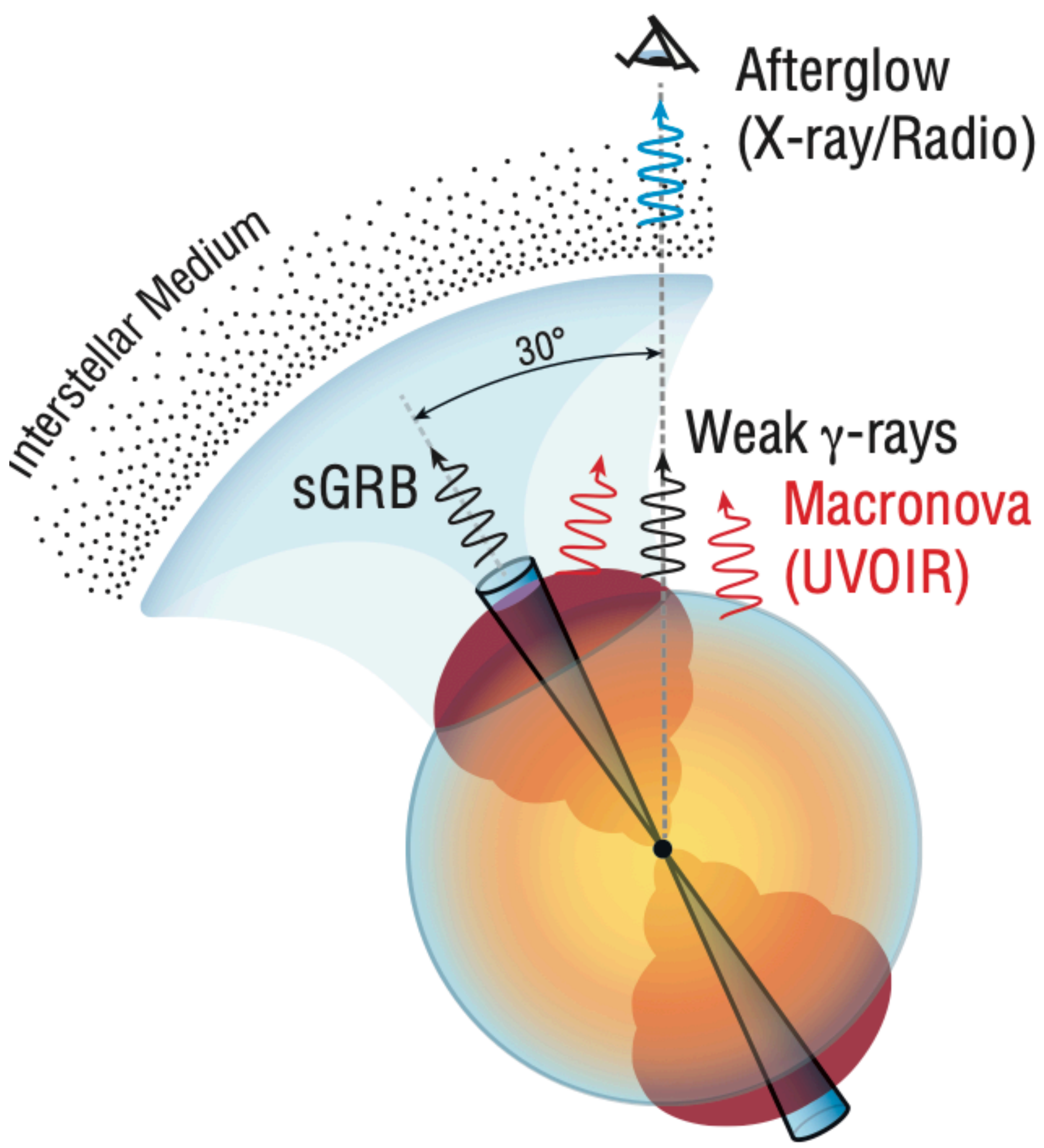
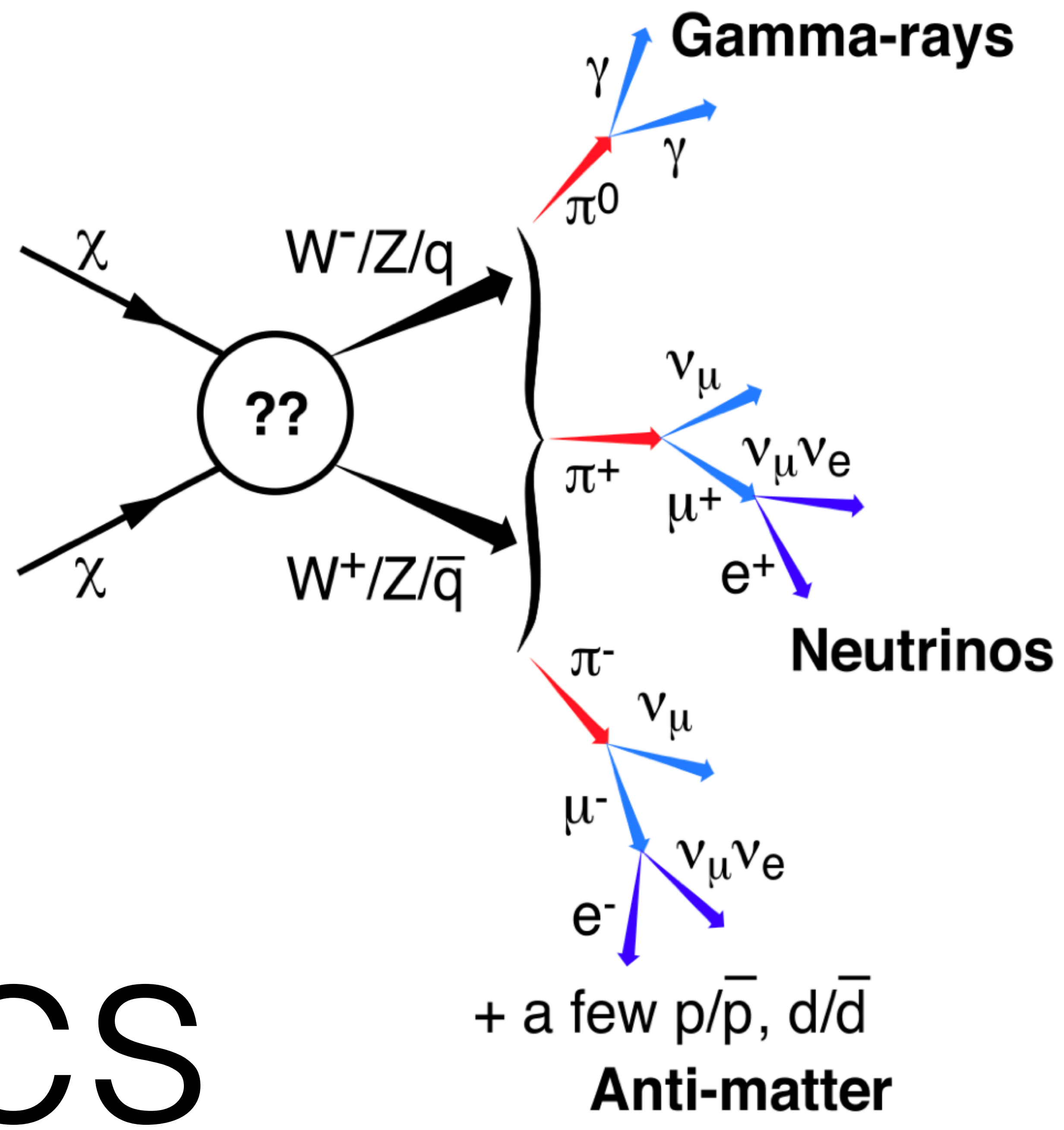




(An introduction to)

Astroparticle Physics

Lecture 2/2

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

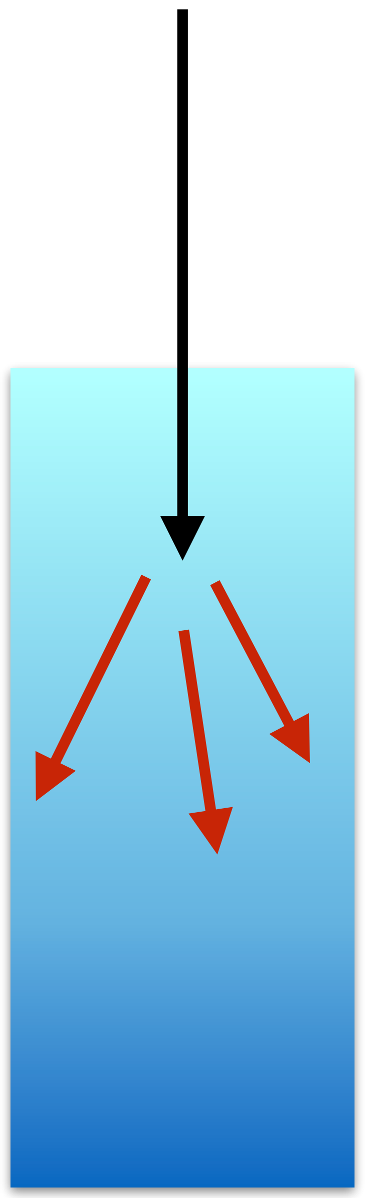
CERN Summer Student Lecture Programme:
Thursday 18th July 2024

Slides here: bradkav.net/talks

Q: First interaction in the atmosphere?

Quantify amount of atmosphere tranverse by the CR using the column depth:

$$X = \int_h^\infty \rho(h')\,\mathrm{d}h'$$



Column depth of first interaction for gamma rays:

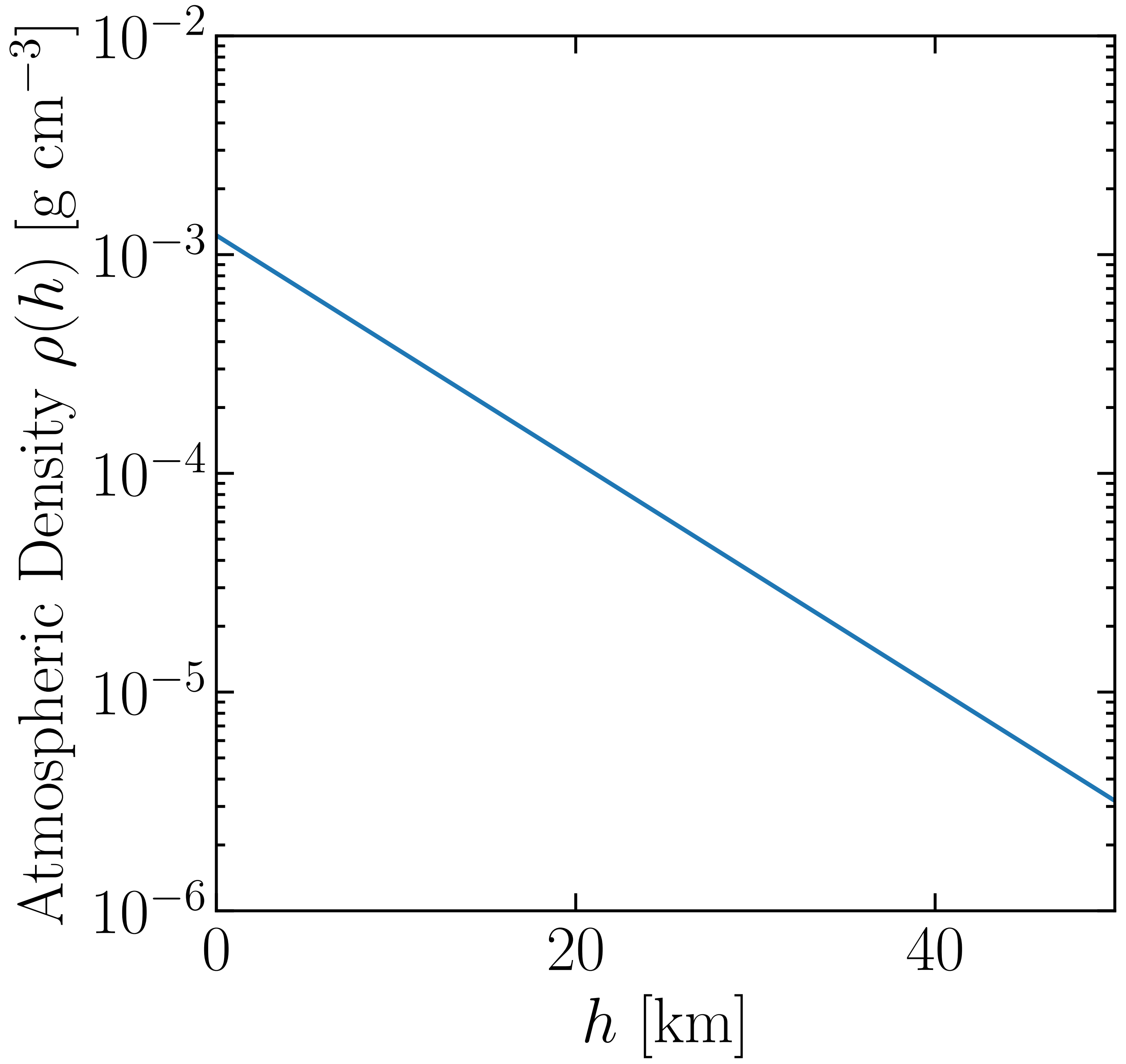
$$X_0^r \approx 37 \text{ g cm}^{-2}$$

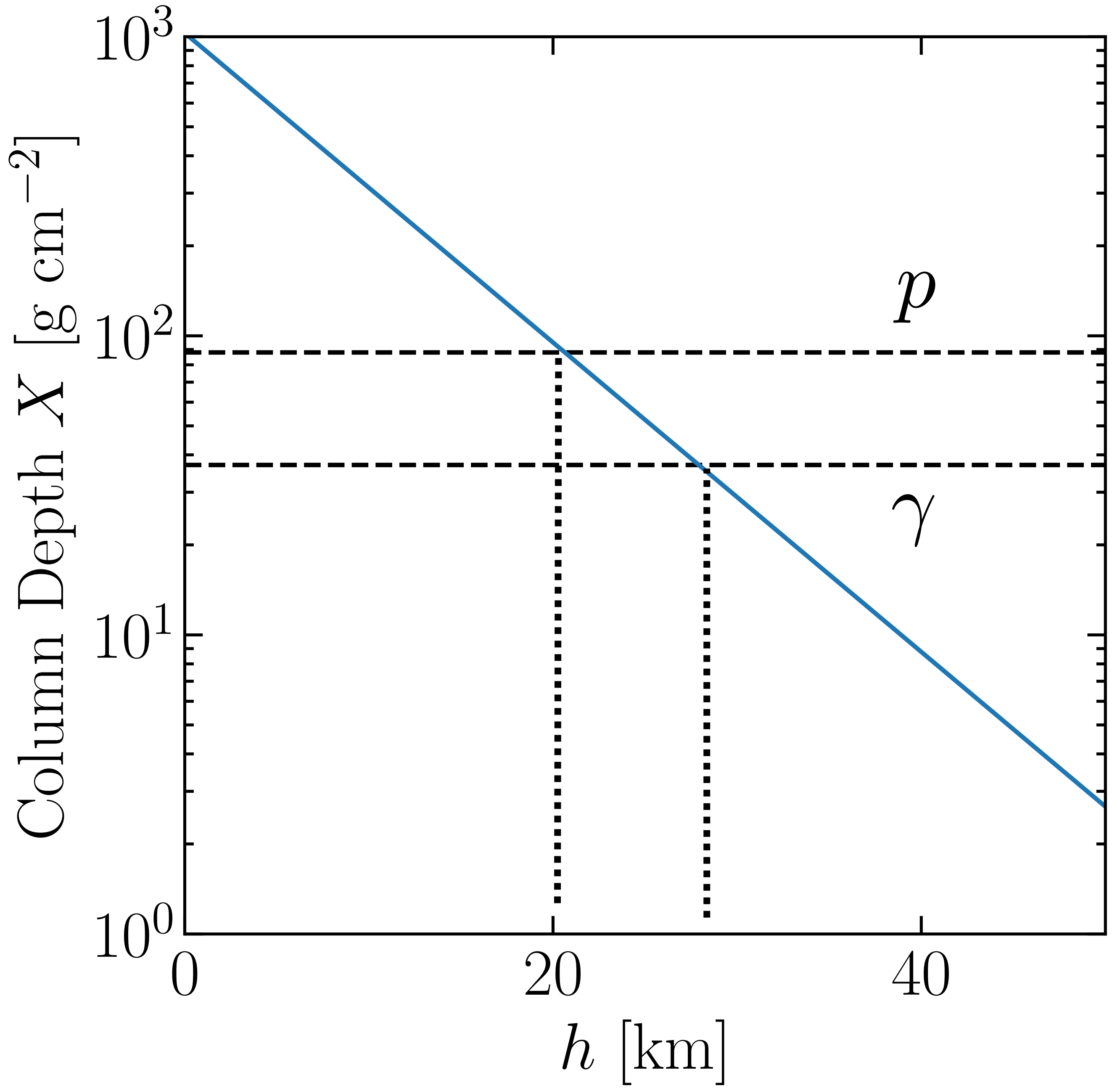
Column depth of first interaction for protons:

$$X_0^p \approx \left[88 - 9\log_{10}\left(\frac{E}{\mathrm{EeV}}\right)\right] \mathrm{gcm}^{-2}$$

Interaction probability approaches 1 as $X \rightarrow X_0$

[arXiv:2401.04460]



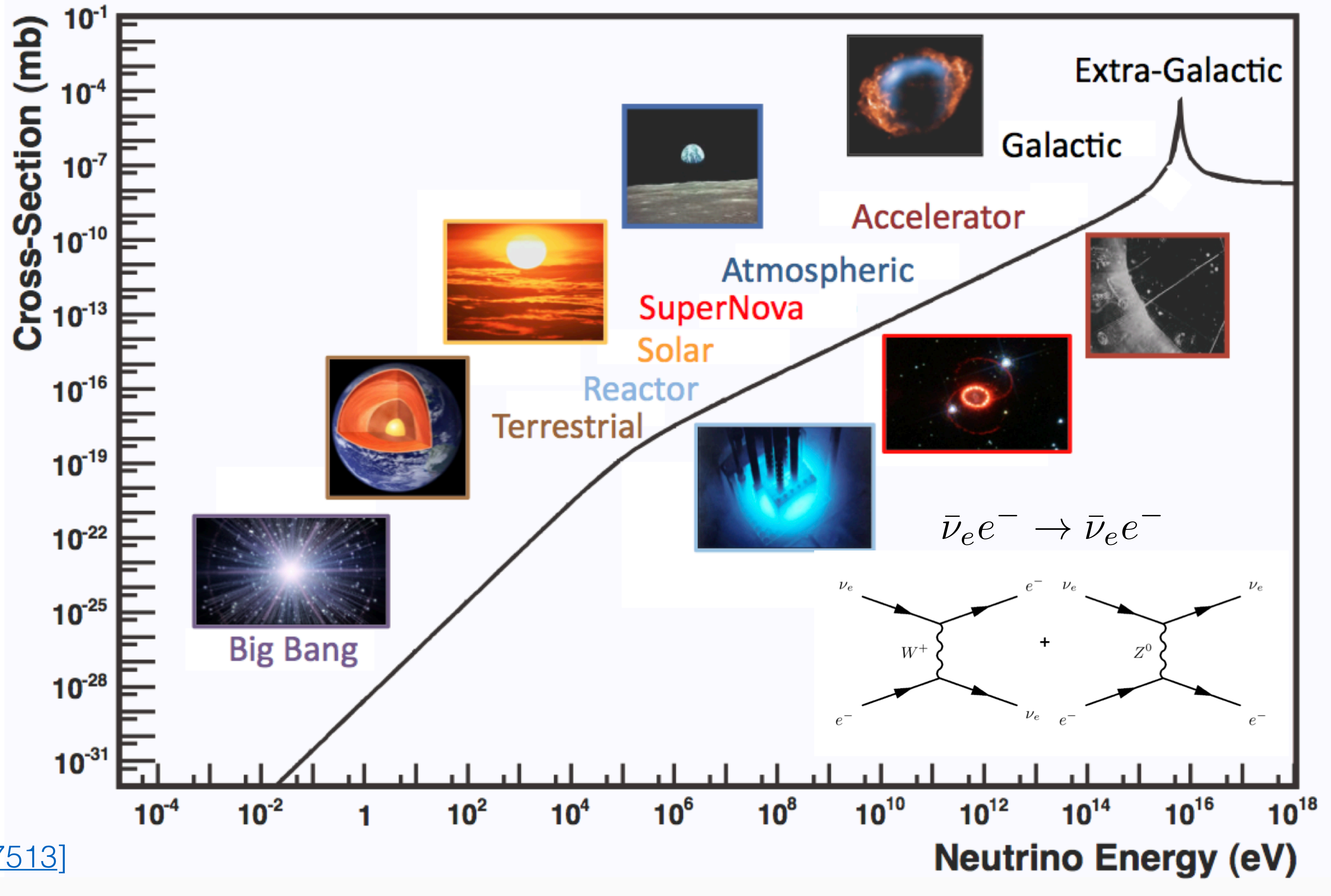


Q: Neutrino Cross-section?

Interaction length in water (at ultra-high energies):

$$\lambda = (n_e \sigma)^{-1} \sim 10^8\,\mathrm{m}$$

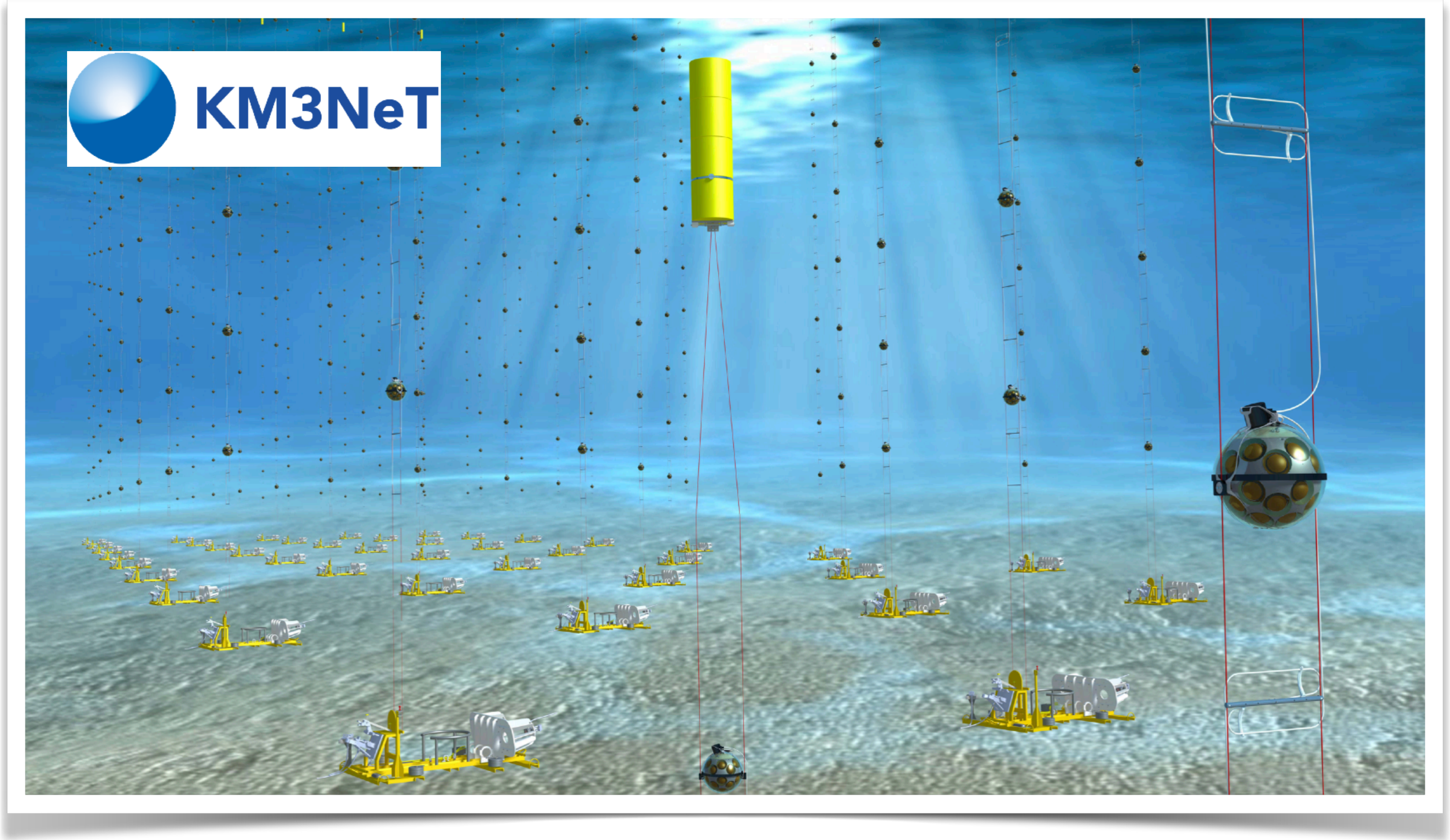
$$1\,\mathrm{mb} = 10^{-27}\,\mathrm{cm}^2$$

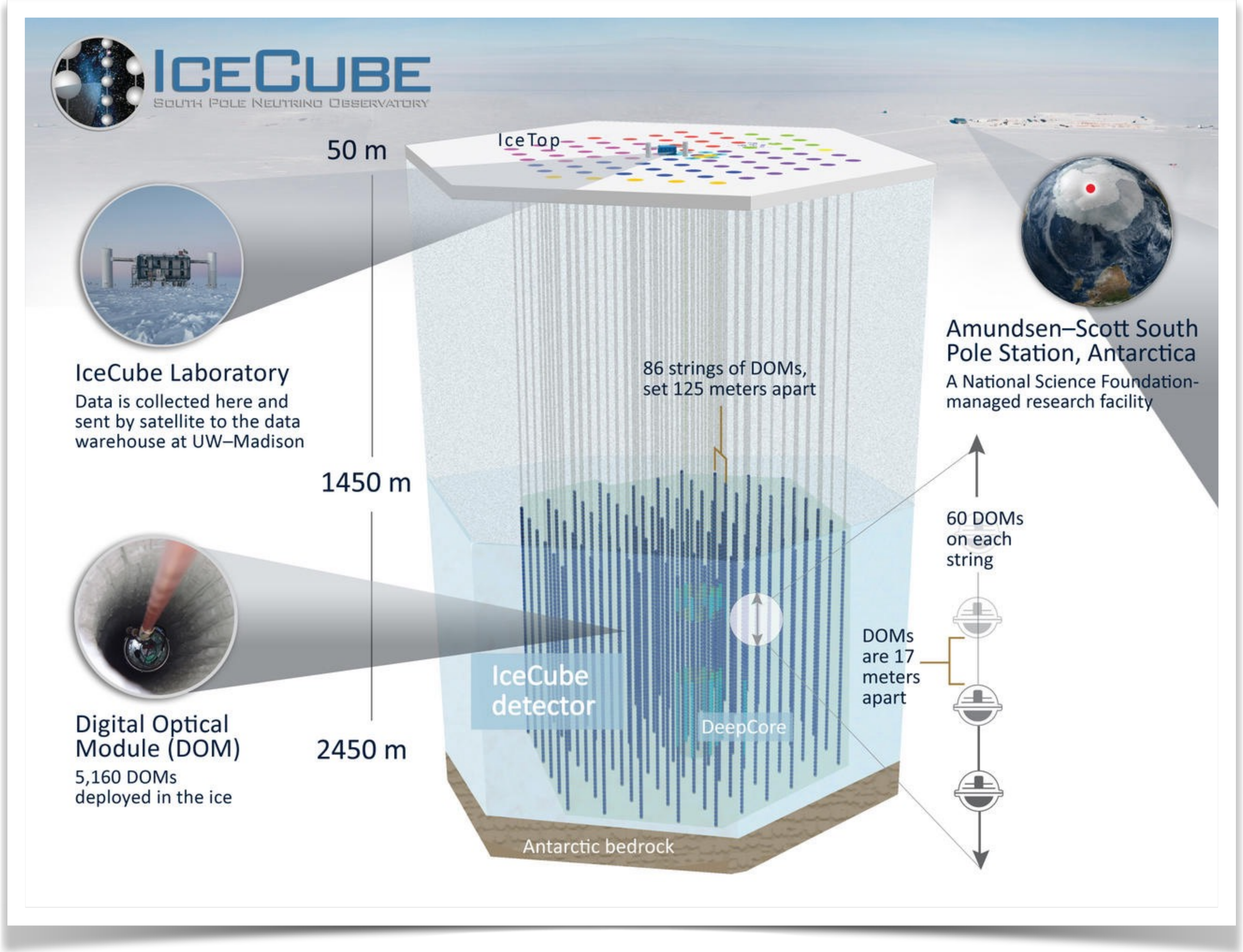


[arXiv:1305.7513]

Q: Water vs Ice for neutrino detection

Light is scattered less in water, providing a better light collection and better angular resolution…





But ice has lower levels of background light (no bioluminescence, and radioactive decays)


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

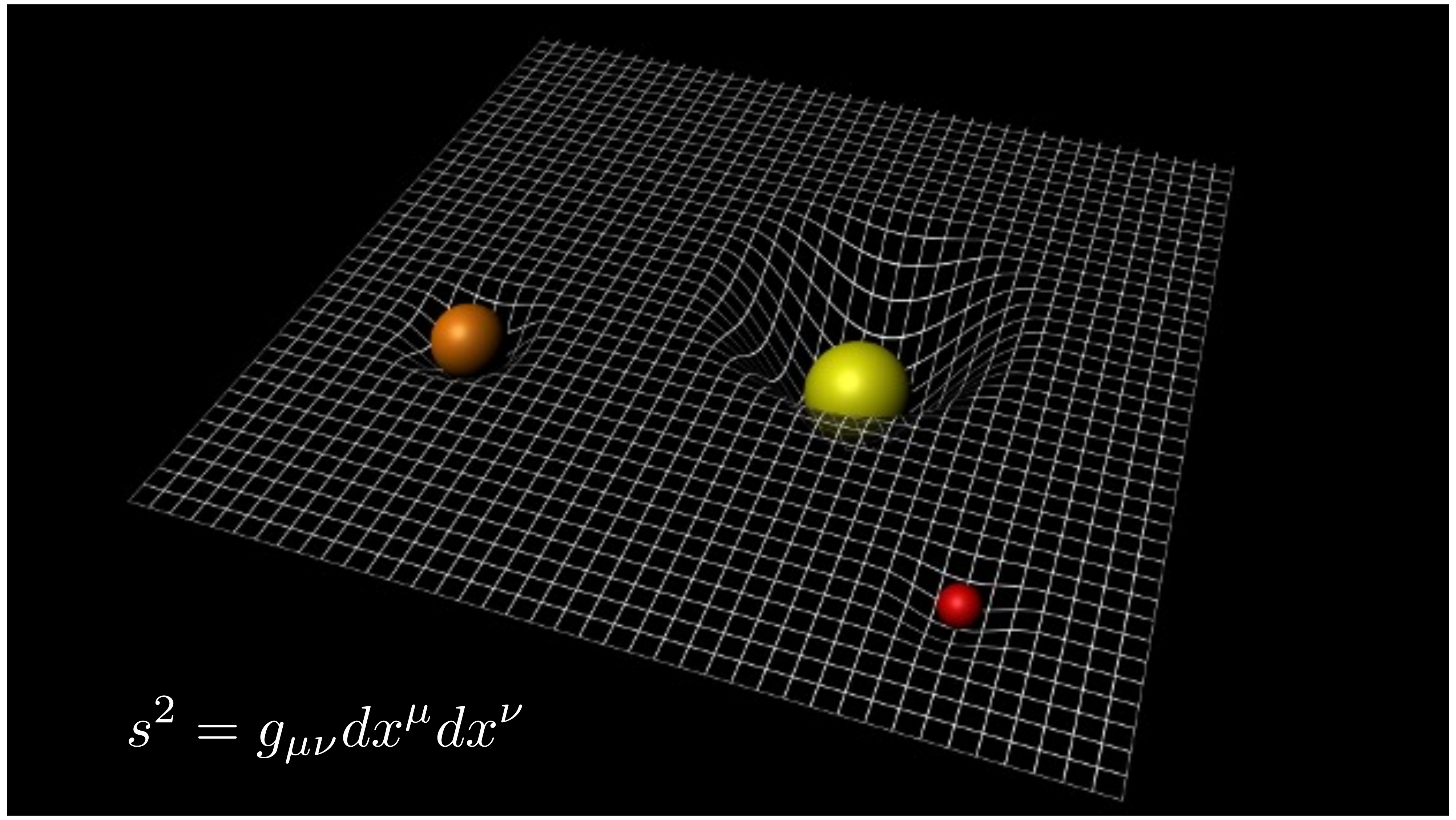
Gravitational Waves

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)**

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

The Gravitational Wave Spectrum

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

f_{GW}: nHz — μHz — mHz — Hz — kHz

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

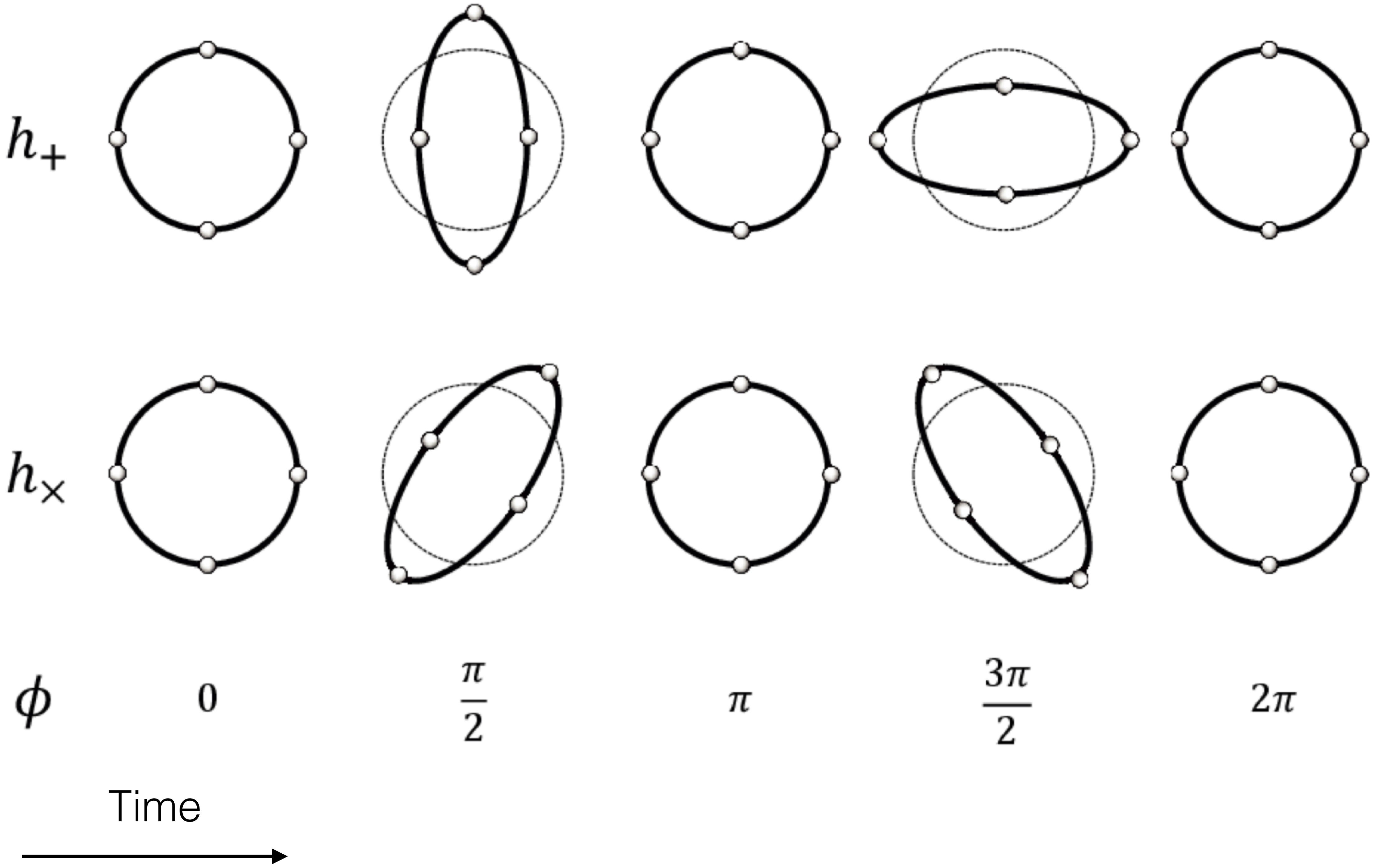
T_{GW}: 30 years — 10 days — 15 minutes — 1 second — 1 ms

SOURCES

DETECTORS?

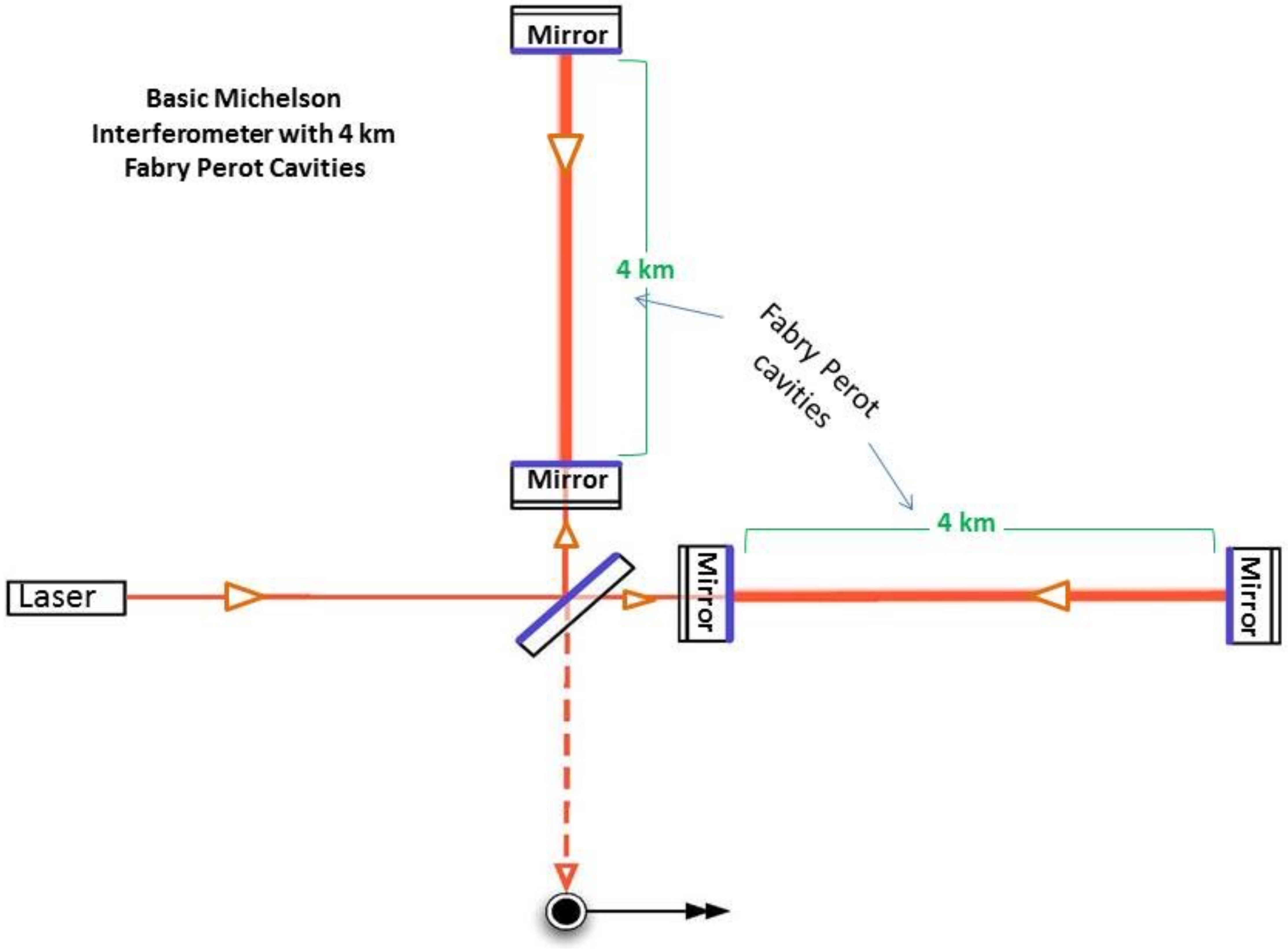
Direct detection of GWs

GW traveling into the screen causes (tiny) distortion:



1708.00918

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

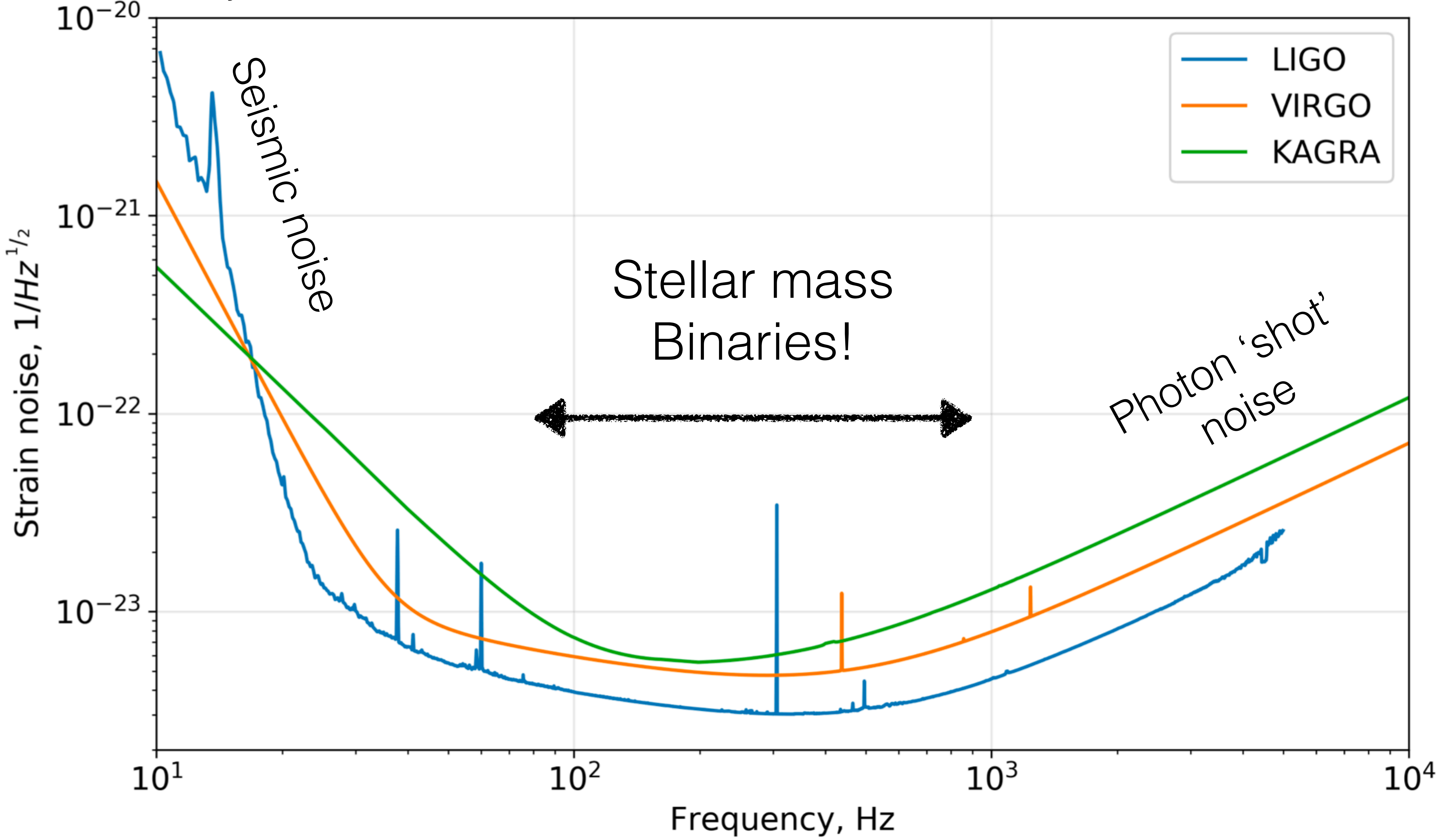


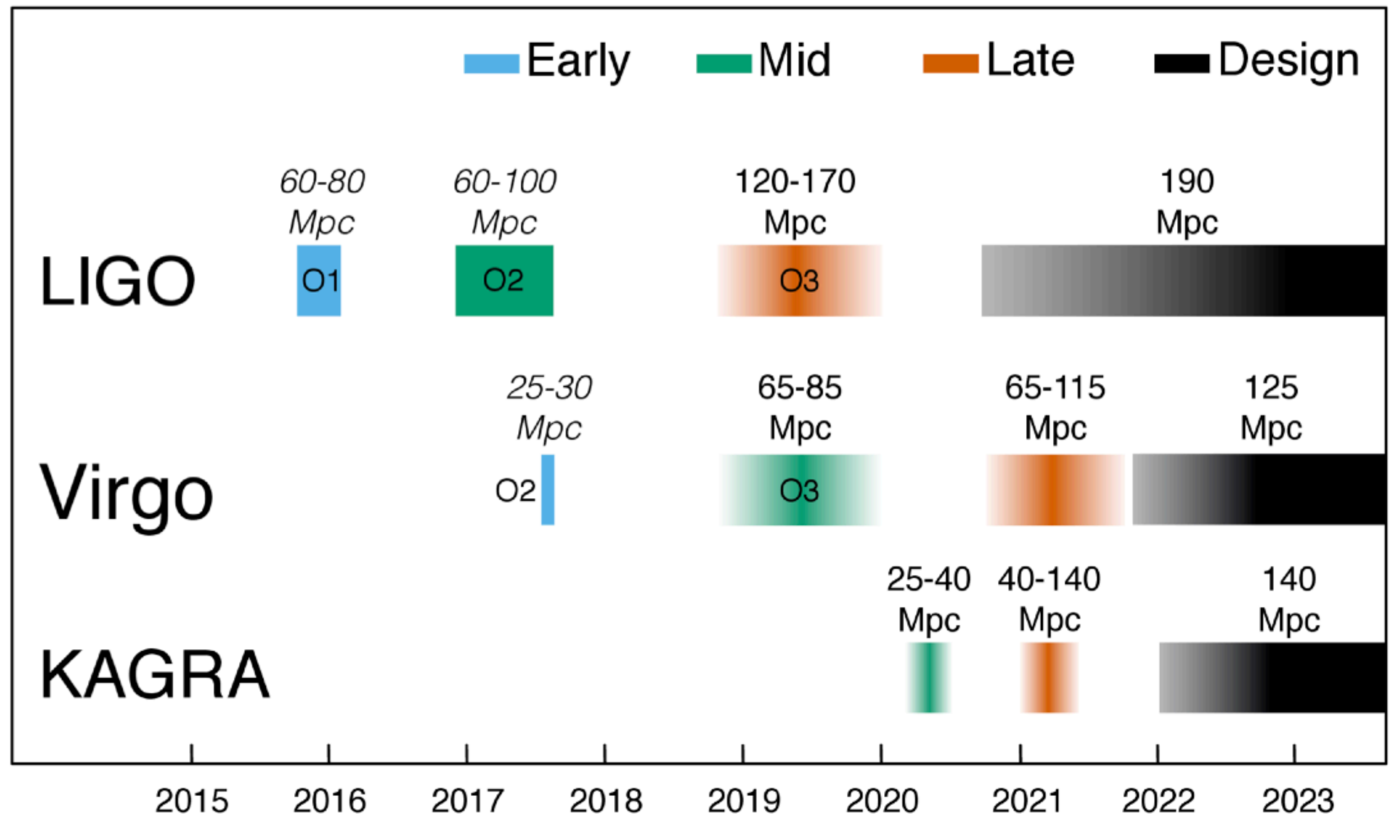
Typical GW strain is $\Delta L/L \sim 10^{-23}$!

LIGO-Virgo-KAGRA (LVK)

Credit: LIGO, VIRGO & KAGRA.

Projected O4 strain noise 2102.10816



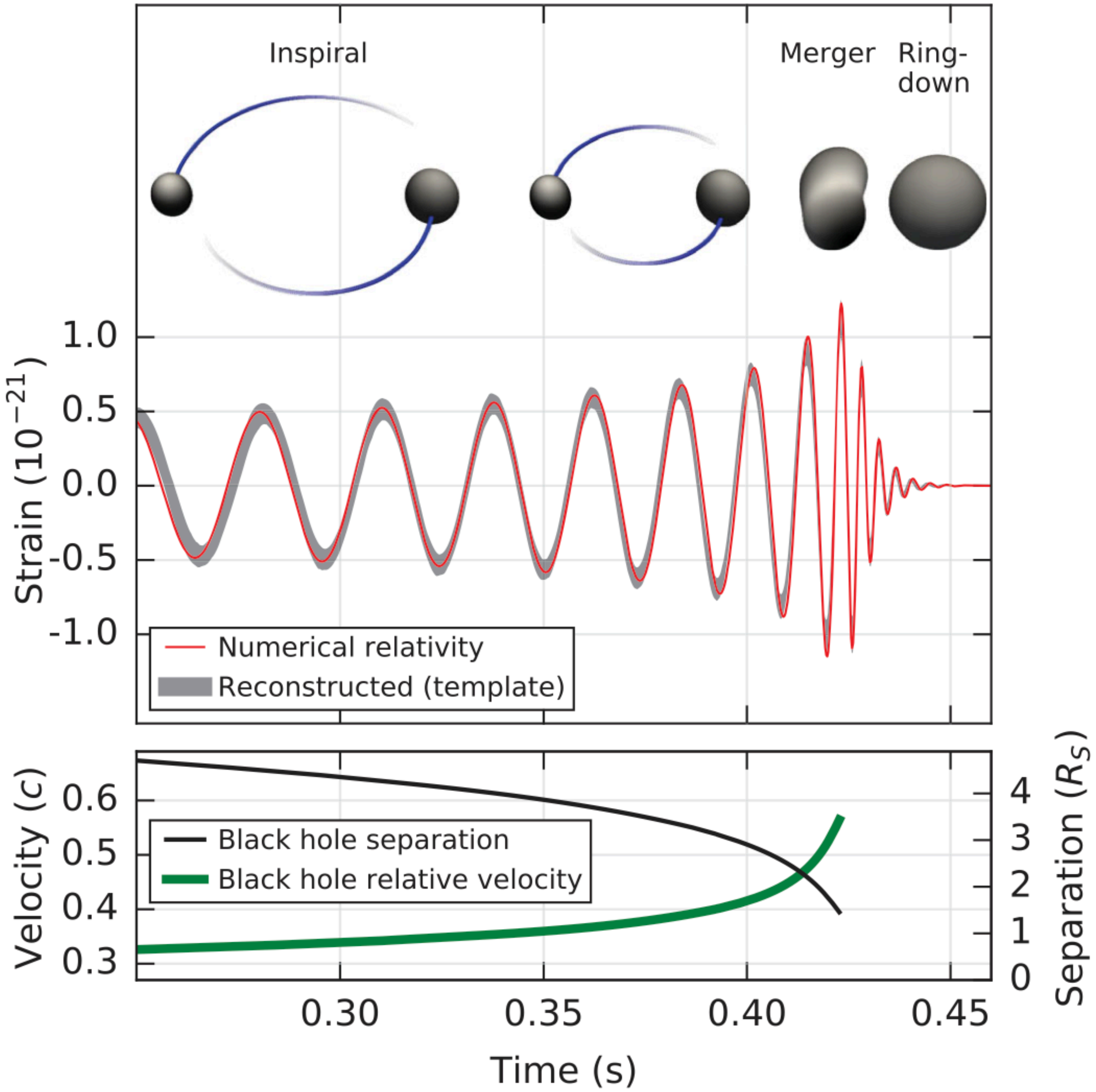


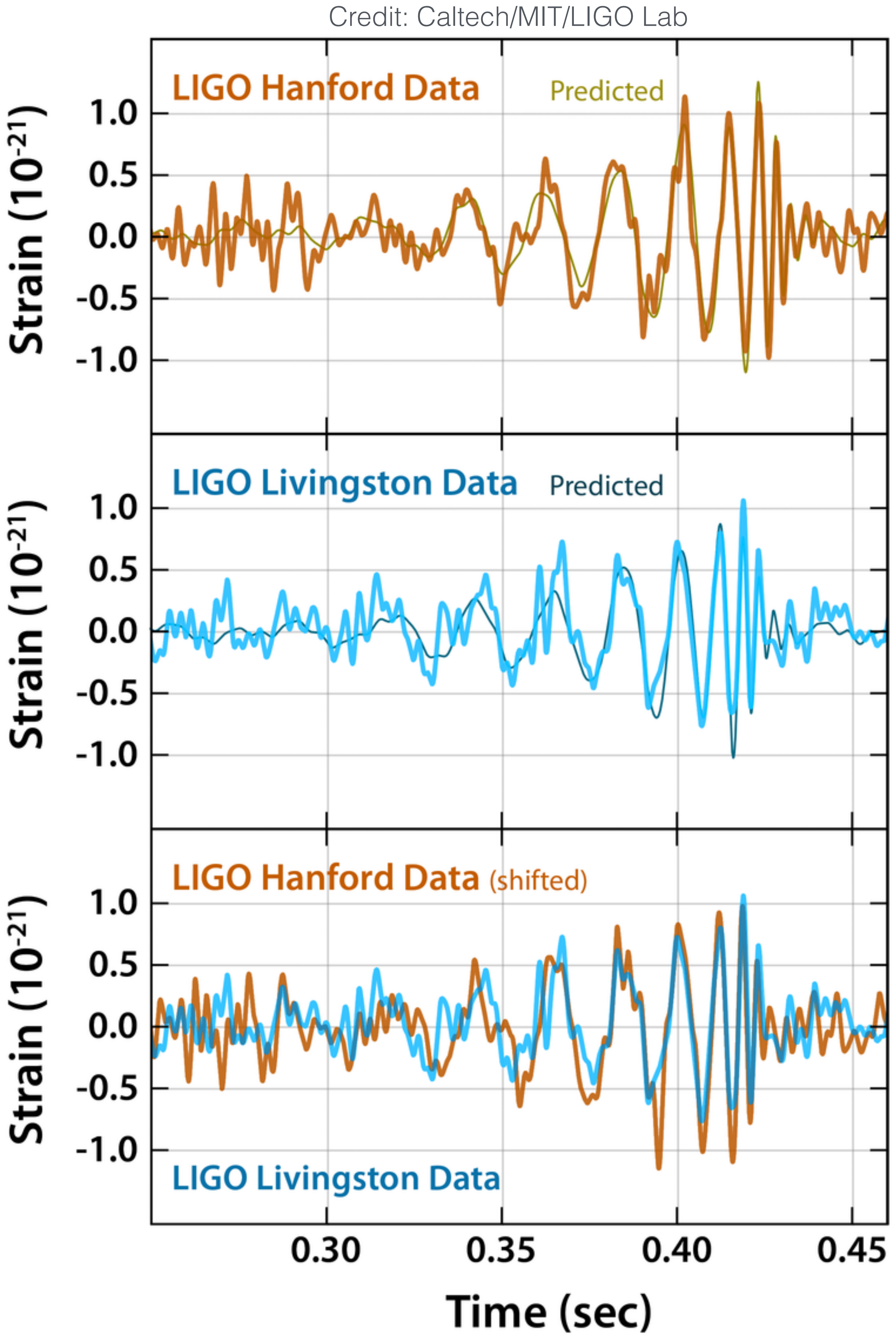
GW frequency ~ twice orbital frequency.

1906.03643

GW150914 - the first BH-BH merger

14 September 2015





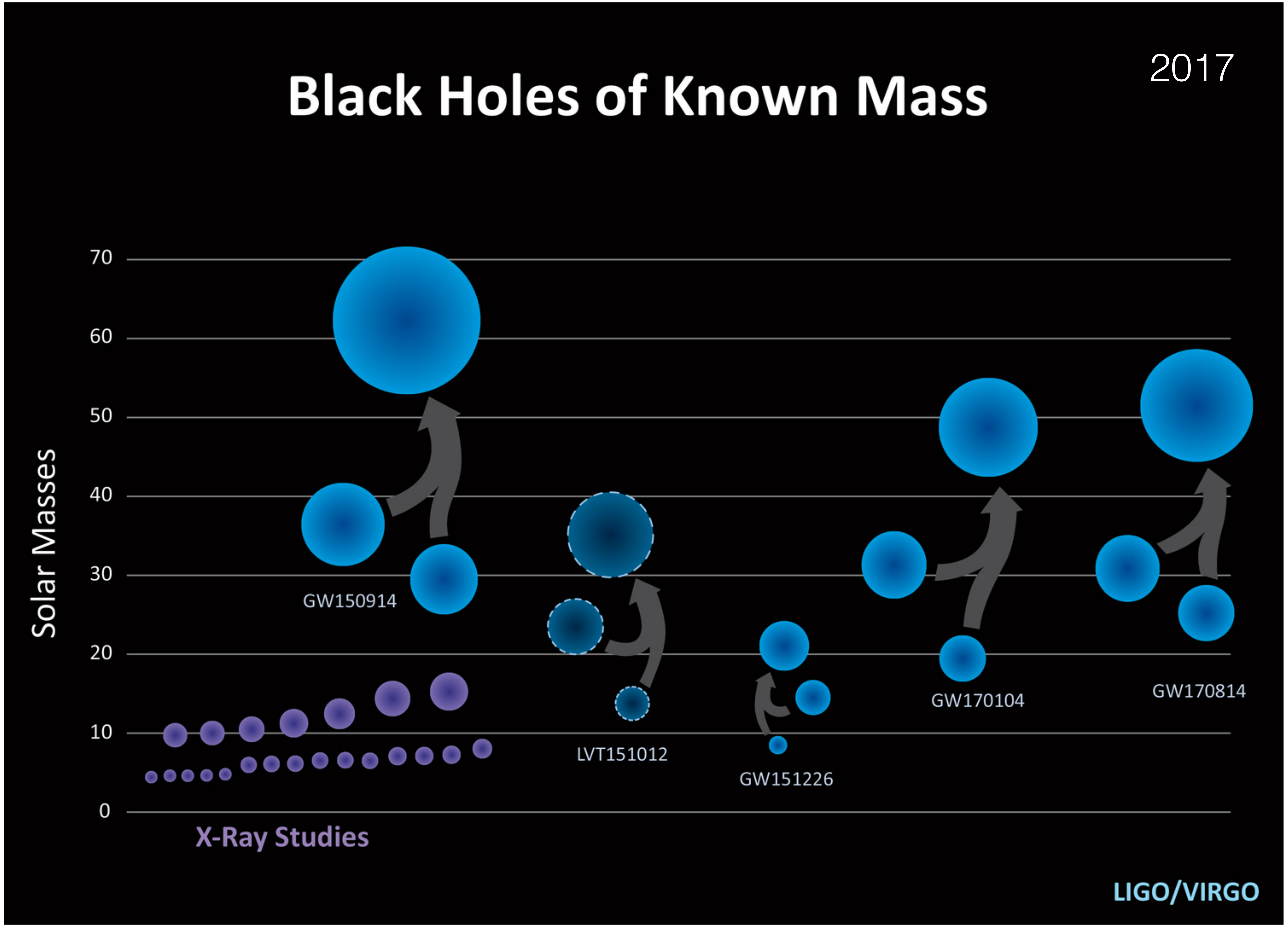
Merger of two BHs - with masses $36\,M_\odot$ and $29\,M_\odot$
at a luminosity distance of $d_L \approx 200 - 600\,\mathrm{Mpc}$

1602.03840

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

The Compact Object Zoo

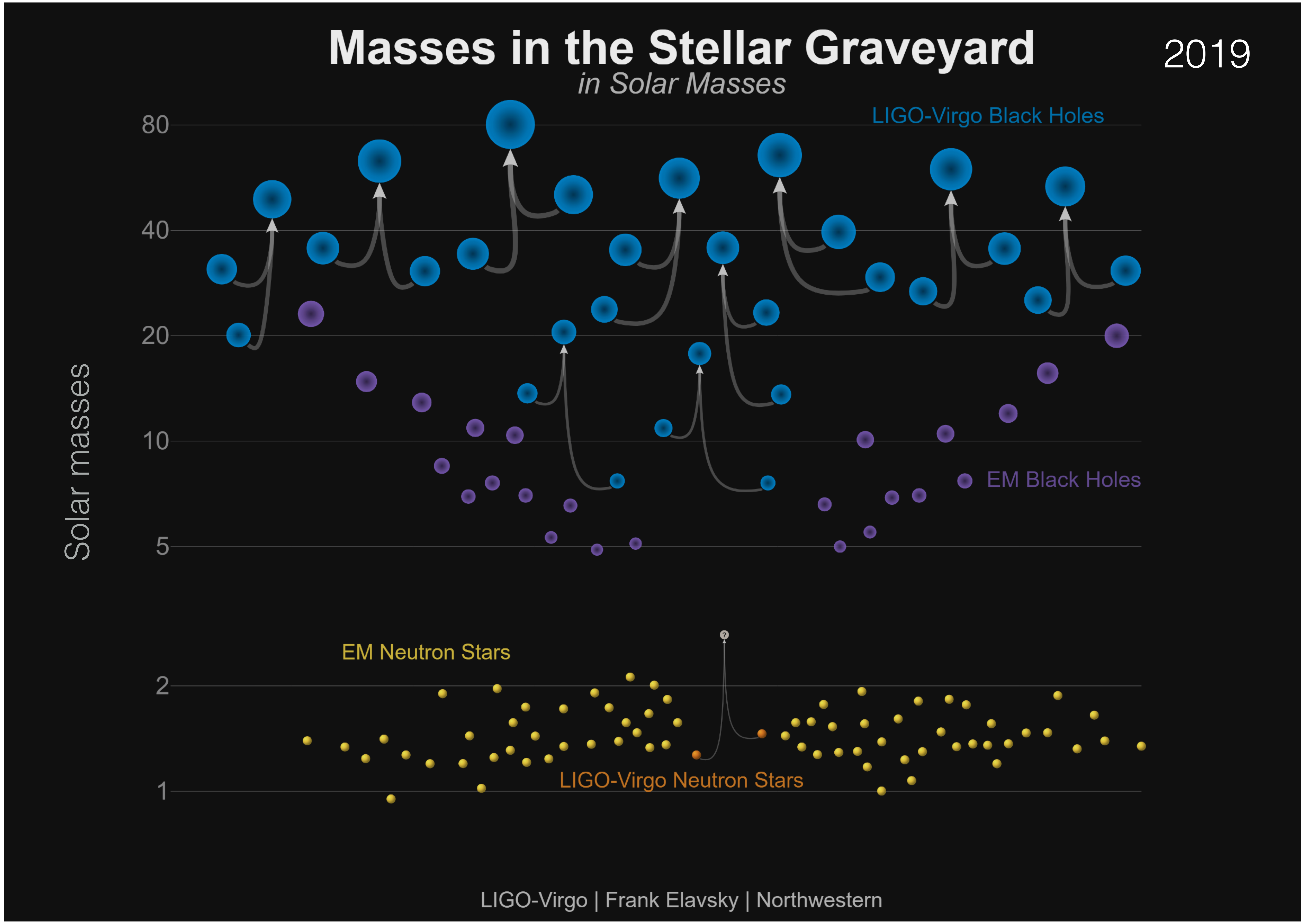
https://media.ligo.northwestern.edu/gallery/mass-plot



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

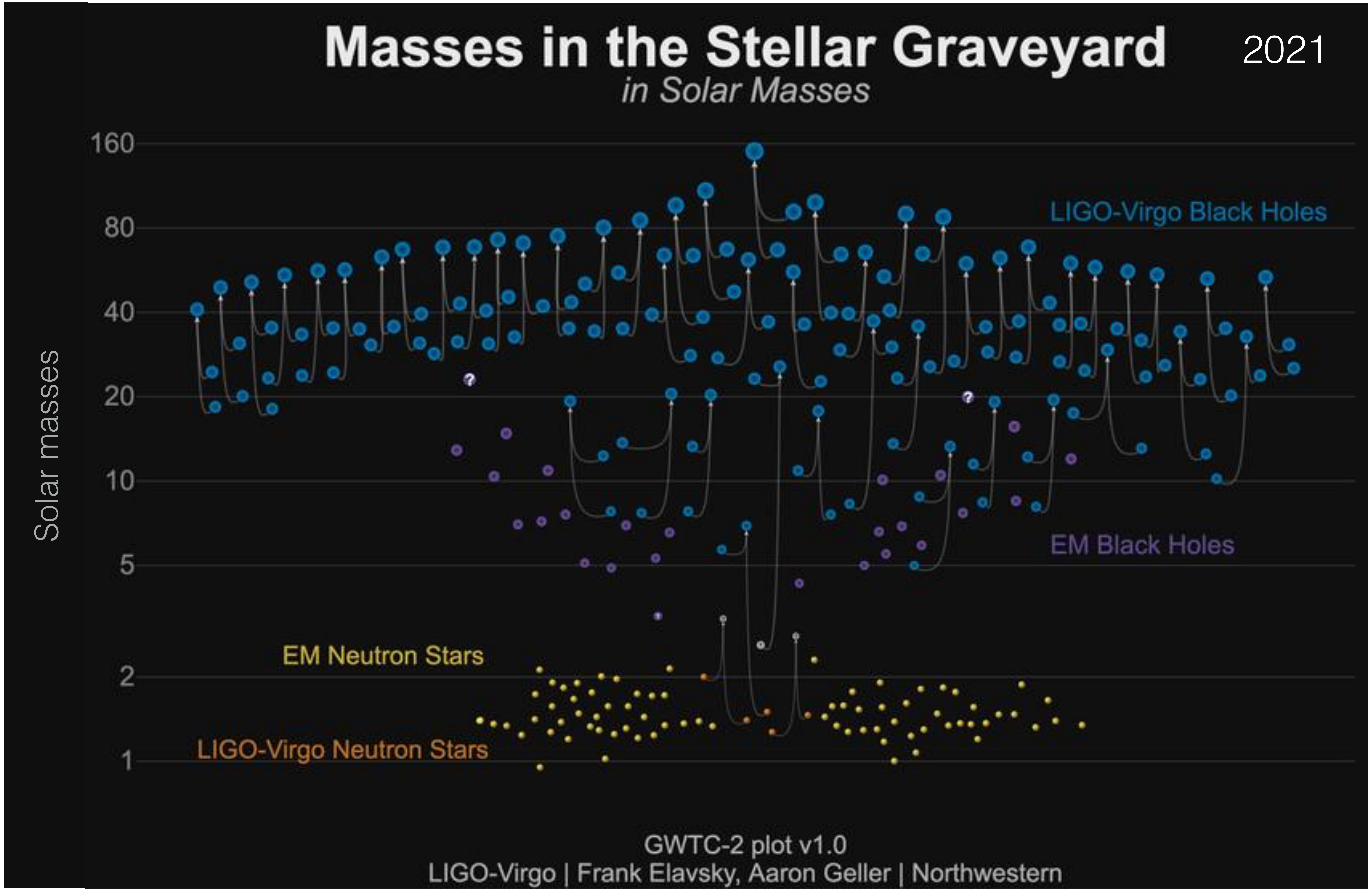
The Compact Object Zoo

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



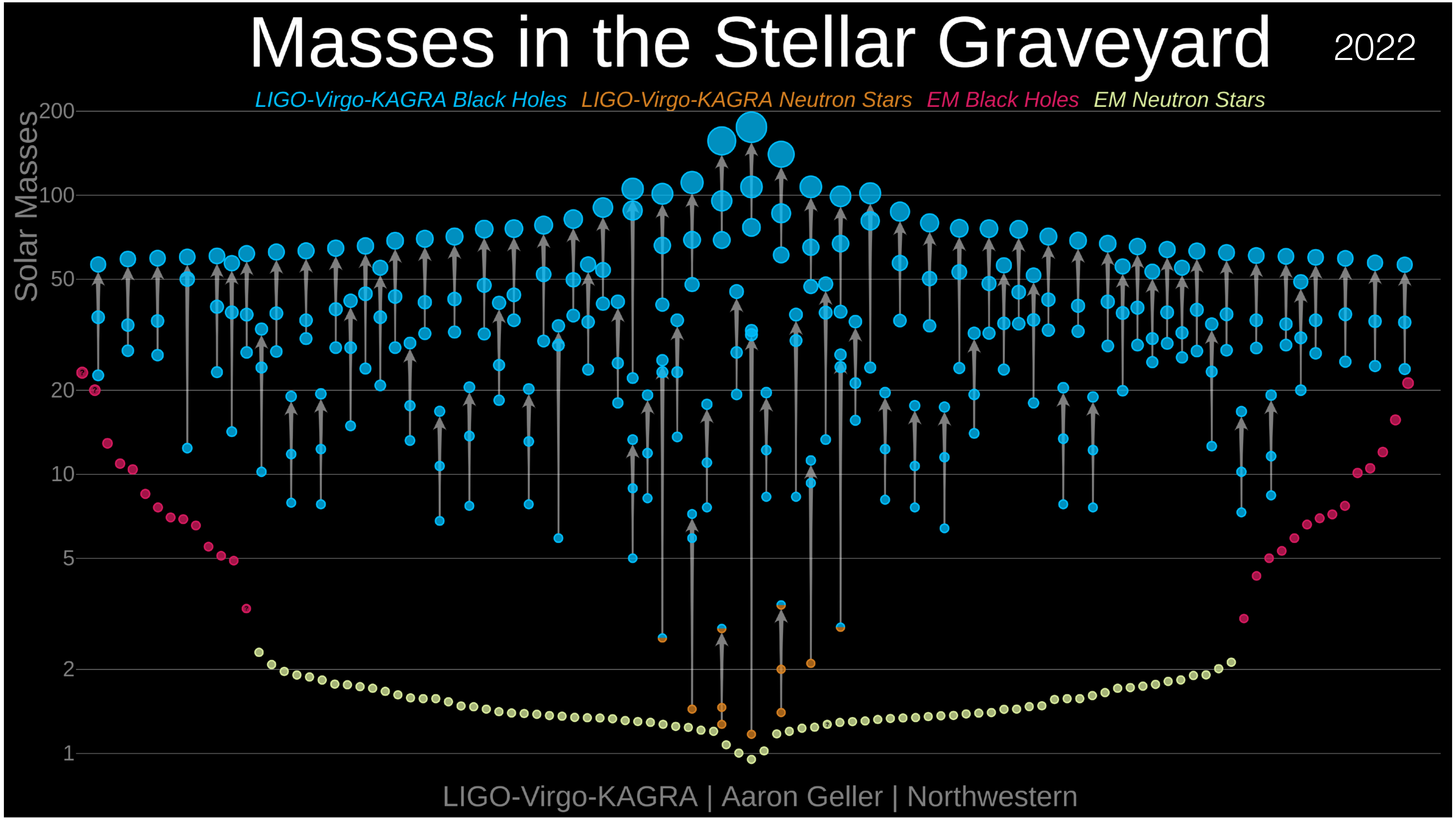
The Compact Object Zoo

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



The Compact Object Zoo

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

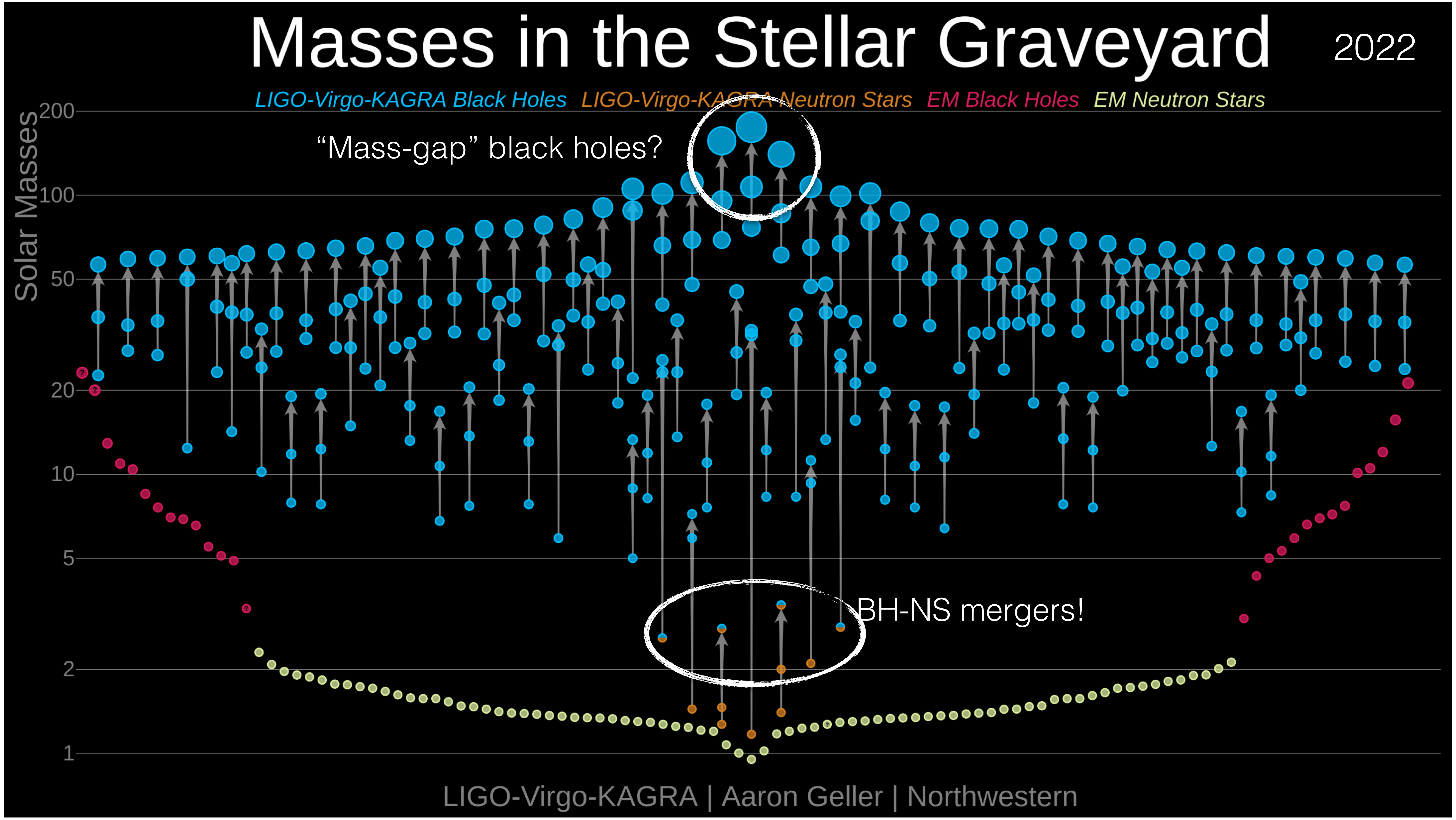


Third Gravitational-wave Transient Catalog (**GWTC-3**) [arXiv:2111.03606, arXiv:2111.03634]

The Compact Object Zoo

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

2007.07889

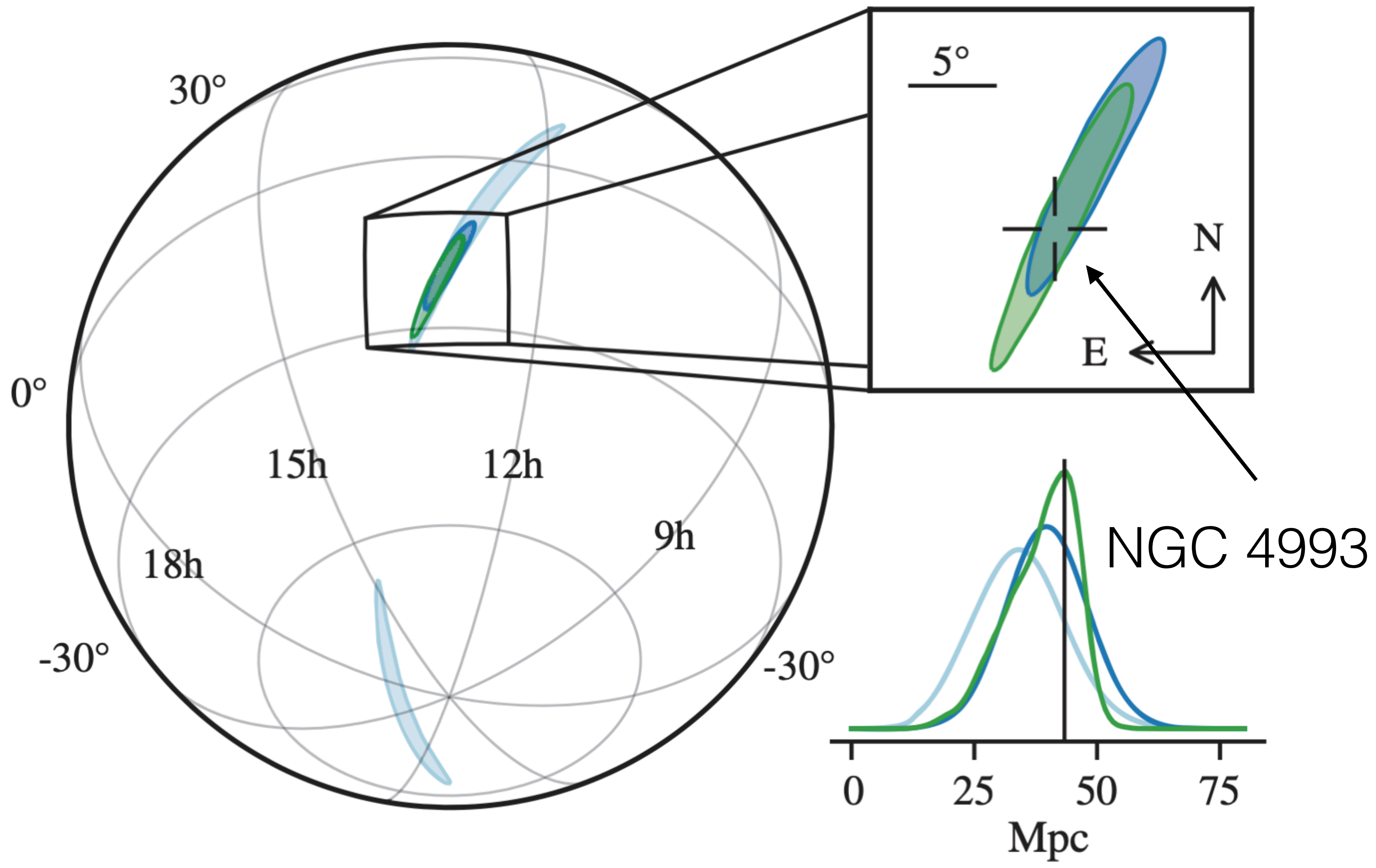


2106.15163

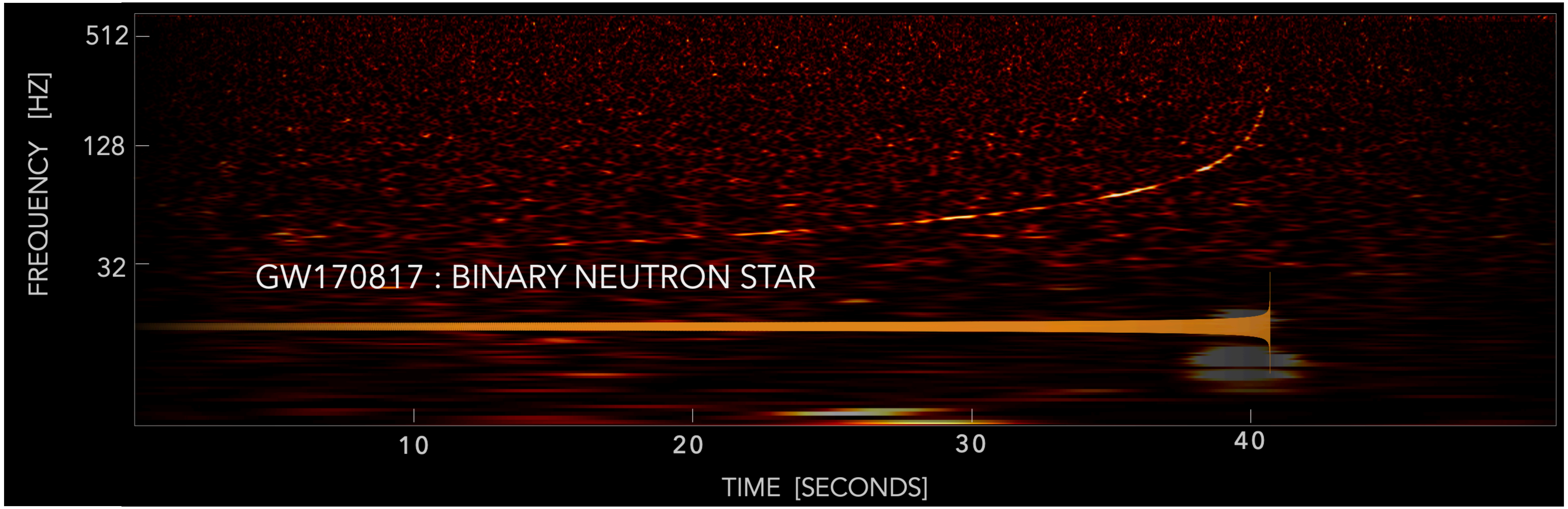
Third Gravitational-wave Transient Catalog (**GWTC-3**) [arXiv:2111.03606, arXiv:2111.03634]

GW170817 - the first NS-NS merger

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



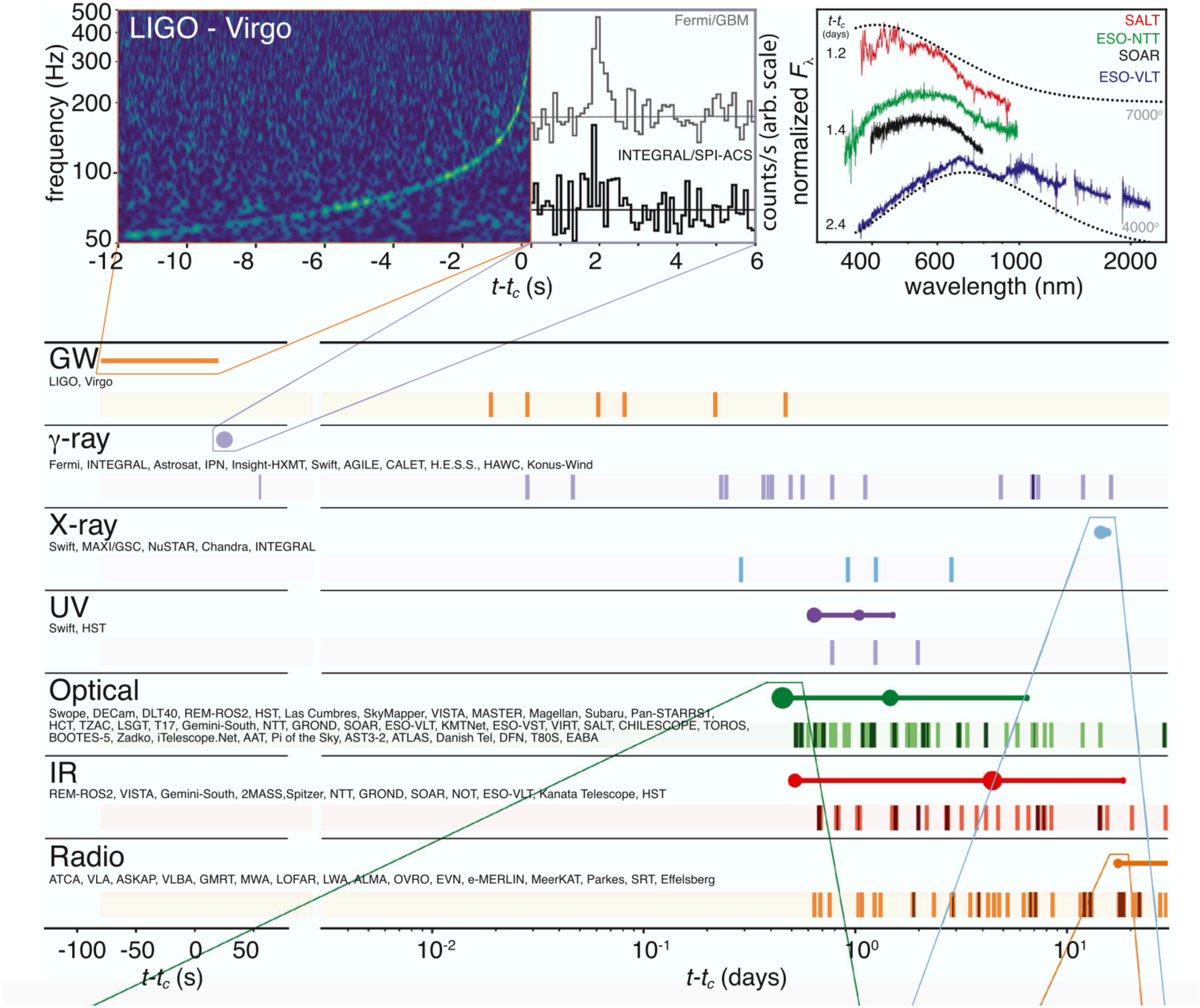
Localised to within ~30 deg²



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

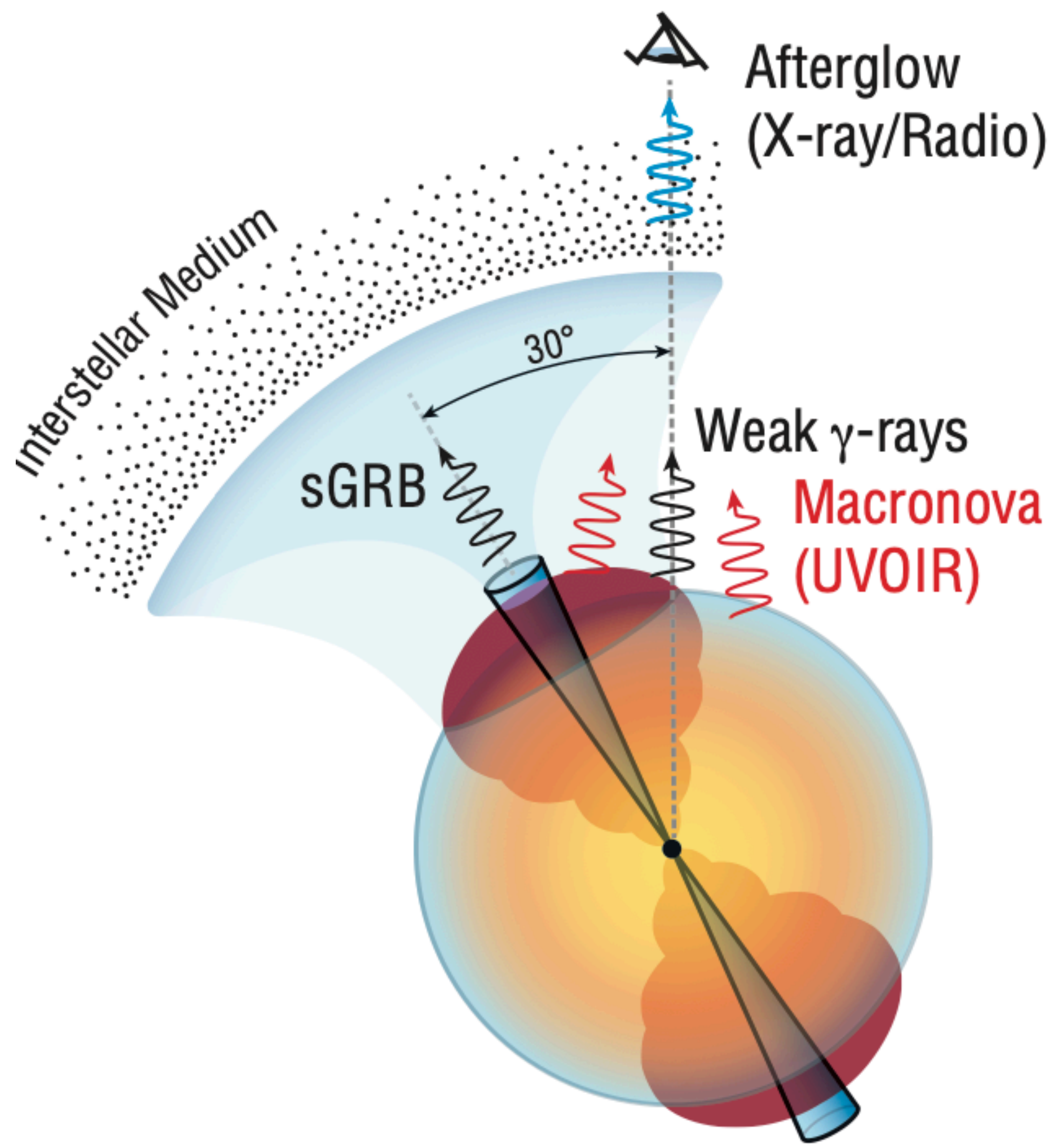
Follow-up observations across the spectrum!

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

The Gravitational Wave Spectrum

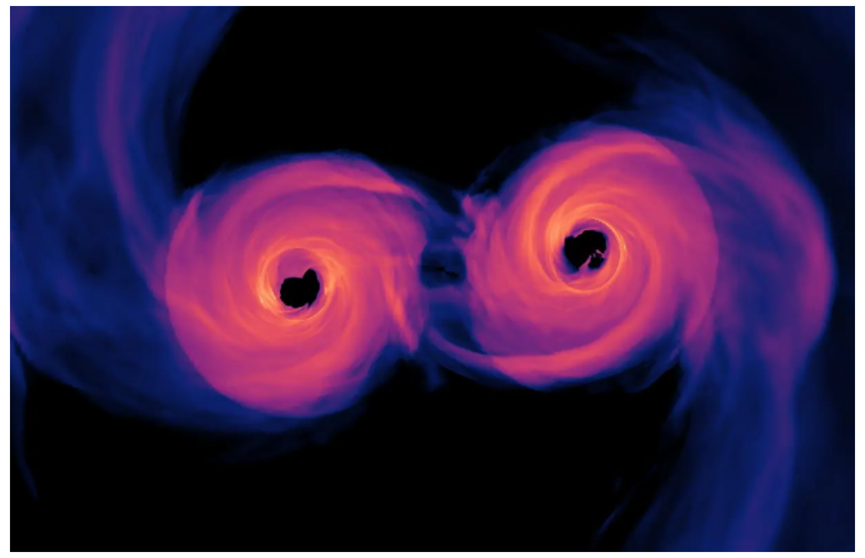
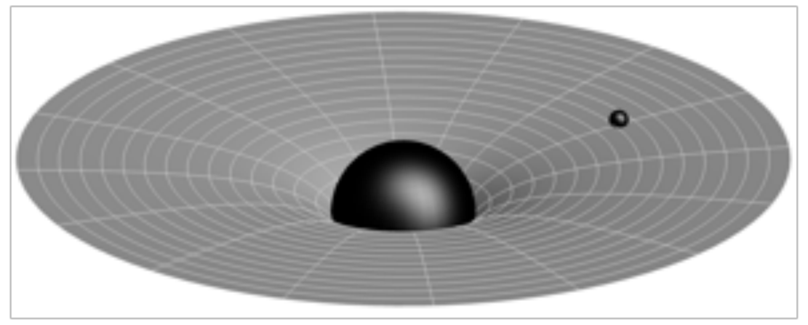
$$c = \lambda_{\mathrm{GW}} \cdot f_{\mathrm{GW}}$$

f_{GW}: nHz — μHz — mHz — Hz — kHz

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

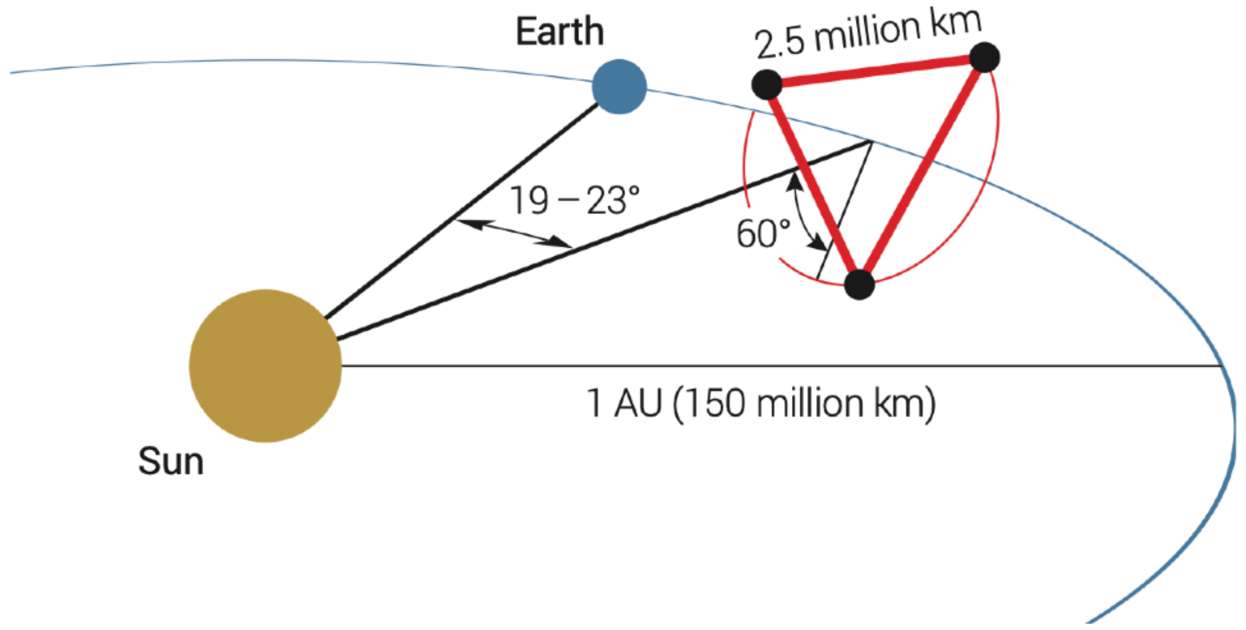
T_{GW}: 30 years — 10 days — 15 minutes — 1 second — 1 ms

SOURCES

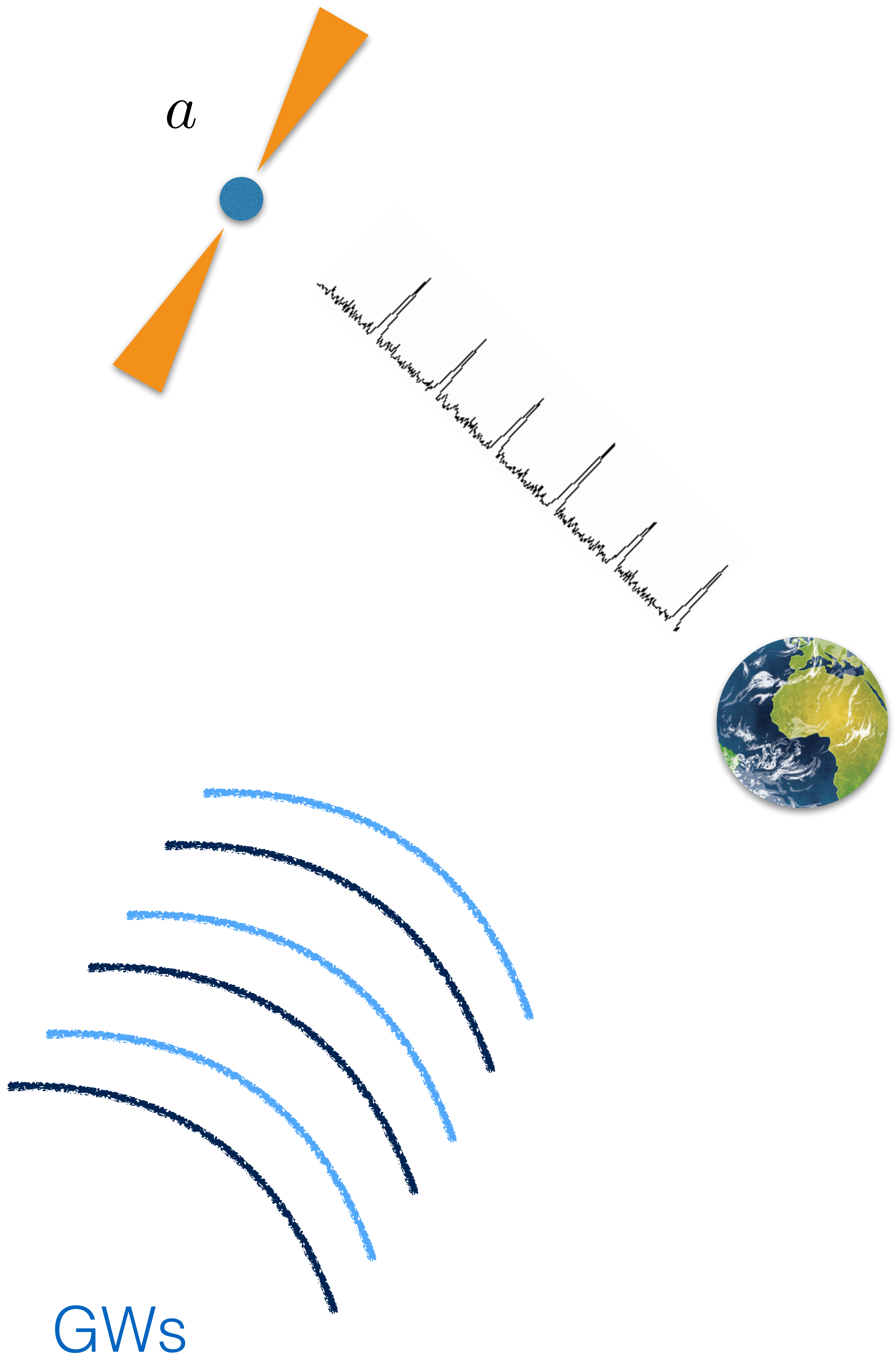



DETECTORS?

?



Pulsar Timing Arrays (PTA)



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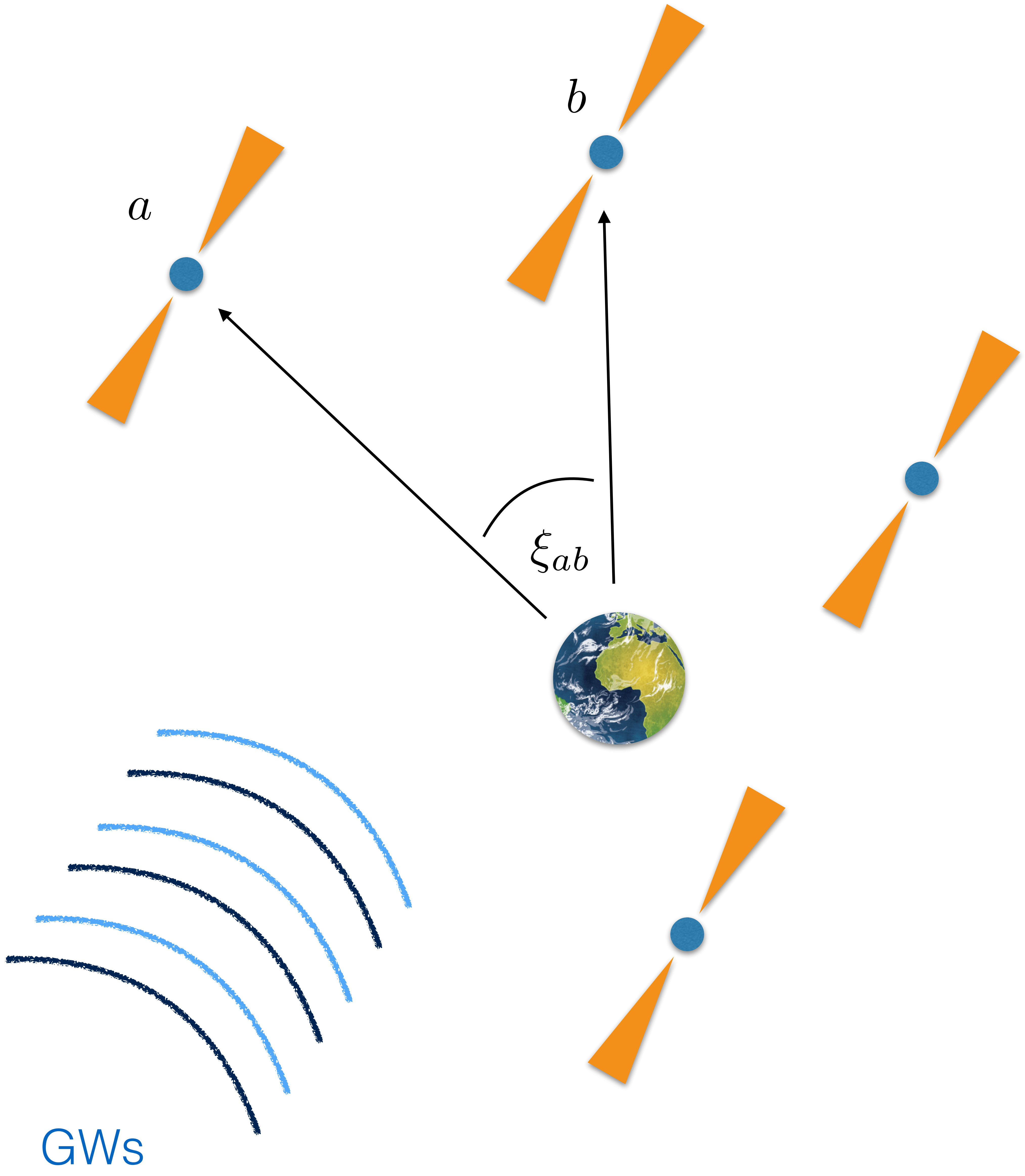

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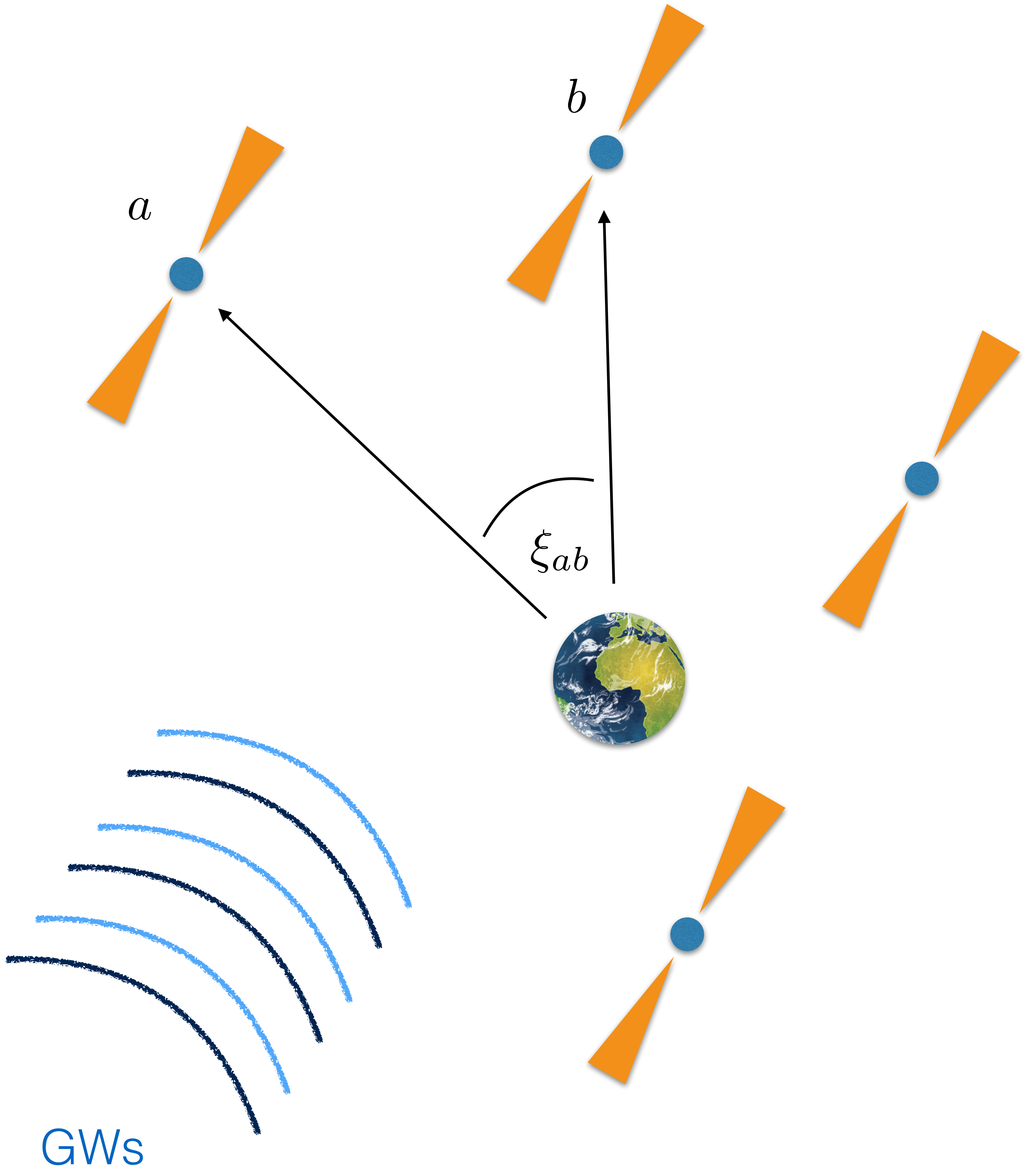
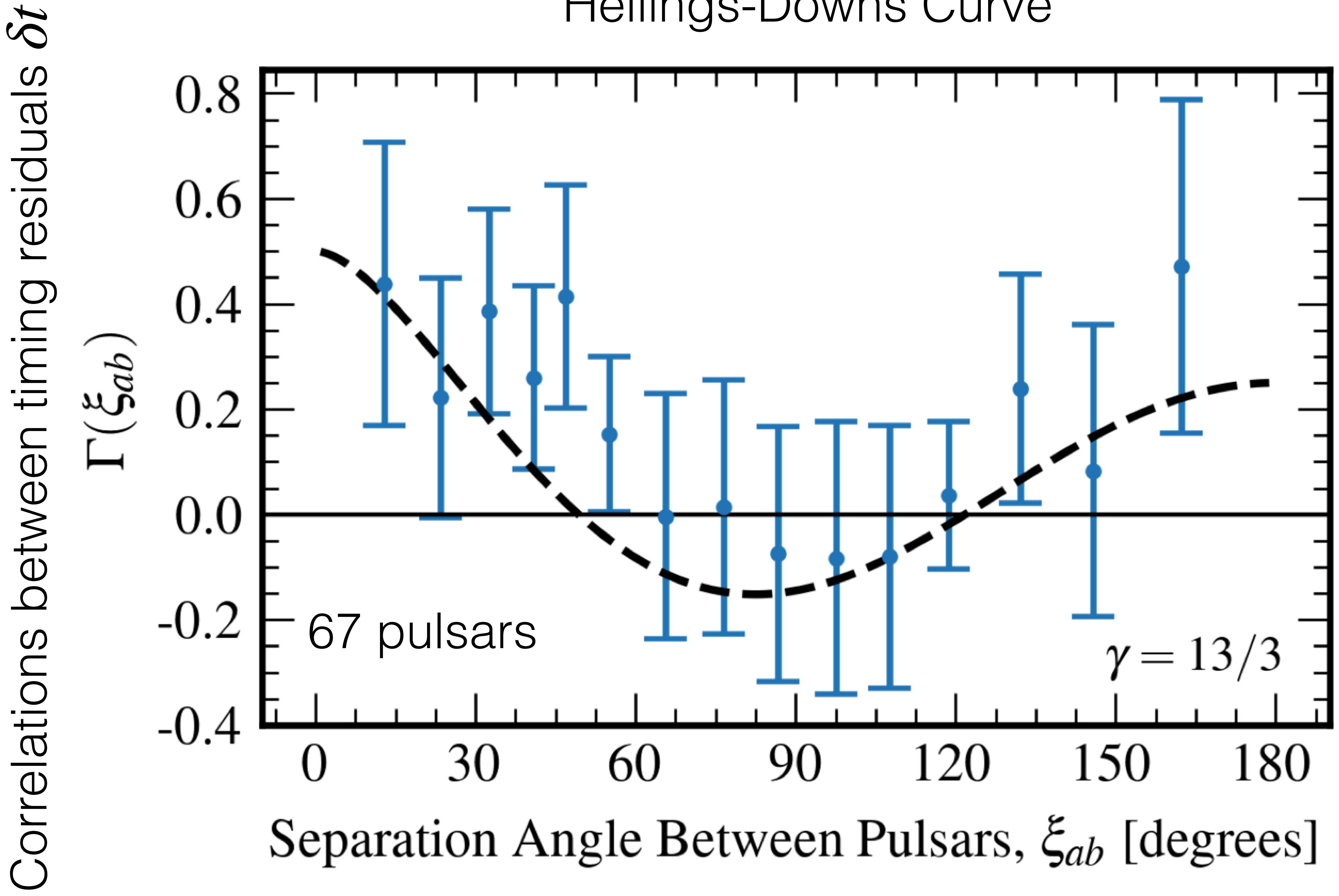


"Hellings-Downs Curve"

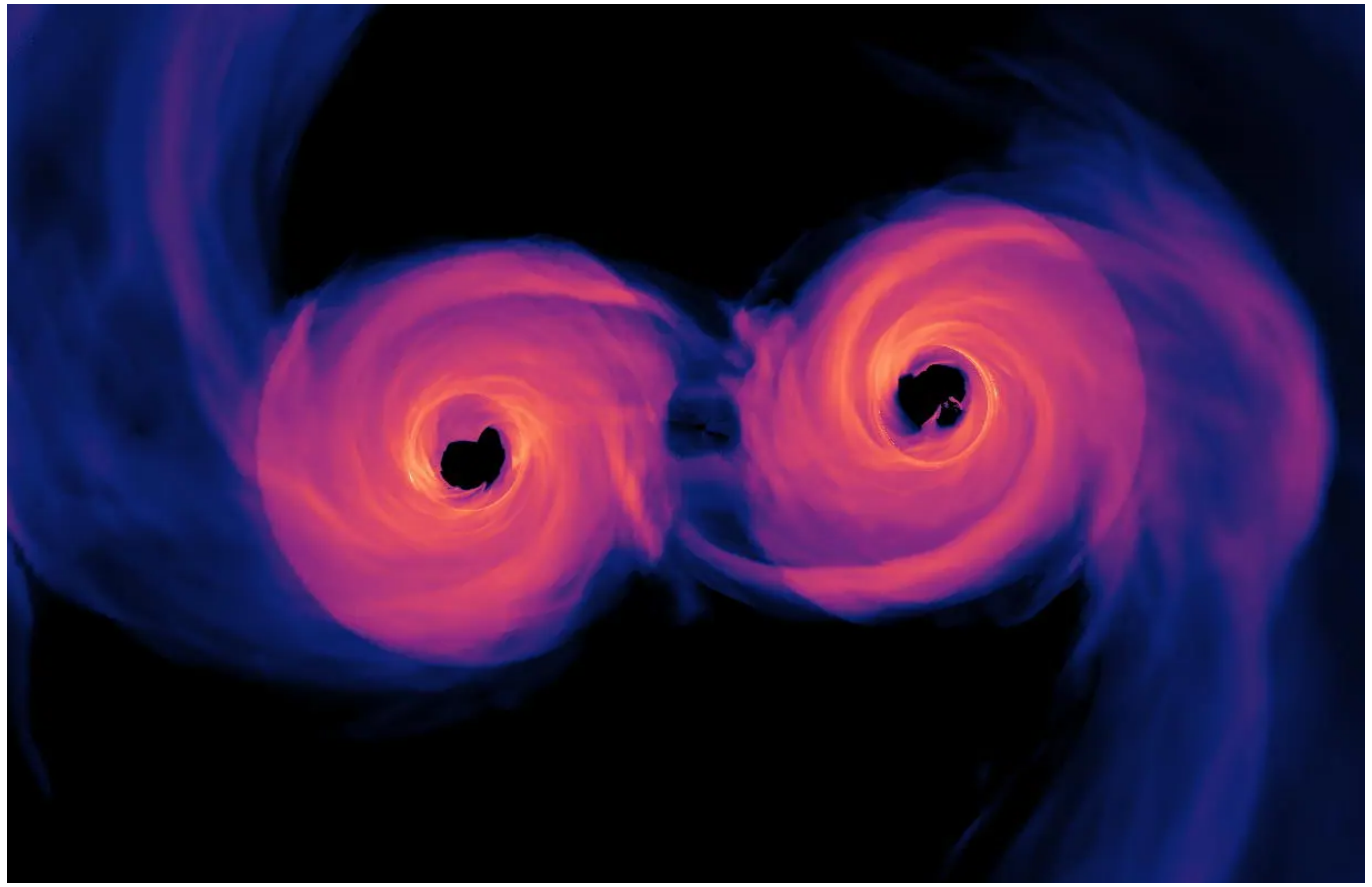


[NANOgrav, 2306.16217, 2306.16213]

Sources of Nanohertz GWs

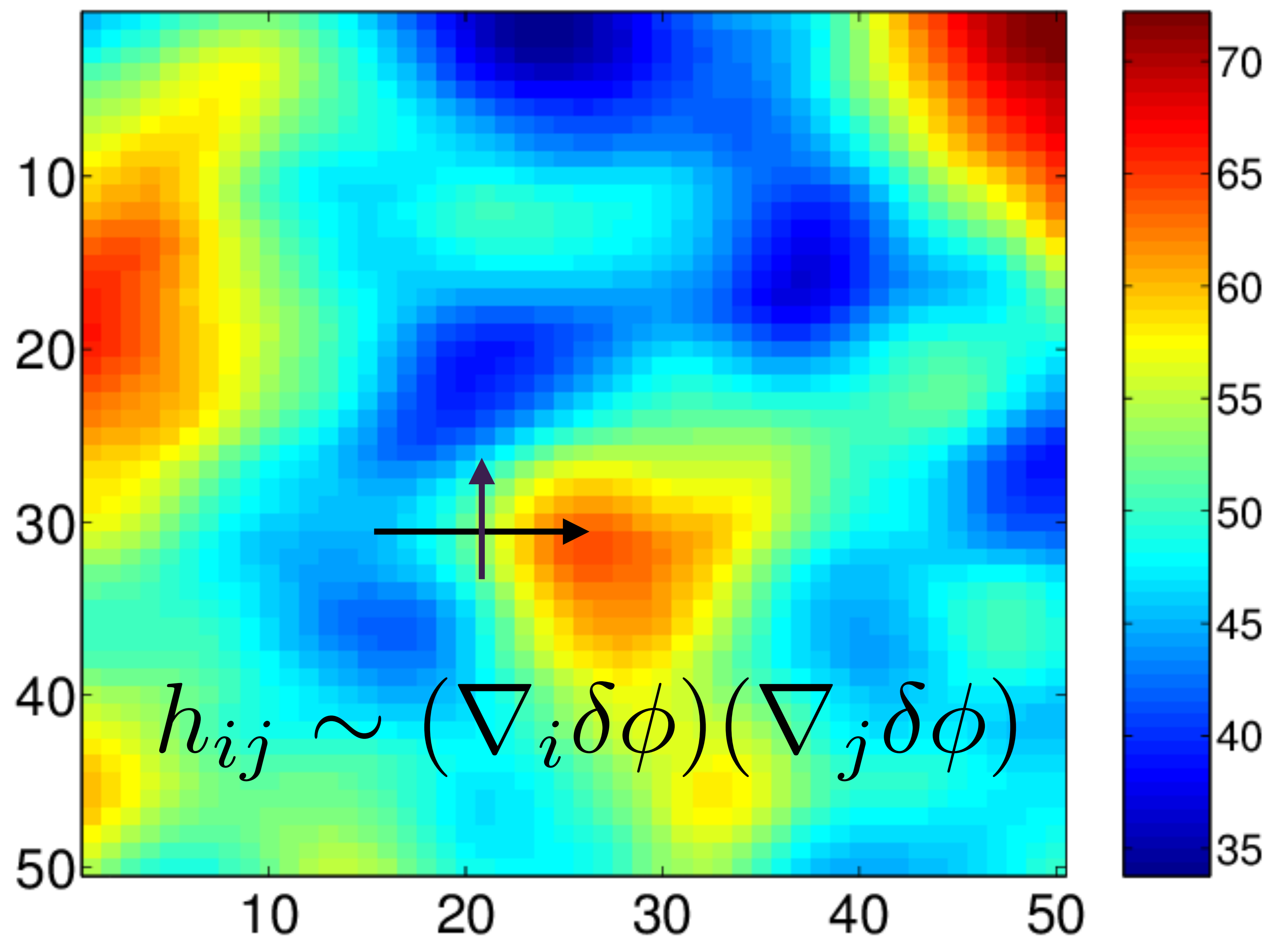
Supermassive Black Holes

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



Scalar-induced GWs?

Could be produced by enhanced scalar perturbations in the early Universe

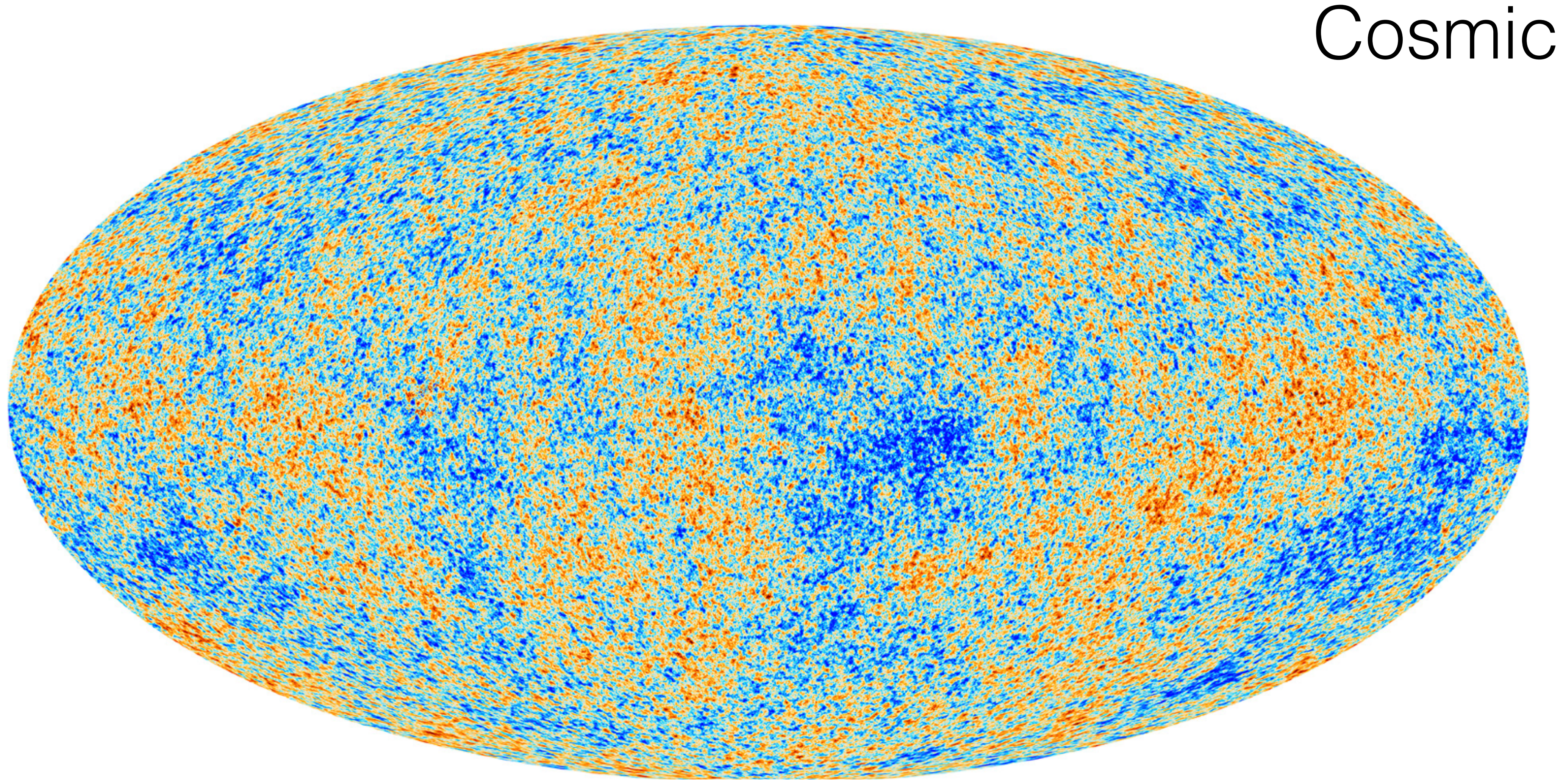


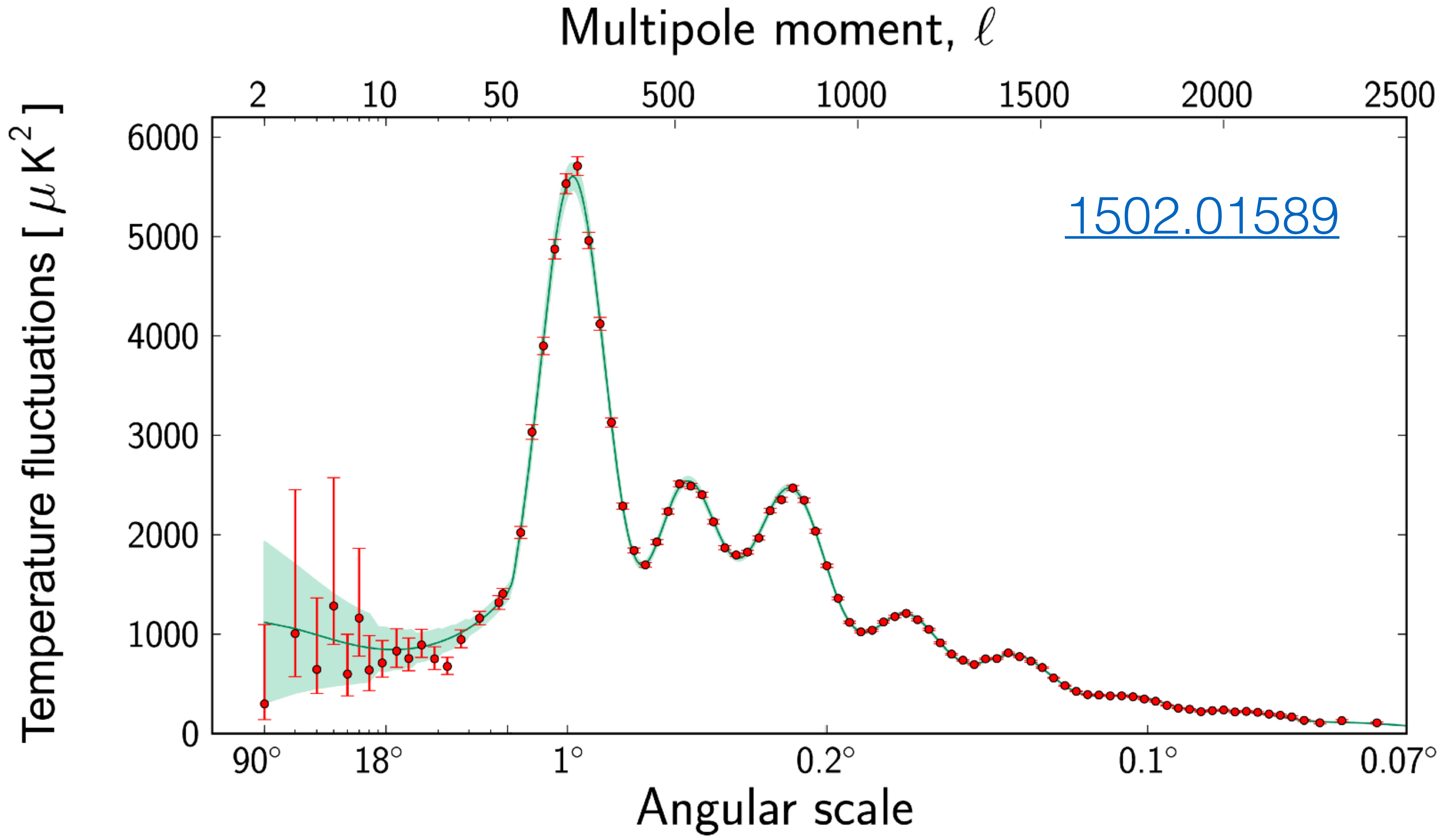
[Domènech, 2109.01398]

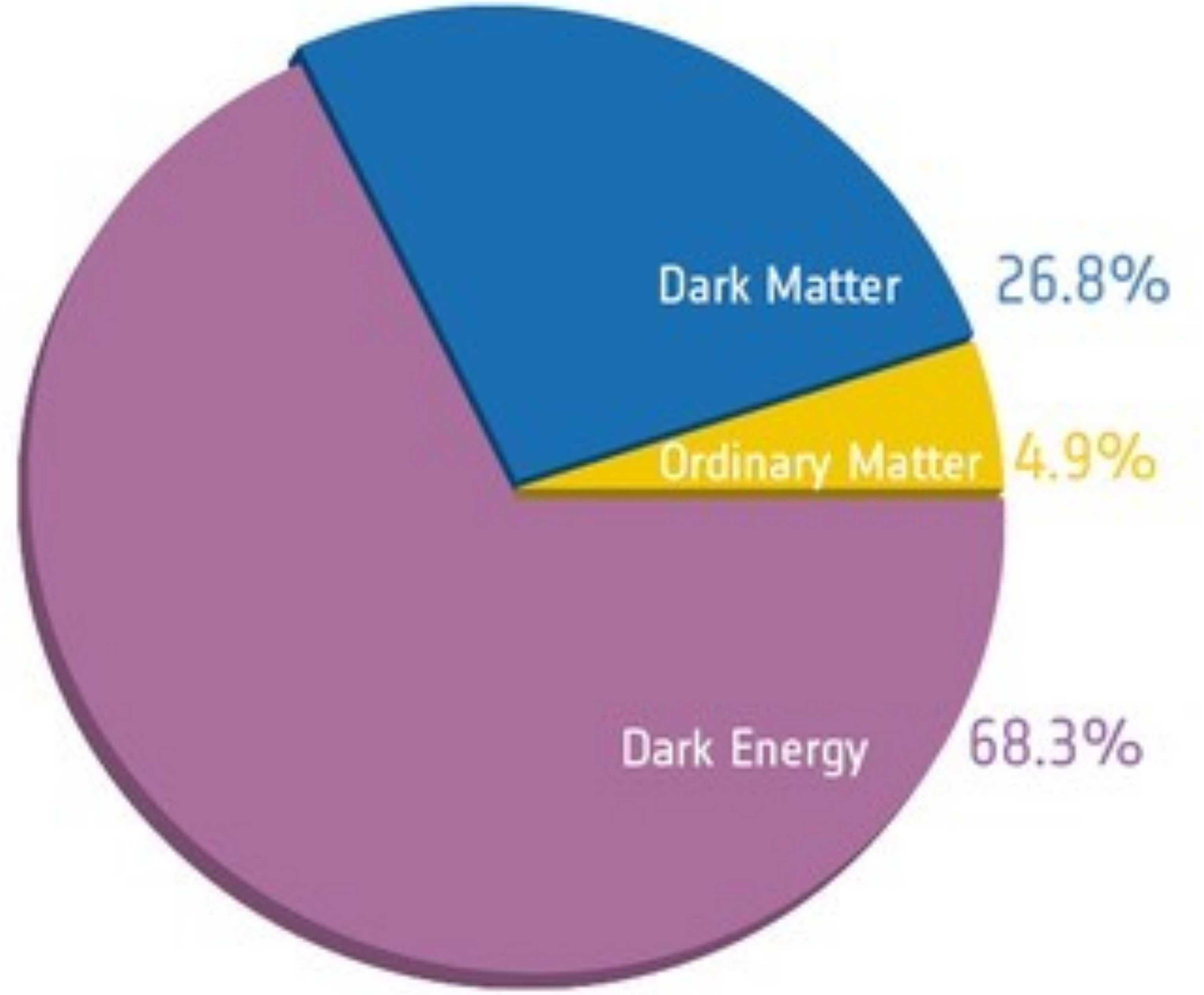
…and other possibilities…

Dark Matter in Cosmology

Cosmic Microwave Background (CMB)





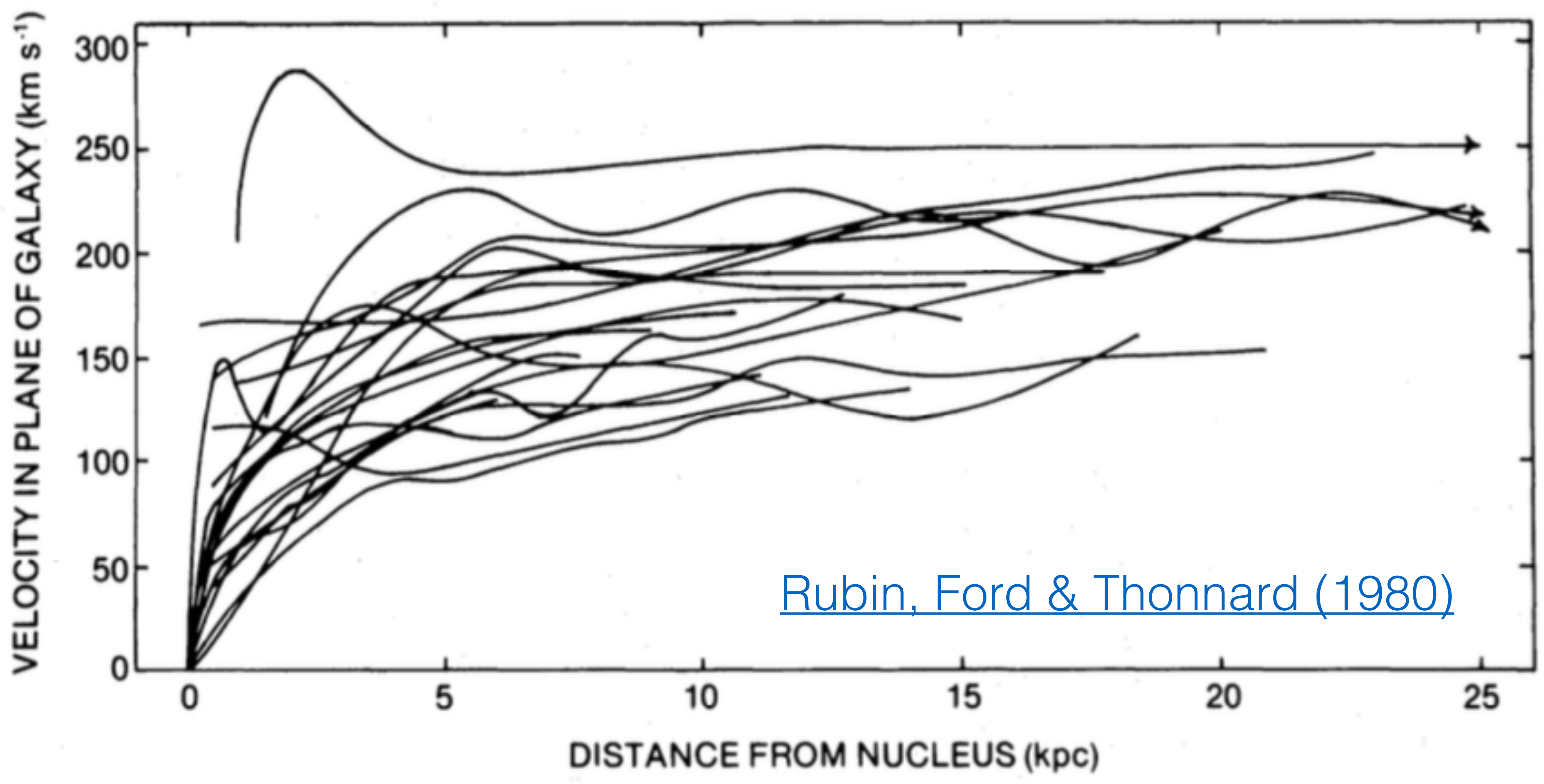


Credit: ESA/Planck Collaboration

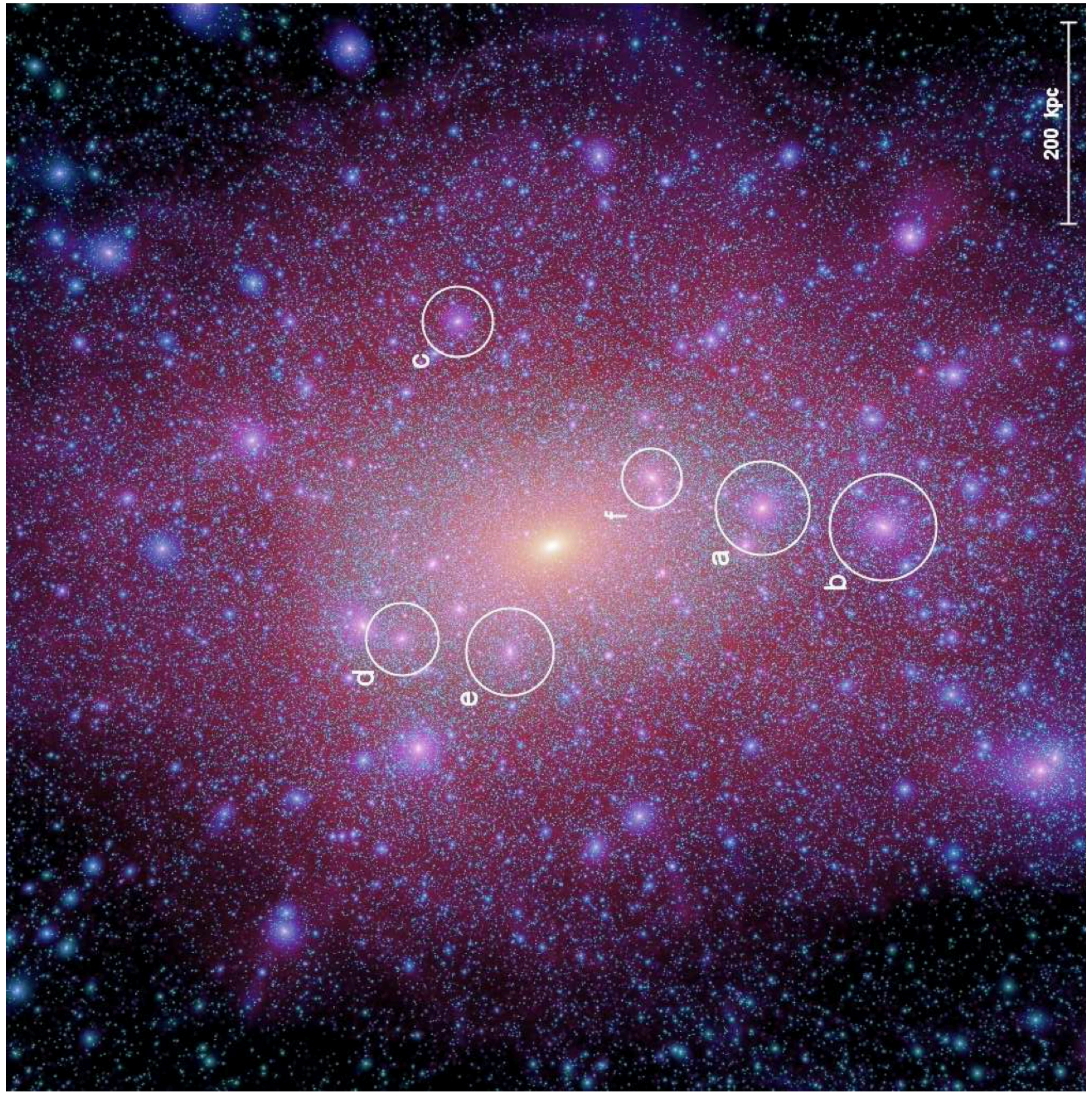
See "Introduction to Cosmology" Lectures by Daniel Baumann

Dark Matter in Galaxies

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



Rubin, Ford & Thonnard (1980)



Aquarius simulation - 0809.0898

DM density at Earth:

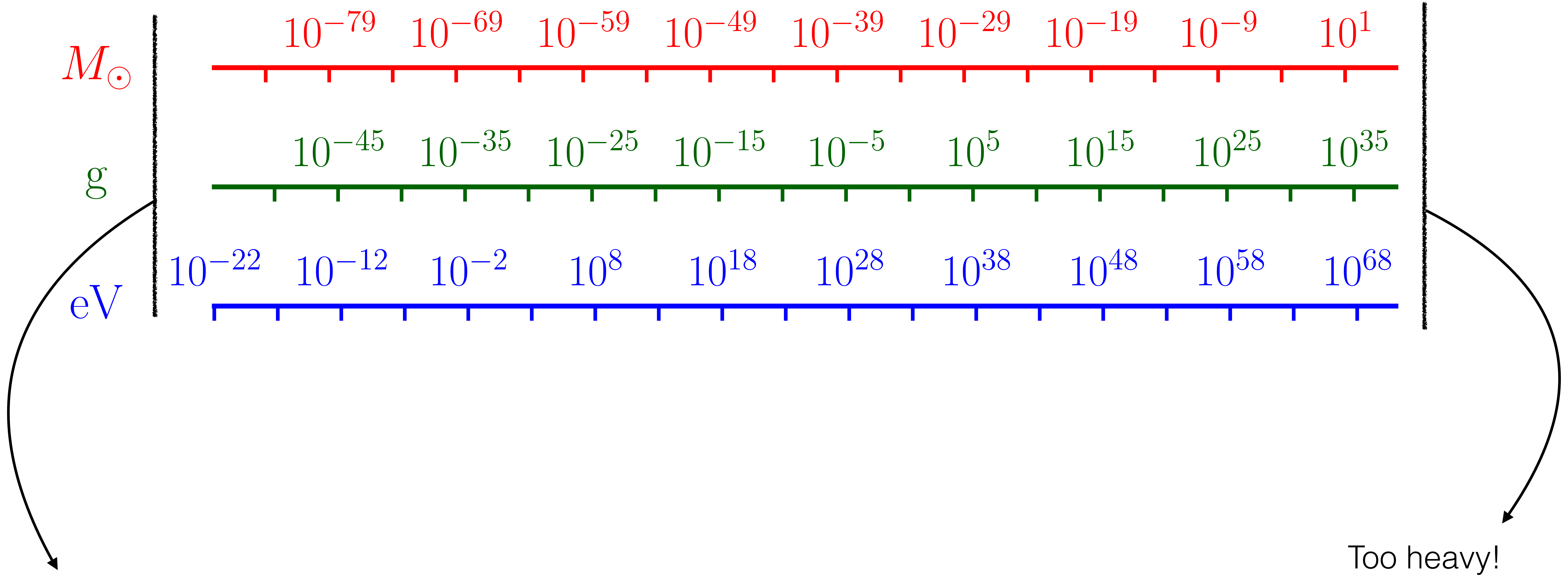
$$\rho_\chi \sim 5 \times 10^{-25}\ \mathrm{g/cm^3}$$
$$\sim 0.3\ \mathrm{GeV/cm^3}$$
$$\sim 0.008\ M_\odot/\mathrm{pc}^3$$

1404.1938

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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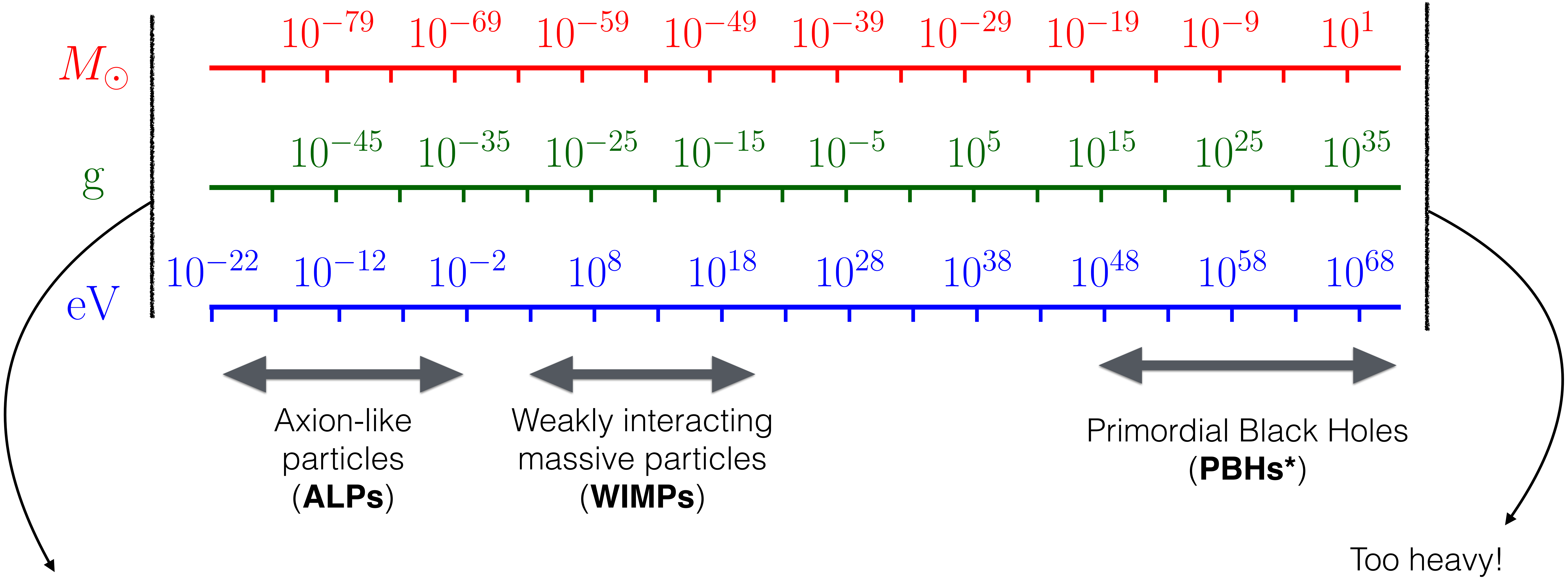

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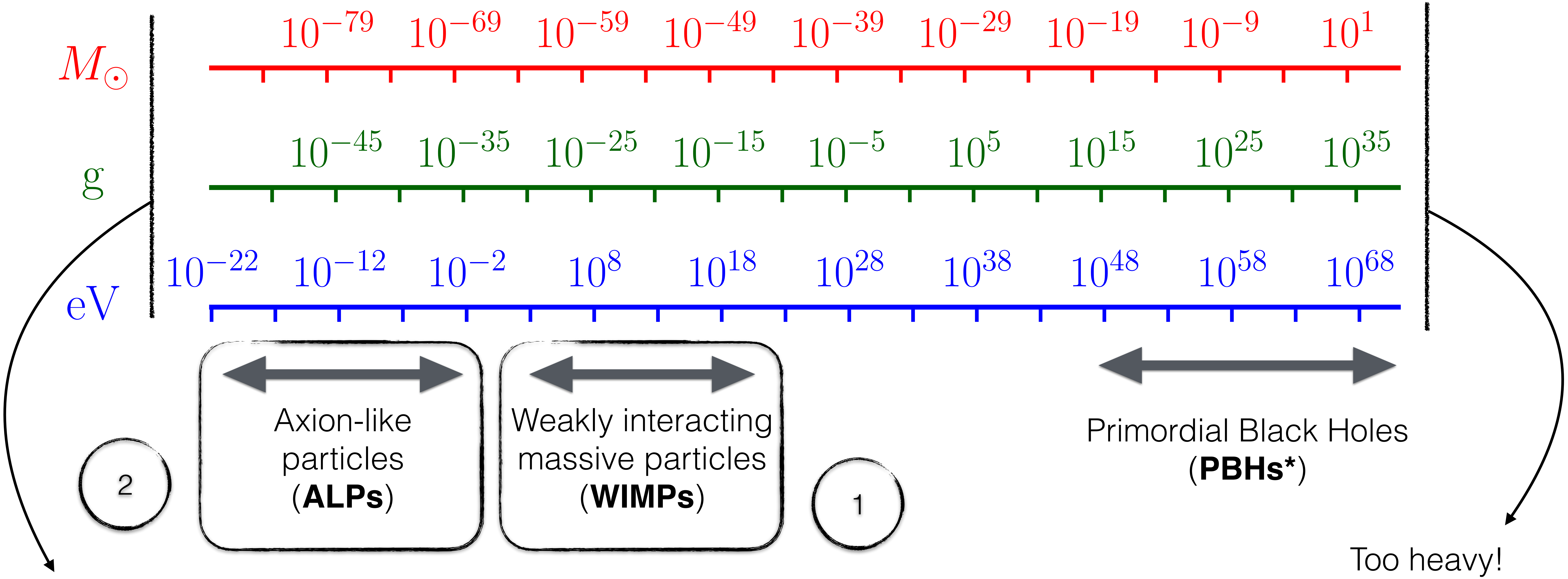


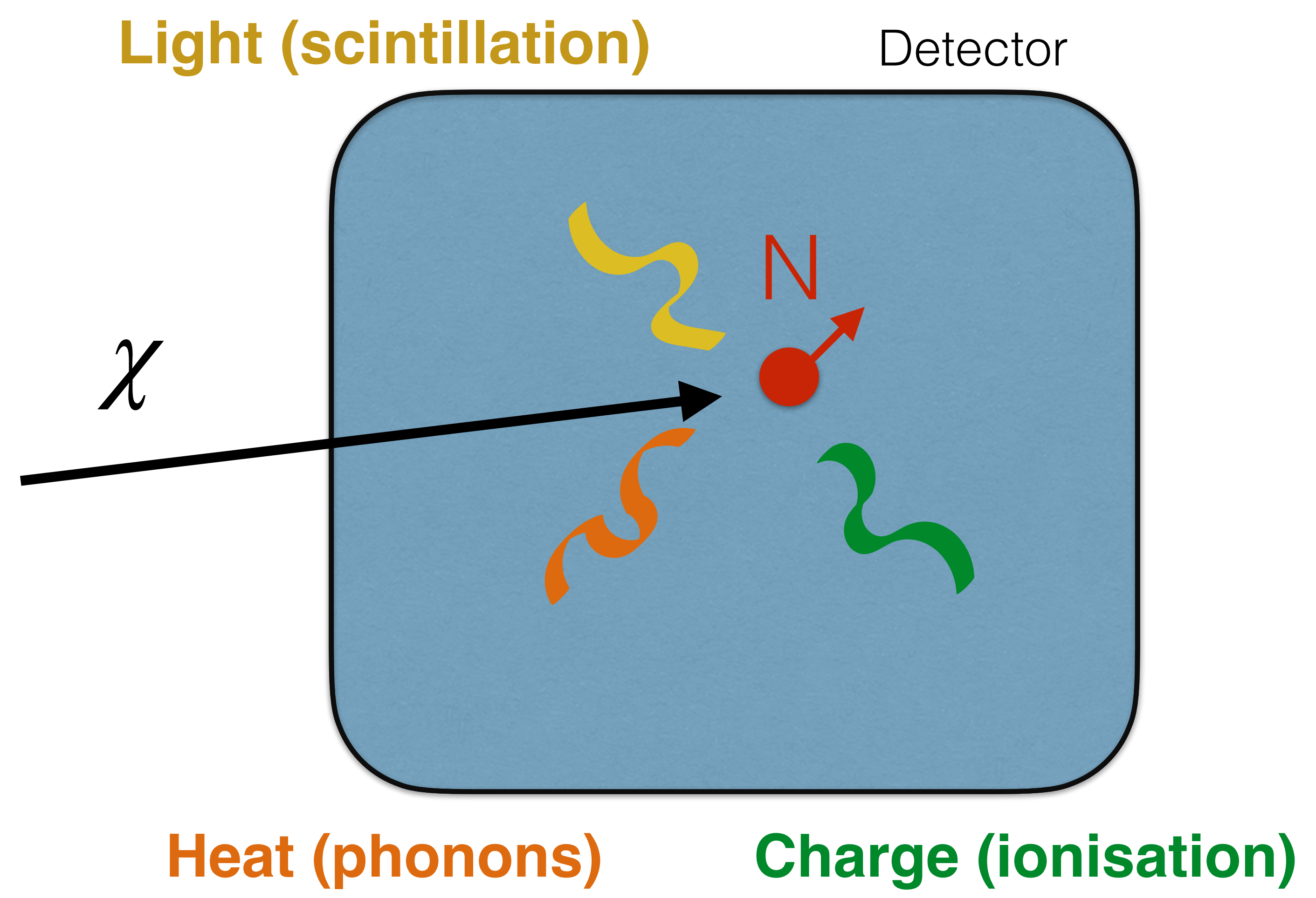
Too light!
Has wave-like properties on galactic scales!

Too heavy!
DM mass comparable to galactic masses!

*See additional slides…

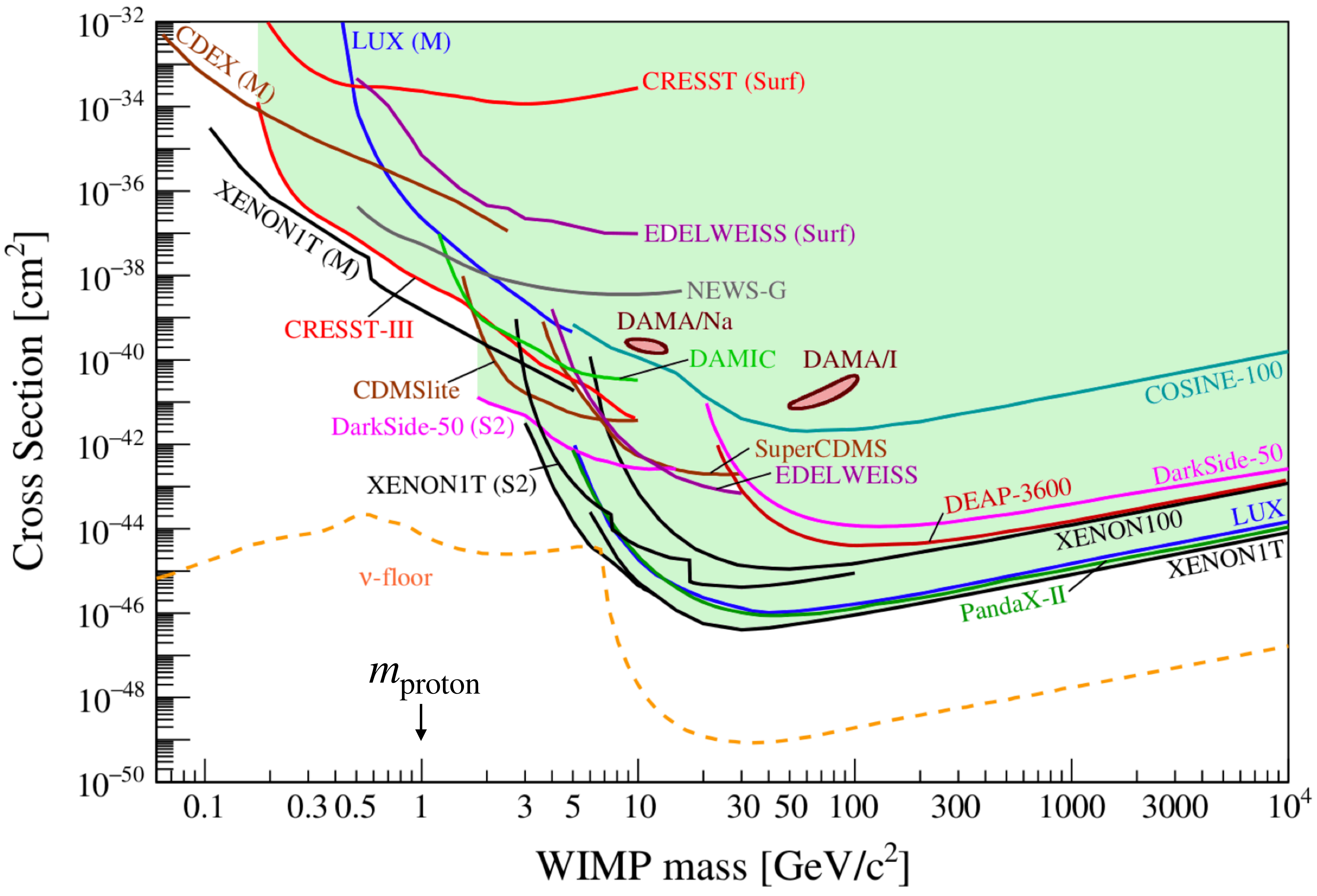
Direct detection of WIMPs on Earth

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

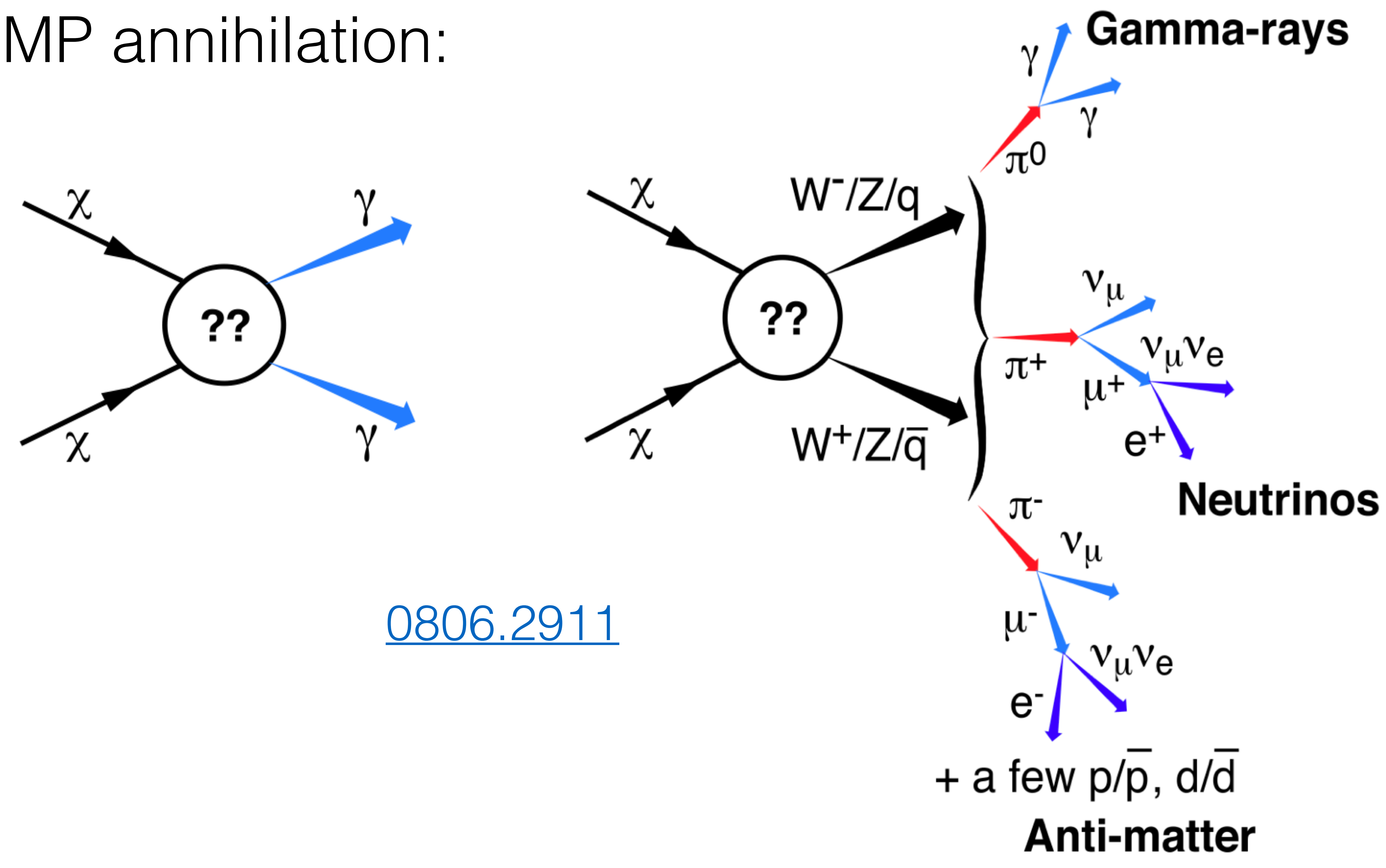
No convincing signal yet!



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

Indirect detection of Dark Matter

WIMP annihilation:



0806.2911

Annihilation cross section
(particle physics)

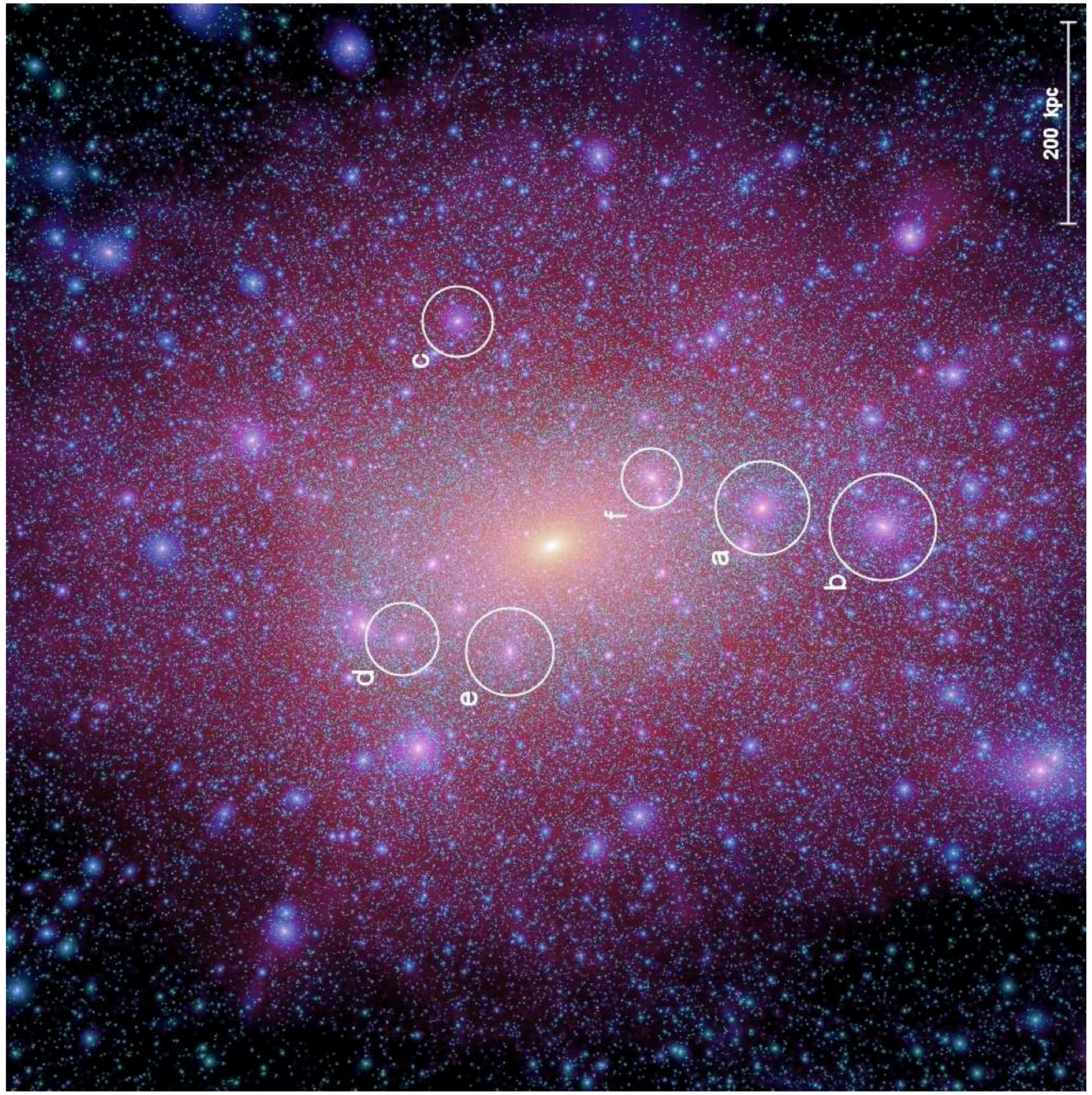
DM density distribution
(astrophysics)

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

Gamma-ray spectrum
(annihilation channel)

1012.4515

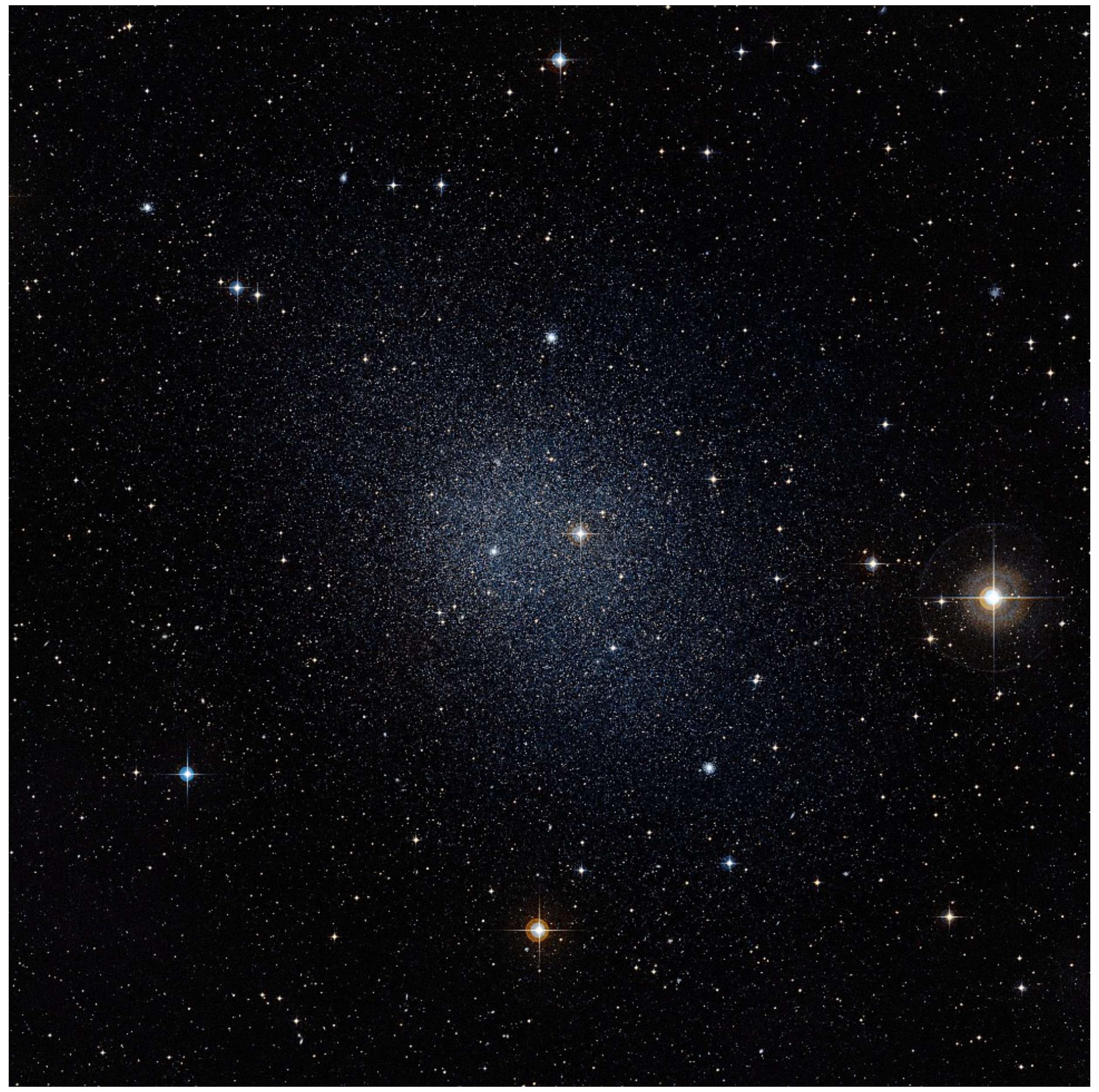
Look for signals of Dark Matter annihilation in regions of large DM density!



Aquarius simulation - 0809.0898

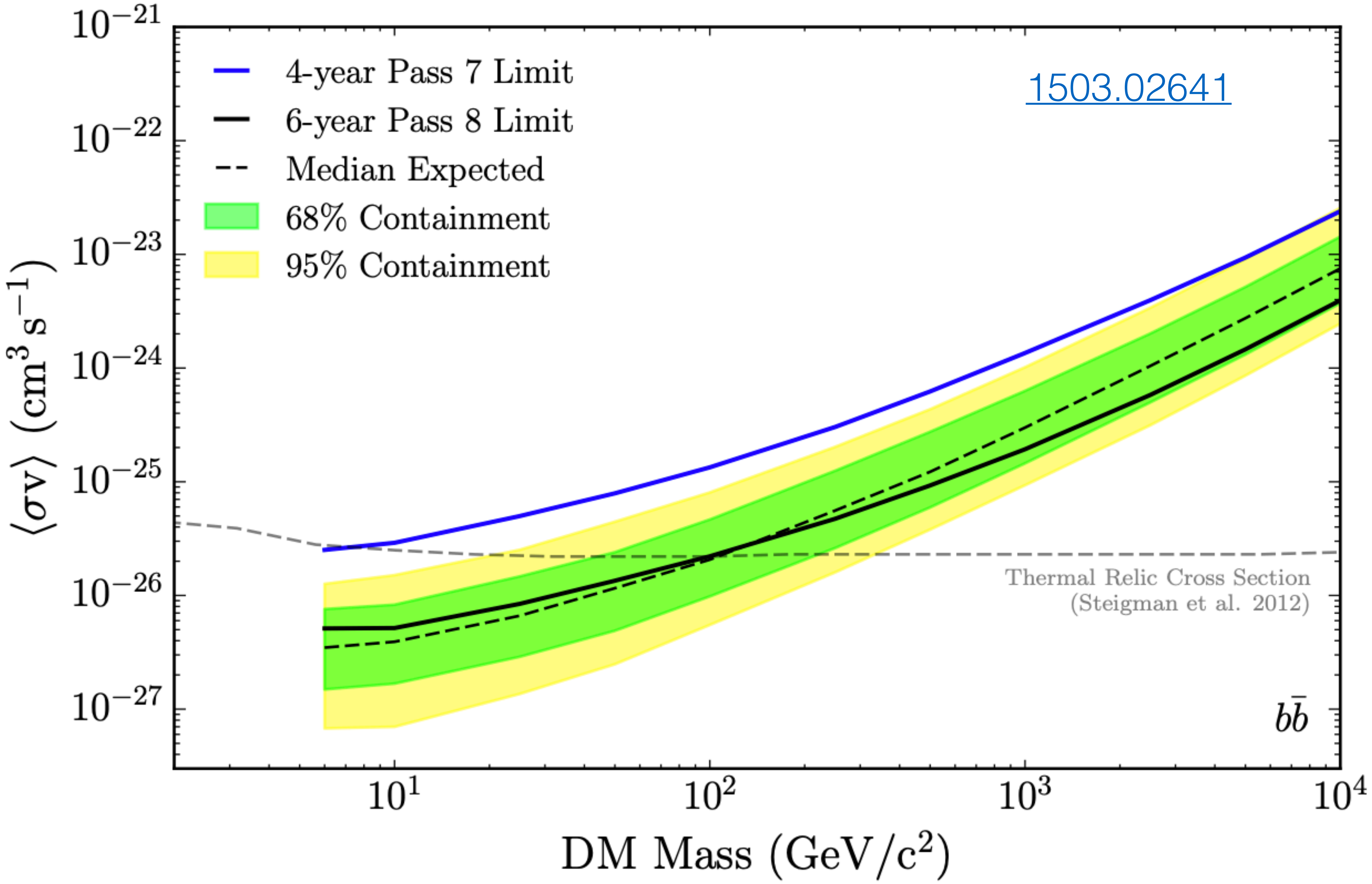
Gamma-ray constraints

Fornax Dwarf Galaxy
(Satellite of the Milky Way)



Credit: ESO/Digitized Sky Survey 2

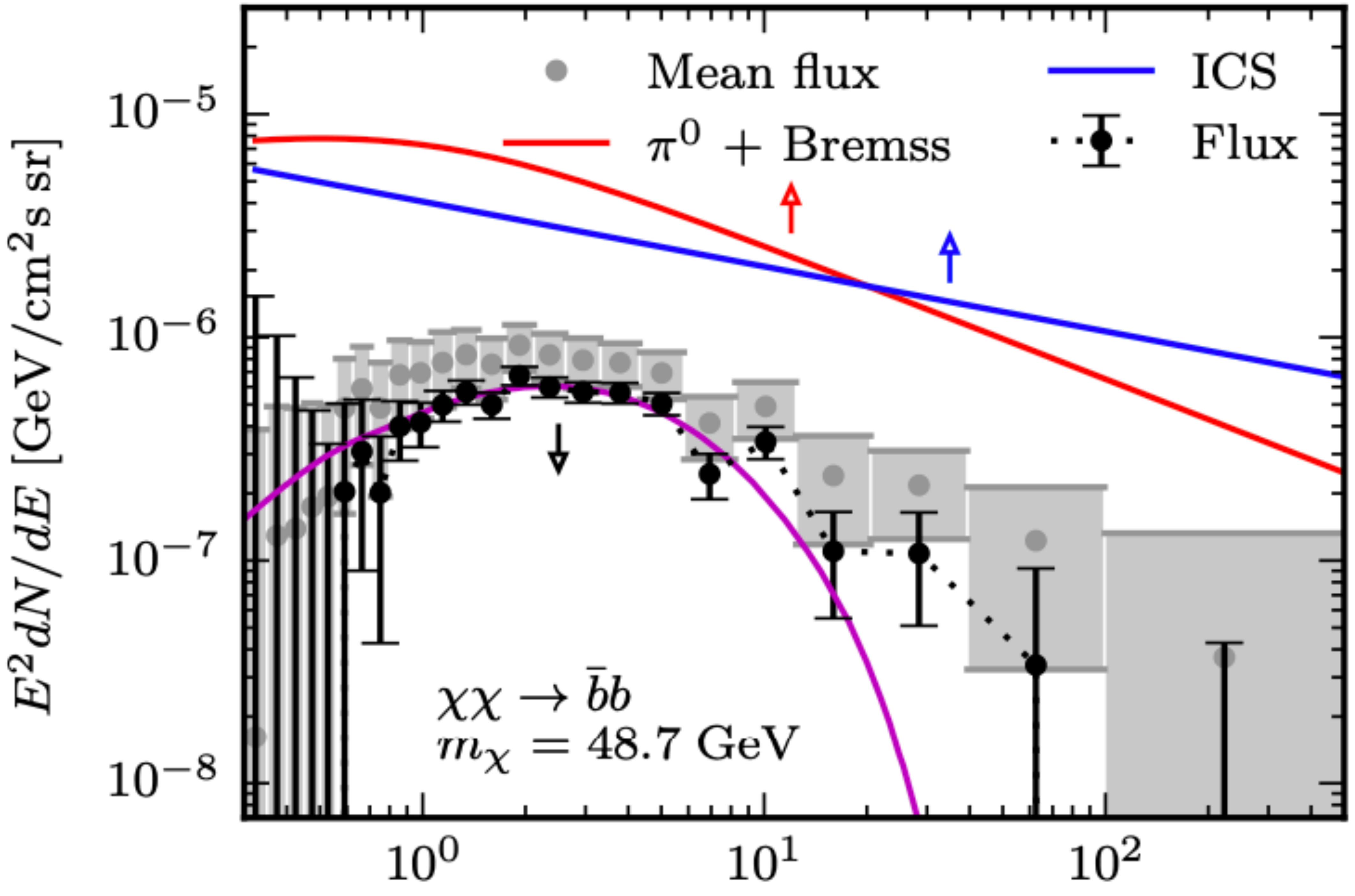
Fermi constraints from 15 Dwarf Spheroidal Galaxies:



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

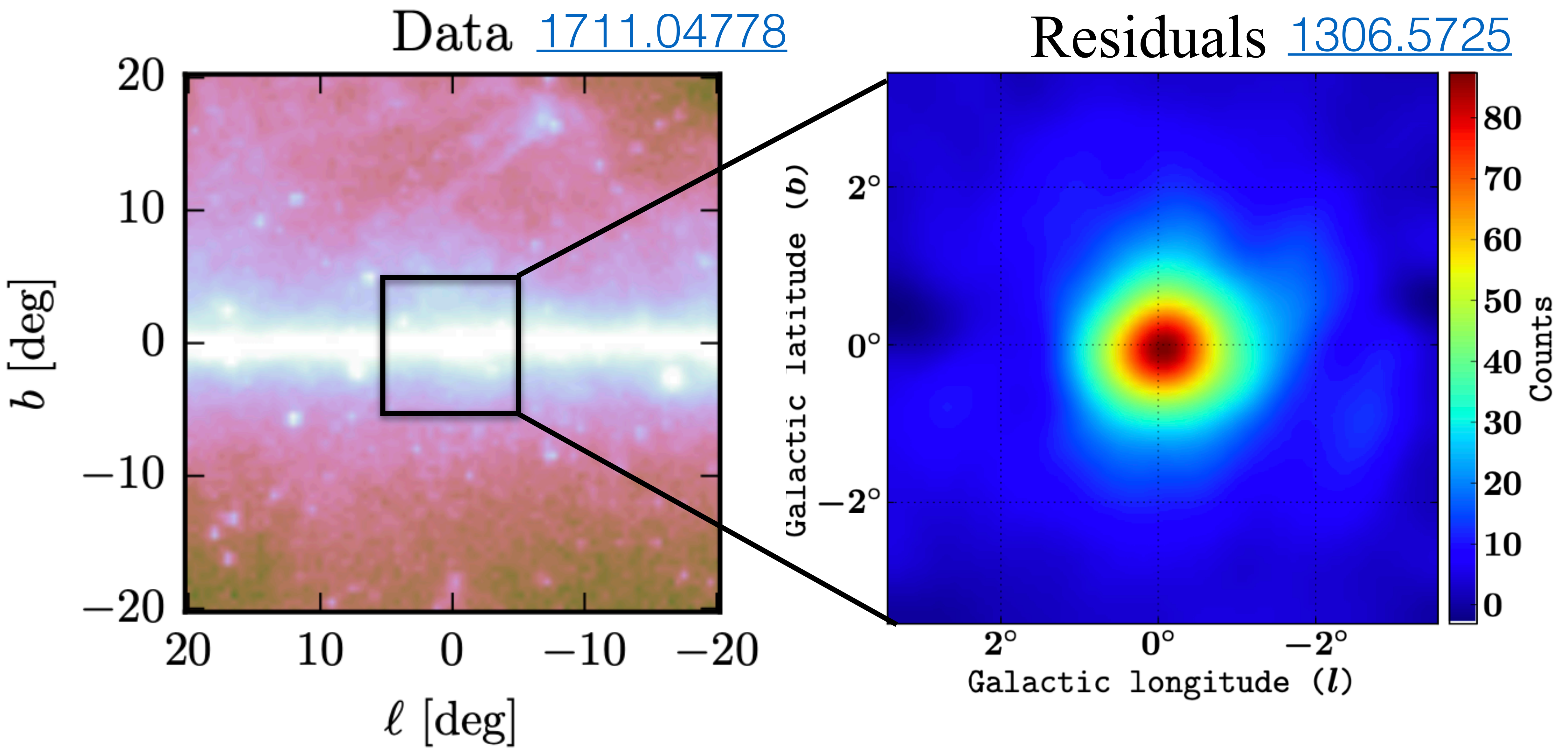
Galactic Centre Excess

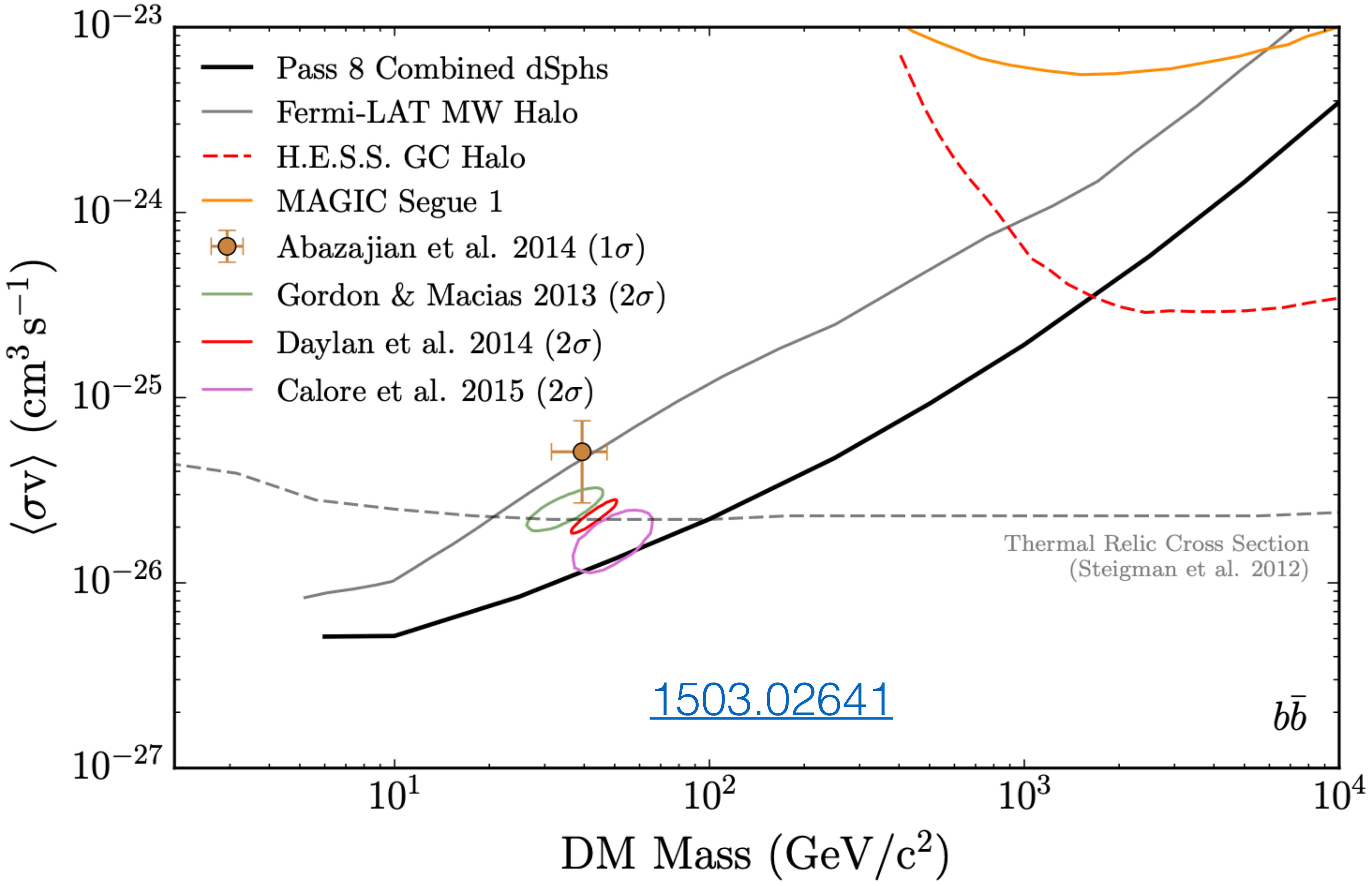
1411.4647



Data 1711.04778

Residuals 1306.5725

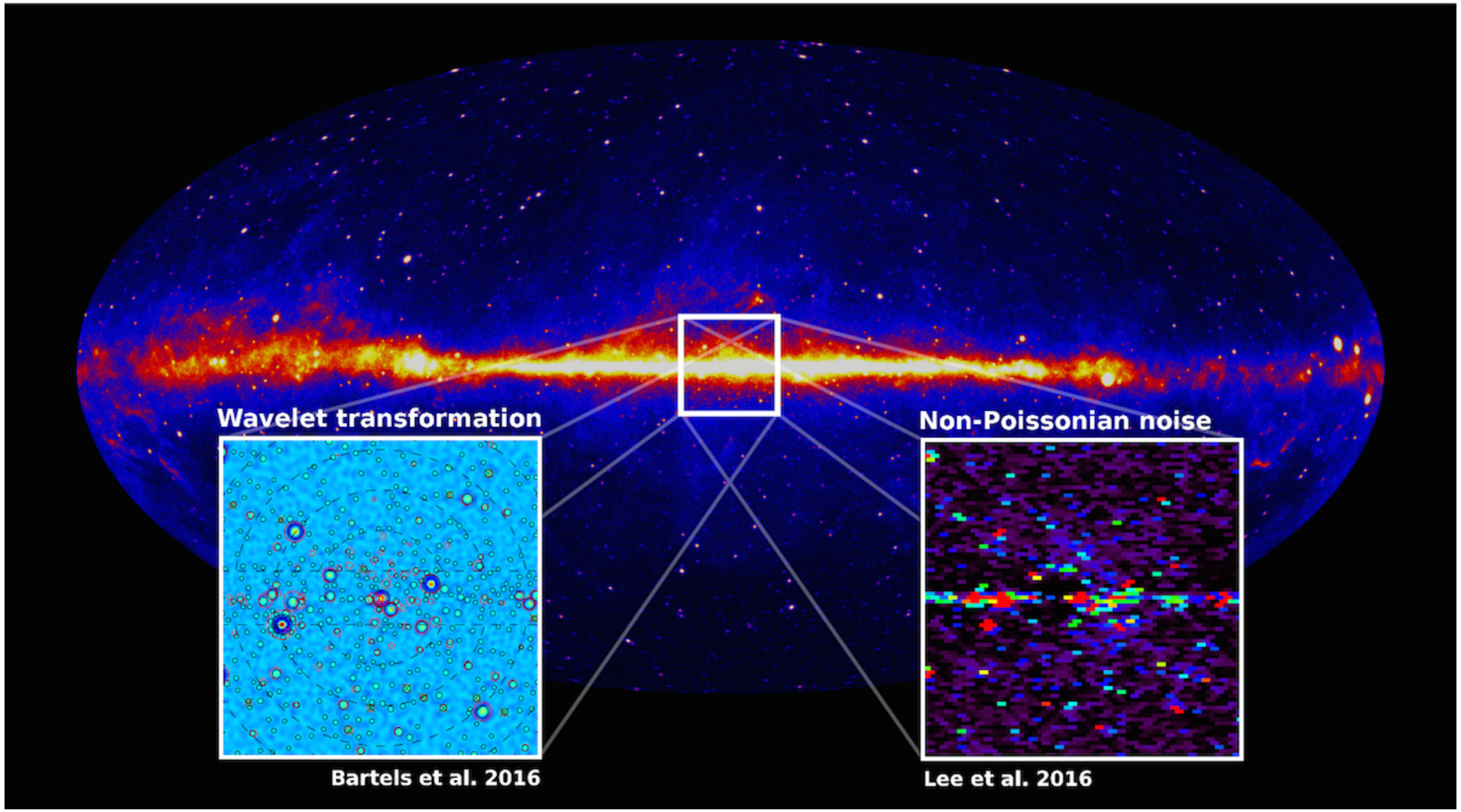




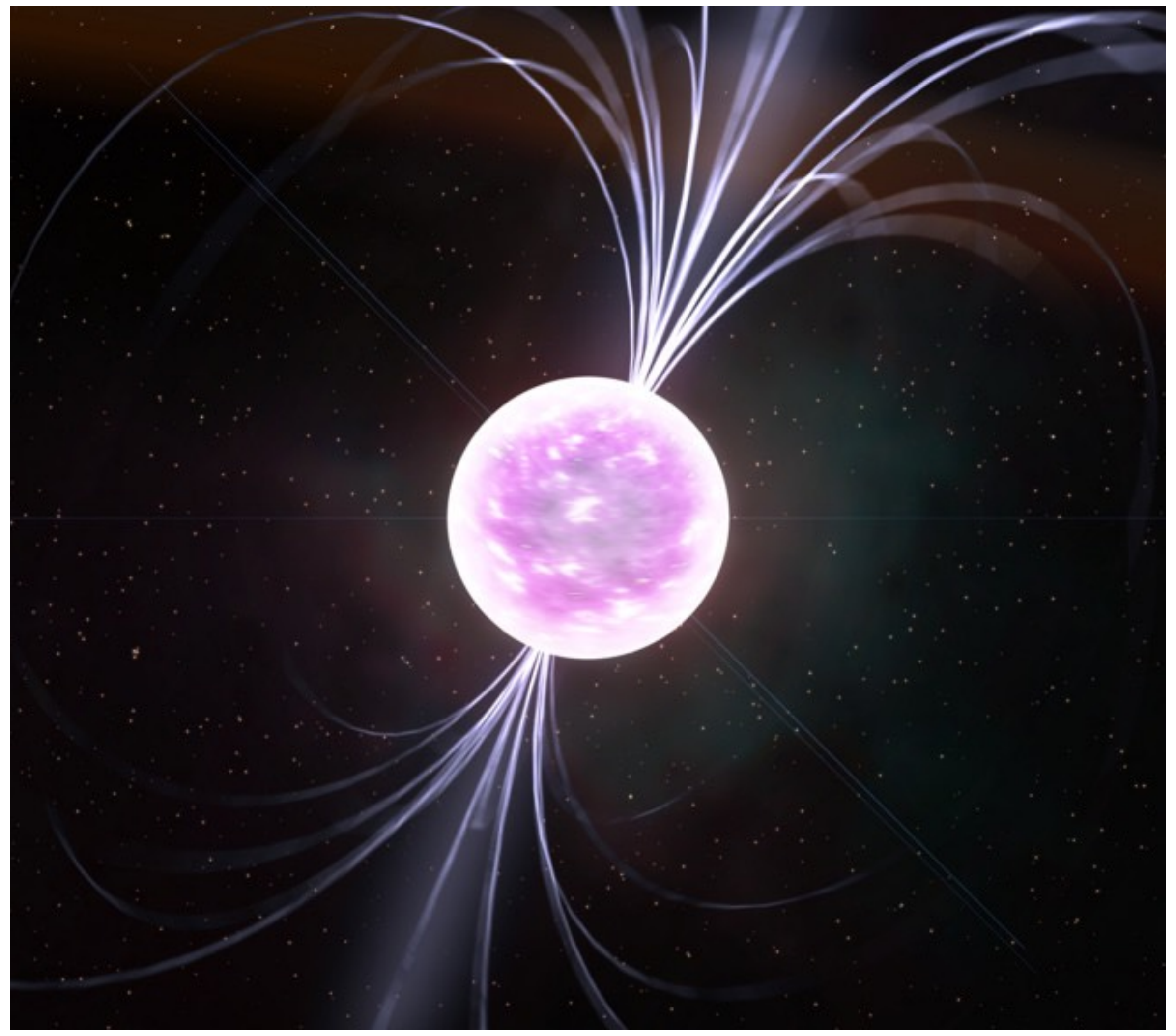
1503.02641

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



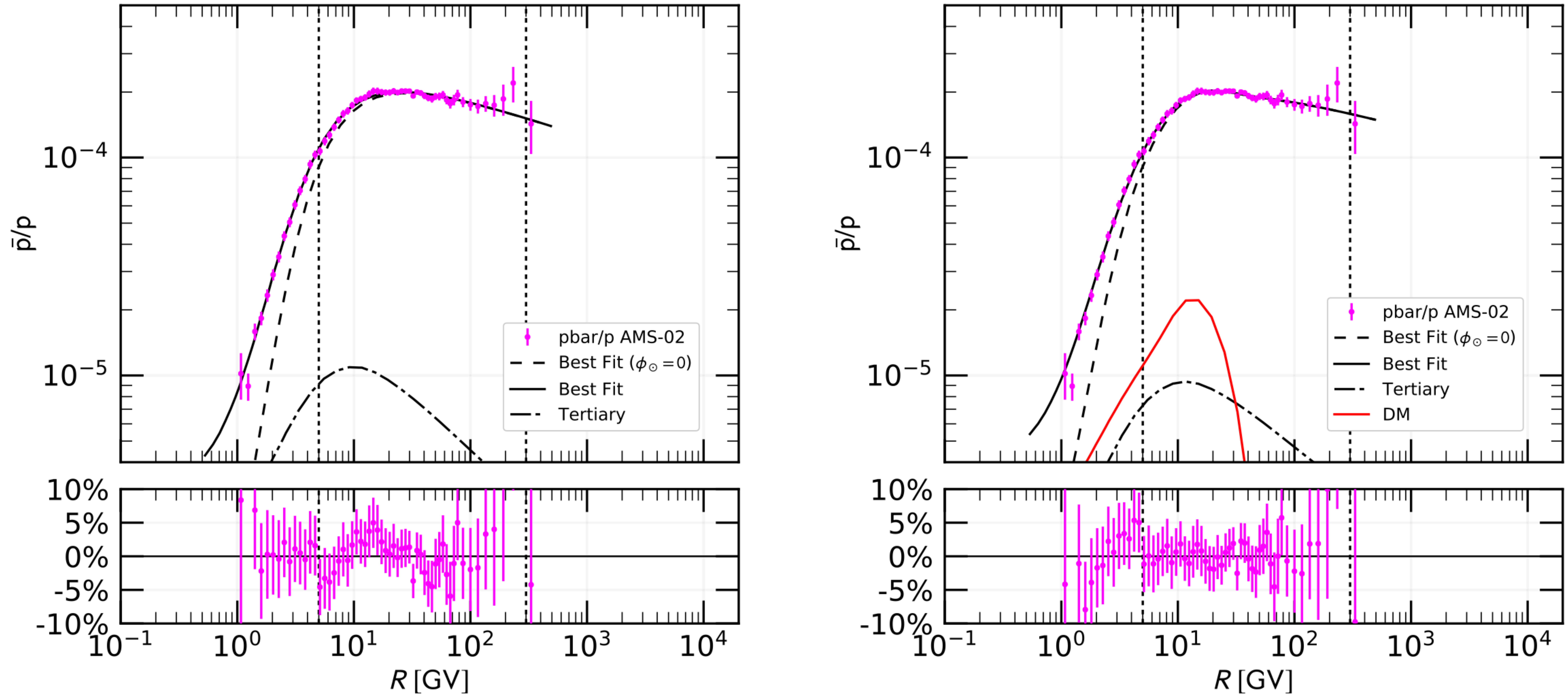
Credit: Kevin Gill / Flickr

Square Kilometer Array (SKA)?

1506.05104, 1711.04778

Anti-proton excess

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



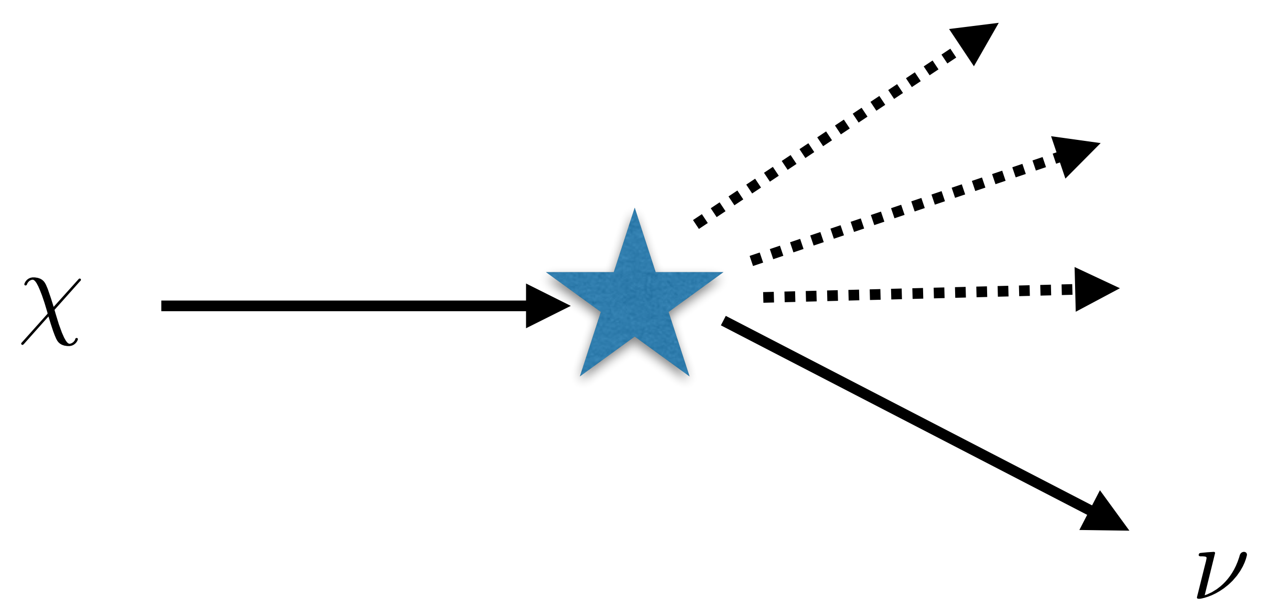
Several excesses point towards 60 GeV Dark Matter -
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

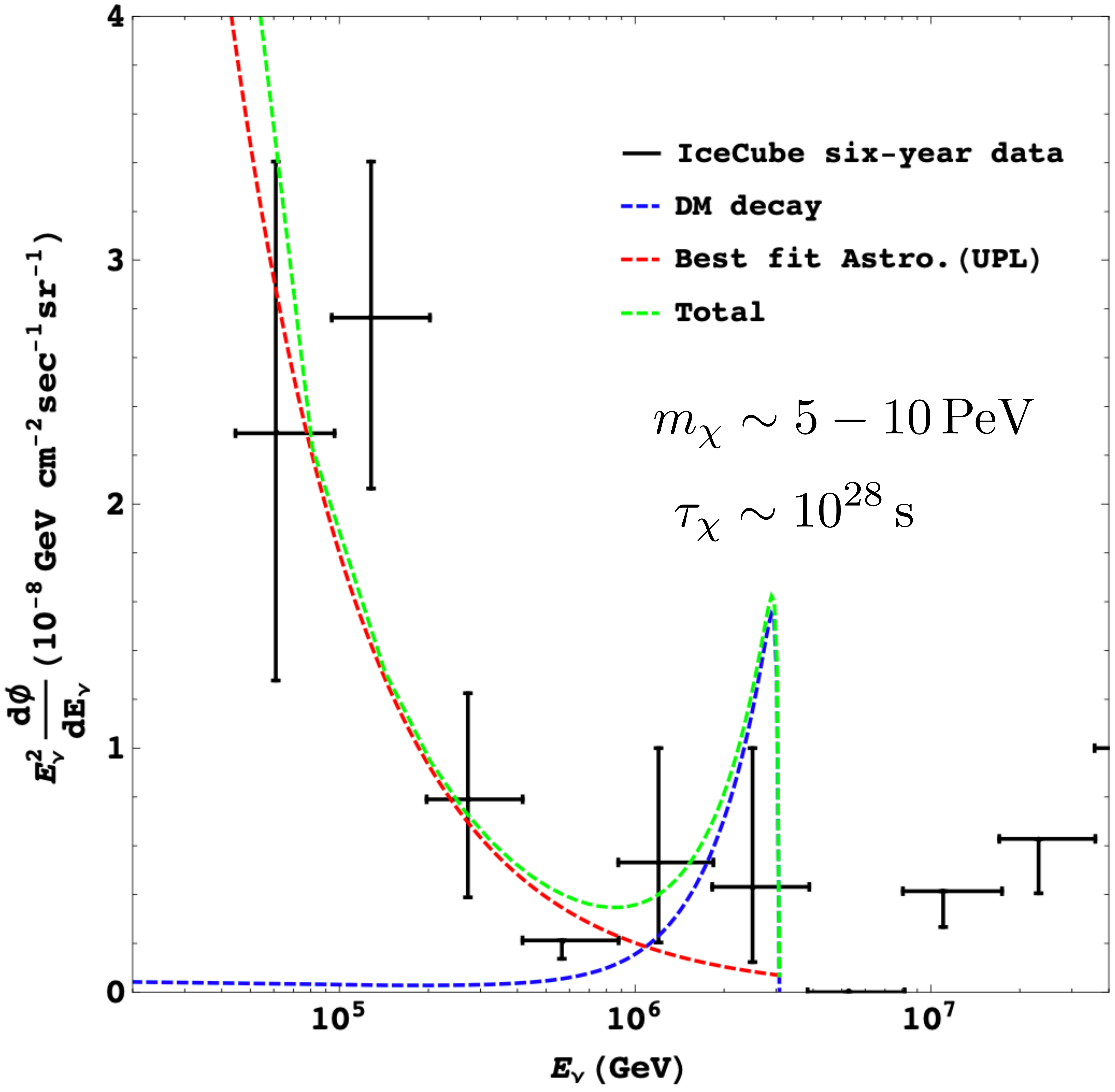
1504.04276, 1610.03071, 1903.01472

High energy neutrinos

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

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

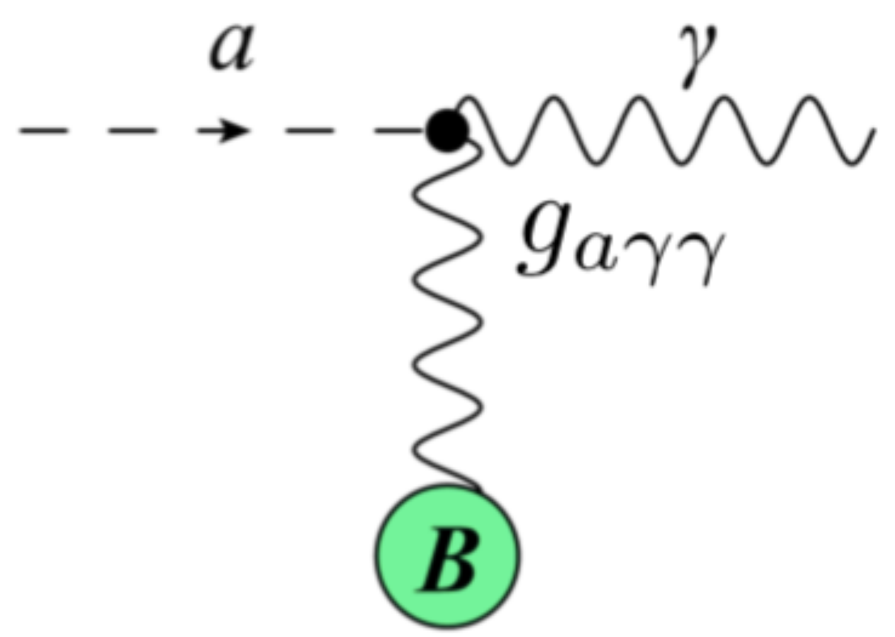


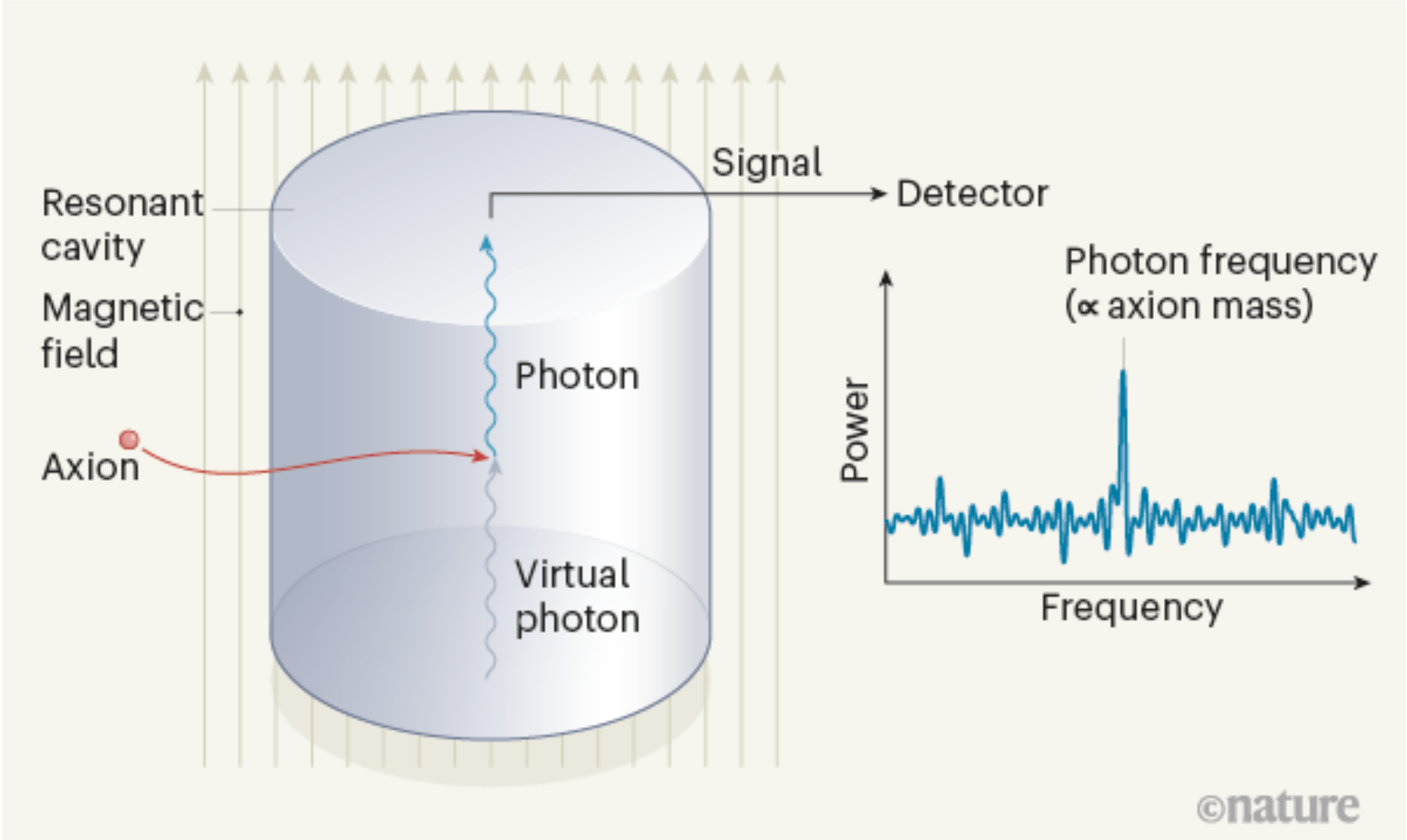


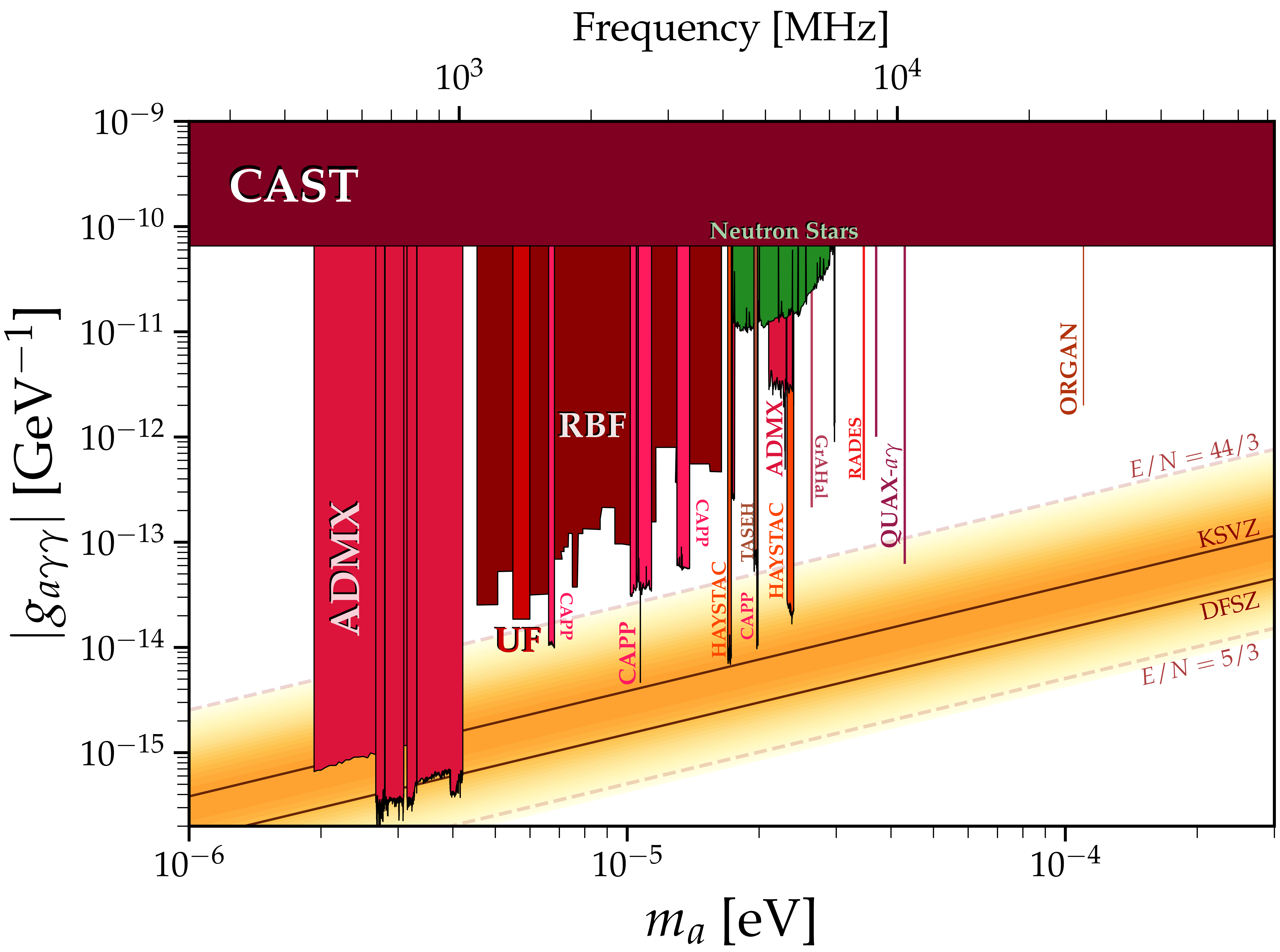
Axion searches in the lab

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

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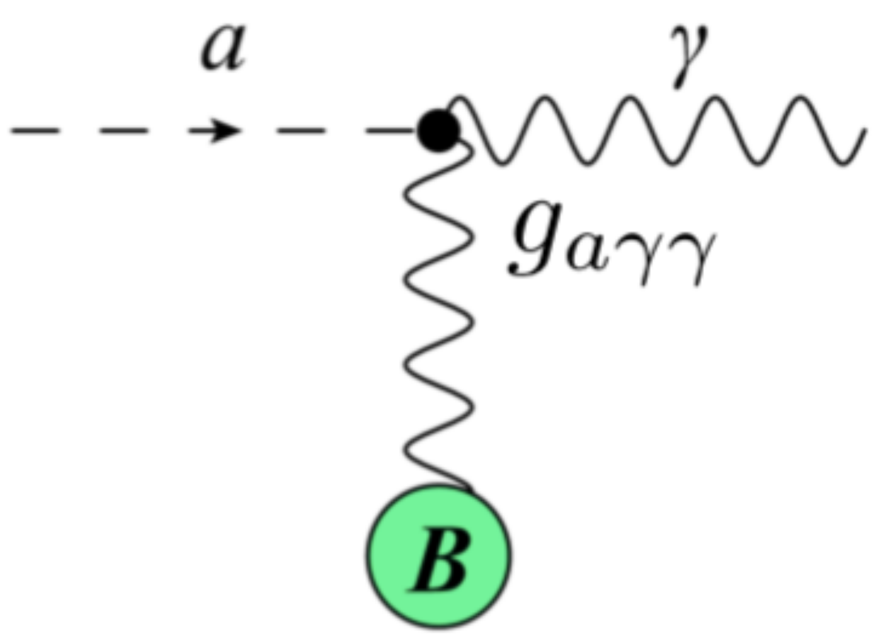
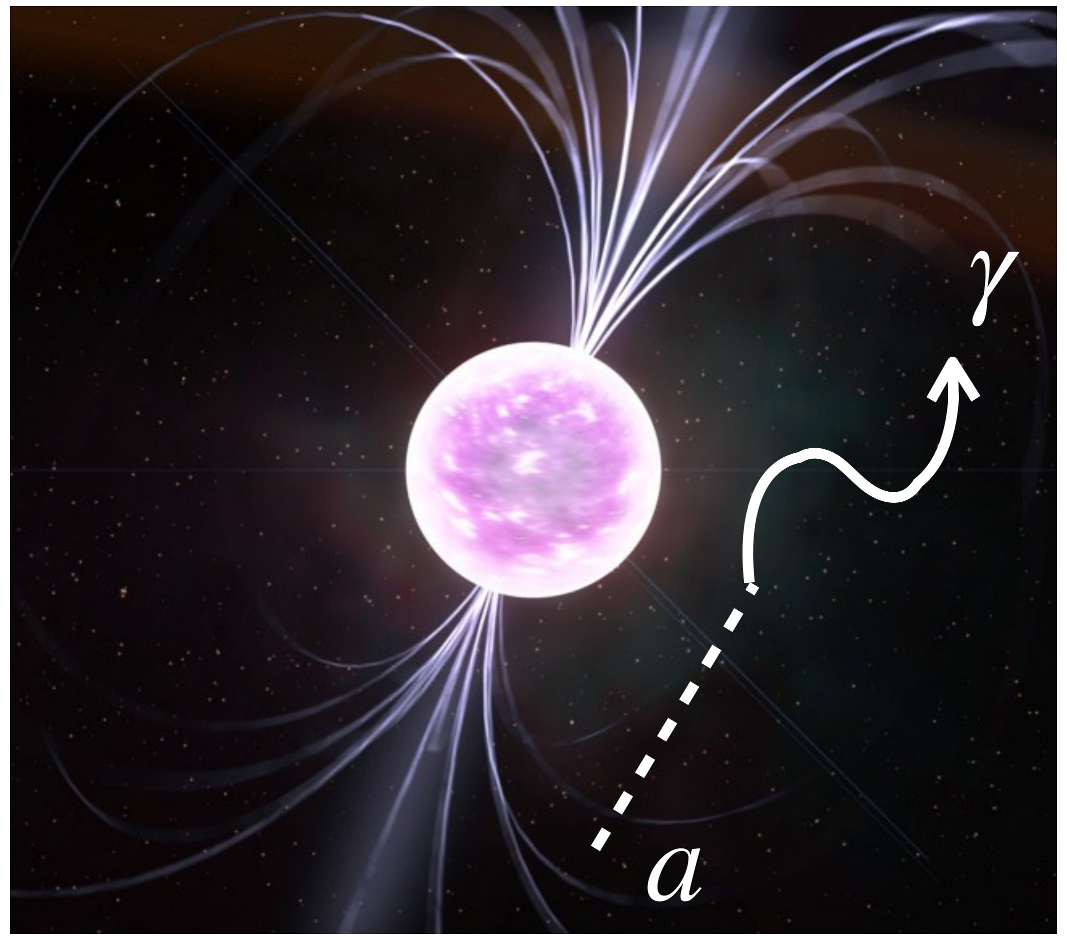
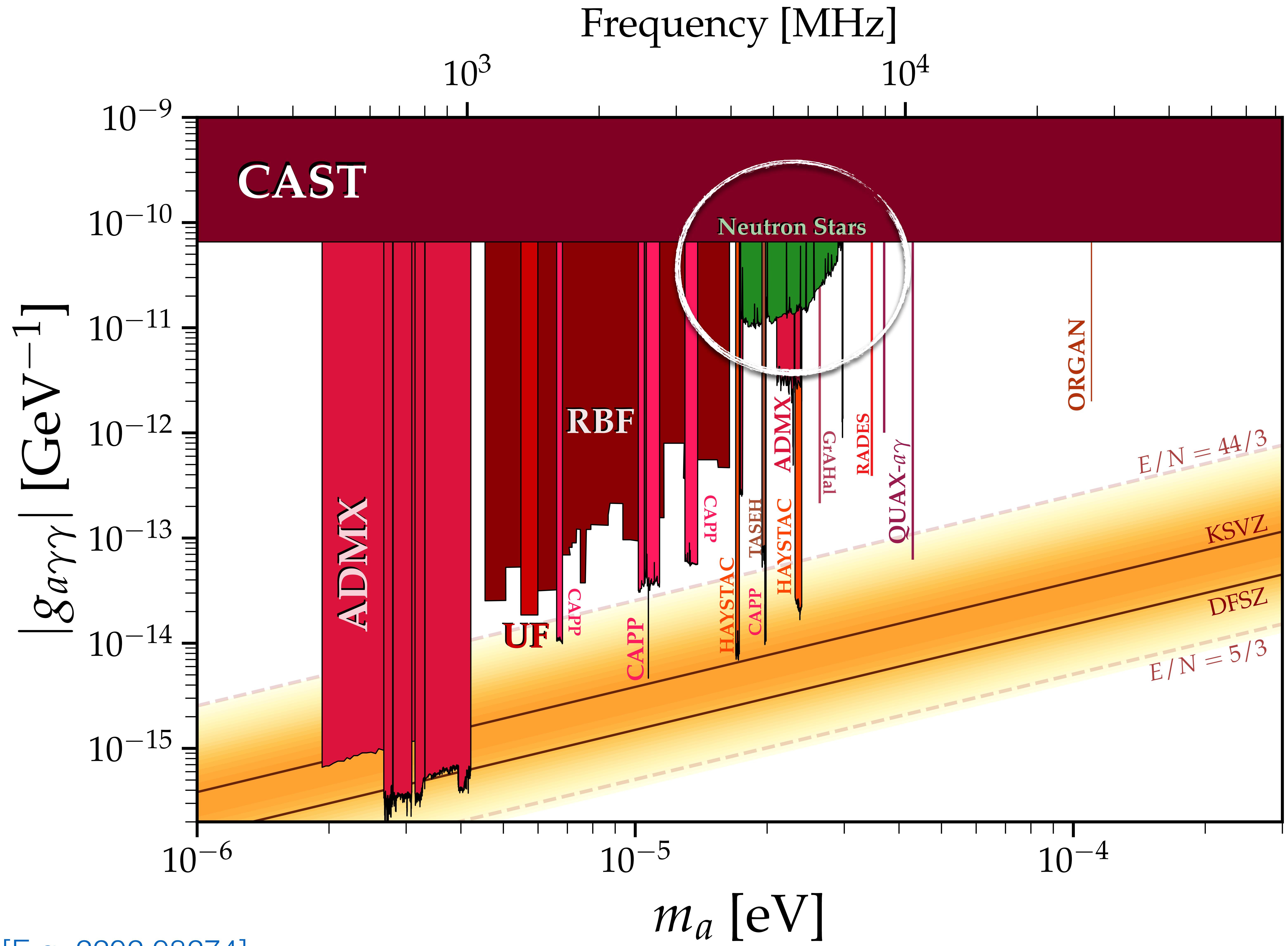






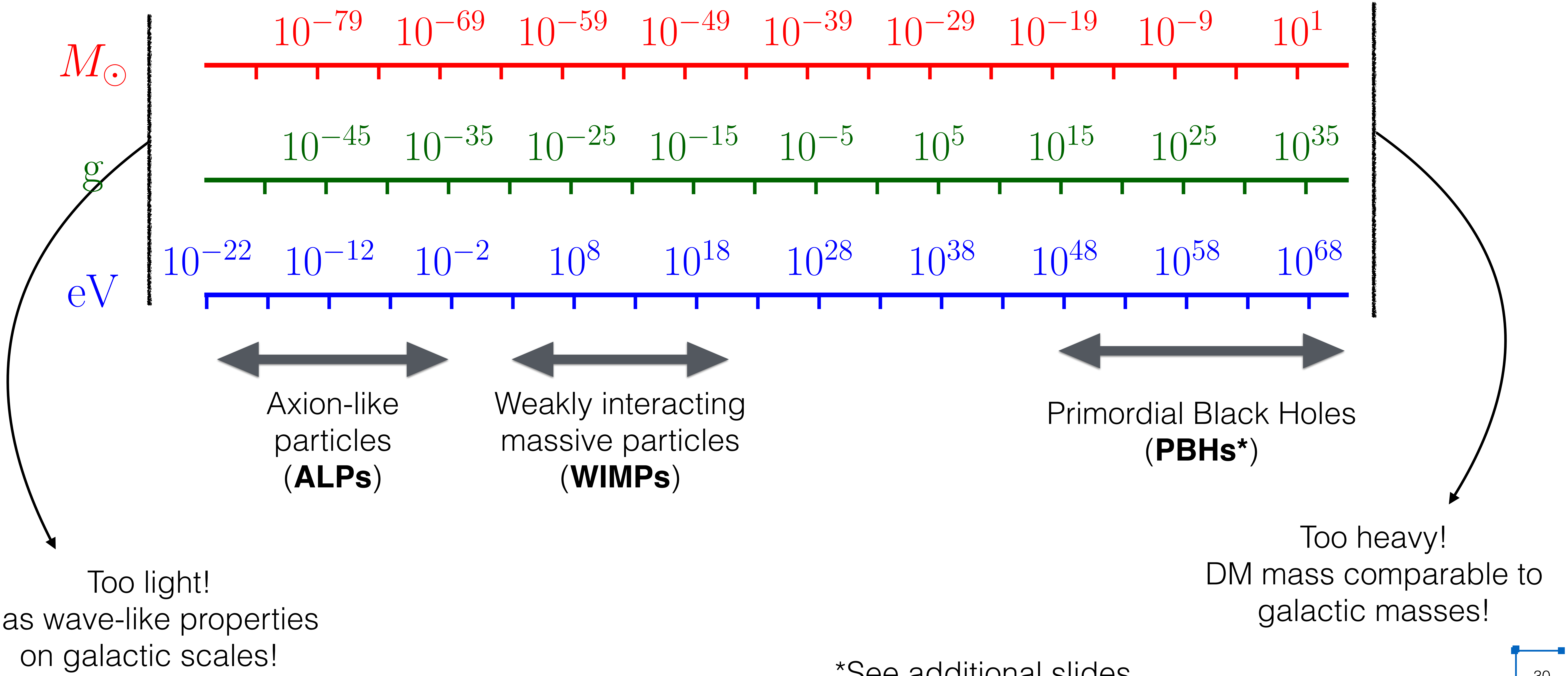
[E.g. 2202.08274]

Credit: Ciaran O'Hare, AxionLimits

Dark Matter properties

Dark Matter must be:

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



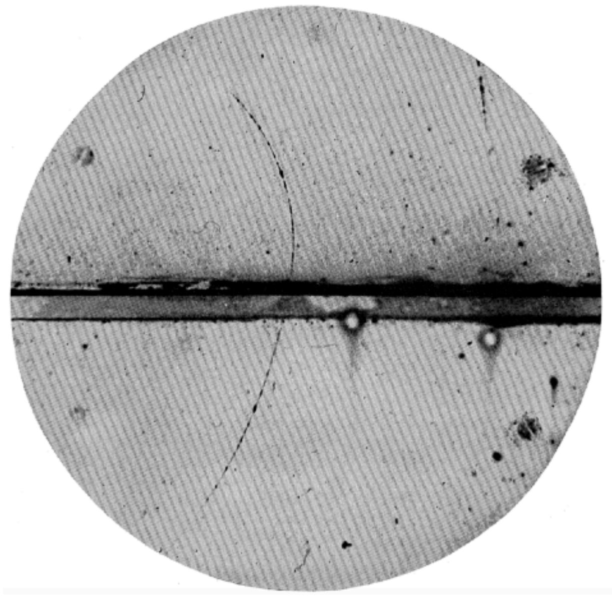
*See additional slides…

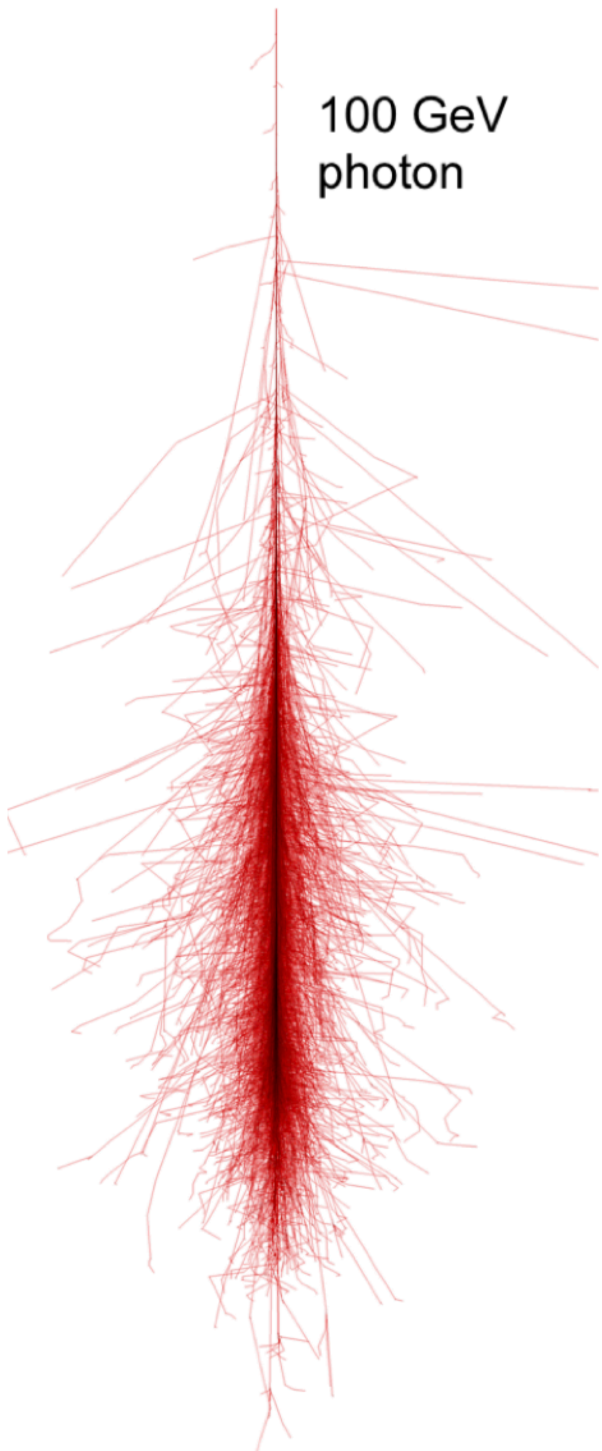

The Sun
Supernovae
Credit: NASA/CXC/SAO
Quasars/AGN
Credit: ESO/M. Kornmesser
Charged Cosmic Rays
$e^{\pm}, p^{\pm}, \ldots$
Dark Matter
χ
Gamma rays γ
Gravitational Waves
$h_{\mu\nu}$
ν
Neutrinos
????
Pulsars
Credit: Kevin Gill / Flickr
BH/NS Mergers
Credit: SXS Lensing

Timeline

1912: Hess discovers cosmic rays

1933: Anderson discovers the positron in Cosmic Ray tracks





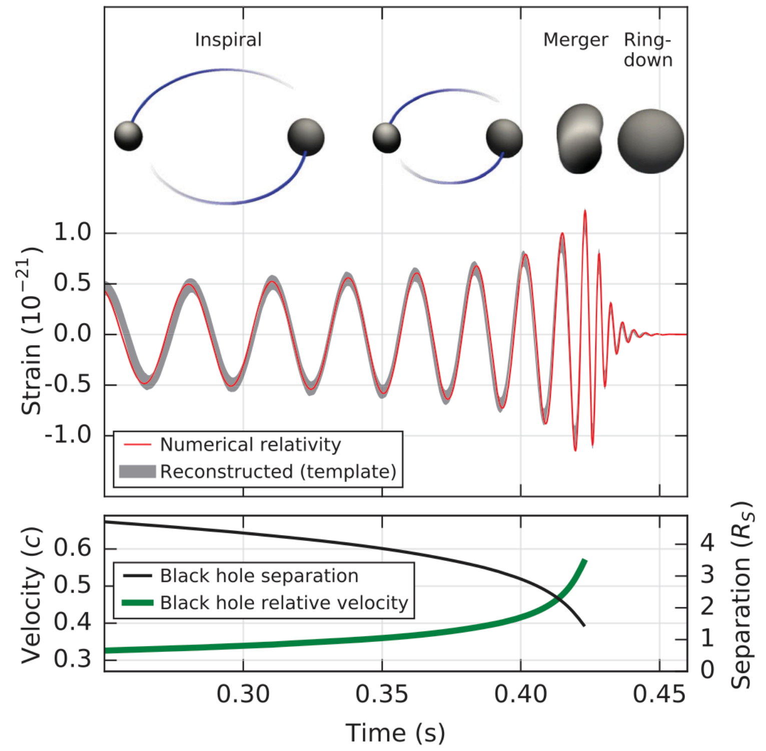
1939: Auger and collaborators demonstrate the existence of Cosmic Ray *air showers*

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

1970s: The “Dark Matter” paradigm coalesces

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

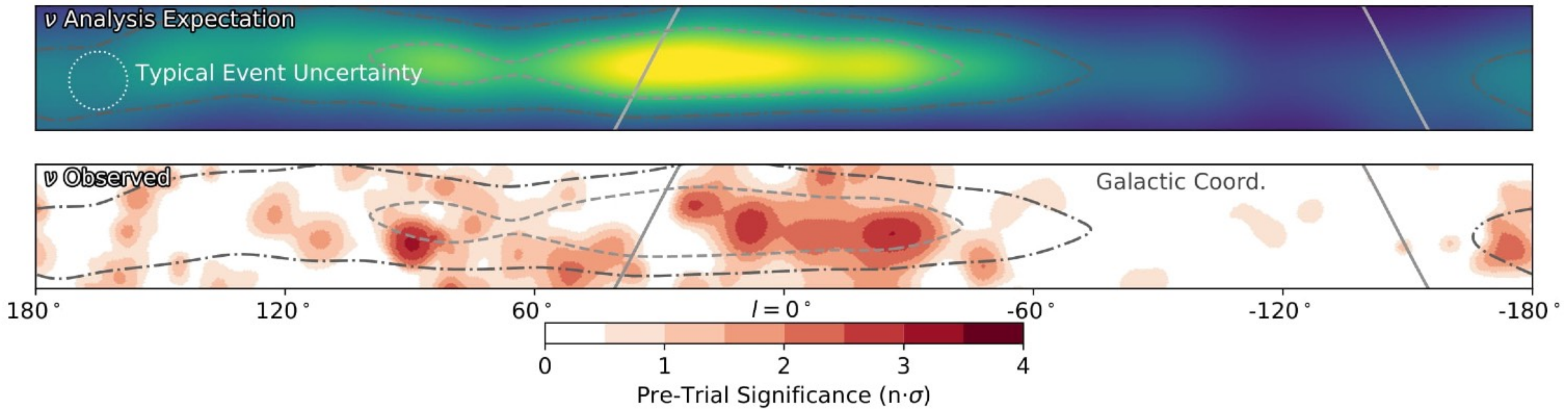
2015: GW150914 - First direct observation of GWs from Black Hole Binary Mergers



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

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

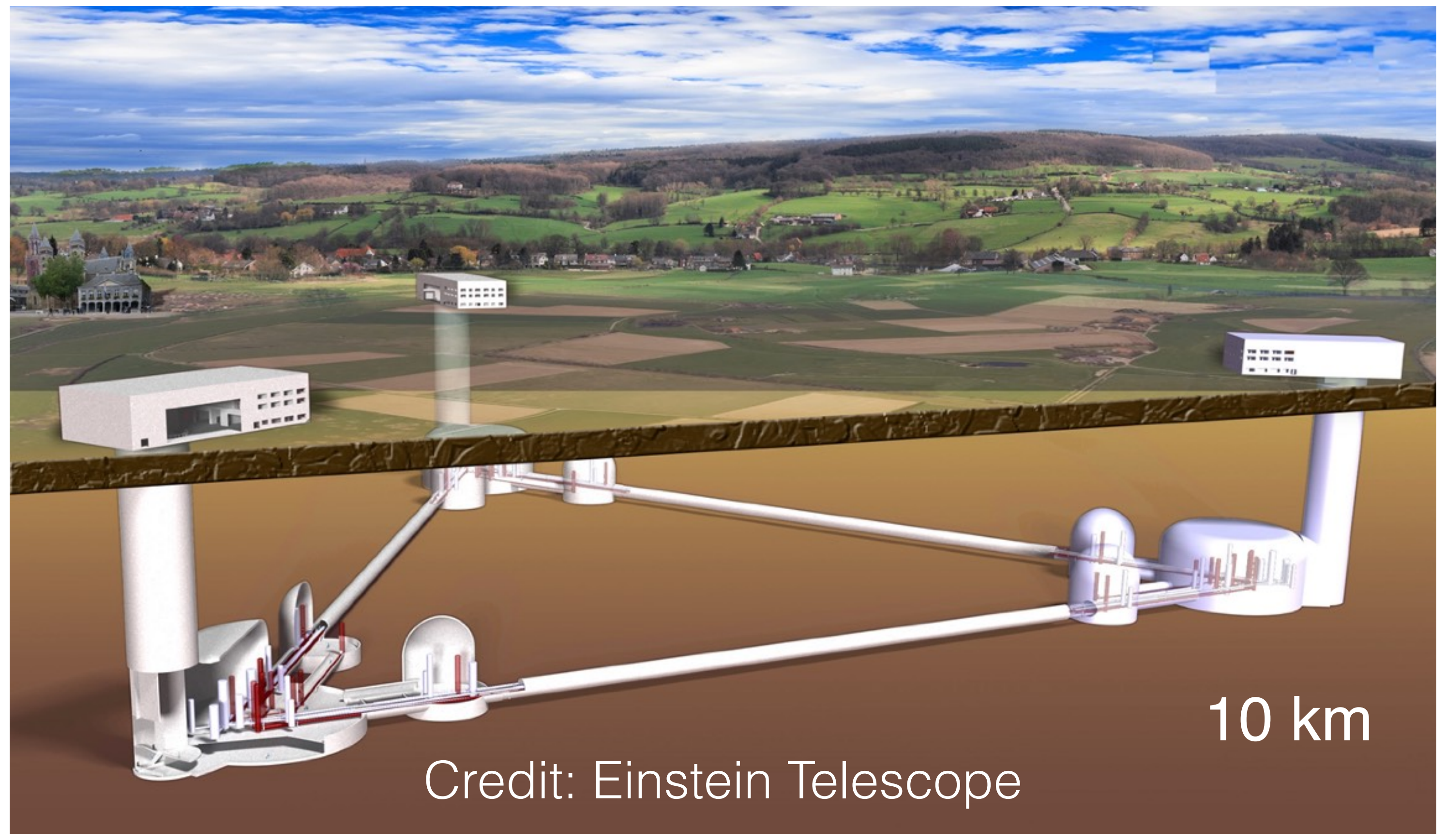
2023: Detection of Milky Way in Neutrinos by IceCube



2023: NANOgrav & IPTA detect nHz Gravitational Waves

New Views into the Universe

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



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

1902.09485

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

http://www.xenon1t.org, 2303.14729

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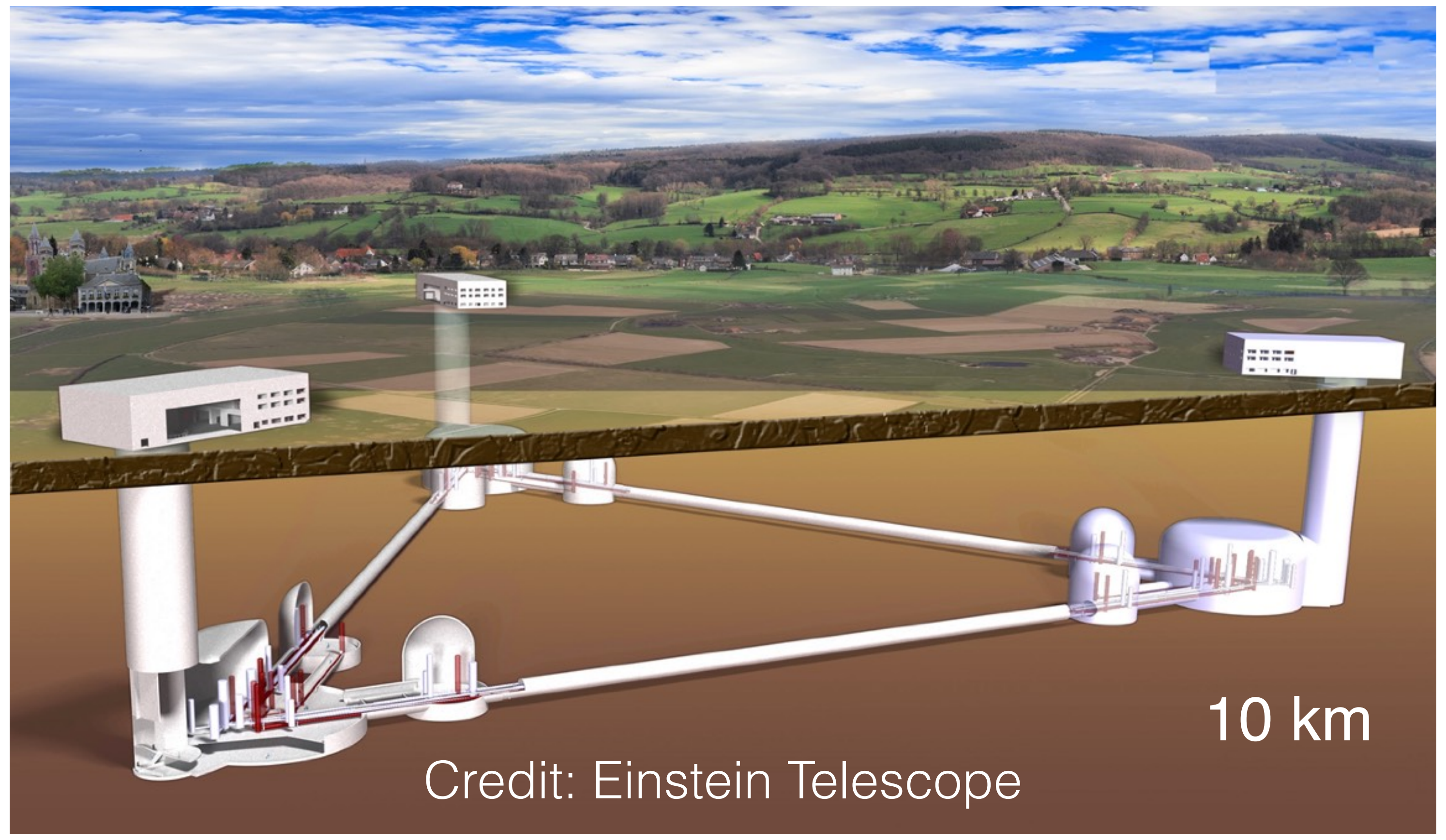

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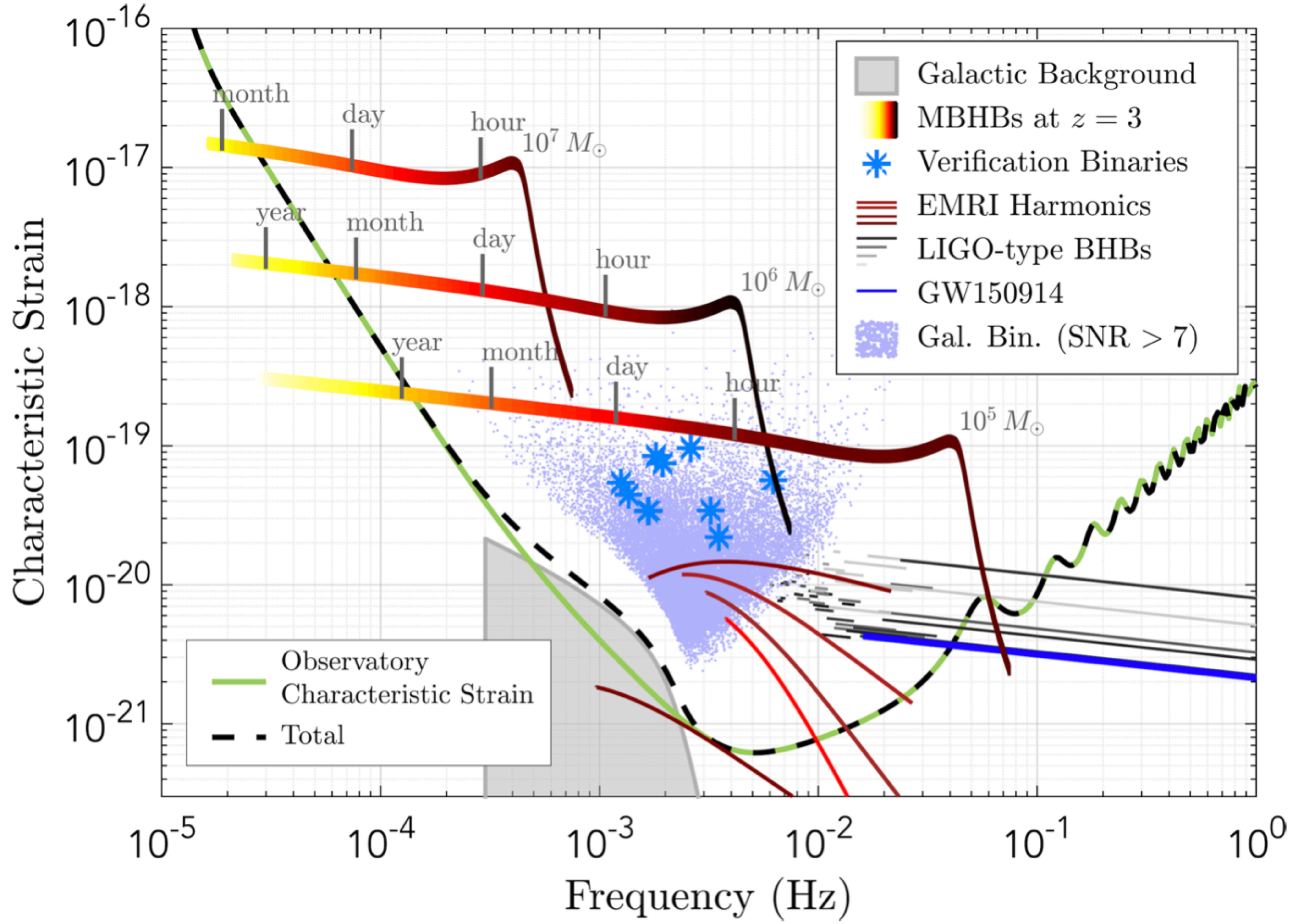
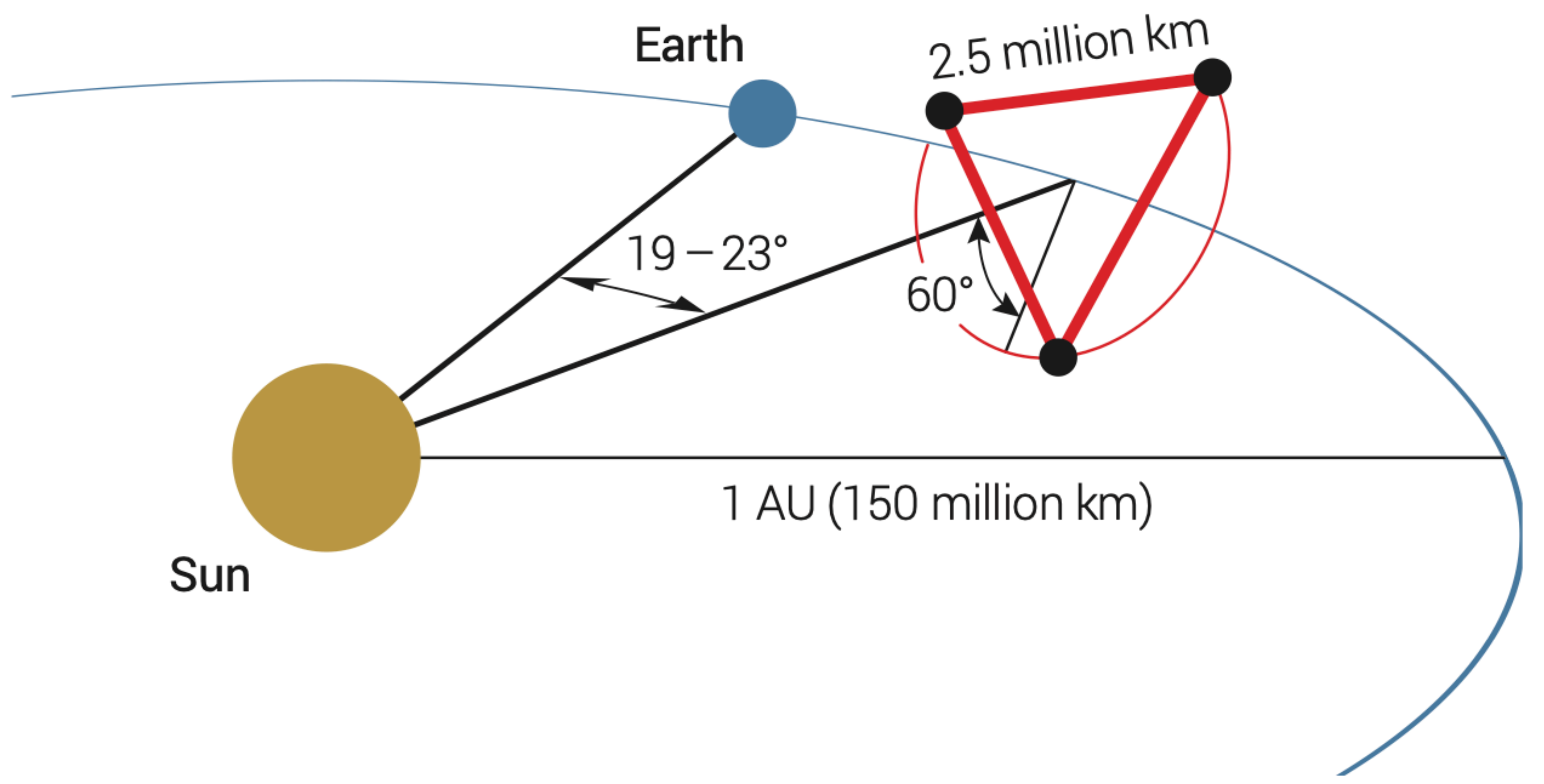
…looking forward to many more unexpected discoveries!

Additional Slides

LISA - GWs in space!

Laser Interferometer Space Antenna
(Planned for the 2030s)



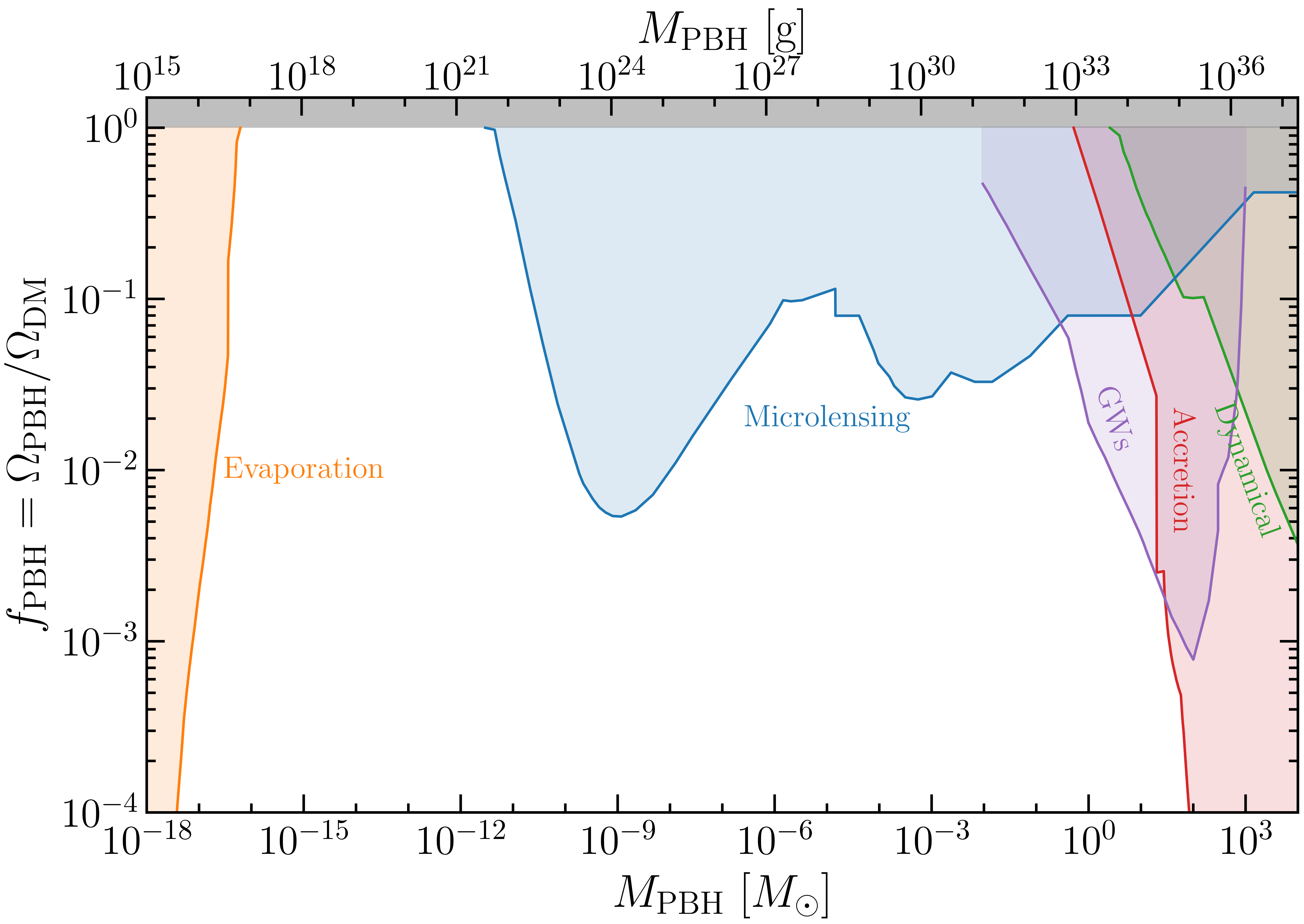


1907.06482

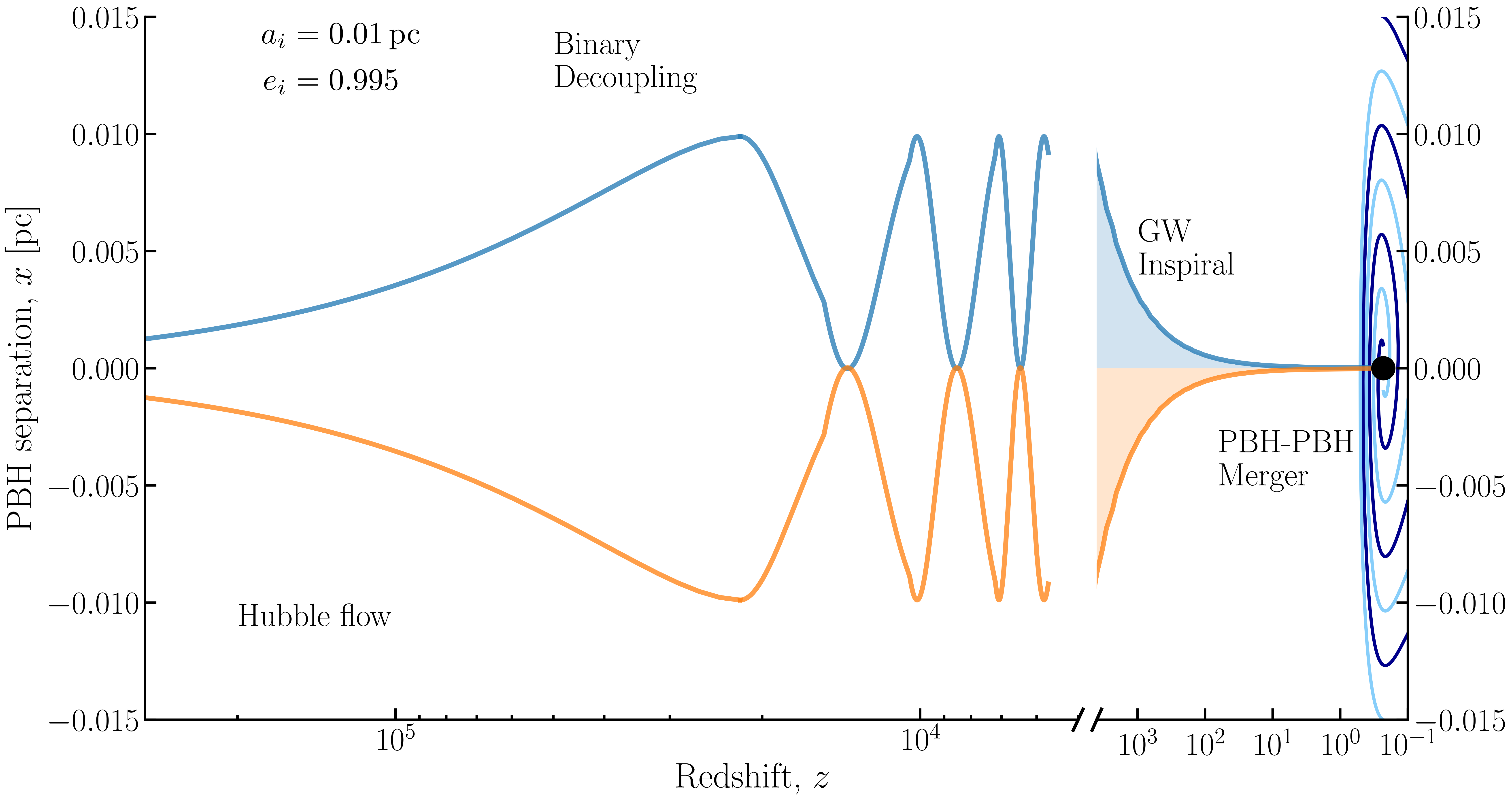
Primordial Black Holes

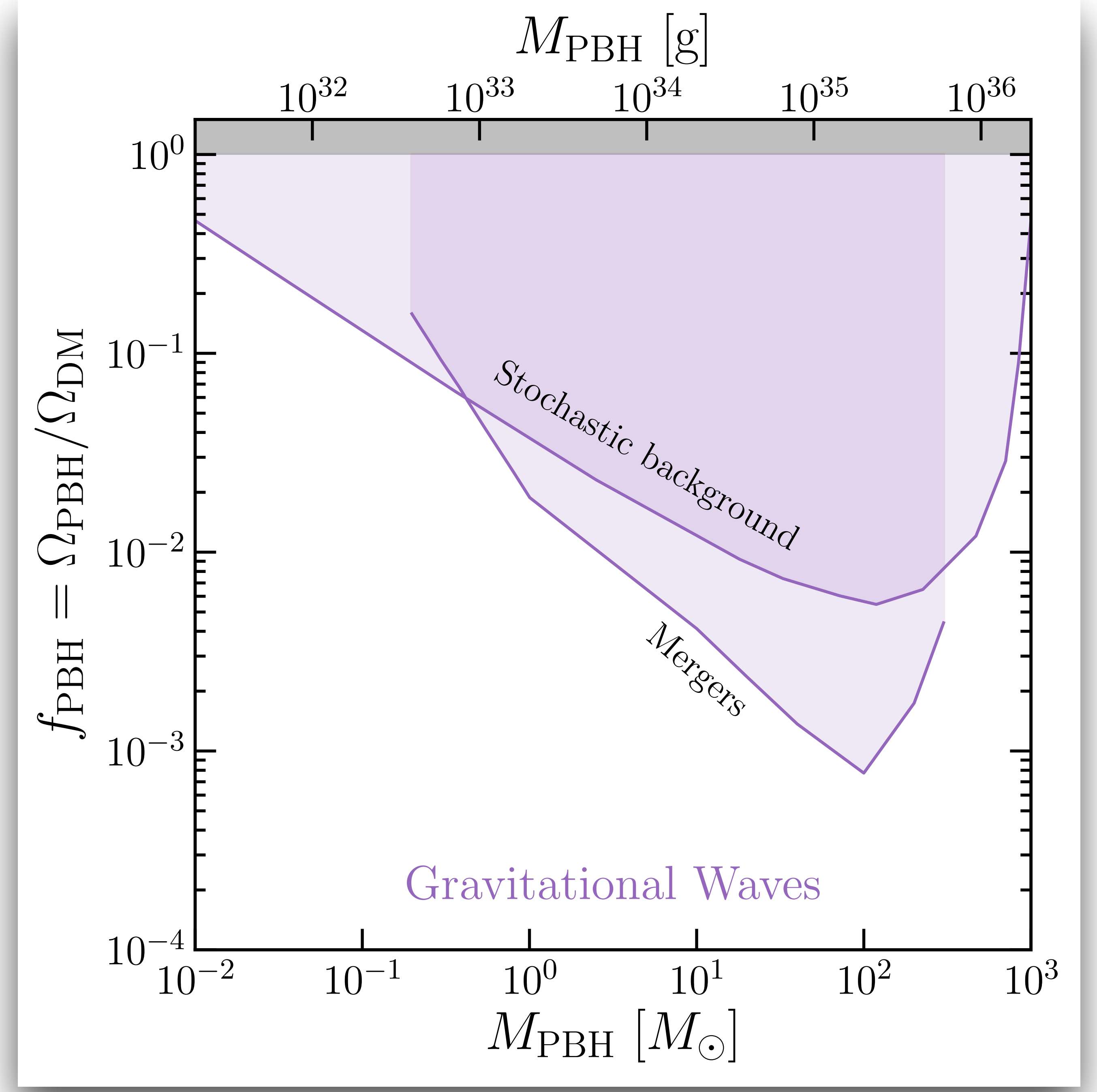
[2007.10722](2007.10722)

Bounds online

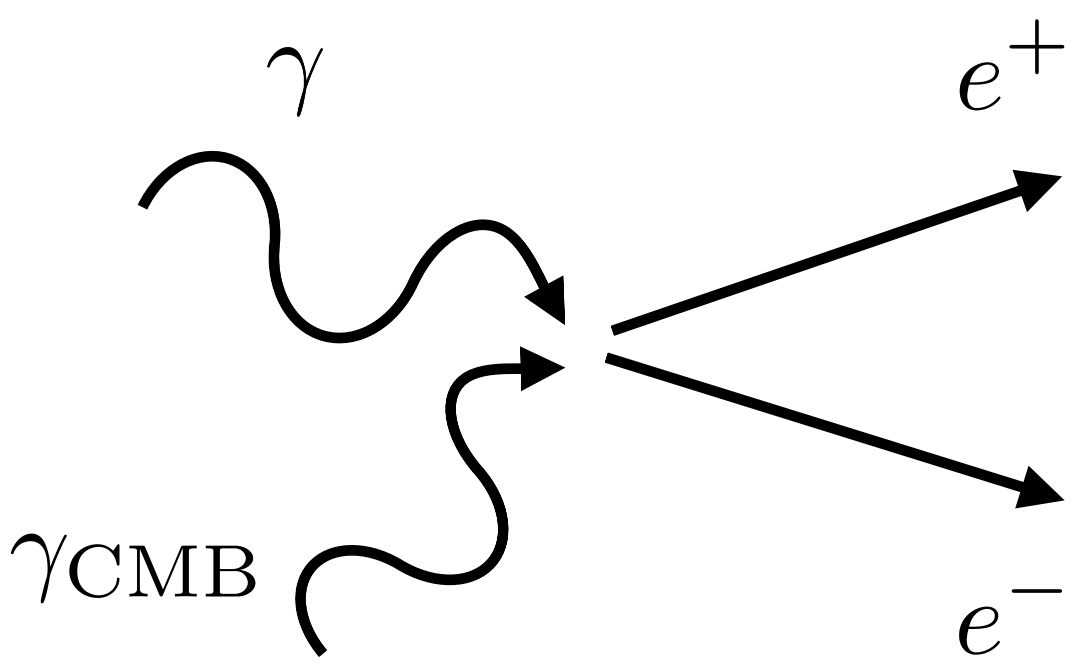


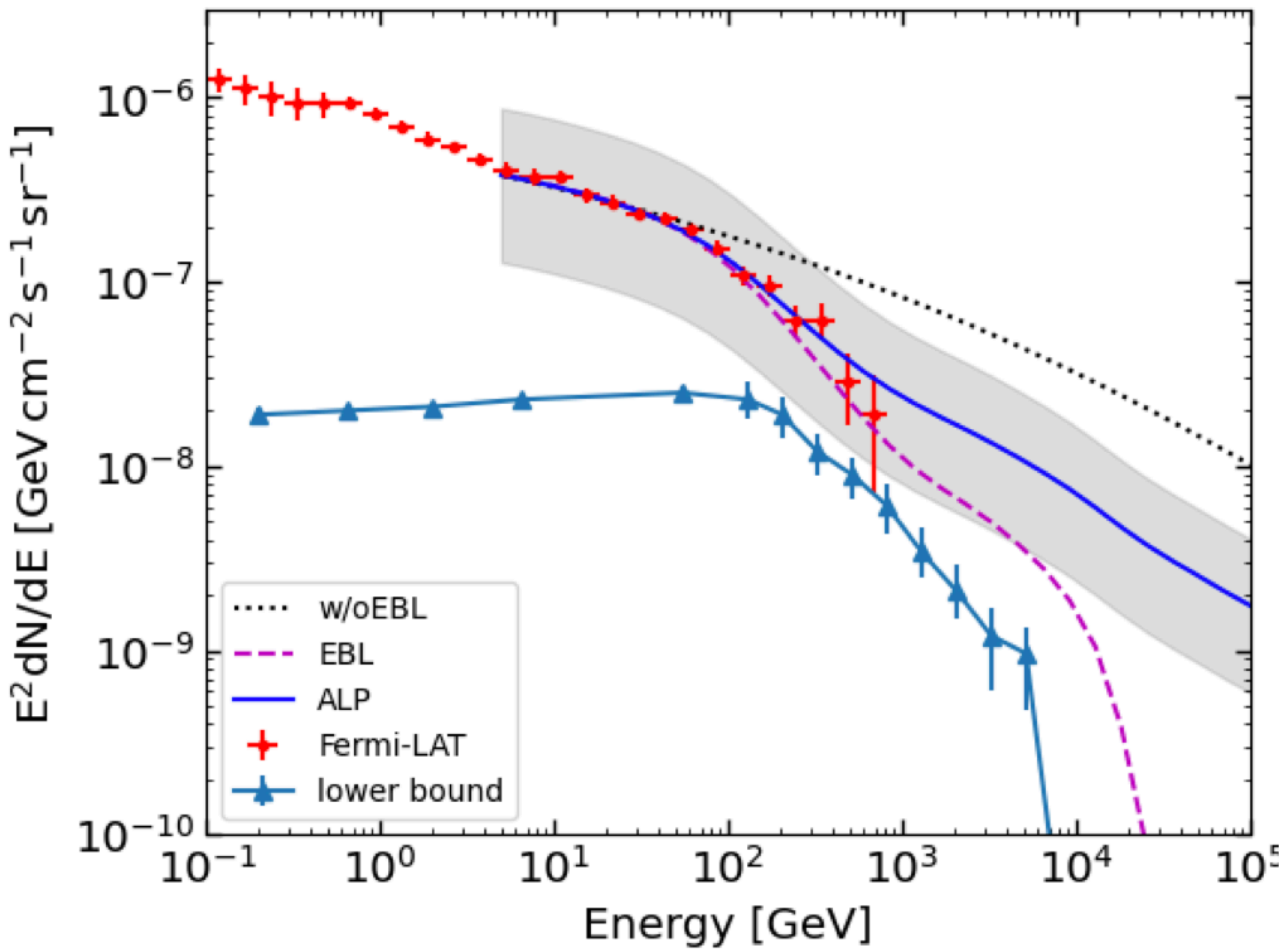
PBHs and Gravitational Waves





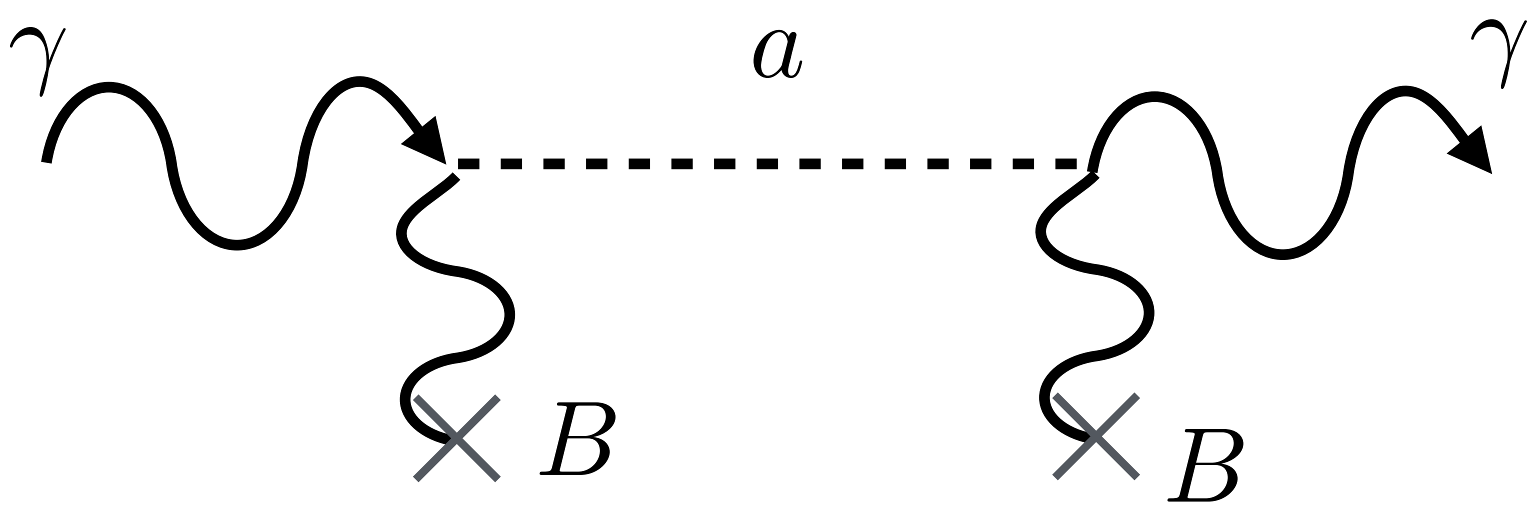
Gamma-ray transparency and axions

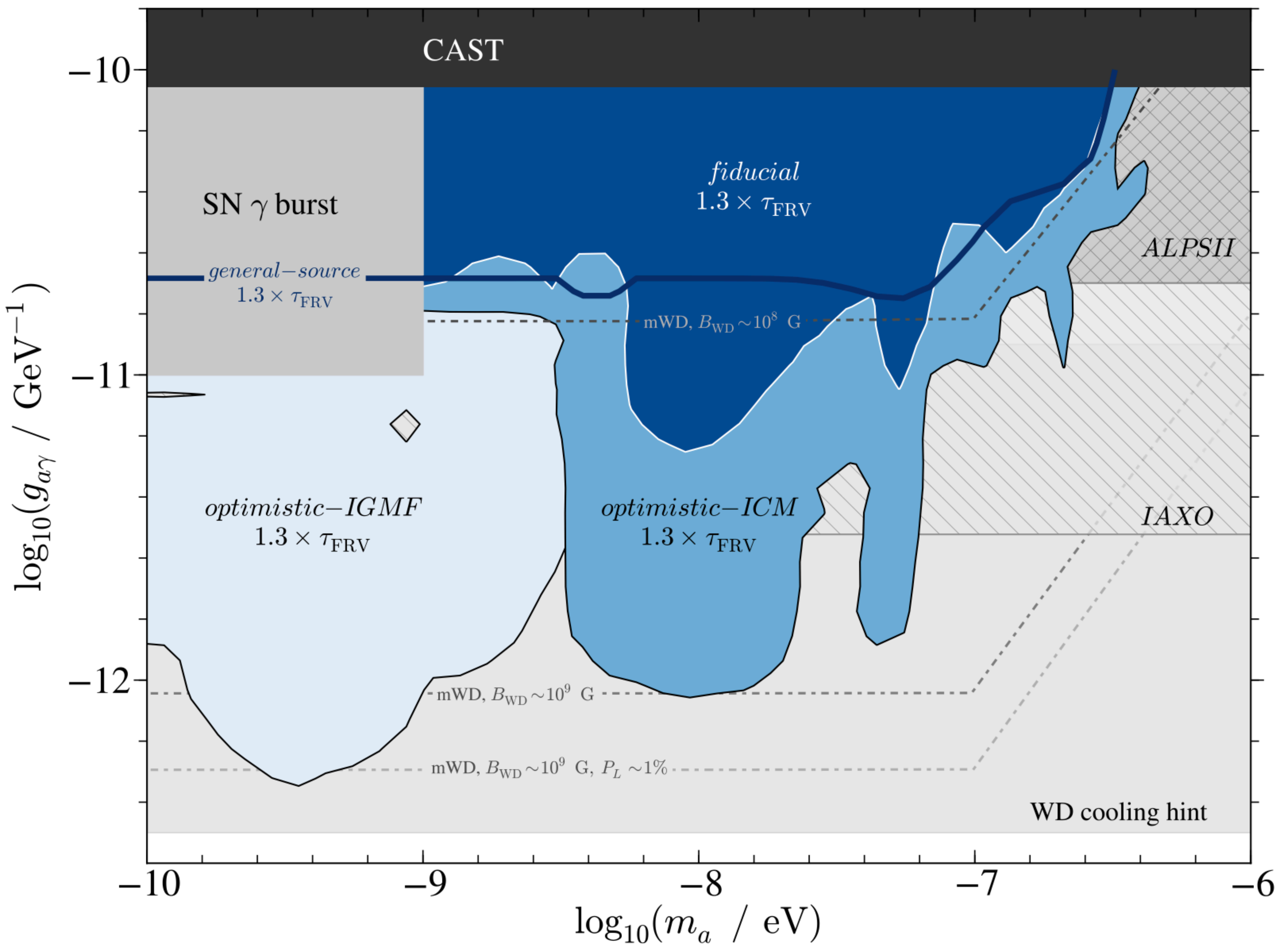




2012.15513

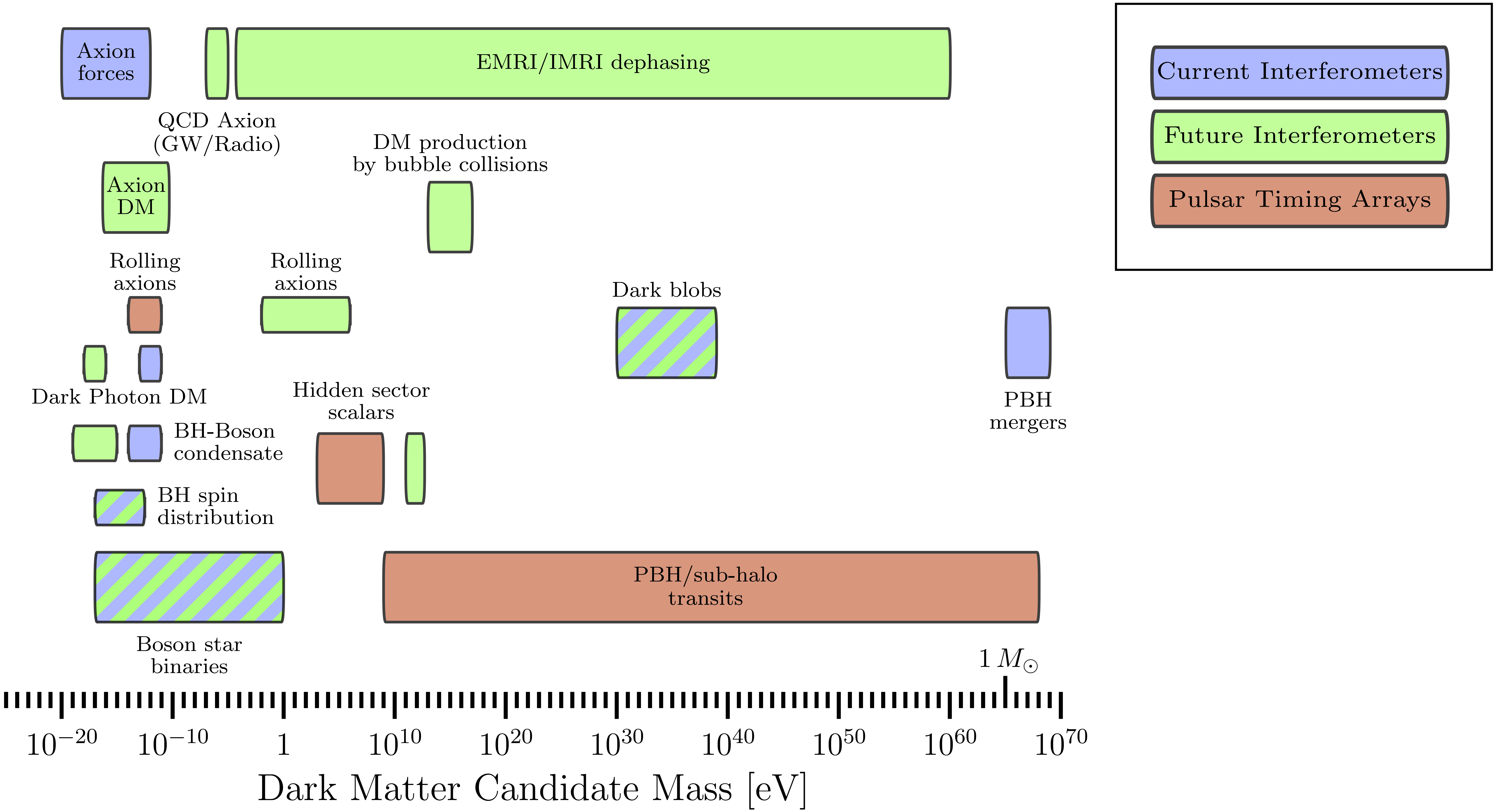
Axion-like particle:





1302.1208

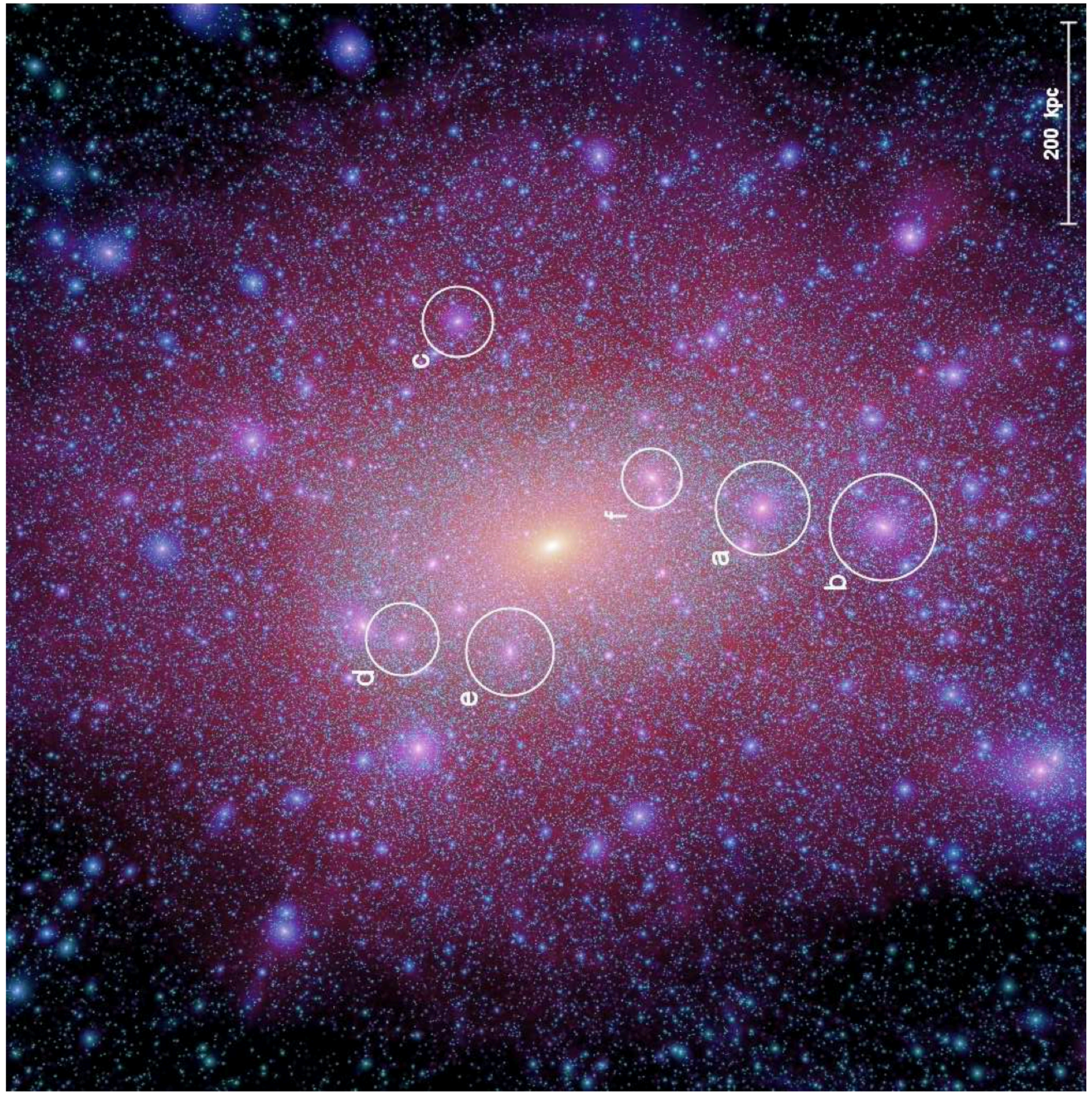
Gravitational Wave probes of DM



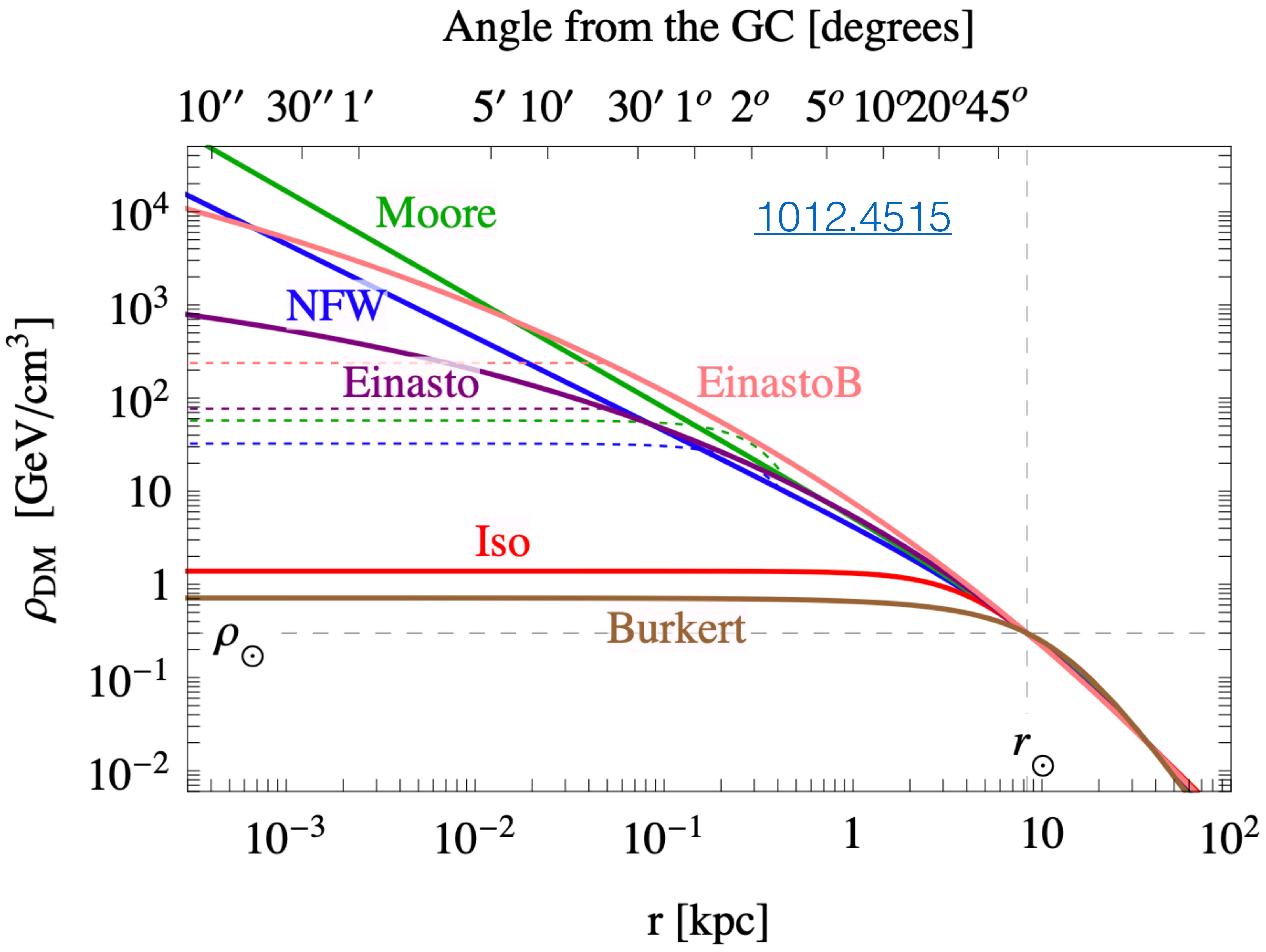
For more information about probing Dark Matter with Gravitational Waves, see 1907.10610

Dark Matter in Galaxies (2)

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



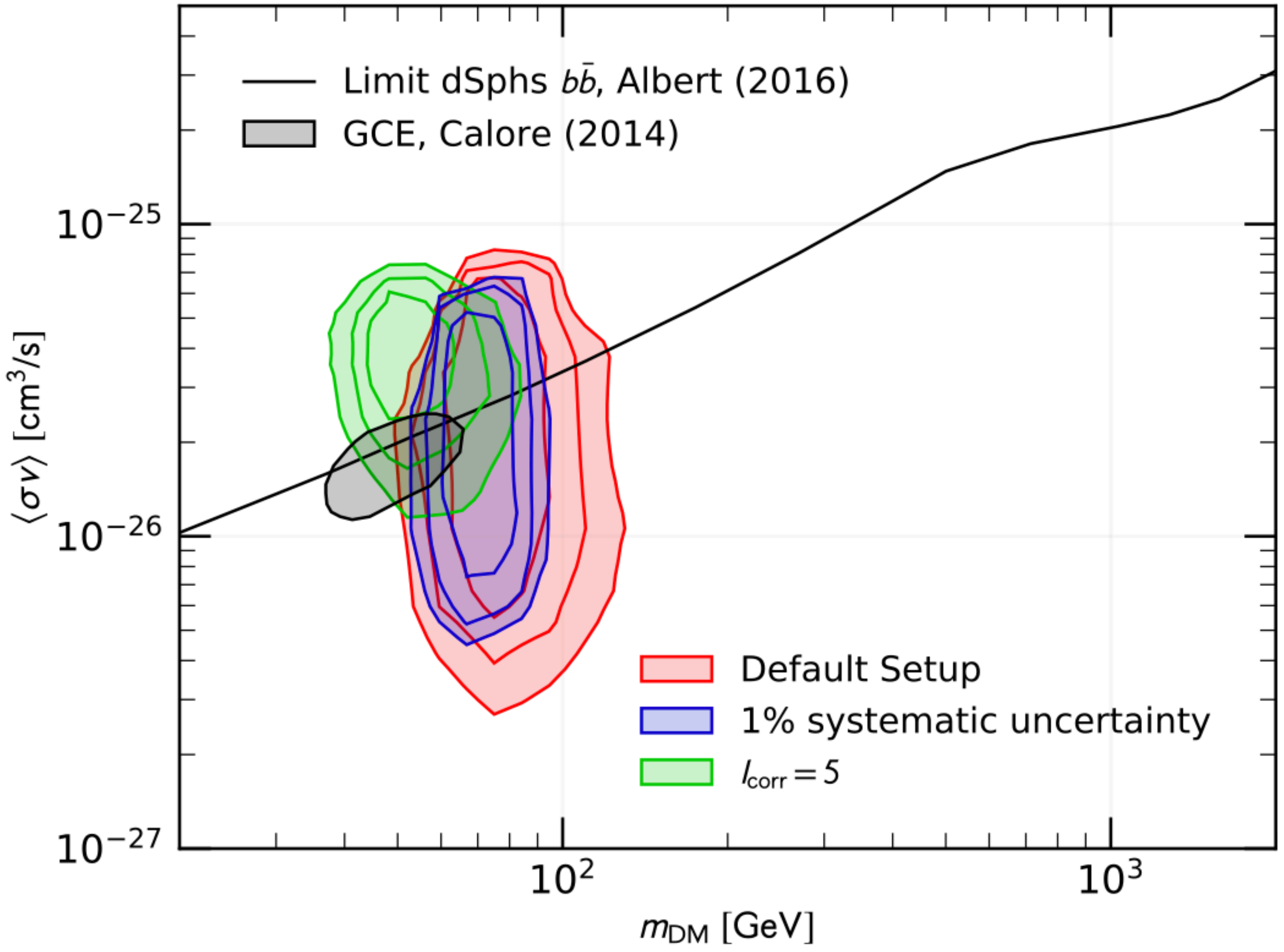
Aquarius simulation - 0809.0898



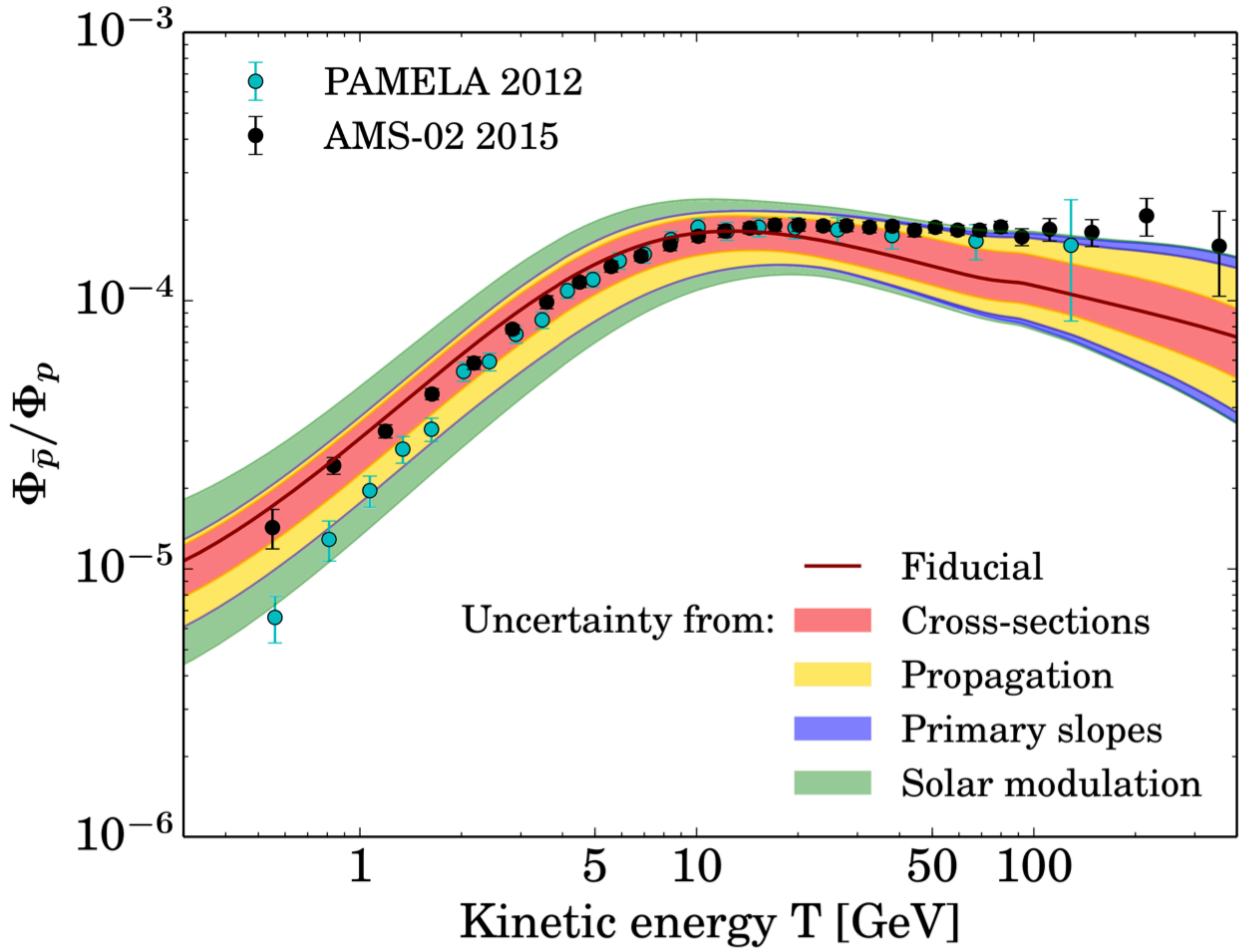
DM density at Earth:

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

Anti-proton excess (2)



1903.01472



1504.04276

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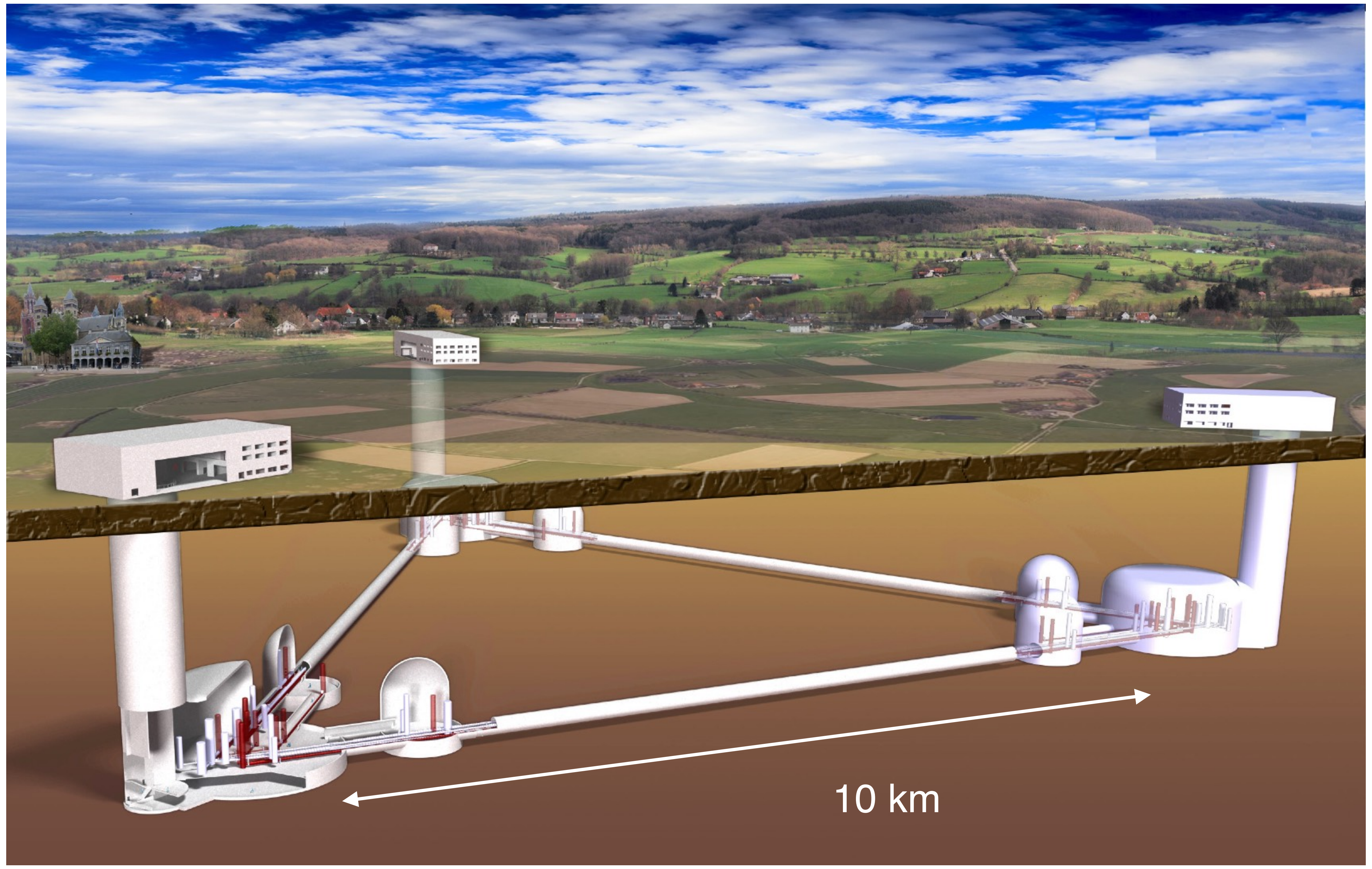
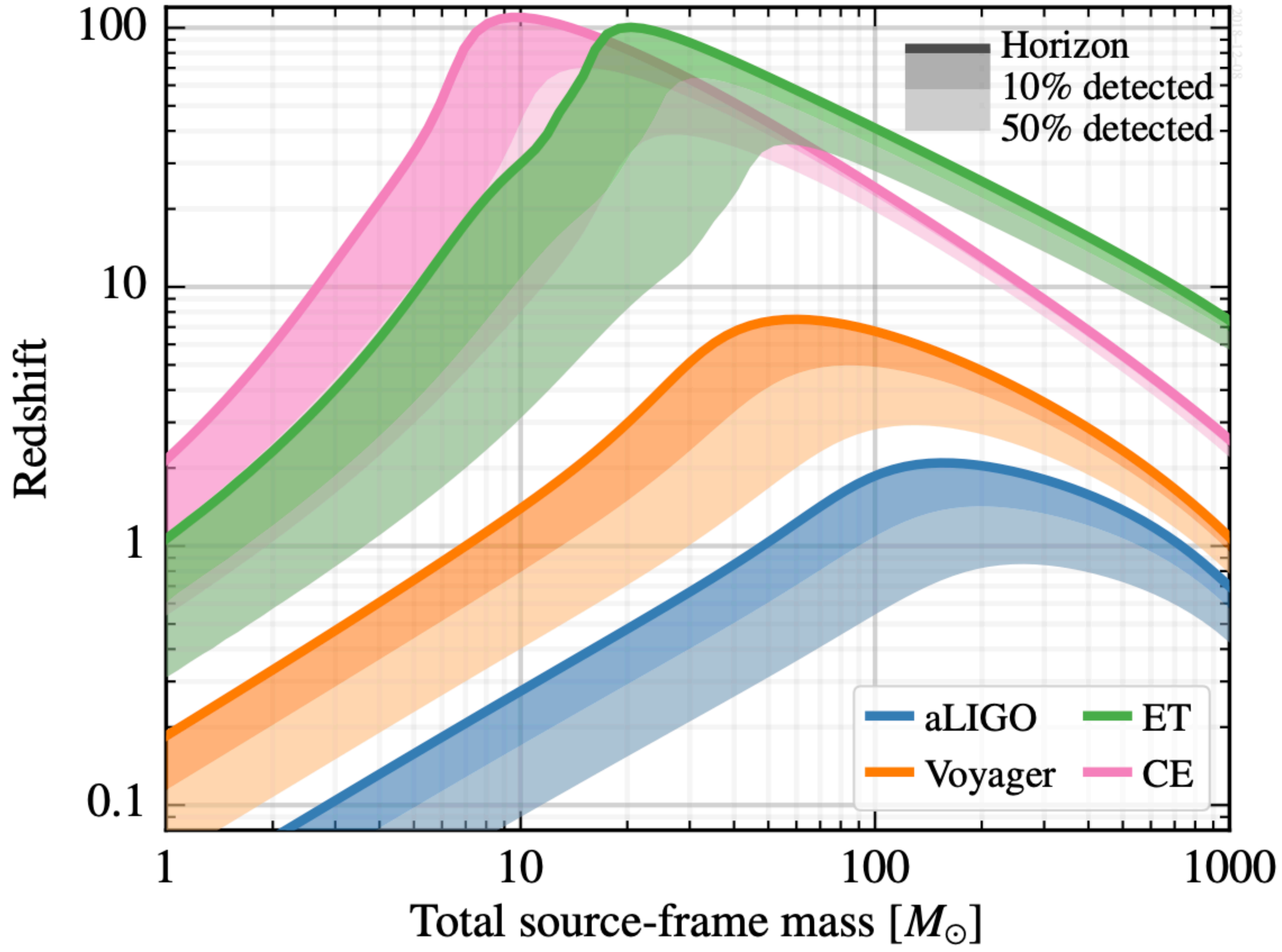
But modeling gamma-ray and cosmic-ray backgrounds is **hard**.

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).