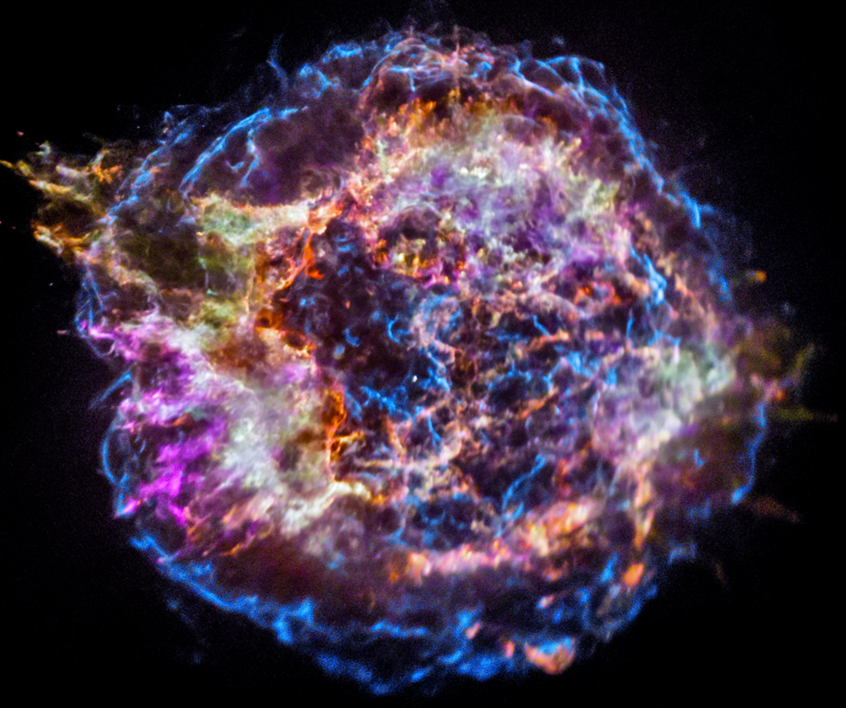


2011.03545

*Note that not all processes lead to substantial neutrino production (e.g. inverse compton)

The Sun

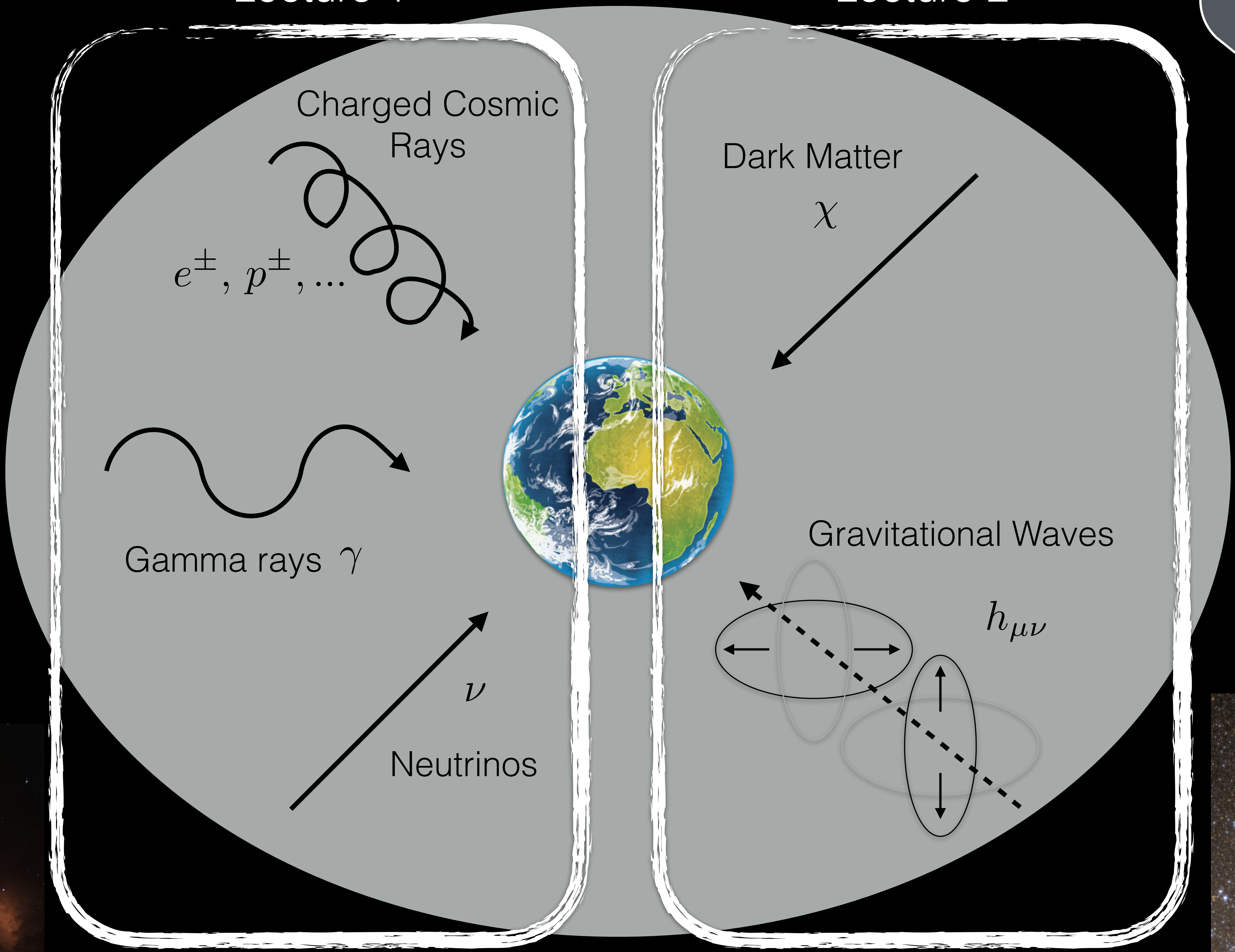
Supernovae

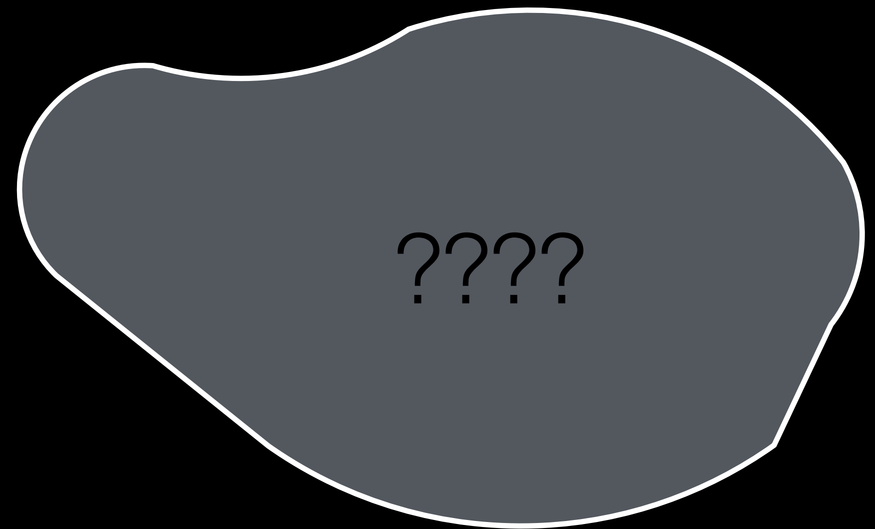


Credit: NASA/CXC/SAO

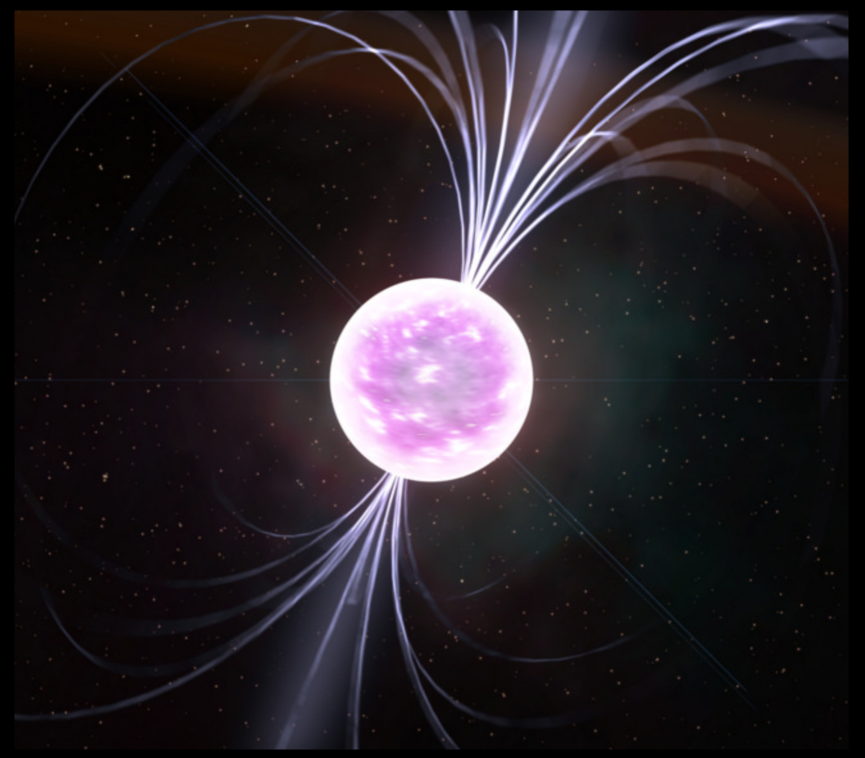
Quasars/AGN

Credit: ESO/M. Kornmesser





Pulsars



Credit: Kevin Gill / Flickr

BH/NS Mergers

Credit: SXS Lensing

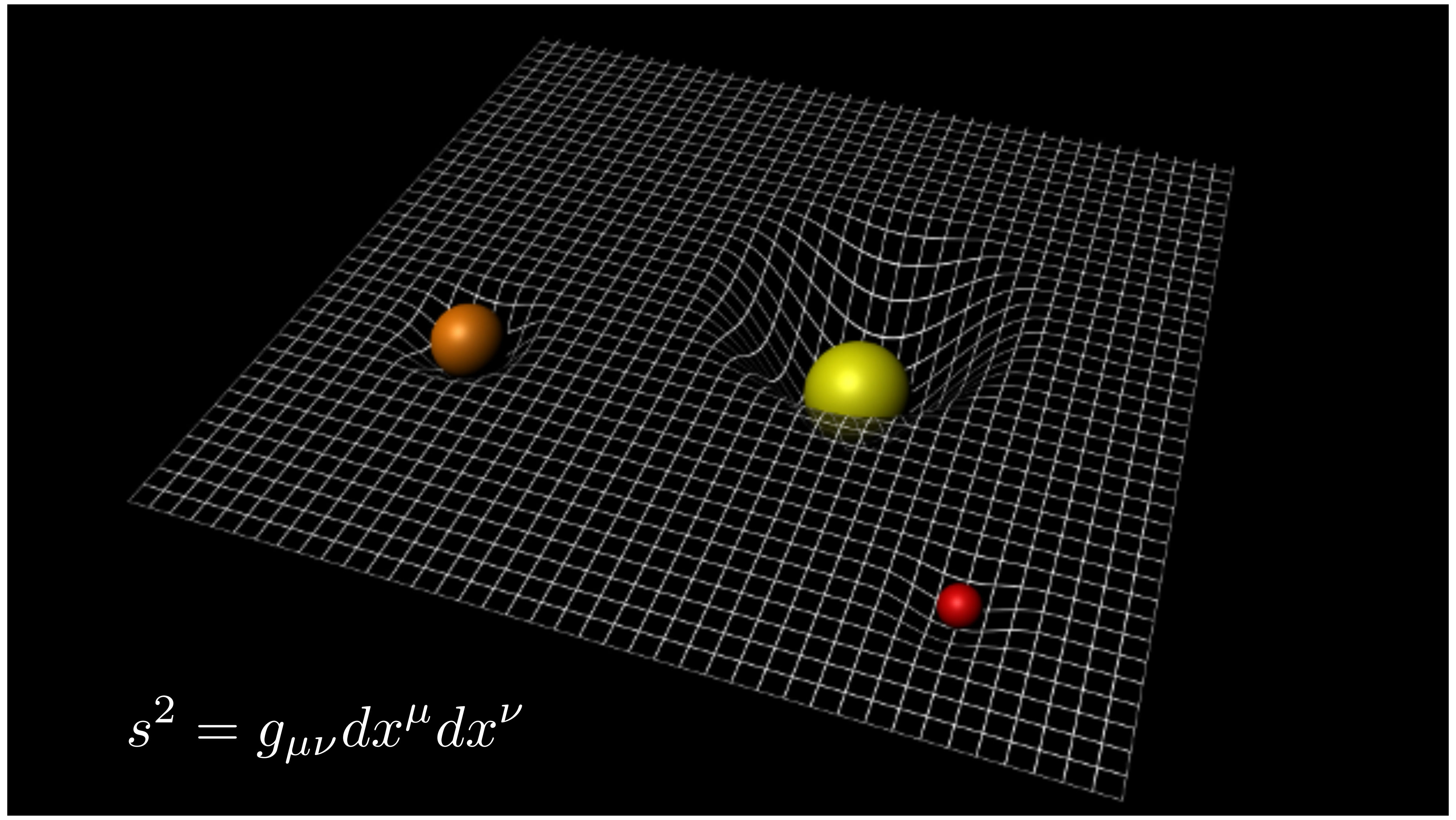
Gravitational Waves

Einstein field equations of General Relativity: $$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein tensor (Gravity)

Stress-energy tensor (Matter)

Space-time curvature specified by the metric, $g_{\mu\nu}$



Credit: ESA/C. Carreau

Linearise the field equations in vacuum:

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

Wave-like solutions! **Gravitational Waves (GWs)**

$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2\right) h_{\mu\nu} = \Box h_{\mu\nu} = 0$$

The Gravitational Wave Spectrum

$$c = \lambda_{\mathrm{GW}} \cdot f_{\mathrm{GW}}$$

f_{GW}: nHz — μHz — mHz — Hz — kHz

λ_{GW}: 10^{13} km ~ pc — 10^{11} km — 10^{8} km — 10^{5} km — 100 km

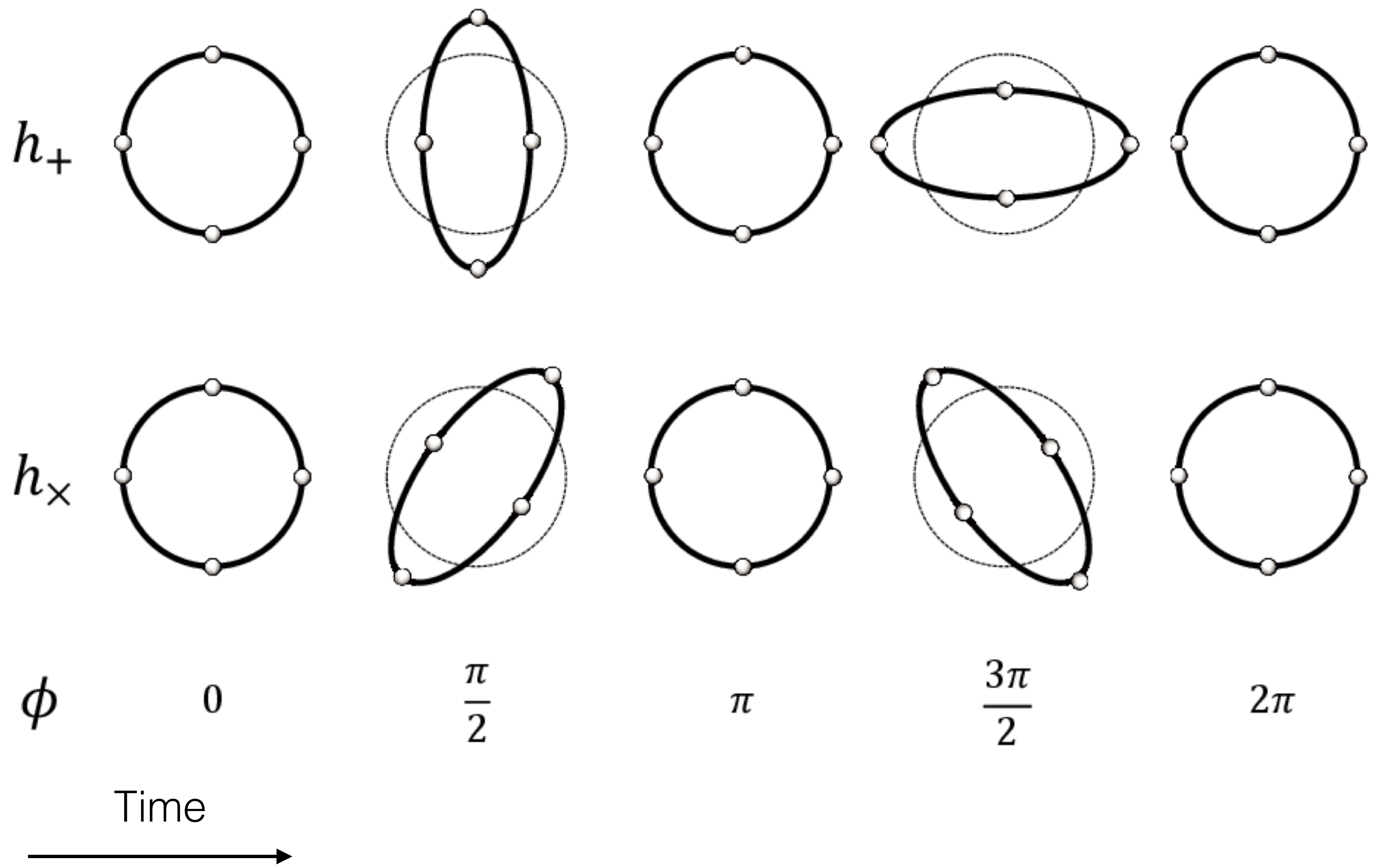
T_{GW}: 30 years — 10 days — 15 minutes — 1 second — 1 ms

SOURCES

DETECTORS?

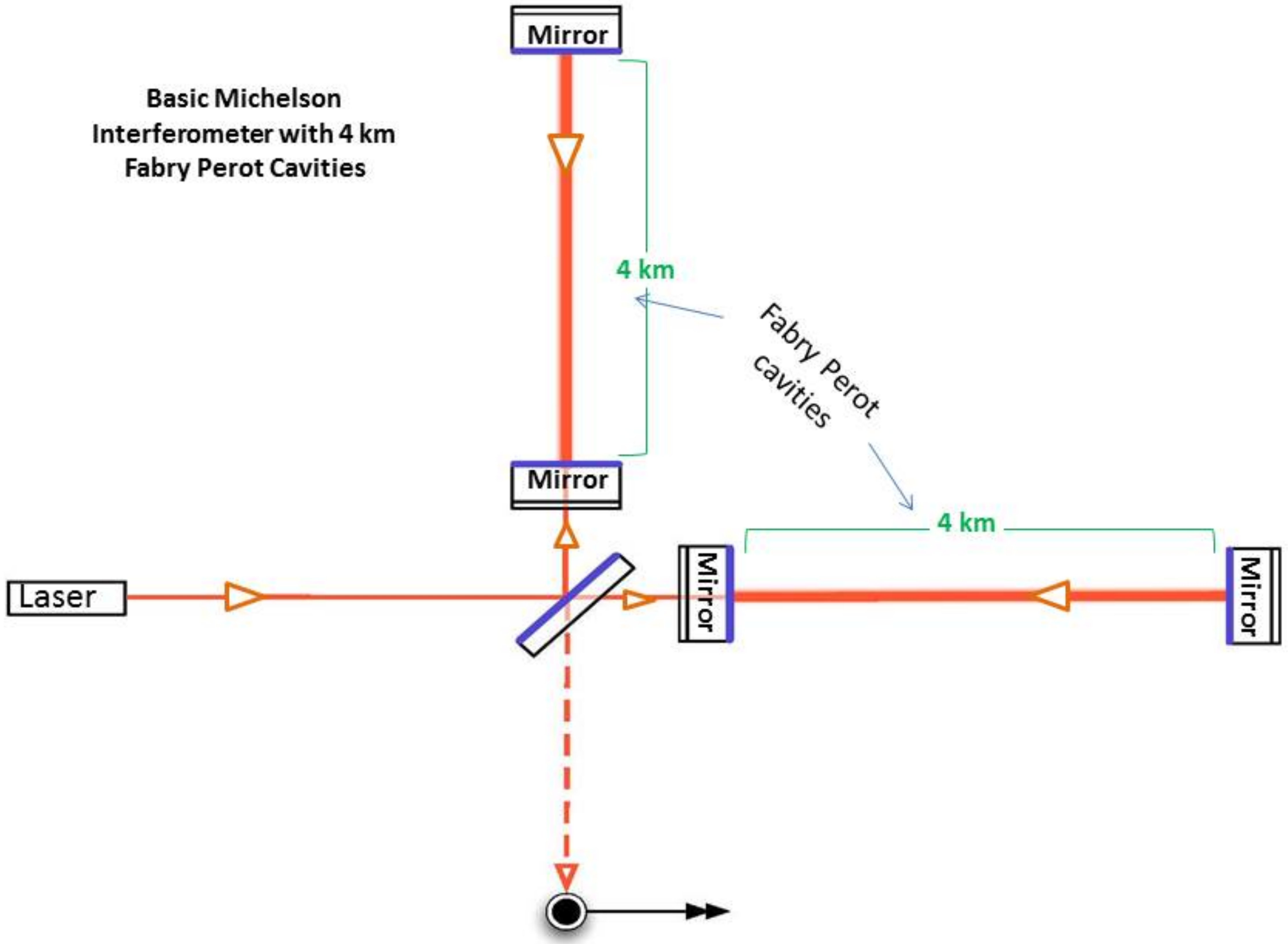
Direct detection of GWs

GW traveling into the screen causes (tiny) distortion:



1708.00918

www.ligo.caltech.edu/page/ligos-ifo

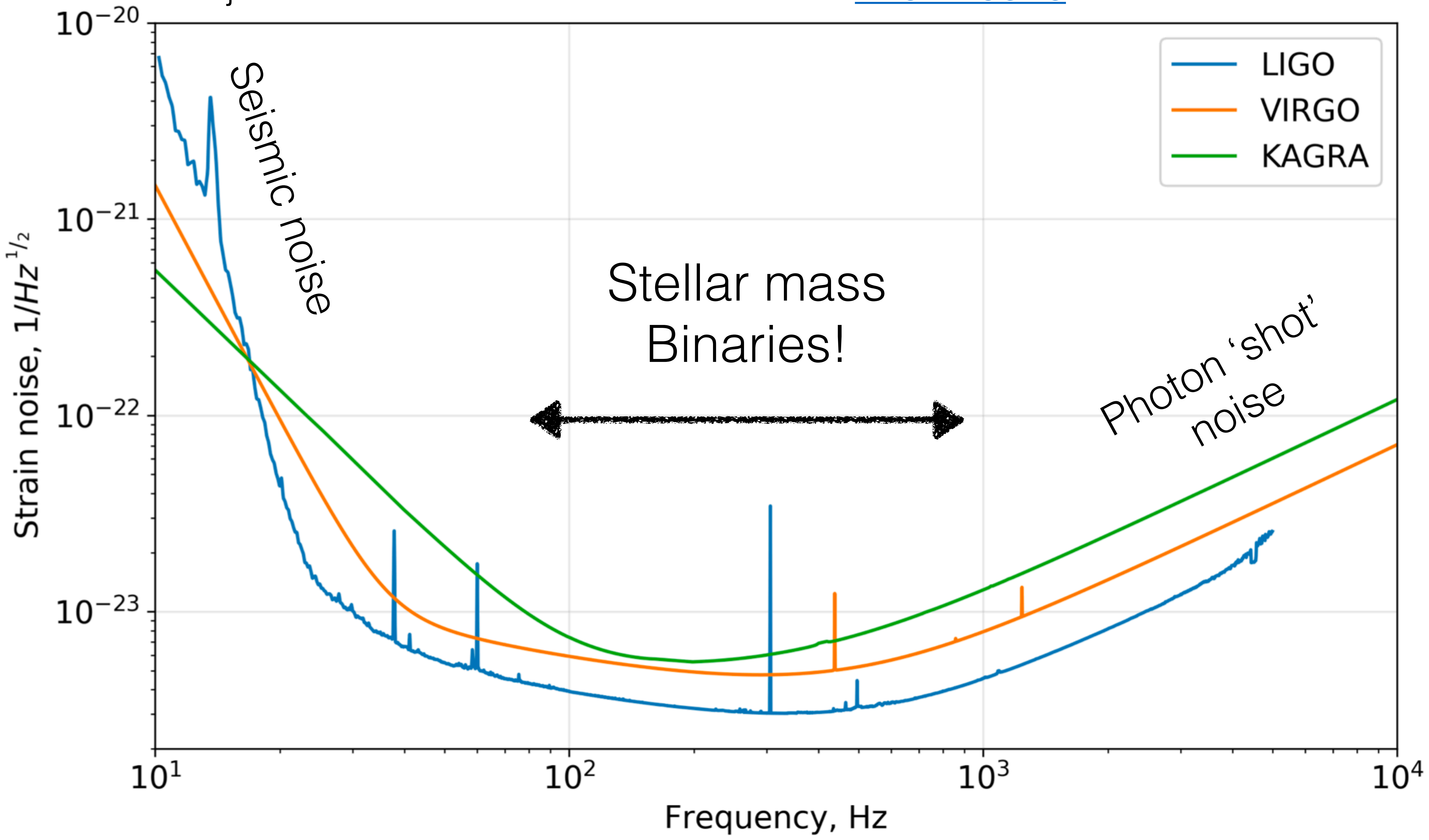


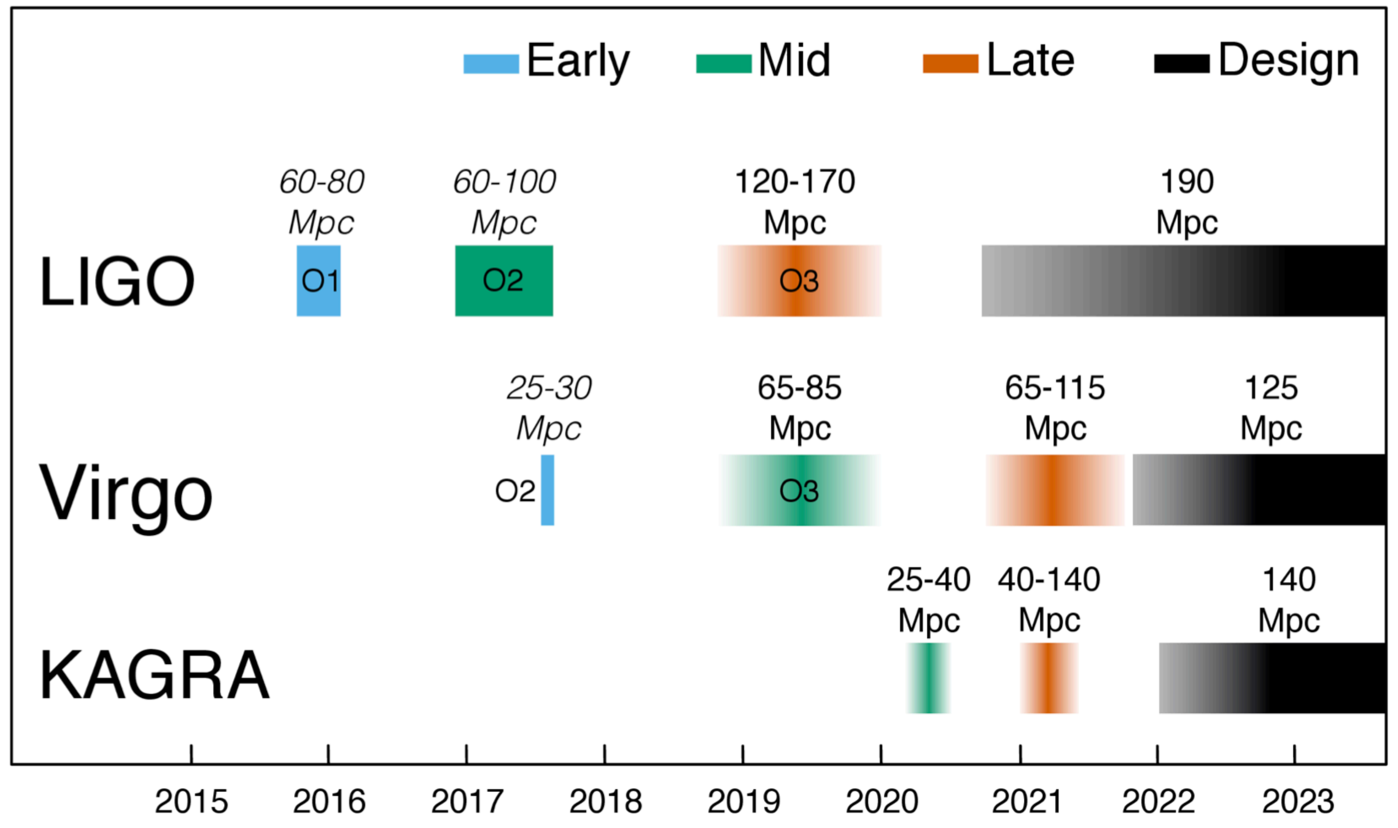
Typical GW strain is $\Delta L/L \sim 10^{-23}$!

LIGO-Virgo-KAGRA (LVK)

Credit: LIGO, VIRGO & KAGRA.

Projected O4 strain noise [2102.10816](2102.10816)



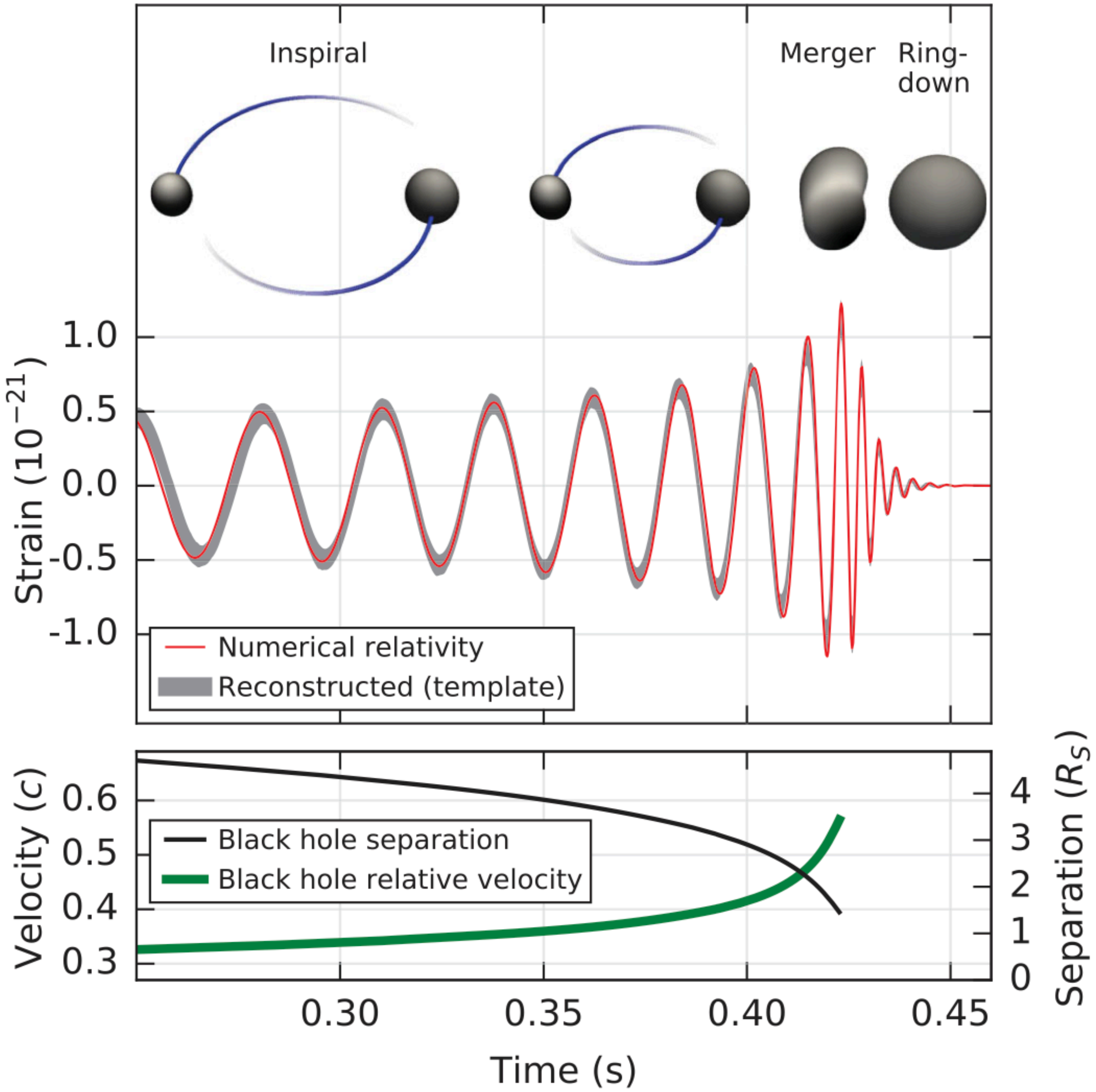


GW frequency ~ twice orbital frequency.

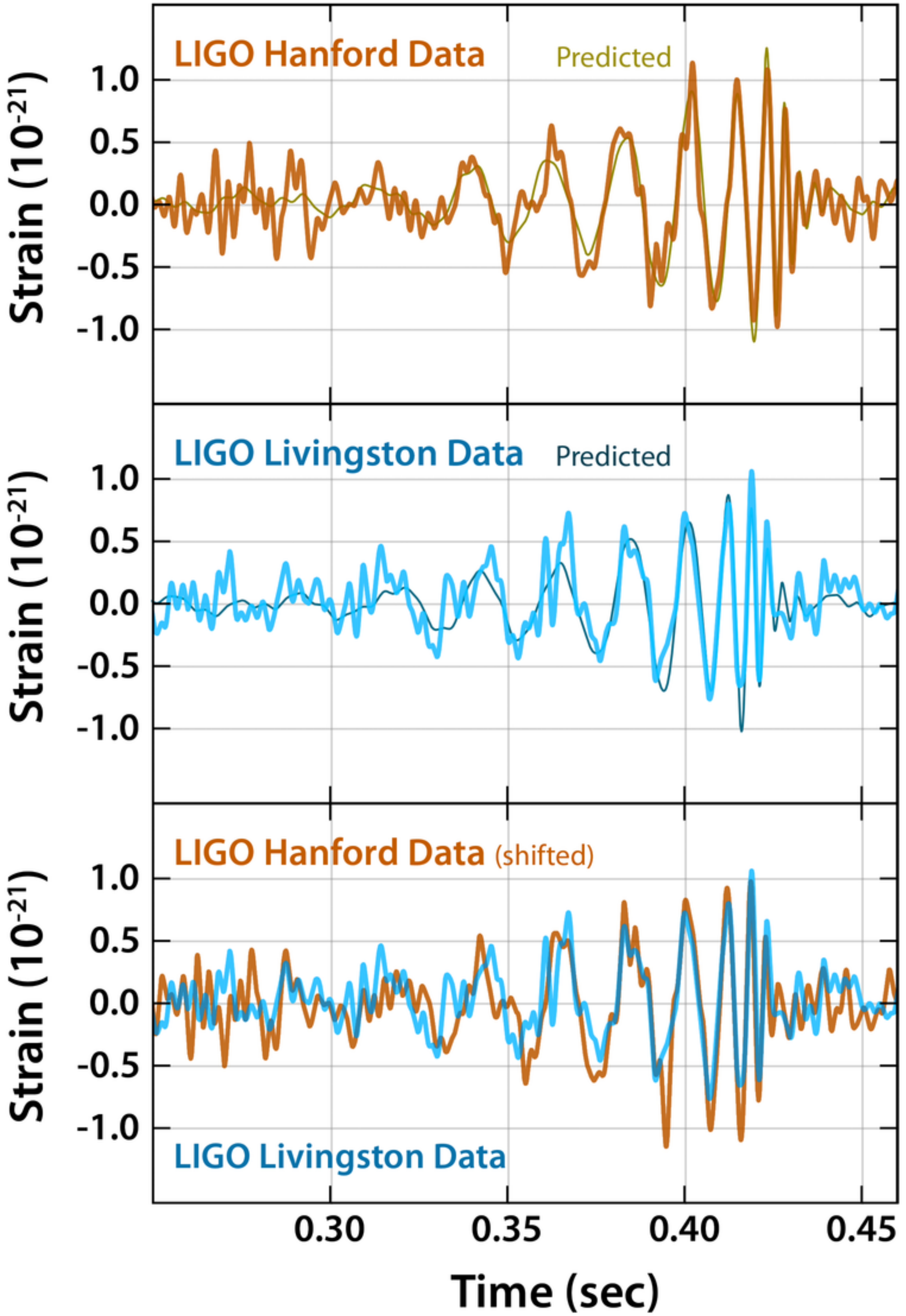
[1906.03643](1906.03643)

GW150914 - the first BH-BH merger

14 September 2015



Credit: Caltech/MIT/LIGO Lab



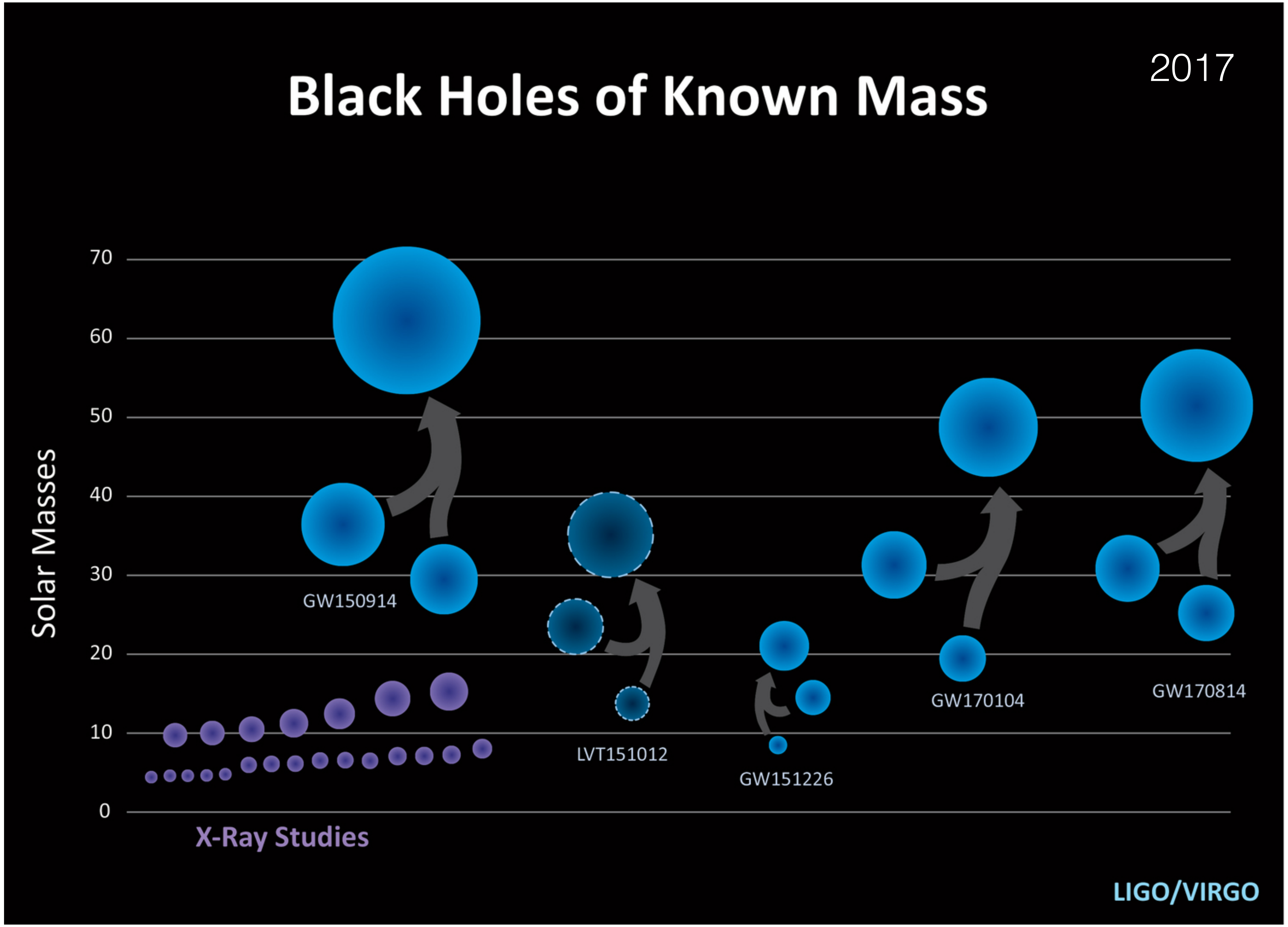
Merger of two BHs - with masses $36\,M_\odot$ and $29\,M_\odot$ at a luminosity distance of $d_L \approx 200 - 600\,\mathrm{Mpc}$!

1602.03840

Try it yourself! - https://www.gw-openscience.org/tutorials/

The Compact Object Zoo

https://media.ligo.northwestern.edu/gallery/mass-plot



Credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)

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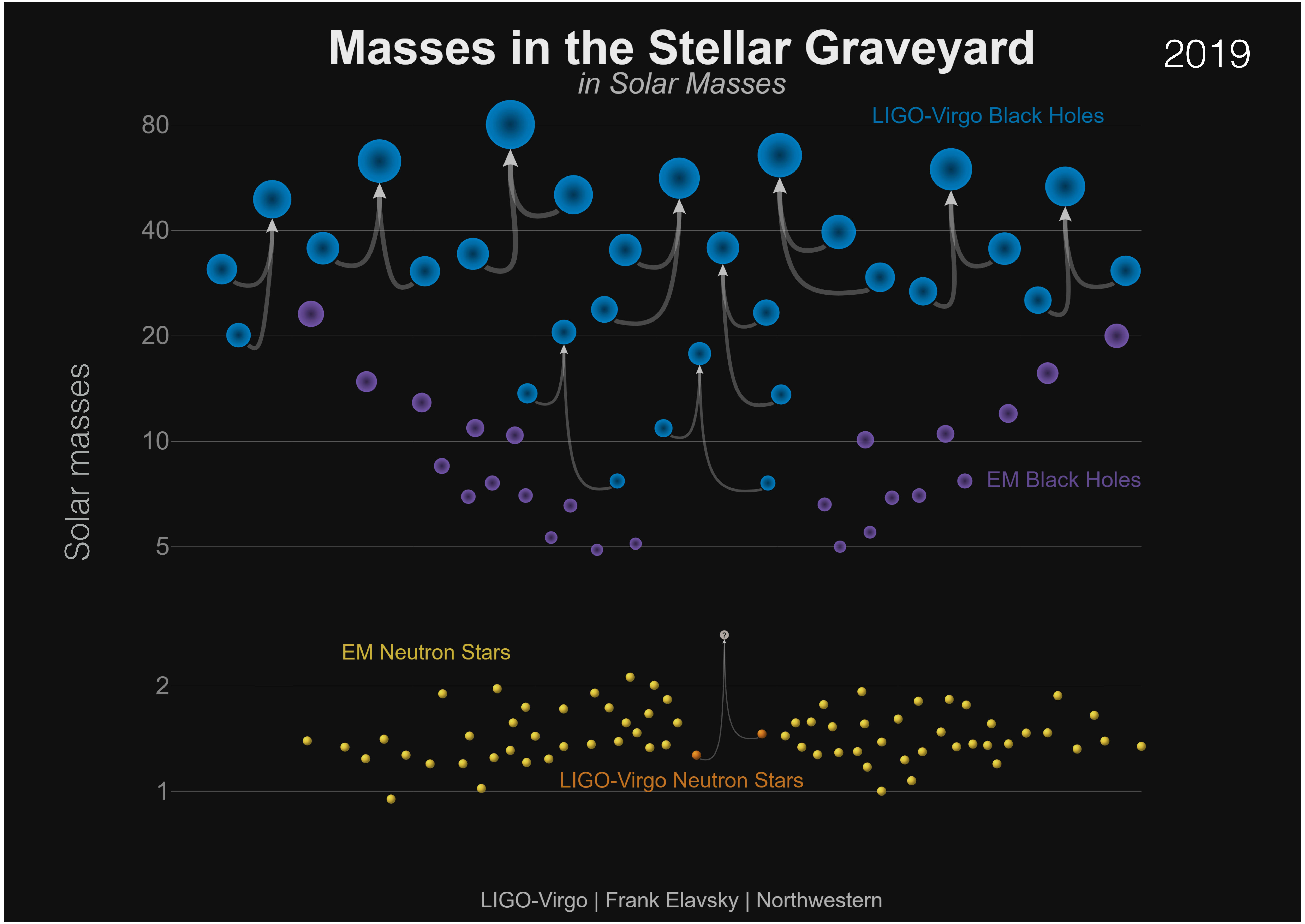
https://media.ligo.northwestern.edu/gallery/mass-plot



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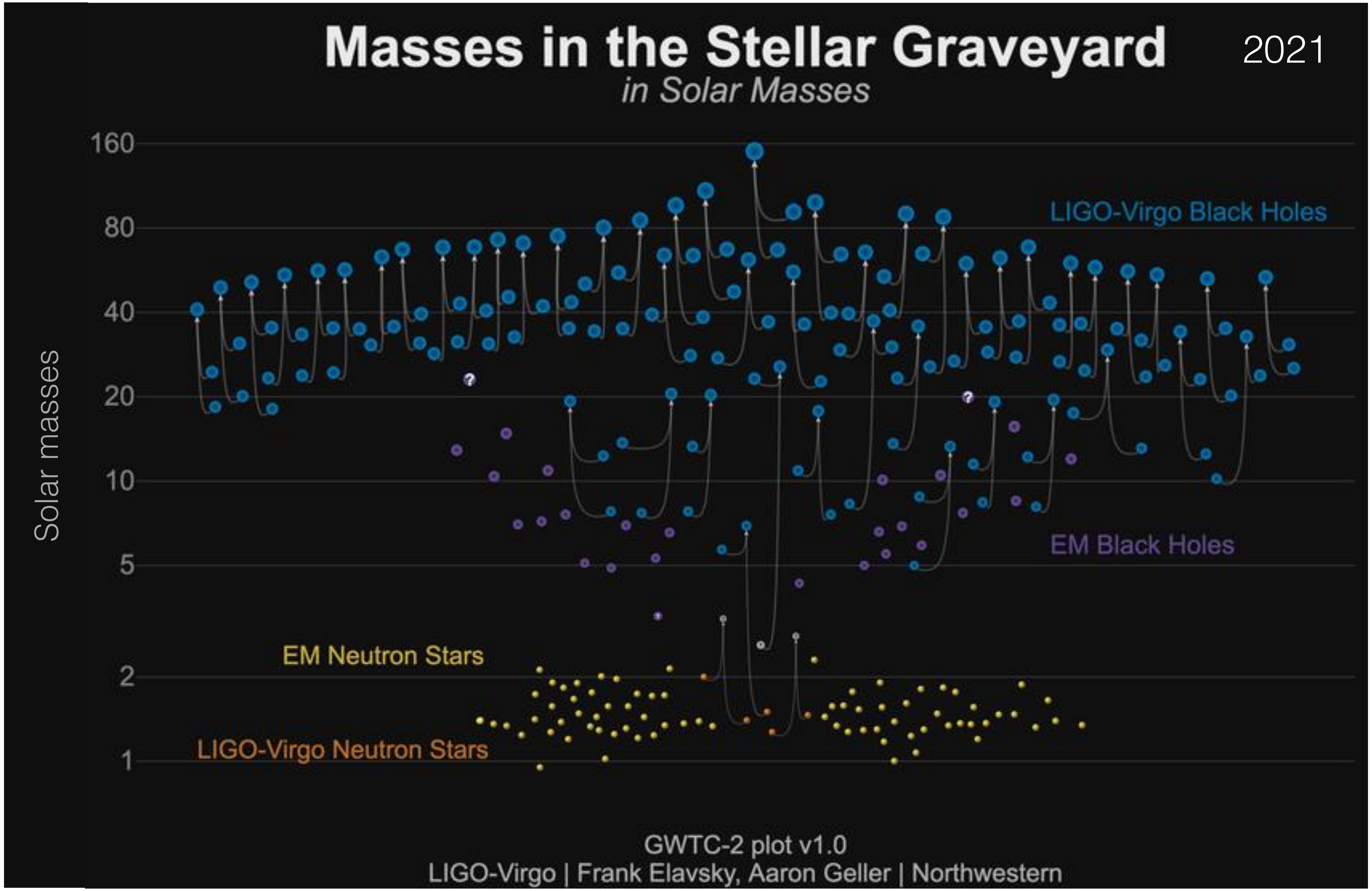

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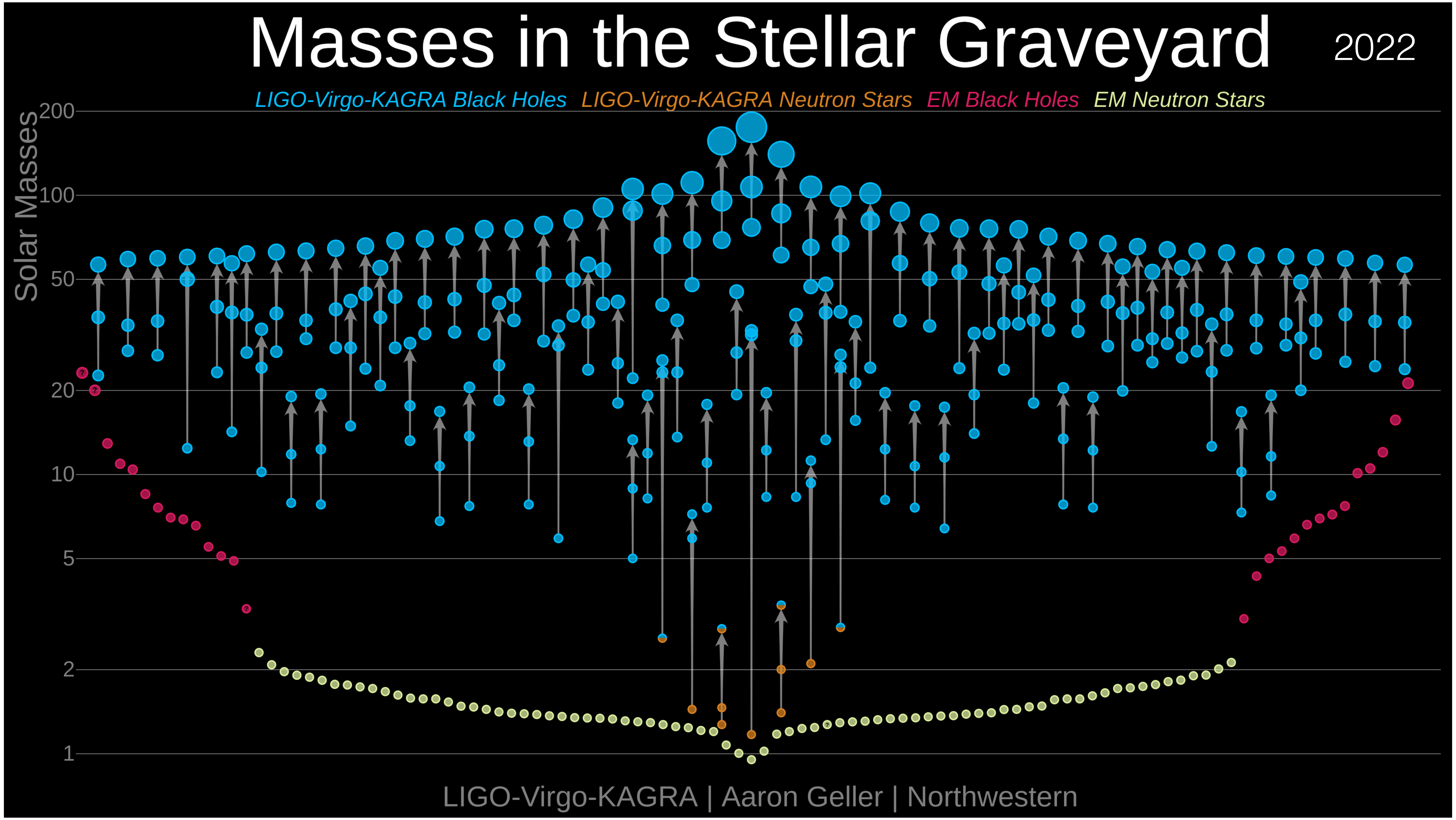
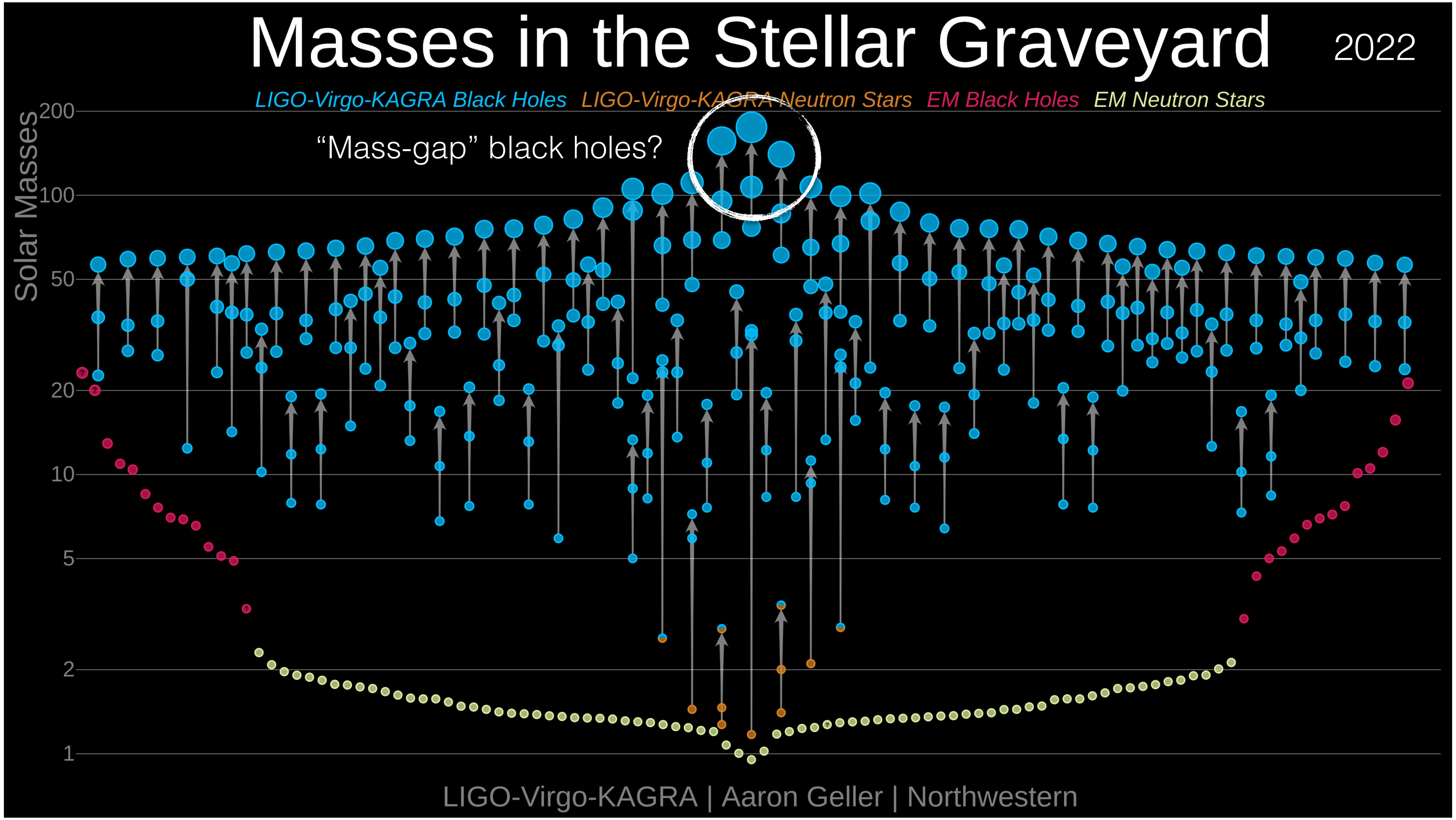


Third Gravitational-wave Transient Catalog (**GWTC-3**) [arXiv:2111.03606, arXiv:2111.03634]

The Compact Object Zoo

https://media.ligo.northwestern.edu/gallery/mass-plot

2007.07889



Third Gravitational-wave Transient Catalog (**GWTC-3**) [arXiv:2111.03606, arXiv:2111.03634]

Mass gap black holes

Models of stellar evolution predict that it should not be possible to form BHs from stellar collapse in the mass range $m_{\rm BH} \sim 50 - 130\,M_\odot$ (so-called *pair-instability* supernovae do not leave behind a BH).

Mass gap black holes

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GW231123: a Binary Black Hole Merger with Total Mass 190-265 $M_{\odot}$

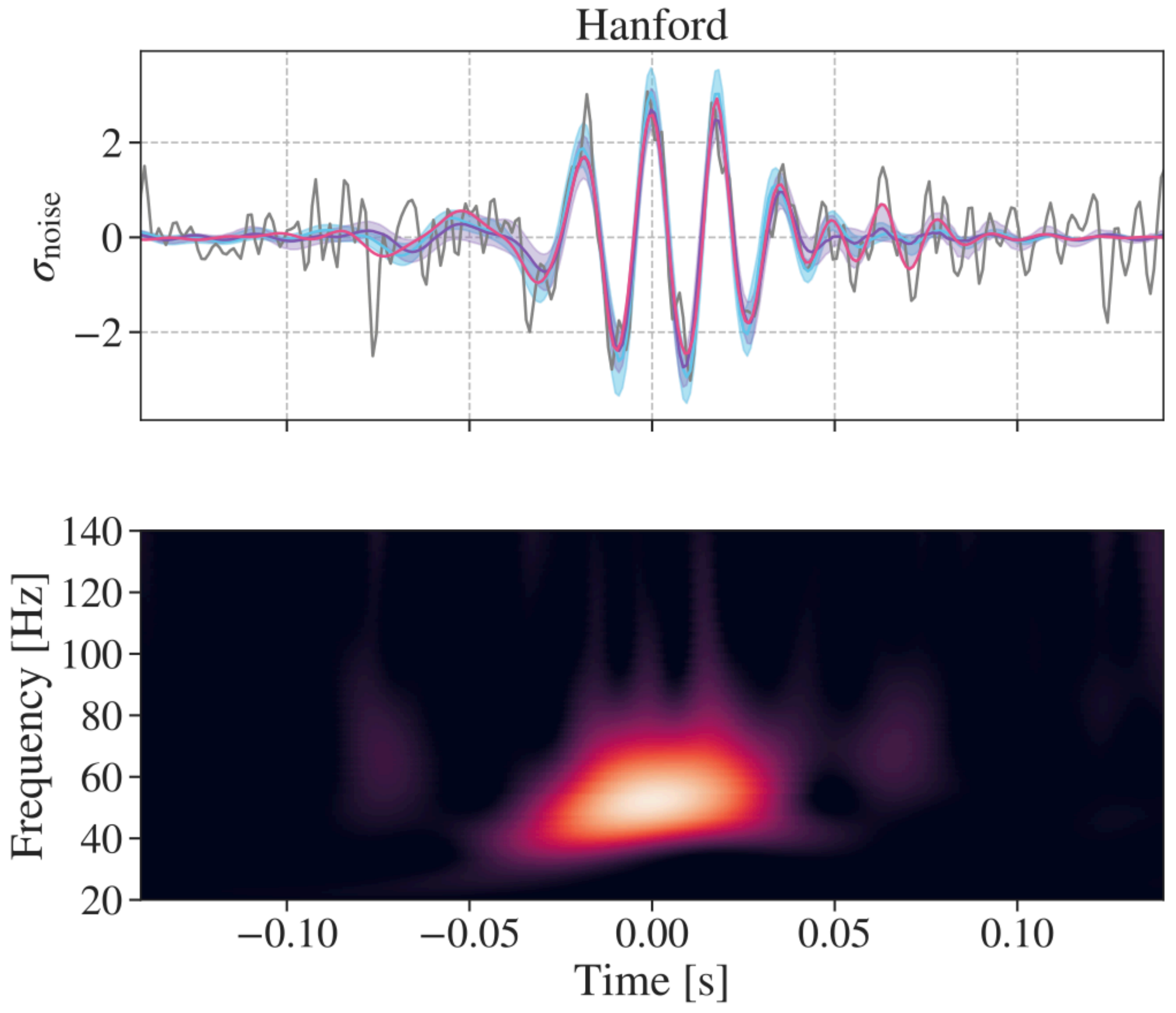
The LIGO Scientific Collaboration, The Virgo Collaboration, and The KAGRA Collaboration

(Compiled: 14 July 2025)

ABSTRACT

On 2023 November 23 the two LIGO observatories both detected GW231123, a gravitational-wave signal consistent with the merger of two black holes with masses $137^{+22}_{-17}\, M_{\odot}$ and $103^{+20}_{-52}\, M_{\odot}$ (90% credible intervals), at luminosity distance 0.7–4.1 Gpc and redshift of $0.39^{+0.27}_{-0.24}$, and a network signal-to-noise ratio of ∼22.5. Both black holes exhibit high spins, $0.90^{+0.10}_{-0.19}$ and $0.80^{+0.20}_{-0.51}$ respectively. A massive black hole remnant is supported by an independent ringdown analysis. Some properties of GW231123 are subject to large systematic uncertainties, as indicated by differences in inferred parameters between signal models. The primary black hole lies within or above the theorized mass gap where black holes between 60–130 $M_{\odot}$ should be rare due to pair instability mechanisms, while the secondary spans the gap. The observation of GW231123 therefore suggests the formation of black holes from channels beyond standard stellar collapse, and that intermediate-mass black holes of mass ∼200 $M_{\odot}$ form through gravitational-wave driven mergers.

[2507.08219]



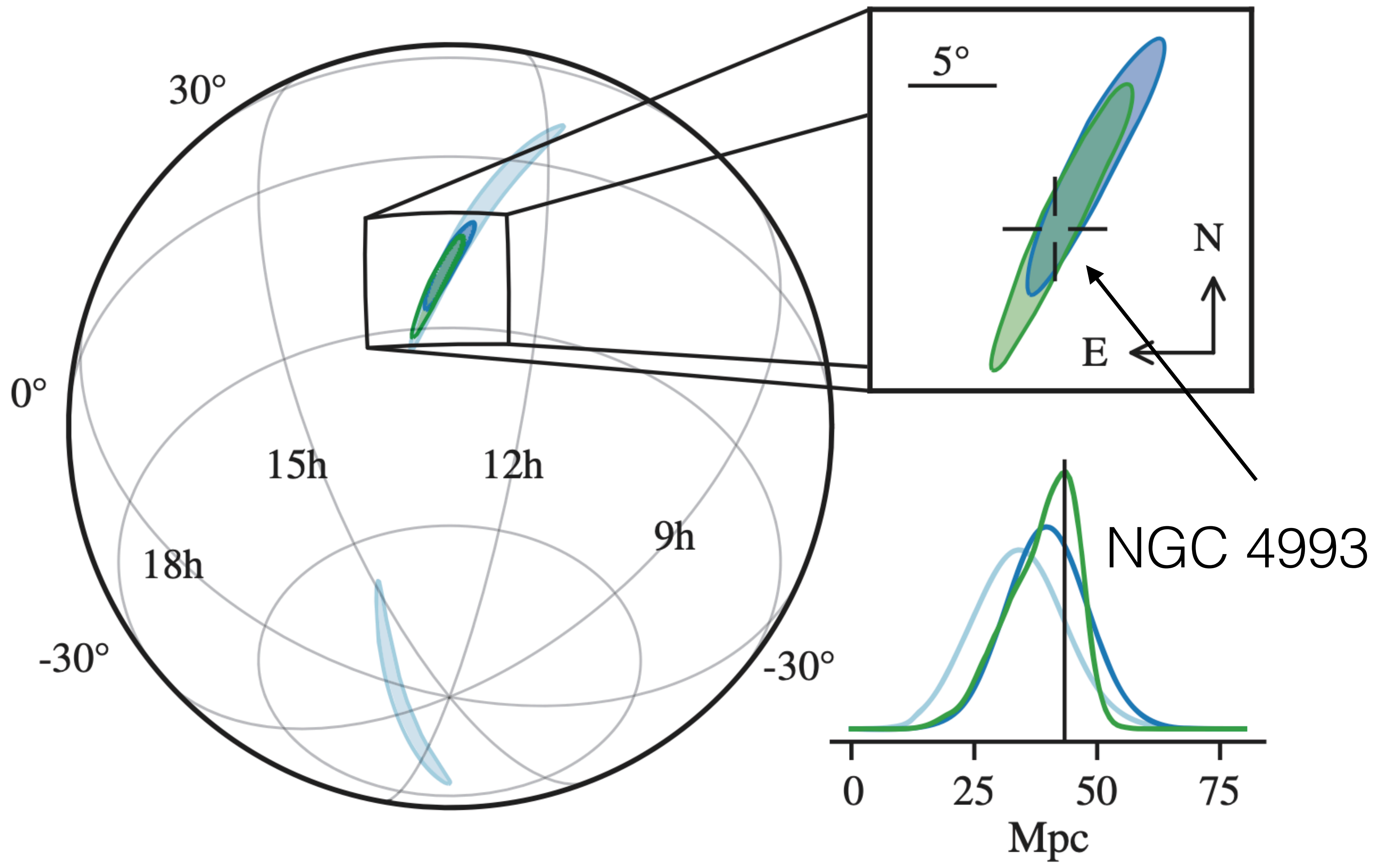
Primary mass $m_1/\mathrm{M}_{\odot}$	137^{+22}_{-17}
Secondary mass $m_2/\mathrm{M}_{\odot}$	103^{+20}_{-52}
Mass ratio $q = m_2/m_1$	$0.75^{+0.22}_{-0.39}$
Total mass $M/\mathrm{M}_{\odot}$	238^{+28}_{-49}
Final mass $M_{\mathrm{f}}/\mathrm{M}_{\odot}$	225^{+26}_{-43}
Primary spin magnitude χ_1	$0.90^{+0.10}_{-0.19}$
Secondary spin magnitude χ_2	$0.80^{+0.20}_{-0.51}$

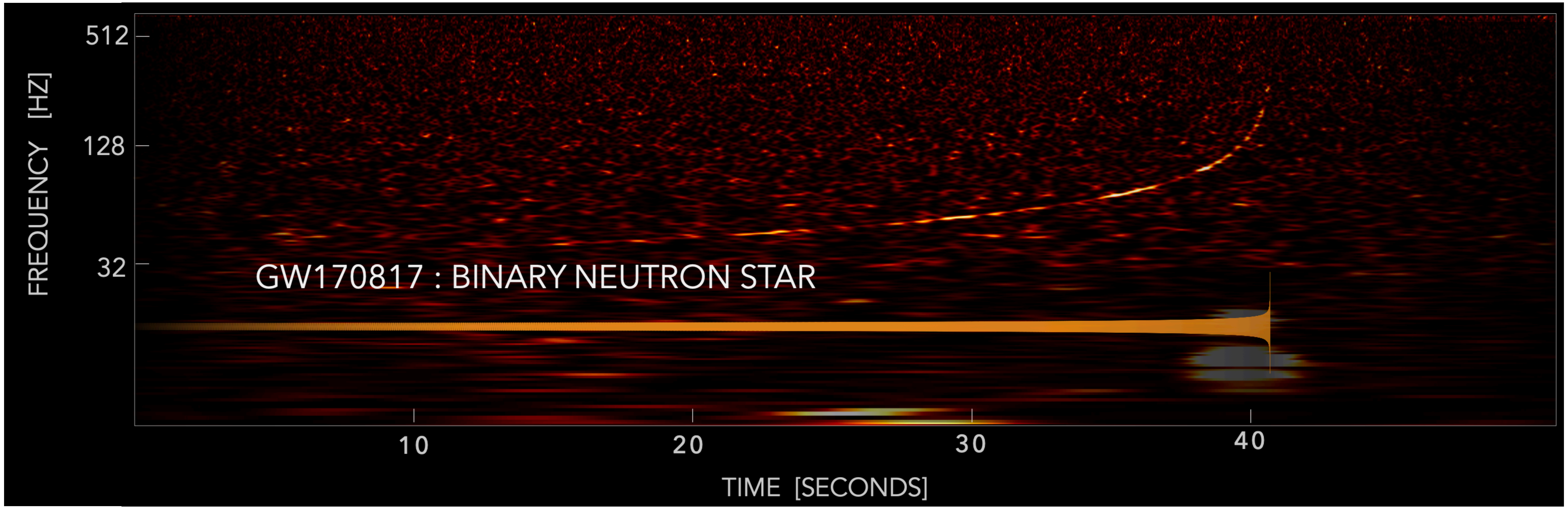
GWTC-4 will be released soon: 213 high-confidence mergers so far!

GW170817 - the first NS-NS merger

17 August 2017 - observation of the merger of two $\sim 1.5 - 2.0\, M_{\odot}$ neutron stars

Localised to within ~30 deg²

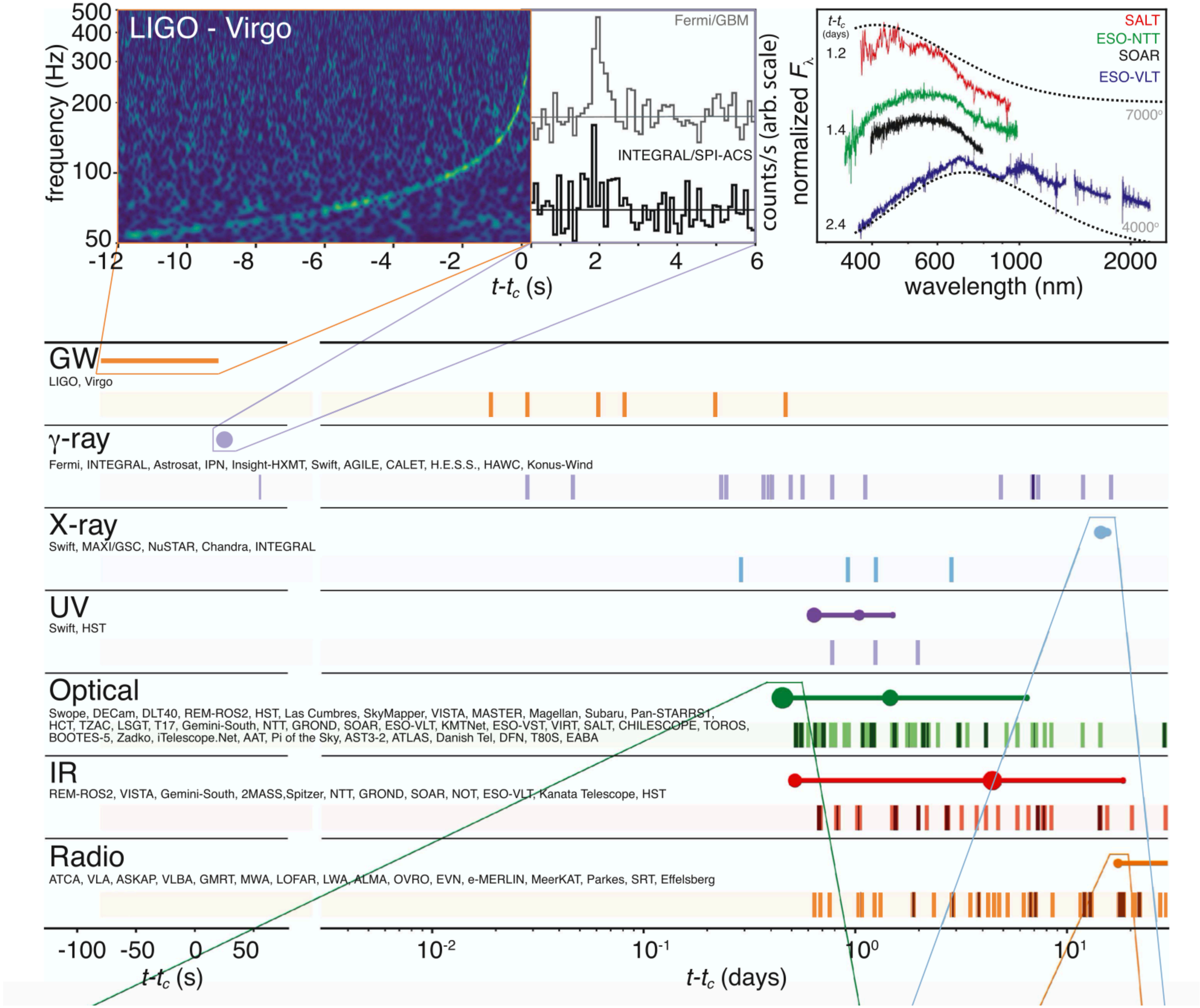




1710.05832, 1805.11579

Credit: LIGO/Virgo/Georgia Tech/S. Ghonge & K. Jani

Multi-messenger follow-up



GW170817 merger occurred just two seconds before the gamma-ray burst GRB 170817A

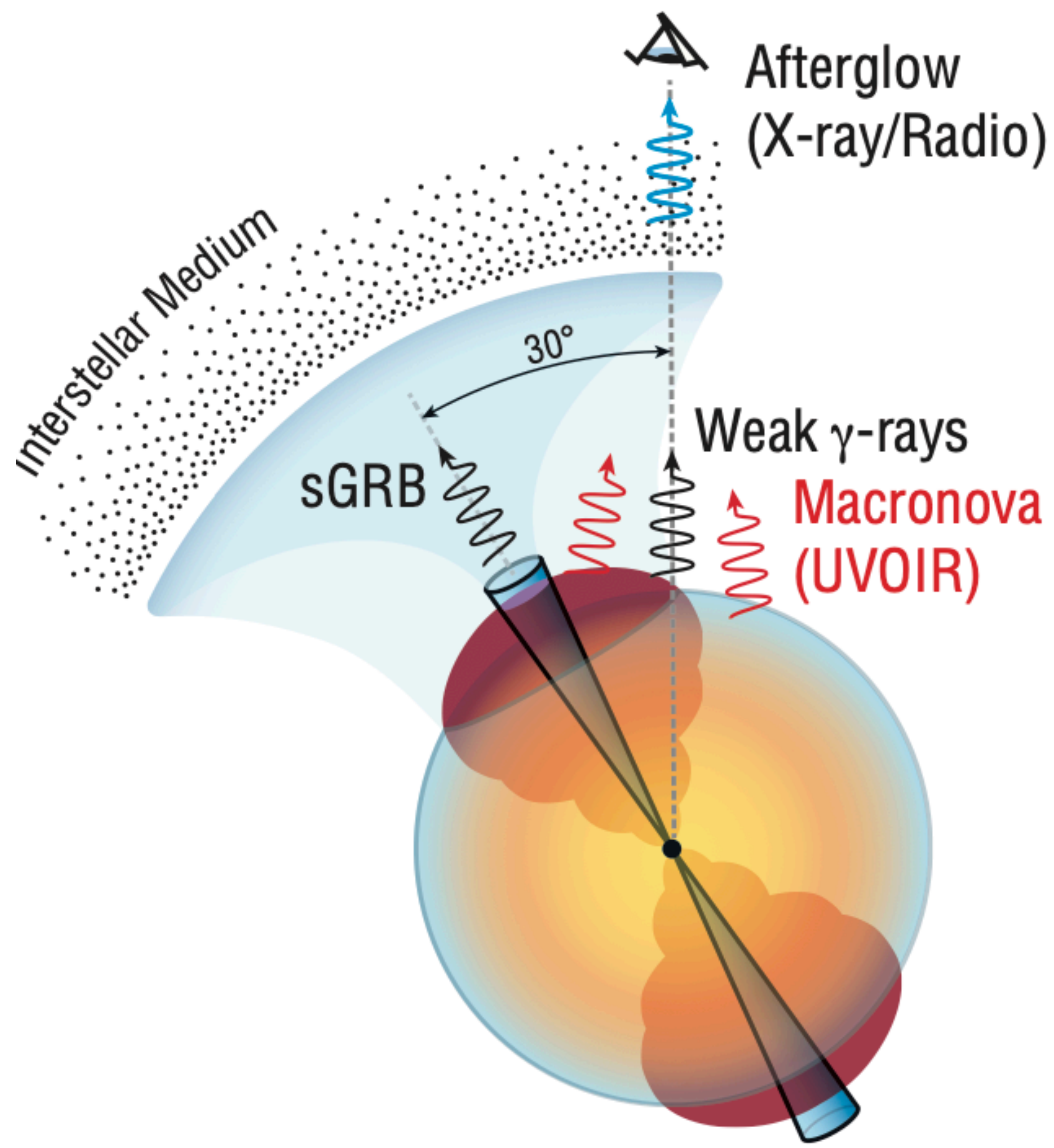
Follow-up observations across the spectrum!

Sadly no neutrinos detected :(

[1710.05833](), [2105.13160]()

What can we learn?

GW170817 resulted in a **kilonova**



[1710.05436](https://arxiv.org/abs/1710.05436)

Synthesis of *r*-process elements in neutron rich ejecta!

[1901.09044](https://arxiv.org/abs/1901.09044)

Extreme nuclear/quark physics!

[2103.16371](https://arxiv.org/abs/2103.16371)

Tests of general relativity!

[1710.06394](https://arxiv.org/abs/1710.06394)

Measurement of the Hubble Constant!

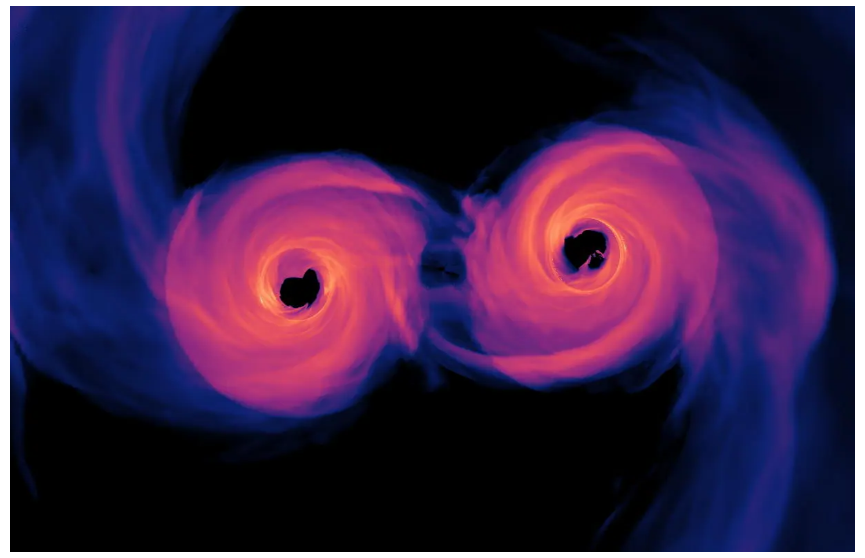
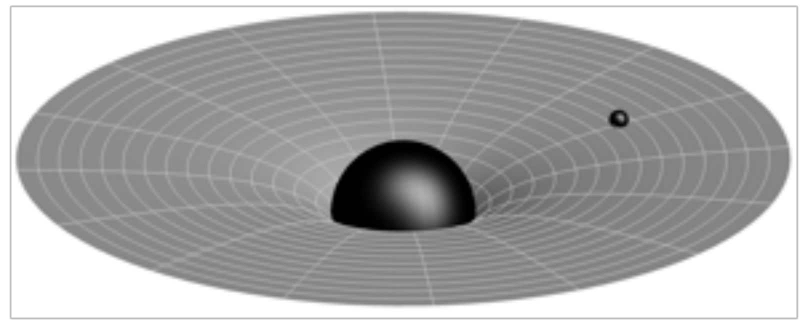
[1710.05835](https://arxiv.org/abs/1710.05835)

The Gravitational Wave Spectrum

$$c = \lambda_{\mathrm{GW}} \cdot f_{\mathrm{GW}}$$

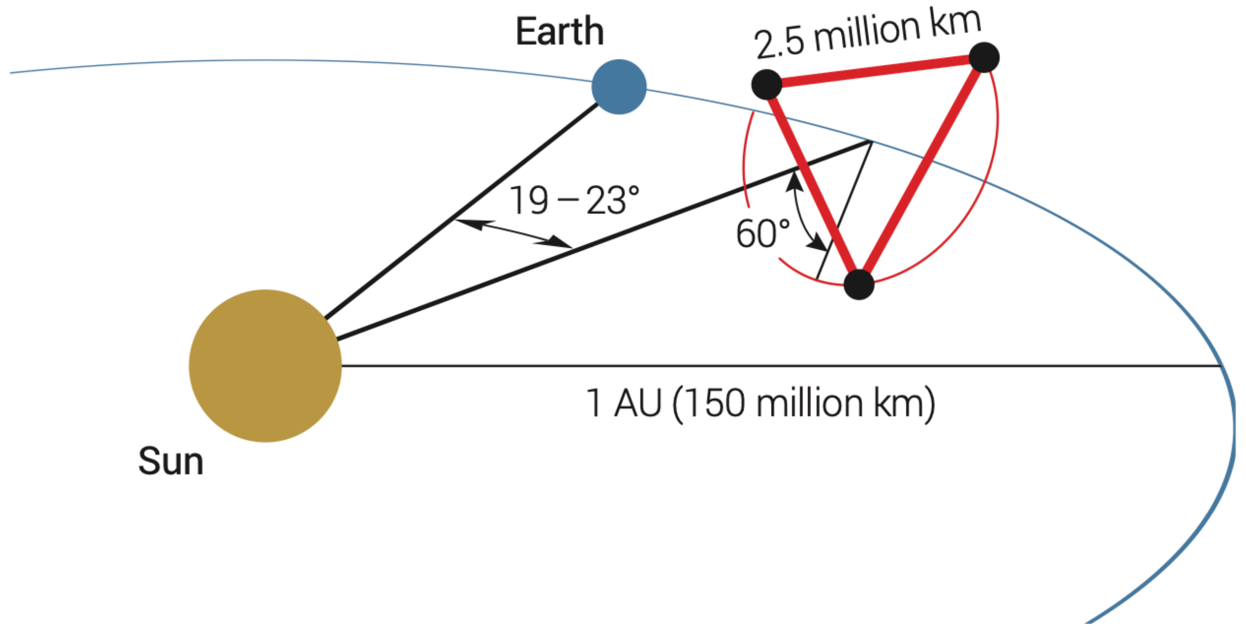
	nHz	μHz	mHz	Hz	kHz
f_{GW}					
	10^{13} km ~ pc	10^{11} km	10^{8} km	10^{5} km	100 km
λ_{GW}					
	30 years	10 days	15 minutes	1 second	1 ms
T_{GW}					

SOURCES

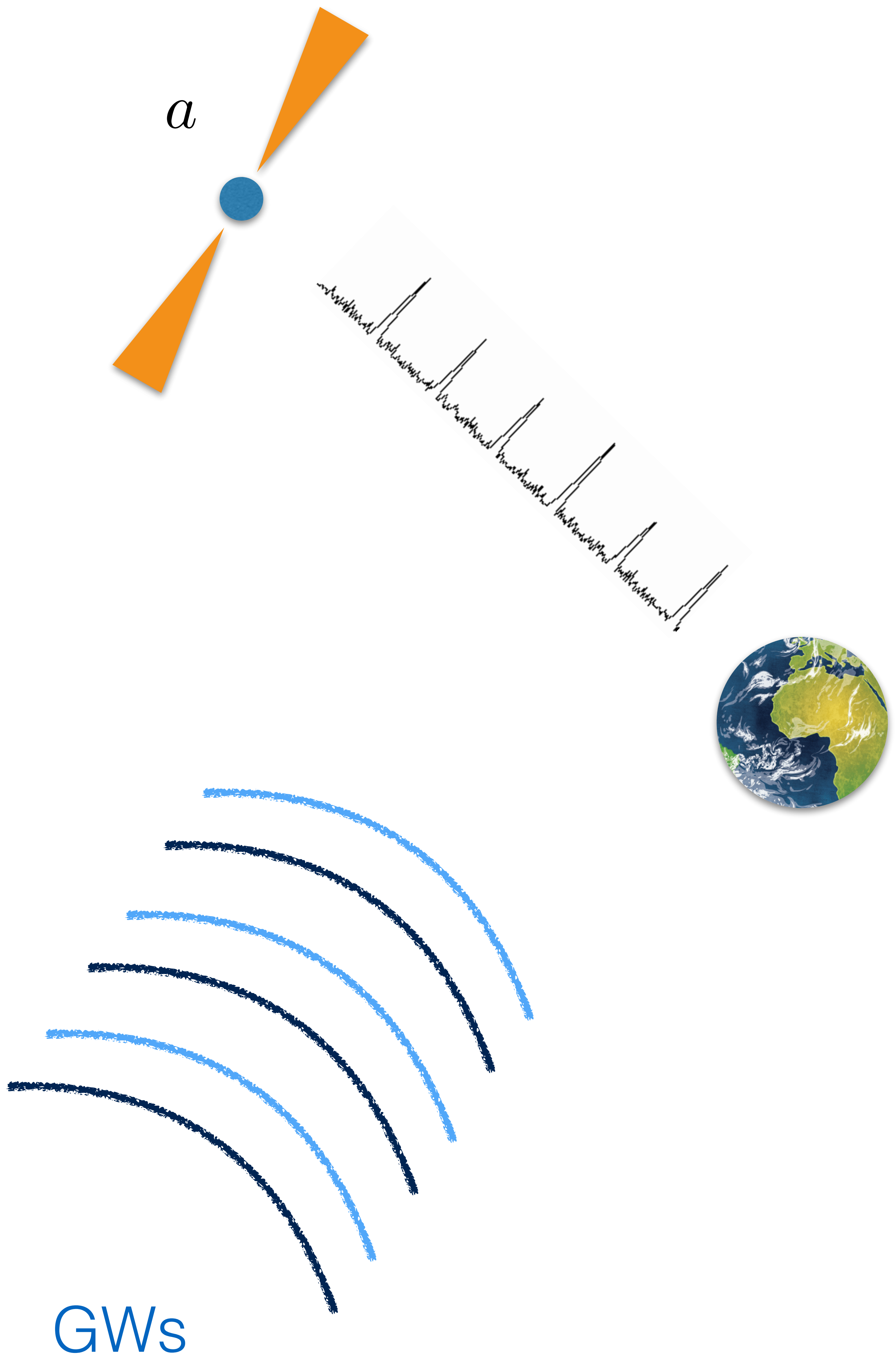



DETECTORS?

?



Pulsar Timing Arrays (PTA)



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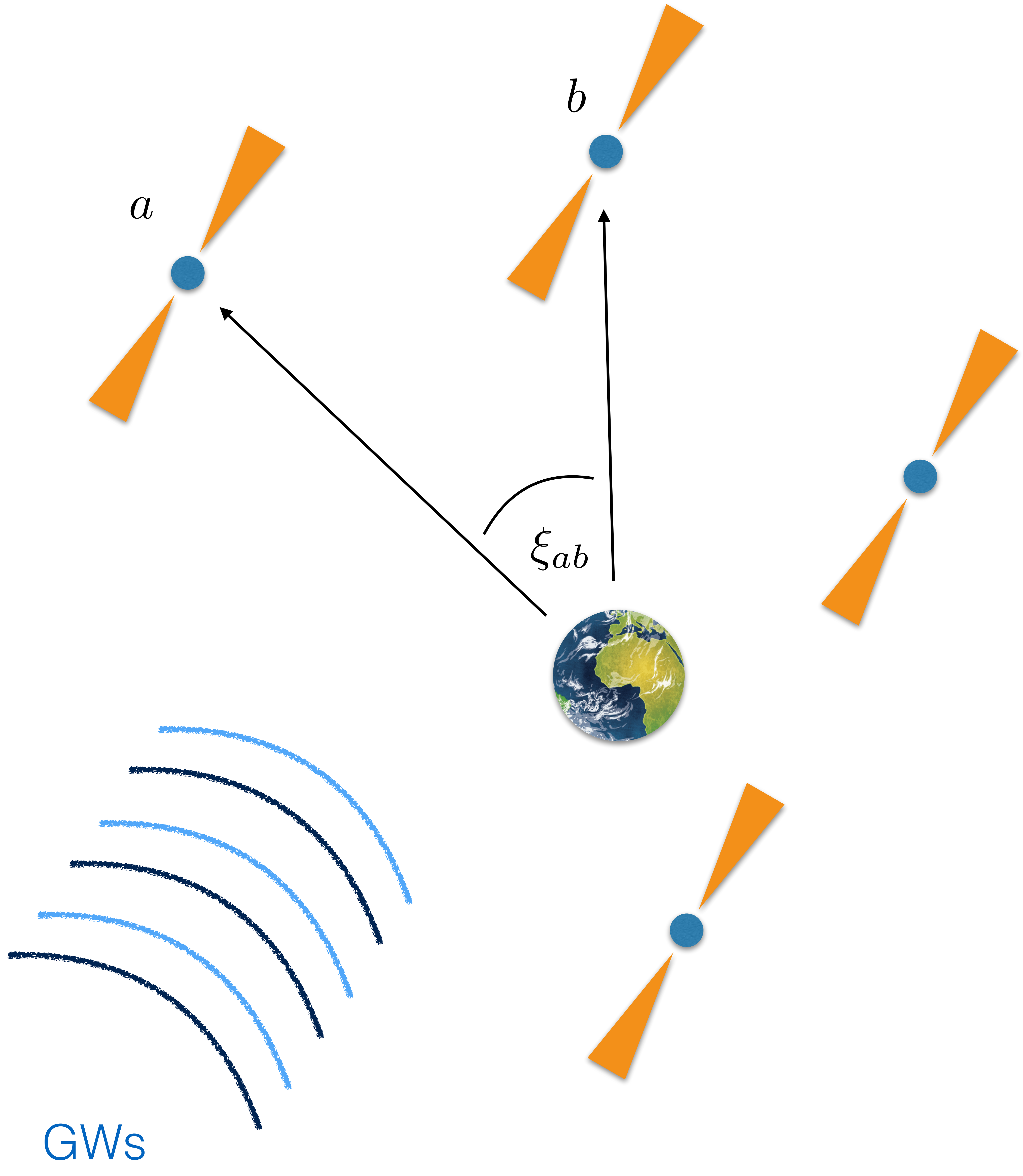

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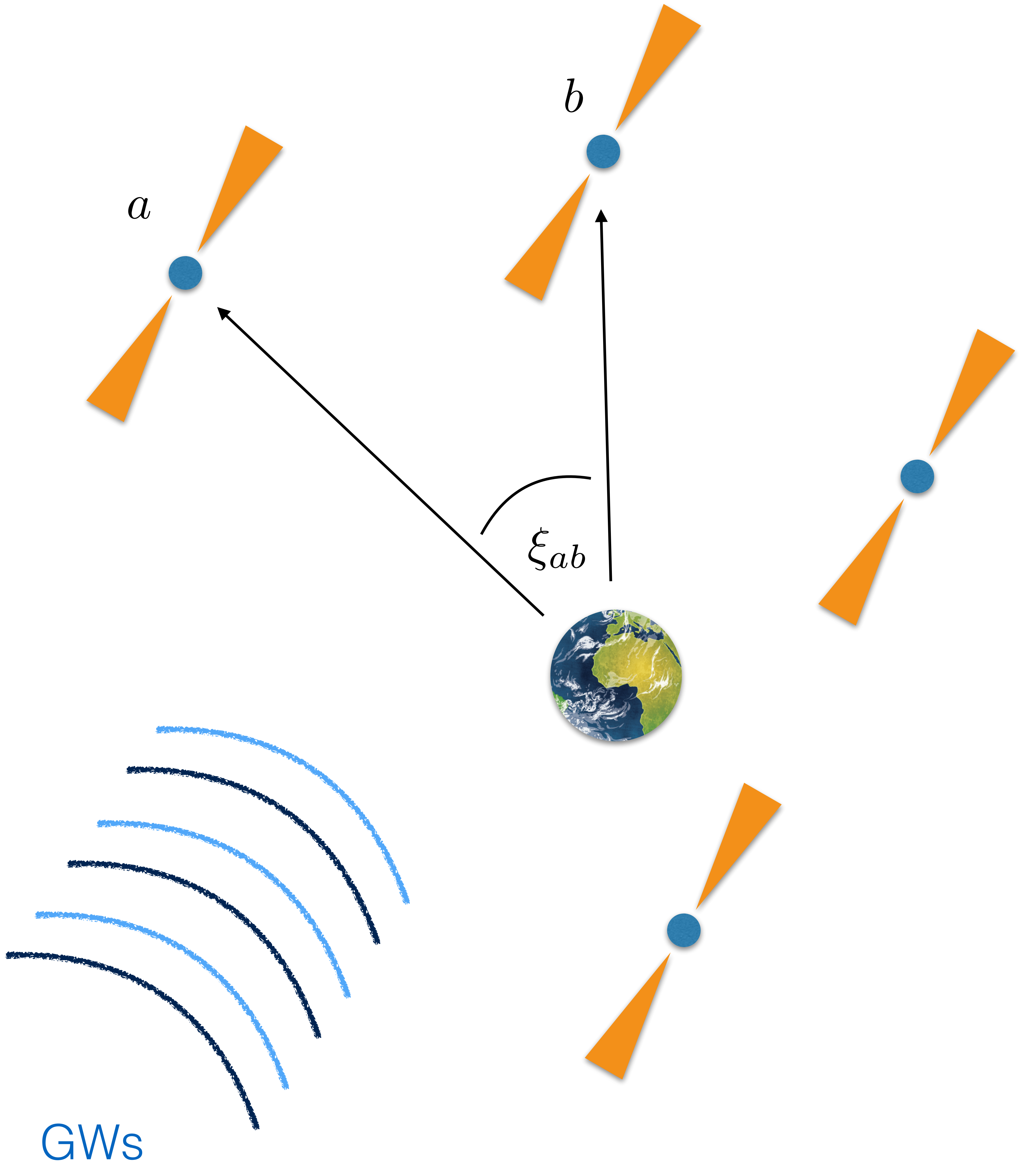
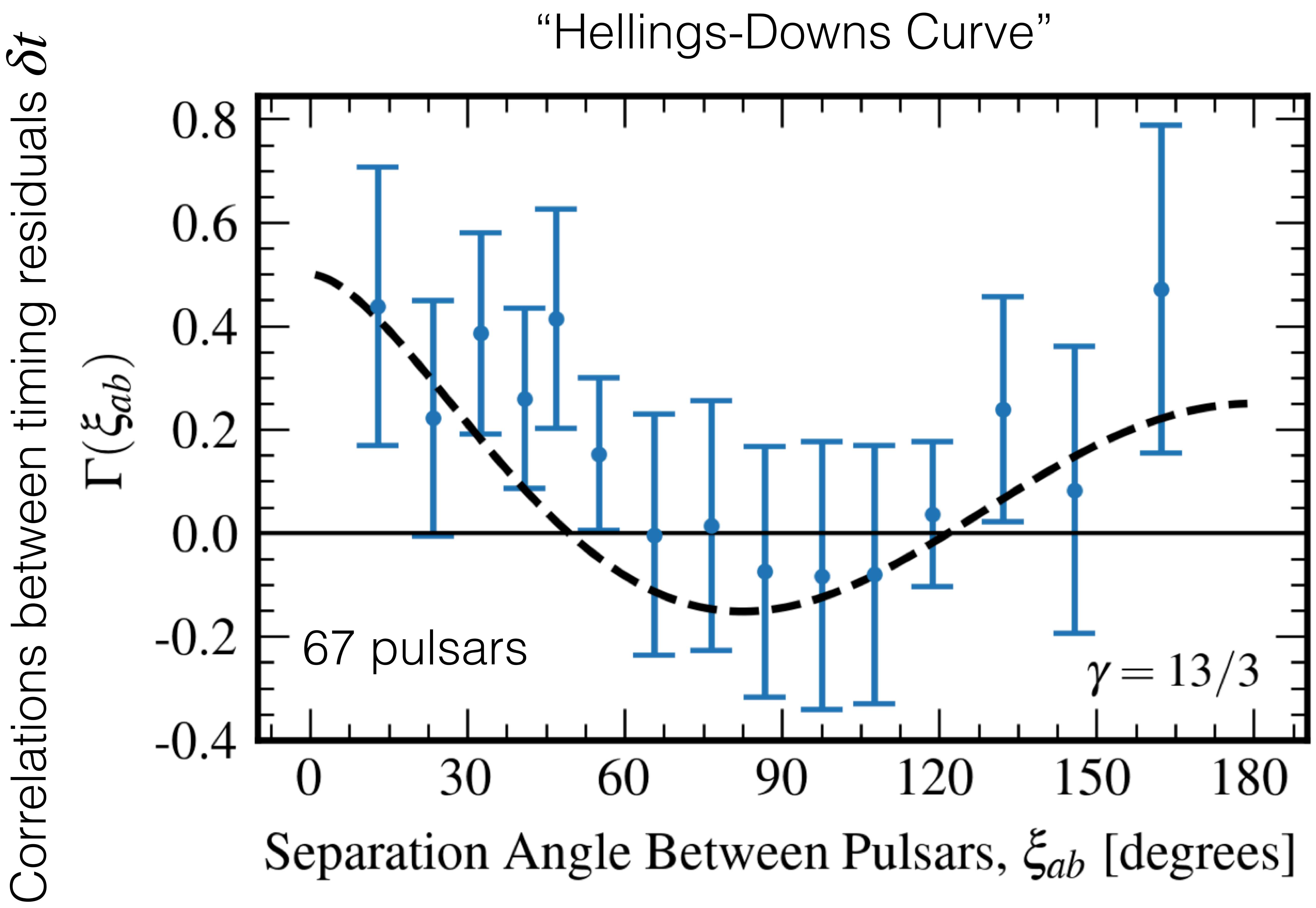


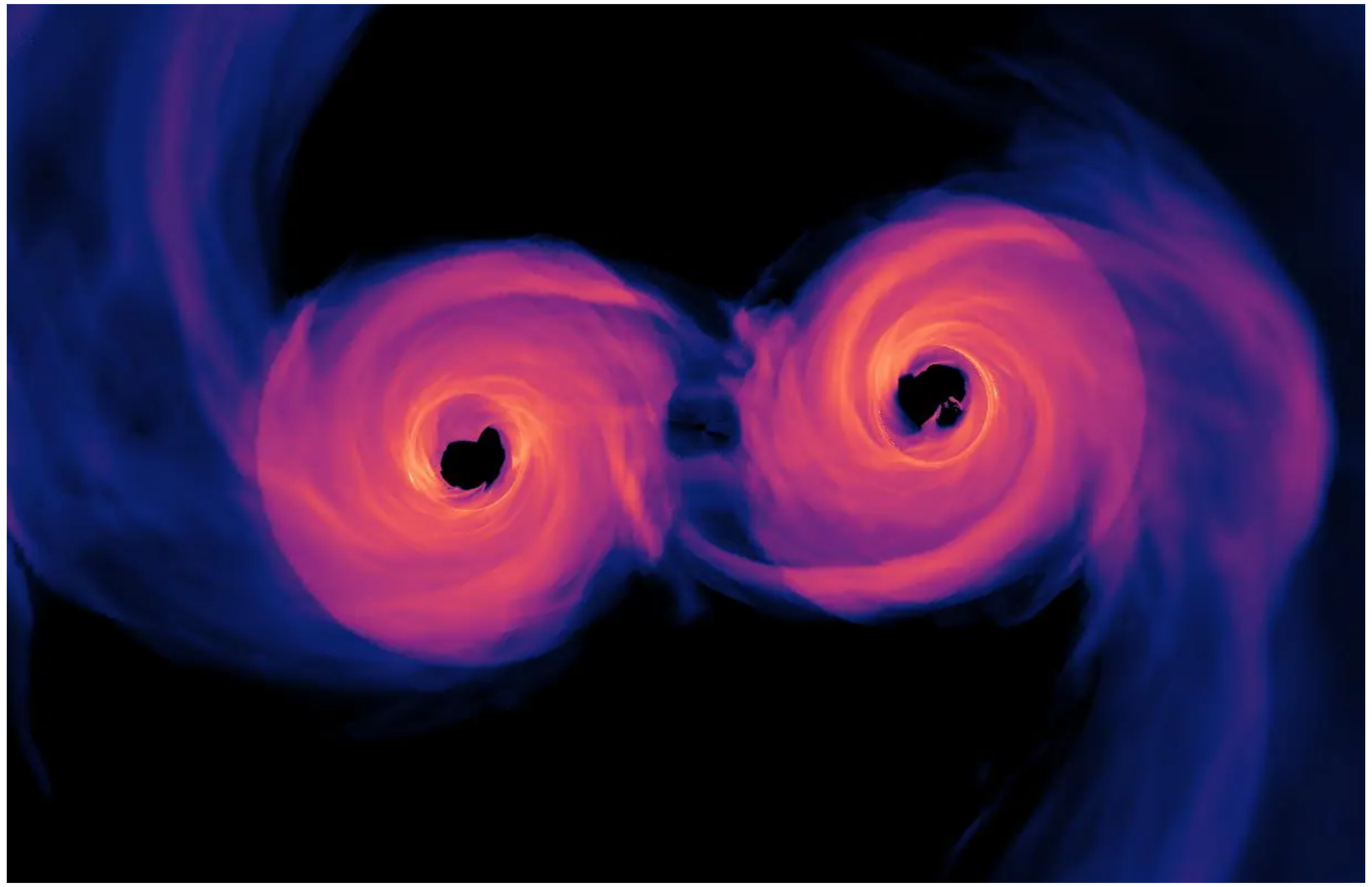


[NANOgrav, 2306.16217, 2306.16213]

Sources of Nanohertz GWs

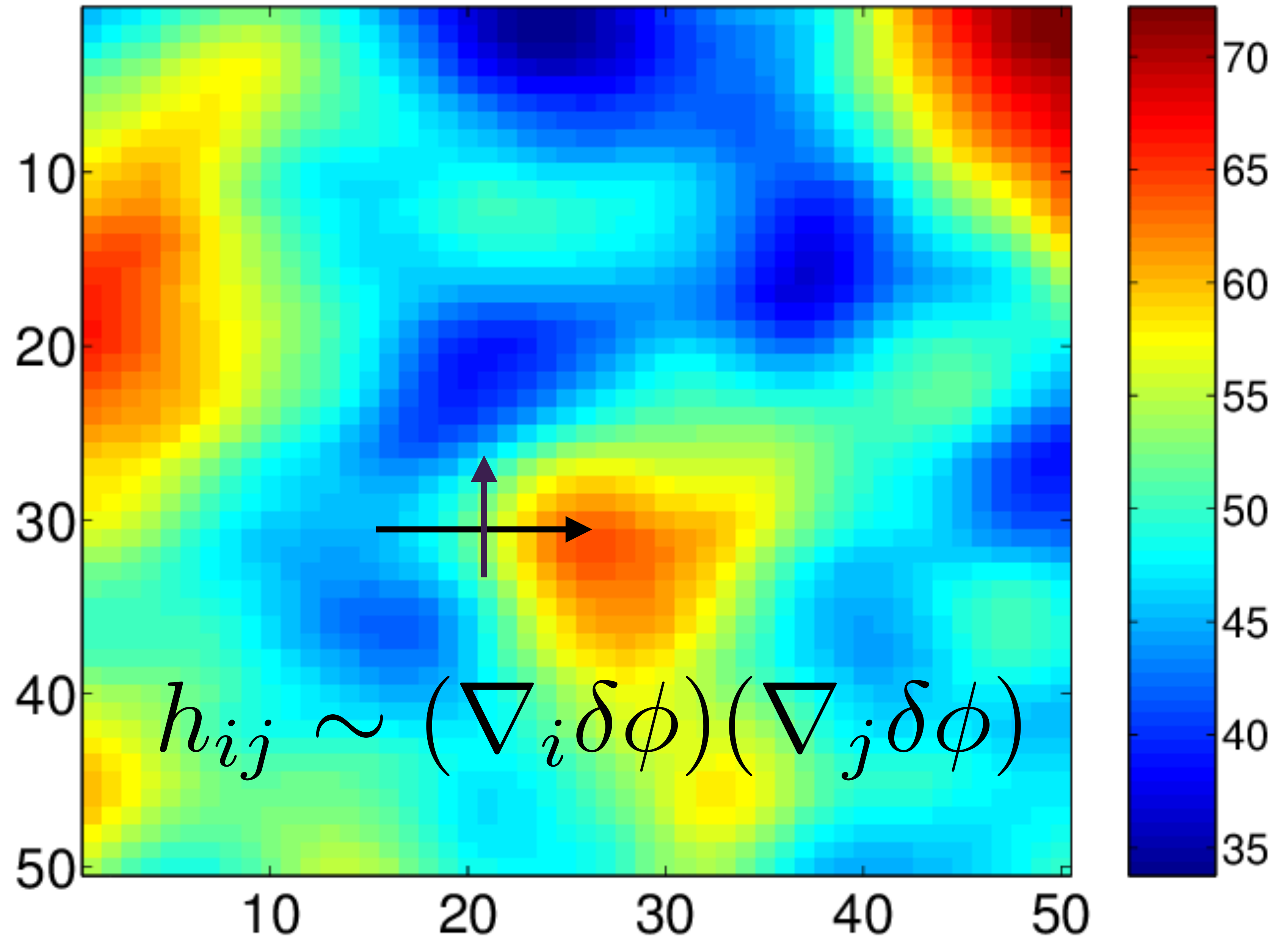
Supermassive Black Holes

$$f_{\rm GW} \sim \left(\frac{r_{\rm ISCO}}{r}\right)^{3/2} \left(\frac{10^6 M_\odot}{M_1}\right) \mathrm{mHz}$$



Scalar-induced GWs?

Could be produced by enhanced scalar perturbations in the early Universe



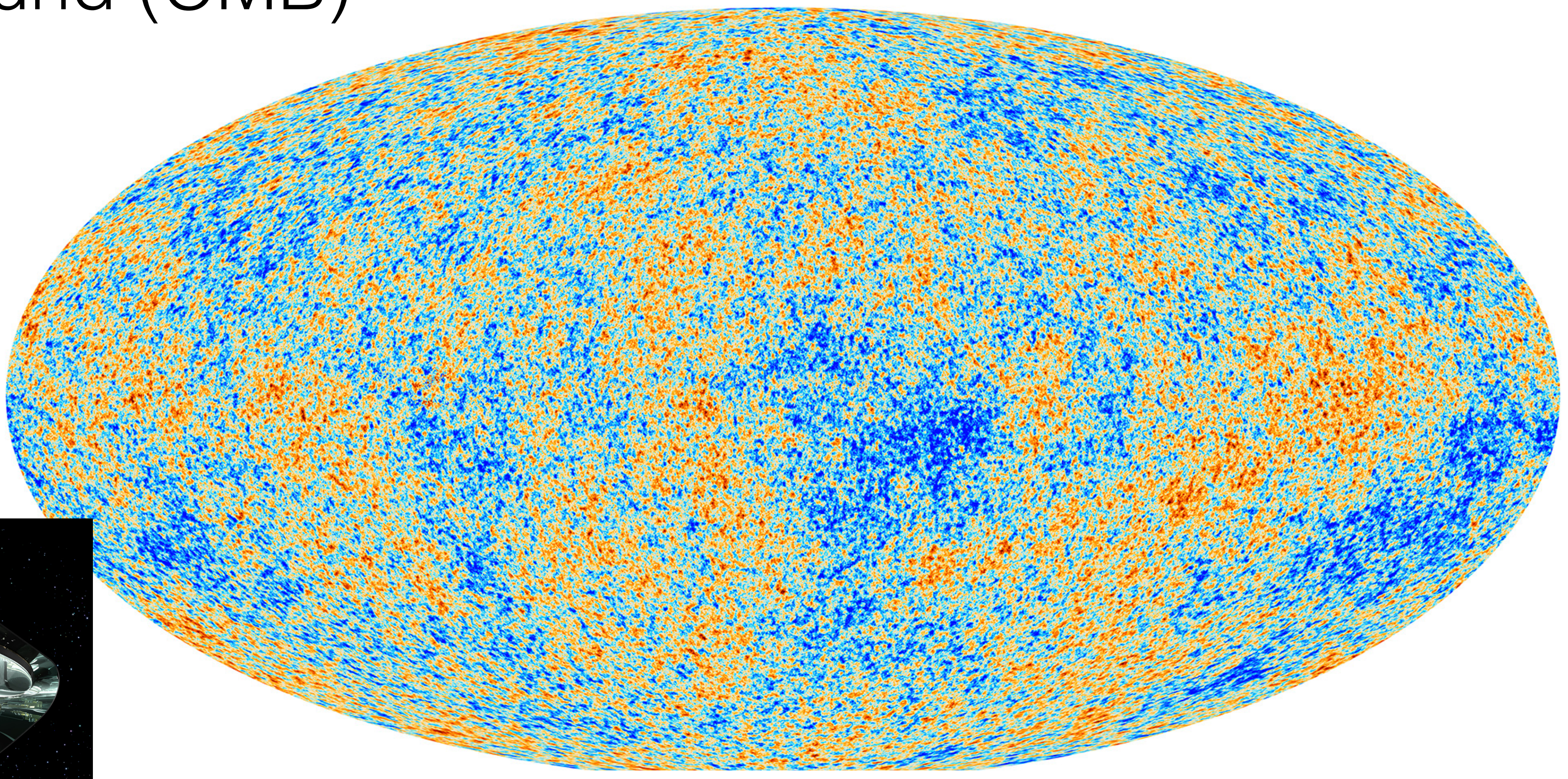
[Domènech, 2109.01398]

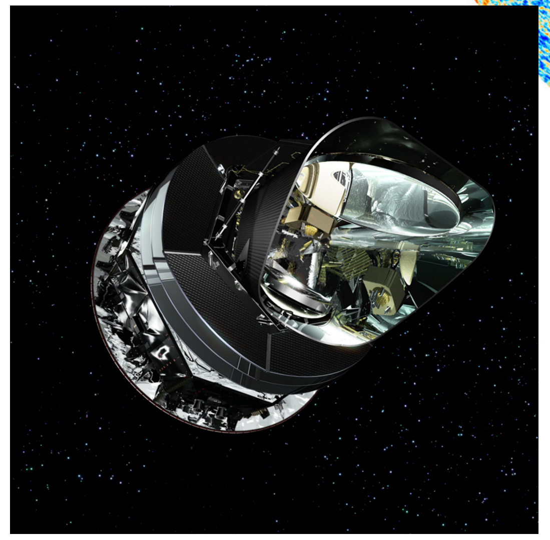
…and other possibilities…

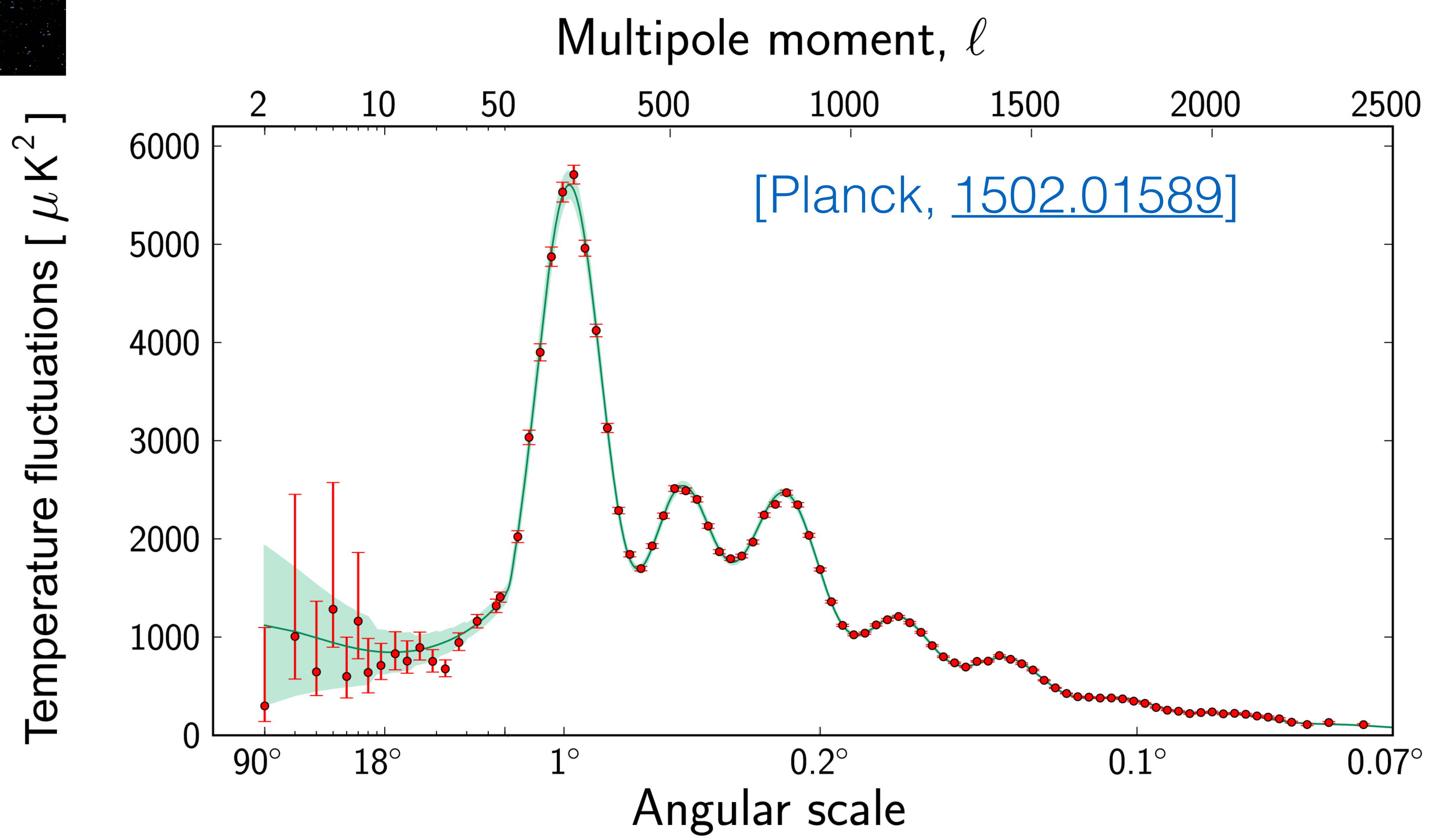
Dark Matter in Cosmology

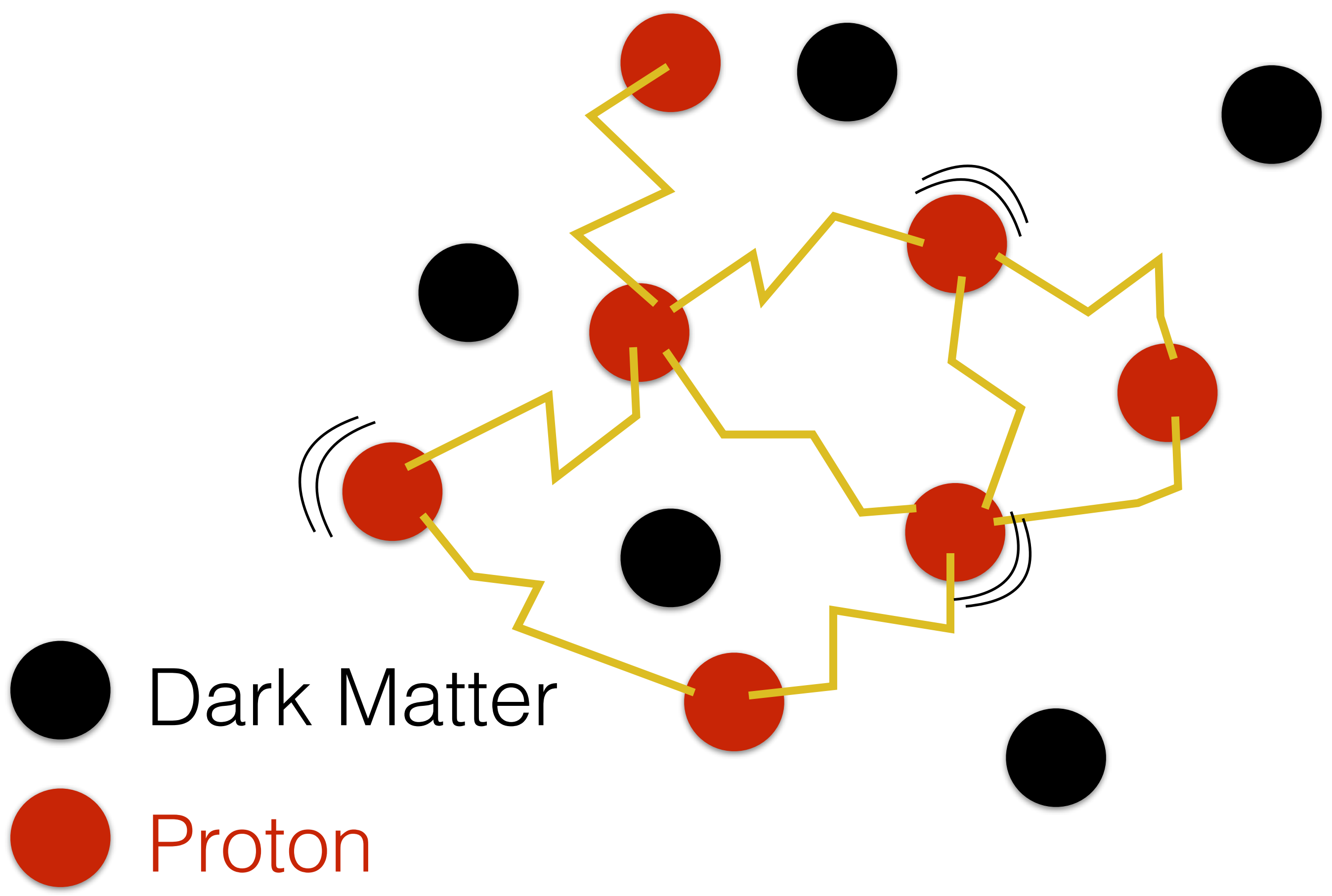
See [“Introduction to Cosmology” Lectures](#) by Miguel Escudero

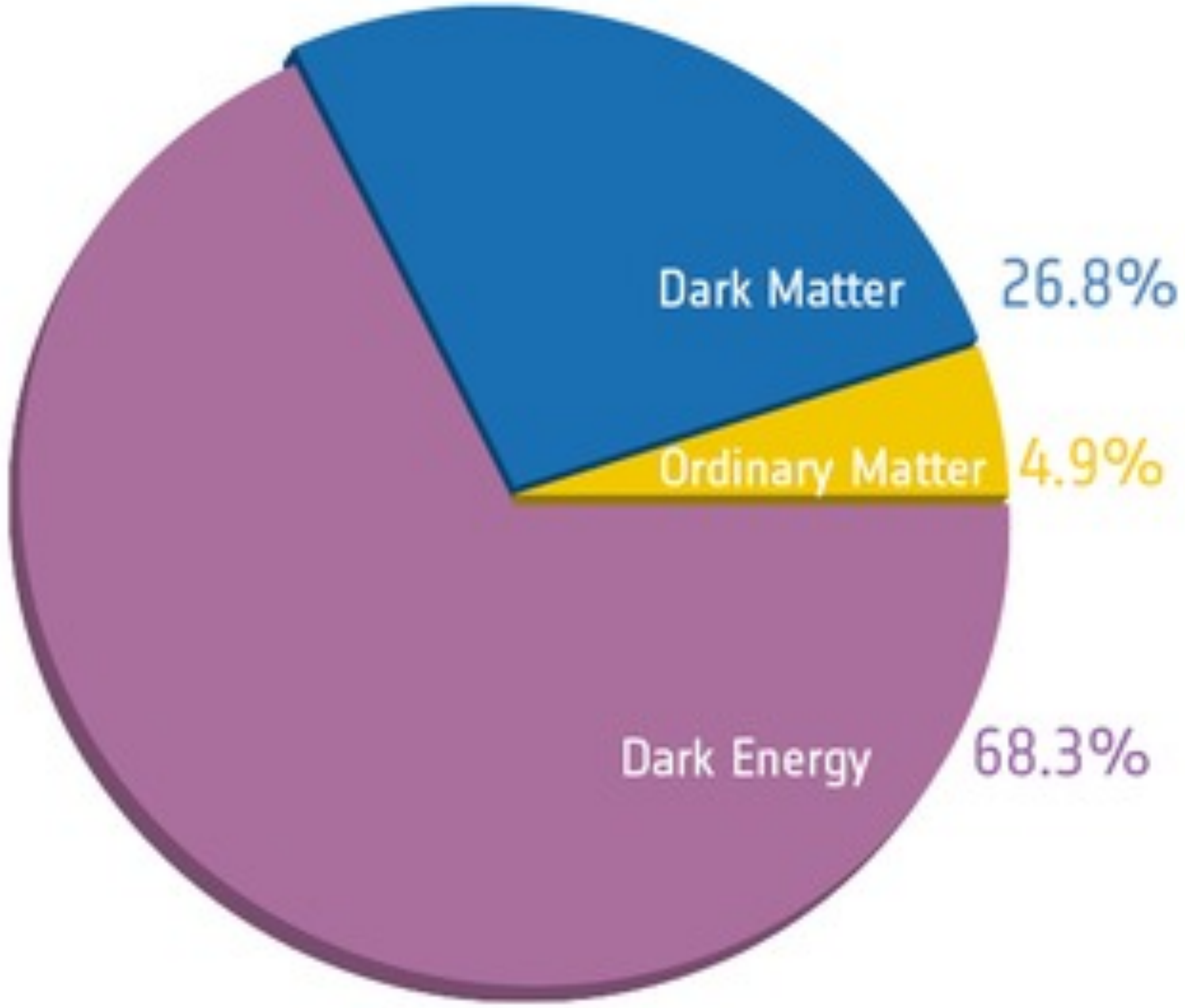
Cosmic Microwave Background (CMB)







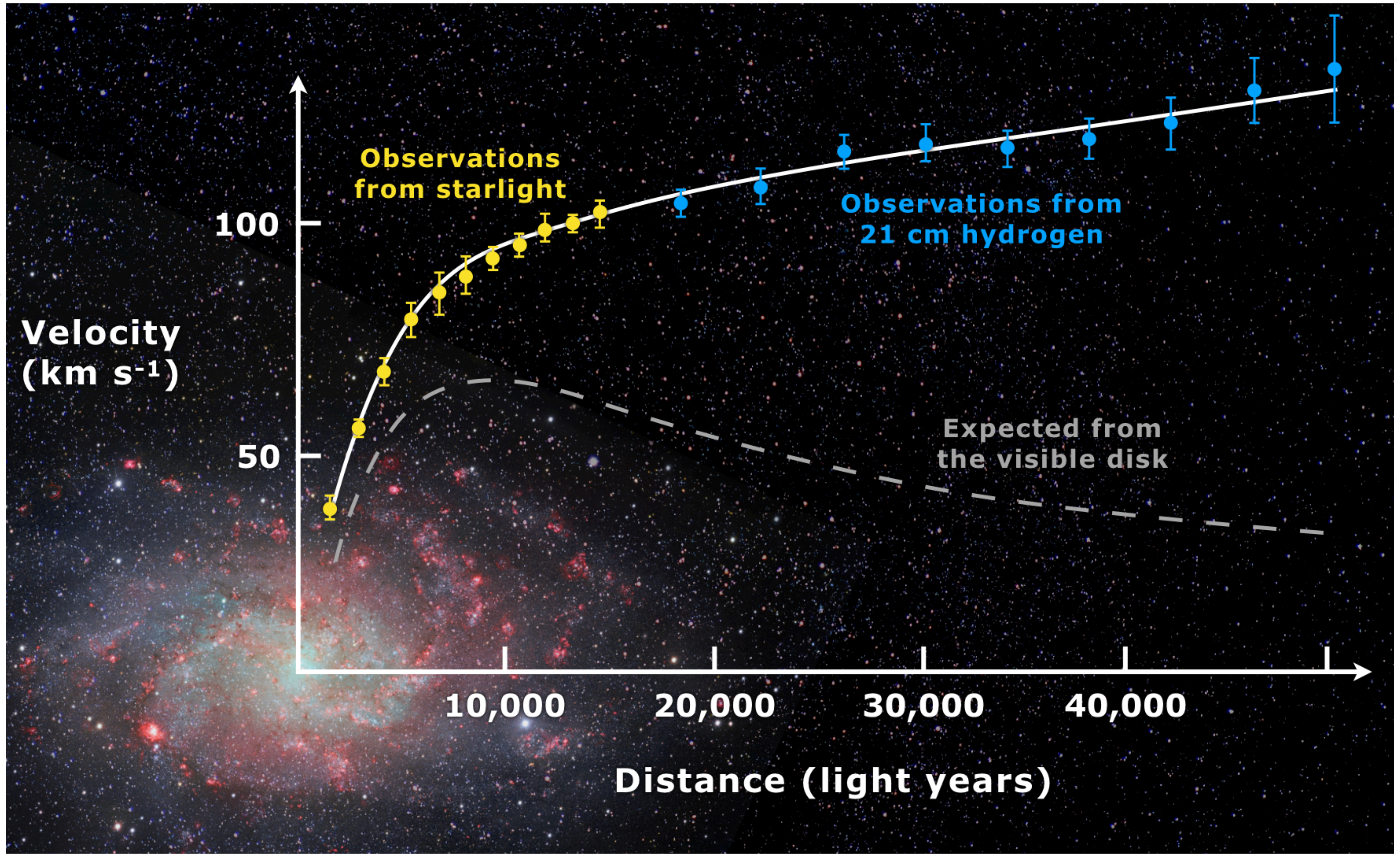


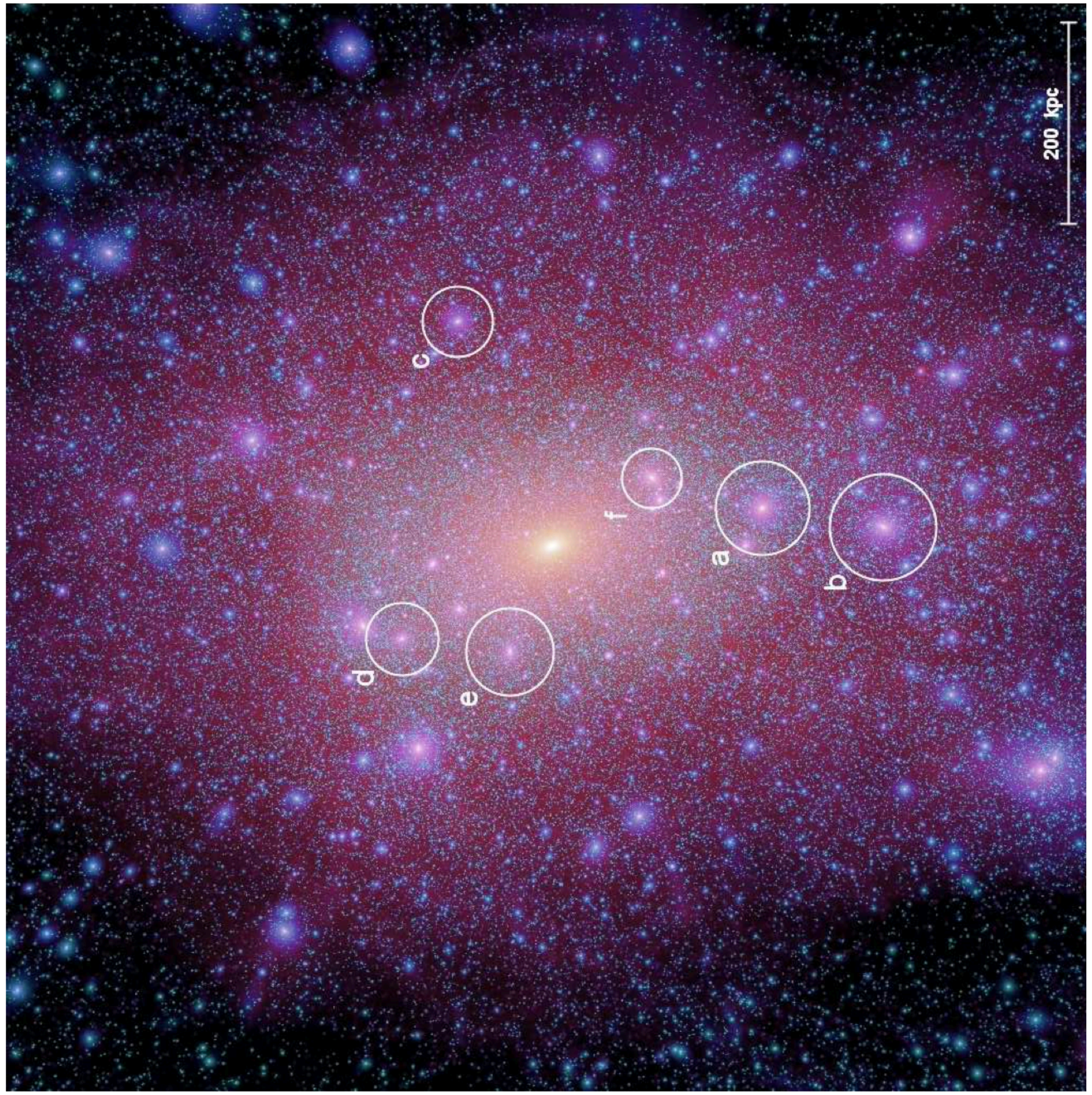


Credit: ESA/Planck Collaboration

Dark Matter in Galaxies

Both observations and simulations tell us: Galaxies contain lots of Dark Matter (DM)!





Aquarius simulation - 0809.0898

DM density at Earth:
$$\rho_\chi \sim 5 \times 10^{-25}\ \mathrm{g/cm^3}$$
$$\sim 0.3\ \mathrm{GeV/cm^3}$$
$$\sim 0.008\ M_\odot/\mathrm{pc}^3$$

1404.1938

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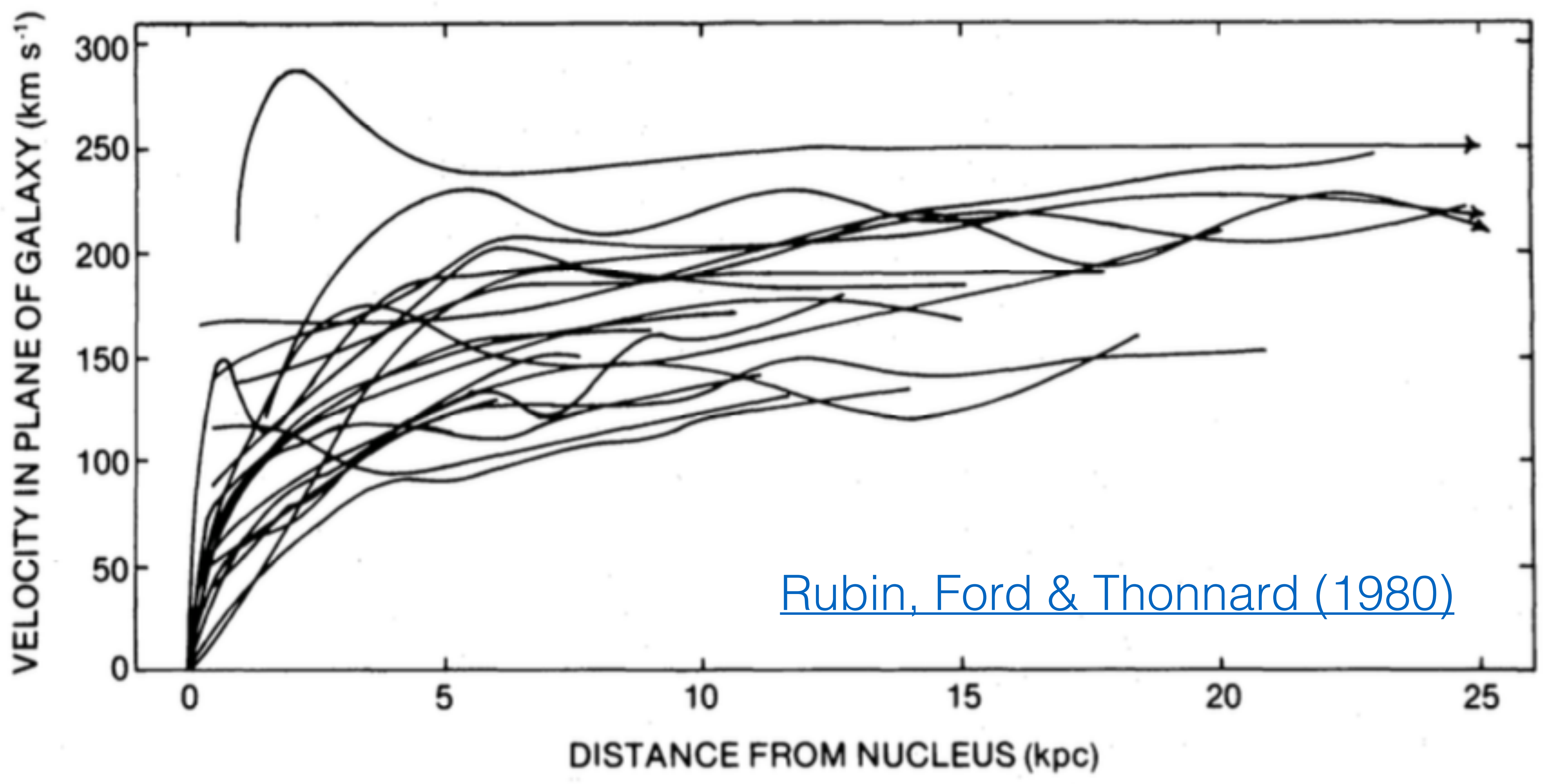
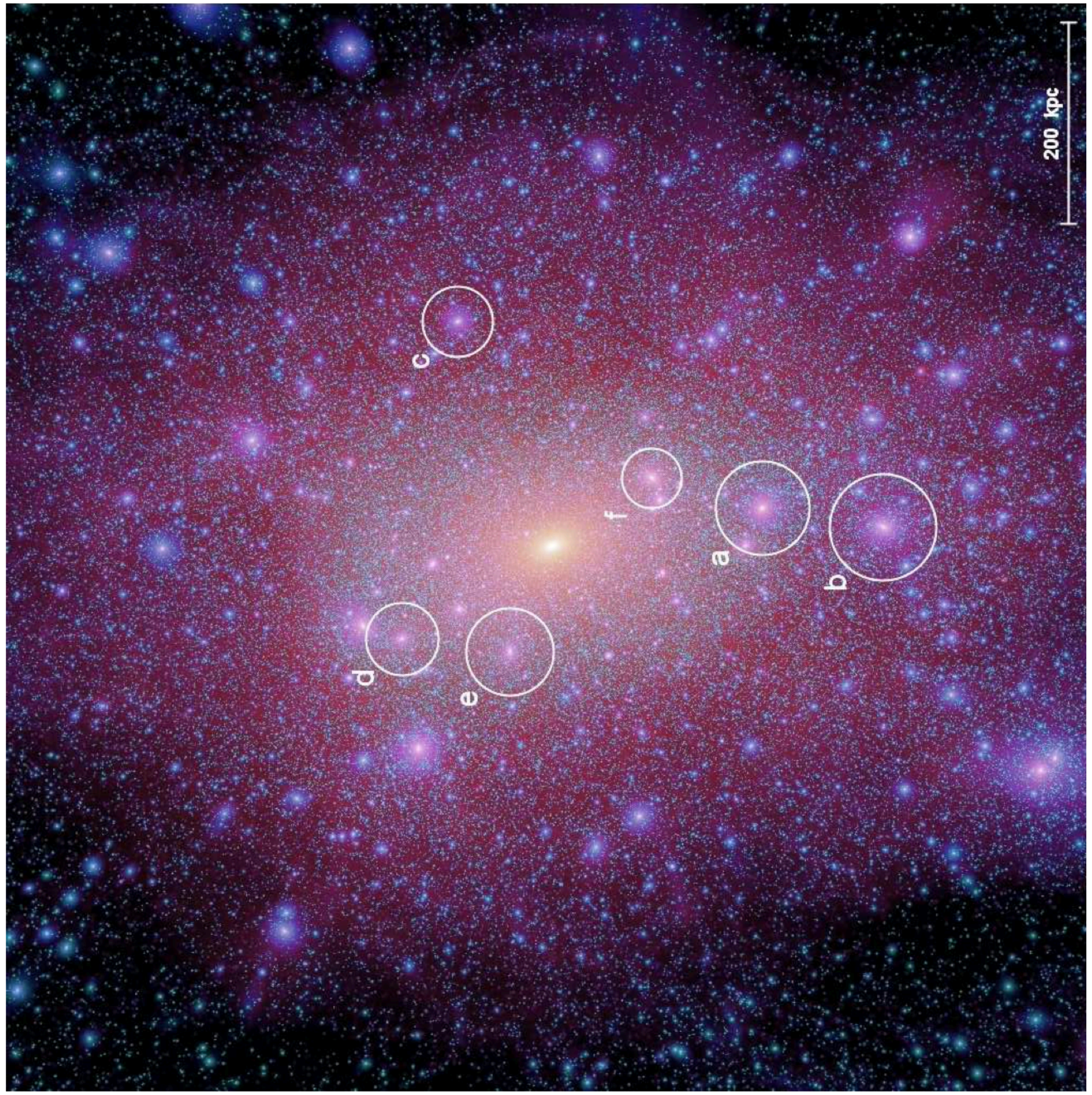


Rubin, Ford & Thonnard (1980)



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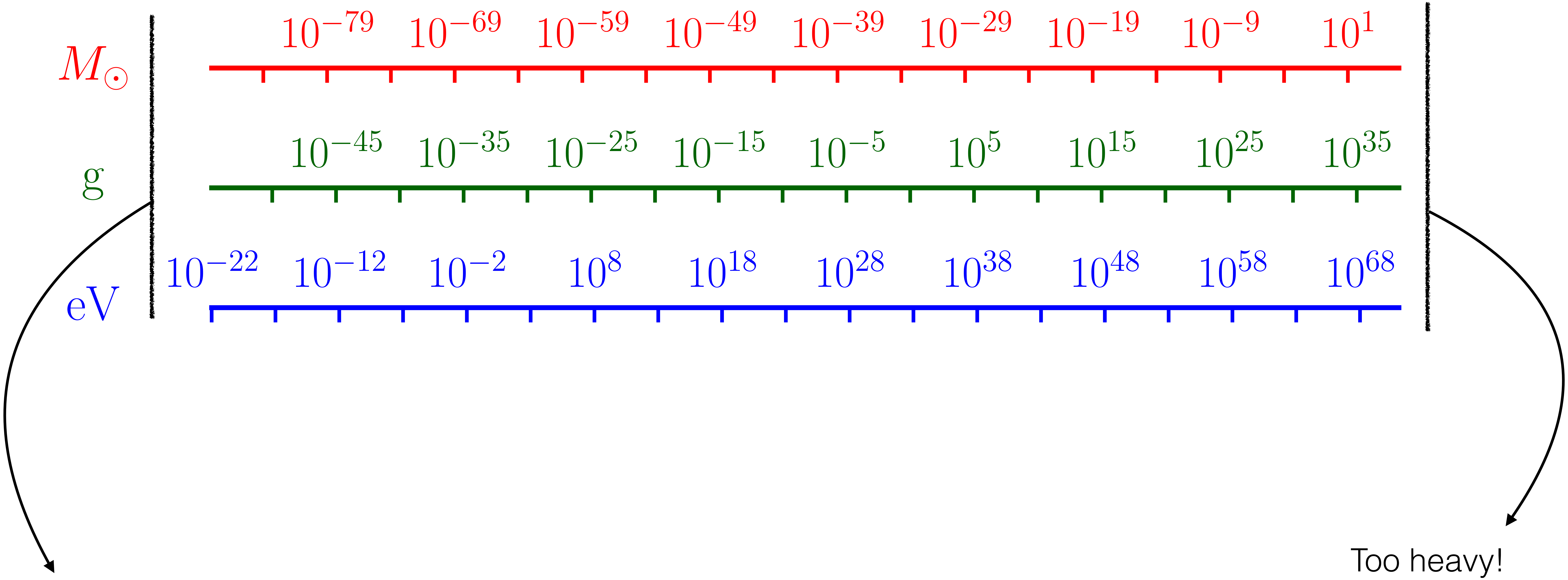
1404.1938

Dark Matter properties

Dark Matter must be:

- Non-baryonic
- Cold (i.e. slow-moving)
- (Almost) electrically neutral



Too light!
Has wave-like properties
on galactic scales!

Too heavy!
DM mass comparable to
galactic masses!

*See additional slides…

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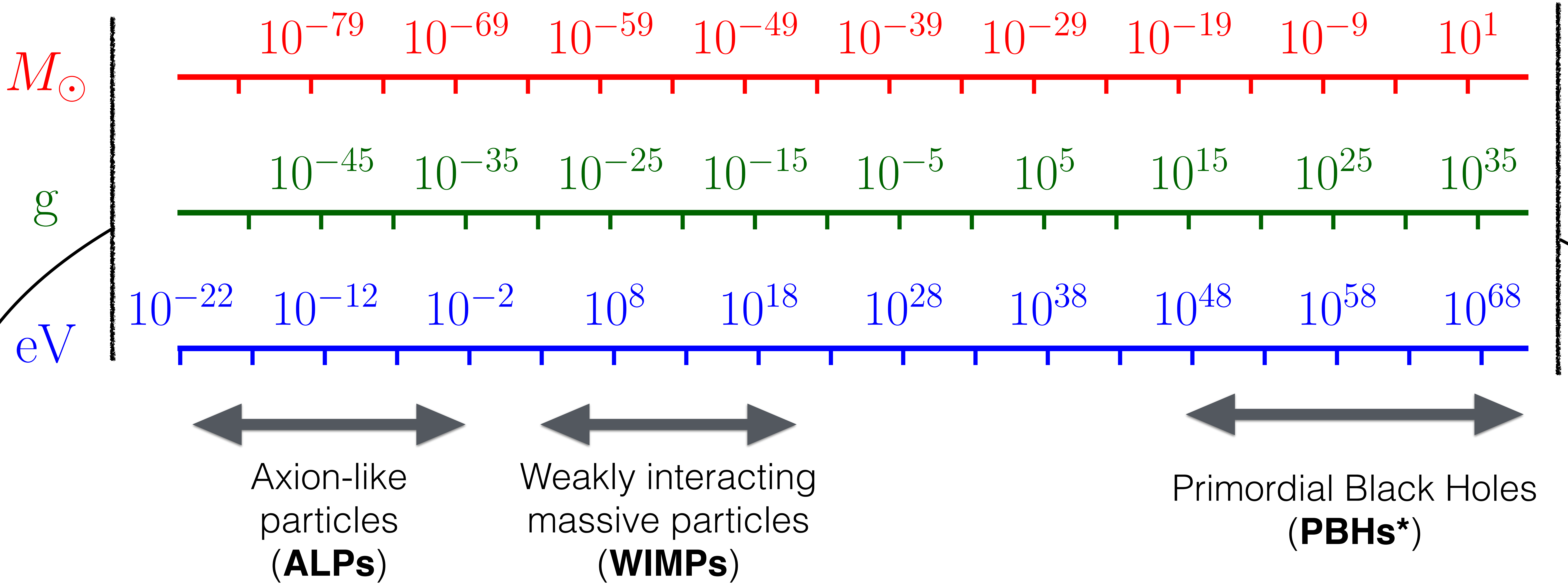

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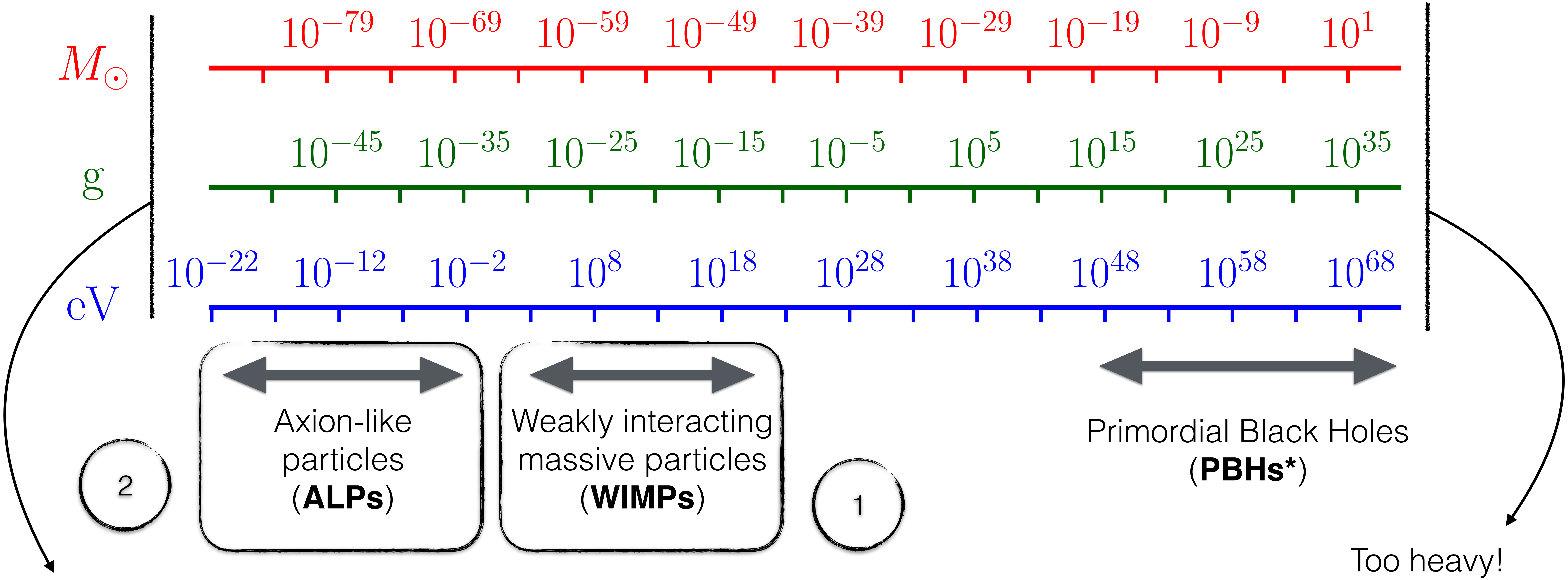

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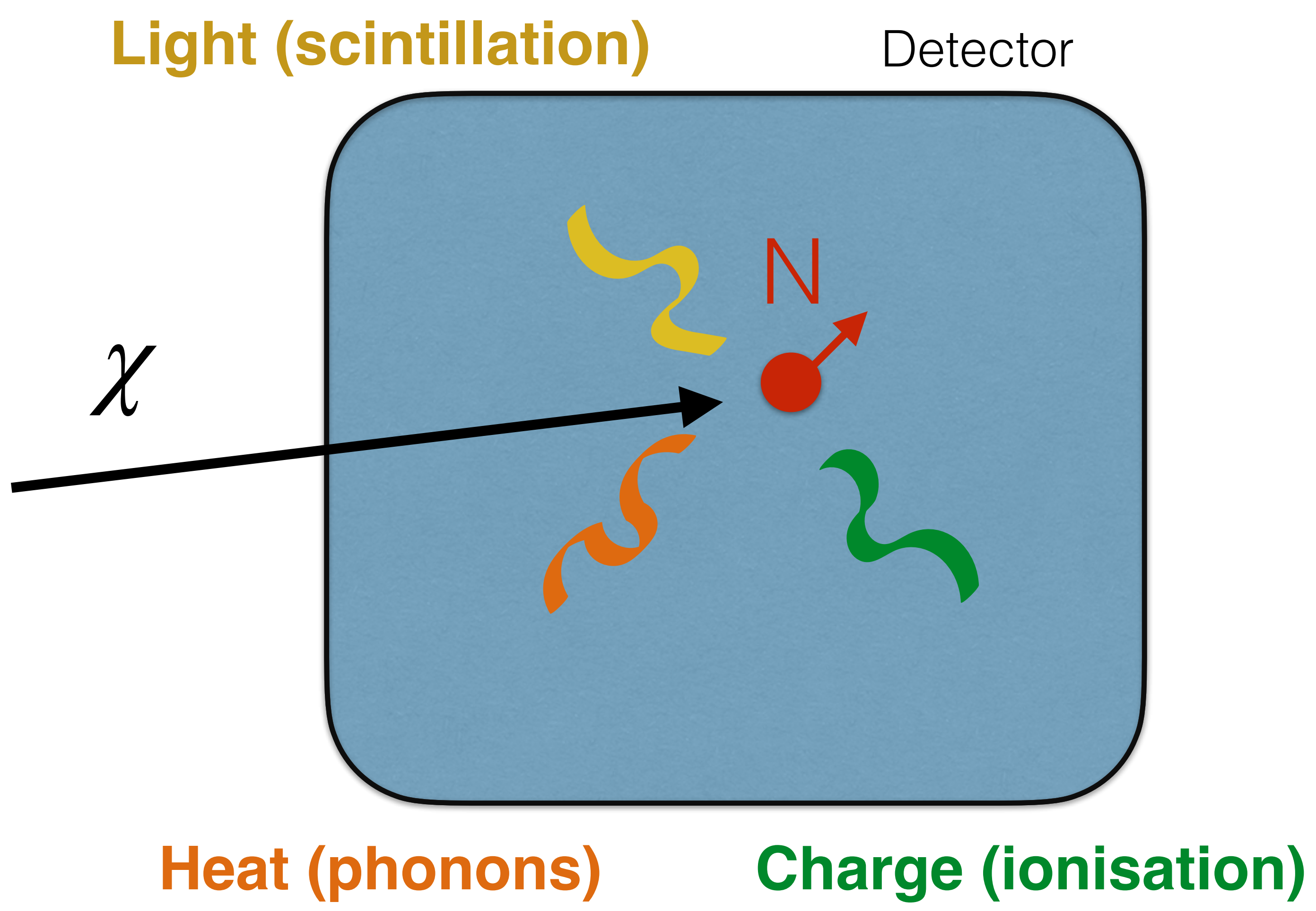
DM mass comparable to galactic masses!

*See additional slides…

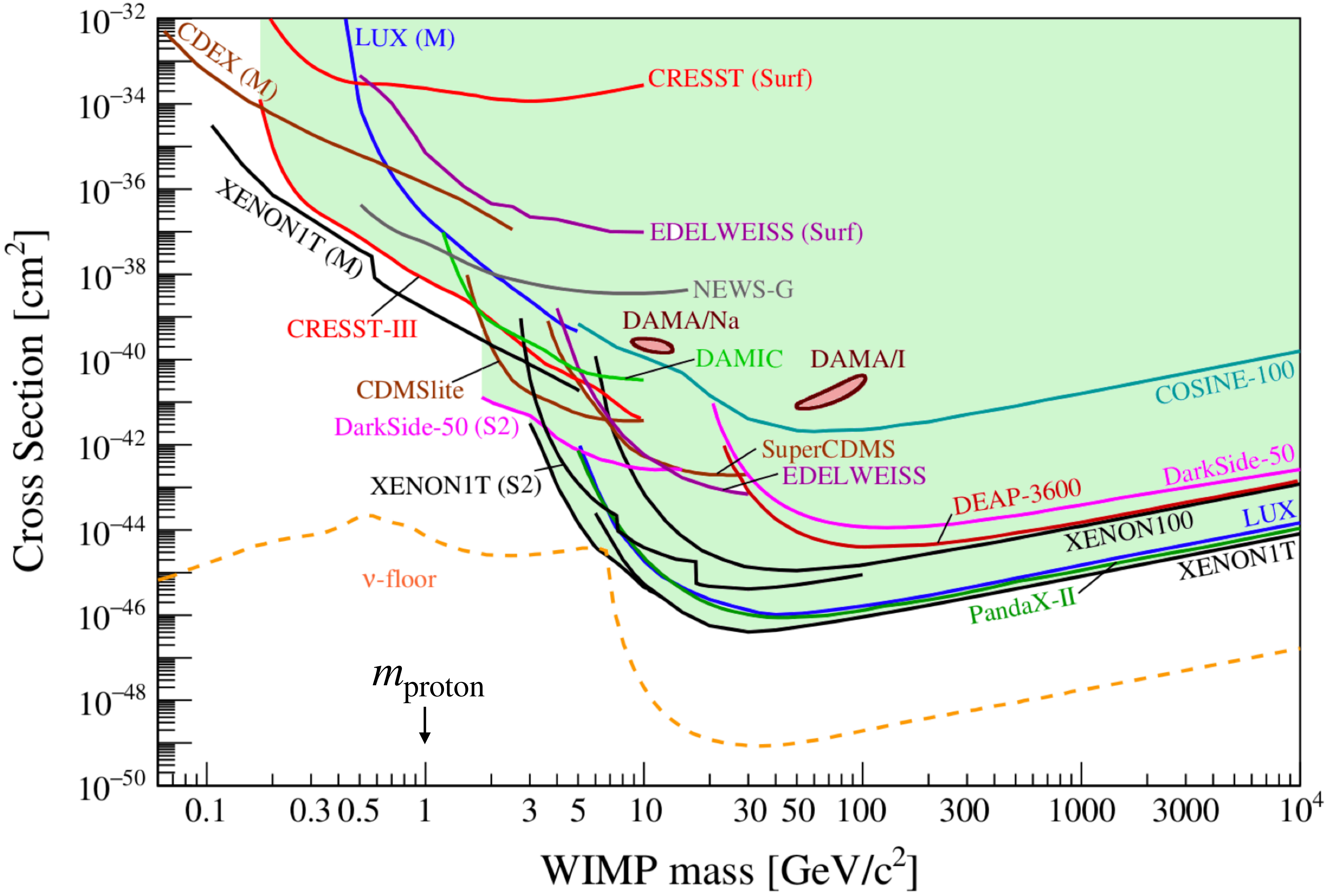
Direct detection of WIMPs on Earth

For WIMPs with GeV-scale masses, expect detectable nuclear recoils of energy O(keV)



For sensible models, expect signal rates on the order of <1 event per kg per keV per day

No convincing signal yet!

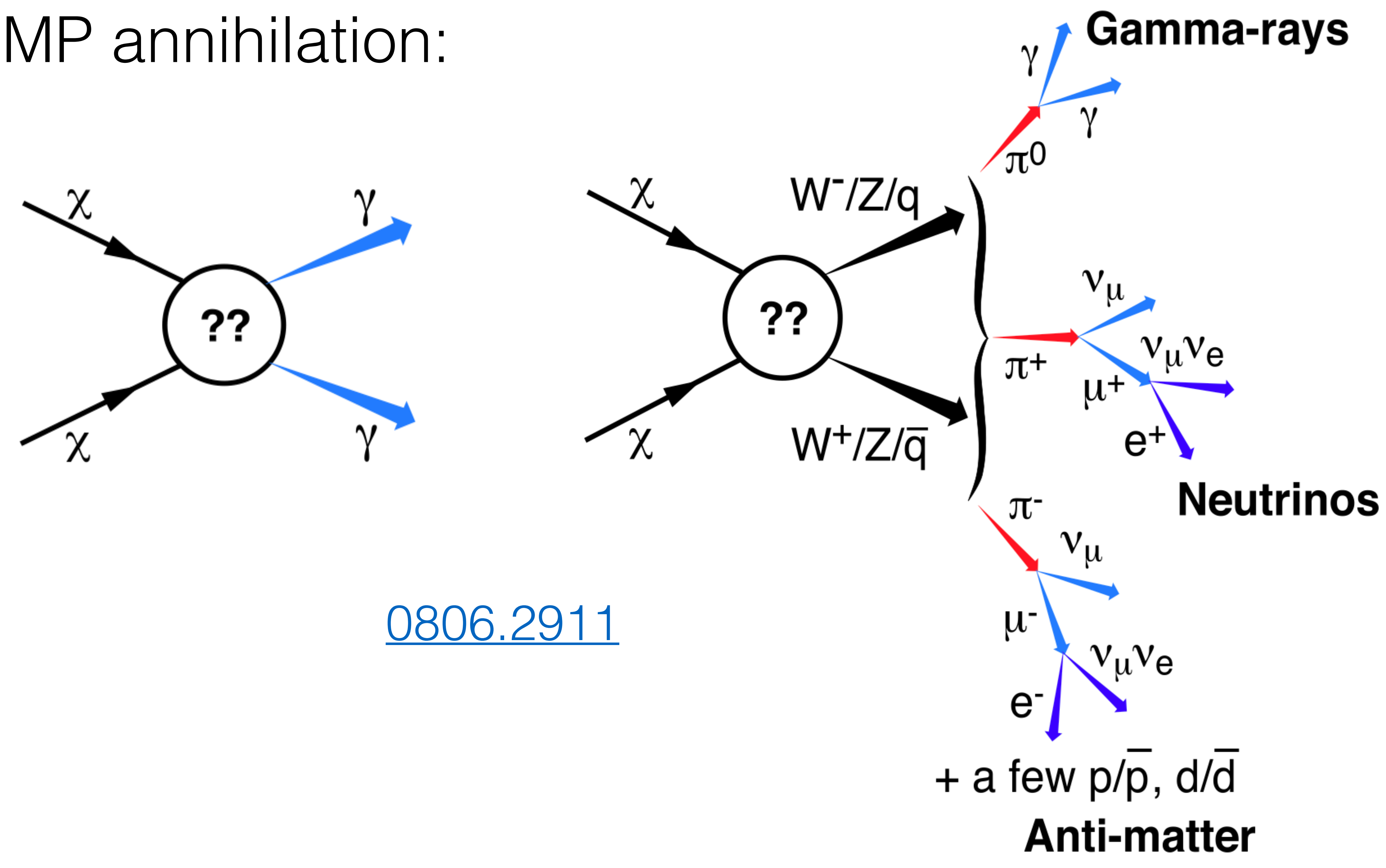


Also possible to look for DM-electron scattering, depending on the model.

Indirect detection of Dark Matter

Look for signals of Dark Matter annihilation in regions of large DM density!

WIMP annihilation:



0806.2911

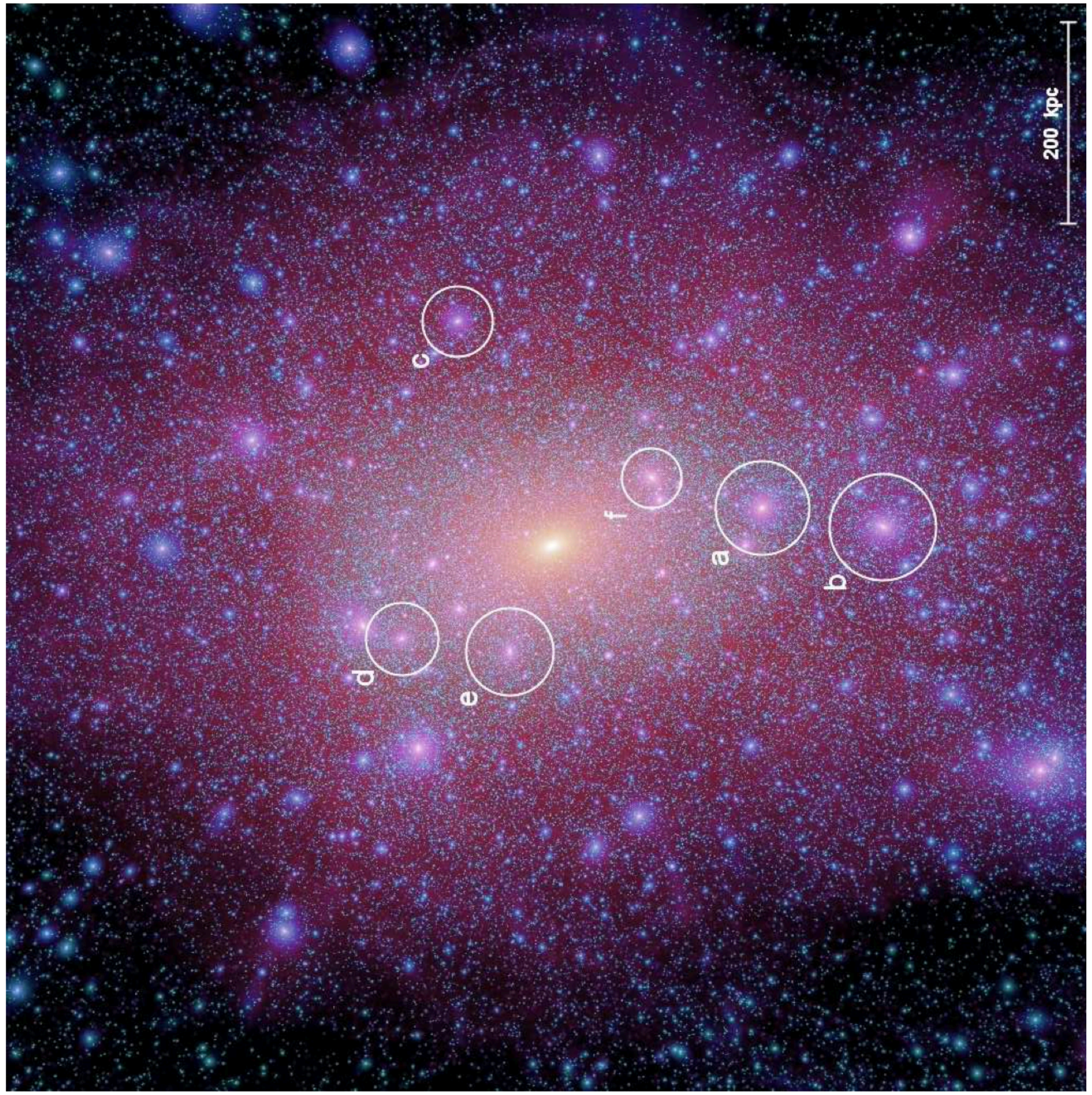
Annihilation cross section (particle physics)

DM density distribution (astrophysics)

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_\chi^2}\frac{dN_\gamma}{dE_\gamma} \times \int_{d\Omega} d\Omega' \int_{los} \rho^2 dl\,(r,\theta')$$

Gamma-ray spectrum (annihilation channel)

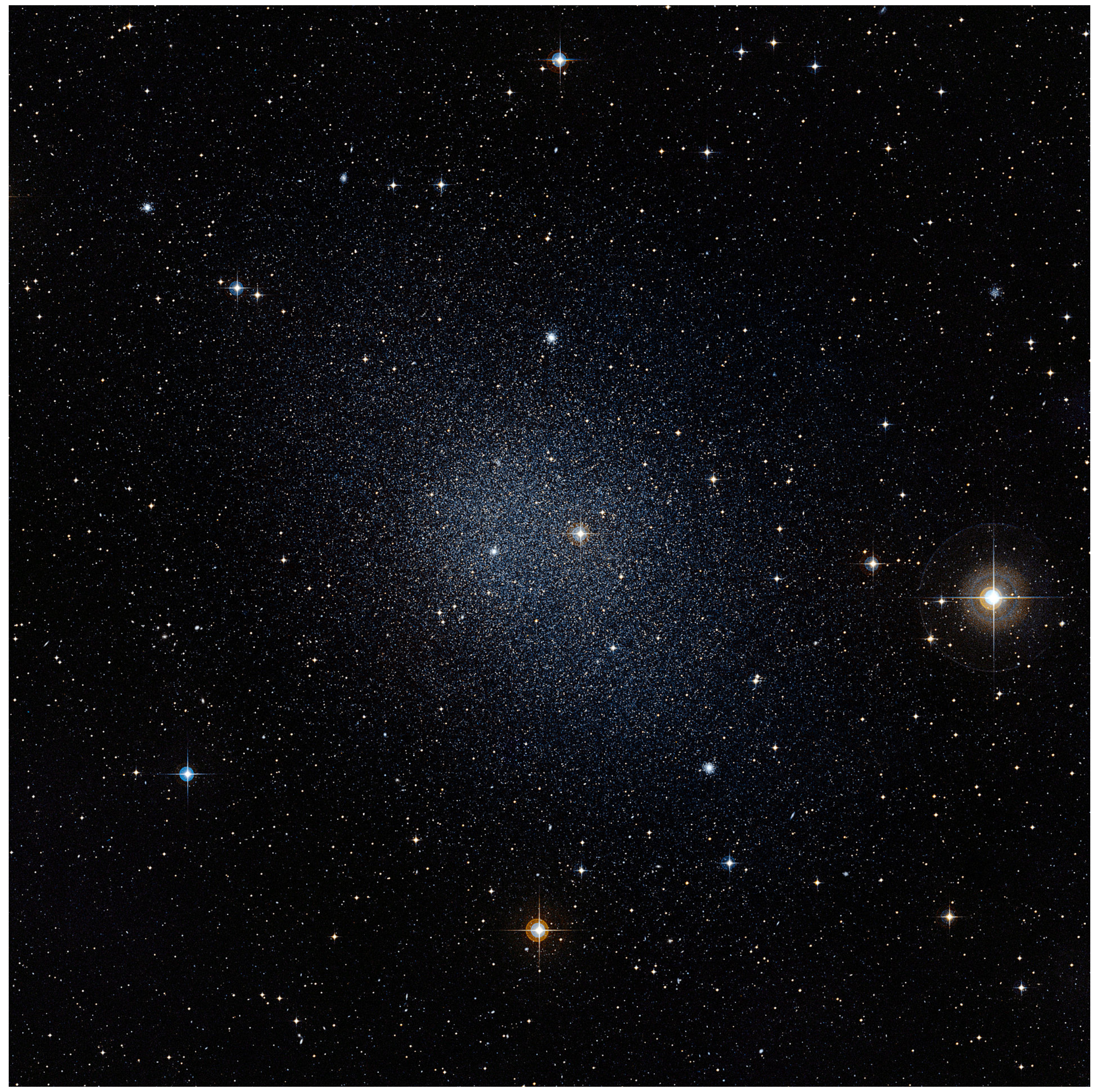
1012.4515



Aquarius simulation - 0809.0898

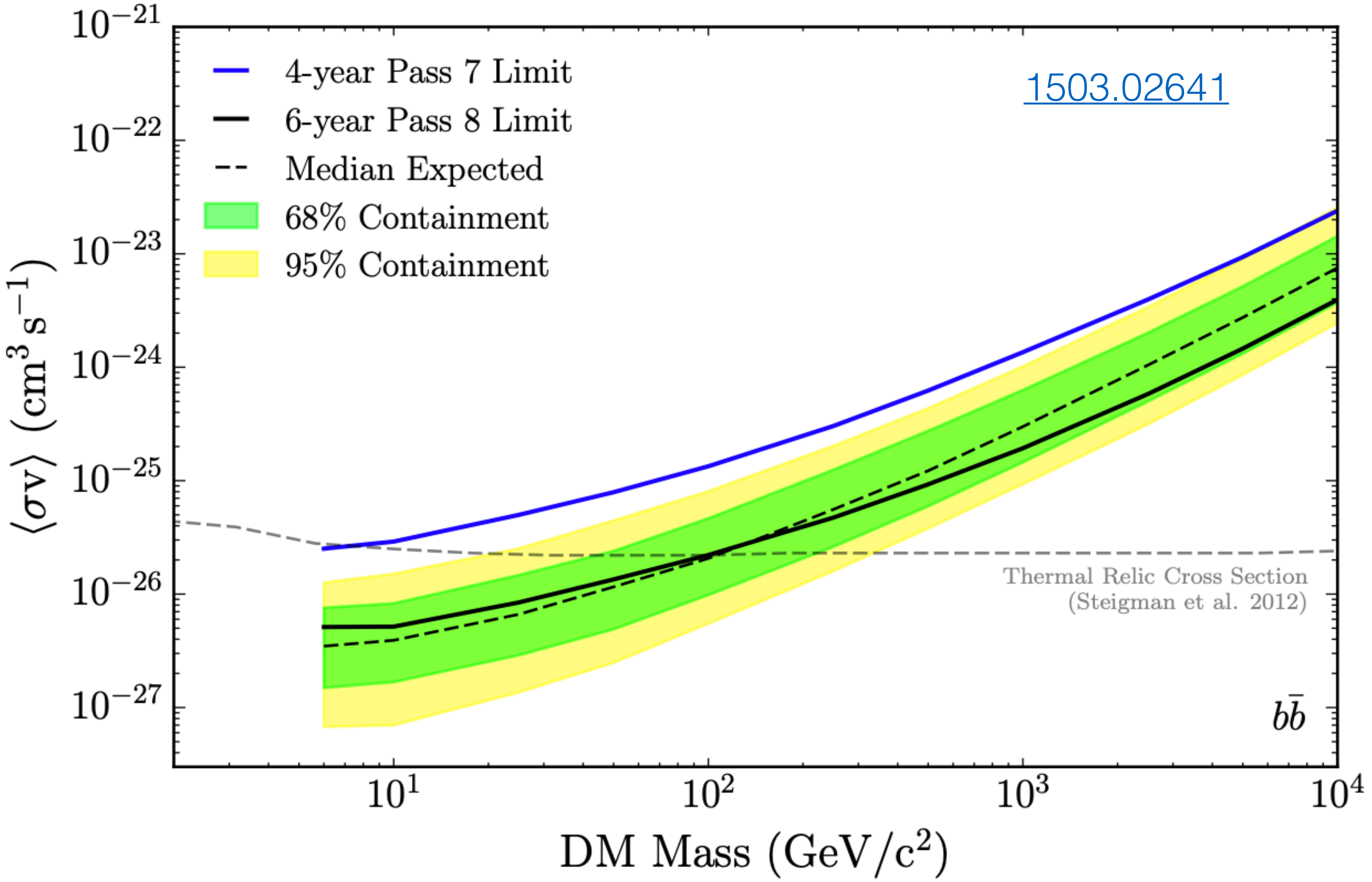
Gamma-ray constraints

Fornax Dwarf Galaxy
(Satellite of the Milky Way)



Credit: ESO/Digitized Sky Survey 2

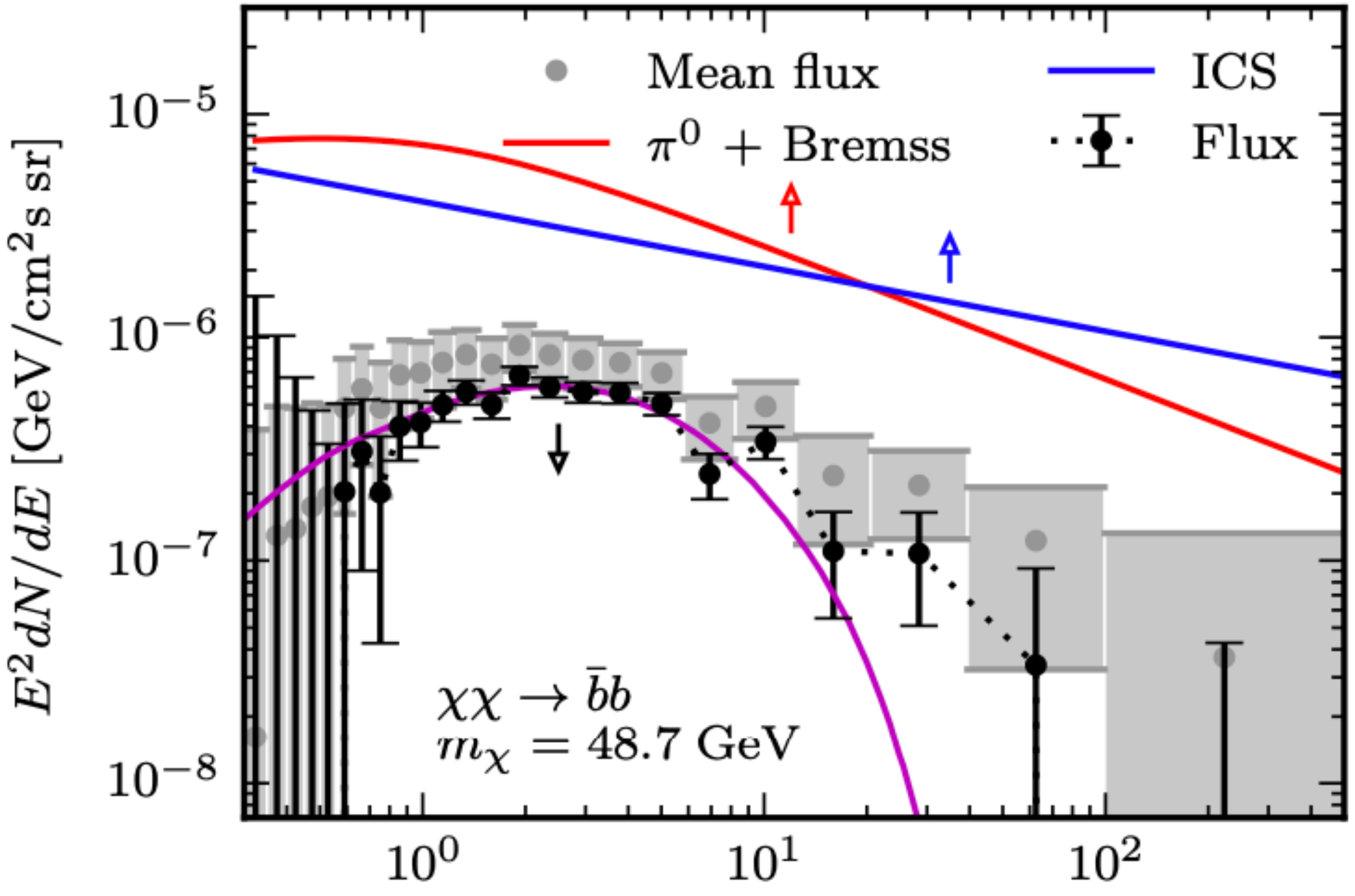
Fermi constraints from 15 Dwarf Spheroidal Galaxies:



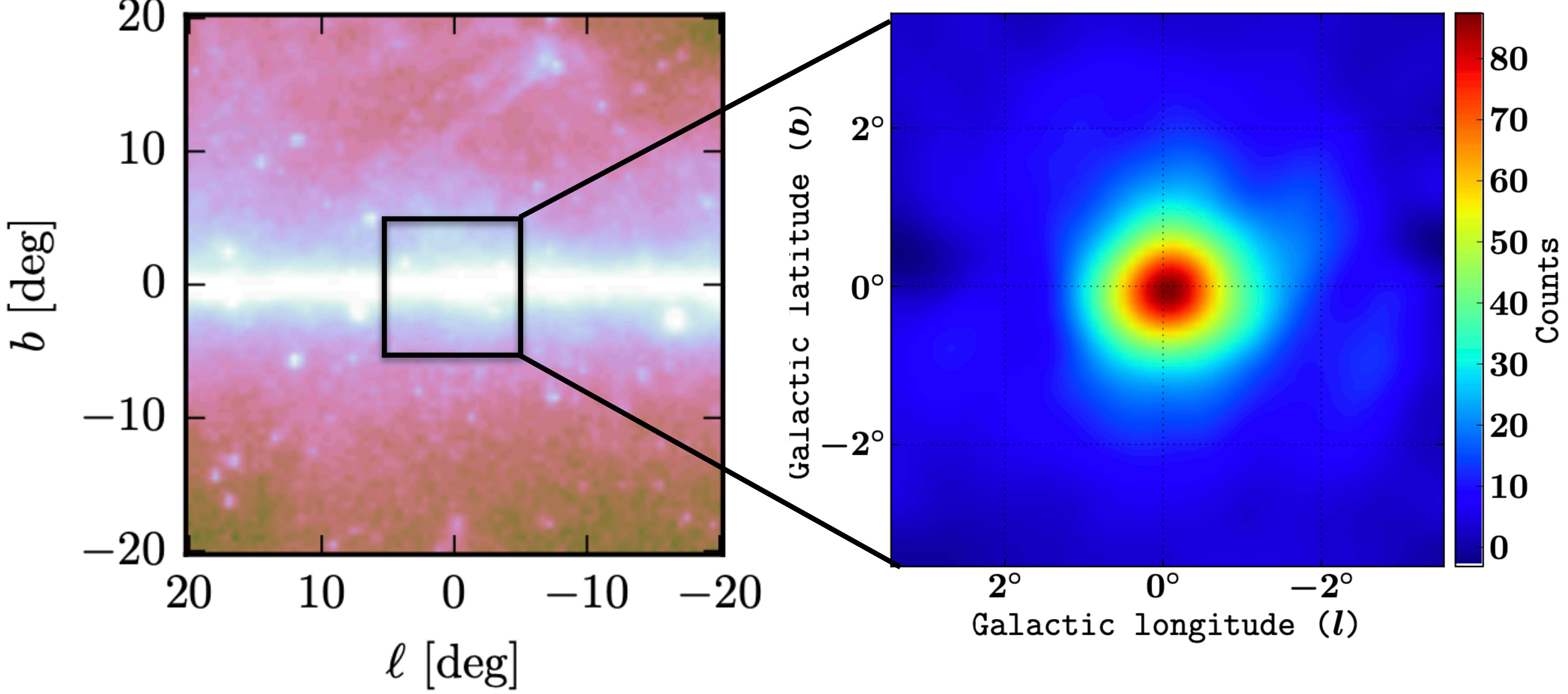
Exact constraints depend on annihilation channel ($\chi\chi \to b\bar{b}, \chi\chi \to W^+W^-, \chi\chi \to e^+e^-$, etc.)

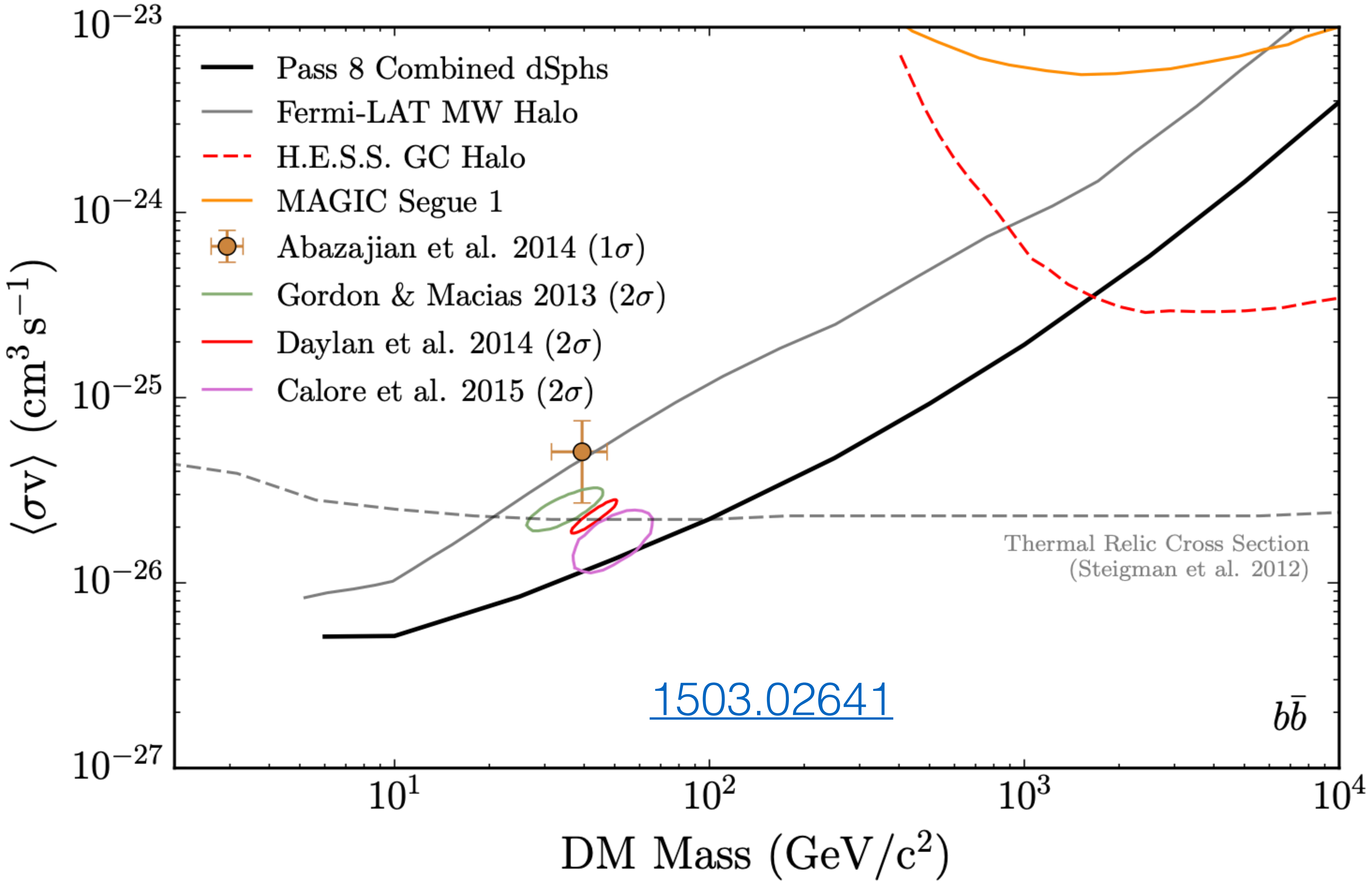
Galactic Centre Excess

1411.4647



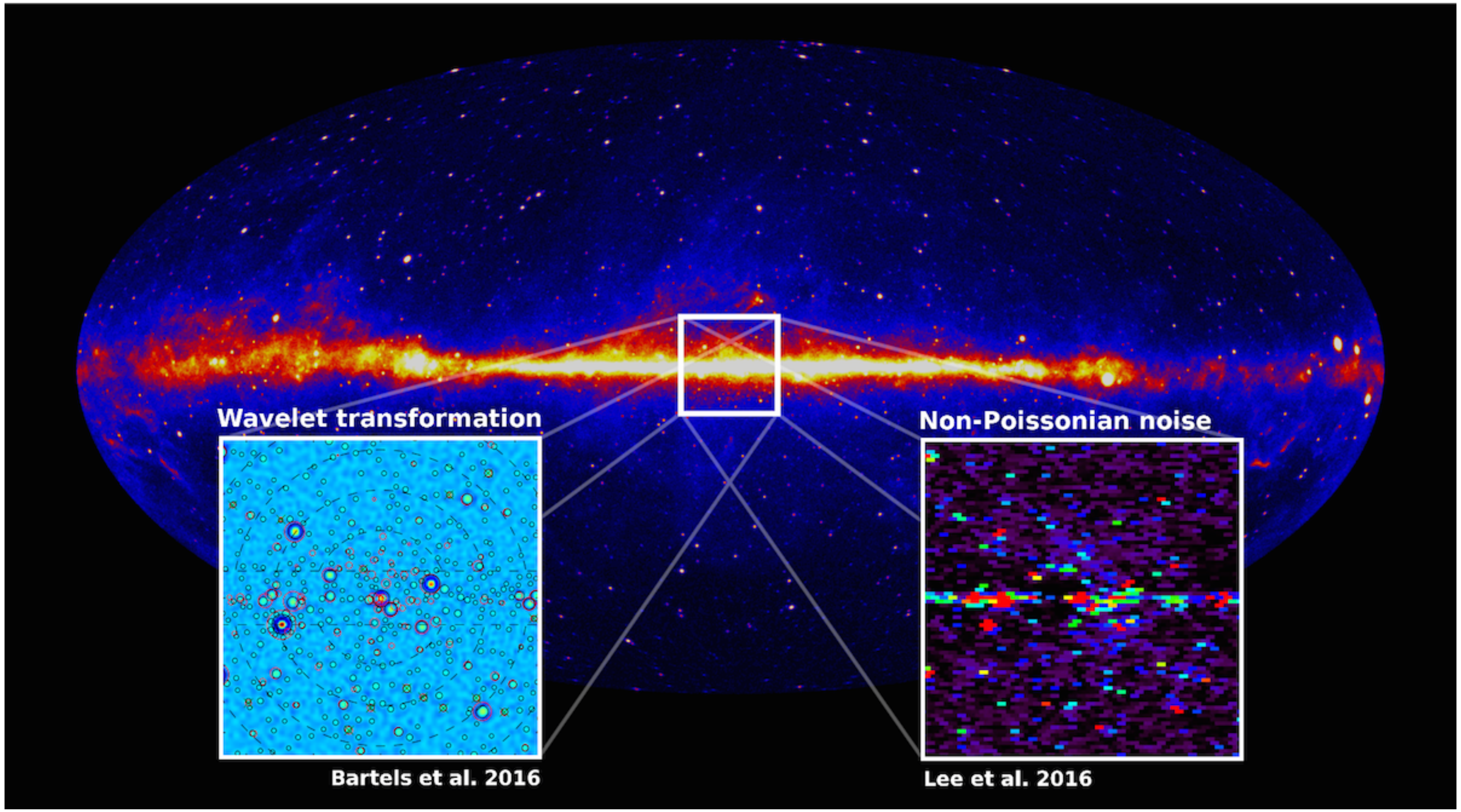
Data 1711.04778 Residuals 1306.5725





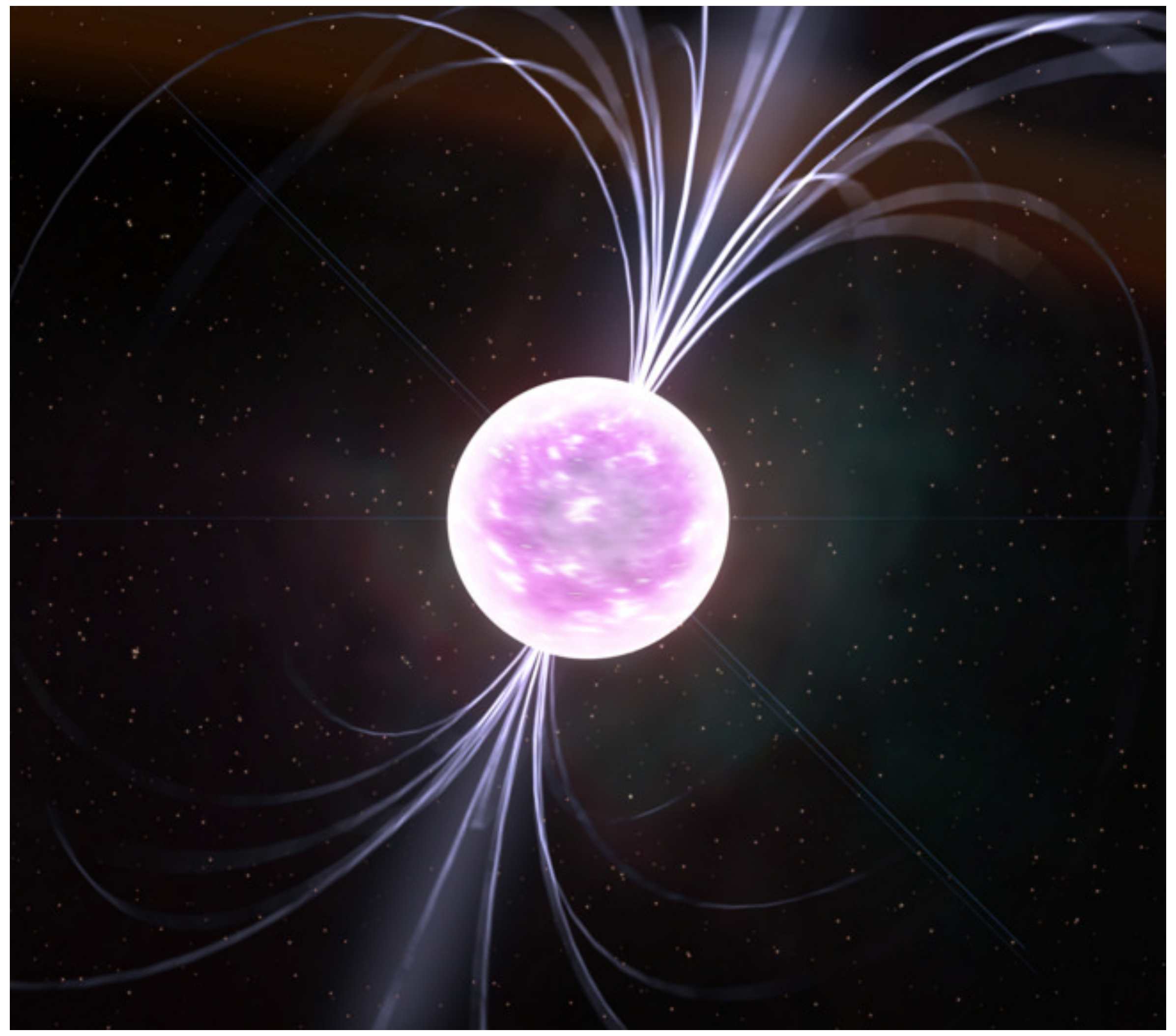
Point sources in the Galactic Centre

Galactic Centre excess could be due to a population of unresolved point sources (millisecond pulsars?)



Credit: Christoph Weniger, UvA , © UvA/Princeton

1506.05104, 1711.04778

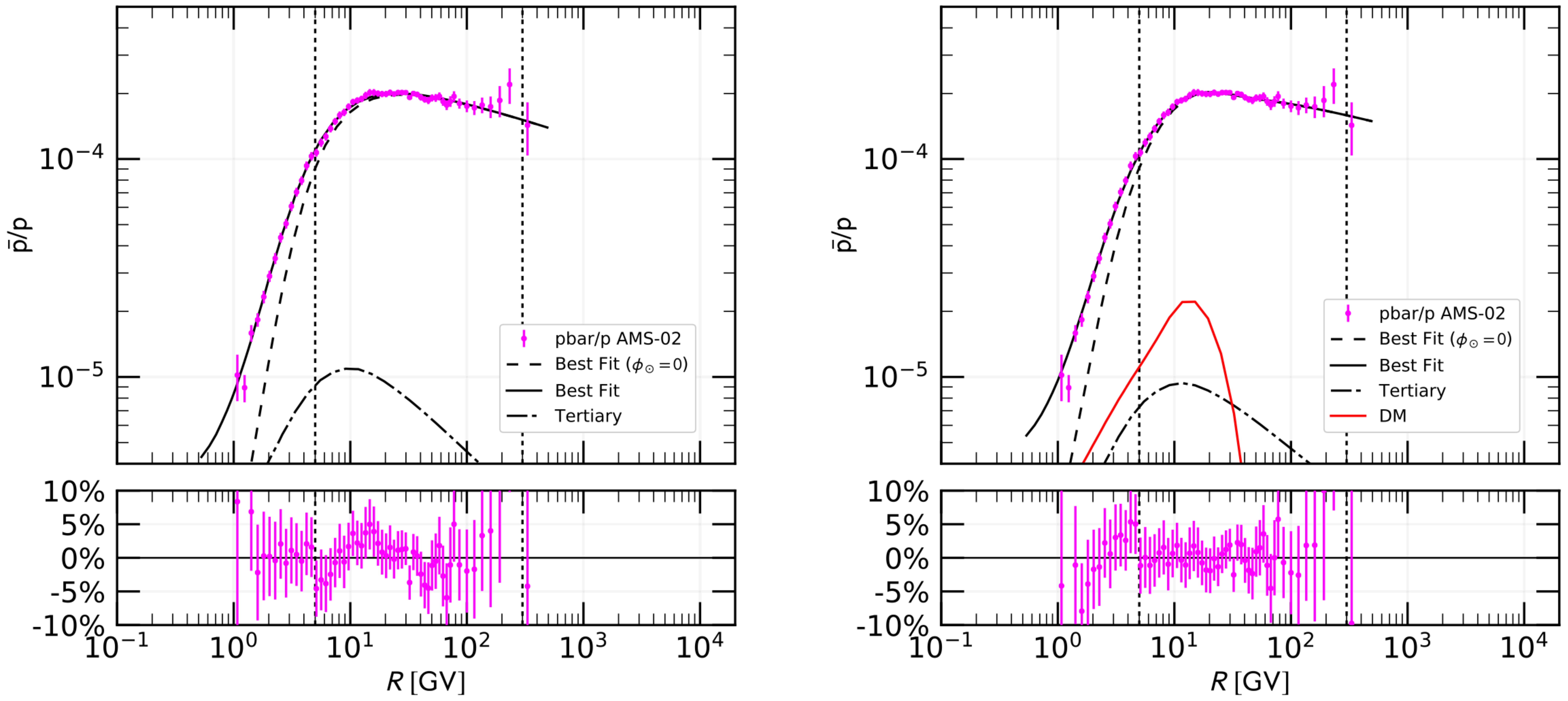


Credit: Kevin Gill / Flickr

Square Kilometer Array (SKA)?

Anti-proton excess

Anti-protons are an excellent probe of New Physics - they're hard to make!



Several excesses point towards 60 GeV Dark Matter -
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

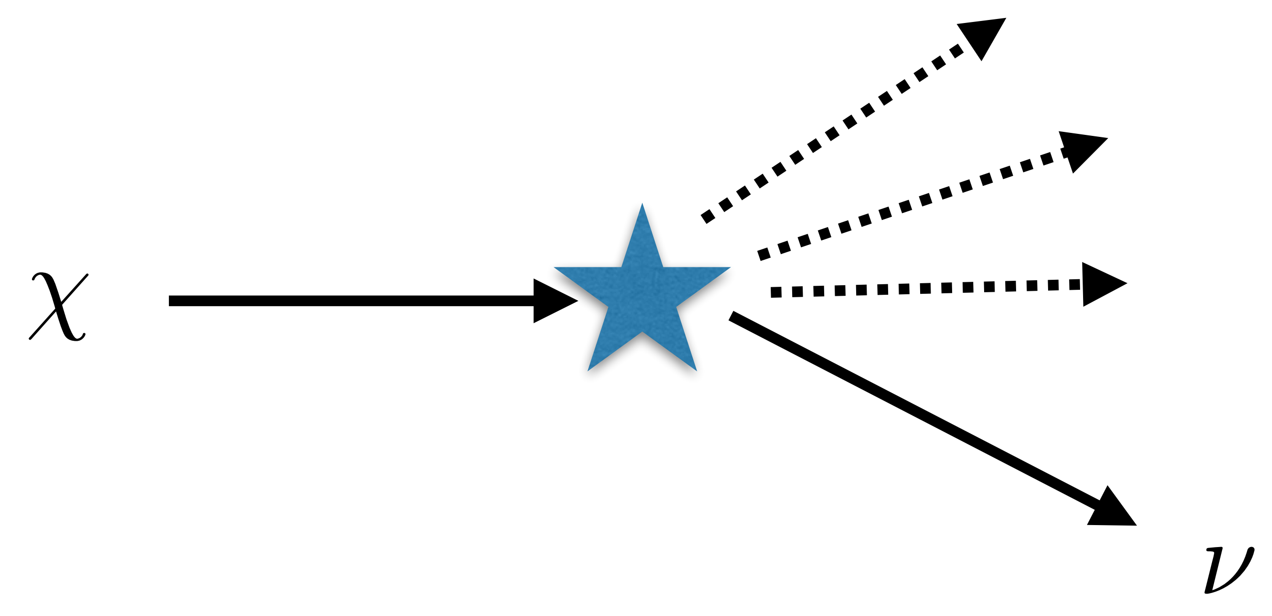
1504.04276, 1610.03071, 1903.01472

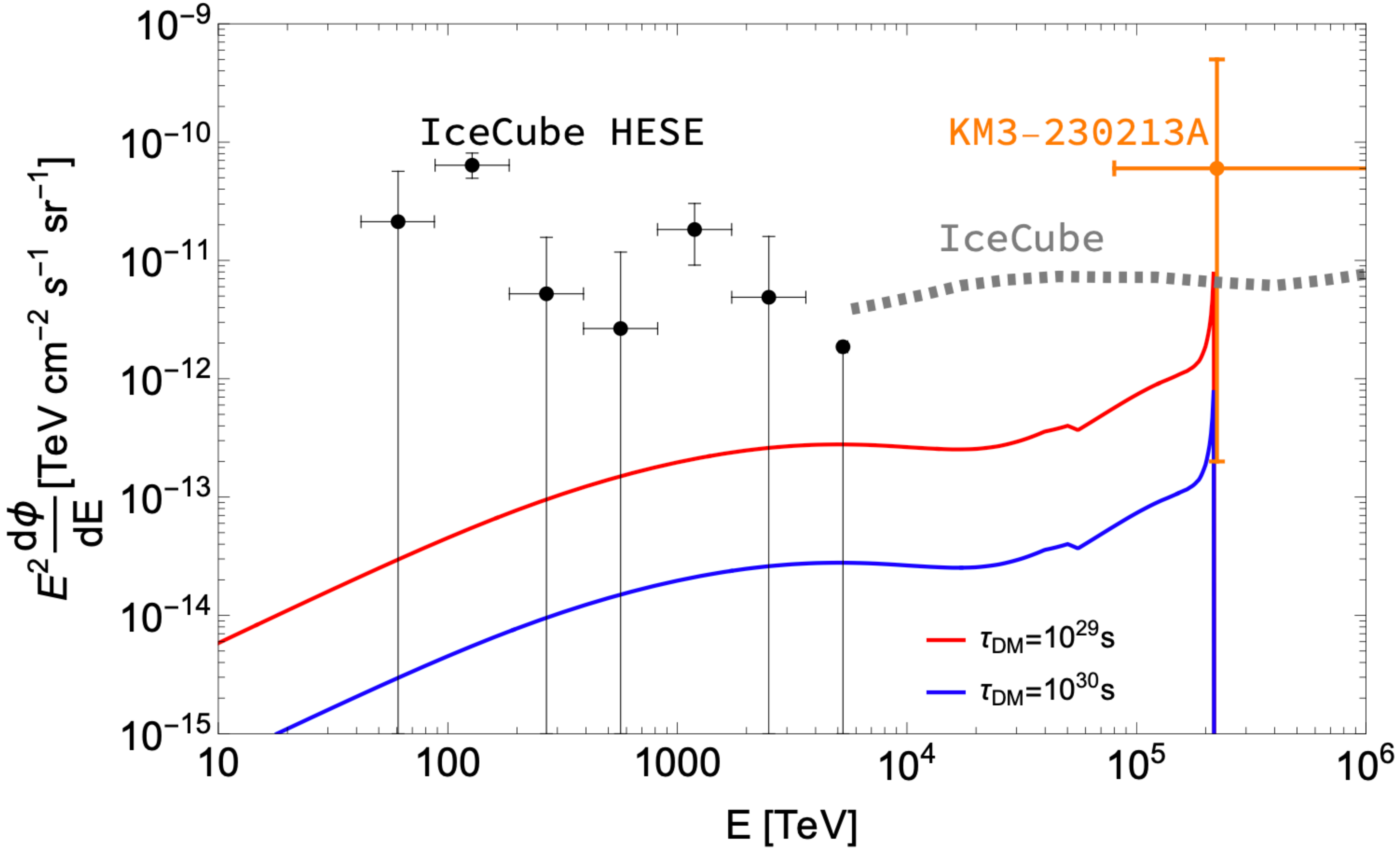
High energy neutrinos

Decays of super-heavy Dark Matter could contribute to the flux of PeV neutrinos:

[1508.02500](), [1712.07138]()

$$m_\chi \sim 220\,\mathrm{PeV}$$
$$\tau_\chi \sim 10^{29}\,\mathrm{s}$$

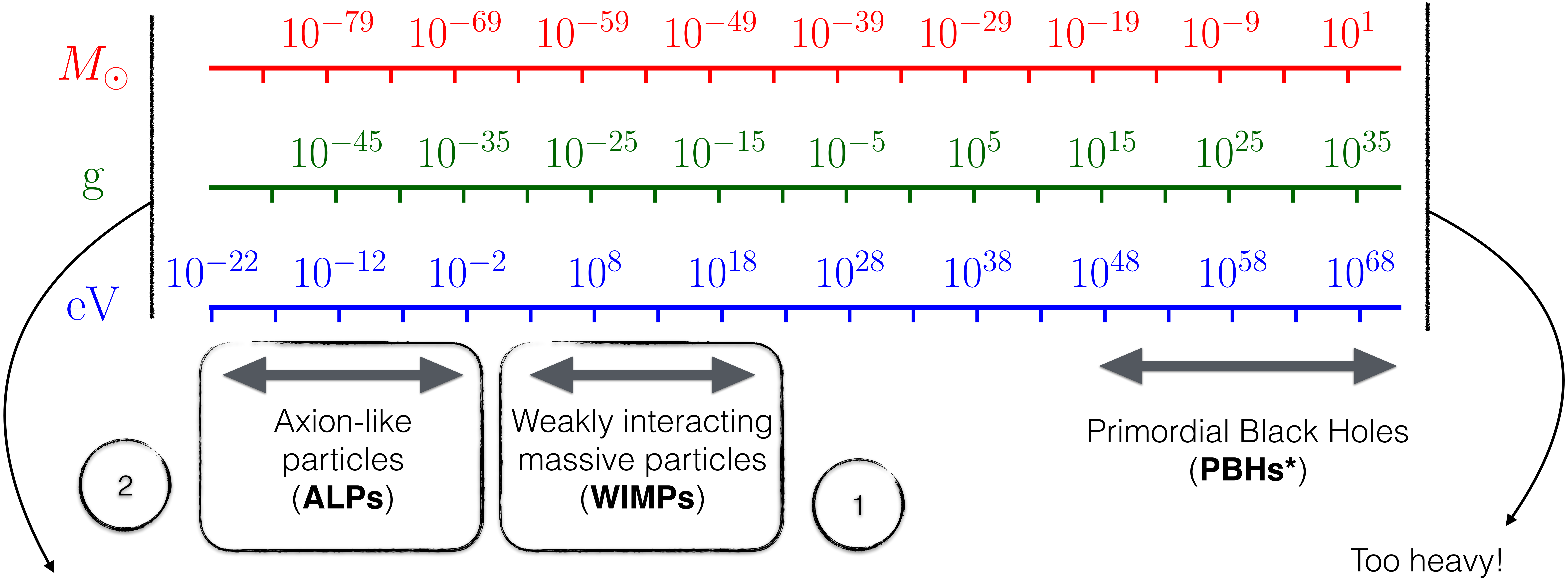




Dark Matter properties

Dark Matter must be:

- Non-baryonic
- Cold (i.e. slow-moving)
- (Almost) electrically neutral



Too light!
Has wave-like properties on galactic scales!

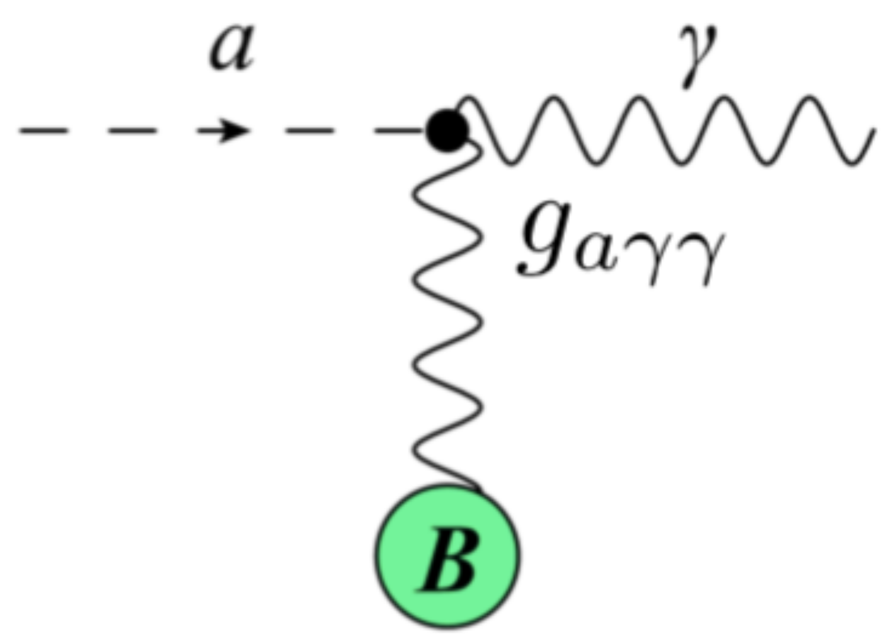
Too heavy!
DM mass comparable to galactic masses!

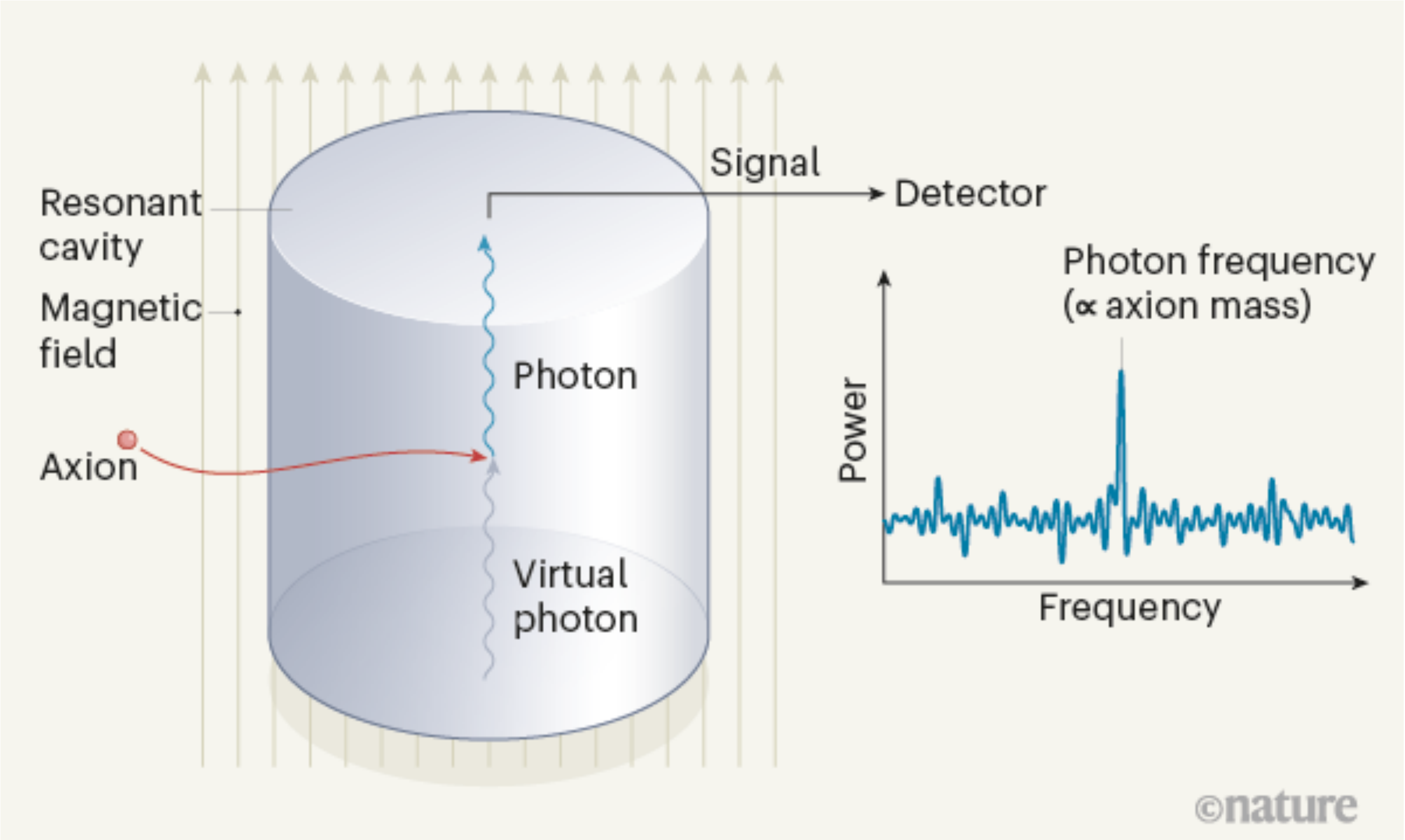
*See additional slides…

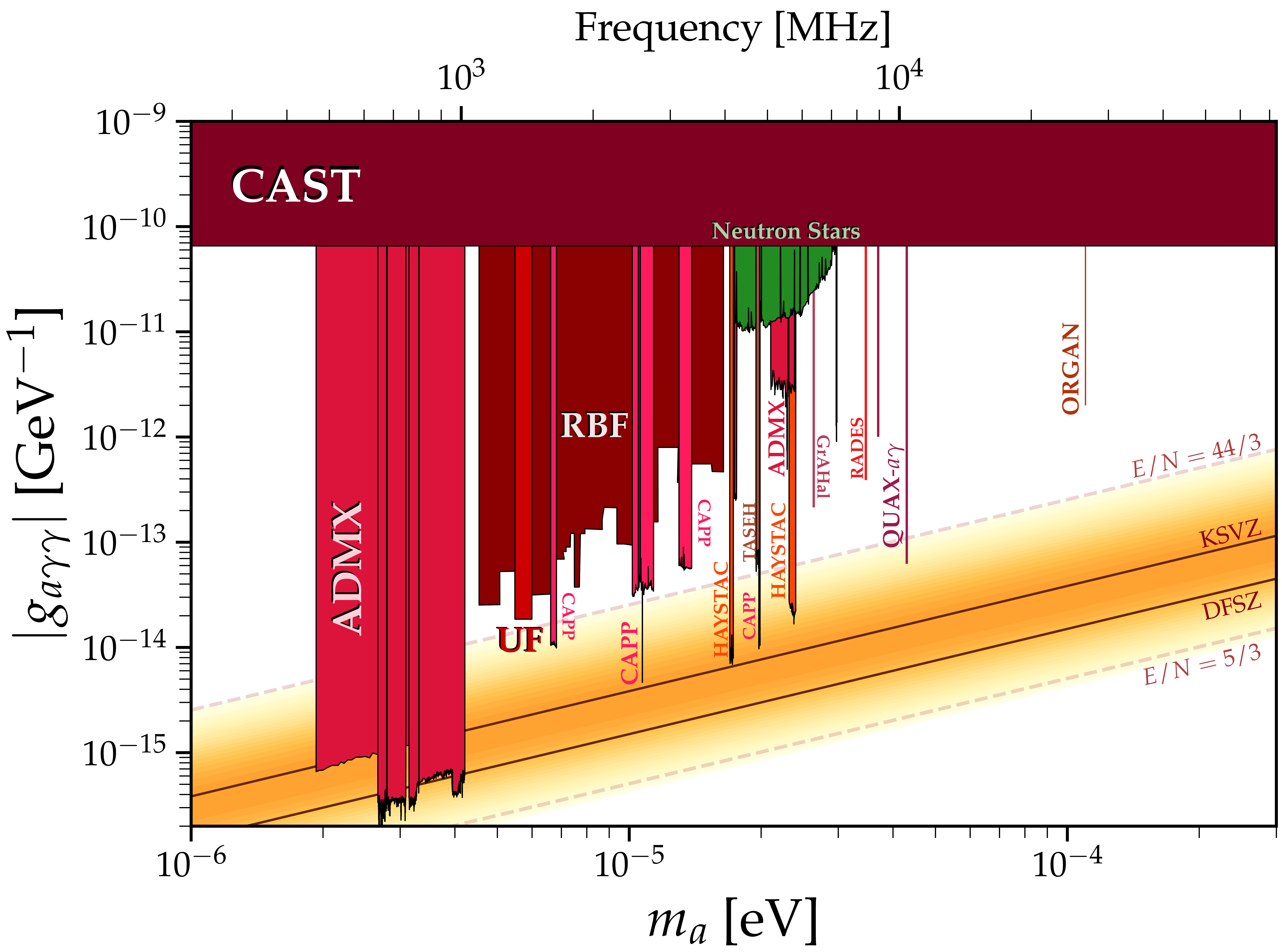
Axion searches in the lab

Axions: light pseudoscalar particles, a

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$= -\frac{1}{4} g_{a\gamma\gamma} a \boldsymbol{E}\cdot\boldsymbol{B}$$





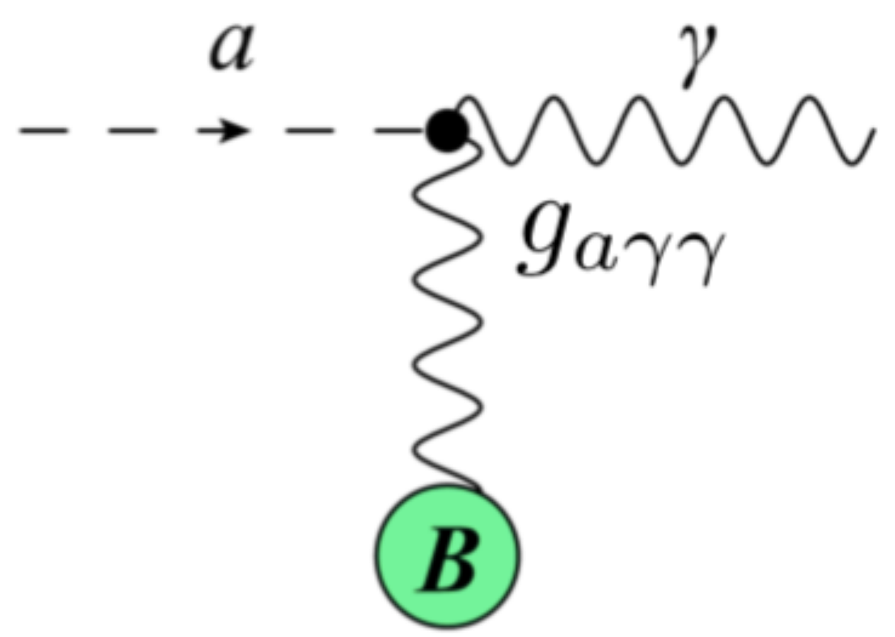


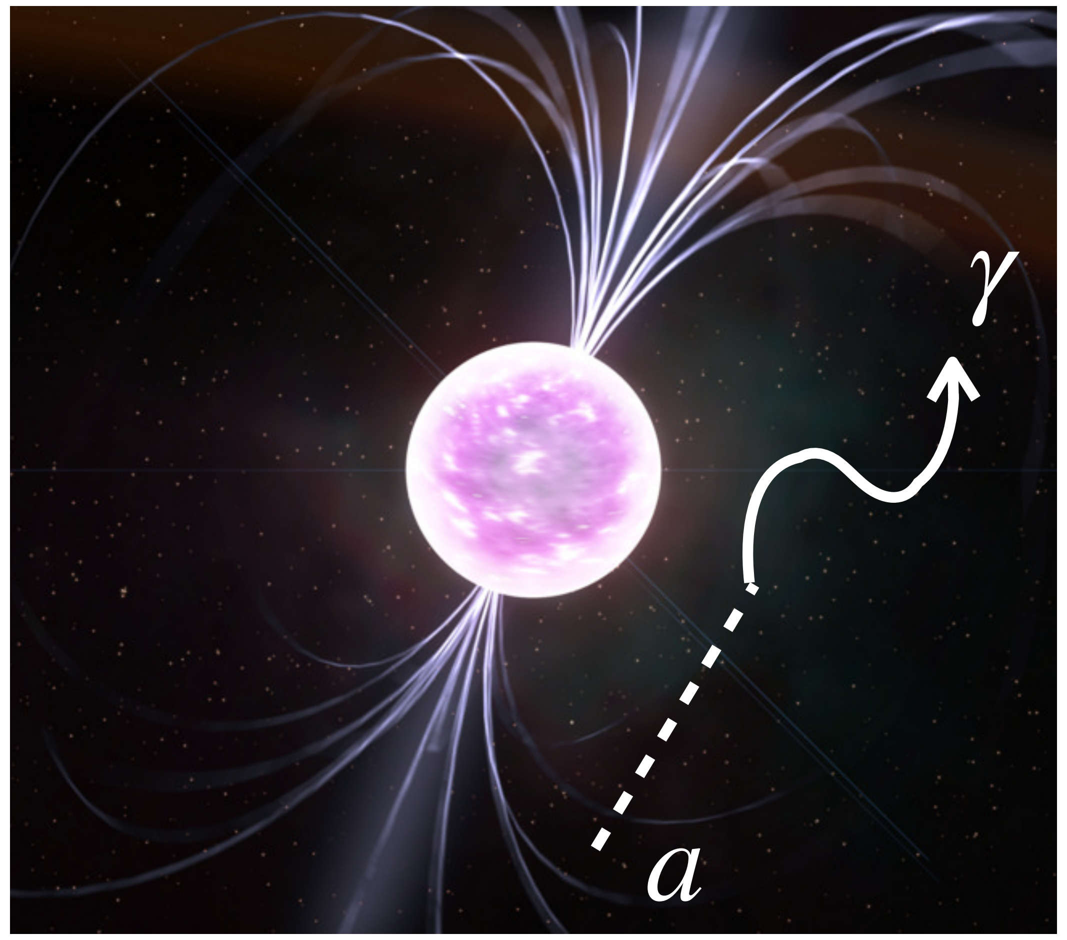
Credit: Ciaran O'Hare, AxionLimits

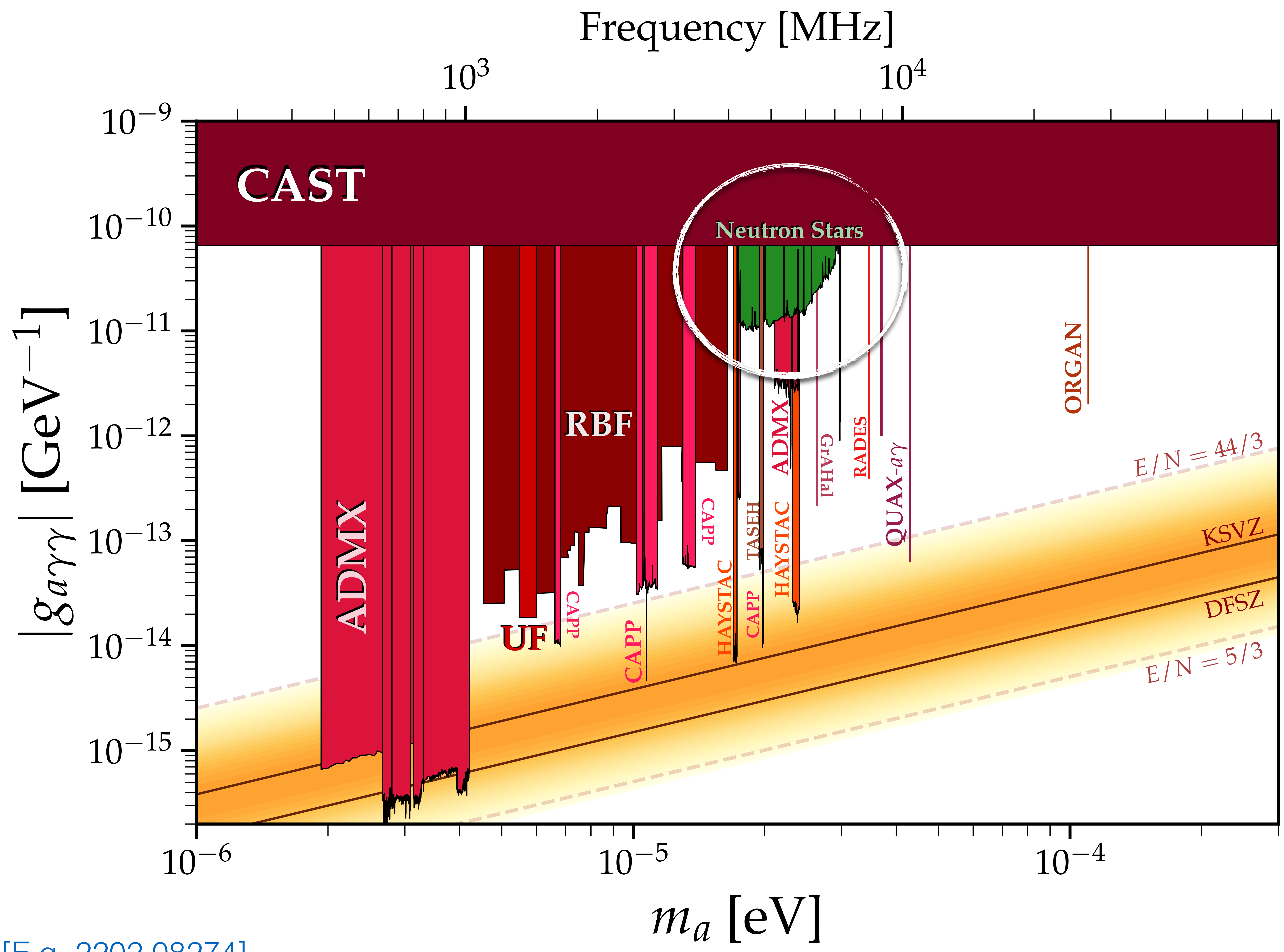
Axion searches and Neutron Stars

Axions: light pseudoscalar particles, a

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$= -\frac{1}{4} g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$







[E.g. 2202.08274]

Credit: Ciaran O'Hare, AxionLimits

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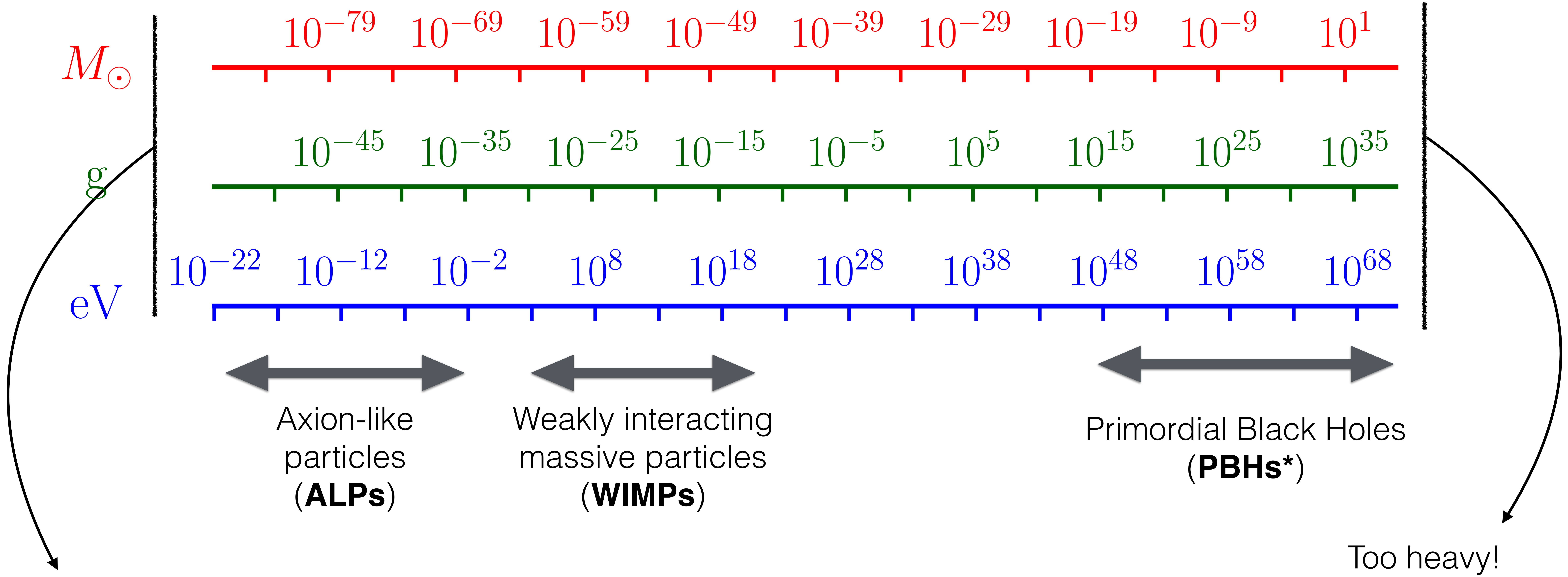
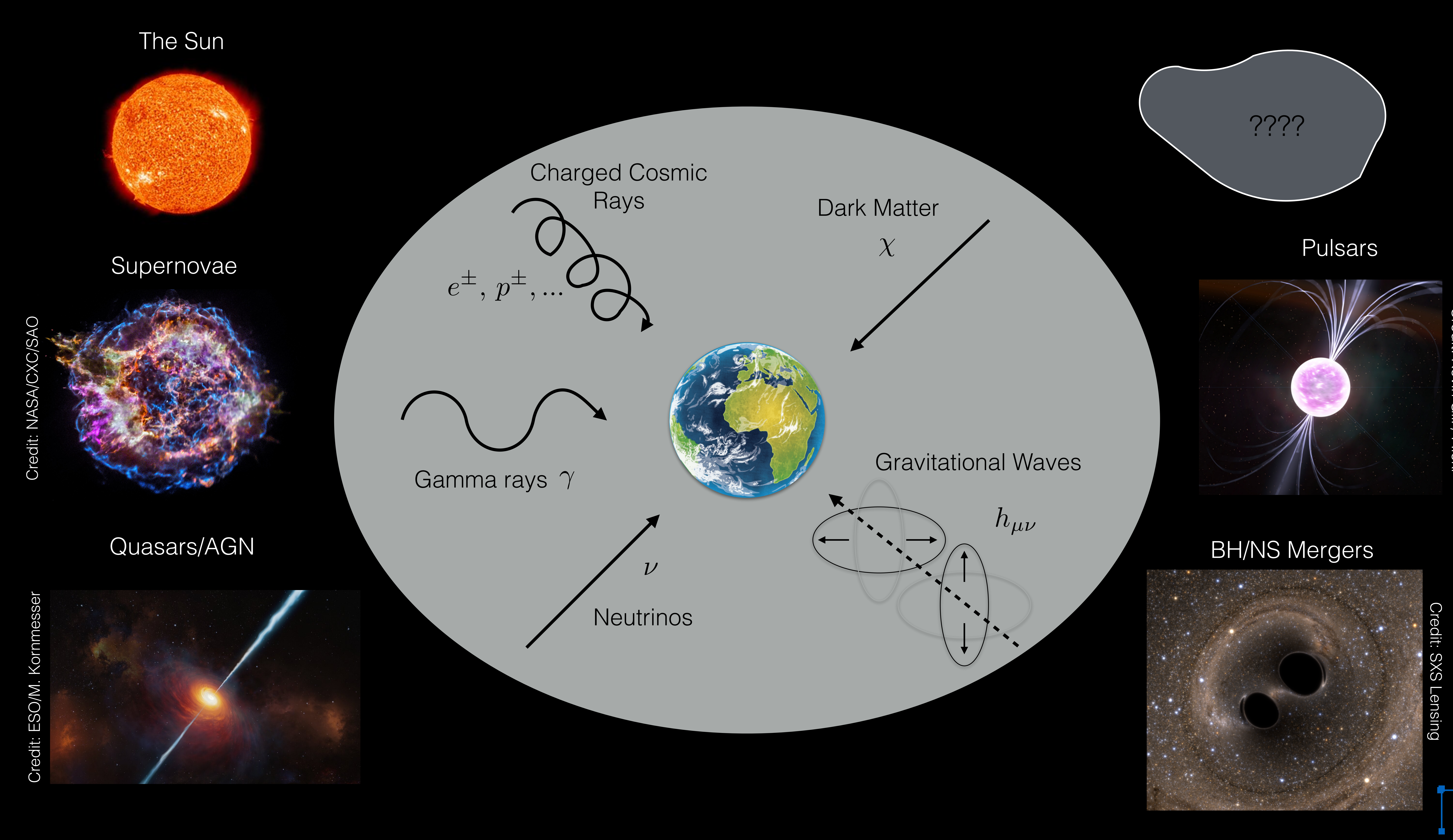


Too light!
Has wave-like properties on galactic scales!

Too heavy!
DM mass comparable to galactic masses!

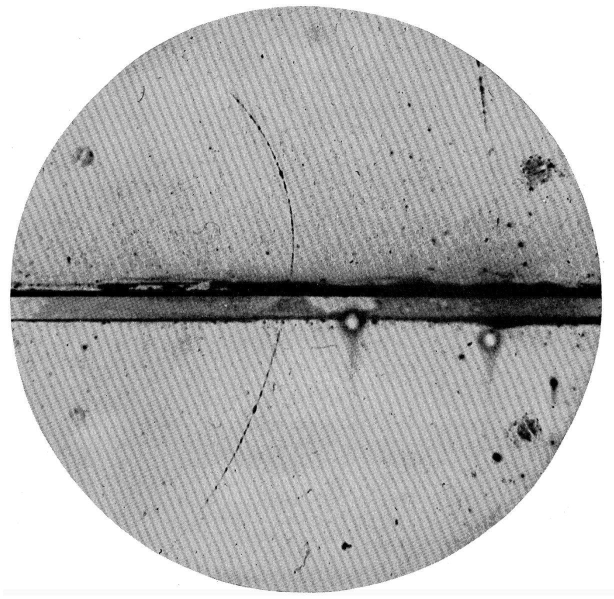
*See additional slides…

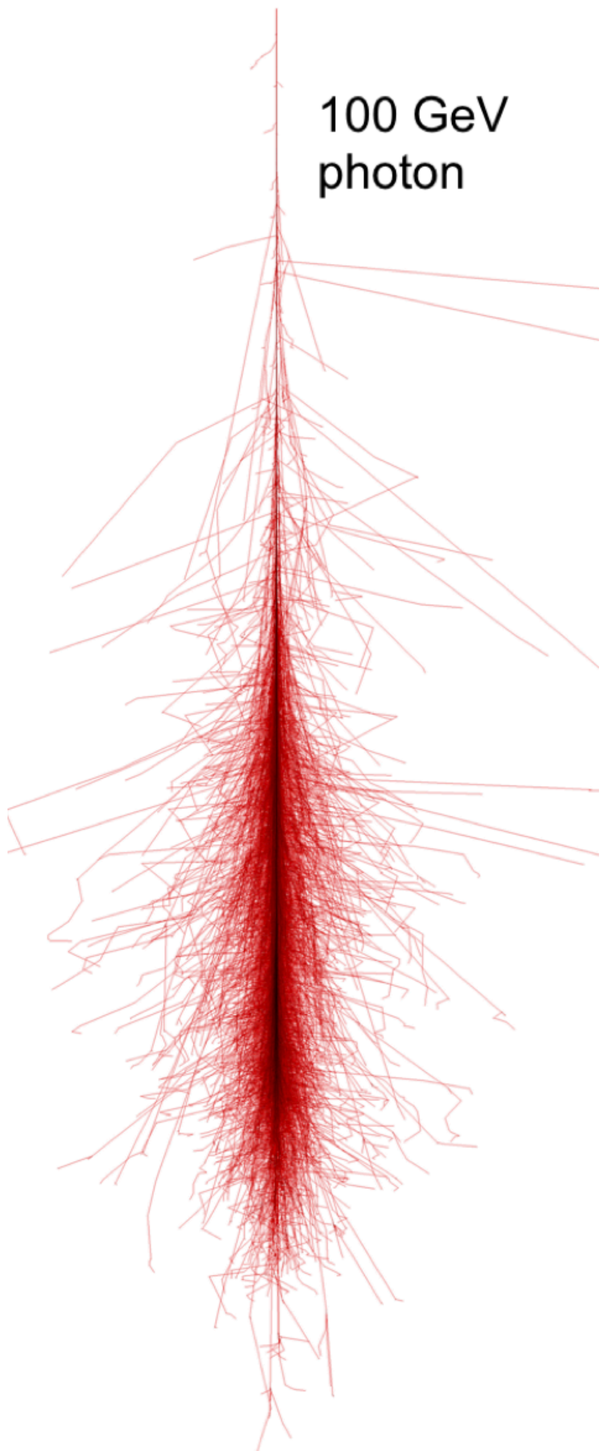

The Sun
Supernovae
Credit: NASA/CXC/SAO
Quasars/AGN
Credit: ESO/M. Kornmesser
Charged Cosmic Rays
$e^{\pm}, p^{\pm}, \ldots$
Dark Matter
χ
Gamma rays γ
Gravitational Waves
$h_{\mu\nu}$
ν
Neutrinos
????
Pulsars
Credit: Kevin Gill / Flickr
BH/NS Mergers
Credit: SXS Lensing

Timeline

1912: Hess discovers cosmic rays

1933: Anderson discovers the positron in Cosmic Ray tracks

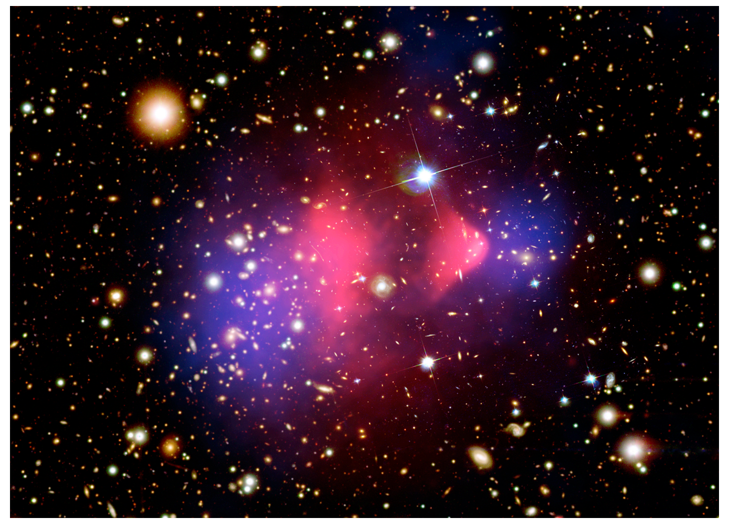




1939: Auger and collaborators demonstrate the existence of Cosmic Ray *air showers*

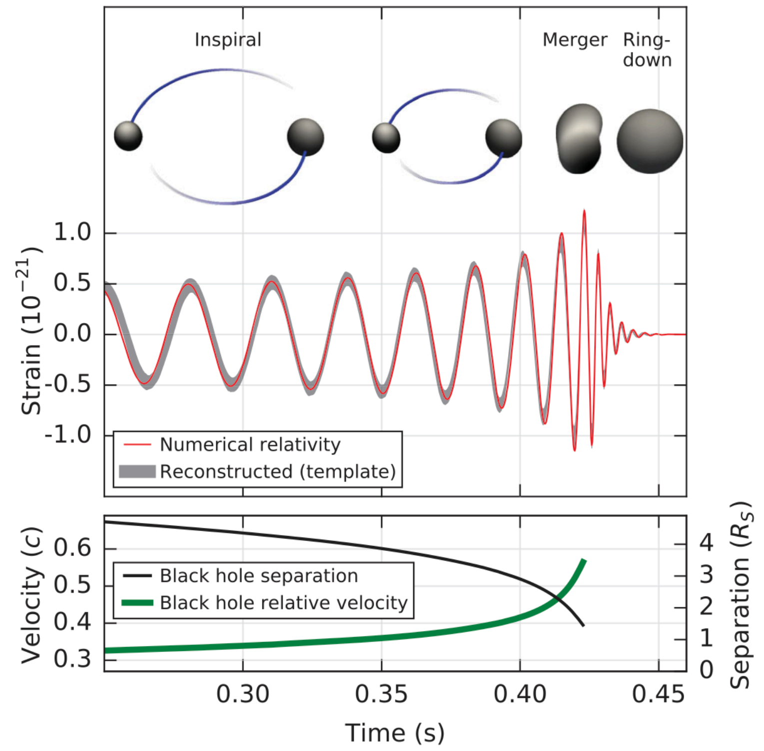
1960s: Homestake Experiment detects Solar Neutrinos (and the Solar Neutrino Problem)

1970s: The “Dark Matter” paradigm coalesces



2010: Discovery of the Fermi gamma-ray bubbles and Galactic centre excess

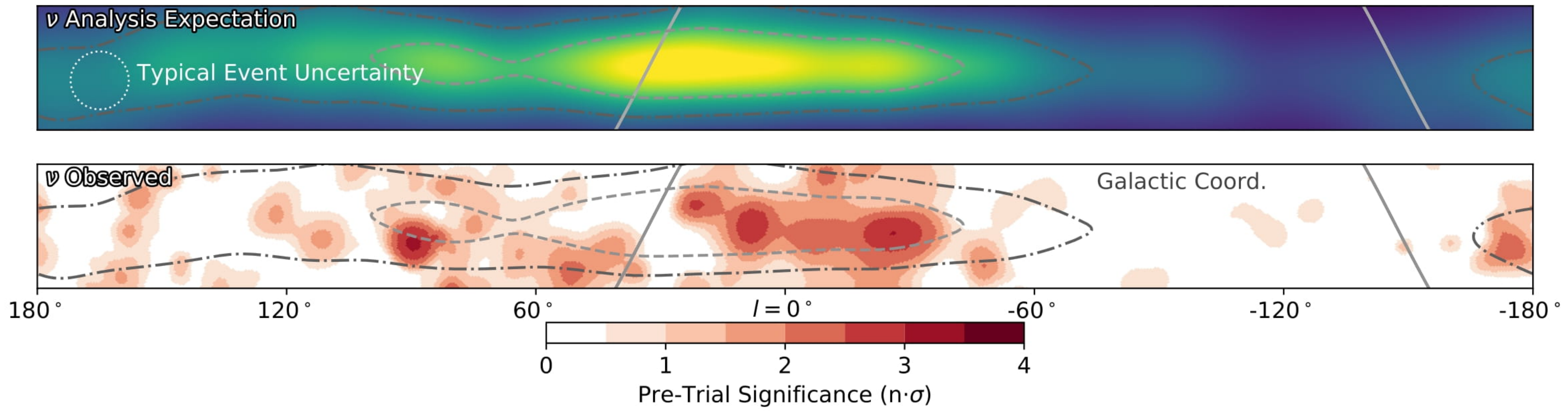
2015: GW150914 - First direct observation of GWs from Black Hole Binary Mergers



2017: TXS 0506+056 - First multimessenger detection of a blazar (neutrinos + gamma rays)

2017: GW170817 - First direct observation of GWs from Neutron Star Mergers by LVK

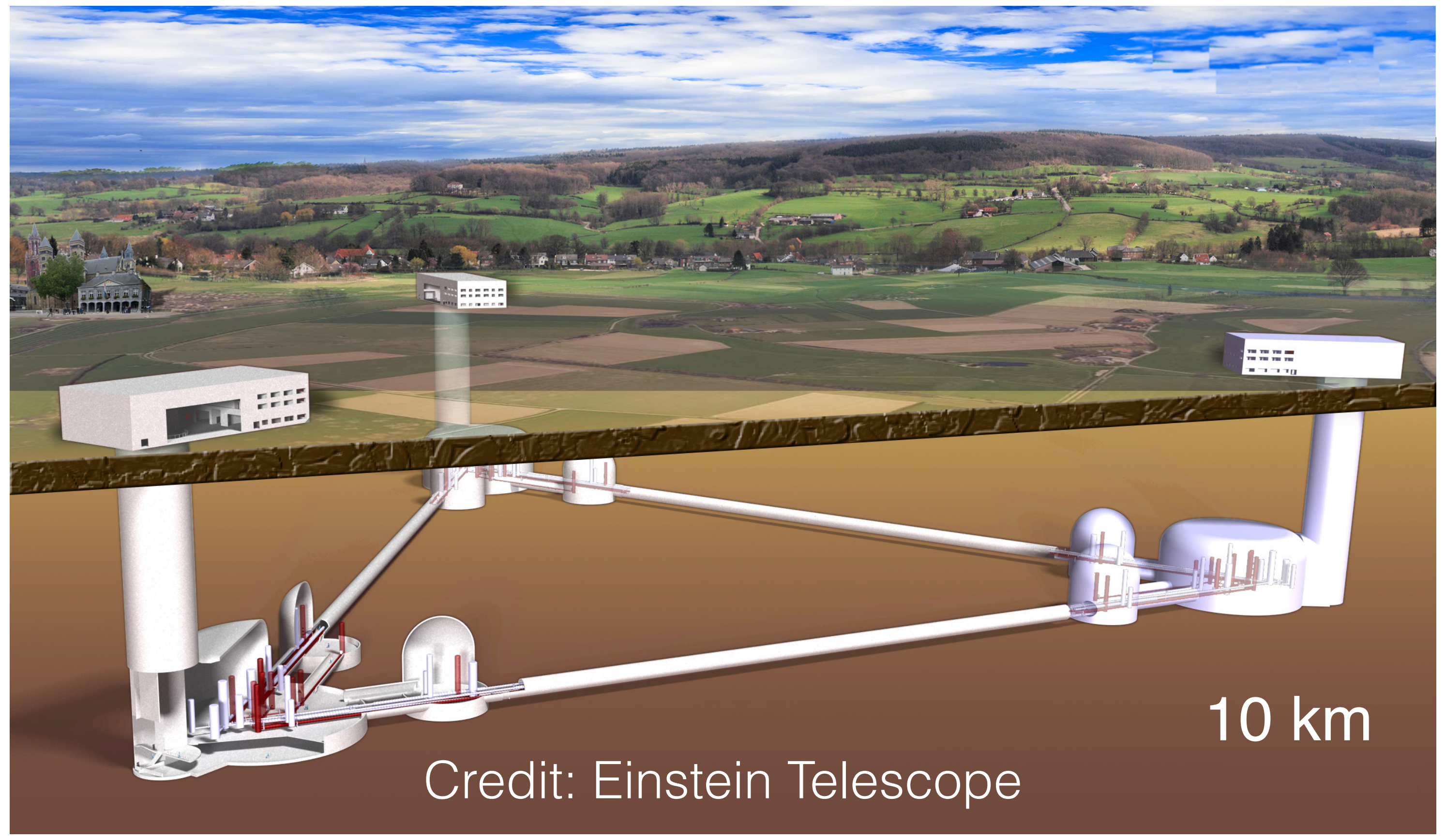
2023: Detection of Milky Way in Neutrinos by IceCube



2023: NANOgrav & IPTA detect nHz Gravitational Waves

New Views into the Universe

The Cherenkov Telescope Array (CTA) will observe very **high energy gamma rays** with very high energy resolutions
https://www.cta-observatory.org

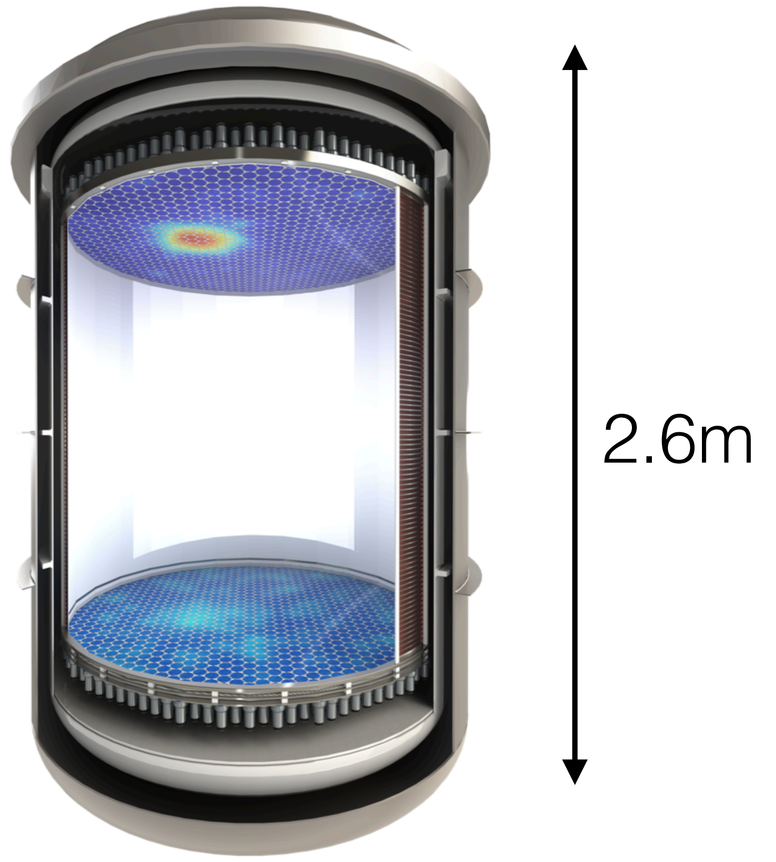


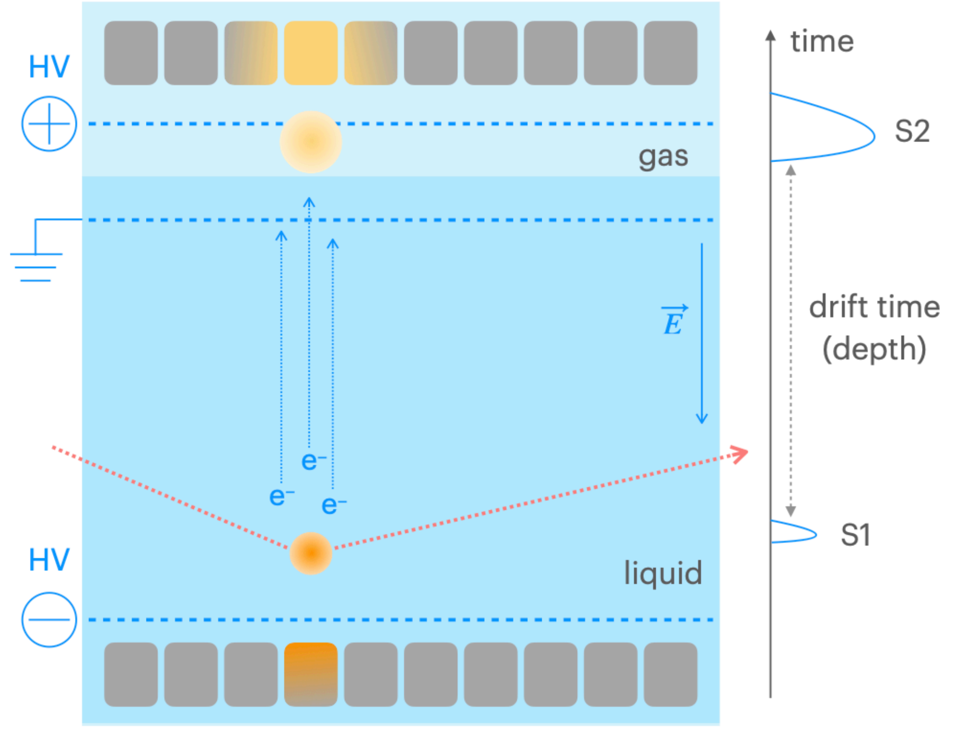
Planned Earth-based GW observatories such as Einstein Telescope will allow us to see every **merging stellar-mass BH** in the Universe

1902.09485

Dark Matter experiments like DARWIN/XLZD will continue to search for **WIMP Dark Matter** with unprecedented sensitivity

https://darwin.physik.uzh.ch/, 2404.19524





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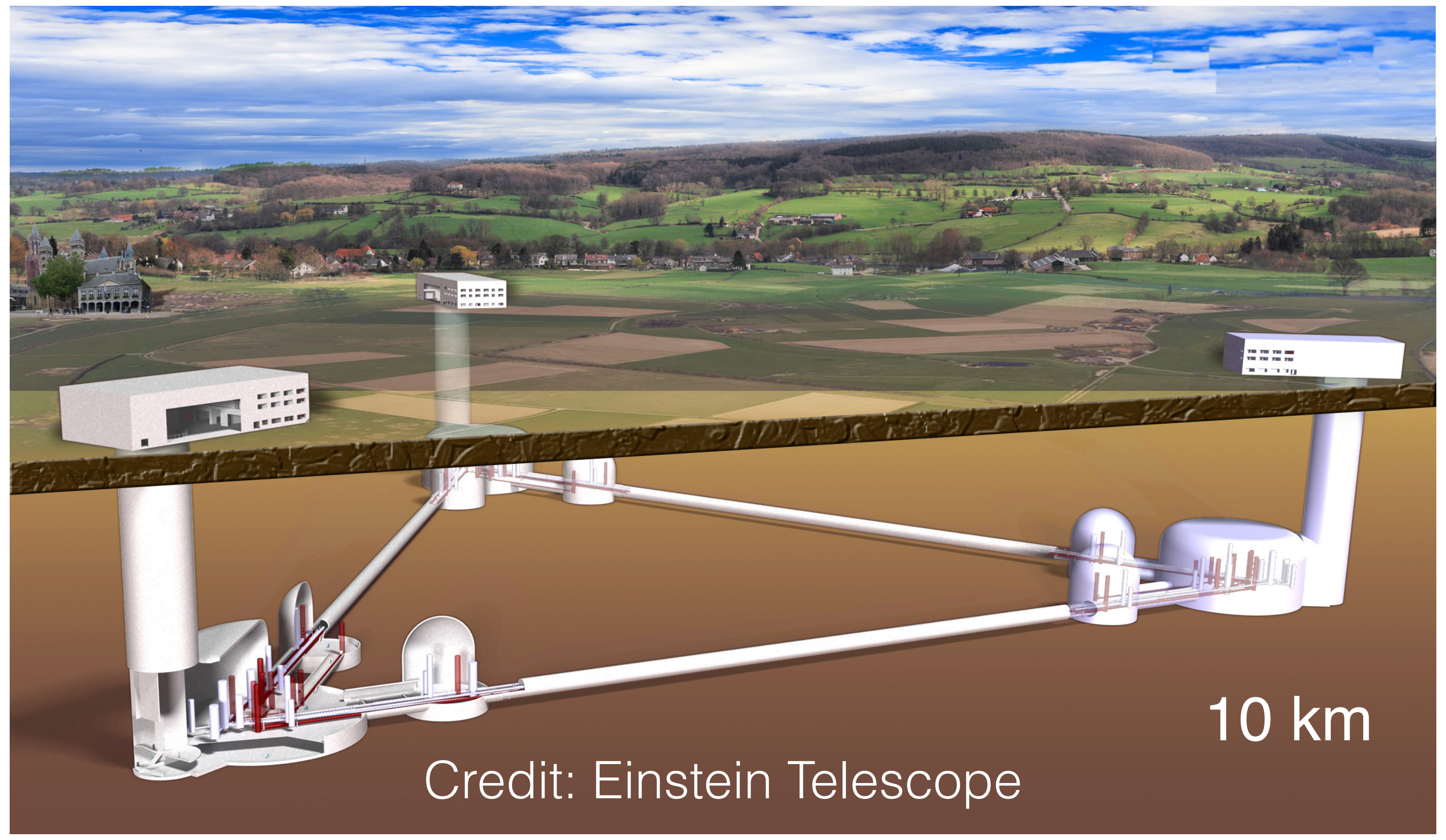

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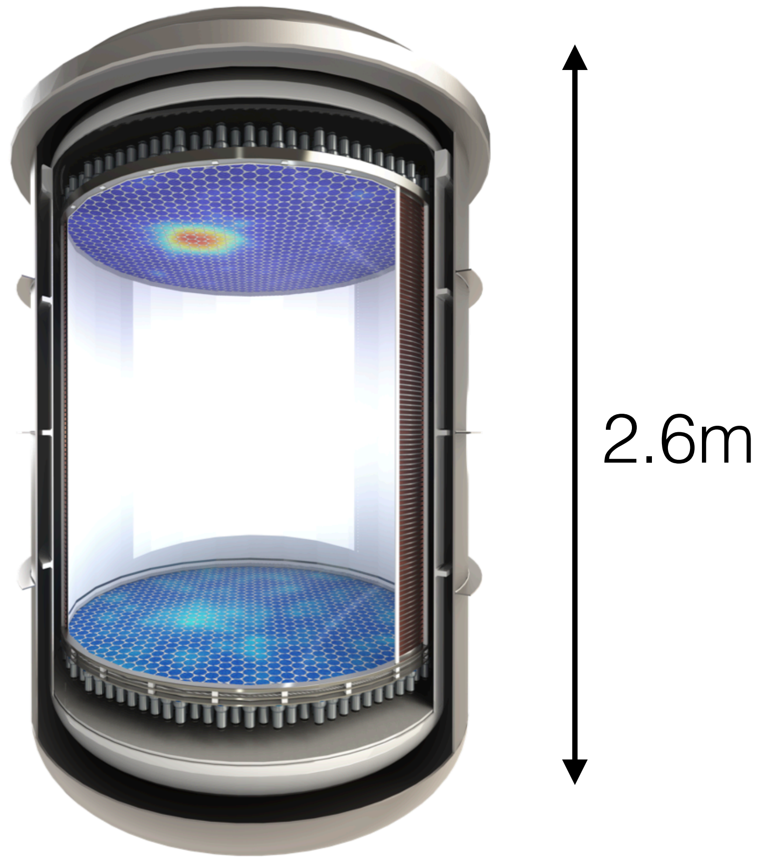
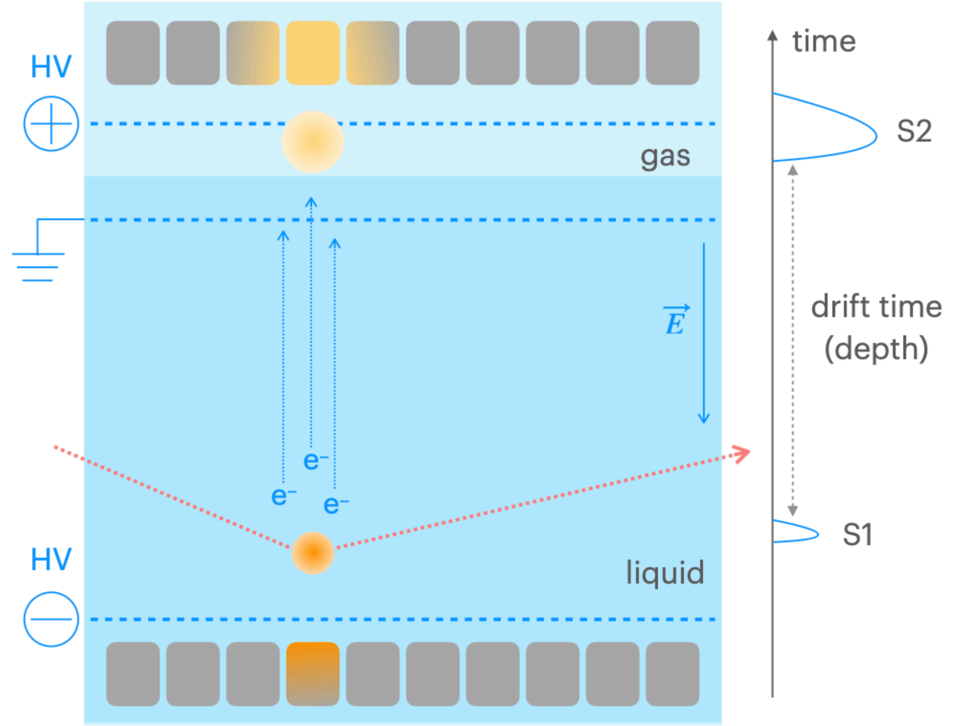
1902.09485





Dark Matter experiments like DARWIN/XLZD will continue to search for **WIMP Dark Matter** with unprecedented sensitivity

https://darwin.physik.uzh.ch/, 2404.19524

…looking forward to many more unexpected discoveries!

Additional Slides

Reading Suggestions

Slides here: bradkav.net/talks

Astroparticle Physics: Theory and Phenomenology, Günter Sigl, Atlantis Press Paris (2017)

Lectures on Astroparticle Physics, Günter Sigl, hep-ph/0408165 (2004)

Introduction to Cosmic Rays, Peter Biermann & Günter Sigl, astro-ph/0202425 (2002)

An Introduction to Particle Dark Matter, Stefano Profumo, Leonardo Giani & Oliver F. Piattella, arXiv:1910.05610 (2019)

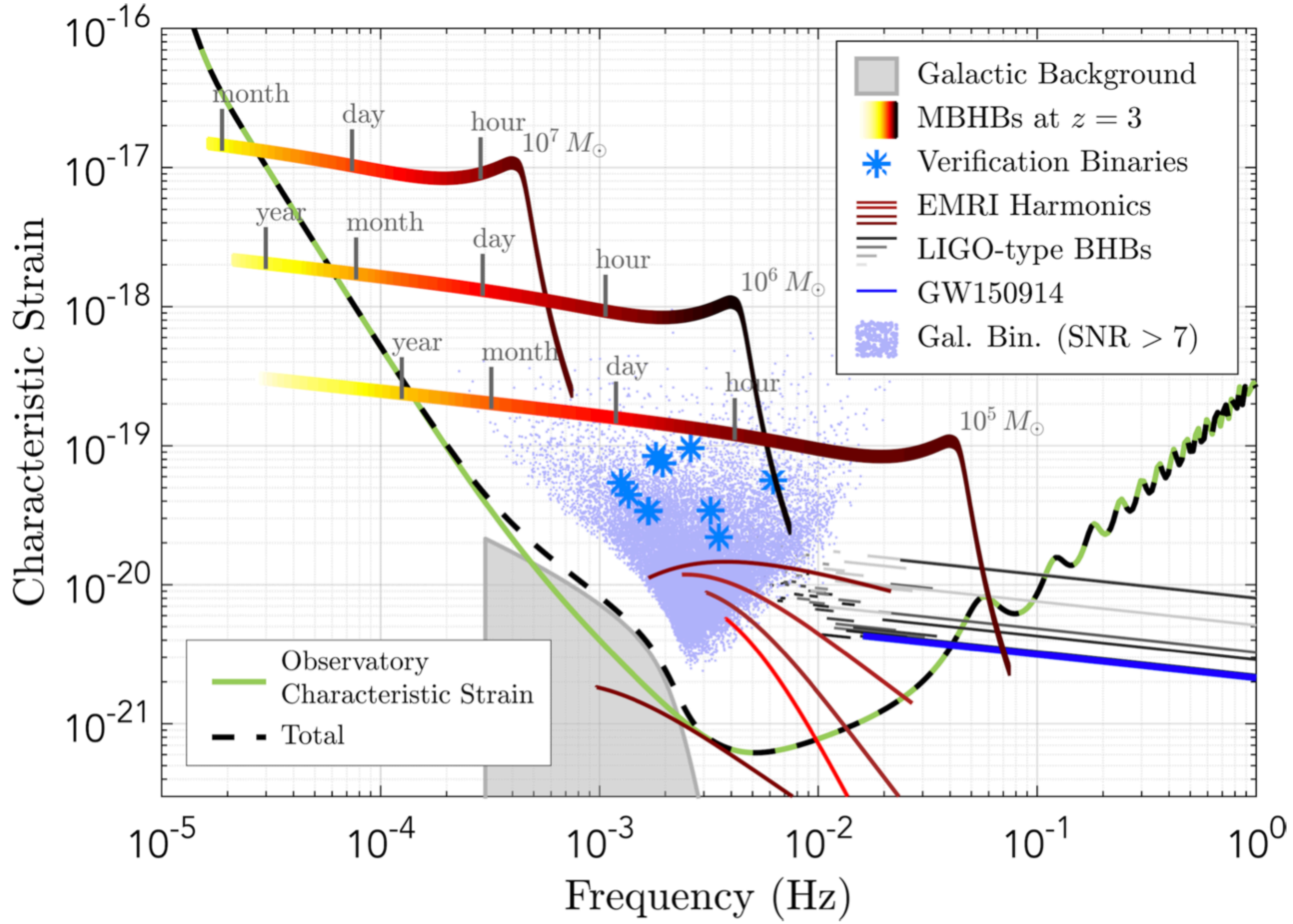
The basic physics of the binary black hole merger GW150914, LIGO & Virgo Collaborations, arXiv:1608.01940 (2016)

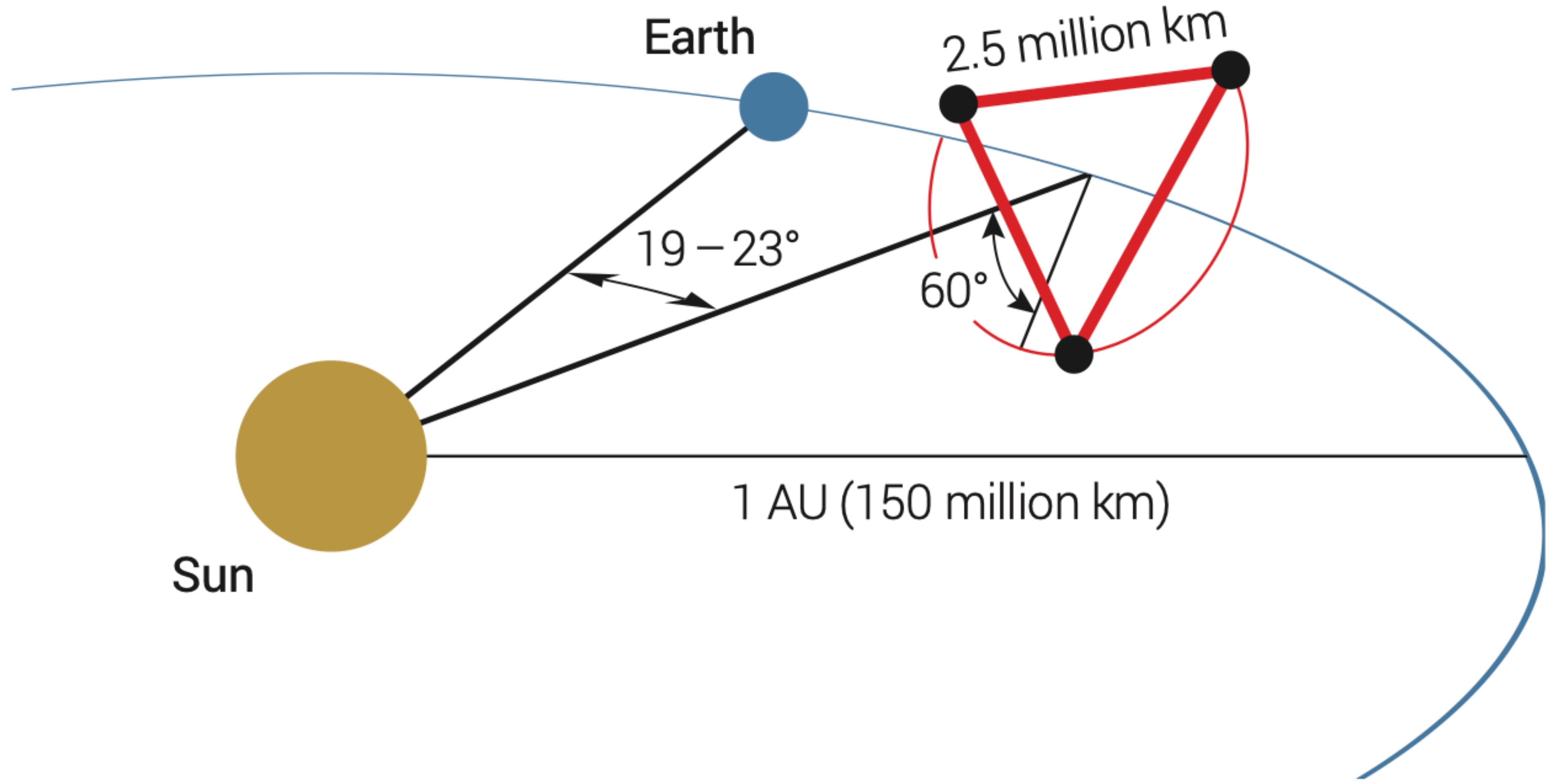
Check arXiv, and summaries on popular blogs like Sunny Vagnozzi's HisDarkCMB or Mauricio Bustamante's Daily arXiv Picks!

Feel free to email me at kavanagh@ifca.unican.es!

LISA - GWs in space!

Laser Interferometer Space Antenna
(Planned for the 2030s)



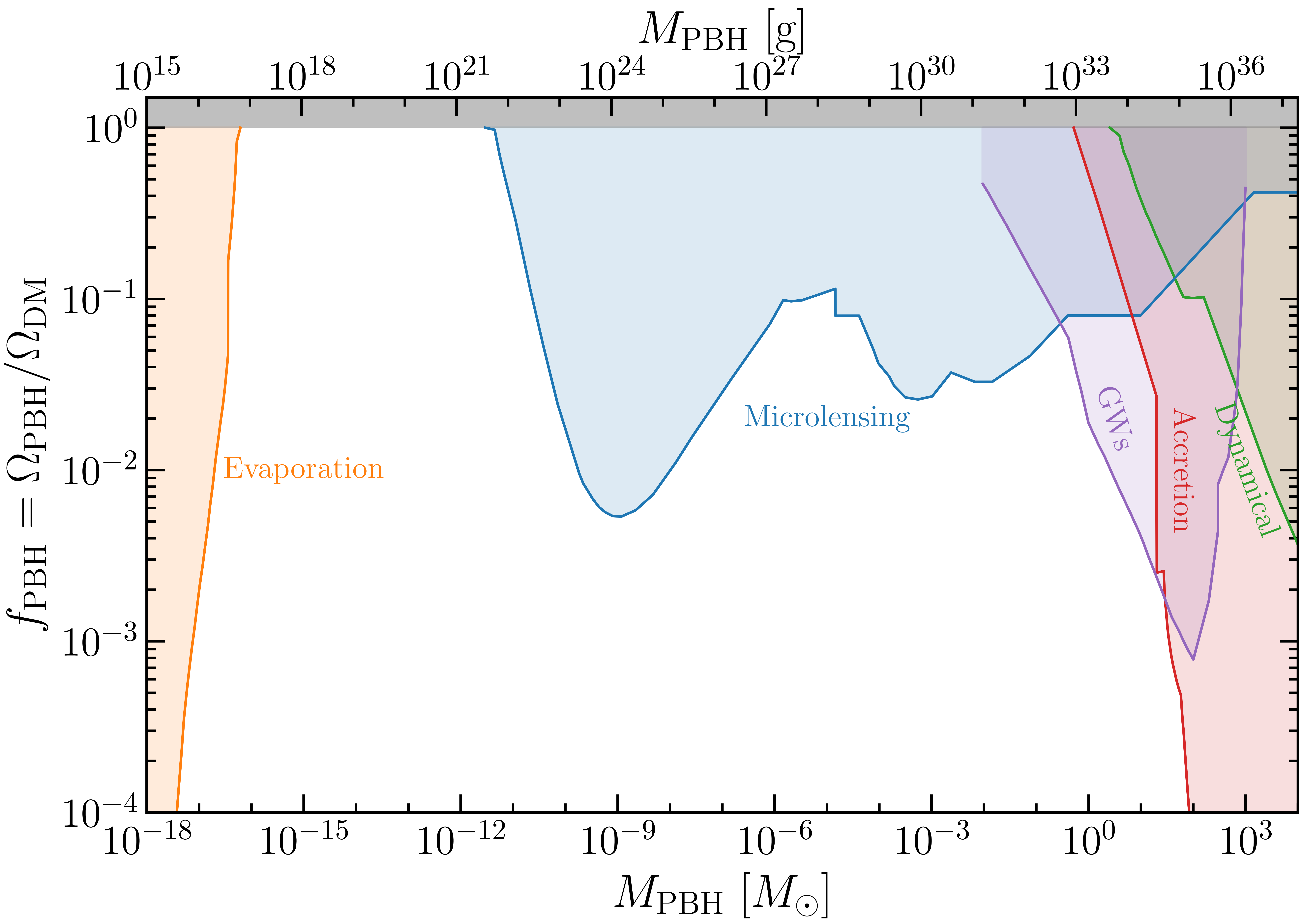


1907.06482

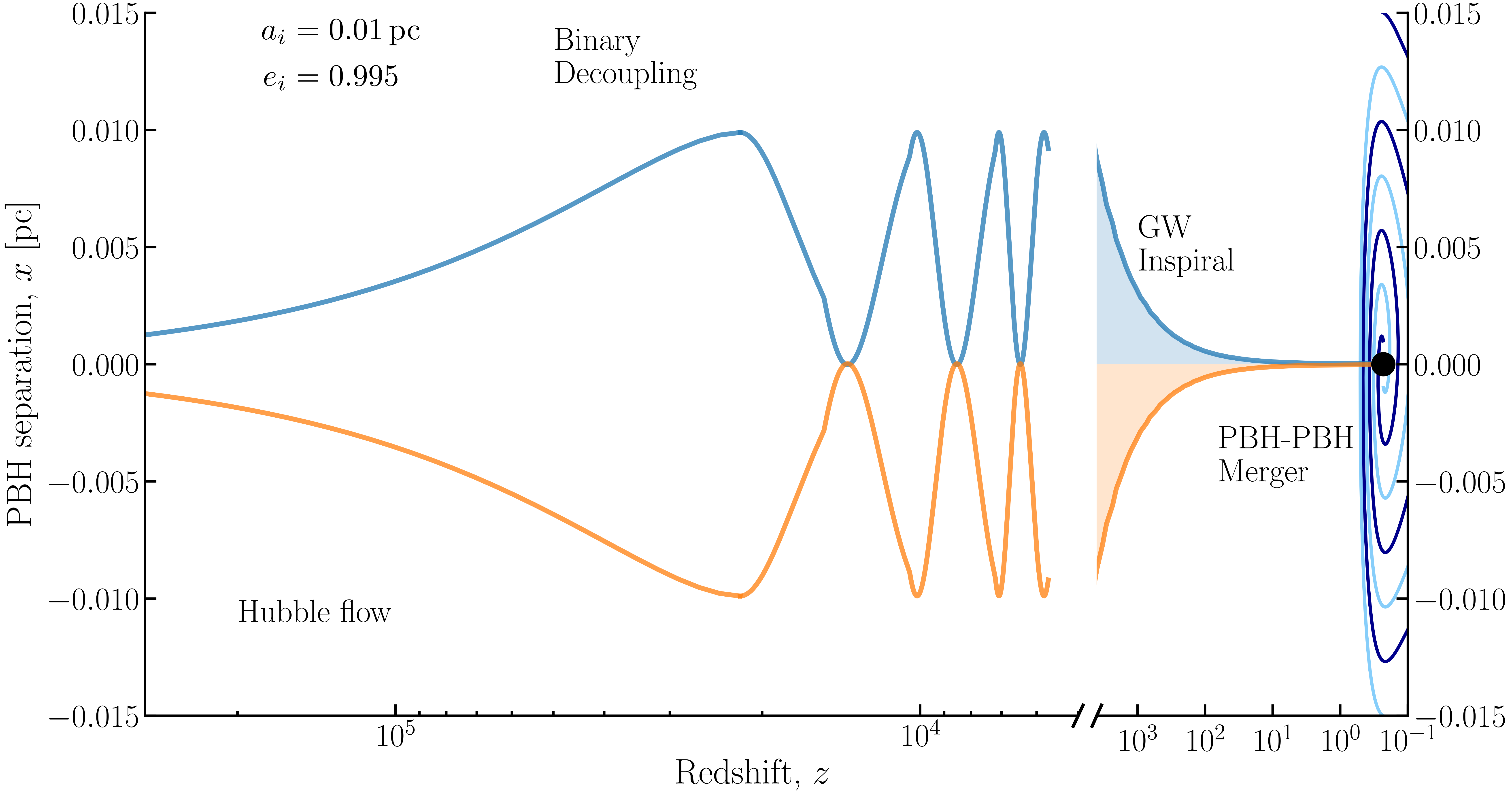
Primordial Black Holes

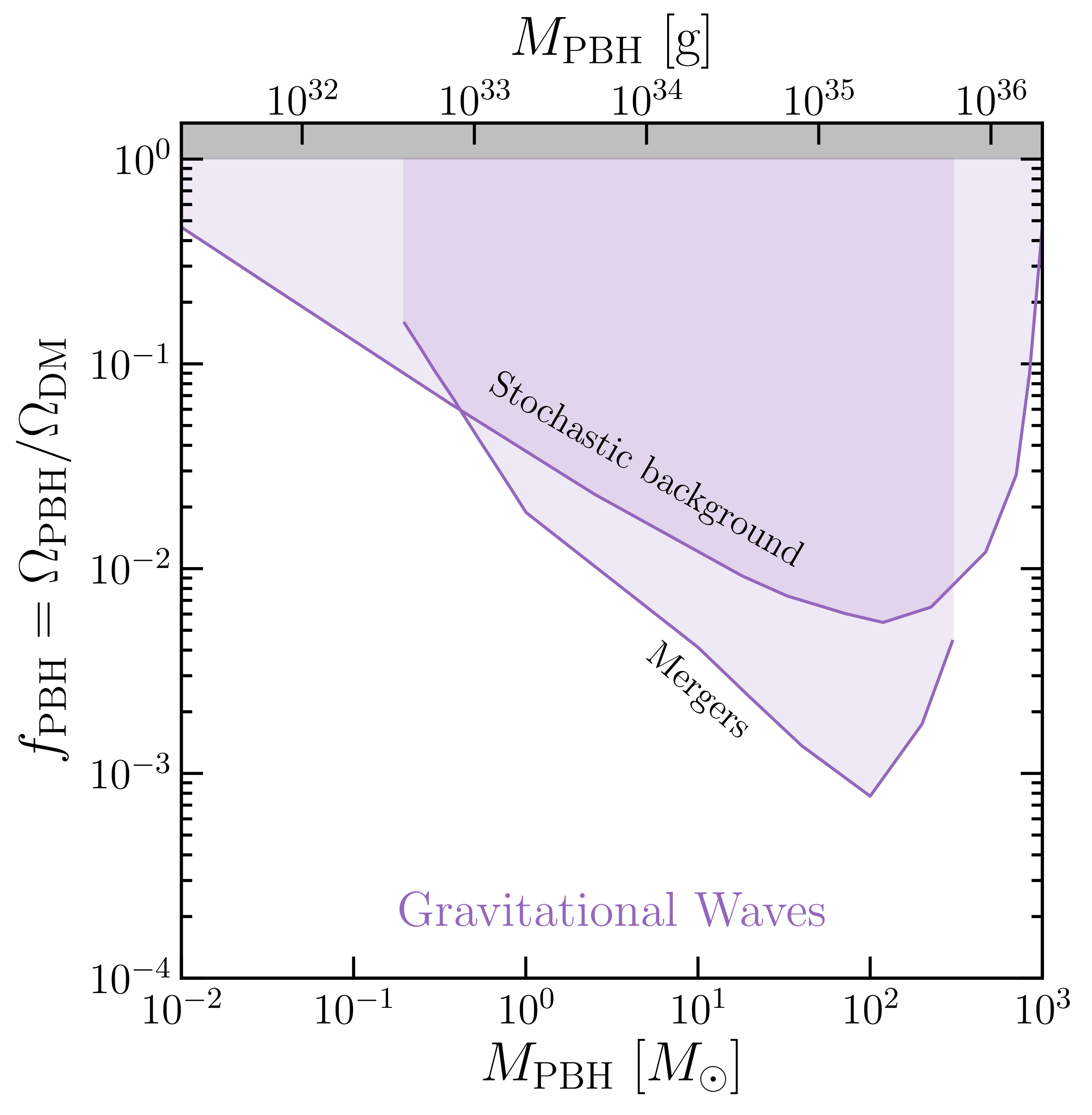
2007.10722

Bounds online

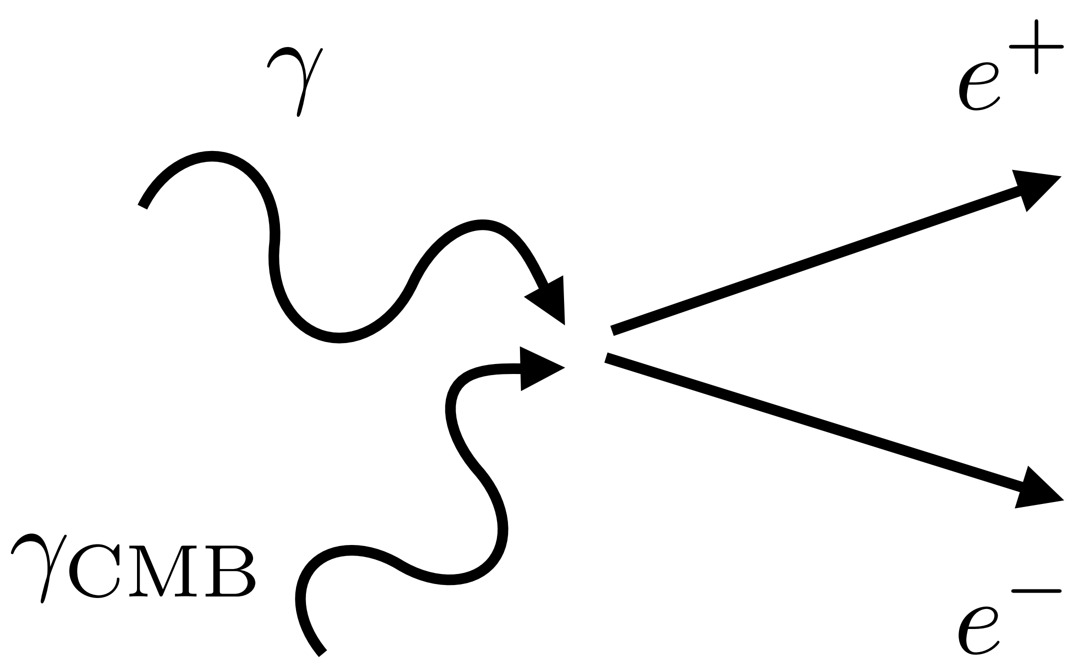


PBHs and Gravitational Waves

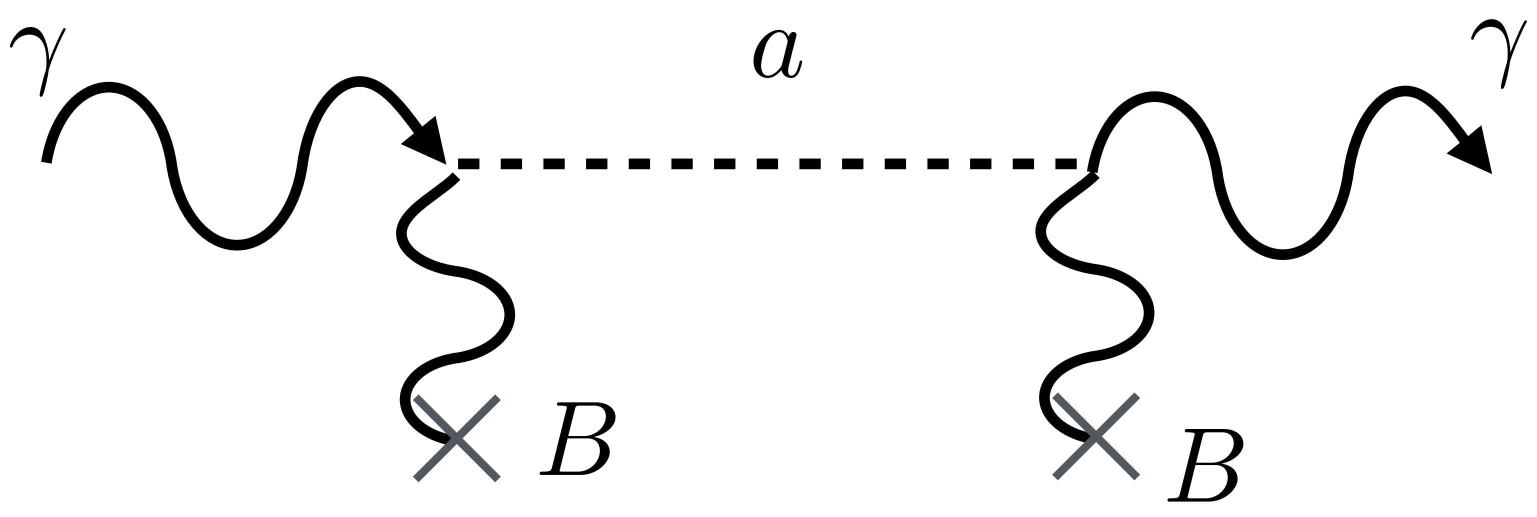


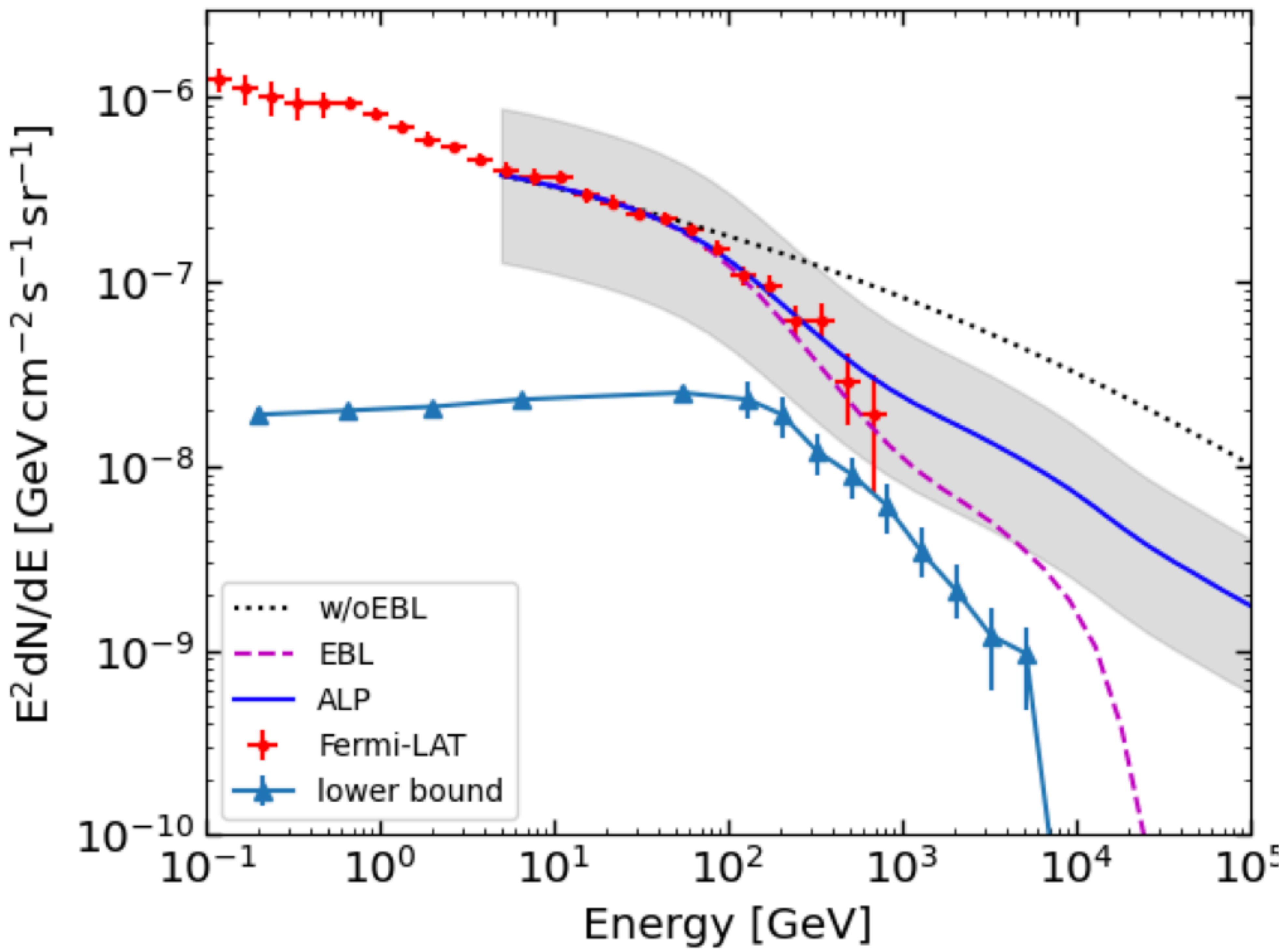


Gamma-ray transparency and axions

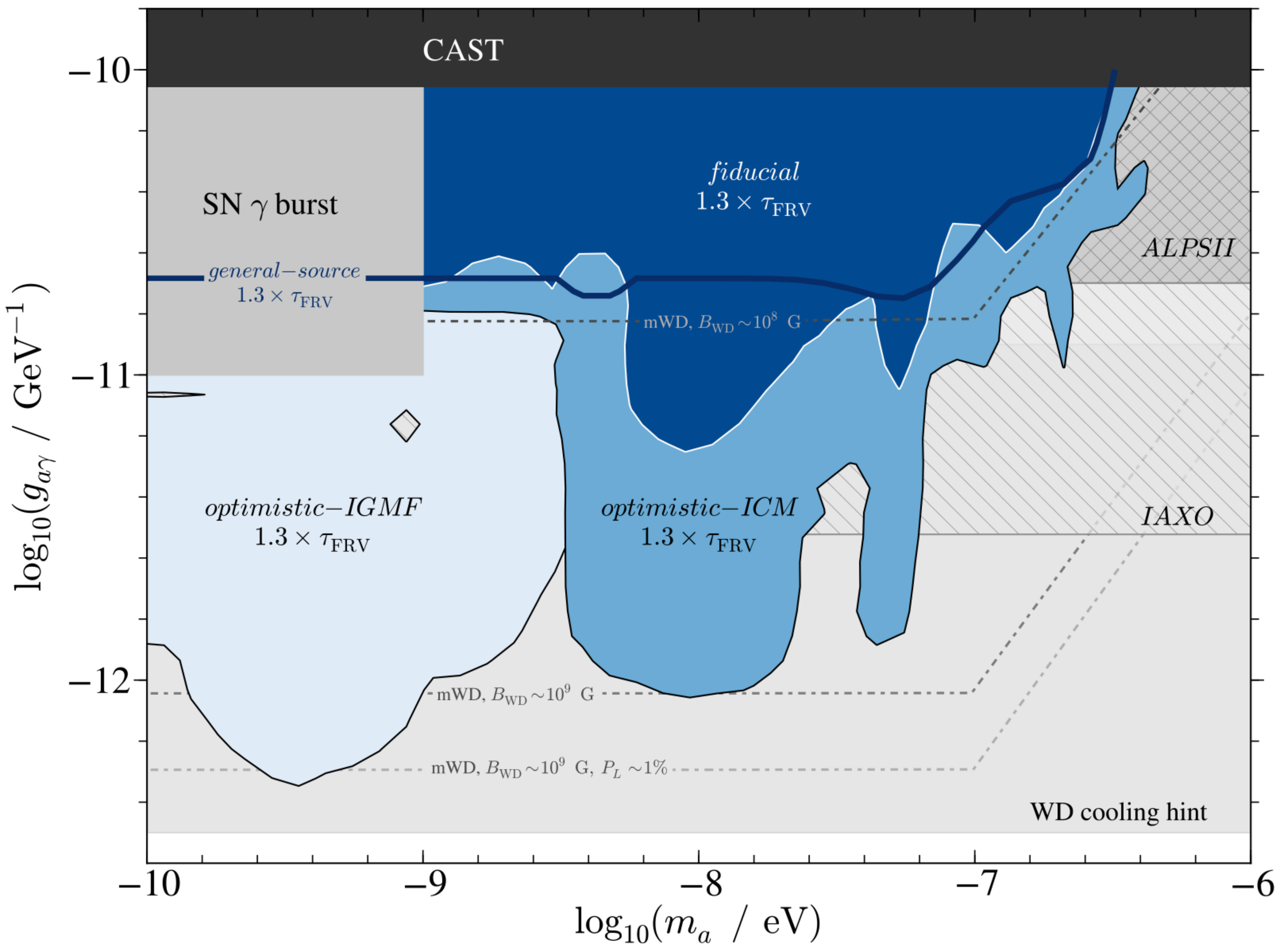


Axion-like particle:



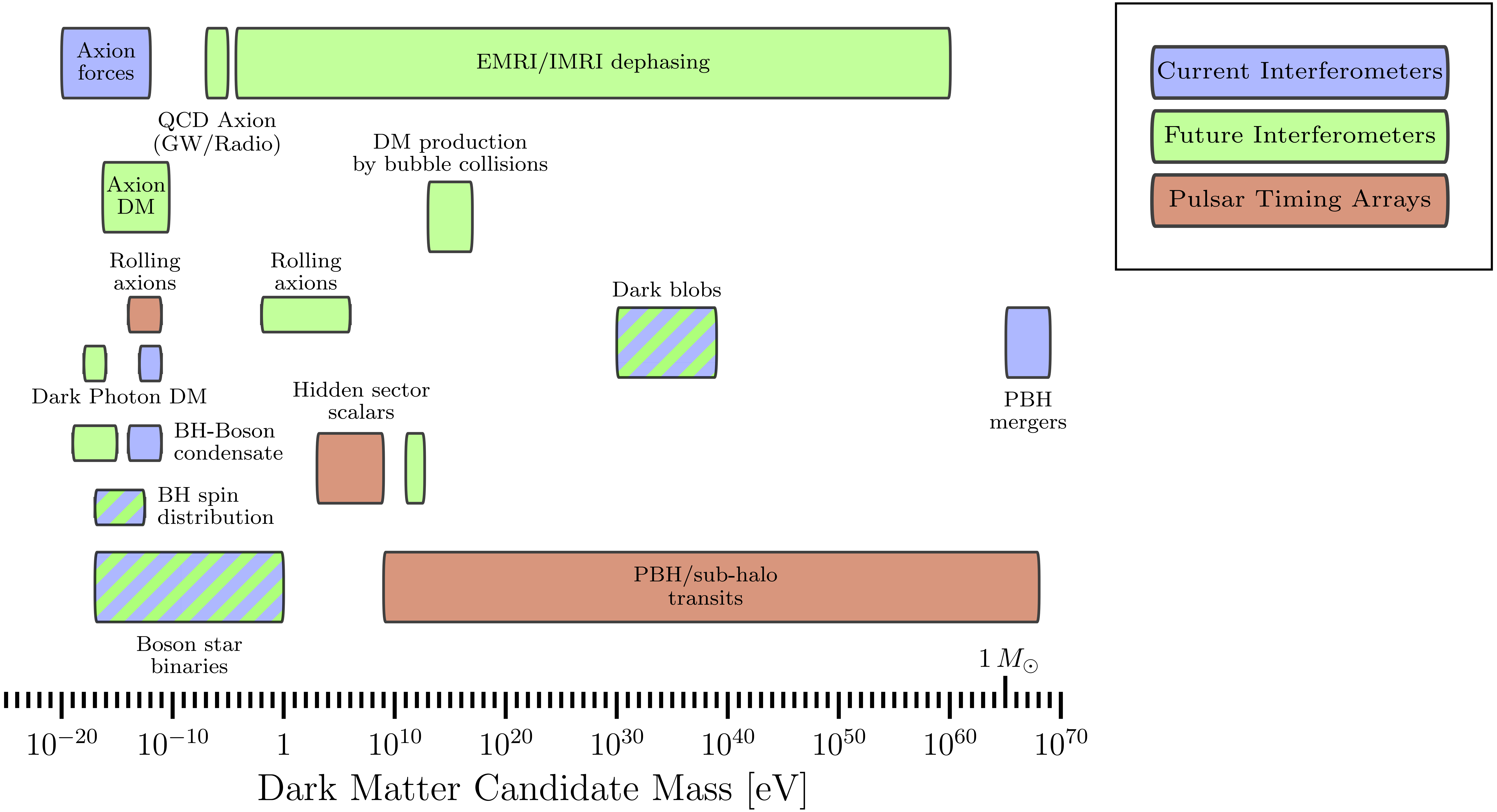


[2012.15513](2012.15513)



[1302.1208](1302.1208)

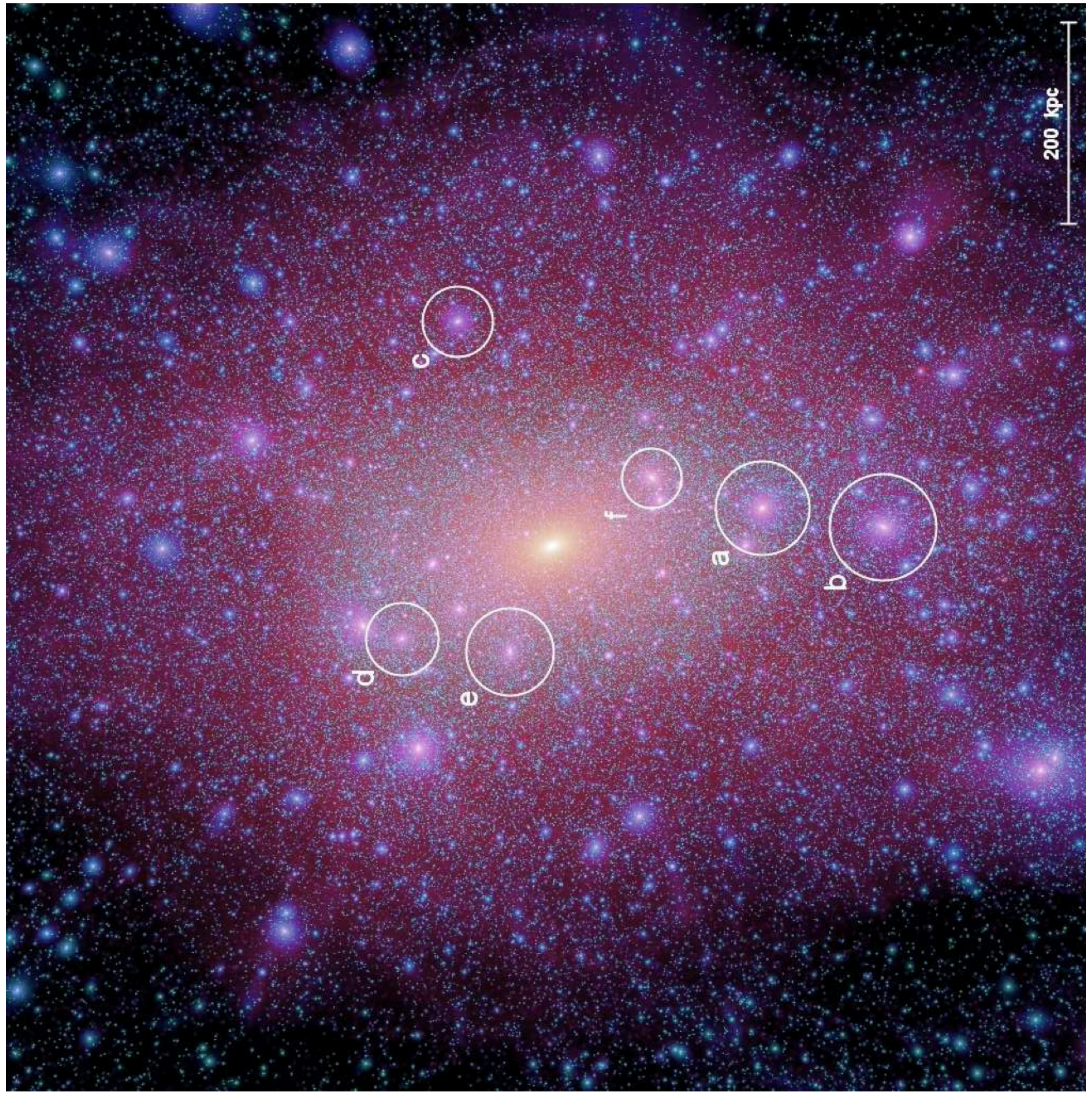
Gravitational Wave probes of DM



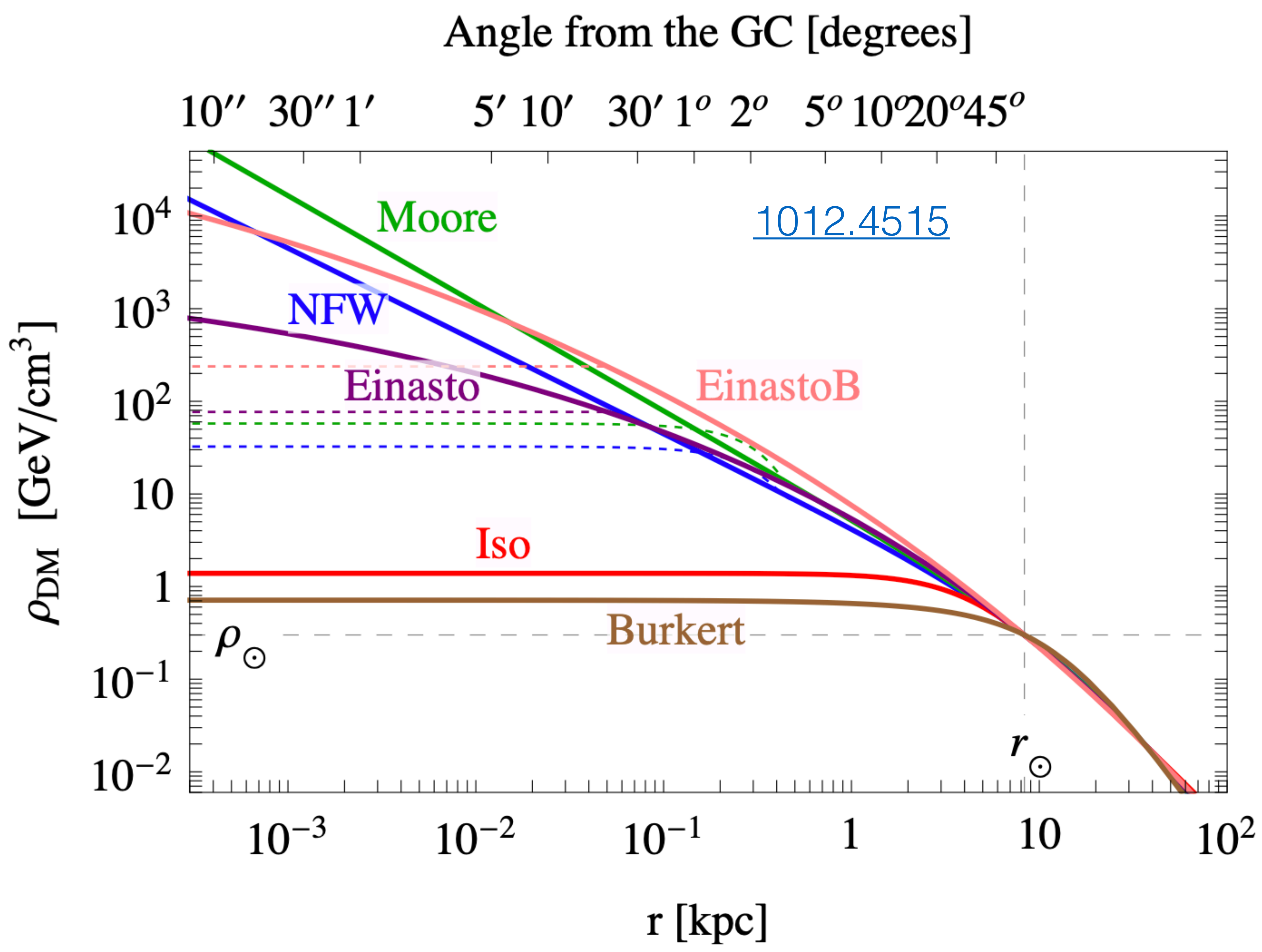
For more information about probing Dark Matter with Gravitational Waves, see 1907.10610

Dark Matter in Galaxies (2)

Simulations point to Dark Matter halos with cuspy NFW density profiles:



Aquarius simulation - 0809.0898

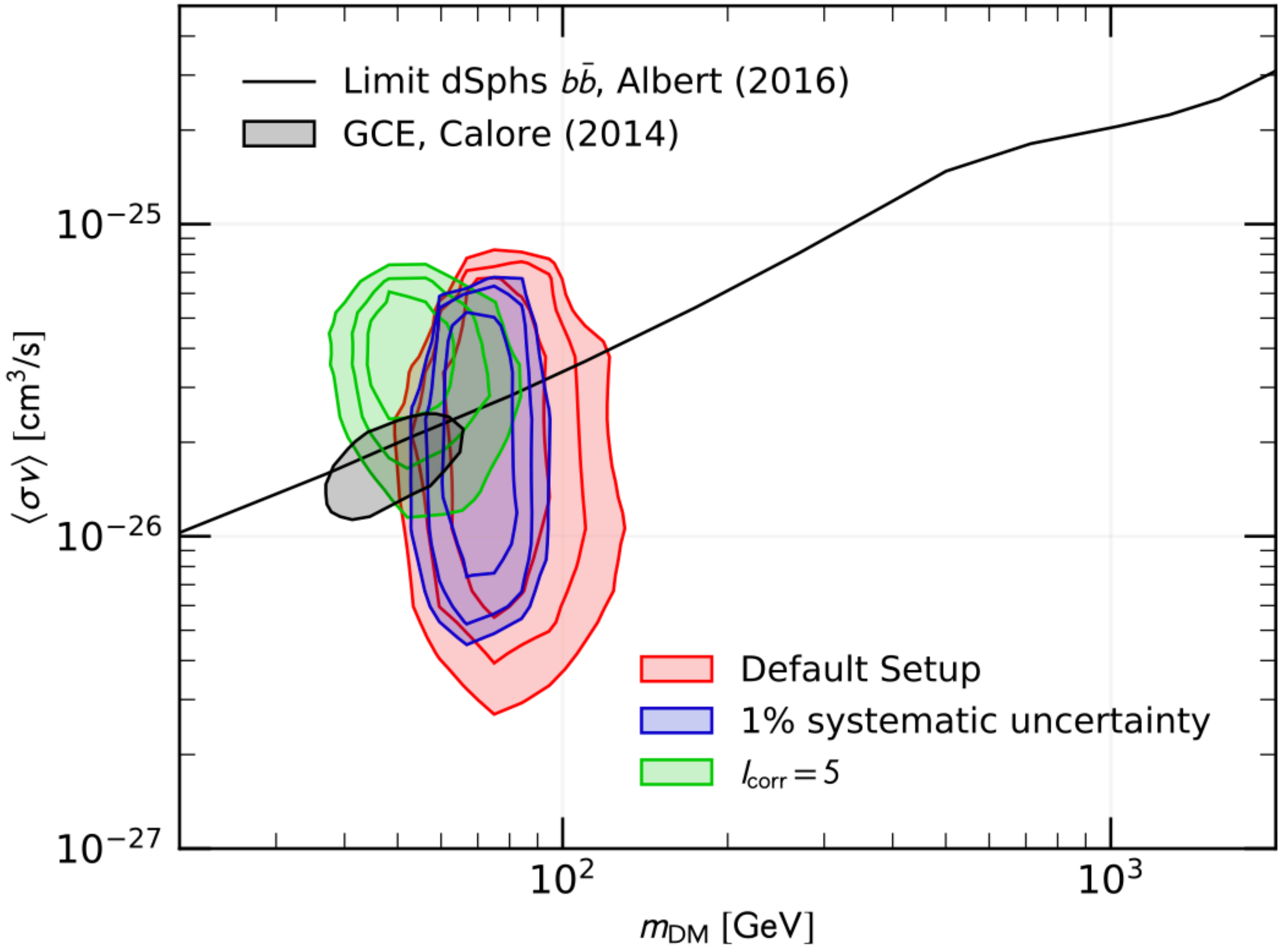


DM density at Earth: $\rho_\chi \sim 5 \times 10^{-25}\ \mathrm{g/cm^3}$

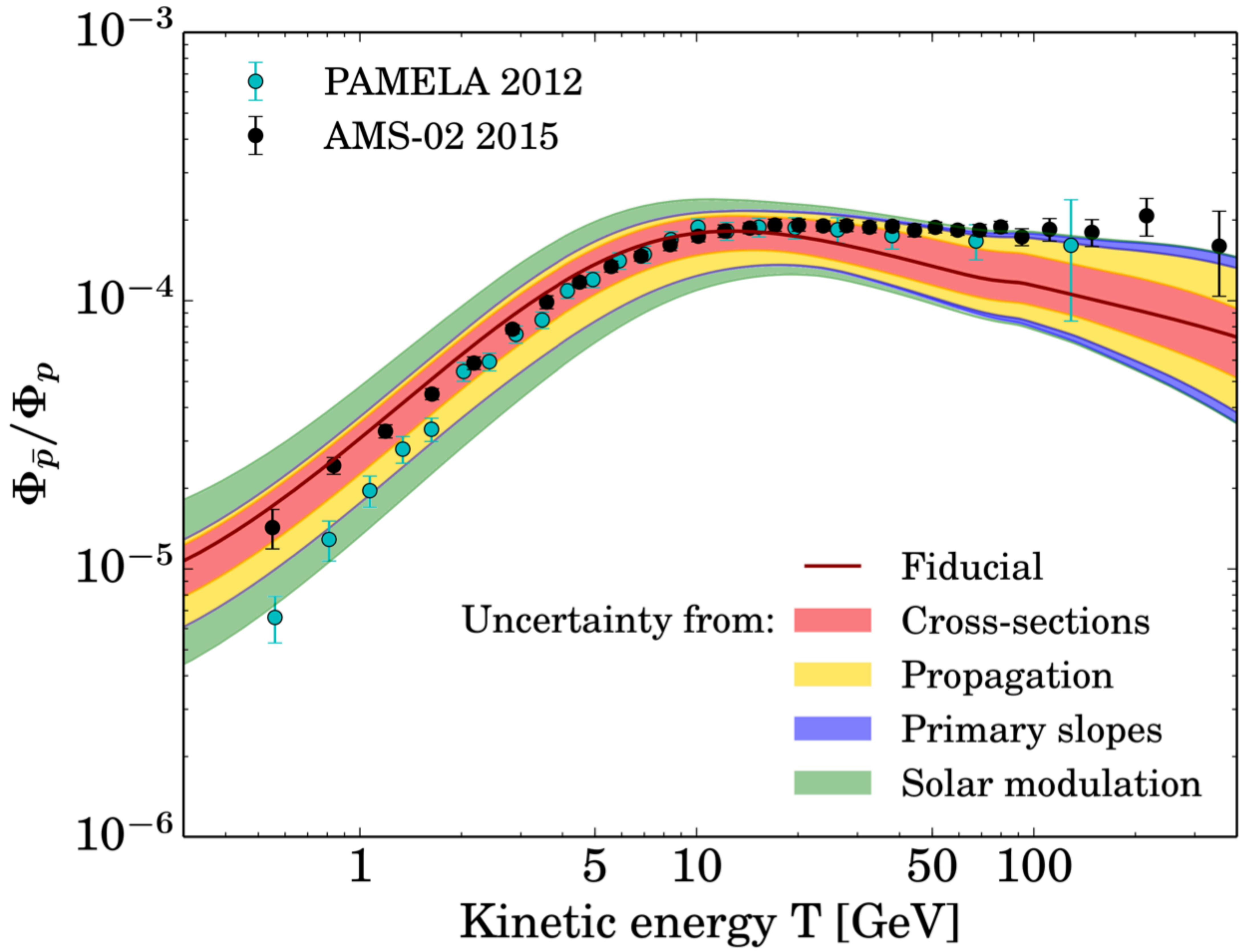
$$\sim 0.3\ \mathrm{GeV/cm^3}$$

$$\sim 0.008\ M_\odot/\mathrm{pc}^3$$

Anti-proton excess (2)



1903.01472

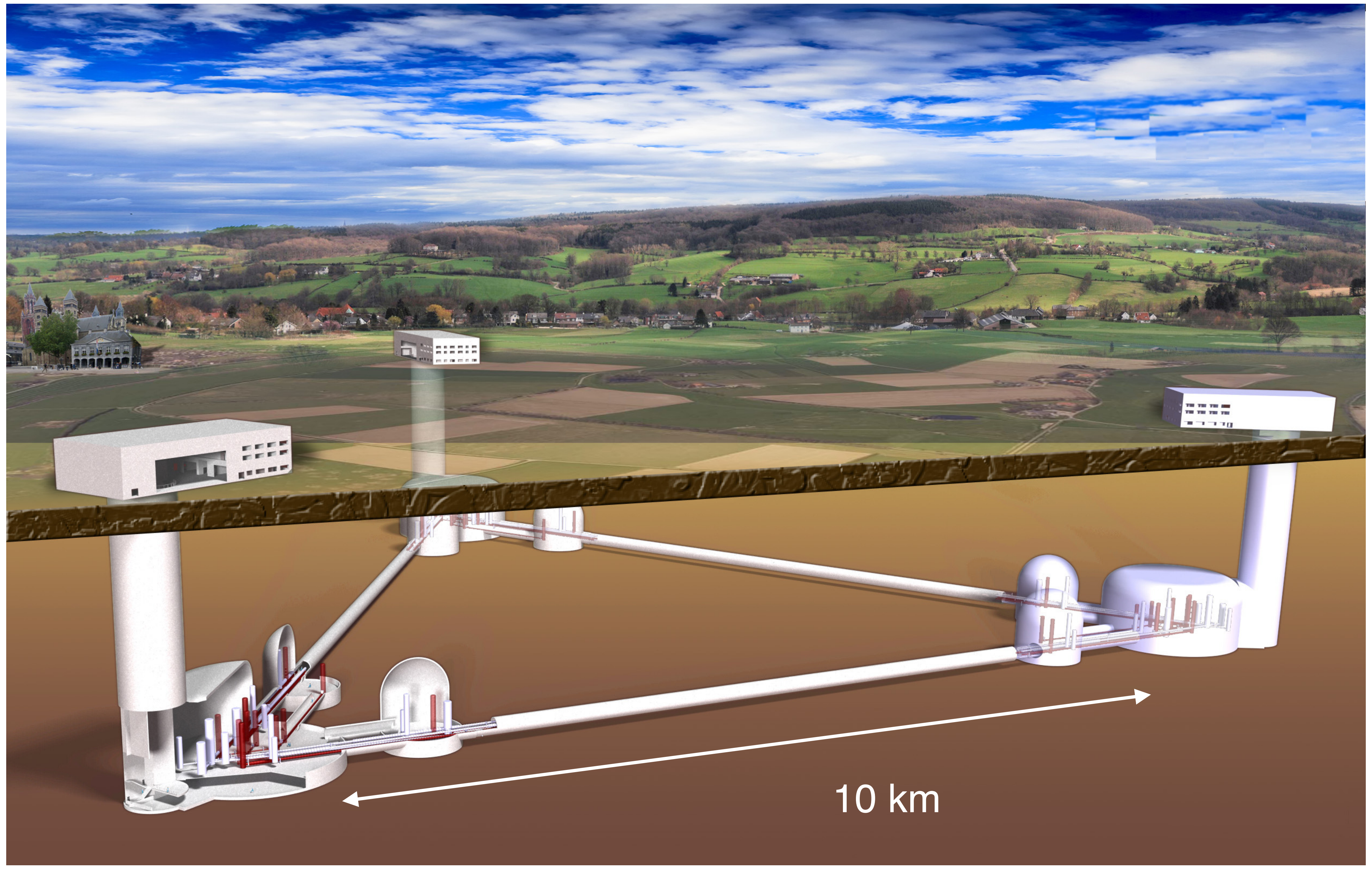


1504.04276

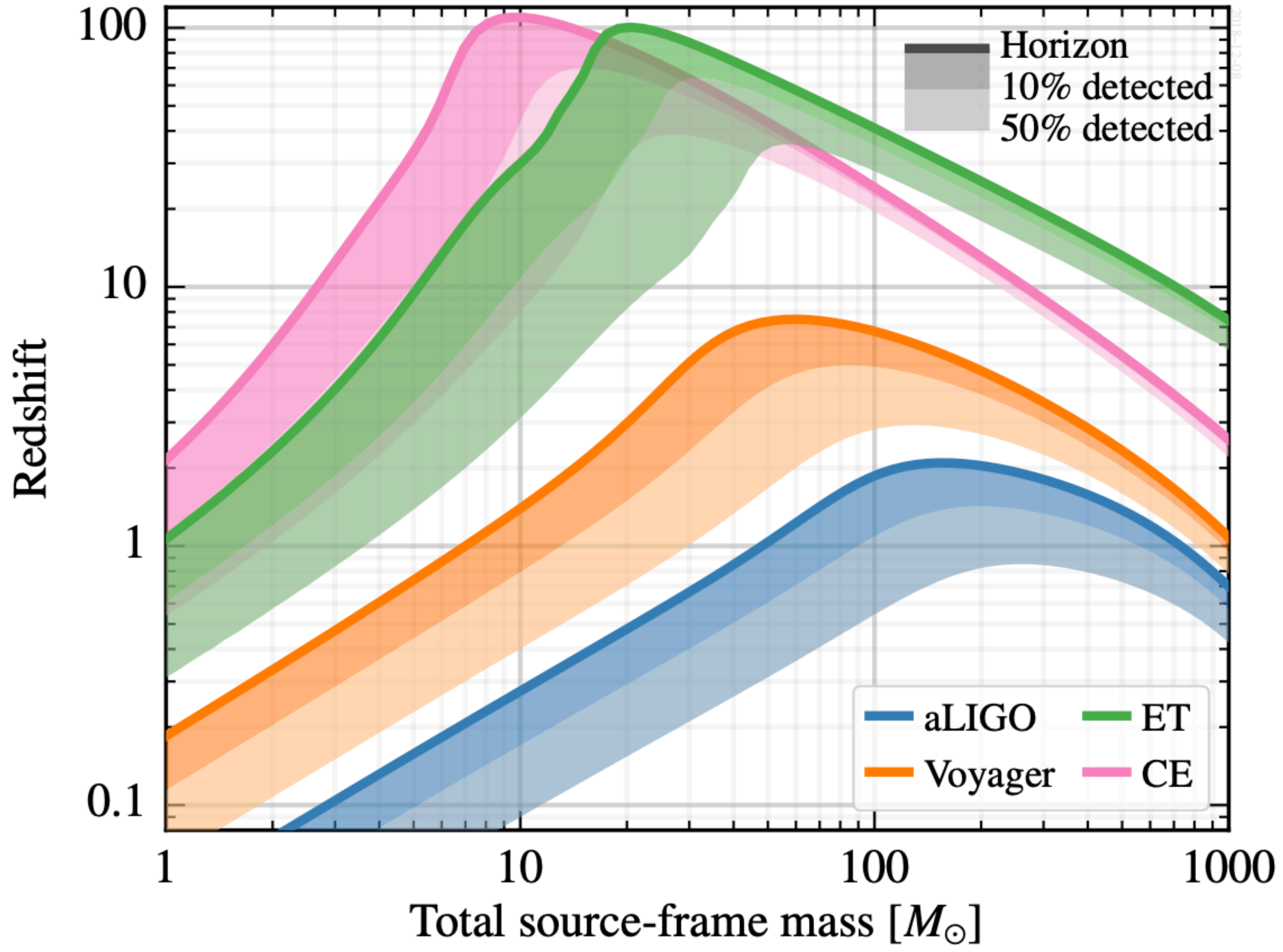
Several excesses point towards 60 GeV Dark Matter -
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

The Gravitational Wave Future

Planned Earth-based observatories such as Einstein Telescope:



Credit: Einstein Telescope



1902.09485

In addition, space-based detectors such as LISA will probe even lower frequencies (mHz) and therefore more massive systems (such as supermassive BH inspirals).