

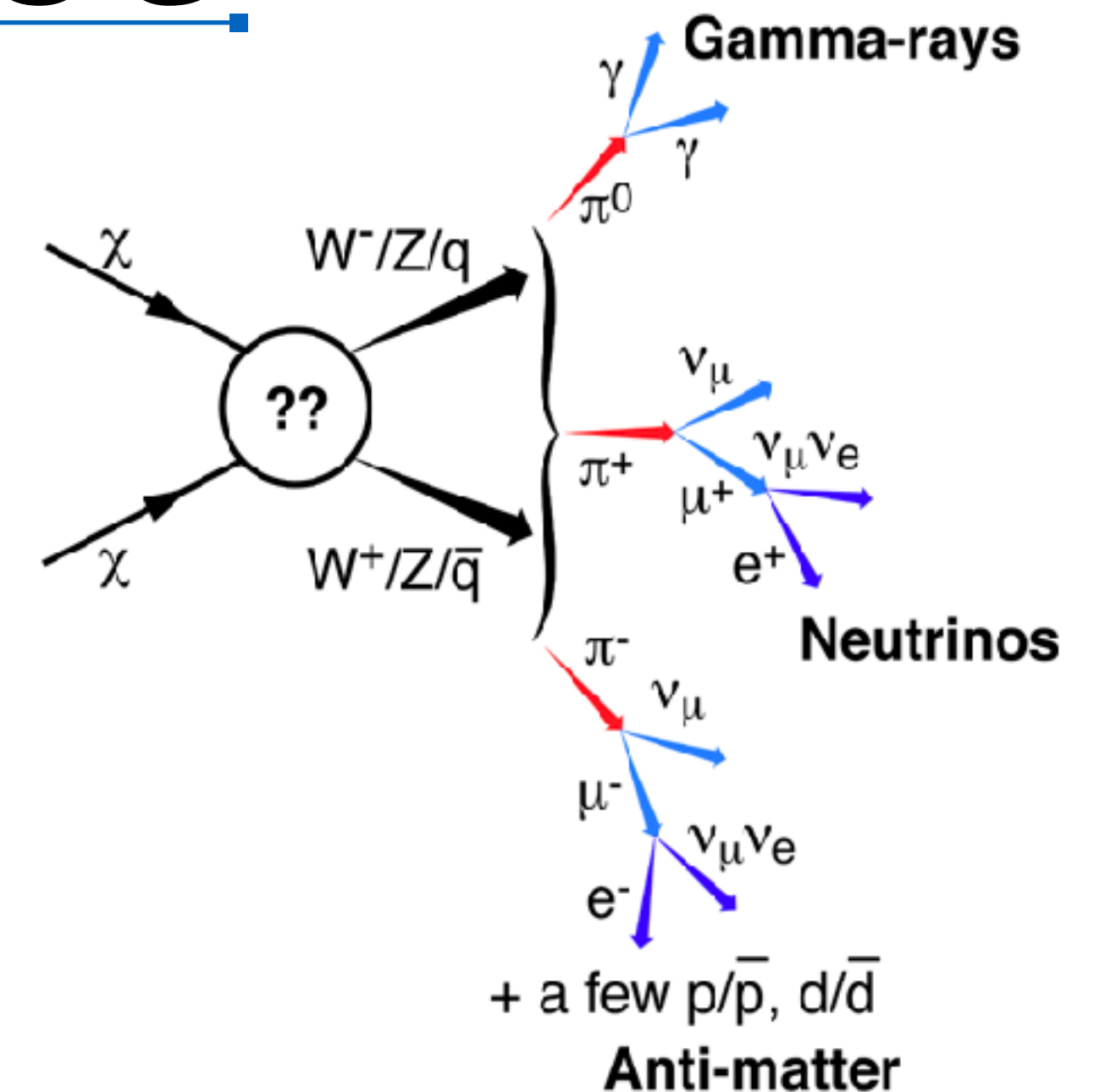
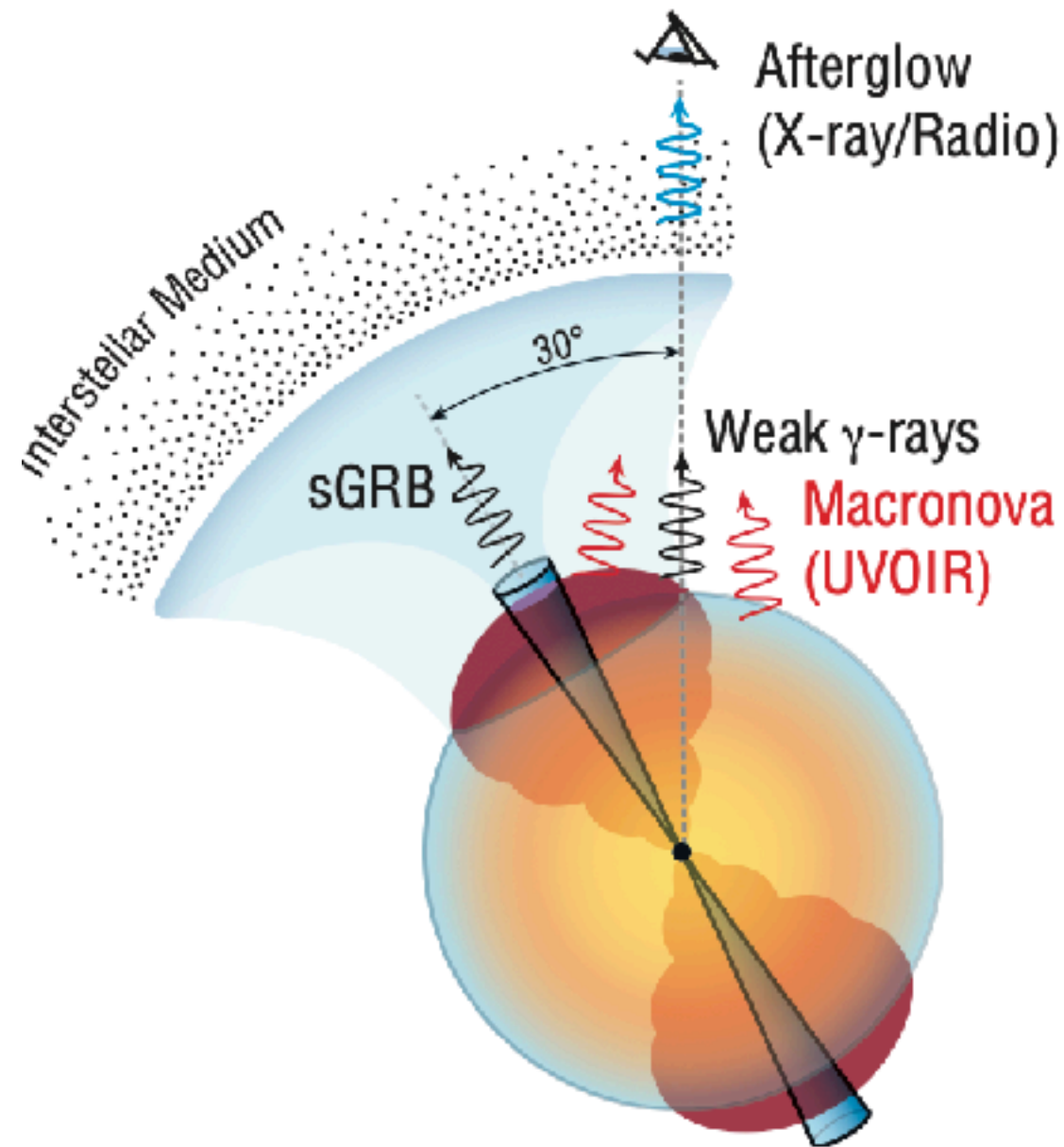
(An introduction to)

Astroparticle Physics

Lecture 2/2

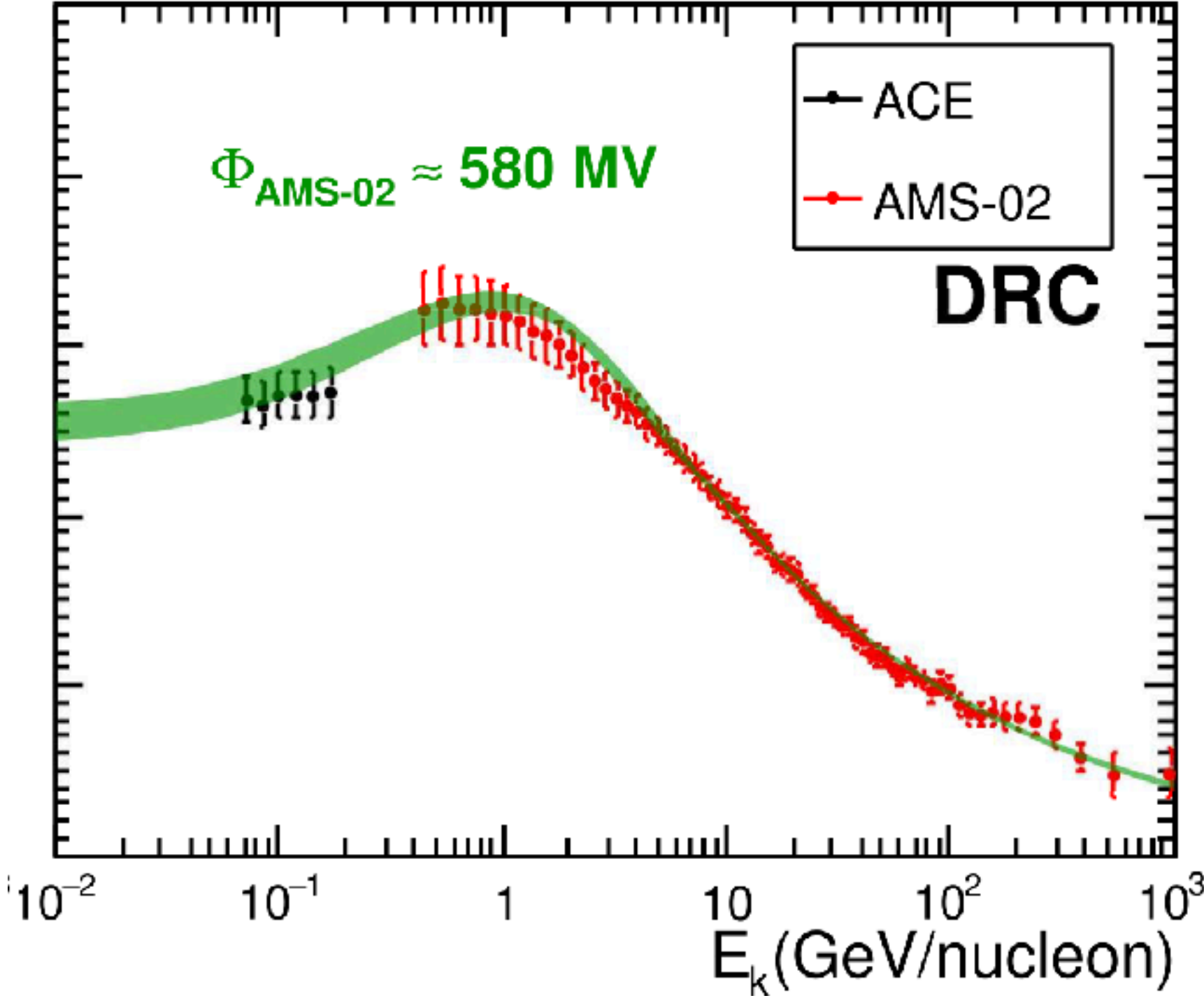
Bradley J Kavanagh [he/him]
Instituto de Física de Cantabria (CSIC-UC)
kavanagh@ifca.es

CERN Summer Student Lecture Programme:
Tuesday 28th July 2026

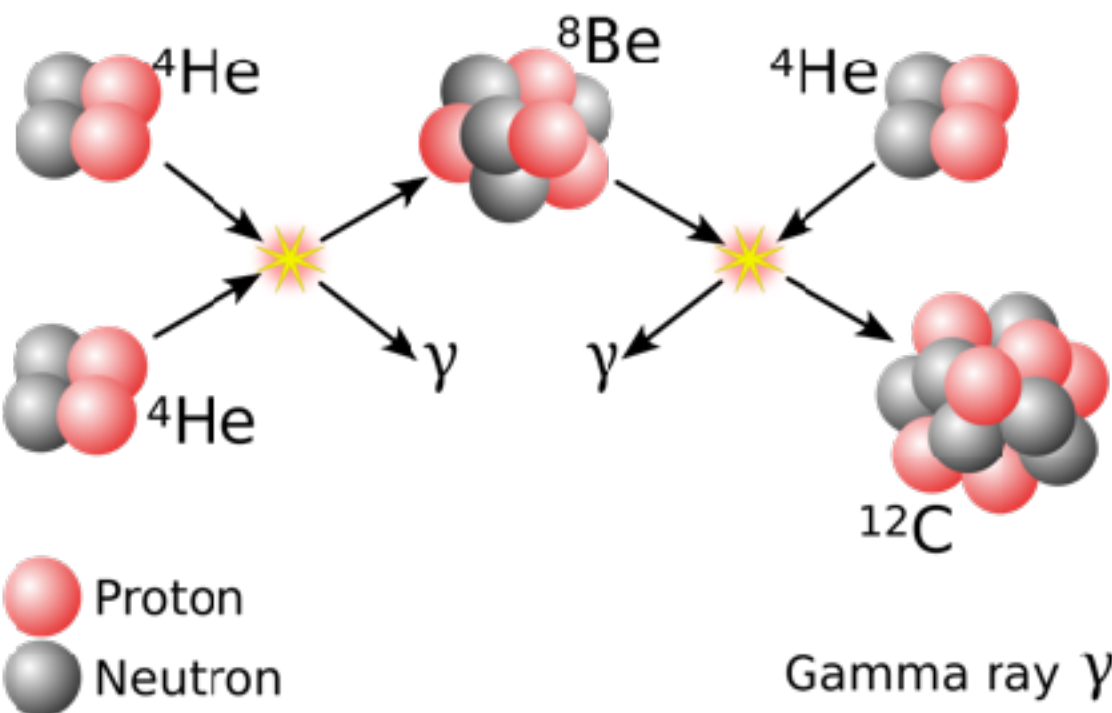


Q: Boron vs Carbon

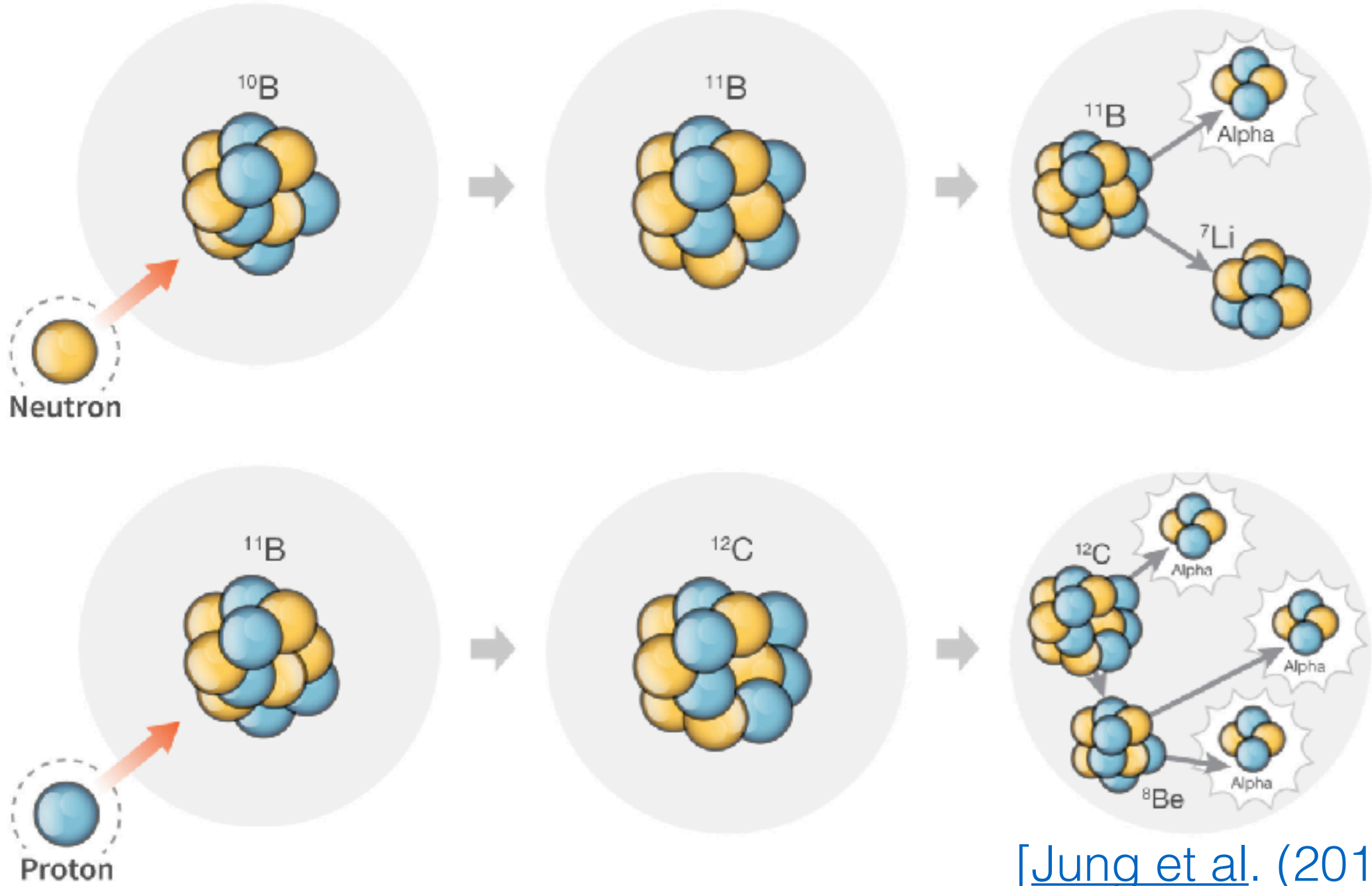
[1701.06149](#)



Carbon (C-12) is formed in stars!



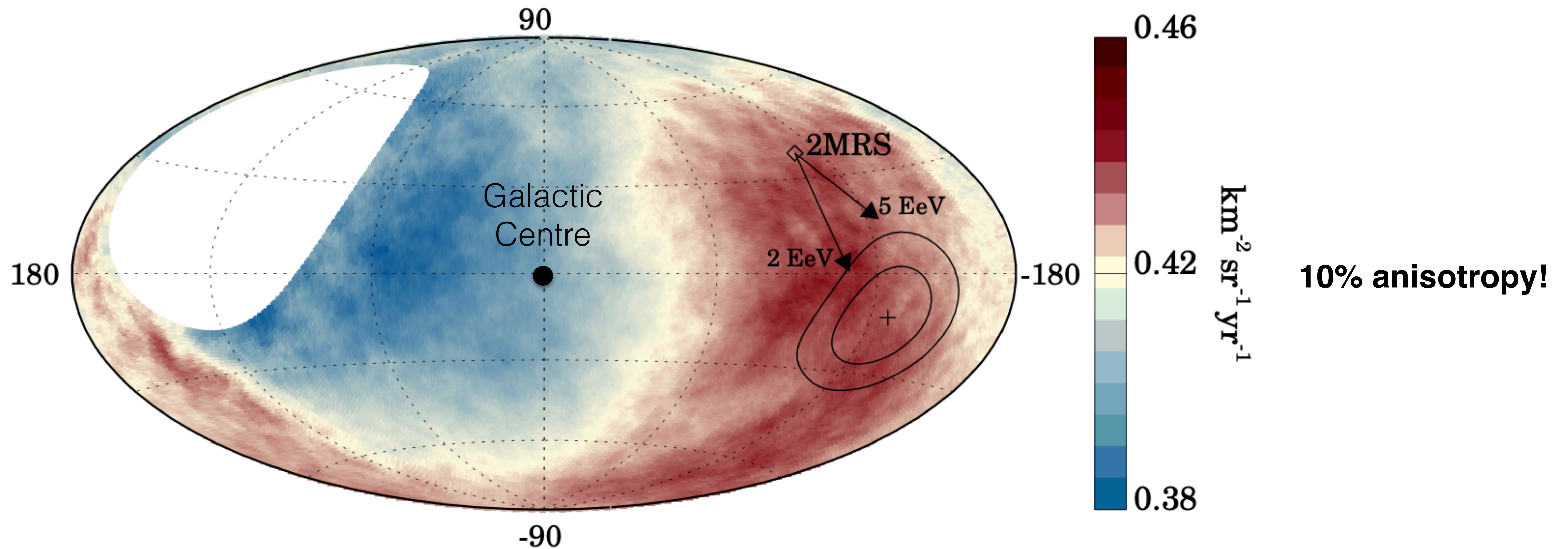
Boron (B-10, B-11) is destroyed in stars!



[Jung et al. (2017)]

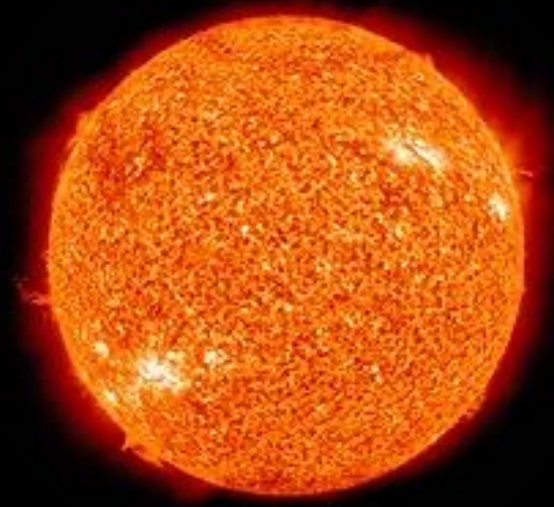
Q: Cosmic Ray Sky Map

Map of cosmic ray arrival directions for ultra-high energy ($E > 8 \times 10^{18}$ eV) from Pierre Auger Observatory:



Roughly consistent with anisotropy in the 2MRS Galaxy Survey
(once magnetic field deflection is taken into account)

The Sun



Supernovae

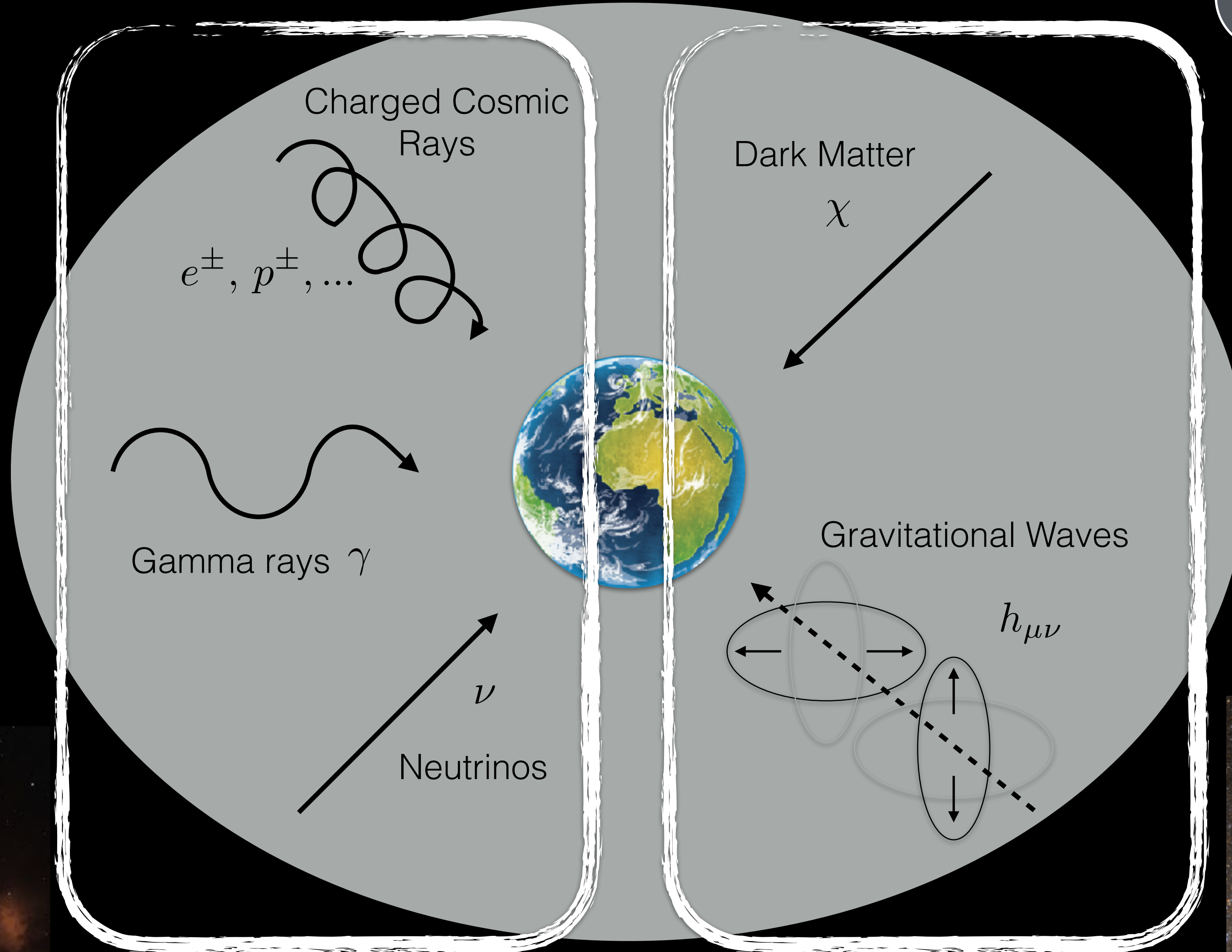


Quasars/AGN



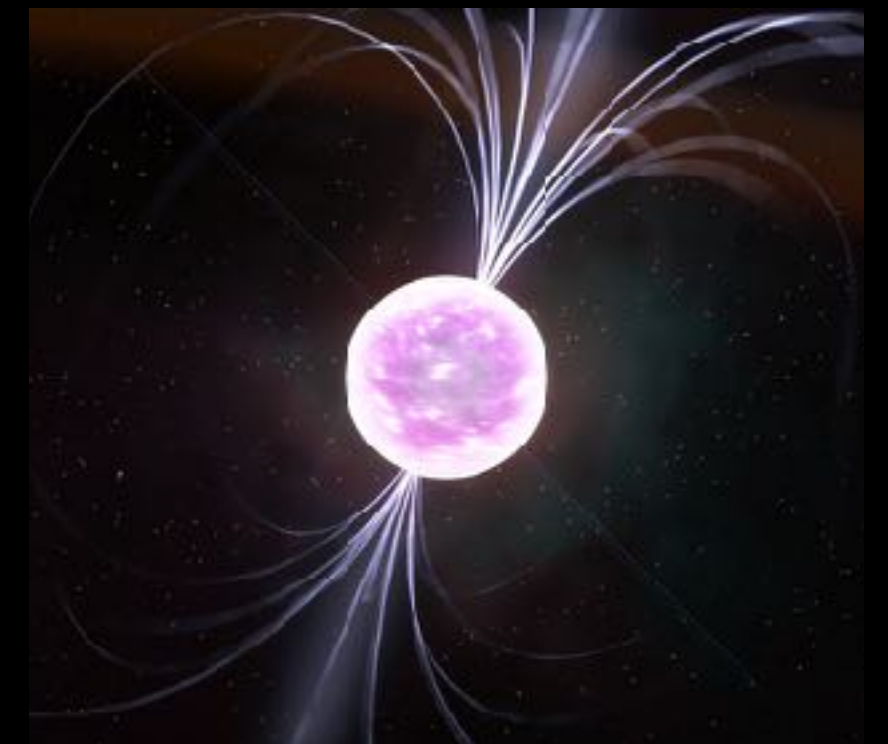
Lecture 1

Lecture 2



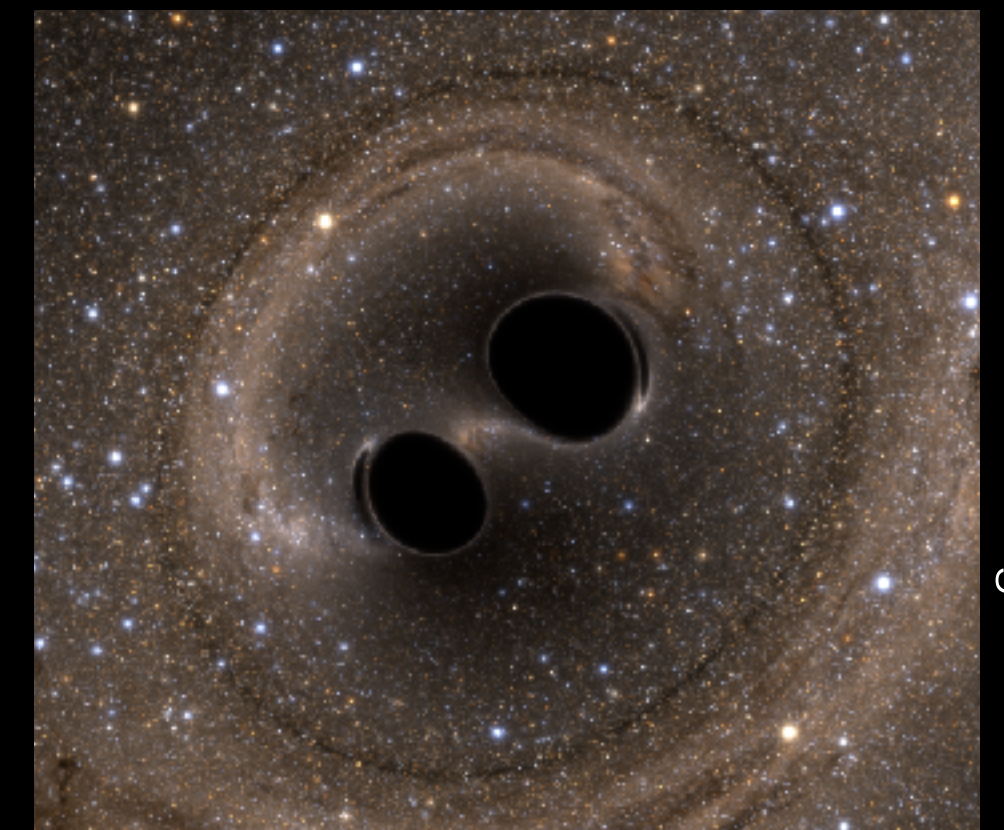
????

Pulsars



Credit: Kevin Gill / Flickr

BH/NS Mergers



Credit: SXS Lensing

Credit: NASA/CXC/SAO

Credit: ESO/M. Kornmesser

Gravitational Waves

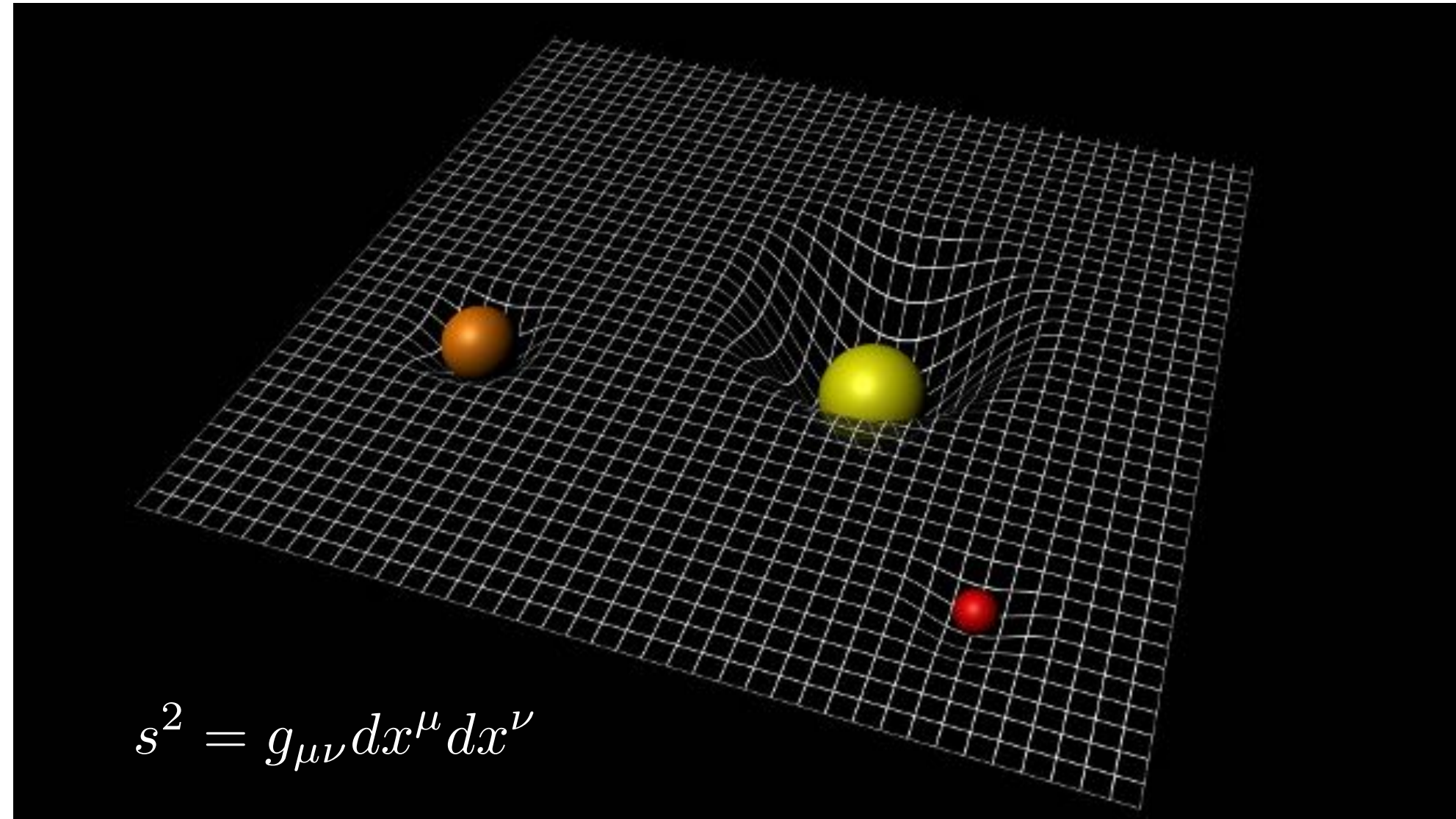
Einstein field equations of General Relativity:

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

Einstein tensor
(Gravity)

Stress-energy tensor
(Matter)

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



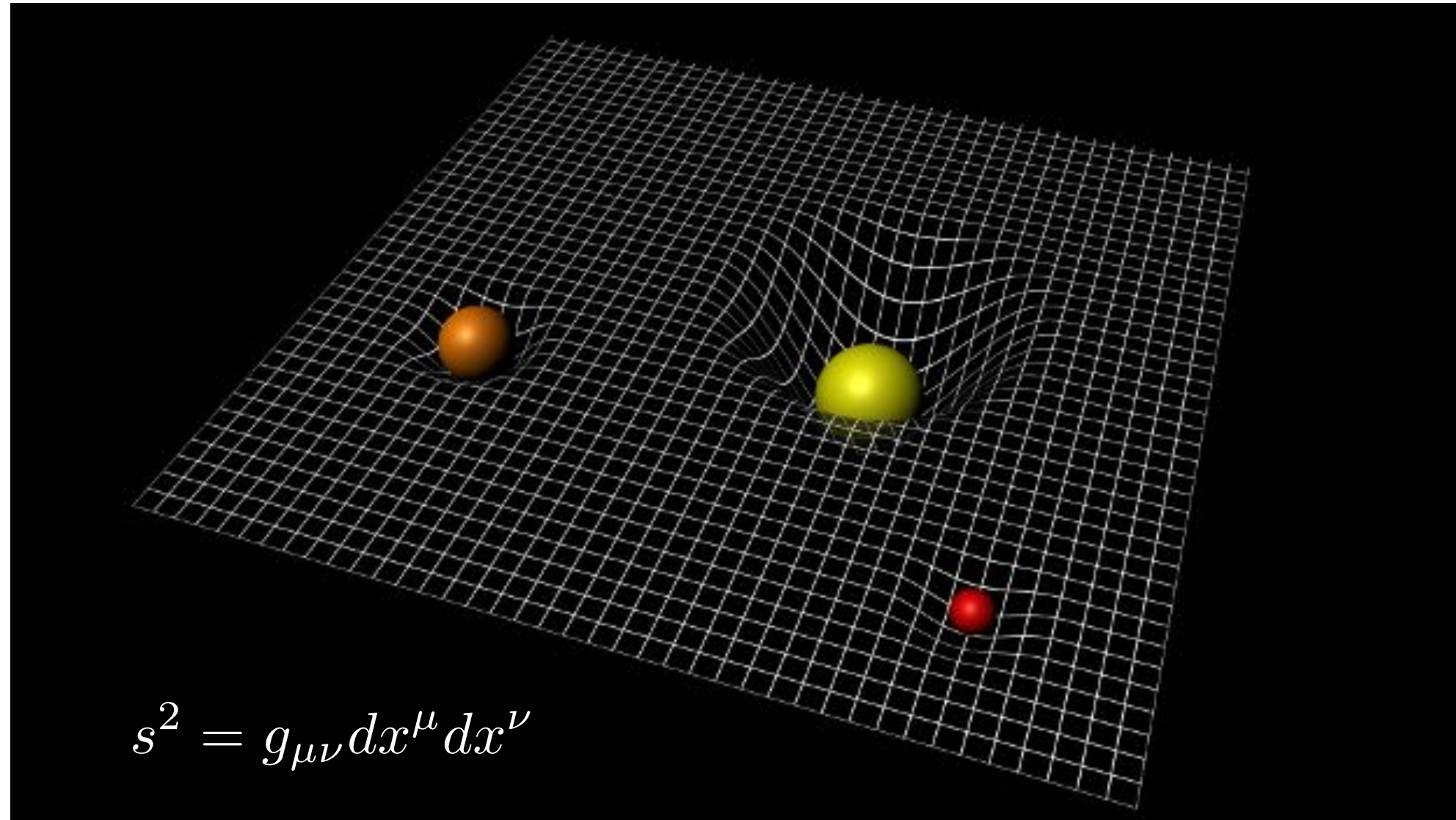
Credit: ESA/C. Carreau

Gravitational Waves

Einstein field equations of General Relativity: $G_{\mu\nu} = 0$

Einstein tensor
(Gravity)

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



Credit: ESA/C. Carreau

Linearise the field equations *in vacuum*:

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

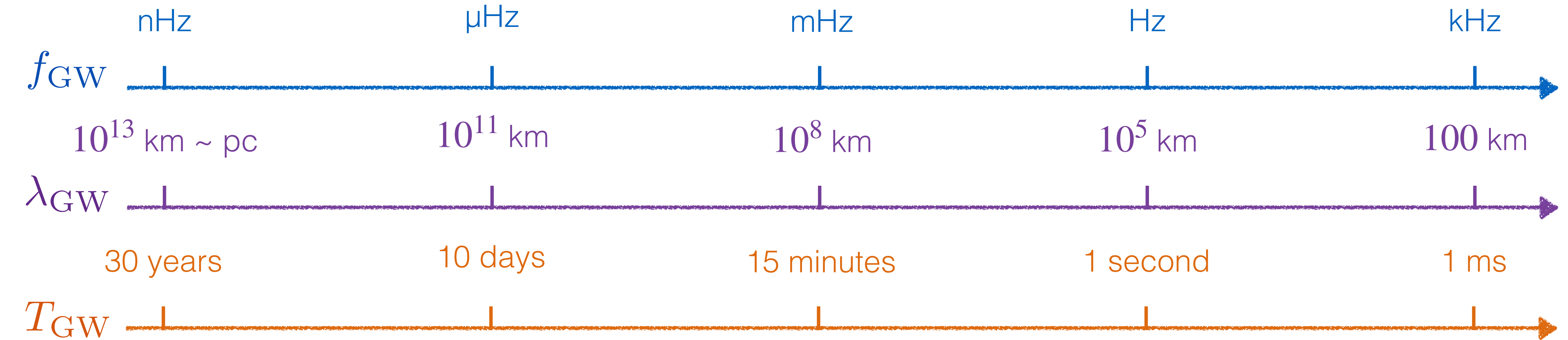
Wave-like solutions! **Gravitational Waves (GWs)**

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

Generated by moving masses...

The Gravitational Wave Spectrum

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



SOURCES



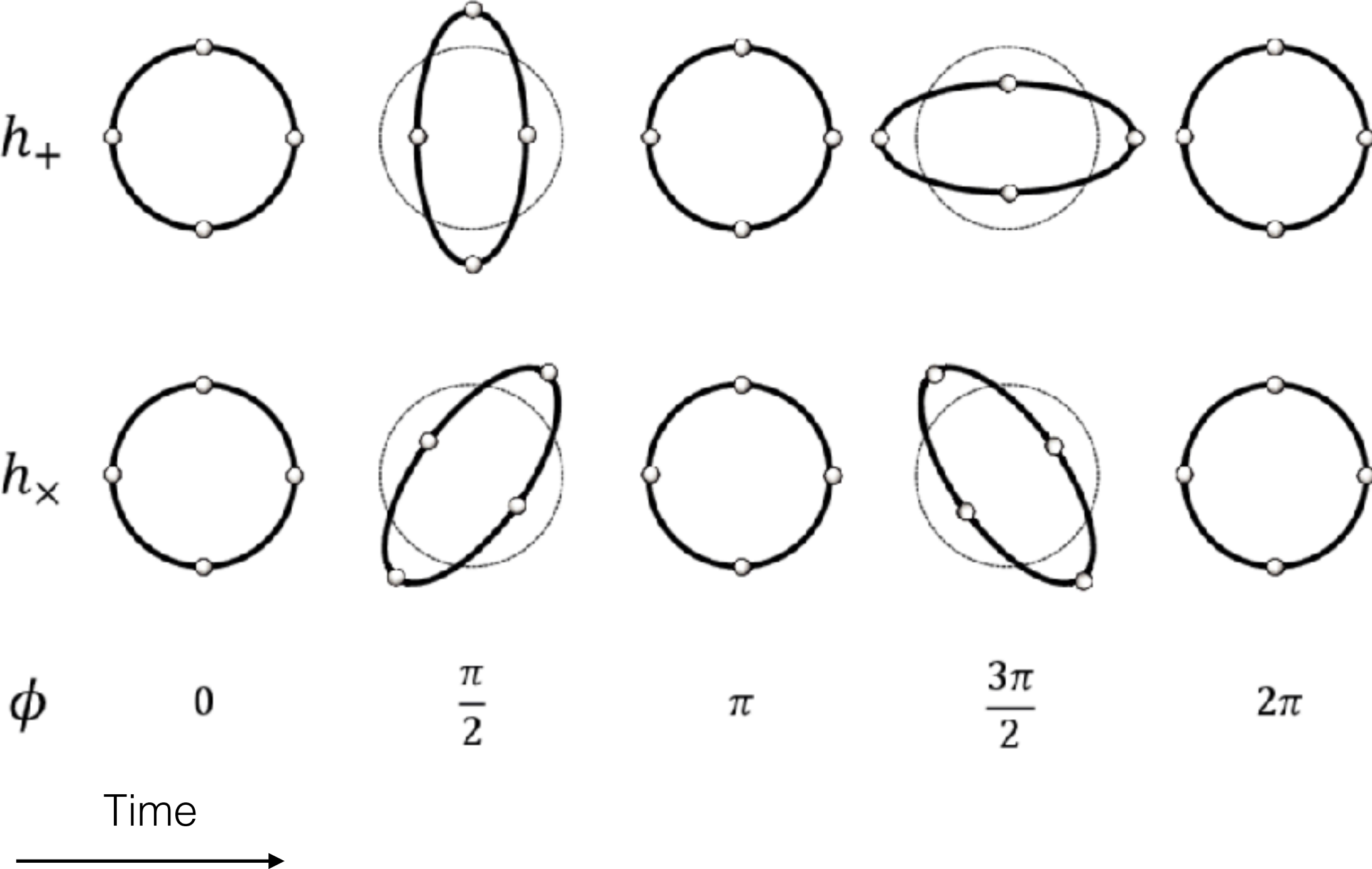
DETECTORS?



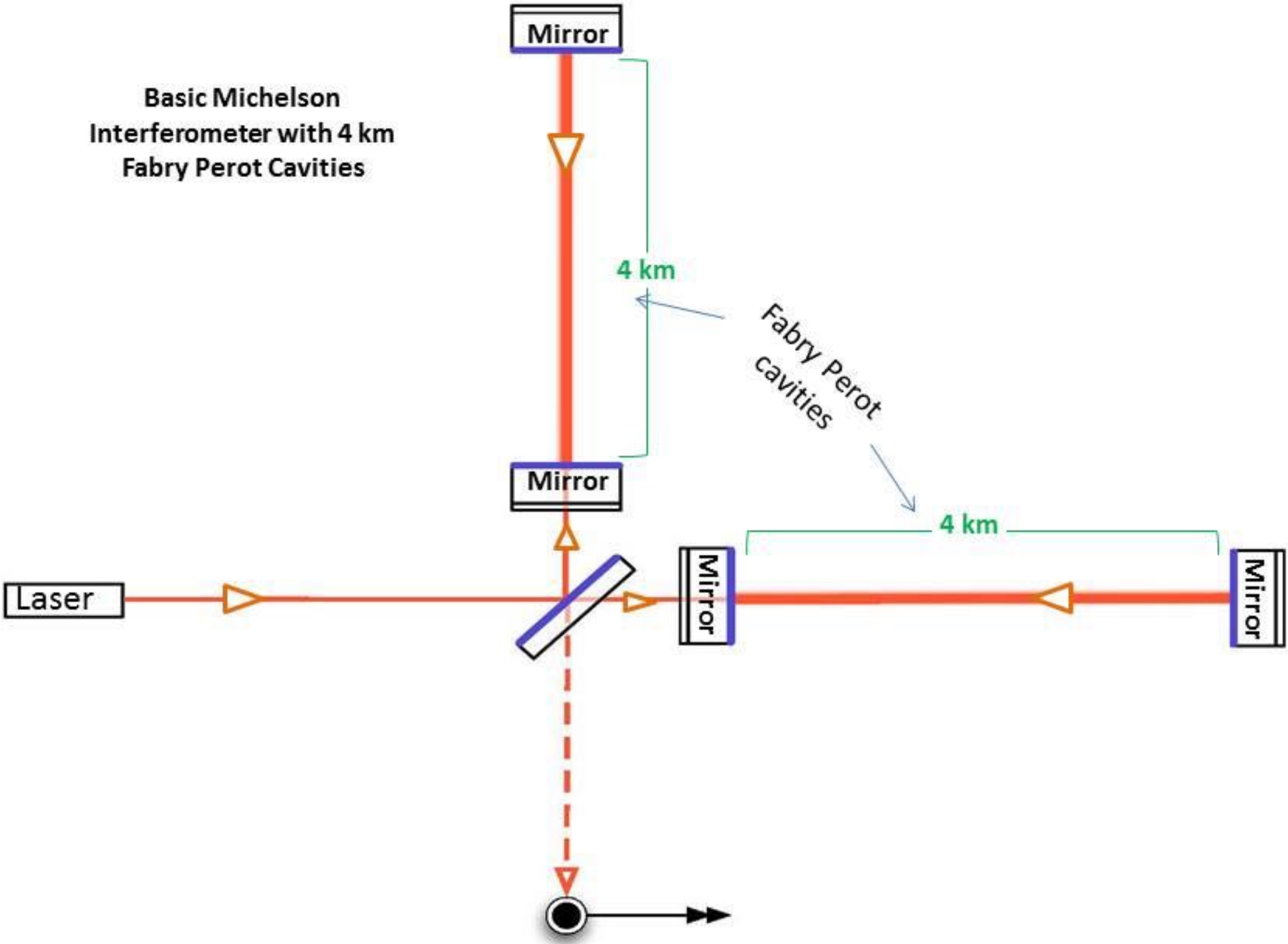
Direct detection of GWs

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

GW traveling into the screen causes (tiny) distortion:



[1708.00918](#)

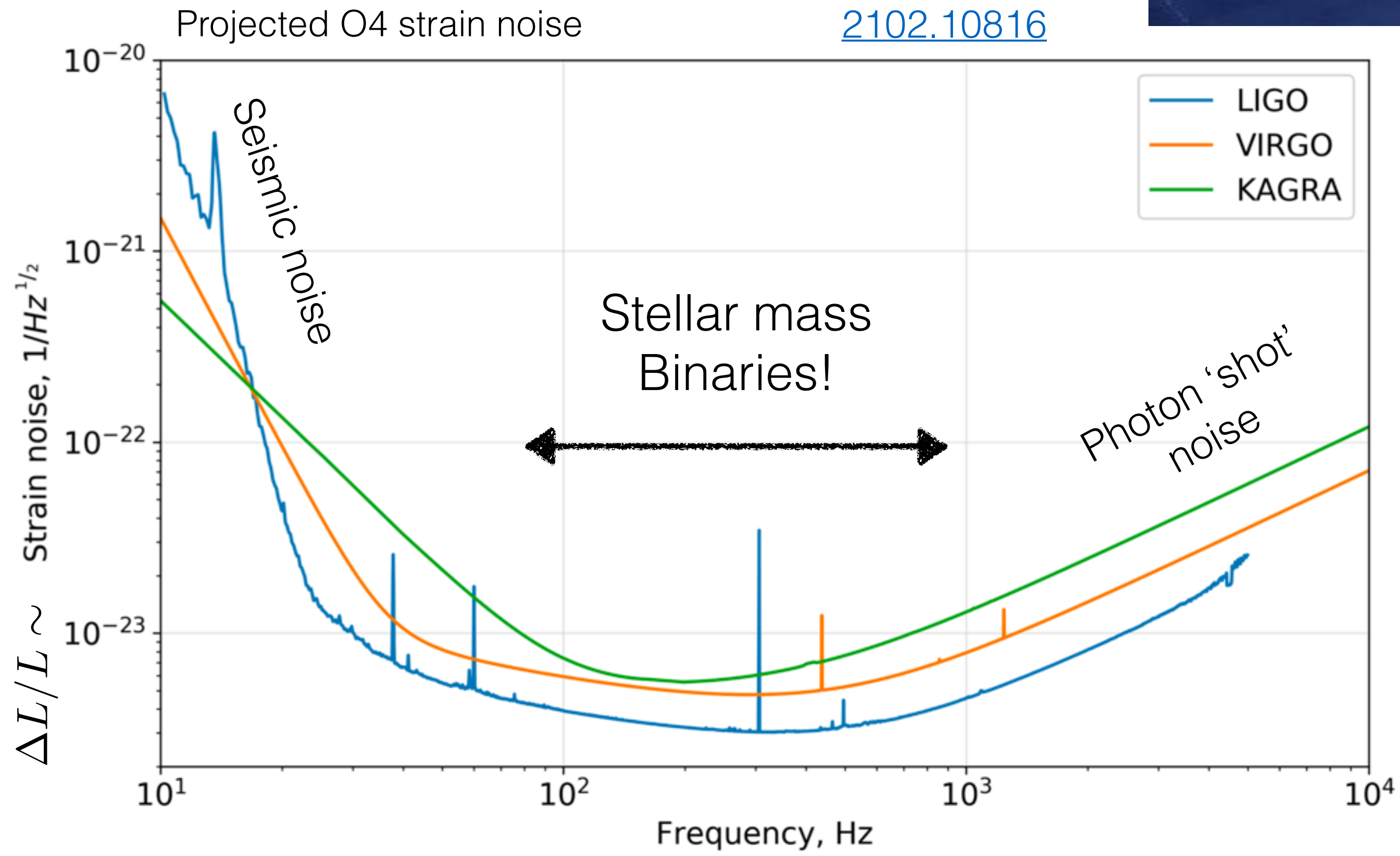


Typical GW strain is $\Delta L/L \sim 10^{-23}$!

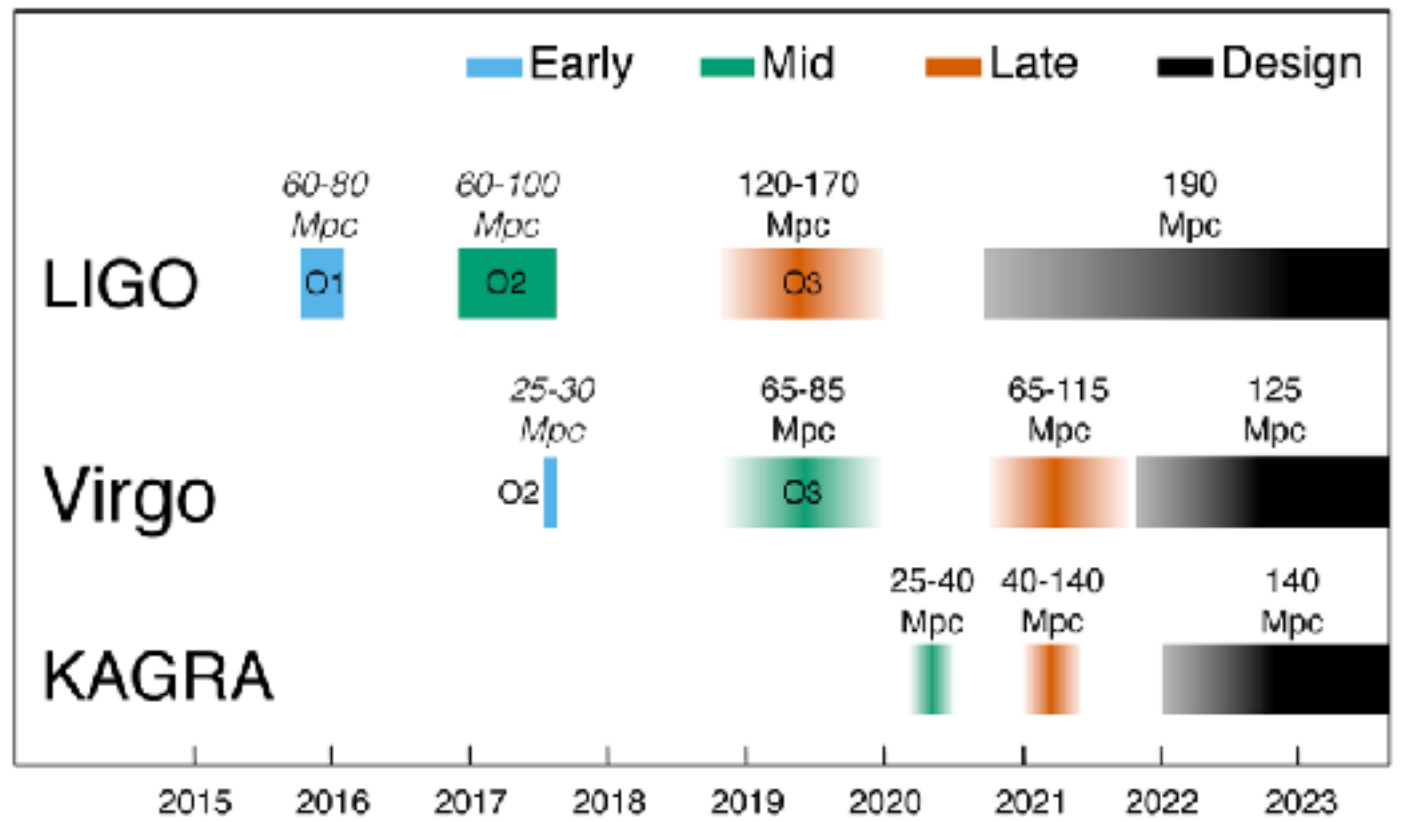
LIGO-Virgo-KAGRA (LVK)



Credit: LIGO, VIRGO & KAGRA.



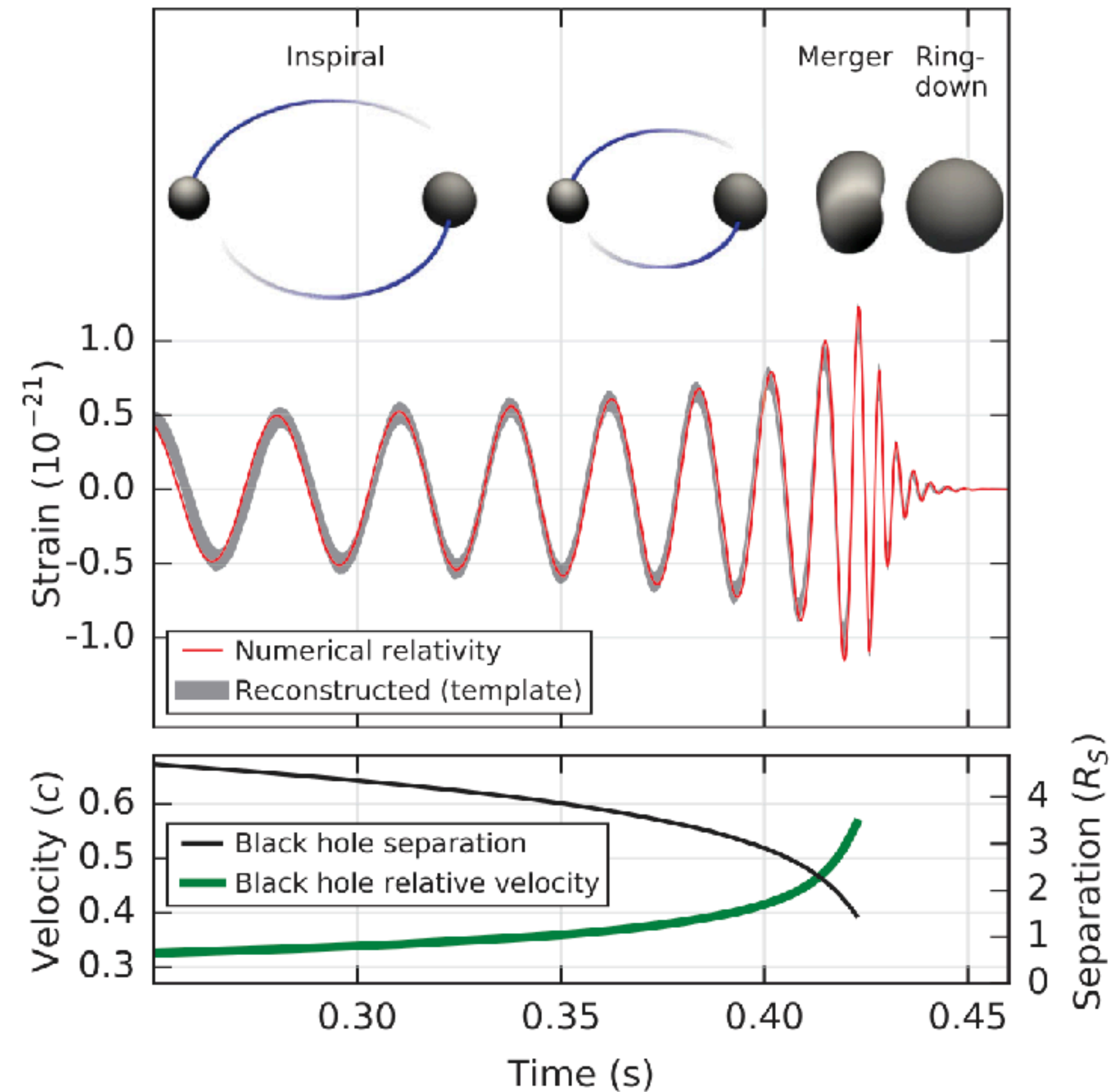
GW frequency ~ twice orbital frequency.



[1906.03643](https://www.ligo.caltech.edu/1906.03643)

GW150914 - the first BH-BH merger

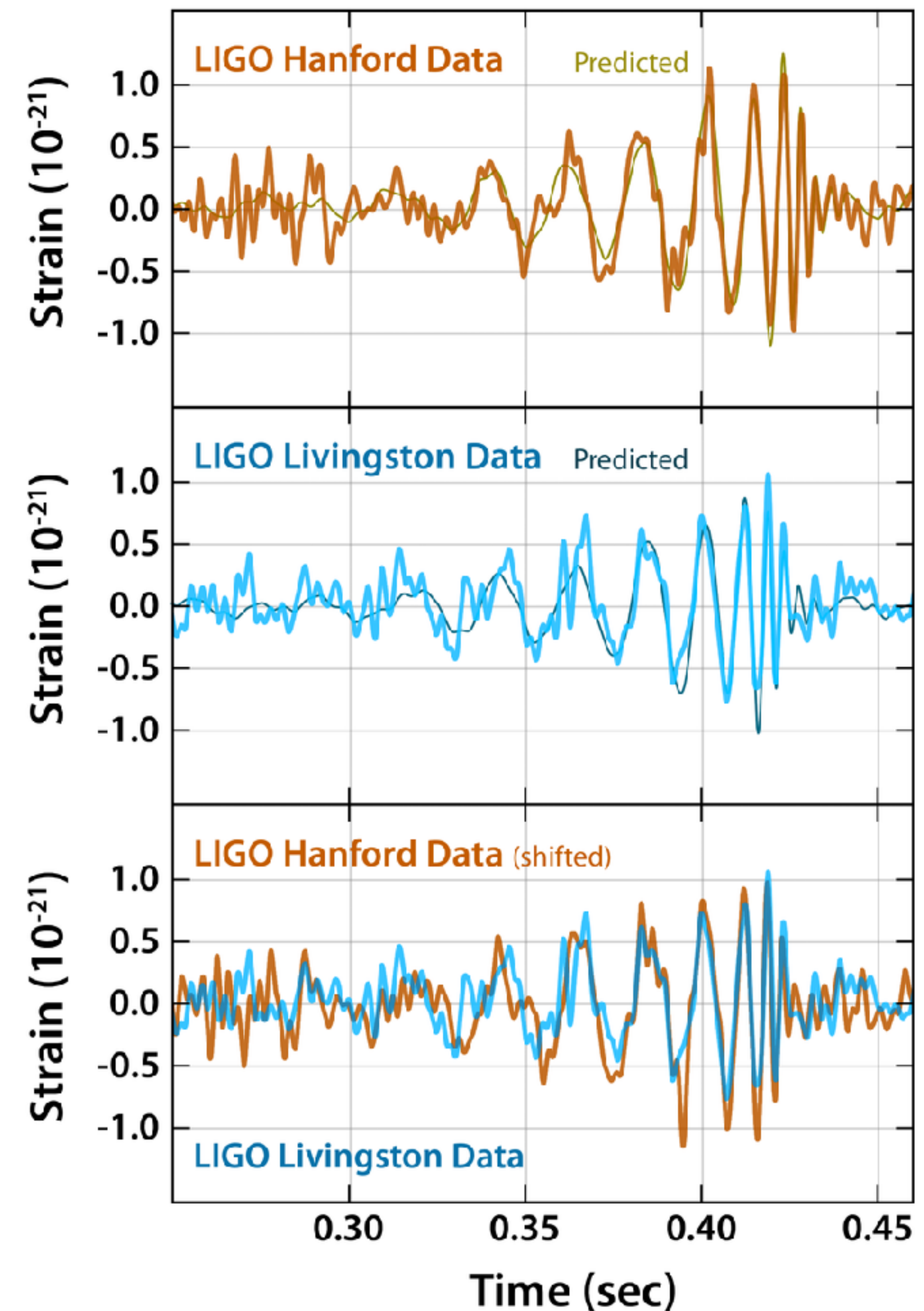
14 September 2015



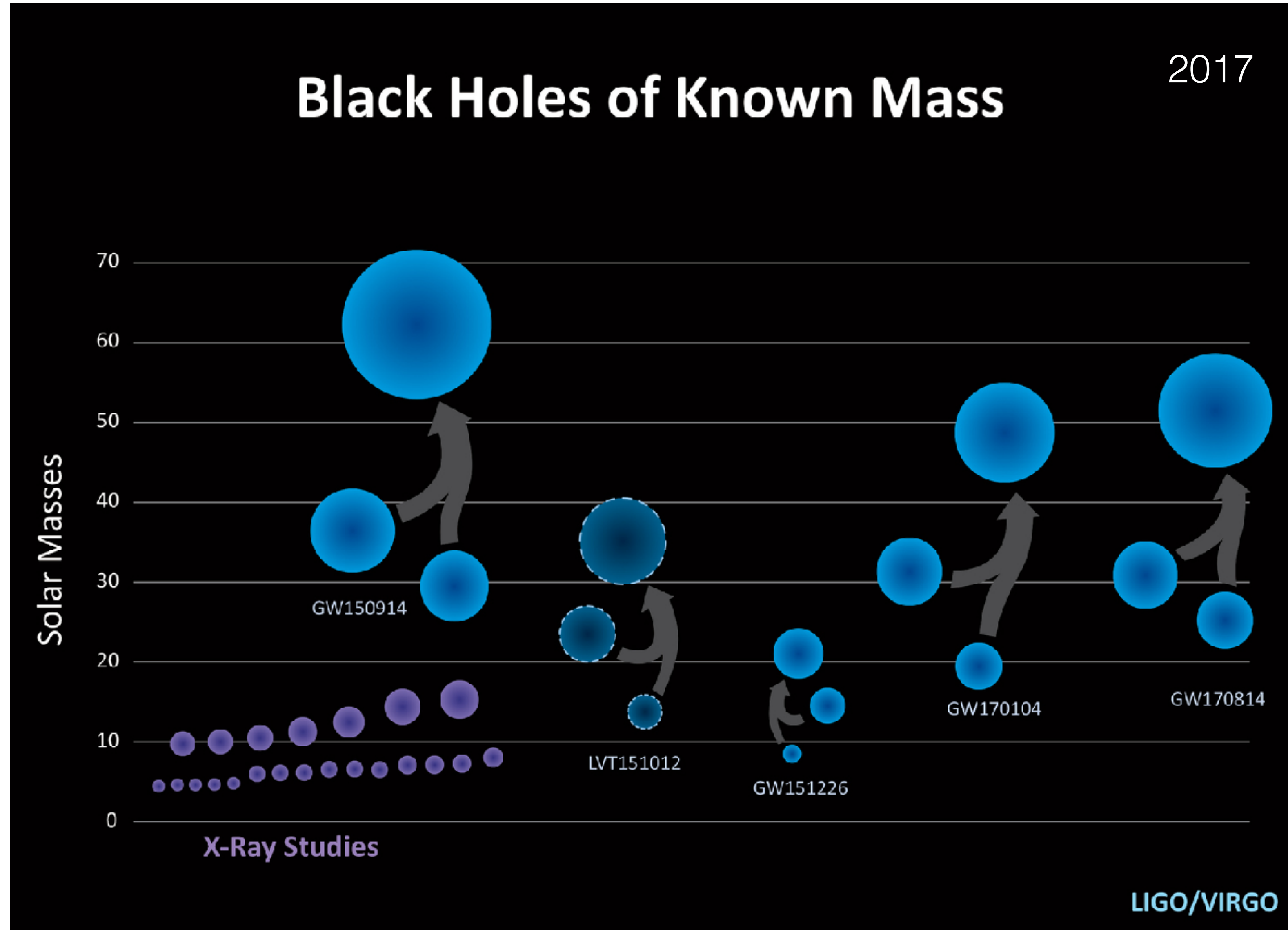
Merger of two BHs - with masses $36 M_{\odot}$ and $29 M_{\odot}$
at a luminosity distance of $d_L \approx 200 - 600$ Mpc!

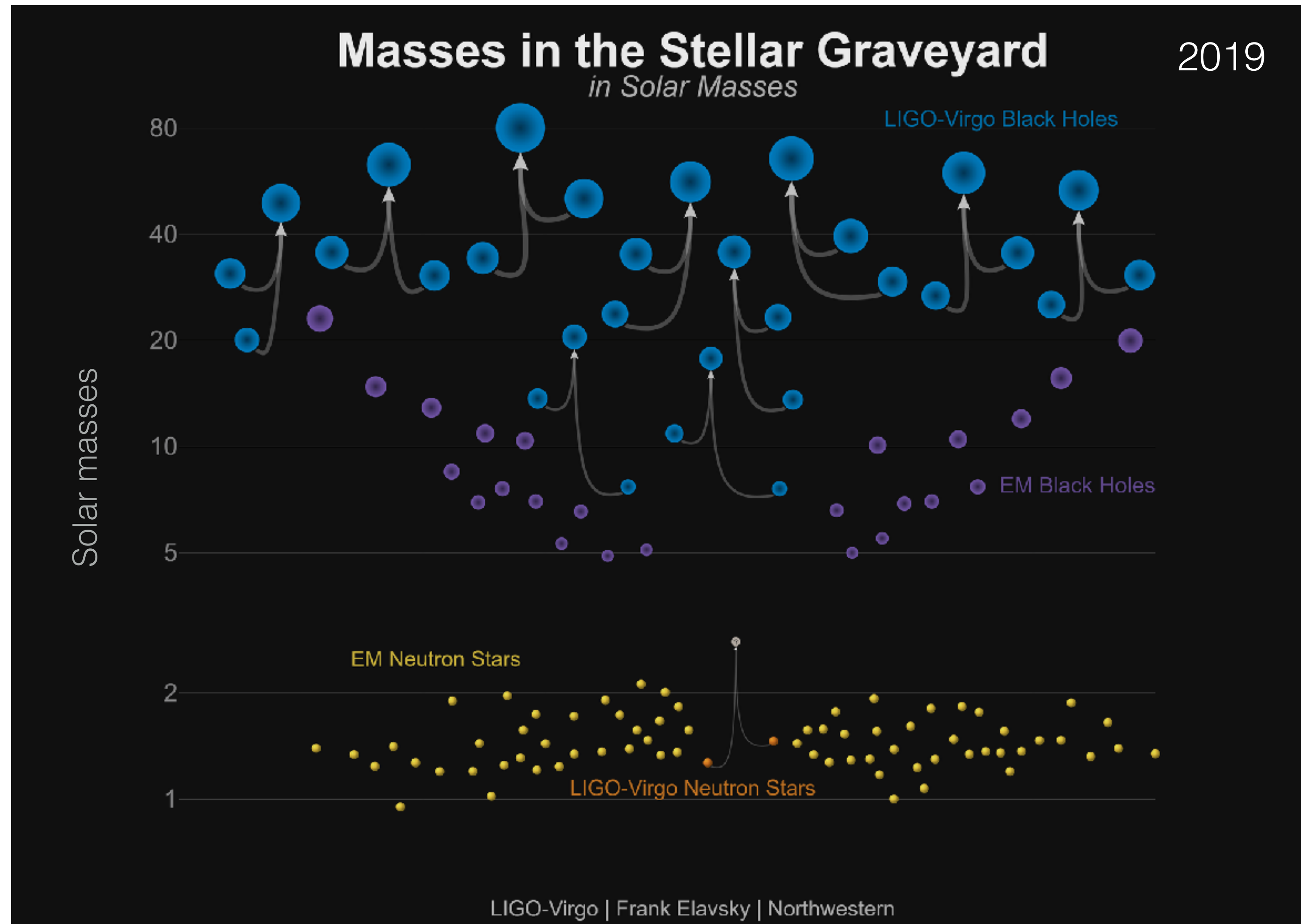
[1602.03840](https://arxiv.org/abs/1602.03840)

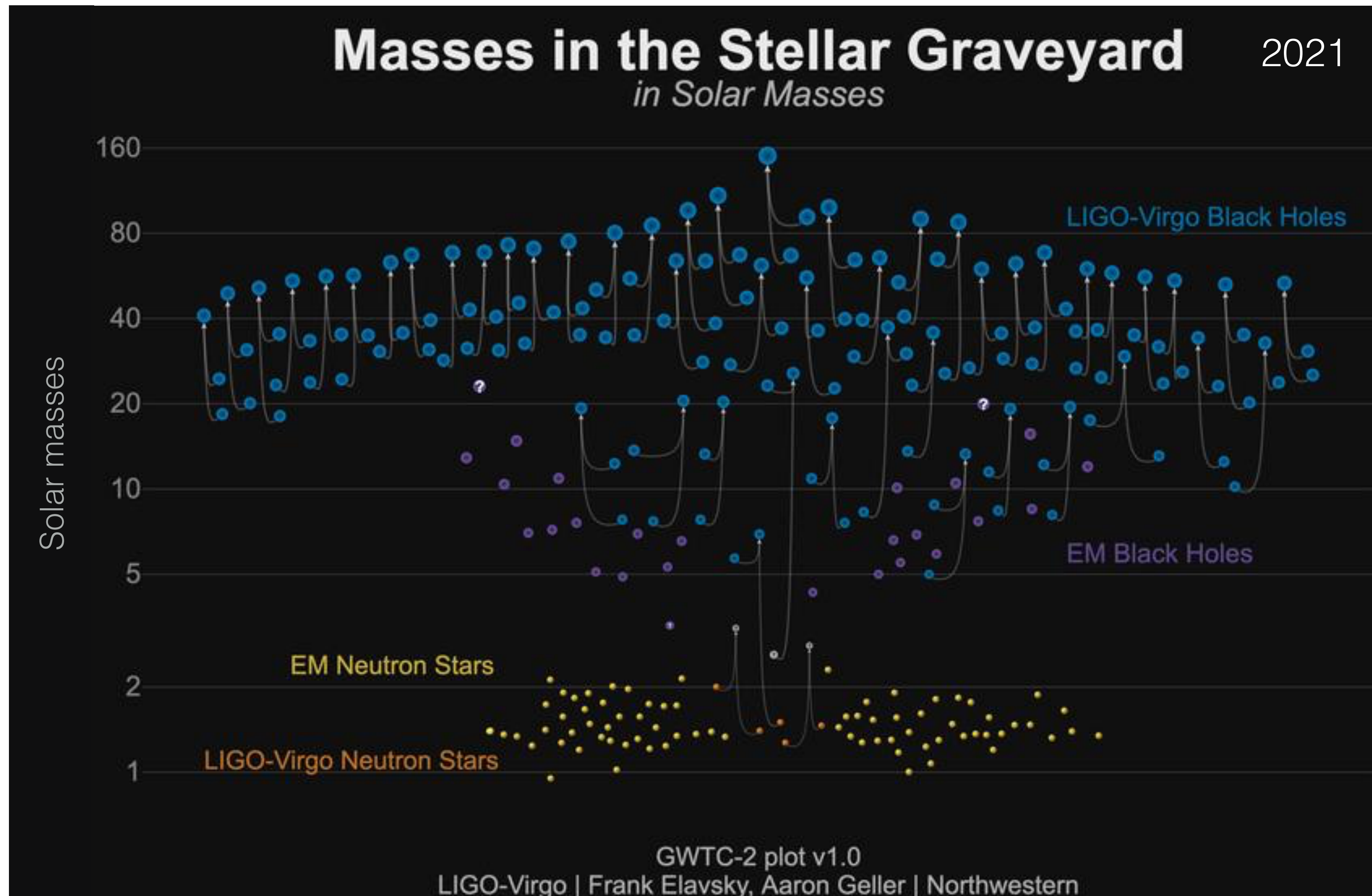
Credit: Caltech/MIT/LIGO Lab

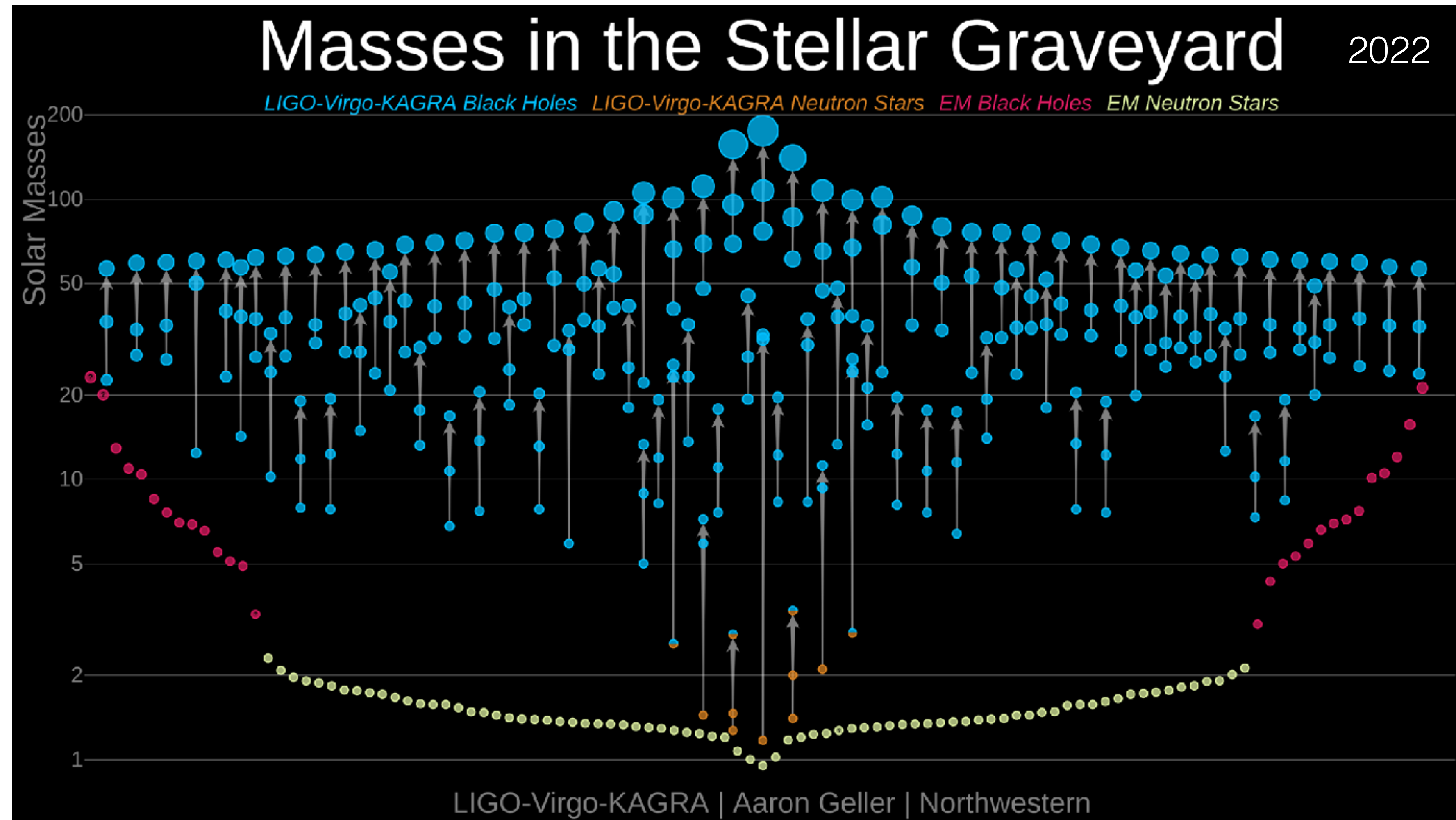


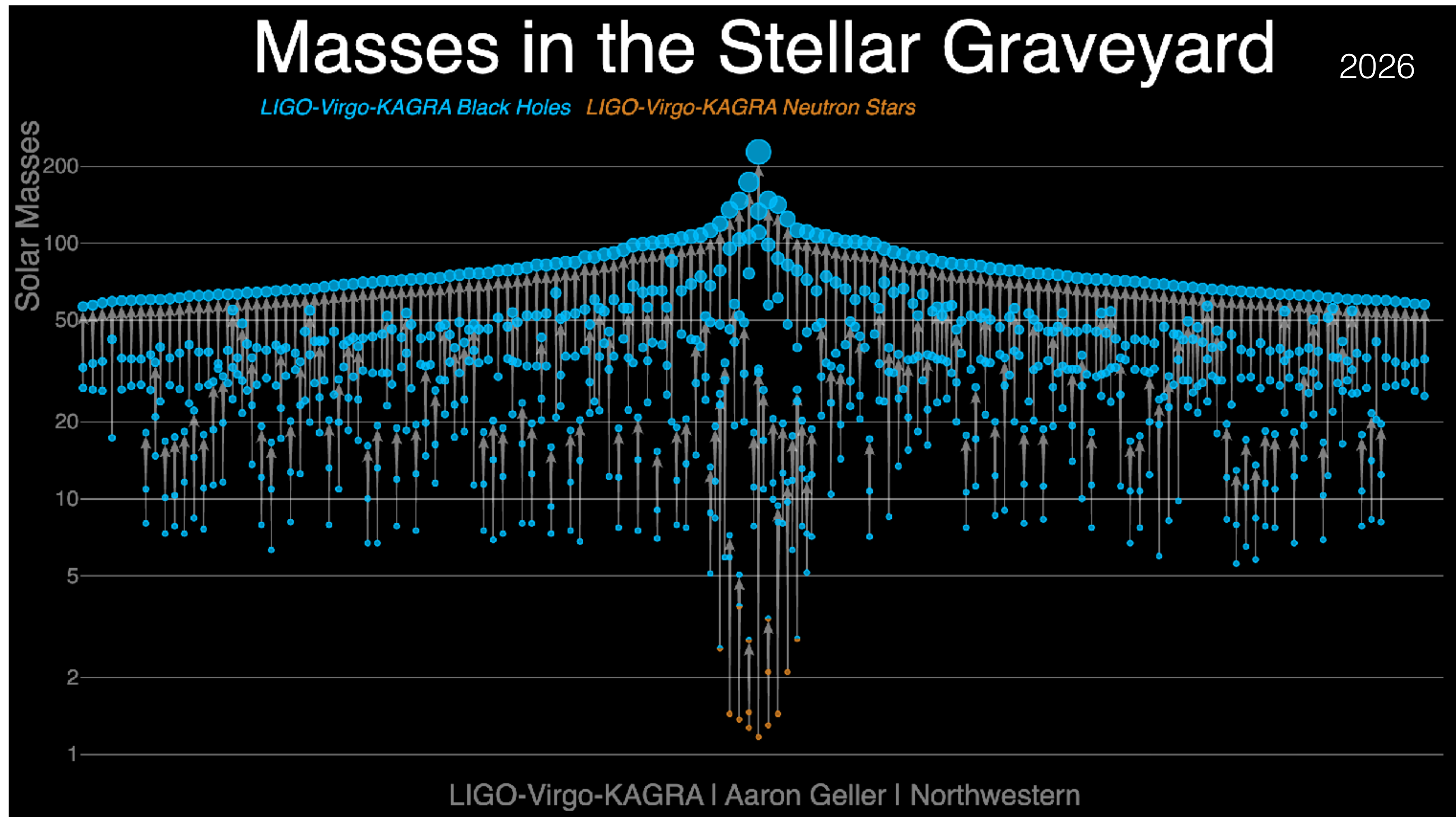
Try it yourself! - <https://www.gw-openscience.org/tutorials/>



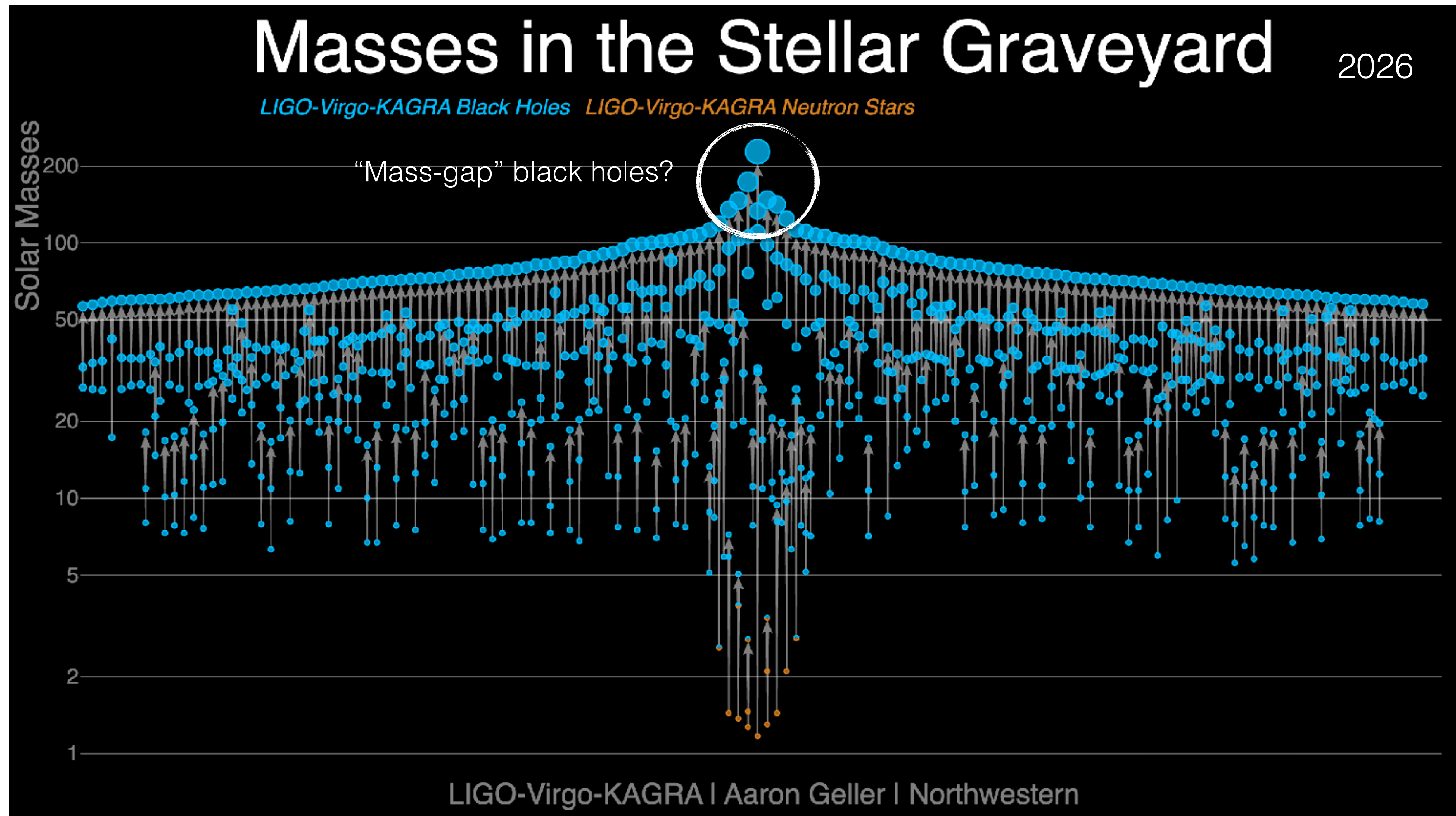








[2007.07889](#)



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 $m_{\text{BH}} \sim 50 - 130 M_{\odot}$ (so-called *pair-instability* supernovae do not leave behind a BH).

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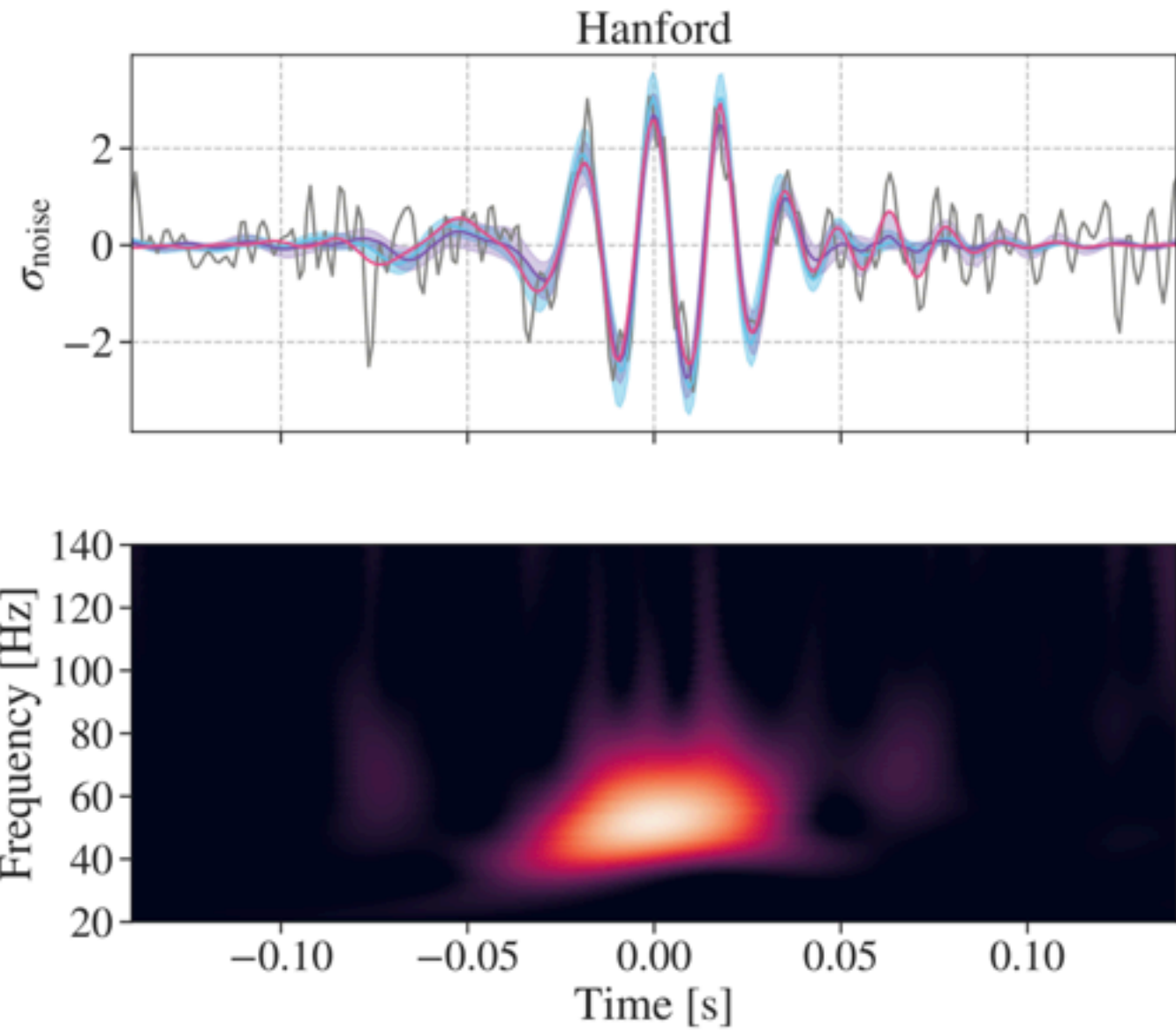
GW231123: a Binary Black Hole Merger with Total Mass 190-265 $M_{\odot}$

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 $60\text{--}130 M_{\odot}$ 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 $\sim 200 M_{\odot}$ form through gravitational-wave driven mergers.



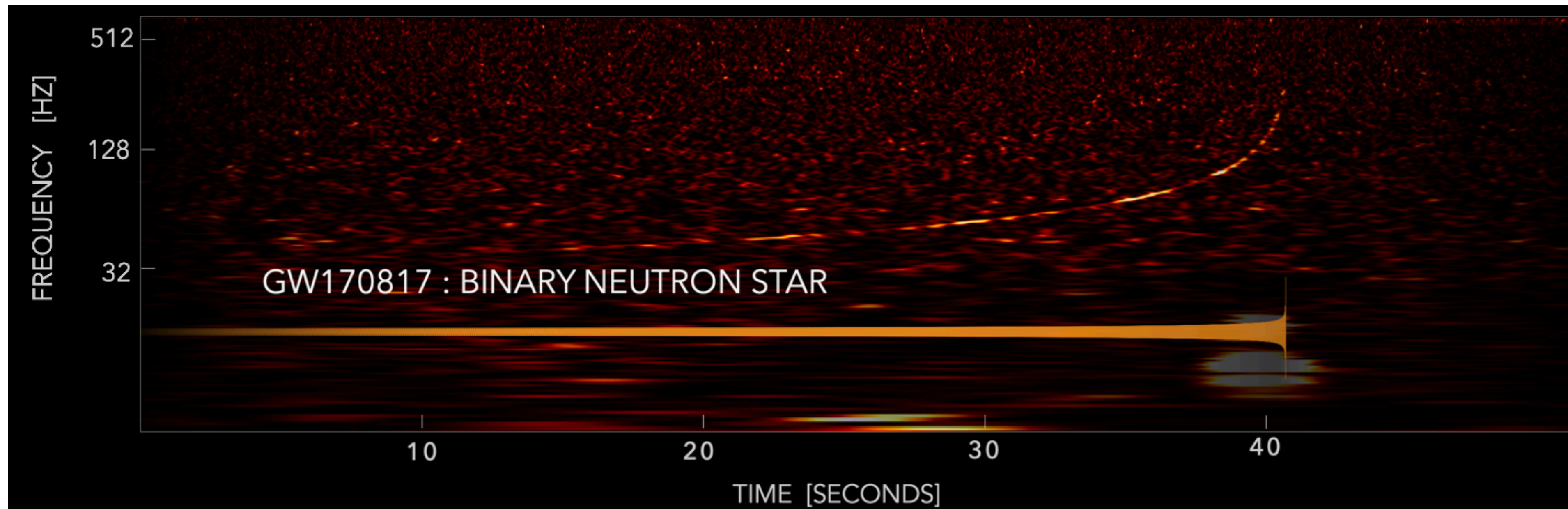
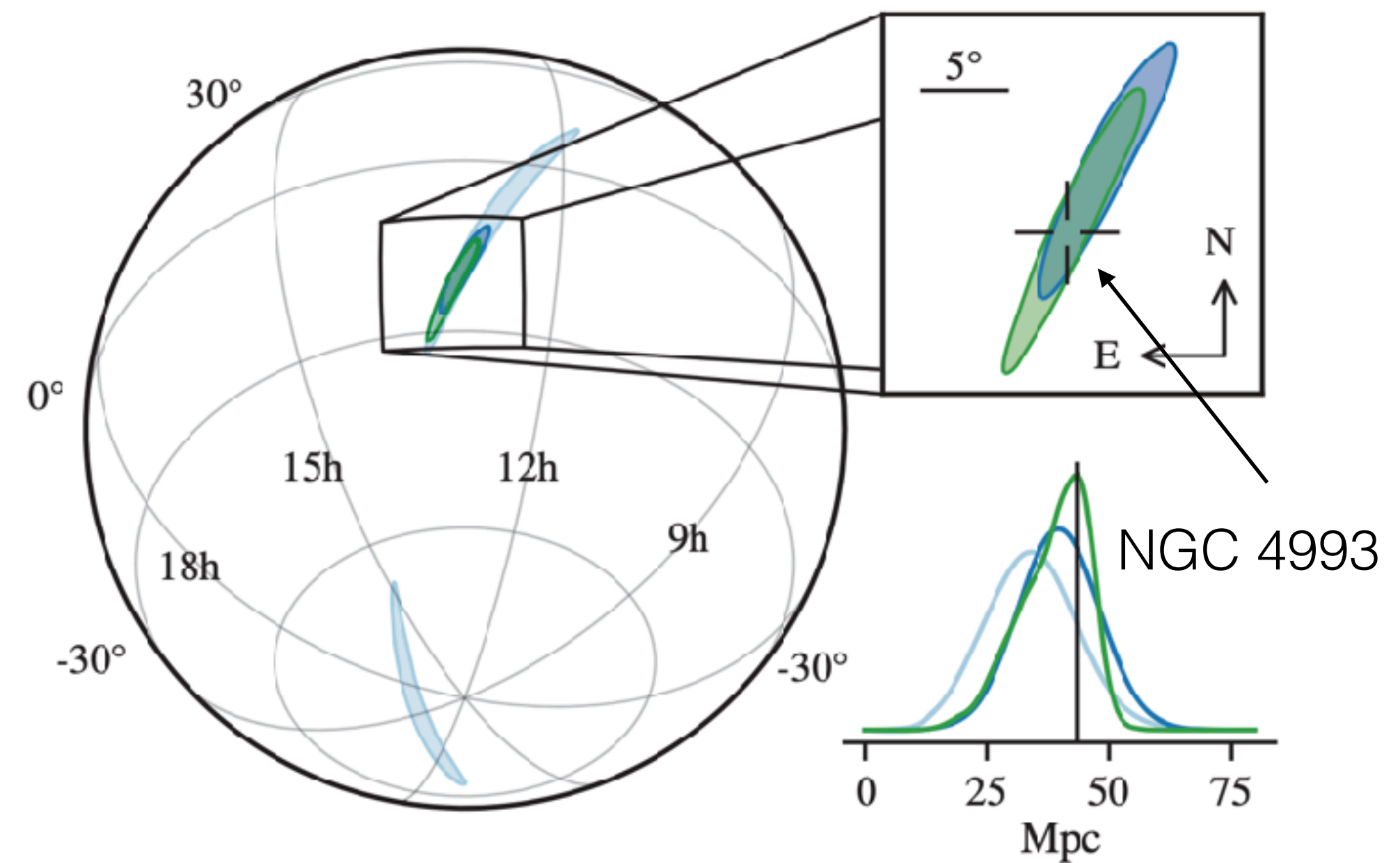
Primary mass $m_1/M_{\odot}$	137^{+22}_{-17}
Secondary mass $m_2/M_{\odot}$	103^{+20}_{-52}
Mass ratio $q = m_2/m_1$	$0.75^{+0.22}_{-0.39}$
Total mass $M/M_{\odot}$	238^{+28}_{-49}
Final mass $M_f/M_{\odot}$	225^{+26}_{-43}
Primary spin magnitude χ_1	$0.90^{+0.10}_{-0.19}$
Secondary spin magnitude χ_2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

[2507.08219]

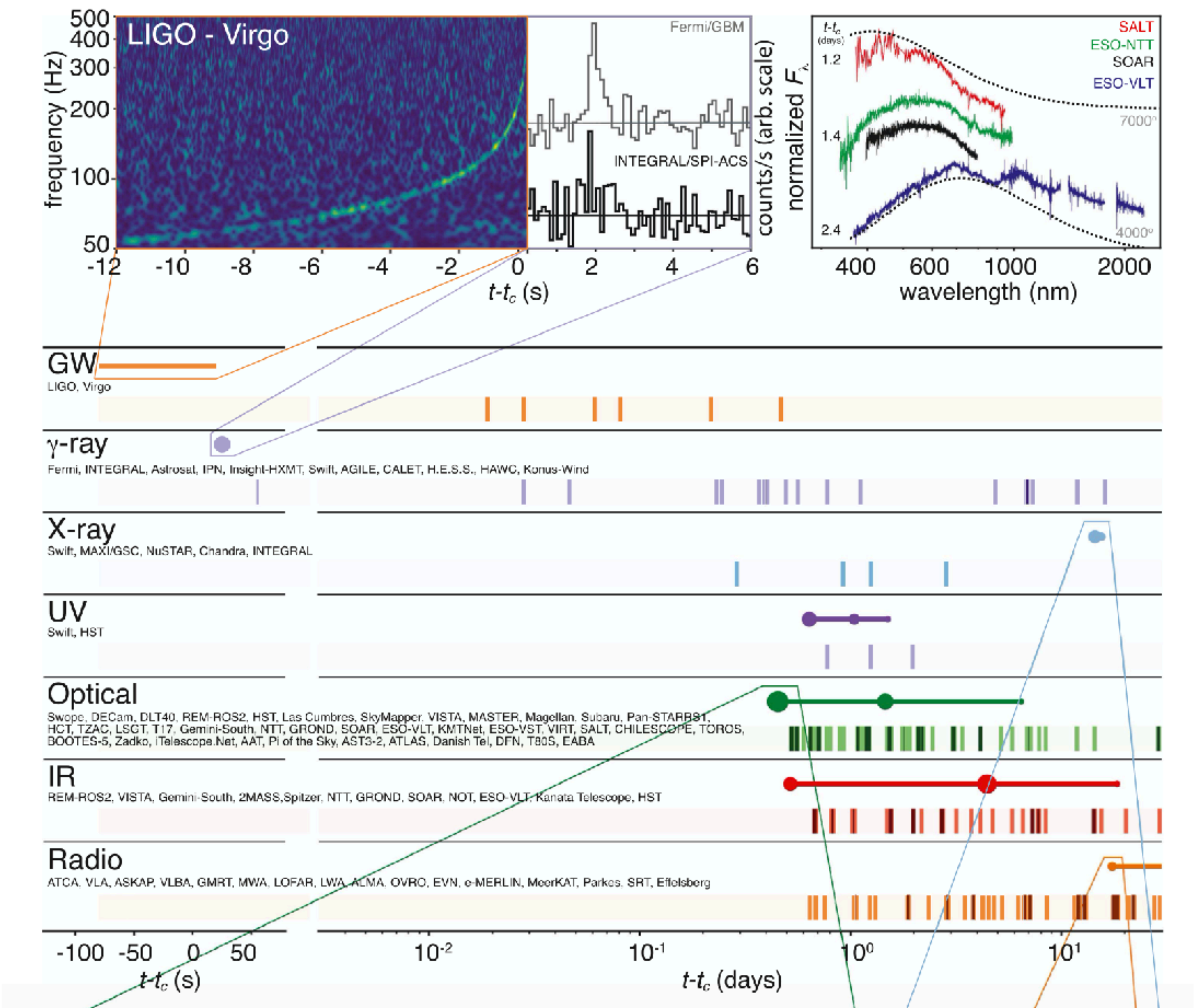
GW170817 - the first NS-NS merger

17 August 2017 - observation of the merger
of two $\sim 1.5 - 2.0 M_{\odot}$ neutron stars
(stars at nuclear density with radii ~ 10 km)

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



Multi-messenger follow-up



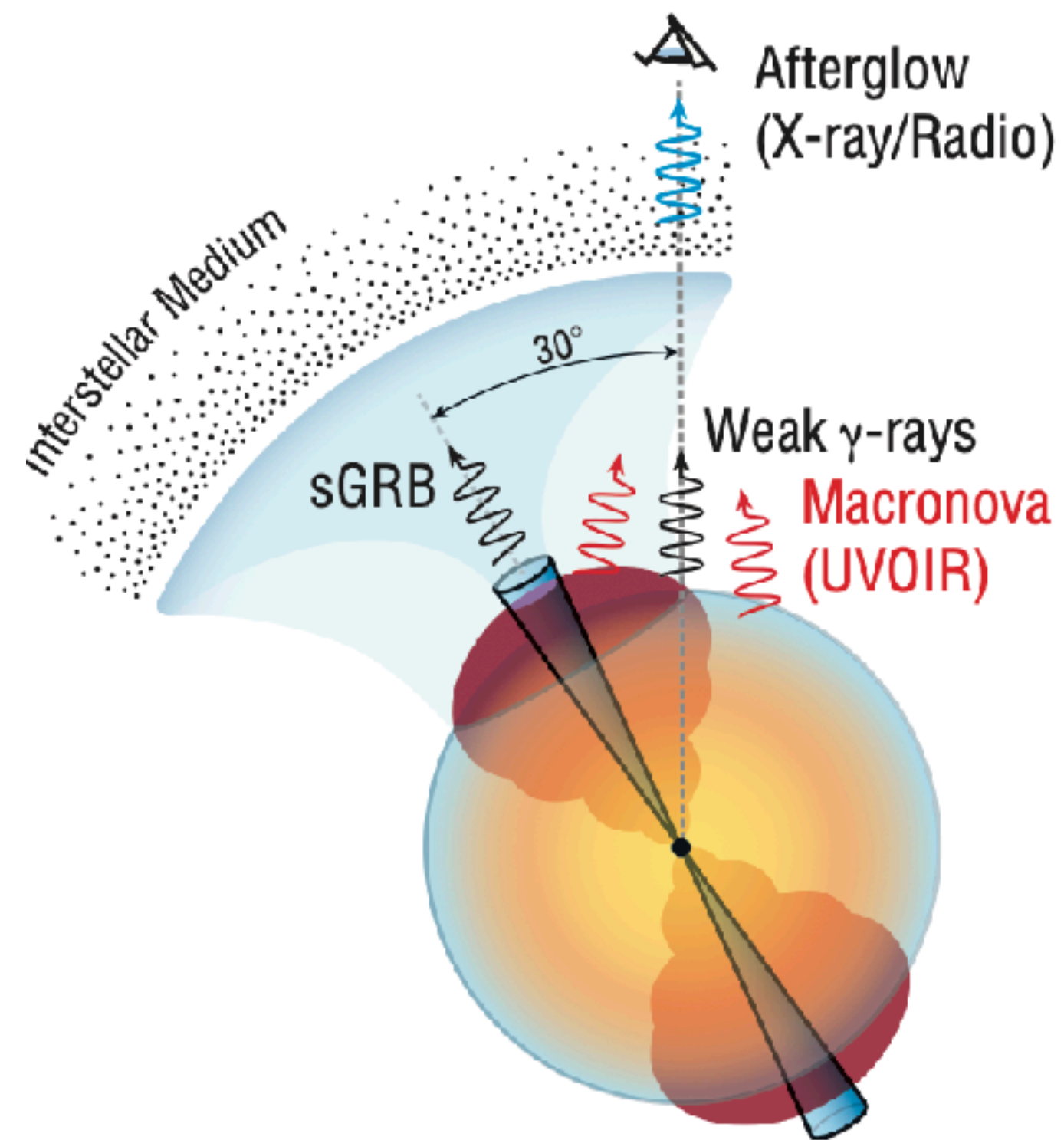
GW170817 merger occurred just two seconds before the gamma-ray burst GRB 170817A

Follow-up observations across the spectrum!

Sadly no neutrinos detected :(

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!

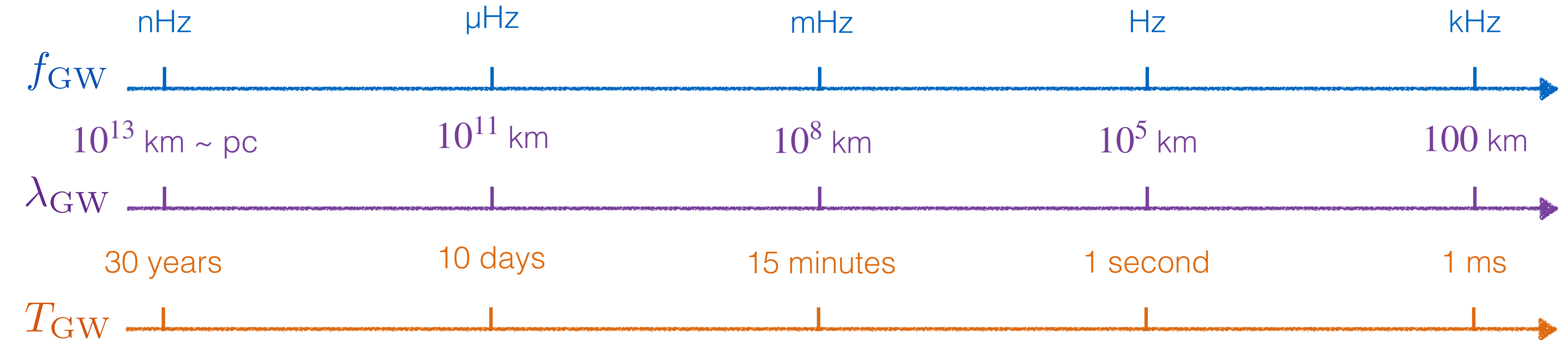
[1710.06394](#)

Measurement of the Hubble Constant!

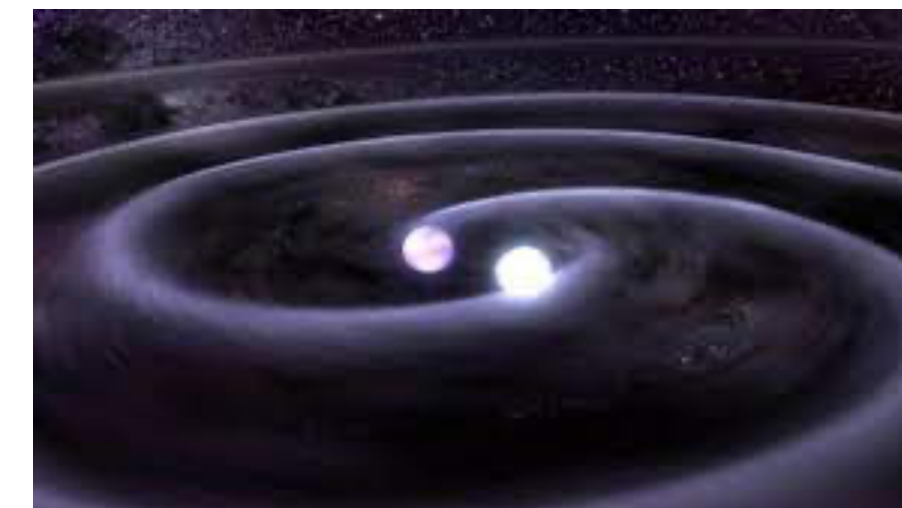
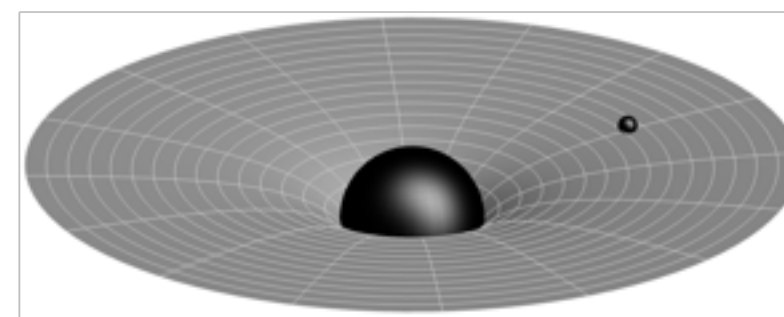
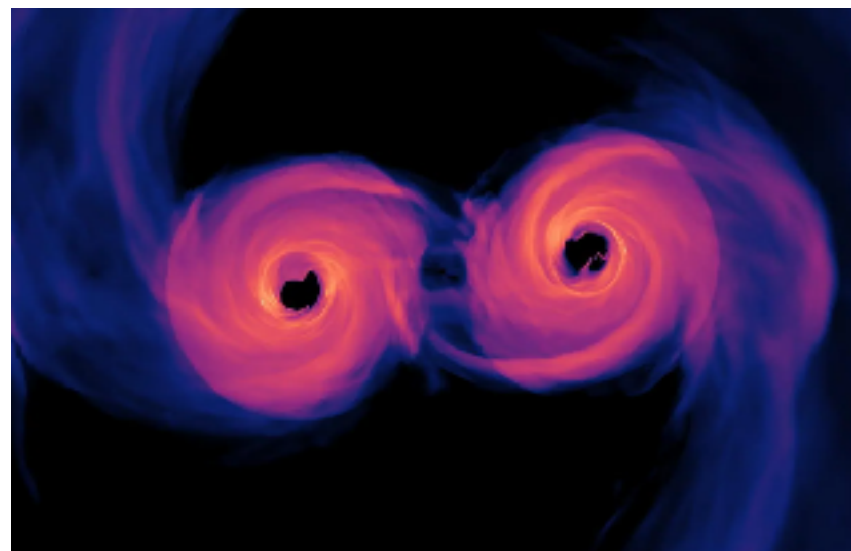
[1710.05835](#)

The Gravitational Wave Spectrum

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

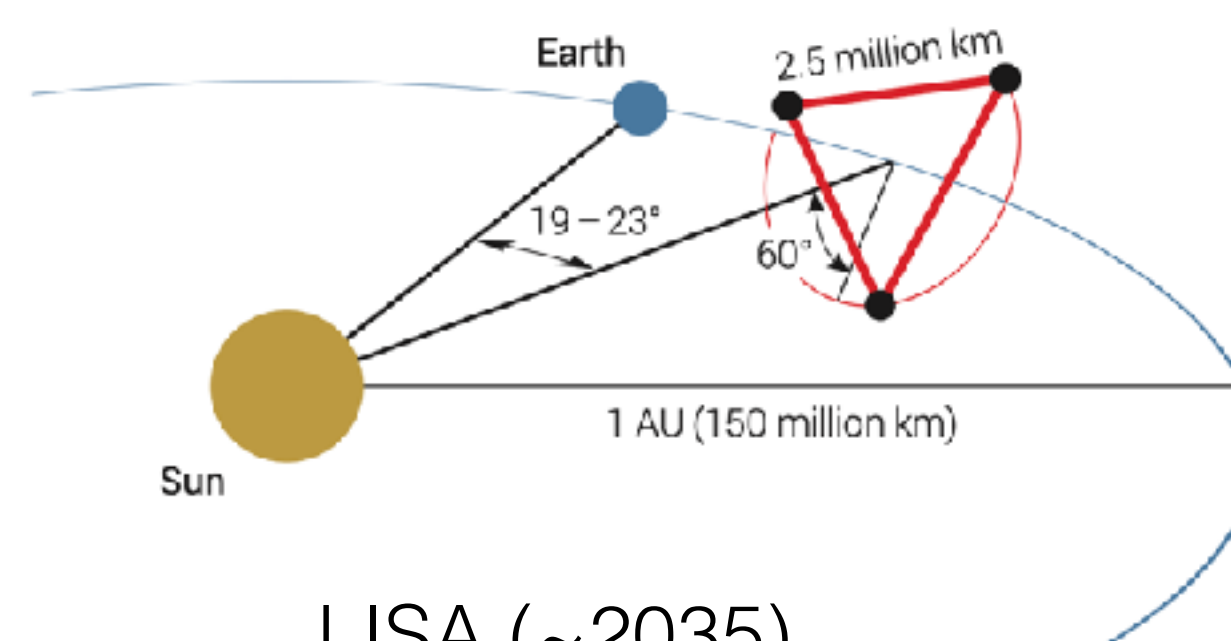


SOURCES



DETECTORS?

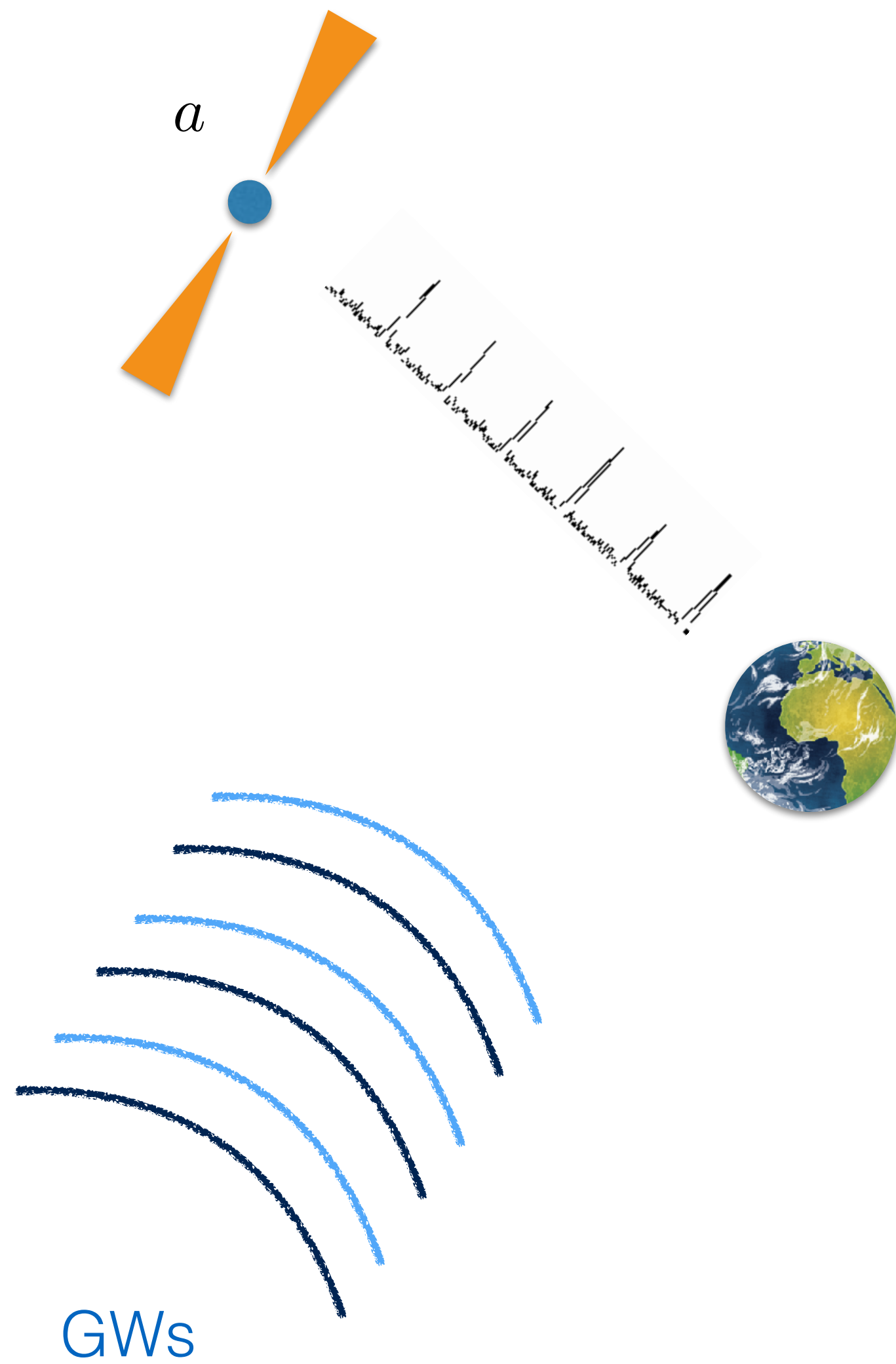
?



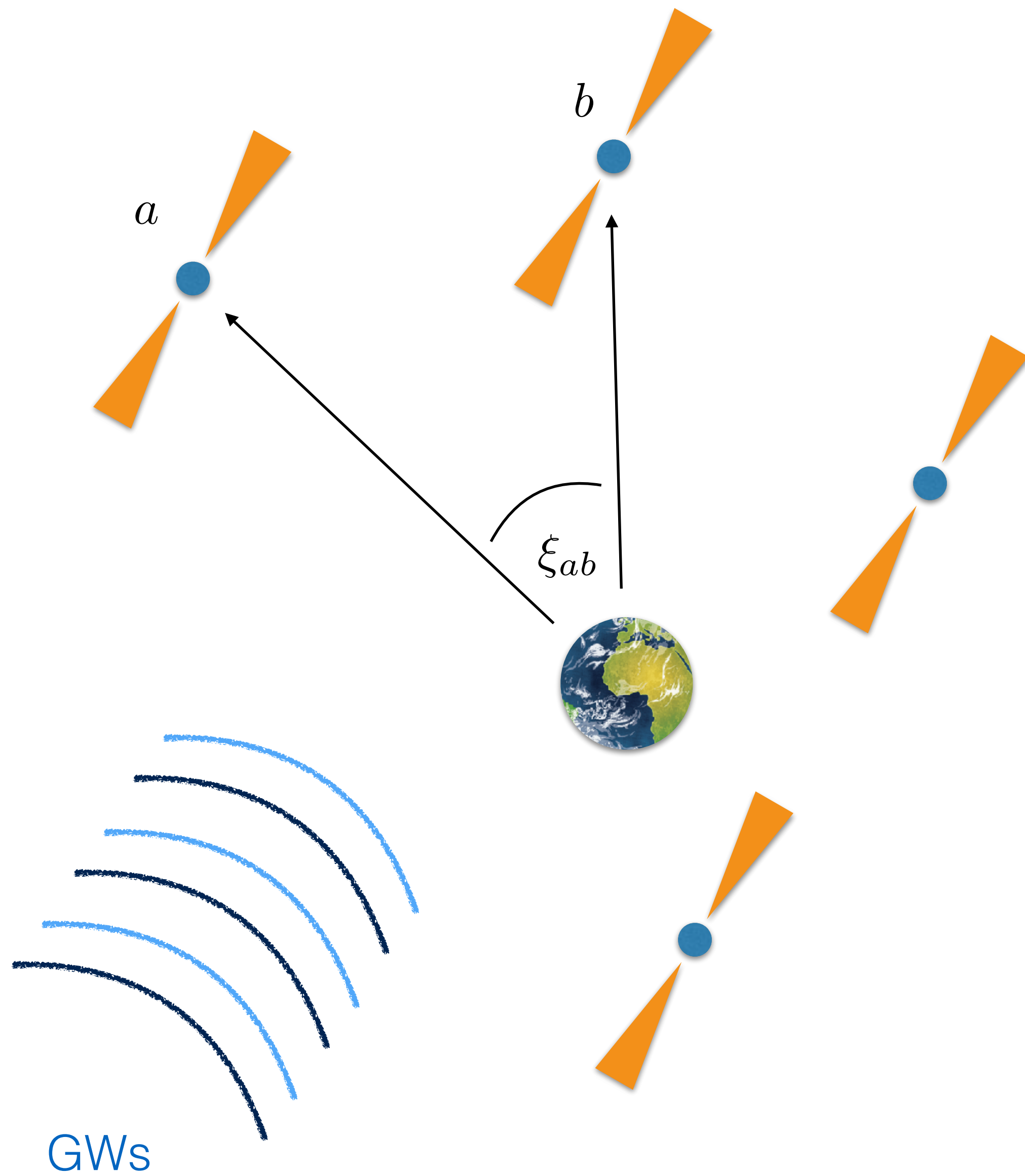
LISA (~2035)



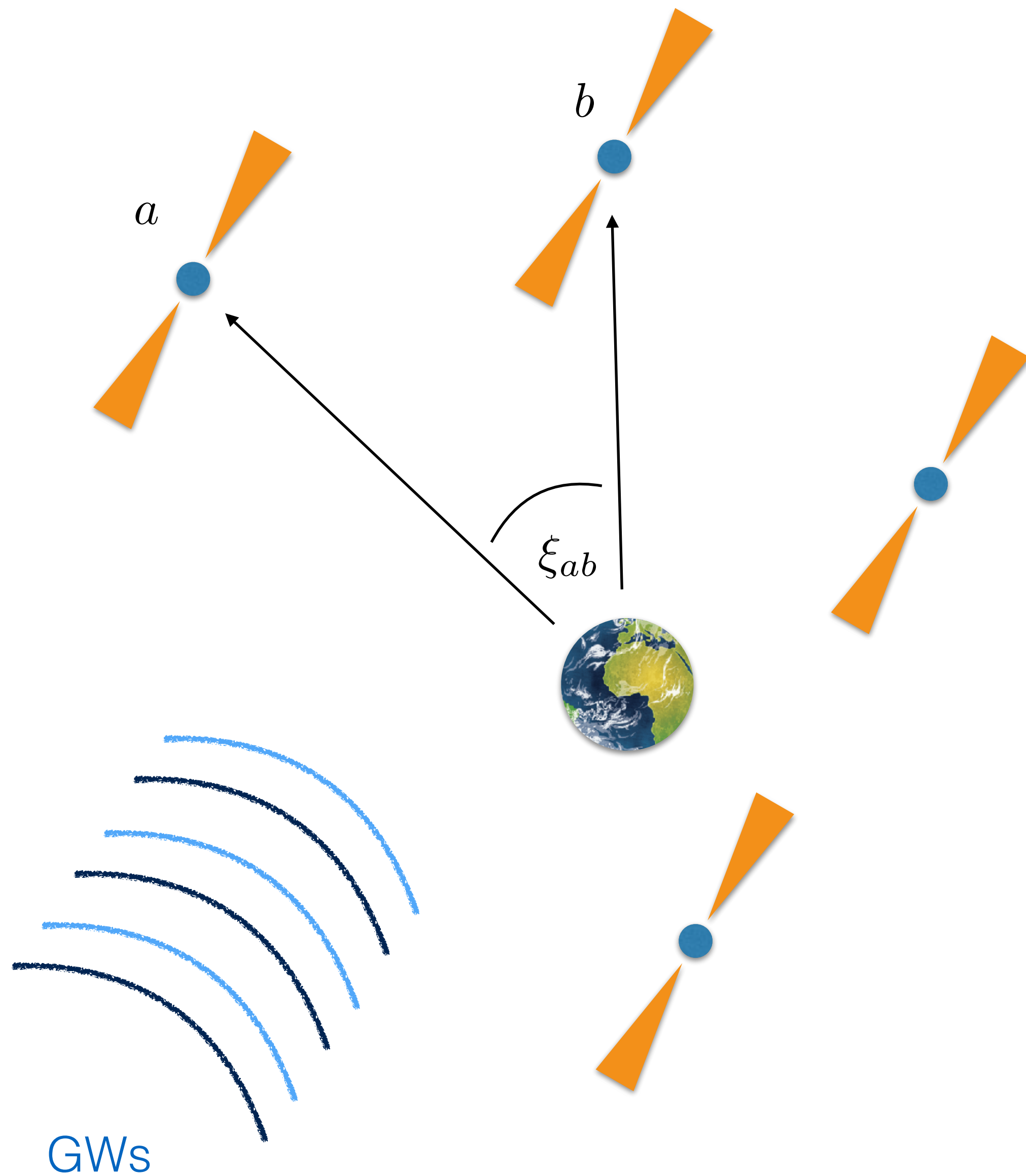
Pulsar Timing Arrays (PTA)



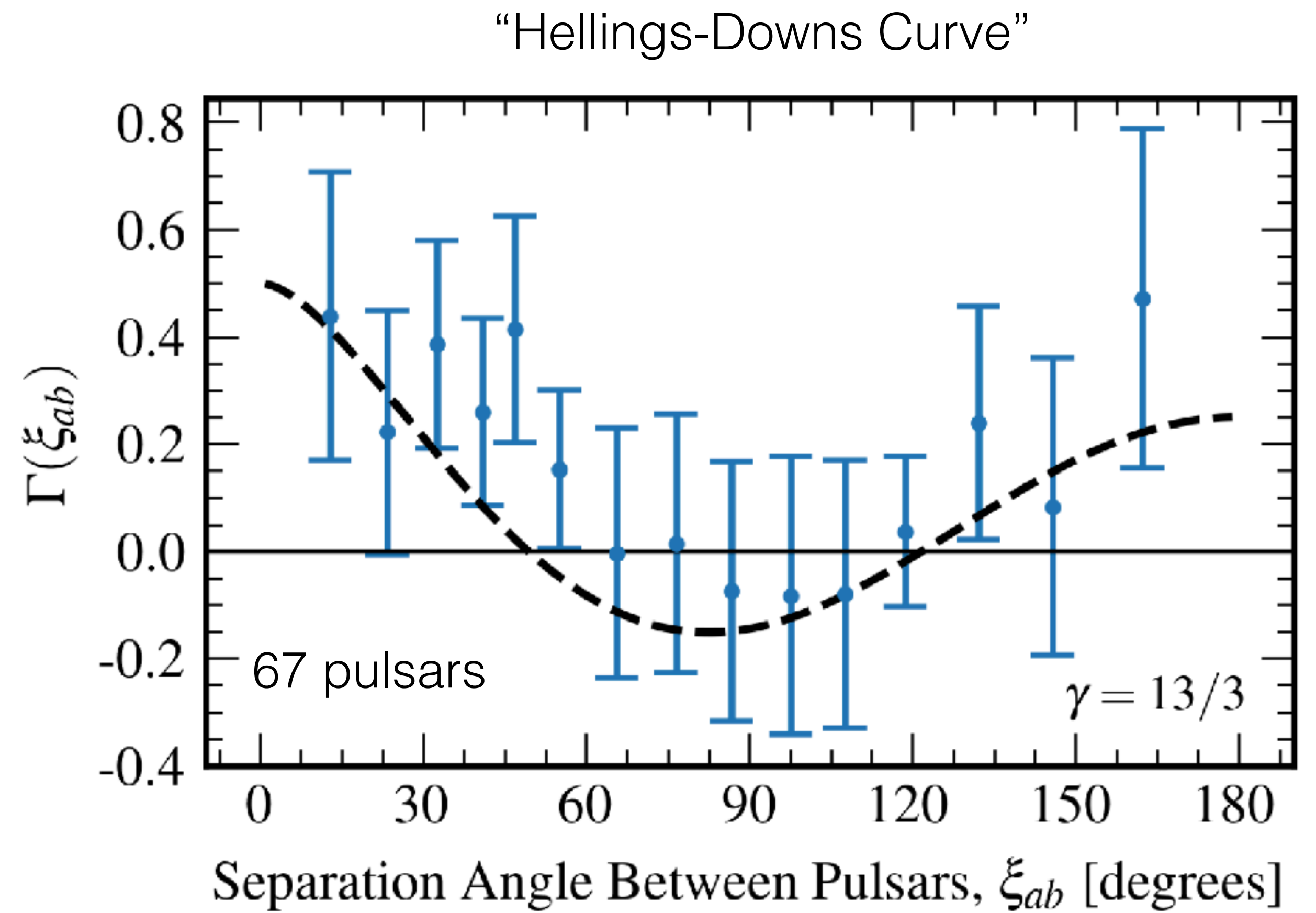
Pulsar Timing Arrays (PTA)



Pulsar Timing Arrays (PTA)



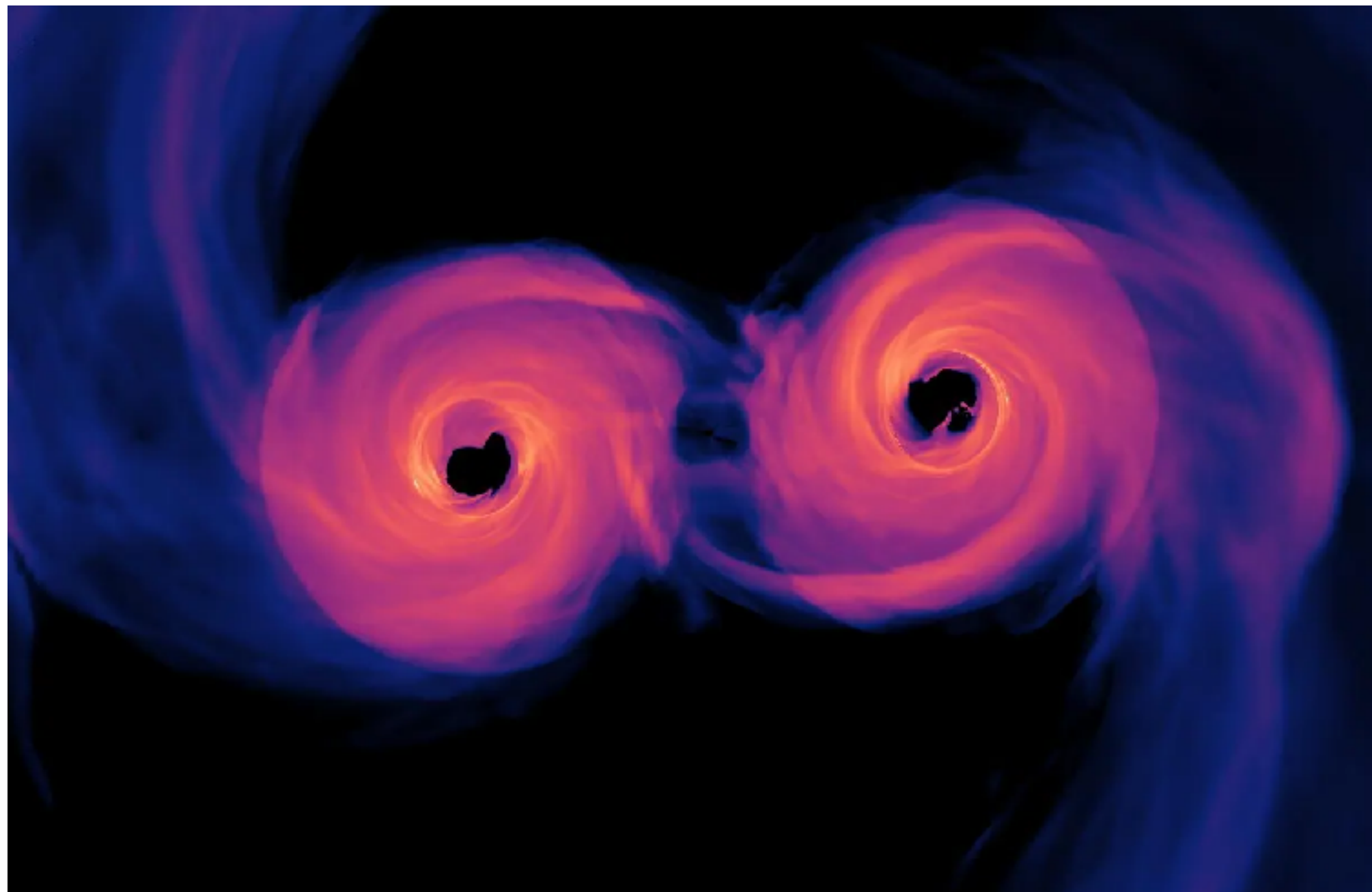
Correlations between timing residuals δt



Sources of Nanohertz GWs

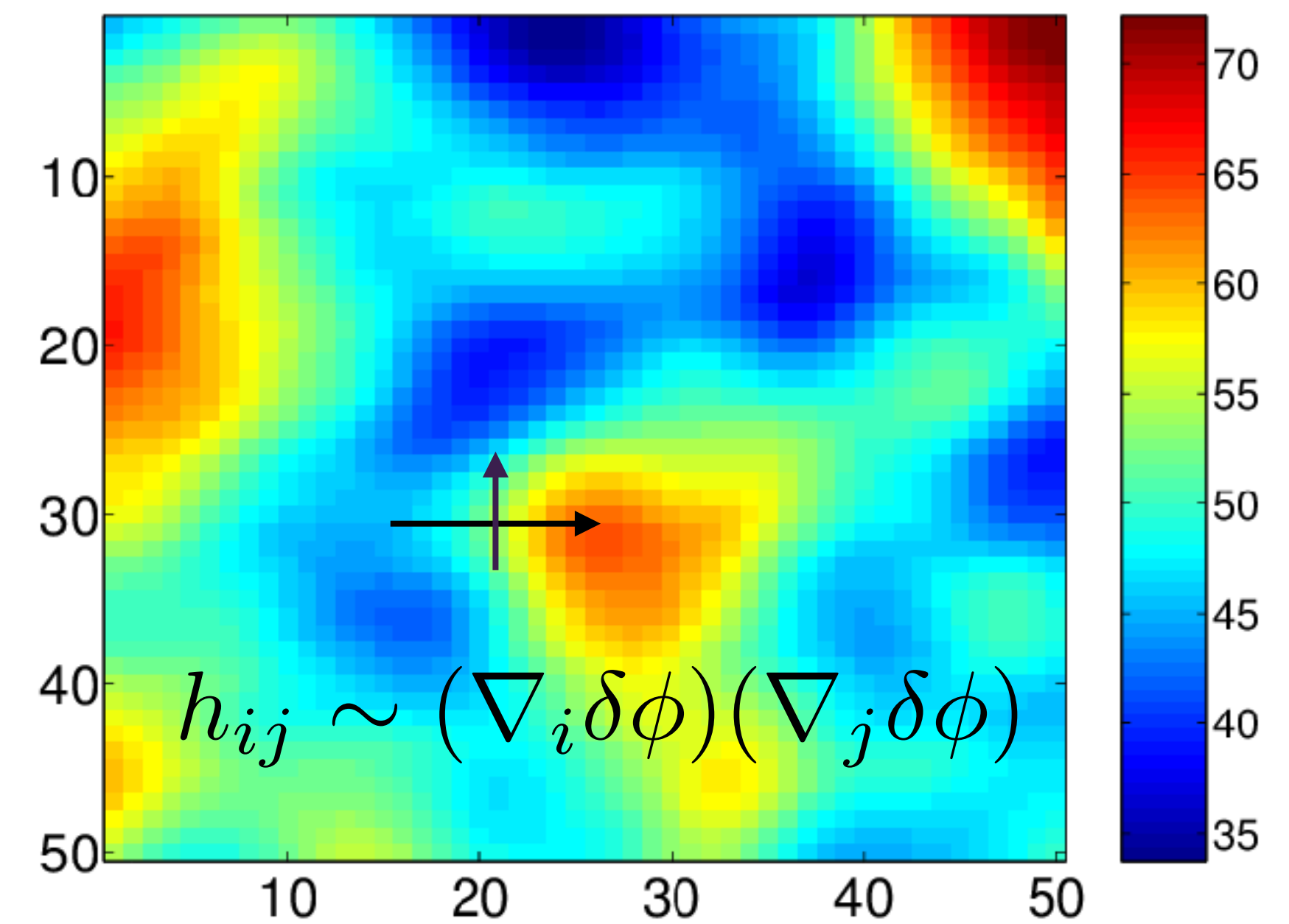
Supermassive Black Holes

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



Scalar-induced GWs?

Could be produced by enhanced scalar perturbations in the early Universe

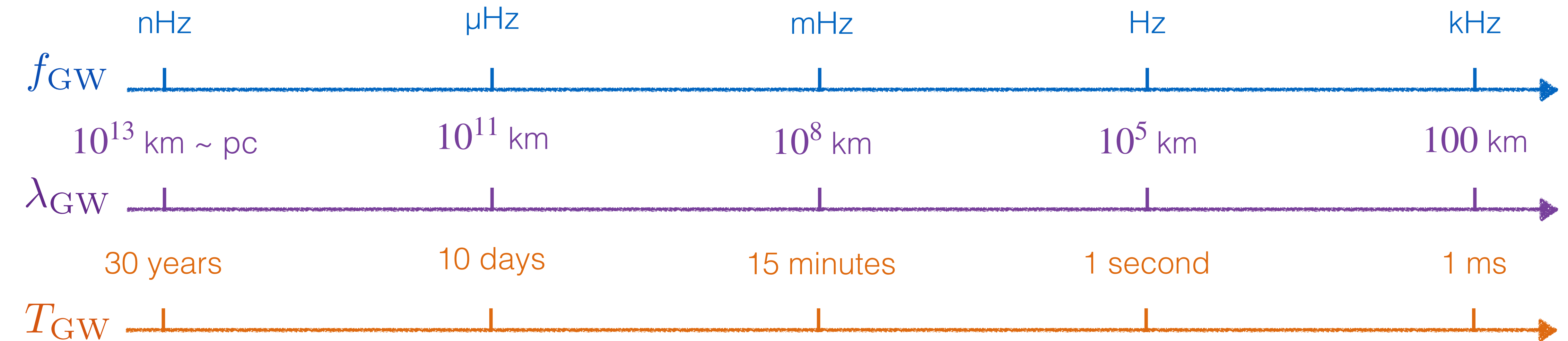


[Domènech, [2109.01398](#)]

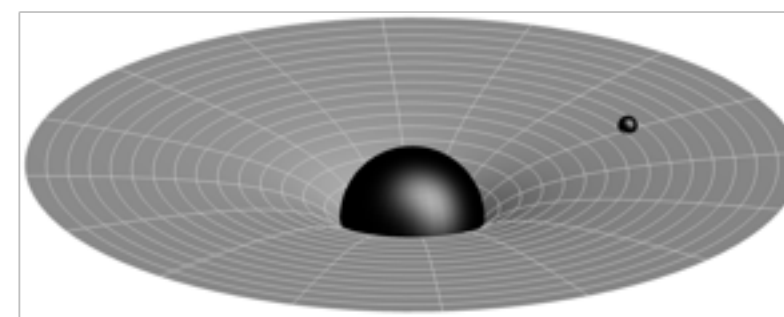
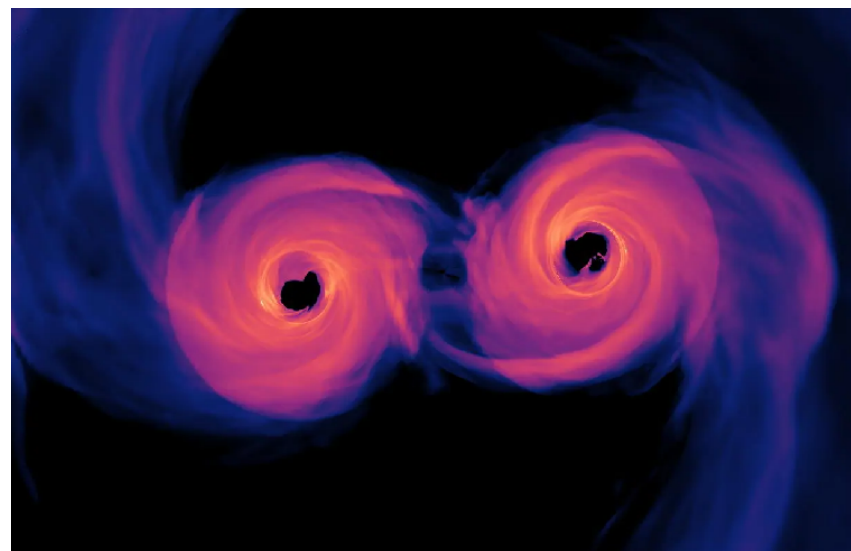
...and other possibilities...

The Gravitational Wave Spectrum

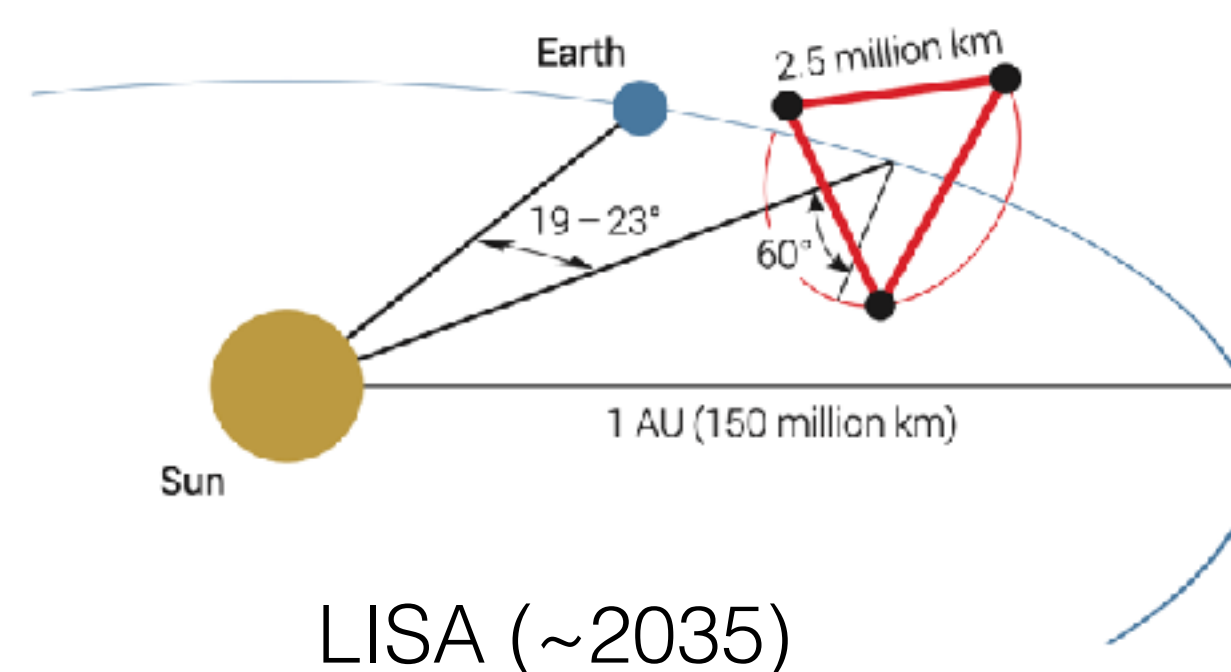
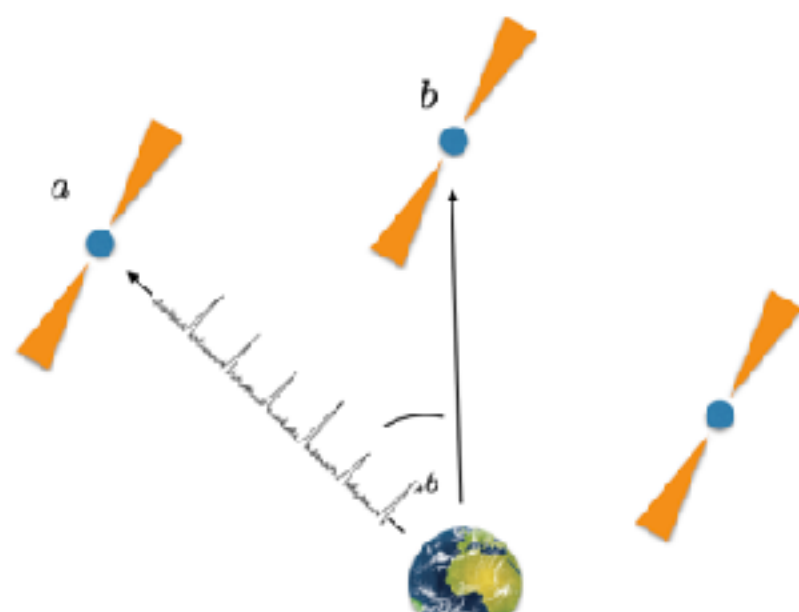
$$c = \lambda_{\text{GW}} \cdot f_{\text{GW}}$$



SOURCES

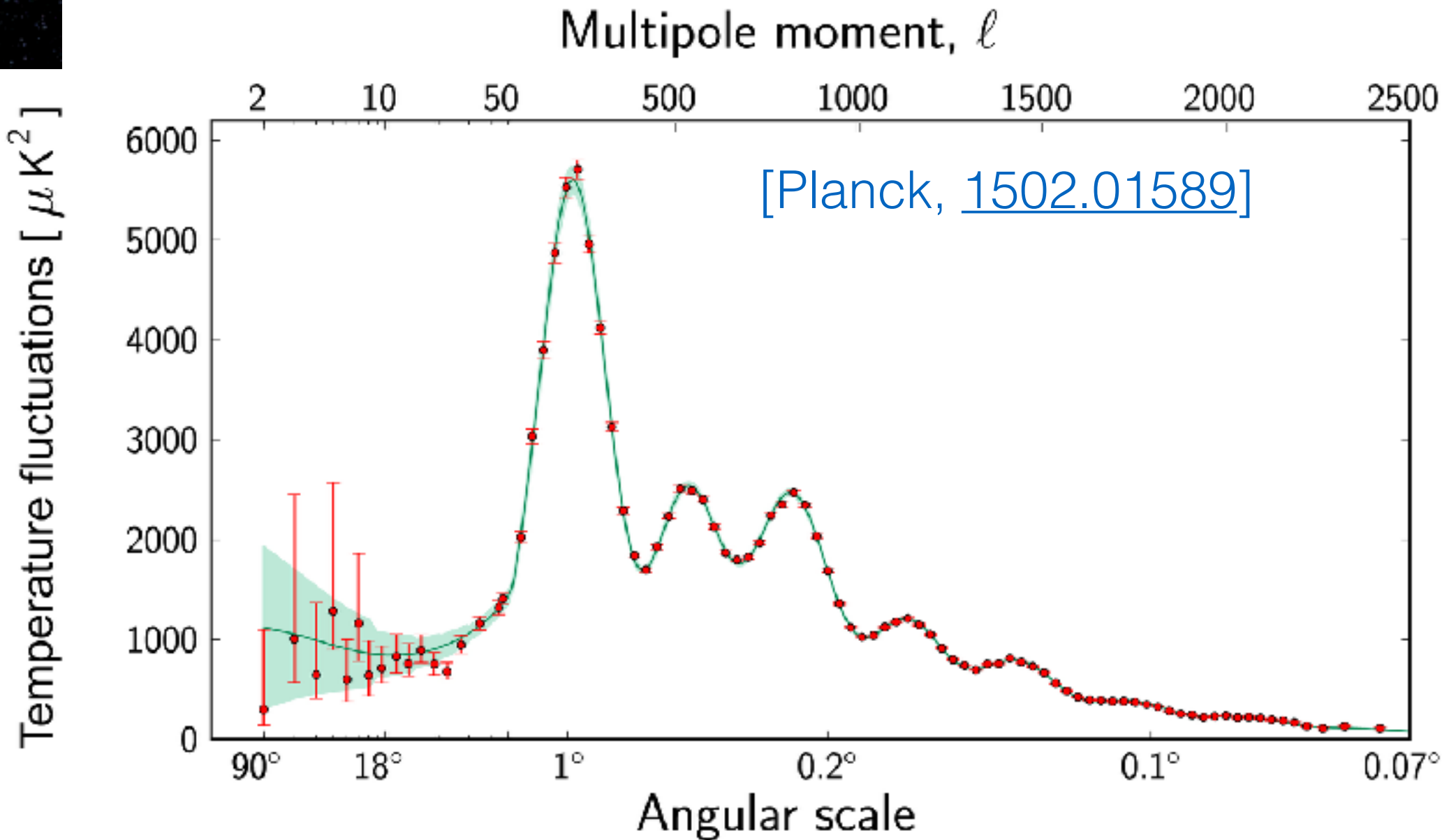
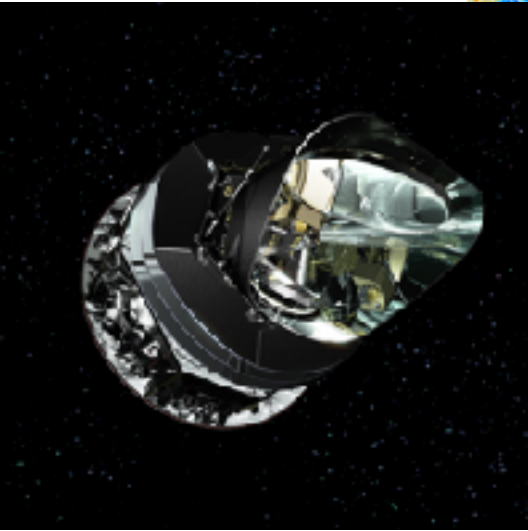
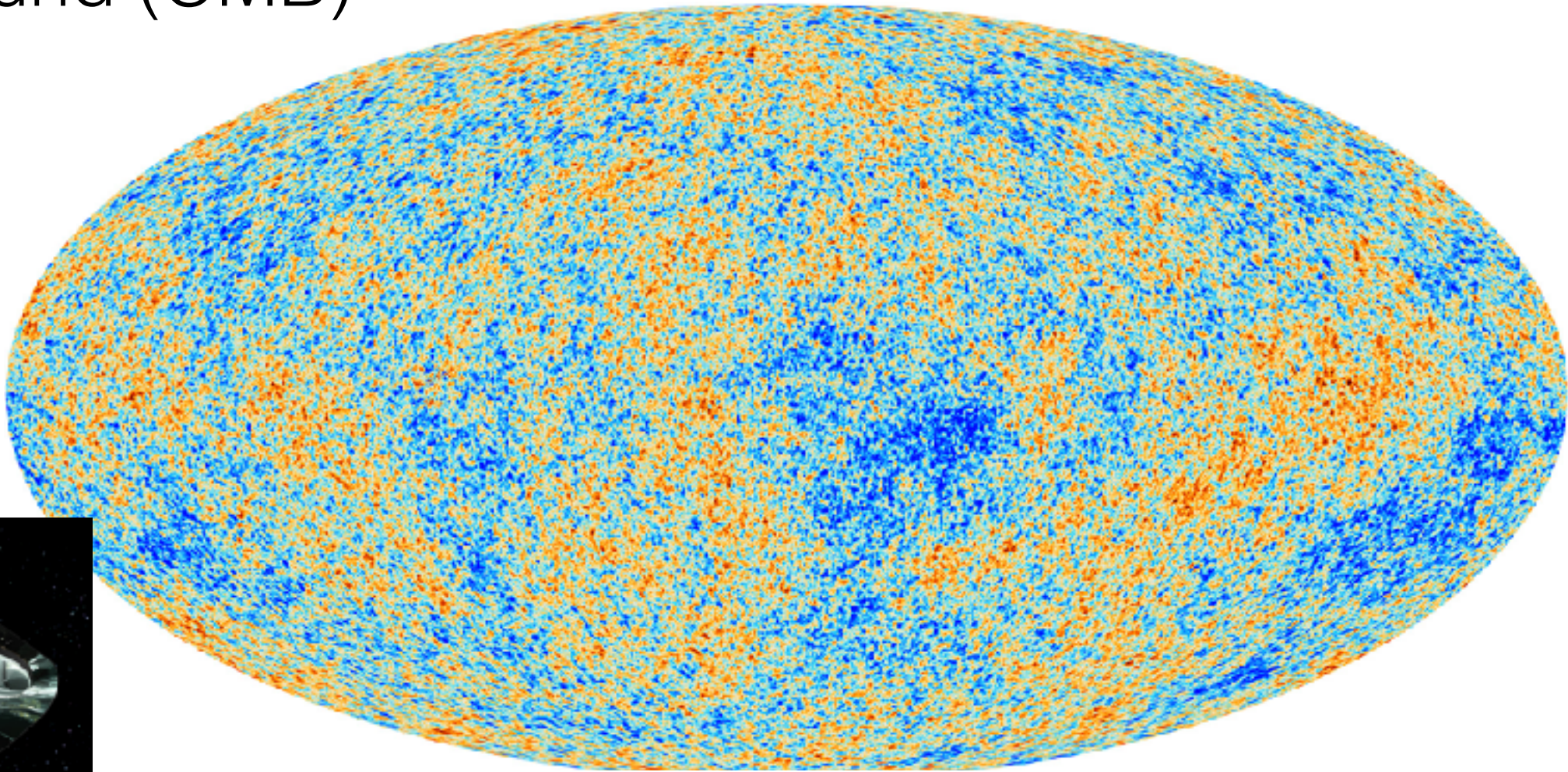


DETECTORS?

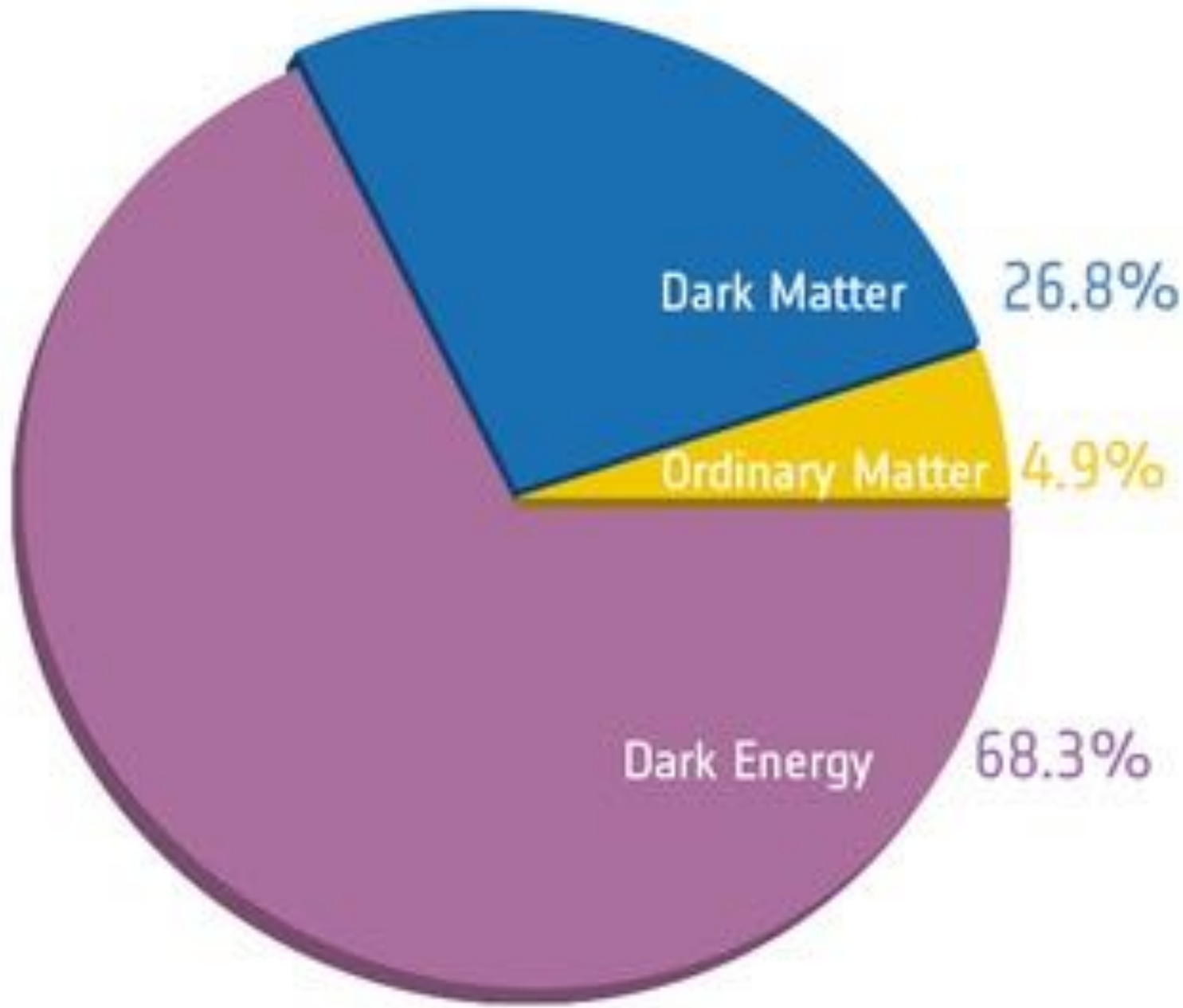
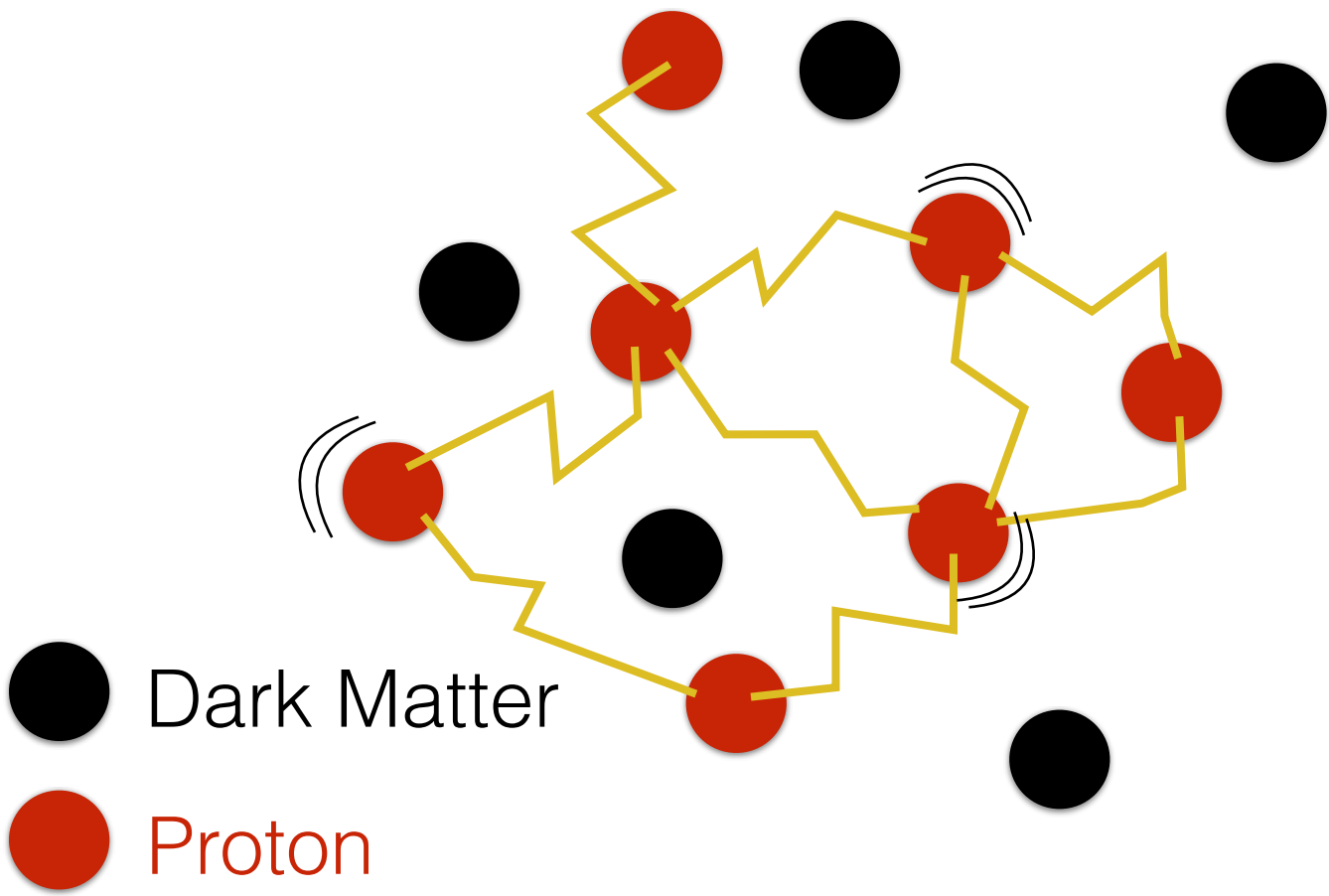


Dark Matter in Cosmology

Cosmic Microwave Background (CMB)



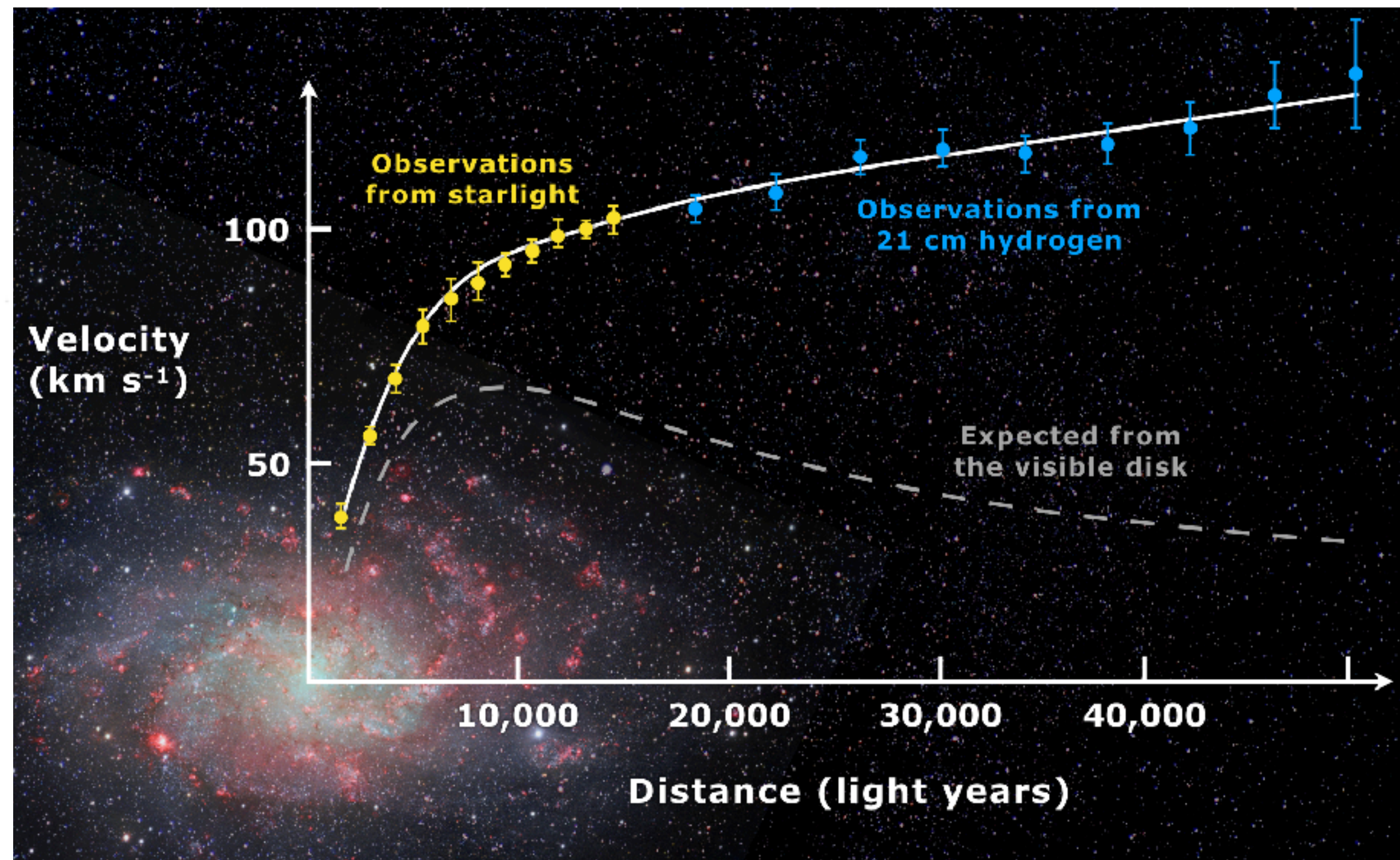
See [“Introduction to Cosmology” Lectures](#) by Miguel Escudero



Credit: ESA/Planck Collaboration

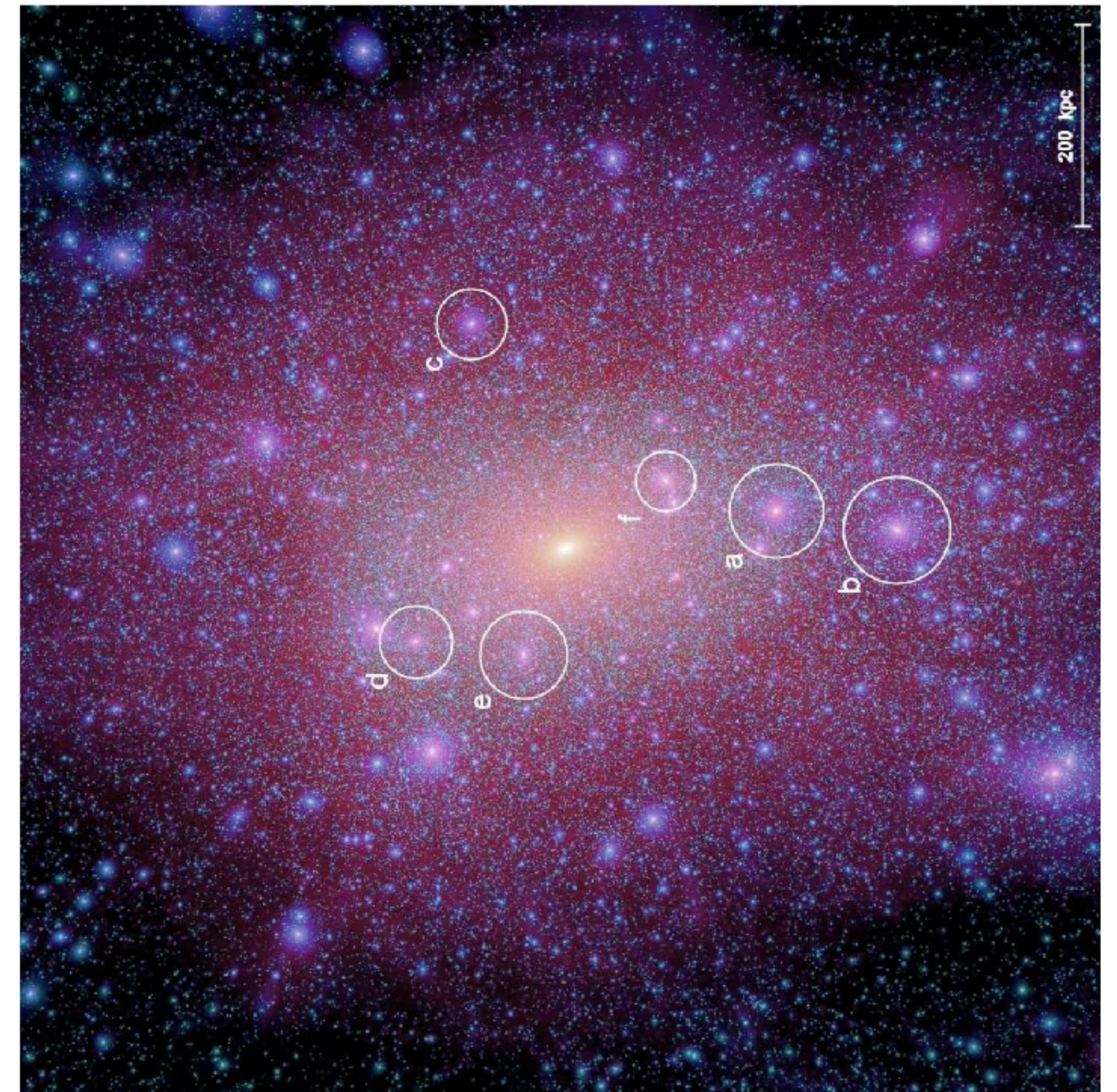
Dark Matter in Galaxies

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



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

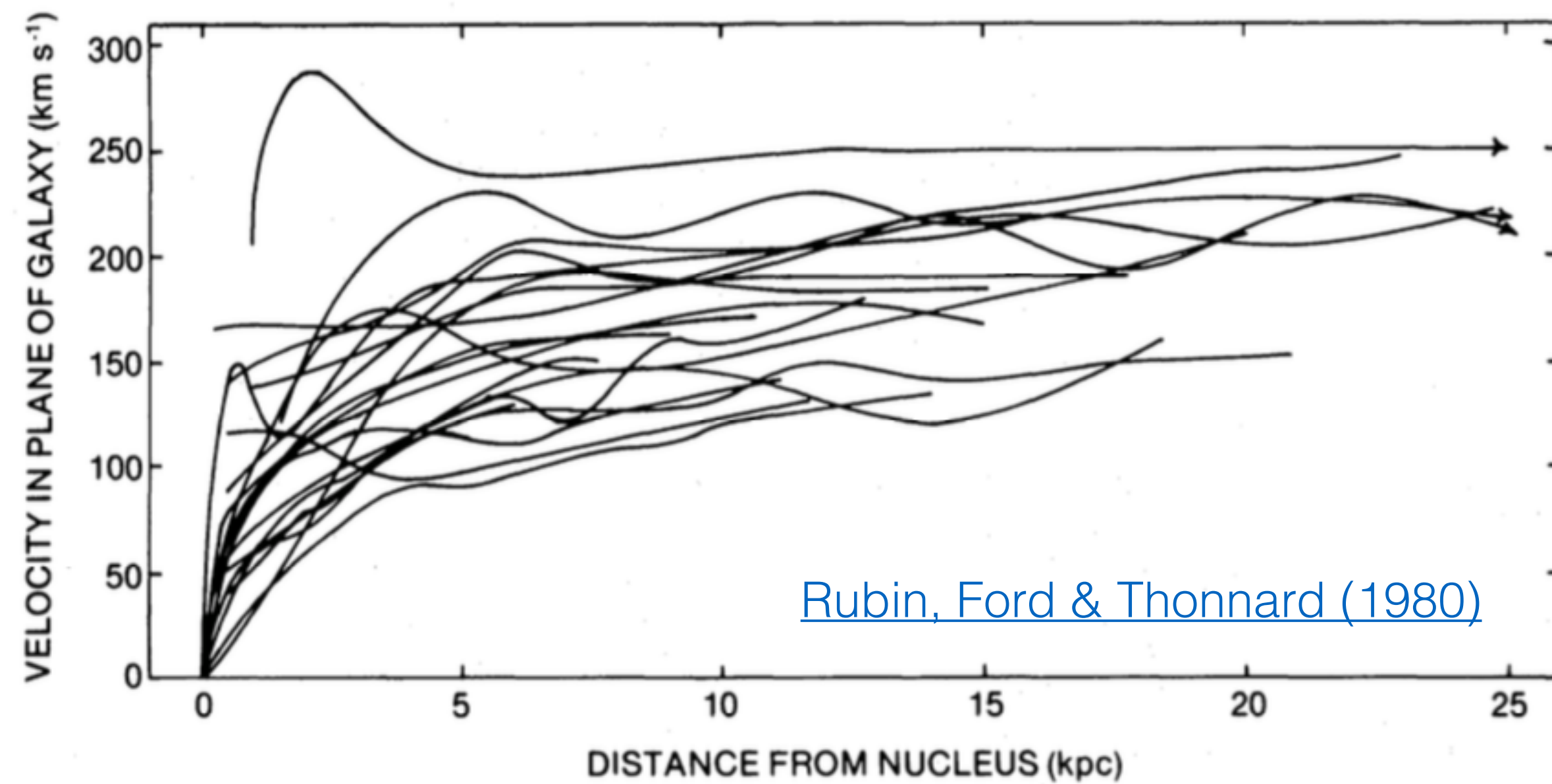
[1404.1938](#)



Aquarius simulation - [0809.0898](#)

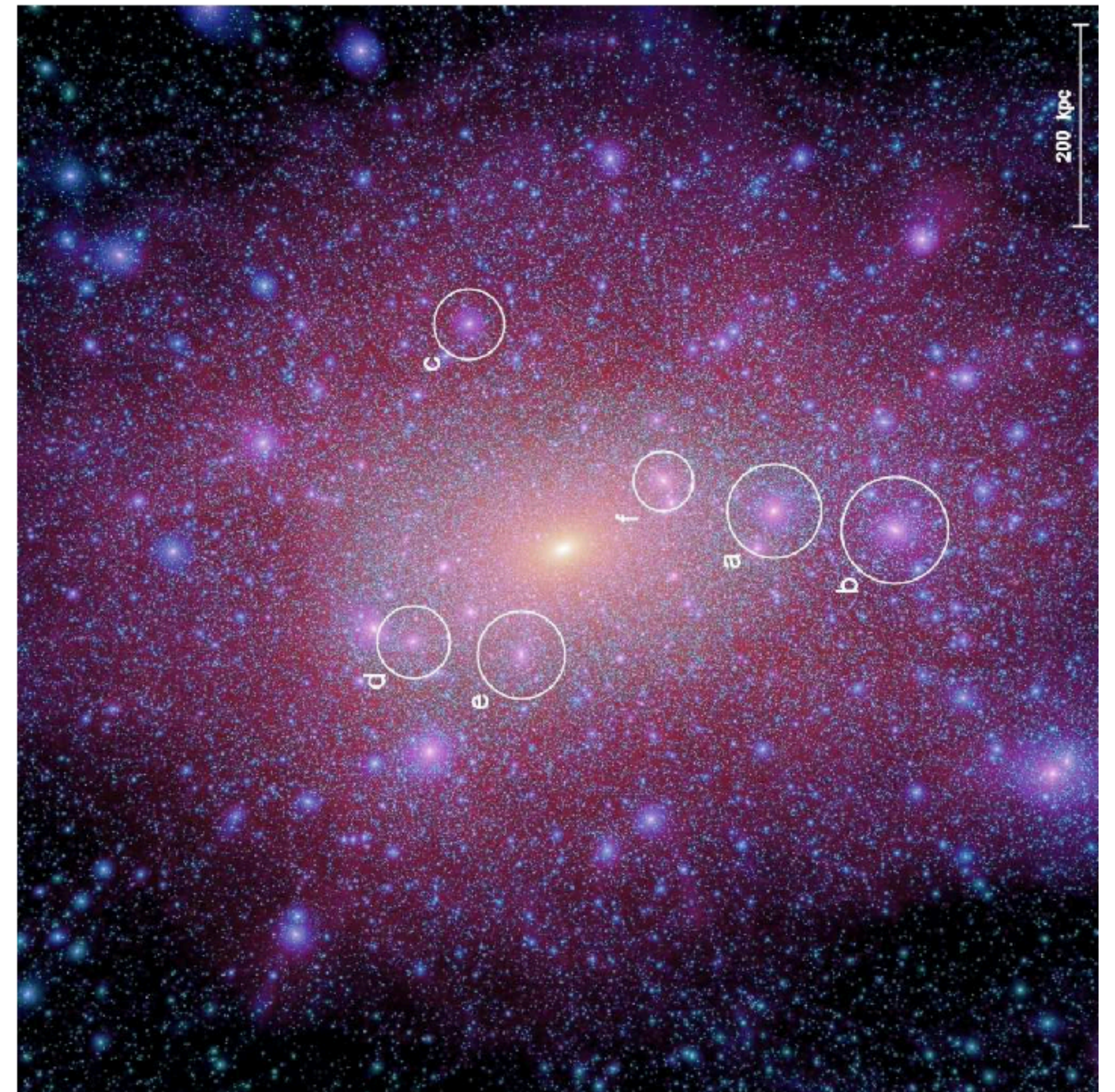
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[1404.1938](#)

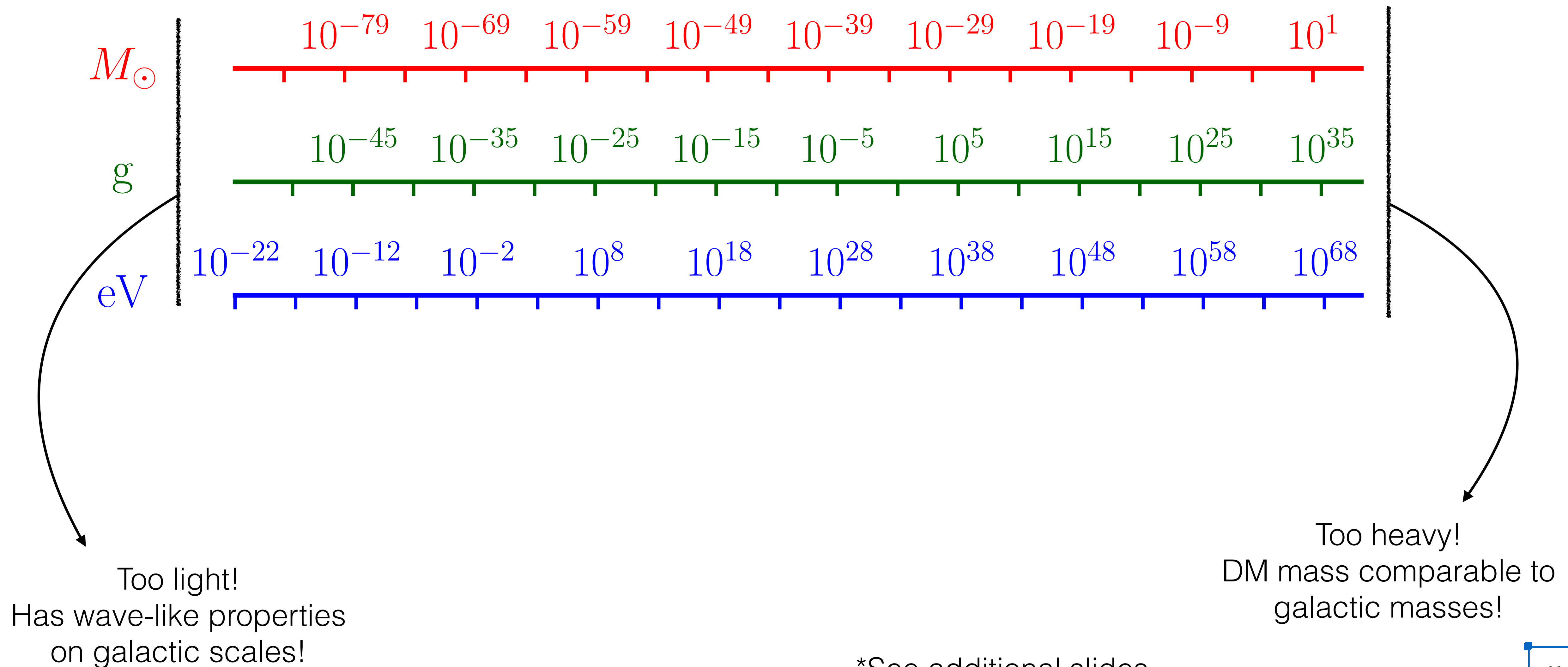


Aquarius simulation - [0809.0898](#)

Dark Matter properties

Dark Matter must be:

- Non-baryonic
- Cold (i.e. slow-moving)

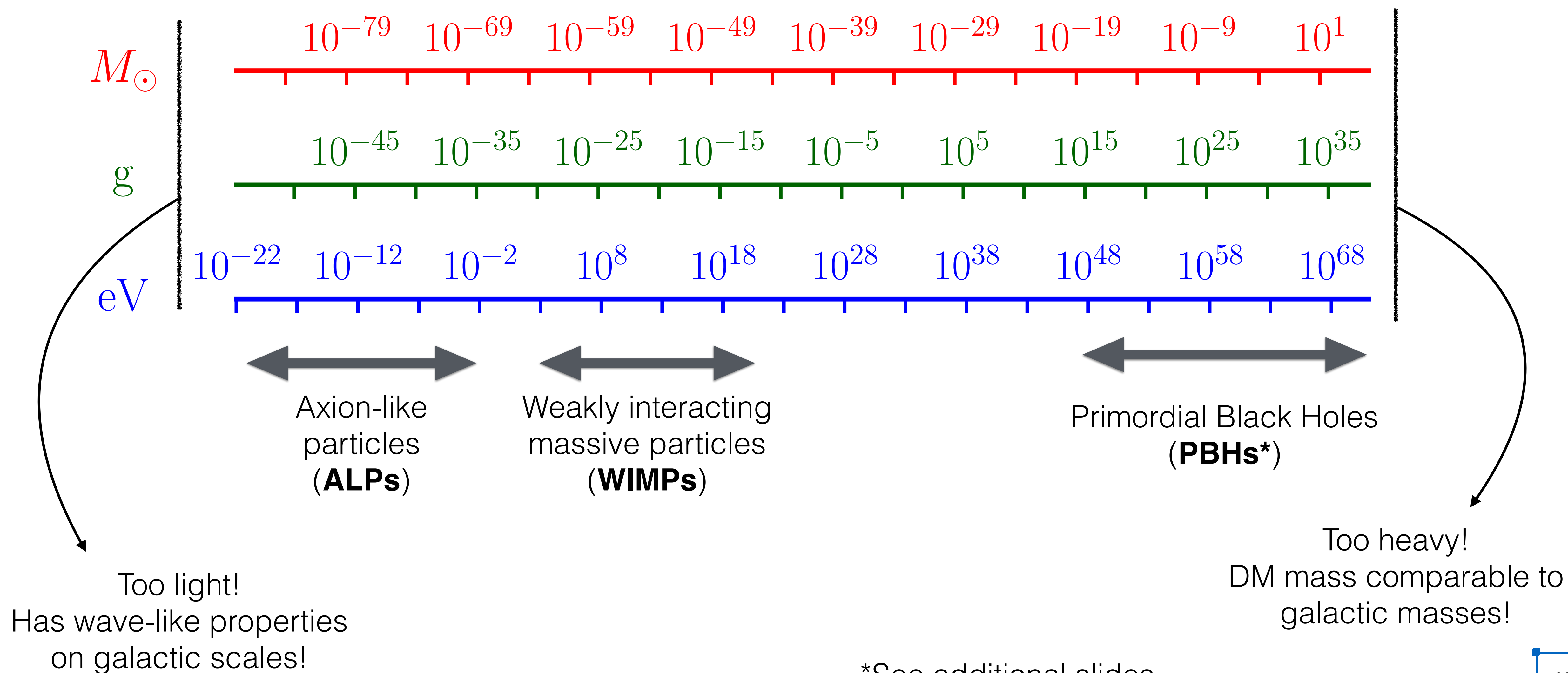


*See additional slides...

Dark Matter properties

Dark Matter must be:

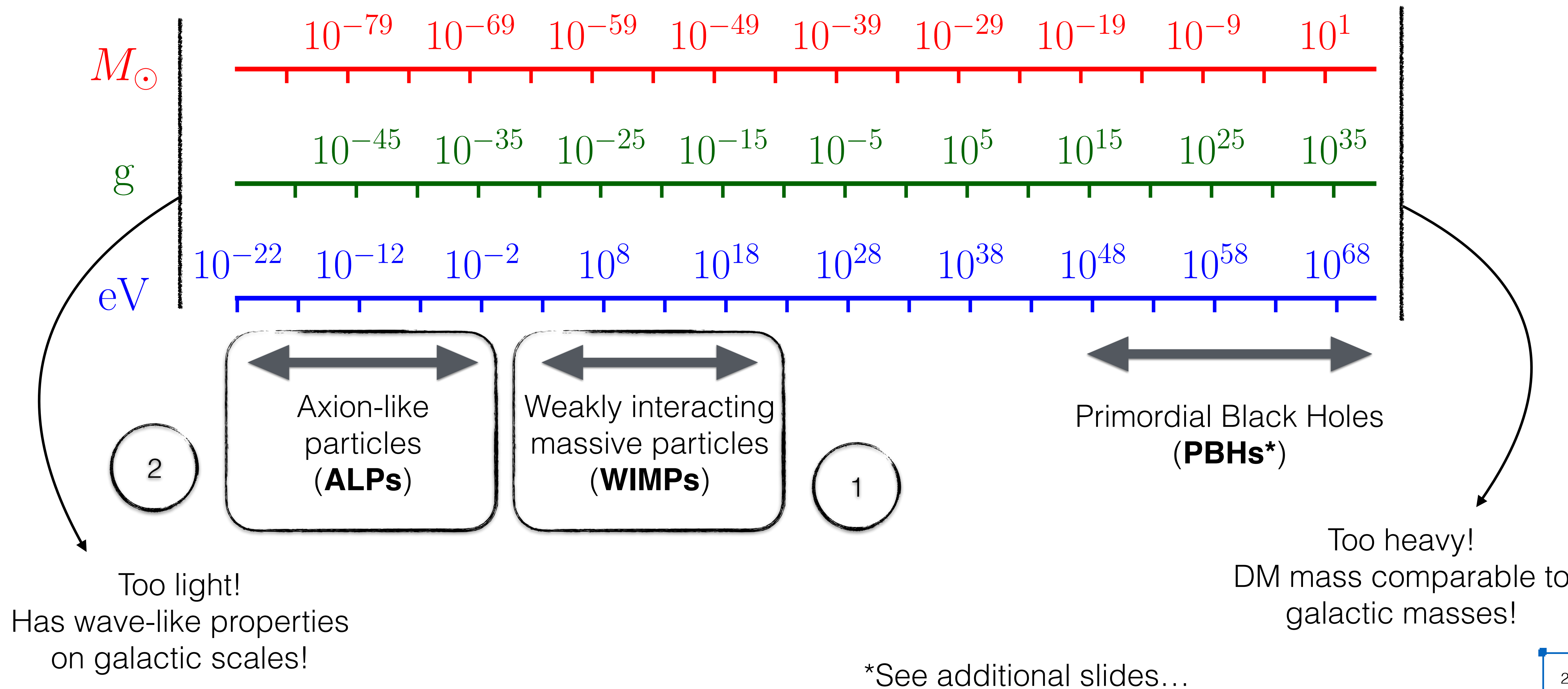
- Non-baryonic
- Cold (i.e. slow-moving)



*See additional slides...

Dark Matter properties

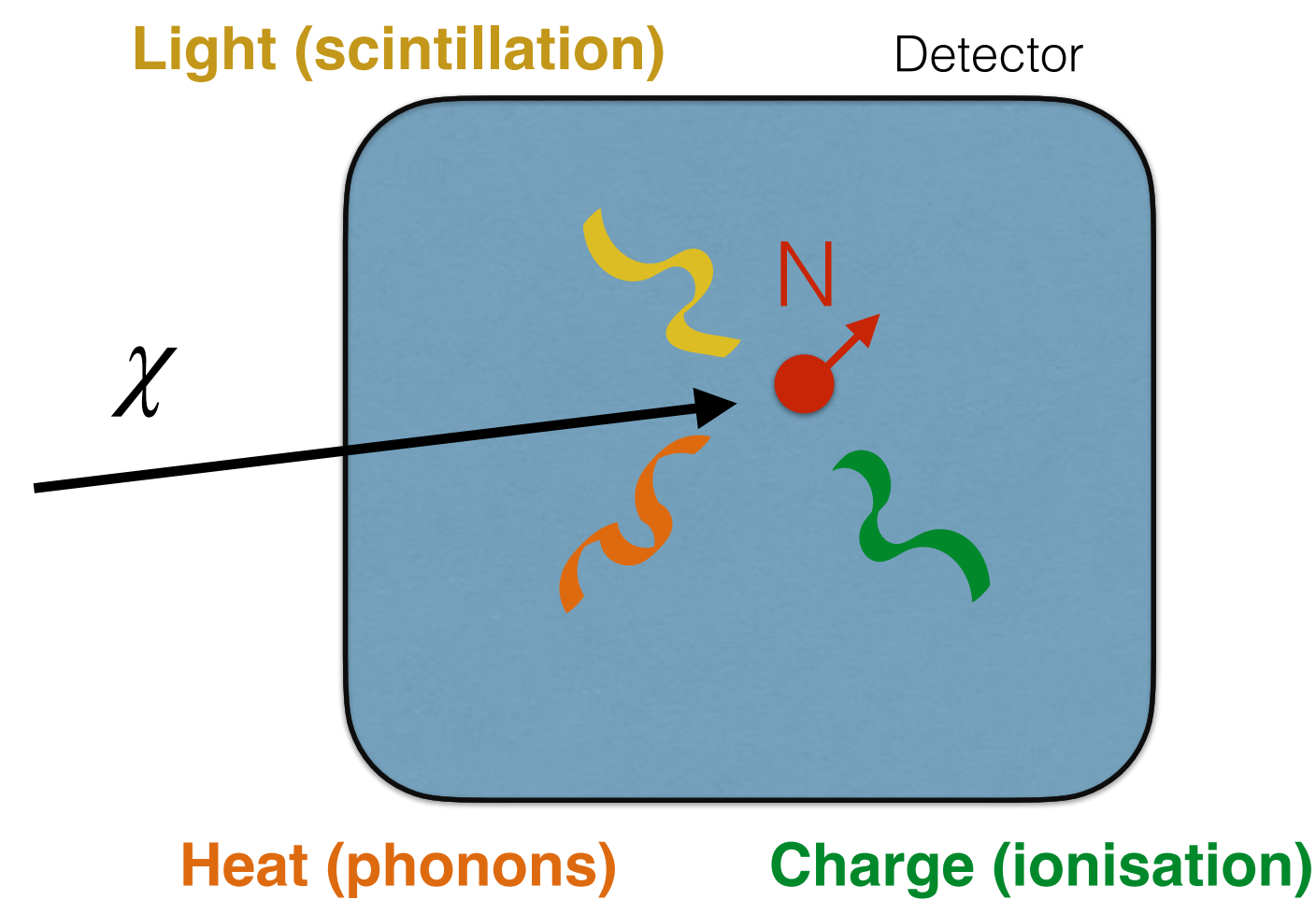
- Dark Matter must be:
- Non-baryonic
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Direct detection of WIMPs on Earth

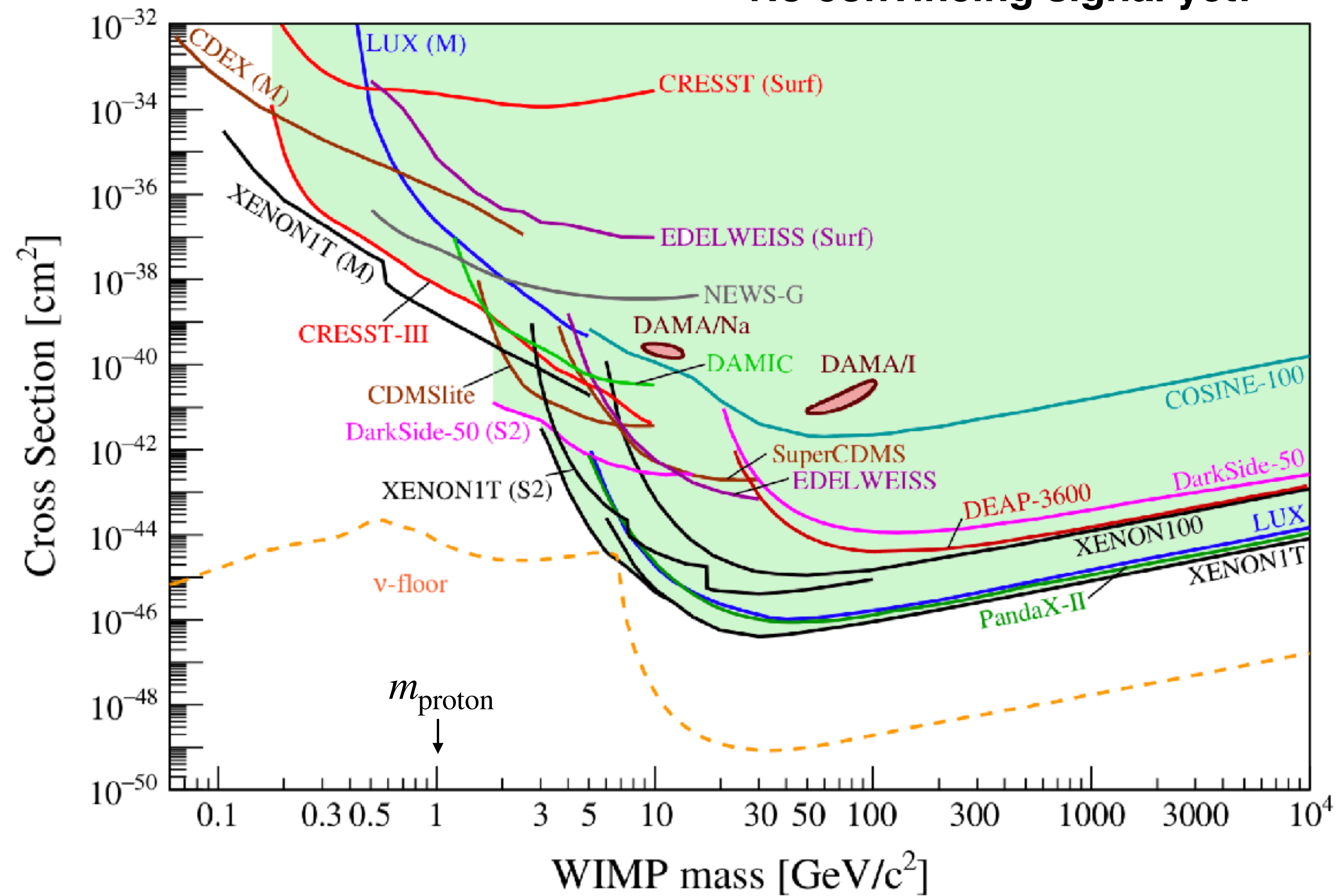
DM in the Milky Way is moving
'slowly': $v \sim 10^{-3} c$

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!

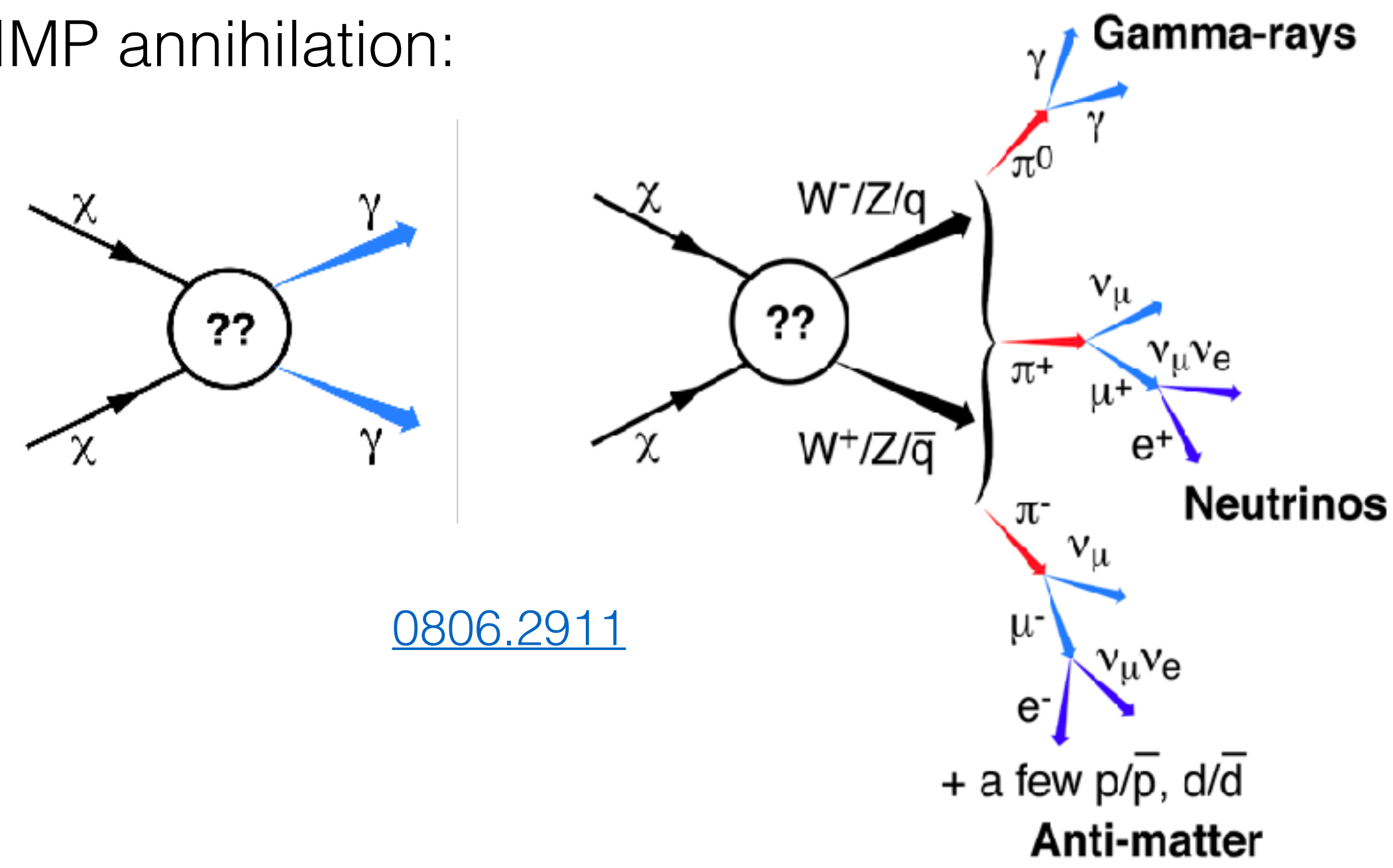


Also possible to look for DM-electron scattering, depending on the model.

Indirect detection of Dark Matter

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

WIMP annihilation:



[0806.2911](#)

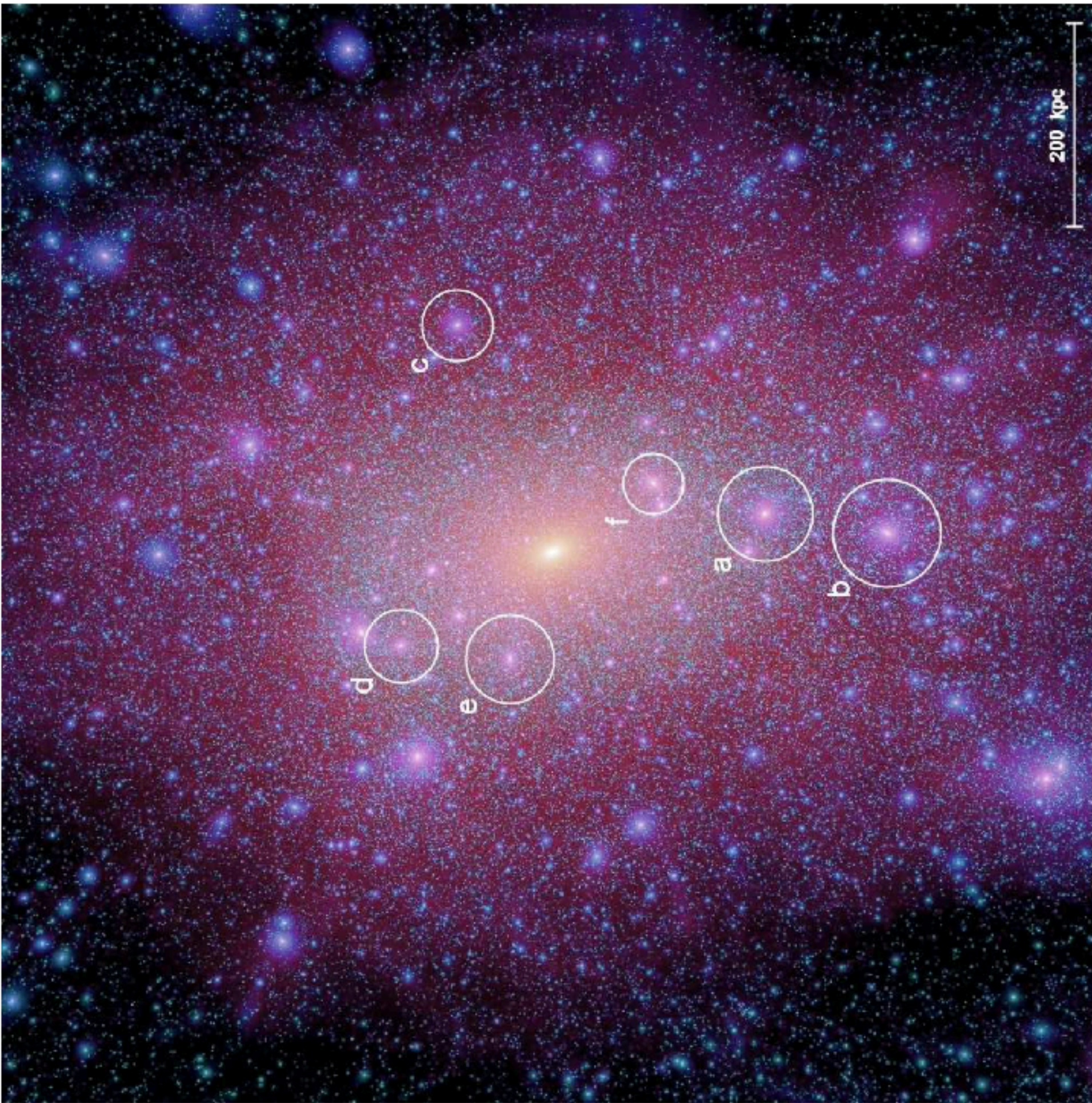
Annihilation cross section
(particle physics)

DM density distribution
(astrophysics)

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

Gamma-ray spectrum
(annihilation channel)

[1012.4515](#)



Aquarius simulation - [0809.0898](#)

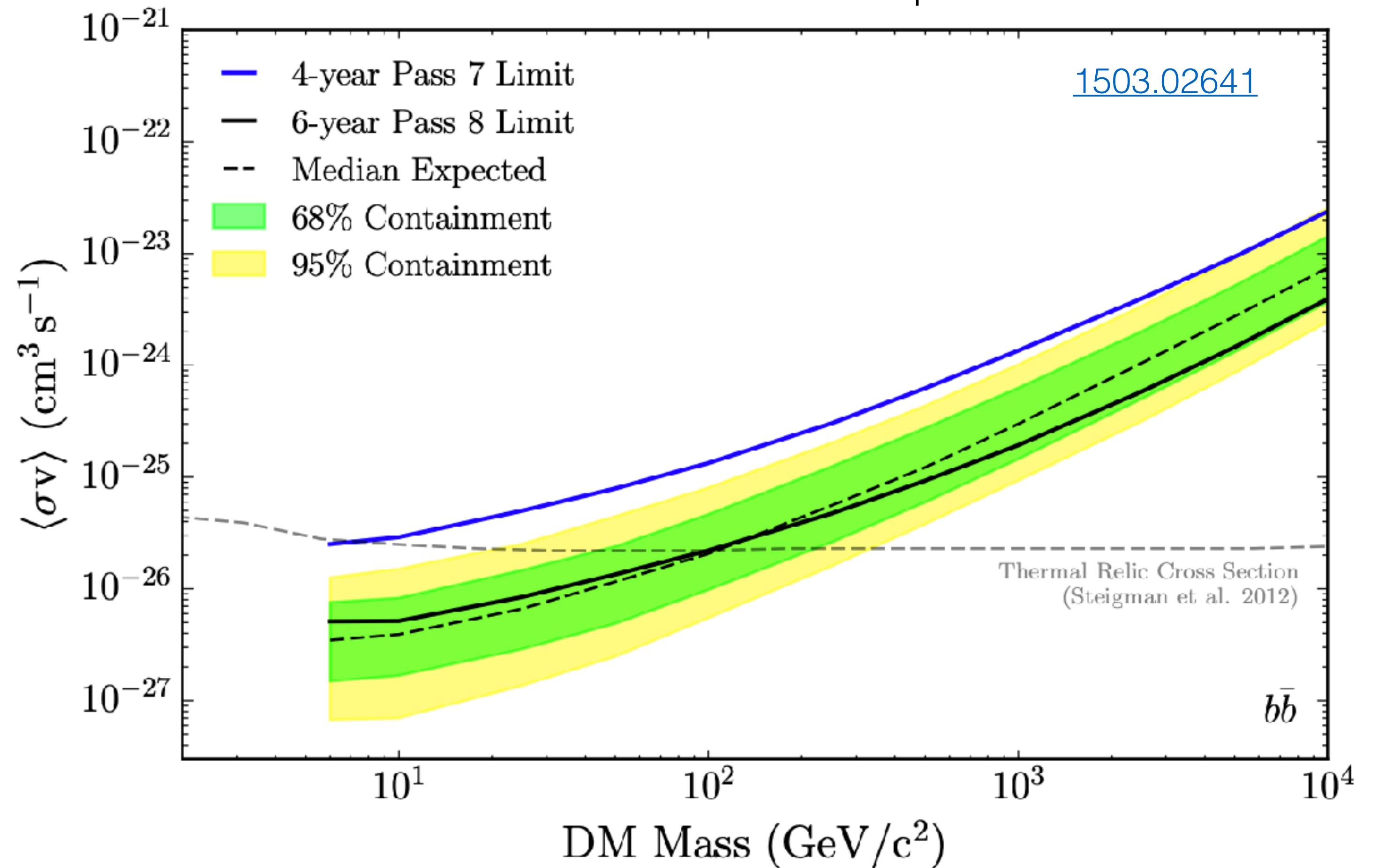
Gamma-ray constraints

Fornax Dwarf Galaxy
(Satellite of the Milky Way)



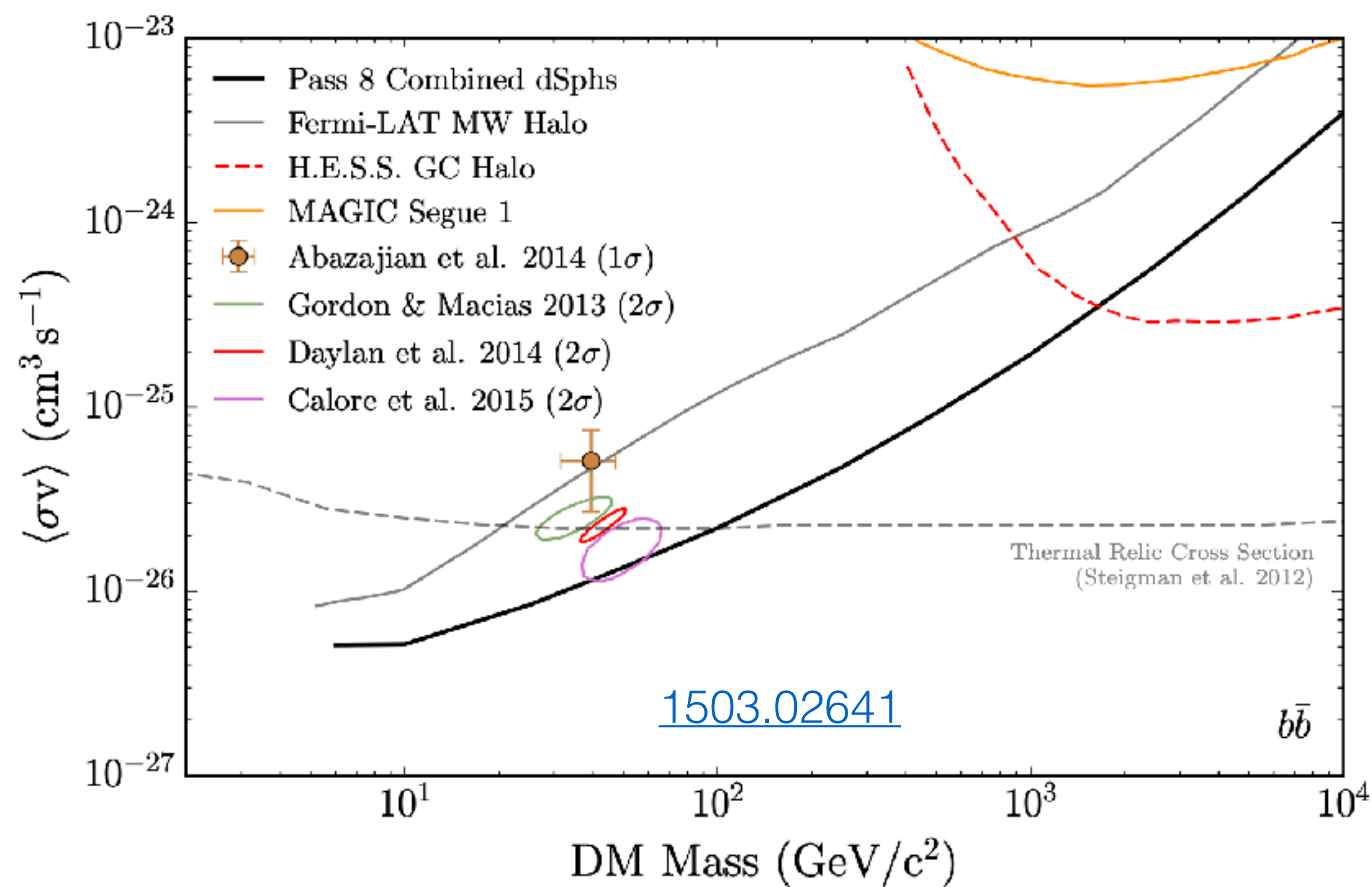
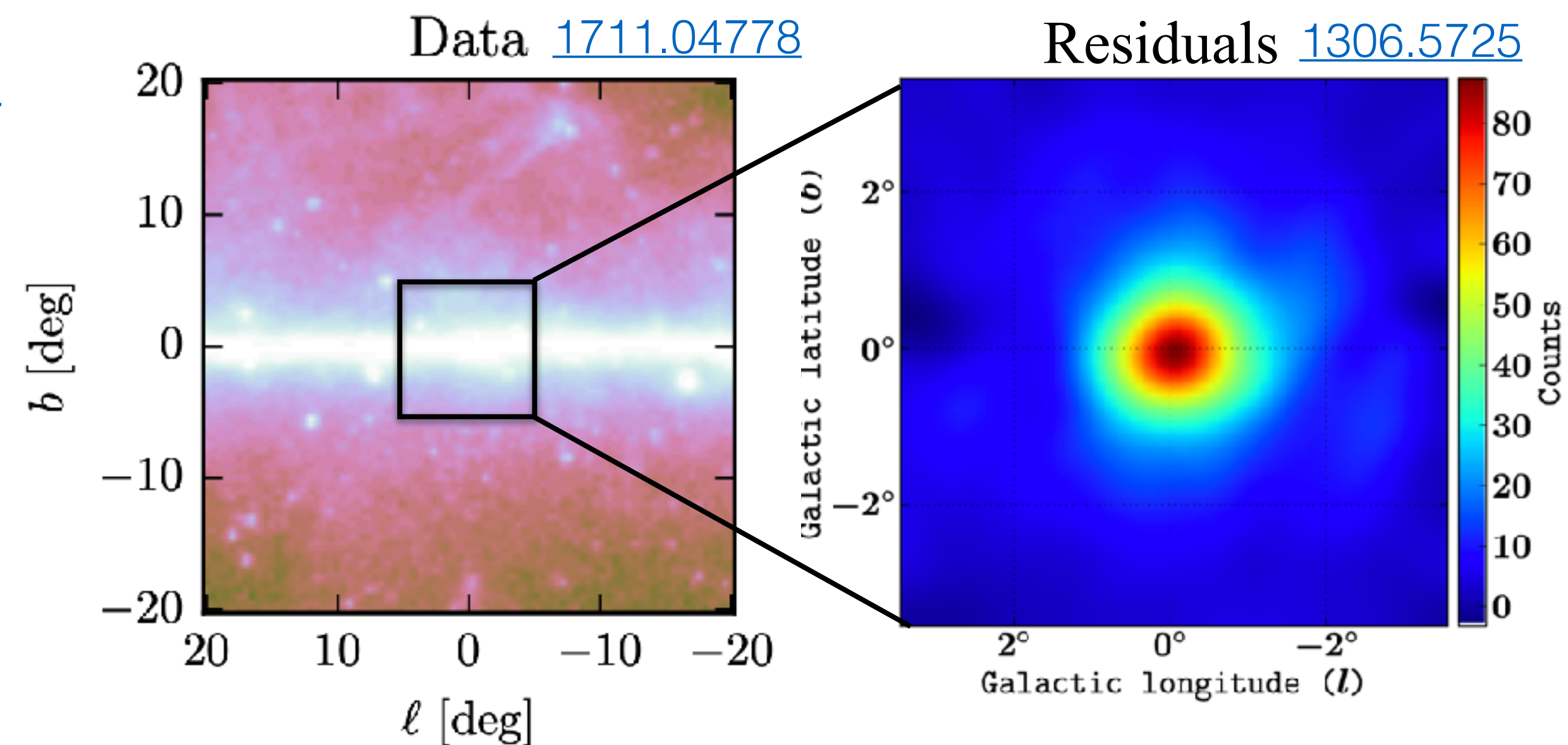
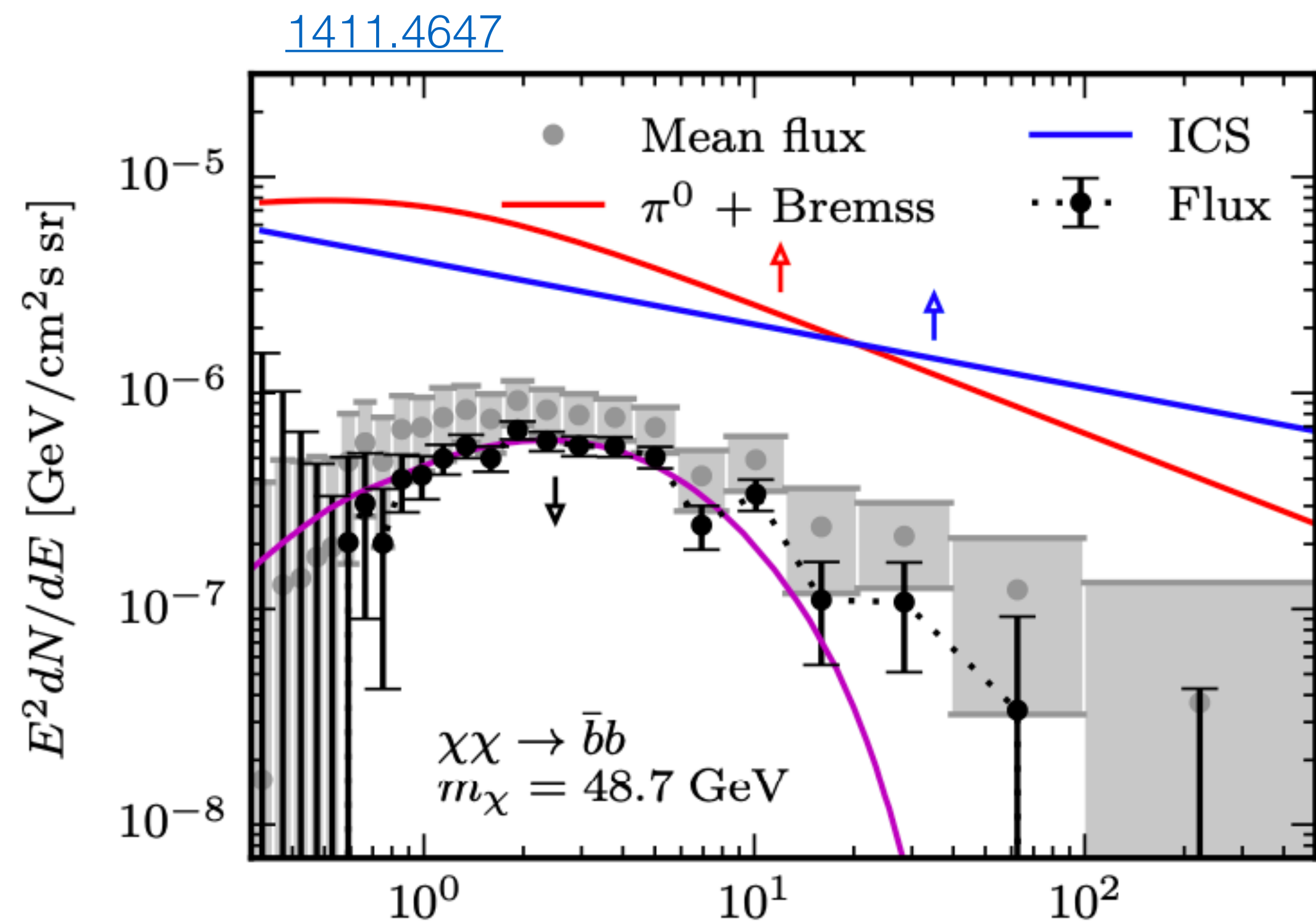
Credit: ESO/Digitized Sky Survey 2

Fermi constraints from 15 Dwarf Spheroidal Galaxies:



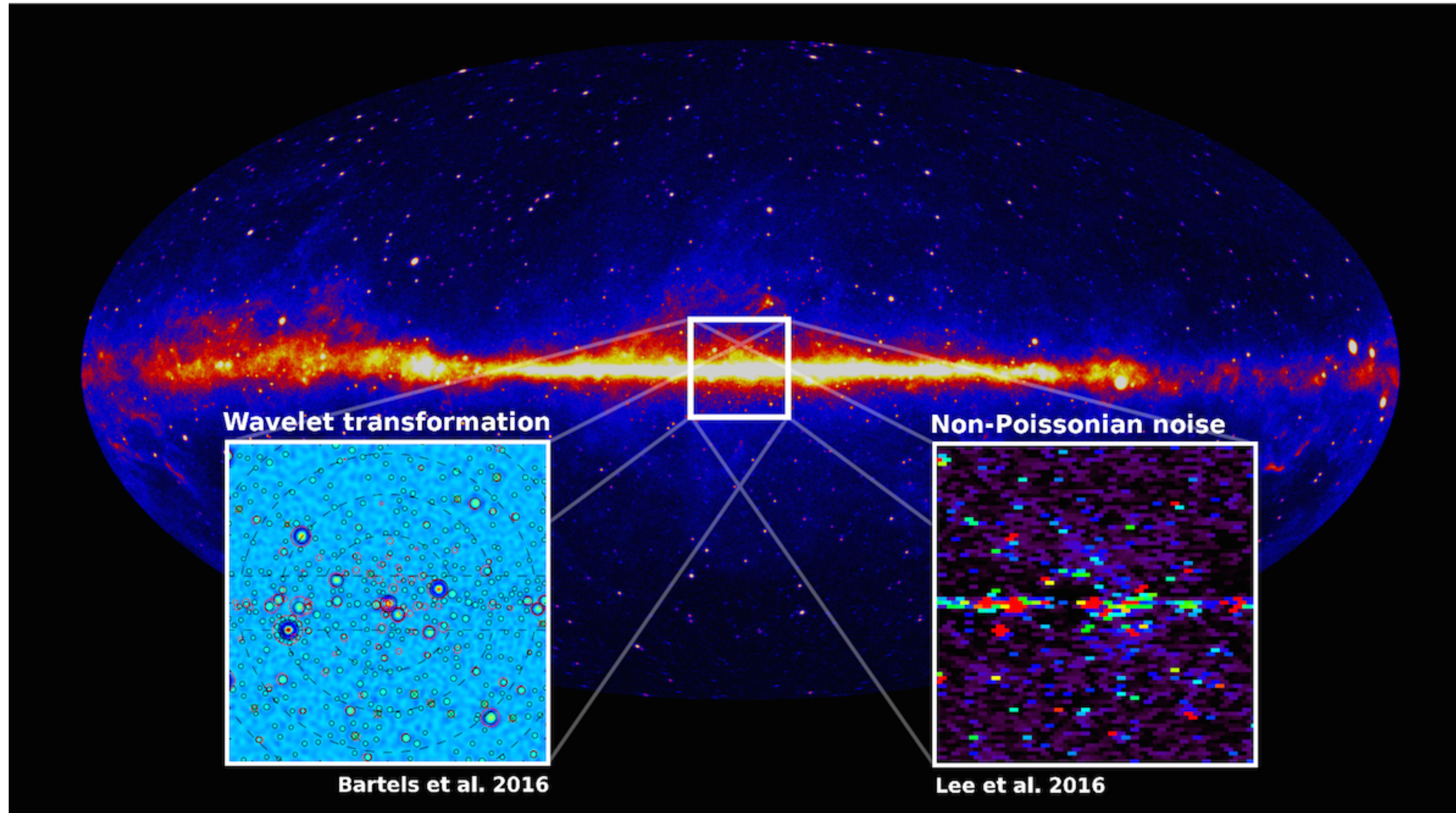
Exact constraints depend on annihilation channel ($\chi\chi \rightarrow b\bar{b}$, $\chi\chi \rightarrow W^+W^-$, $\chi\chi \rightarrow e^+e^-$, etc.)

Galactic Centre Excess



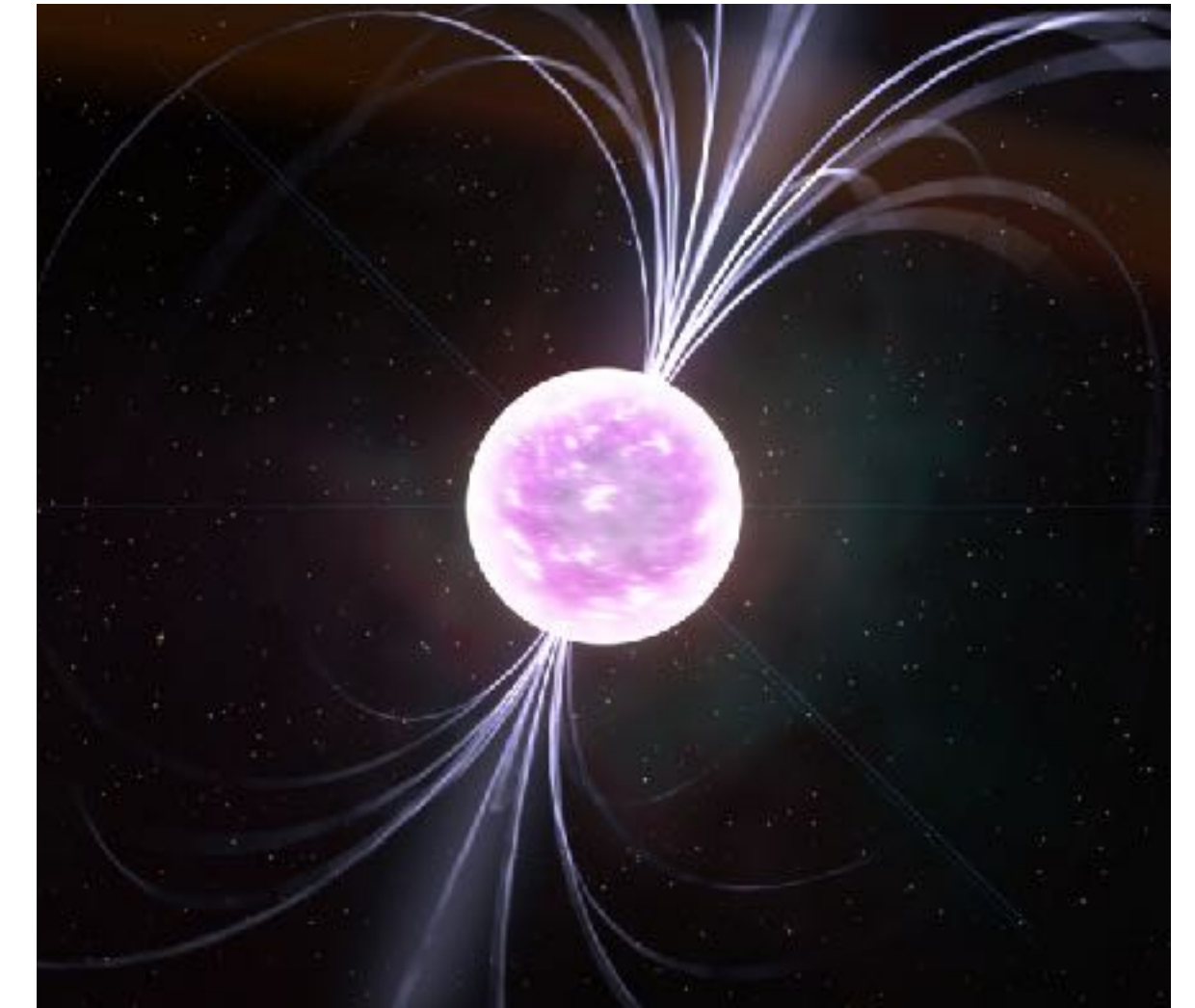
Point sources in the Galactic Centre

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



Credit: Christoph Weniger, UvA , © UvA/Princeton

[1506.05104](#), [1711.04778](#)



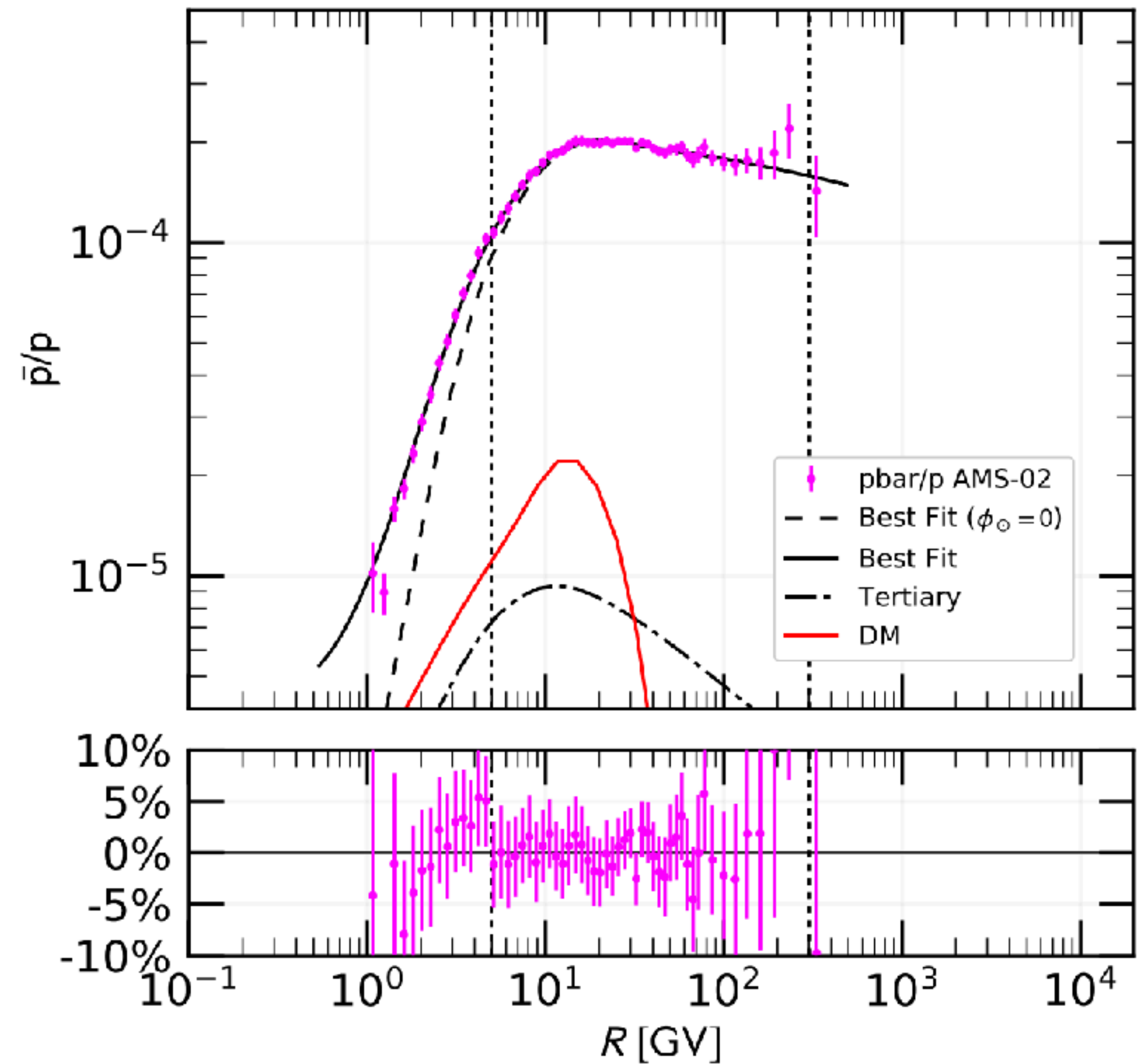
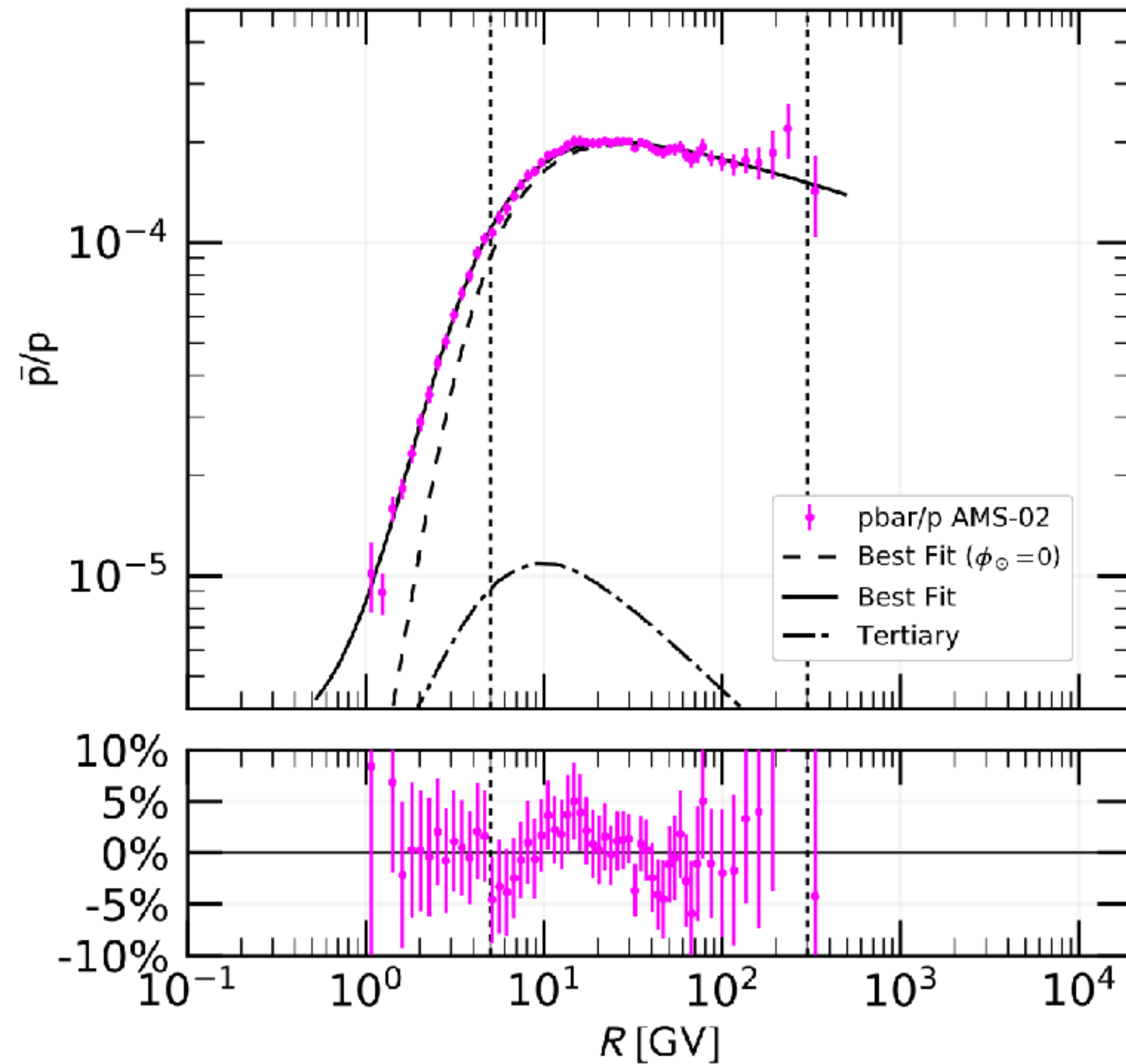
Credit: Kevin Gill / Flickr



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**.

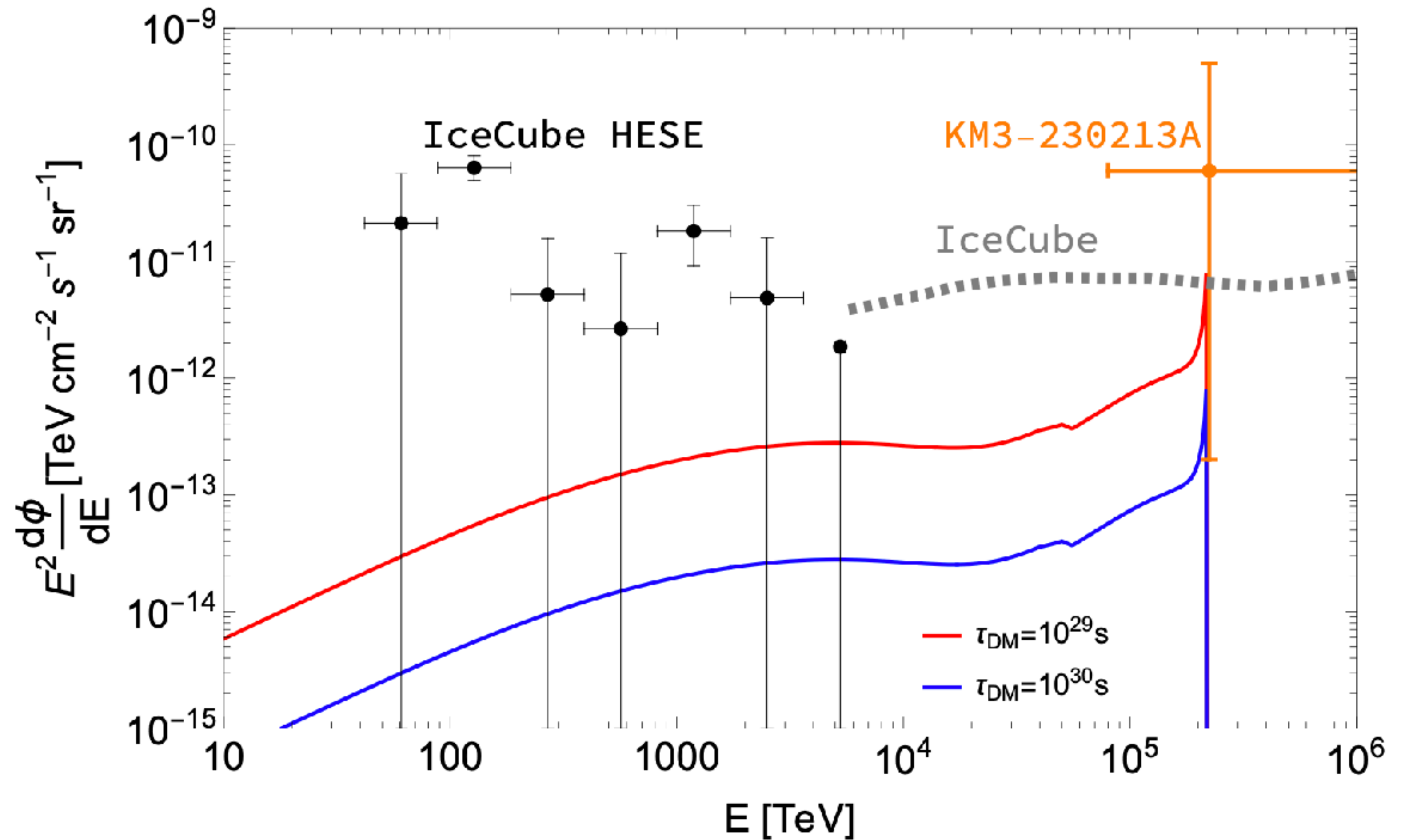
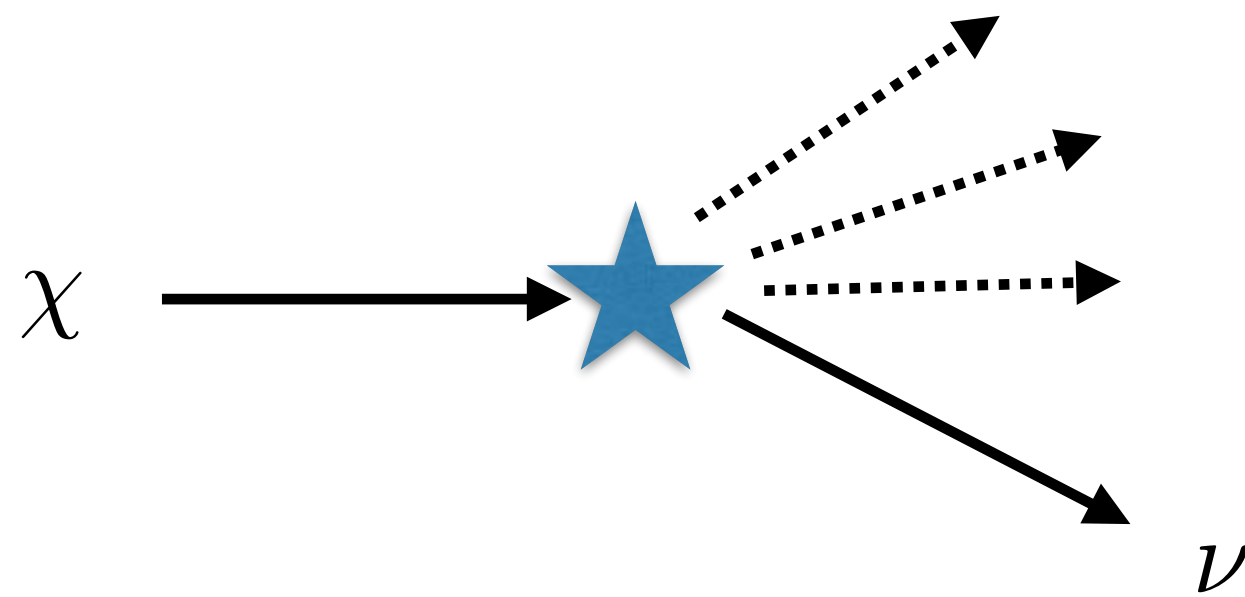
[1504.04276](#), [1610.03071](#), [1903.01472](#)

High energy neutrinos

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

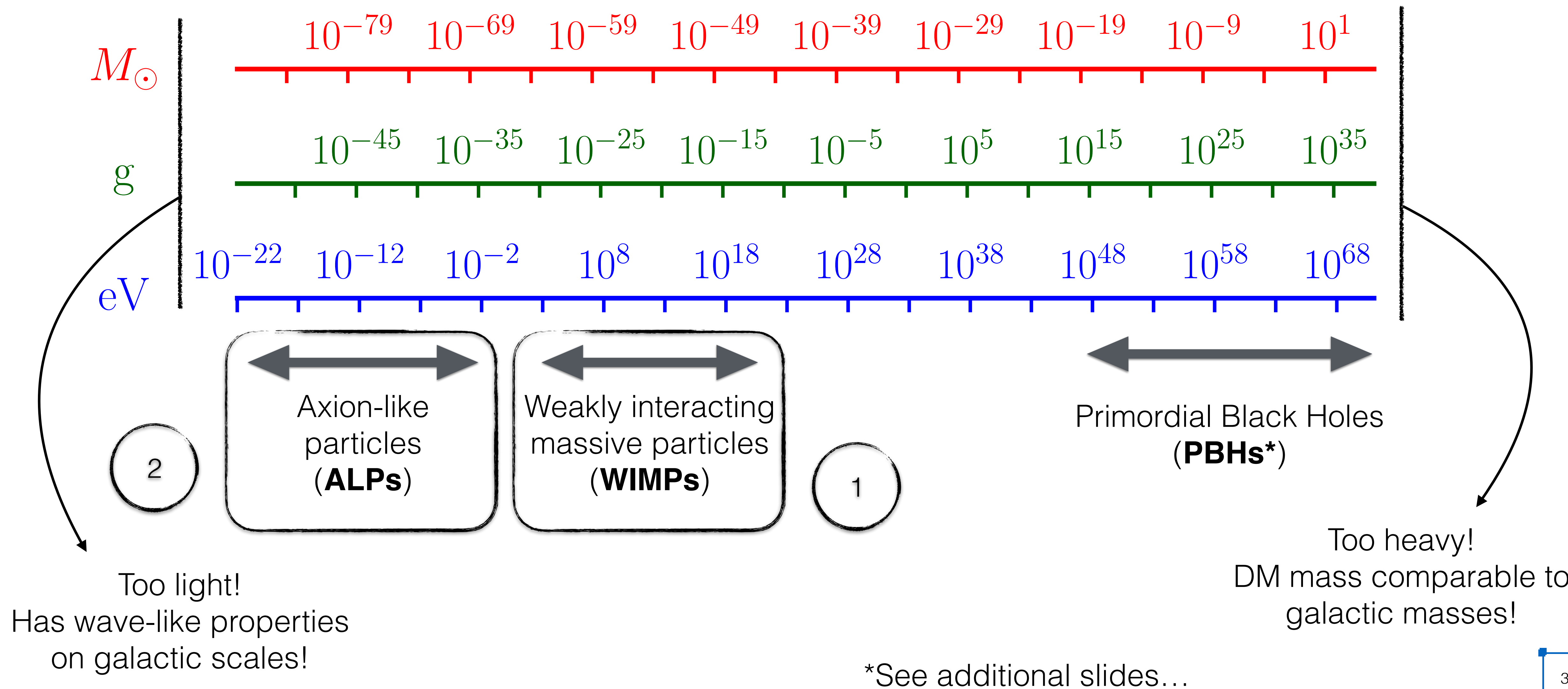
[1508.02500](#), [1712.07138](#)

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



Dark Matter properties

- Dark Matter must be:
- Non-baryonic
 - Cold (i.e. slow-moving)

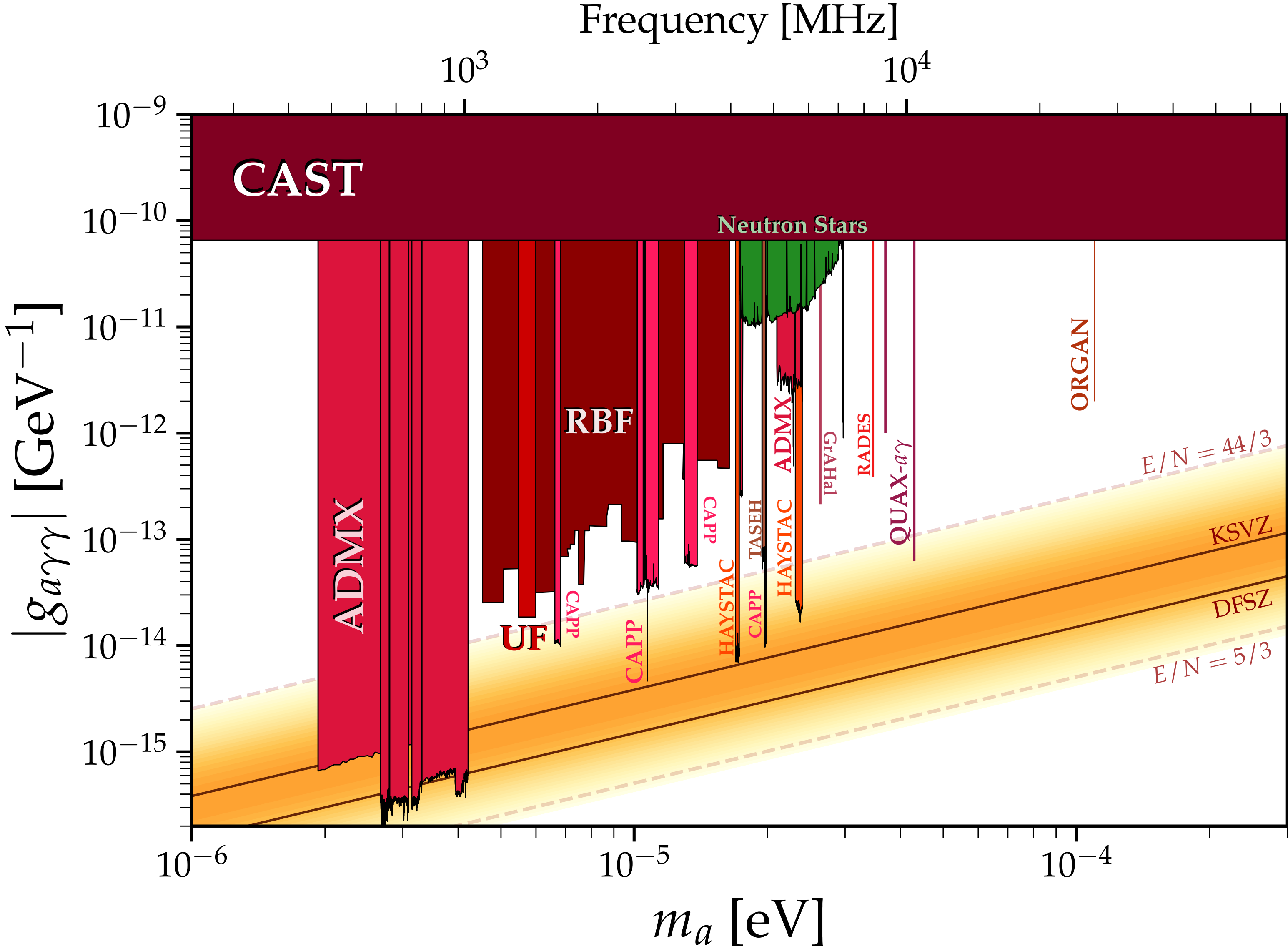
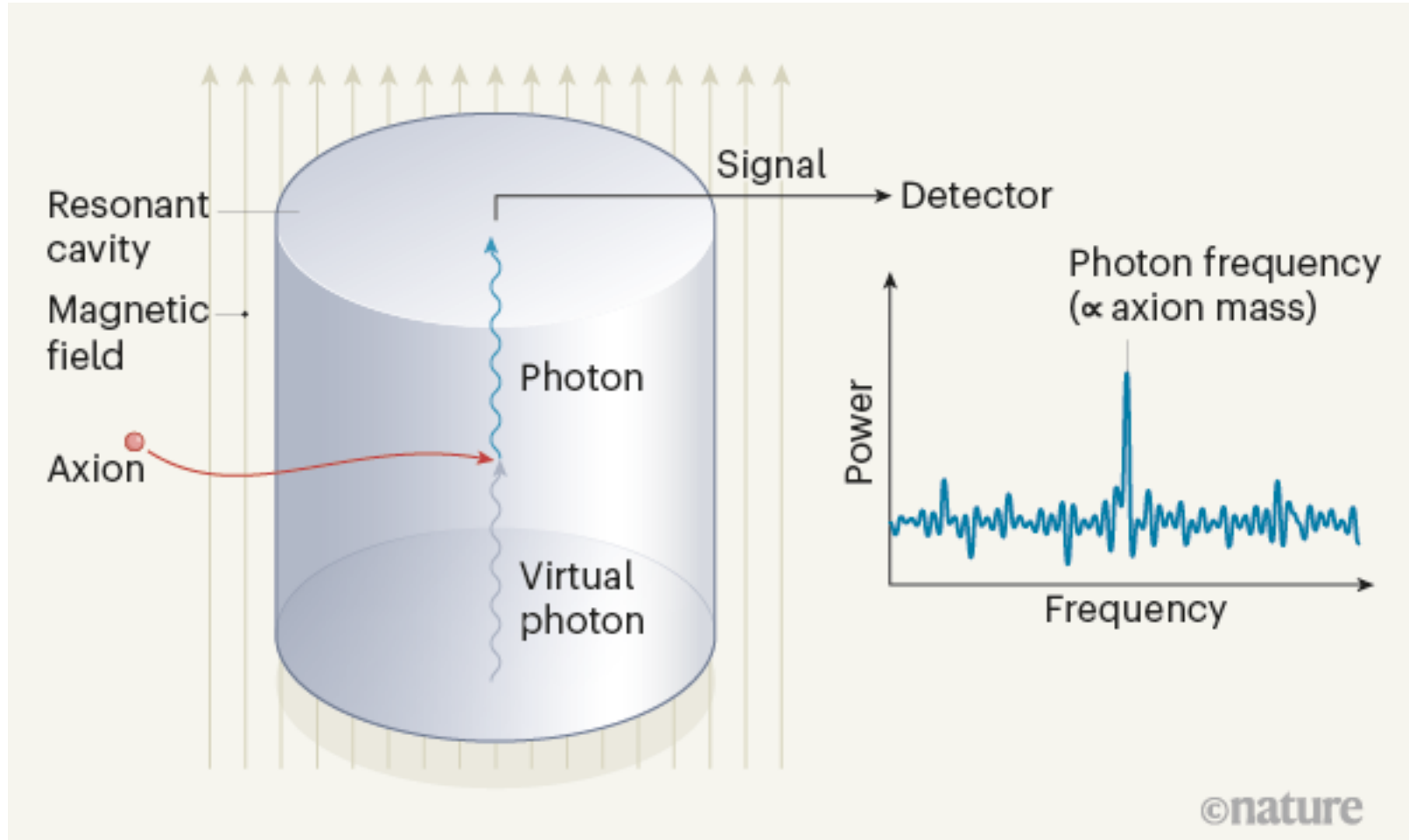
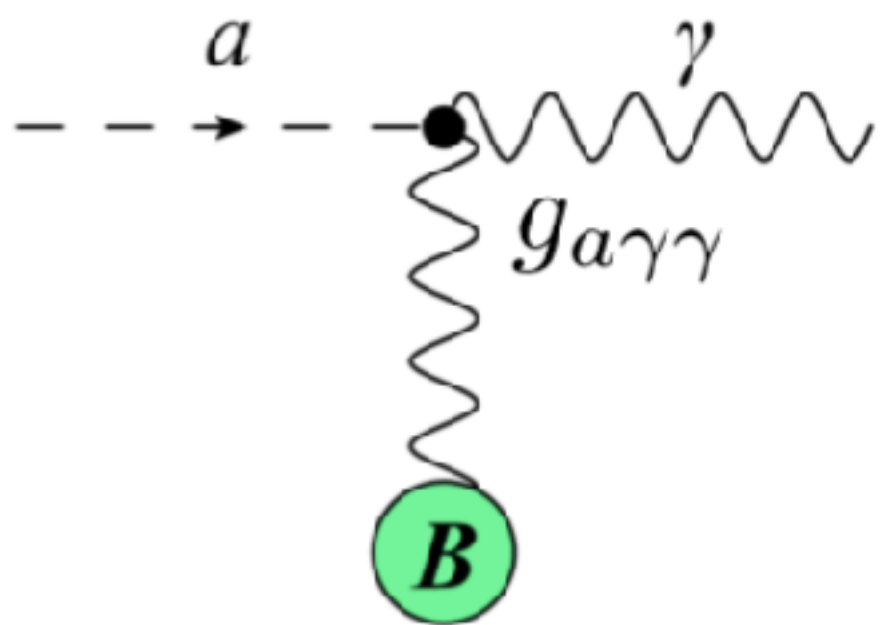


*See additional slides...

Axion searches in the lab

Axions: light pseudoscalar particles, a

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

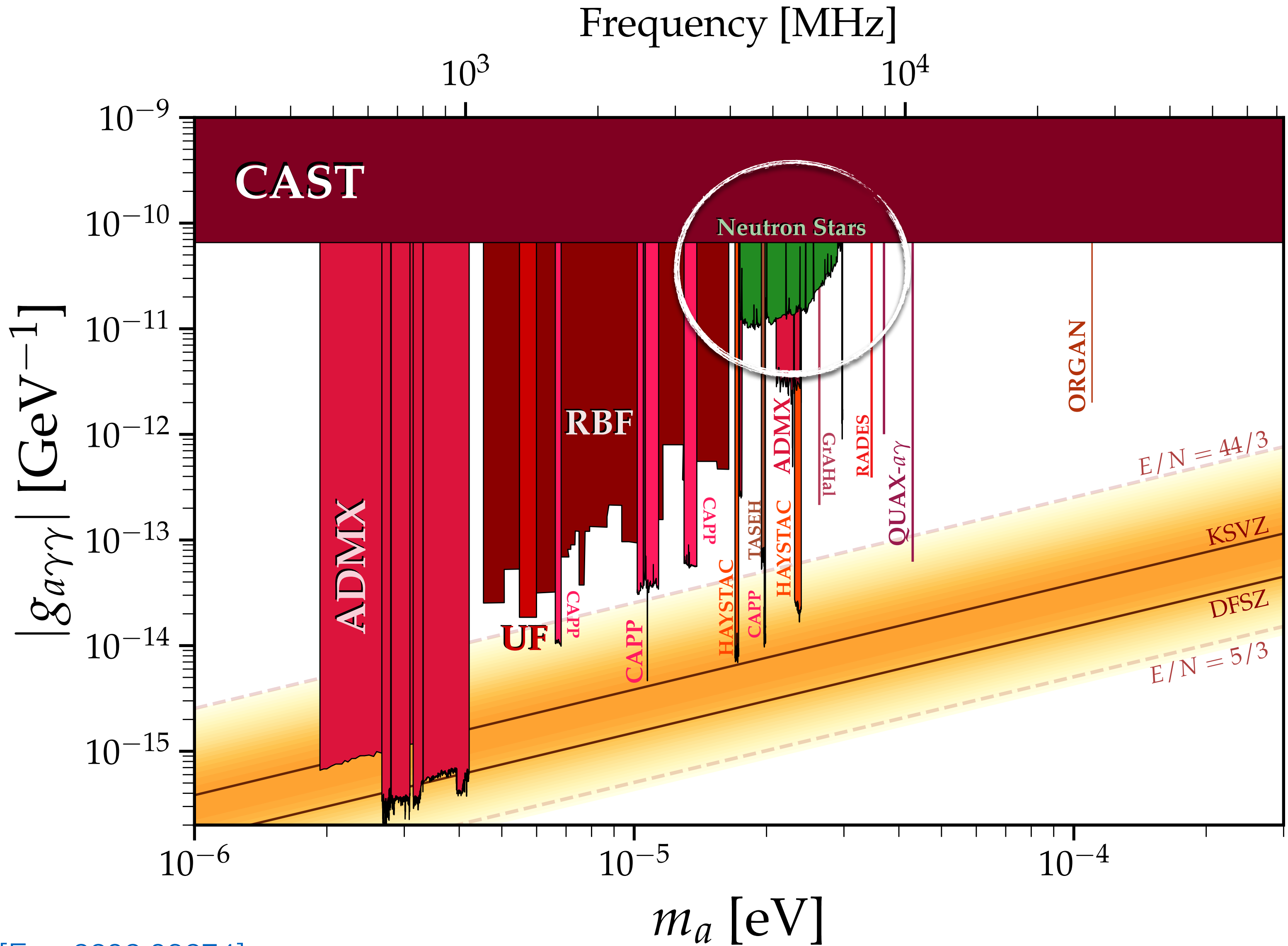
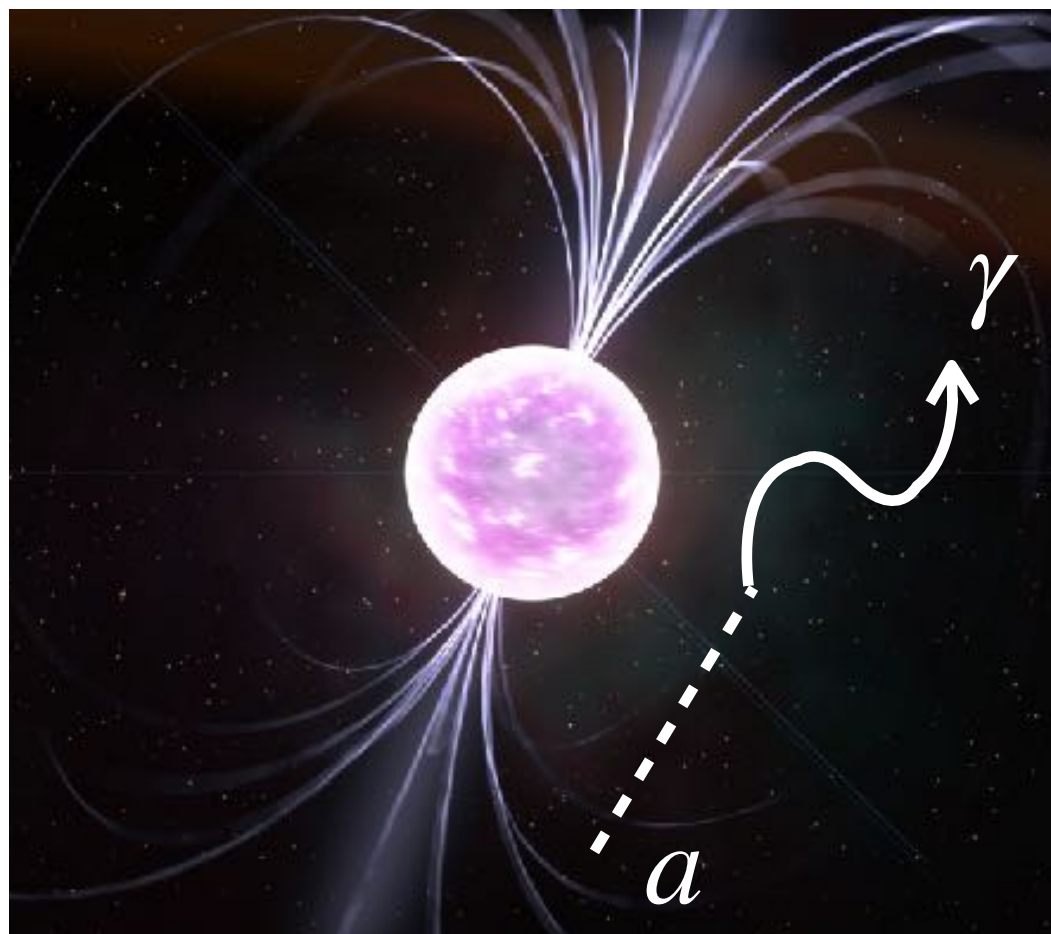
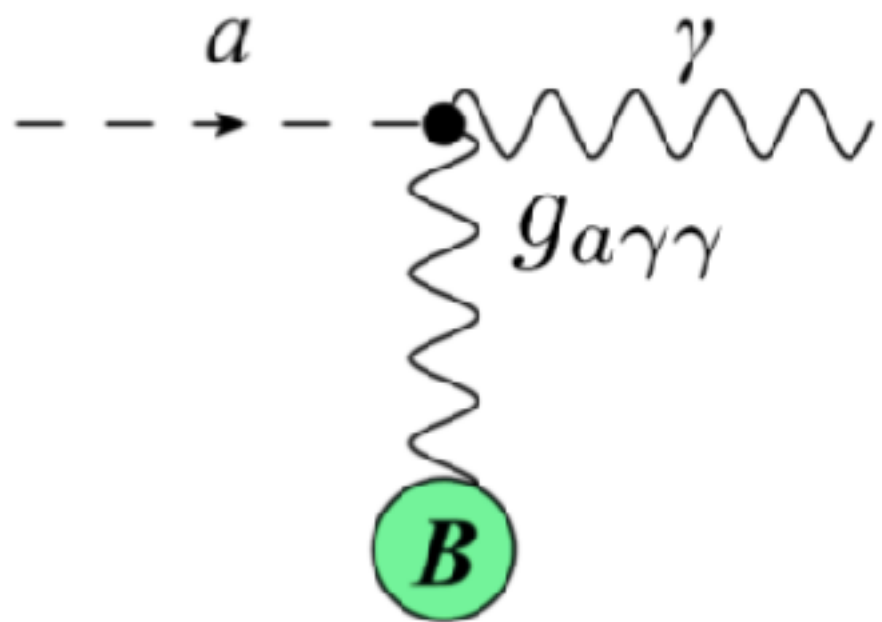


Credit: Ciaran O'Hare, [AxionLimits](#)

Axion searches and Neutron Stars

Axions: light pseudoscalar particles, a

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



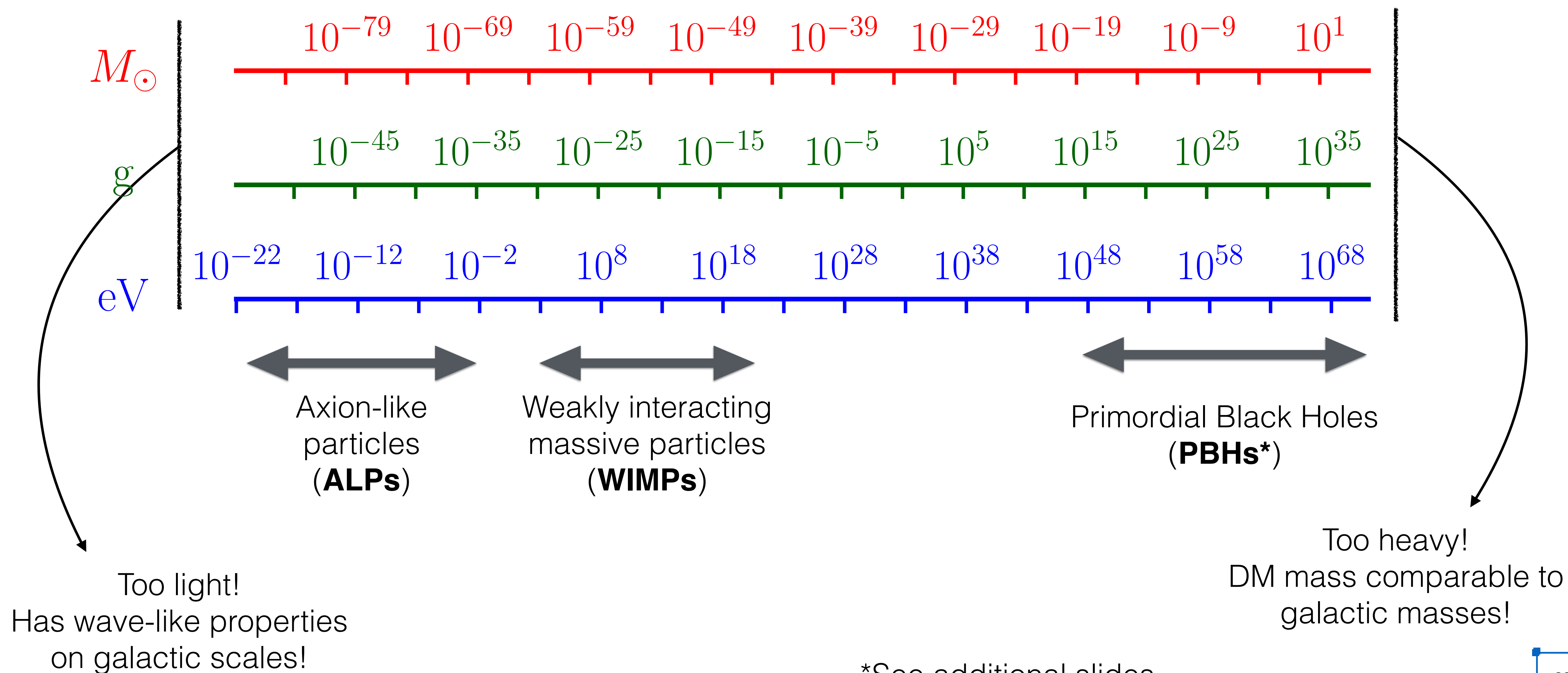
[E.g. [2202.08274](#)]

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

Dark Matter properties

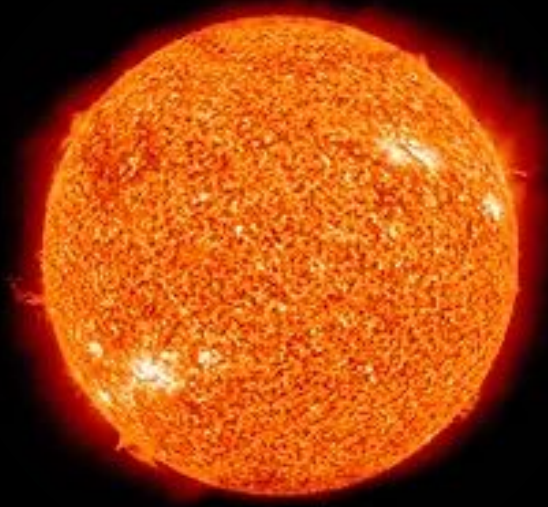
Dark Matter must be:

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*See additional slides...

The Sun



Supernovae

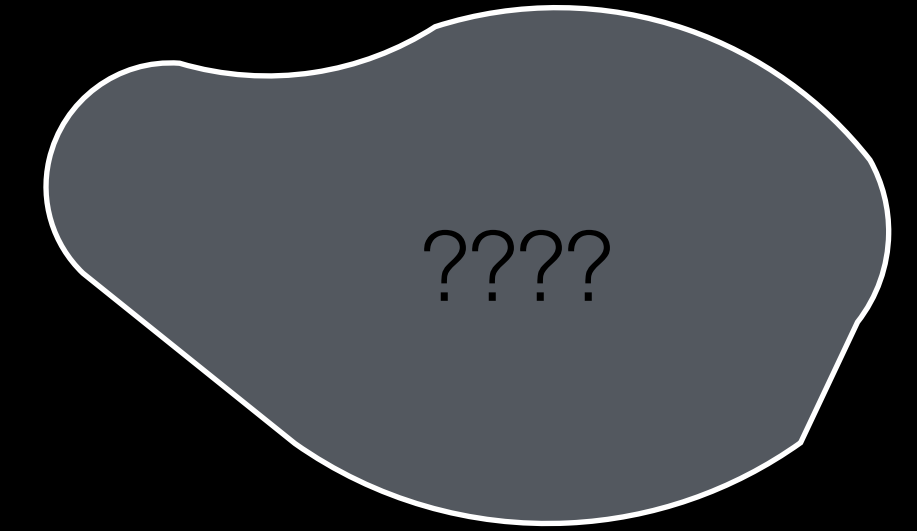
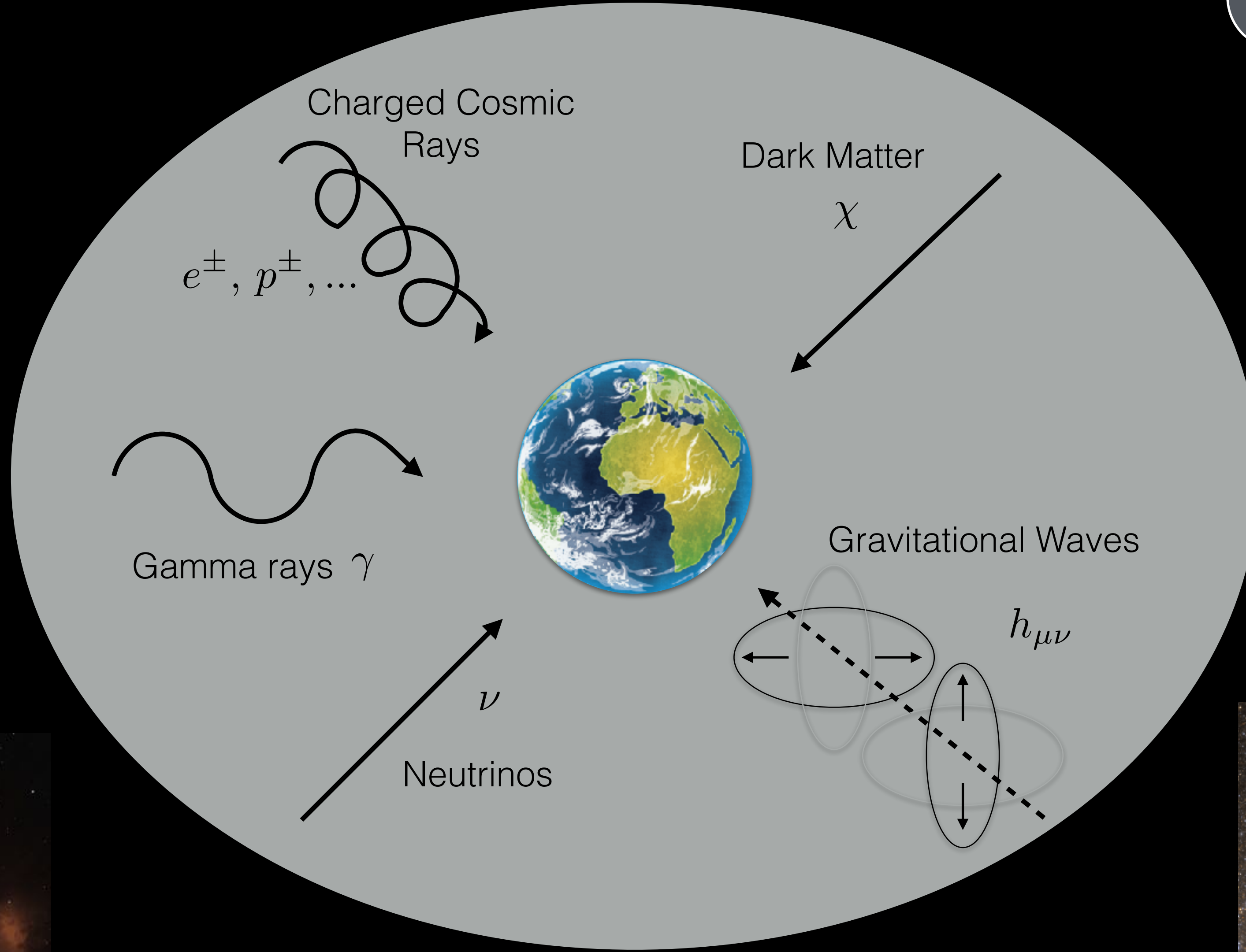


Quasars/AGN

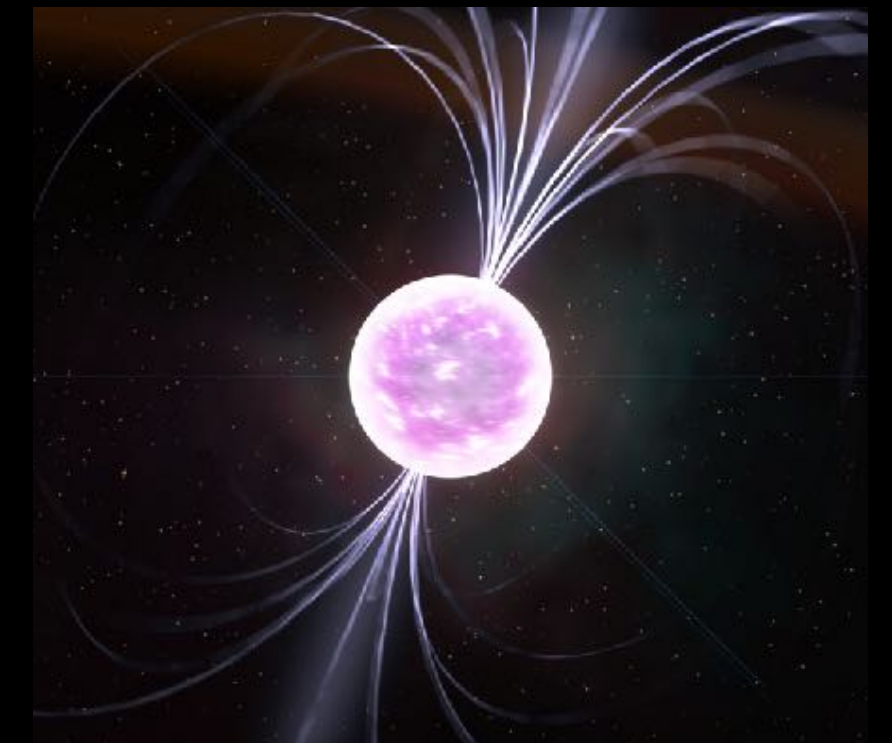


Credit: NASA/CXC/SAO

Credit: ESO/M. Kornmesser

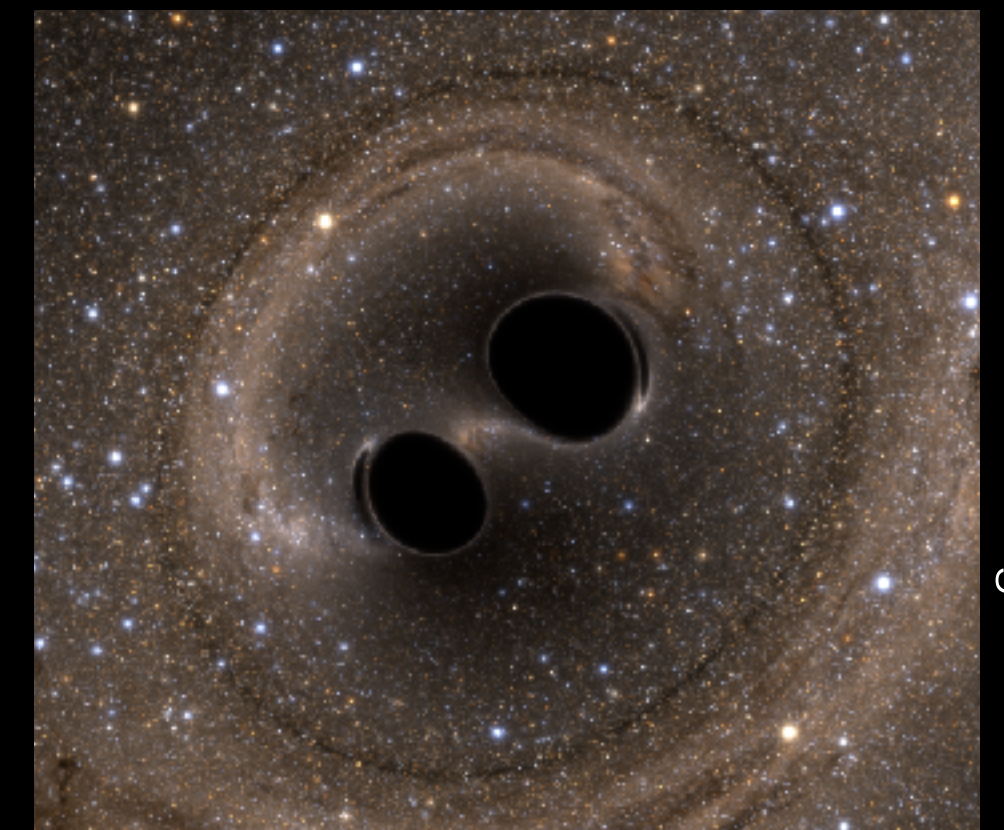


Pulsars



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

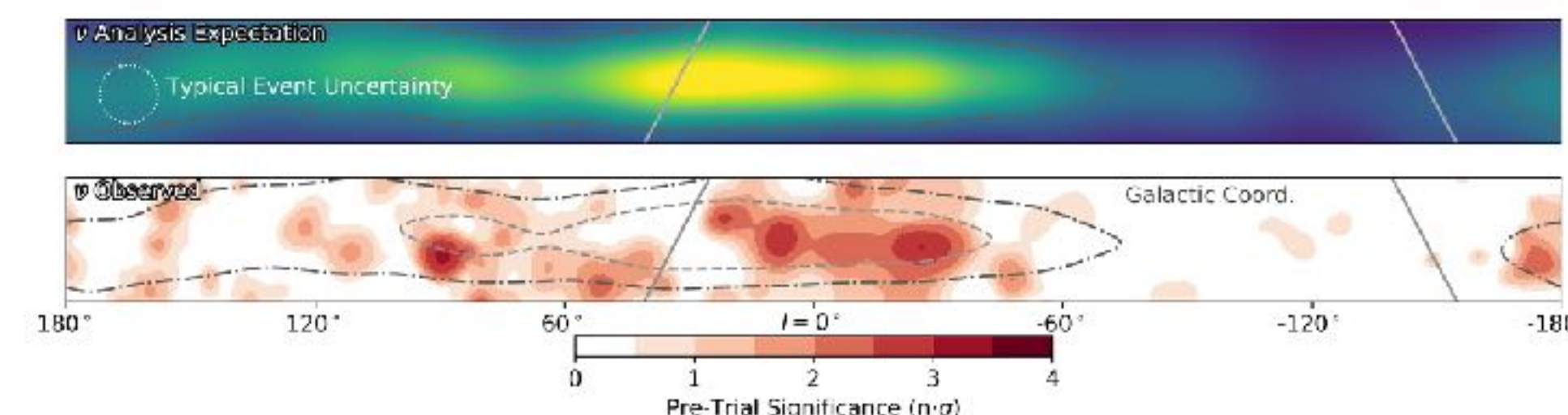
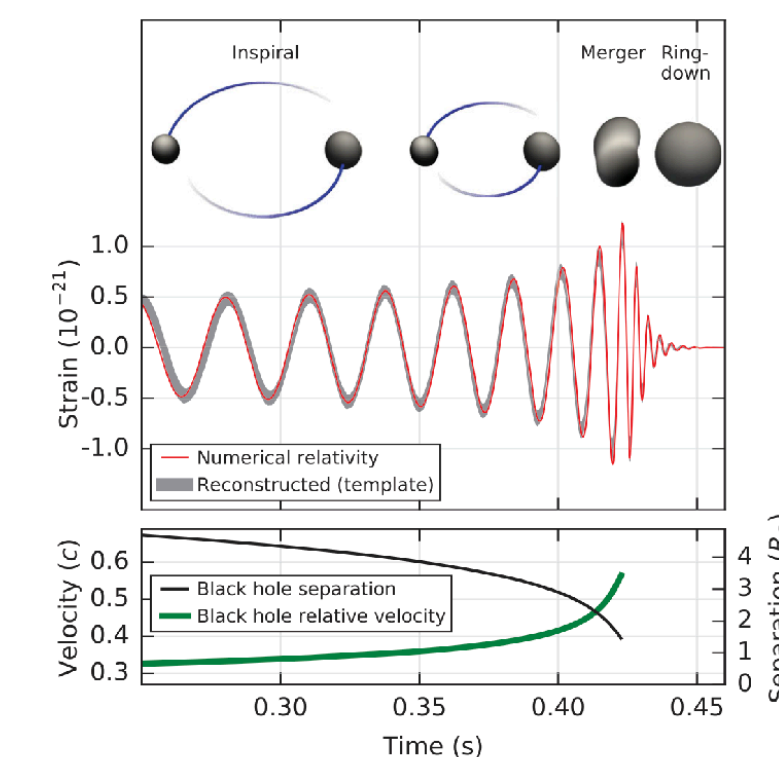
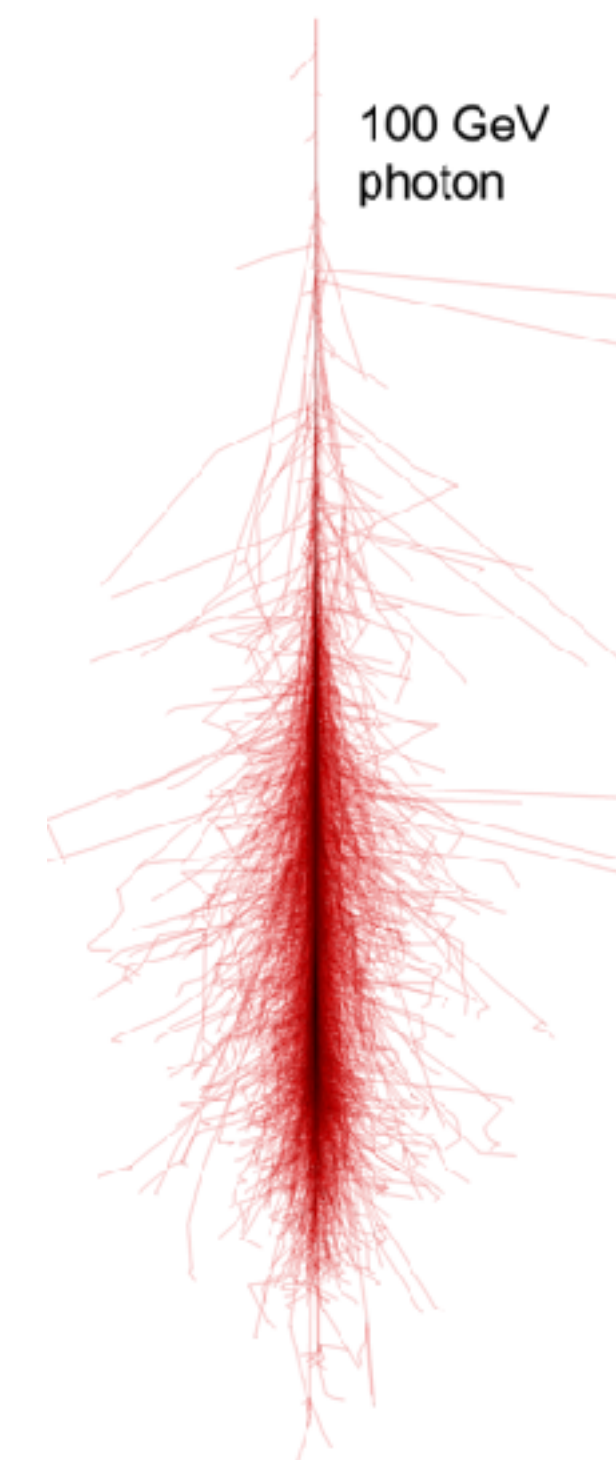
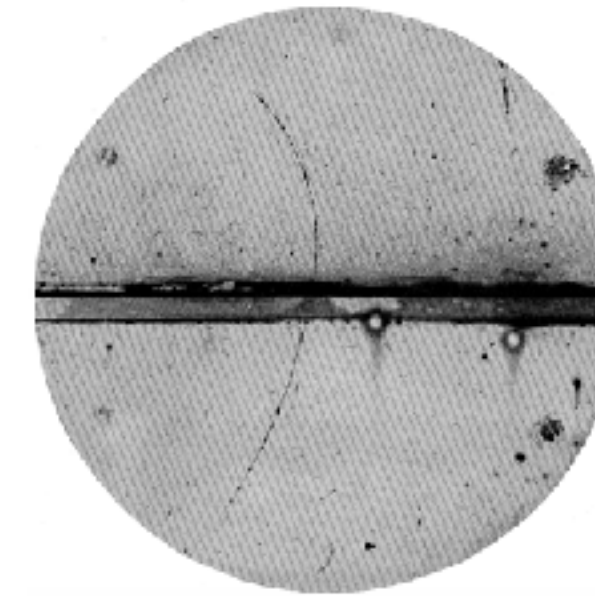
2015: GW150914 - First direct observation of GWs from Black Hole Binary Mergers

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

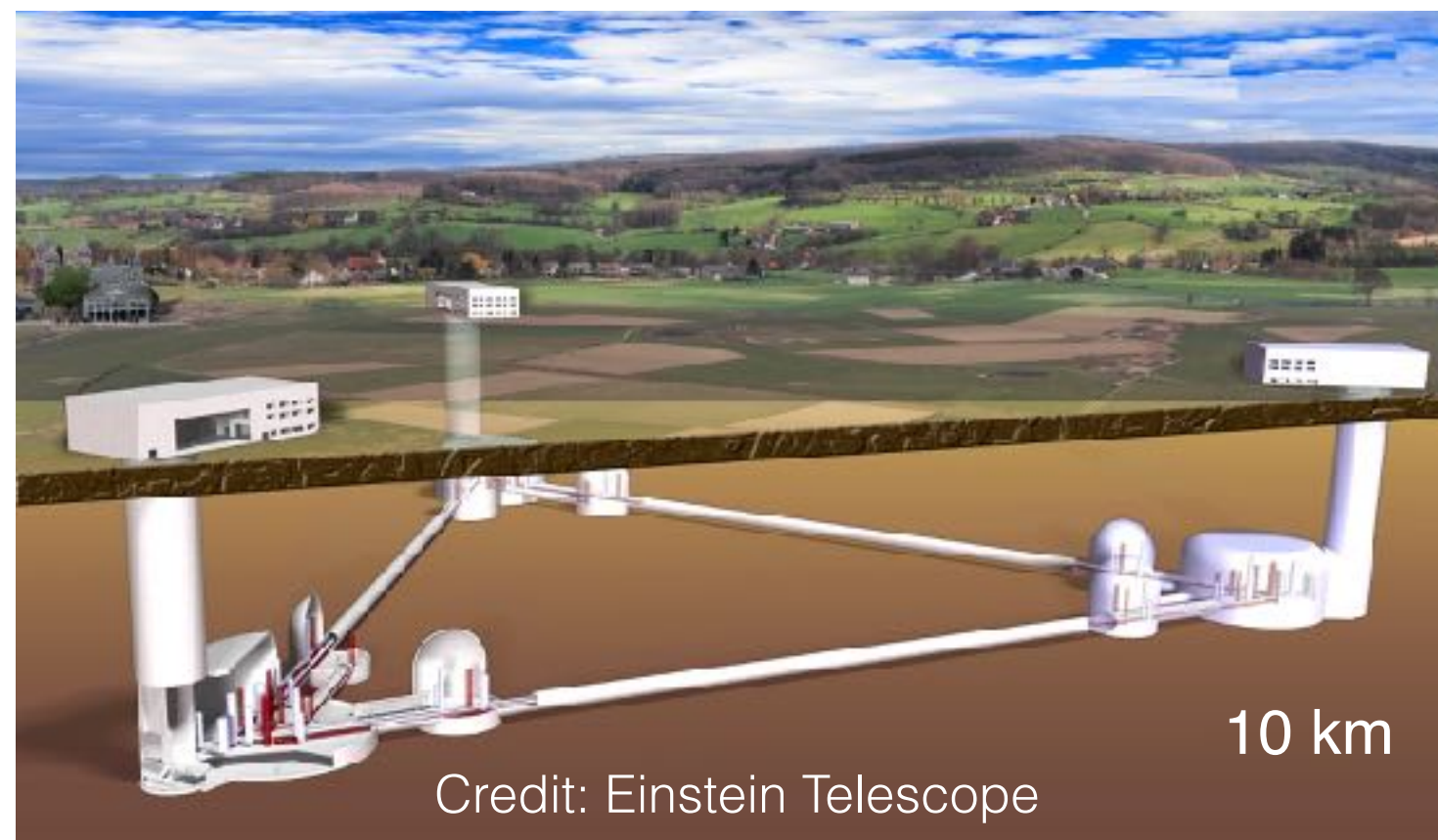
2023: NANOgrav & IPTA detect nHz Gravitational Waves



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>

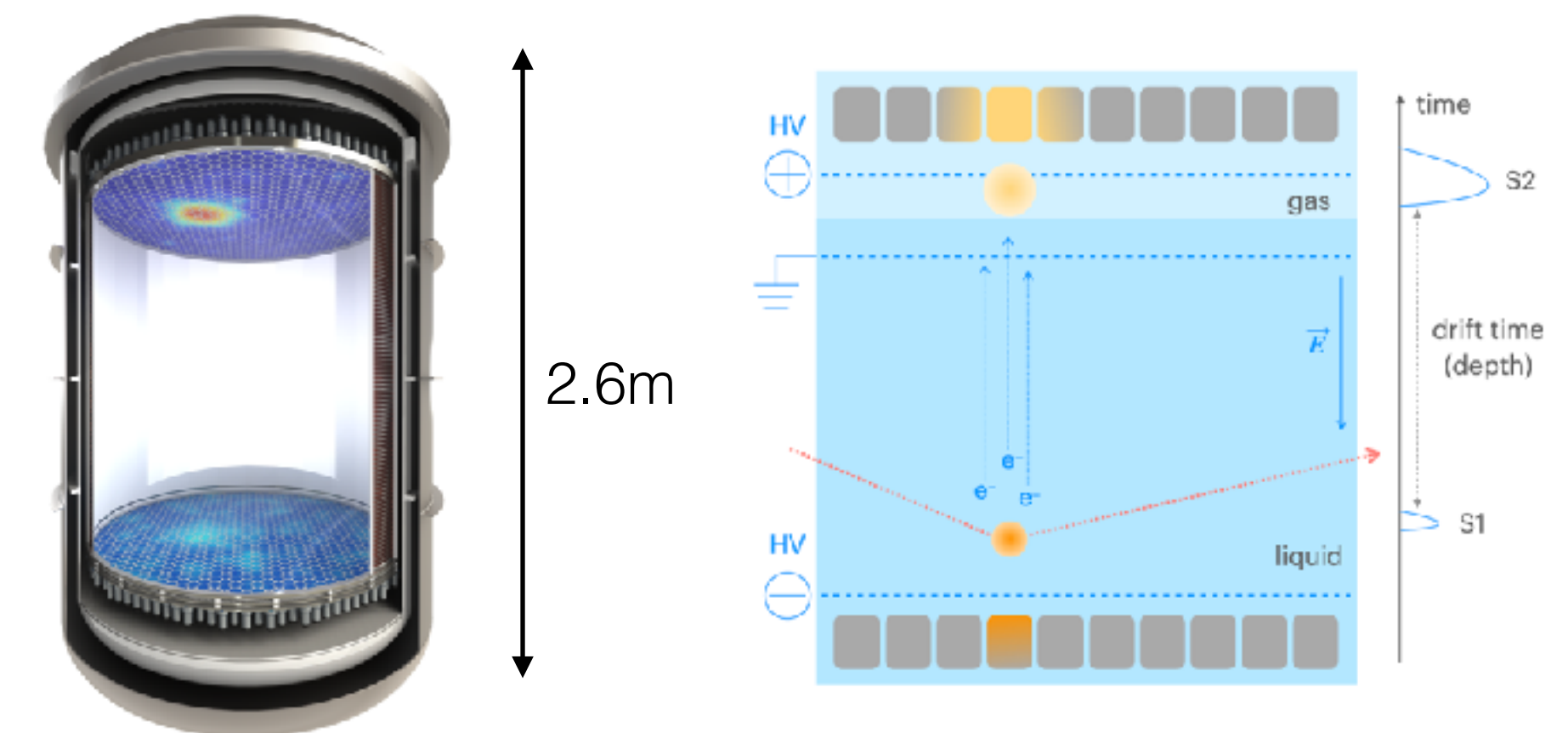


Planned Earth-based GW observatories such as Einstein Telescope will allow us to see every **merging stellar-mass BH** in the Universe

[1902.09485](https://arxiv.org/abs/1902.09485)

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

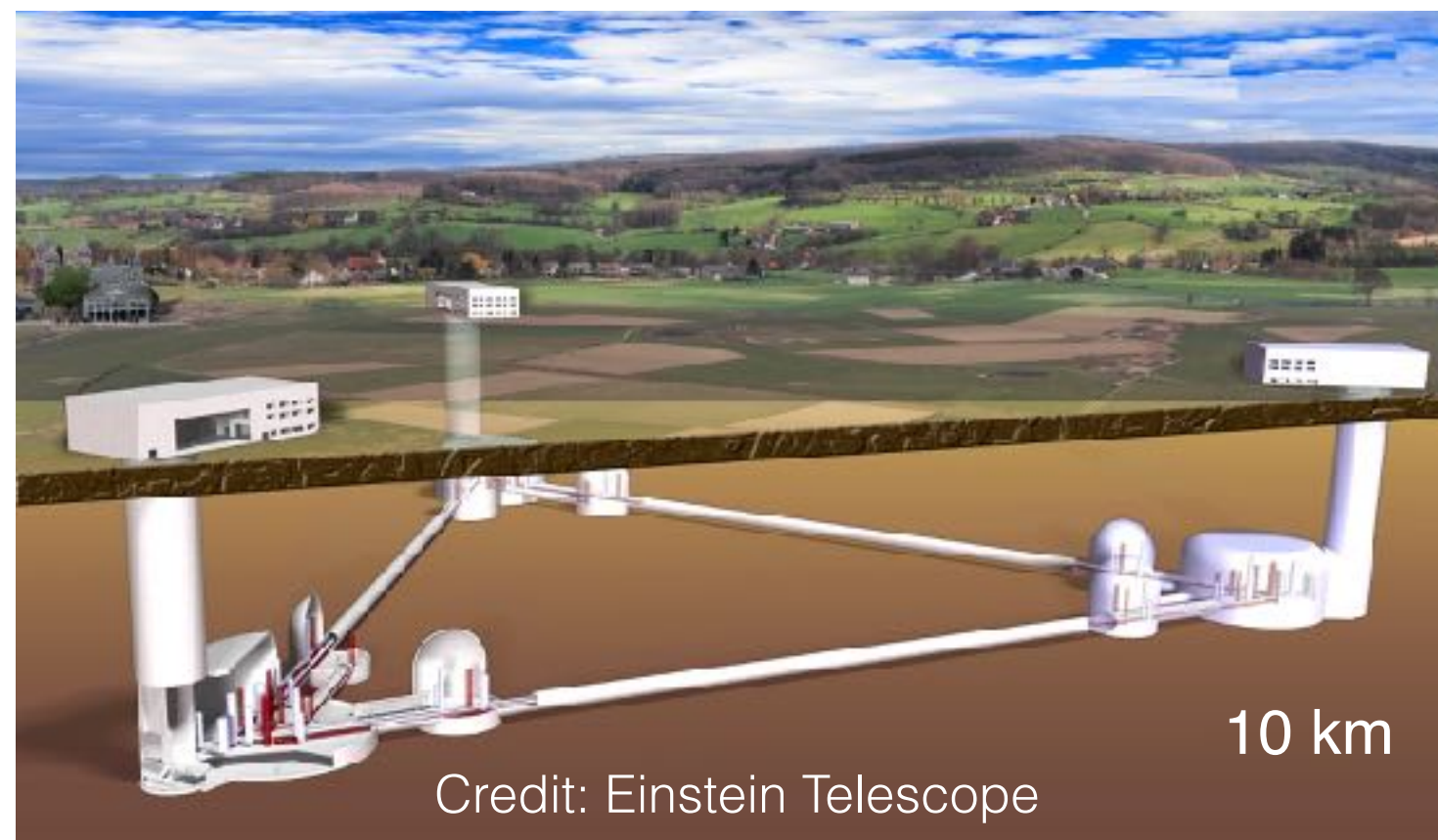
<https://darwin.physik.uzh.ch/>, [2404.19524](https://arxiv.org/abs/2404.19524)



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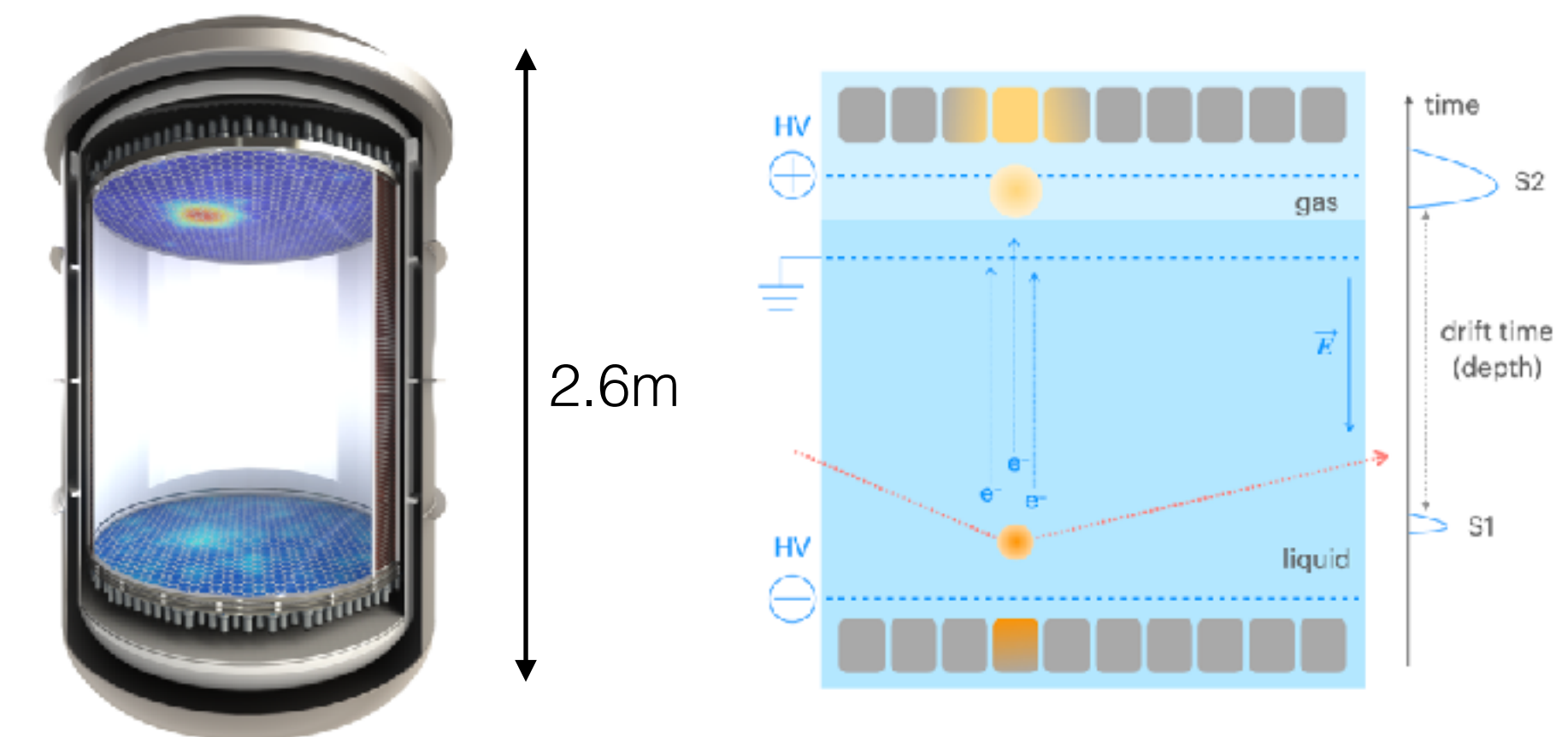


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<https://darwin.physik.uzh.ch/>, [2404.19524](https://arxiv.org/abs/2404.19524)



...looking forward to many more unexpected discoveries!

Additional Slides

Astroparticle Physics: Theory and Phenomenology, Günter Sigl, [Atlantis Press Paris](http://atlantispress.com) (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](http://arxiv.org/abs/1910.05610) (2019)

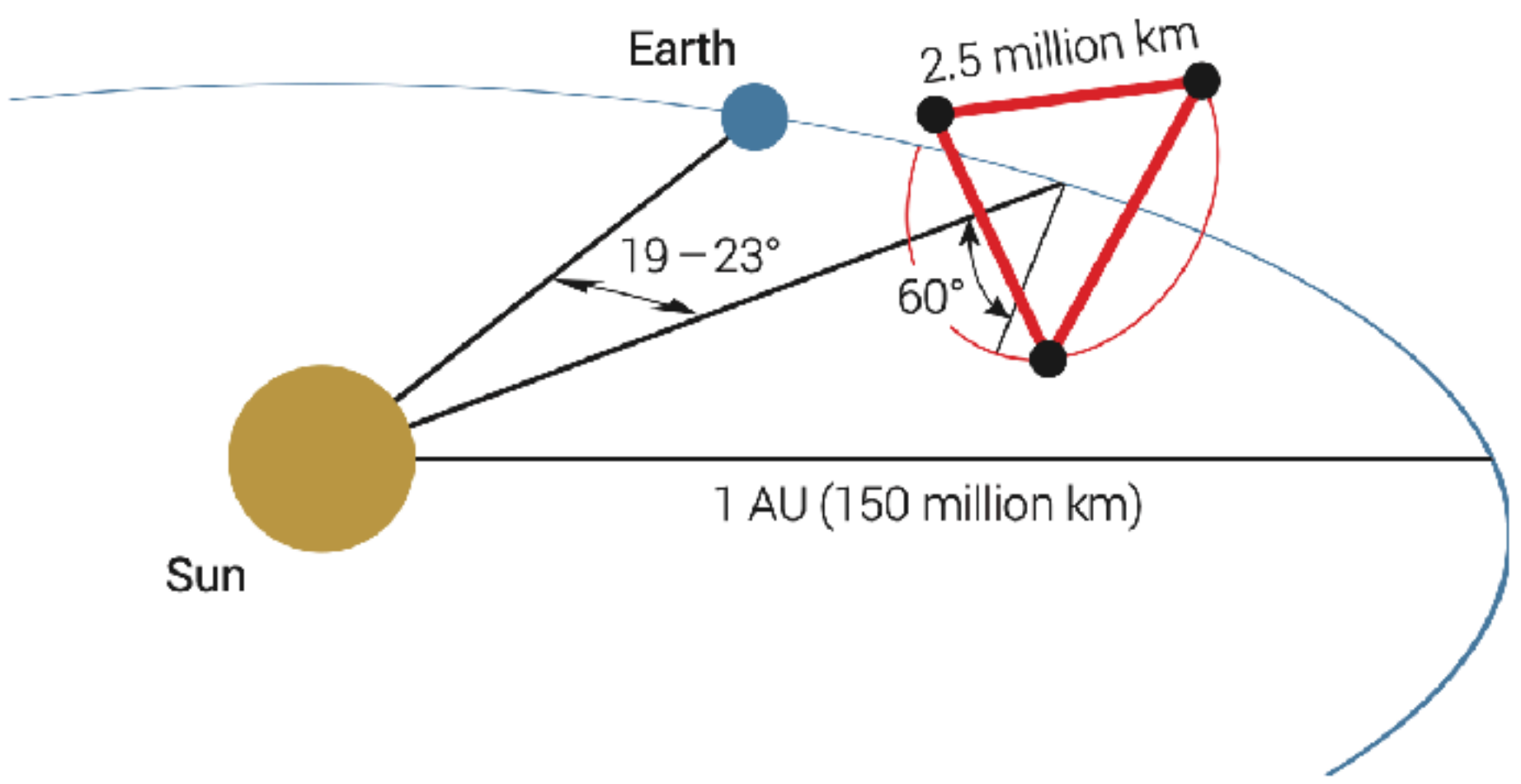
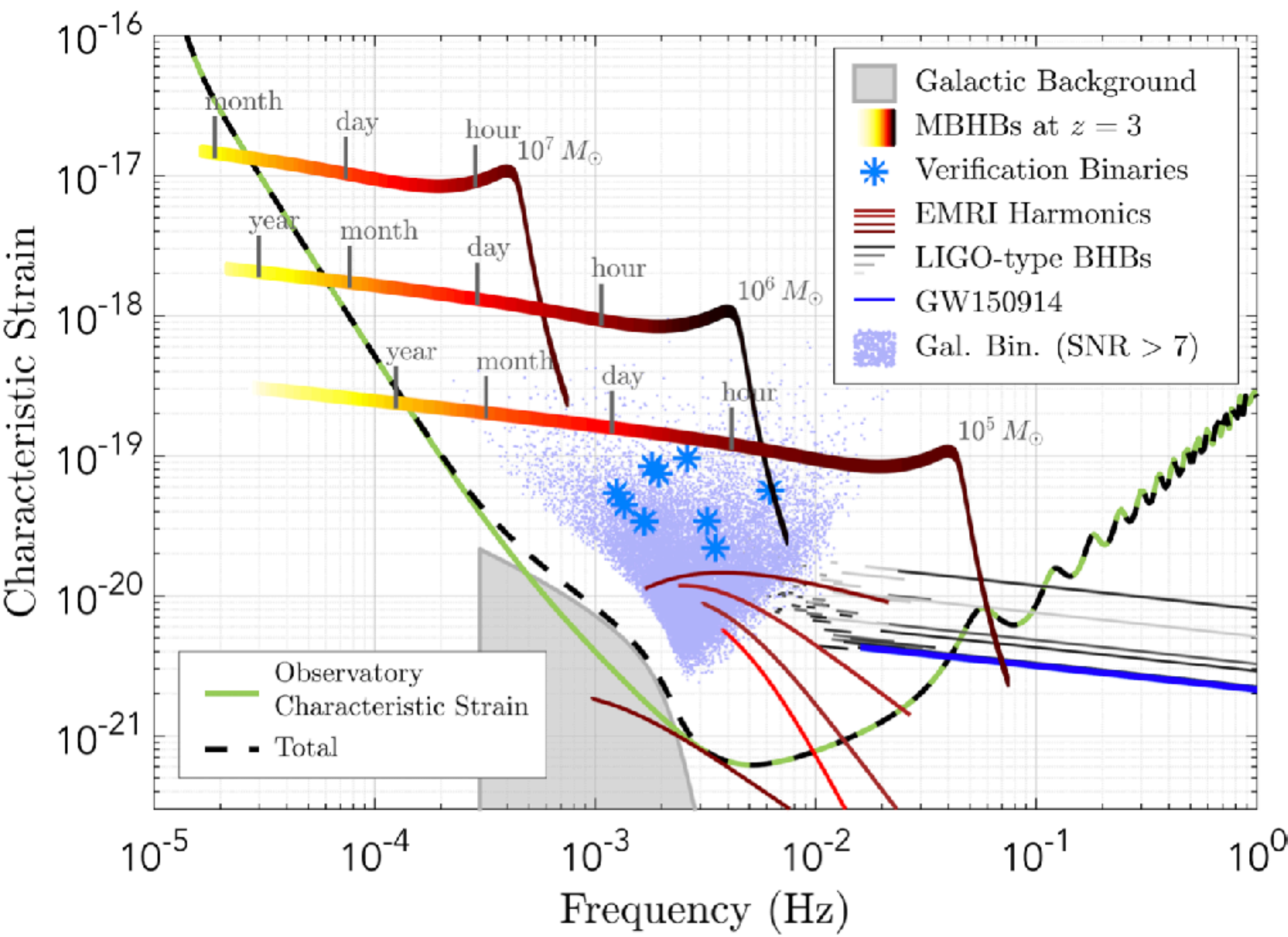
The basic physics of the binary black hole merger GW150914, LIGO & Virgo Collaborations, [arXiv:1608.01940](http://arxiv.org/abs/1608.01940) (2016)

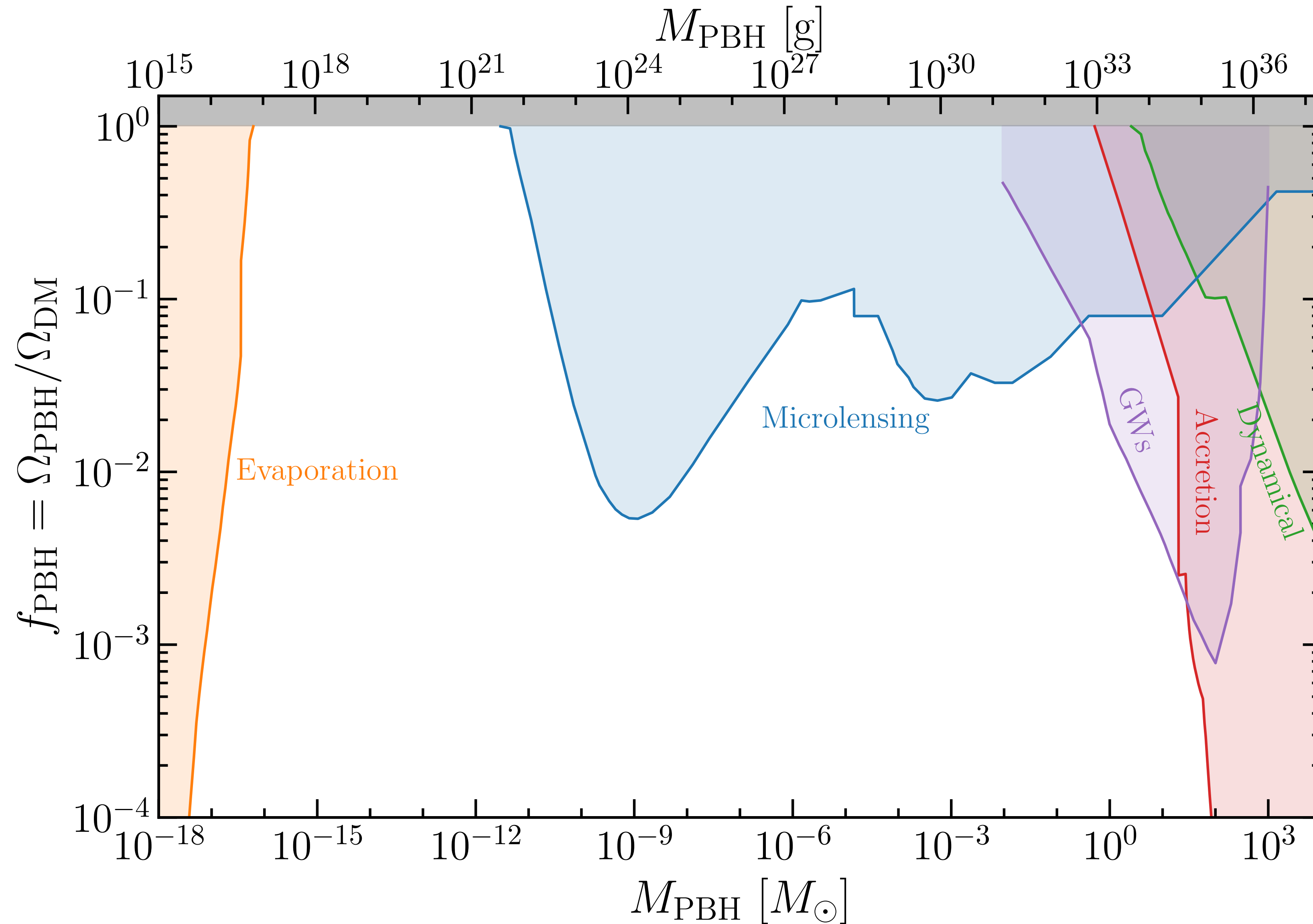
Check [arXiv](http://arxiv.org), and summaries on popular blogs like Sunny Vagnozzi's [HisDarkCMB](http://hisdarkcmb.com) or Mauricio Bustamante's [Daily arXiv Picks](http://dailyarxivpicks.com)!

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

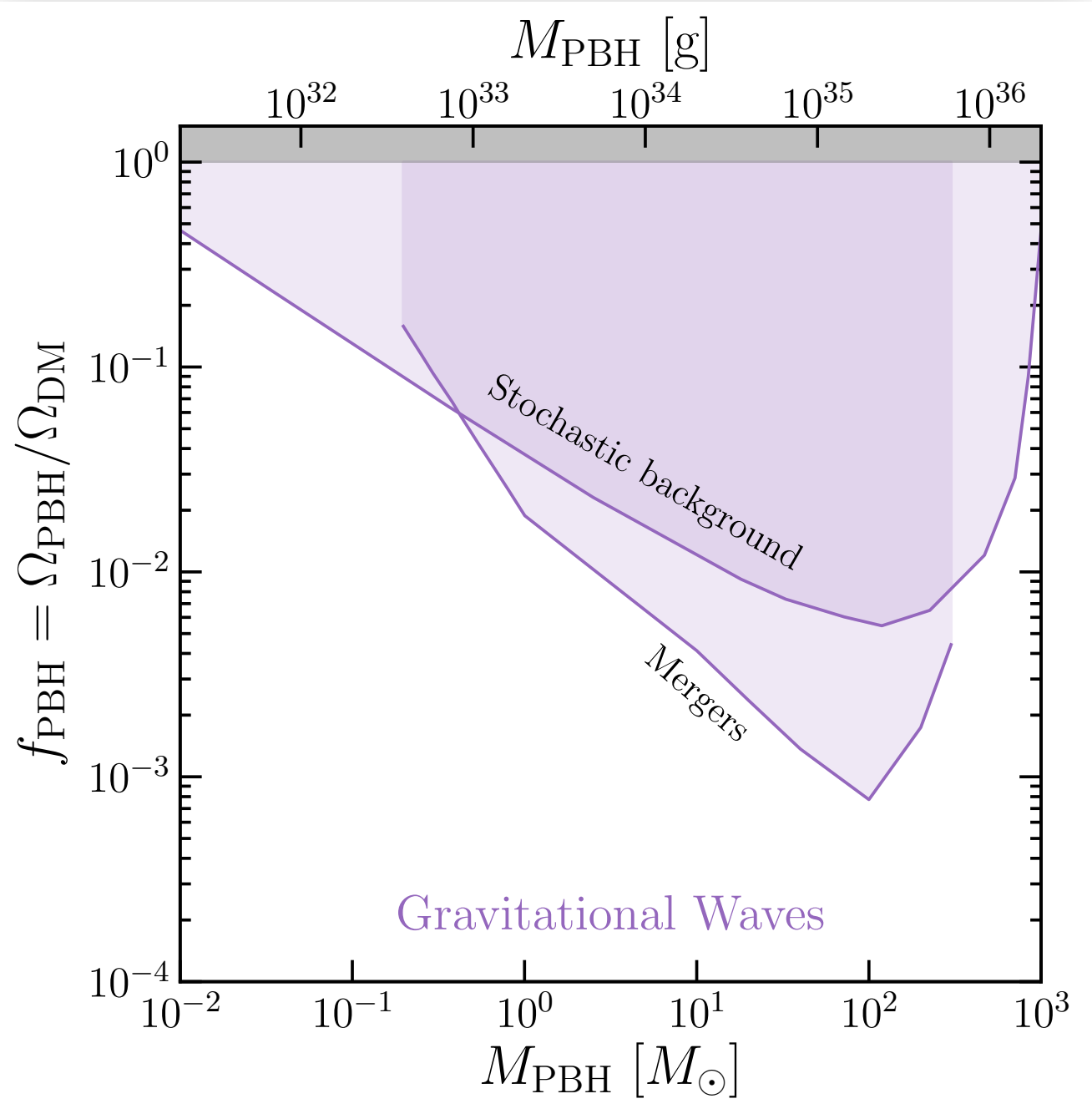
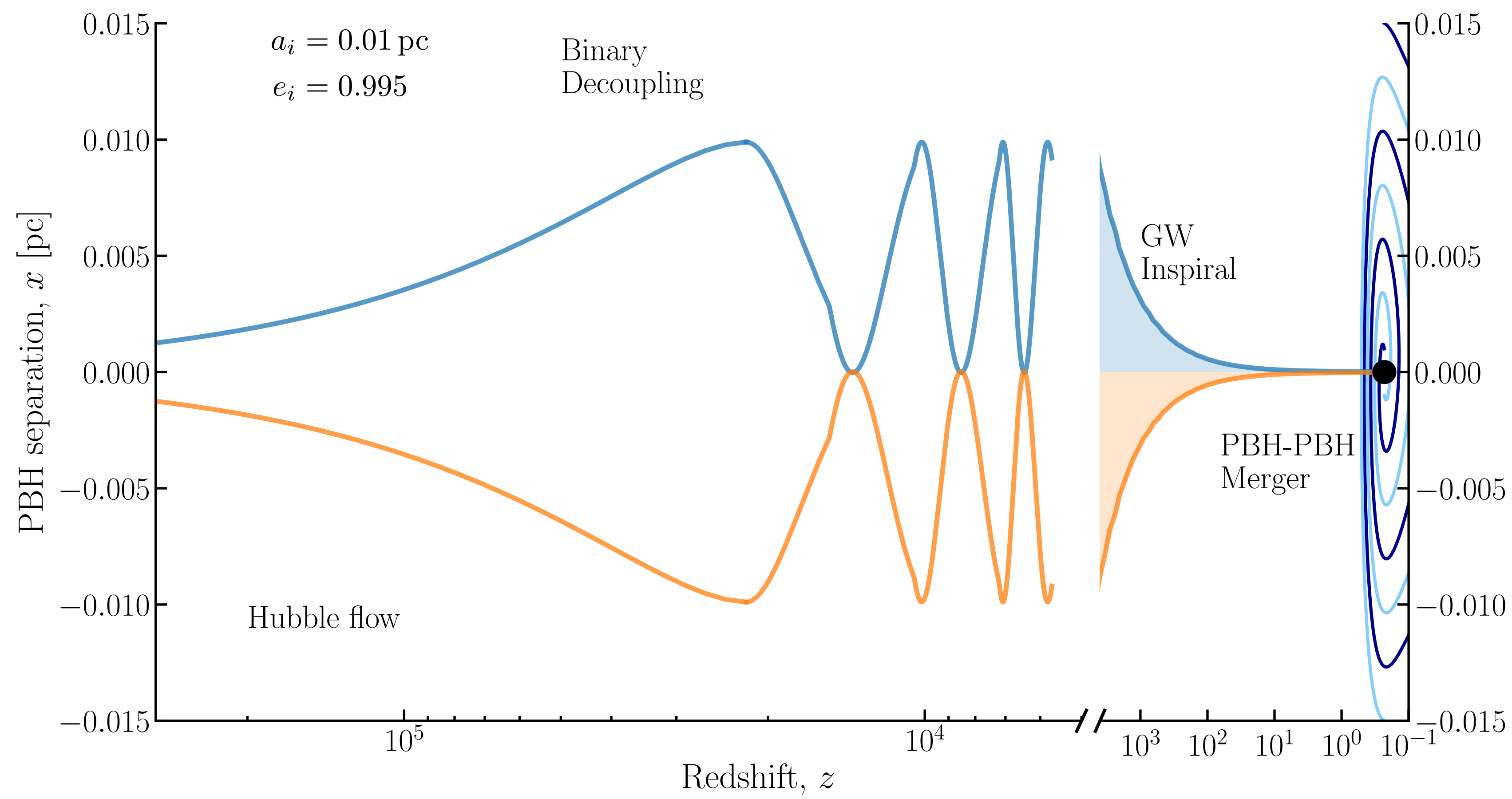
LISA - GWs in space!

Laser Interferometer Space Antenna
(Planned for the 2030s)

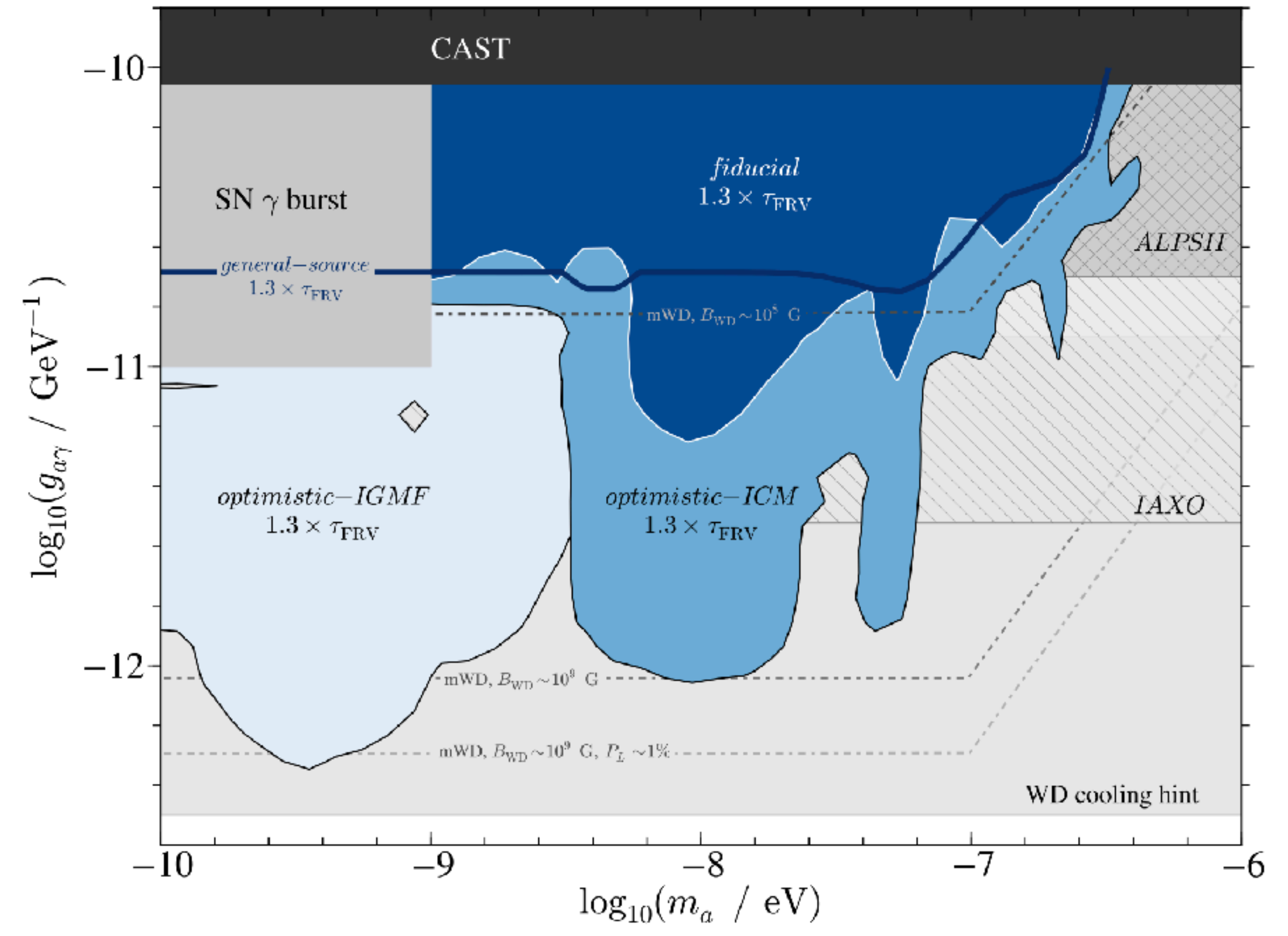
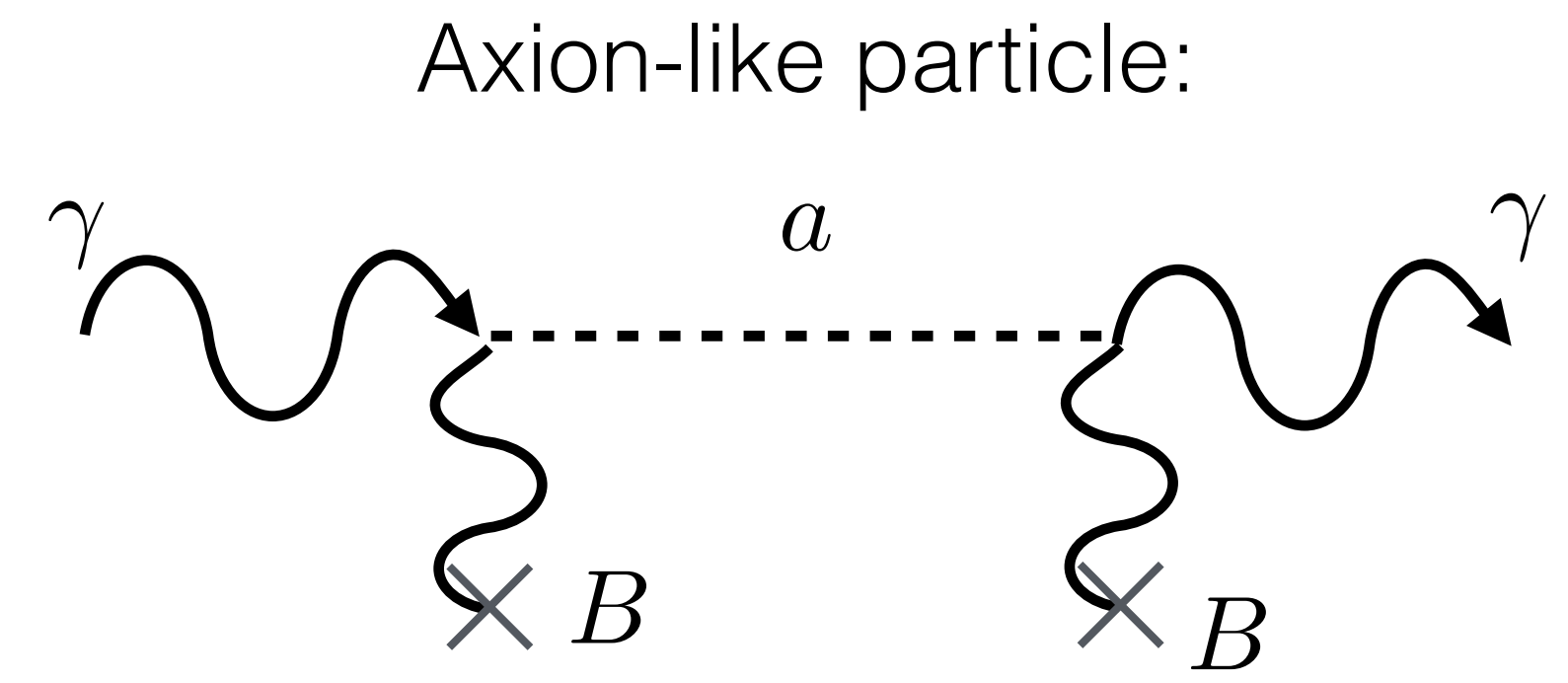
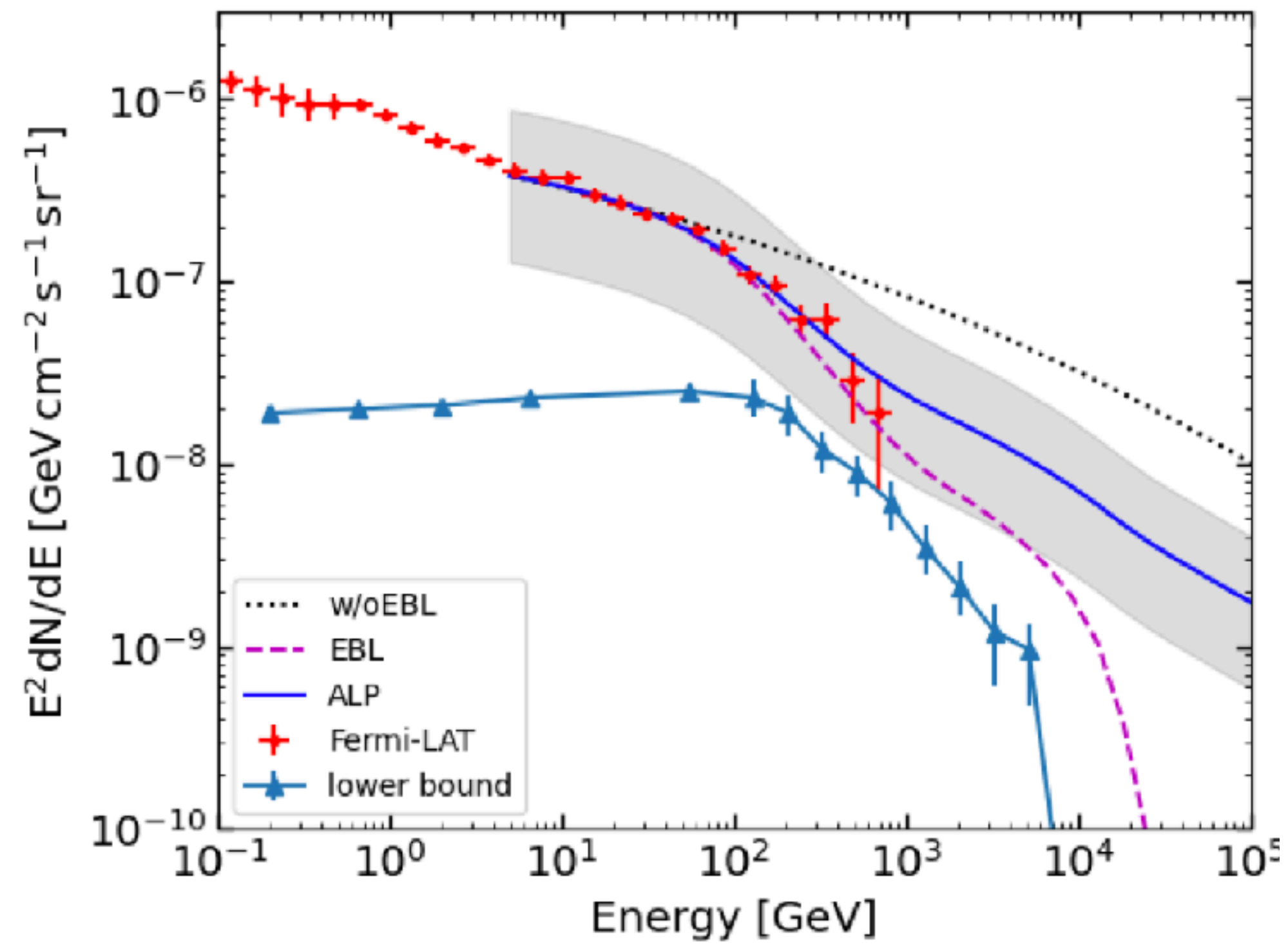
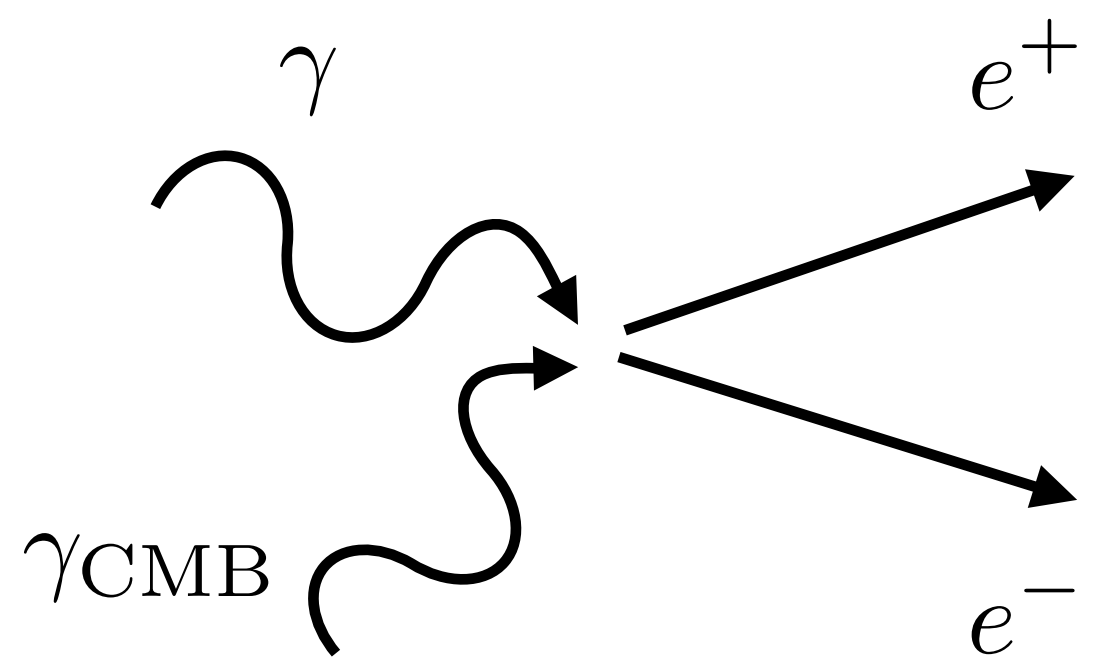




PBHs and Gravitational Waves



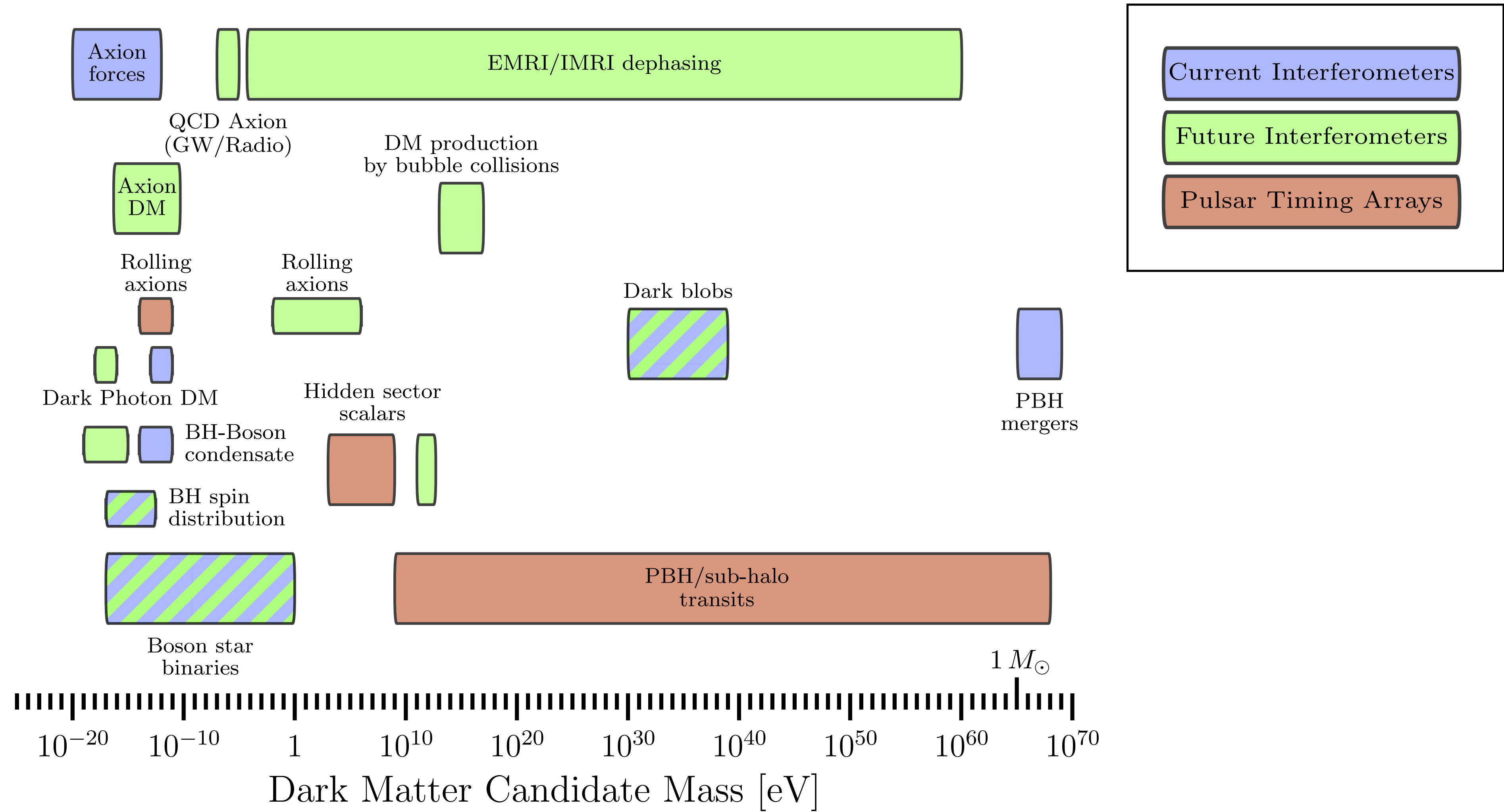
Gamma-ray transparency and axions



[2012.15513](#)

[1302.1208](#)

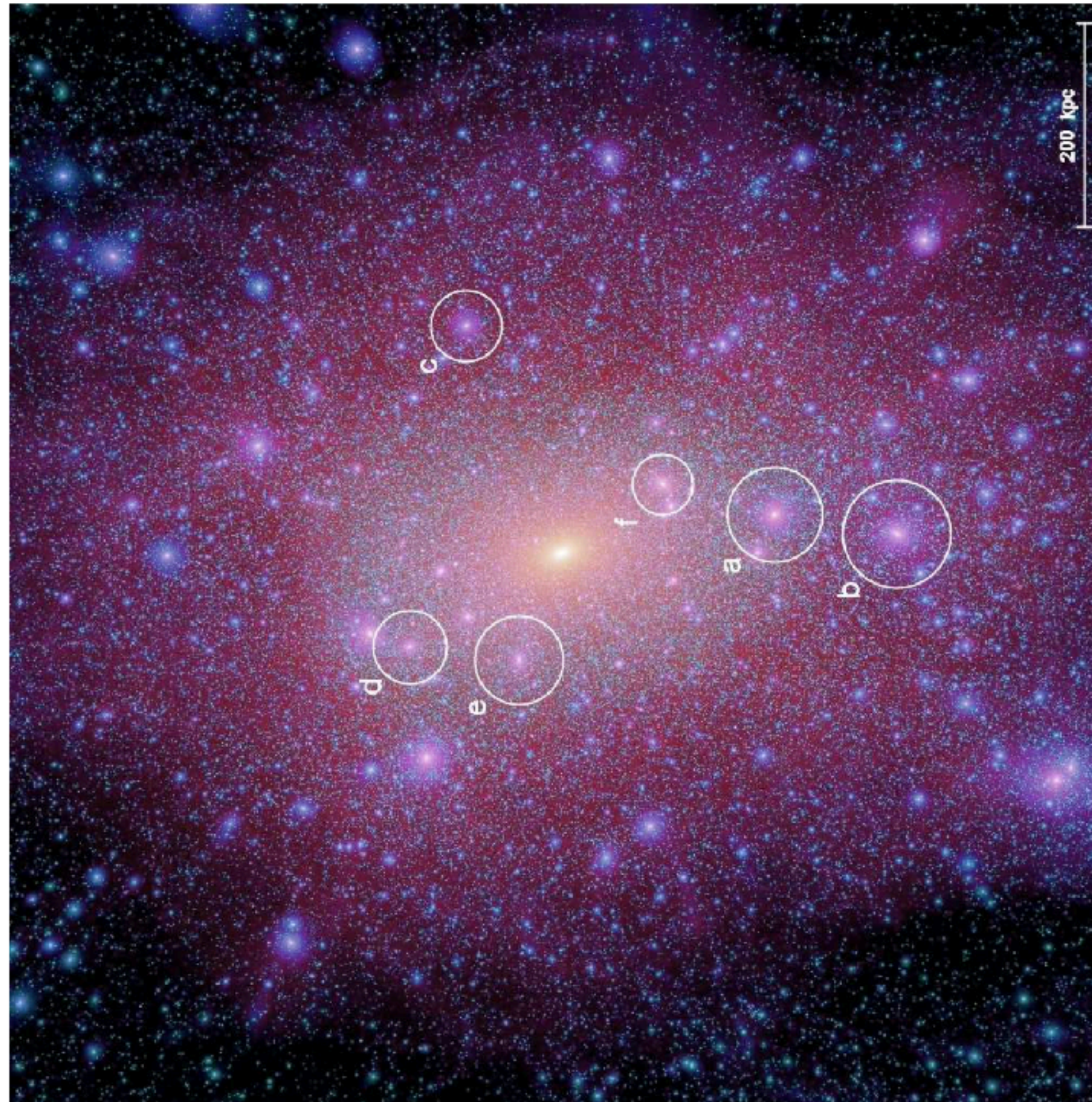
Gravitational Wave probes of DM



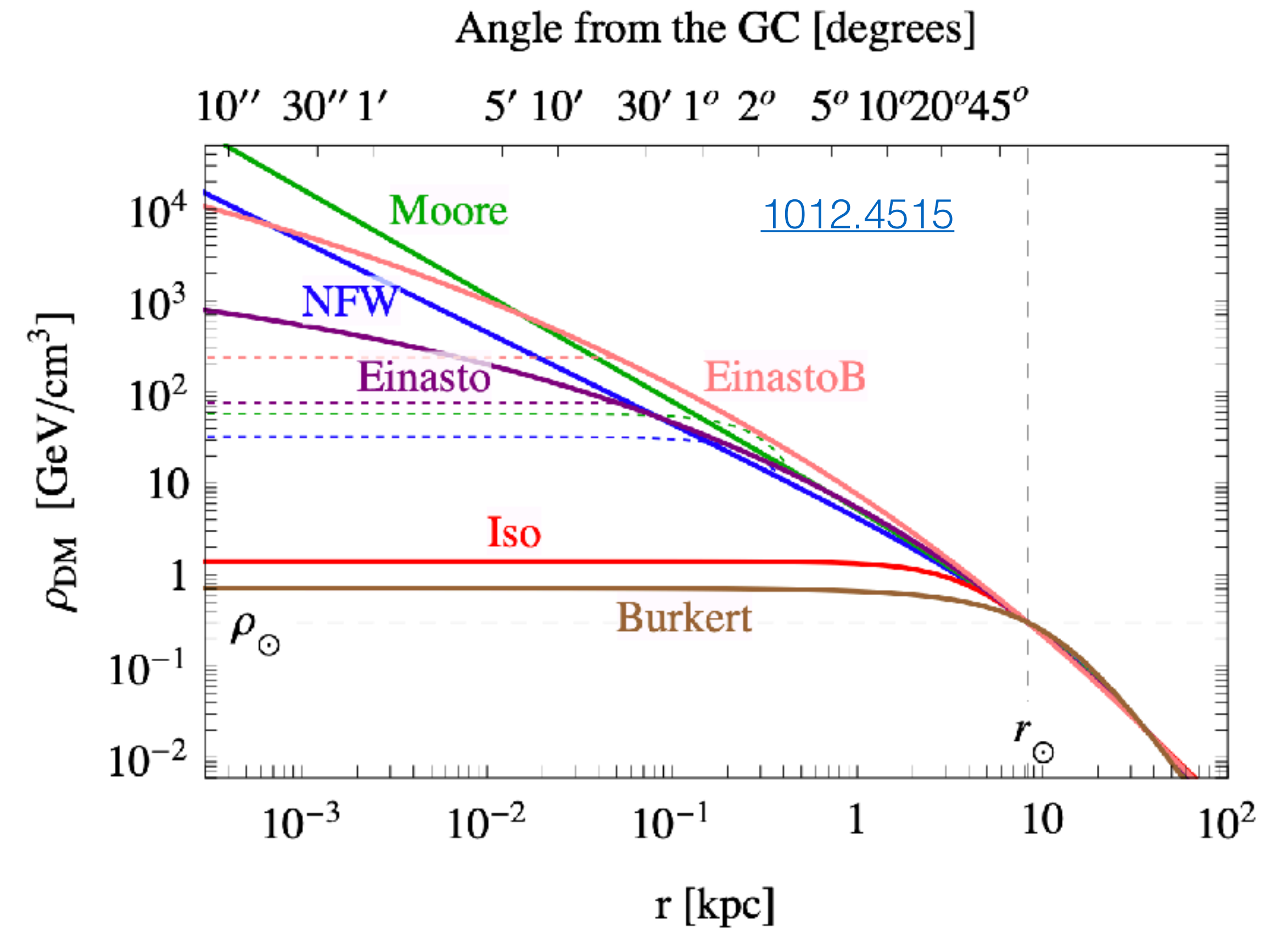
For more information about probing Dark Matter with Gravitational Waves, see [1907.10610](#)

Dark Matter in Galaxies (2)

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

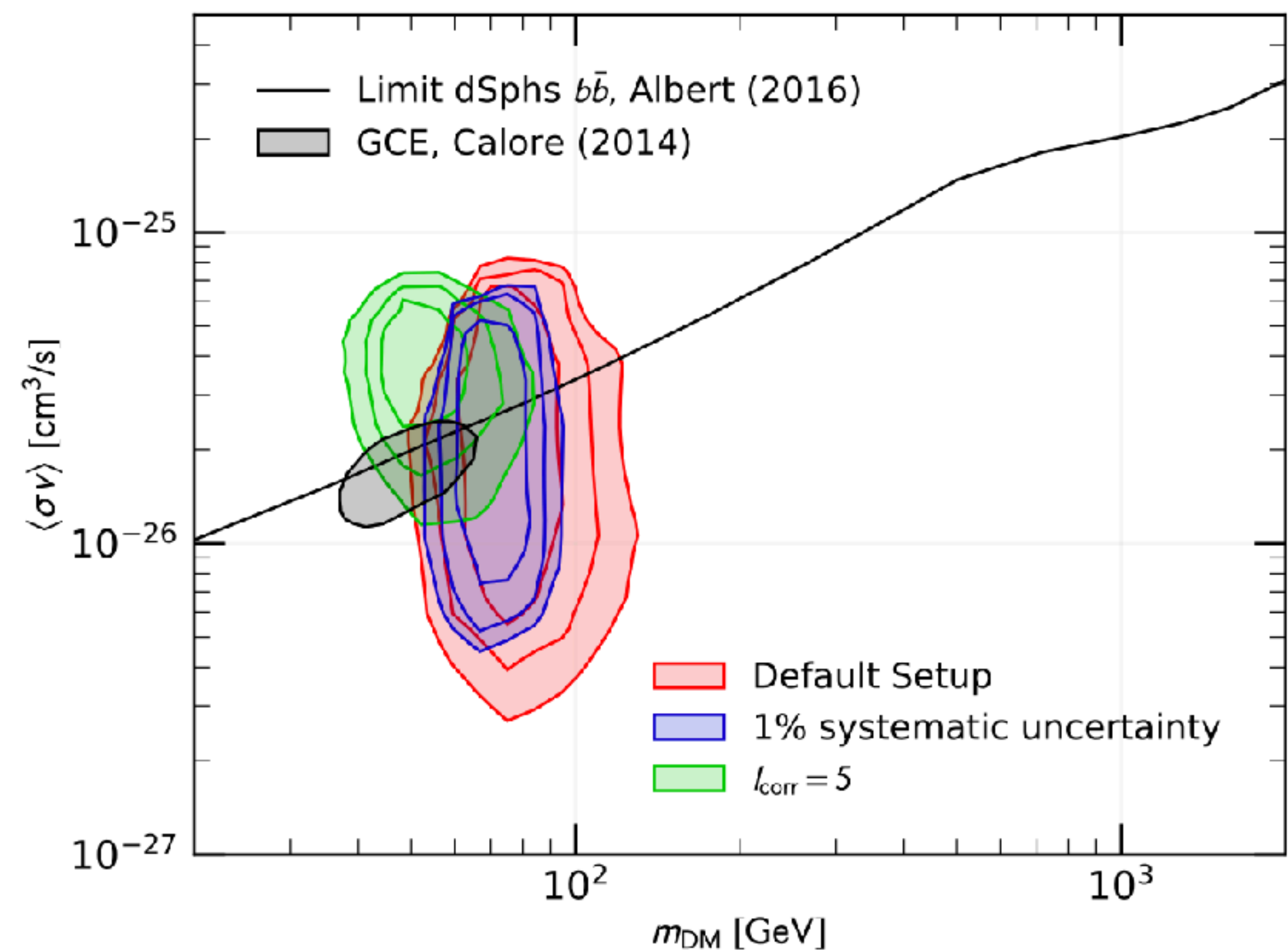


Aquarius simulation - [0809.0898](#)

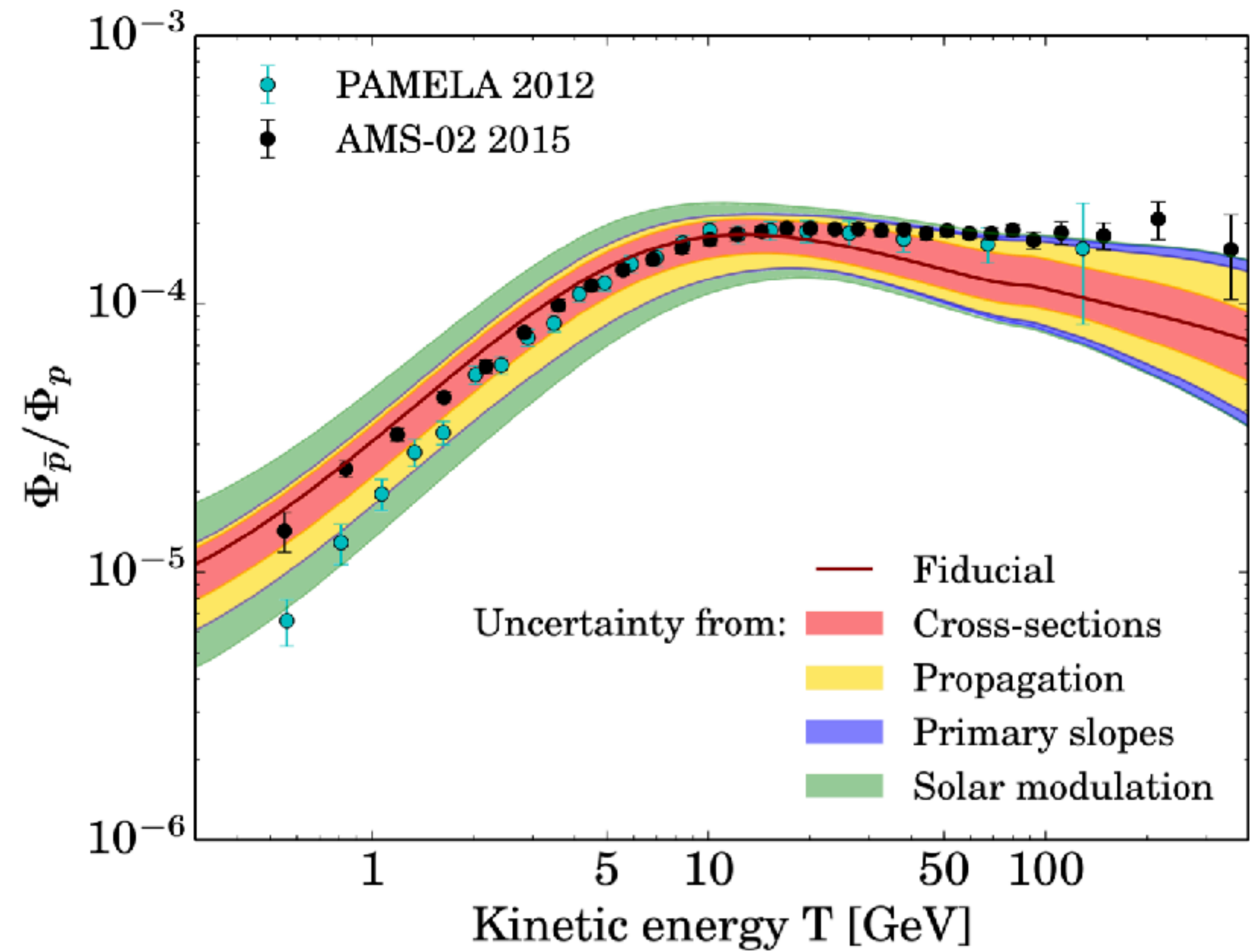


DM density at Earth: $\rho_\chi \sim 5 \times 10^{-25} \text{ g/cm}^3$
 $\sim 0.3 \text{ GeV/cm}^3$
 $\sim 0.008 M_\odot/\text{pc}^3$

Anti-proton excess (2)



[1903.01472](#)

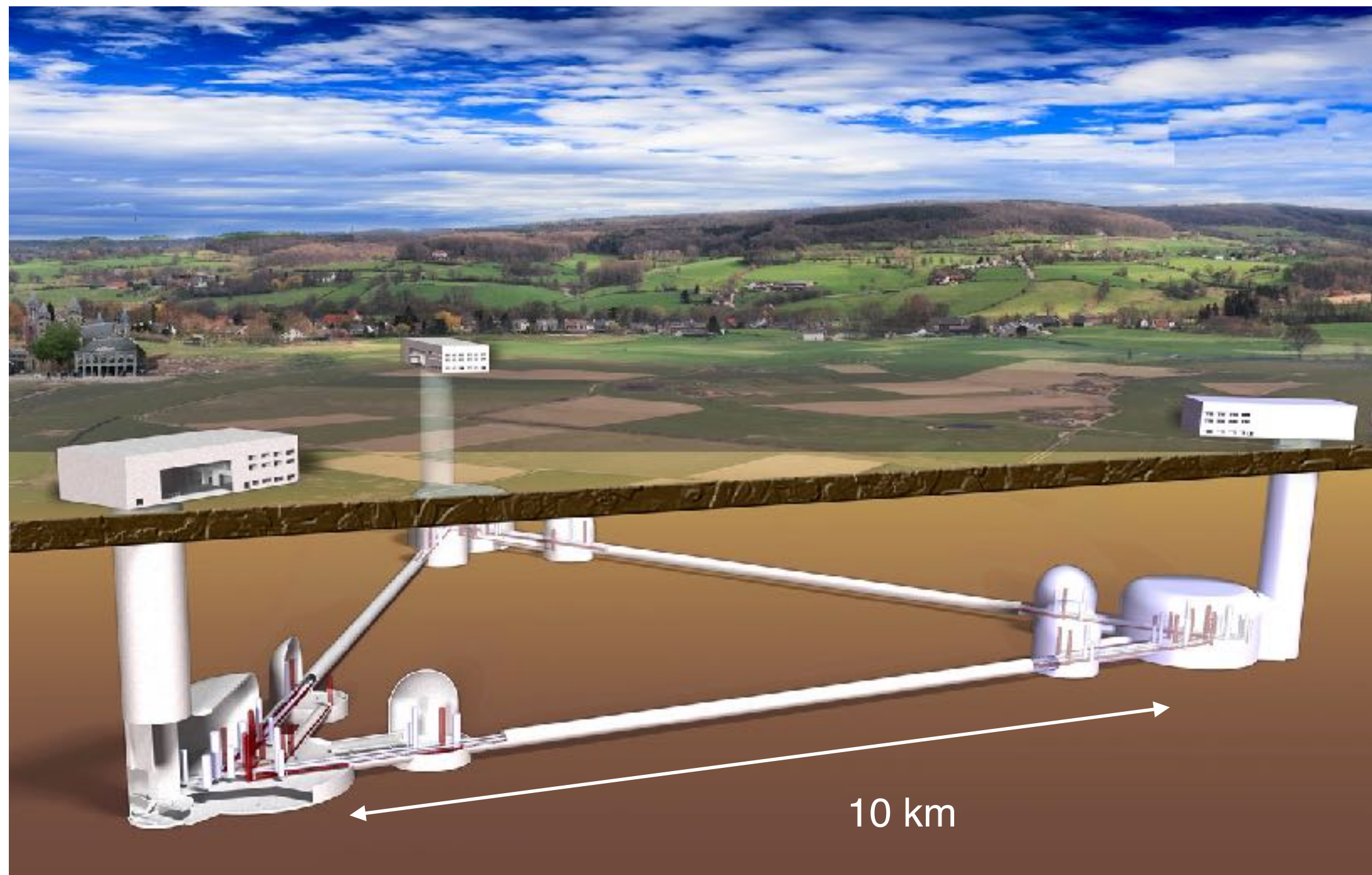


[1504.04276](#)

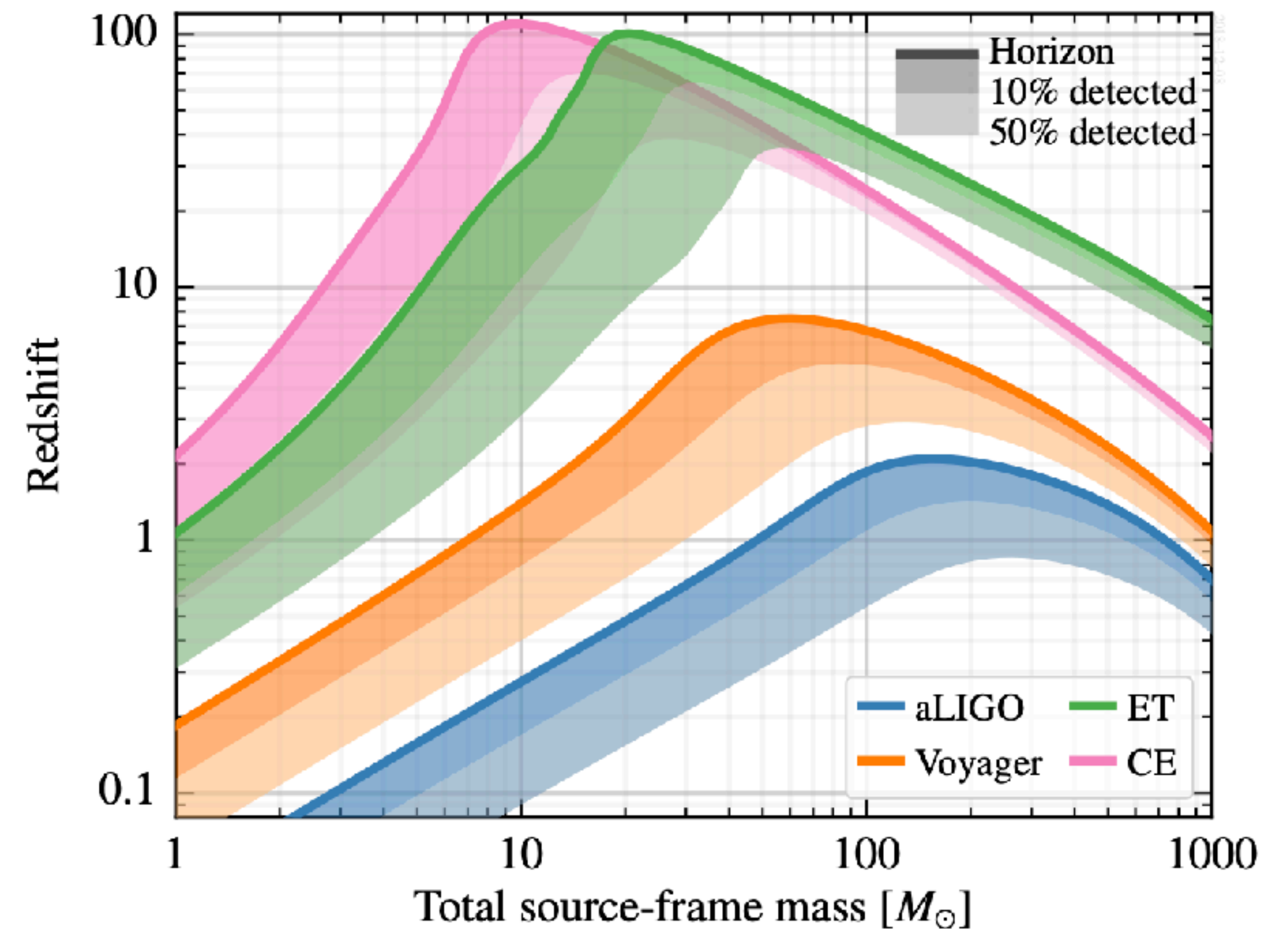
Several excesses point towards 60 GeV Dark Matter -
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

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).