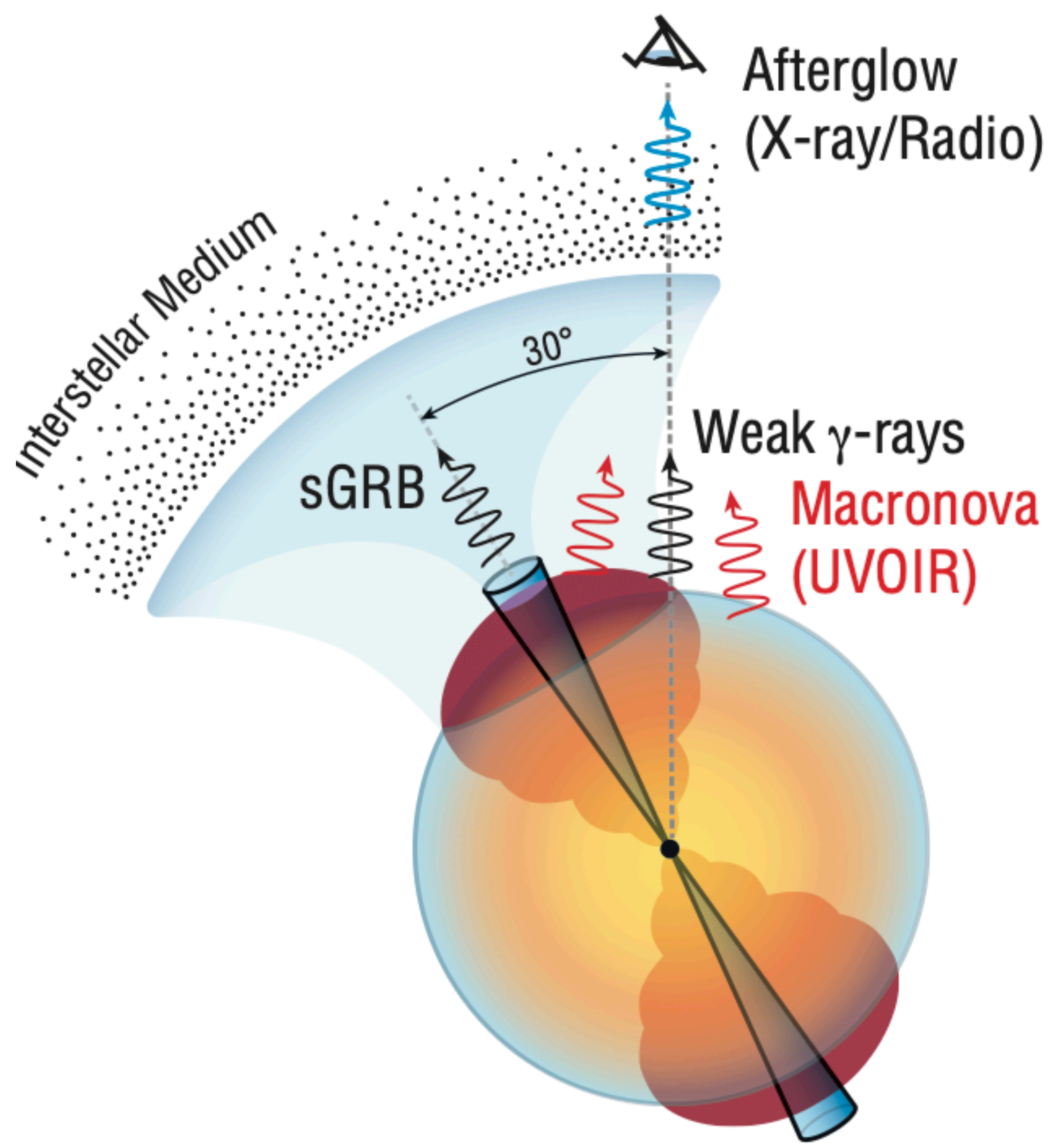
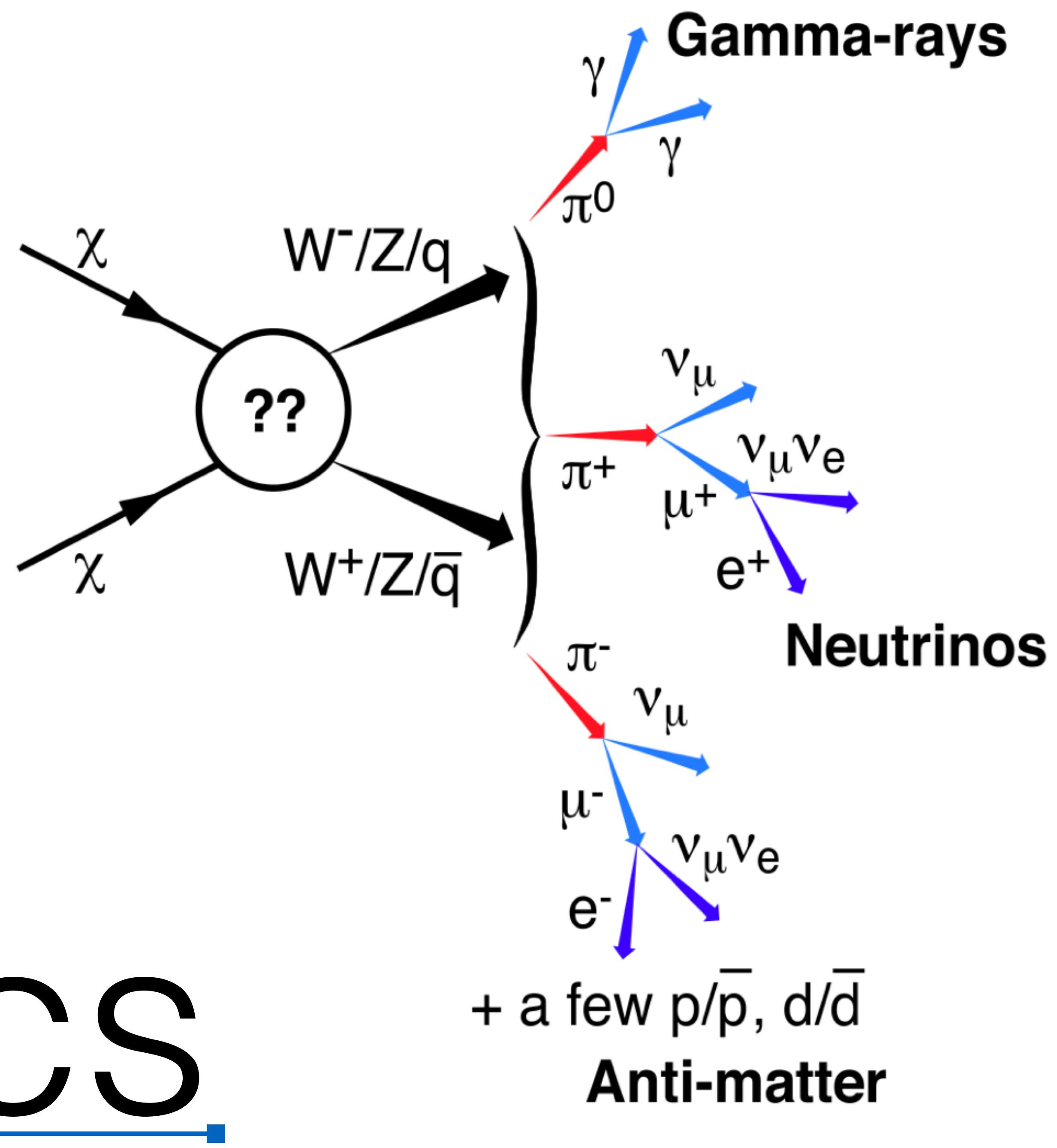




(An introduction to)

Astroparticle Physics

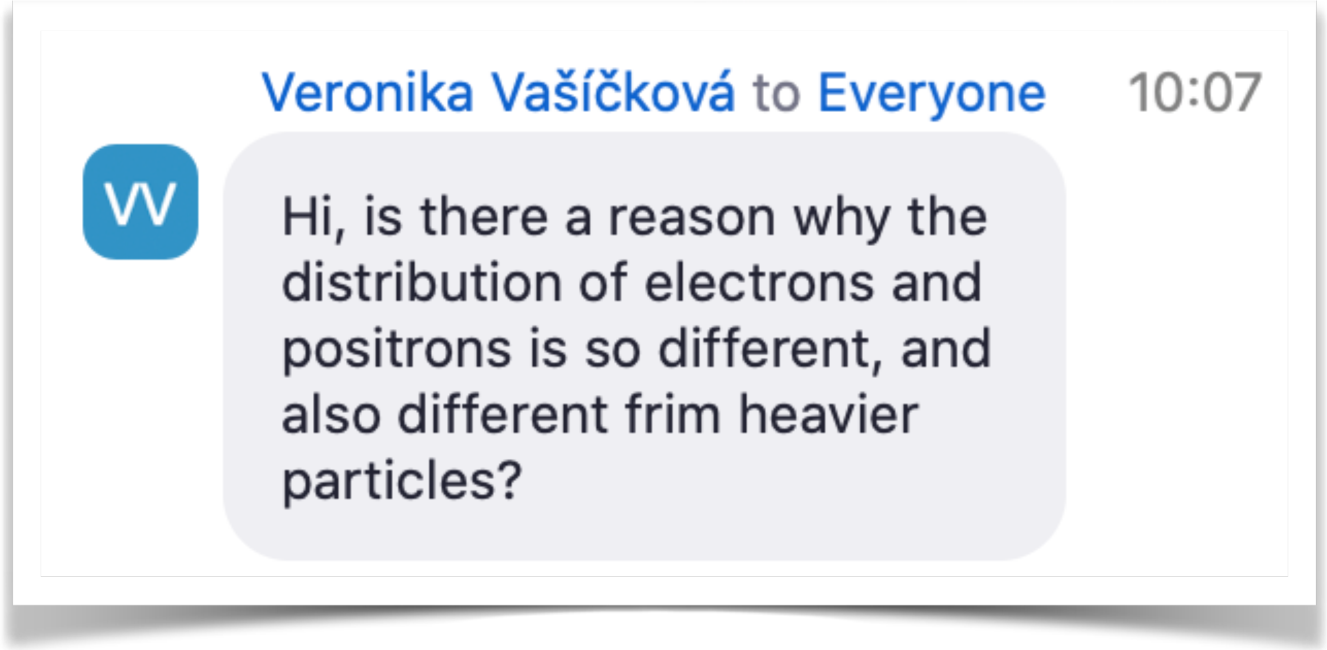
Lecture 2/2

Bradley J Kavanagh
Instituto de Fisica de Cantabria (CSIC-UC)
kavanagh@ifca.unican.es

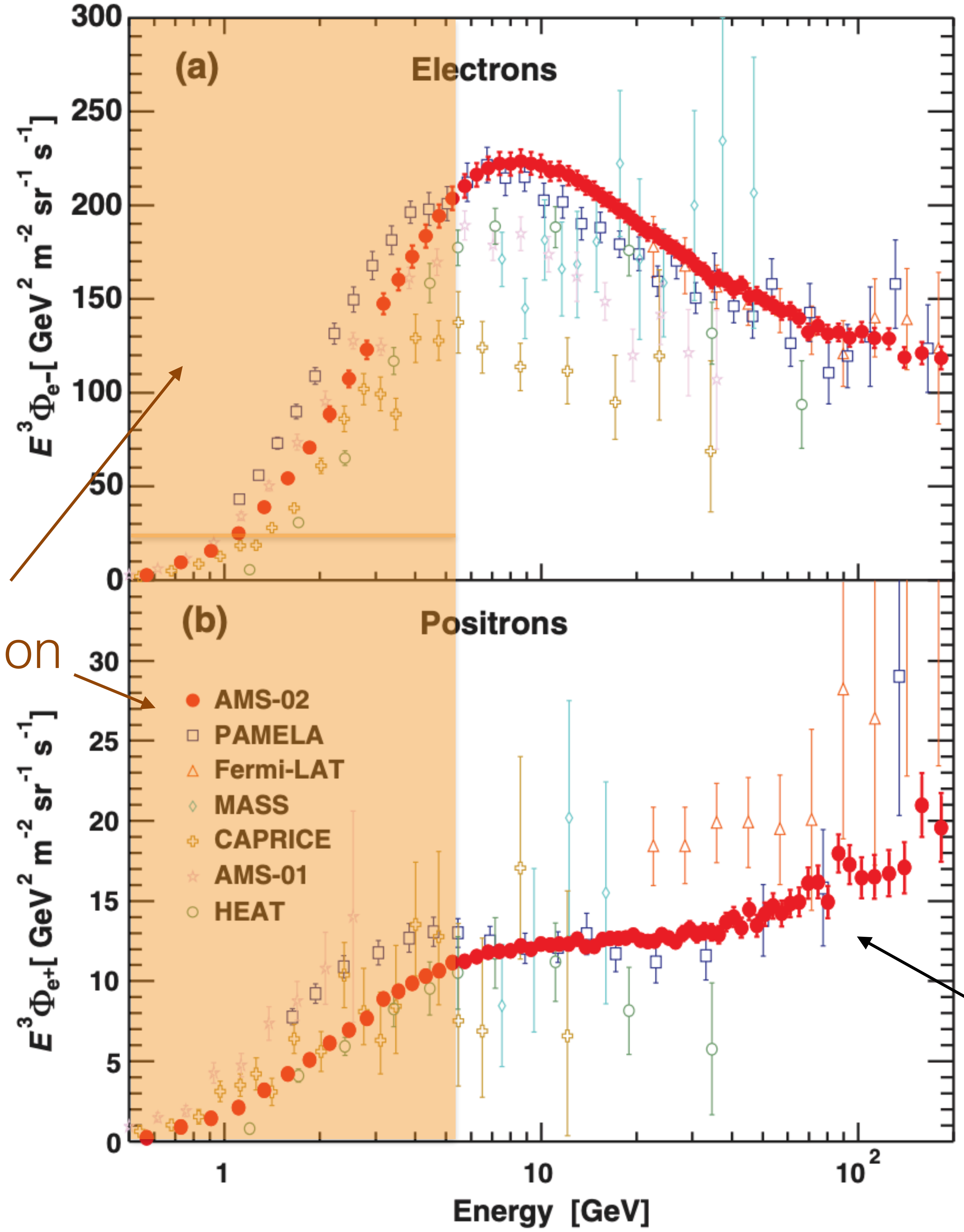
Summer Student Lecture Programme - Friday 15th July 2022

Slides here: bradkav.net/talks

Electrons vs Positrons



Solar modulation



Electrons can be directly accelerated (i.e. **primary cosmic rays**)

Positrons are only produced by the collisions of other cosmic rays (i.e. **secondary cosmic rays**)

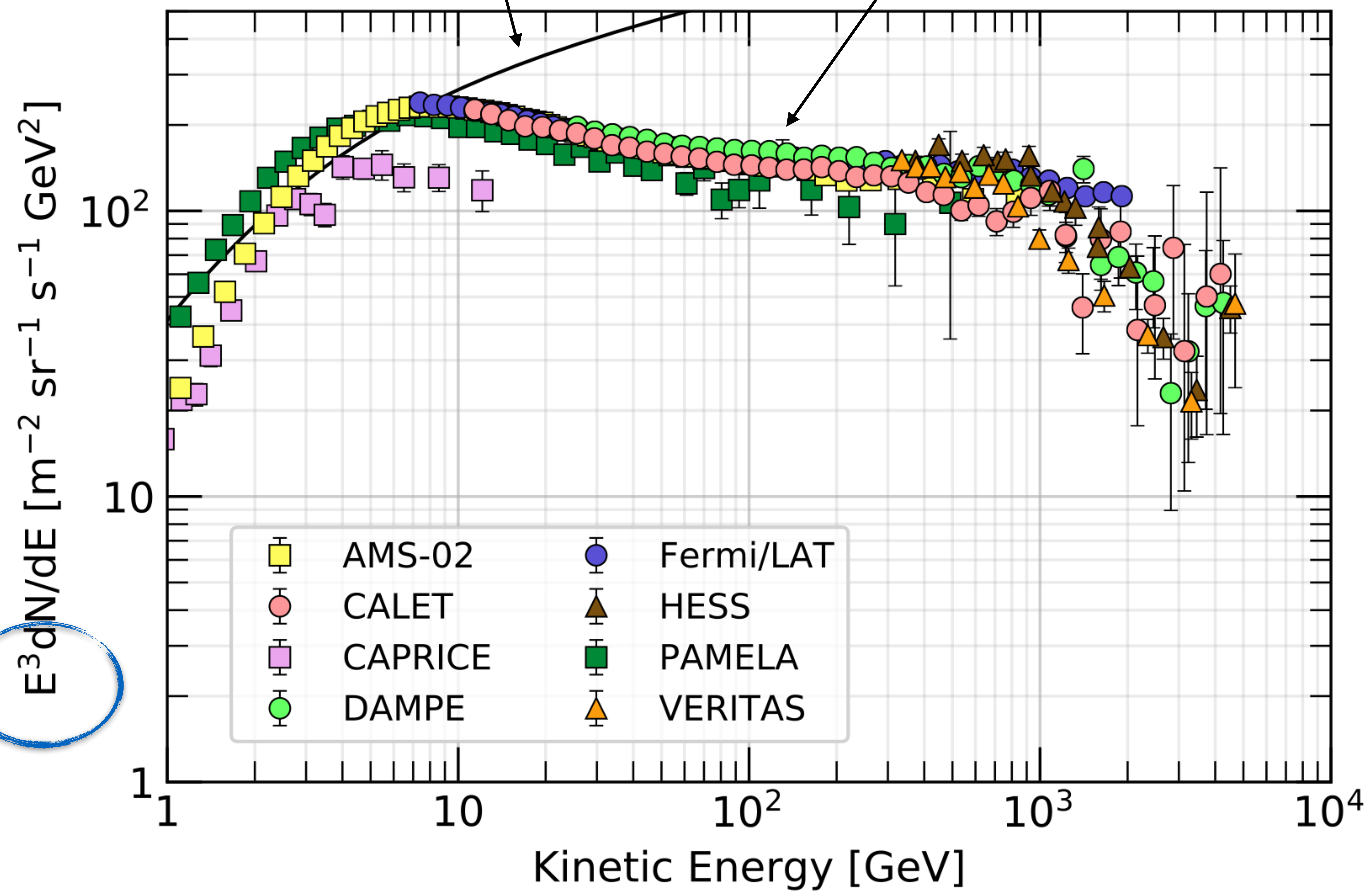
Expect different spectra. But, rise in positron flux at high energy is still not yet understood ("positron excess")!

E.g. [1303.0530]

Electrons vs Protons

Proton Spectrum (x0.01)

Electron + Positron Spectrum



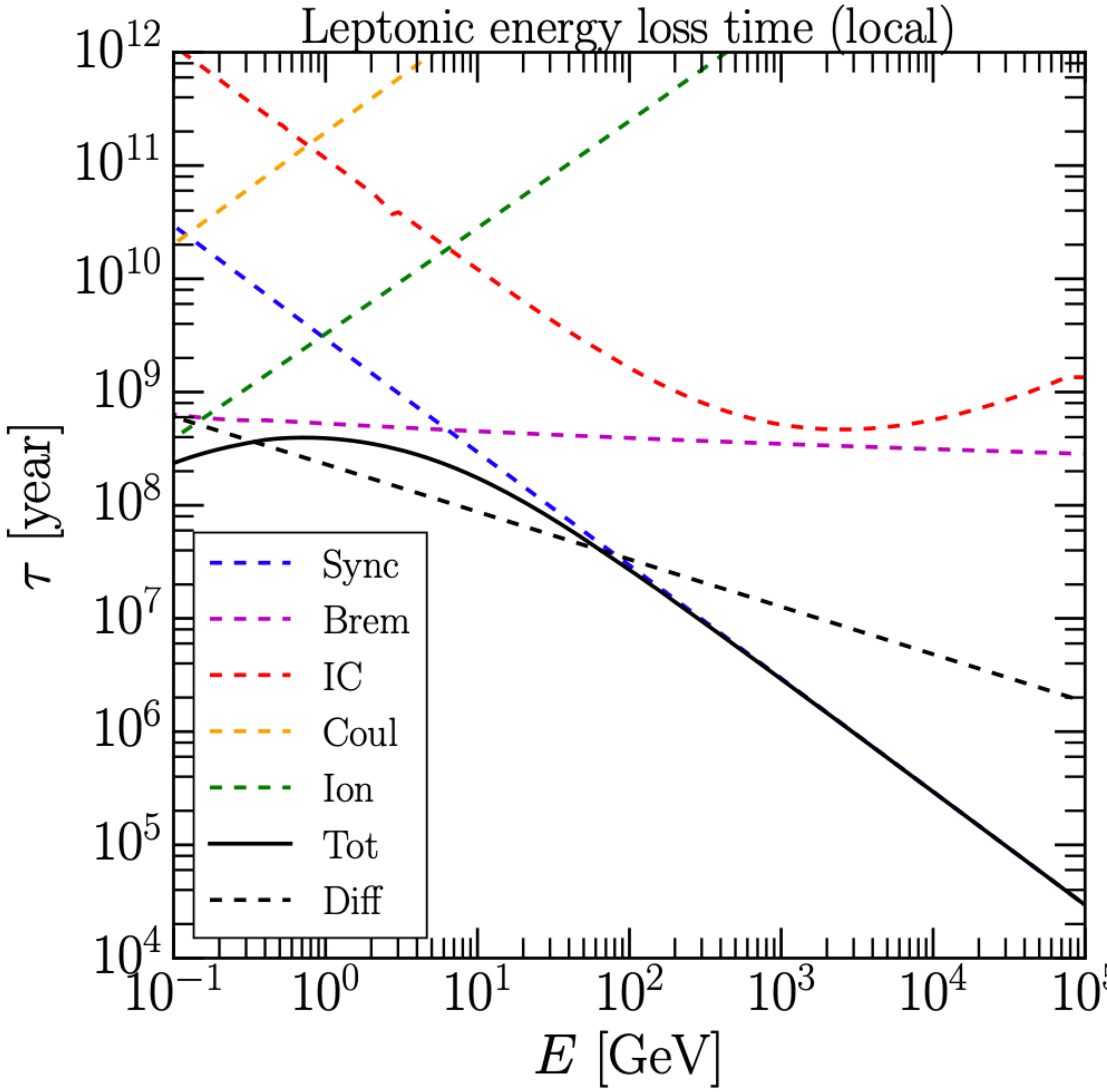
Credit: [Particle Data Group (2020)]

Veronika Vašíčková to Everyone 10:07

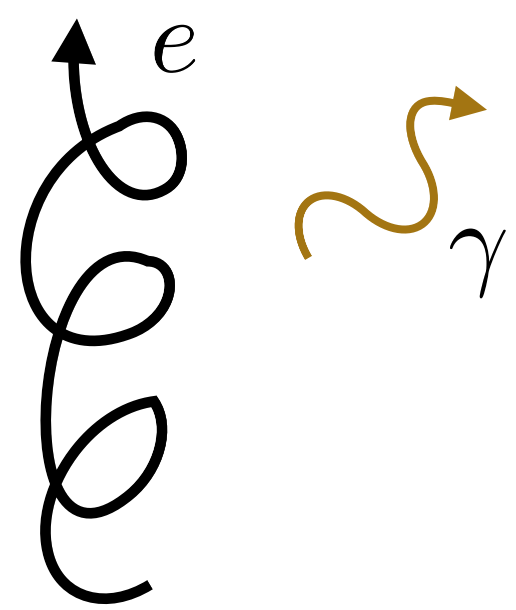
VV

Hi, is there a reason why the distribution of electrons and positrons is so different, and also different frim heavier particles?

Electrons and positrons lose energy much more rapidly (than nuclei) as they move through the Galaxy



Synchrotron



See e.g. Appendix C of 1607.07886


The Sun
Supernovae
Credit: NASA/CXC/SAO
Quasars/AGN
Credit: ESO/M. Kornmesser
Lecture 1
Gamma rays
γ
Neutrinos
ν
Charged Cosmic Rays
$e^{\pm}, p^{\pm}, \ldots$
Lecture 2
Dark Matter
χ
Gravitational Waves
$h_{\mu\nu}$
????
Pulsars
Credit: Kevin Gill / Flickr
BH/NS Mergers
Credit: SXS Lensing

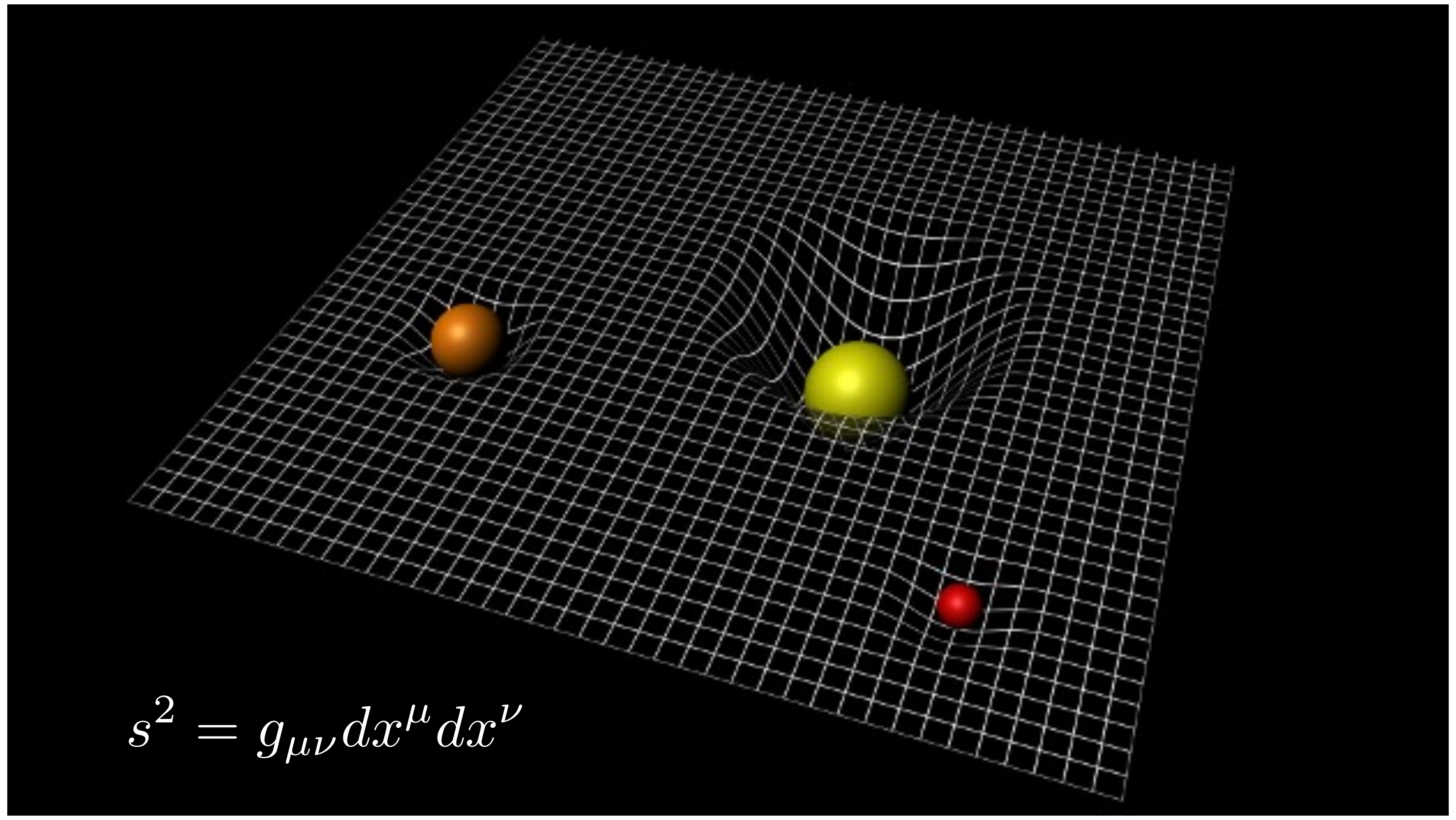
Gravitational Waves

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:

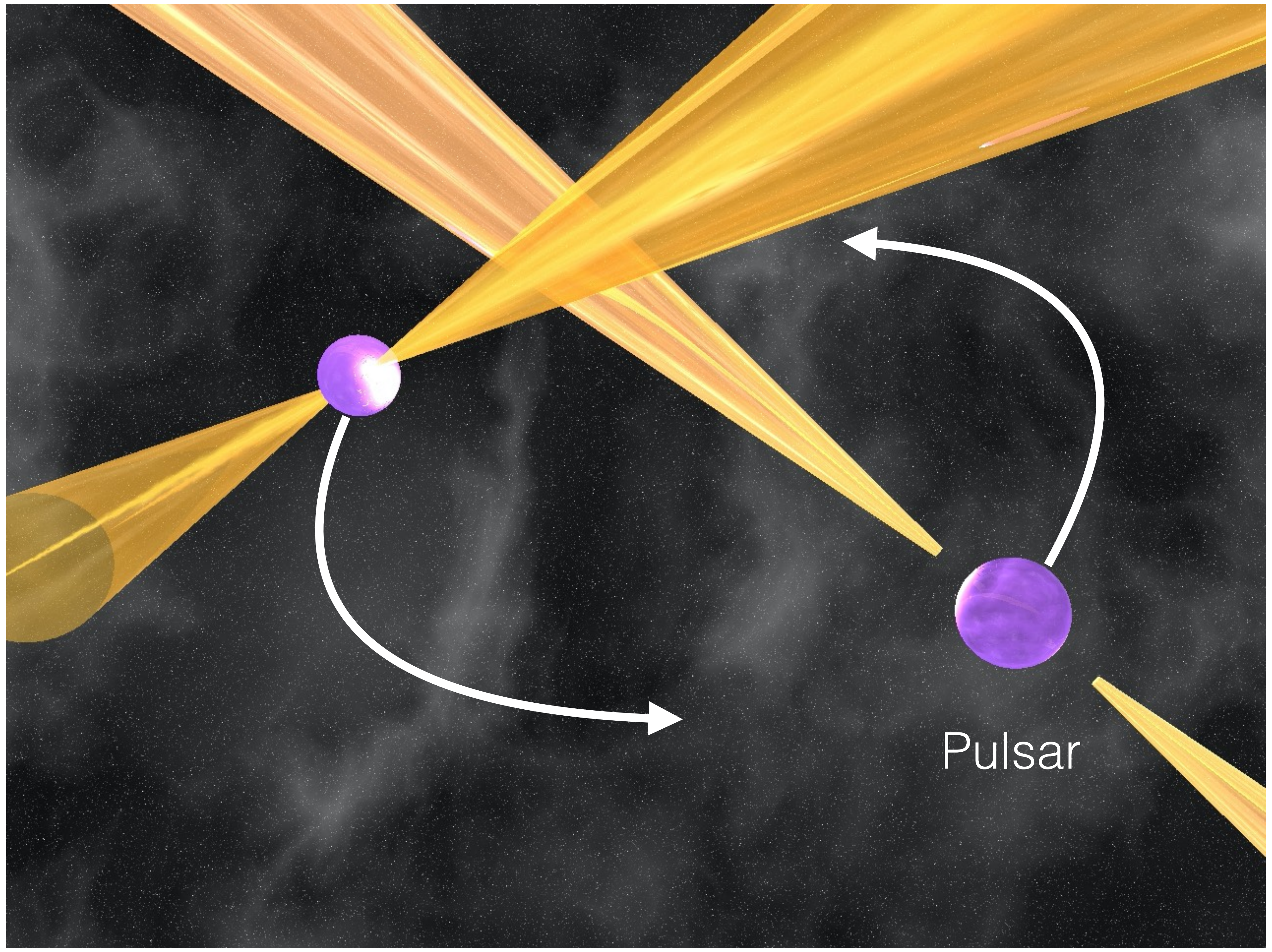
$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

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

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

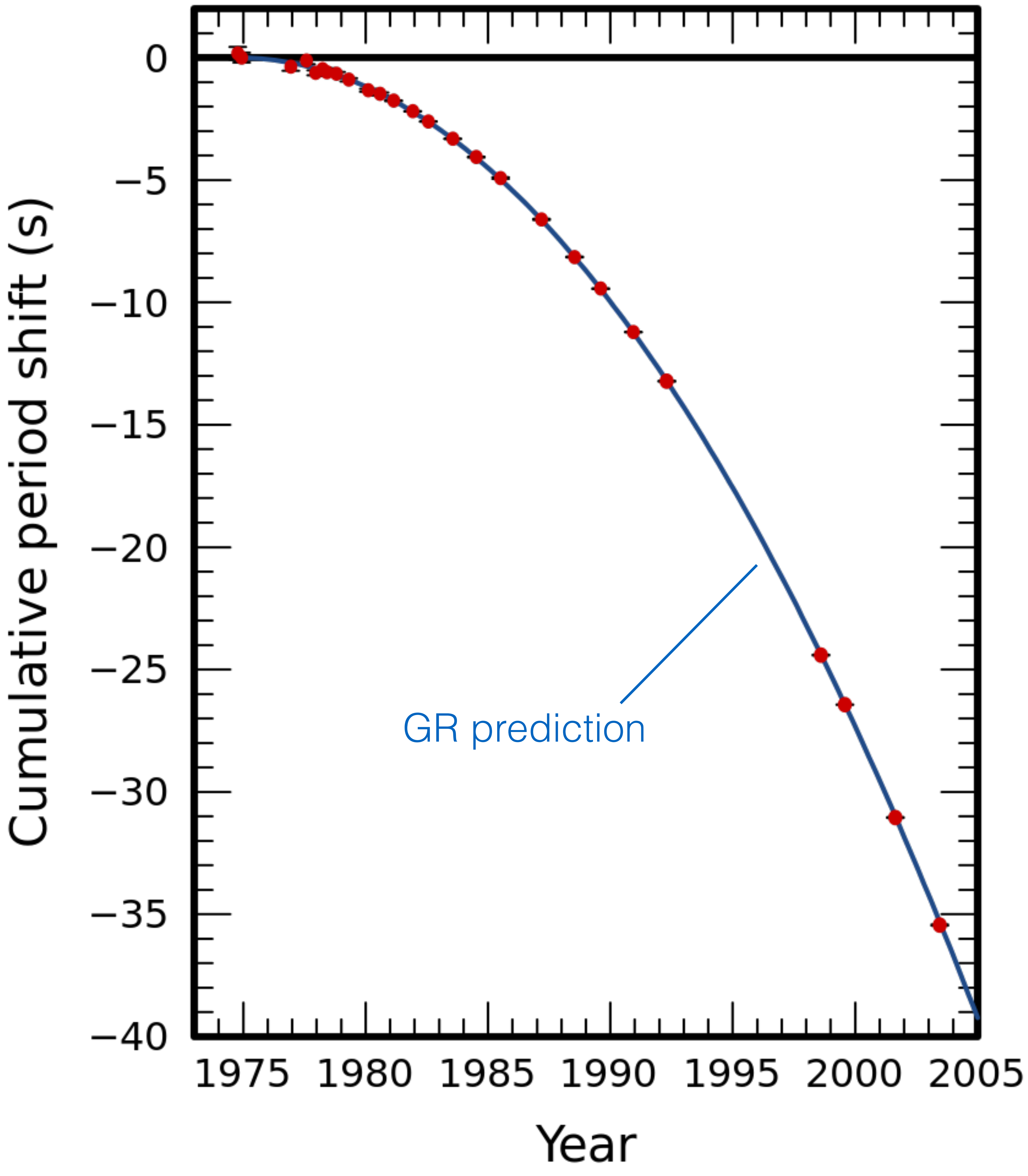
Indirect observation of GWs

GWs sourced by a time-dependent mass quadrupole moment.
E.g. compact object binaries…



Credit: Michael Kramer/Jodrell Bank Observatory/University of Manchester)

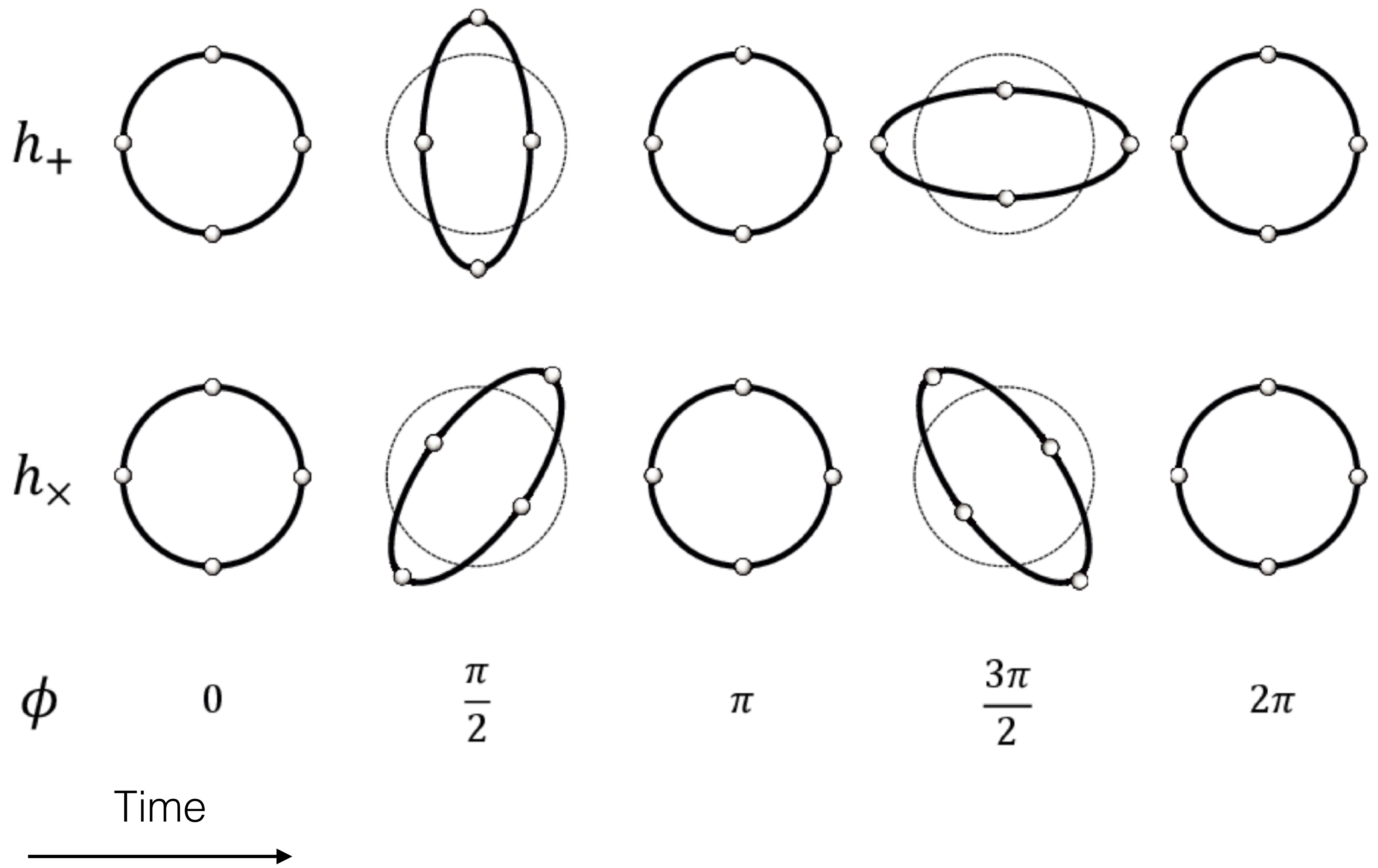
PSR B1913+16 ("Hulse-Taylor Binary")



See e.g. astro-ph/0407149

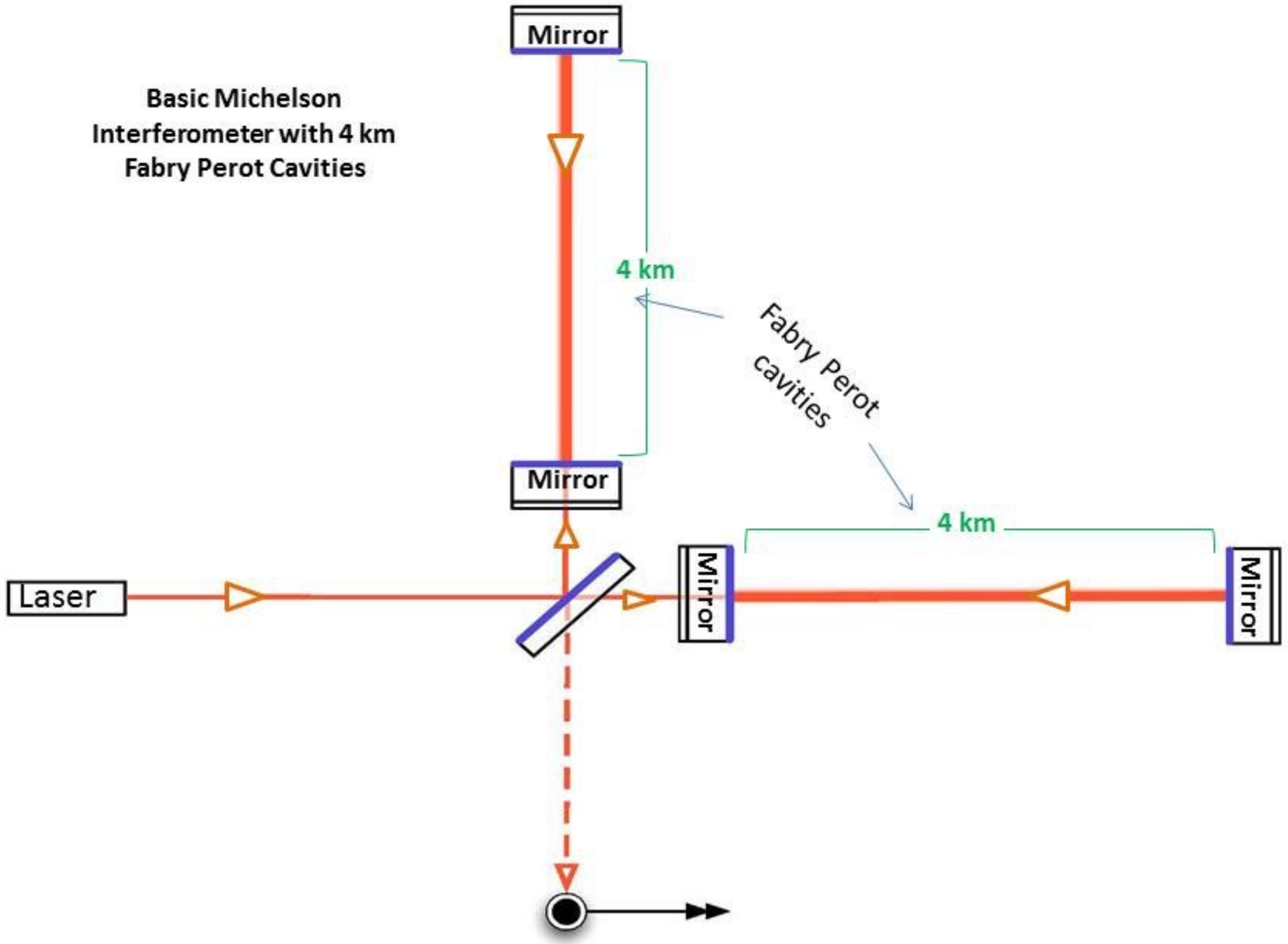
Direct detection of GWs

GW traveling into the screen causes (tiny) distortion:



[1708.00918](1708.00918)

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

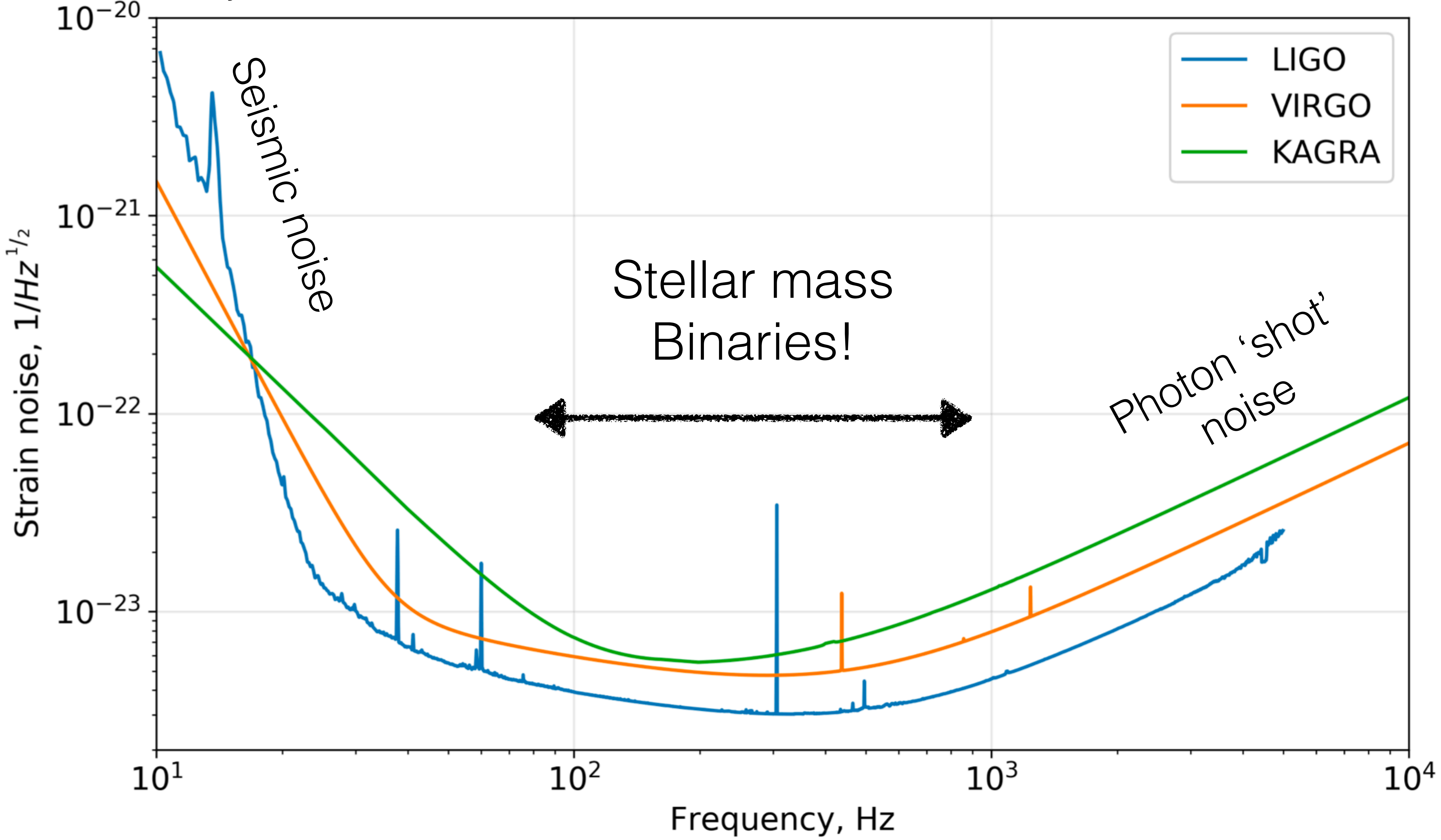


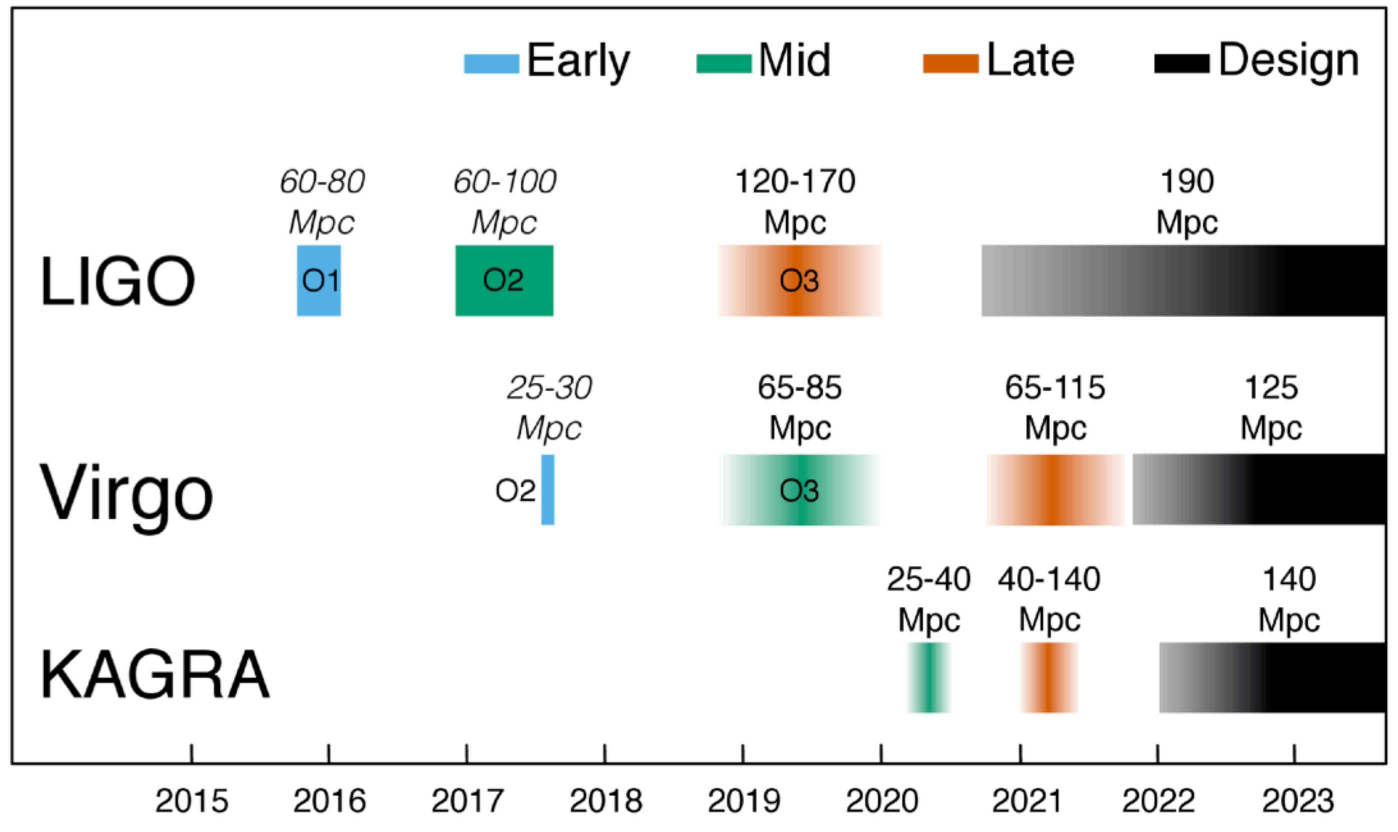
Typical GW strain is $\Delta L/L \sim 10^{-23}$!

LIGO-Virgo-KAGRA (LVK)

Credit: LIGO, VIRGO & KAGRA.

Projected O4 strain noise [2102.10816]



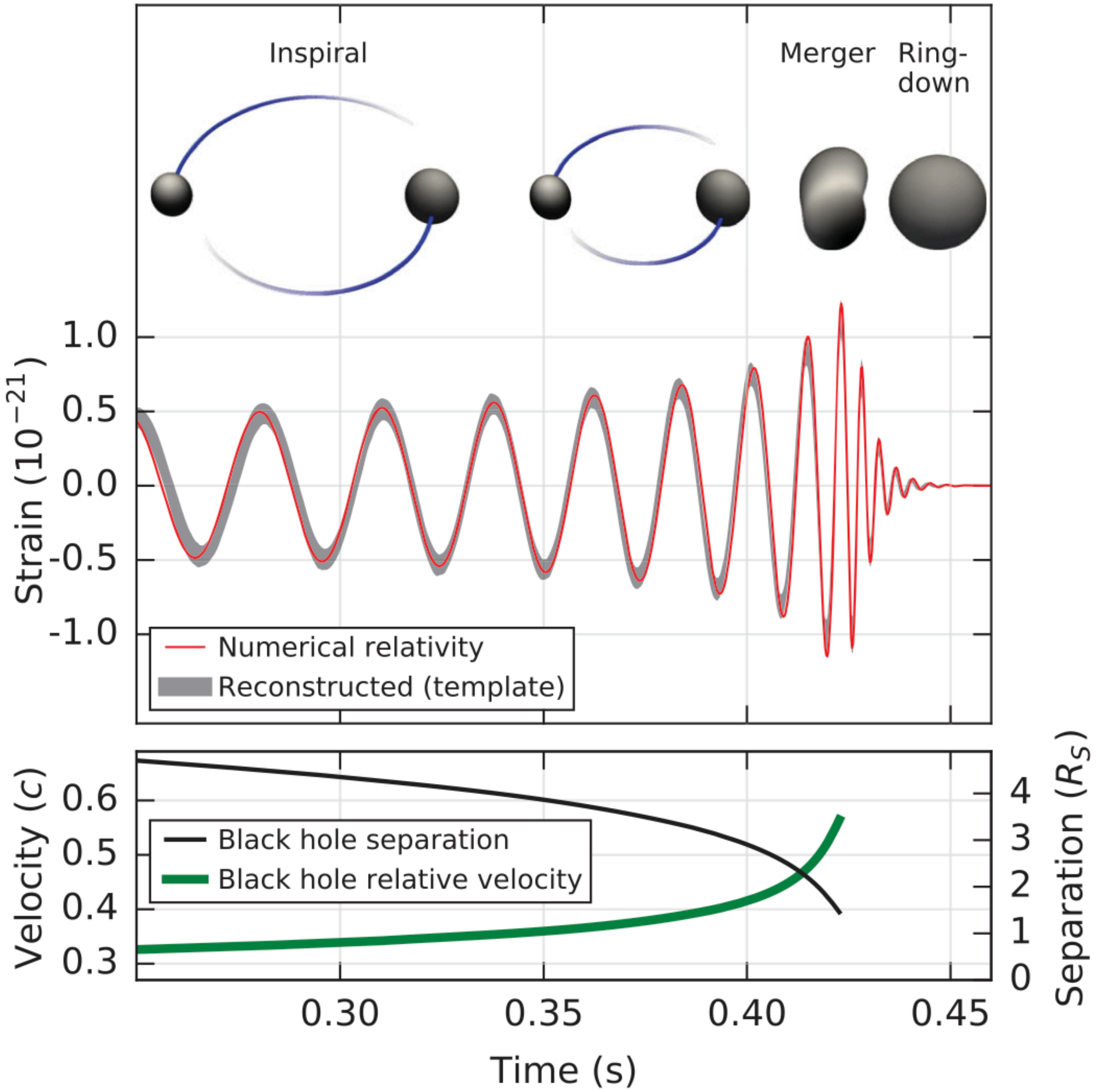


[1906.03643]

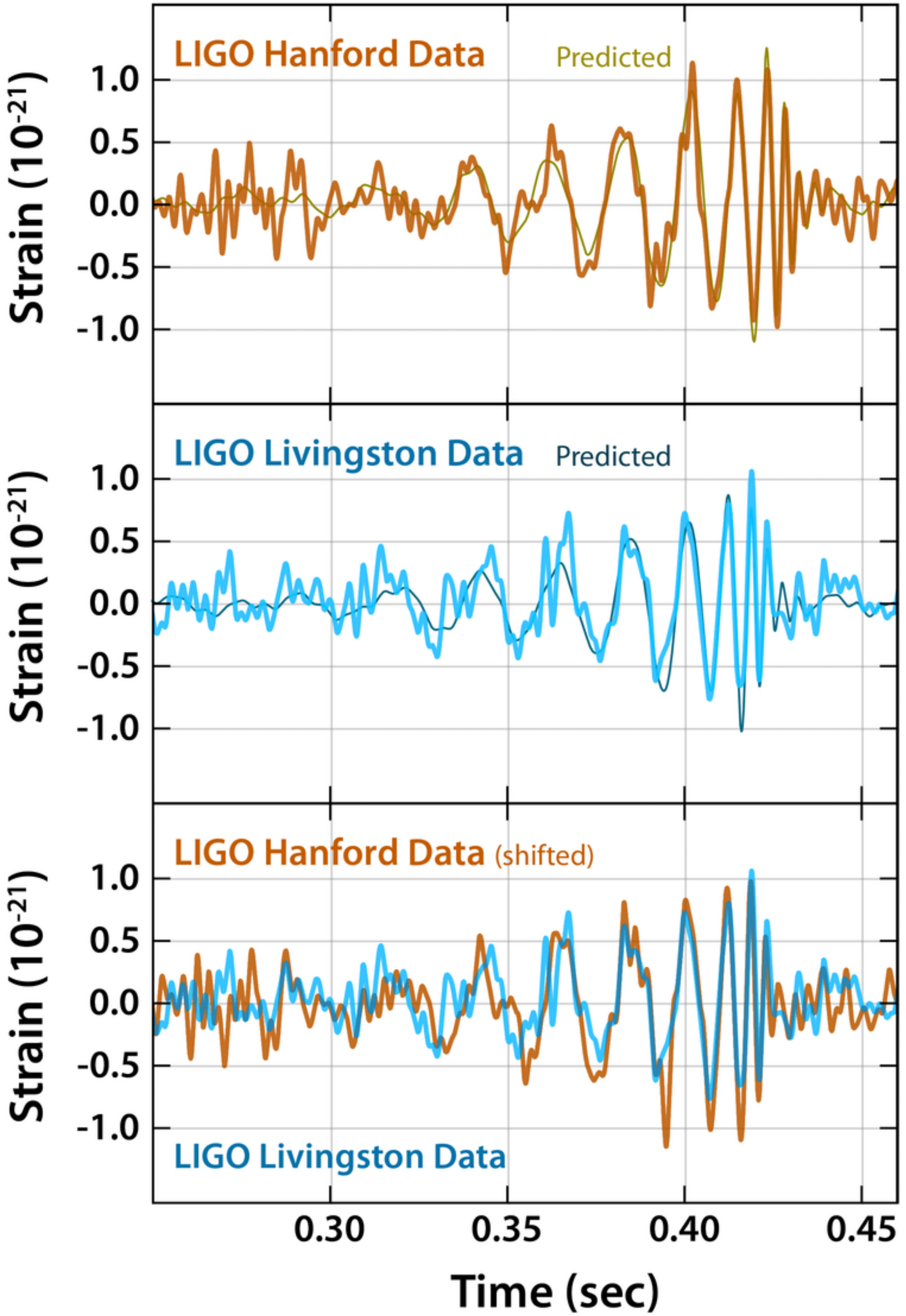
GW frequency ~ twice orbital frequency.

GW150914 - the first BH-BH merger

14 September 2015



Credit: Caltech/MIT/LIGO Lab



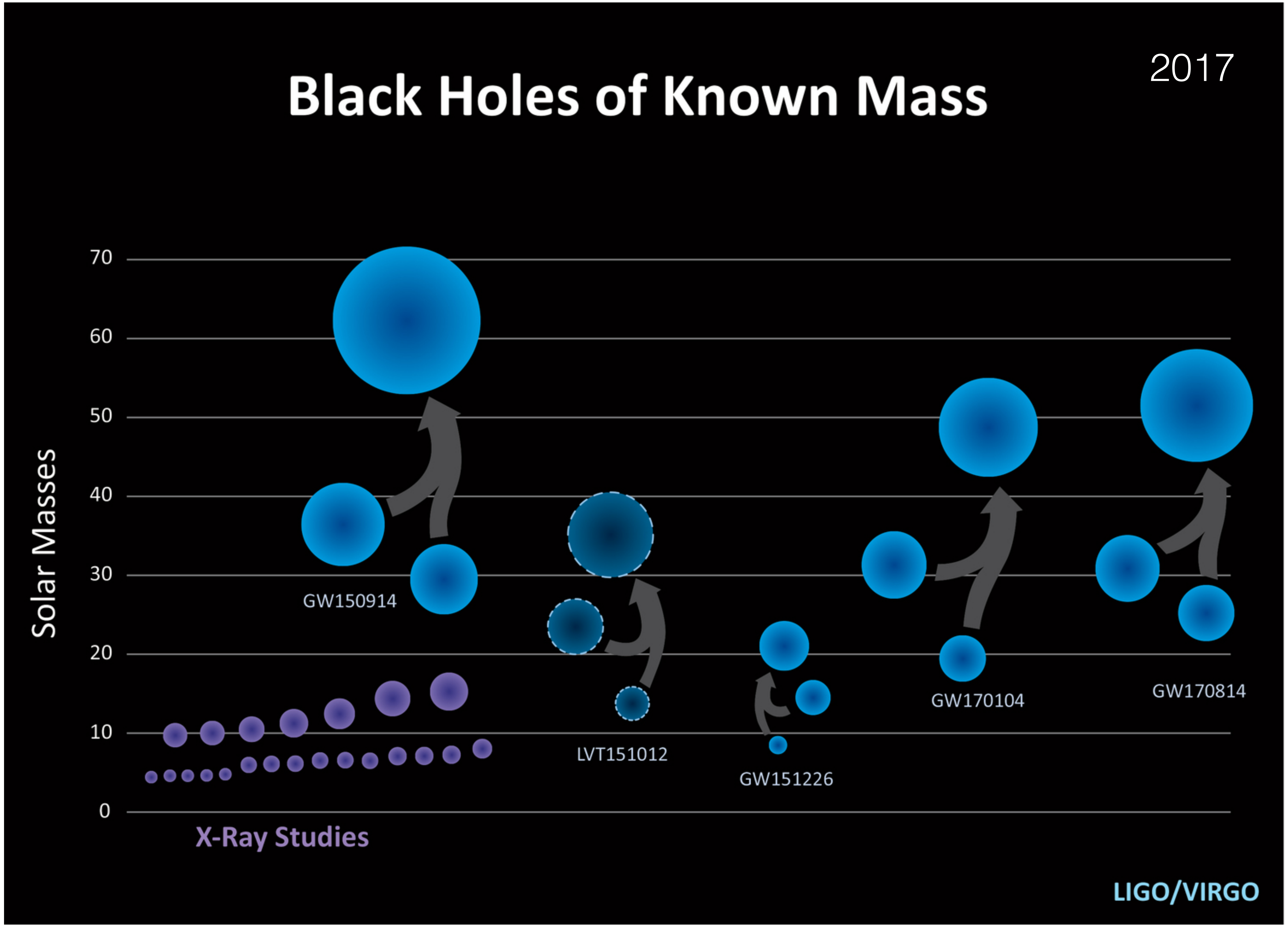
Merger of two BHs - with masses $36\,M_\odot$ and $29\,M_\odot$
at a luminosity distance of $d_L \approx 200 - 600\,\mathrm{Mpc}$

1602.03840

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

The Compact Object Zoo

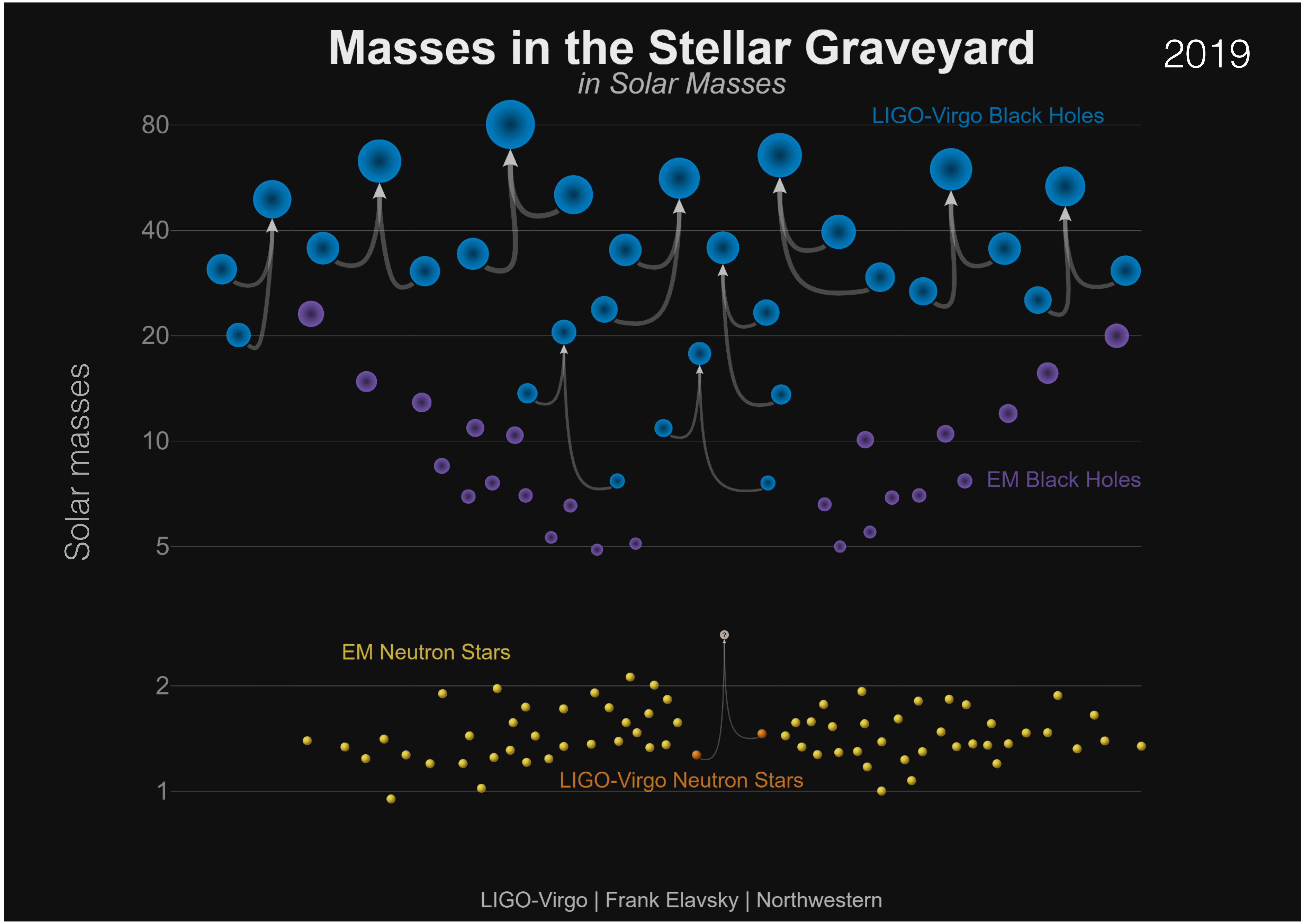
https://media.ligo.northwestern.edu/gallery/mass-plot



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

The Compact Object Zoo

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



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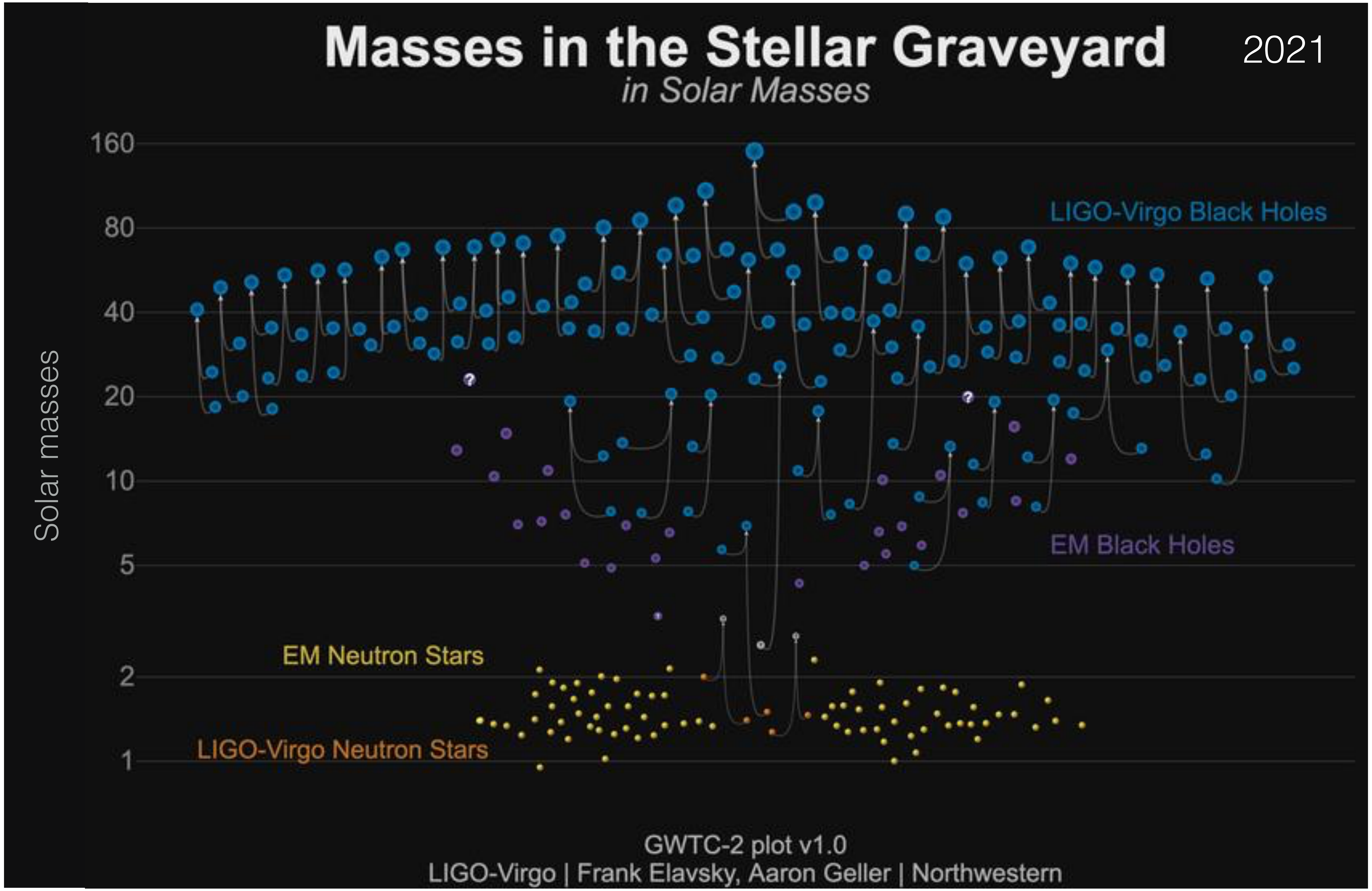

The Compact Object Zoo

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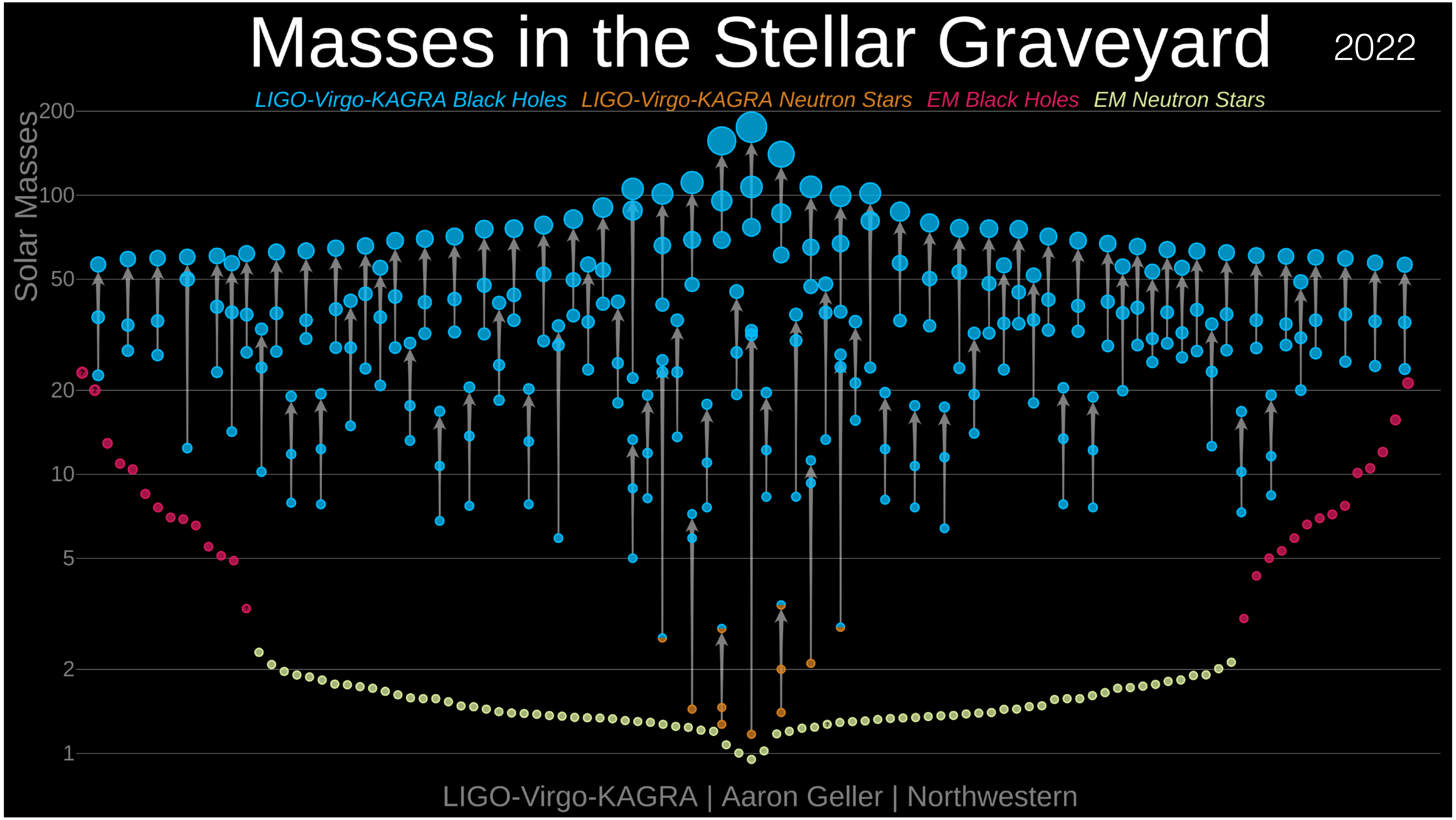
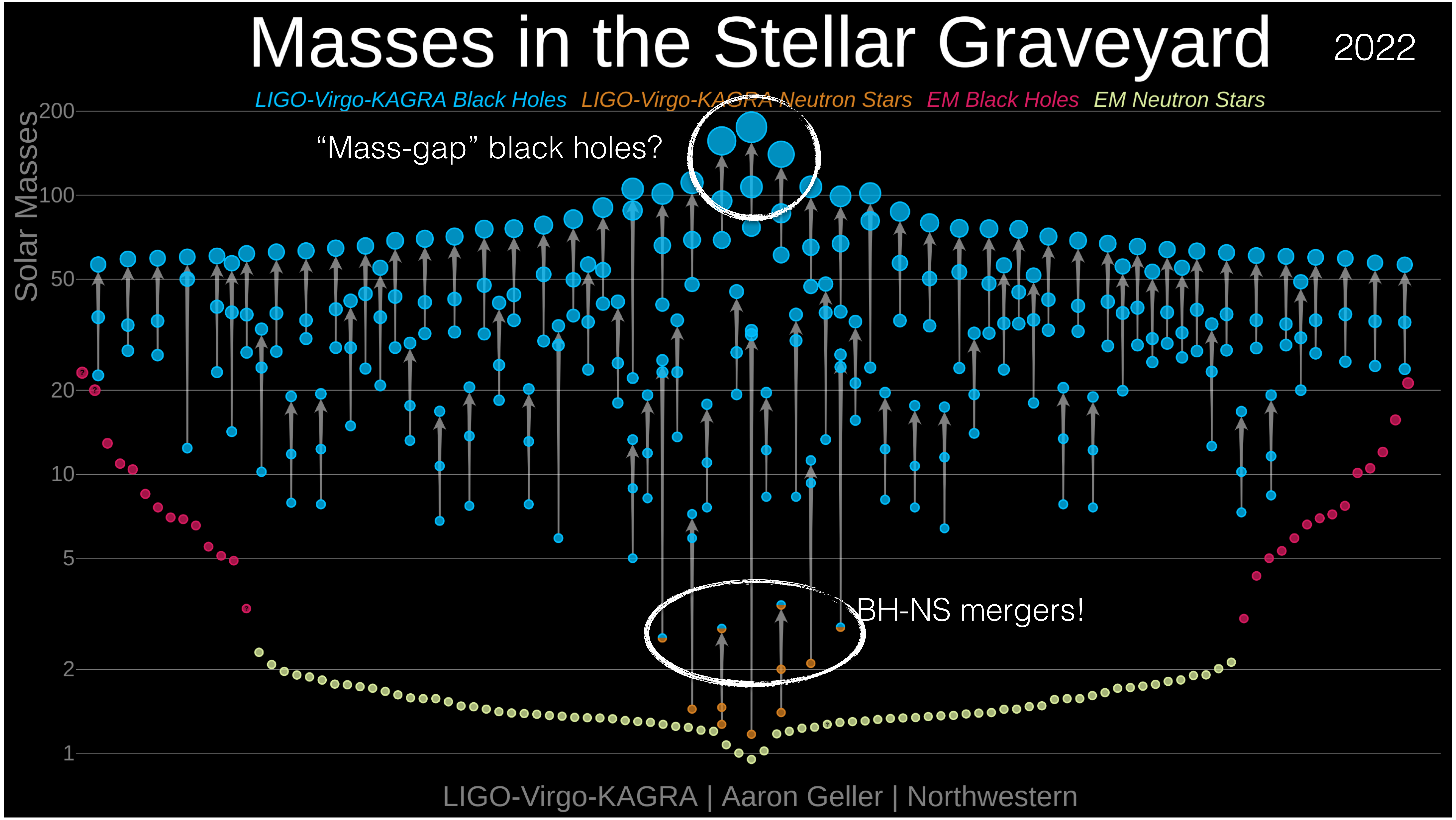


The Compact Object Zoo

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

2007.07889

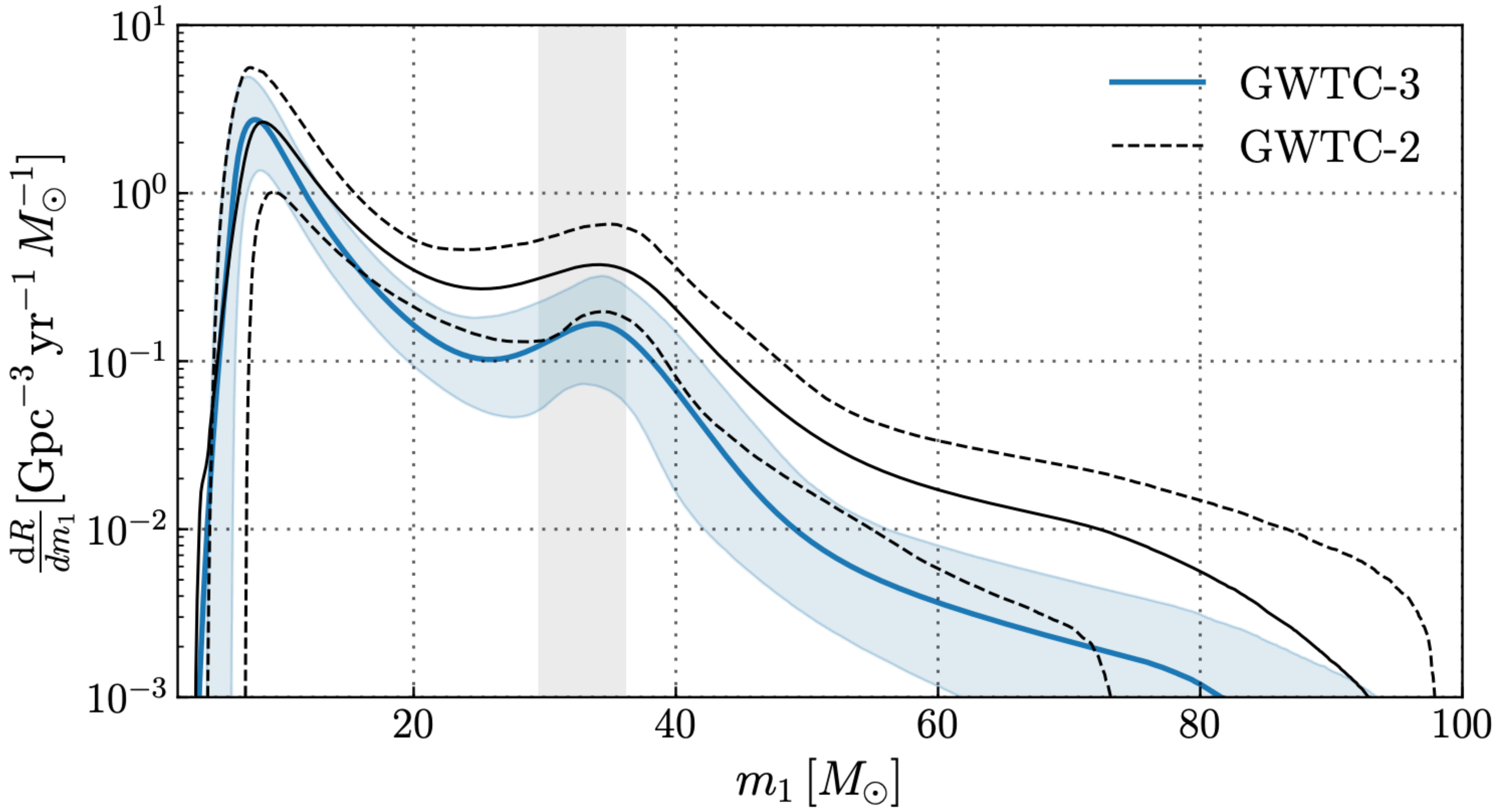


2106.15163

A Whole Catalog!

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

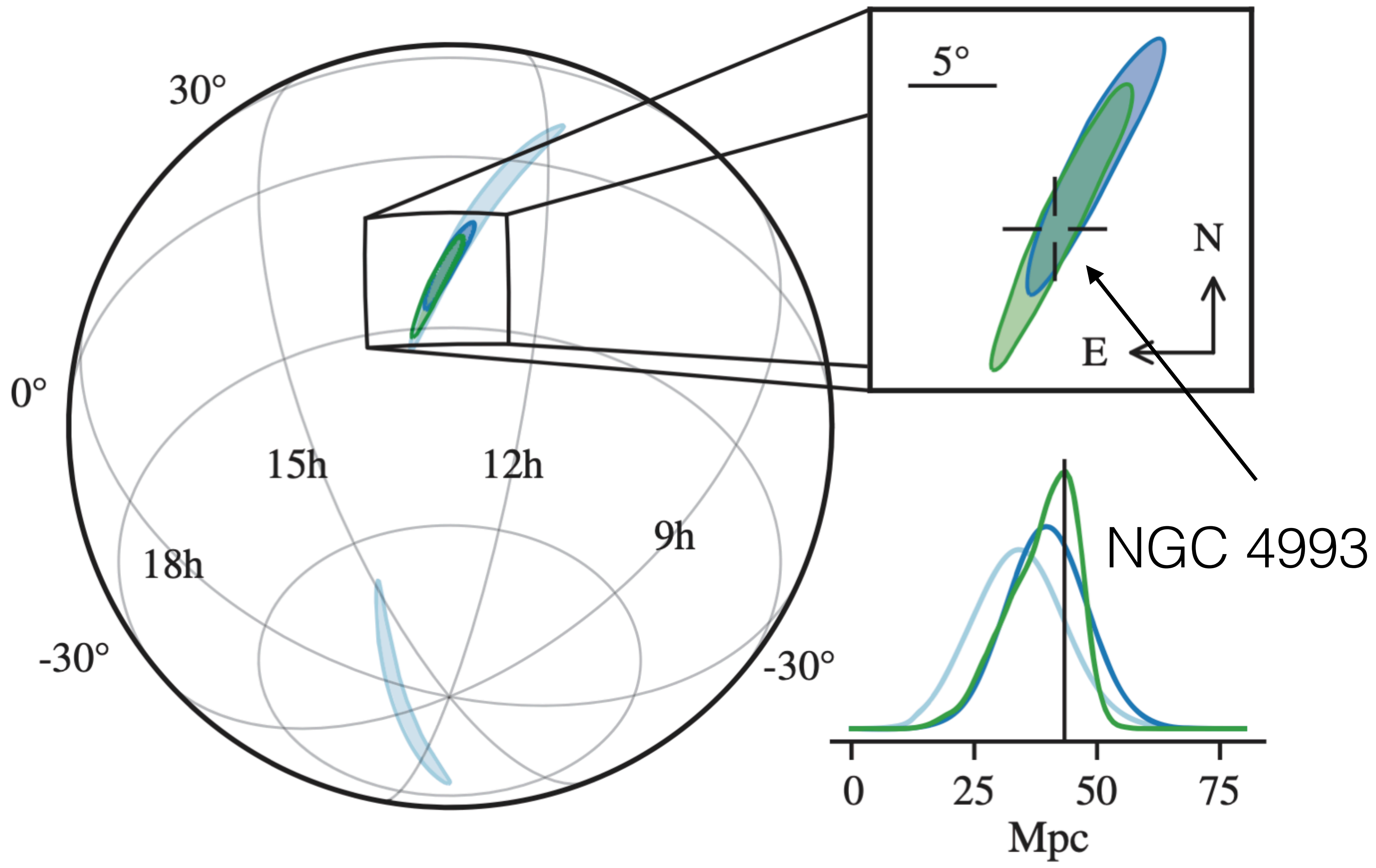
With ~90 events, we can start to infer the properties of the *population* of merging Black Holes!

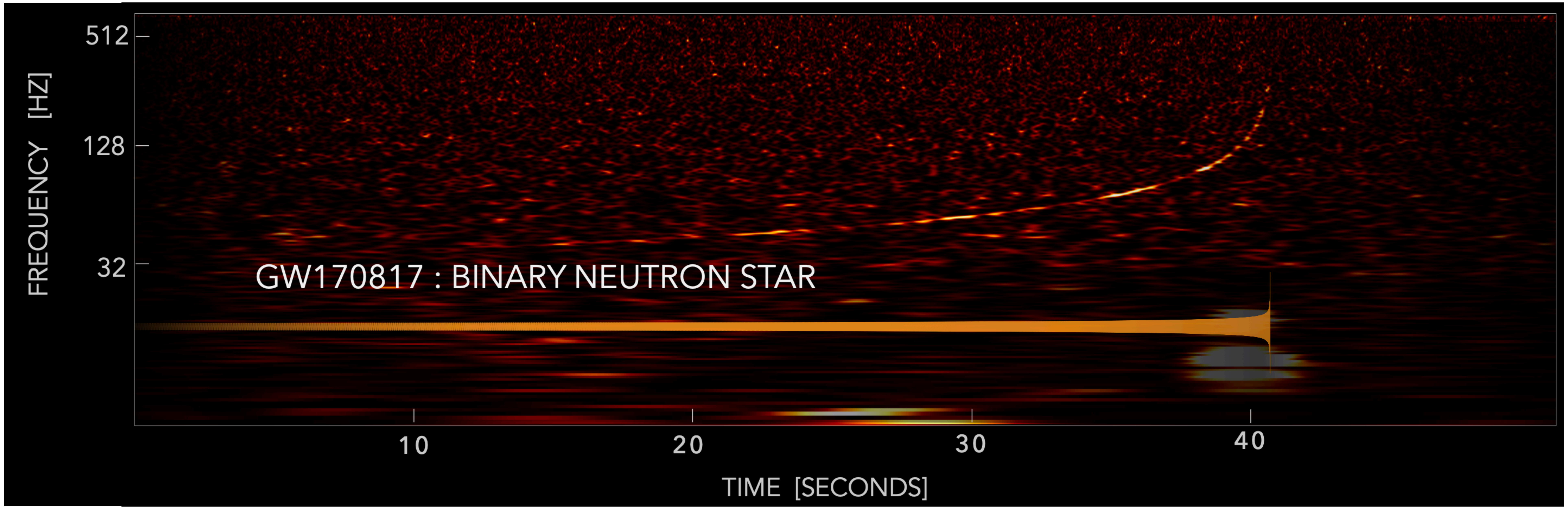


GW170817 - the first NS-NS merger

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

Localised to within ~30 deg²

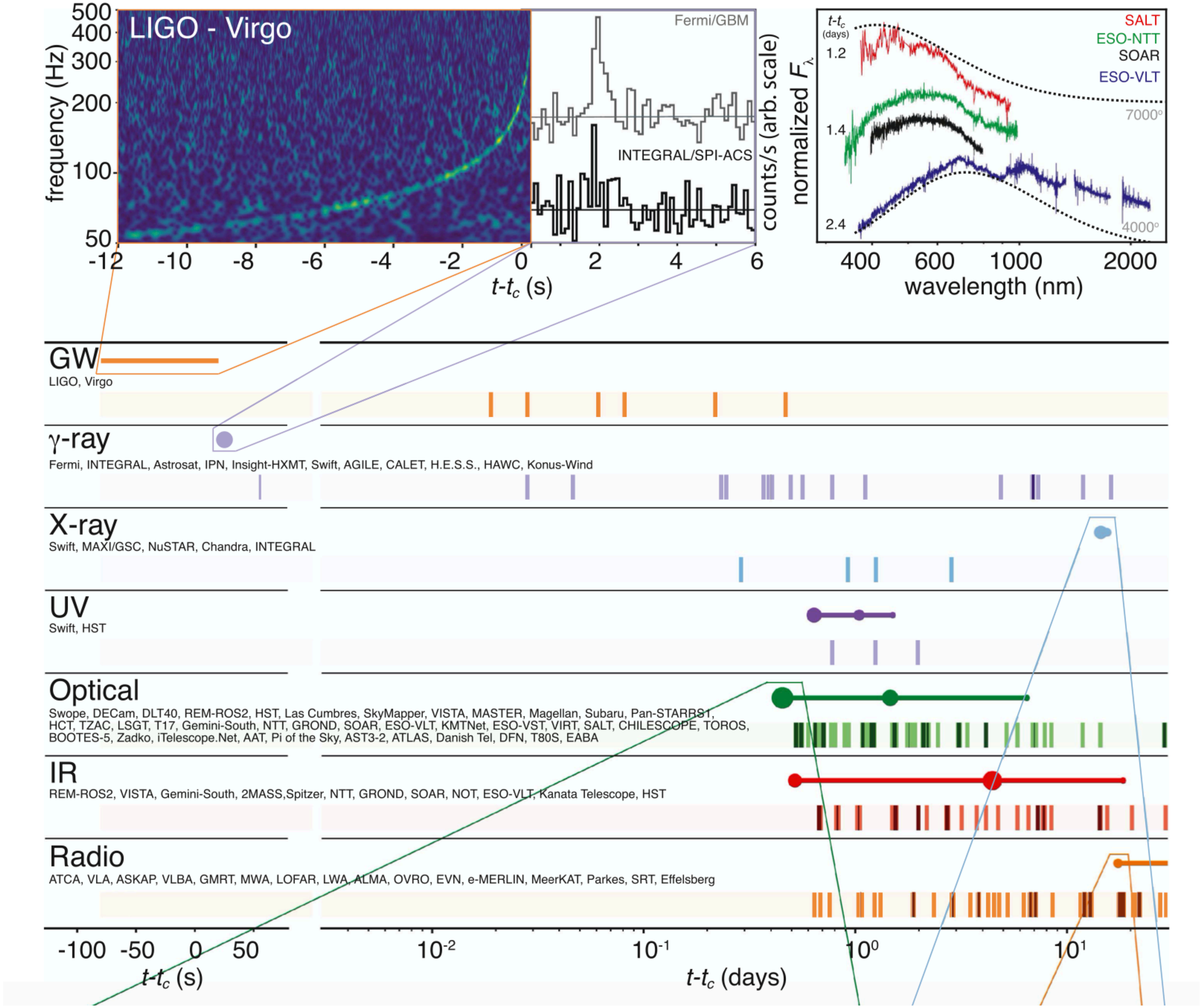




[1710.05832](), [1805.11579]()

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

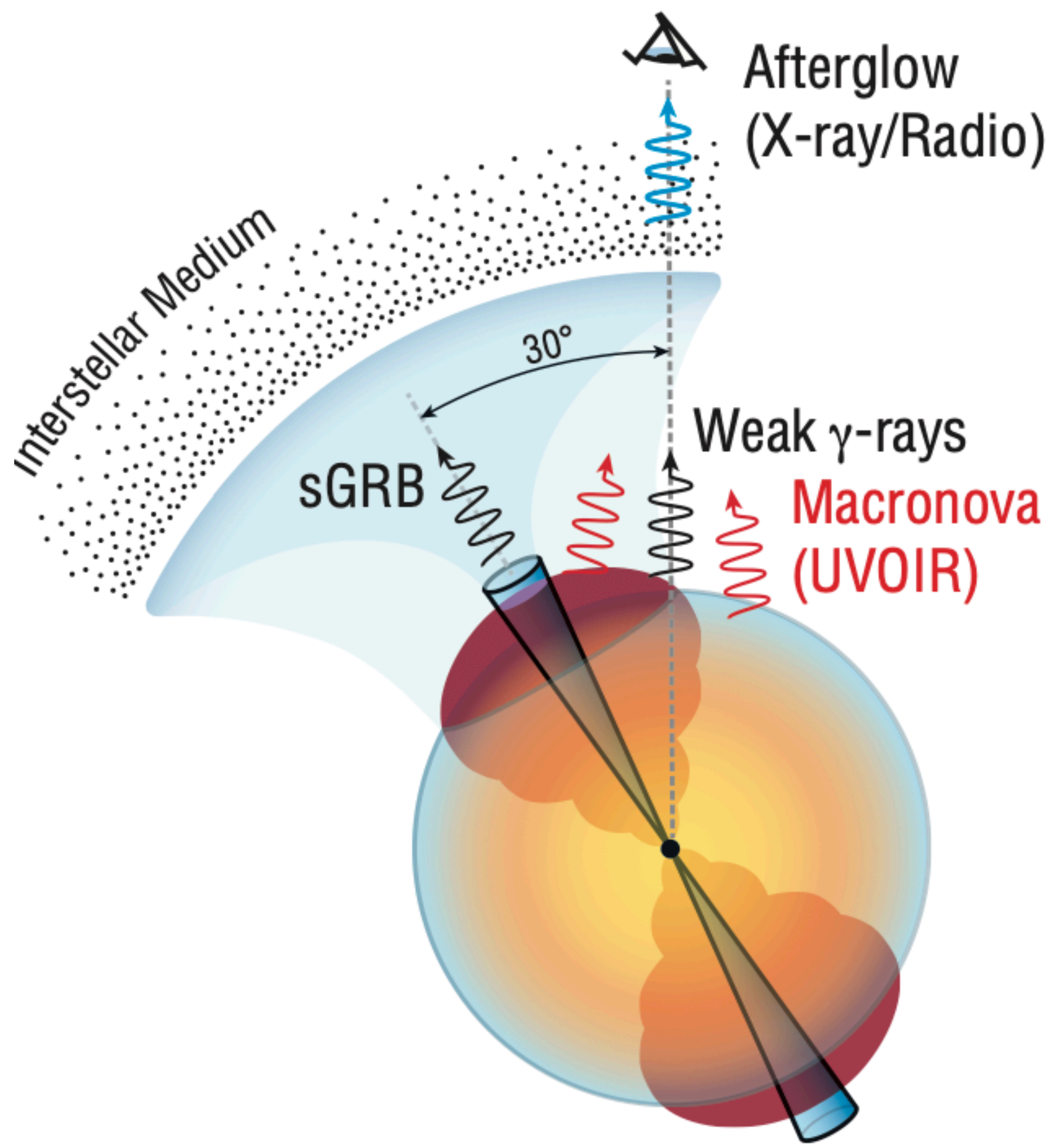
Follow-up observations across the spectrum!

Sadly no neutrinos detected :(

[1710.05833](), [2105.13160]()

What can we learn?

GW170817 resulted in a **kilonova**



1710.05436

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

1901.09044

Extreme nuclear/quark physics!

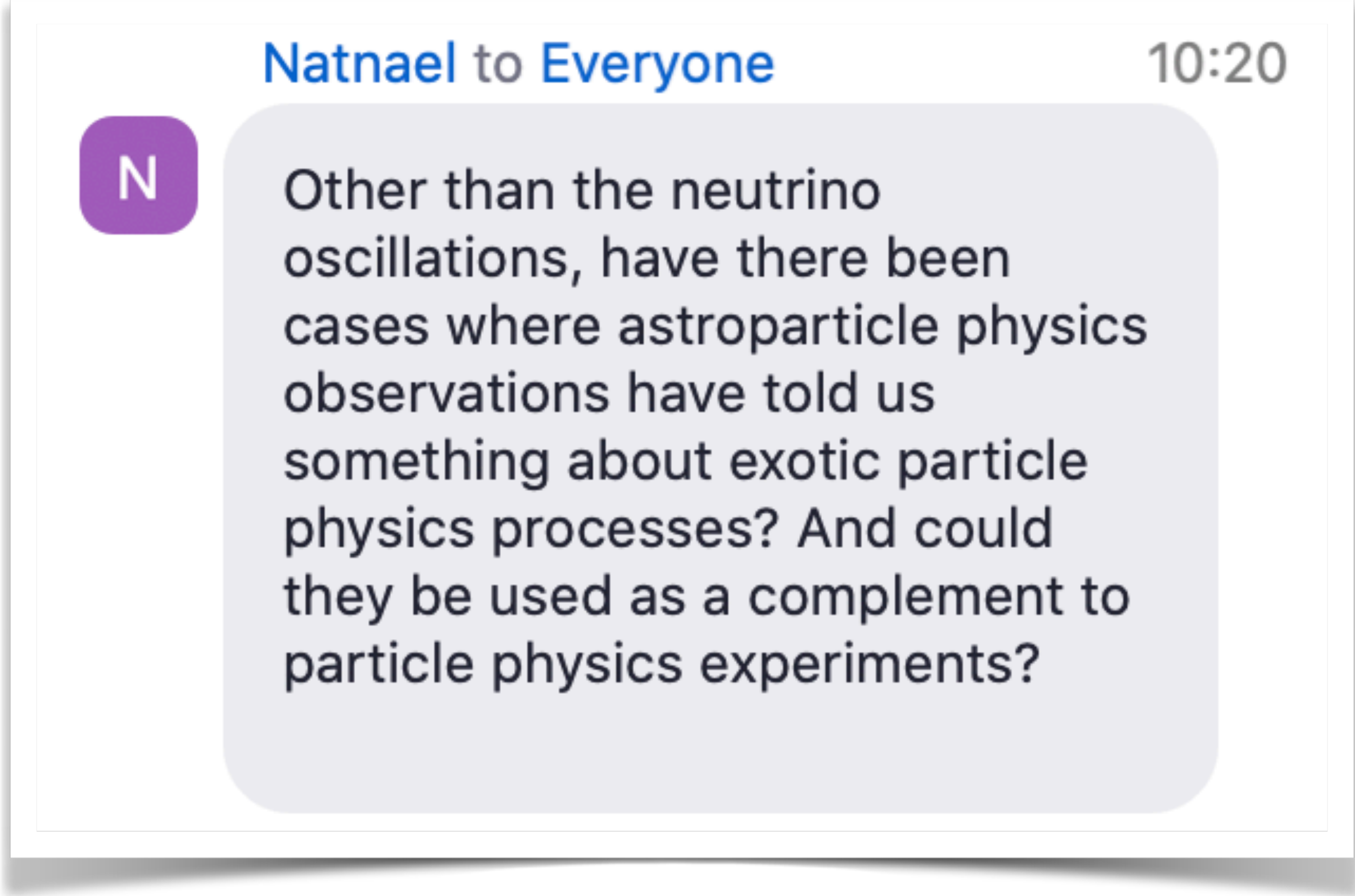
2103.16371

Tests of general relativity!

1710.06394

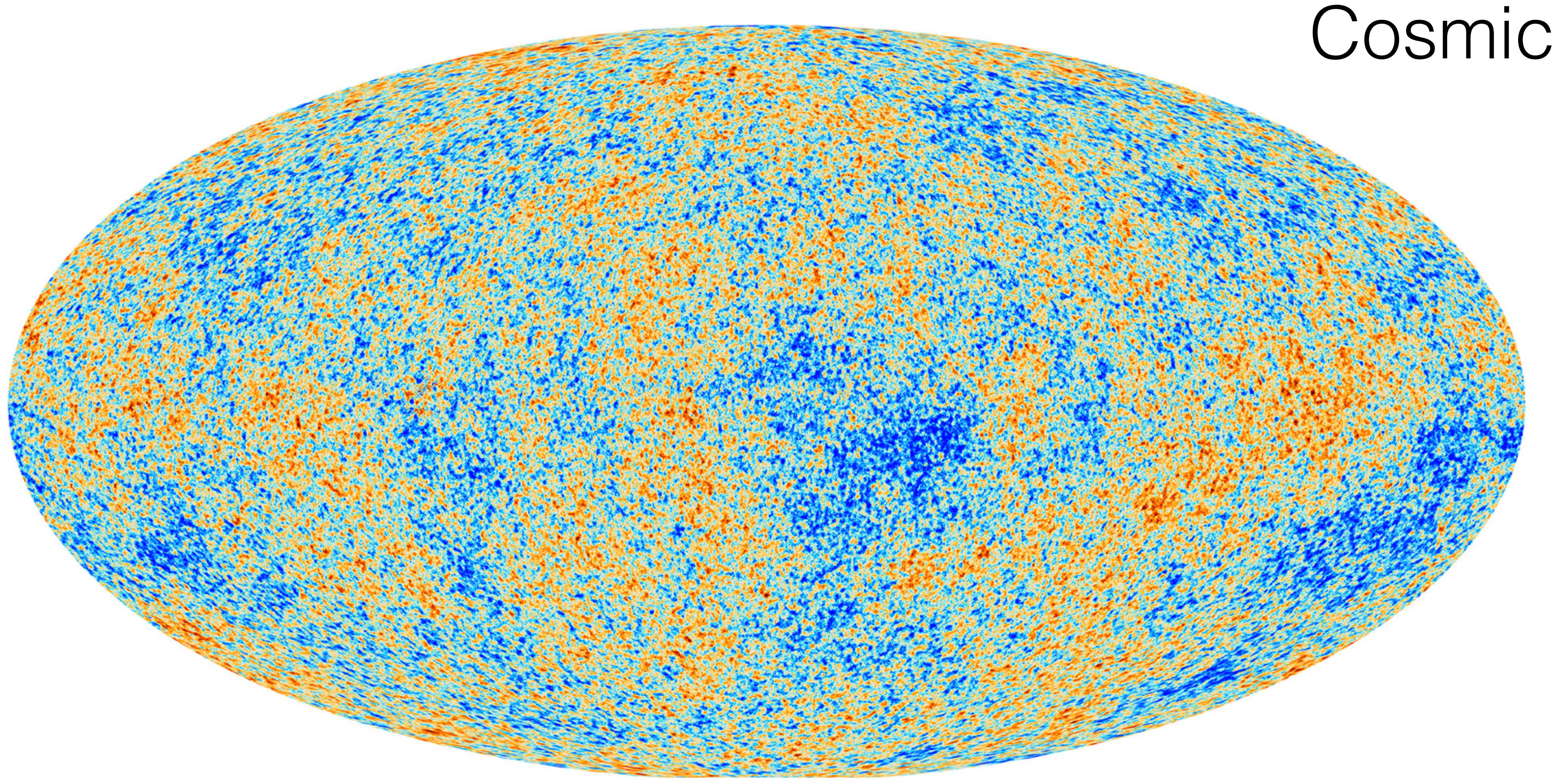
Measurement of the Hubble Constant!

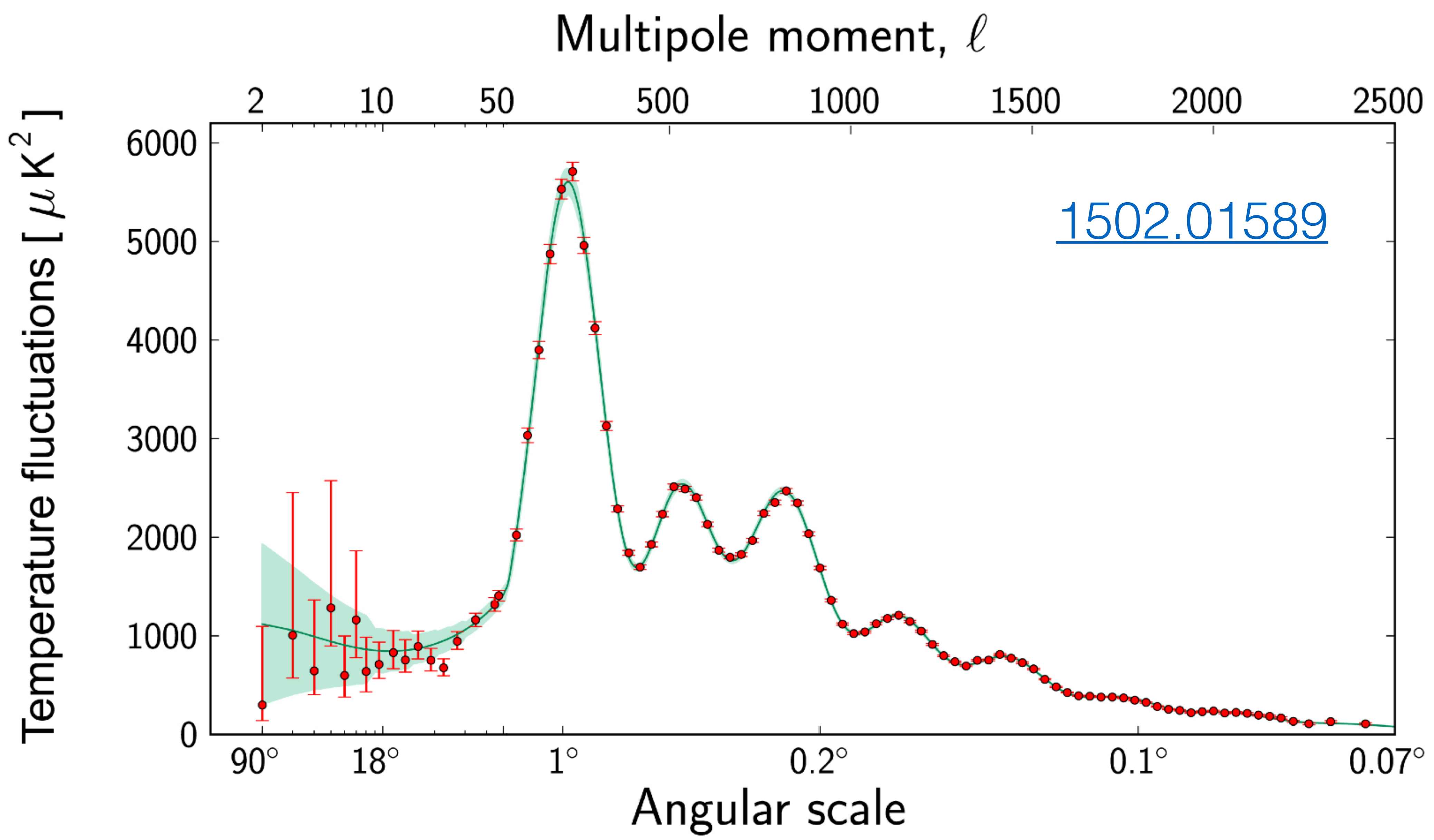
1710.05835

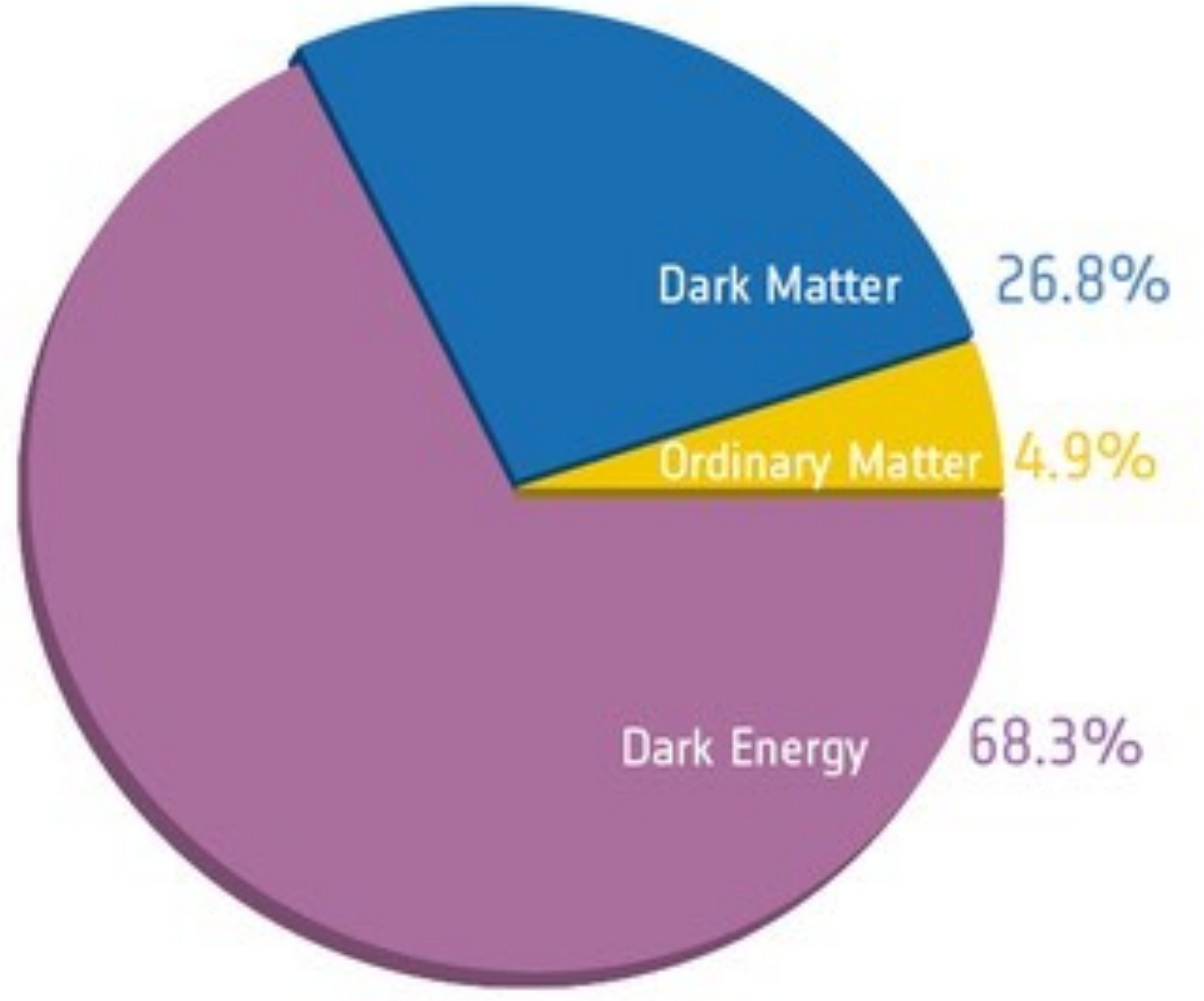


Dark Matter in Cosmology

Cosmic Microwave Background (CMB)





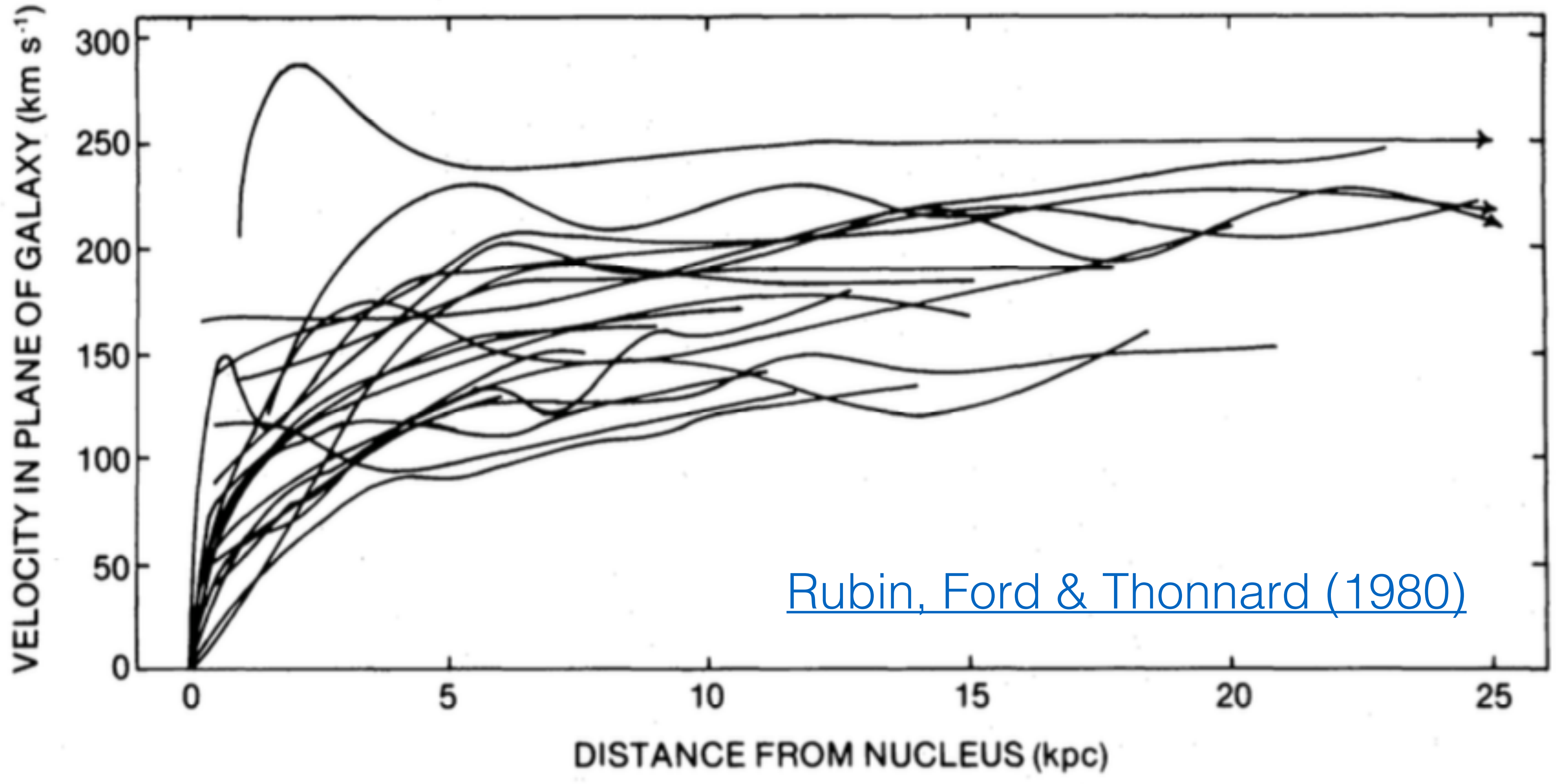


Credit: ESA/Planck Collaboration

See "Introduction to Cosmology" Lectures by Daniel Baumann

Dark Matter in Galaxies

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

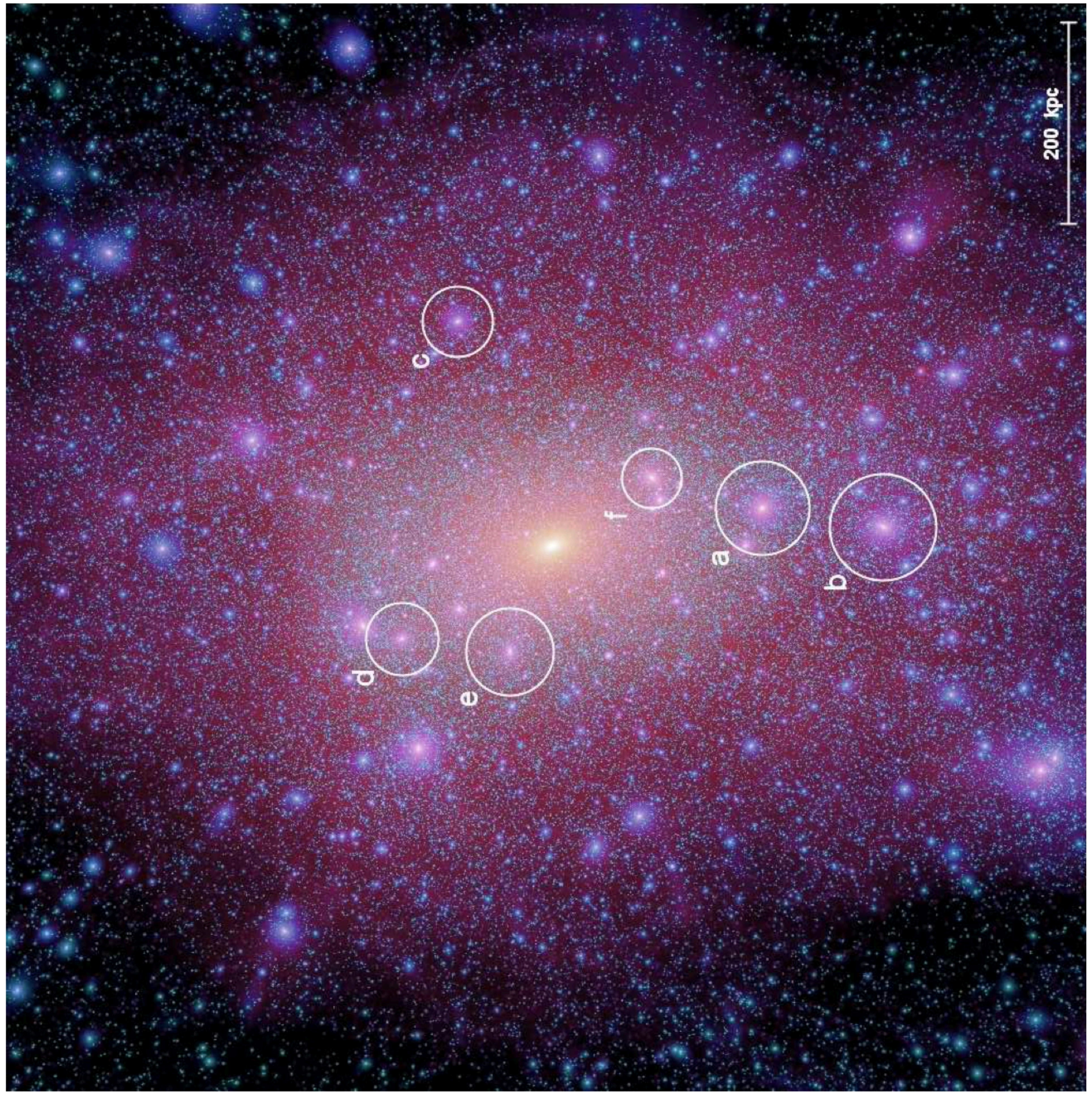


Rubin, Ford & Thonnard (1980)

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

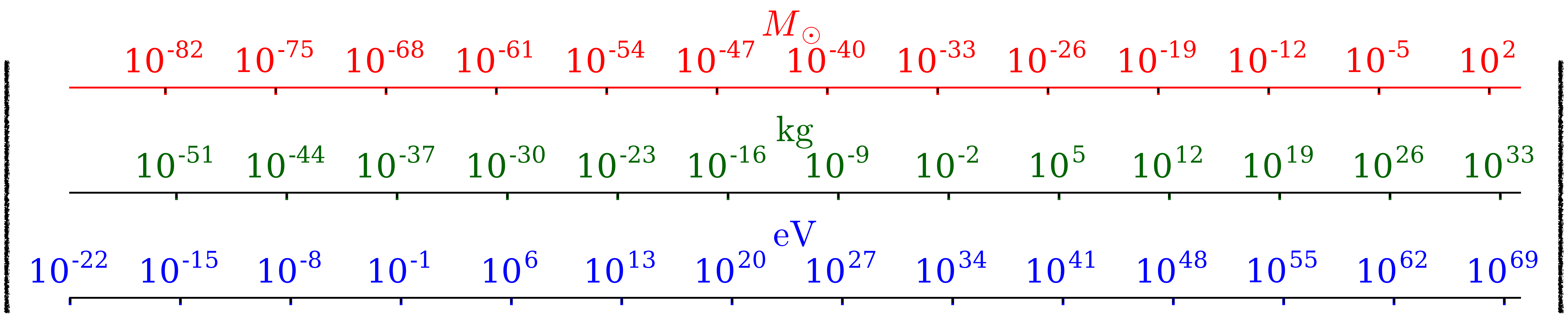


Aquarius simulation - 0809.0898

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…

Dark Matter properties

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- Non-baryonic
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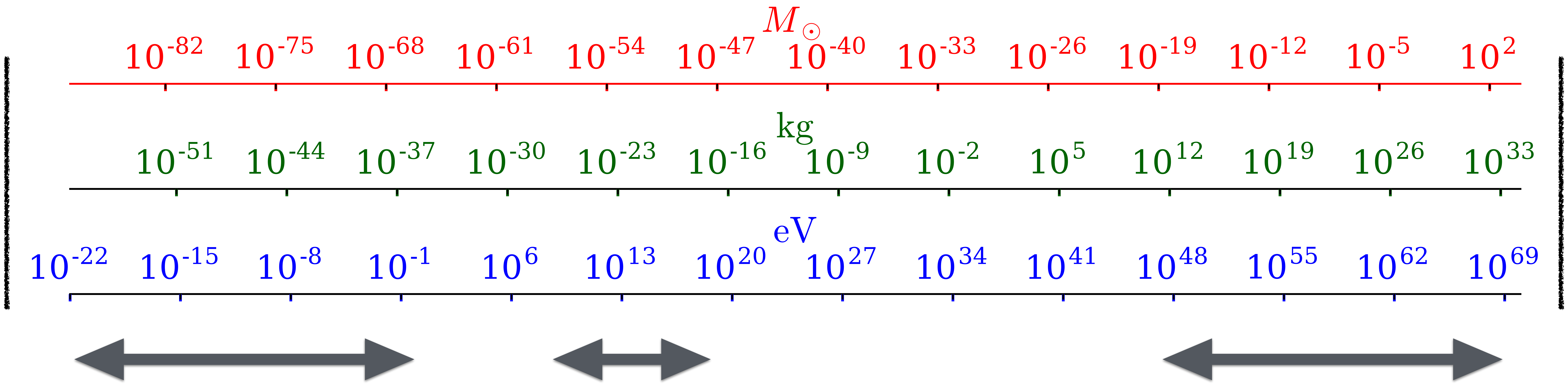

Axion-like particles
(**ALPs**)

Weakly interacting
massive particles
(**WIMPs**)

Primordial Black Holes
(**PBHs***)

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

Too heavy!
DM mass comparable to
galactic masses!

*See additional slides…

Dark Matter properties

Dark Matter must be:

- Non-baryonic
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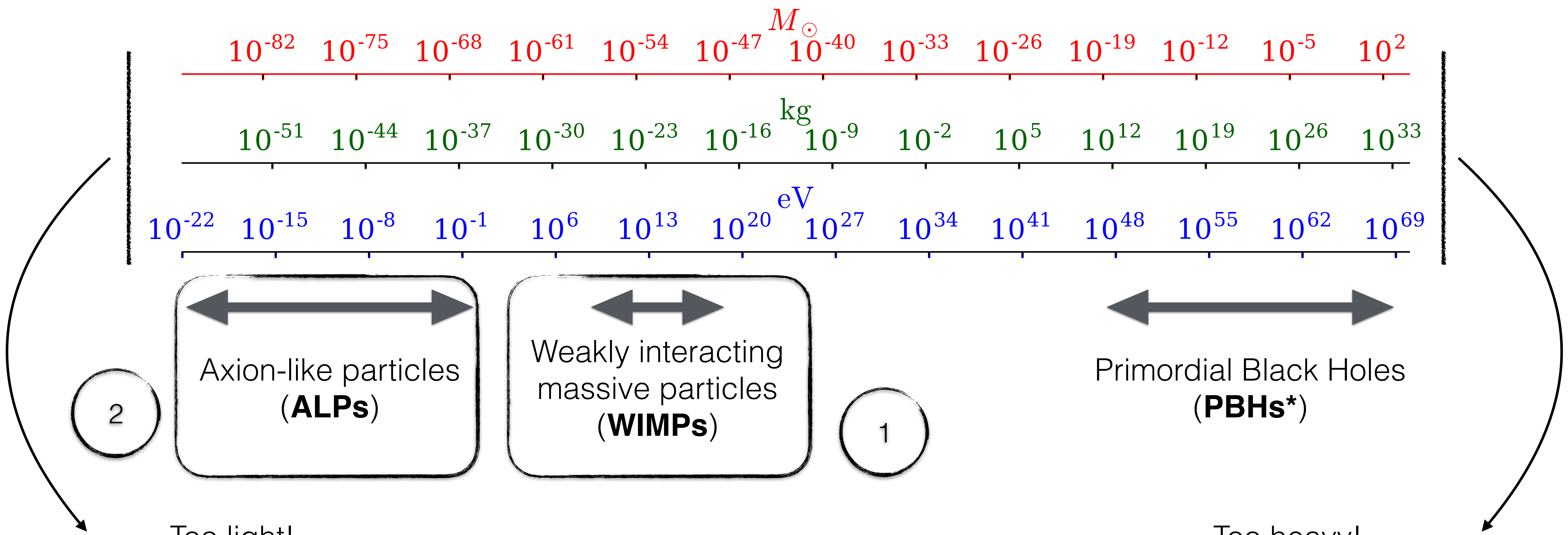


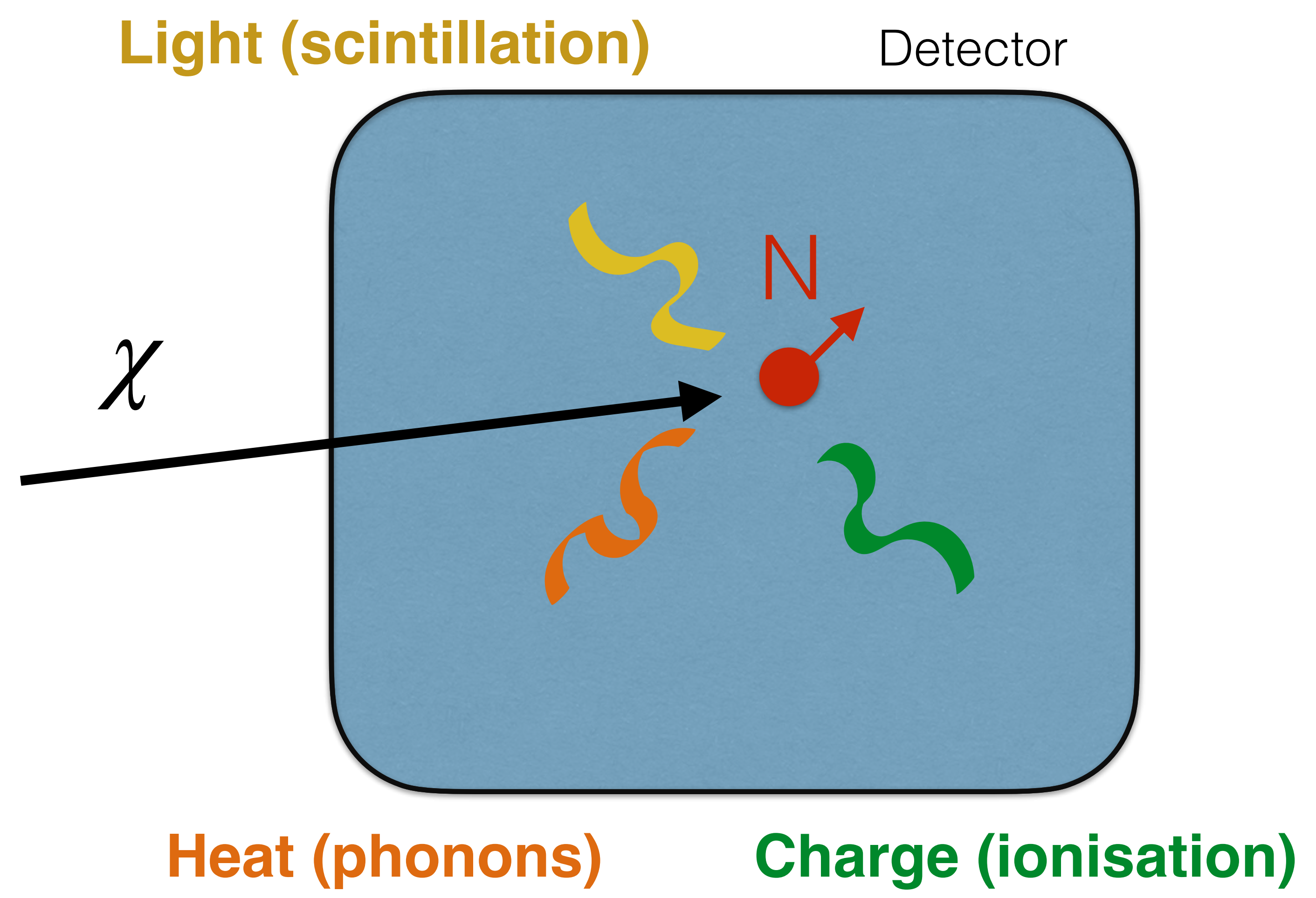
Too light!
Has wave-like properties on galactic scales!

Too heavy!
DM mass comparable to galactic masses!

*See additional slides…

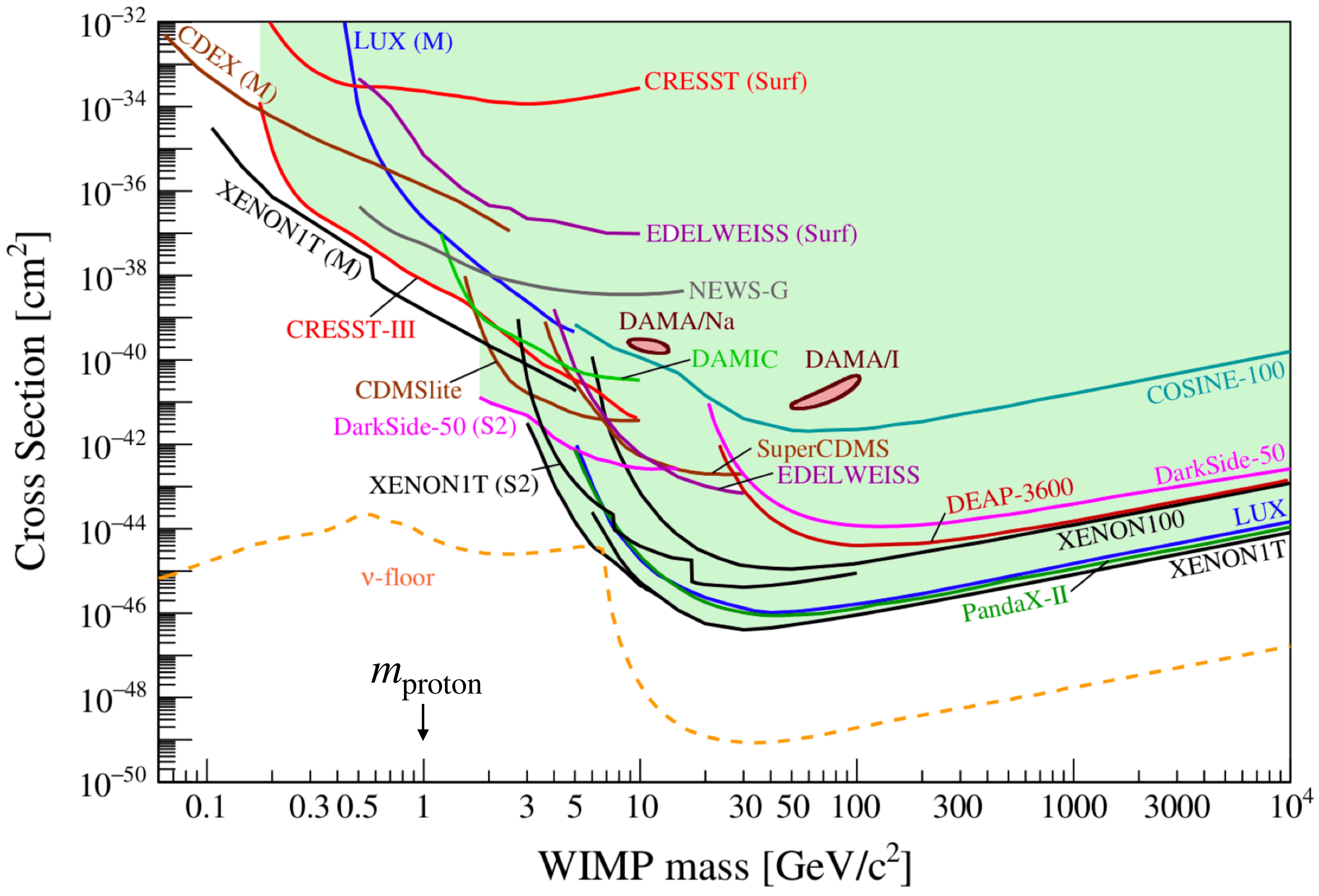
Direct detection of WIMPs on Earth

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!

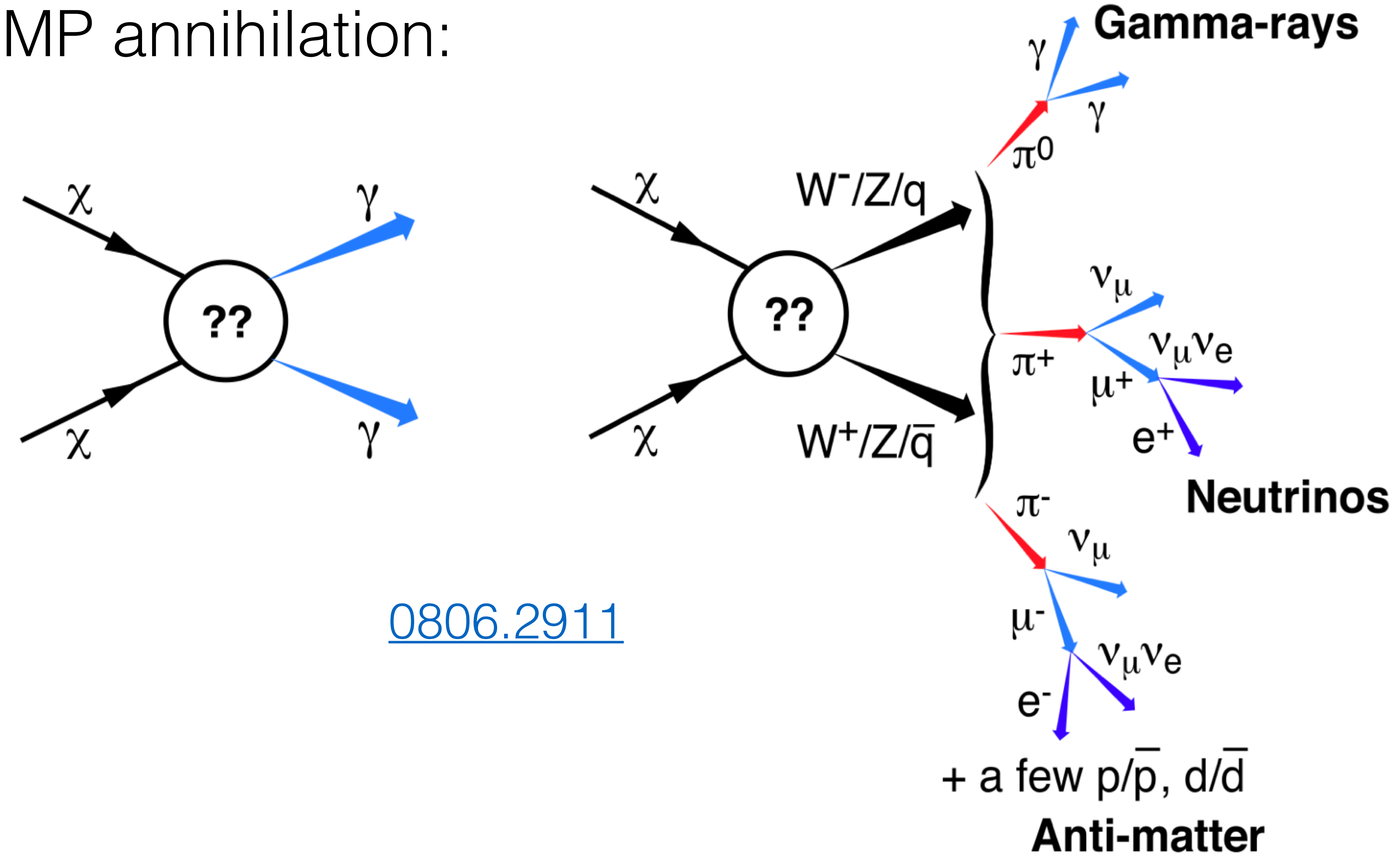


Also possible to look for DM-electron scattering, depending on the model.

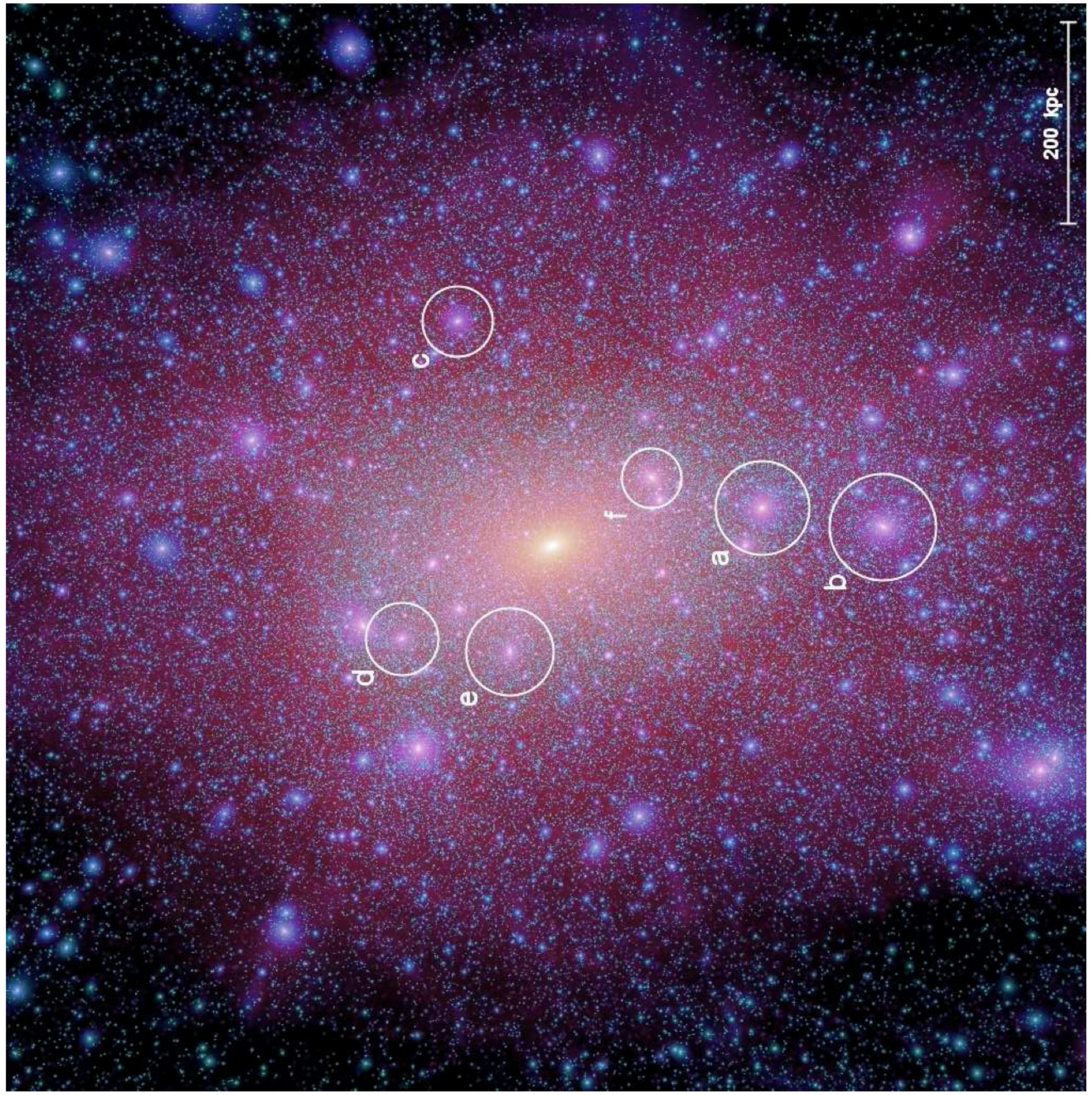
Indirect detection of Dark Matter

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

WIMP annihilation:



0806.2911



Aquarius simulation - 0809.0898

Annihilation cross section (particle physics)

DM density distribution (astrophysics)

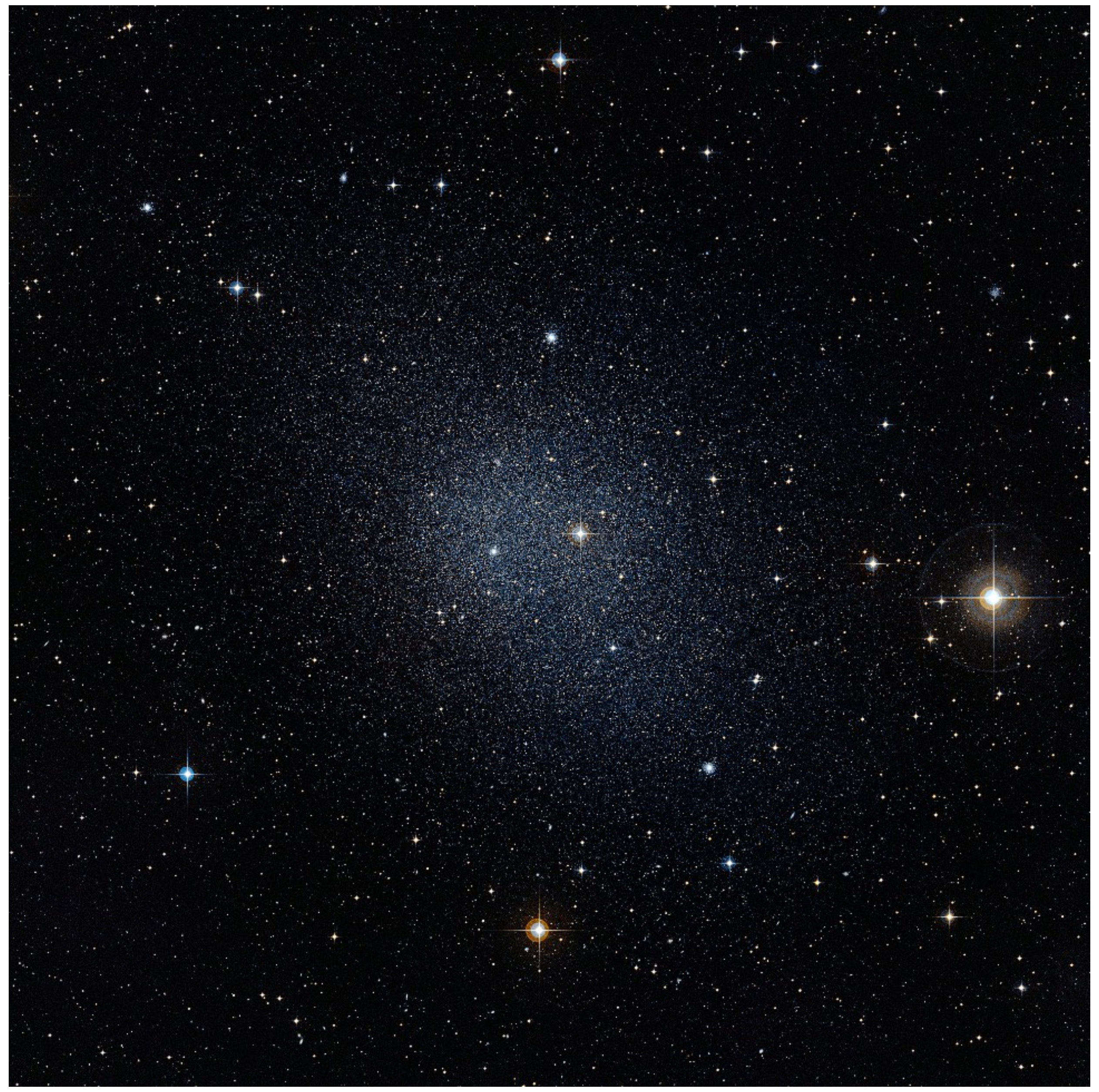
$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \int_{\mathrm{d}\Omega}\mathrm{d}\Omega' \int_{los}\rho^2 \mathrm{d}l\,(r,\theta')$$

Gamma-ray spectrum (annihilation channel)

1012.4515

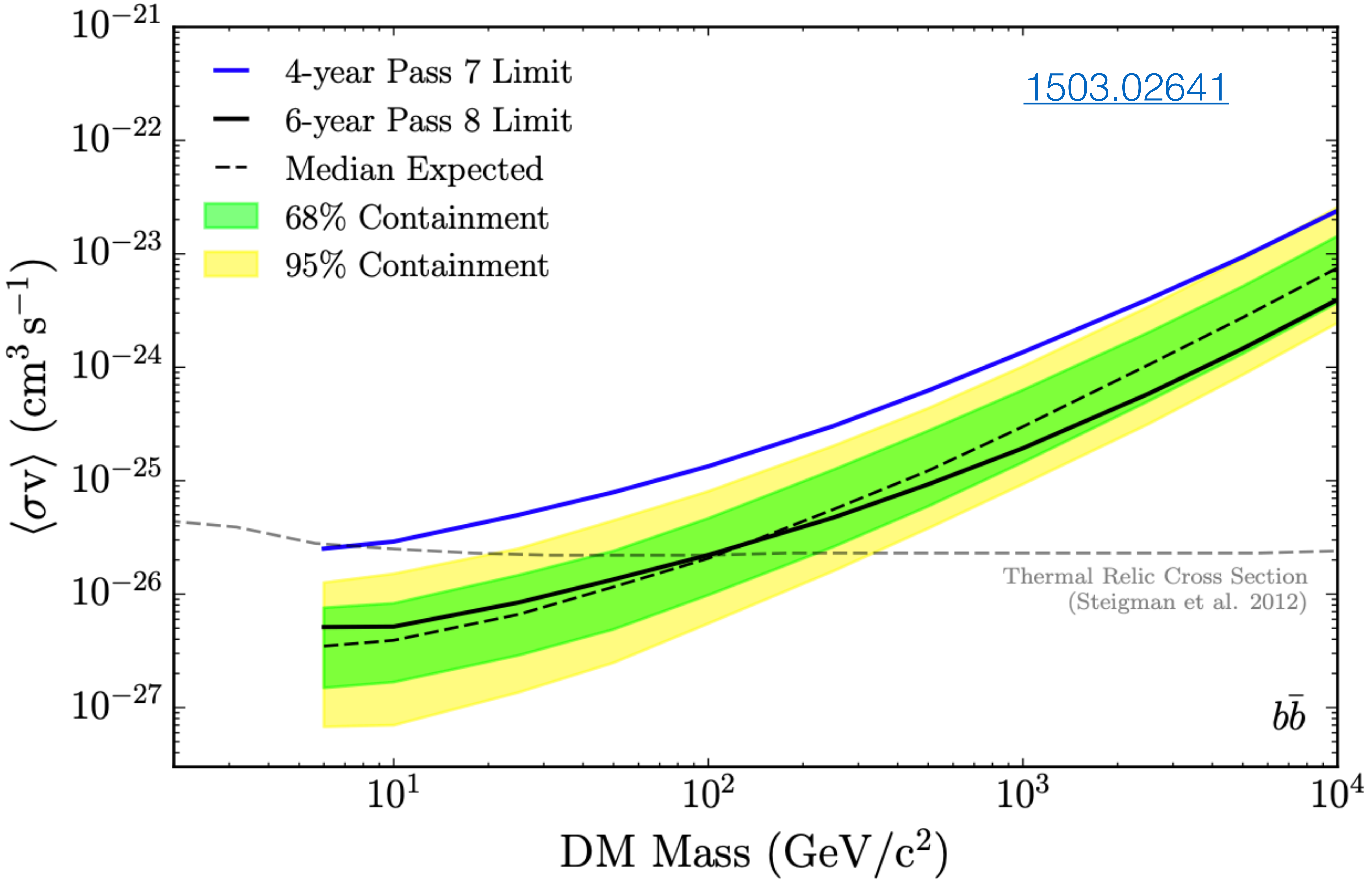
Gamma-ray constraints

Fornax Dwarf Galaxy
(Satellite of the Milky Way)



Credit: ESO/Digitized Sky Survey 2

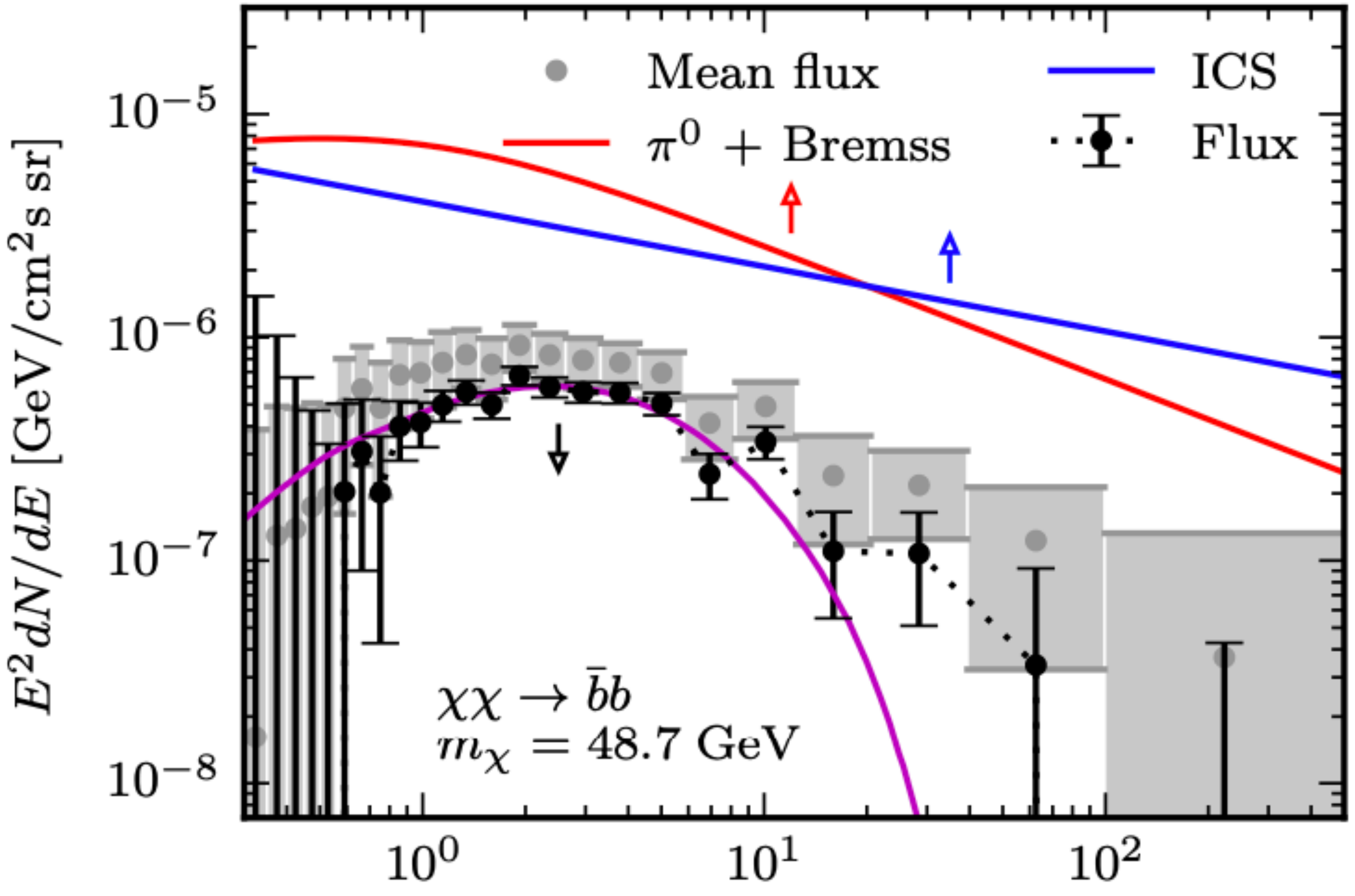
Fermi constraints from 15 Dwarf Spheroidal Galaxies:



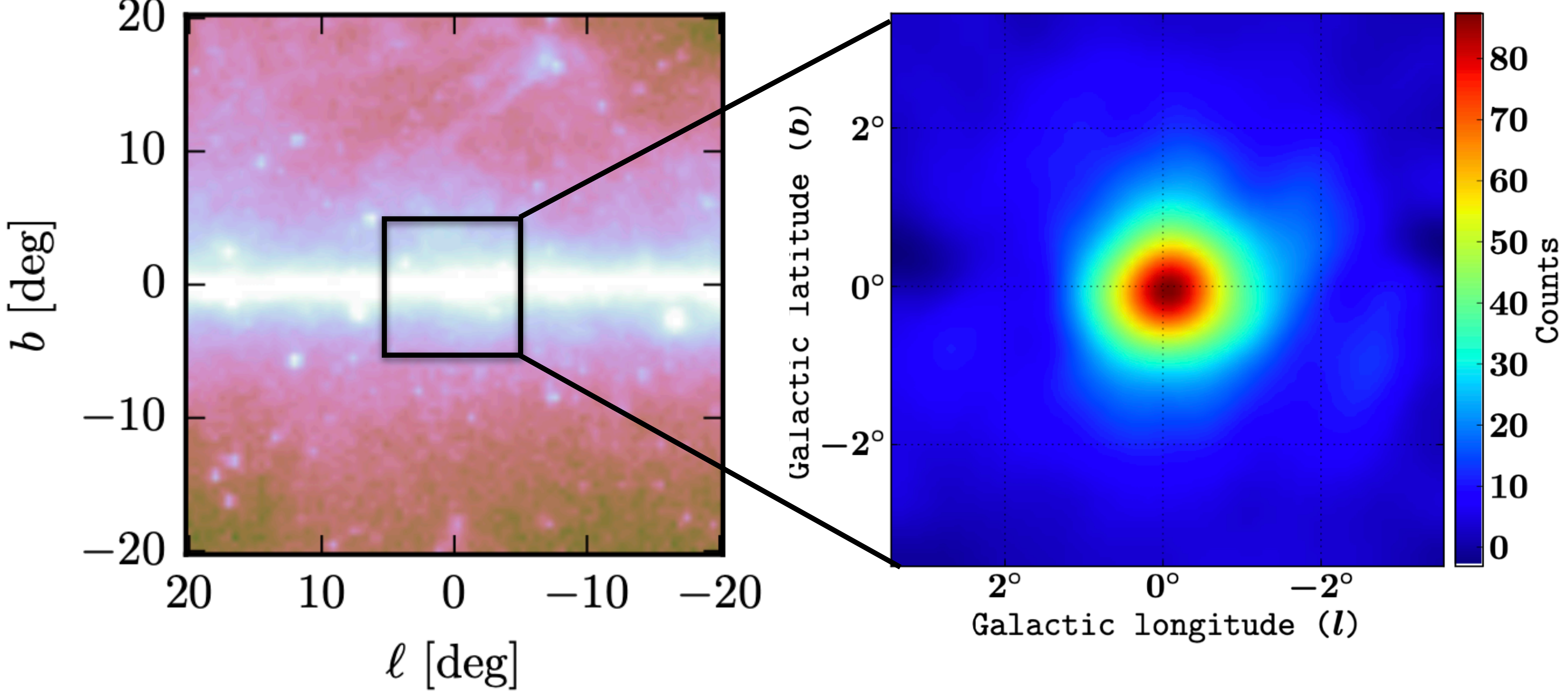
Exact constraints depend on annihilation channel ($\chi\chi \to b\bar{b}, \chi\chi \to W^+W^-, \chi\chi \to e^+e^-$, etc.)

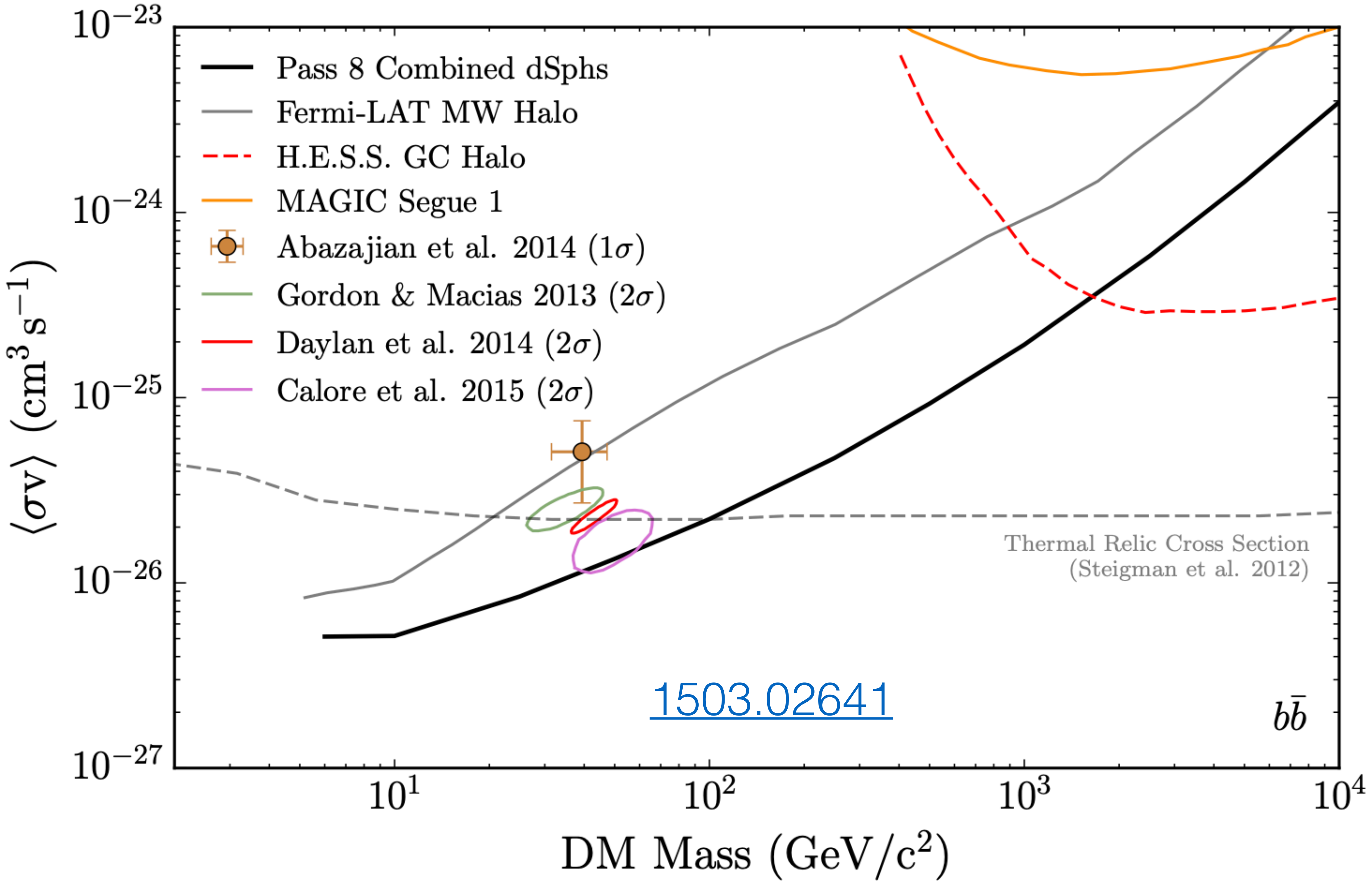
Galactic Centre Excess

1411.4647



Data 1711.04778 Residuals 1306.5725

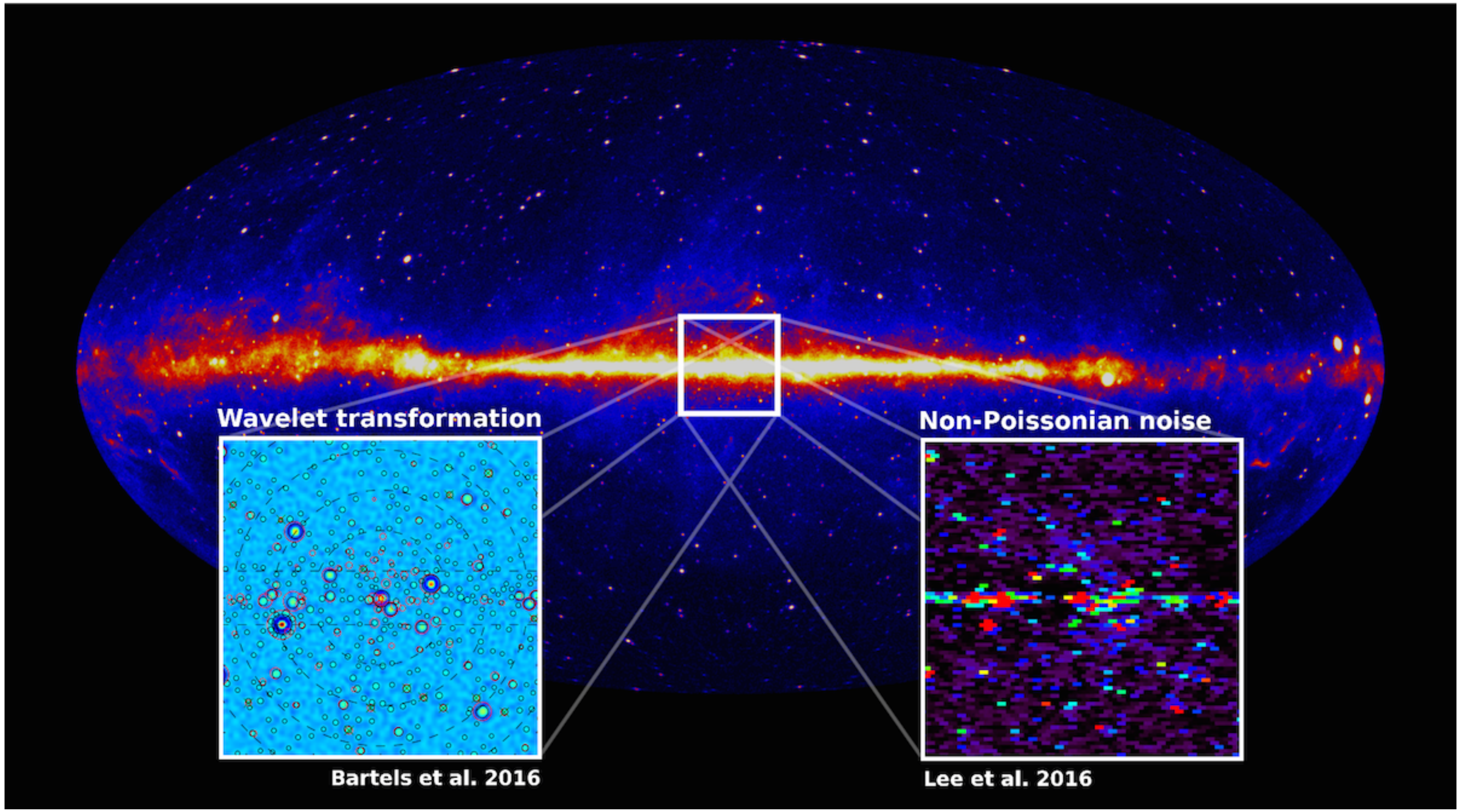




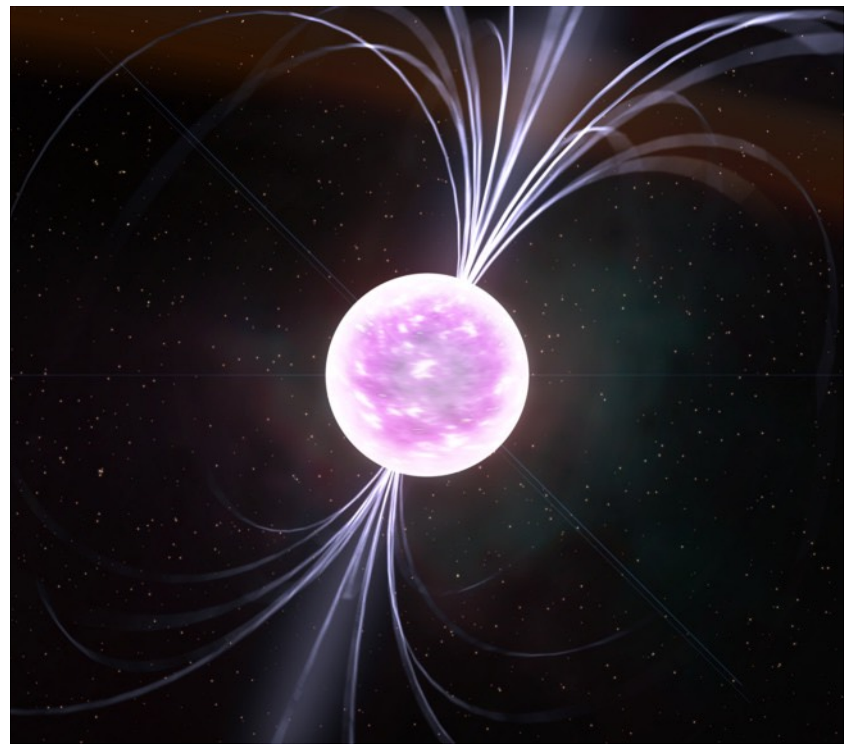
1503.02641

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

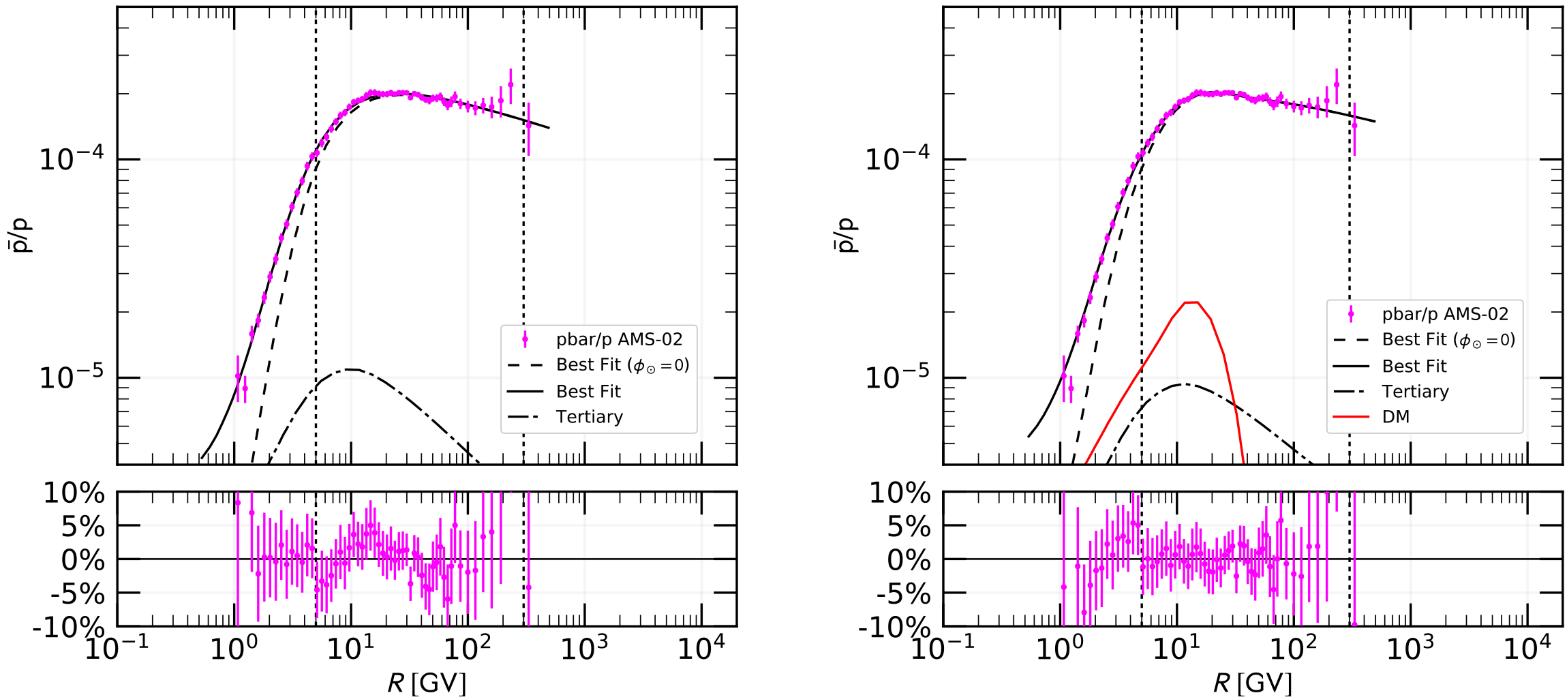


Credit: Kevin Gill / Flickr

1506.05104, 1711.04778

Anti-proton excess

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



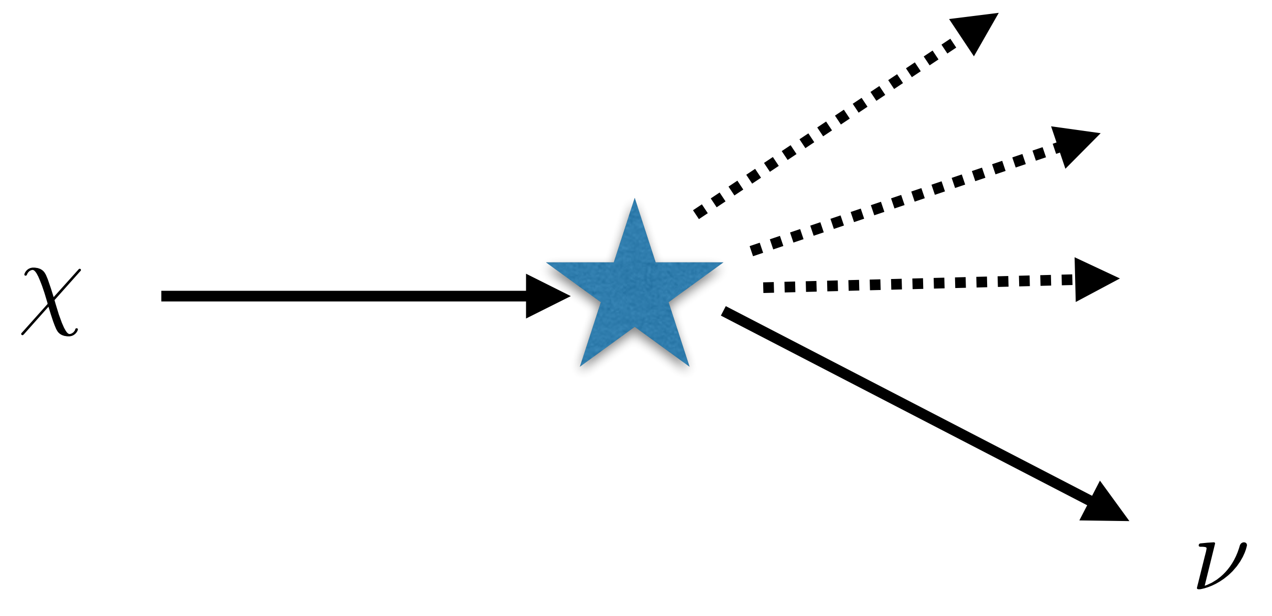
Several excesses point towards 60 GeV Dark Matter -
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

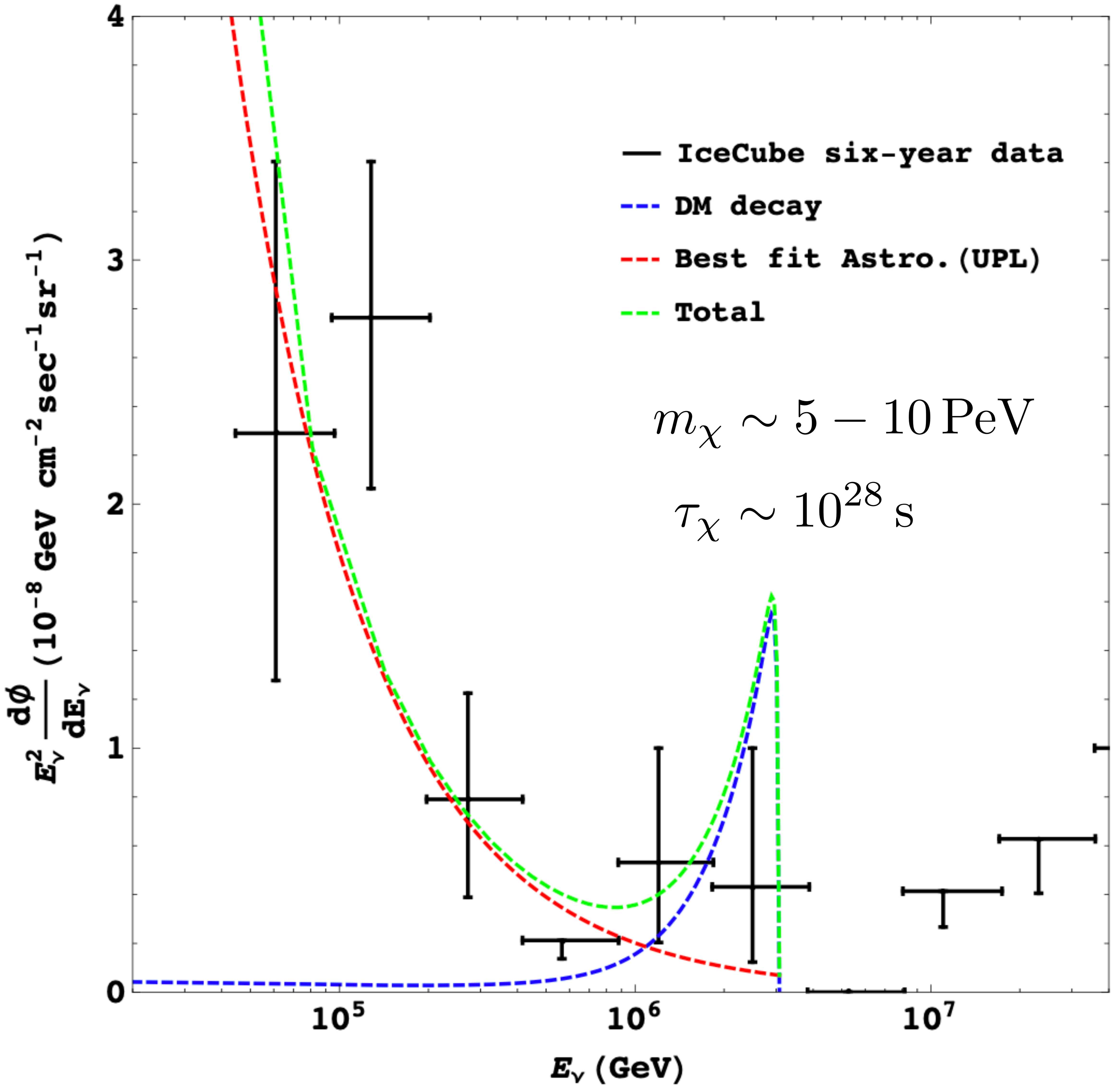
1504.04276, 1610.03071, 1903.01472

High energy neutrinos

1508.02500, 1712.07138

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

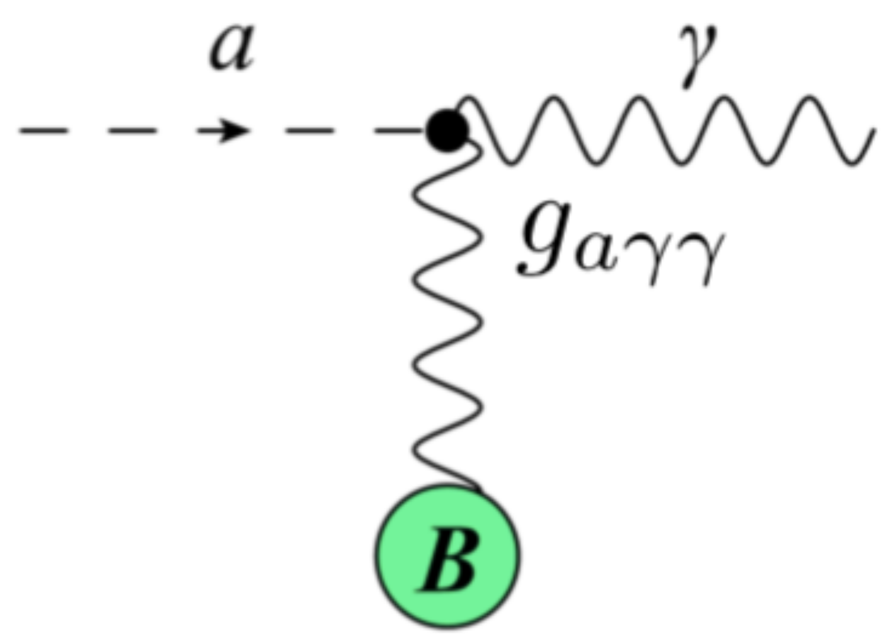


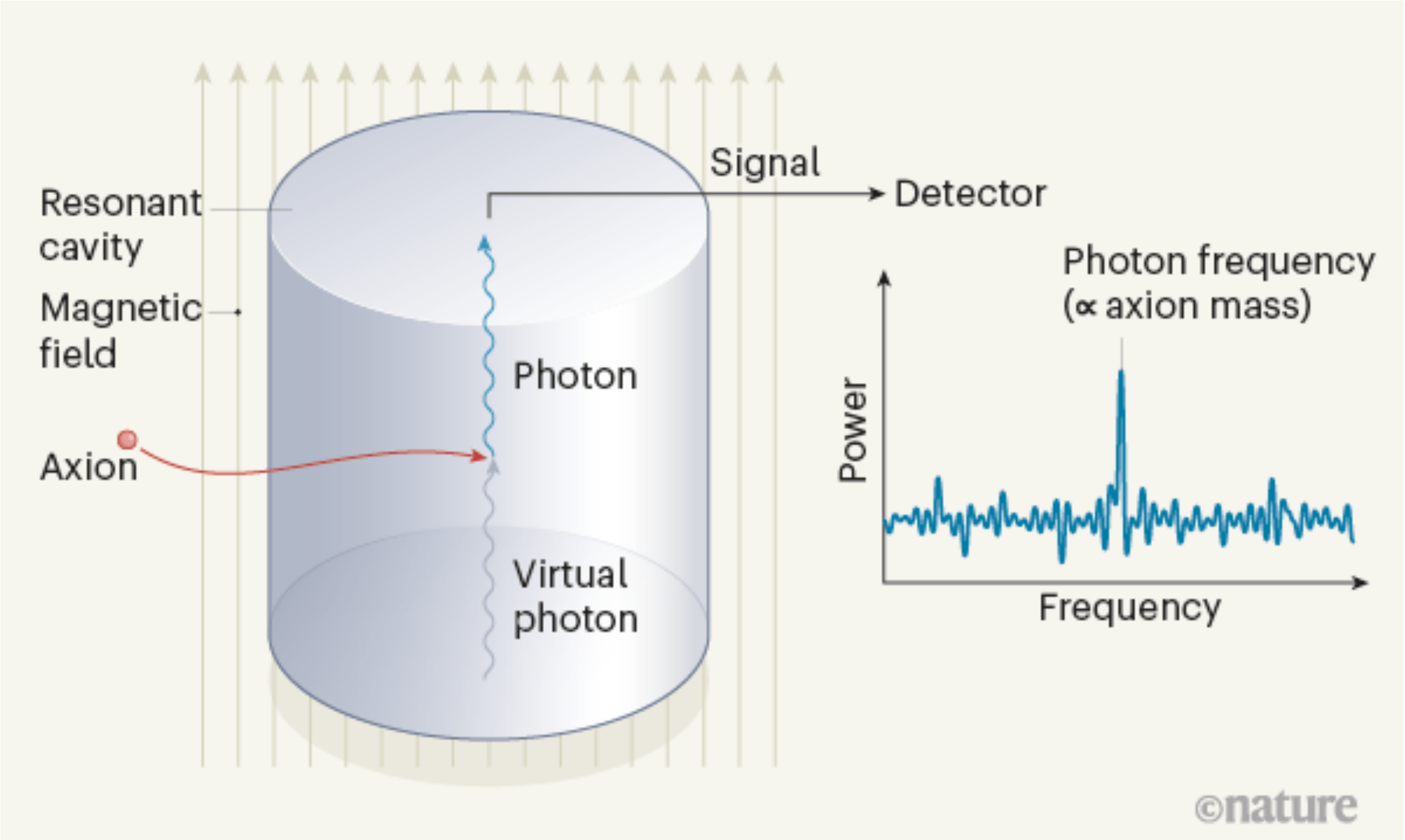


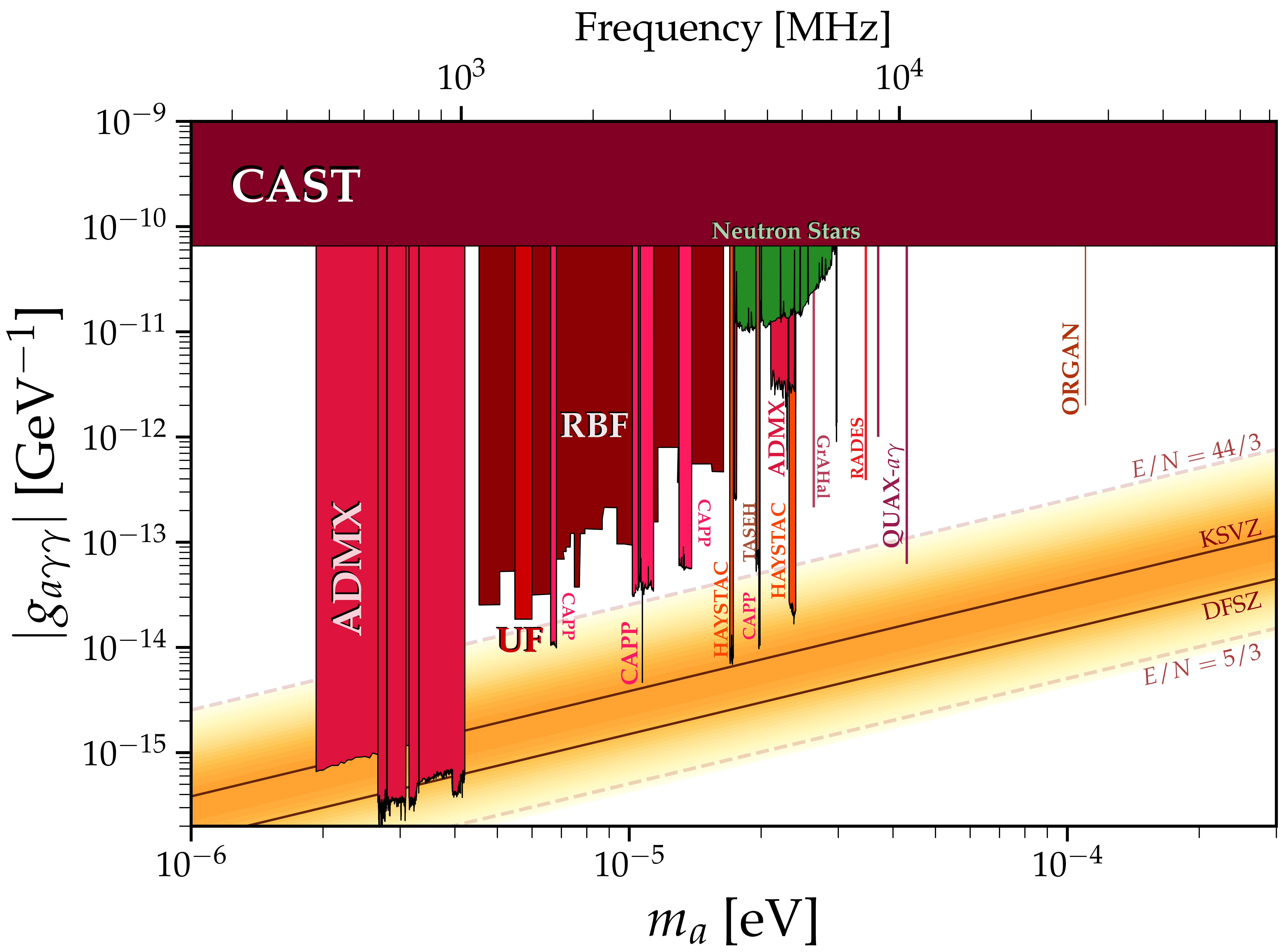
Axion searches in the lab

Axions: light pseudoscalar particles, a

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





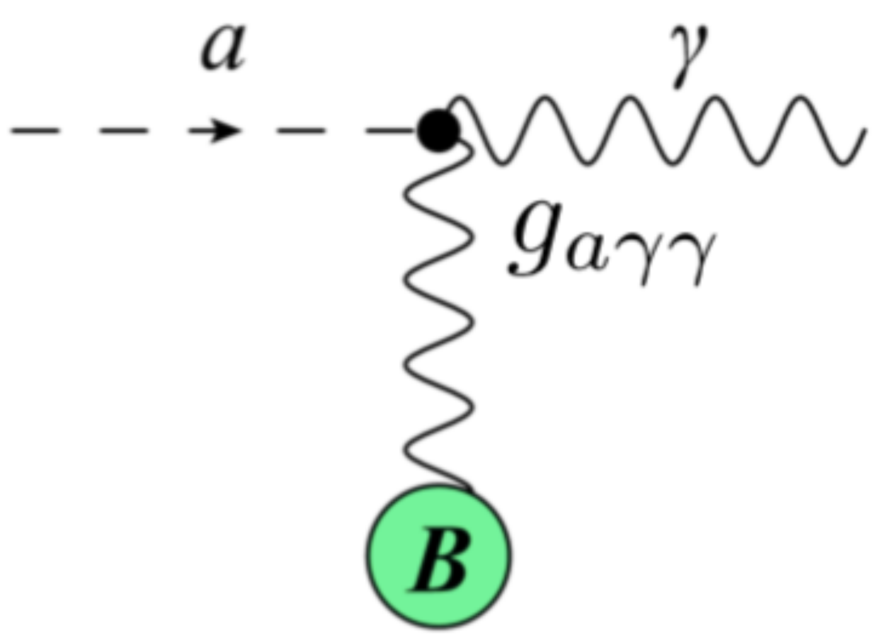


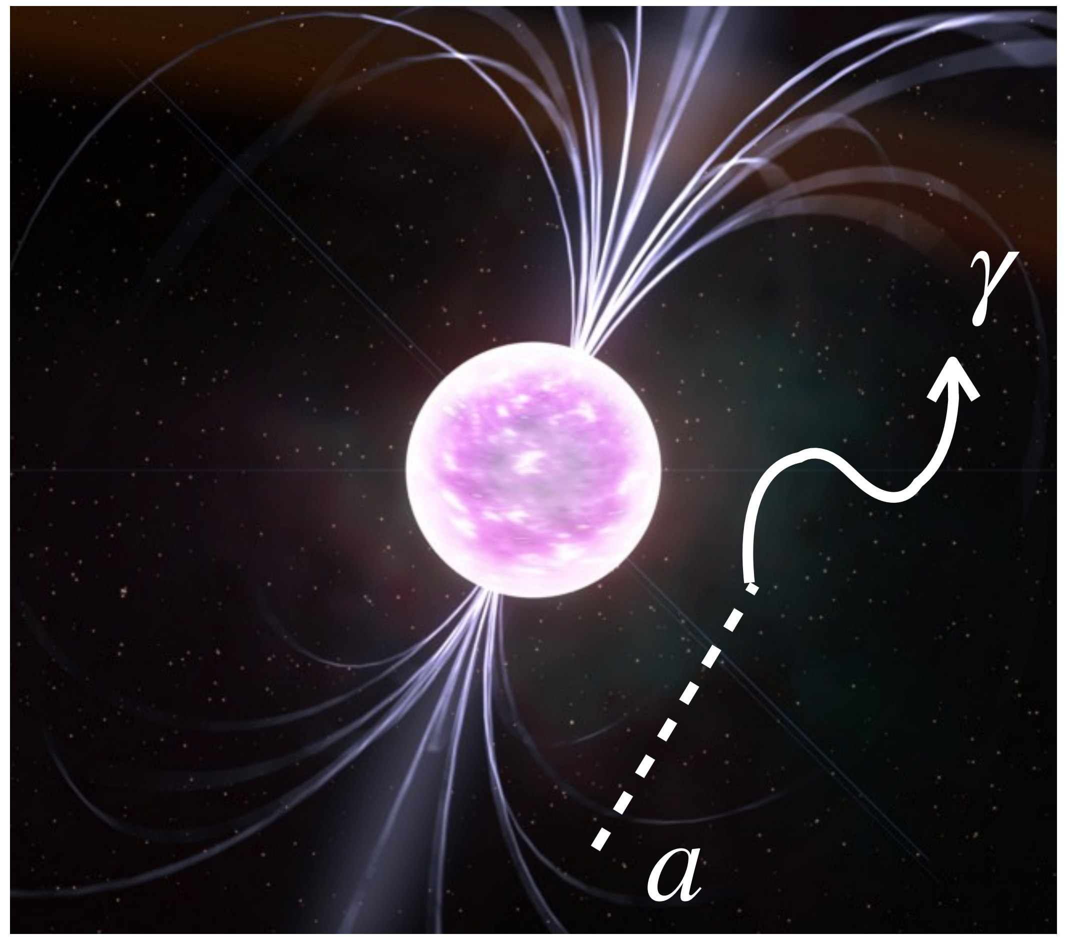
Credit: Ciaran O'Hare, AxionLimits

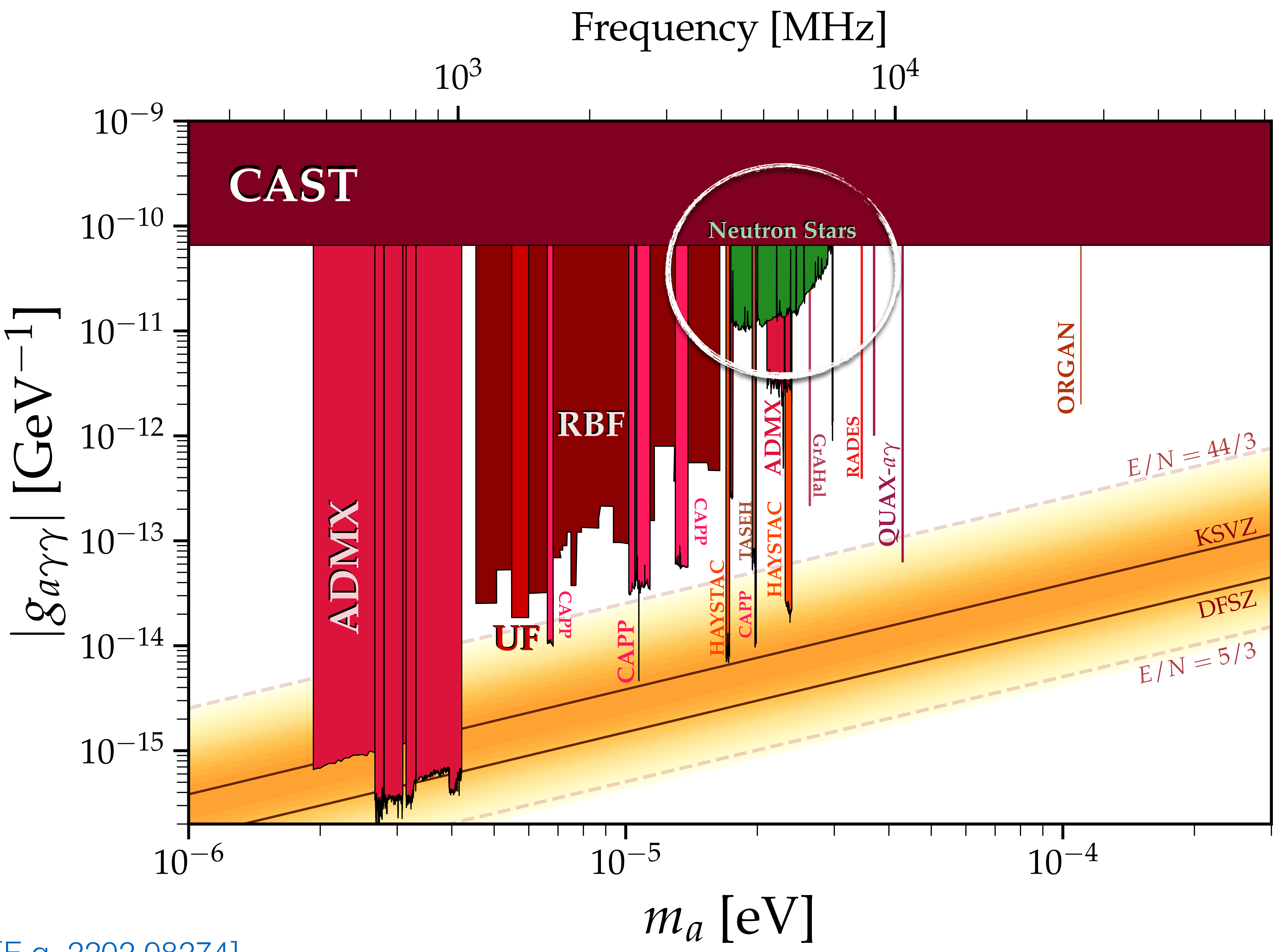
Axion searches and Neutron Stars

Axions: light pseudoscalar particles, a

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

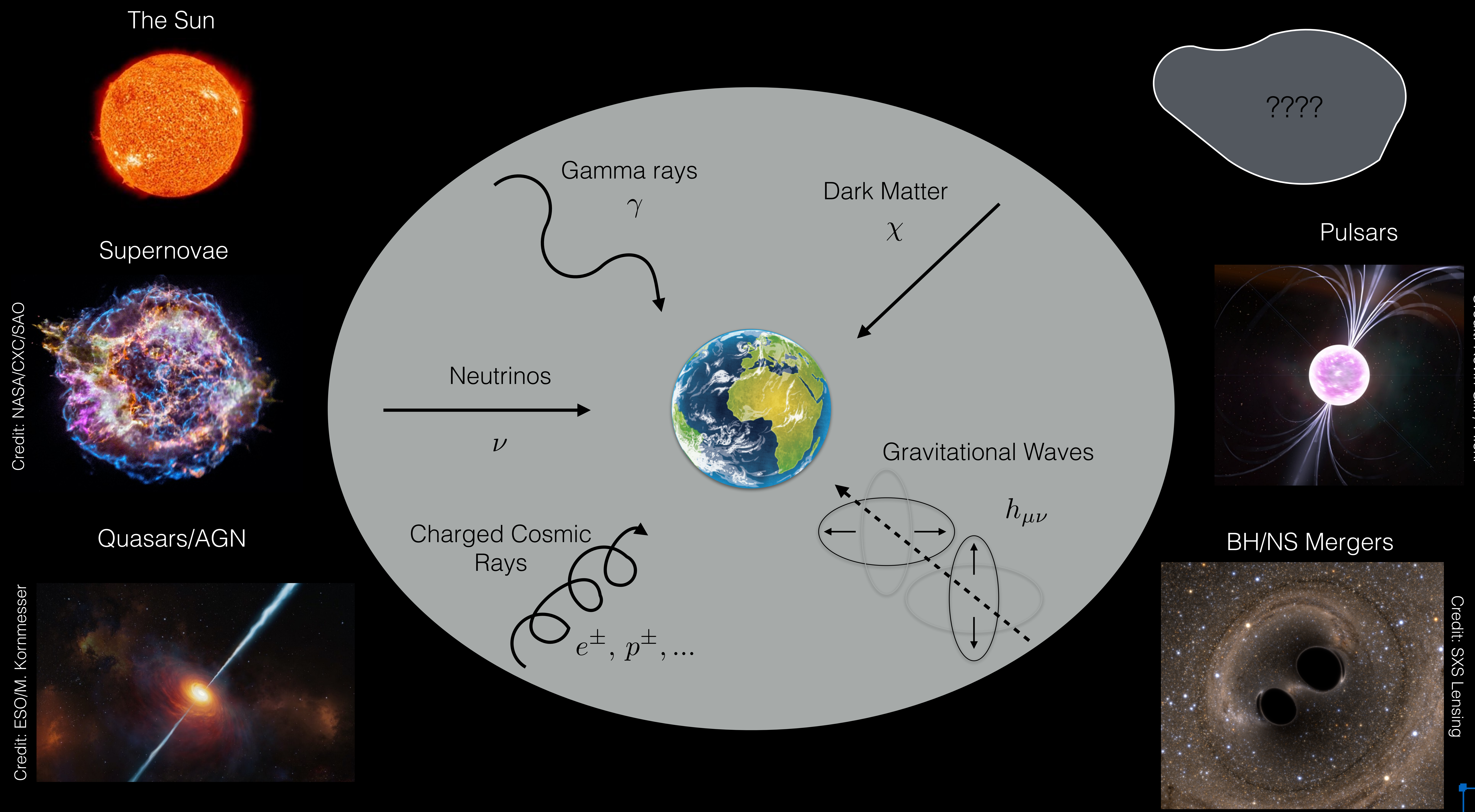




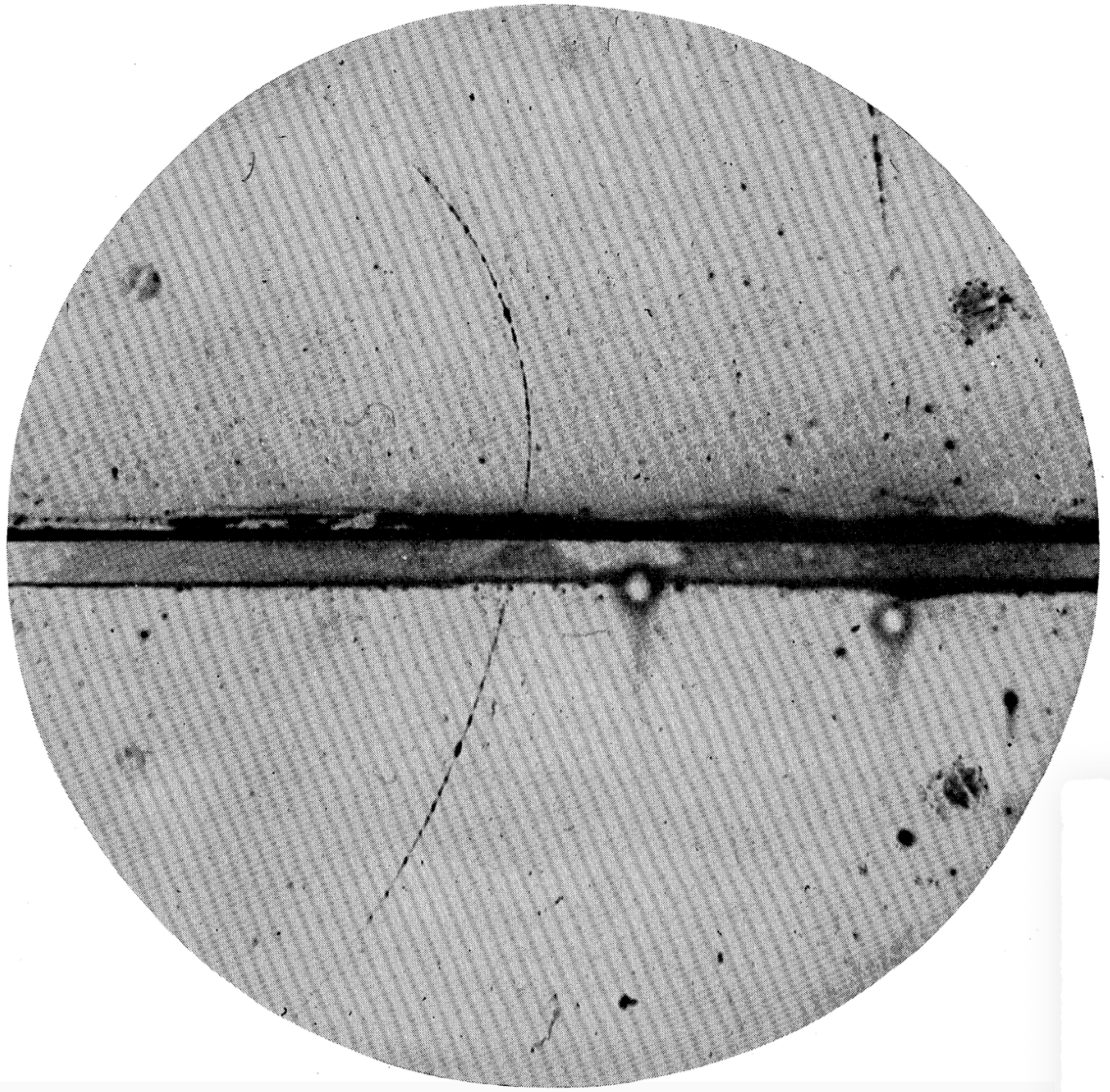


[E.g. 2202.08274]

Credit: Ciaran O'Hare, AxionLimits

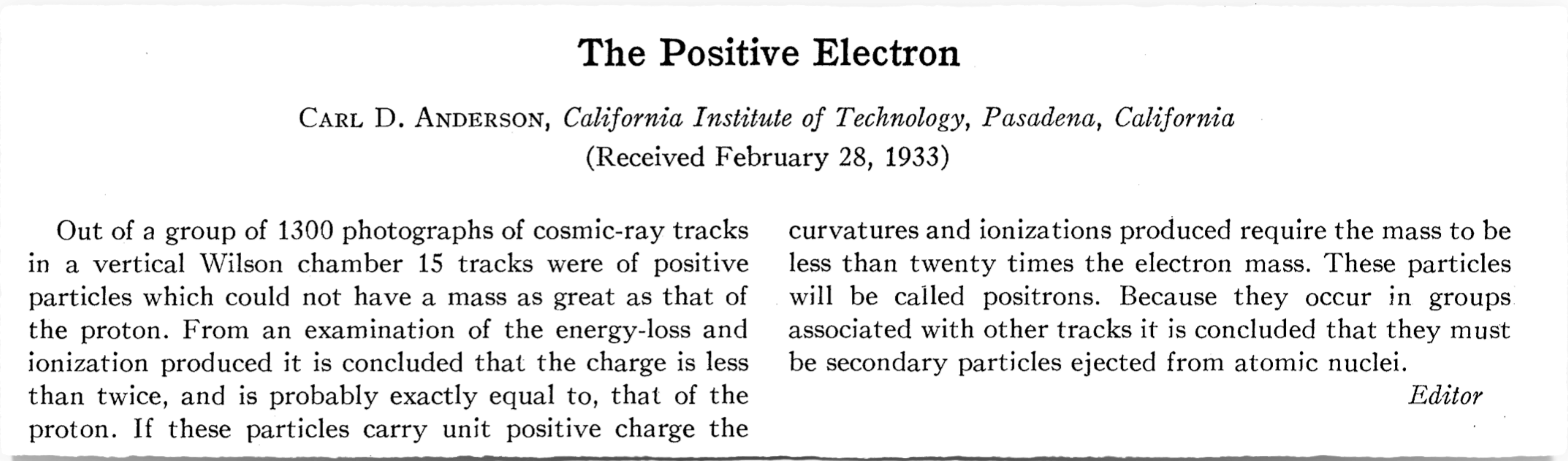

The Sun
Supernovae
Credit: NASA/CXC/SAO
Quasars/AGN
Credit: ESO/M. Kornmesser
Gamma rays
γ
Dark Matter
χ
Neutrinos
ν
Gravitational Waves
$h_{\mu\nu}$
Charged Cosmic Rays
$e^{\pm}, p^{\pm}, \ldots$
????
Pulsars
Credit: Kevin Gill / Flickr
BH/NS Mergers
Credit: SXS Lensing

The Positive Electron



Natnael to Everyone 10:20

Other than the neutrino oscillations, have there been cases where astroparticle physics observations have told us something about exotic particle physics processes? And could they be used as a complement to particle physics experiments?



The Positive Electron

CARL D. ANDERSON, *California Institute of Technology, Pasadena, California*

(Received February 28, 1933)

Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the curvatures and ionizations produced require the mass to be less than twenty times the electron mass. These particles will be called positrons. Because they occur in groups associated with other tracks it is concluded that they must be secondary particles ejected from atomic nuclei.

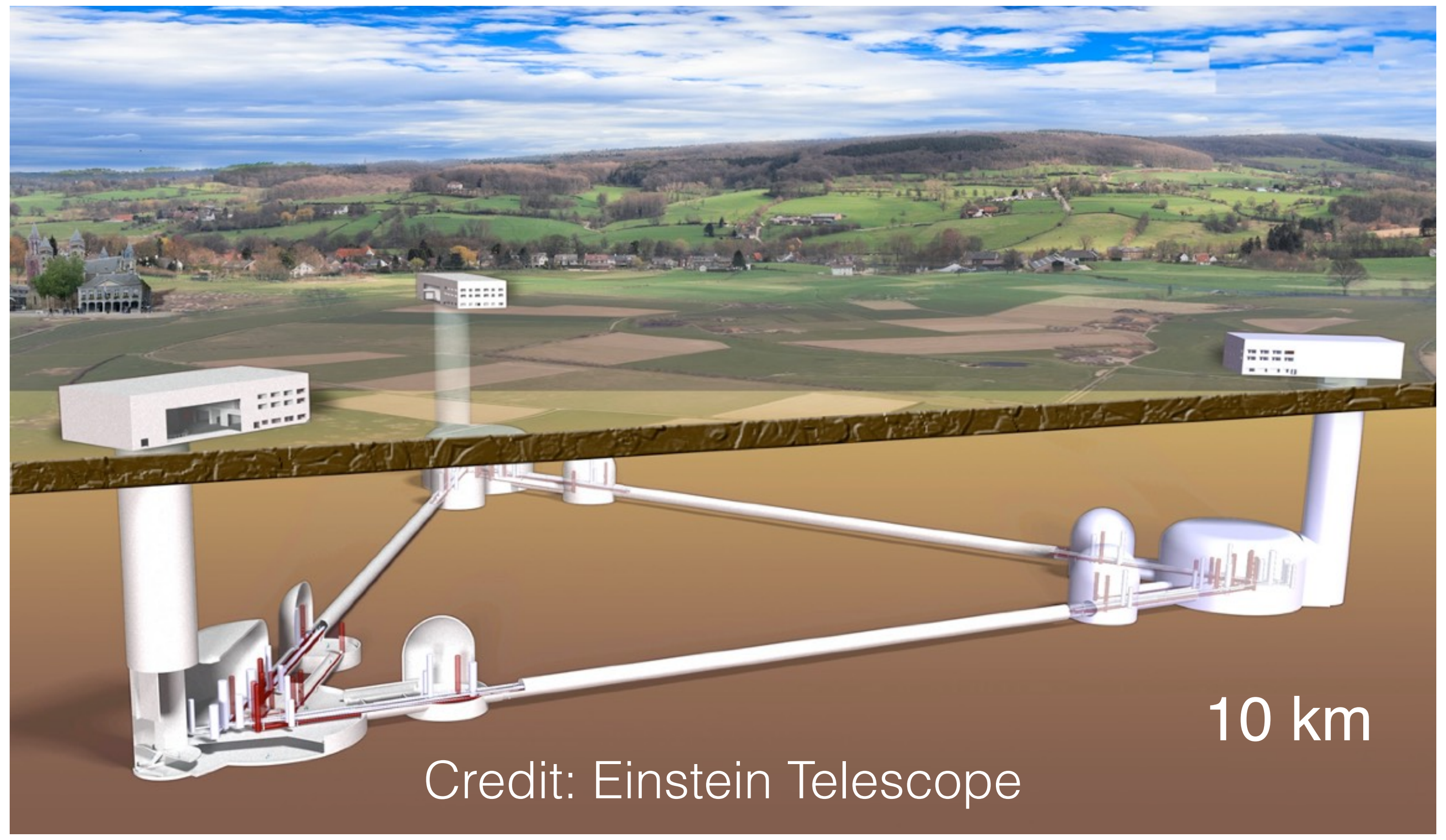
Editor

Phys. Rev. 43, 491 (1933)

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


Credit: Gabriel Pérez Diaz, IAC



Credit: Einstein Telescope

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 XENONnT will search for **WIMP Dark Matter** with unprecedented sensitivity

http://www.xenon1t.org

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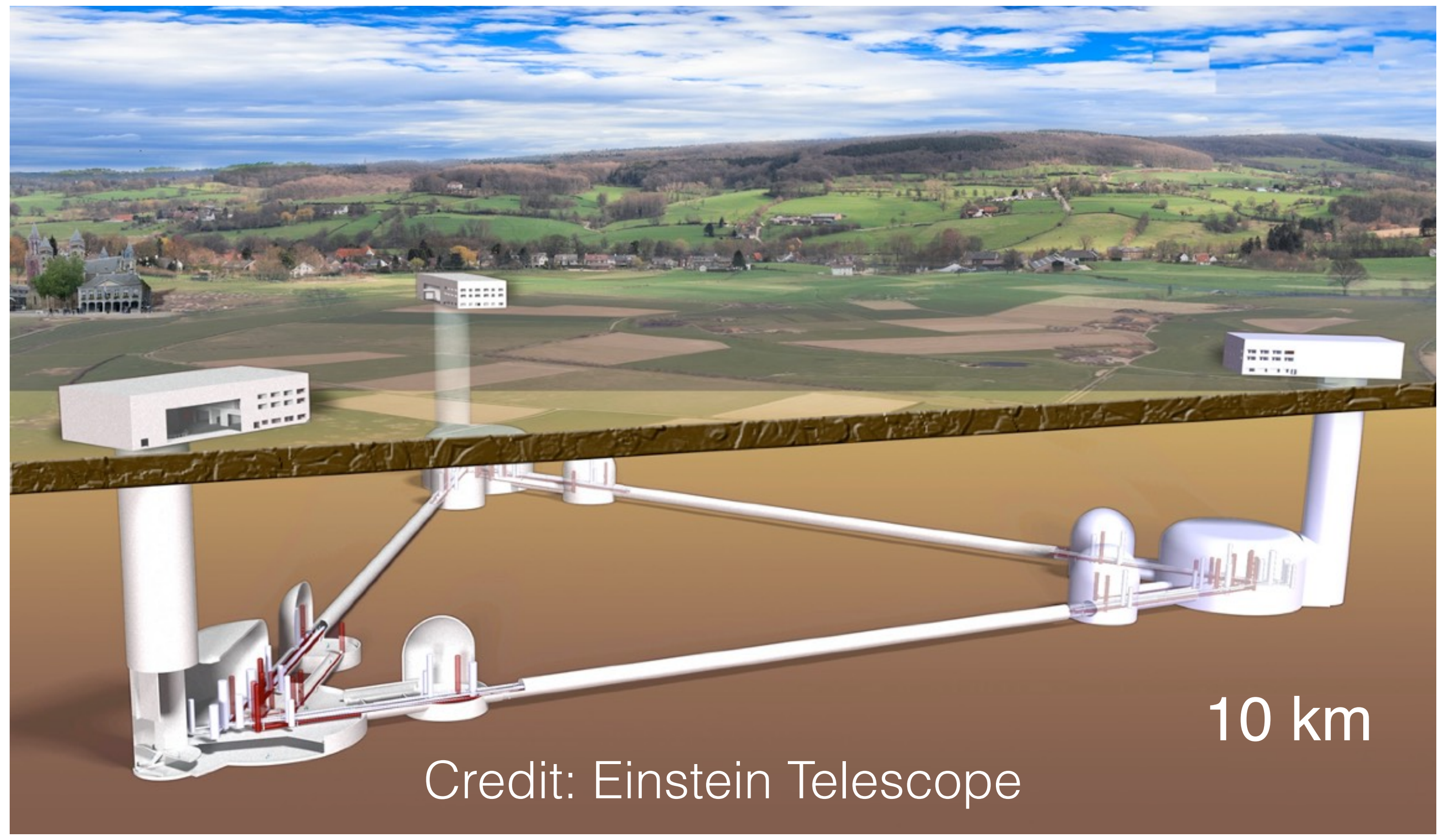

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1902.09485

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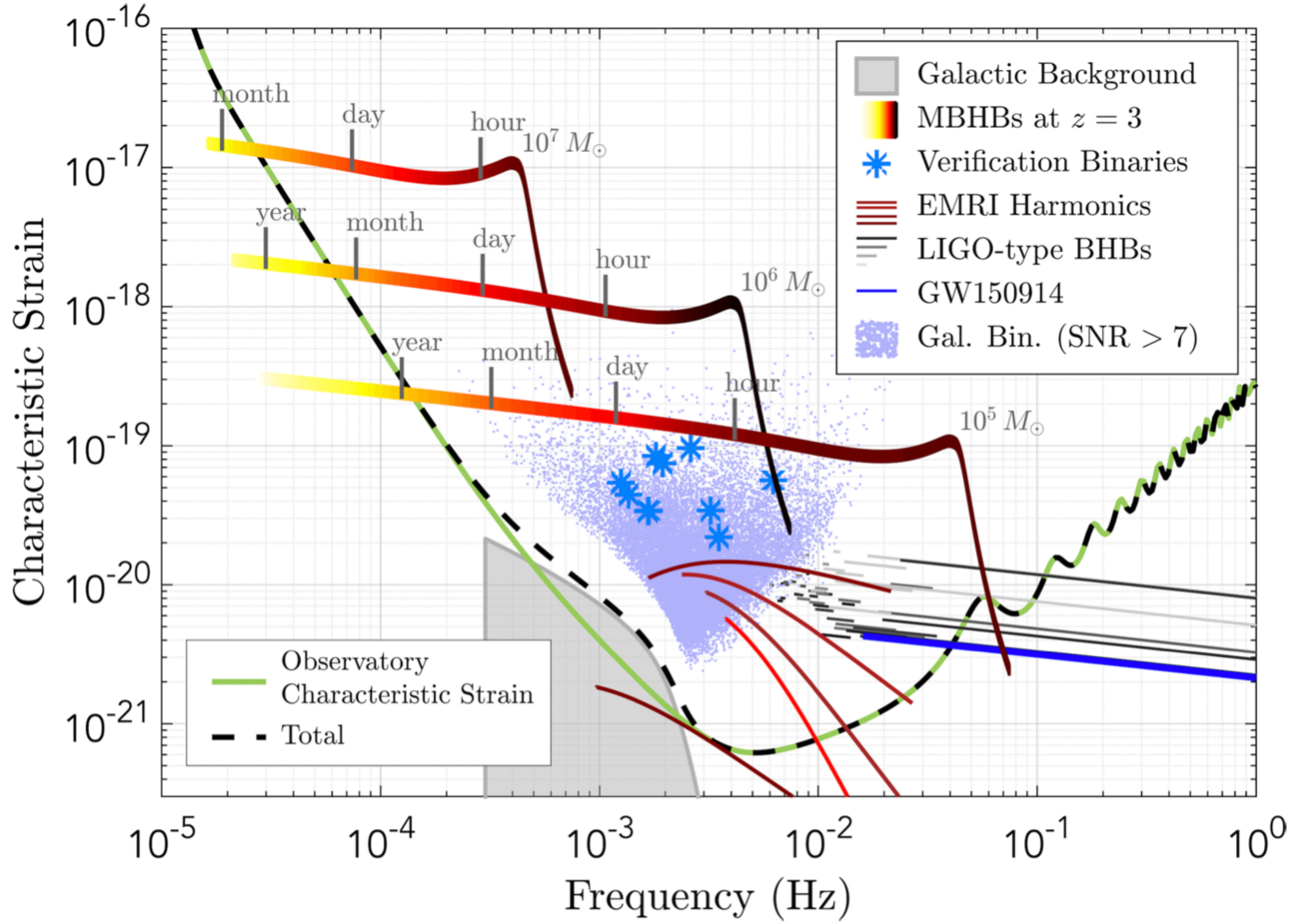
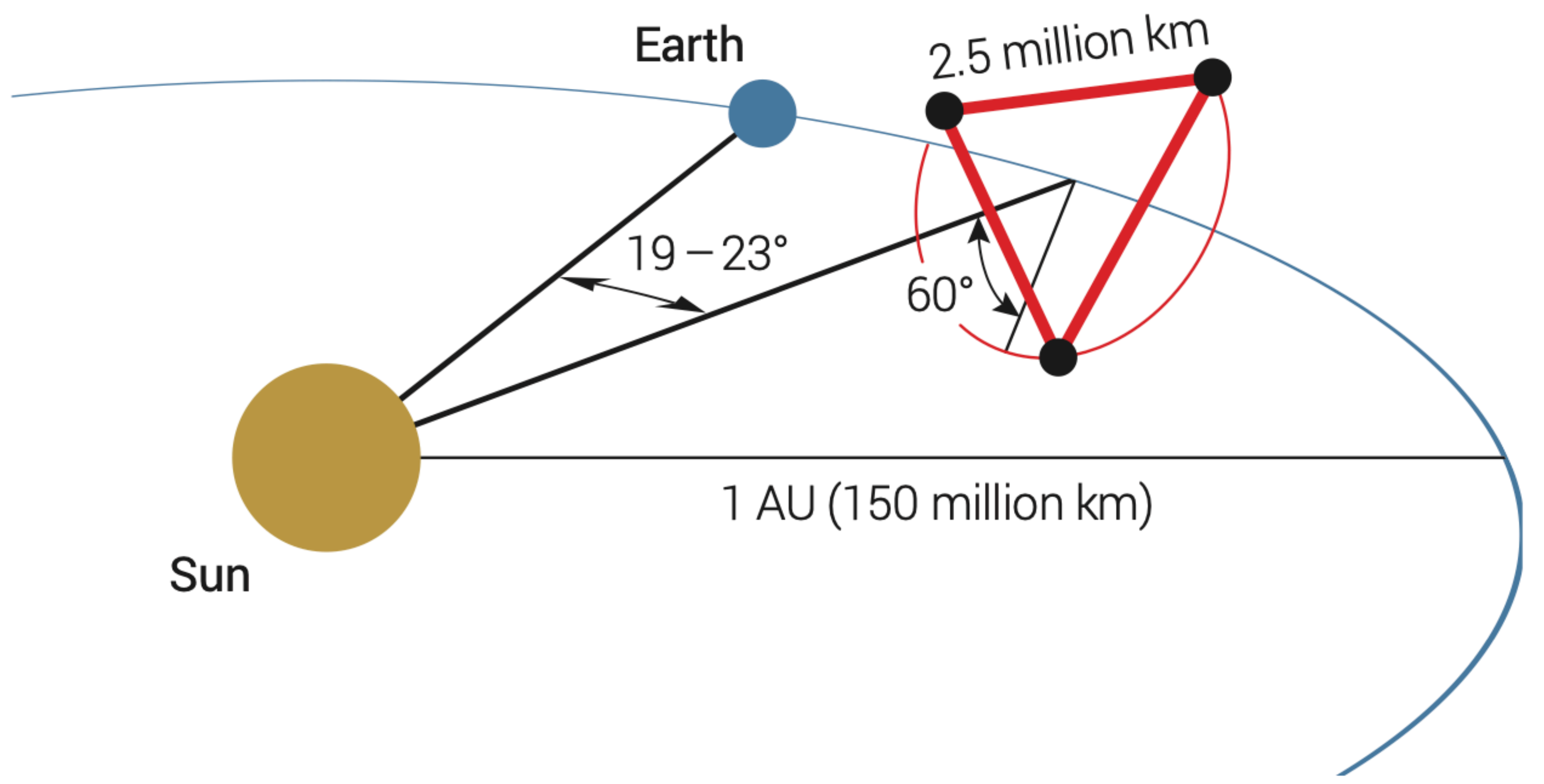
…looking forward to many more unexpected discoveries!

Additional Slides

LISA - GWs in space!

Laser Interferometer Space Antenna
(Planned for the 2030s)



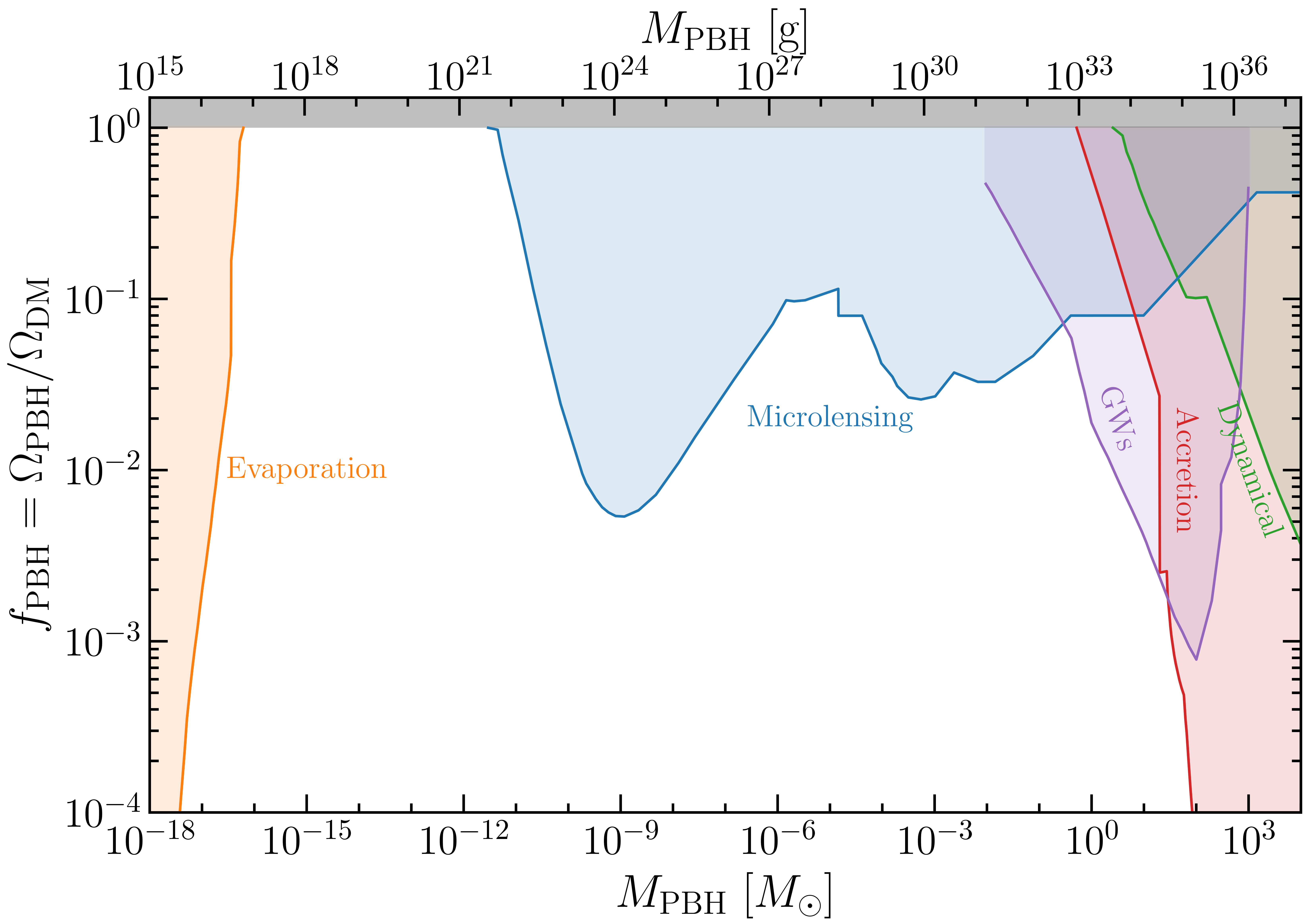


1907.06482

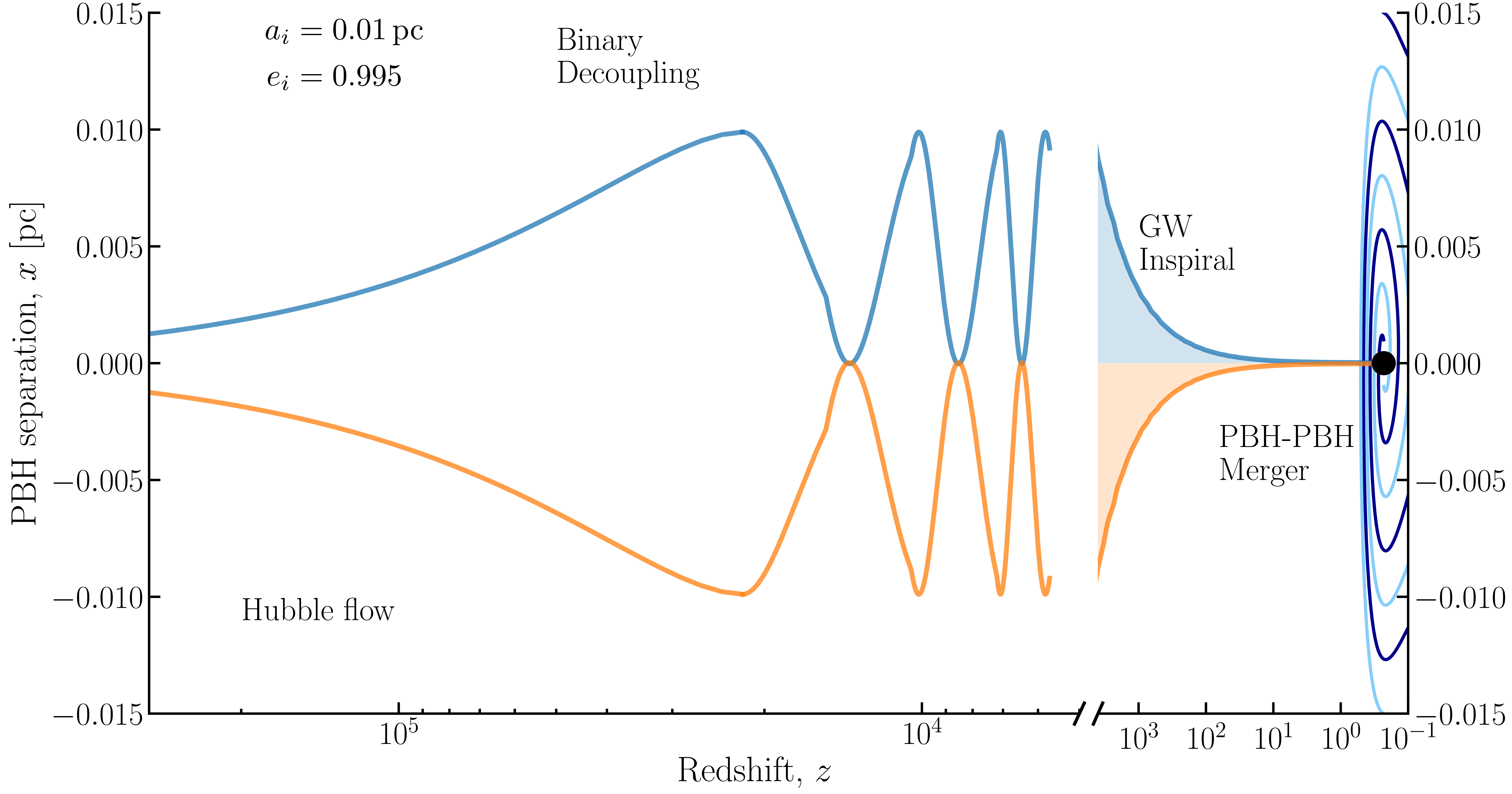
Primordial Black Holes

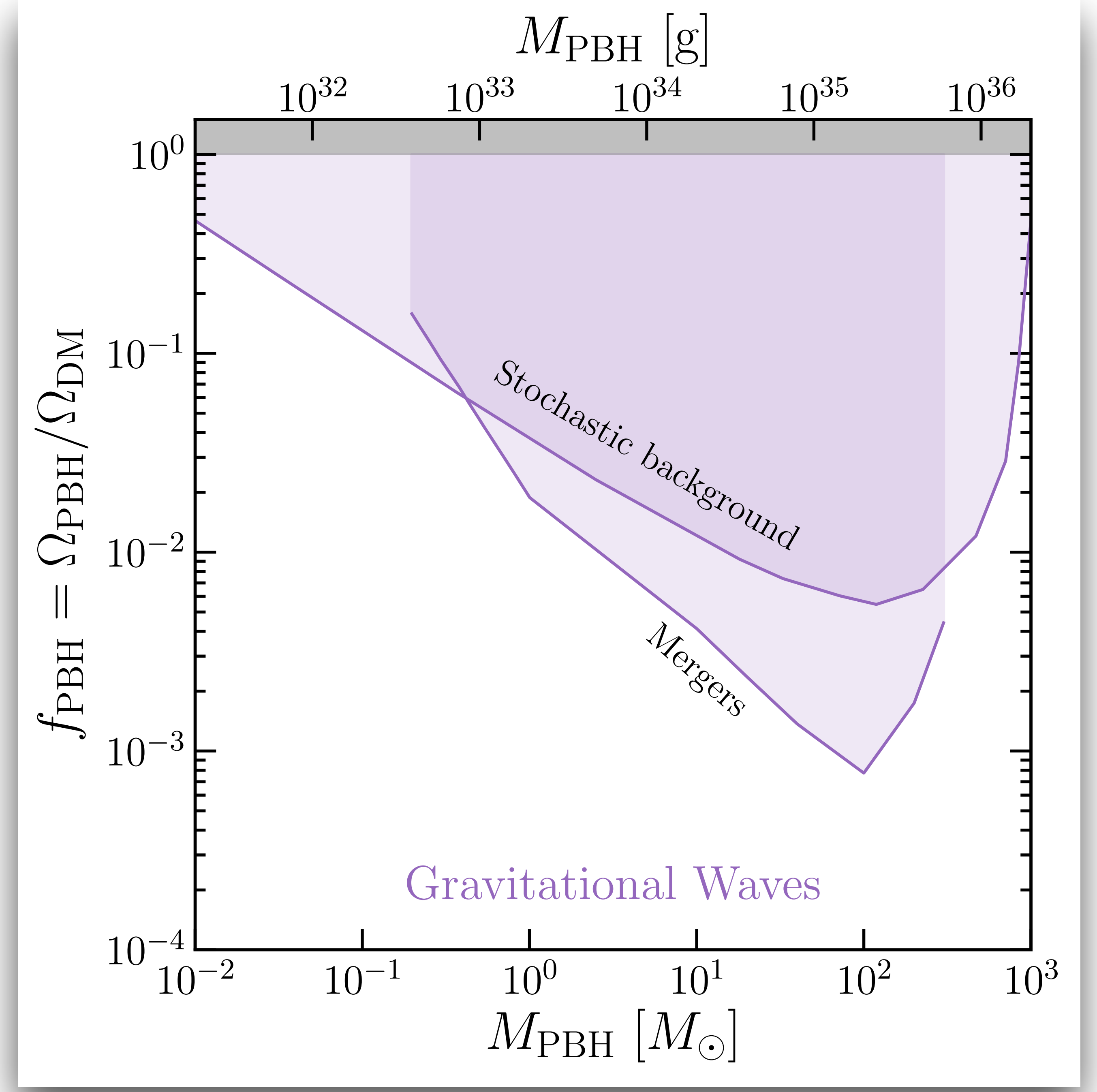
2007.10722

Bounds online

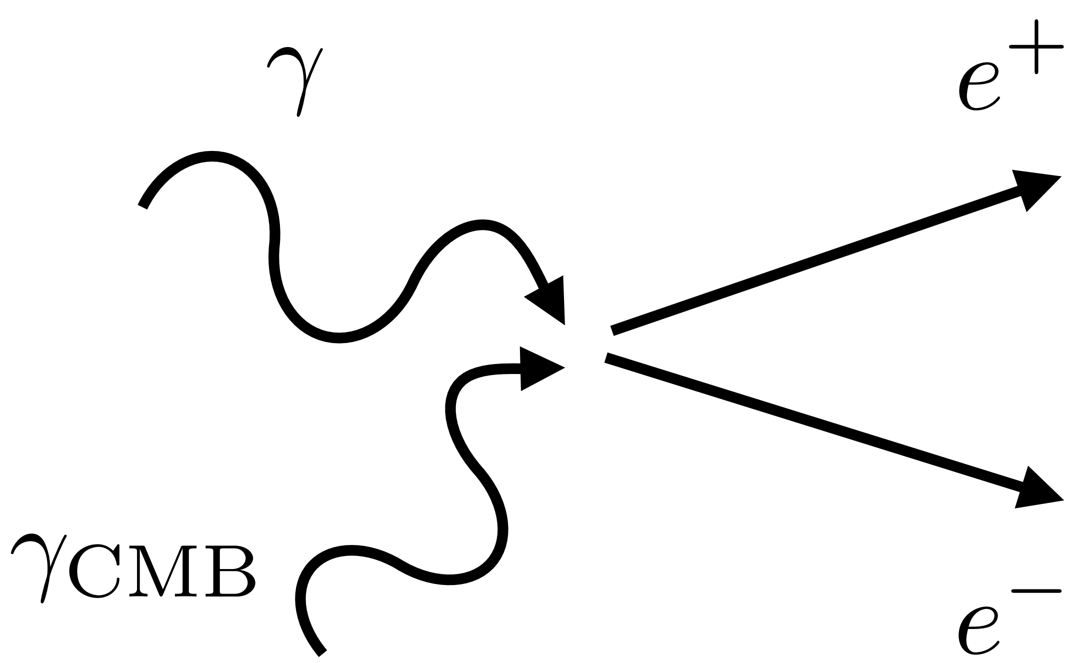


PBHs and Gravitational Waves

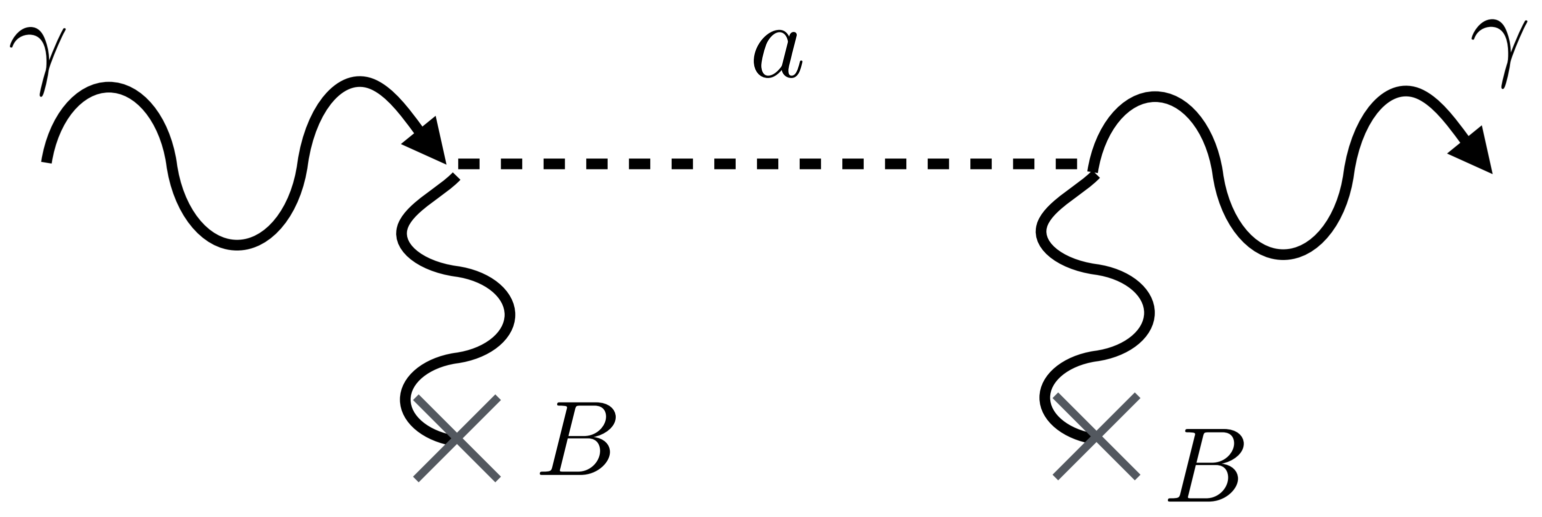


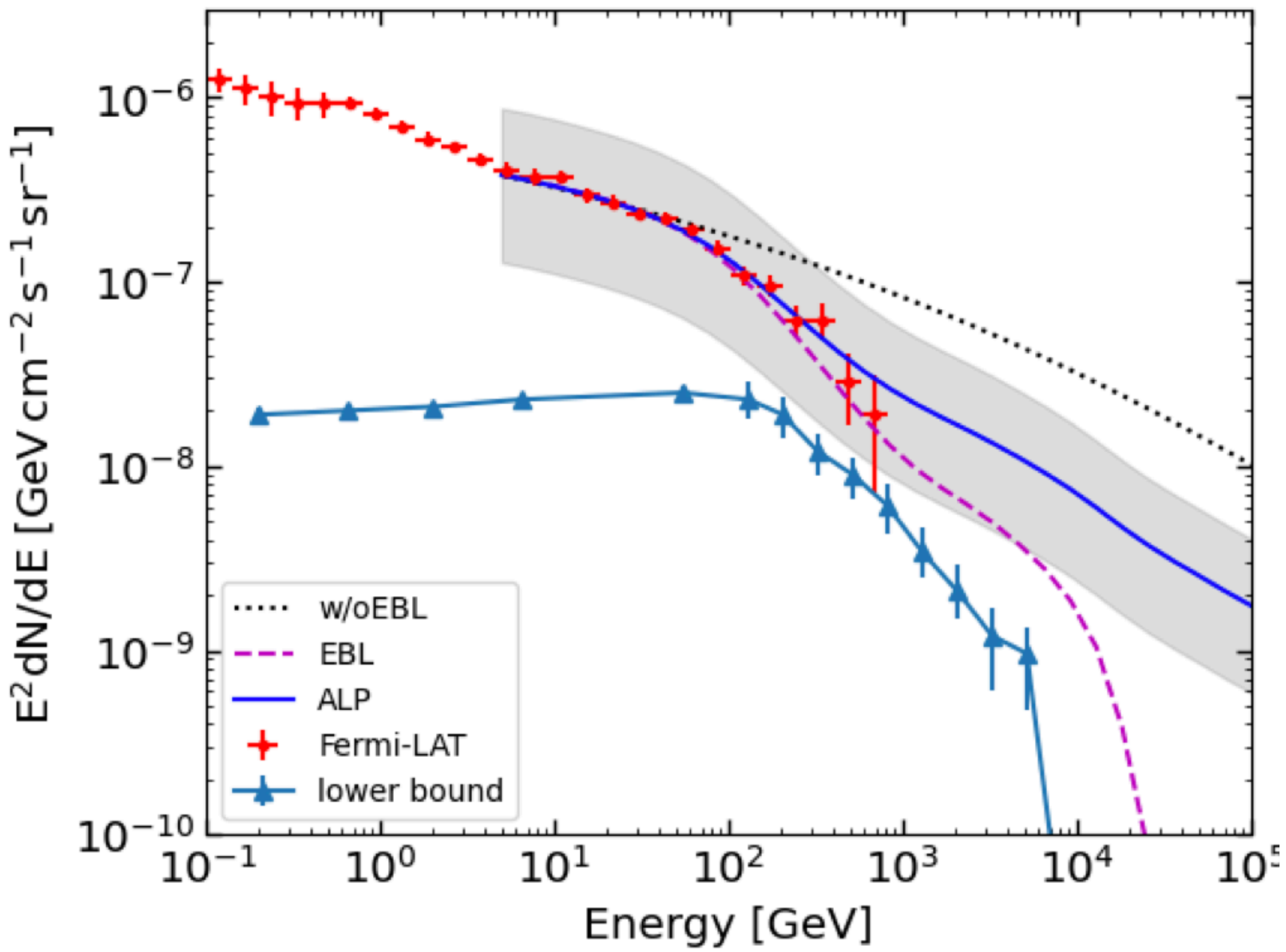


Gamma-ray transparency and axions

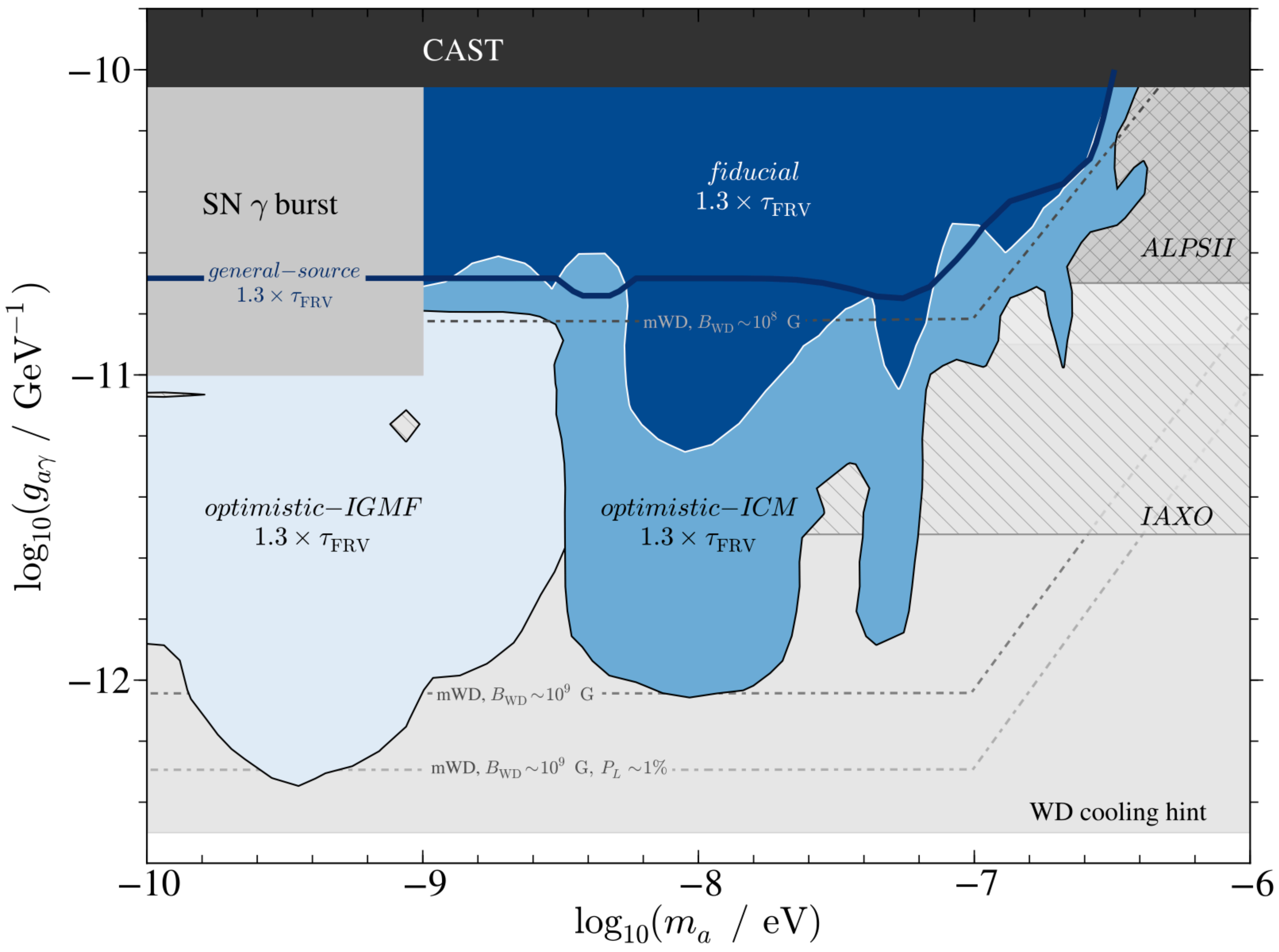


Axion-like particle:



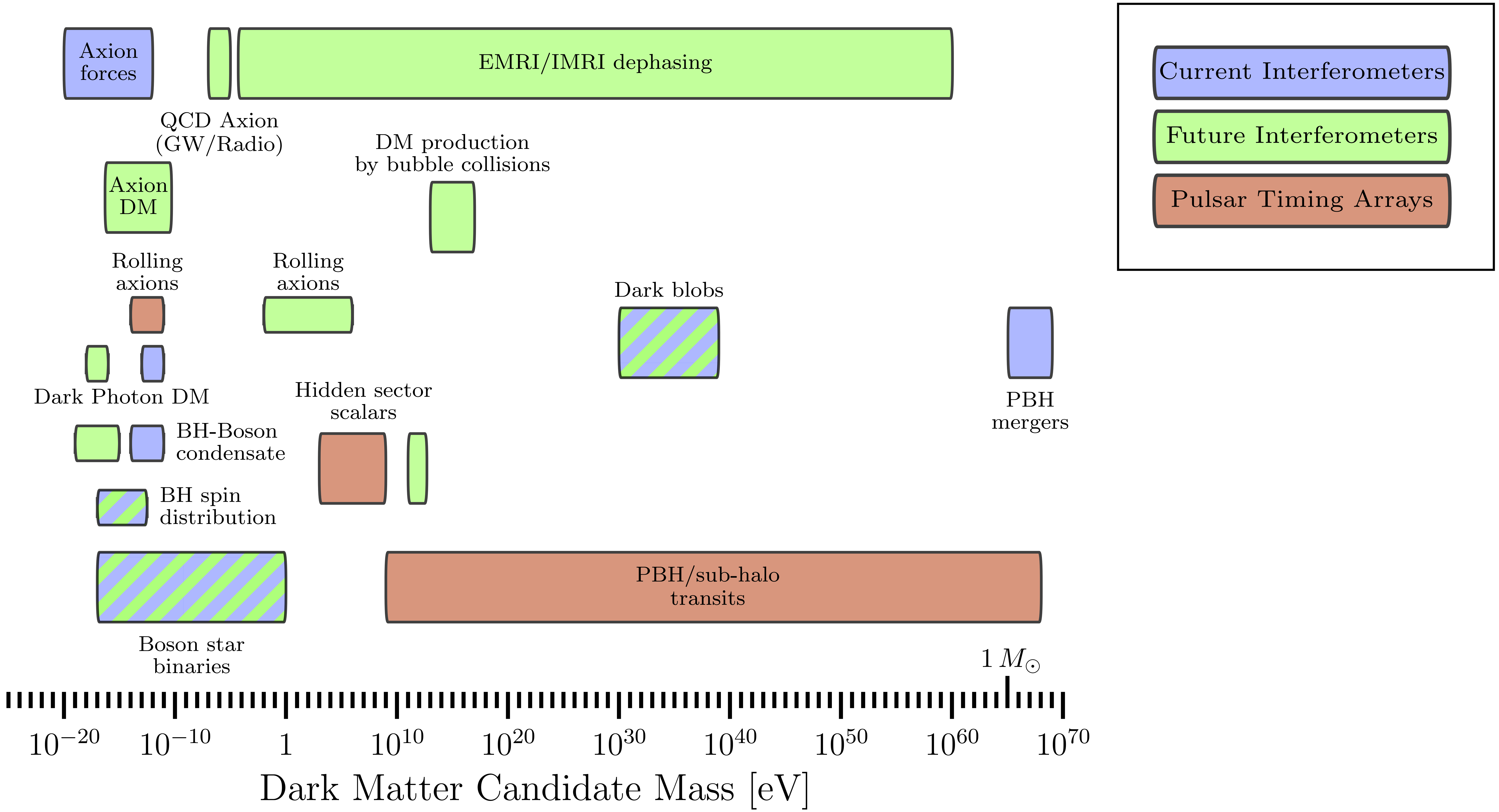


[2012.15513](https://arxiv.org/abs/2012.15513)



[1302.1208](https://arxiv.org/abs/1302.1208)

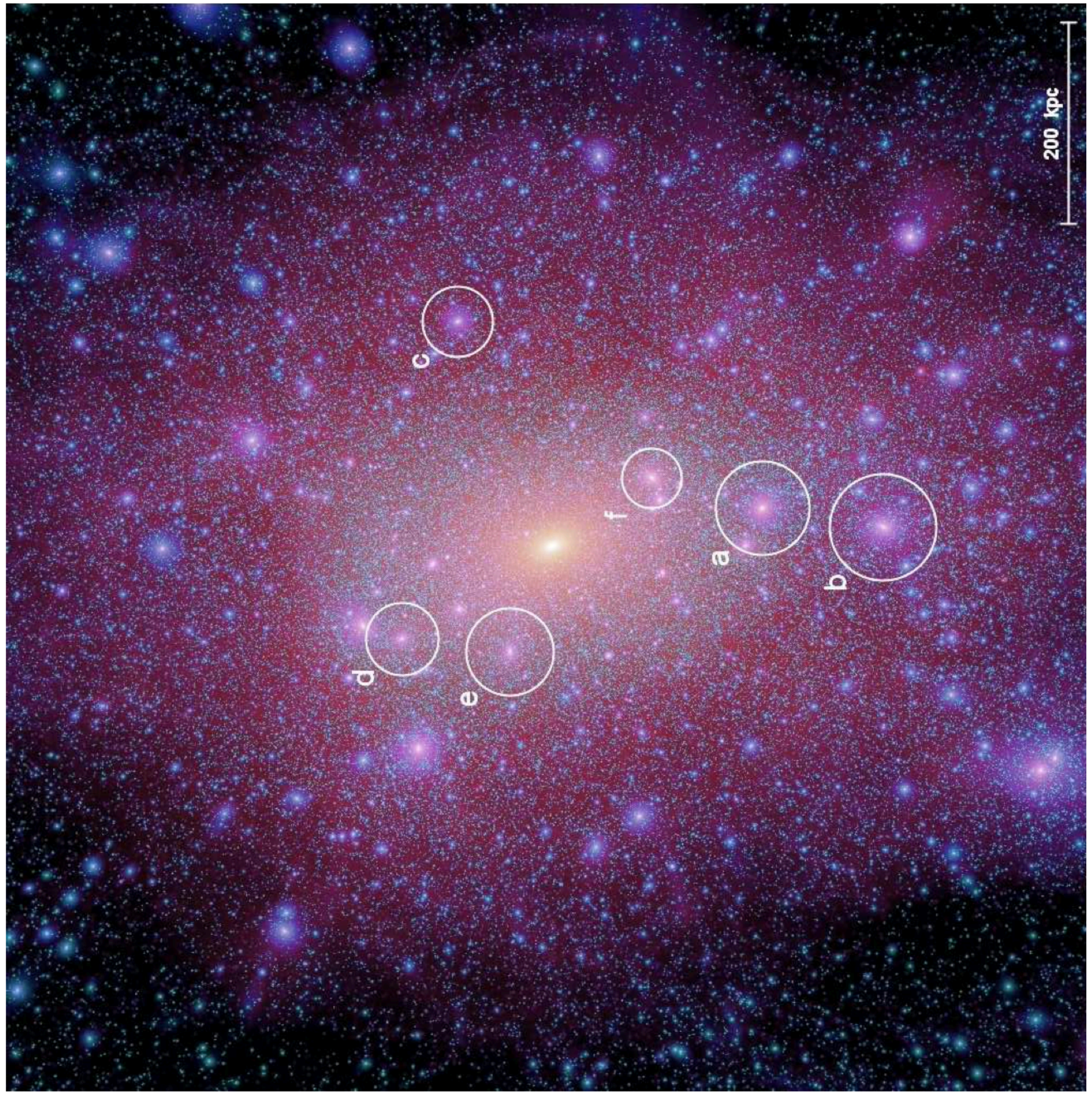
Gravitational Wave probes of DM



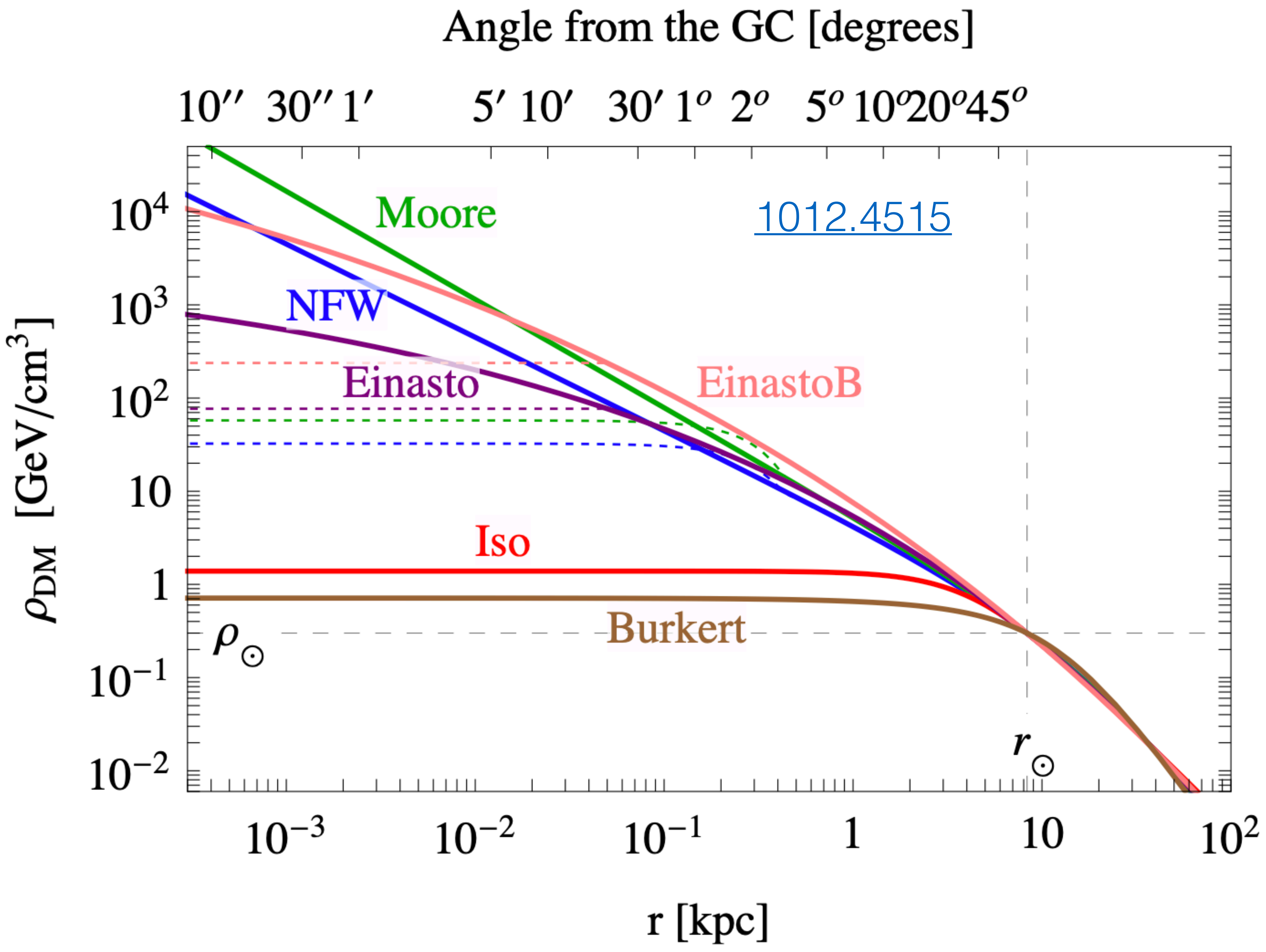
For more information about probing Dark Matter with Gravitational Waves, see 1907.10610

Dark Matter in Galaxies (2)

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



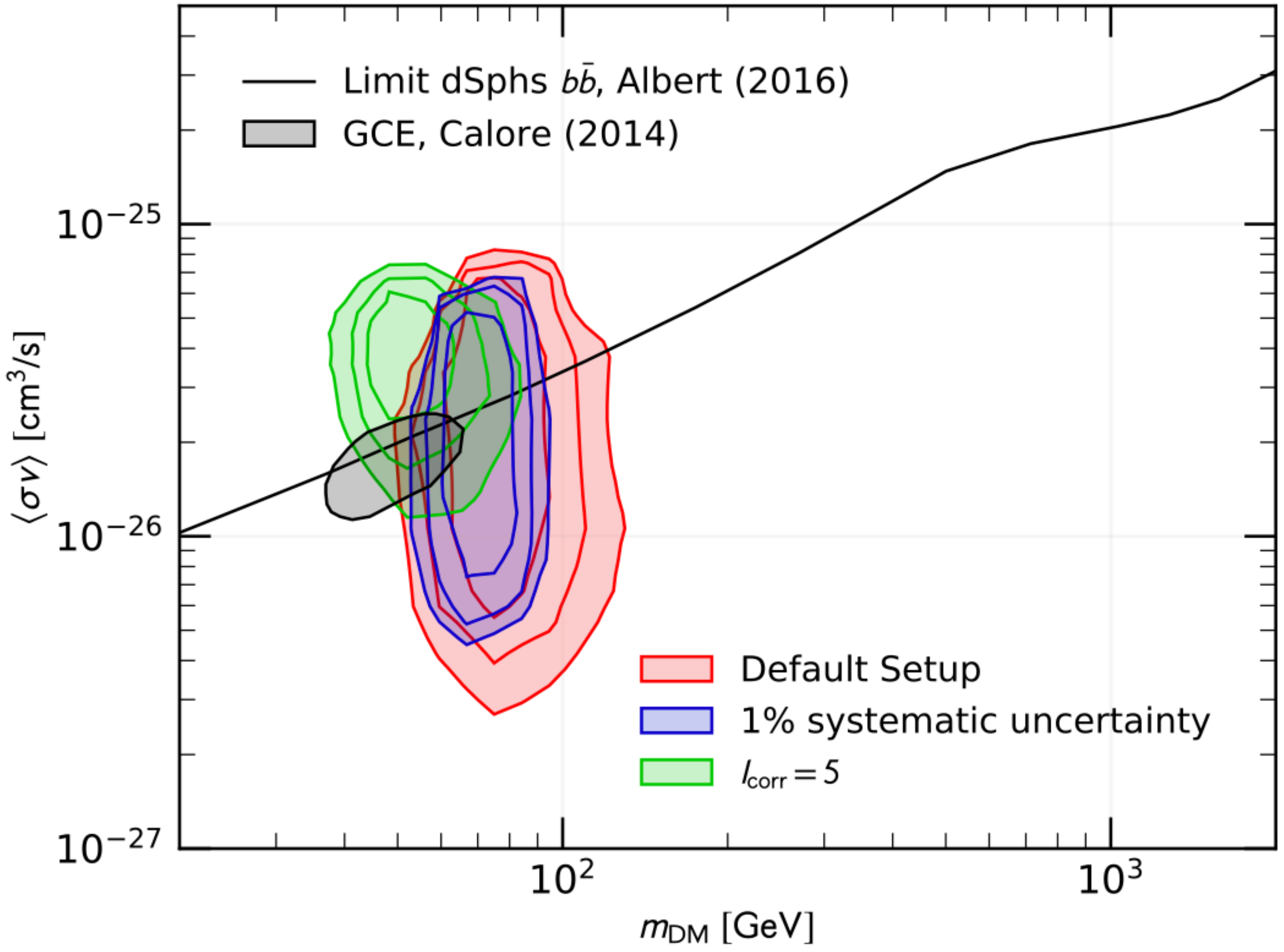
Aquarius simulation - 0809.0898



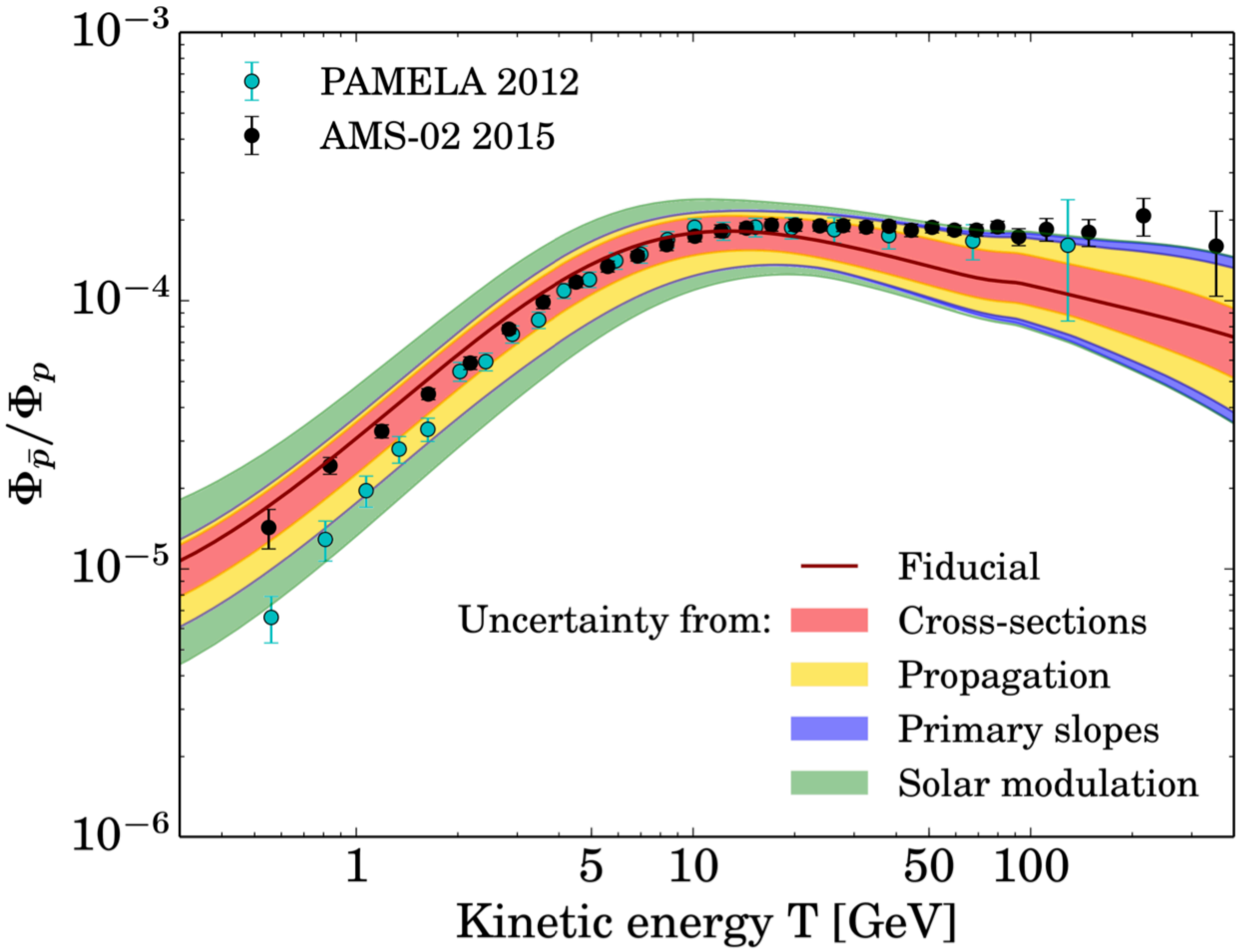
DM density at Earth:

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

Anti-proton excess (2)



1903.01472

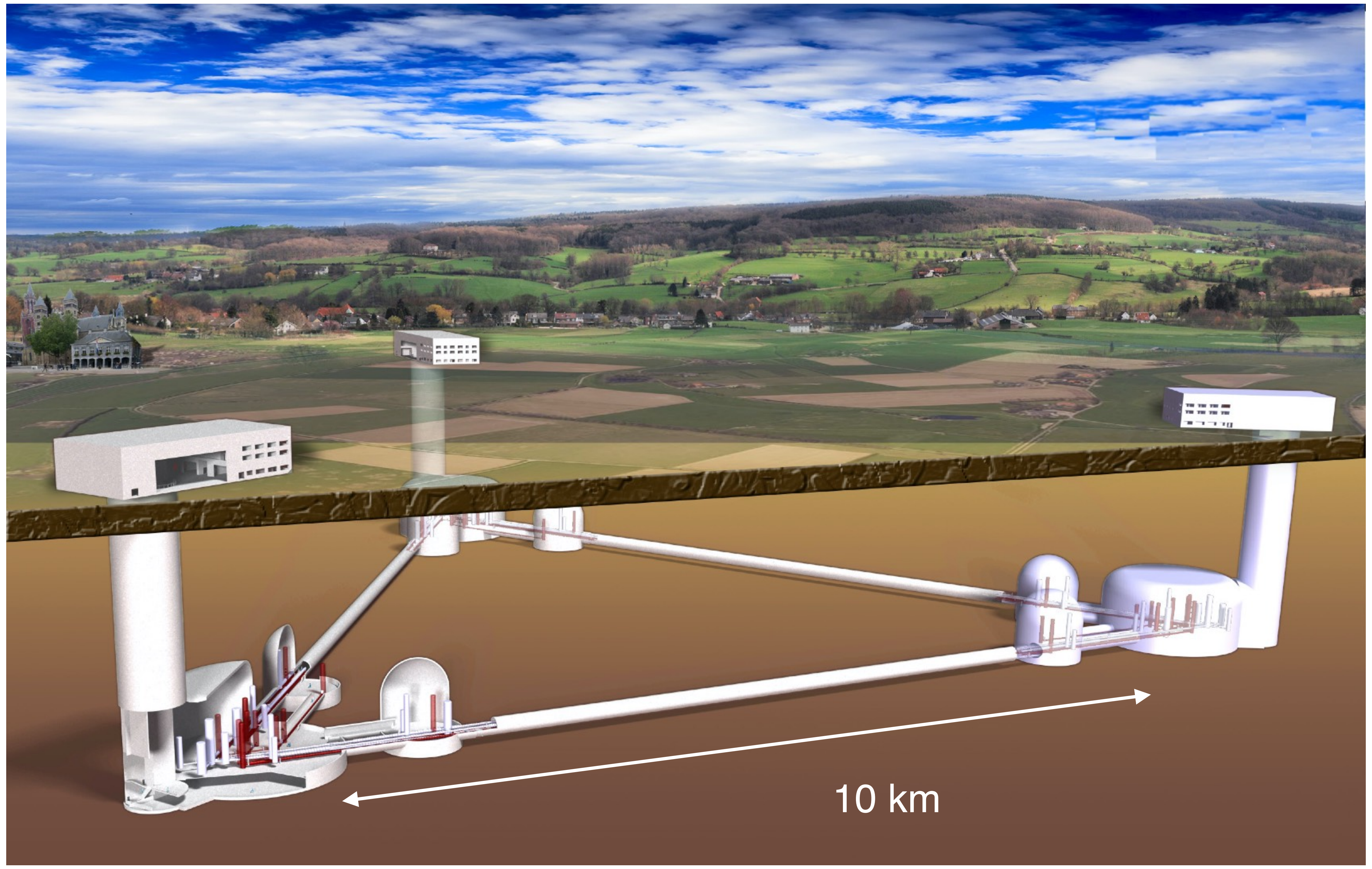


1504.04276

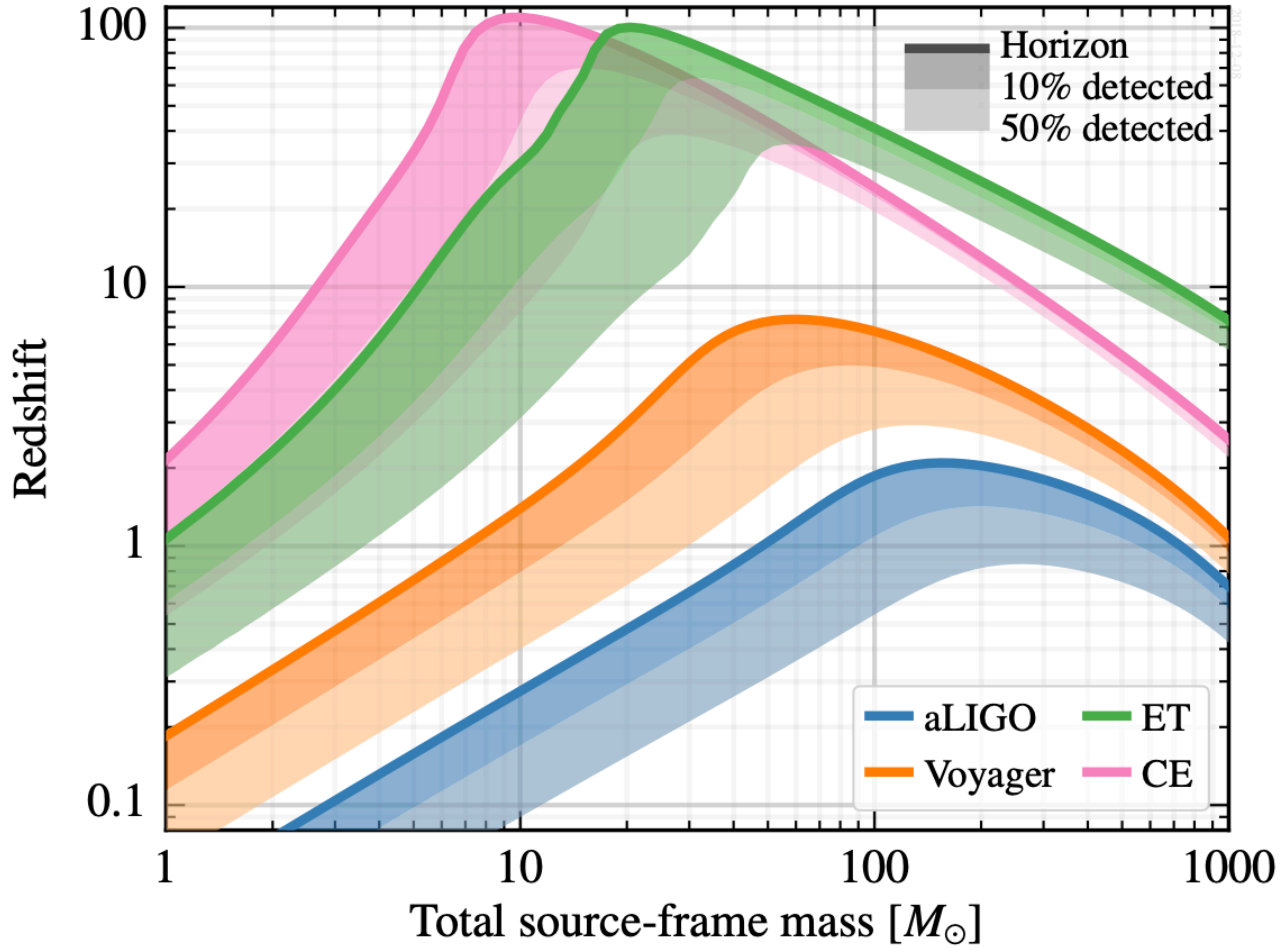
Several excesses point towards 60 GeV Dark Matter -
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

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).