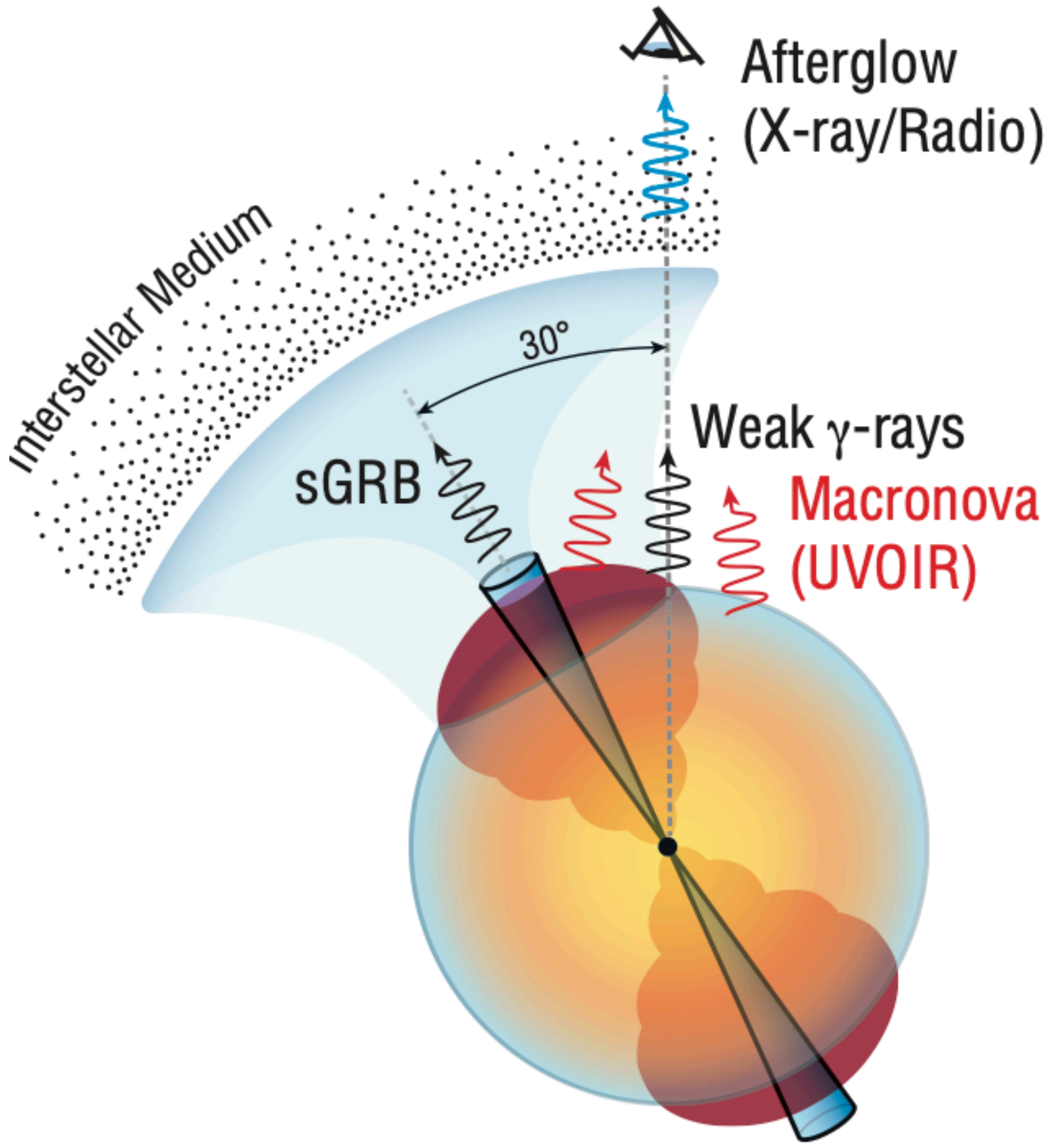
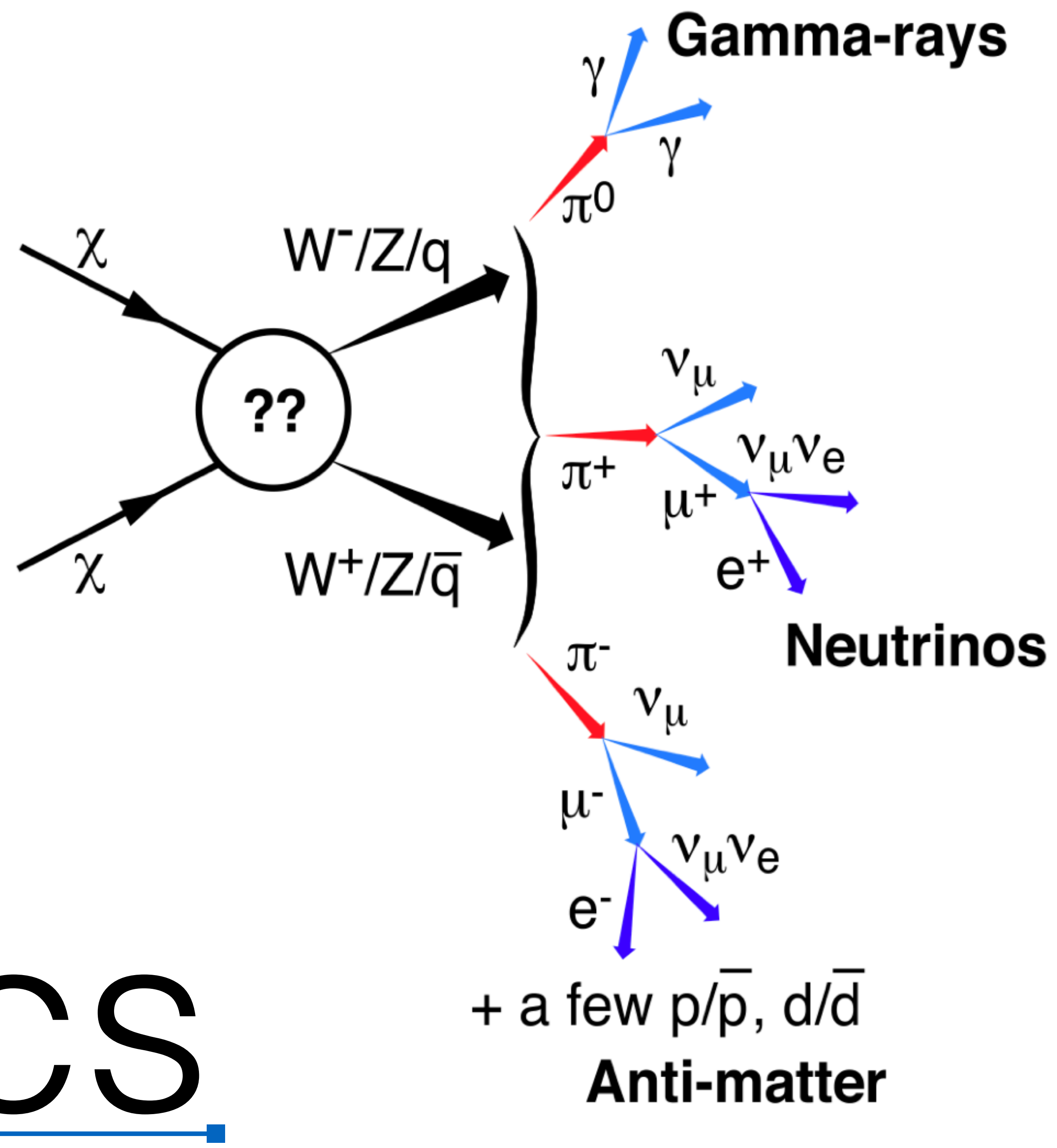




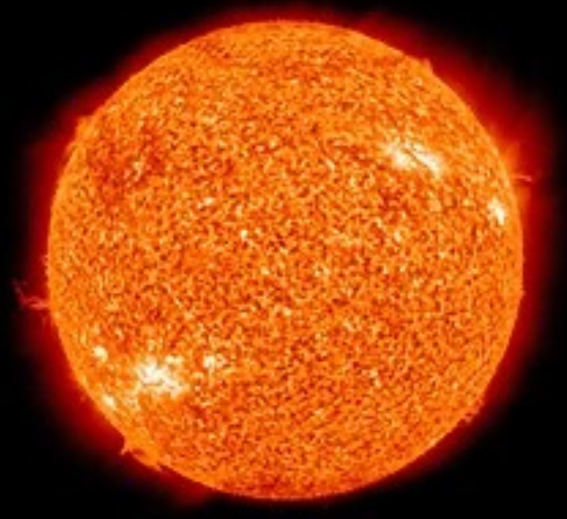
Astroparticle Physics

Lecture 2/2

Bradley J Kavanagh
Instituto de Fisica de Cantabria (CSIC-UC)

CERN Summer School - Tuesday 13th July 2021

The Sun



Supernovae

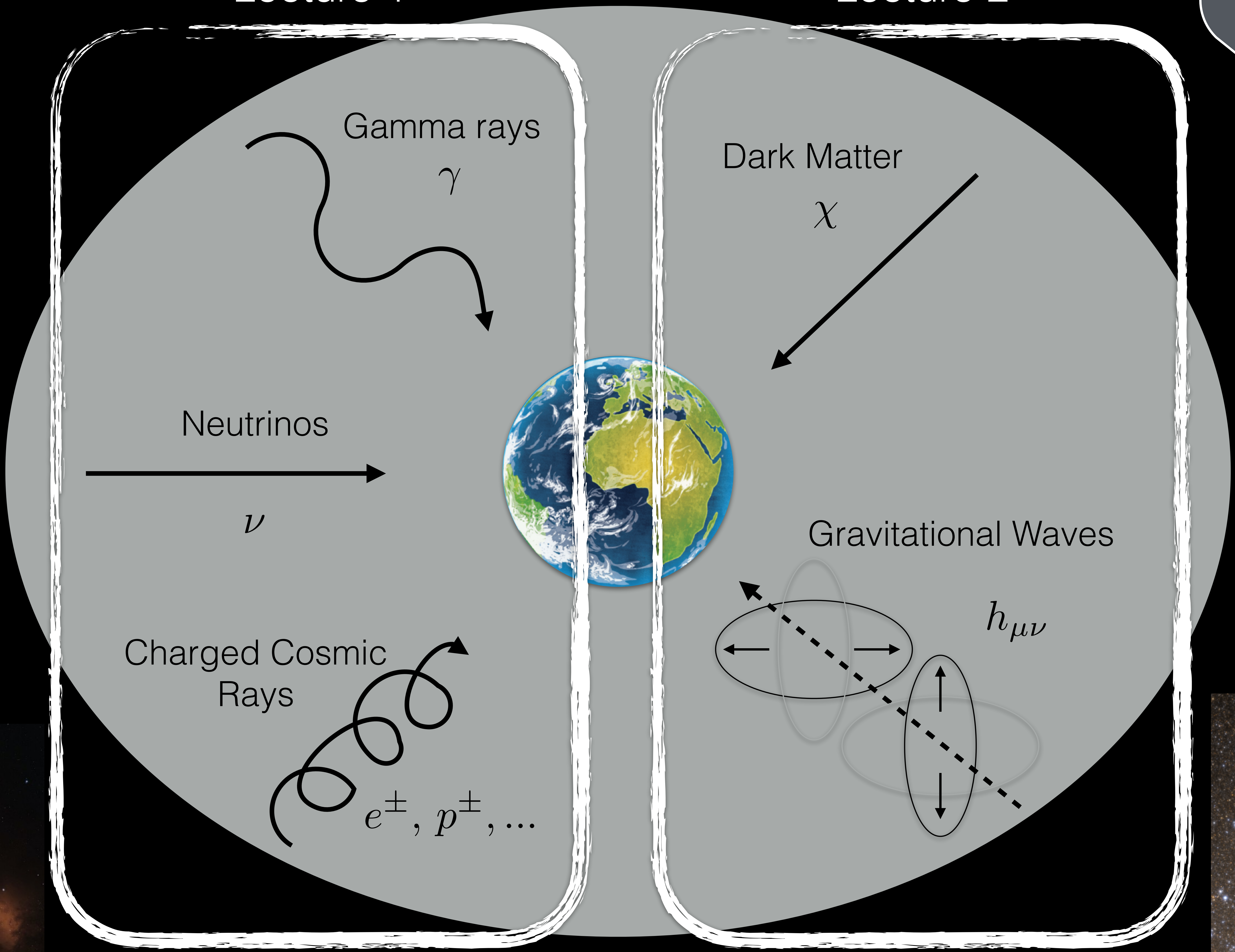
Credit: NASA/CXC/SAO

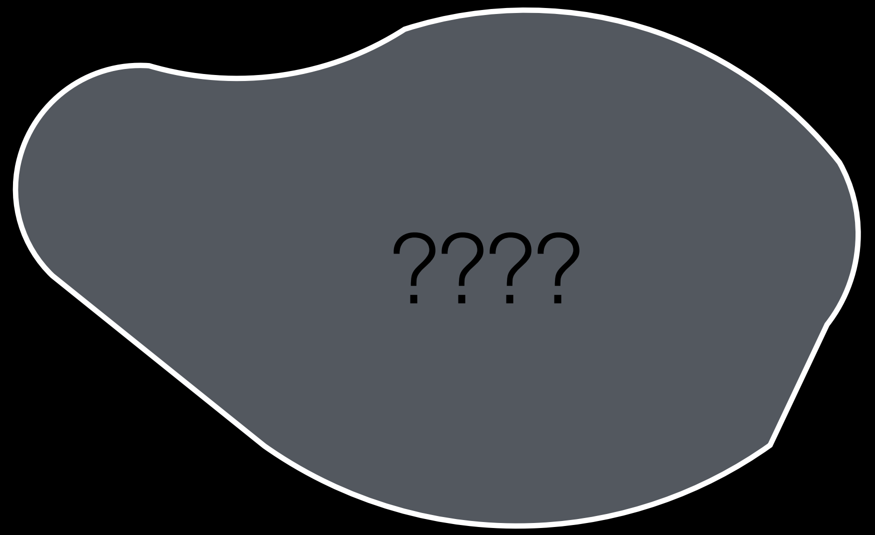
Quasars/AGN

Credit: ESO/M. Kornmesser

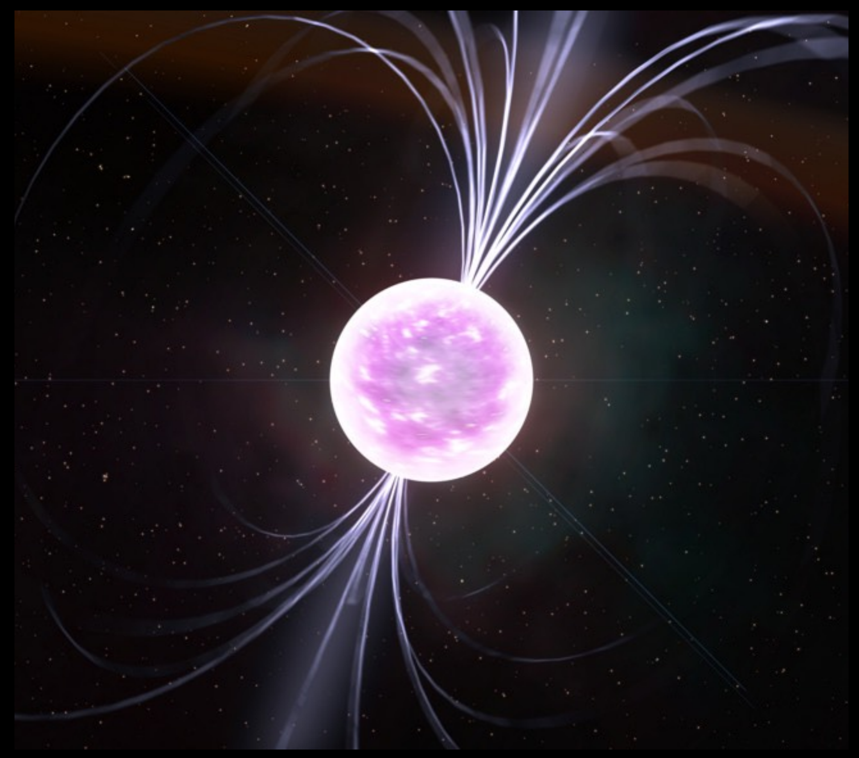
Lecture 1

Lecture 2





Pulsars



Credit: Kevin Gill / Flickr

BH/NS Mergers

Credit: SXS Lensing

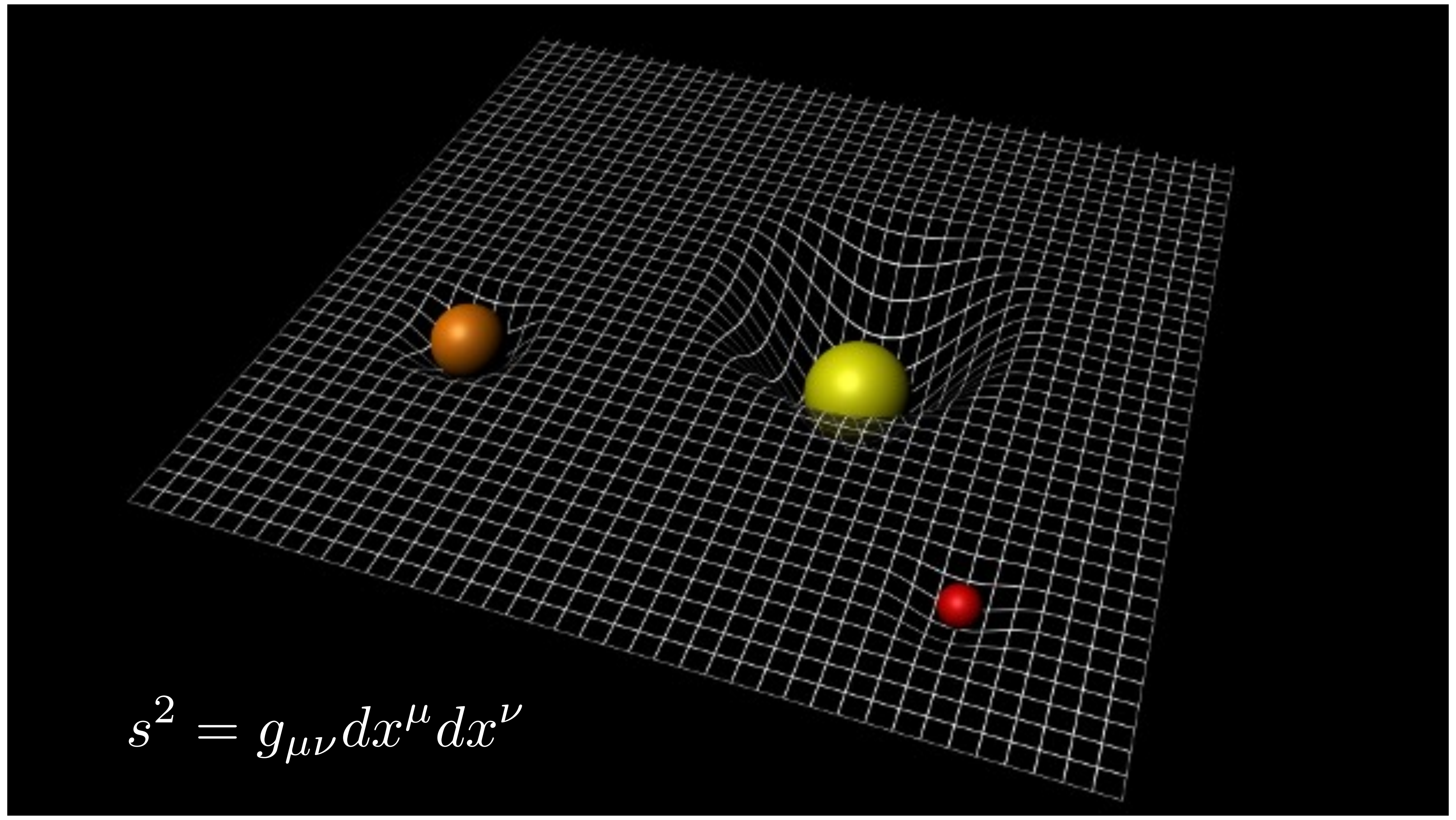
Gravitational Waves

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:

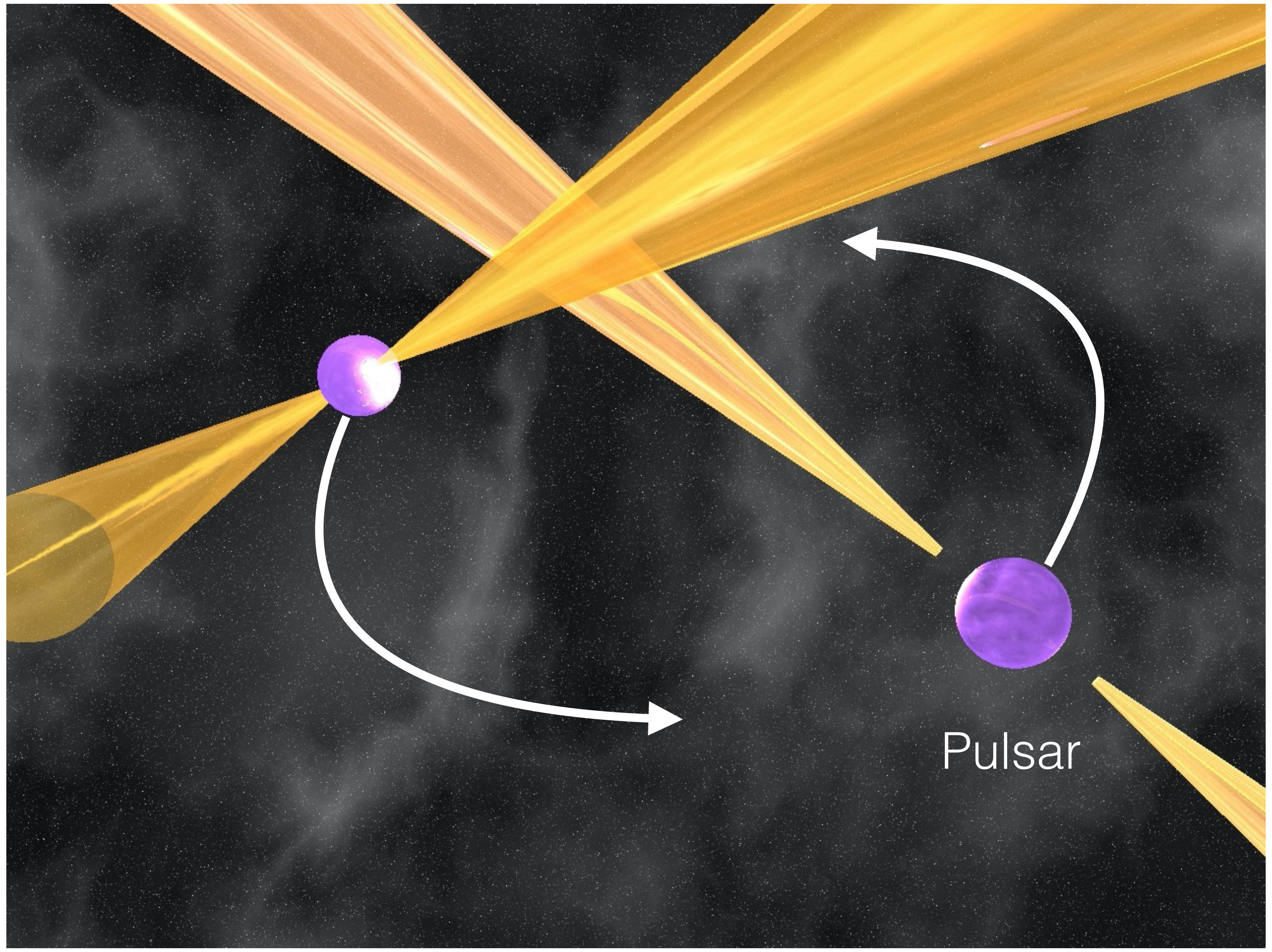
$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

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

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

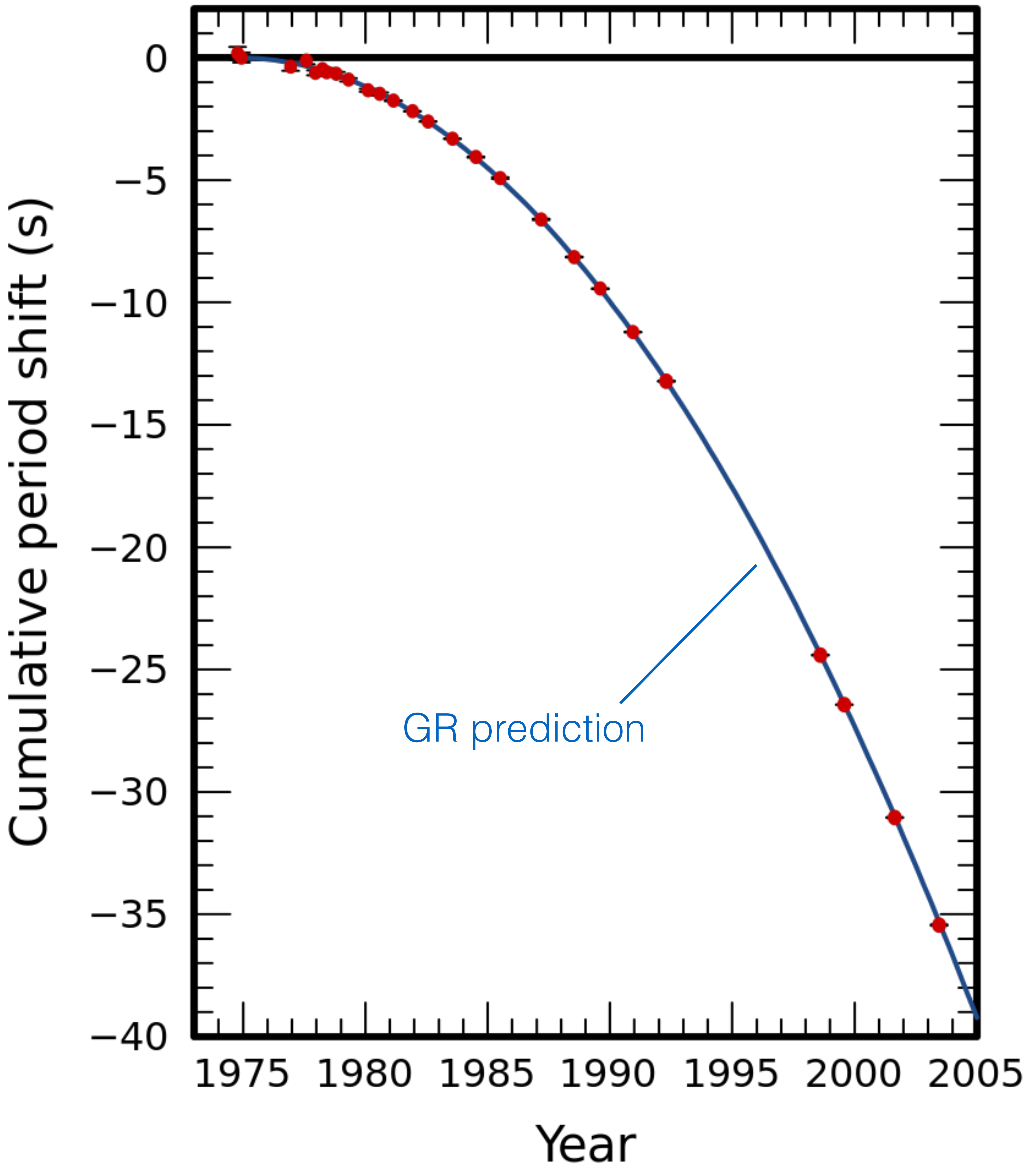
Indirect observation of GWs

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



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

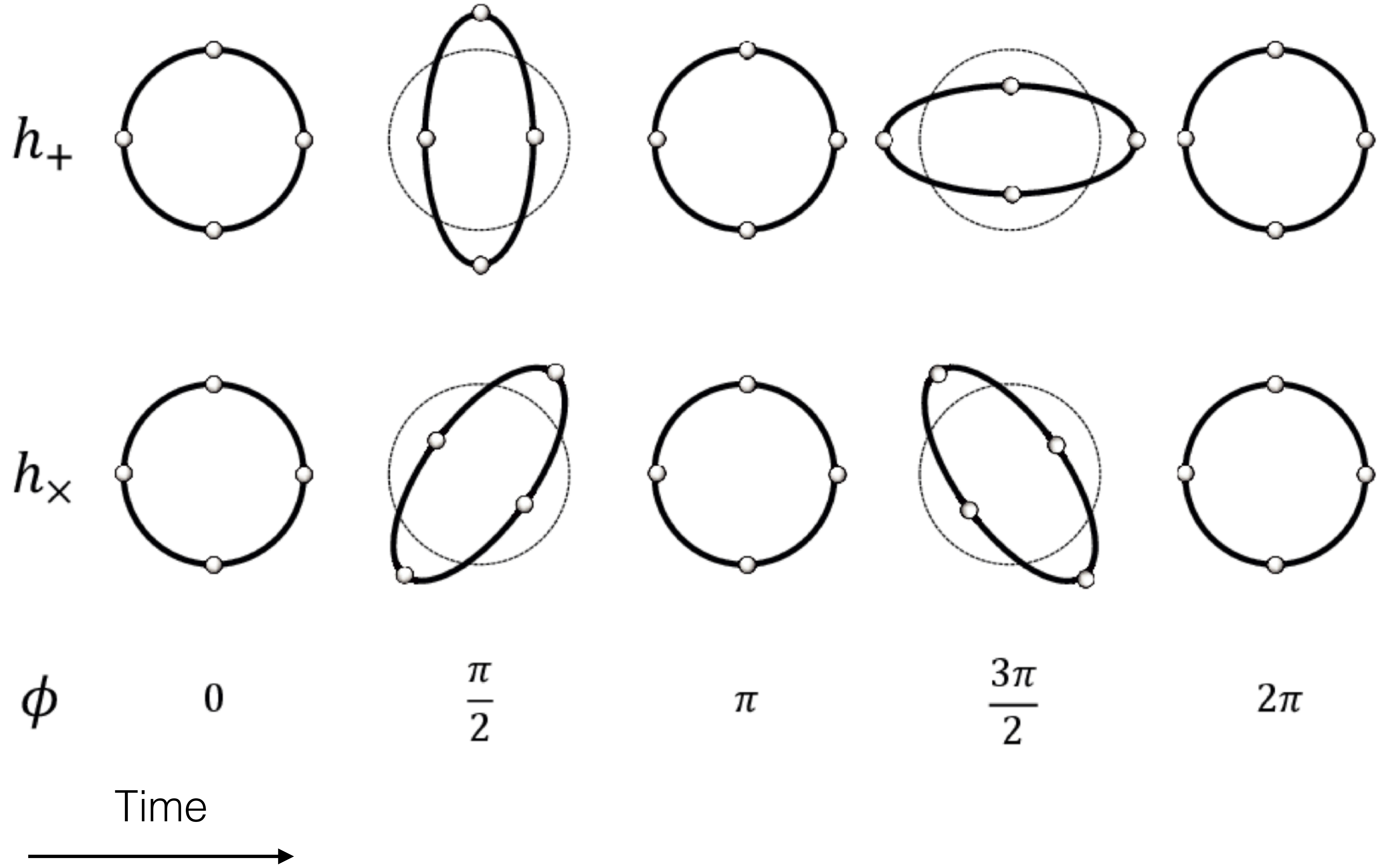
PSR B1913+16 (“Hulse-Taylor Binary”)



See e.g. astro-ph/0407149

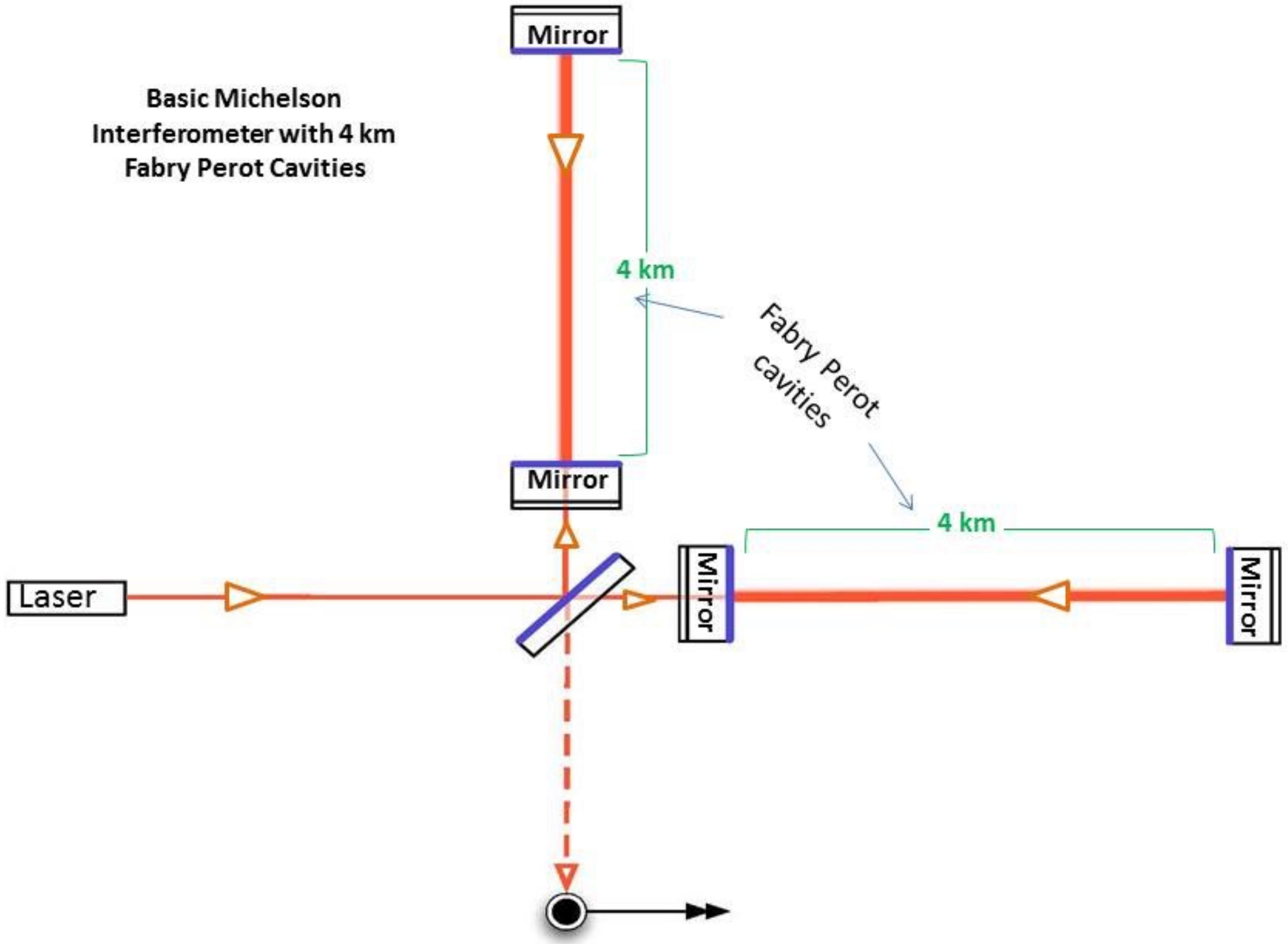
Direct detection of GWs

GW traveling into the screen causes (tiny) distortion:



1708.00918

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

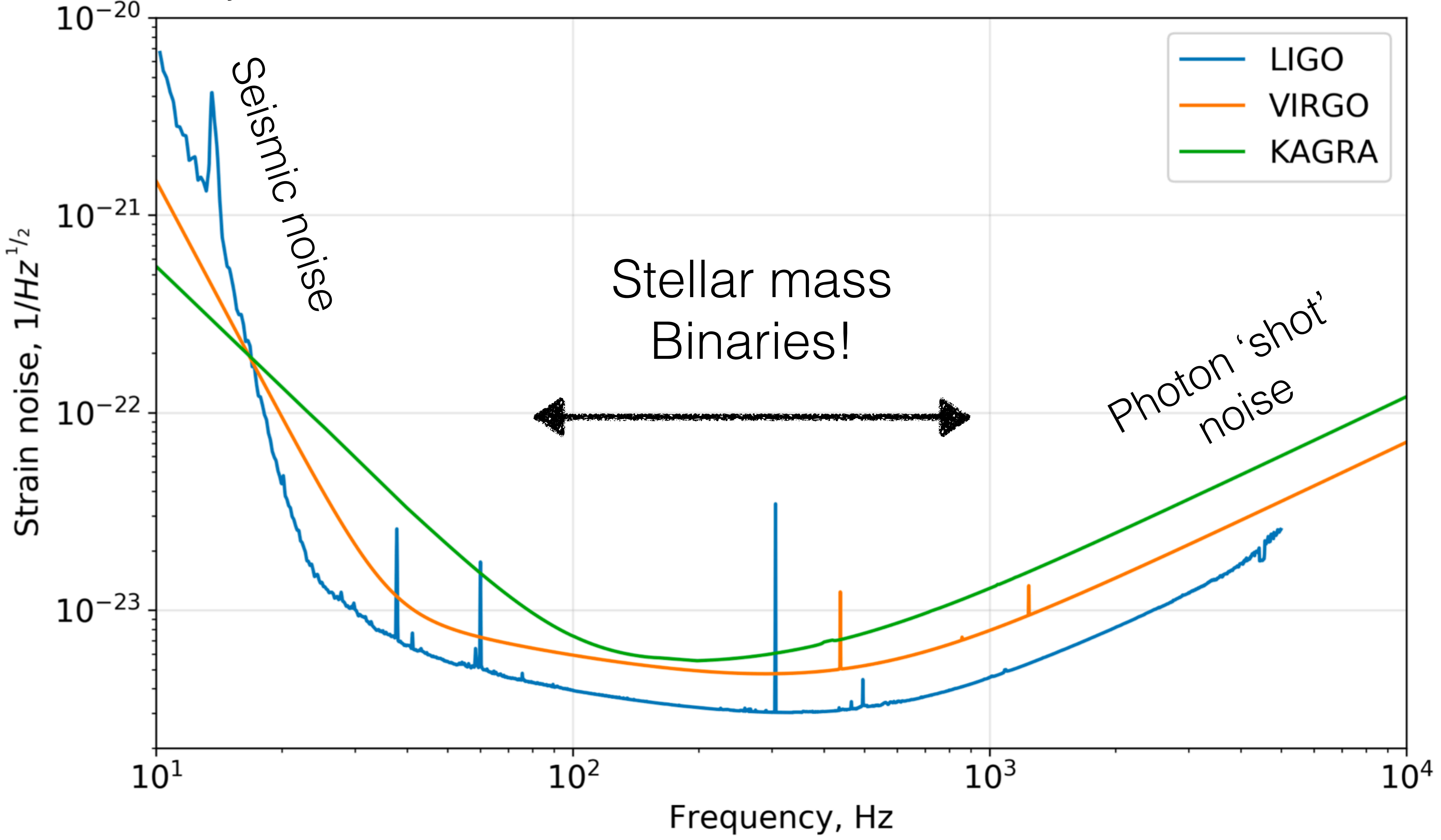


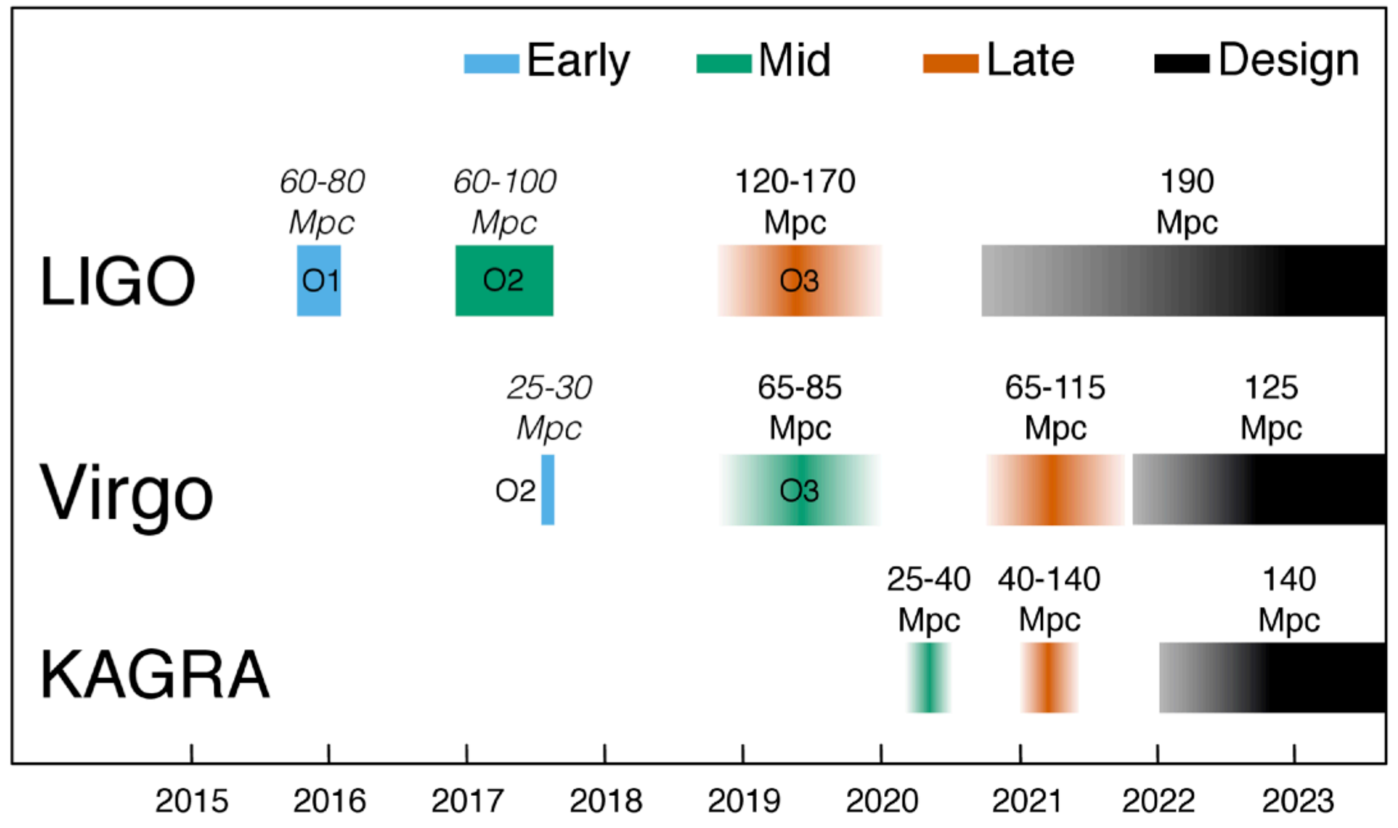
Typical GW strain is $\Delta L/L \sim 10^{-23}$!

LIGO-Virgo-KAGRA (LVK)

Credit: LIGO, VIRGO & KAGRA.

Projected O4 strain noise [2102.10816](2102.10816)



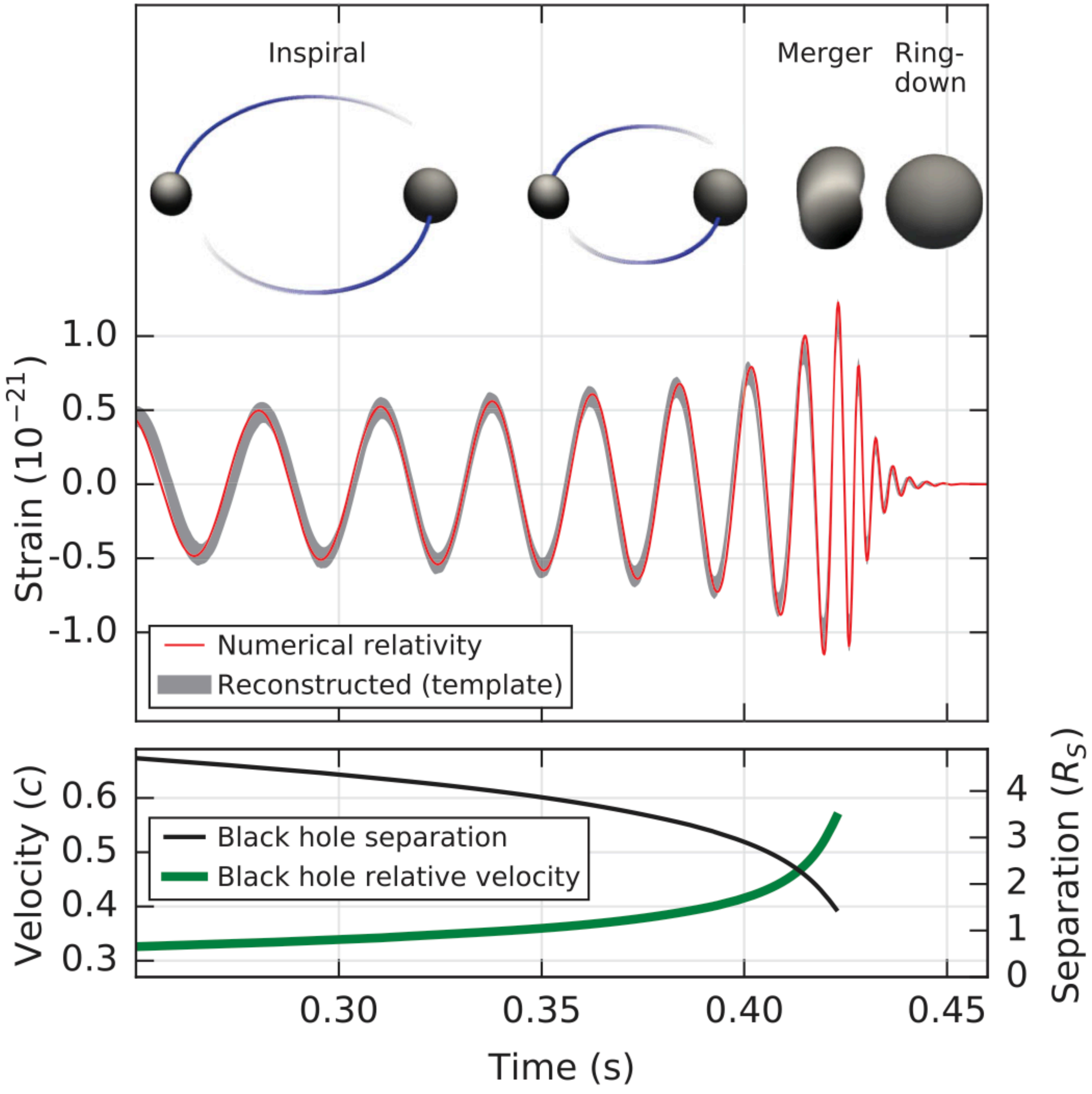


GW frequency ~ twice orbital frequency.

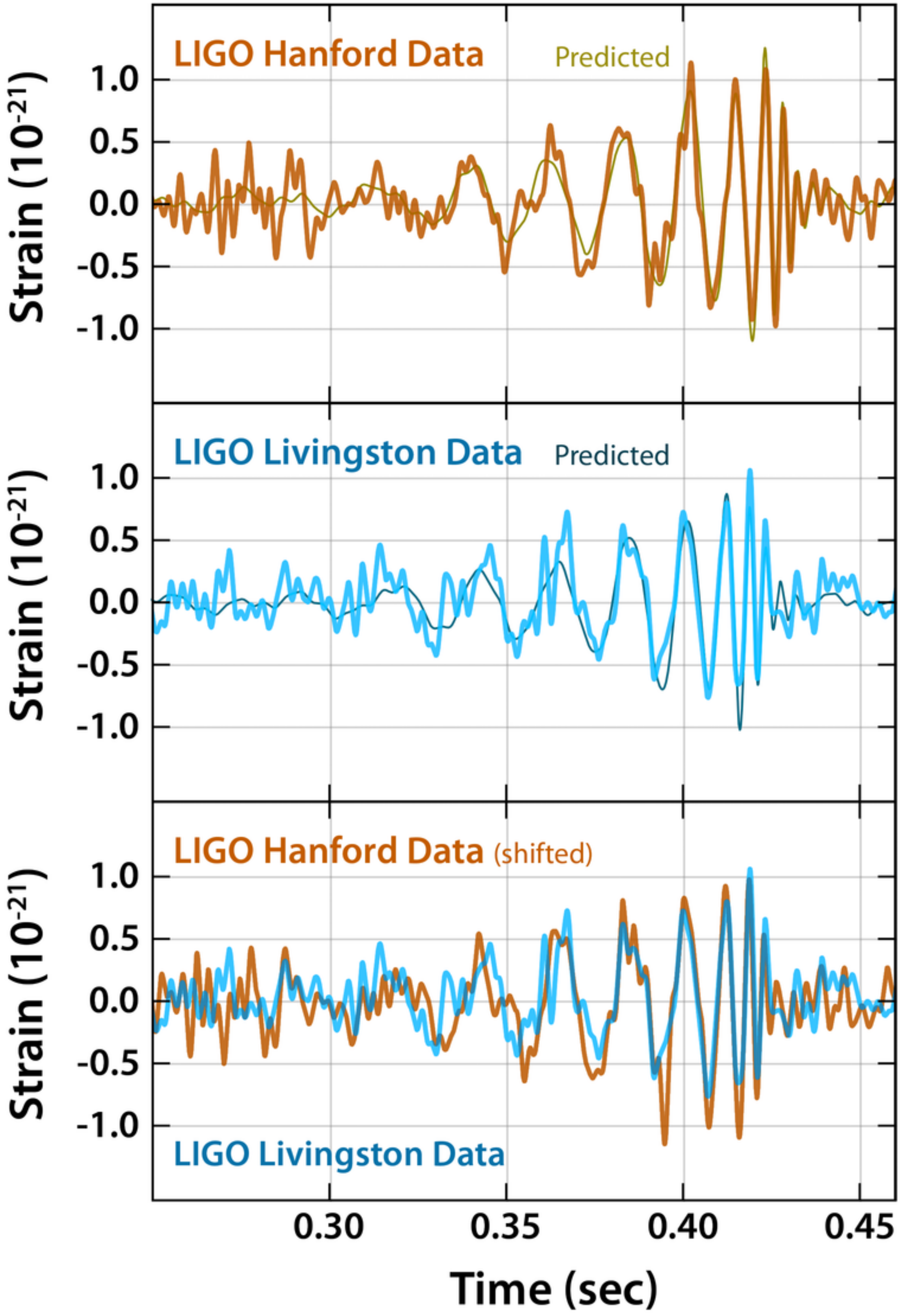
[1906.03643](1906.03643)

GW150914 - the first BH-BH merger

14 September 2015



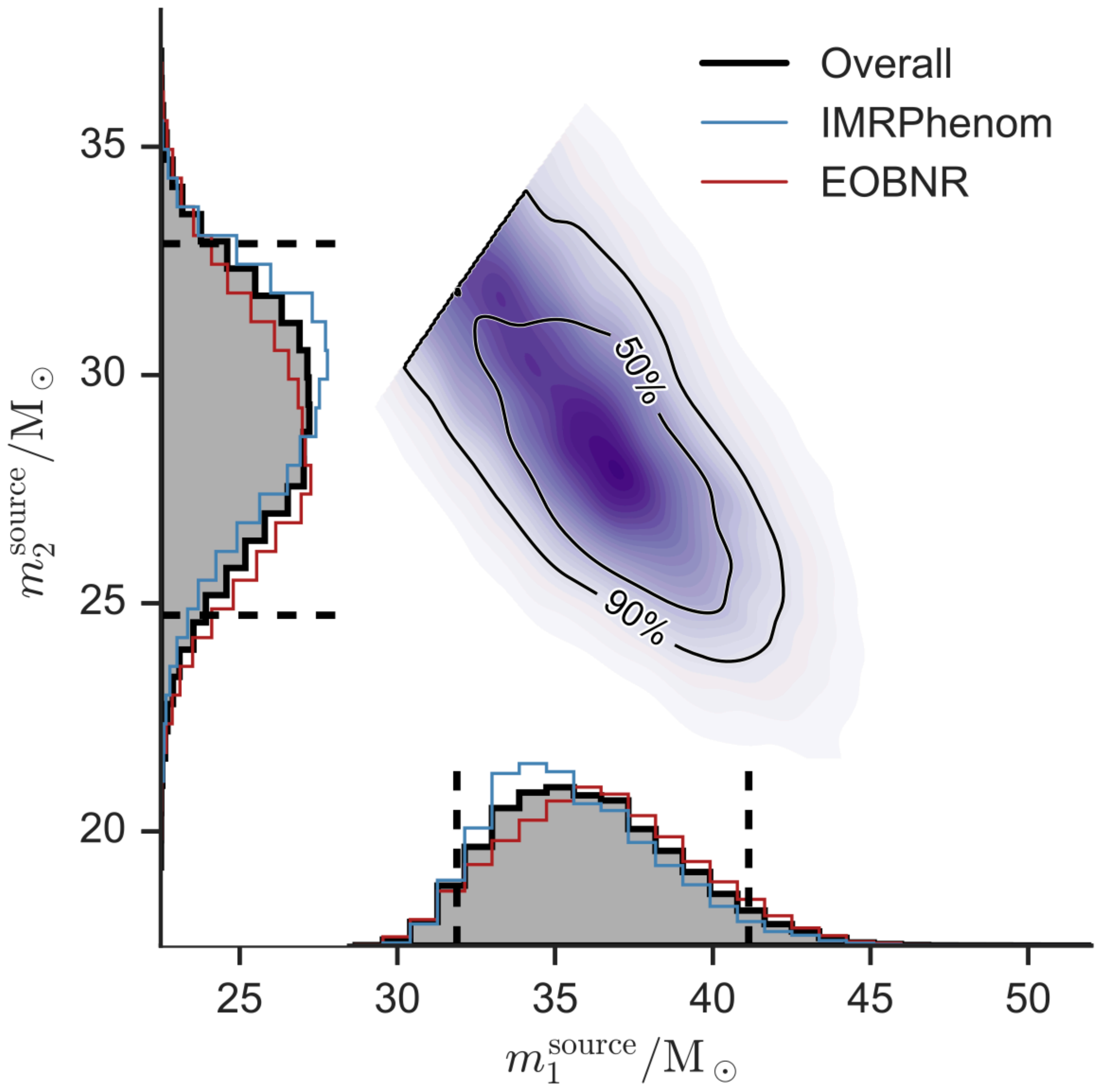
Credit: Caltech/MIT/LIGO Lab



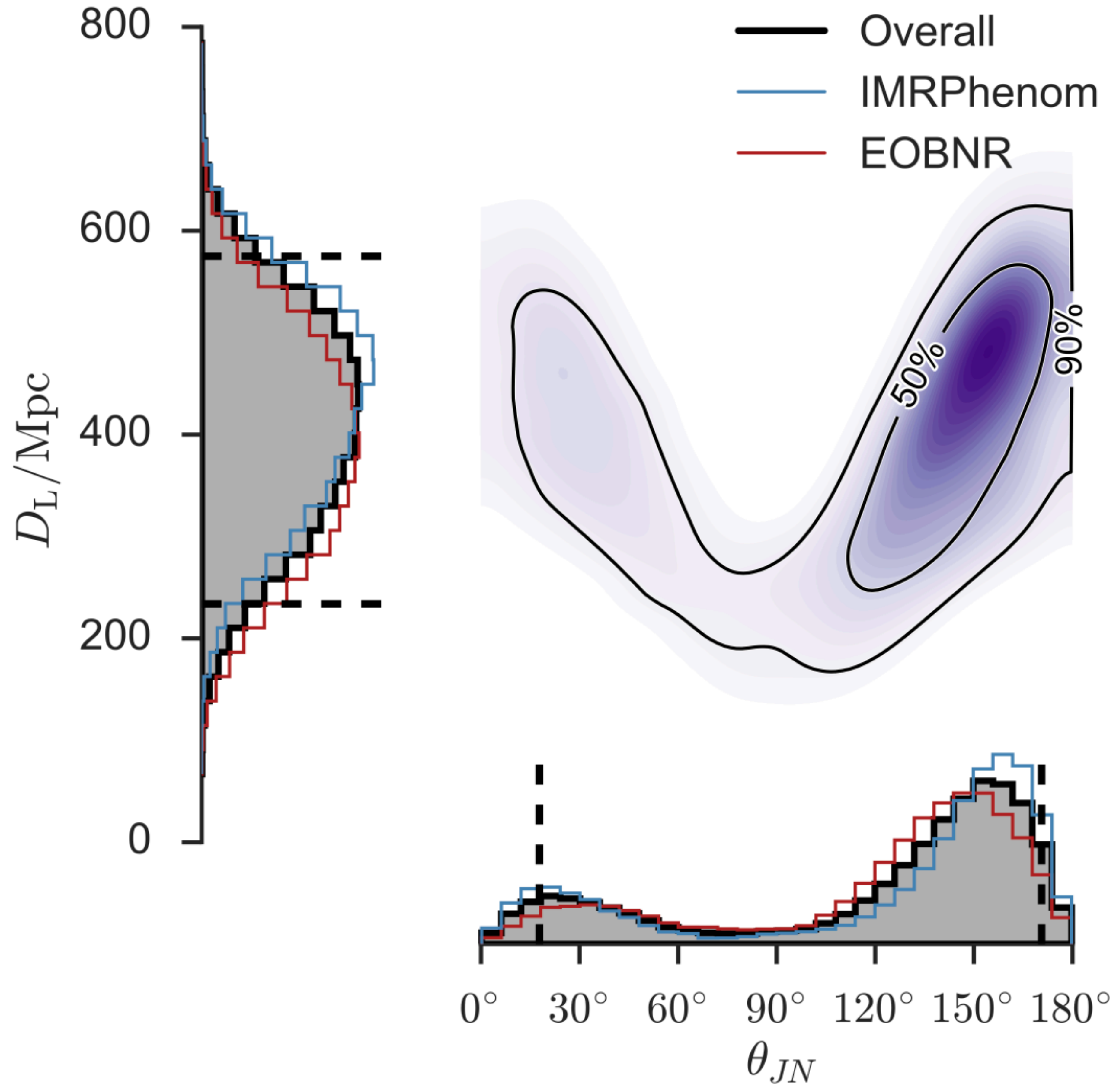
Try it yourself! - https://www.gw-openscience.org/tutorials/

Properties of GW150914

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



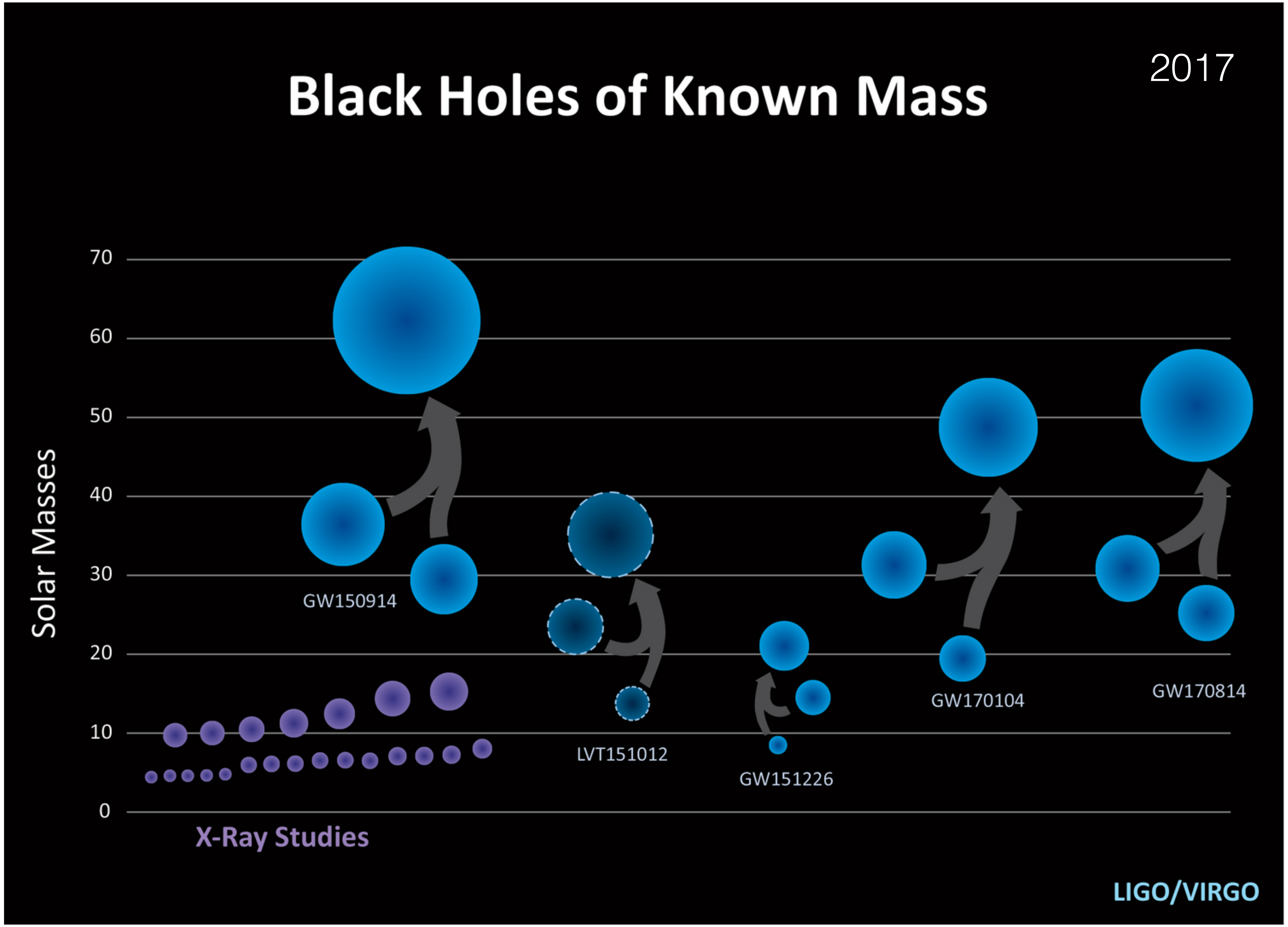
Combination $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$ (the chirp mass) is most tightly constrained.



Some degeneracy between distance and binary orientation.

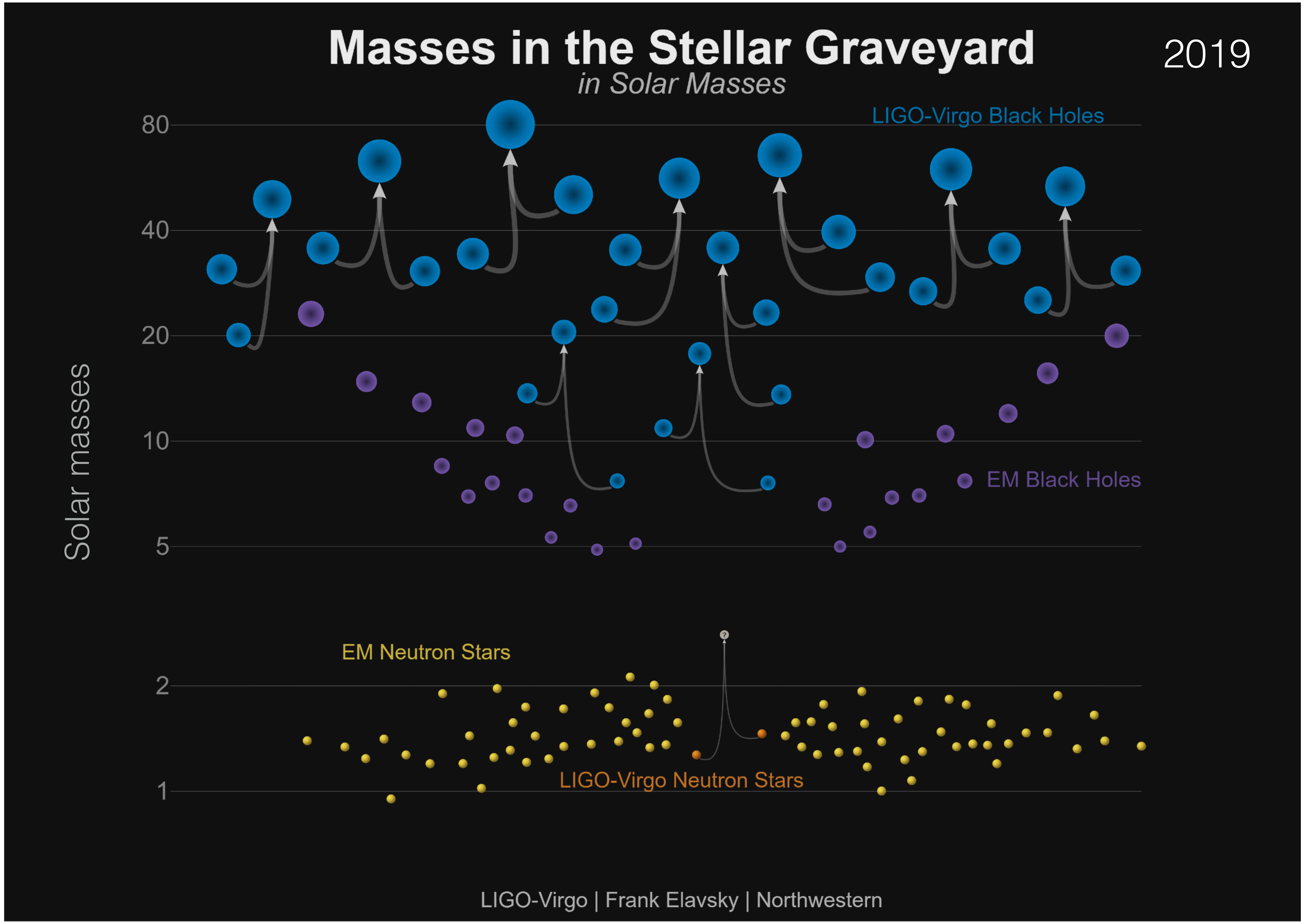
1602.03840

A whole catalog



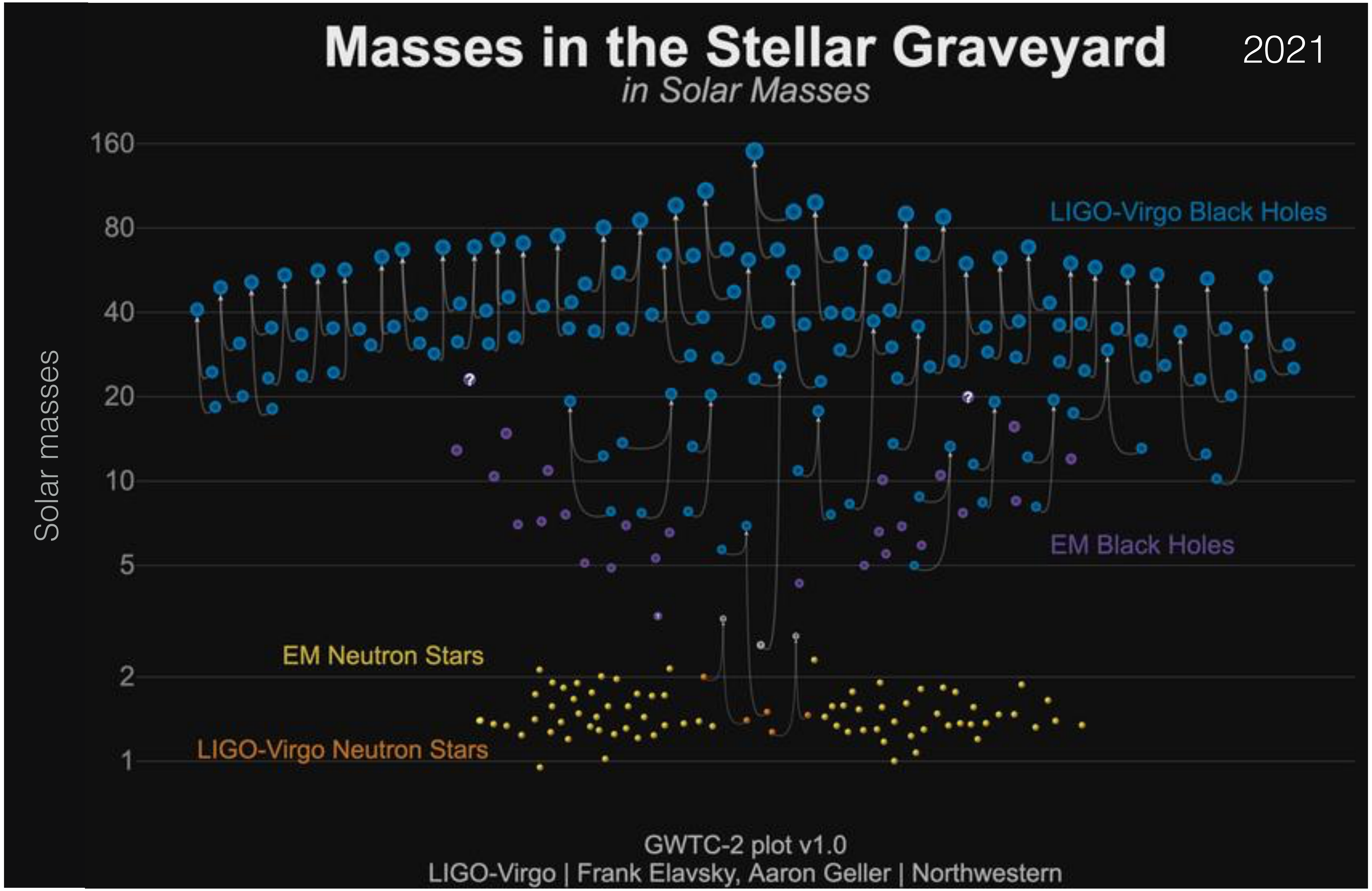
Credit: LIGO/Caltech/Sonoma State (Aurore Simonnet)

A whole catalog



A whole catalog

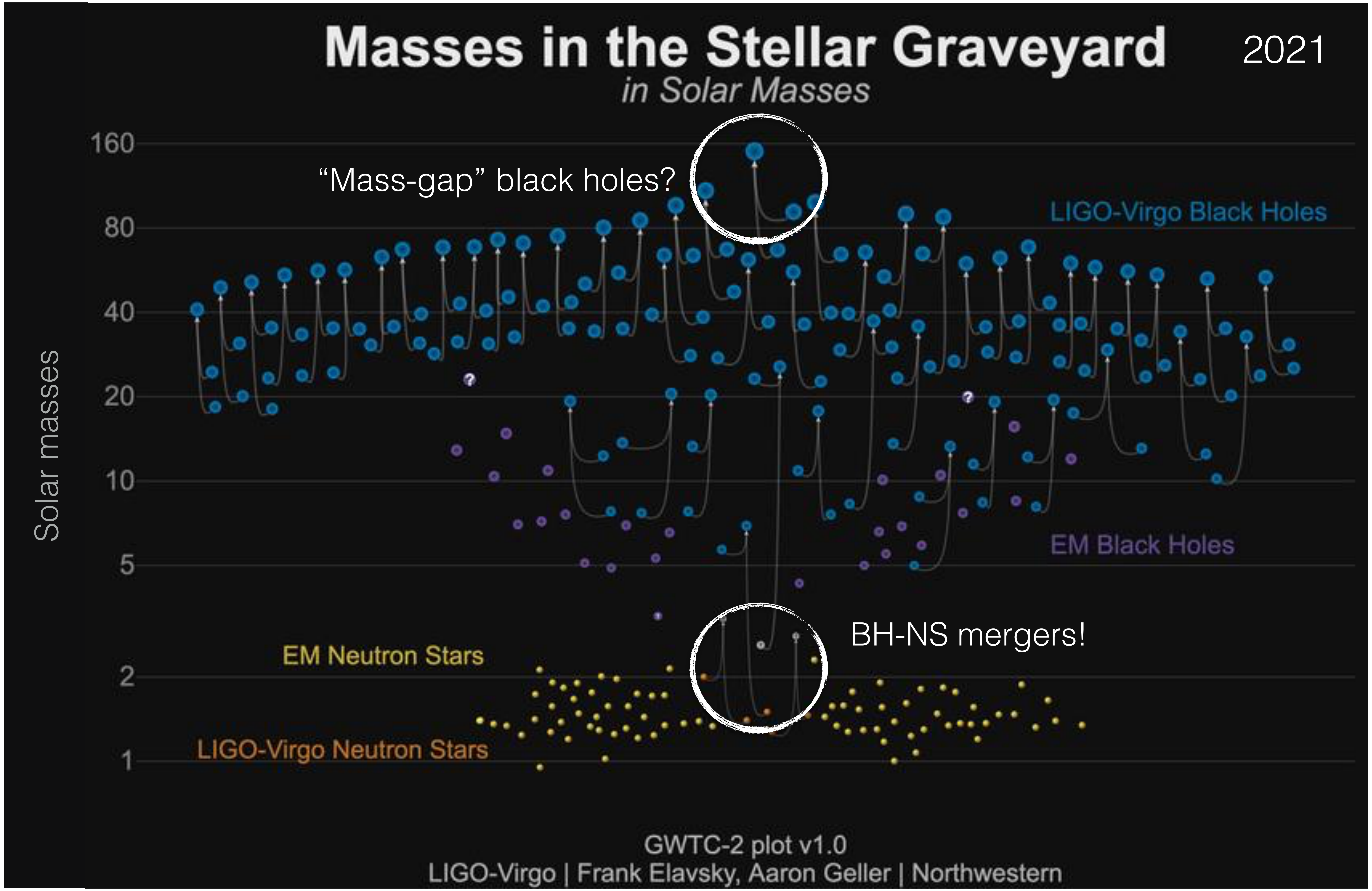
~ 50 GW merger events observed so far



A whole catalog

~ 50 GW merger events observed so far

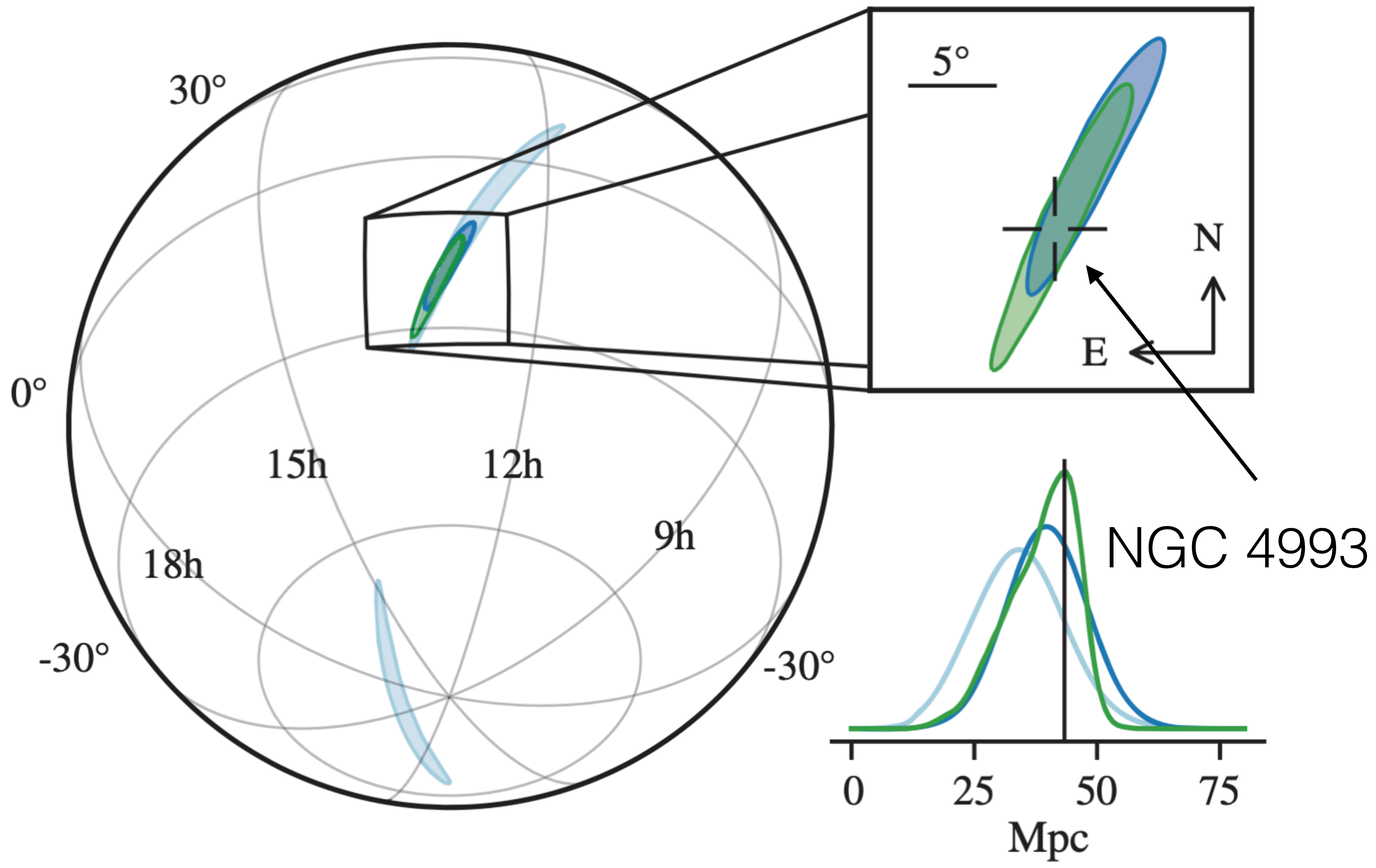
2007.07889



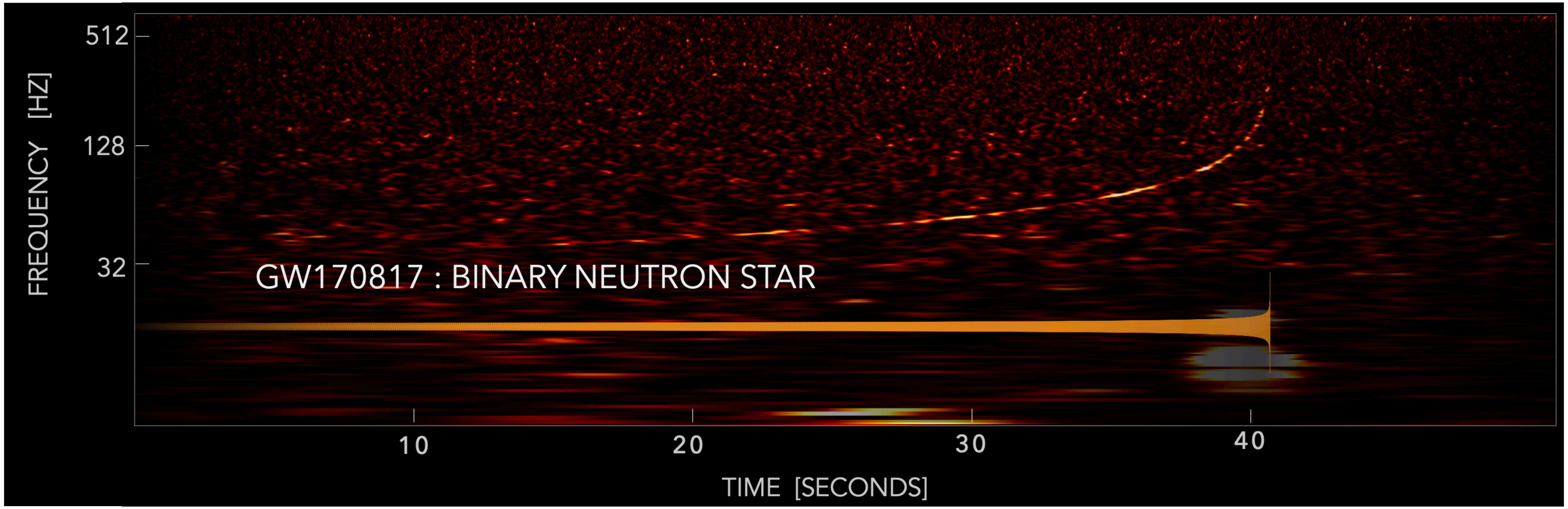
2106.15163

GW170817 - the first NS-NS merger

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



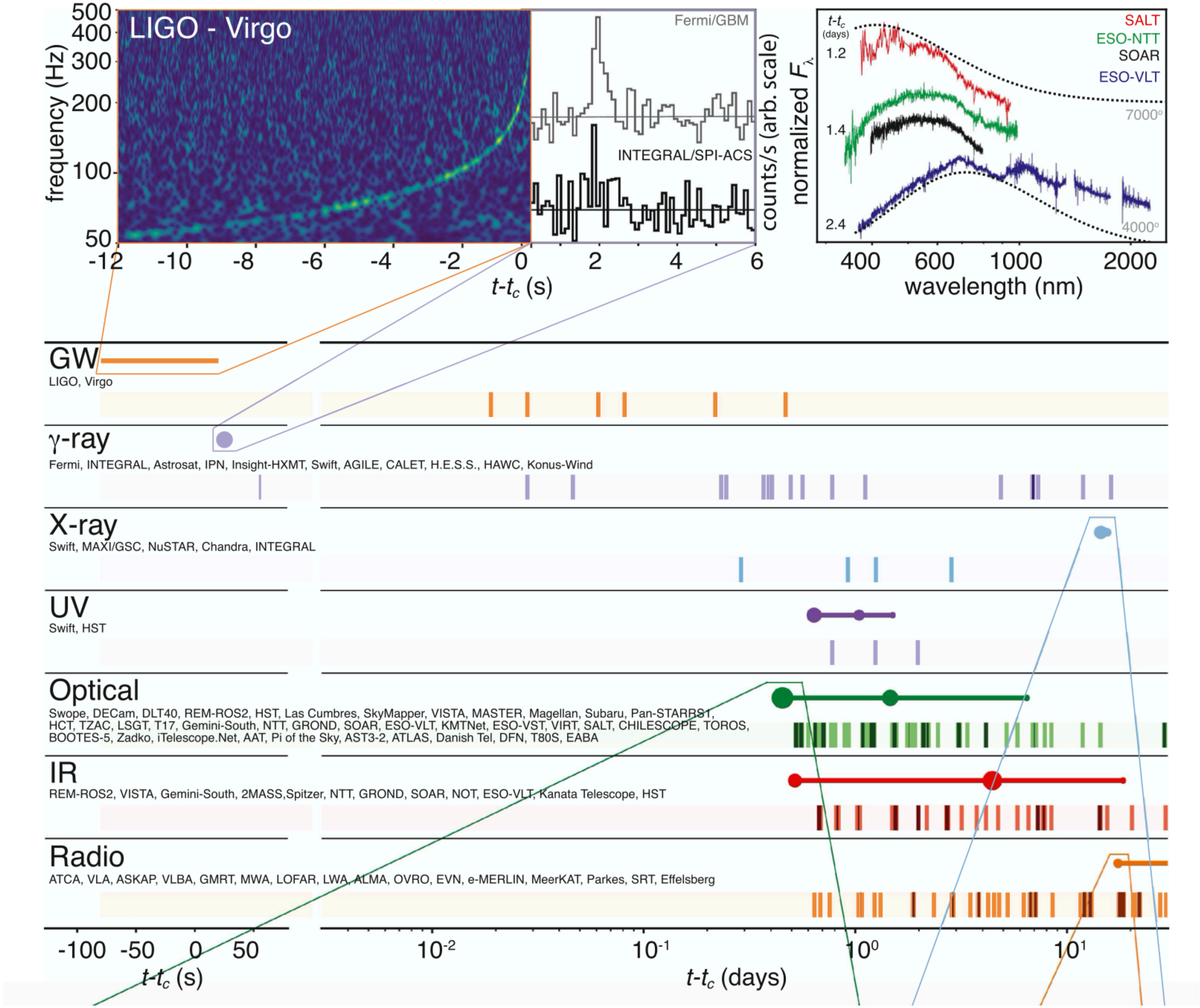
Localised to within ~30 deg^2



[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

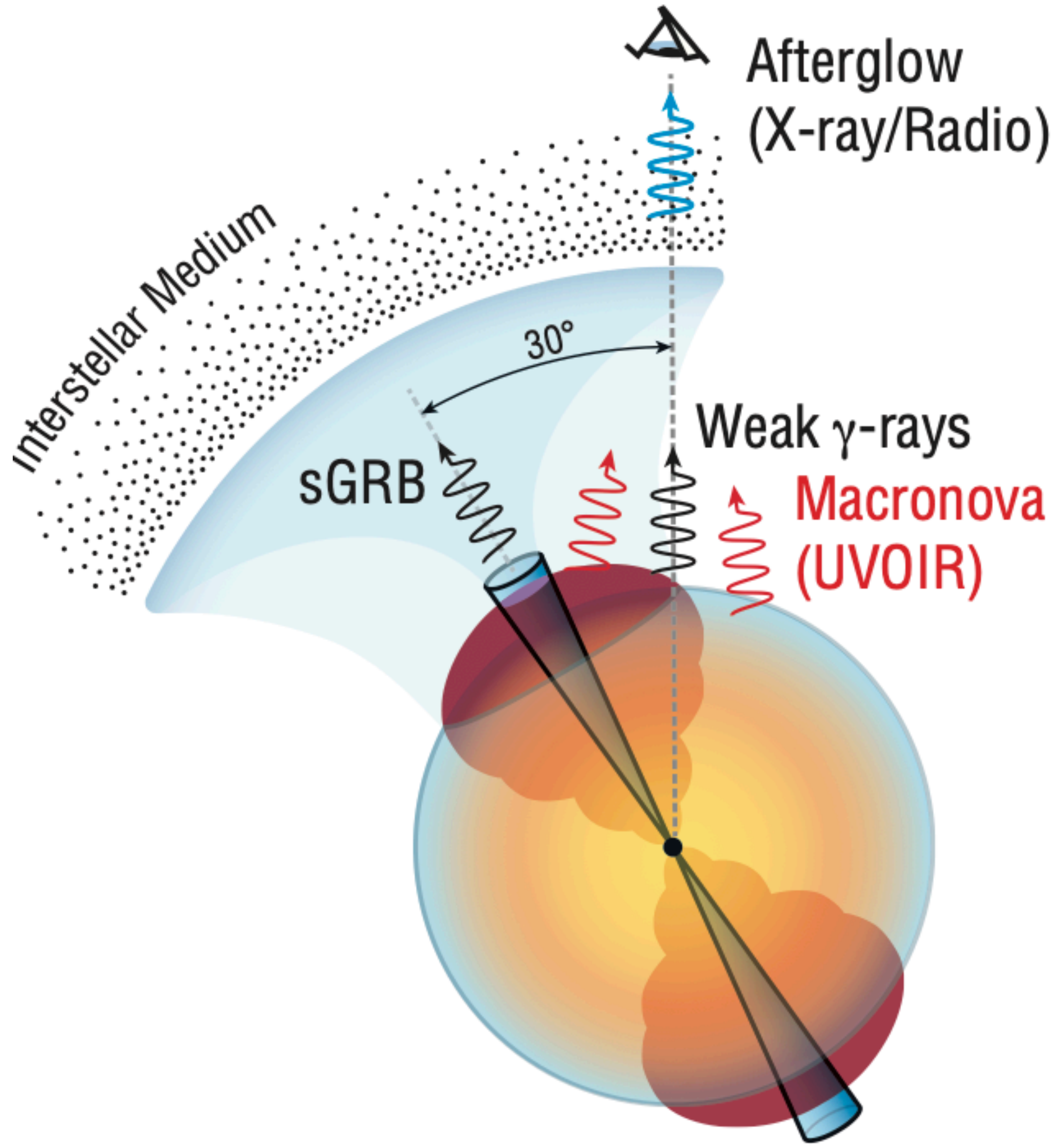
Follow-up observations across the spectrum!

Sadly no neutrinos detected :(

[1710.05833](1710.05833), [2105.13160](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!

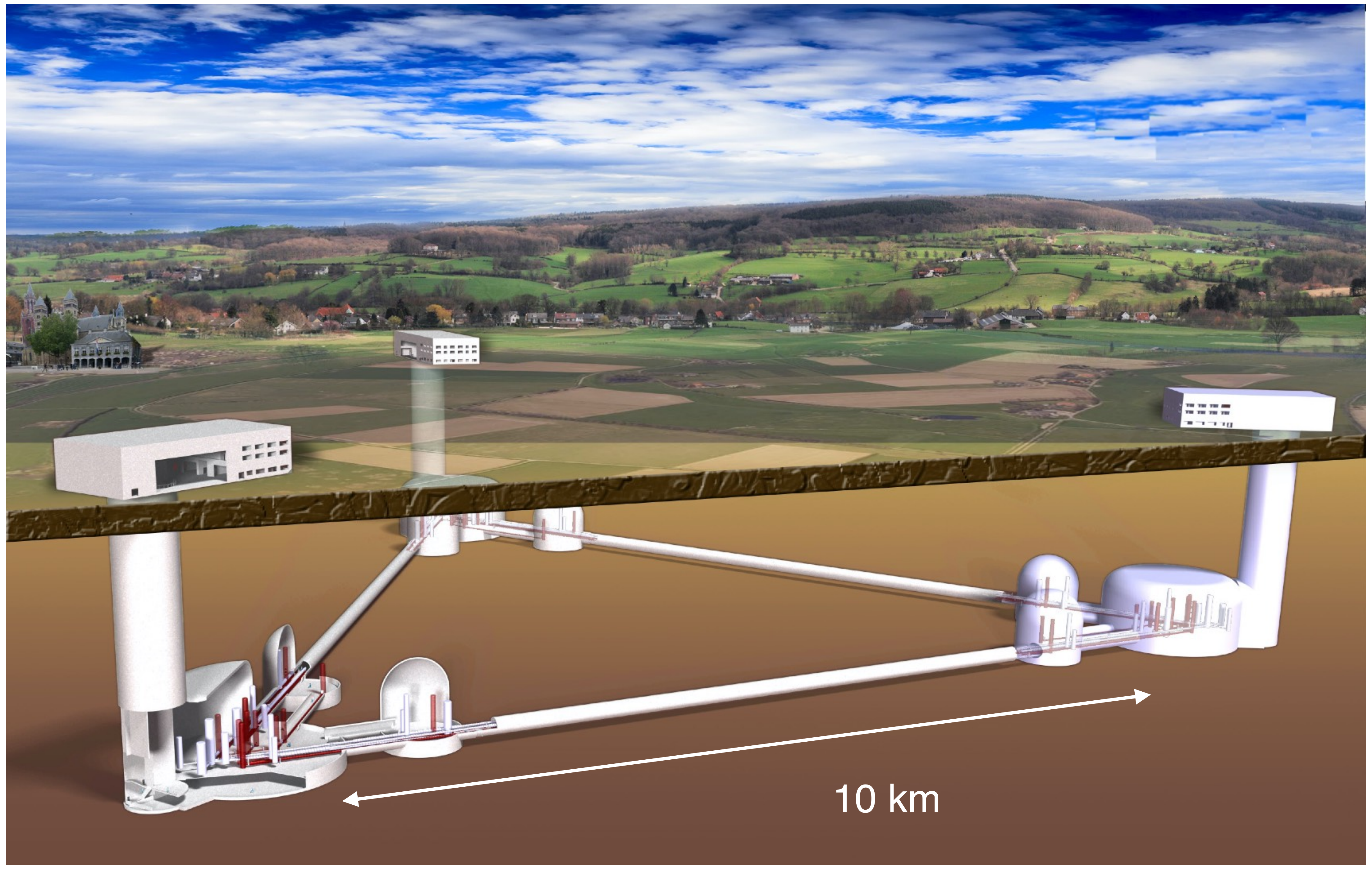
1710.06394

Measurement of the Hubble Constant!

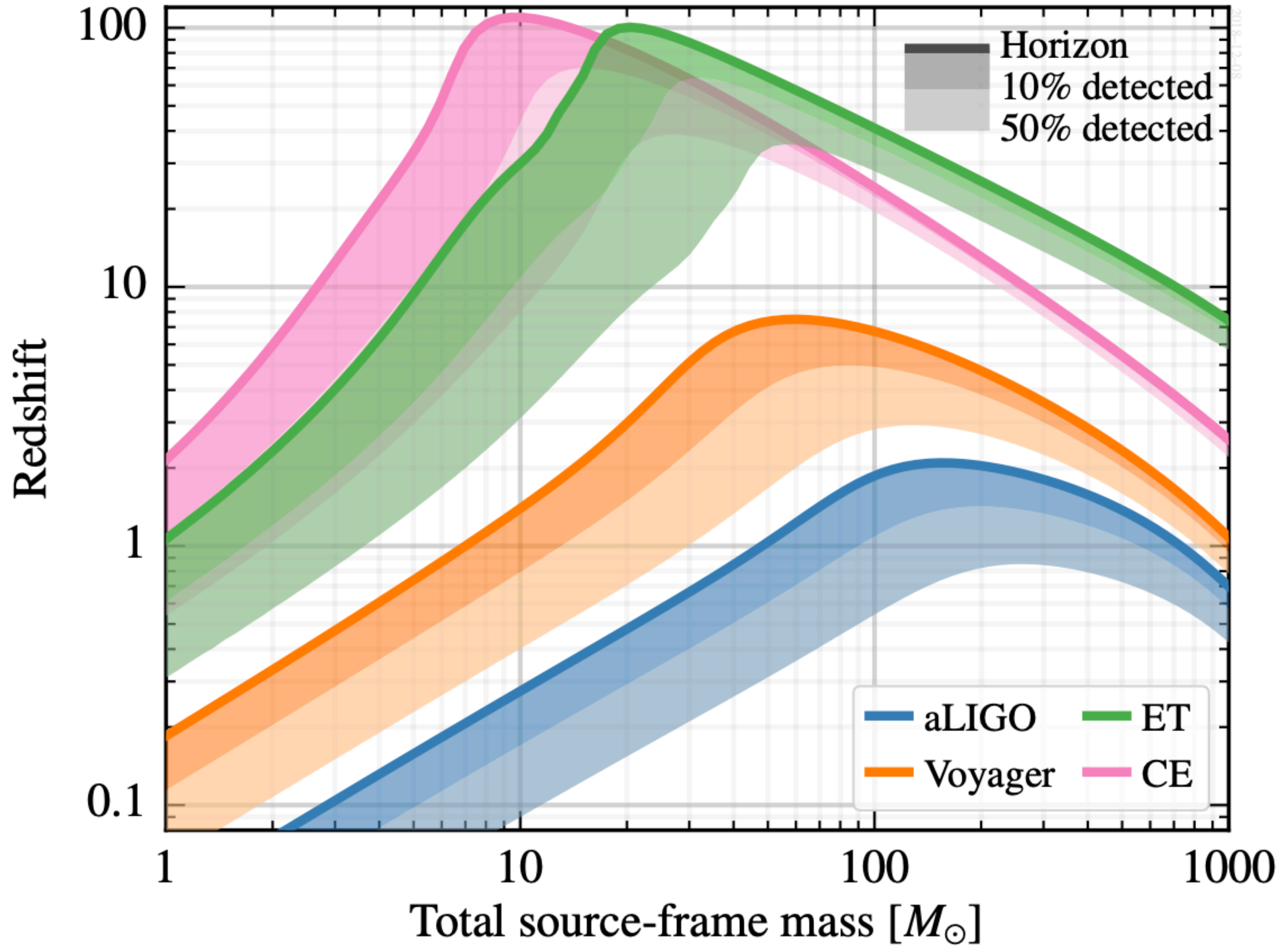
1710.05835

The Gravitational Wave Future

Planned Earth-based observatories such as Einstein Telescope:



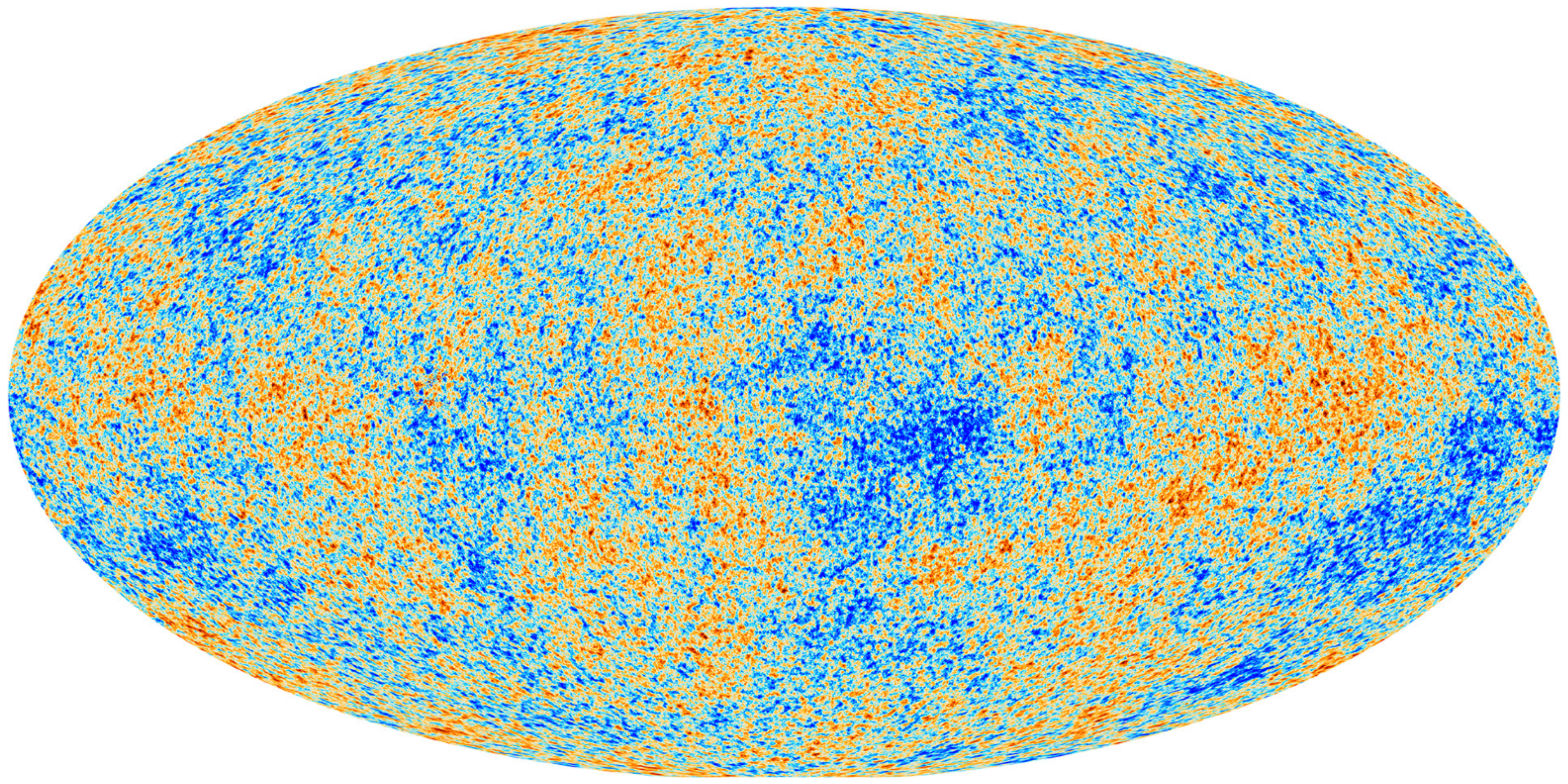
Credit: Einstein Telescope

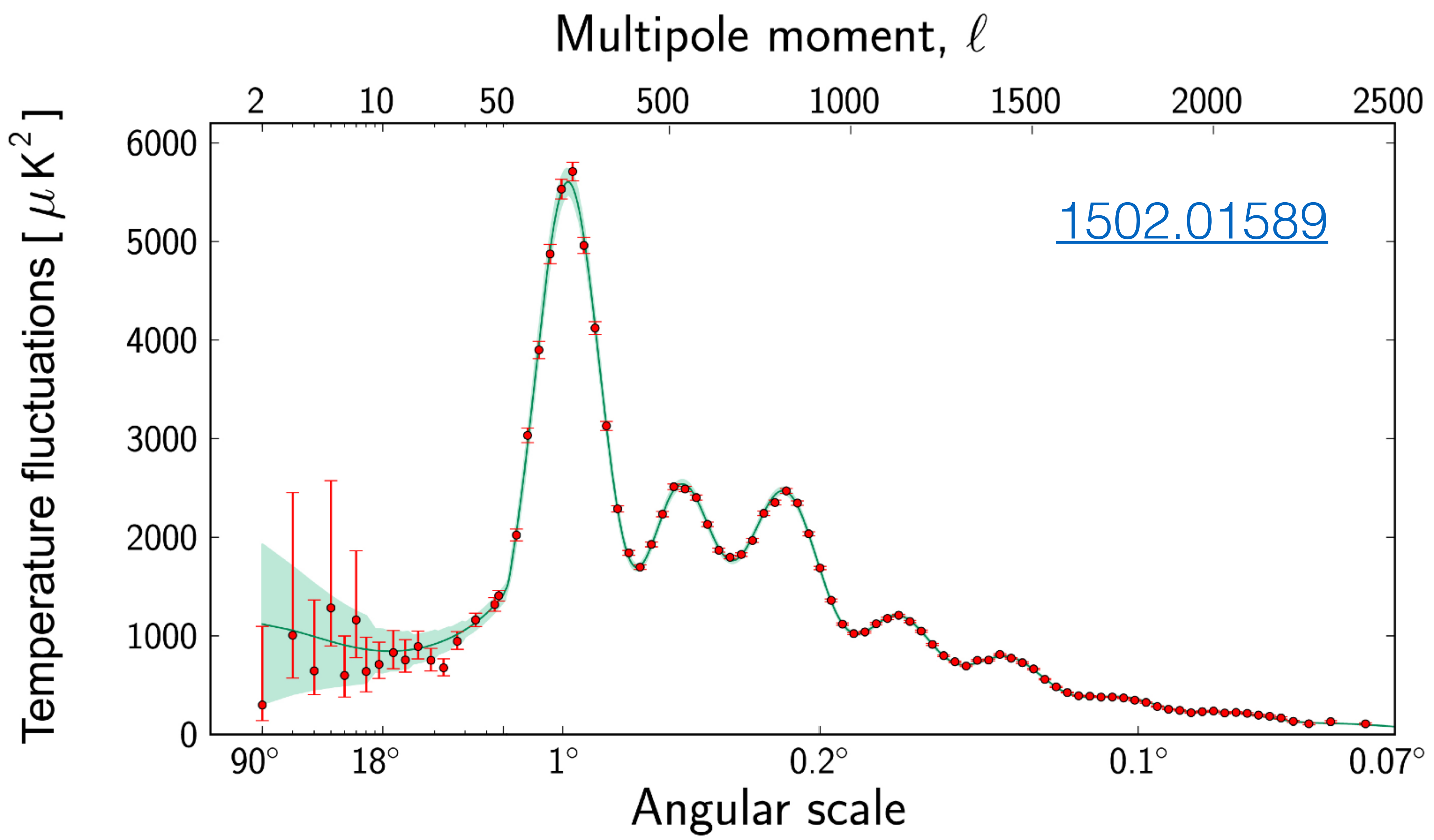


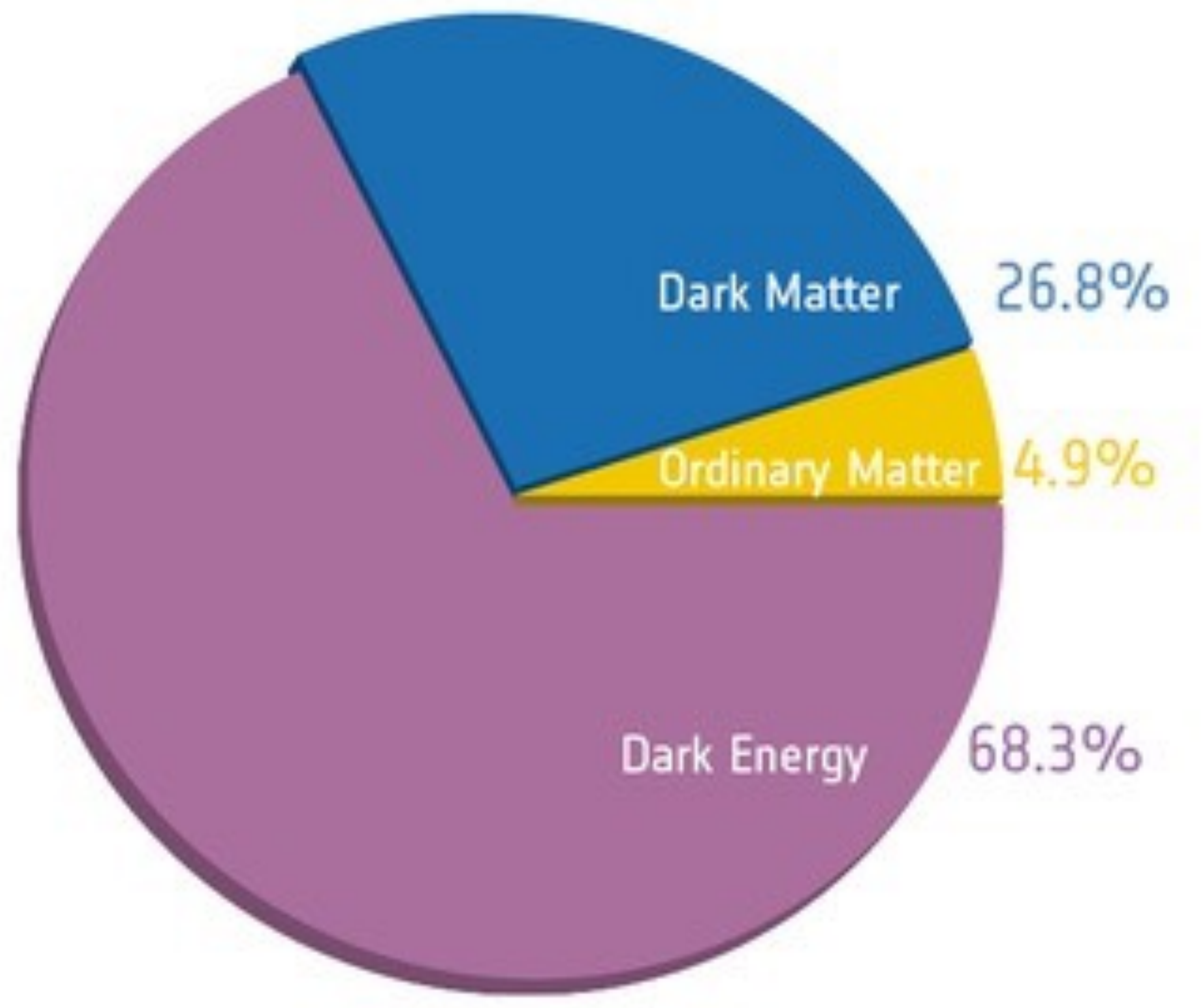
1902.09485

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

Dark Matter in Cosmology





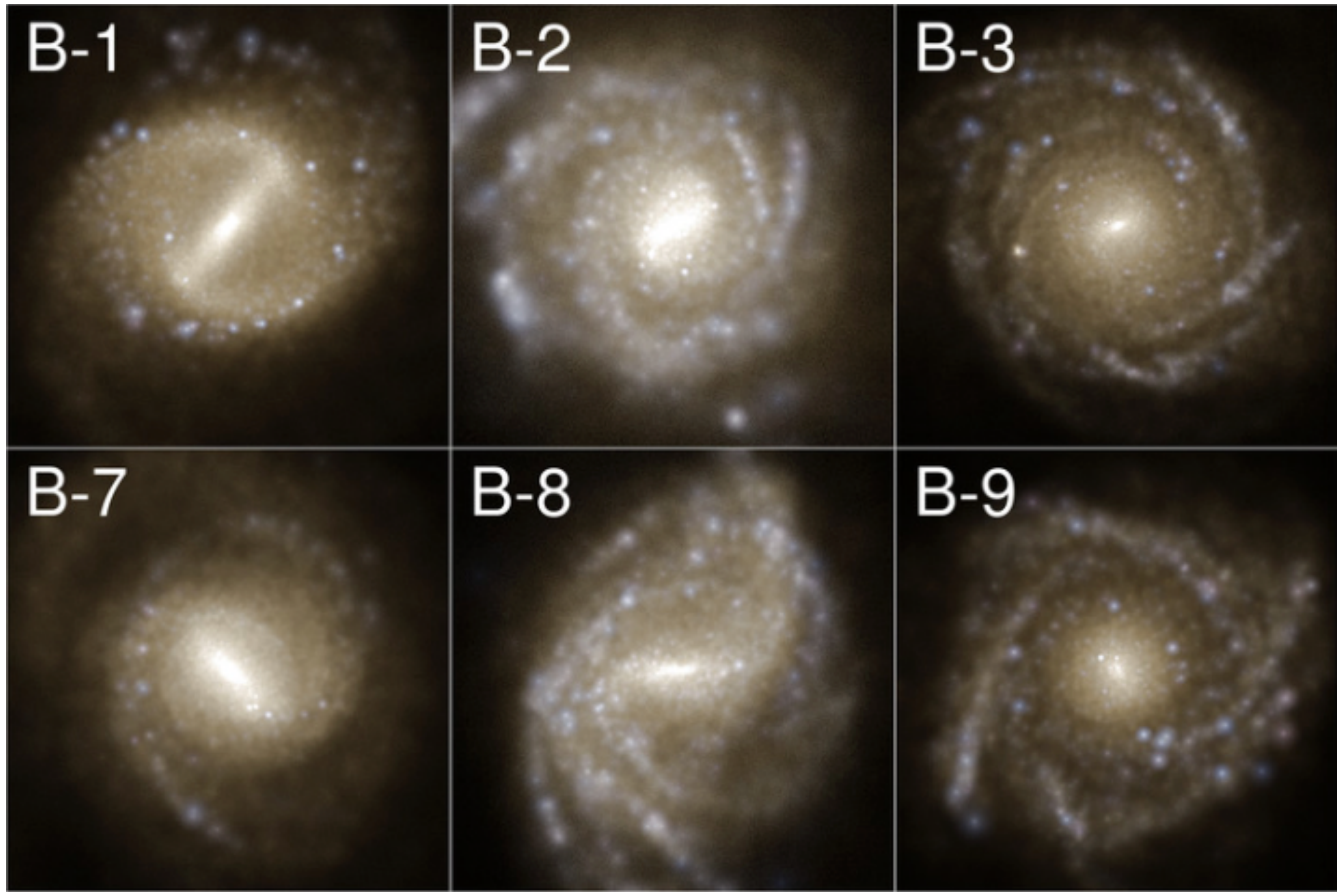


Credit: ESA/Planck Collaboration

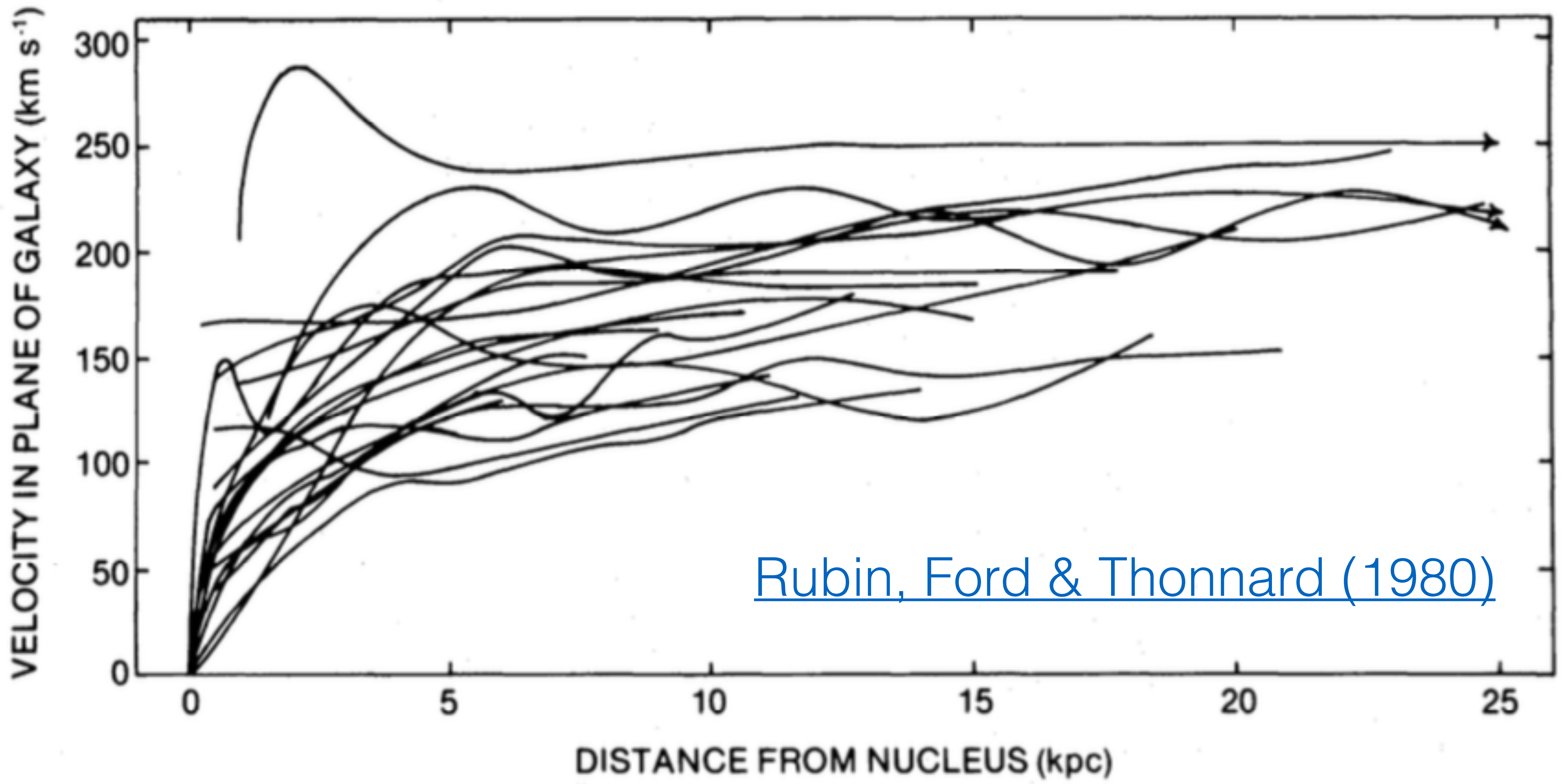
See "Introduction to Cosmology" Lectures by Paolo Creminelli

Dark Matter in Galaxies (1)

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



Illustris simulation - 1405.2921

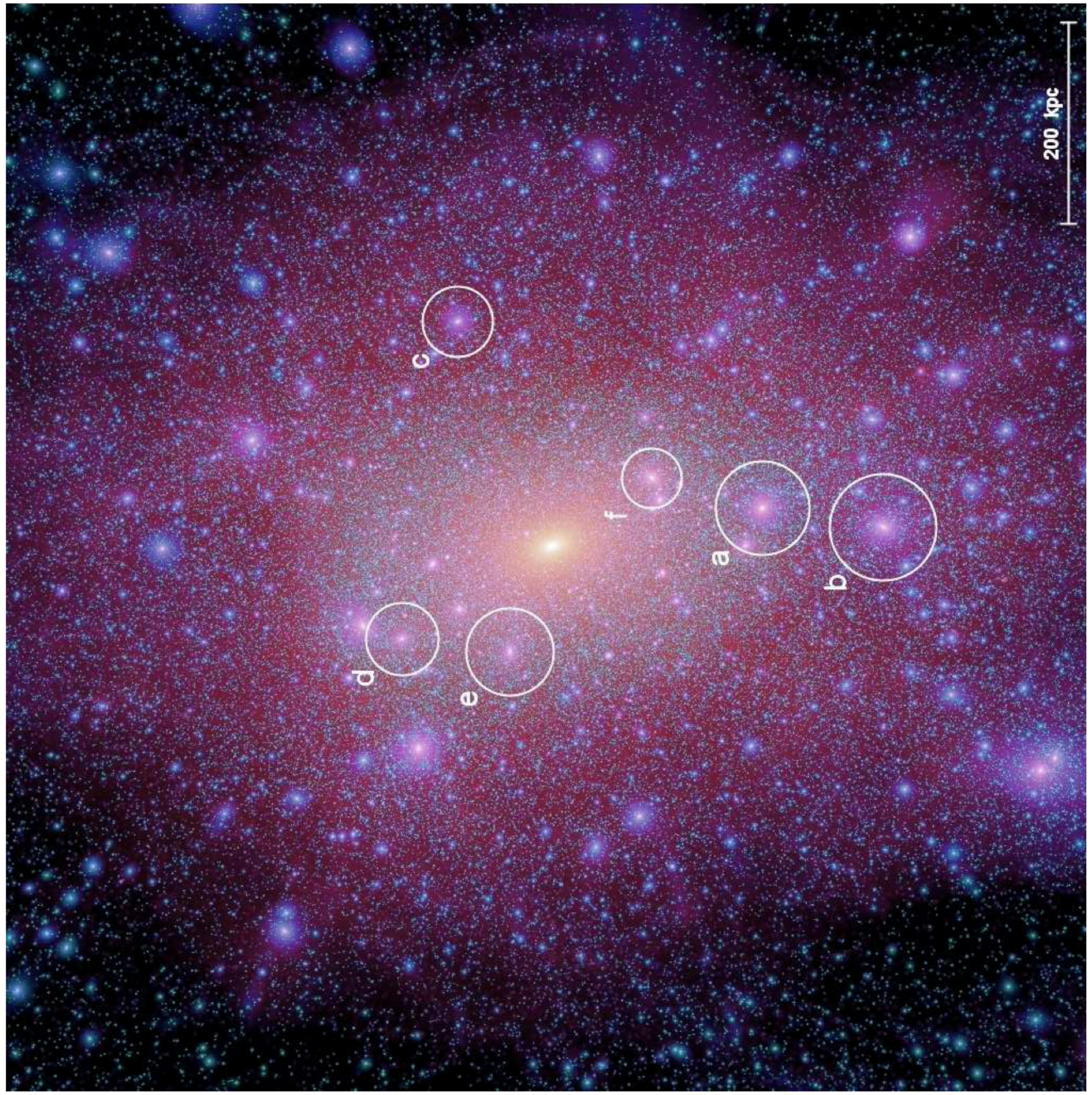


Rubin, Ford & Thonnard (1980)

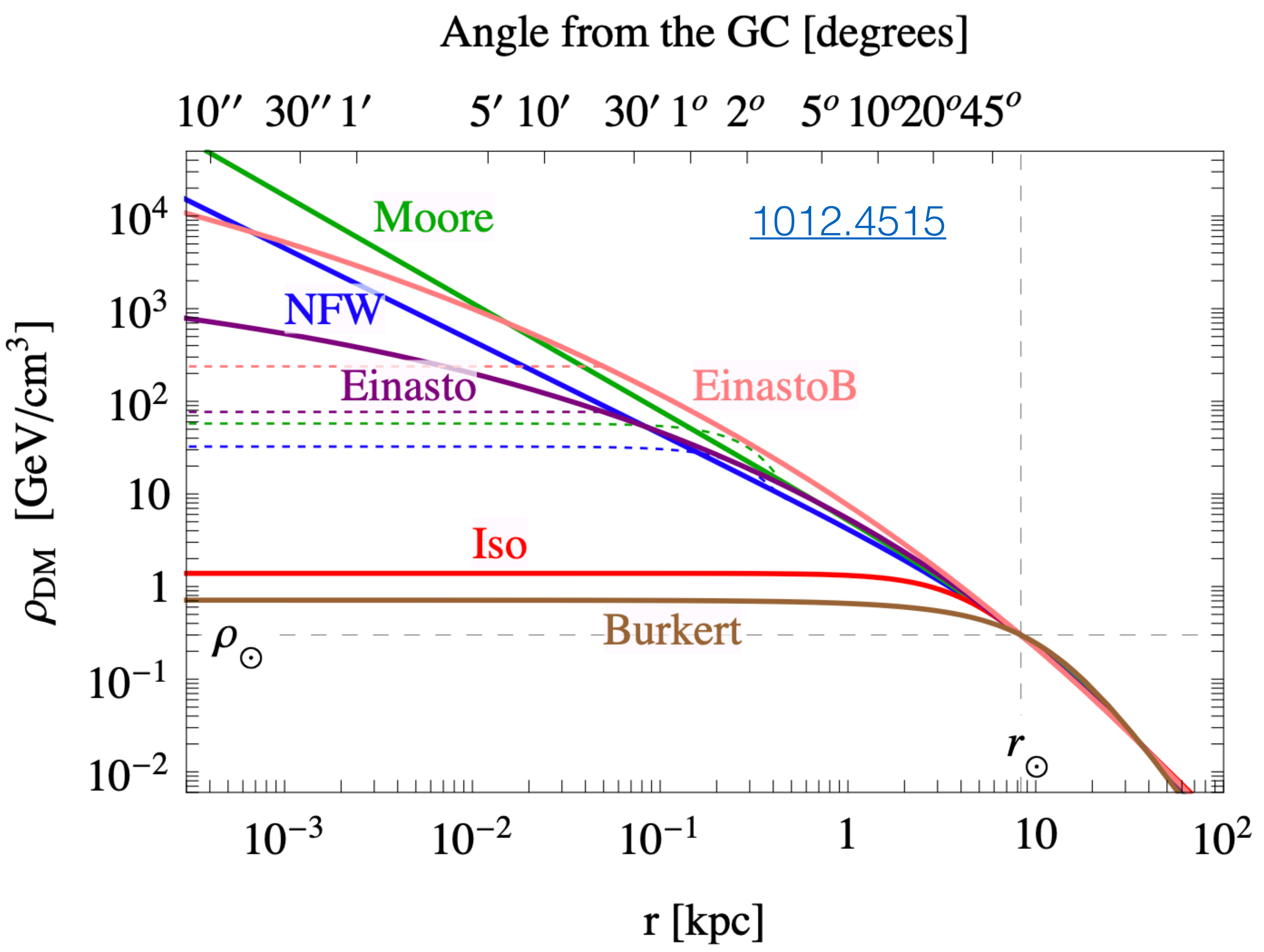
NB: Galaxy formation is messy and non-linear and still not fully understood e.g. 1609.05917 vs 1610.07663

Dark Matter in Galaxies (2)

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



Aquarius simulation - 0809.0898



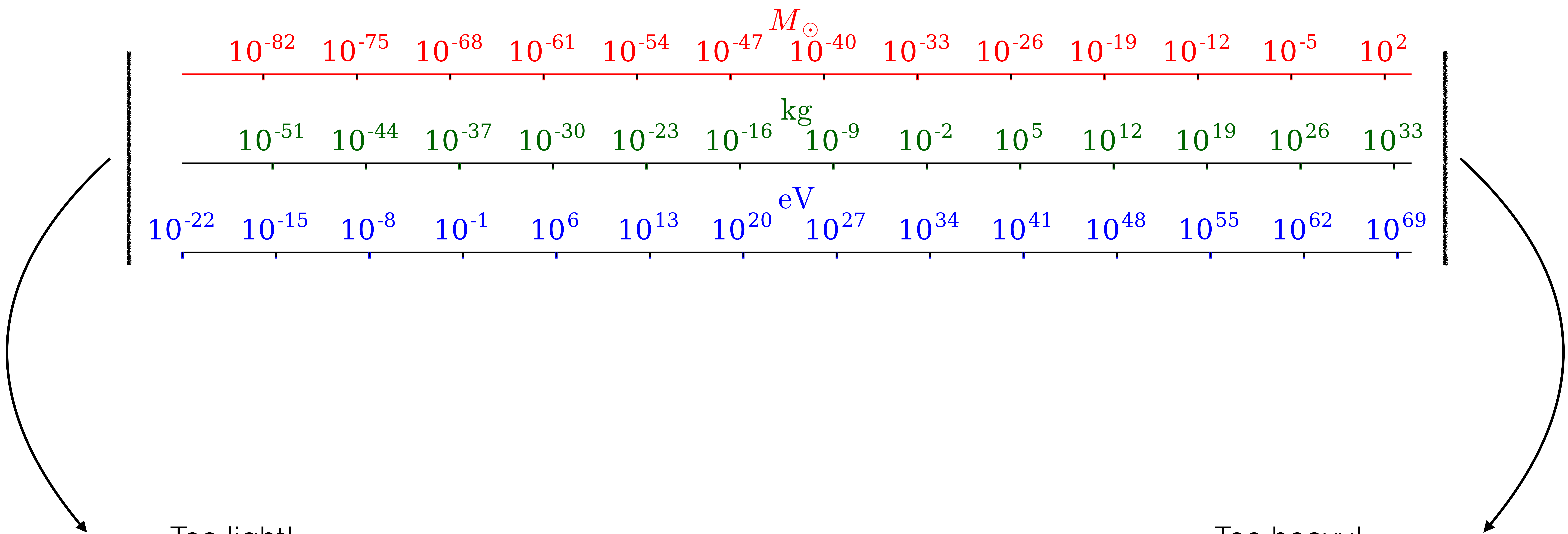
DM density at Earth:

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

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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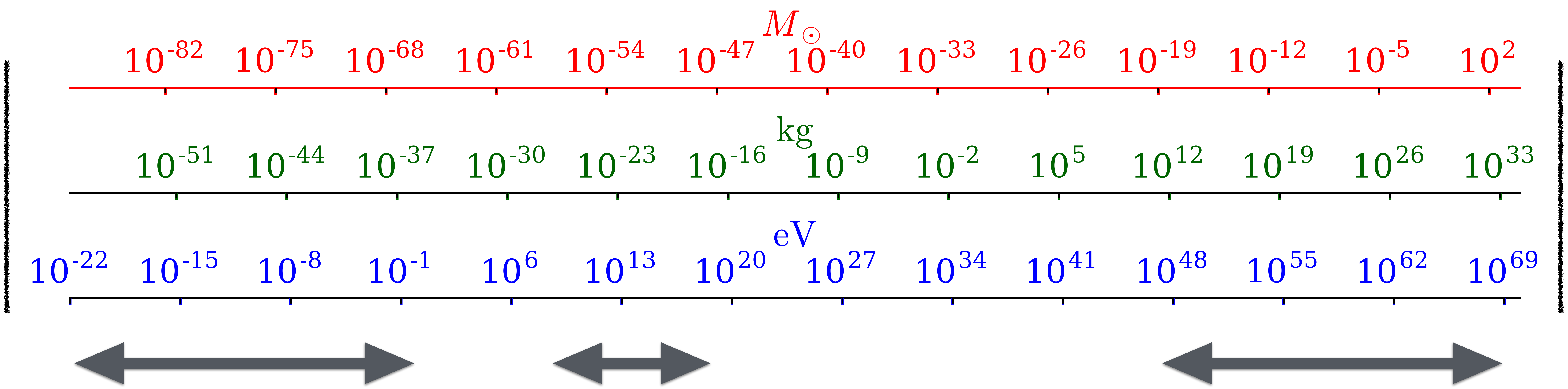

Axion-like particles
(**ALPs**)

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:

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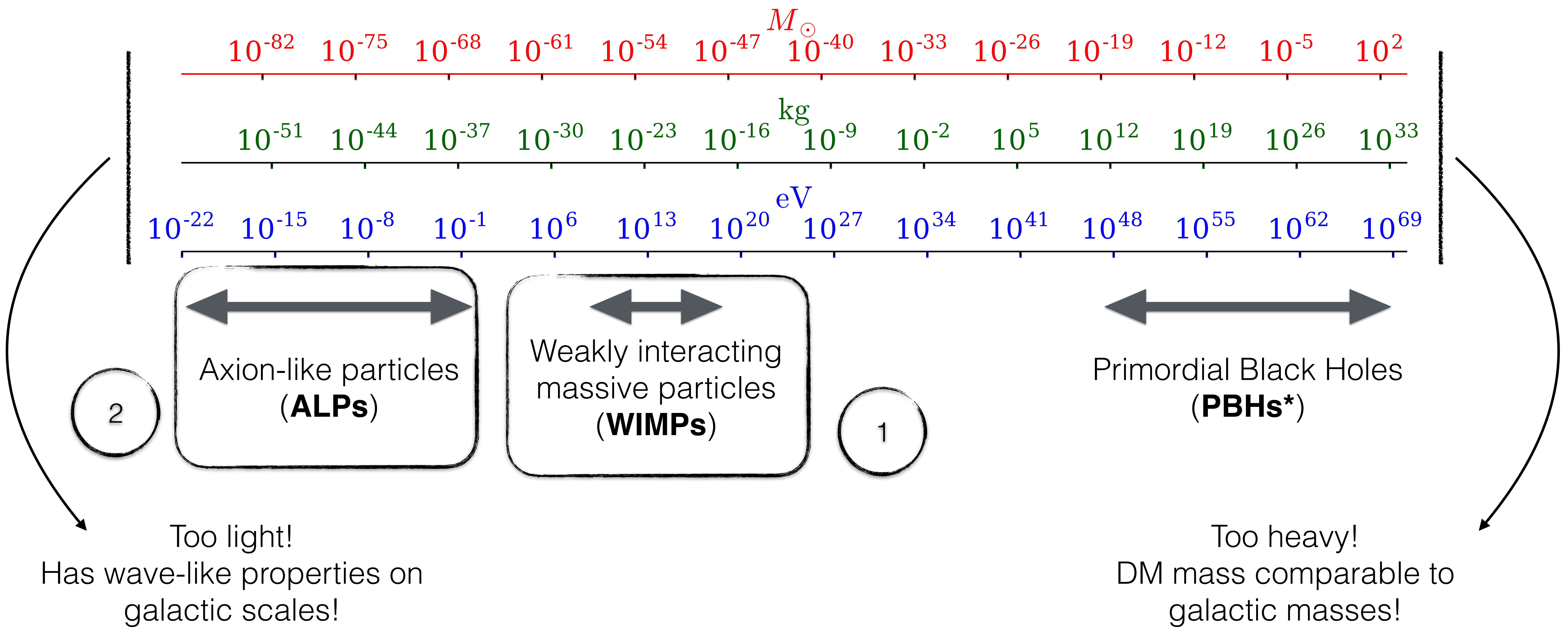
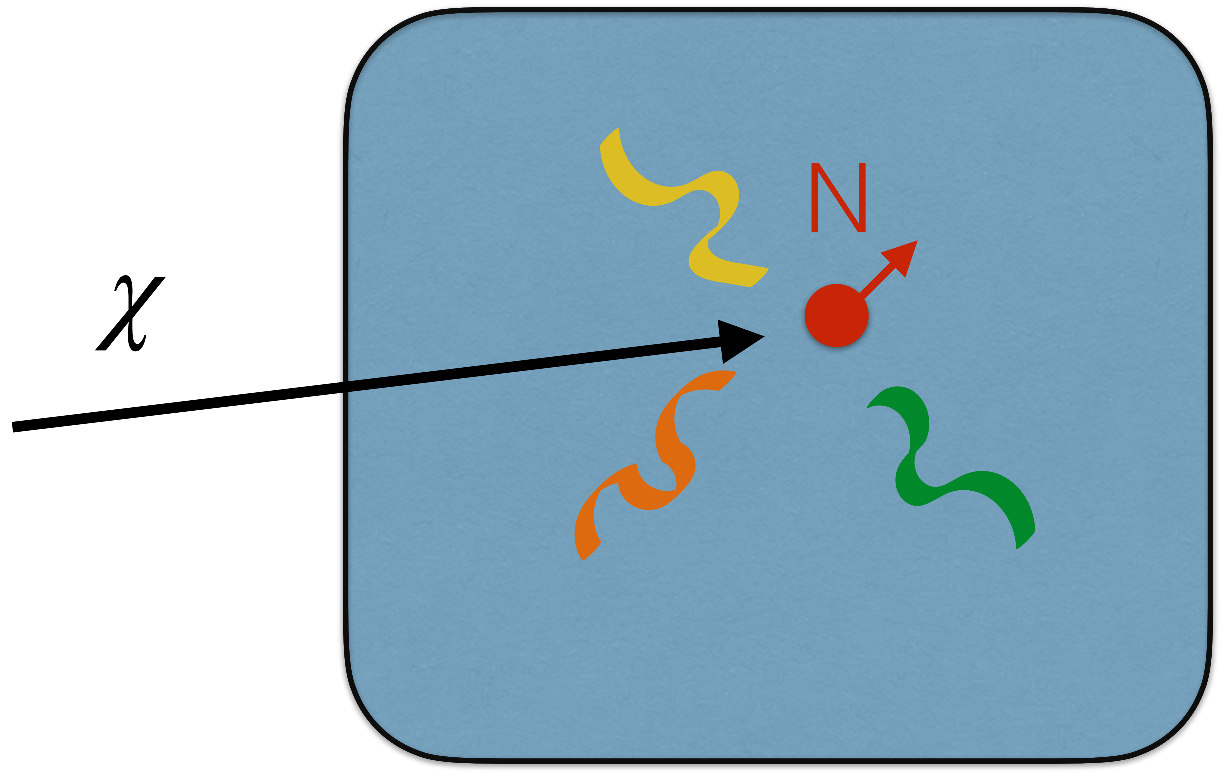


*See additional slides…

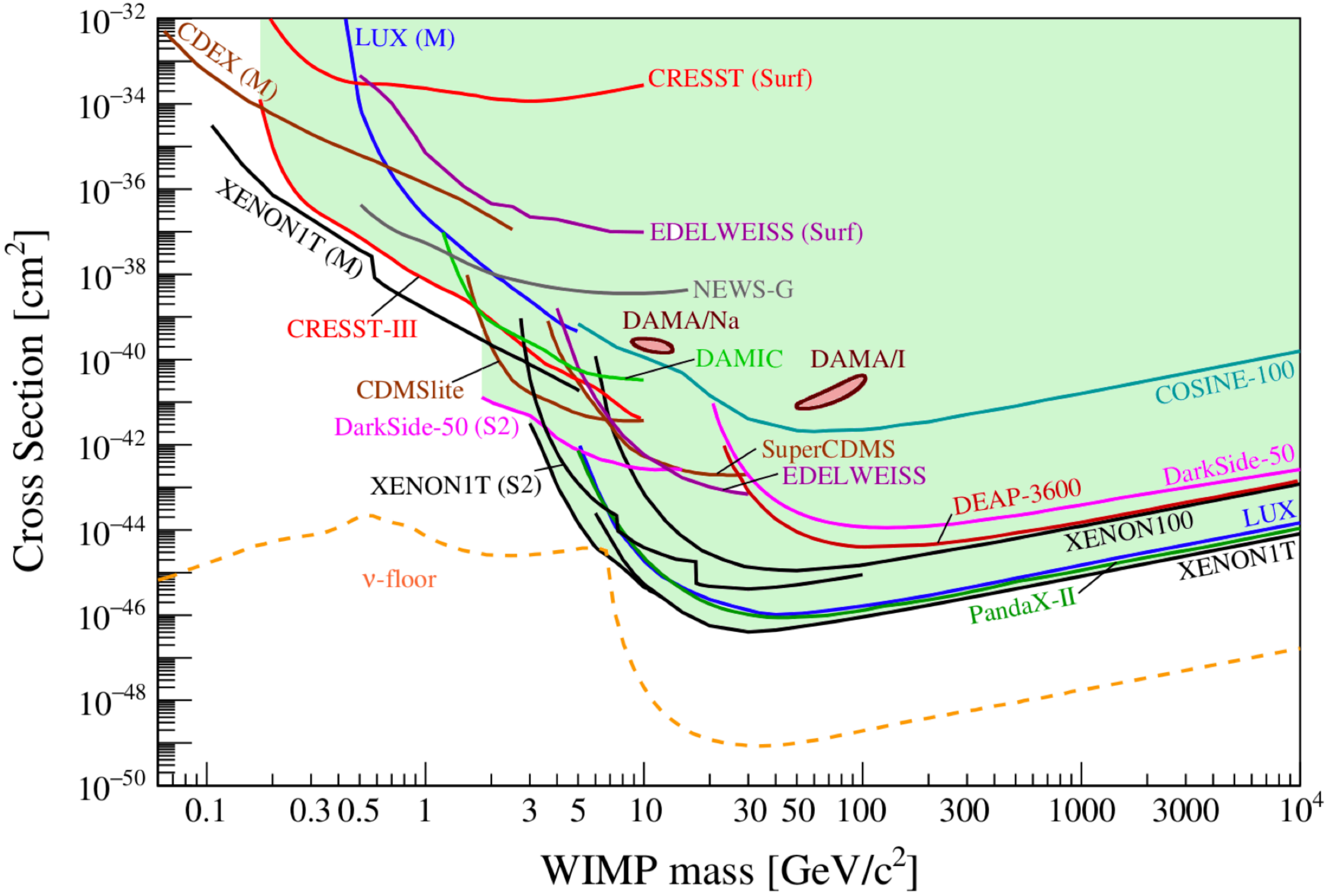
Direct detection of WIMPs on Earth

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!

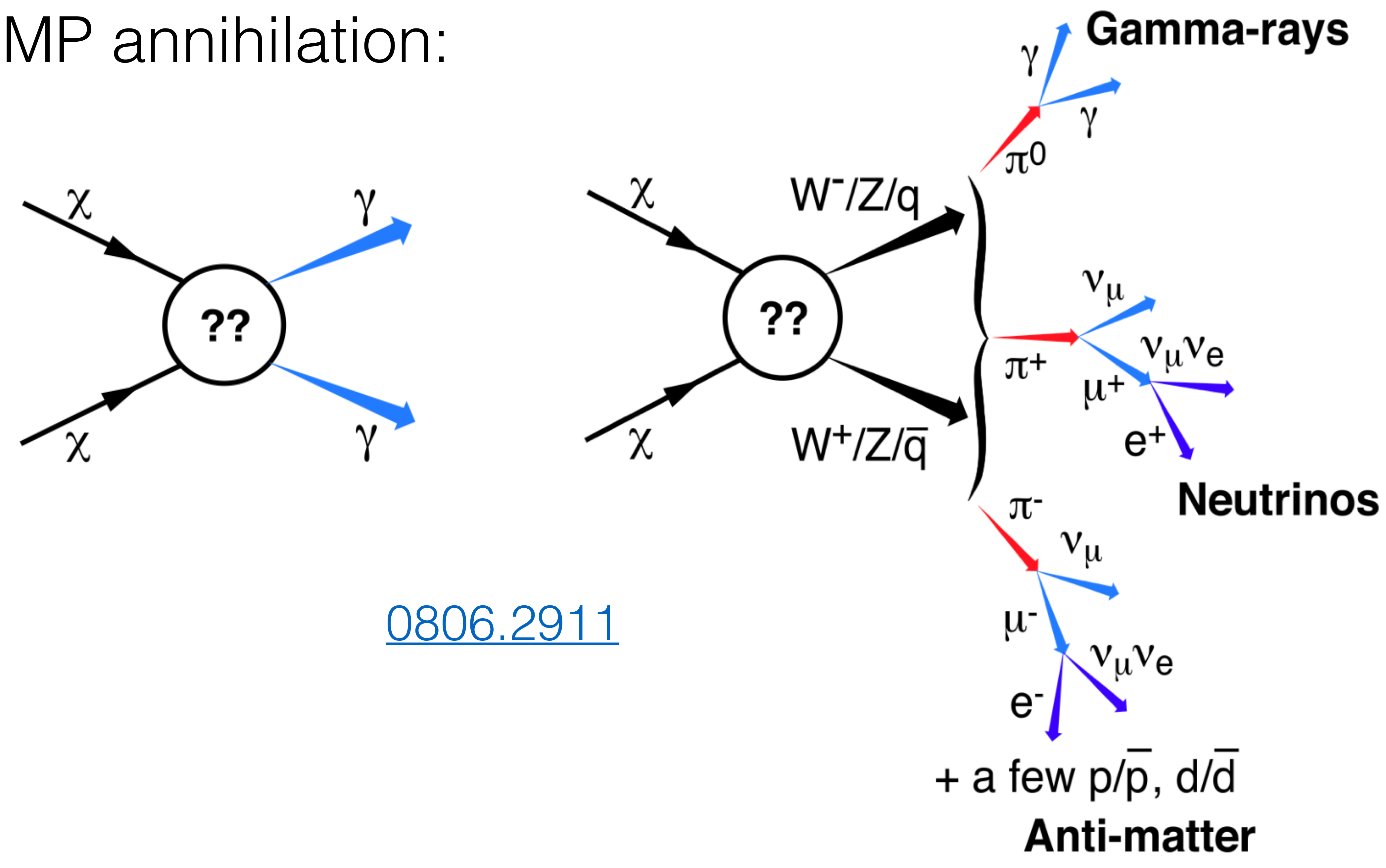


Also possible to look for DM-electron scattering, depending on the model.

Indirect detection of Dark Matter

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

WIMP annihilation:



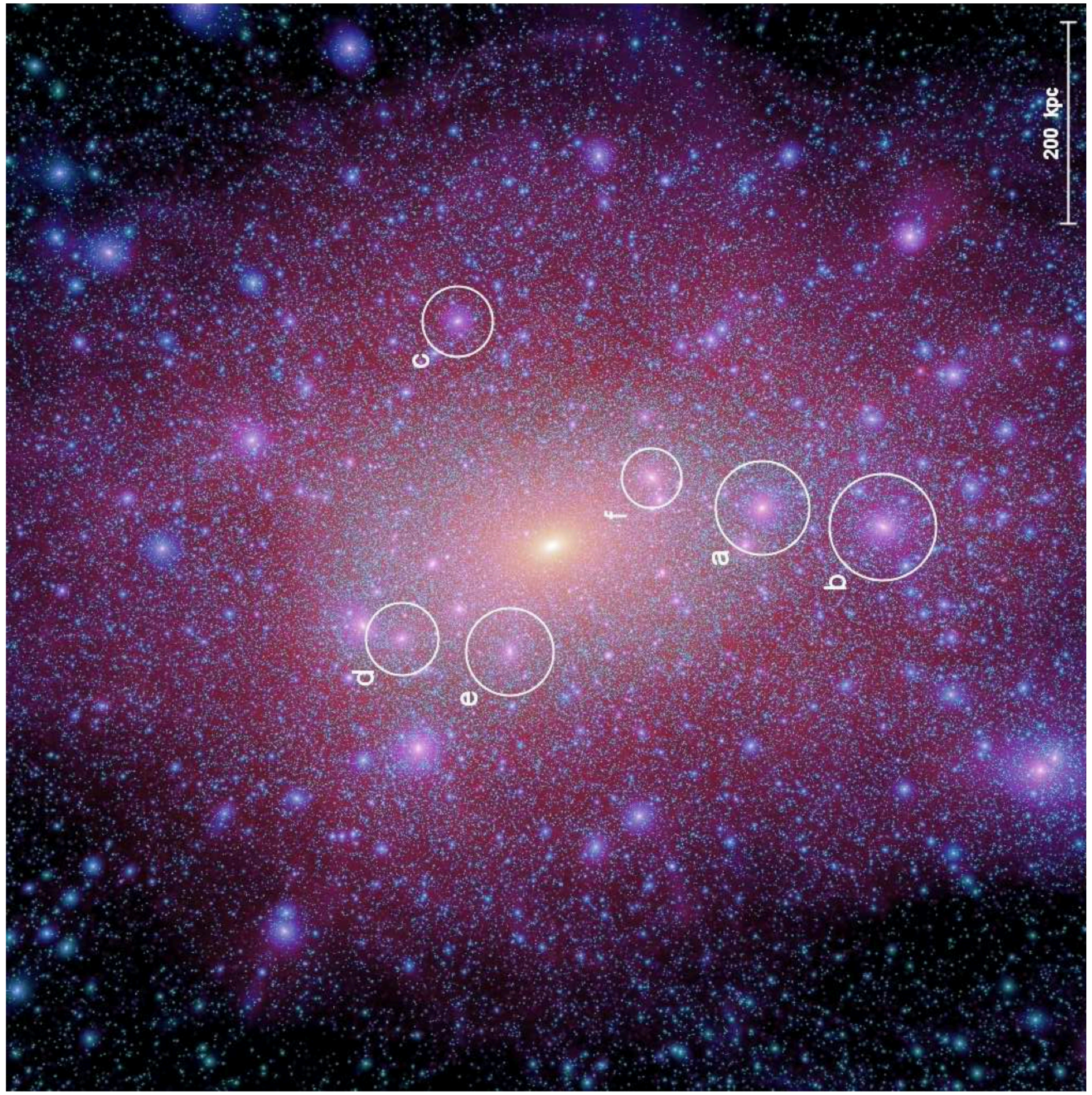
[0806.2911](0806.2911)

Annihilation cross section
(particle physics)

DM density distribution
(astrophysics)

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

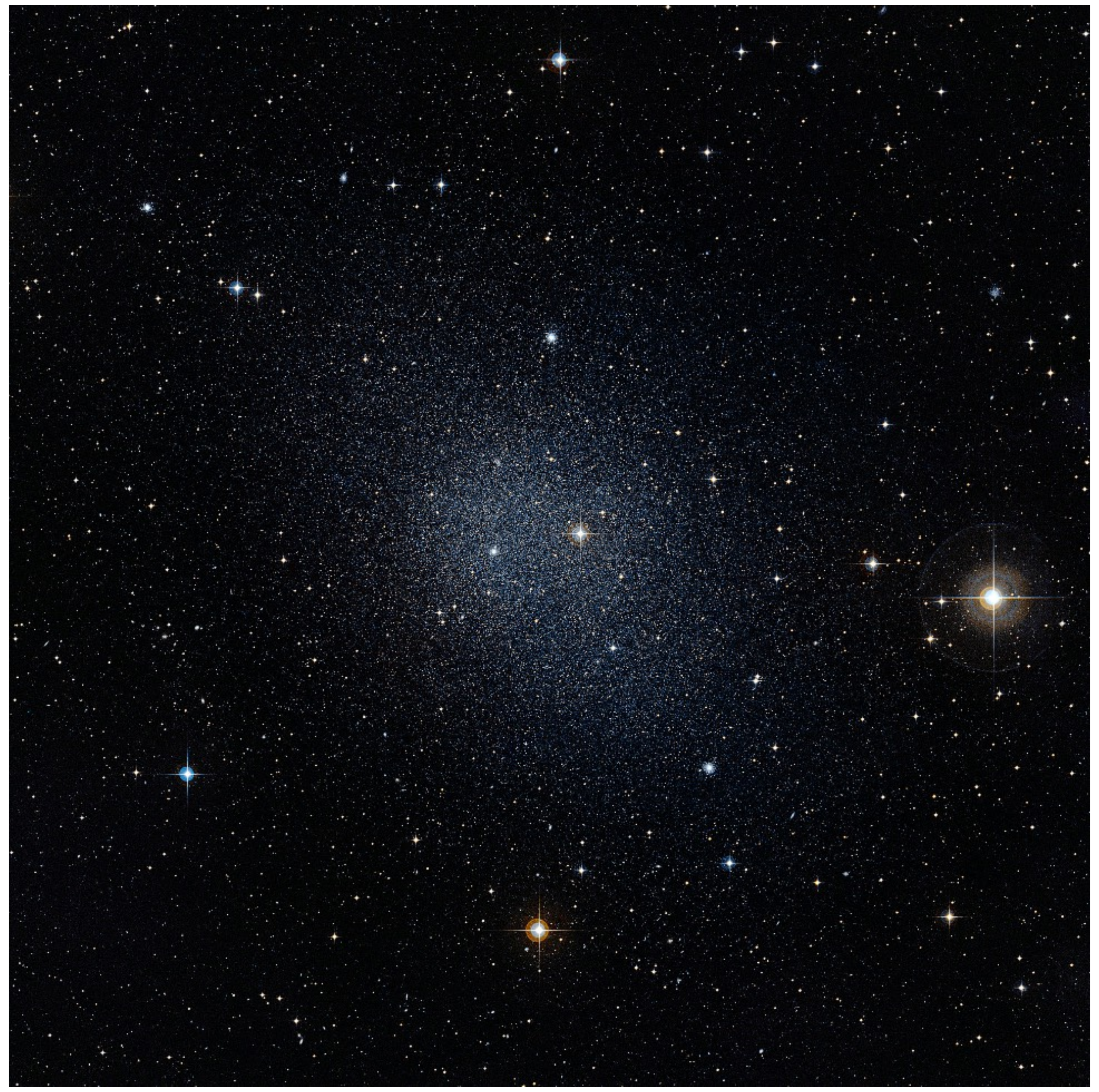
Gamma-ray spectrum
(annihilation channel)



Aquarius simulation - [0809.0898](0809.0898)

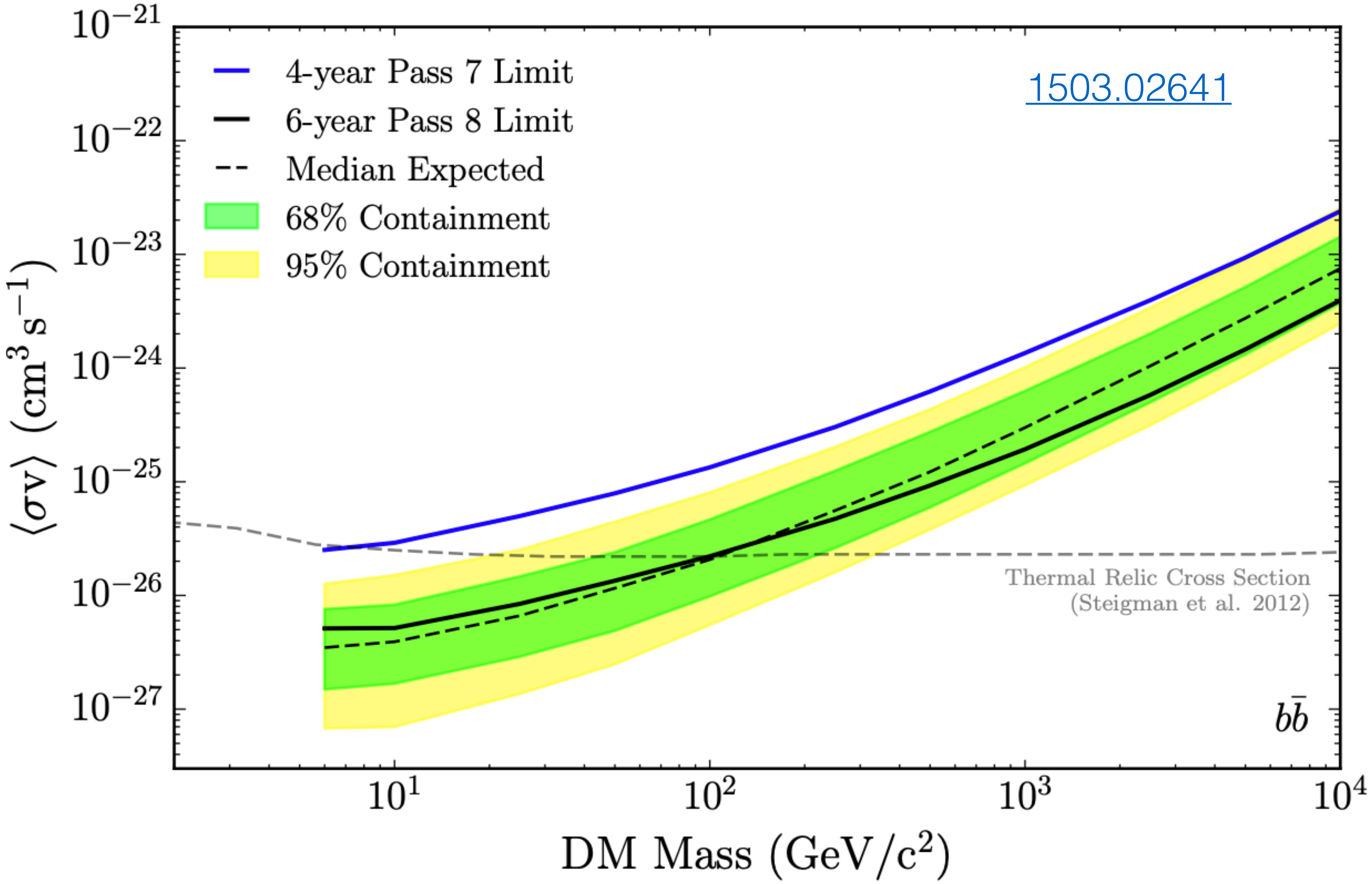
Gamma-ray constraints

Fornax Dwarf Galaxy
(Satellite of the Milky Way)



Credit: ESO/Digitized Sky Survey 2

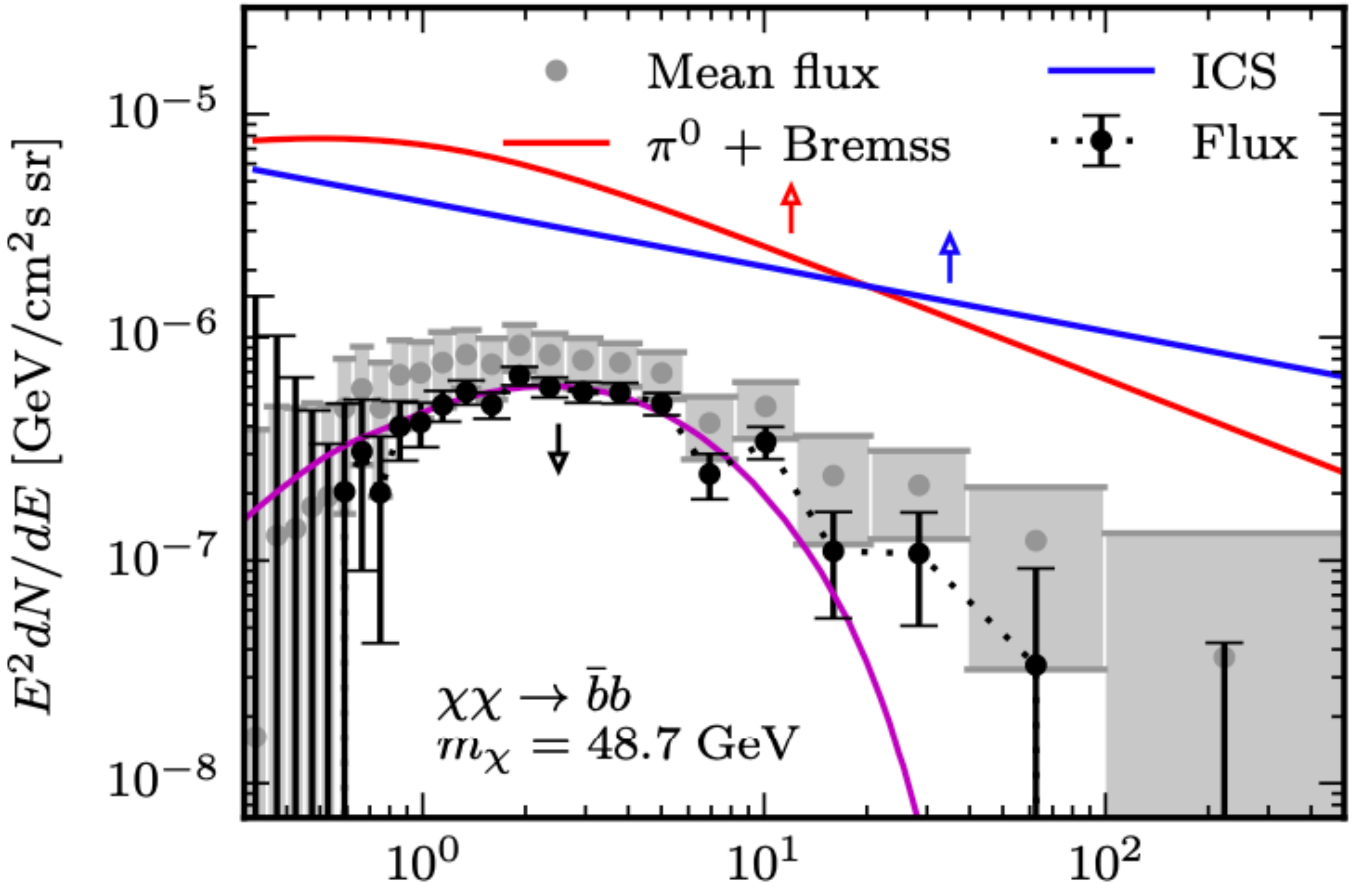
Fermi constraints from 15 Dwarf Spheroidal Galaxies:



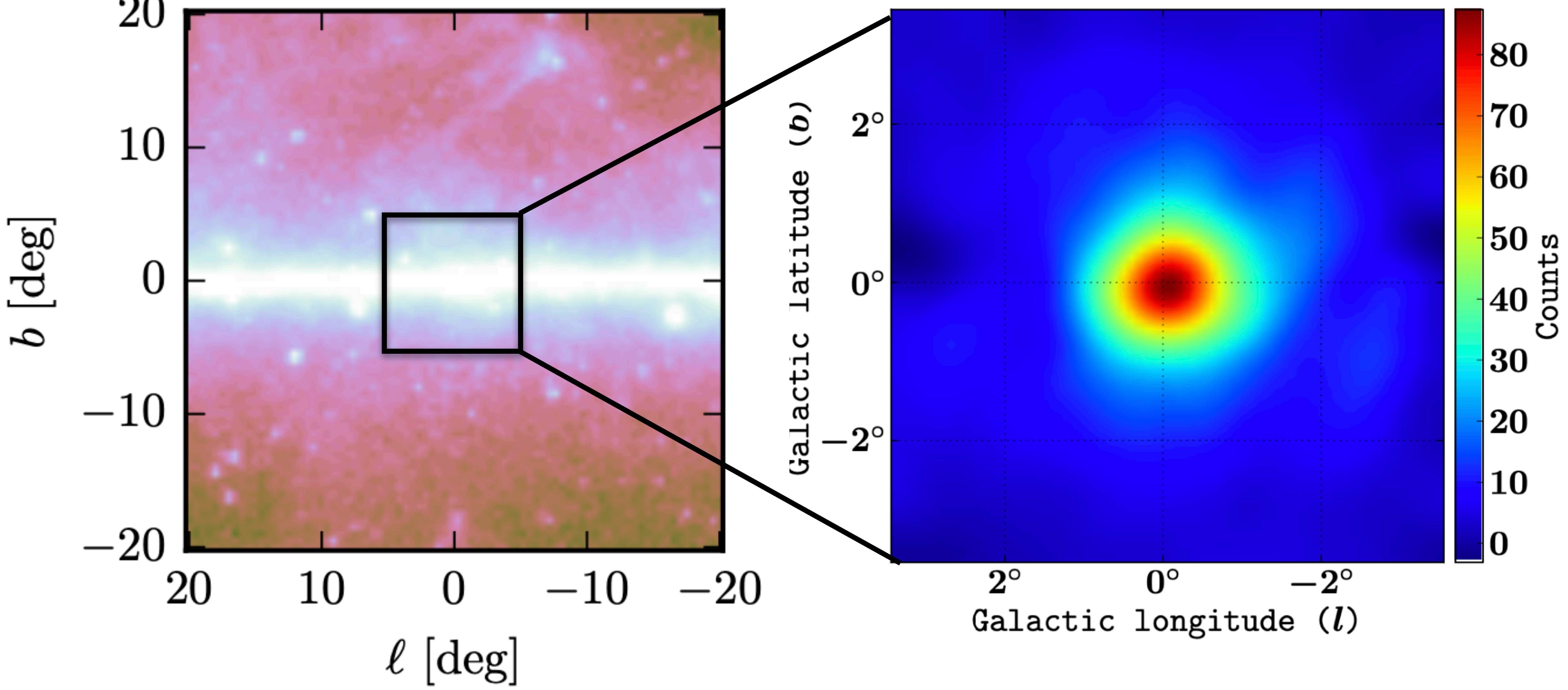
Exact constraints depend on annihilation channel ($\chi\chi \to b\bar{b}, \chi\chi \to W^+W^-, \chi\chi \to e^+e^-$, etc.)

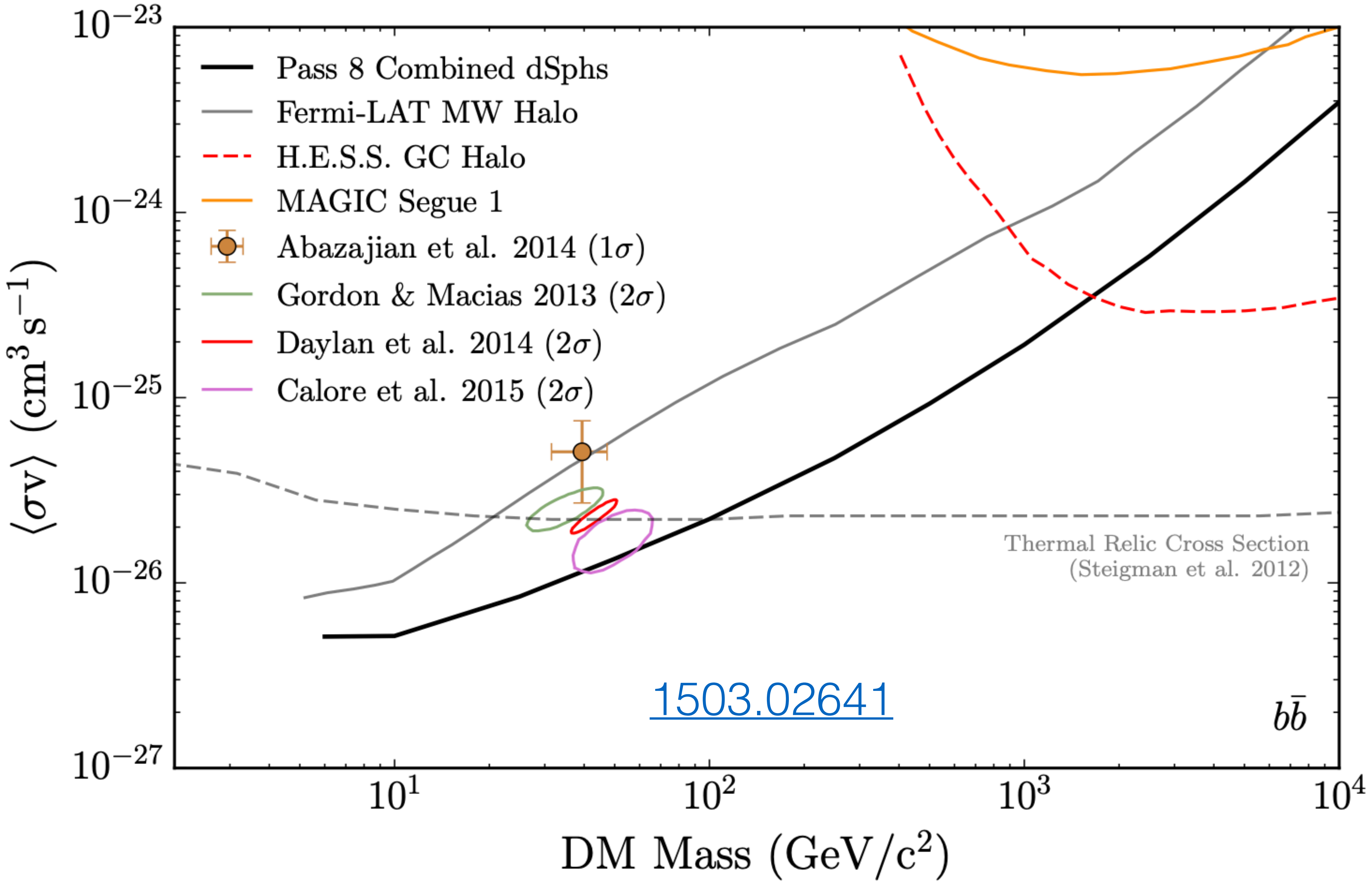
Galactic Centre Excess

1411.4647



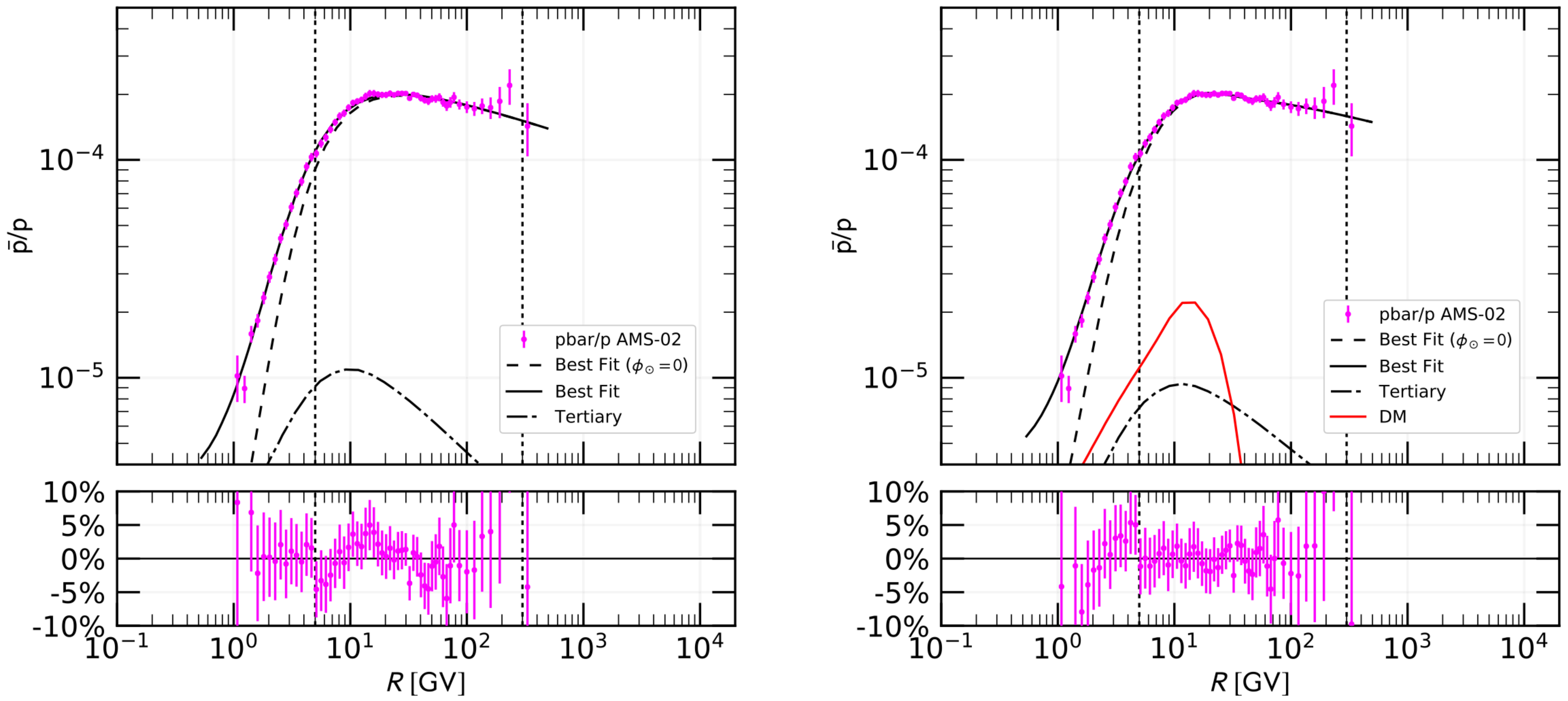
Data 1711.04778 Residuals 1306.5725





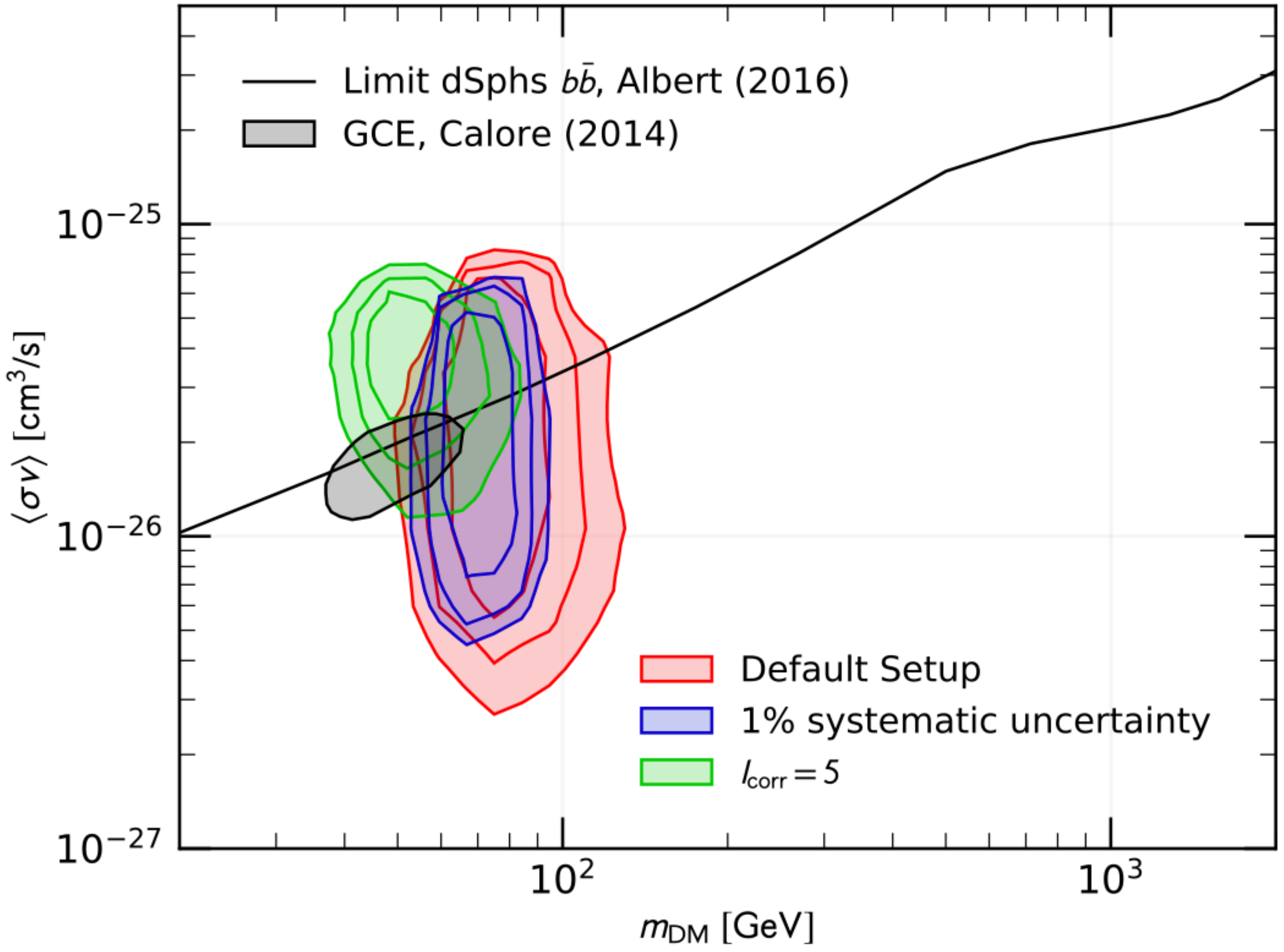
Anti-proton excess (1)

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

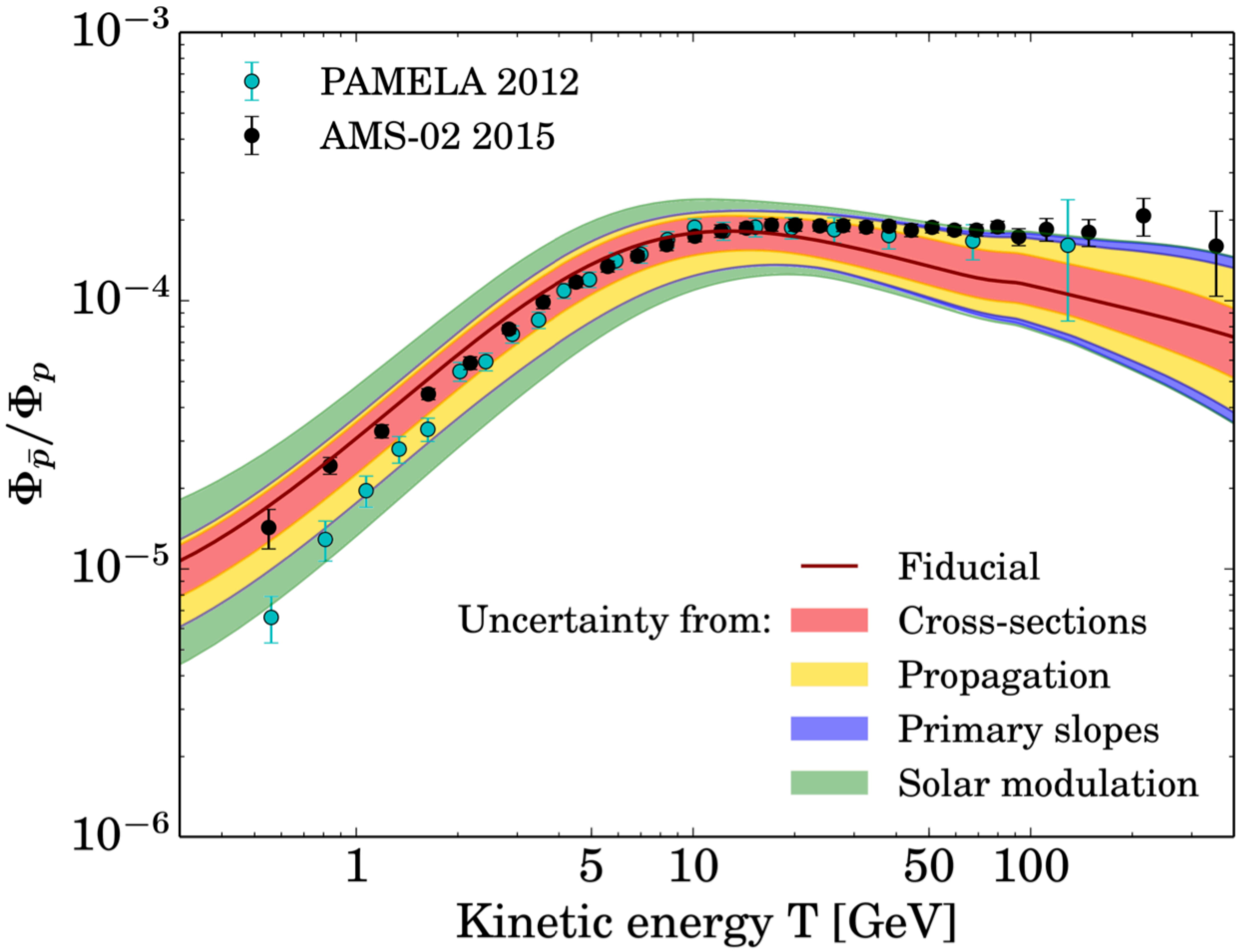


1610.03071, 1903.01472

Anti-proton excess (2)



[1903.01472](https://arxiv.org/abs/1903.01472)

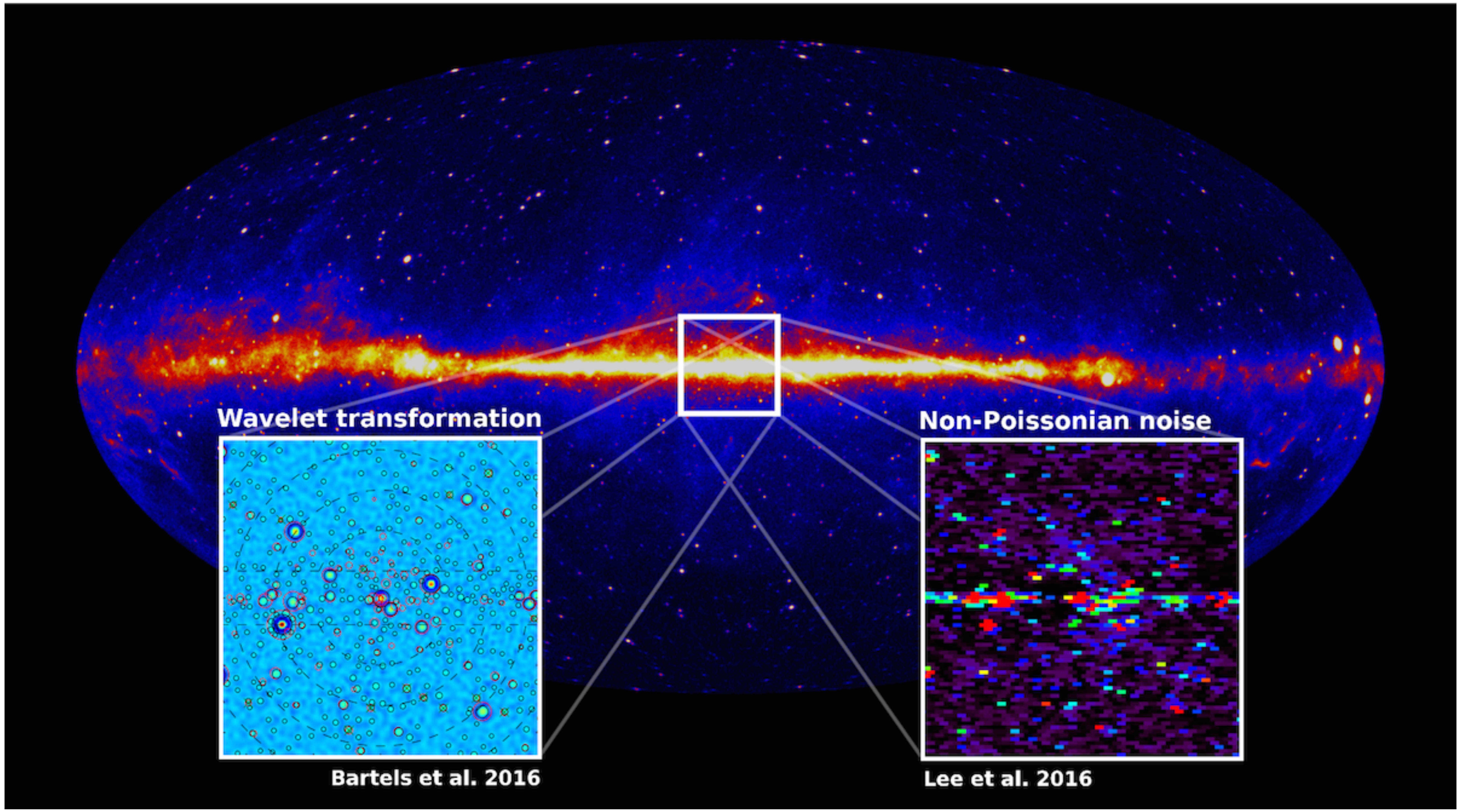


[1504.04276](https://arxiv.org/abs/1504.04276)

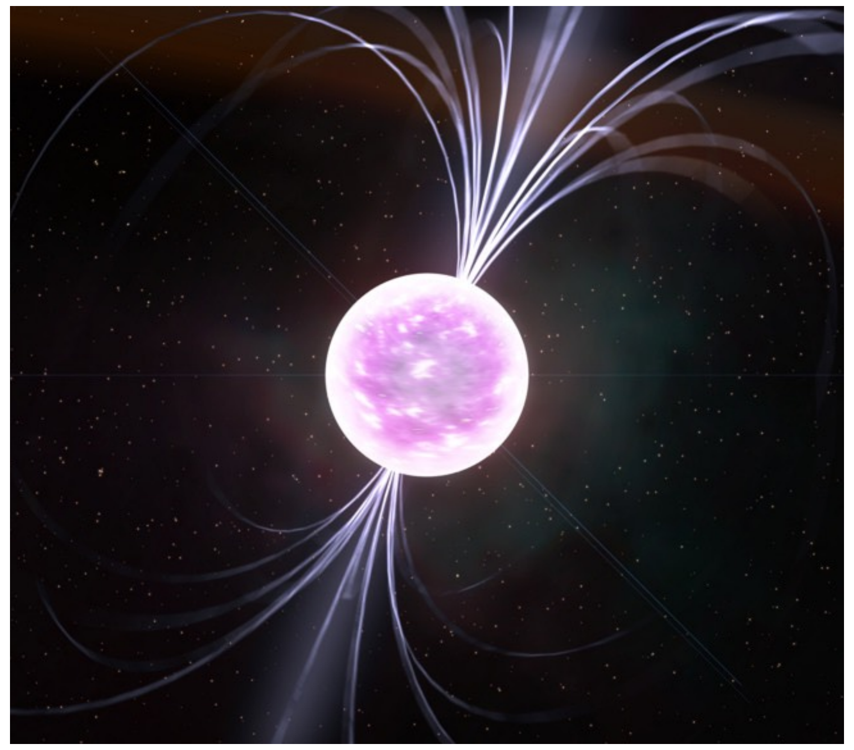
Several excesses point towards 60 GeV Dark Matter -
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

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



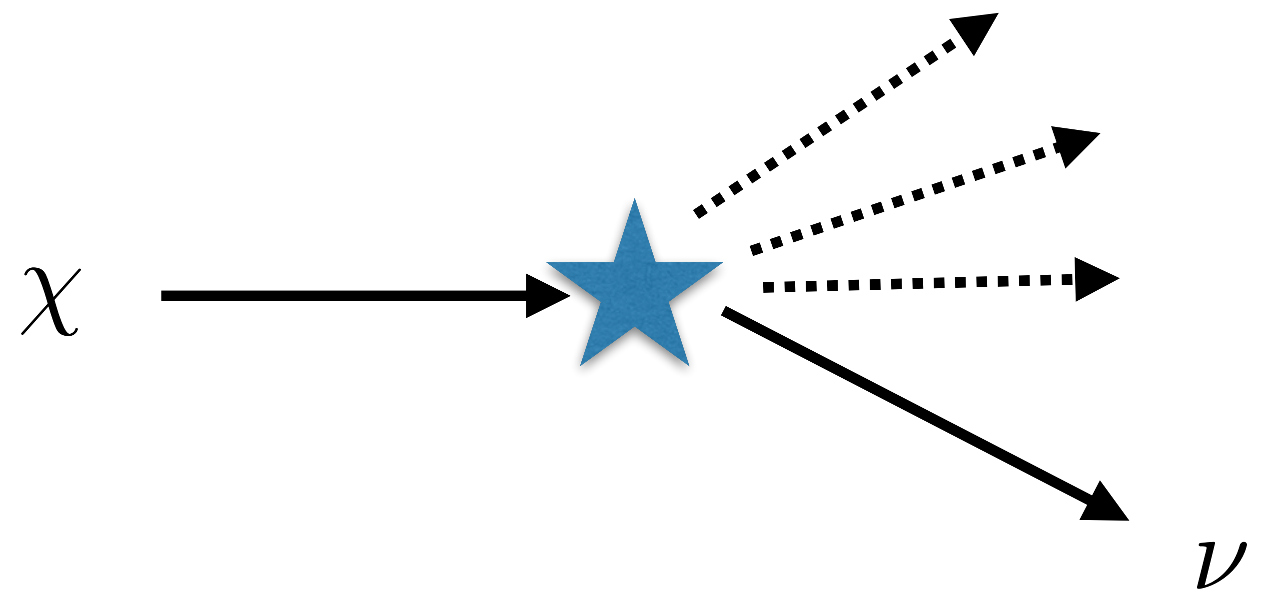
Credit: Kevin Gill / Flickr

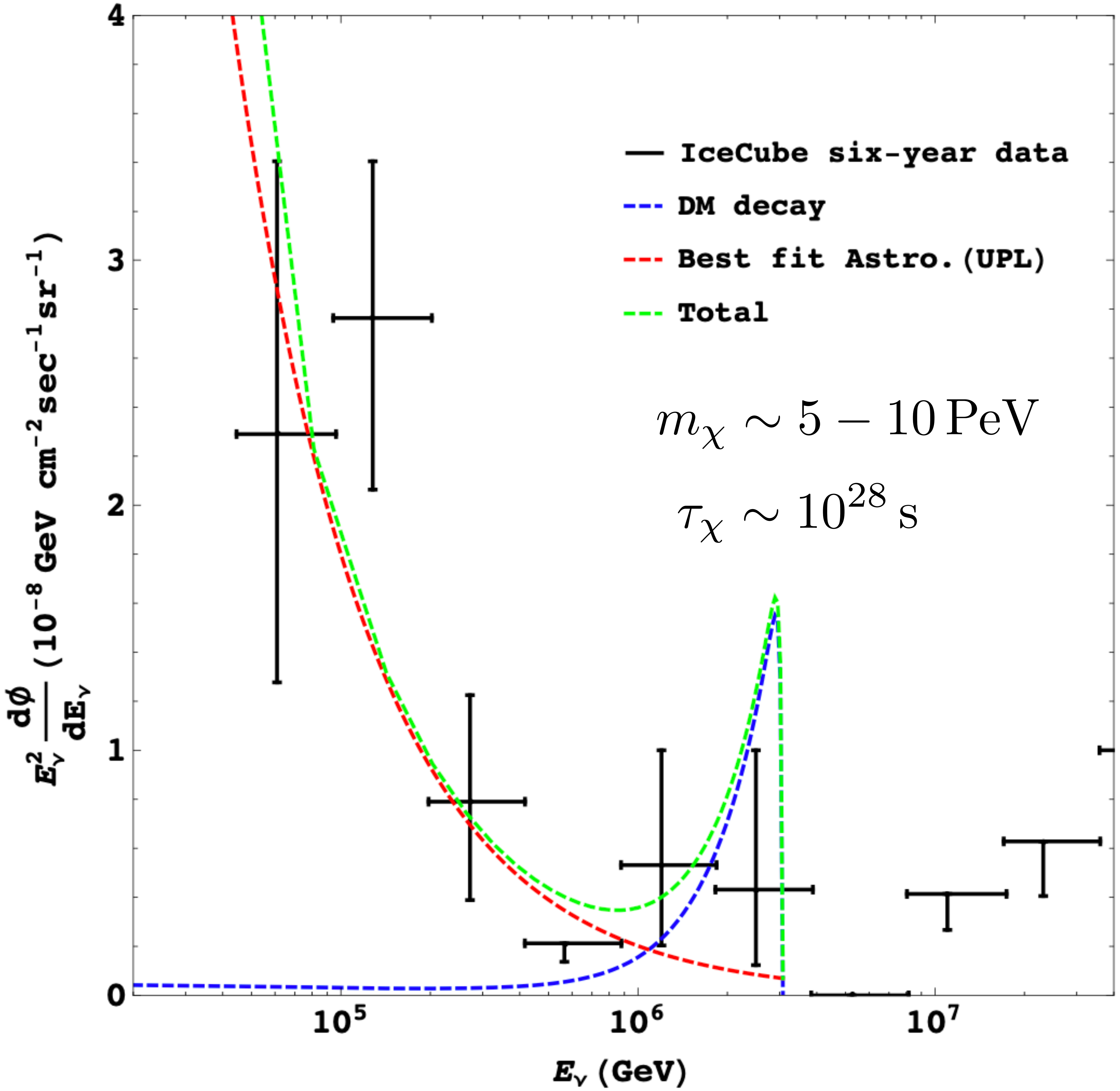
1506.05104, 1711.04778

High energy neutrinos

1508.02500, 1712.07138

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

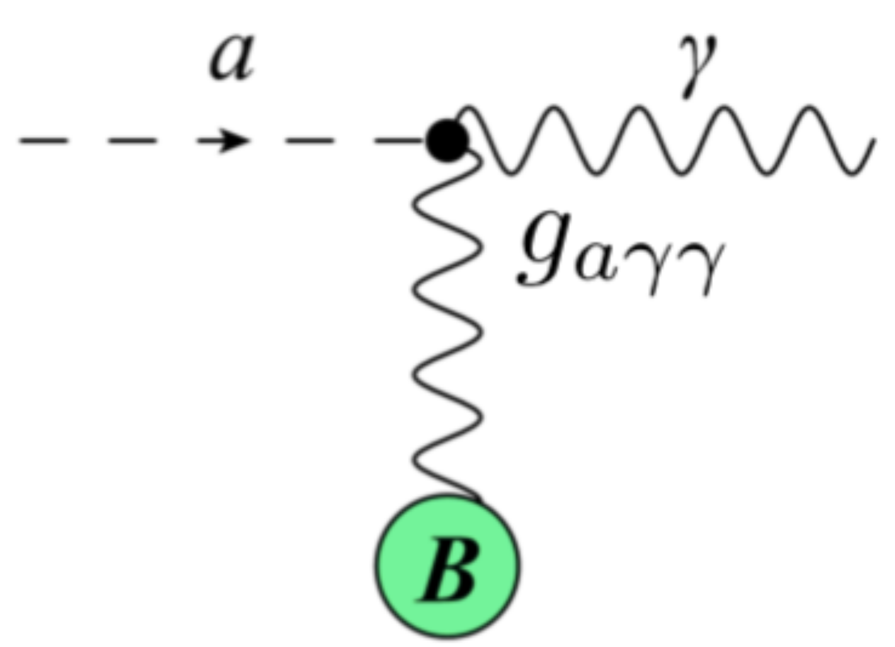


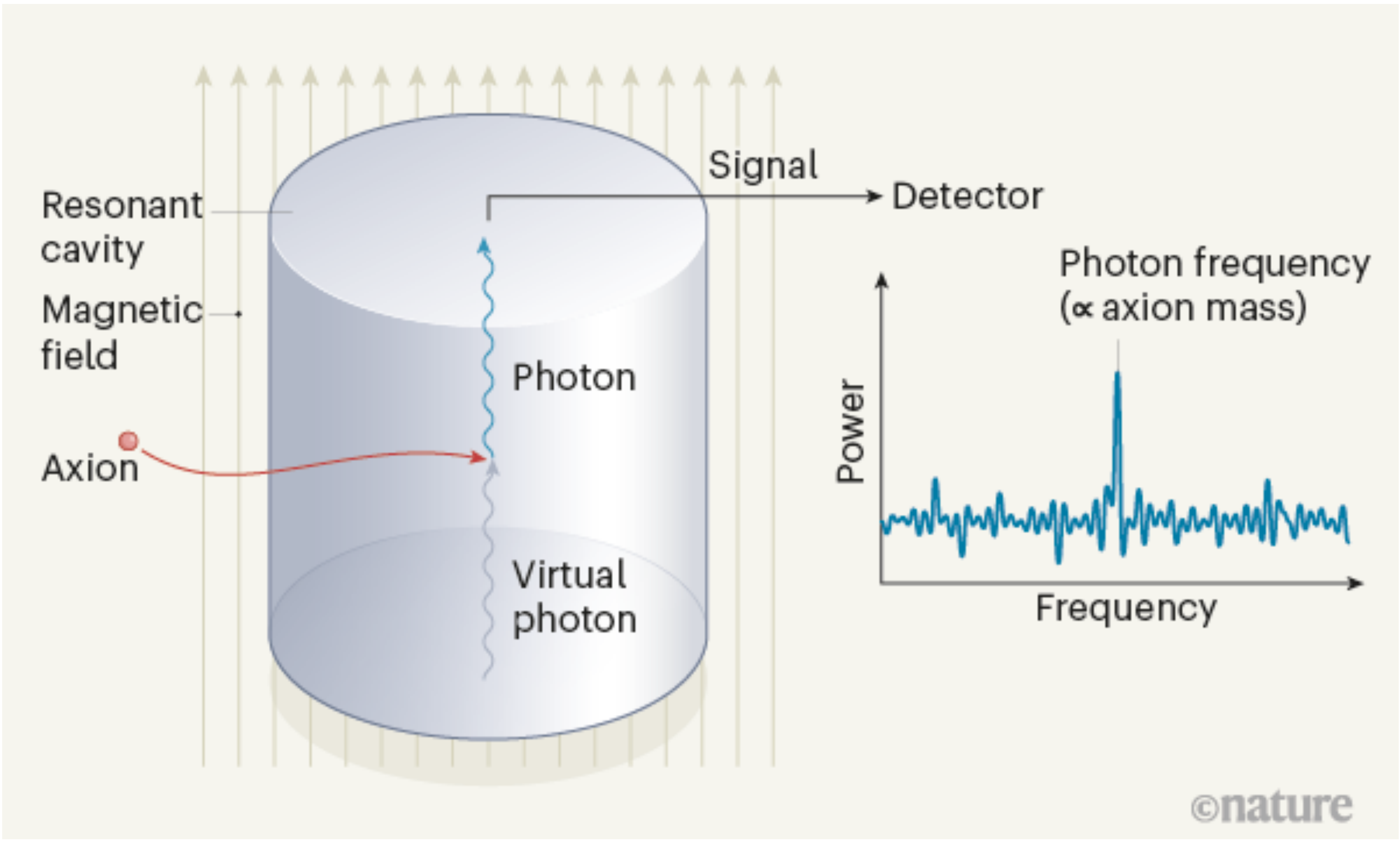


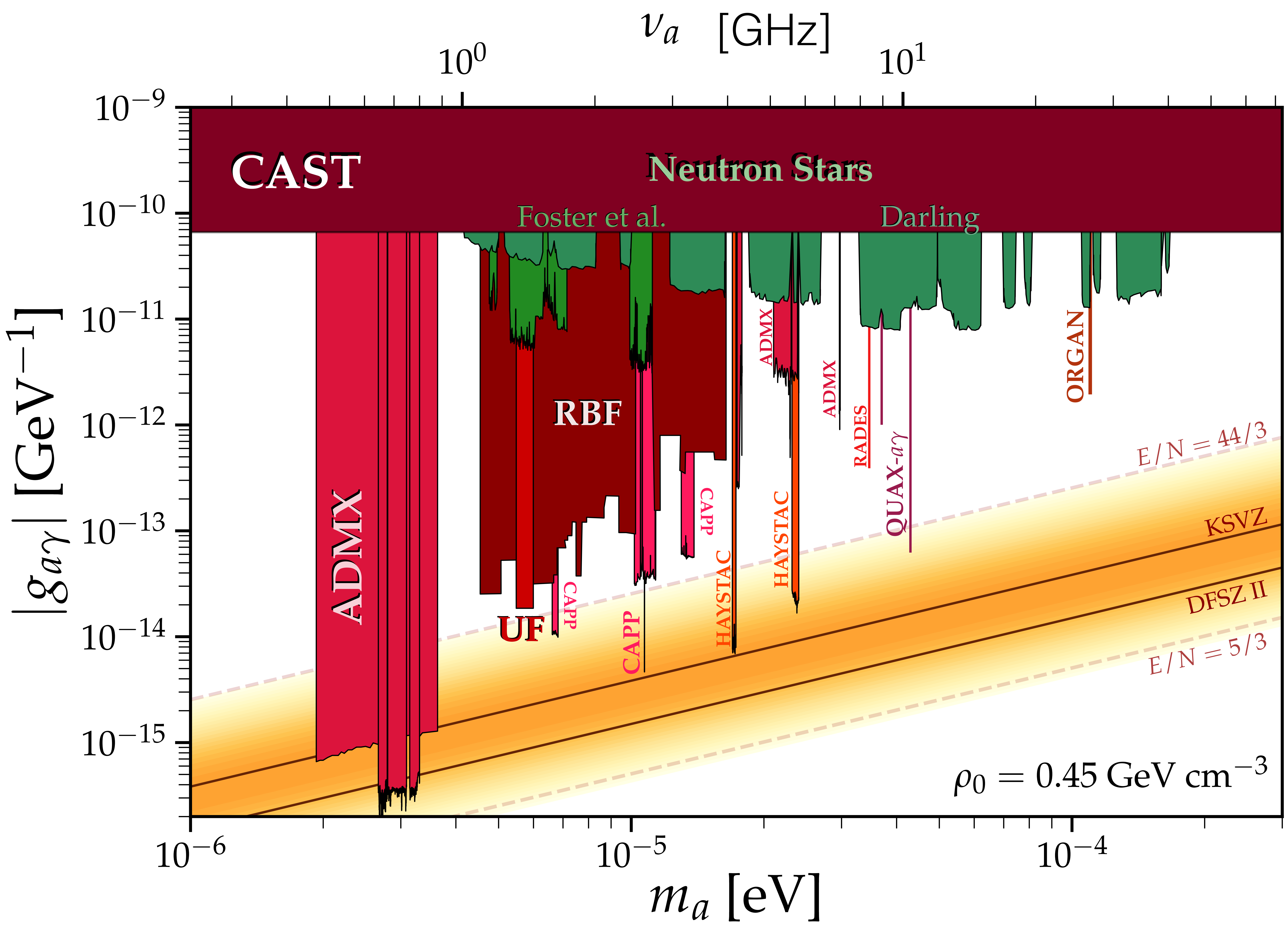
Axion searches in the lab

Axions: light pseudoscalar particles

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

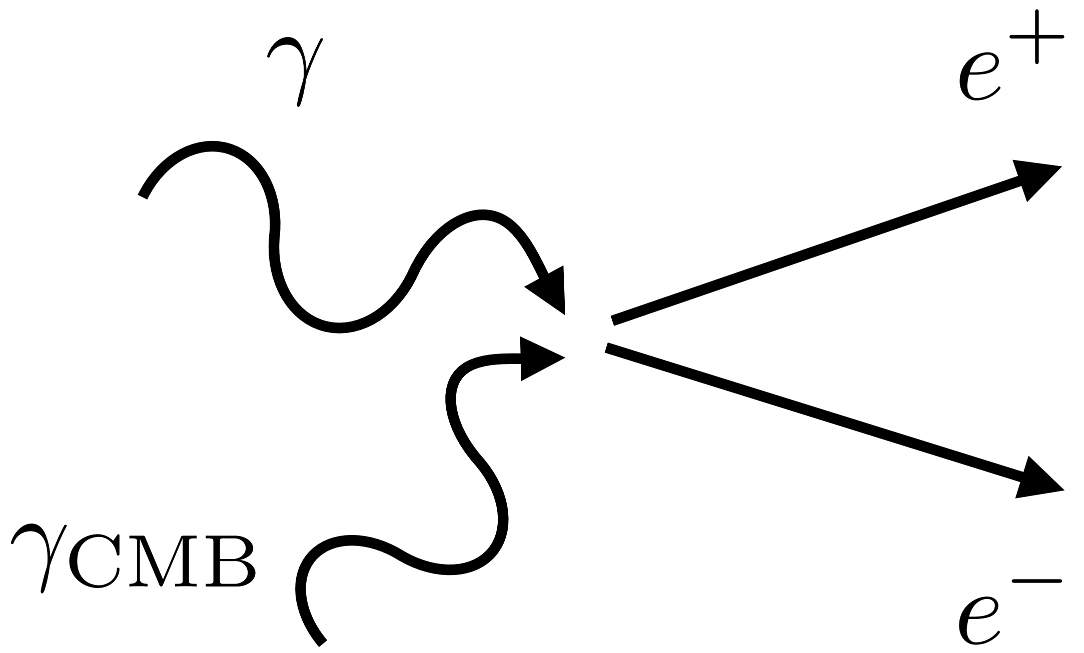


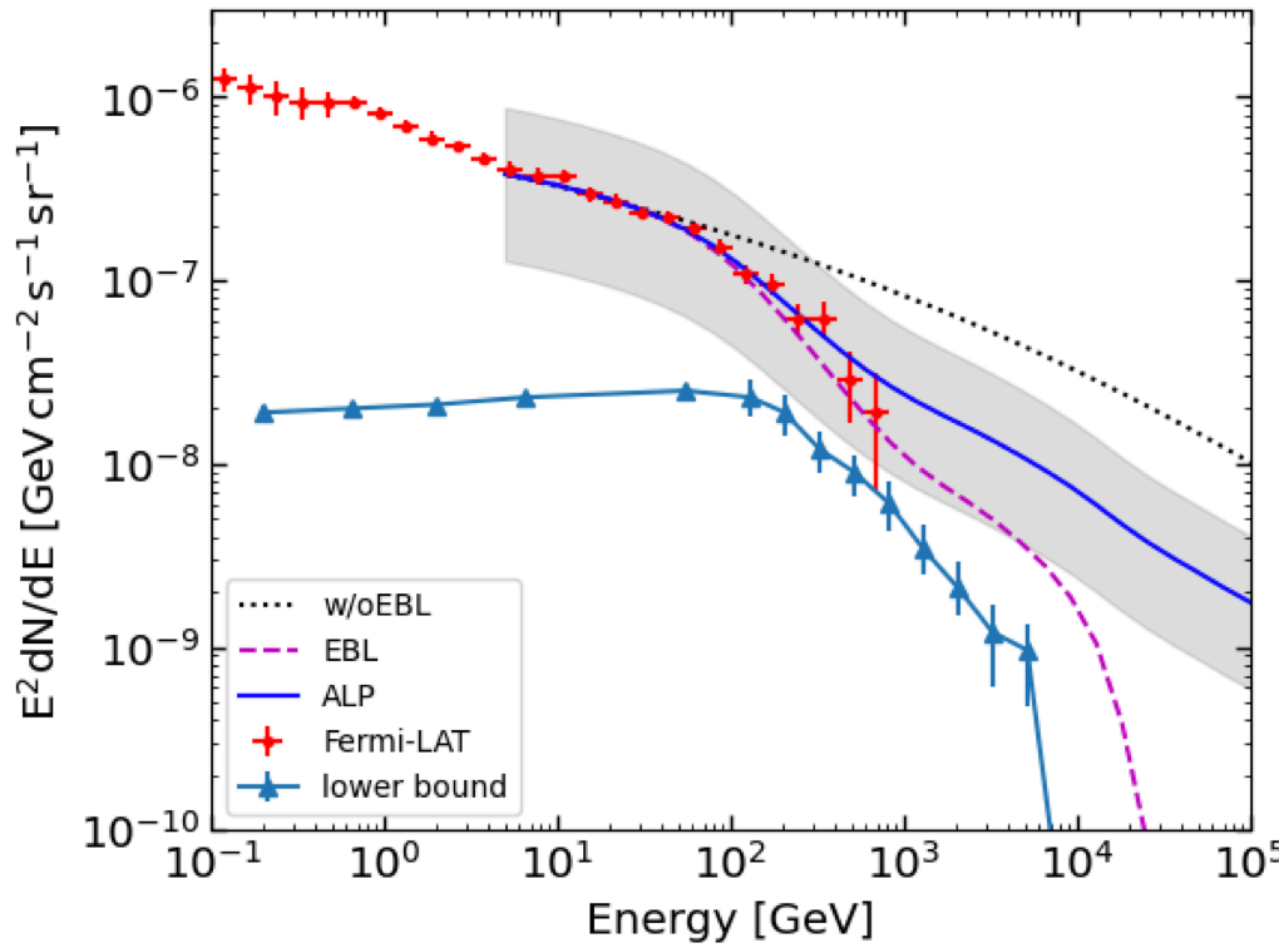




Credit: Ciaran O'Hare, AxionLimits

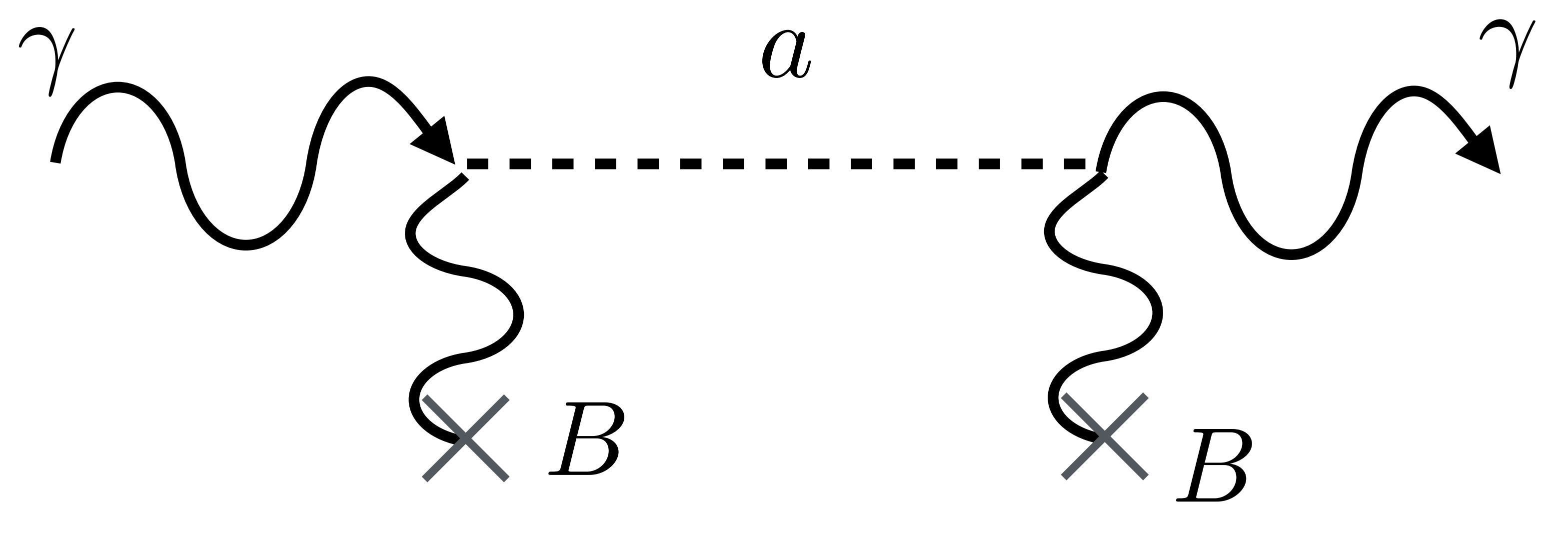
Gamma-ray transparency and axions

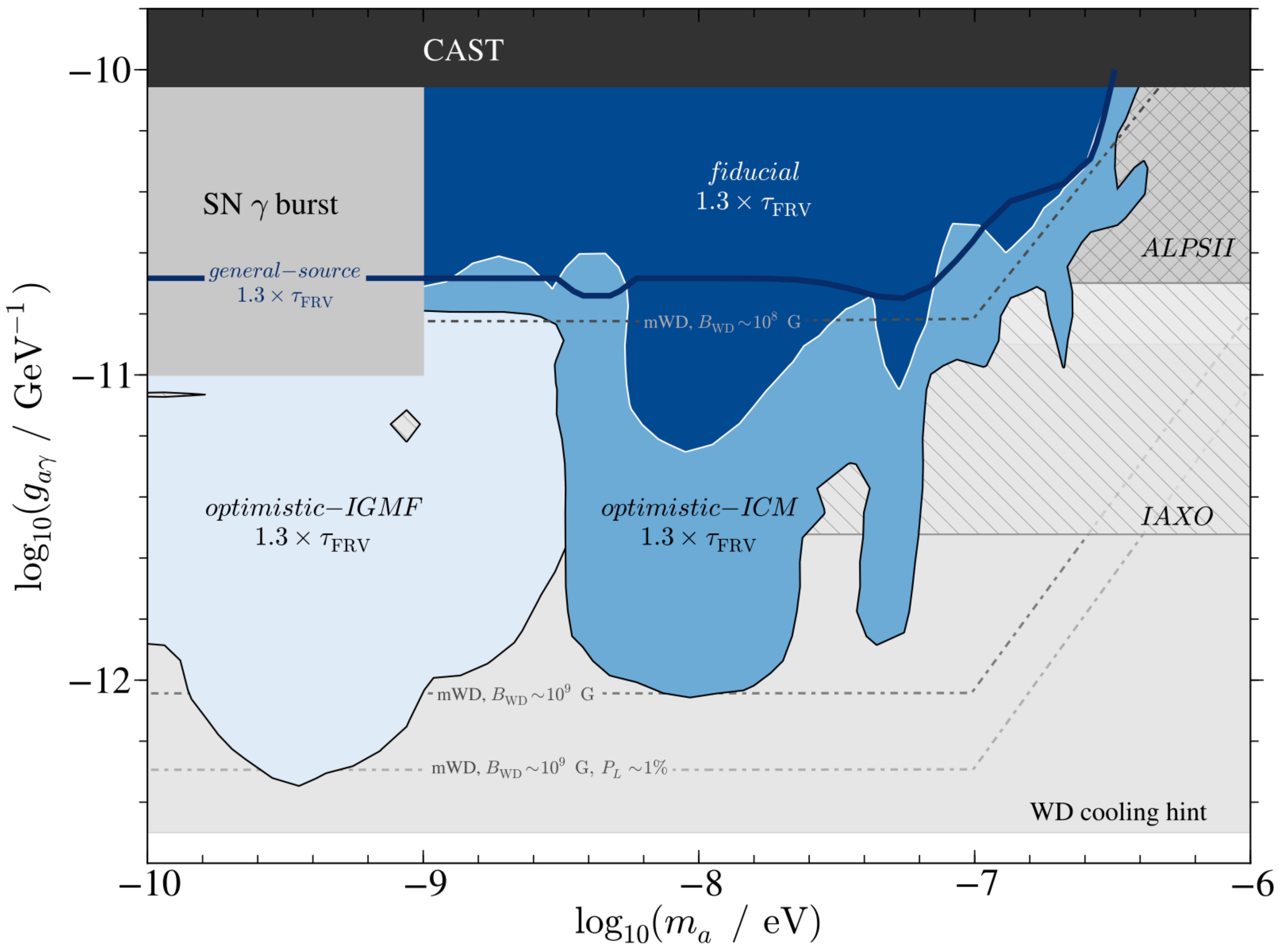




2012.15513

Axion-like particle:





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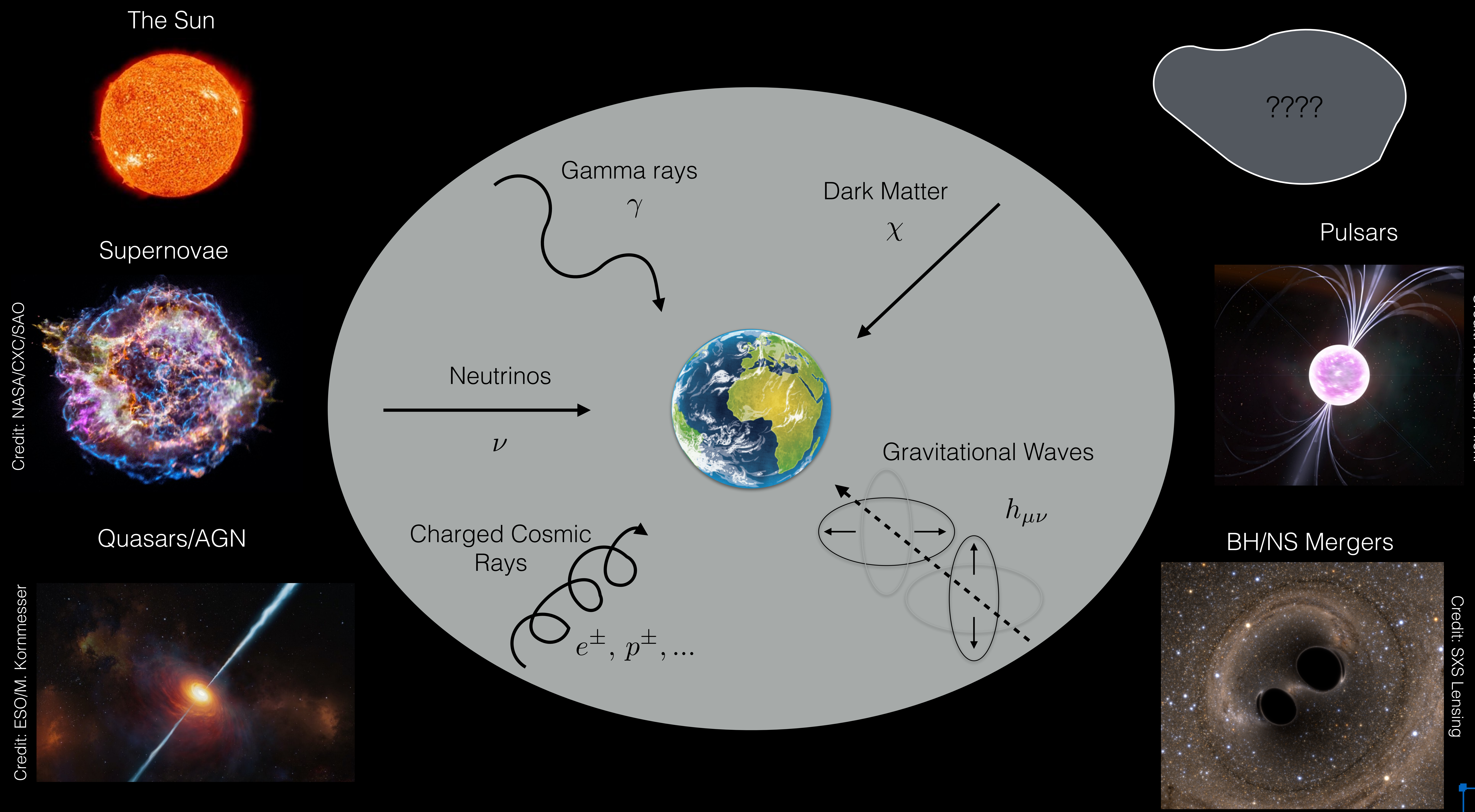
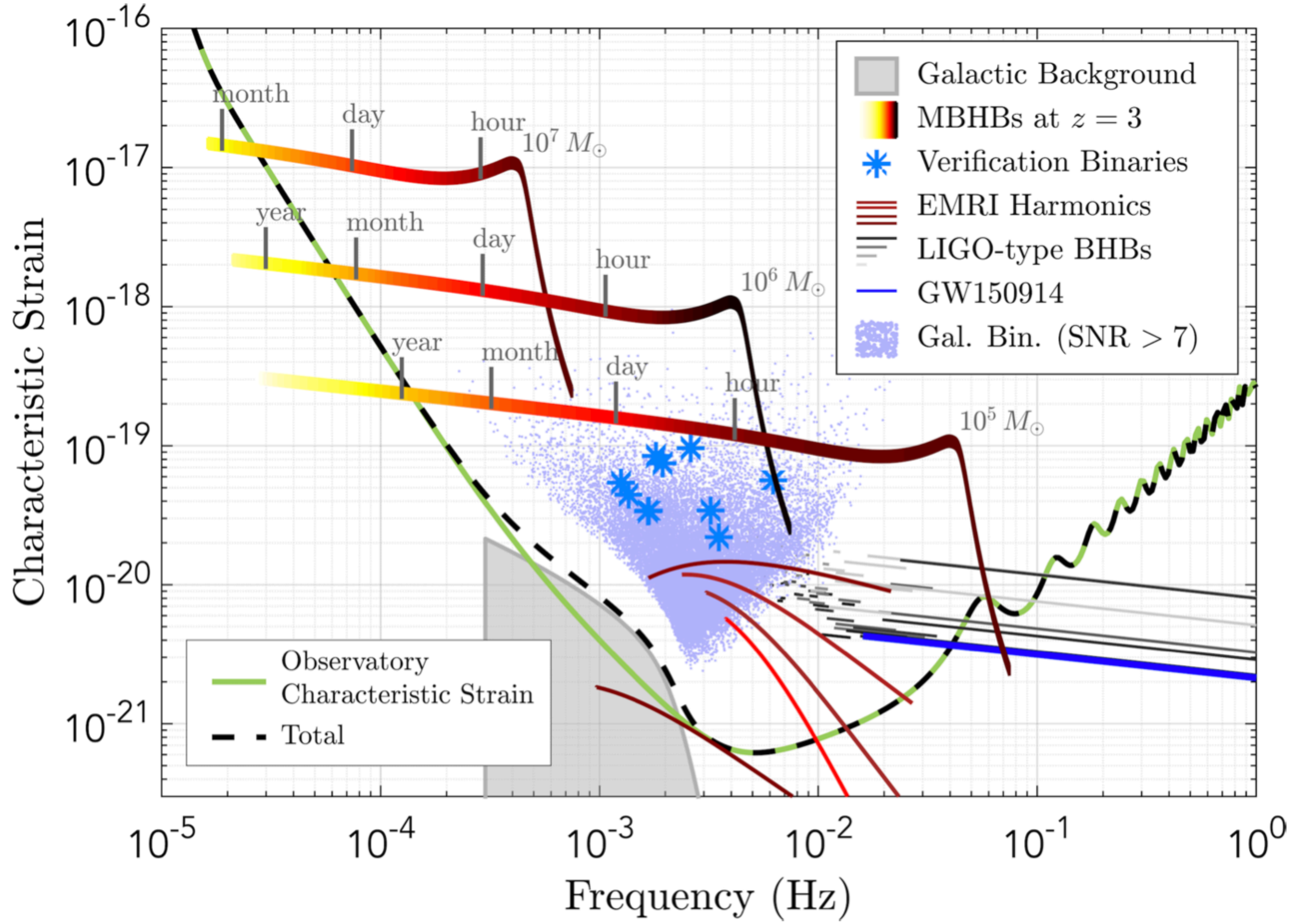
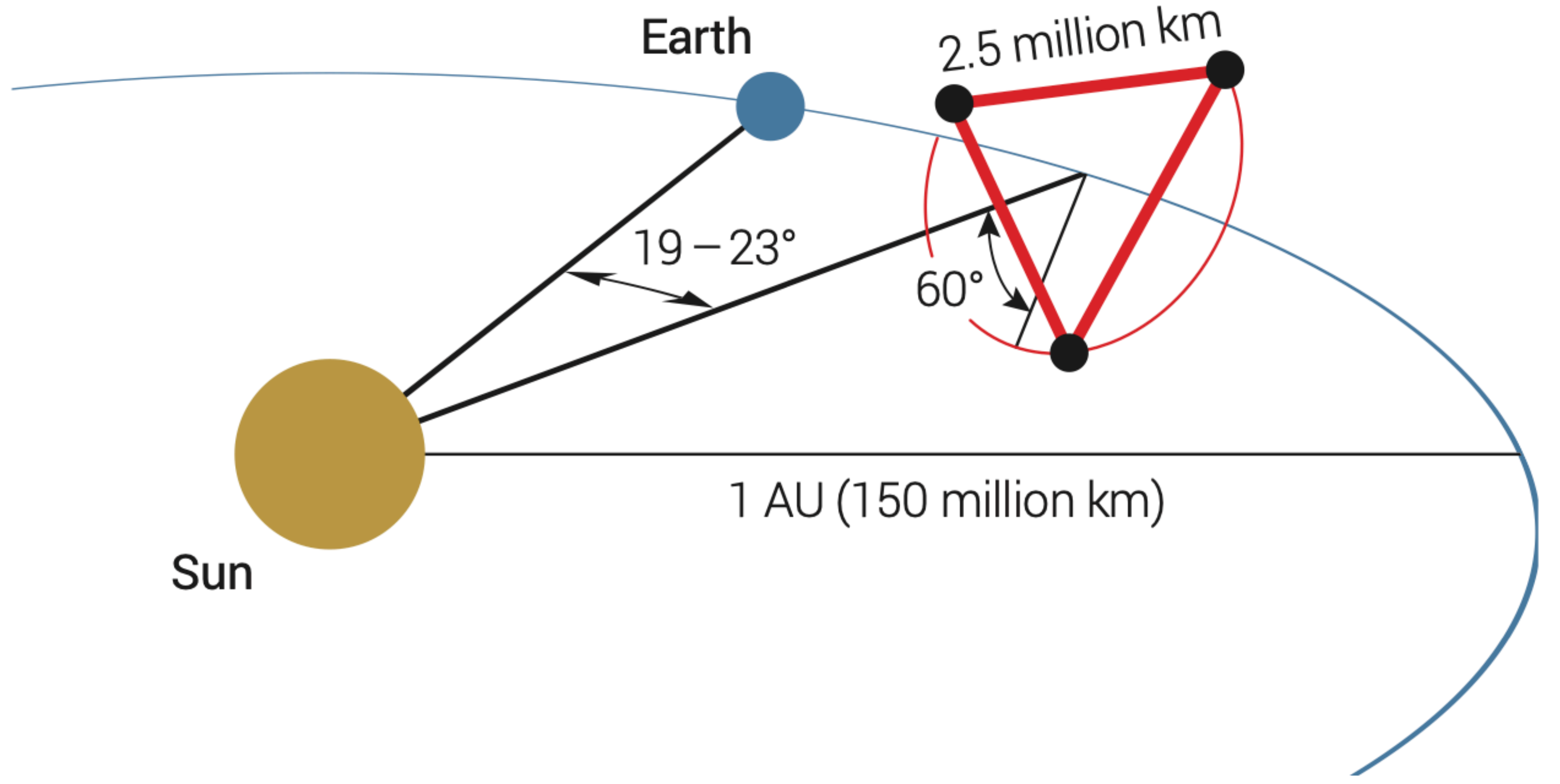

The Sun
Supernovae
Credit: NASA/CXC/SAO
Quasars/AGN
Credit: ESO/M. Kornmesser
Gamma rays
γ
Dark Matter
χ
Neutrinos
ν
Gravitational Waves
$h_{\mu\nu}$
Charged Cosmic Rays
$e^{\pm}, p^{\pm}, \ldots$
????
Pulsars
Credit: Kevin Gill / Flickr
BH/NS Mergers
Credit: SXS Lensing

Additional Slides

LISA - GWs in space!

Laser Interferometer Space Antenna
(Planned for the 2030s)



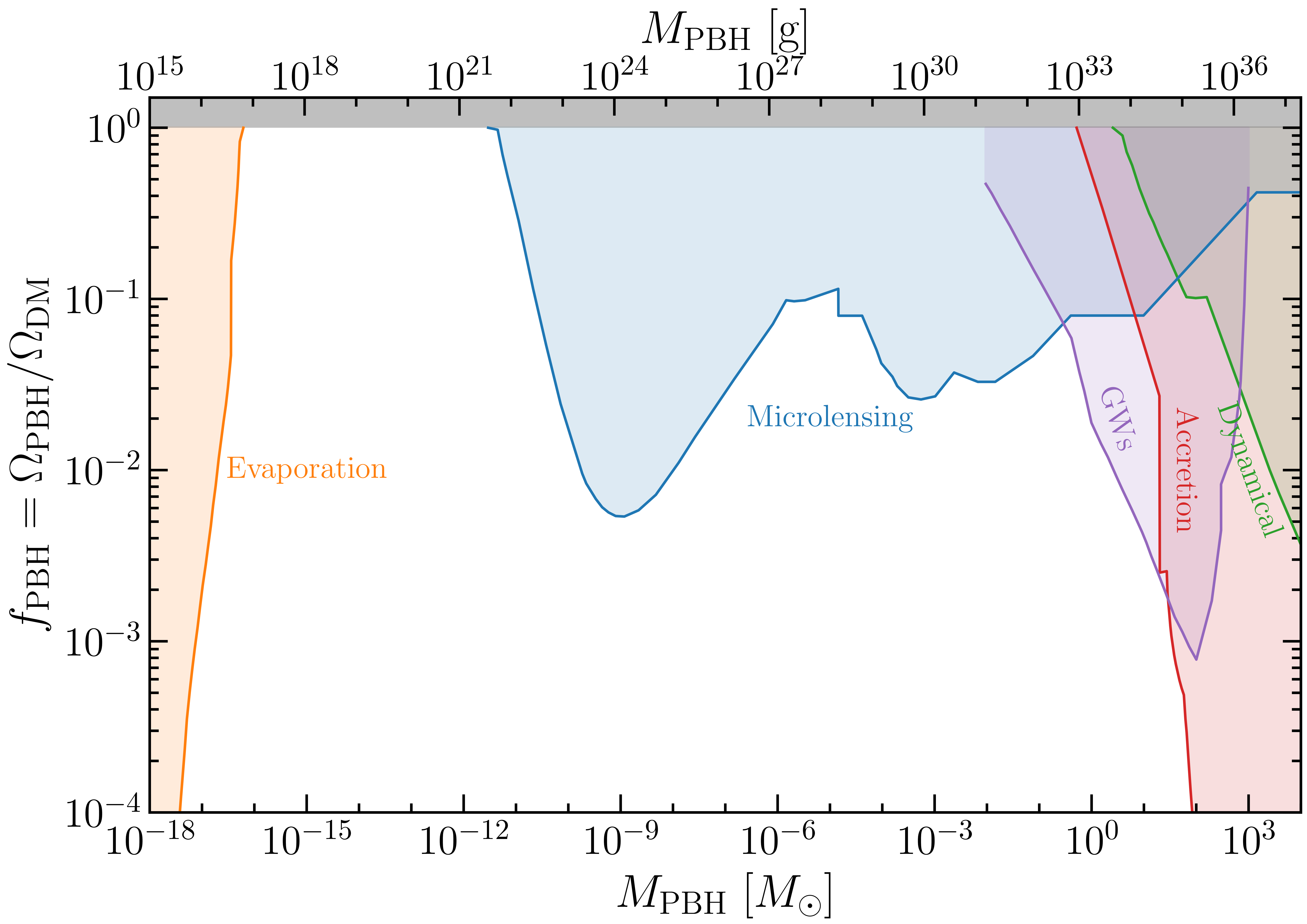


1907.06482

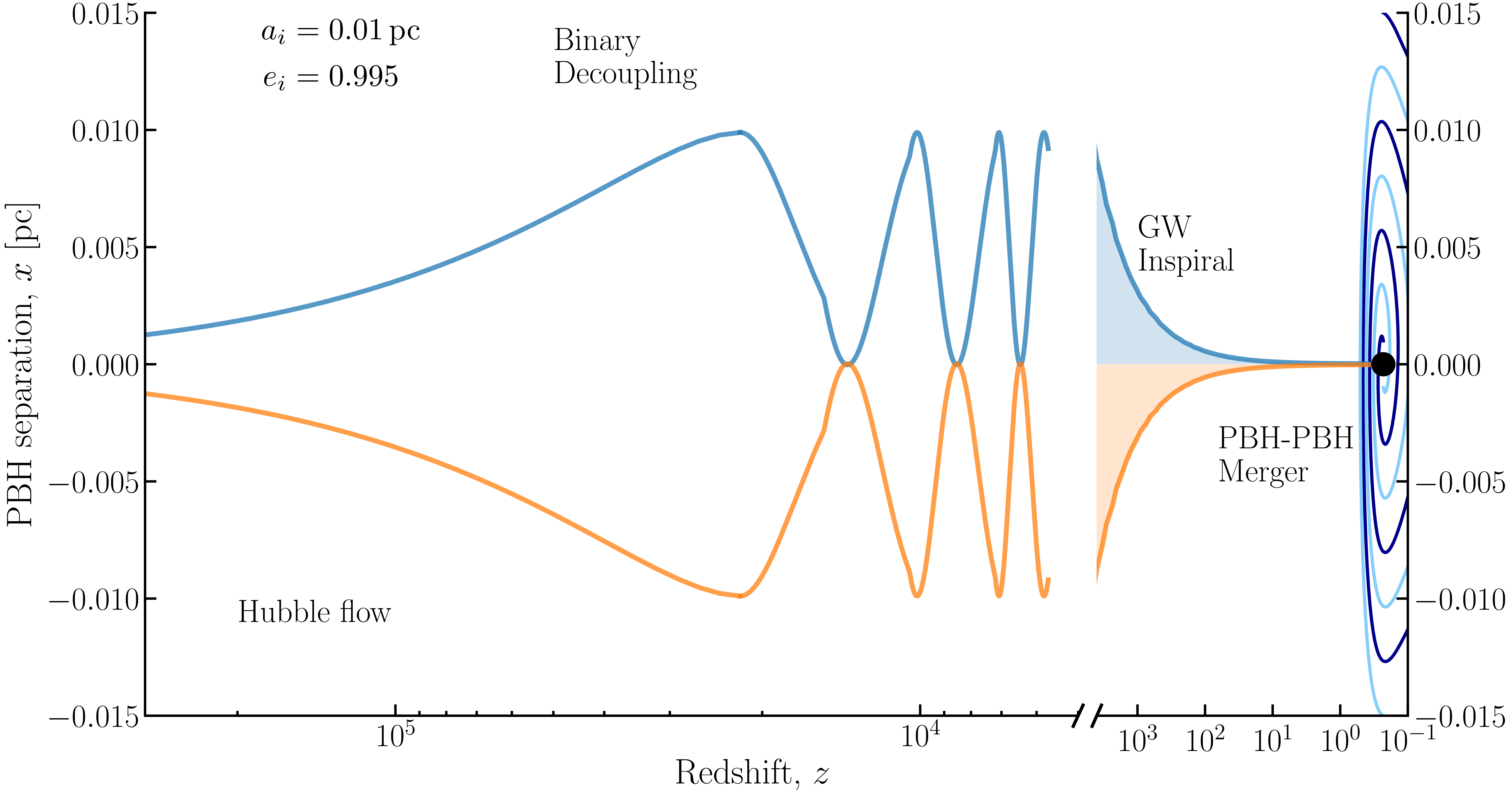
Primordial Black Holes

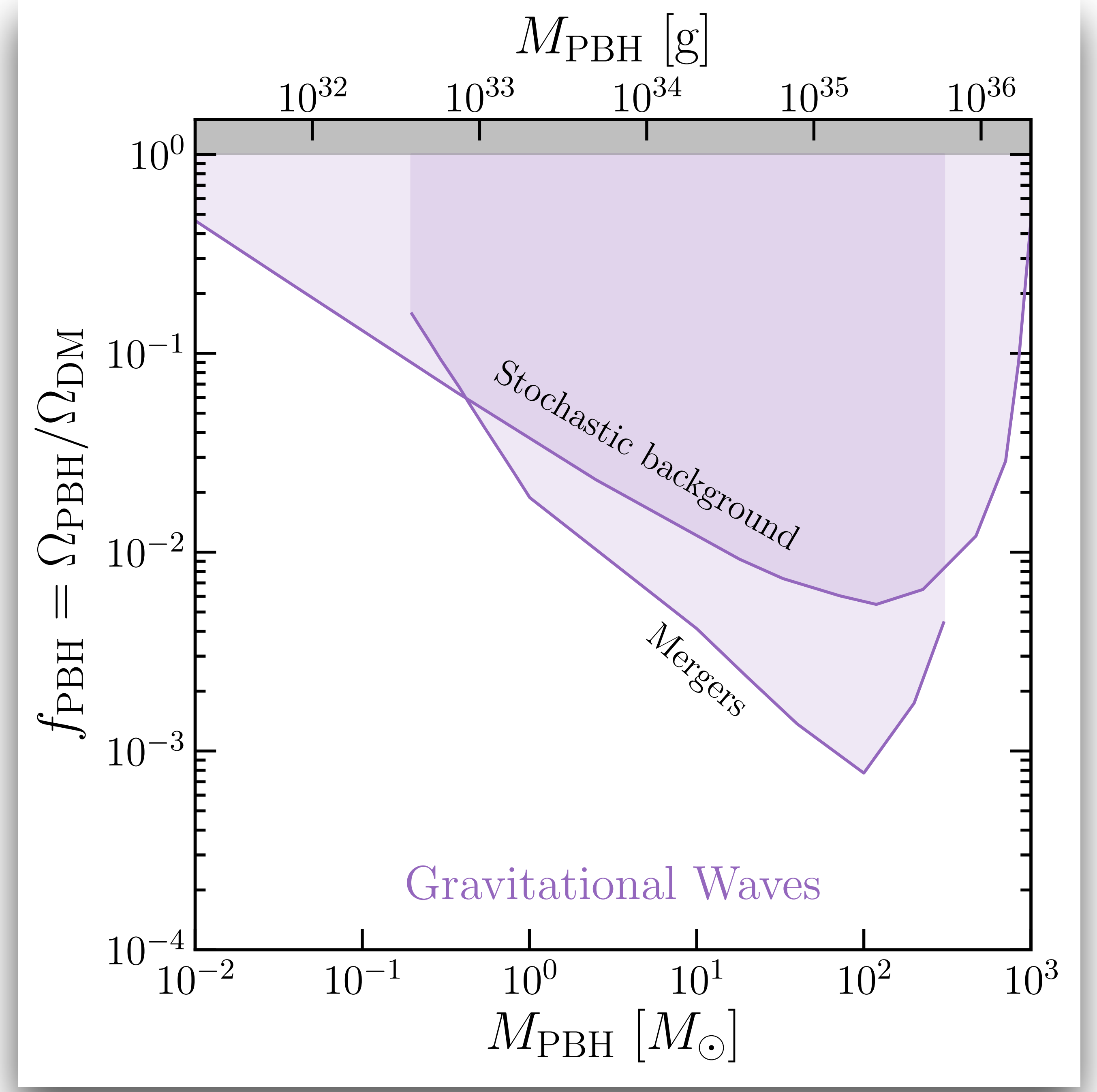
2007.10722

Bounds online

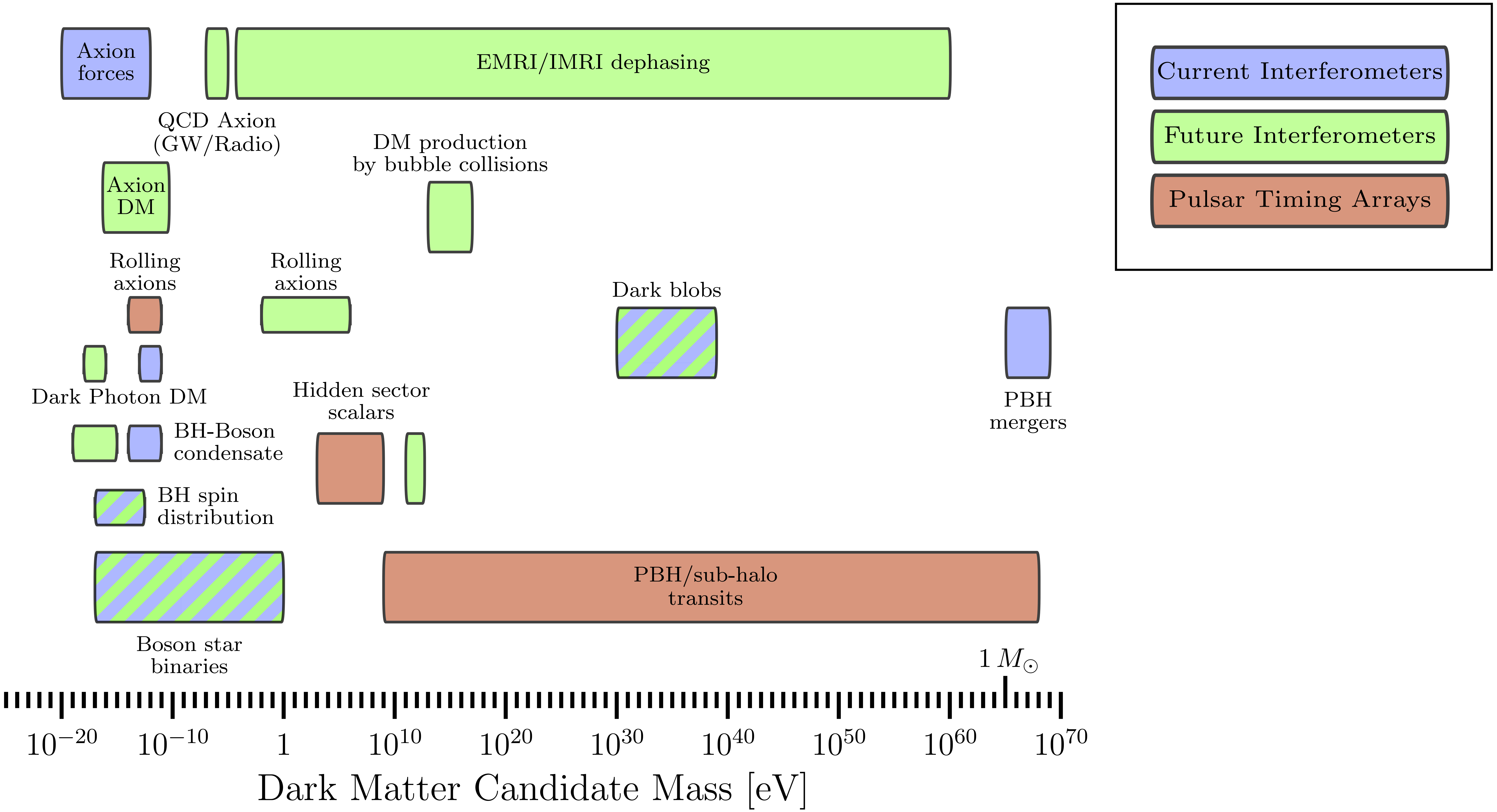


PBHs and Gravitational Waves





Gravitational Wave probes of DM



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