

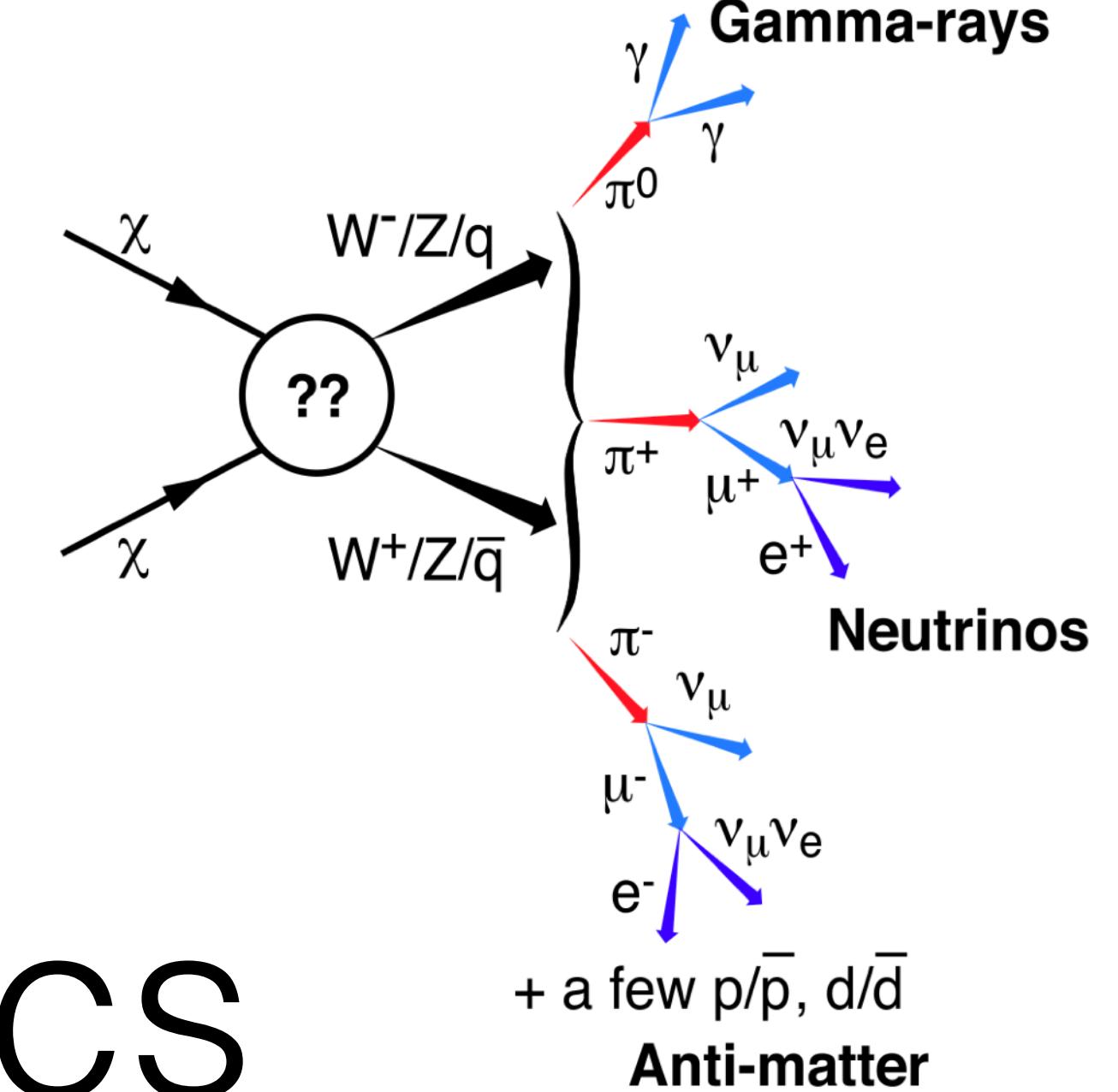
# (An introduction to) Astroparticle Physics

## Lecture 2/2

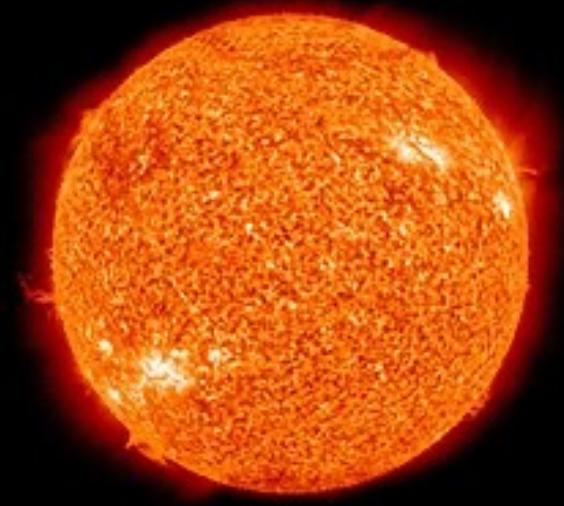
Bradley J Kavanagh [he/him]  
Instituto de Fisica de Cantabria (CSIC-UC)  
[kavanagh@ifca.unican.es](mailto:kavanagh@ifca.unican.es)

CERN Summer Student Lecture Programme:  
Thursday 20th July 2023

Slides here: [bradkav.net/talks](http://bradkav.net/talks)

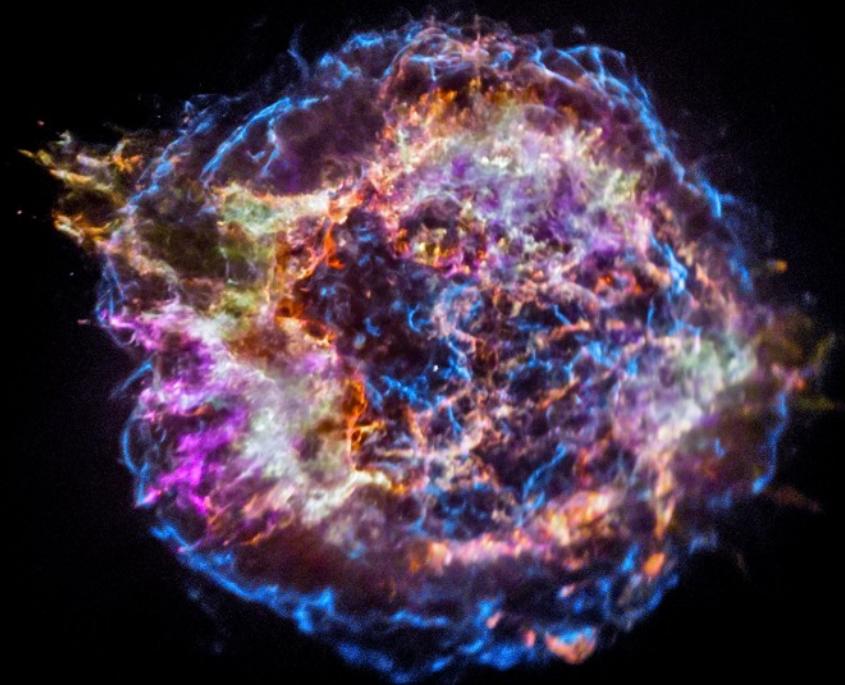


The Sun



Credit: NASA/CXC/SAO

Supernovae

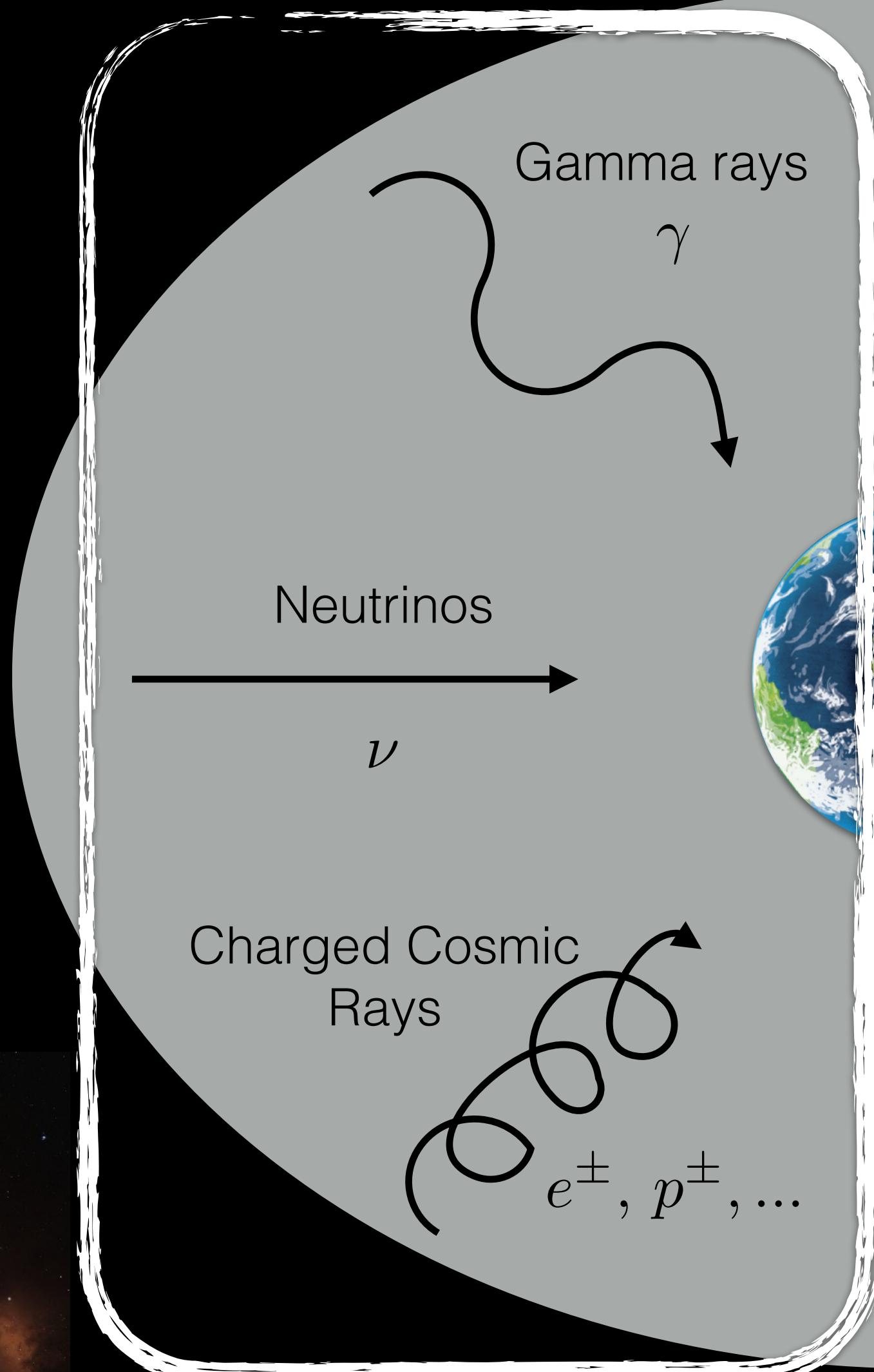


Credit: ESO/M. Kornmesser

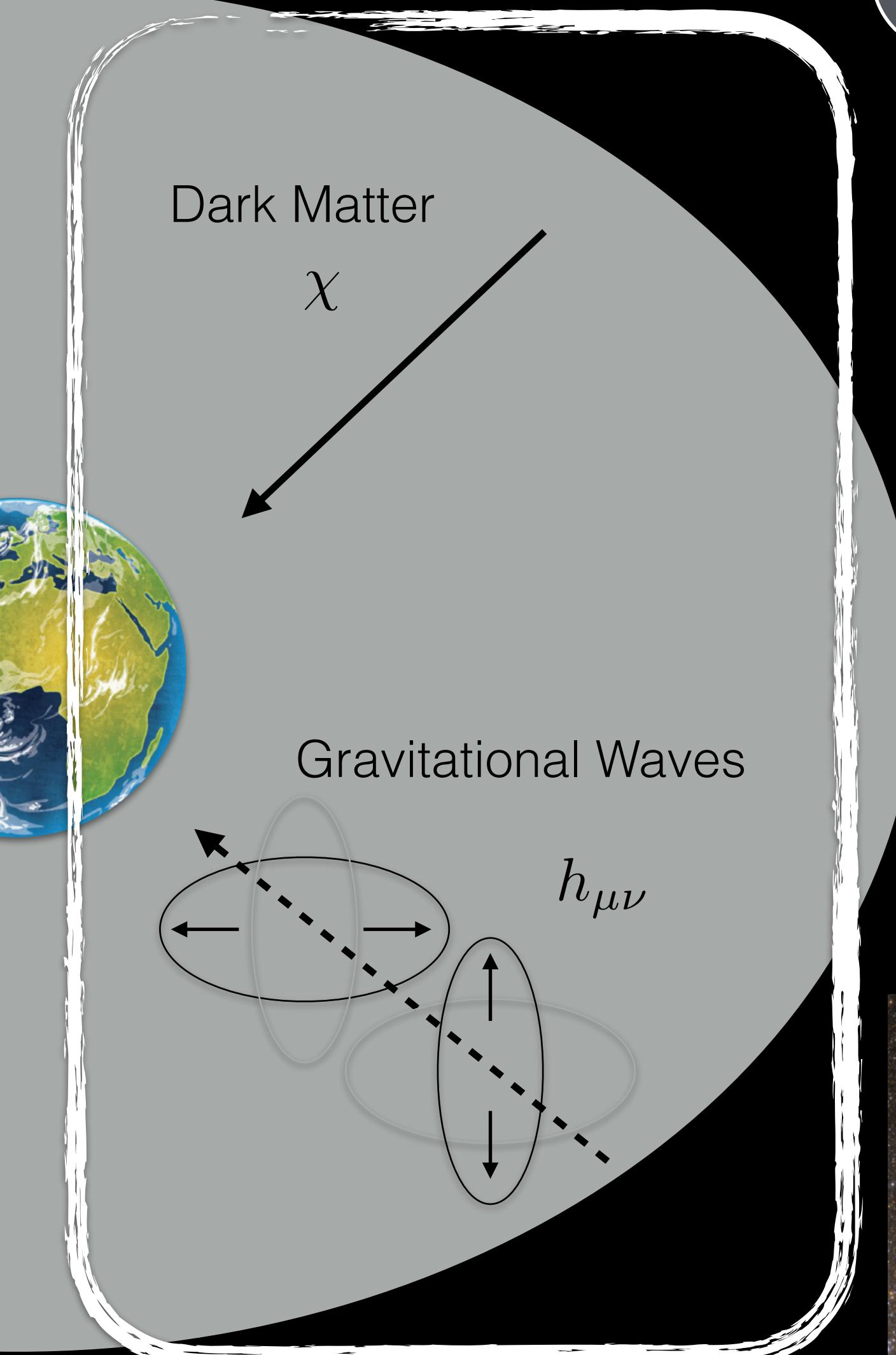
Quasars/AGN



Lecture 1

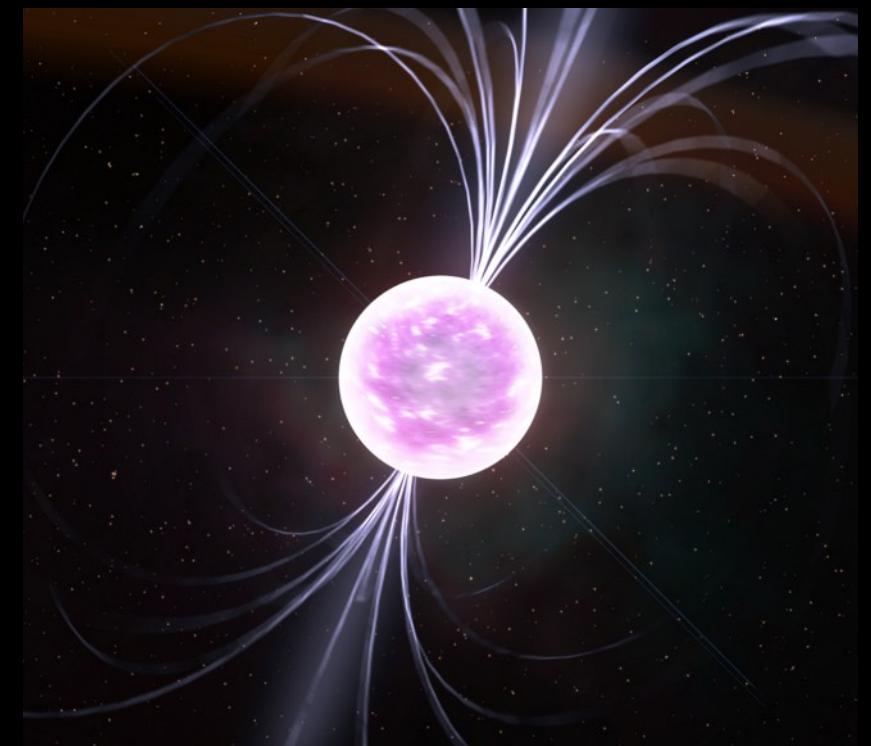


Lecture 2



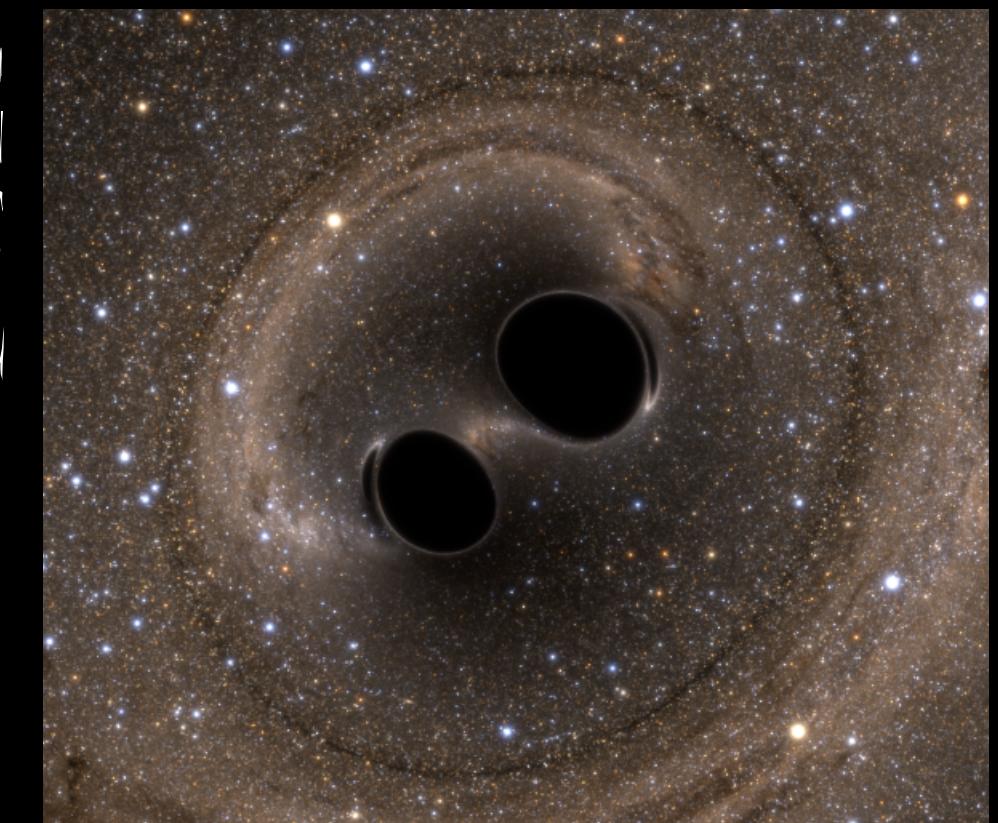
????

Pulsars



Credit: Kevin Gill / Flickr

BH/NS Mergers



Credit: SXS Lensing

# Gravitational Waves

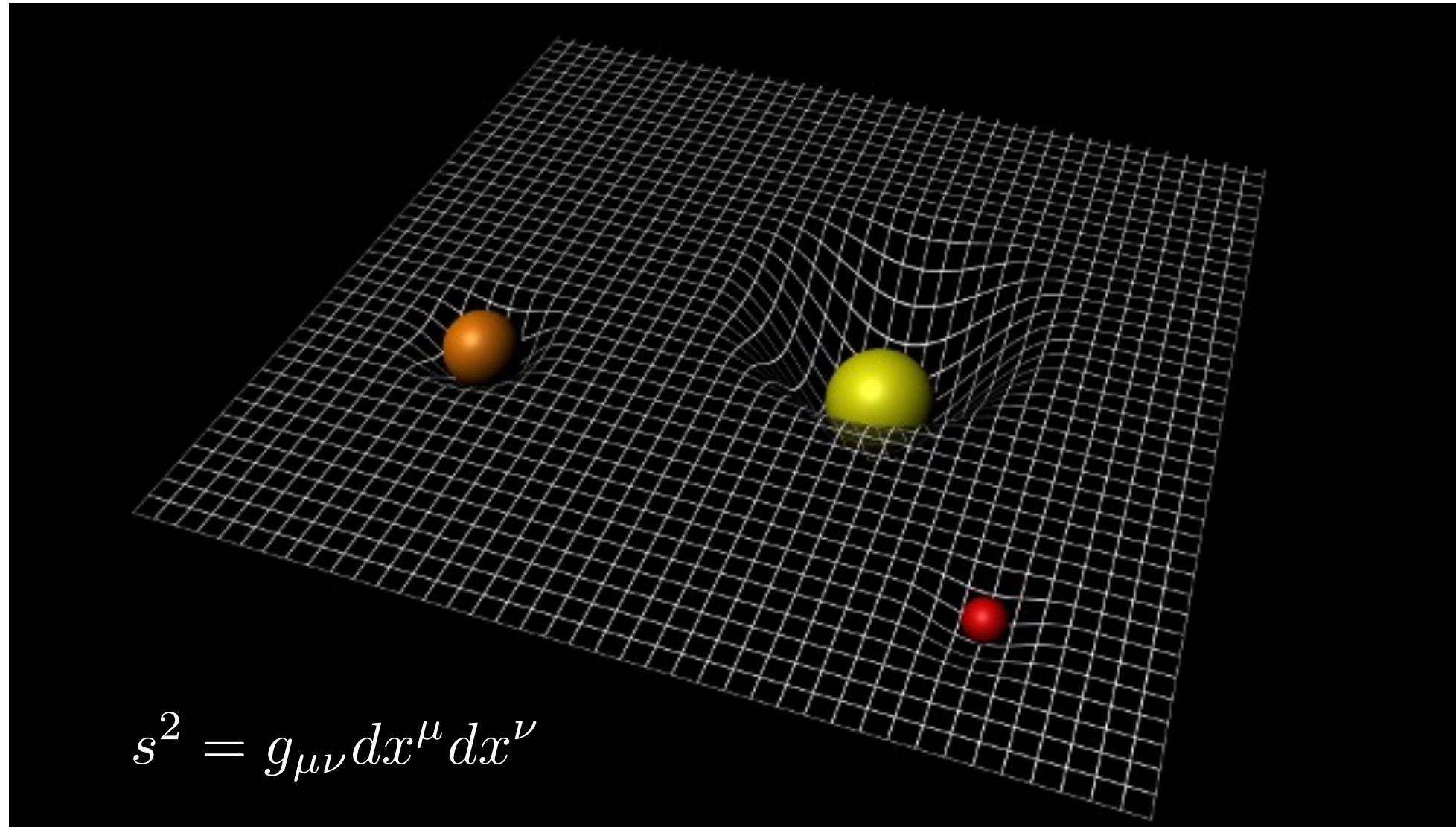
Einstein field equations of General Relativity:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein tensor  
(Gravity)

Stress-energy tensor  
(Matter)

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



Credit: ESA/C. Carreau

$$s^2 = g_{\mu\nu} dx^\mu dx^\nu$$

Linearise the field equations in vacuum:

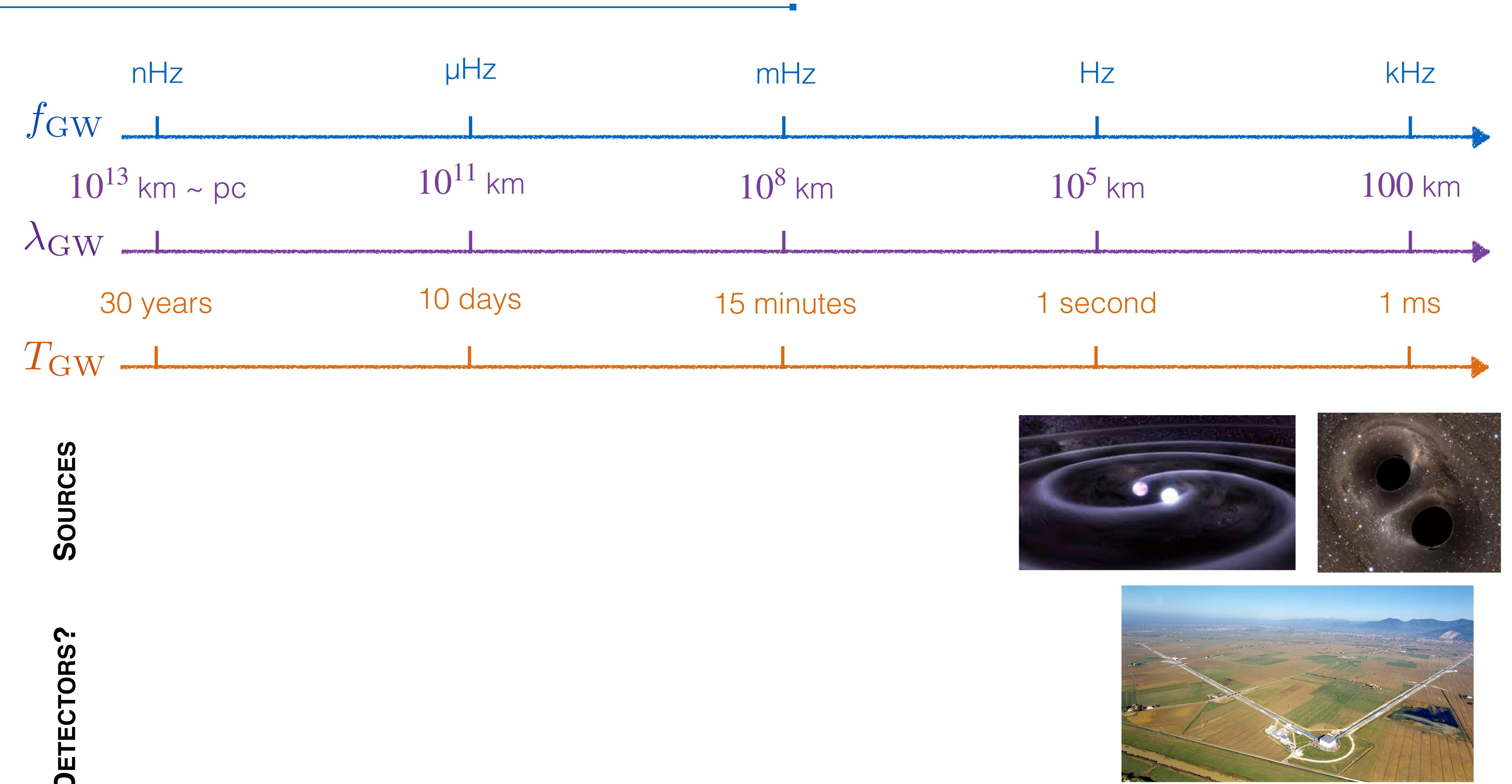
$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

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

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

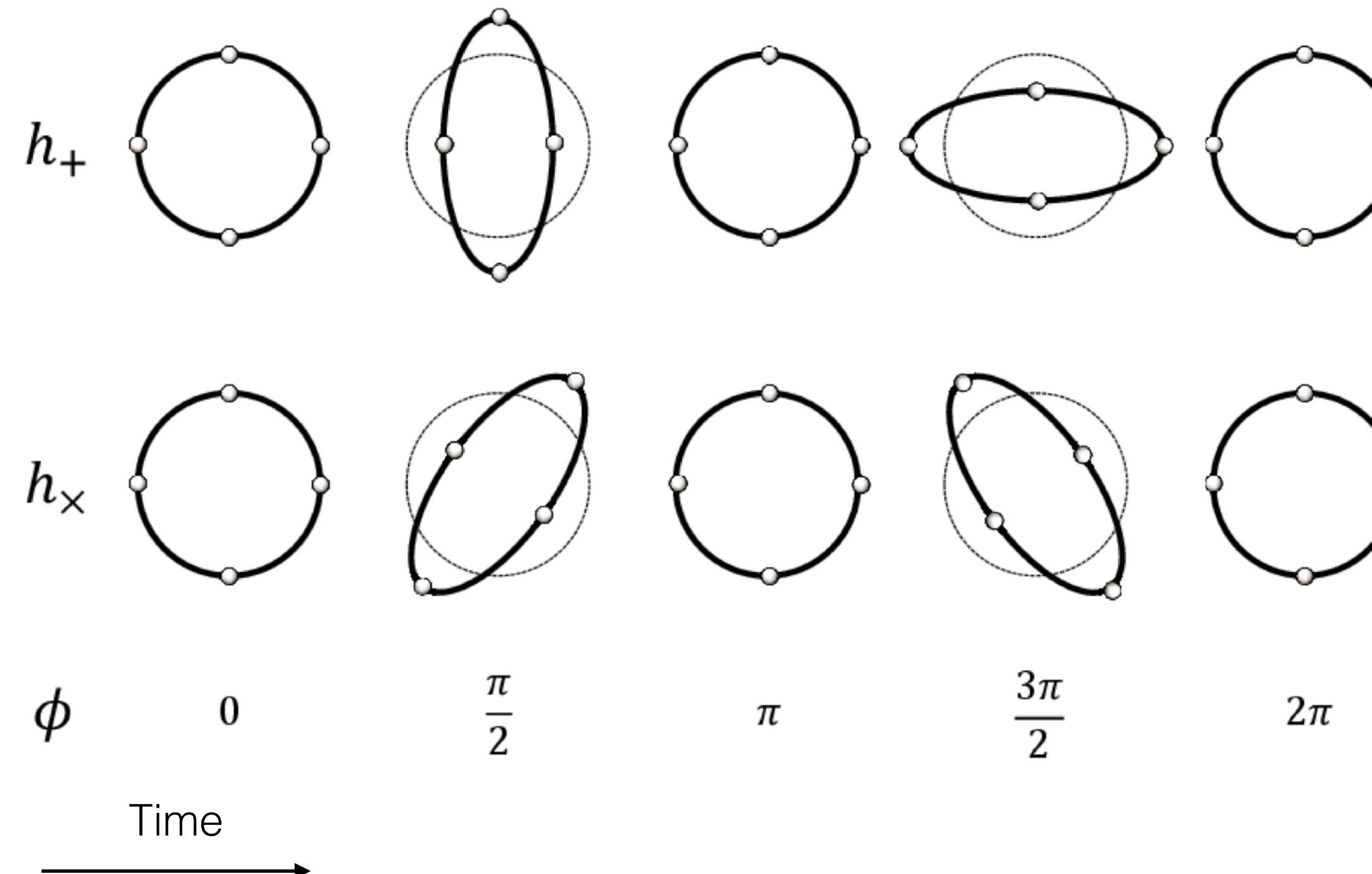
# The Gravitational Wave Spectrum

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



# Direct detection of GWs

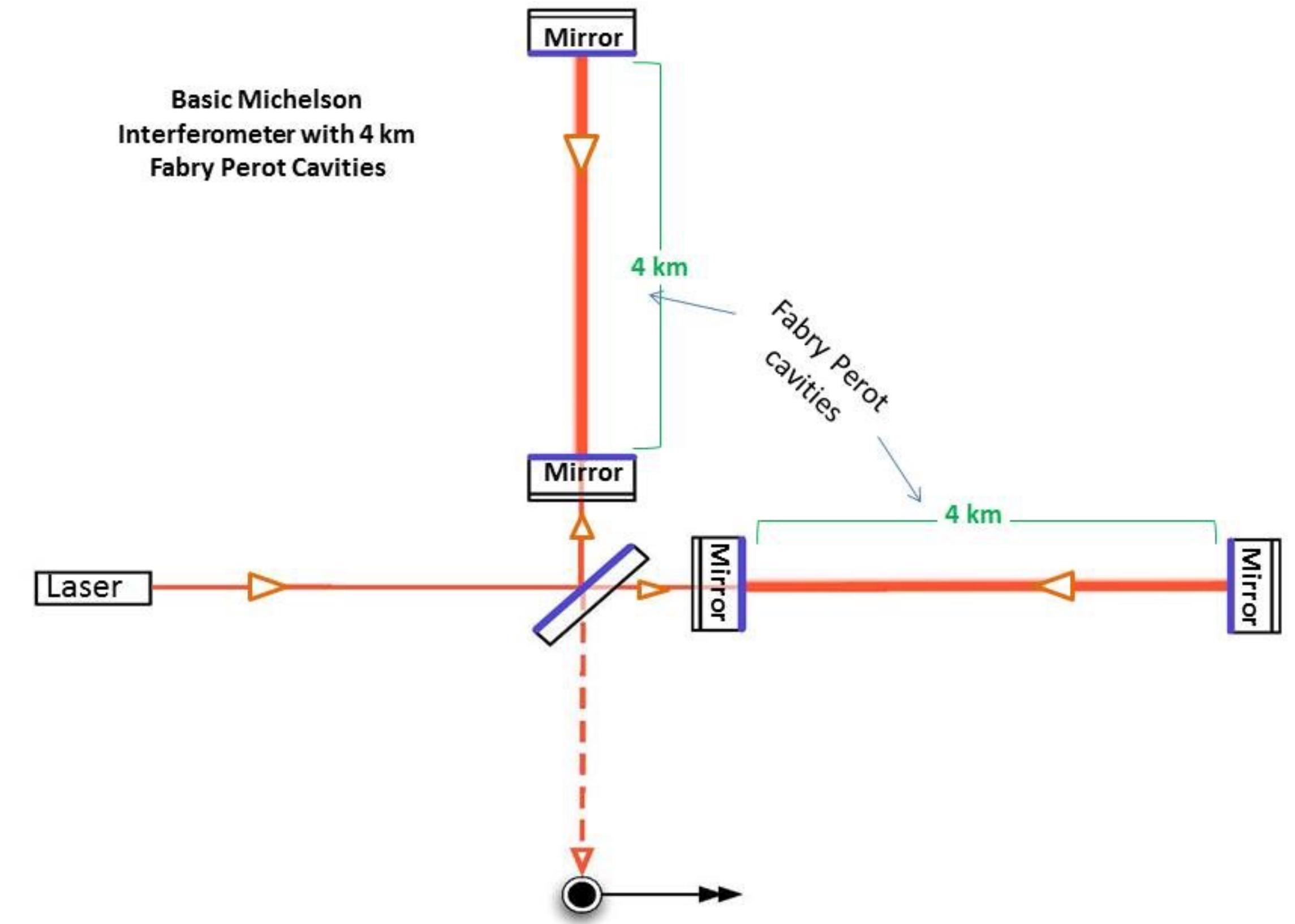
GW traveling into the screen causes (tiny) distortion:



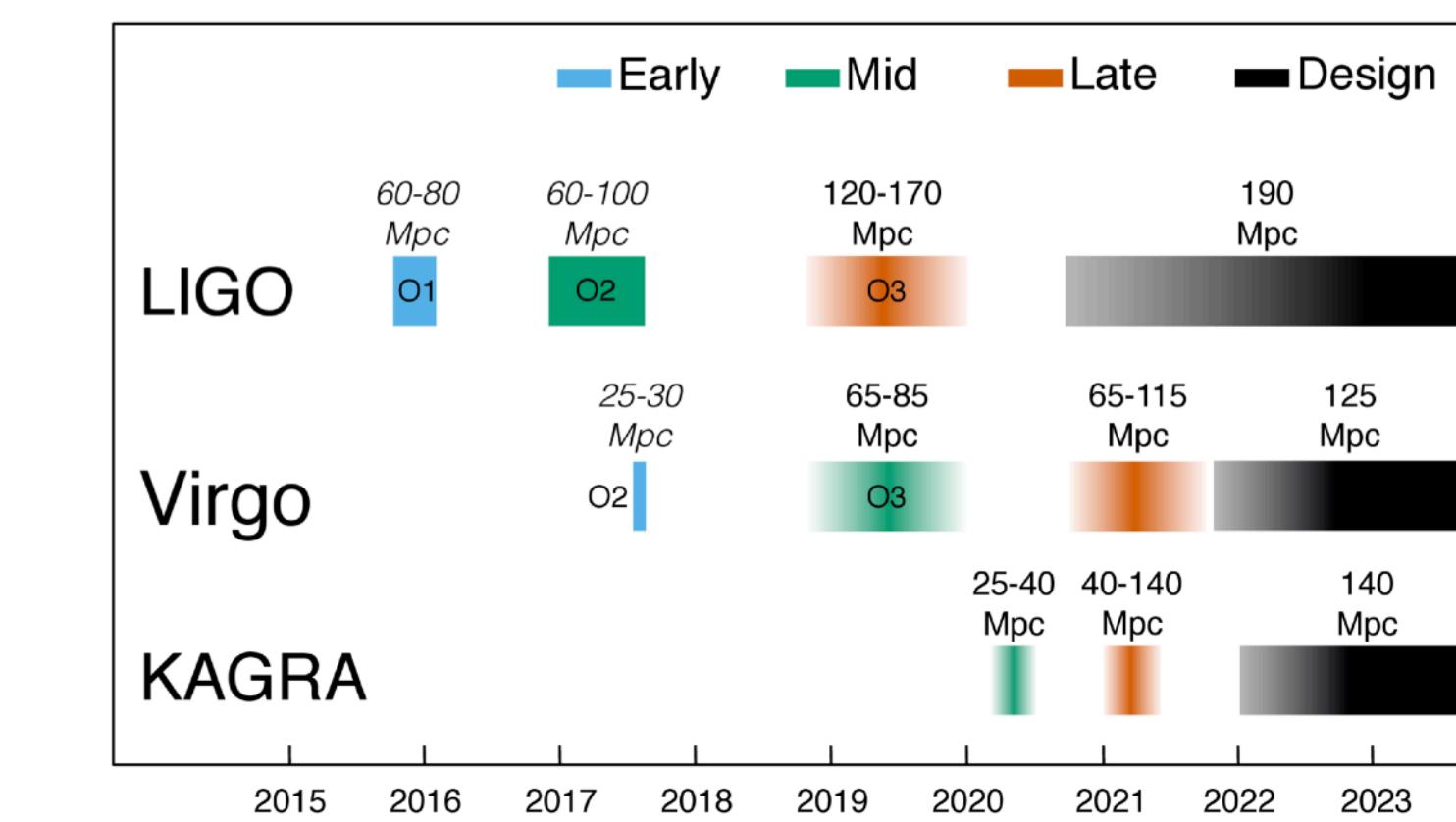
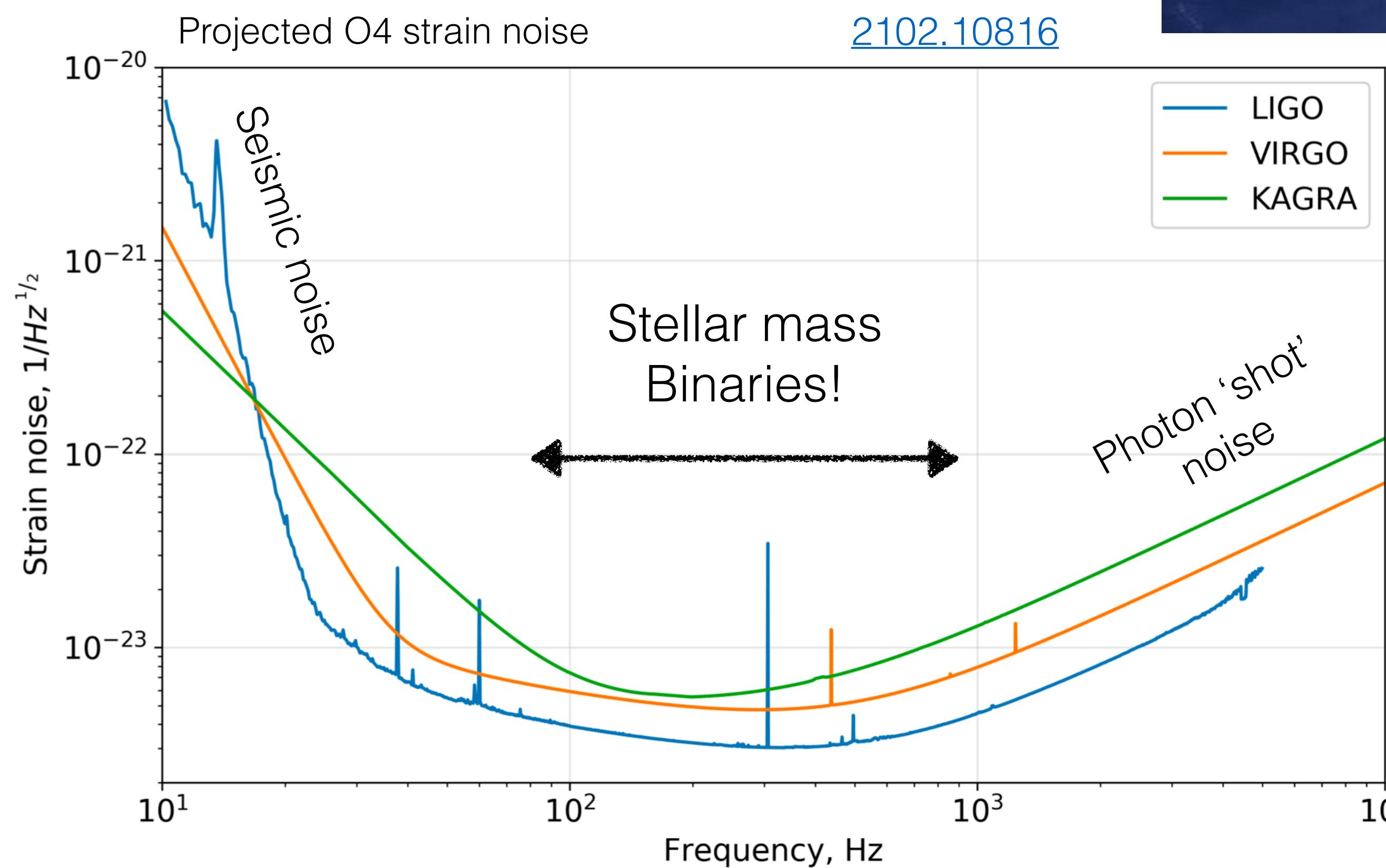
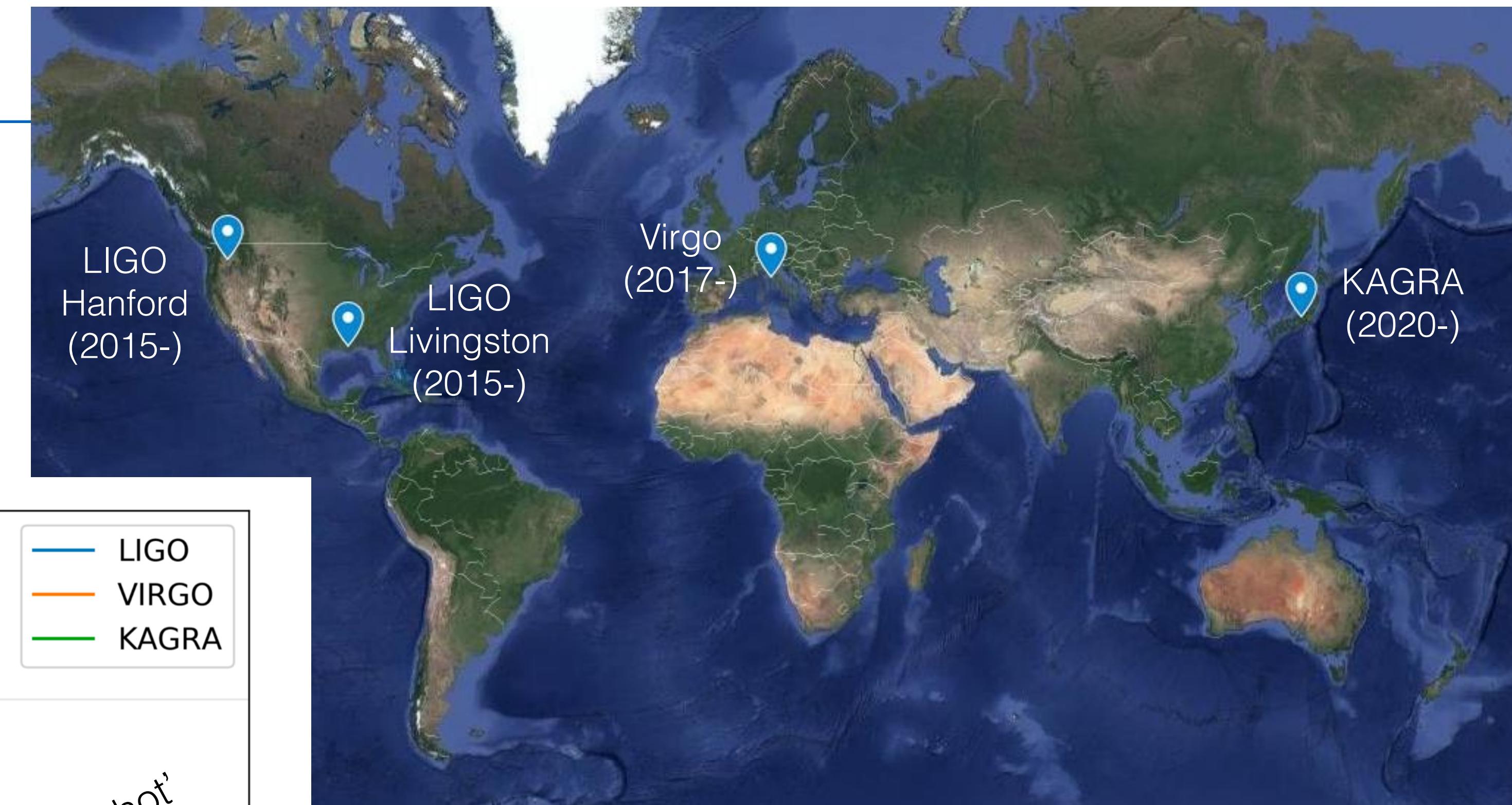
[1708.00918](https://arxiv.org/abs/1708.00918)

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

[www.ligo.caltech.edu/page/ligos-if0](http://www.ligo.caltech.edu/page/ligos-if0)



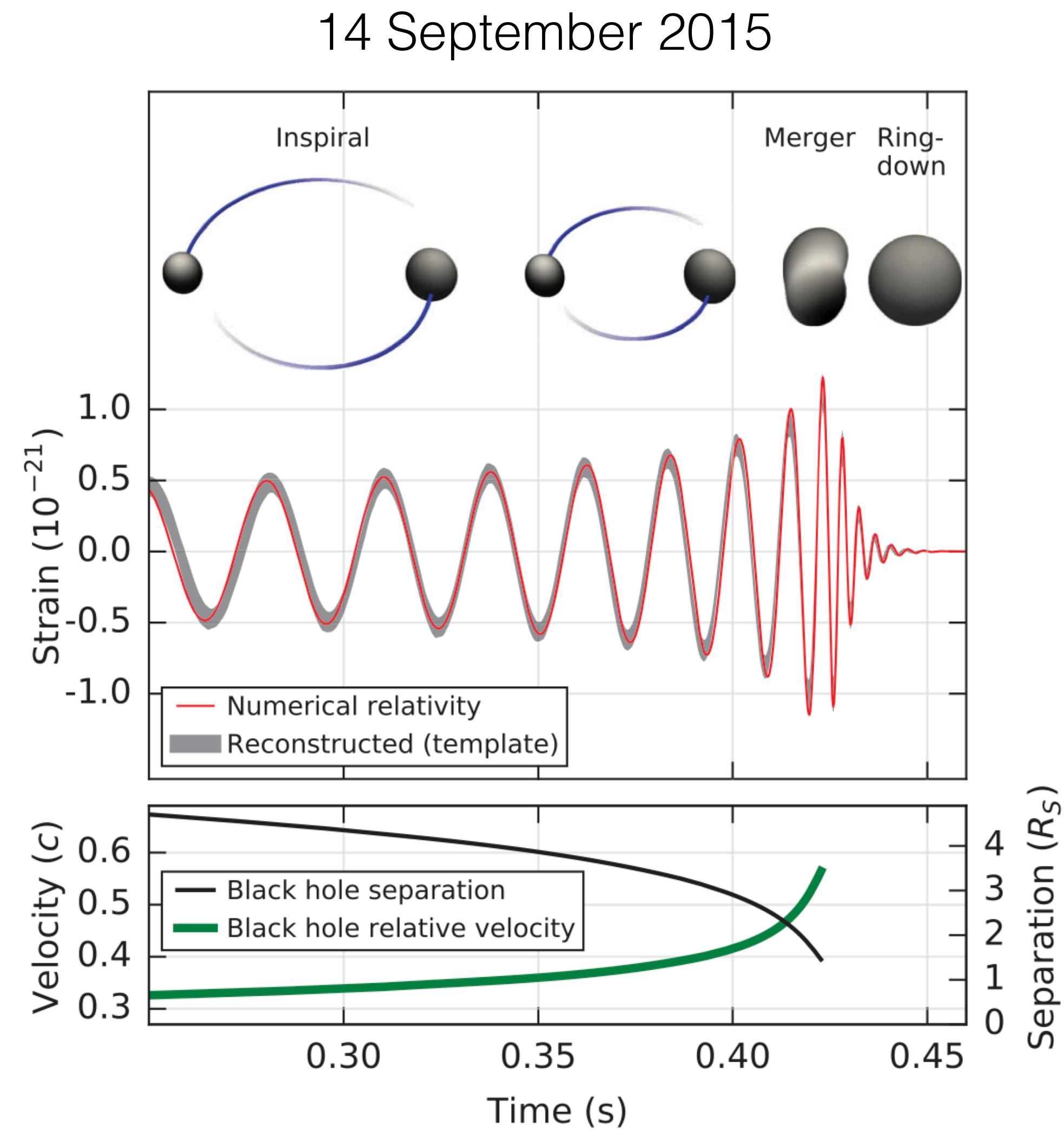
# LIGO-Virgo-KAGRA (LVK)



GW frequency  $\sim$  twice orbital frequency.

[1906.03643](#)

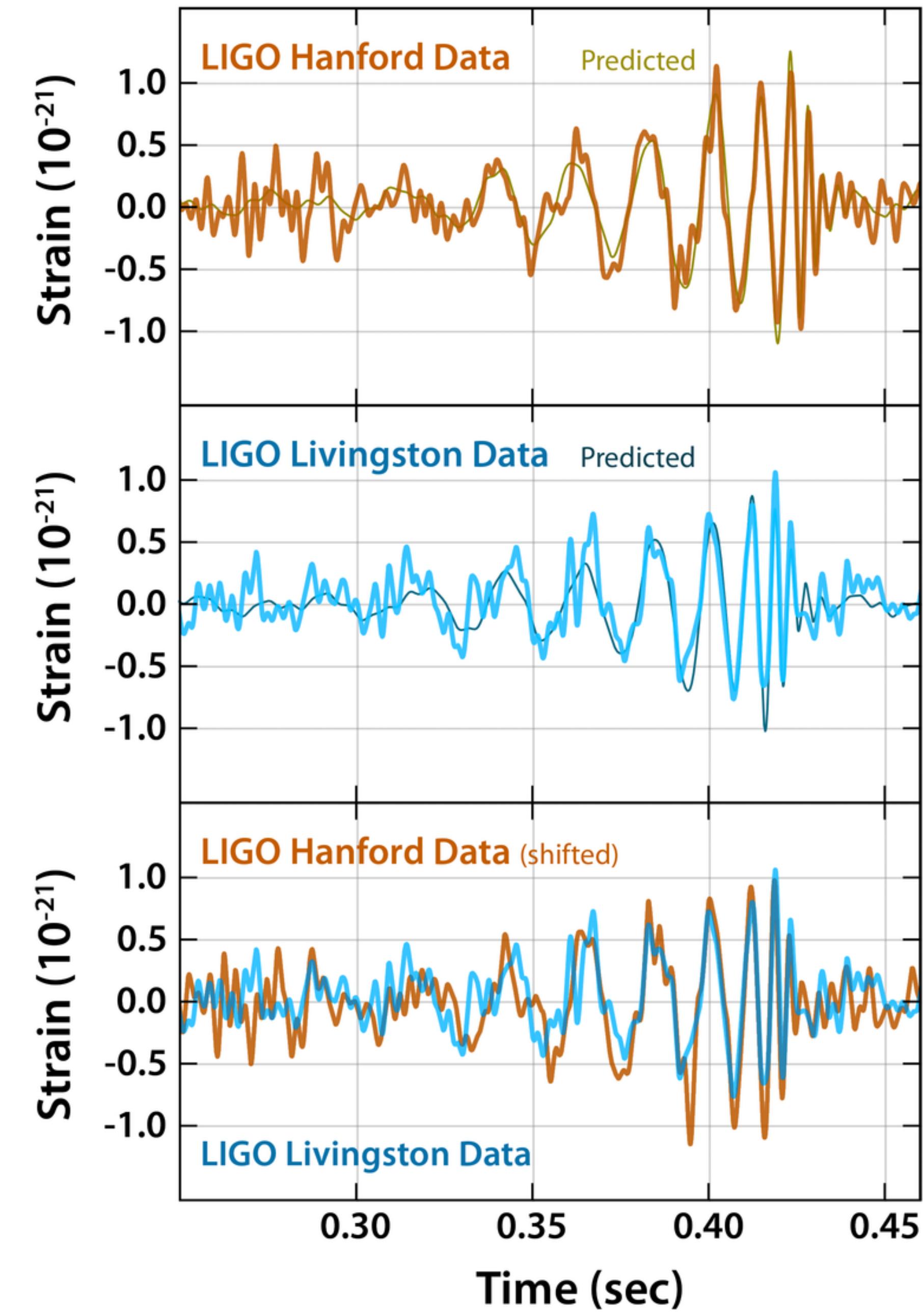
# GW150914 - the first BH-BH merger



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

[1602.03840](https://arxiv.org/abs/1602.03840)

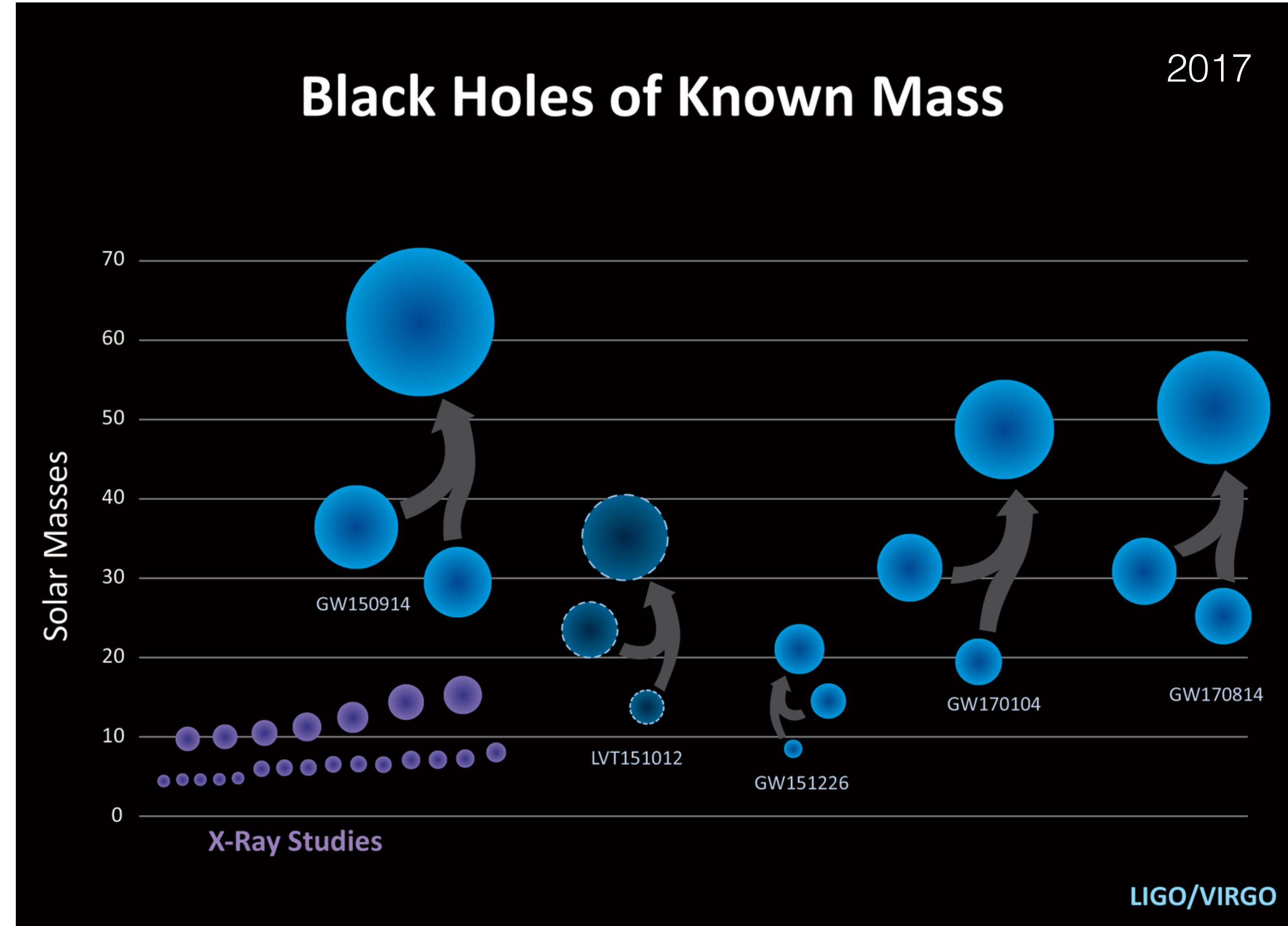
Credit: Caltech/MIT/LIGO Lab



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

# The Compact Object Zoo

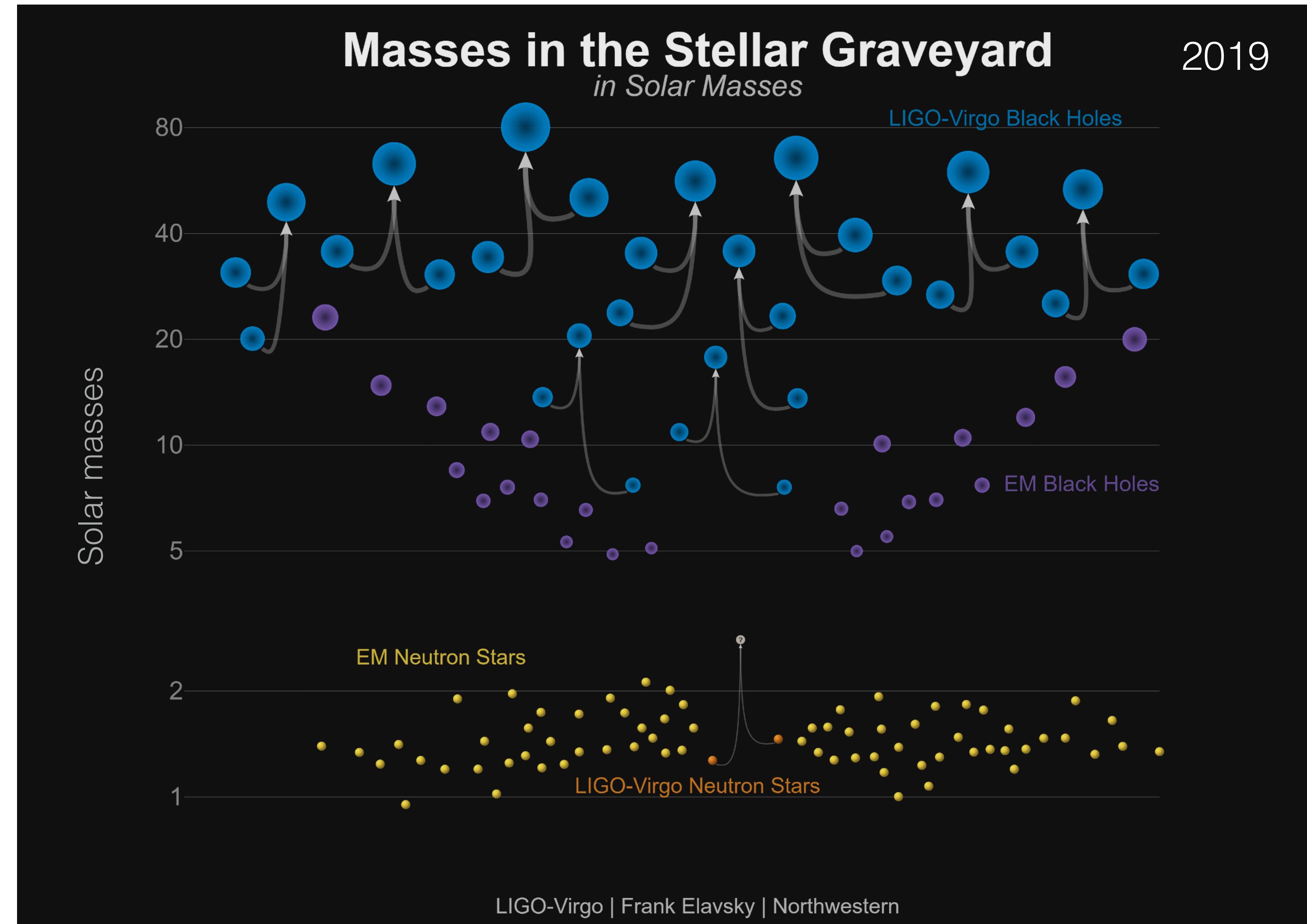
<https://media.ligo.northwestern.edu/gallery/mass-plot>



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

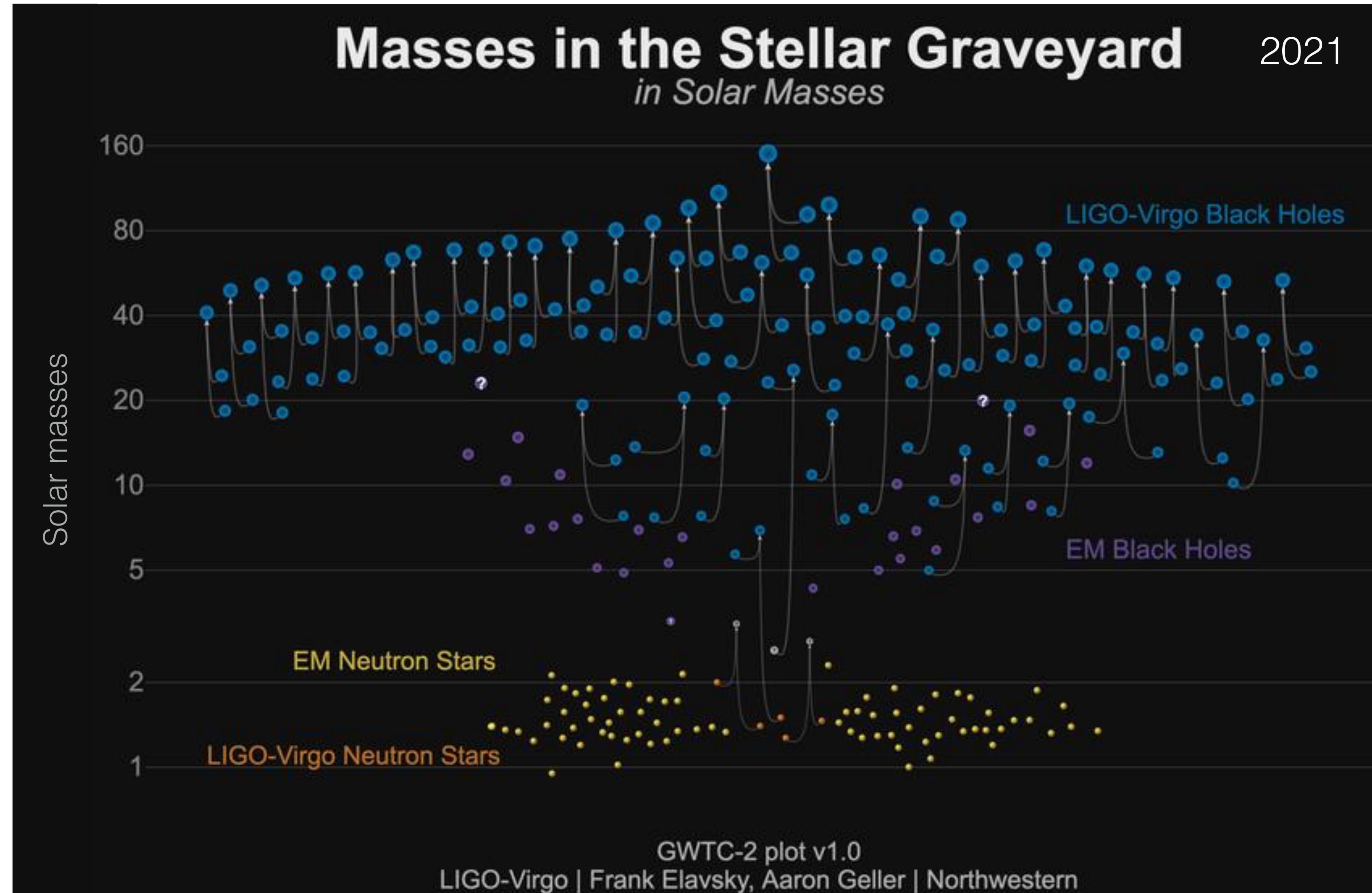
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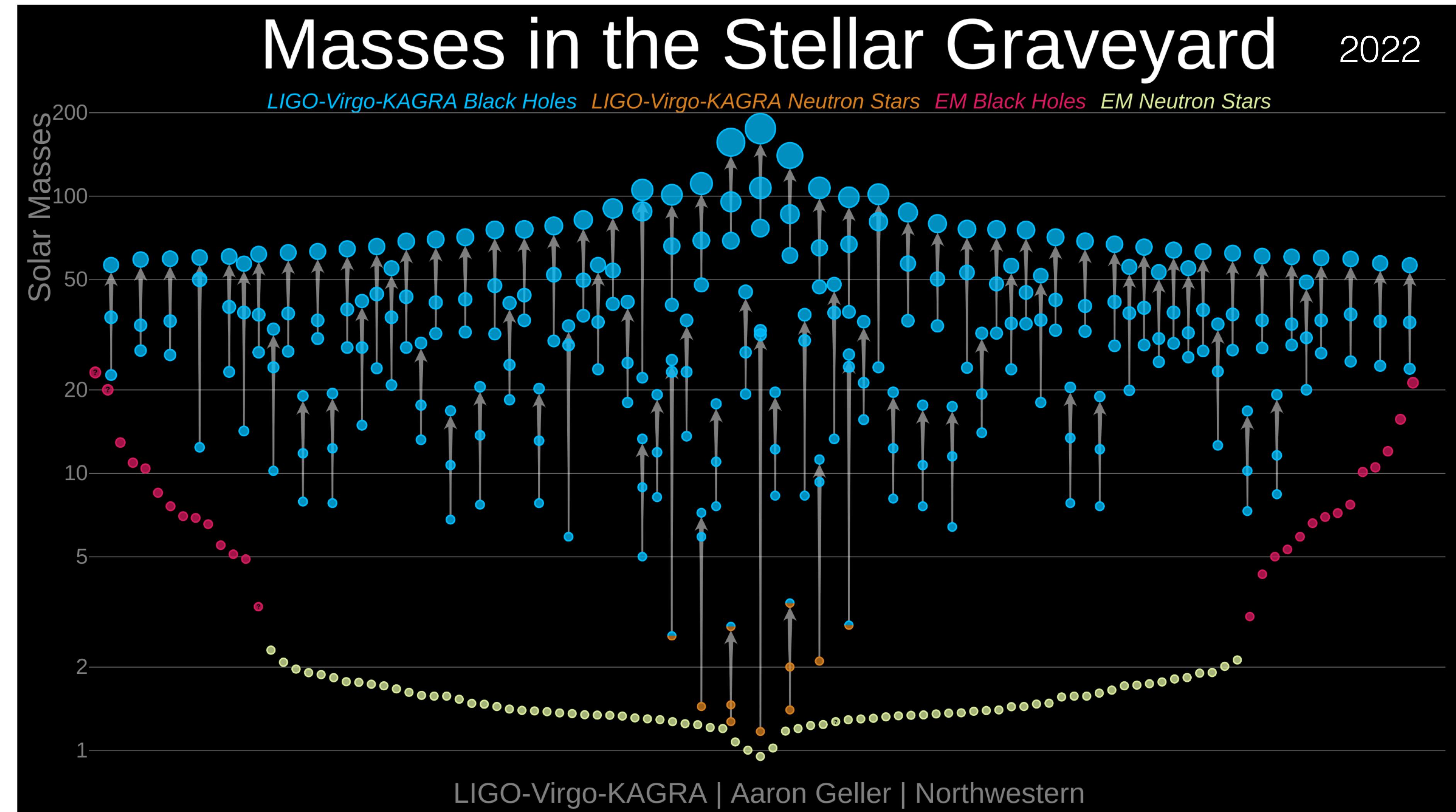
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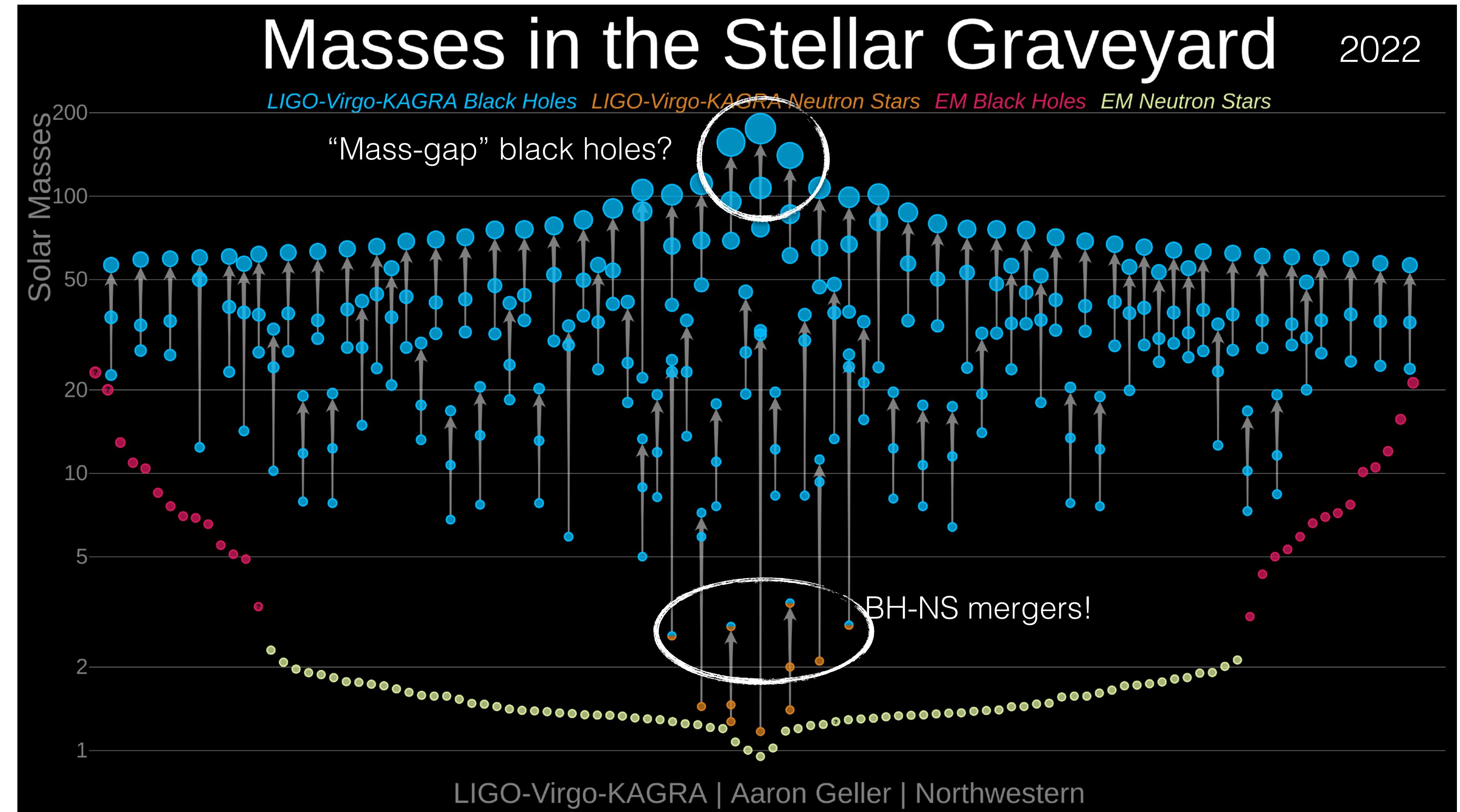


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<https://media.ligo.northwestern.edu/gallery/mass-plot>



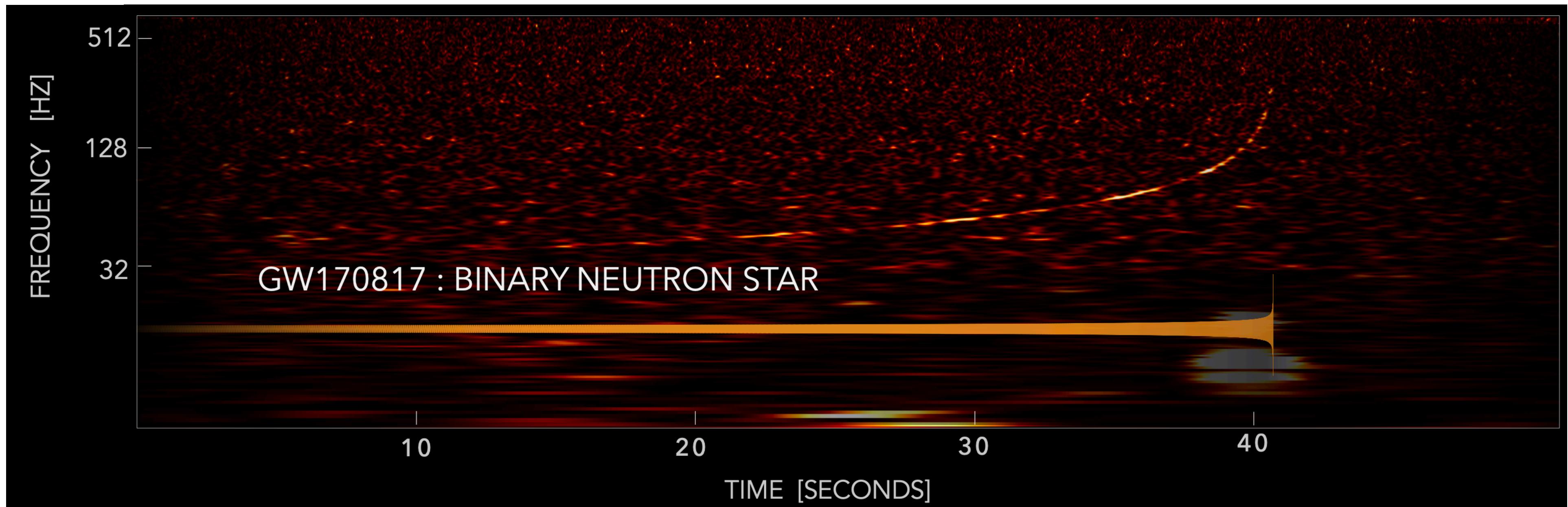
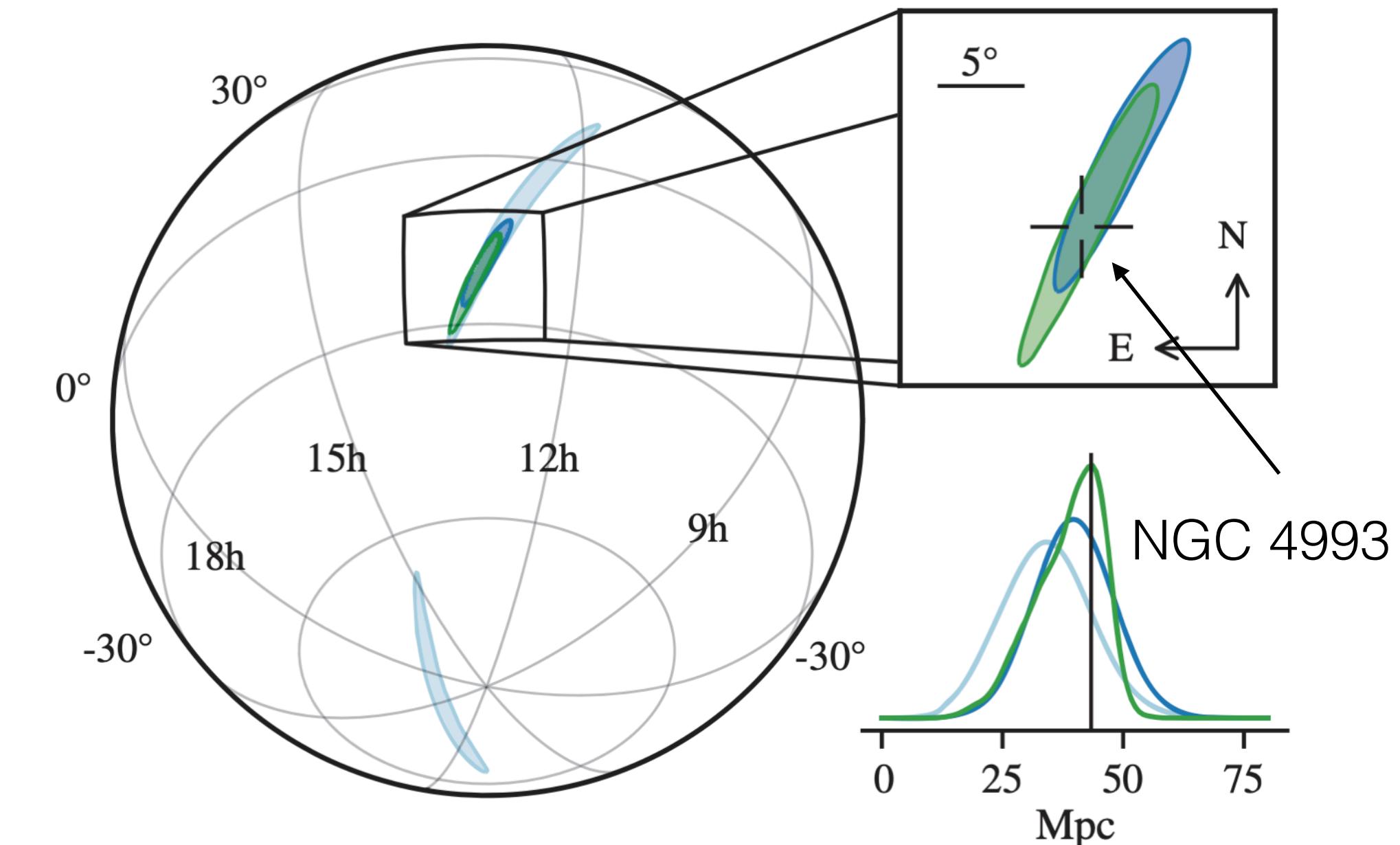




# GW170817 - the first NS-NS merger

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

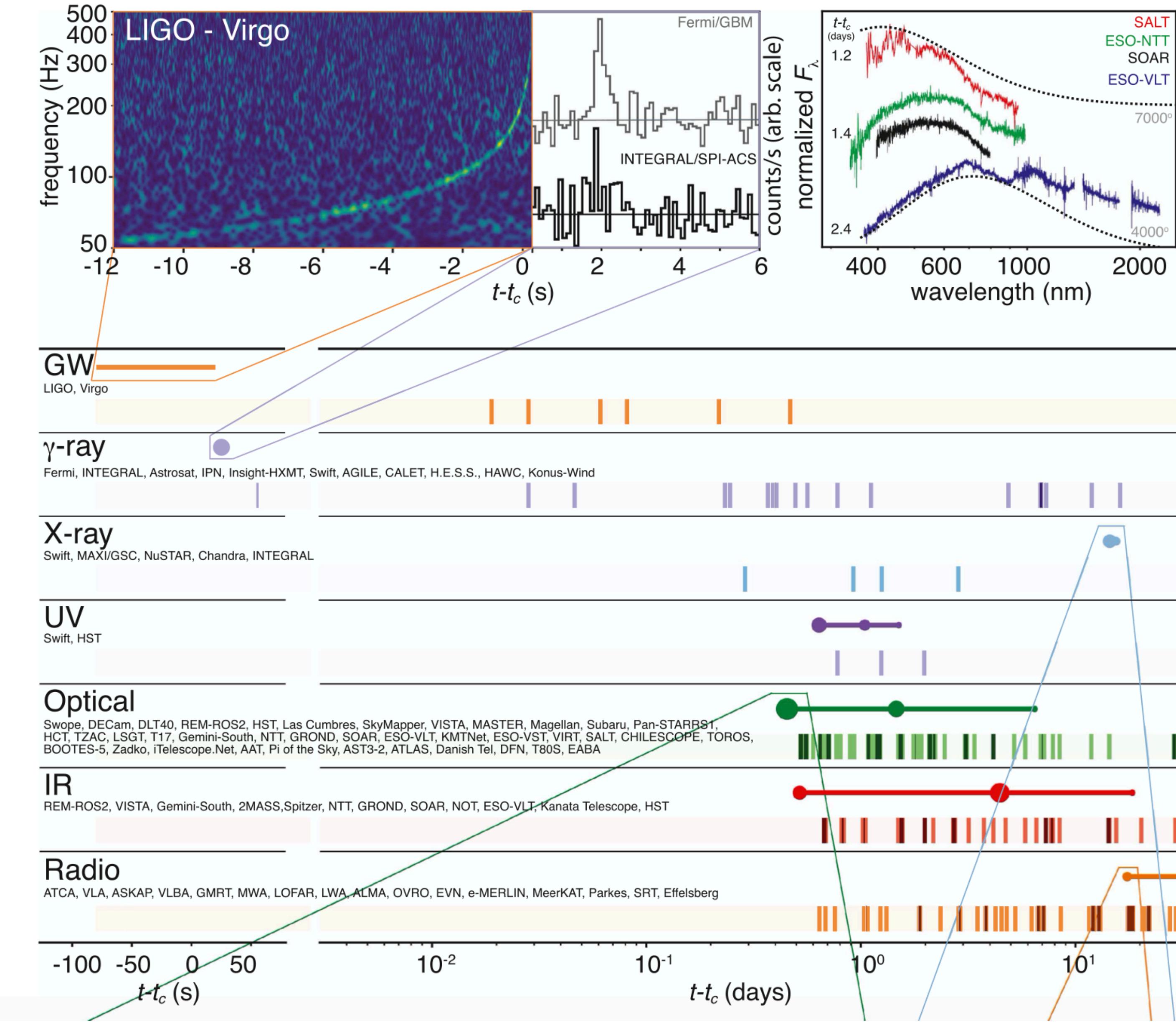
Localised to  
within  $\sim 30 \text{ deg}^2$



[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

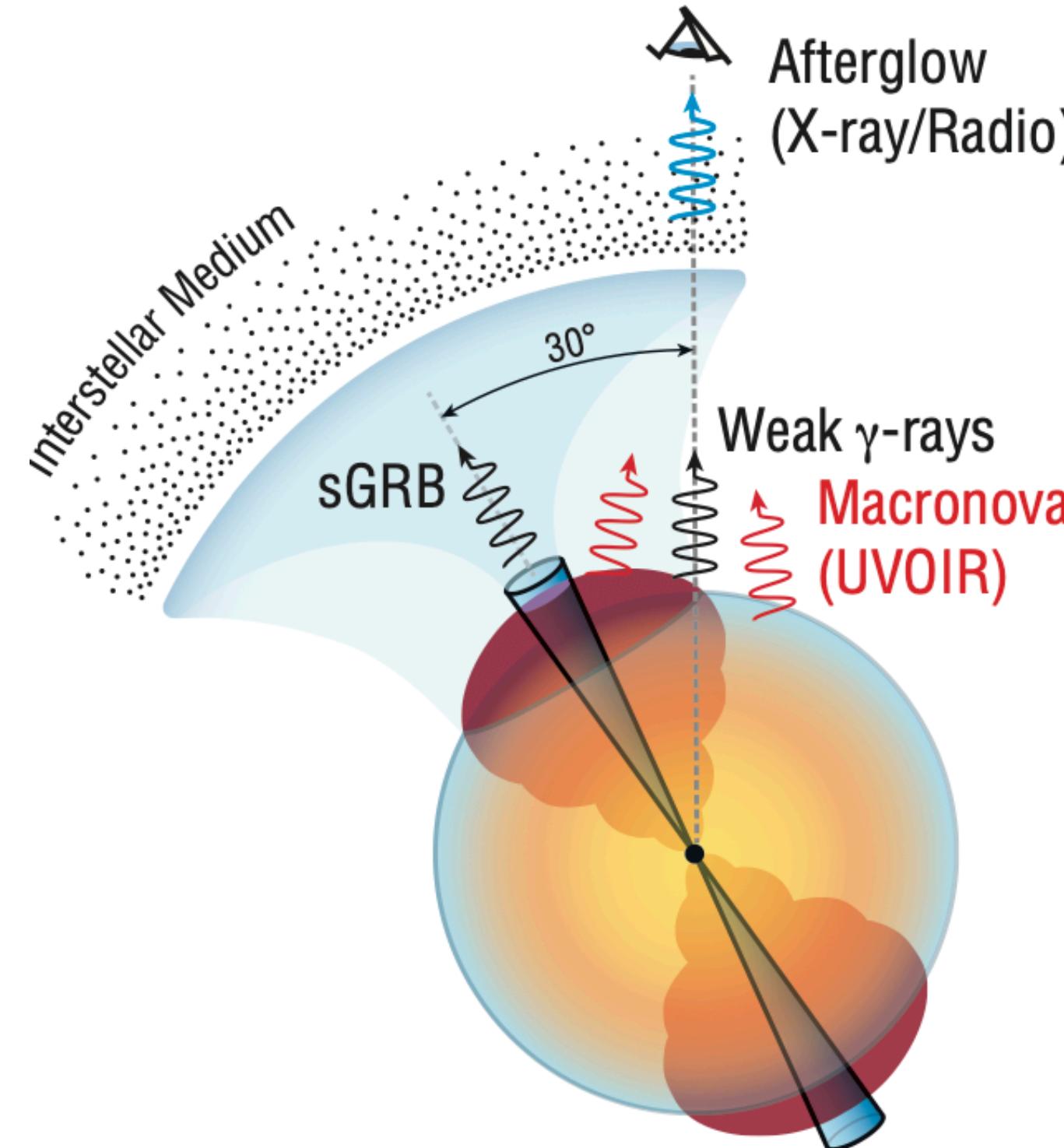
Follow-up observations  
across the spectrum!

Sadly no neutrinos detected :(

[1710.05833](#), [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!

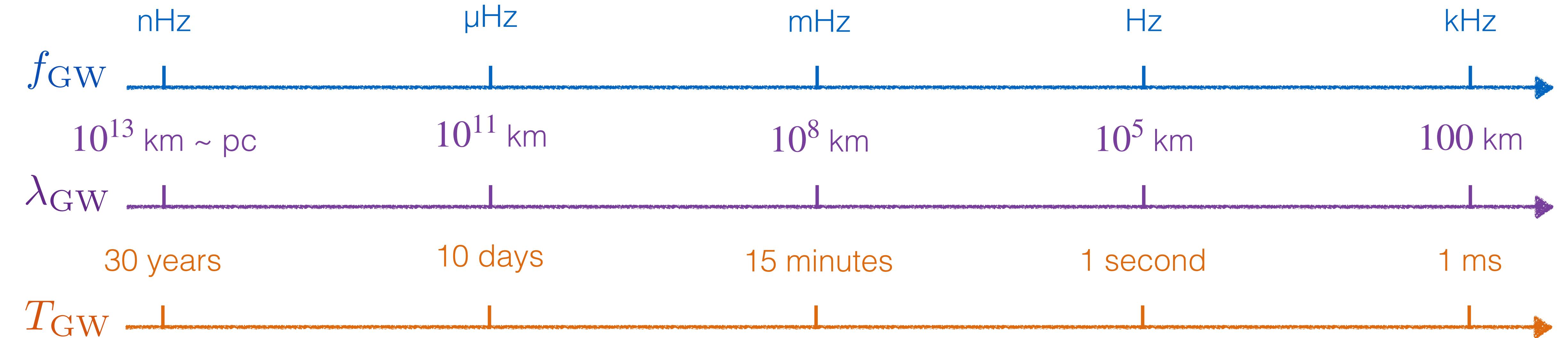
[1710.06394](#)

Measurement of the Hubble Constant!

[1710.05835](#)

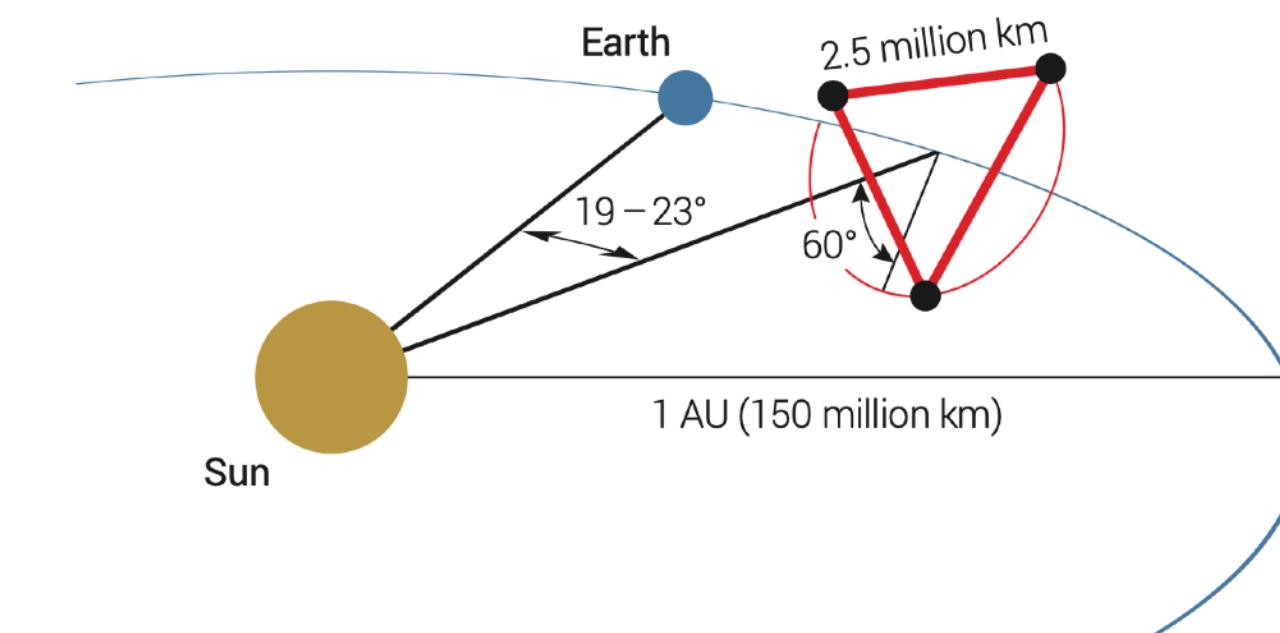
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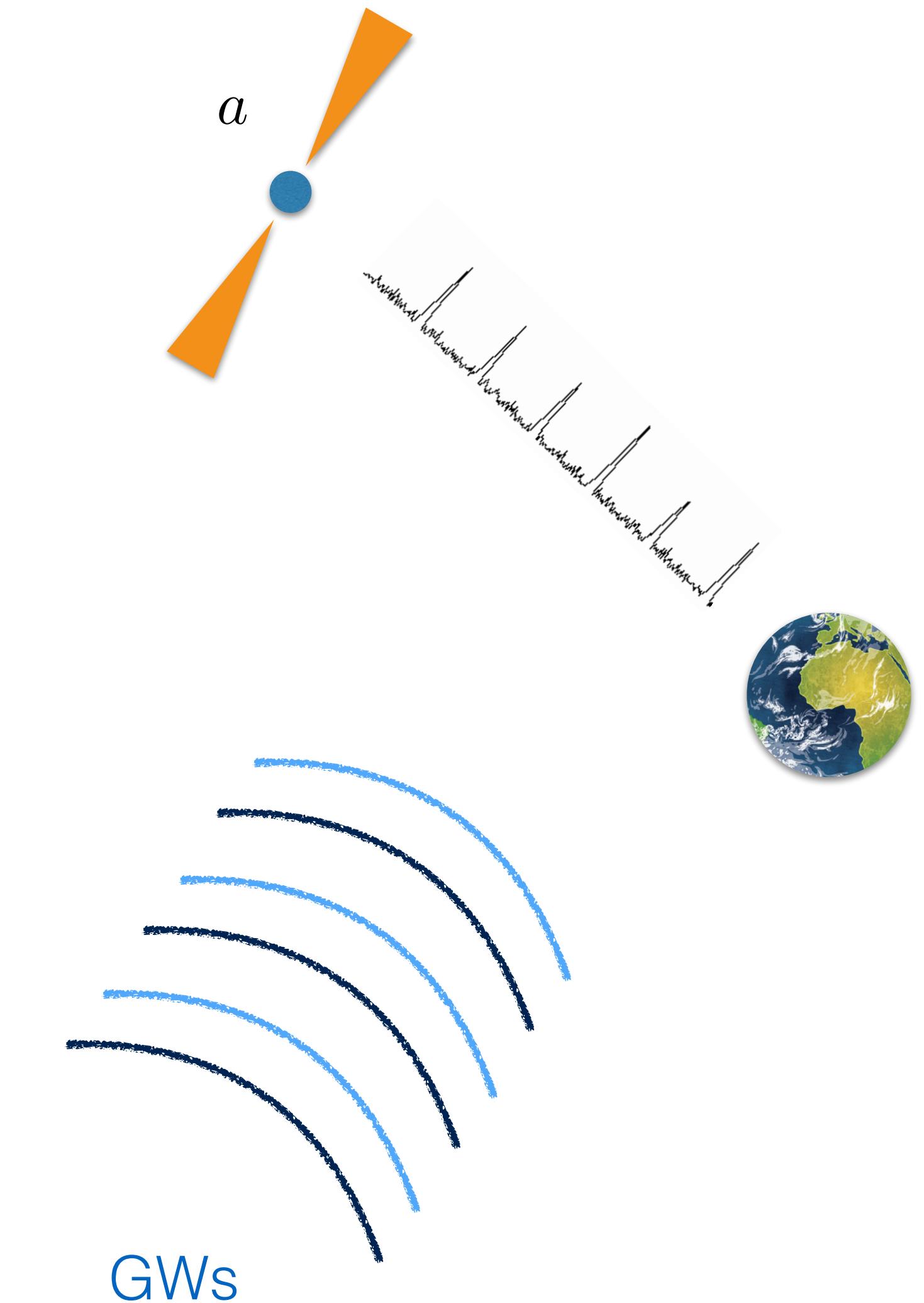


DETECTORS?

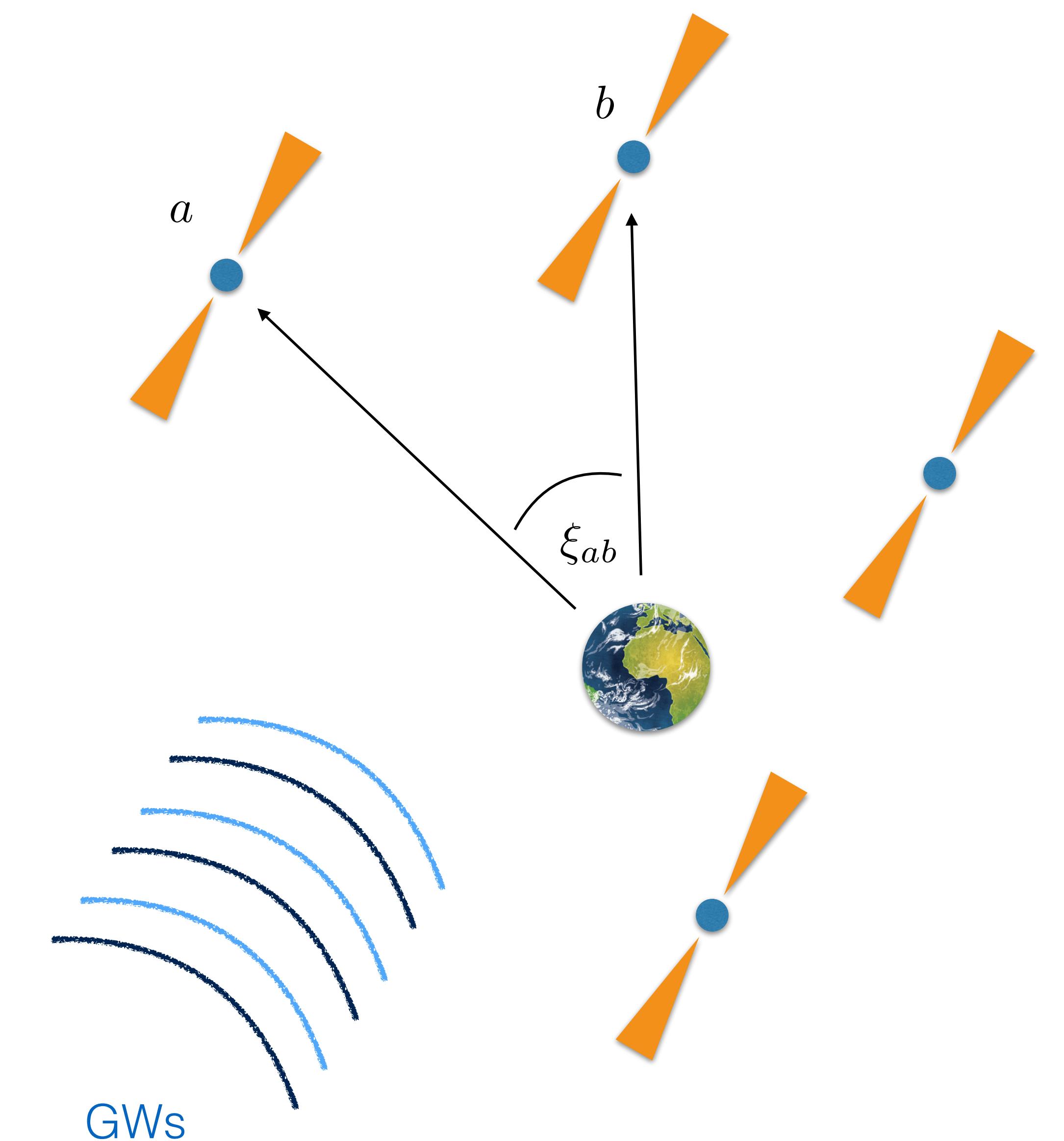
?



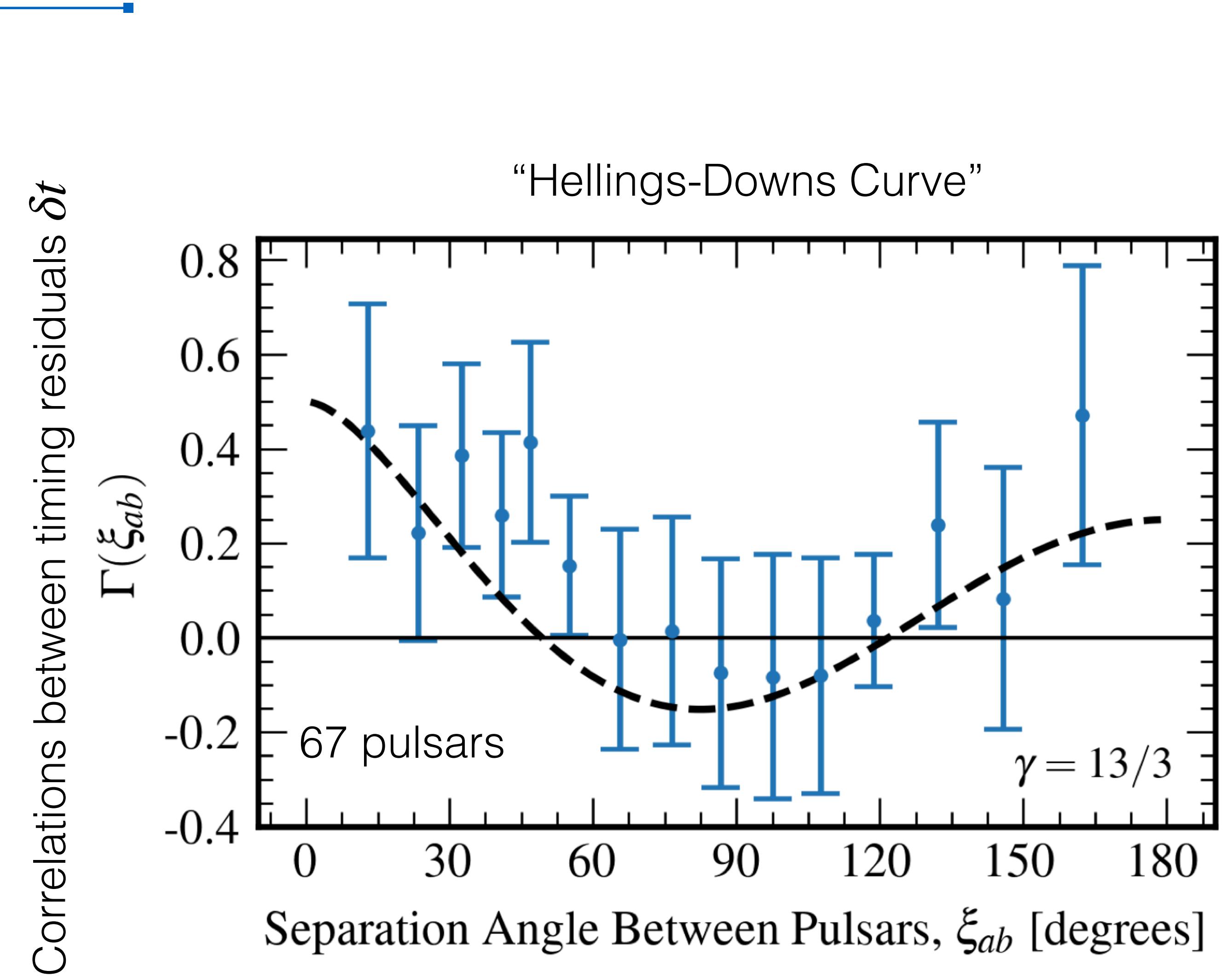
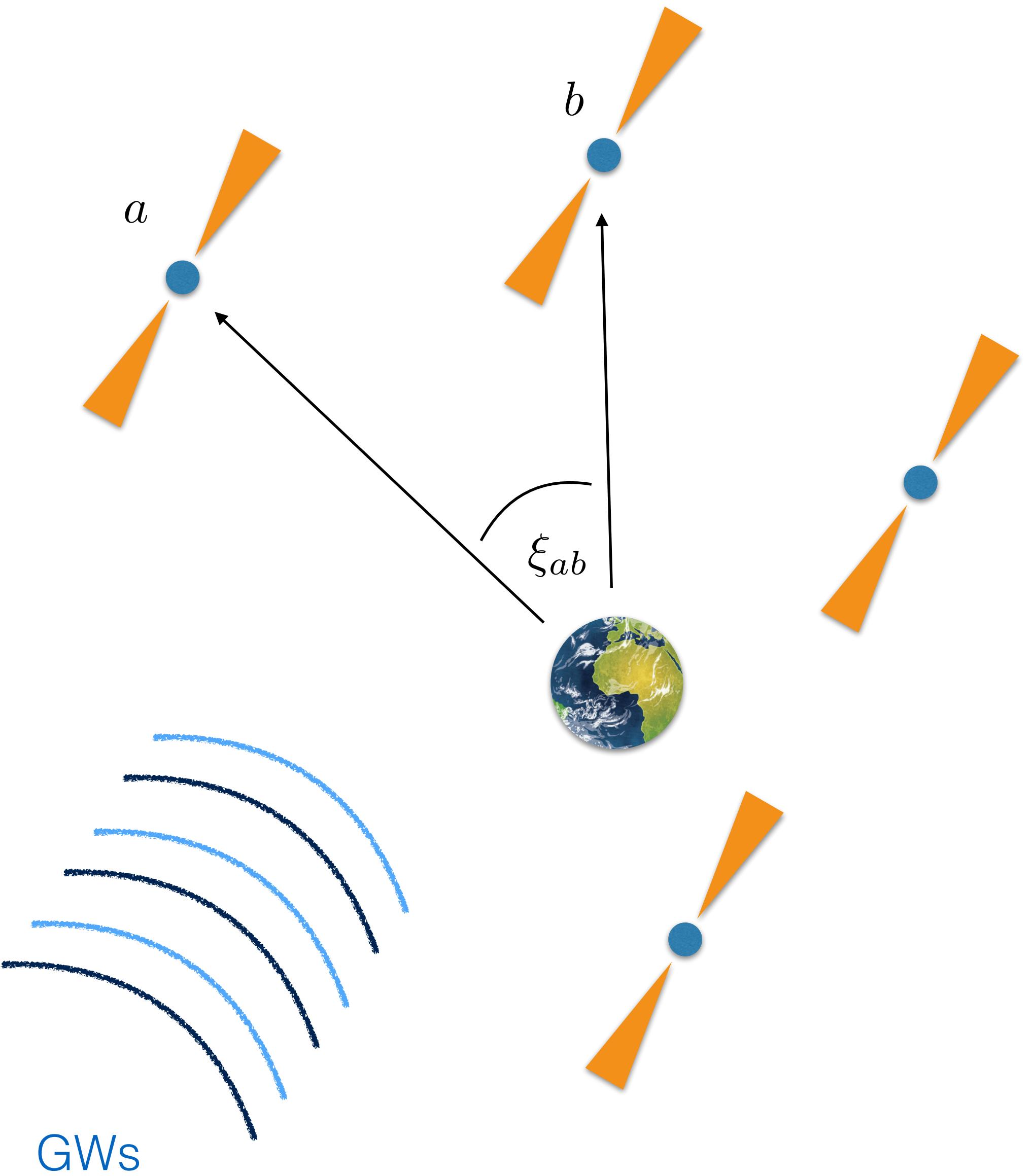
# Pulsar Timing Arrays (PTA)



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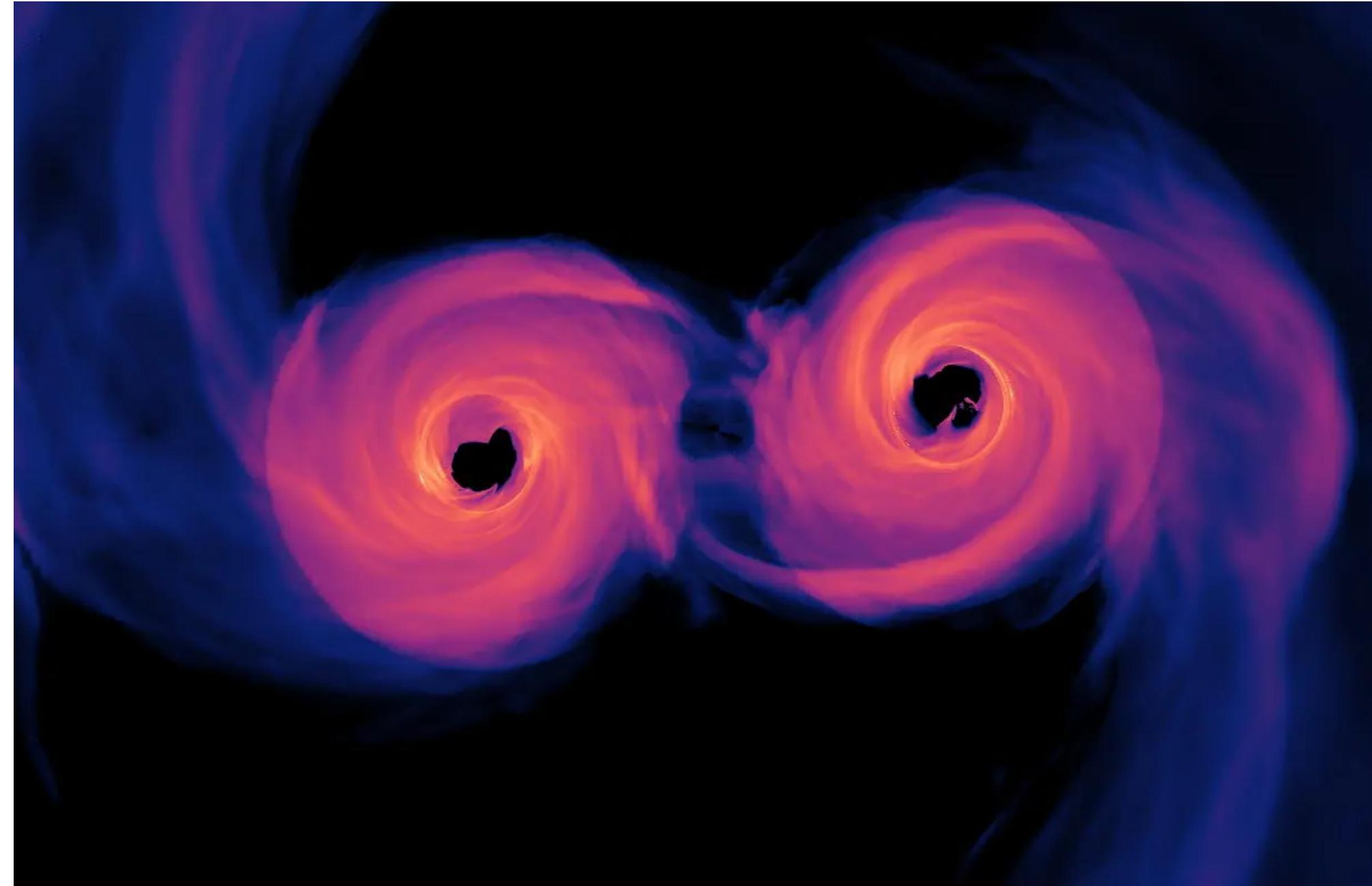


[NANOgrav, [2306.16217](#), [2306.16213](#)]

# Sources of Nanohertz GWs

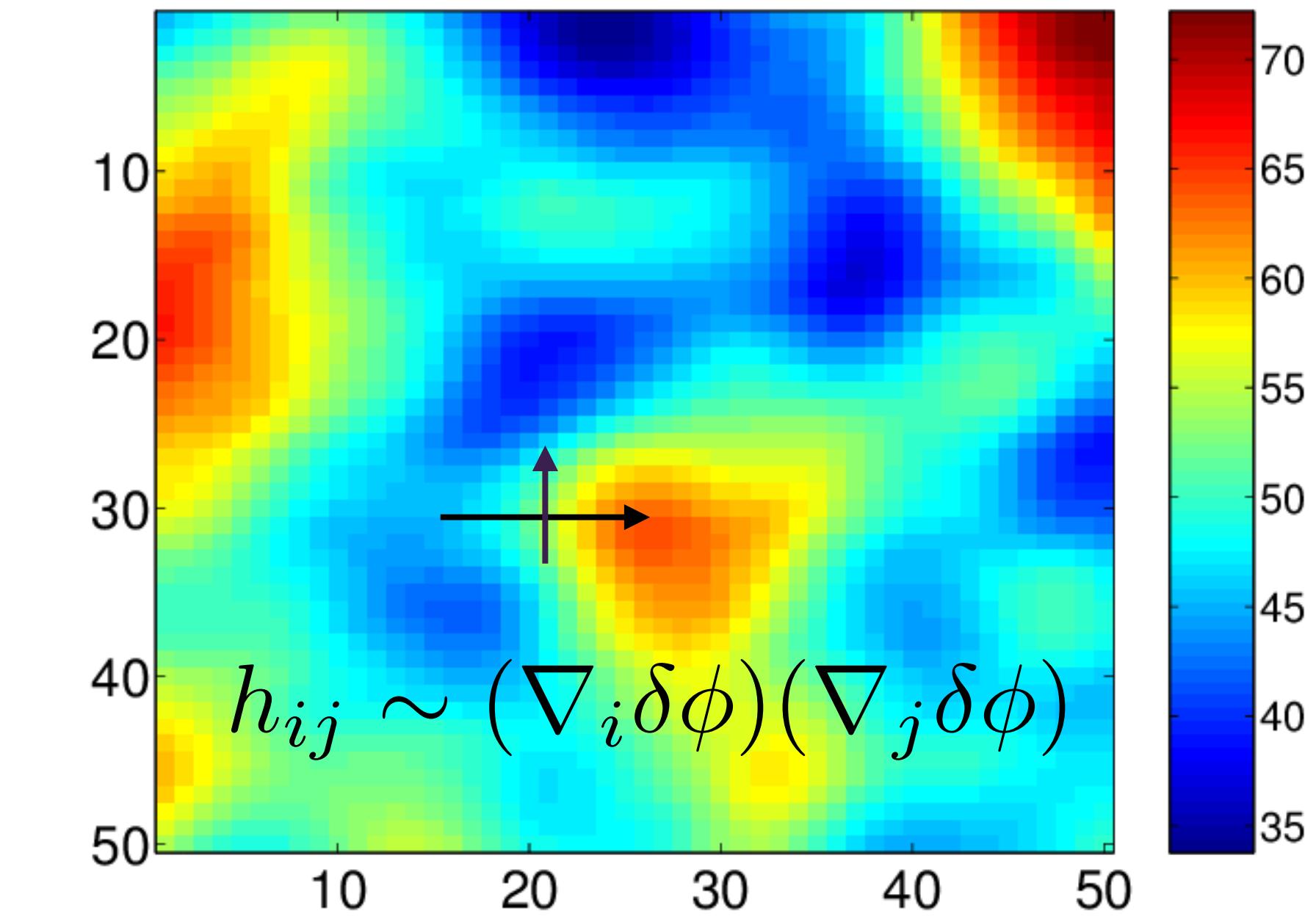
## Supermassive Black Holes

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



## Scalar-induced GWs?

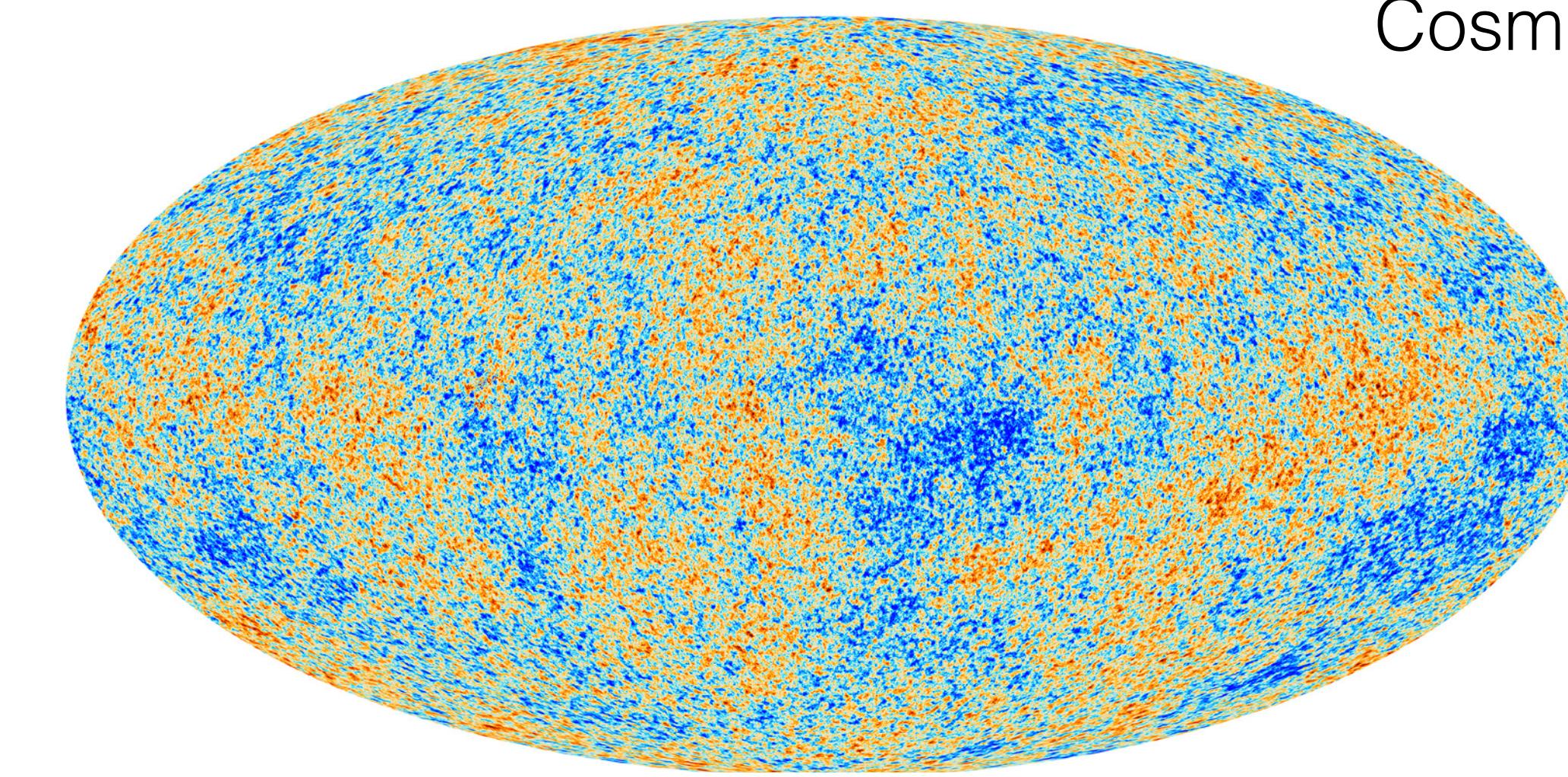
Could be produced by enhanced scalar perturbations in the early Universe



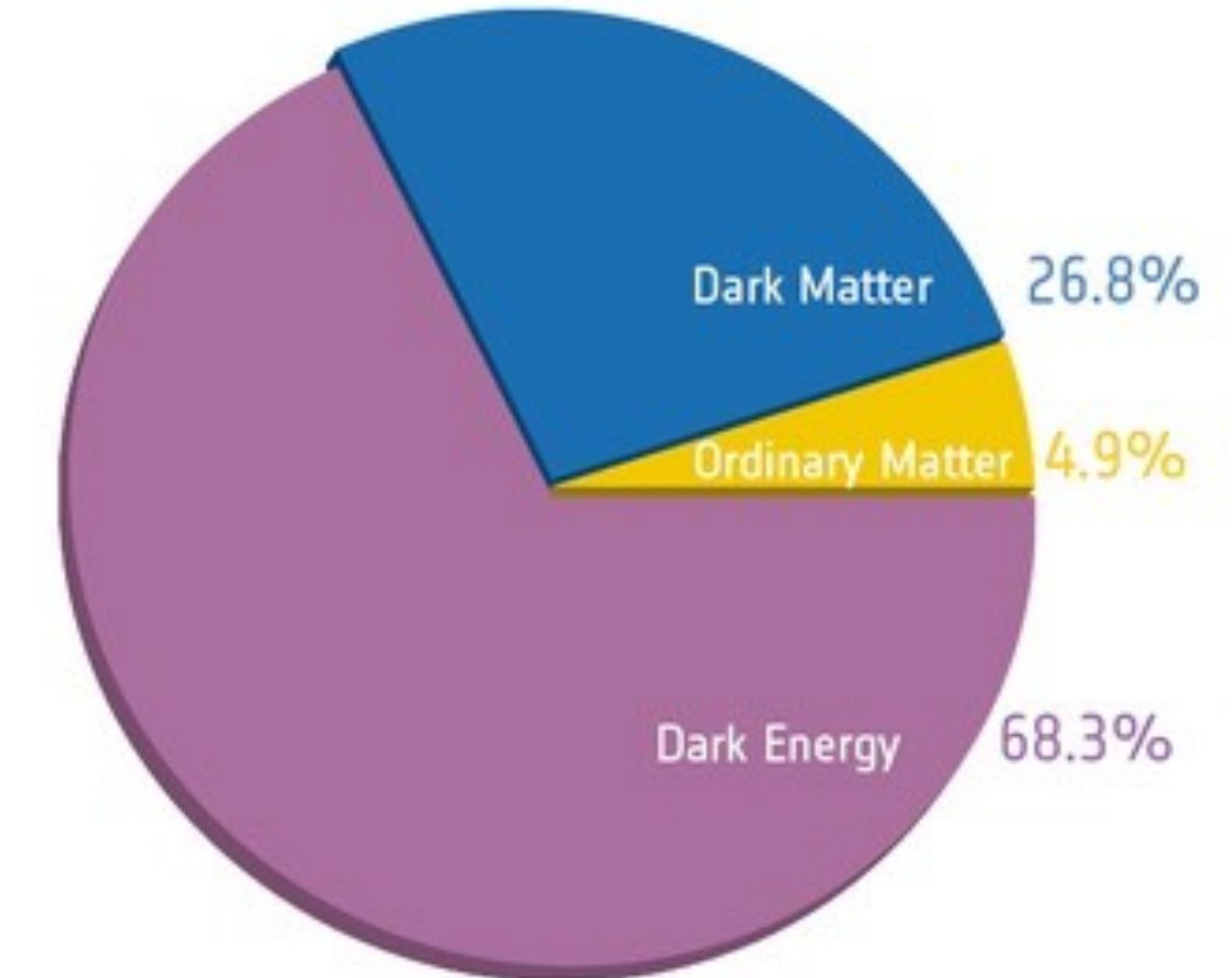
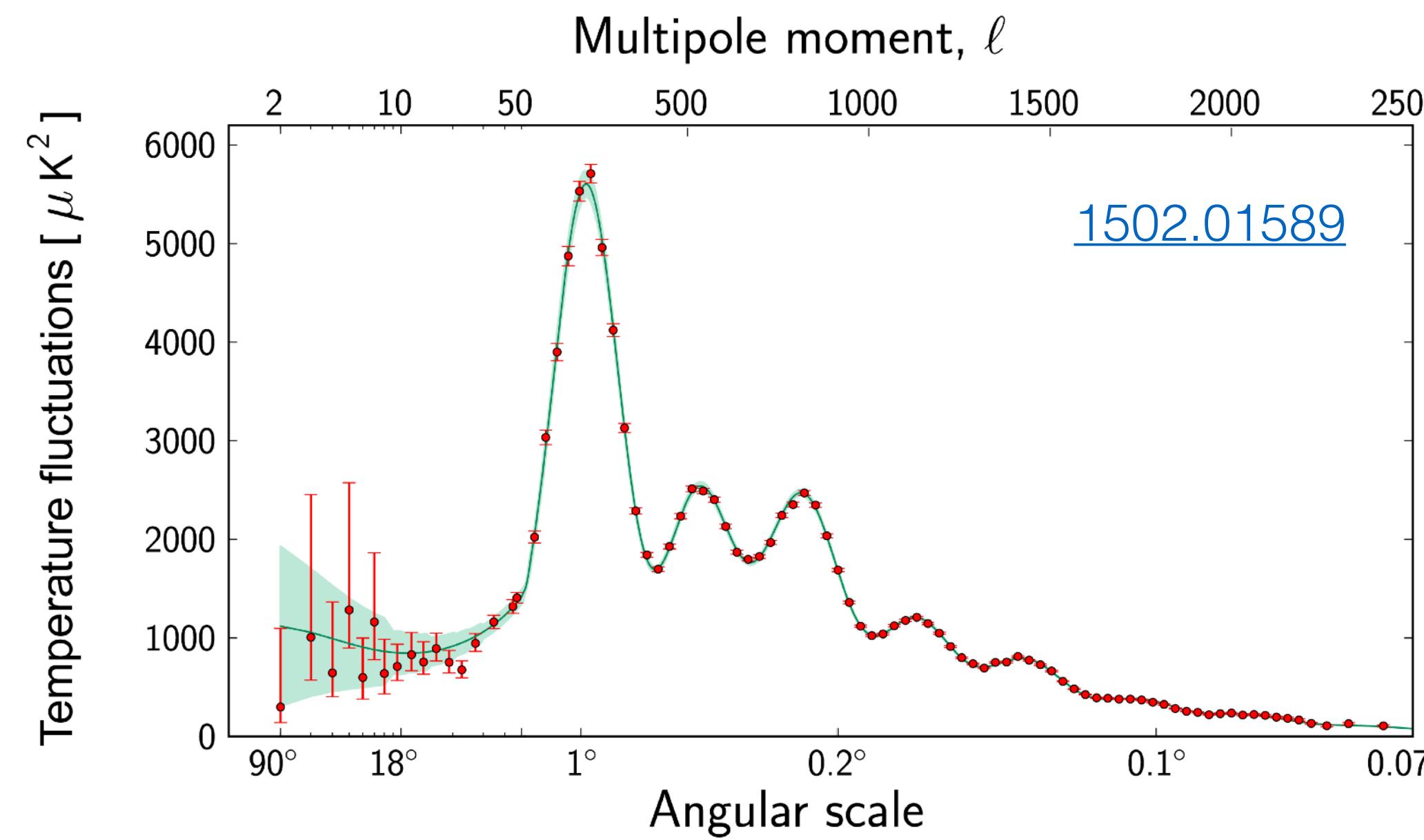
[Domènech, [2109.01398](#)]

...and other possibilities...

# Dark Matter in Cosmology



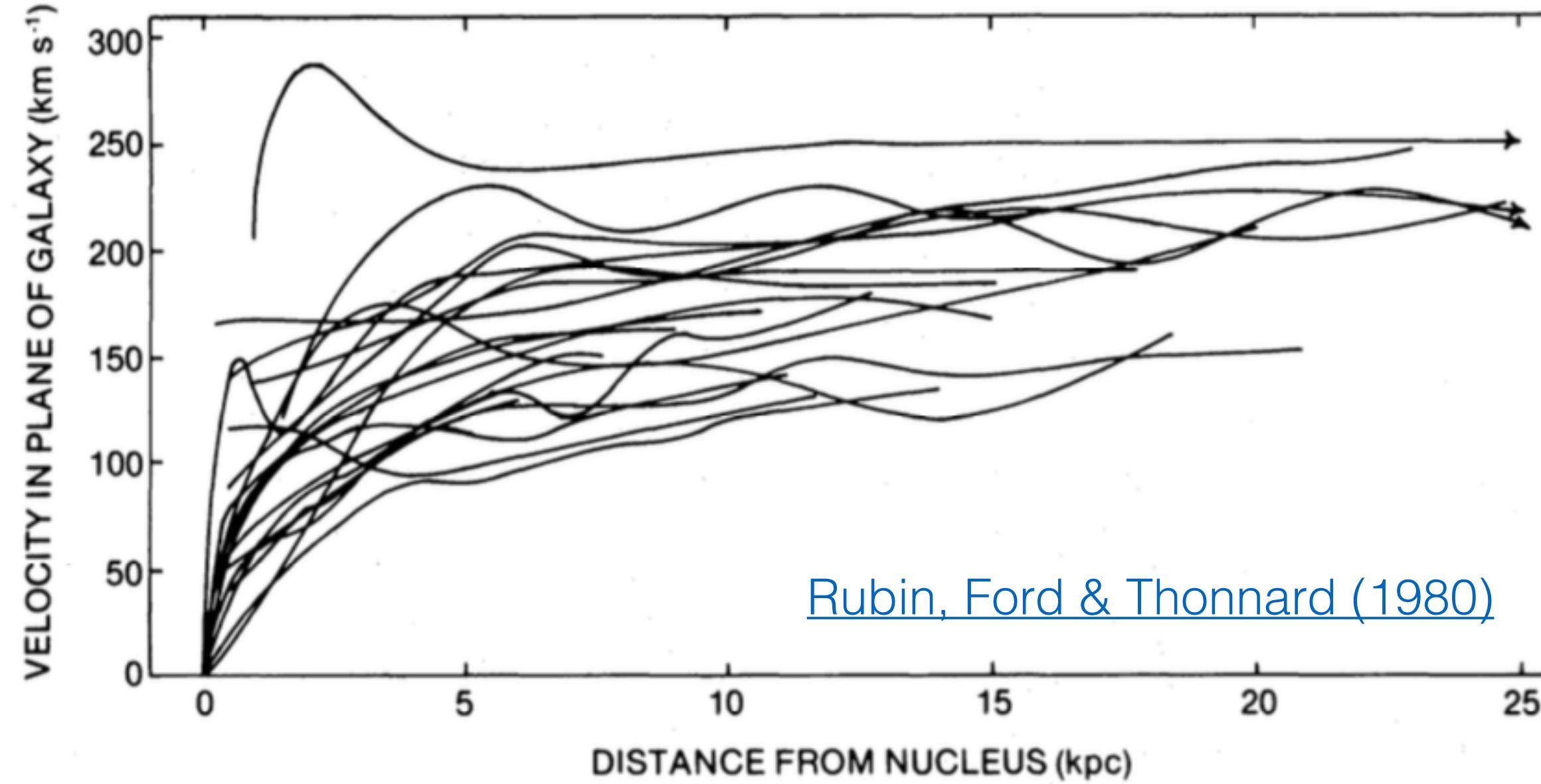
Cosmic Microwave Background (CMB)



See "[Introduction to Cosmology](#)" Lectures by Daniel Baumann

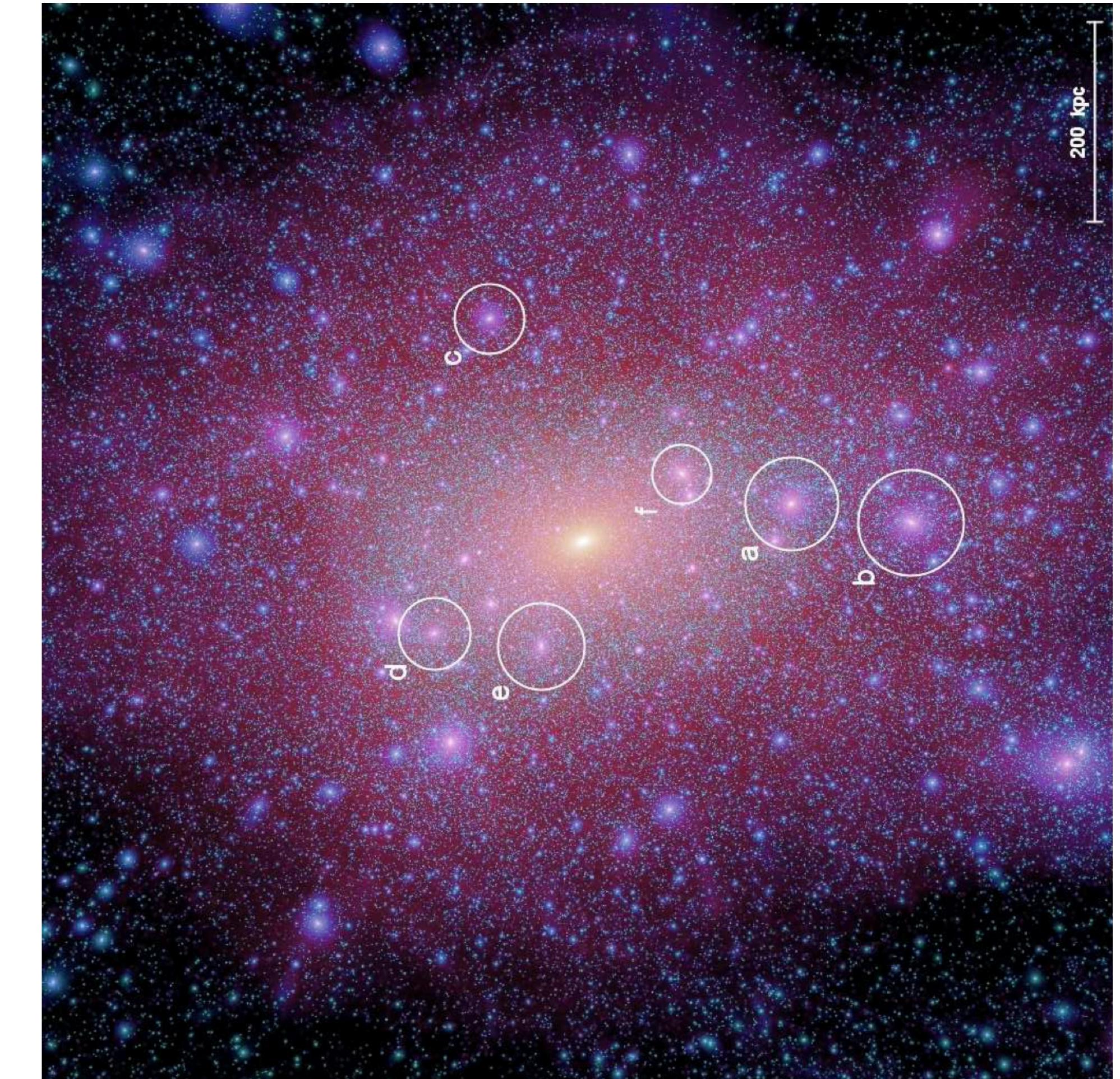
# Dark Matter in Galaxies

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



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

[1404.1938](#)

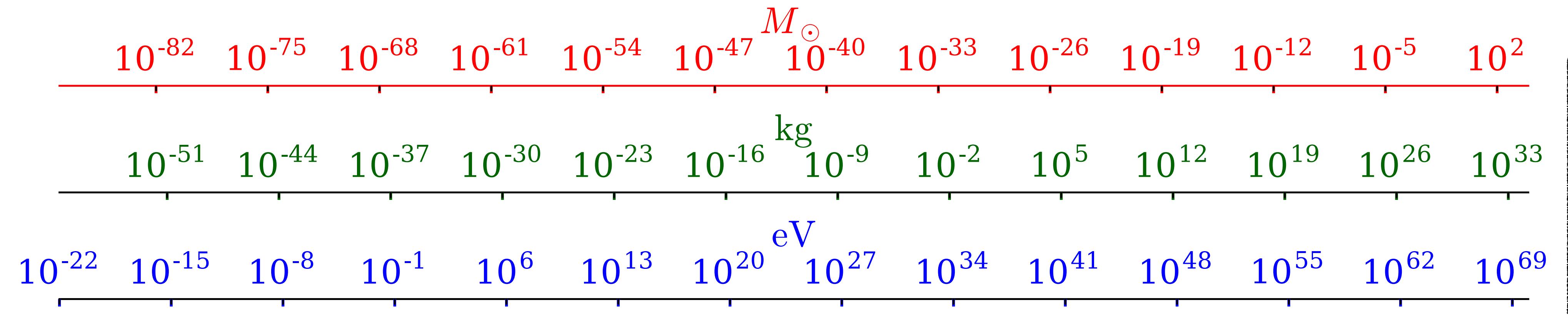


Aquarius simulation - [0809.0898](#)

# 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!

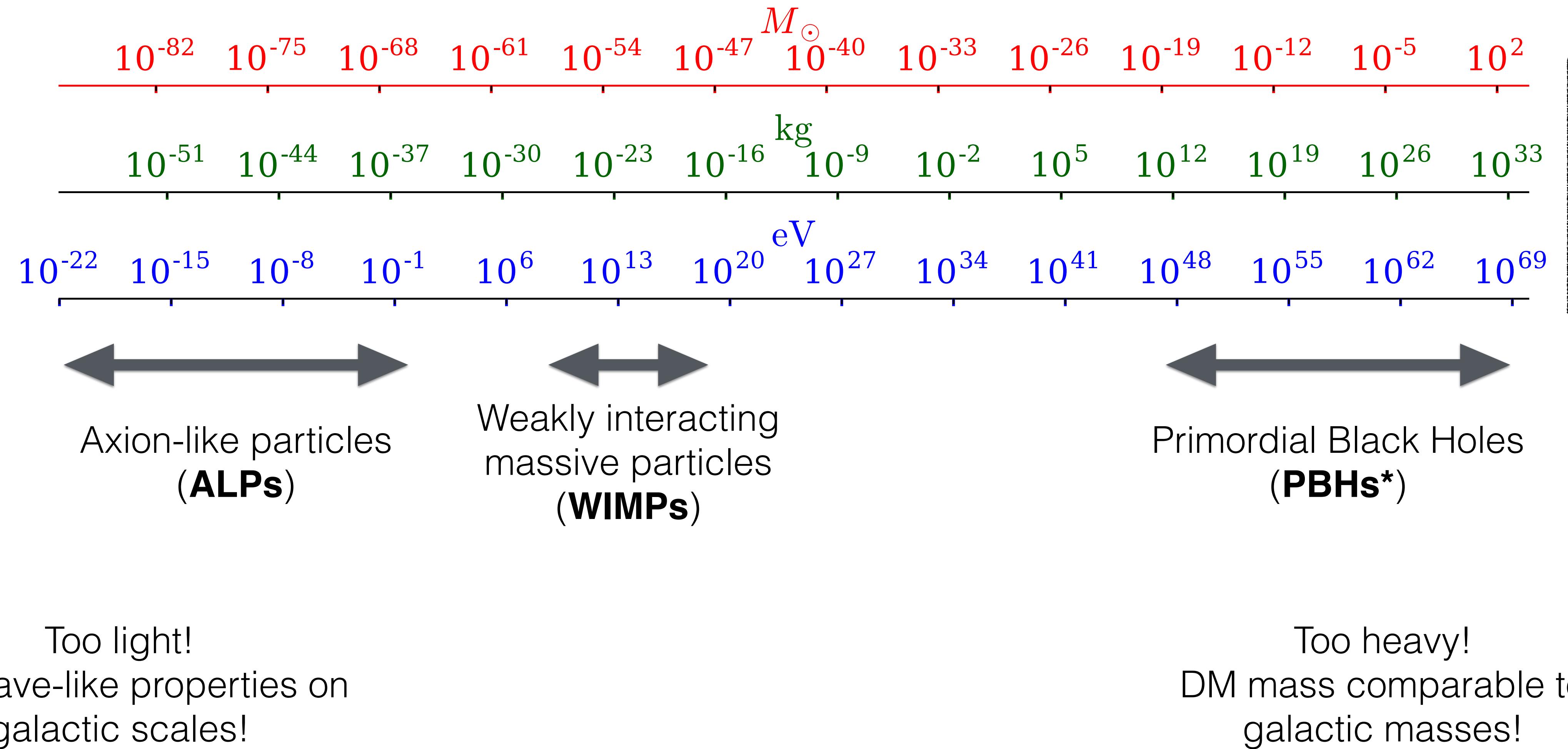
DM mass comparable to  
galactic masses!

\*See additional slides...

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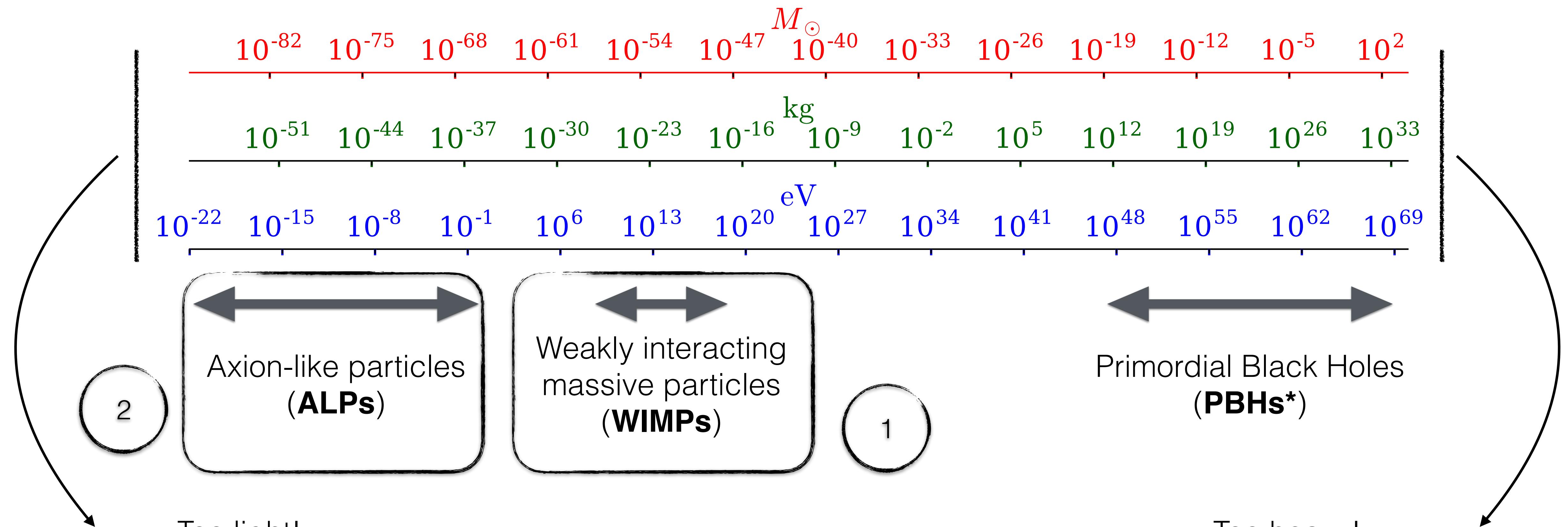


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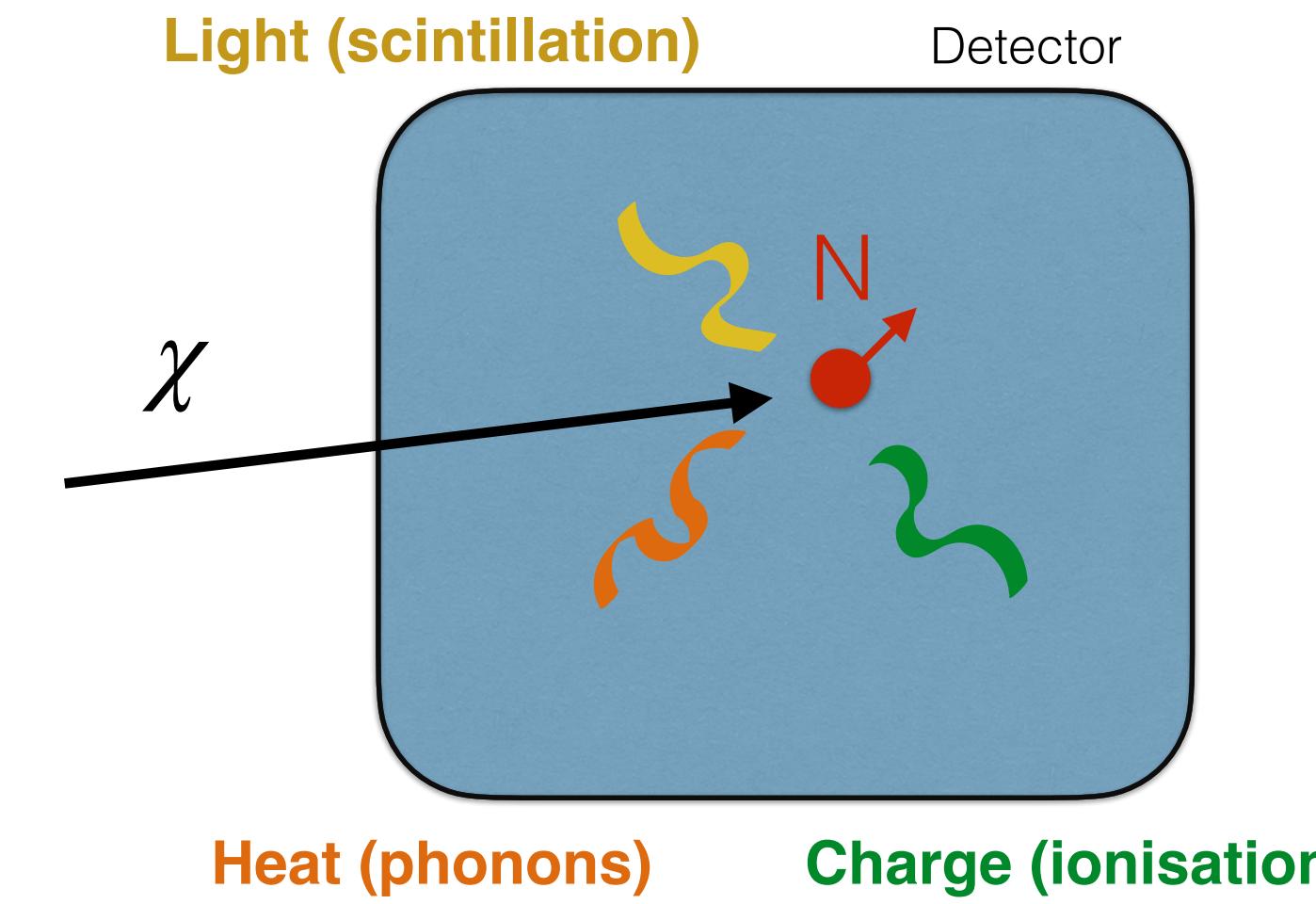
Too light!  
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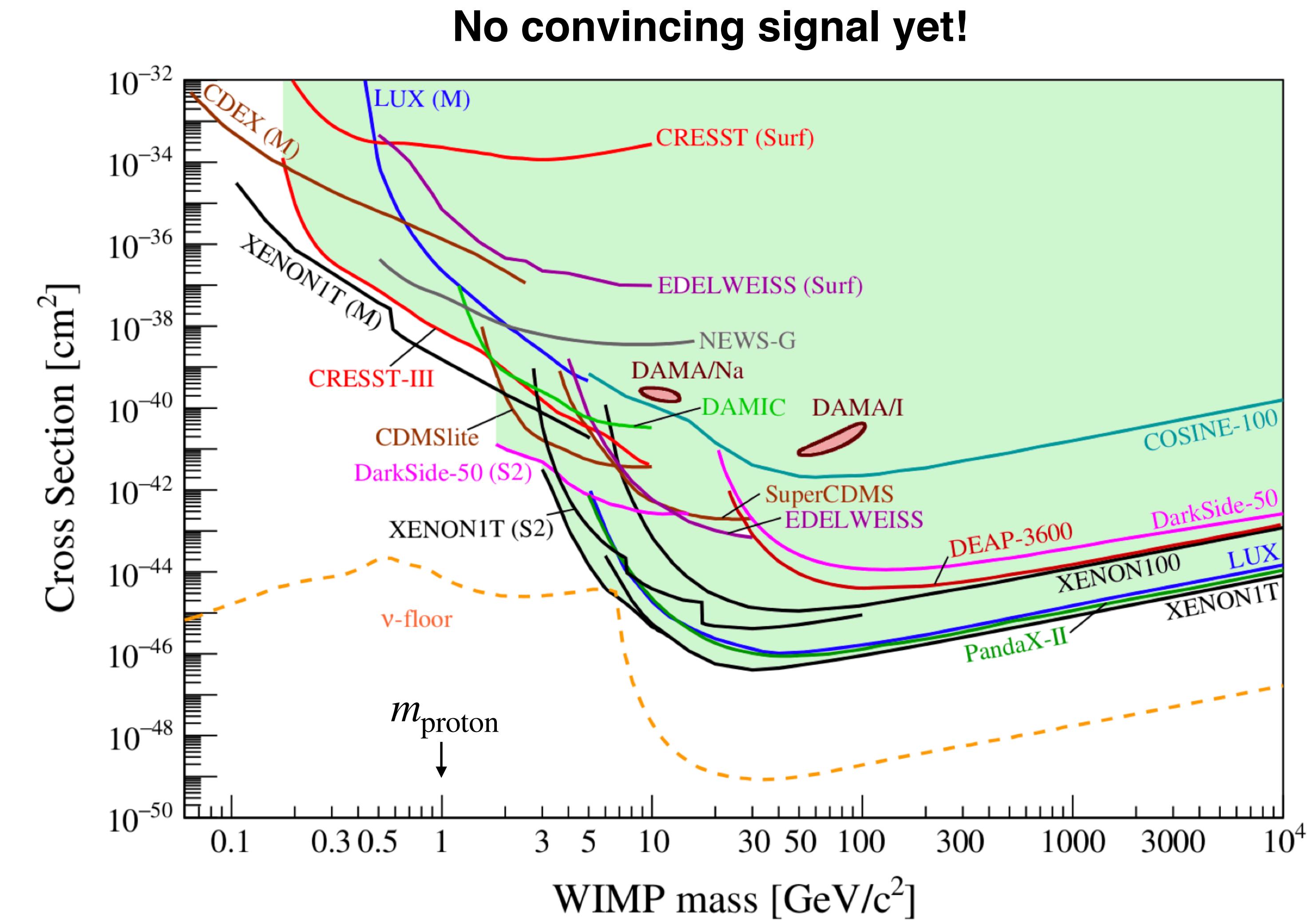
\*See additional slides...

# Direct detection of WIMPs on Earth

For WIMPs with GeV-scale masses,  
expect detectable nuclear recoils of  
energy  $O(\text{keV})$



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

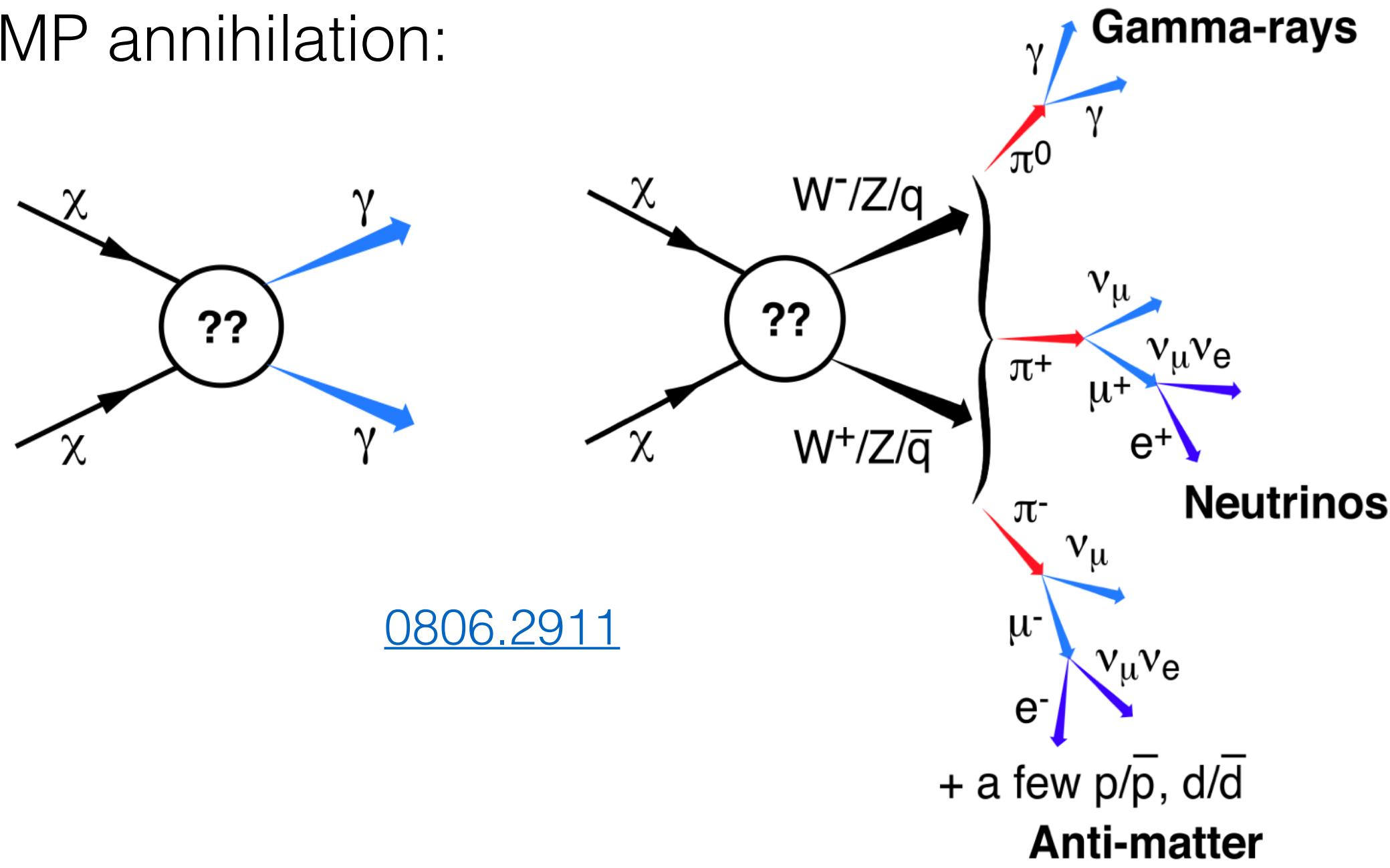


Also possible to look for DM-electron scattering, depending on the model.

# Indirect detection of Dark Matter

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

WIMP annihilation:

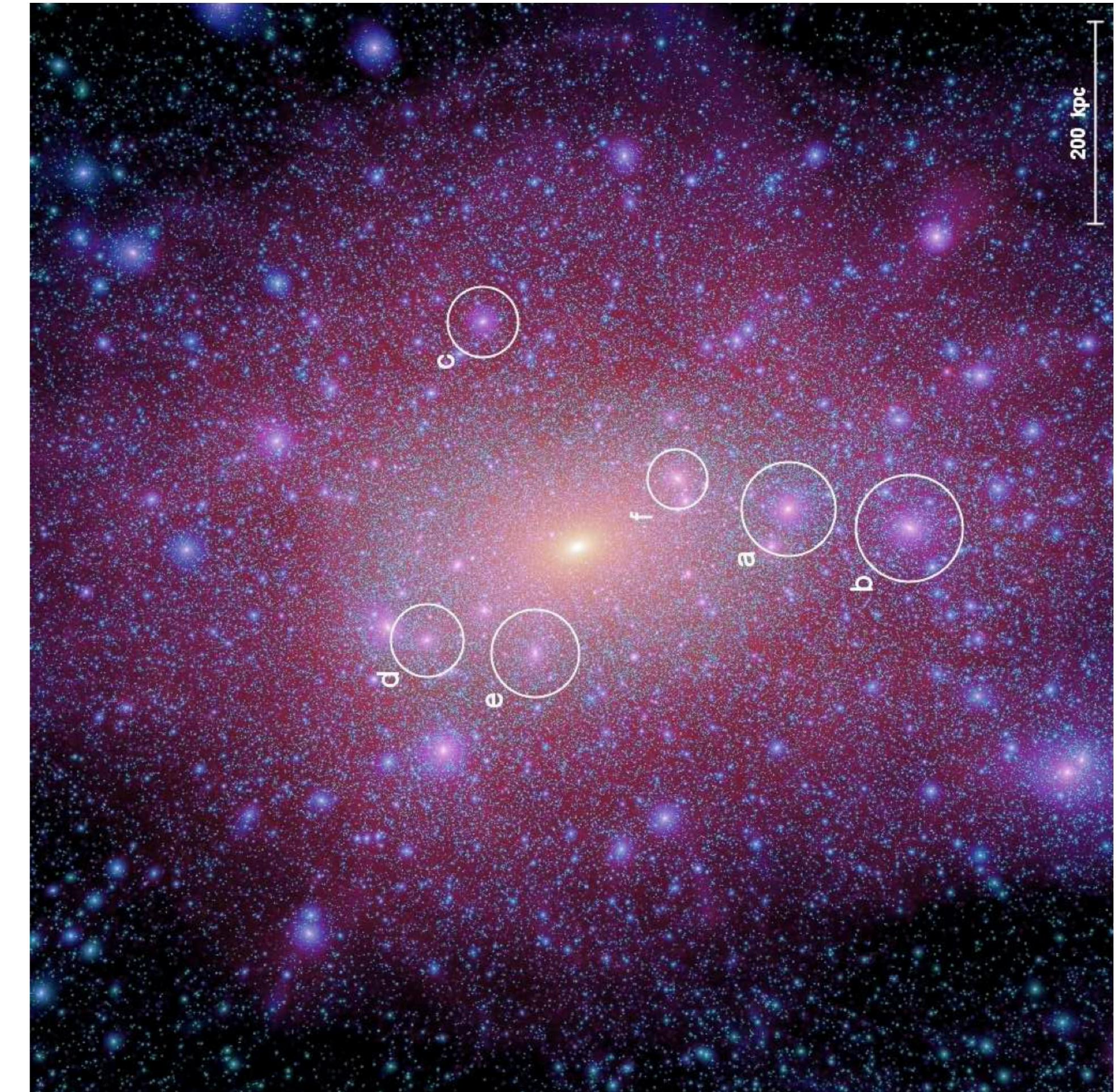


Annihilation cross section  
(particle physics)

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

[1012.4515](#)

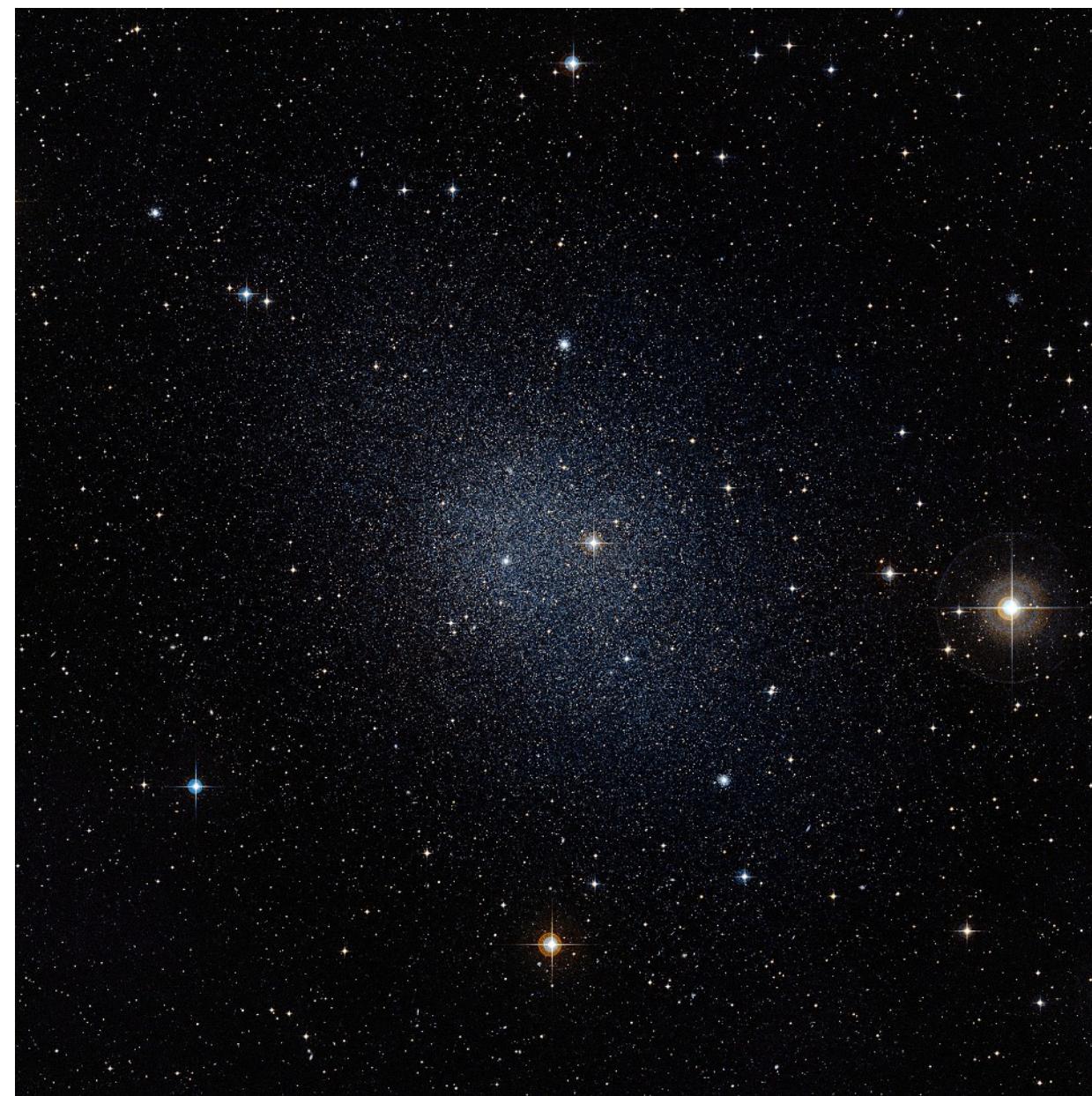
Gamma-ray spectrum  
(annihilation channel)



Aquarius simulation - [0809.0898](#)

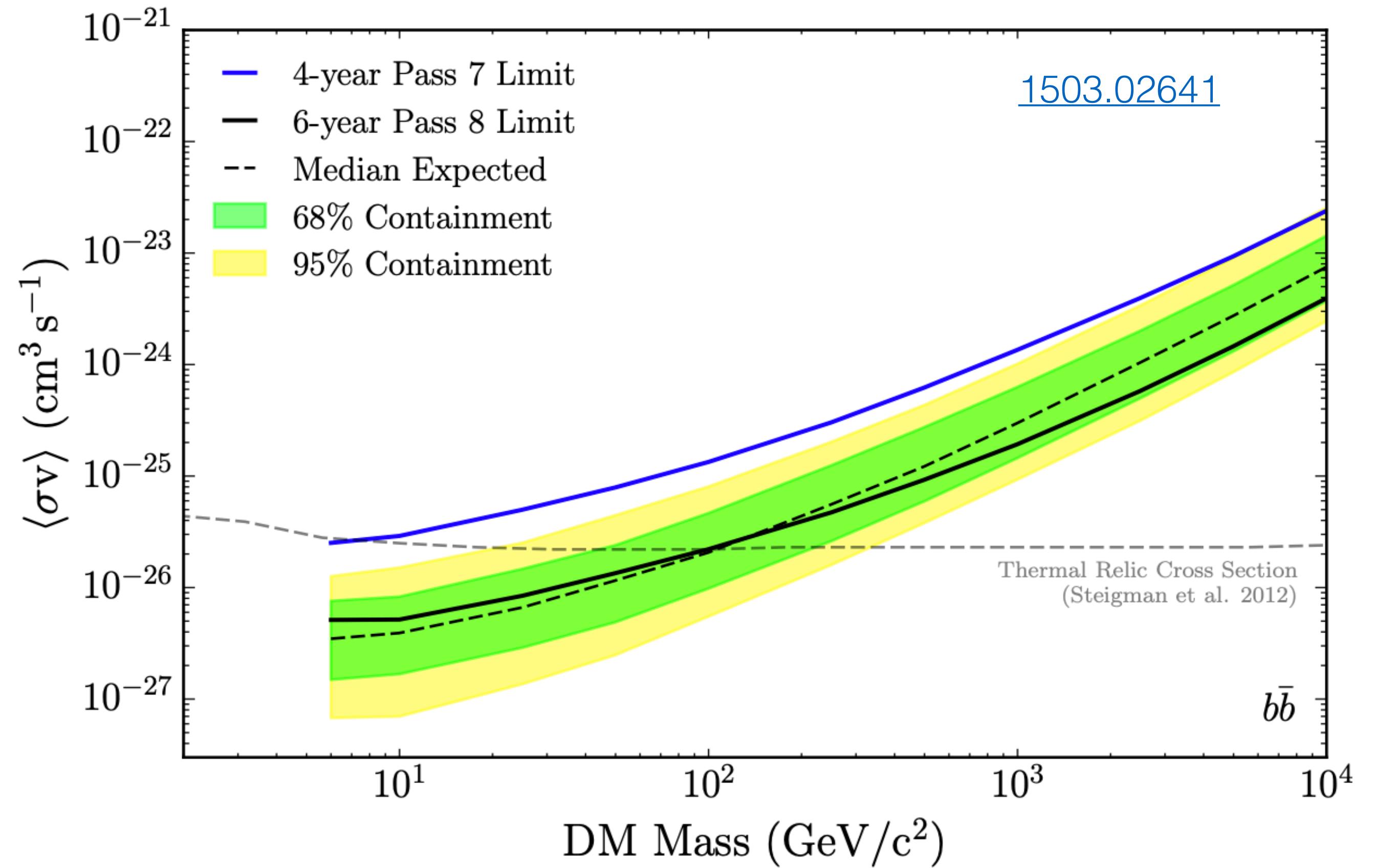
# Gamma-ray constraints

Fornax Dwarf Galaxy  
(Satellite of the Milky Way)



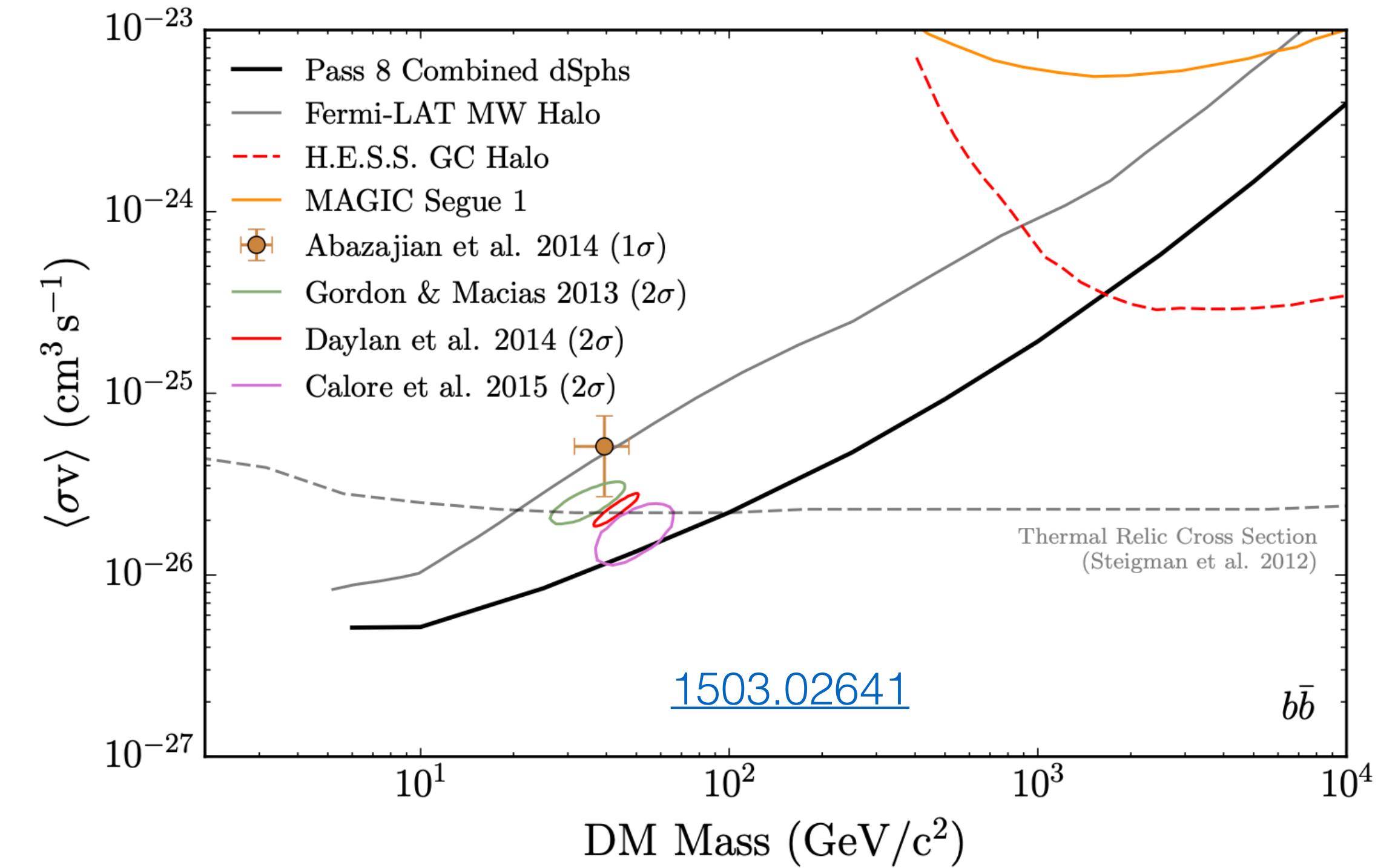
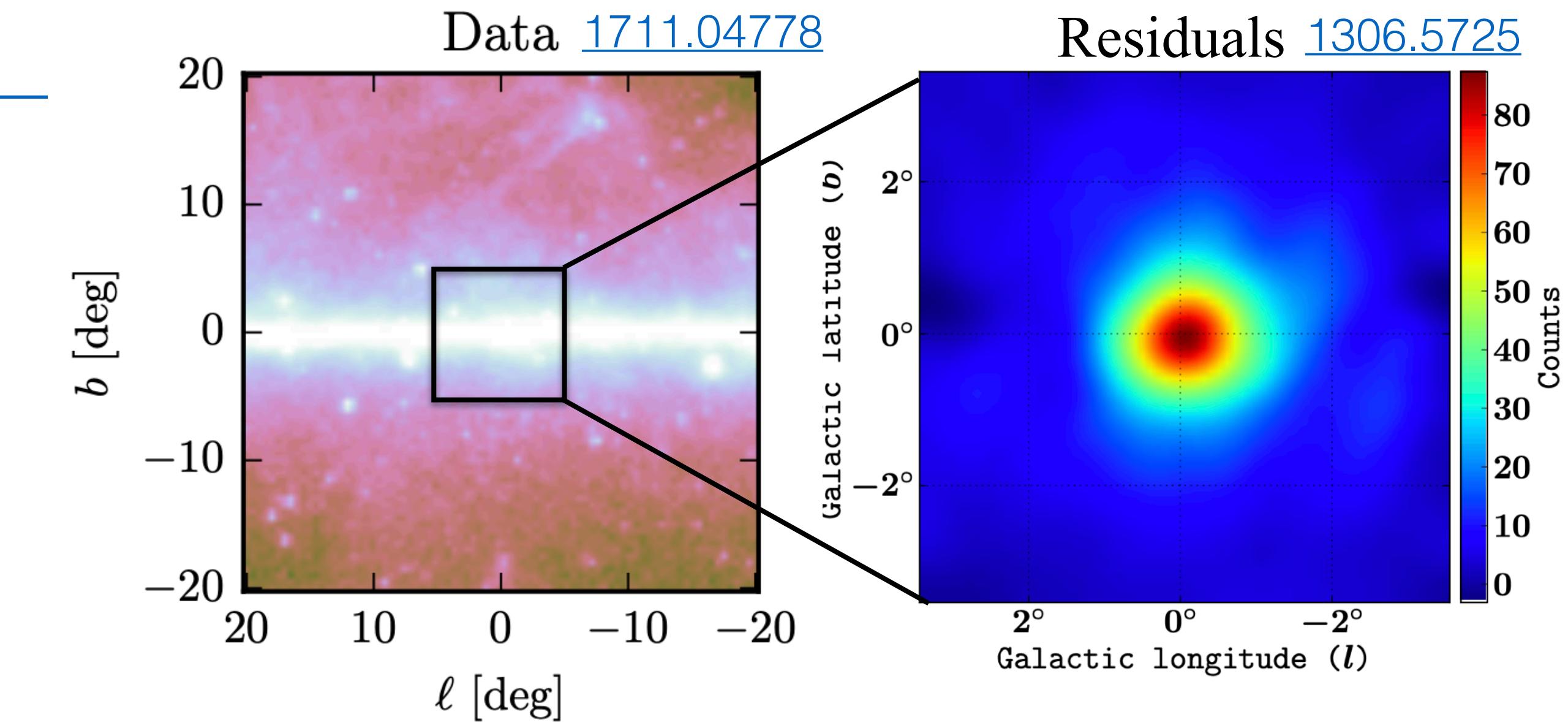
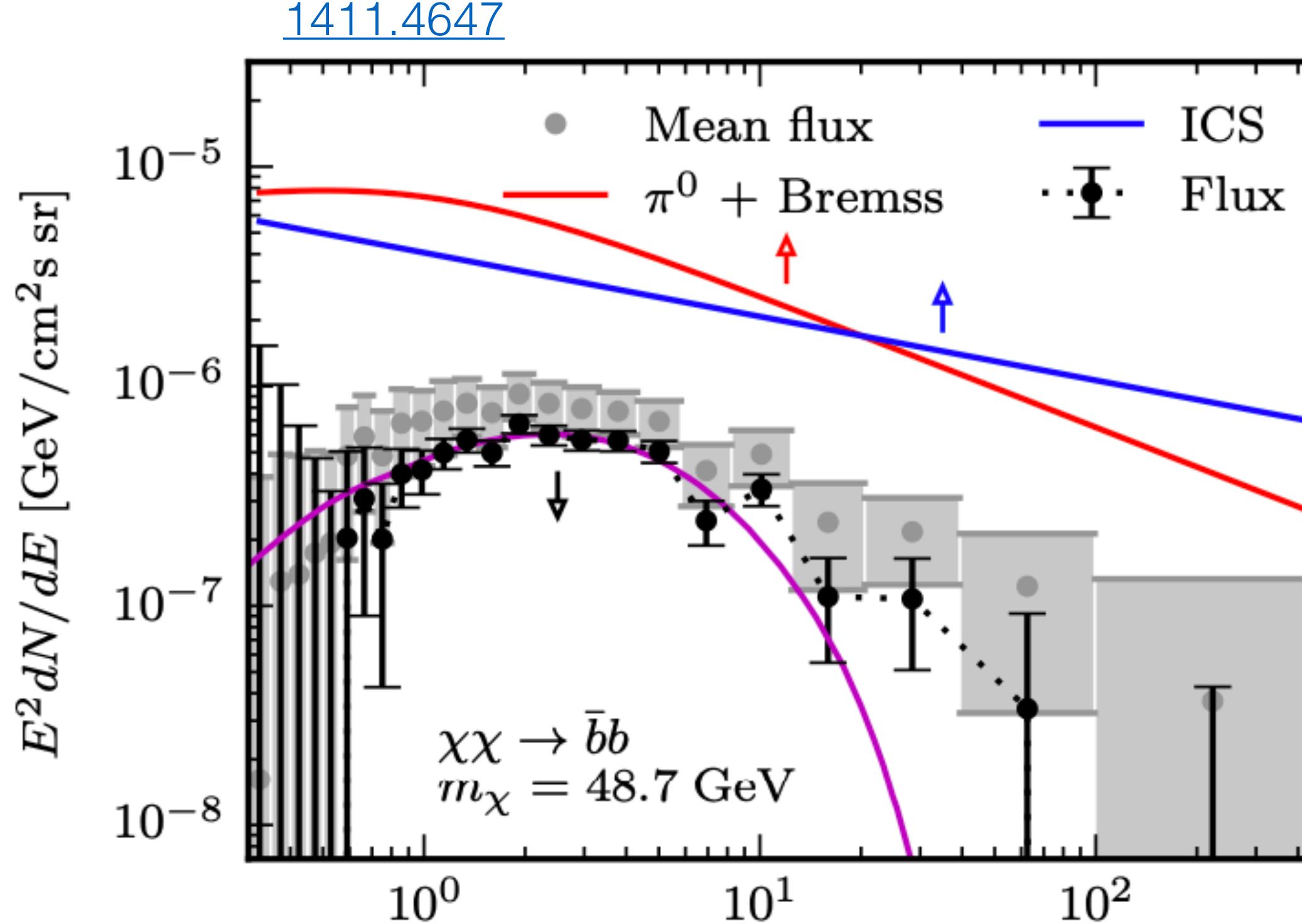
Credit: ESO/Digitized Sky Survey 2

Fermi constraints from 15 Dwarf Spheroidal Galaxies:



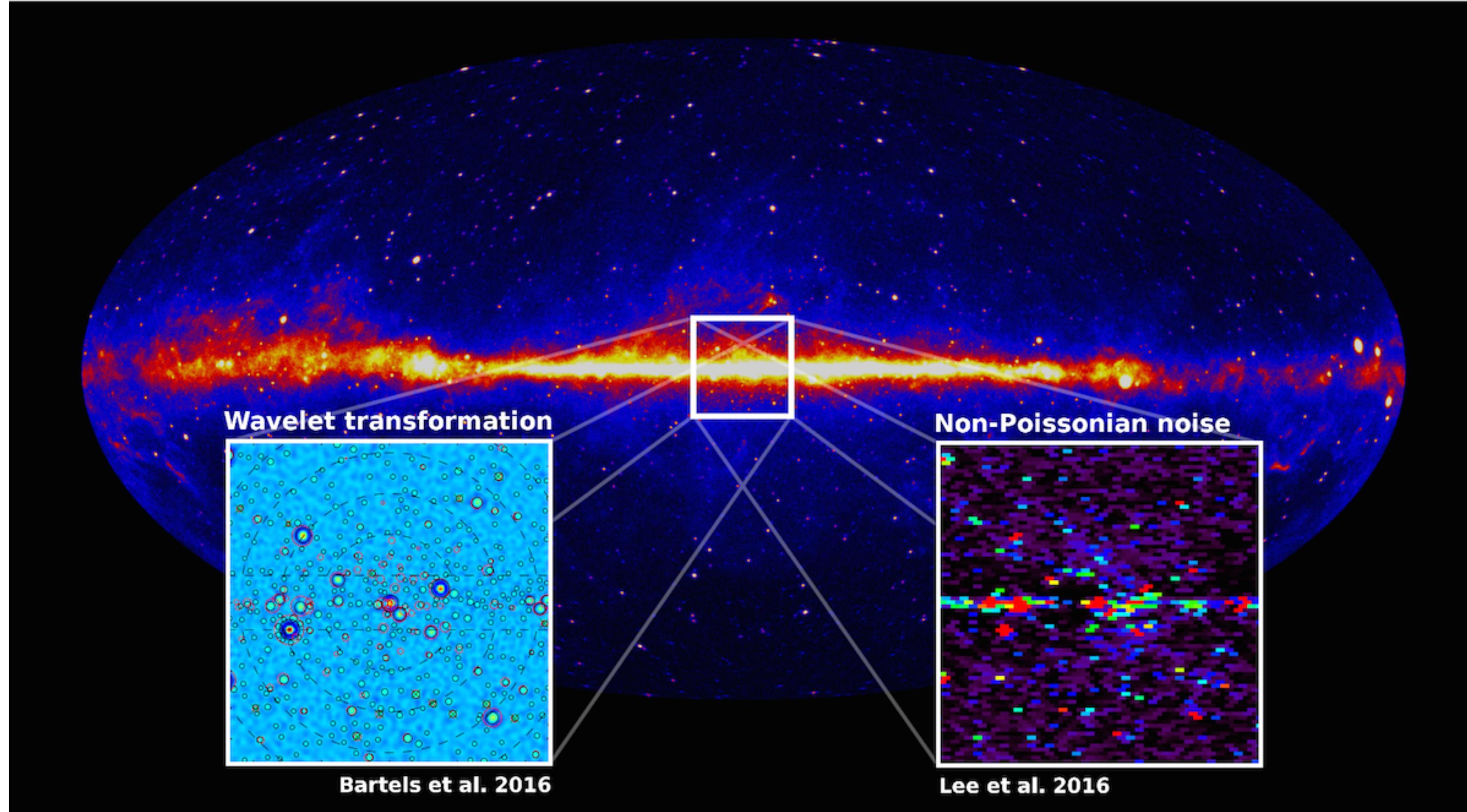
Exact constraints depend on annihilation channel ( $\chi\chi \rightarrow b\bar{b}, \chi\chi \rightarrow W^+W^-, \chi\chi \rightarrow e^+e^-$ , etc.)

# Galactic Centre Excess

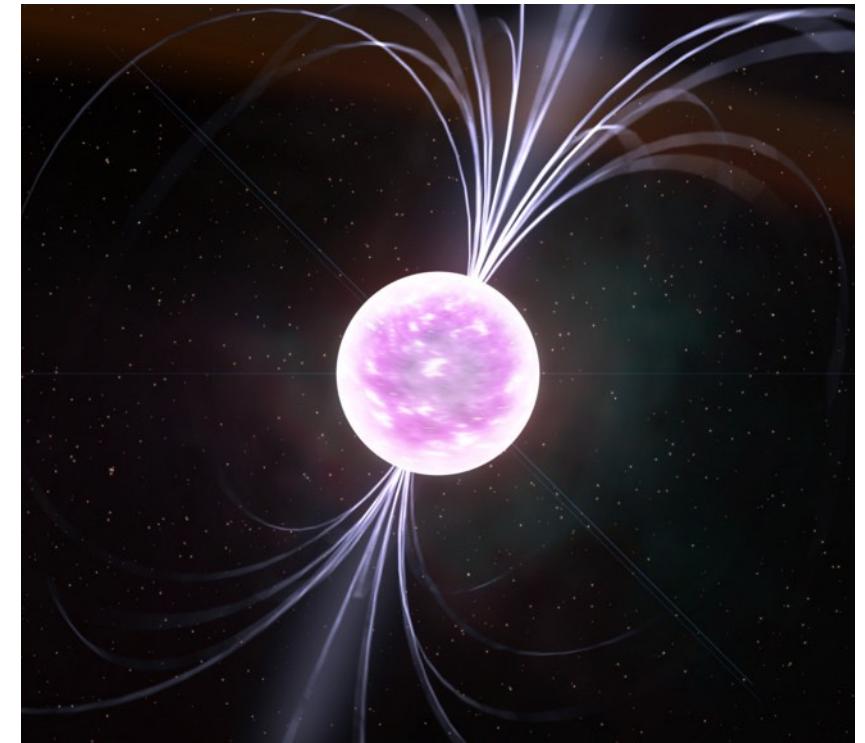


# Point sources in the Galactic Centre

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



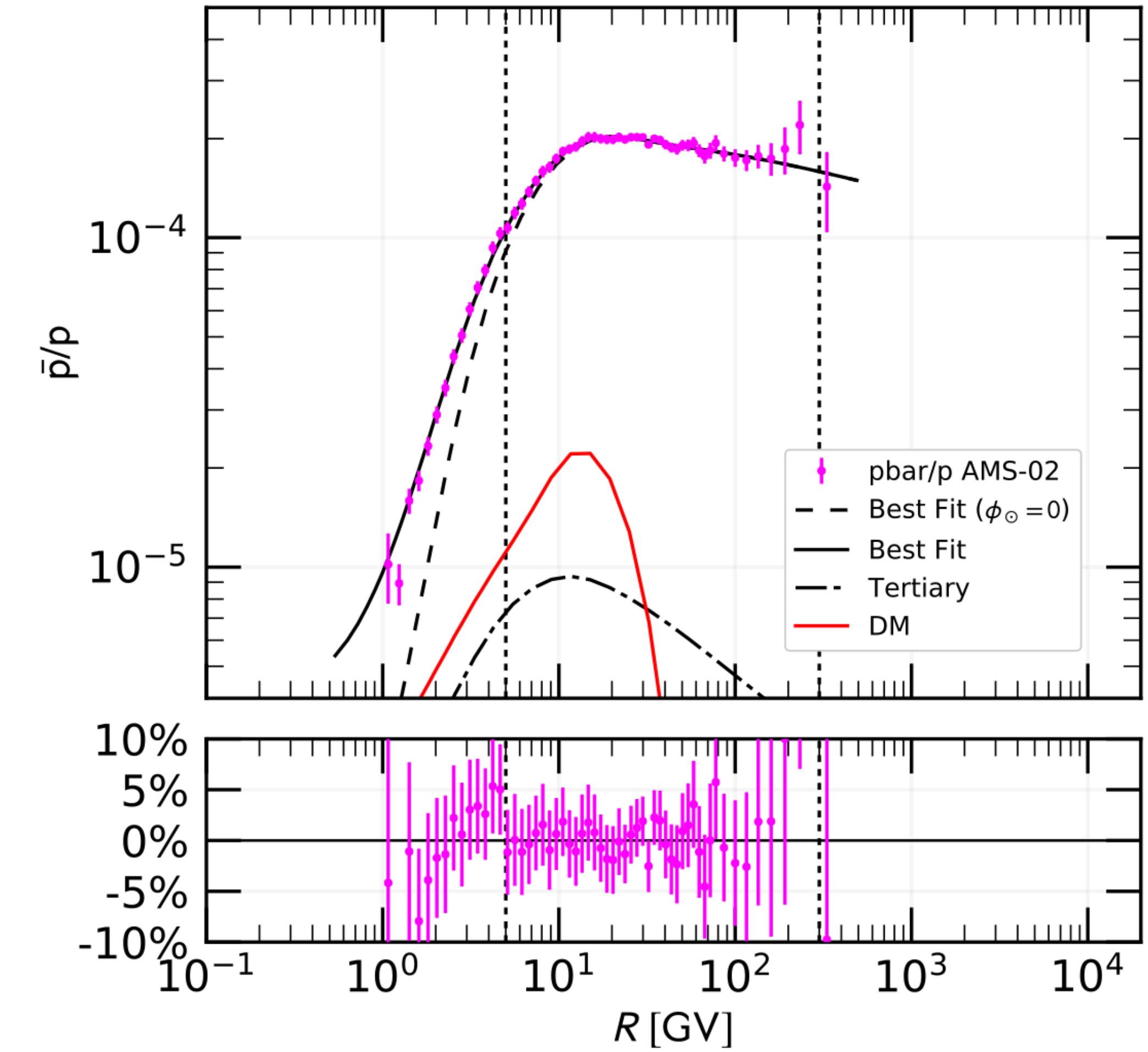
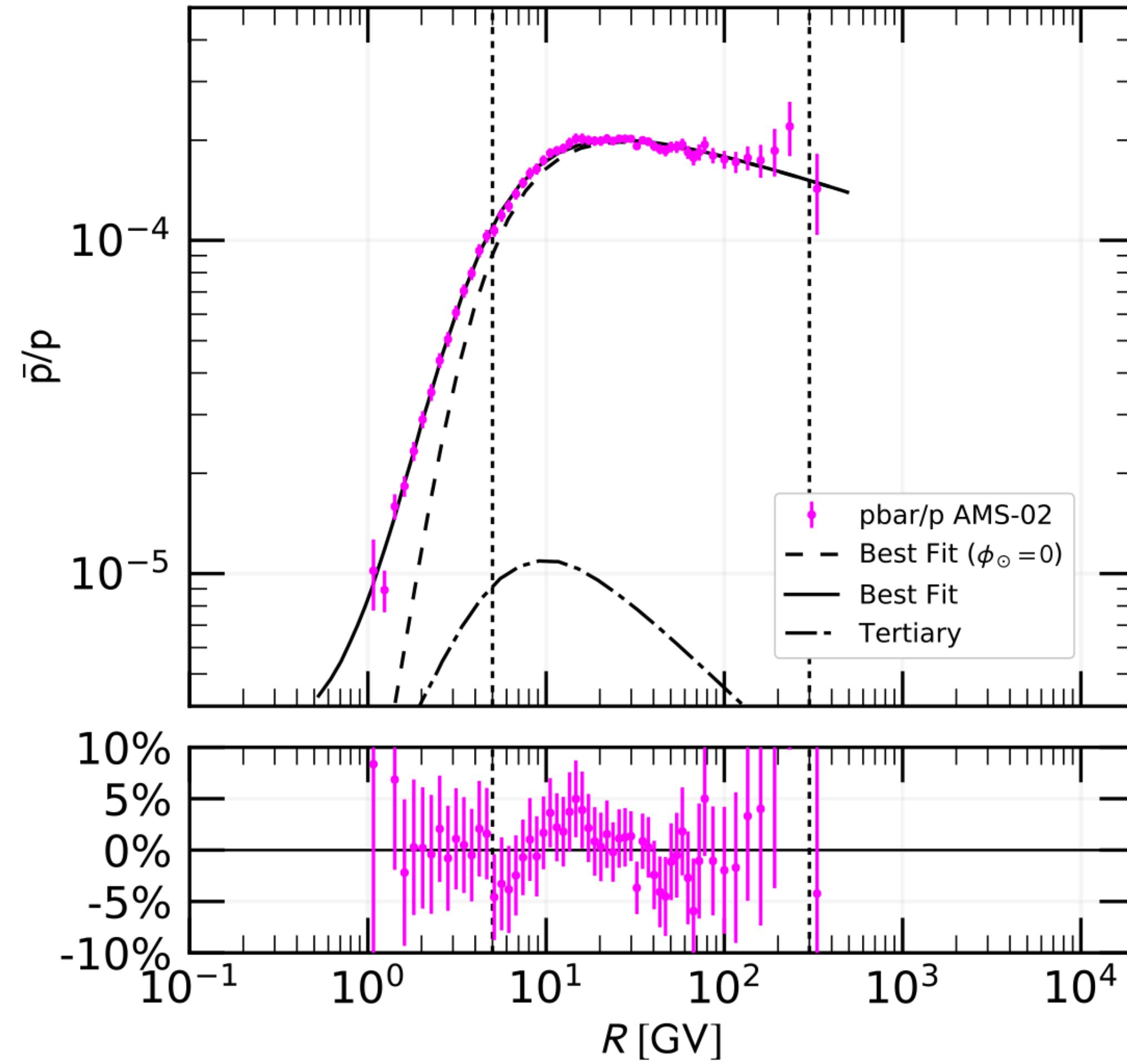
Credit: Christoph Weniger, UvA , © UvA/Princeton



Credit: Kevin Gill / Flickr

# Anti-proton excess

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



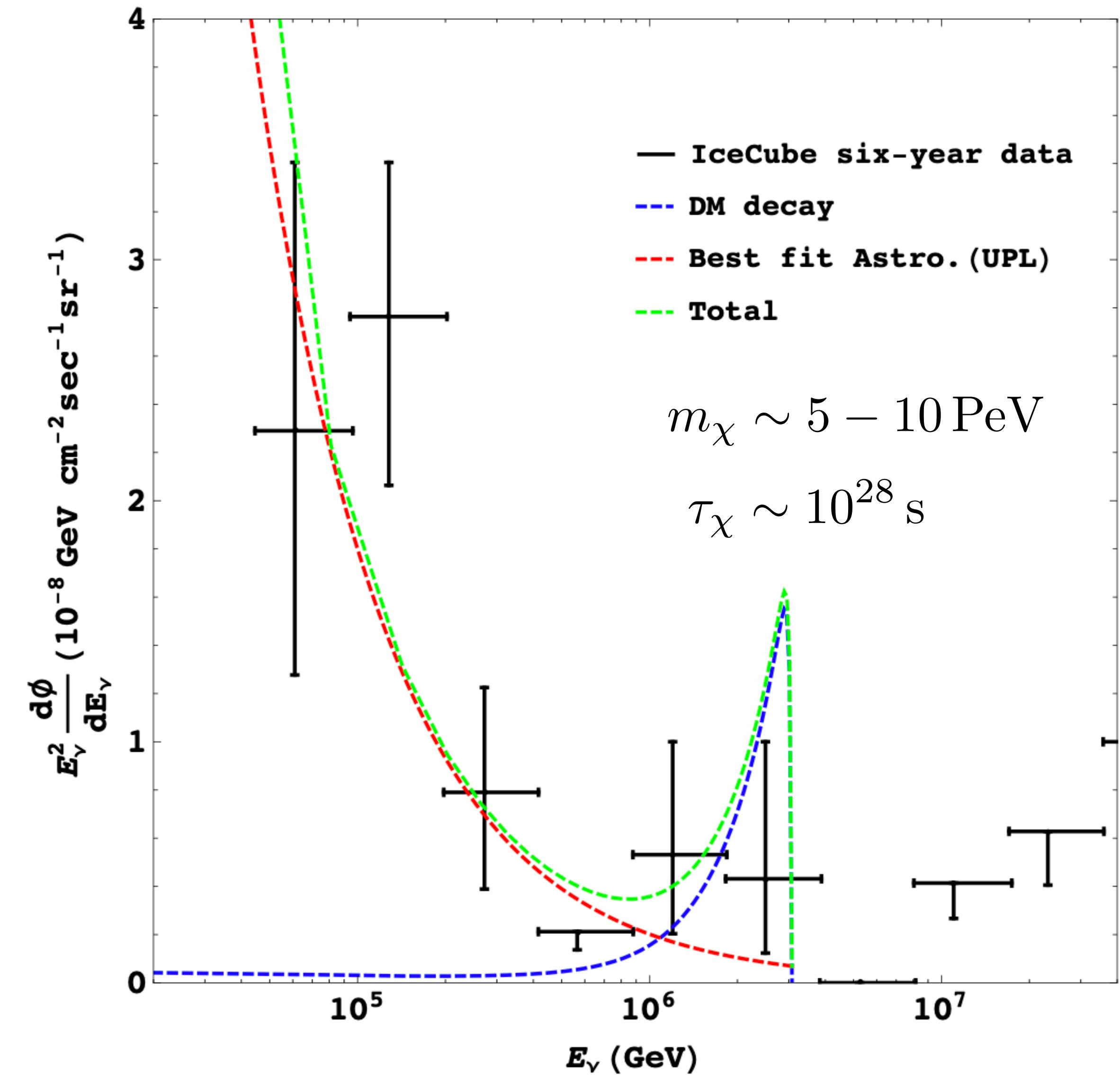
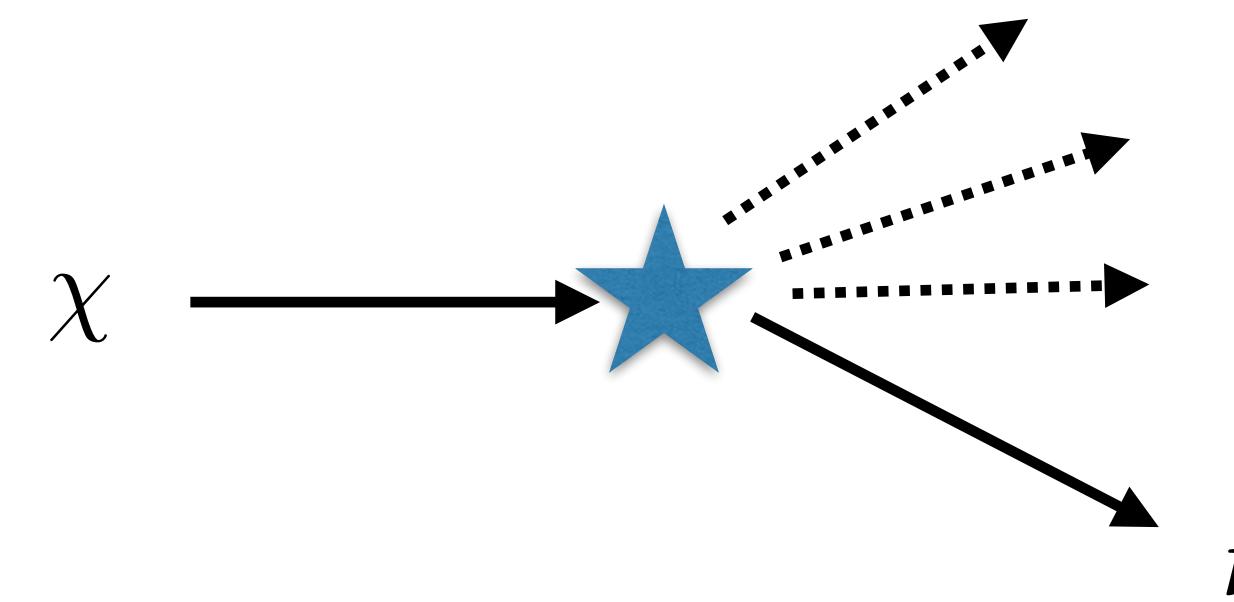
Several excesses point towards 60 GeV Dark Matter -  
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

[1504.04276](https://arxiv.org/abs/1504.04276), [1610.03071](https://arxiv.org/abs/1610.03071), [1903.01472](https://arxiv.org/abs/1903.01472)

# High energy neutrinos

[1508.02500](#), [1712.07138](#)

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

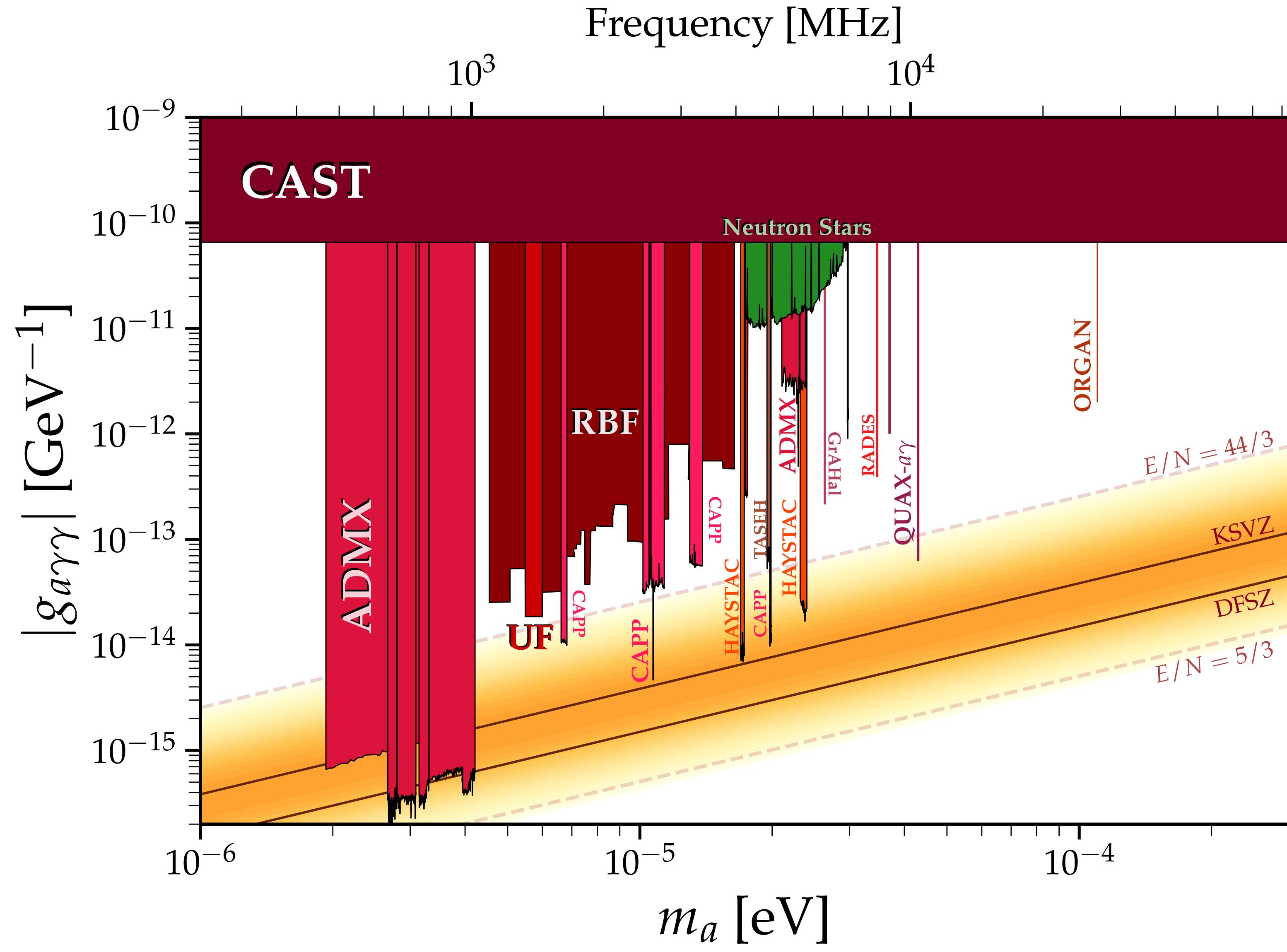
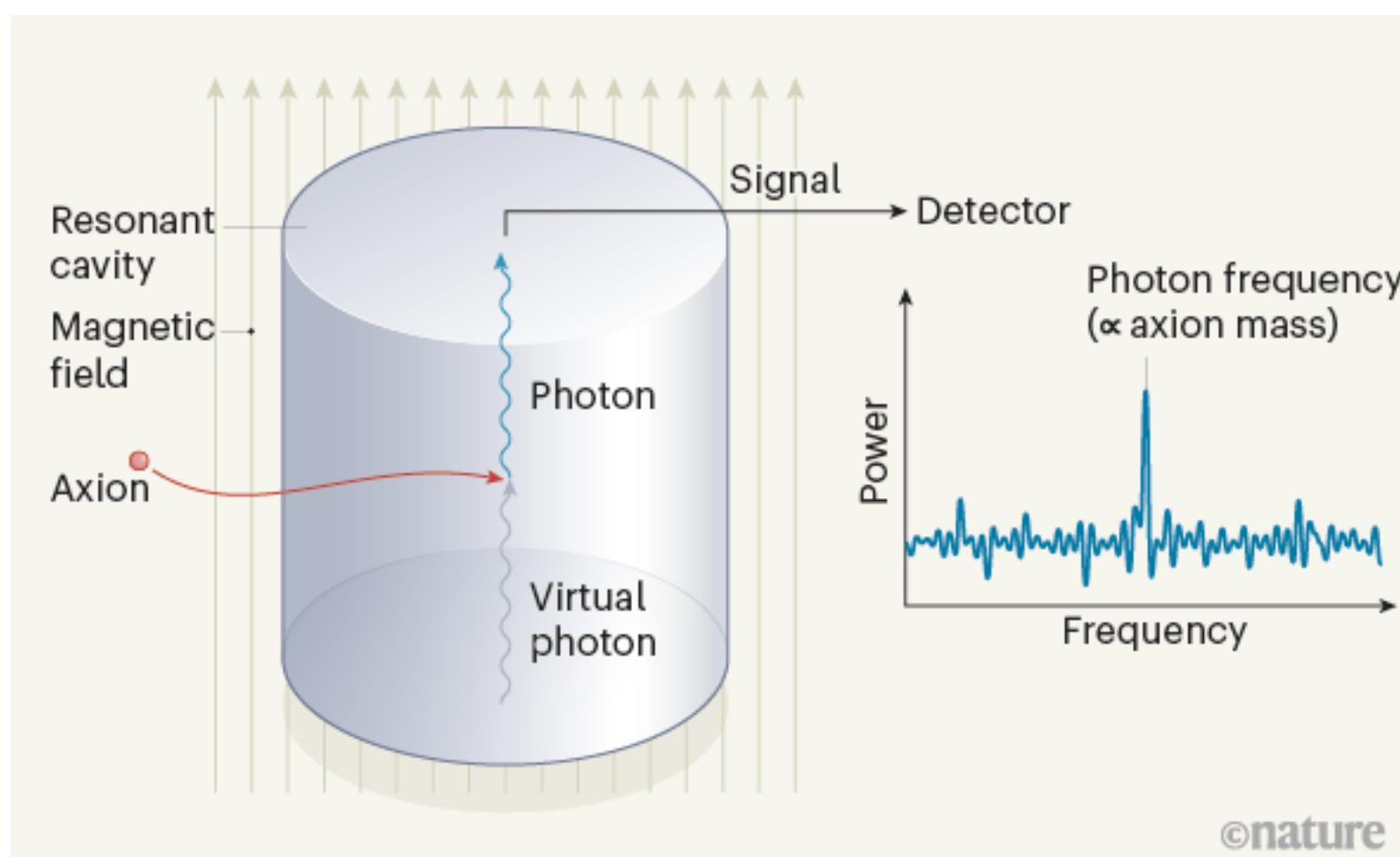
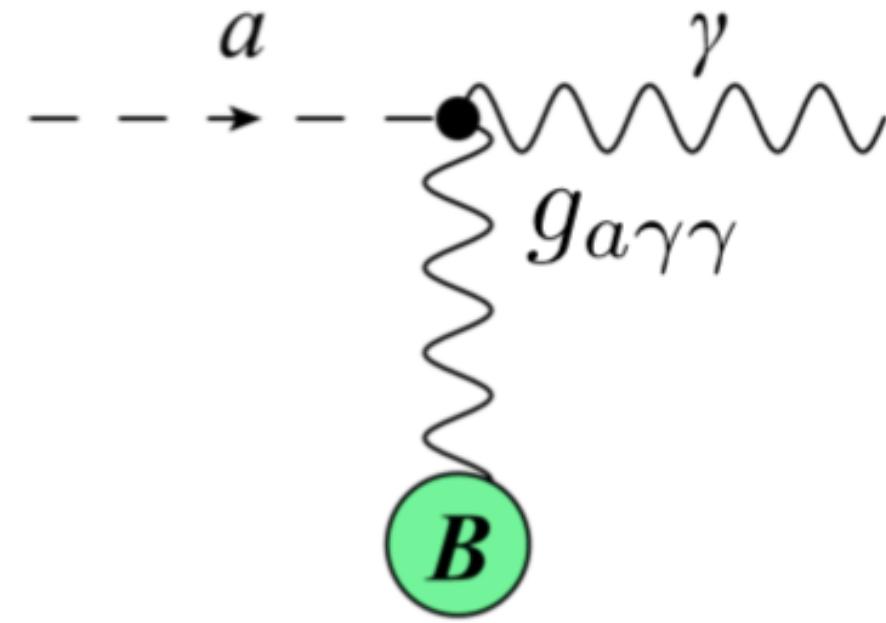


# Axion searches in the lab

**Axions:** light pseudoscalar particles,  $a$

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

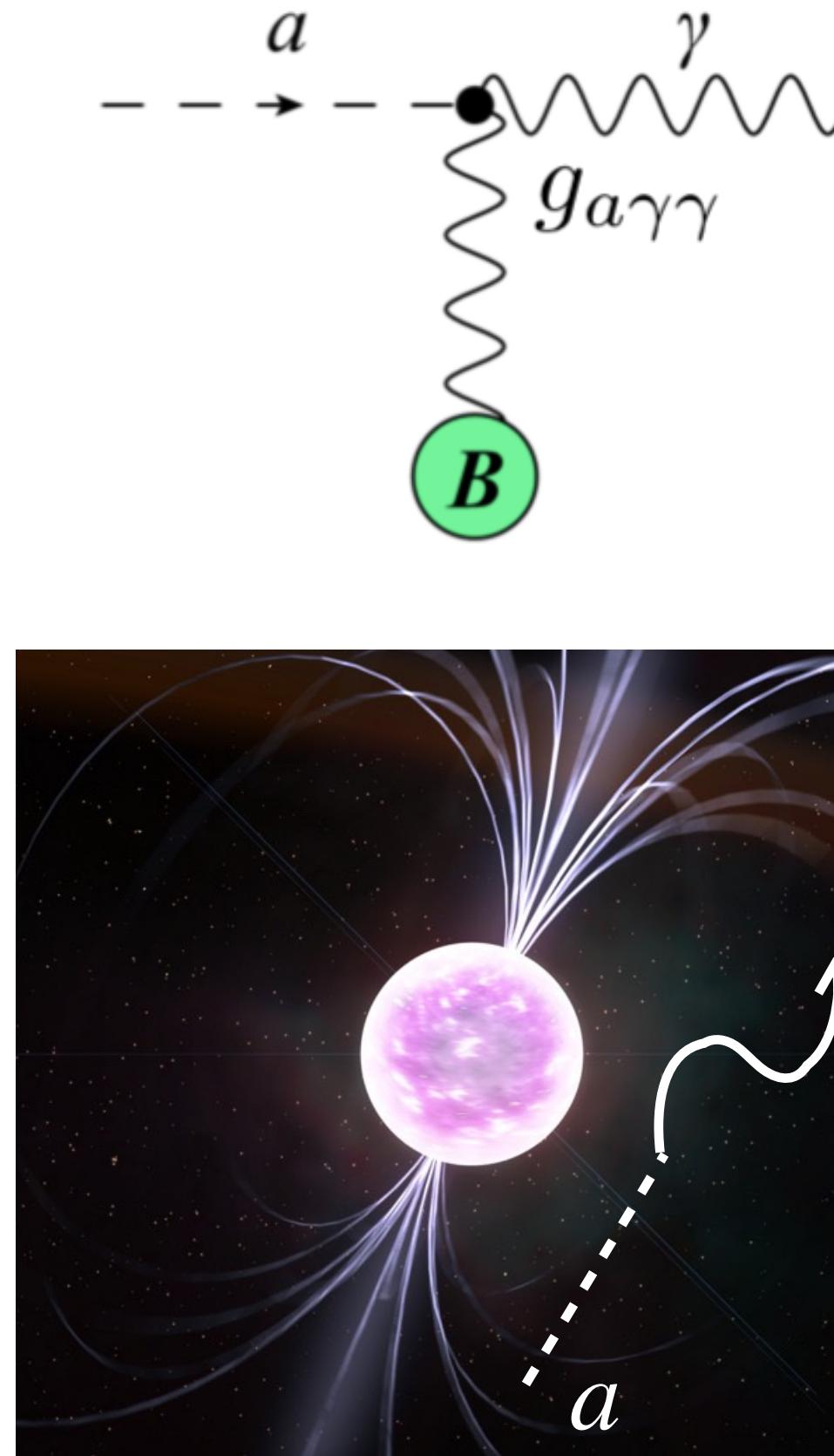
$$= -\frac{1}{4} g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



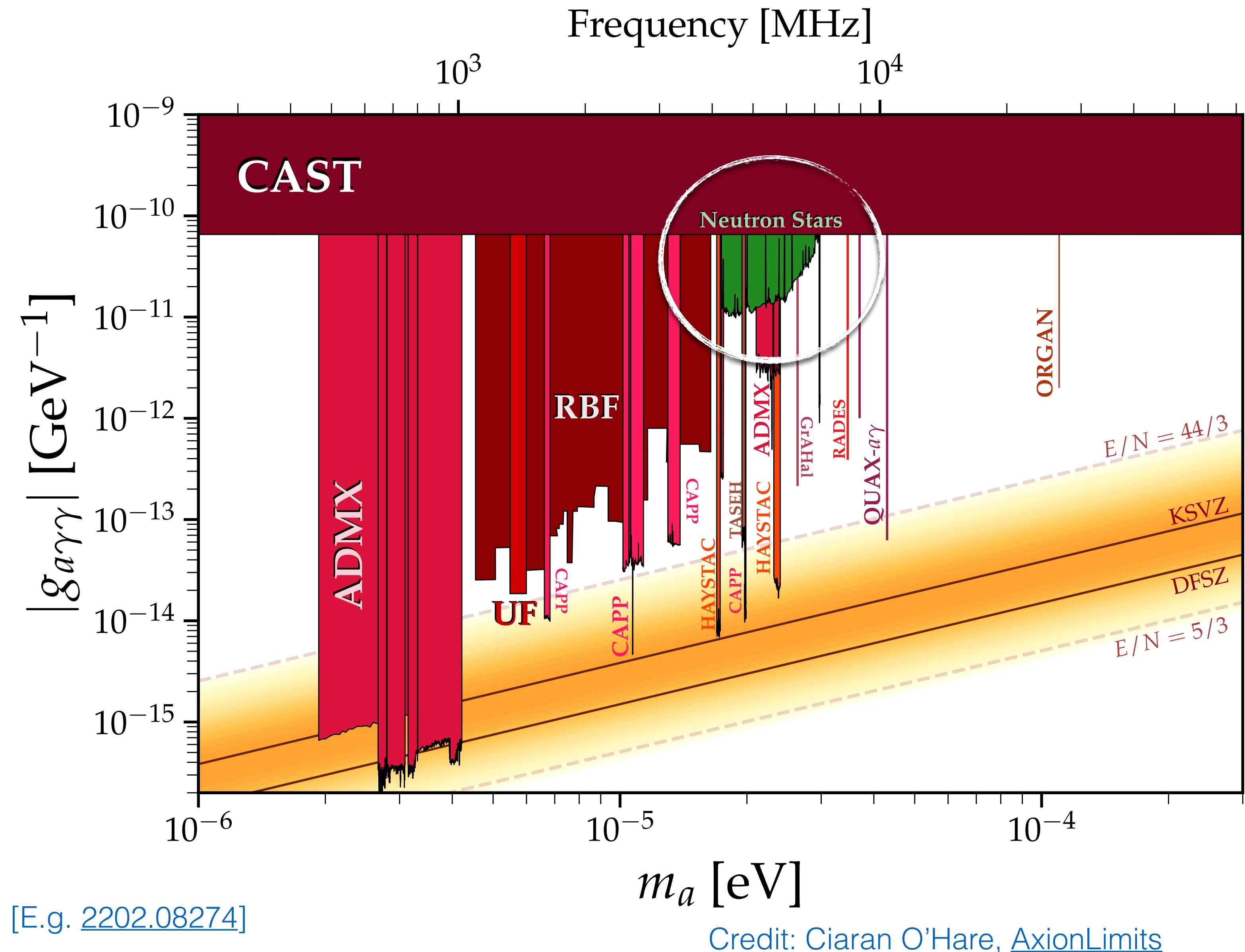
Credit: Ciaran O'Hare, [AxionLimits](#)

# Axion searches and Neutron Stars

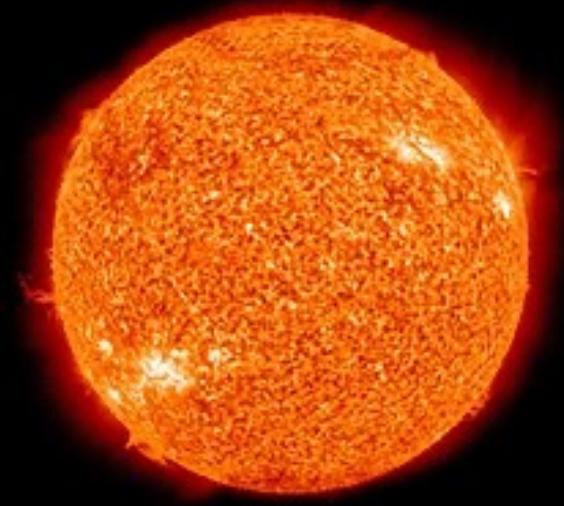
$$\begin{aligned}\mathcal{L} &\supset -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} \\ &= -\frac{1}{4}g_{a\gamma\gamma}a\mathbf{E} \cdot \mathbf{B}\end{aligned}$$



**Axions:** light pseudoscalar particles,  $a$

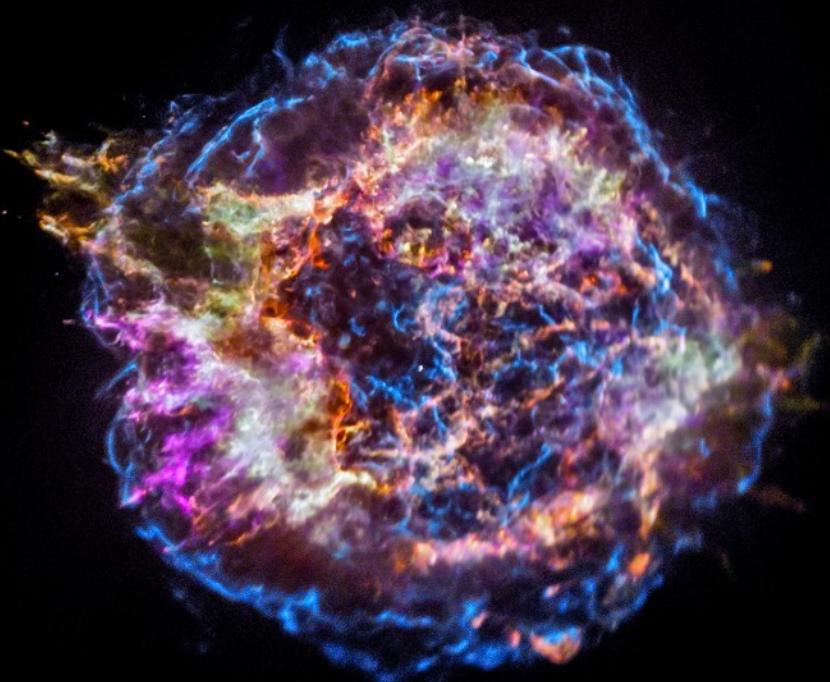


The Sun



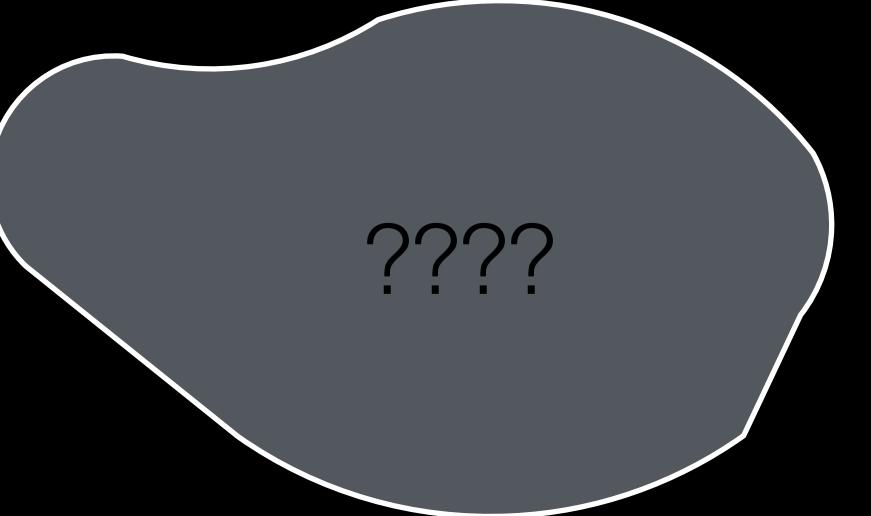
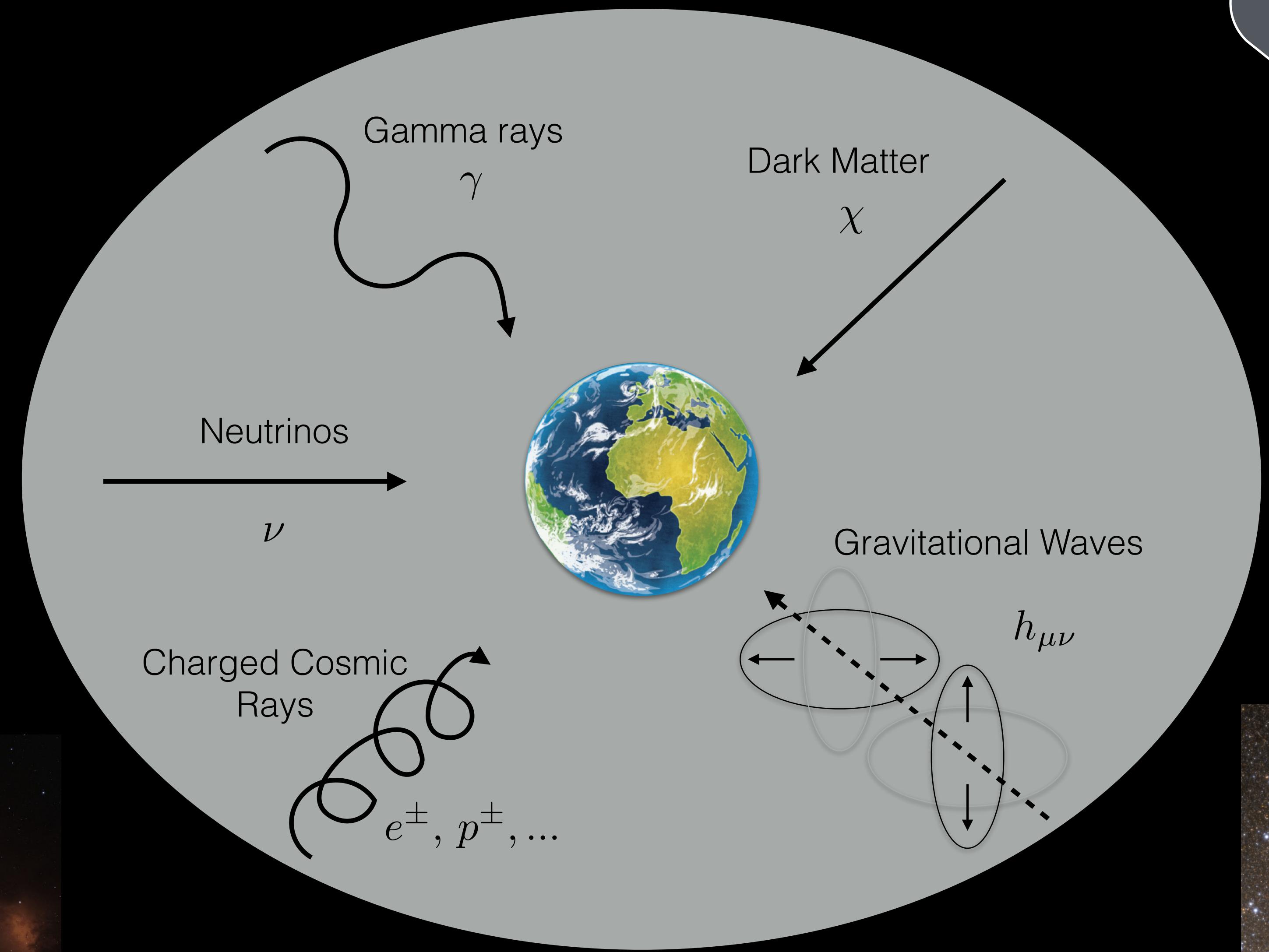
Credit: NASA/CXC/SAO

Supernovae

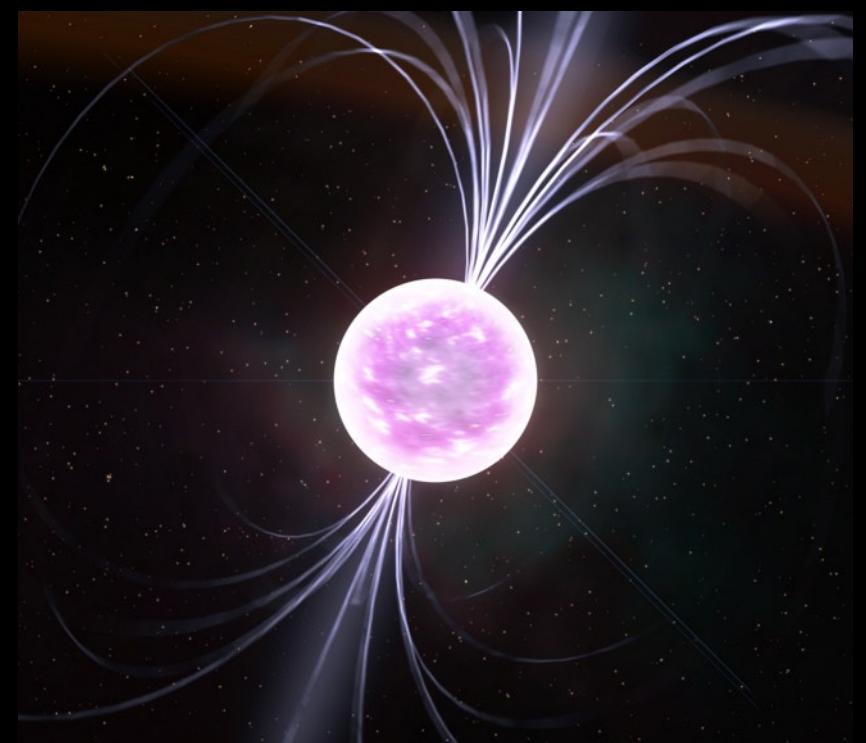


Credit: ESO/M. Kornmesser

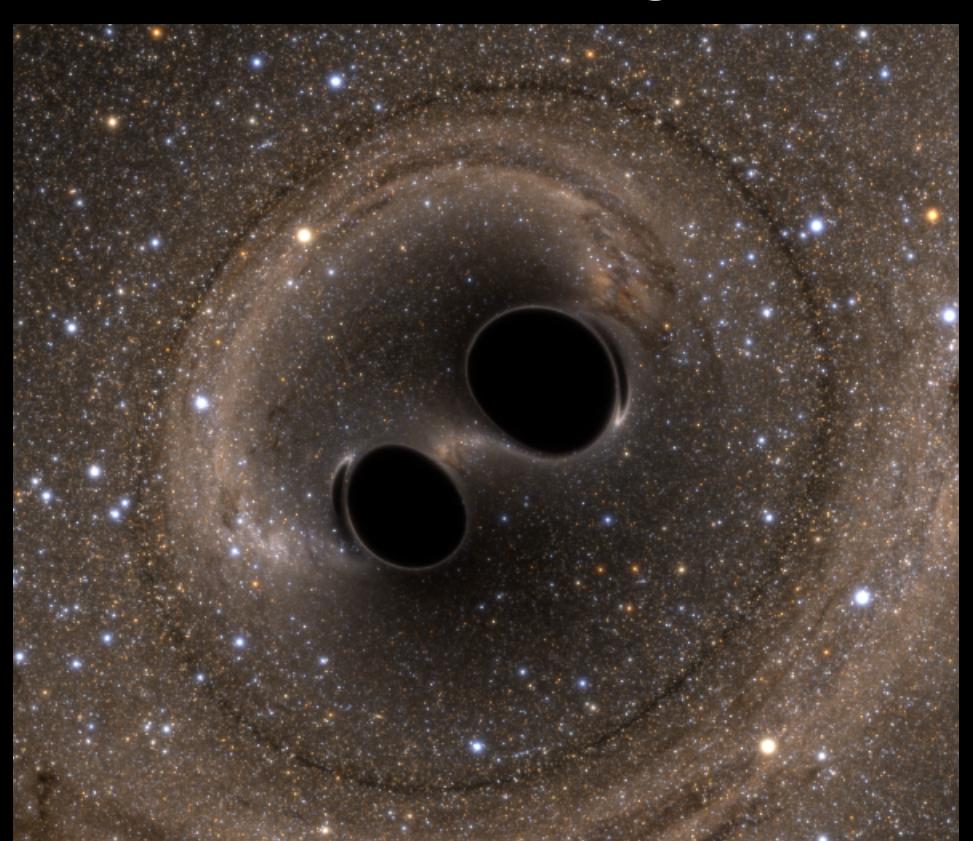
Quasars/AGN



Pulsars



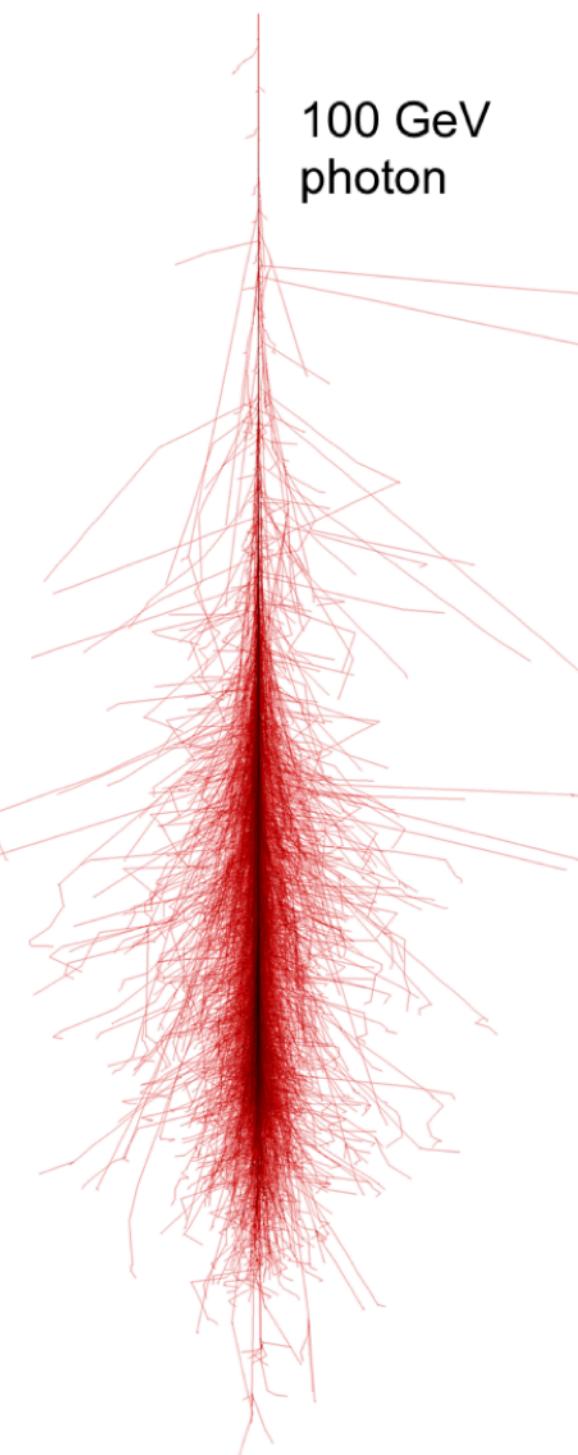
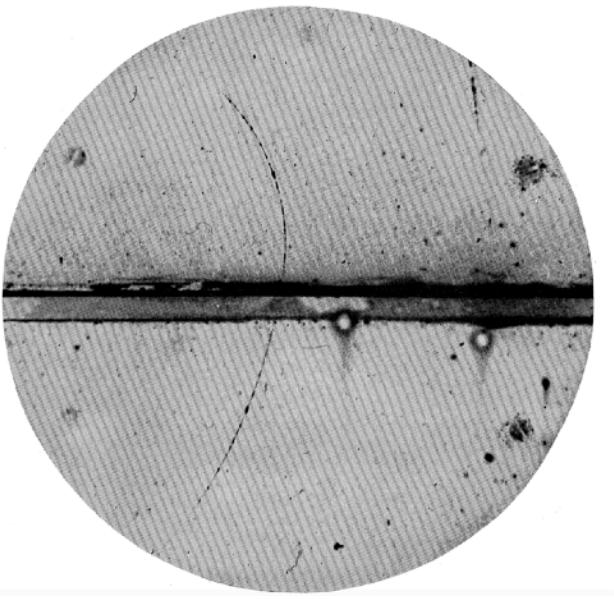
Credit: Kevin Gill / Flickr



Credit: SXS Lensing

# Timeline

**1912:** Hess discovers cosmic rays



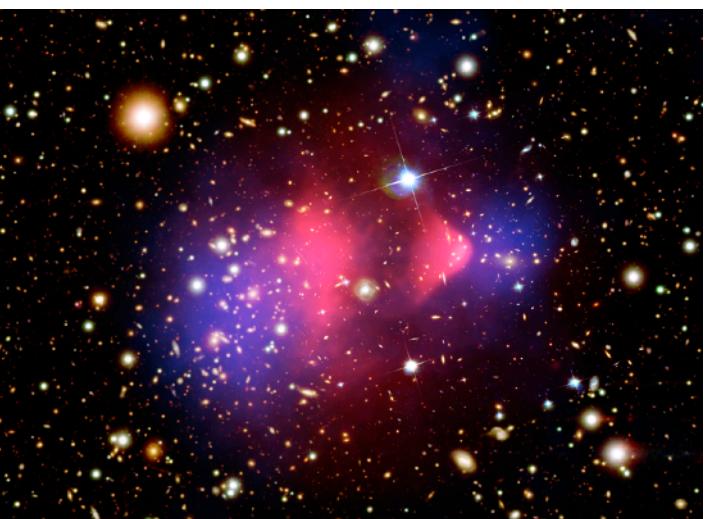
**1933:** Anderson discovers the positron in Cosmic Ray tracks

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

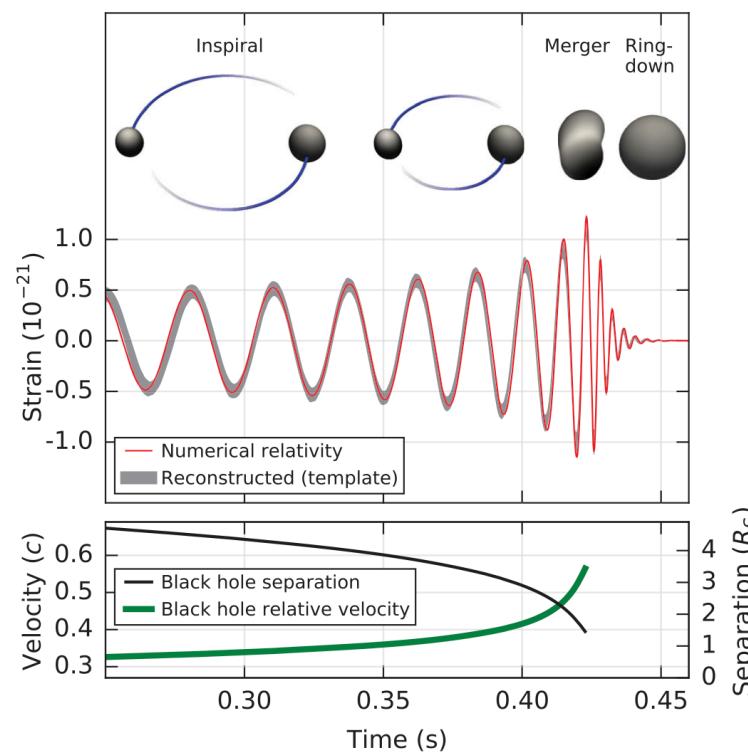
**1960s:** Homestake Experiment detects Solar Neutrinos (and the Solar Neutrino Problem)

**1970s:** The “Dark Matter” paradigm coalesces

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



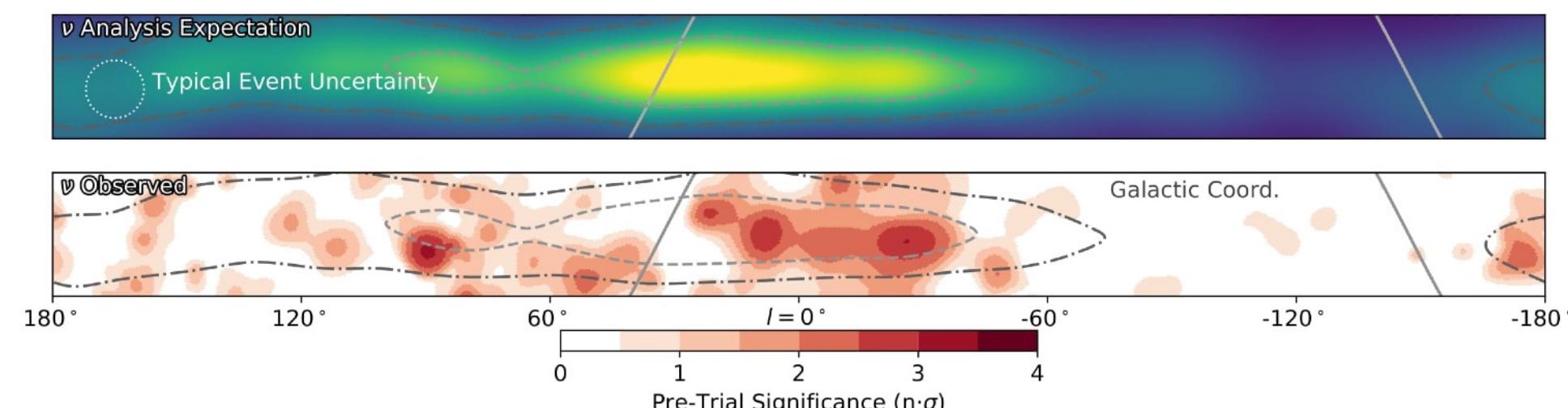
**2015:** GW150914 - First direct observation of GWs from Black Hole Binary Mergers



**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

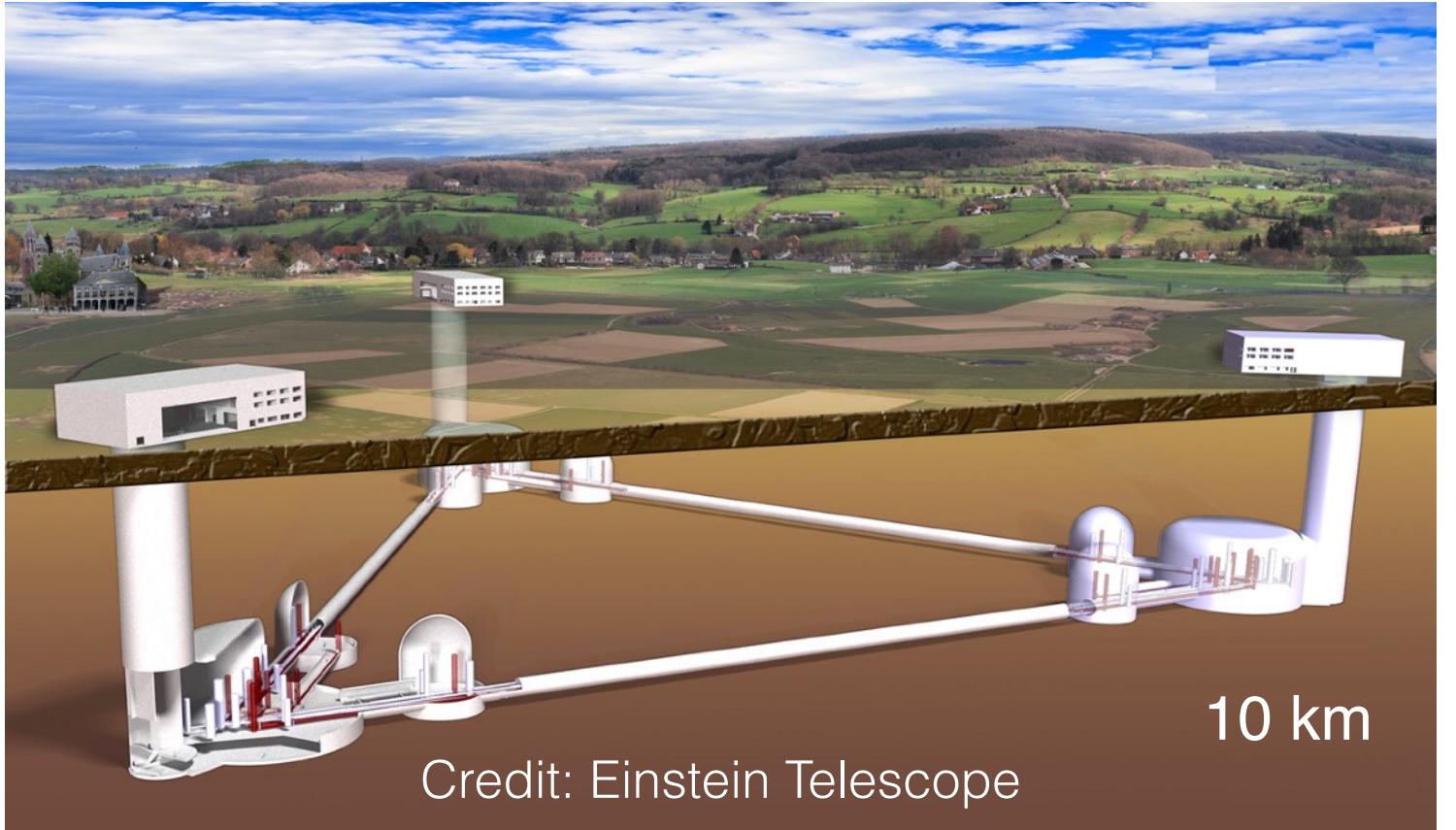
# New Views into the Universe

The Cherenkov Telescope Array (CTA) will observe very **high energy gamma rays** with very high energy resolutions

<https://www.cta-observatory.org>



Credit: Gabriel Pérez Diaz, IAC



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



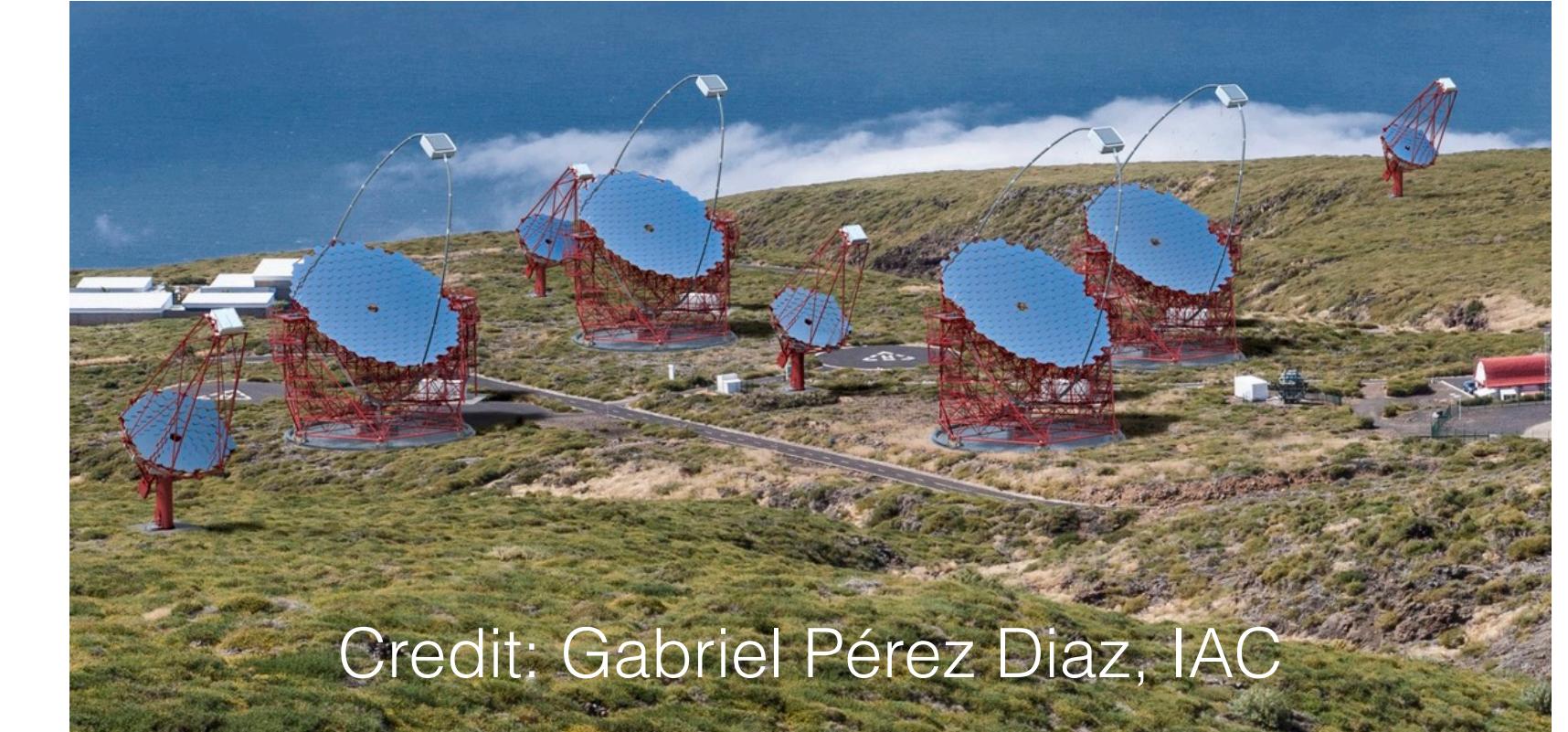
Dark Matter experiments like XENONnT will search for **WIMP Dark Matter** with unprecedented sensitivity

<http://www.xenon1t.org>

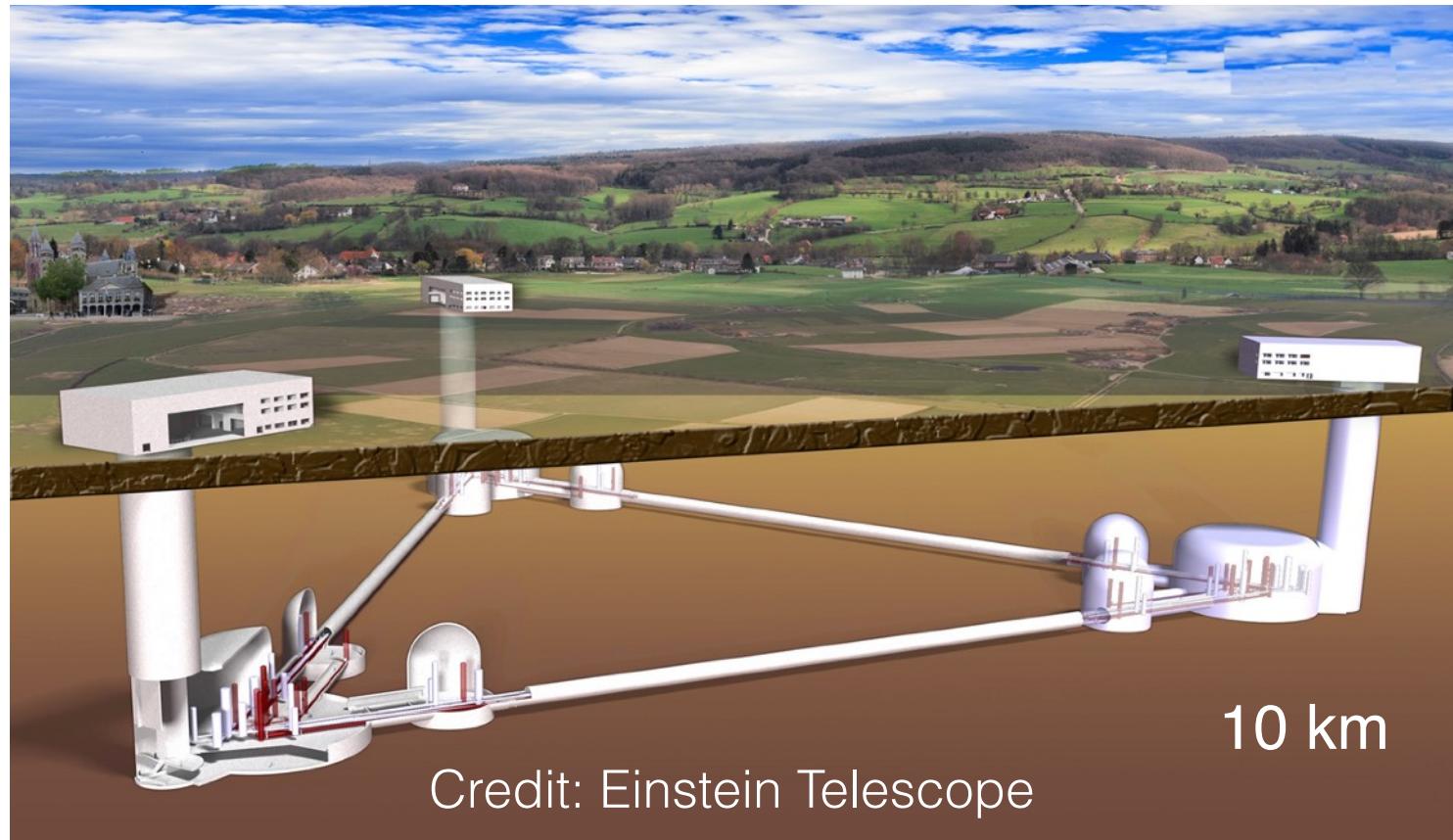
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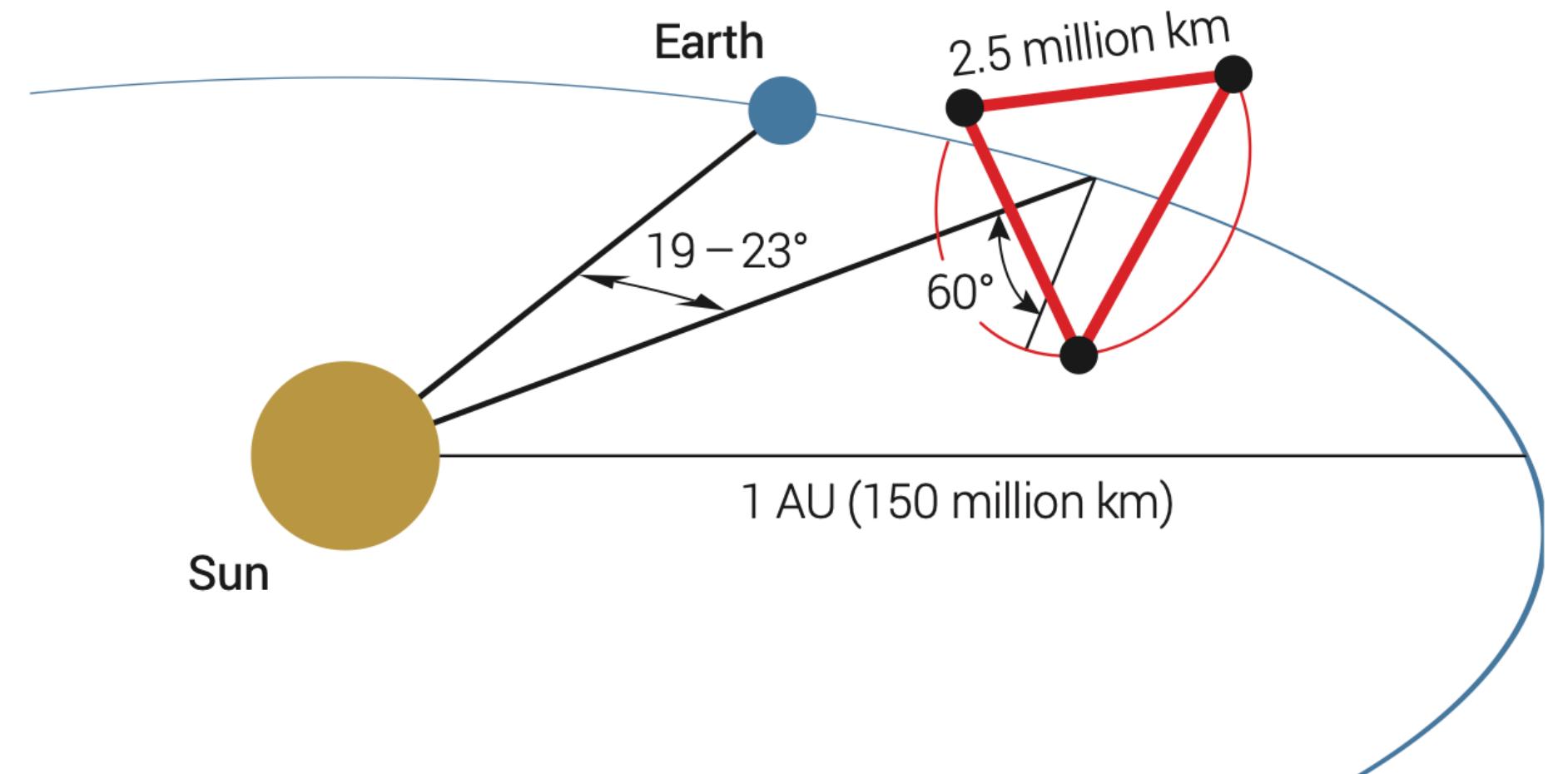
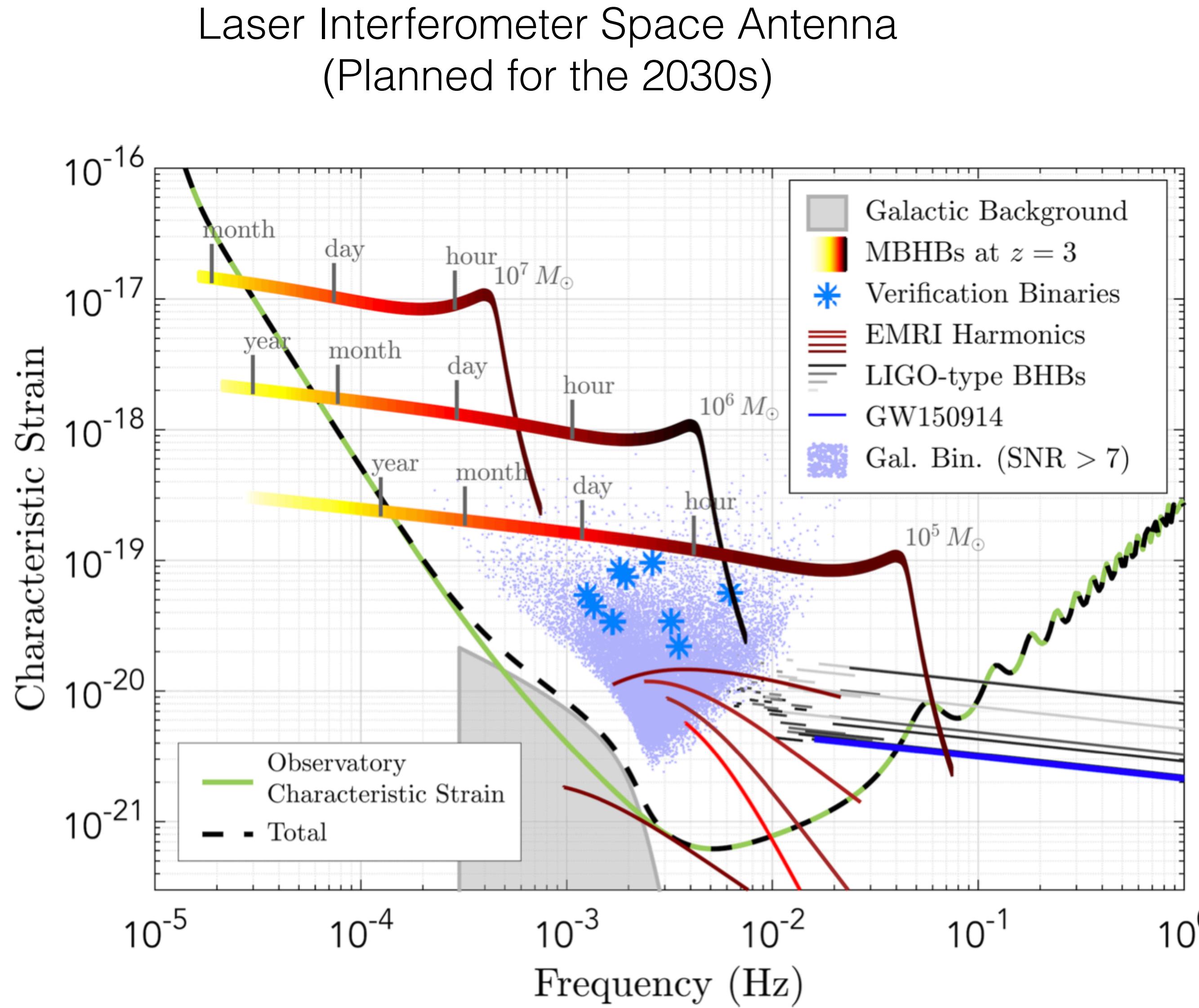
Dark Matter experiments like XENONnT will search for **WIMP Dark Matter** with unprecedented sensitivity

<http://www.xenon1t.org>

...looking forward to many more unexpected discoveries!

## Additional Slides

# LISA - GWs in space!

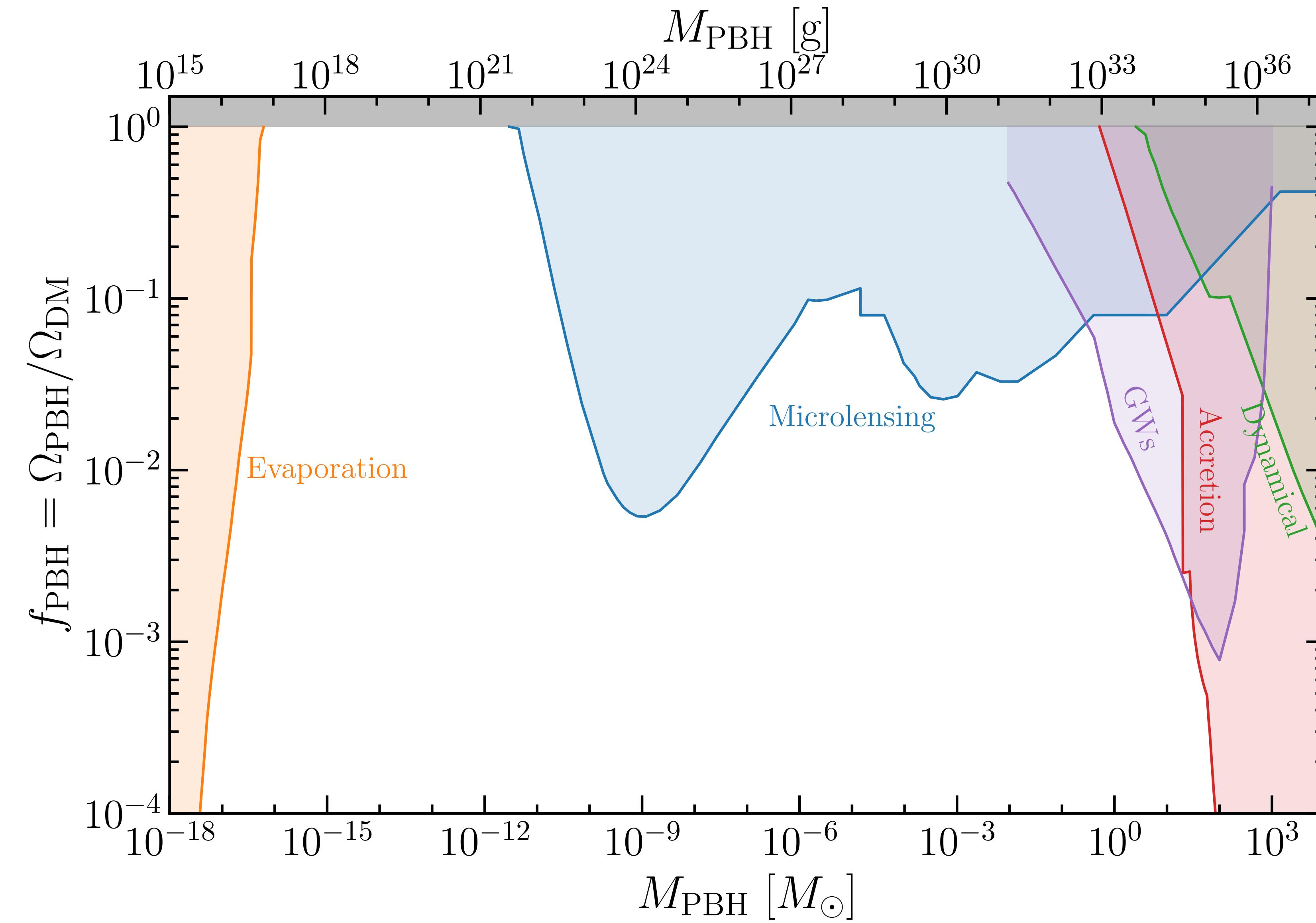


[1907.06482](#)

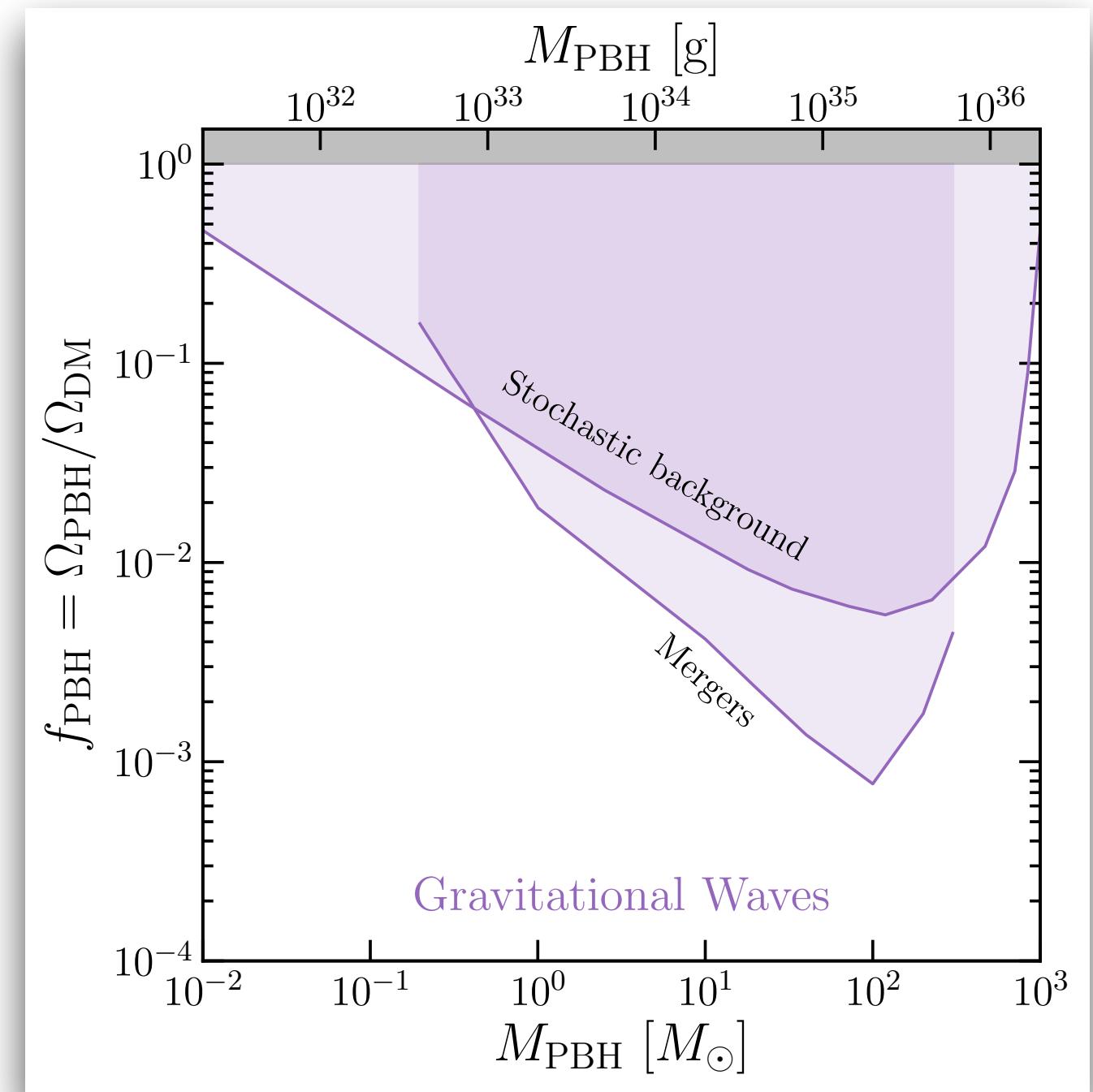
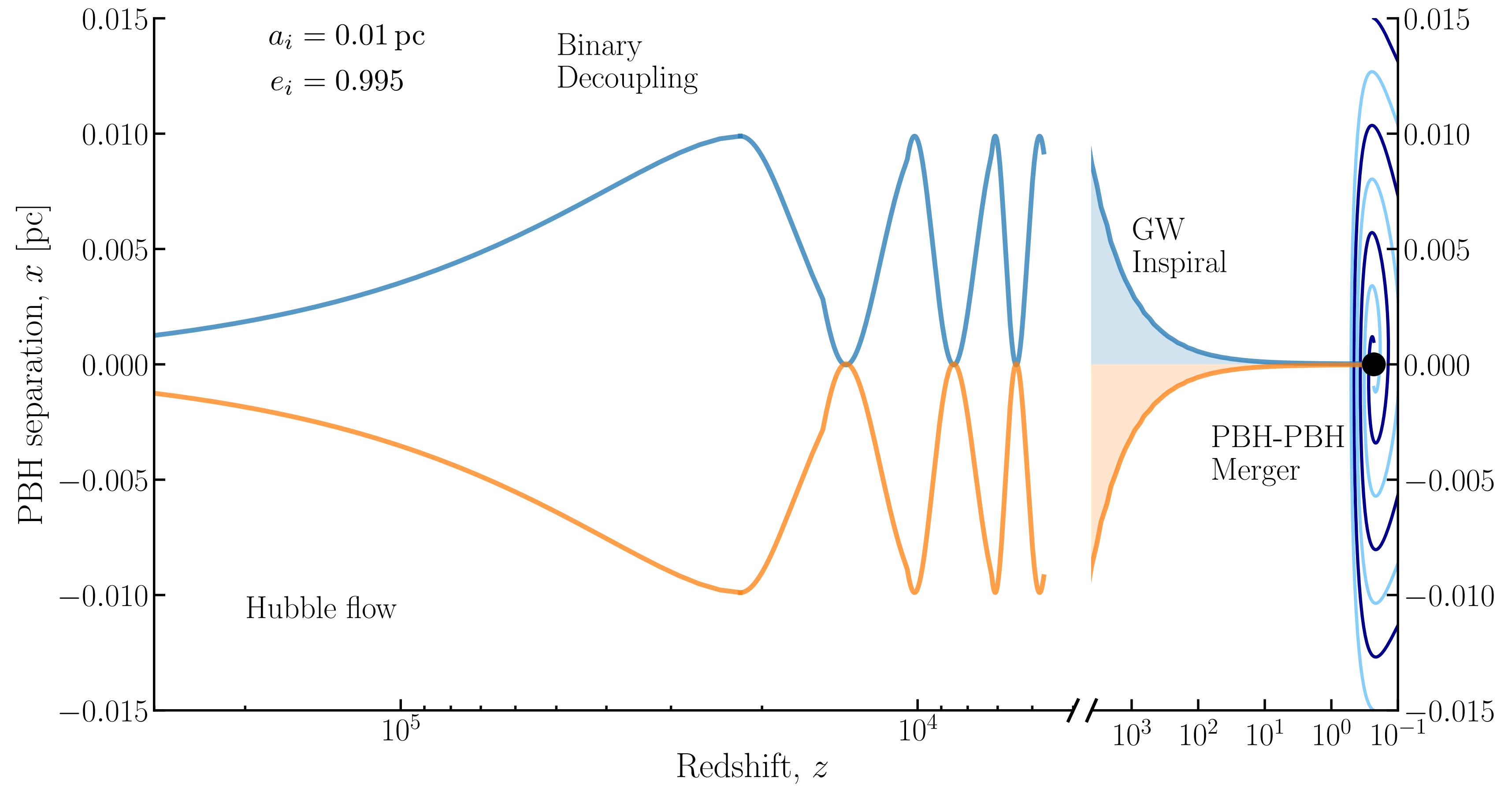
# Primordial Black Holes

[2007.10722](#)

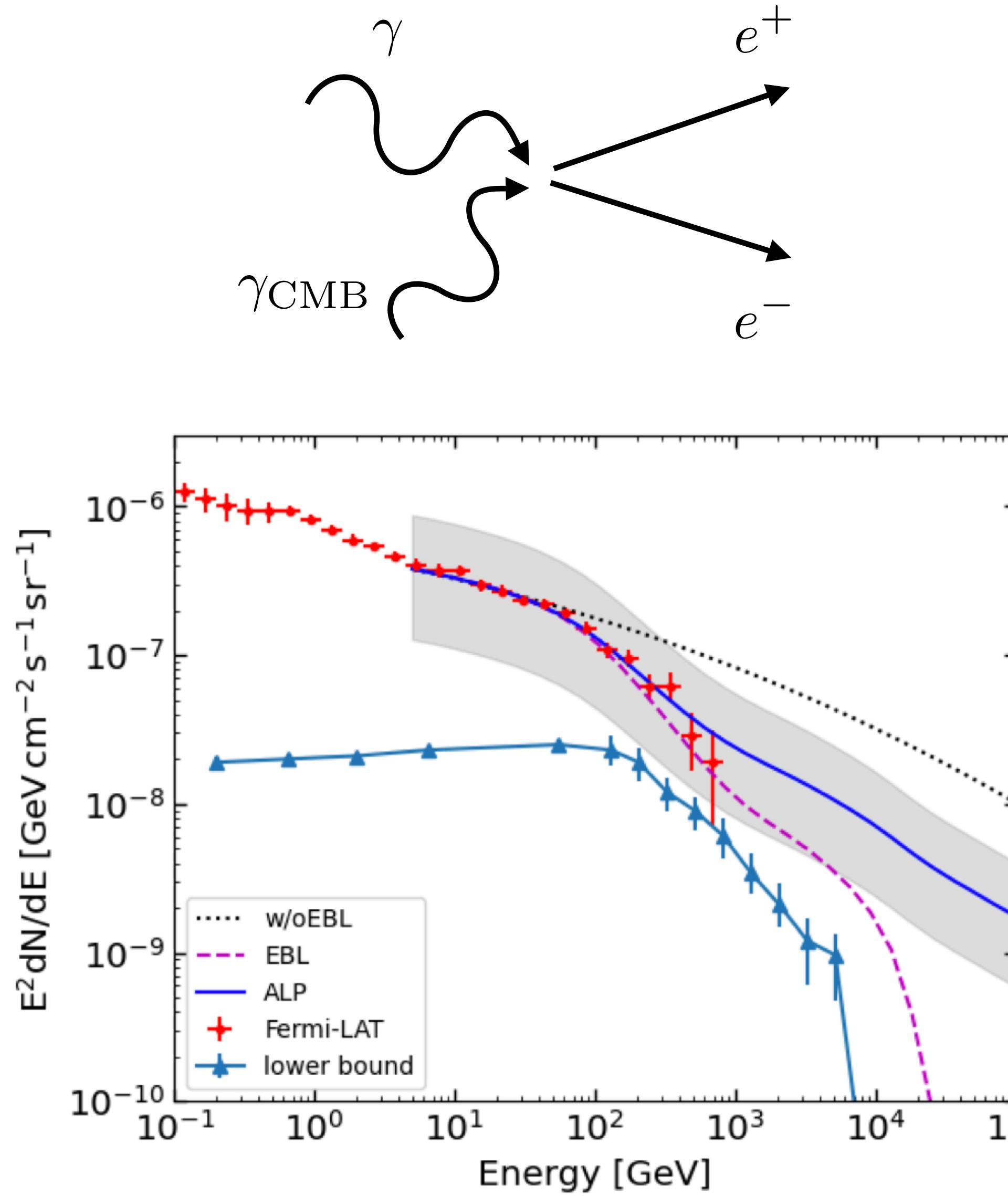
[Bounds online](#)



# PBHs and Gravitational Waves

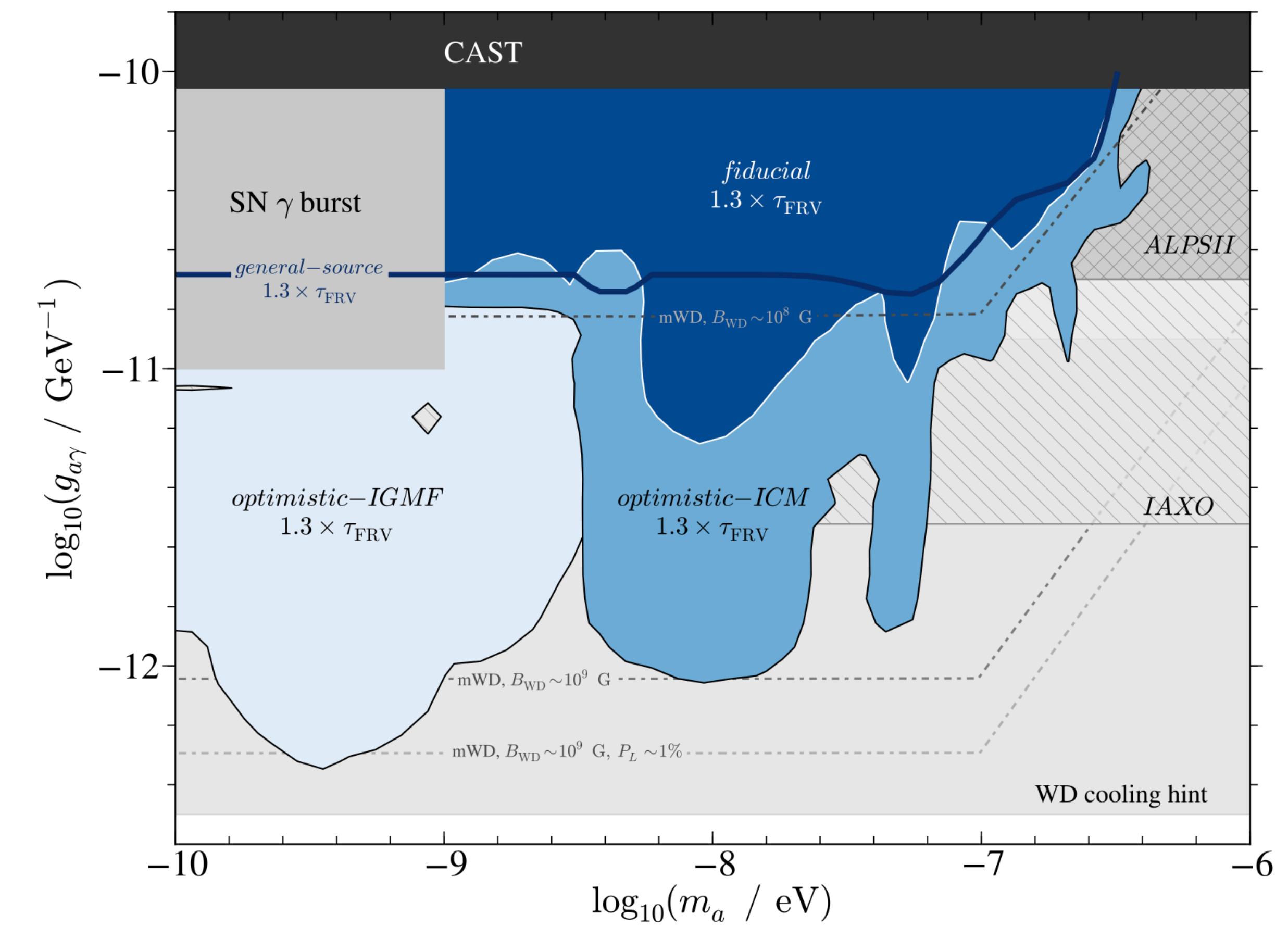
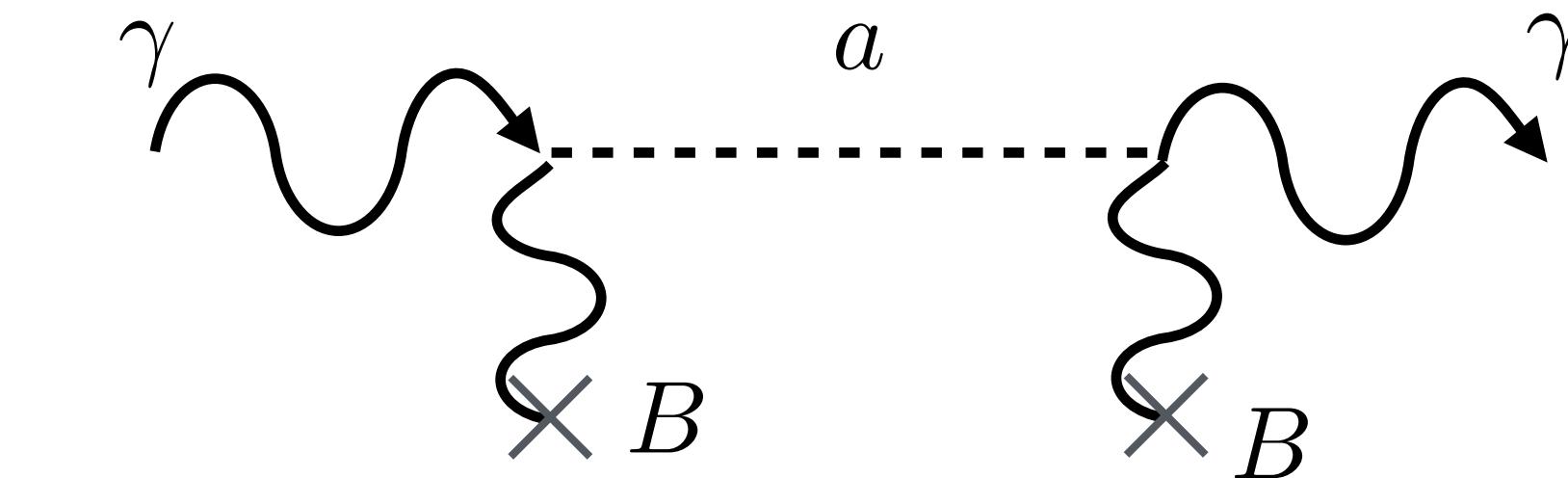


# Gamma-ray transparency and axions



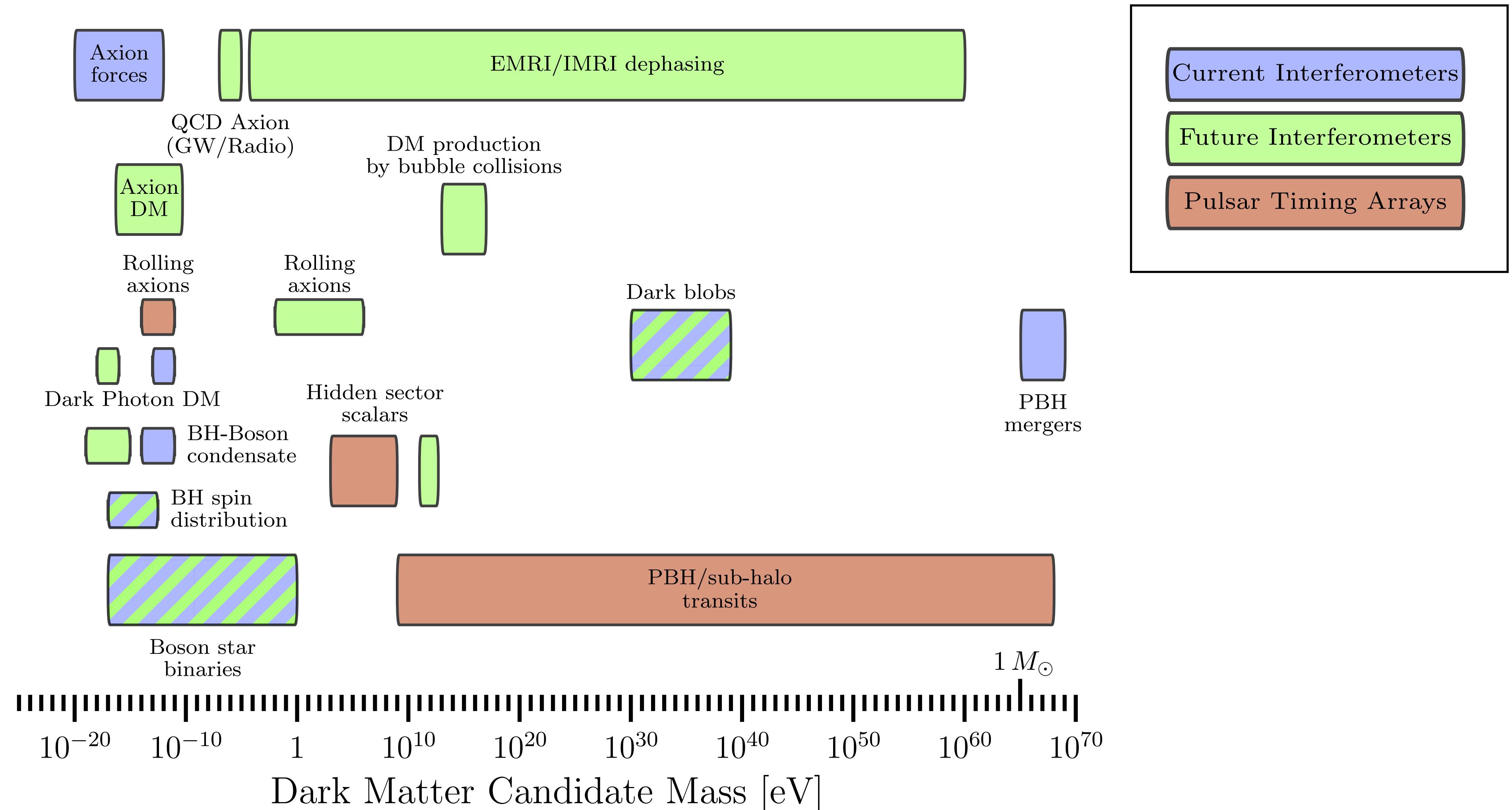
[2012.15513](#)

Axion-like particle:



[1302.1208](#)

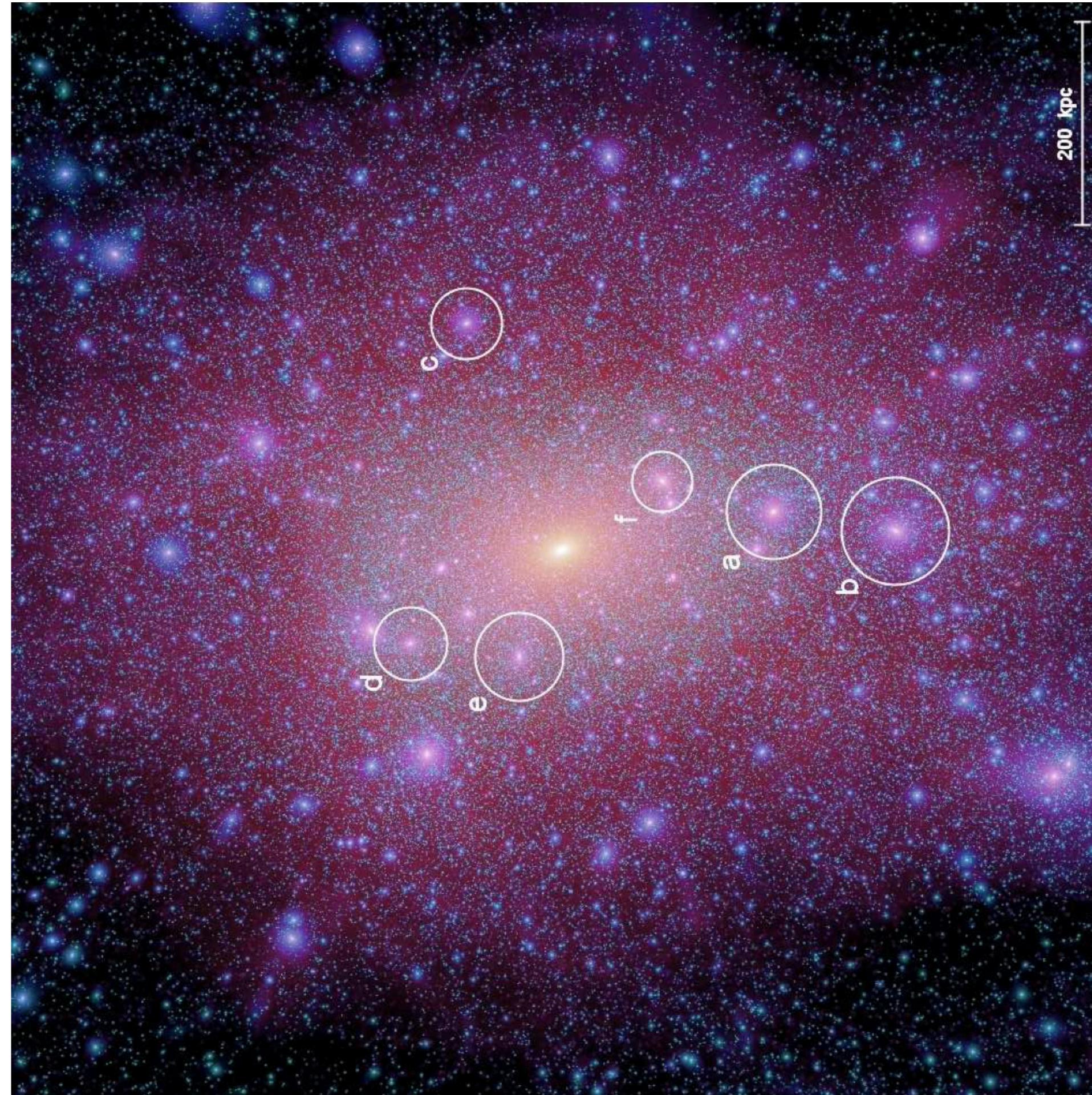
# Gravitational Wave probes of DM



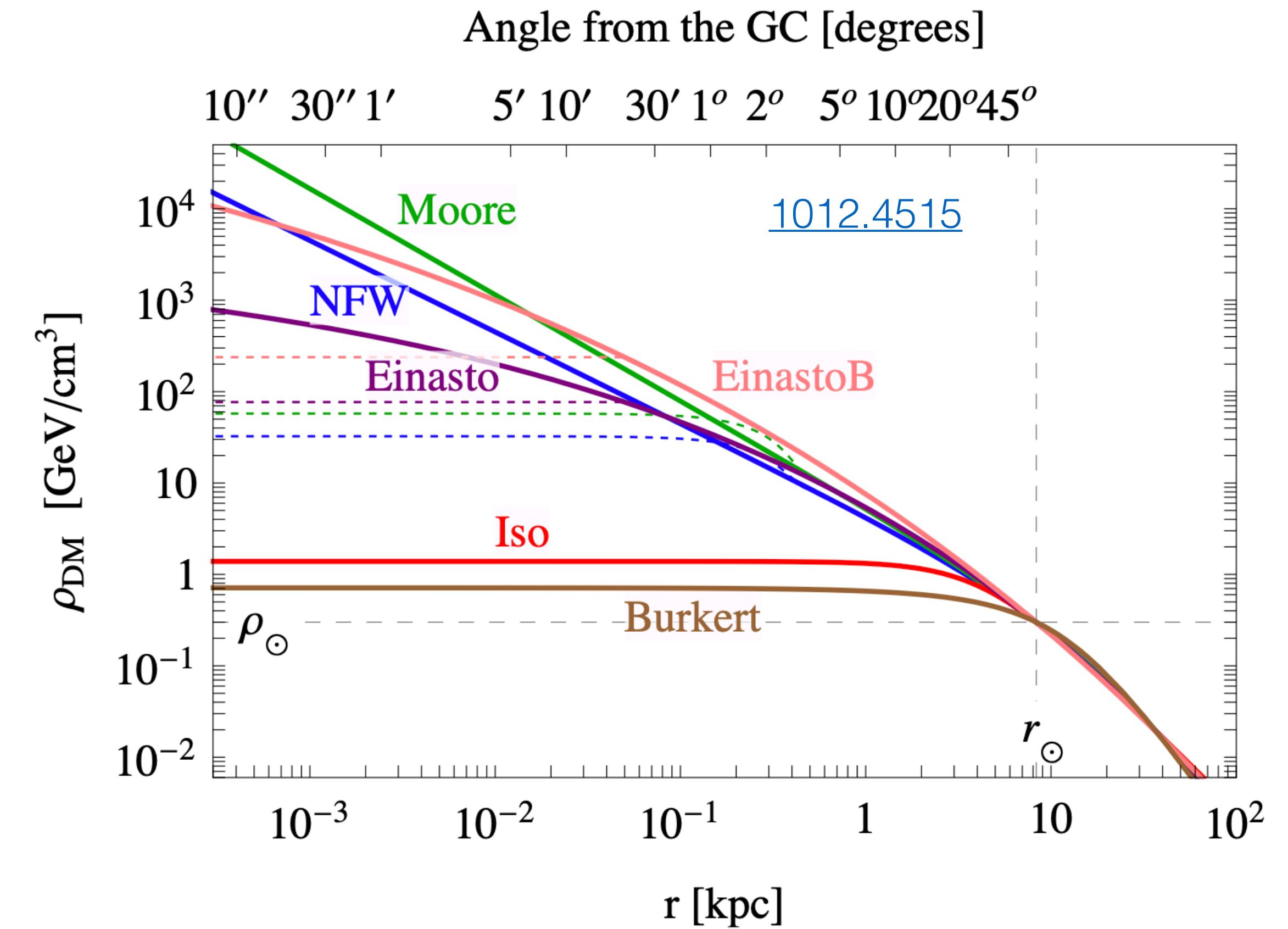
For more information about probing Dark Matter with Gravitational Waves, see [1907.10610](#)

# Dark Matter in Galaxies (2)

Simulations point to Dark Matter halos with cuspy [NFW density profiles](#):



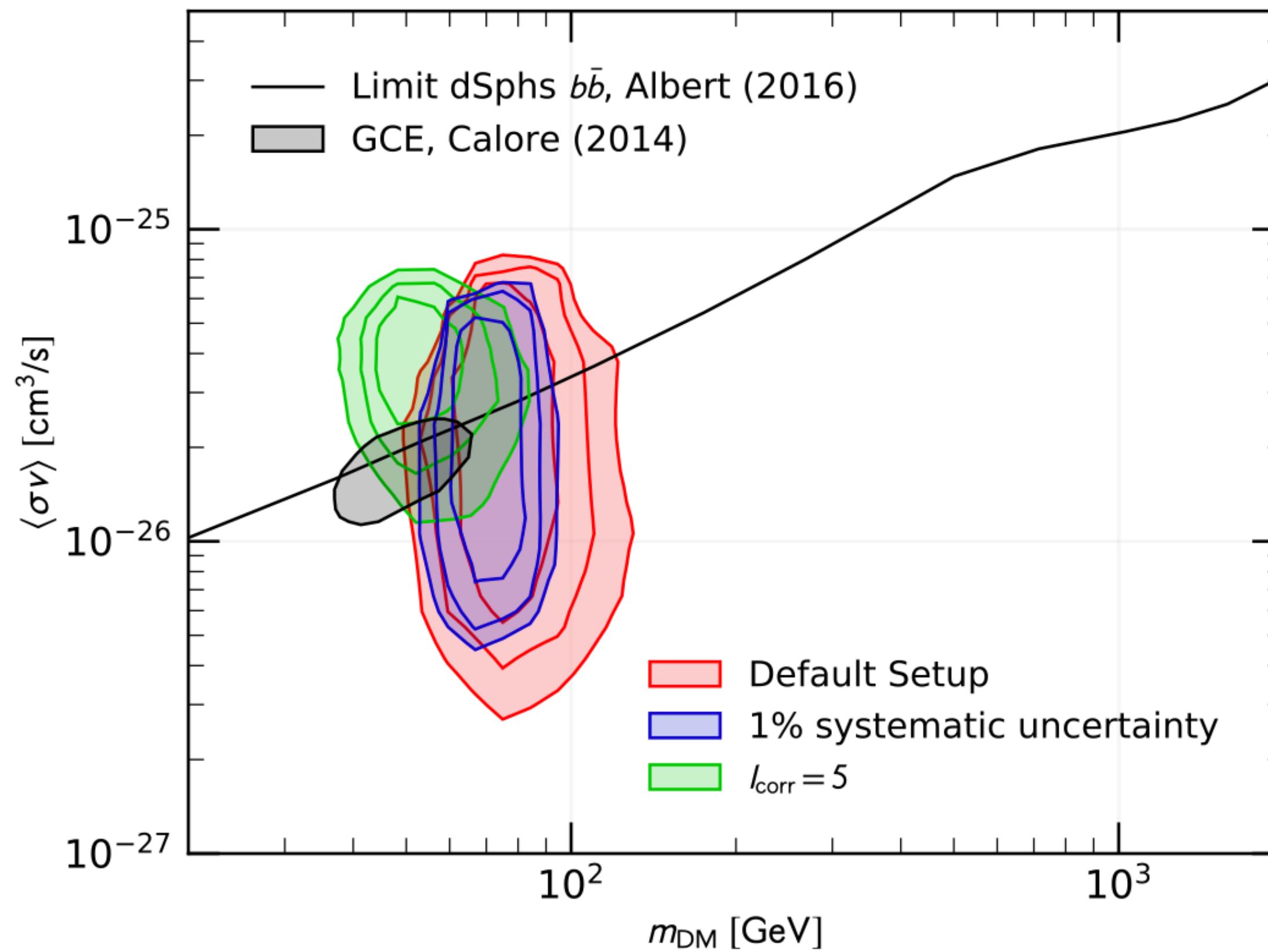
Aquarius simulation - [0809.0898](#)



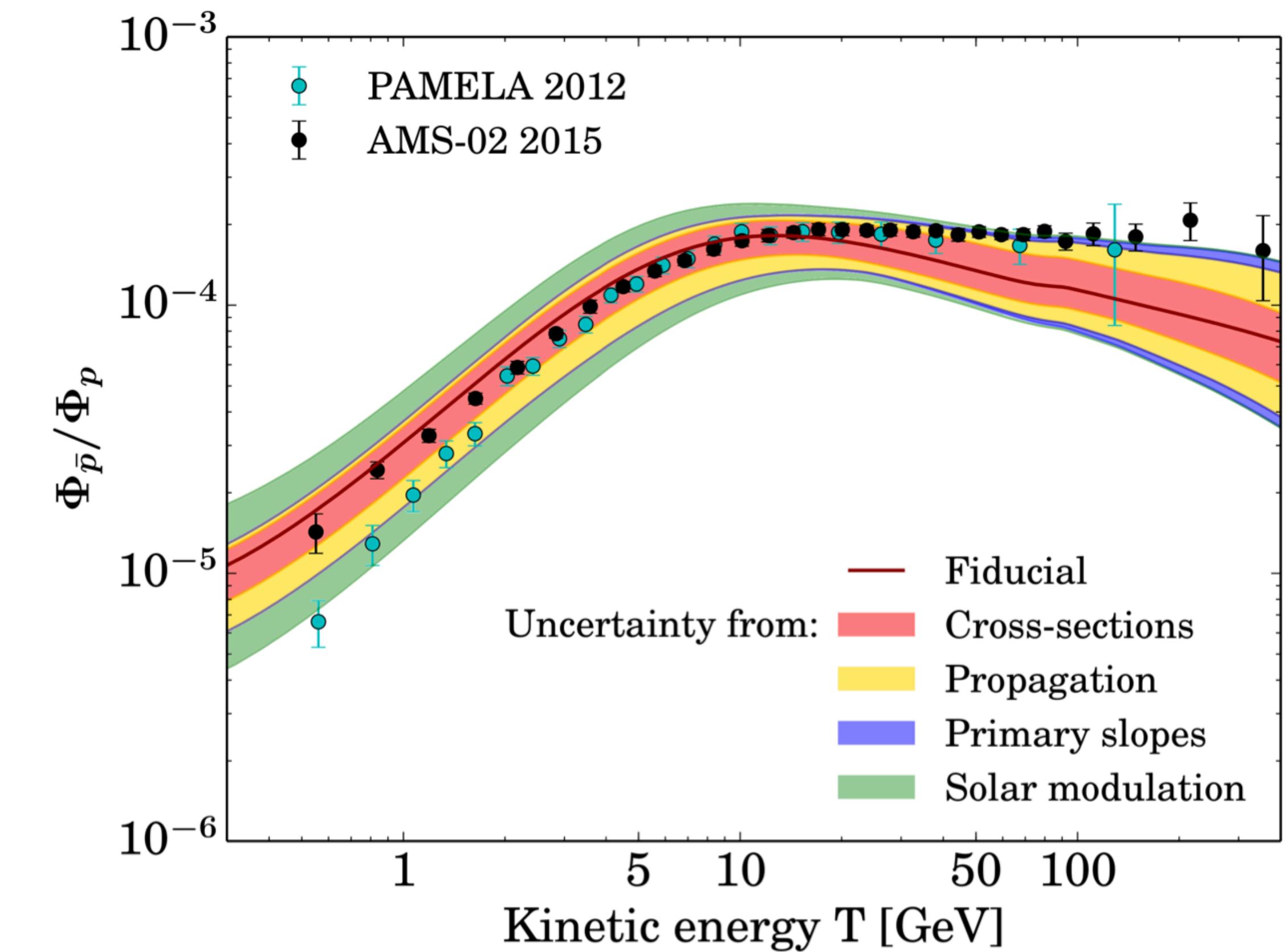
DM density at Earth:

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

# Anti-proton excess (2)



[1903.01472](#)

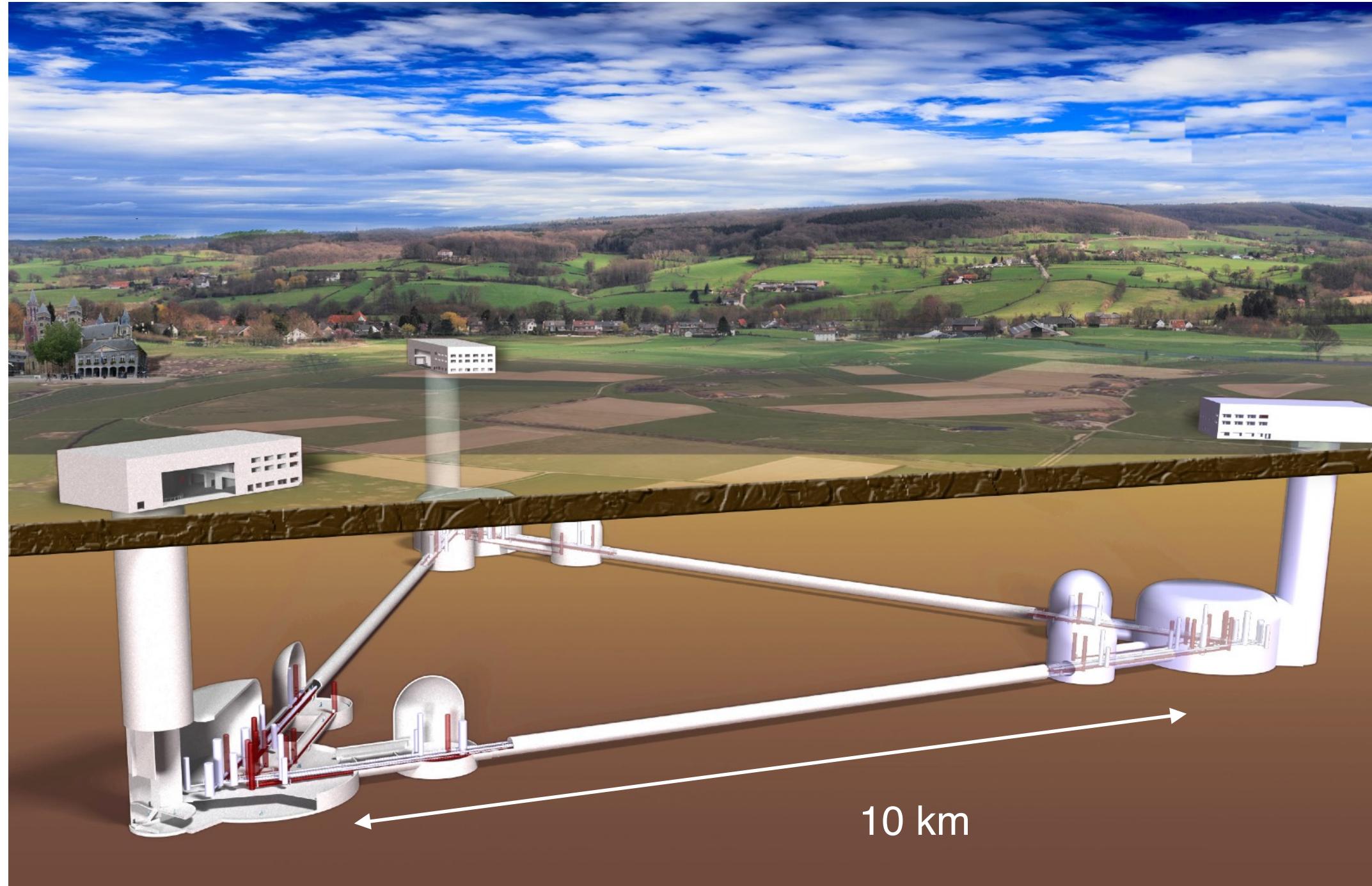


[1504.04276](#)

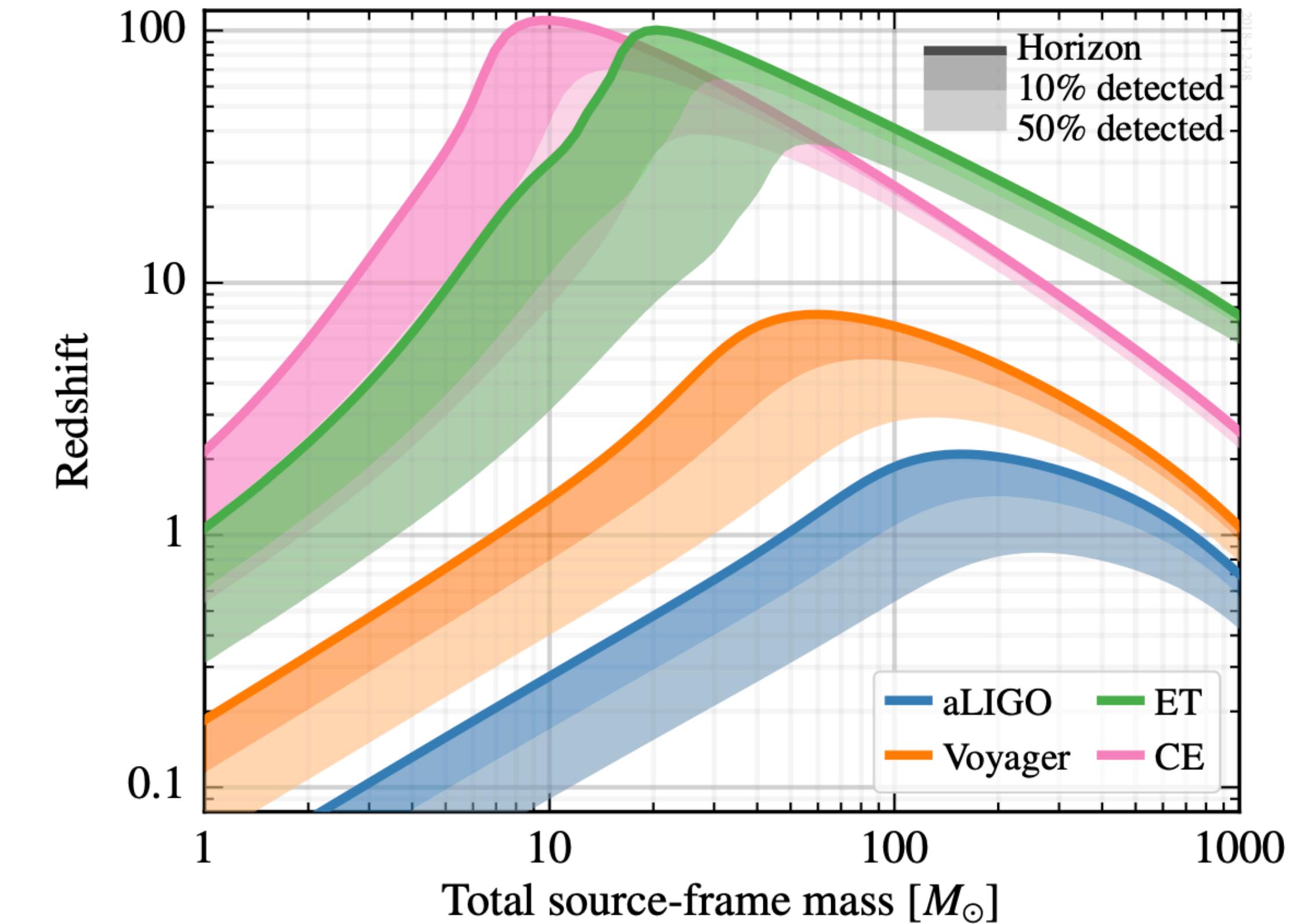
Several excesses point towards 60 GeV Dark Matter -  
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

# 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).