Multi-messenger Cosmology

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UK Theory 2021 Durham

King's College London
University of London
GRChombo
Leverhulme Trust
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A slightly fictionalized account…

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Great! Can you talk about "Multi-messenger Cosmology"?

Absolutely!

Crap, what the heck is Multi-messenger Cosmology?

Outline

- **Who are the Messengers : Multi-messenger Astronomy.**
- **Overview of some Multi-messenger Cosmology applications (speaker biased)**
- **Axion Dark Matter cosmology : the next Multi-messenger cosmology frontier?**
- **Final Thoughts**

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Apologies in advance : if I miss or misquote your work, please let me know!

Who are the Messengers?

Classify by association with the 4 fundamental forces.

- Electromagnetic force : Photons, multi wavelength astronomy
- Weak Force : neutrinos
- Strong force : cosmic rays (e.g. high energy protons), nuclear physics
- Gravity : gravitational waves

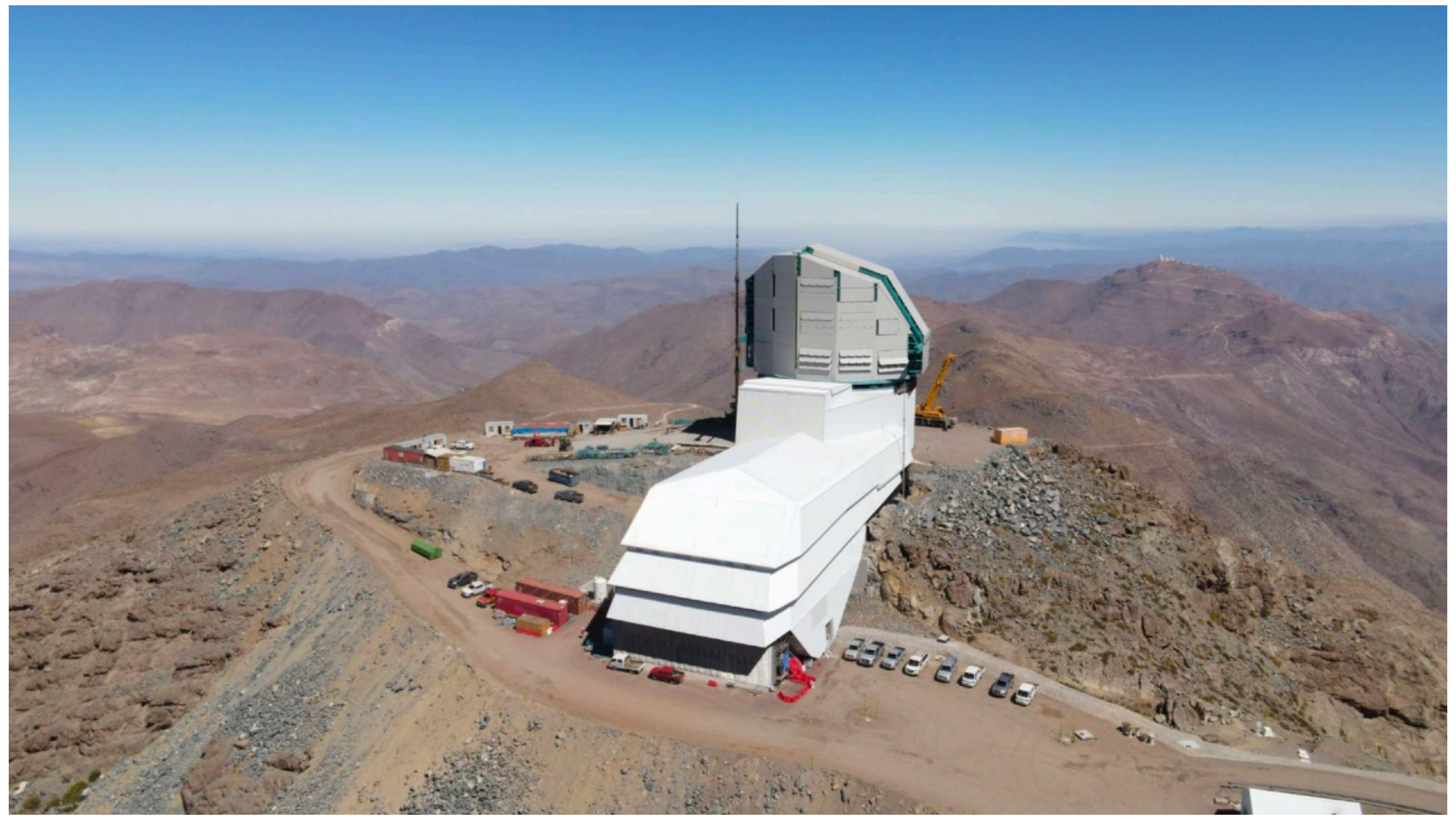
Photons

- Historically the first and “easiest” (our own eyes and optical telescopes).

- Recent advances : multi wavelengths observatories from Radio, X-Rays, gamma rays.

- Into the time-domain : Zwicky Transient Facility (ZTF), Vera Rubin Observatory (VRO)

Radio (Jansky VLA)



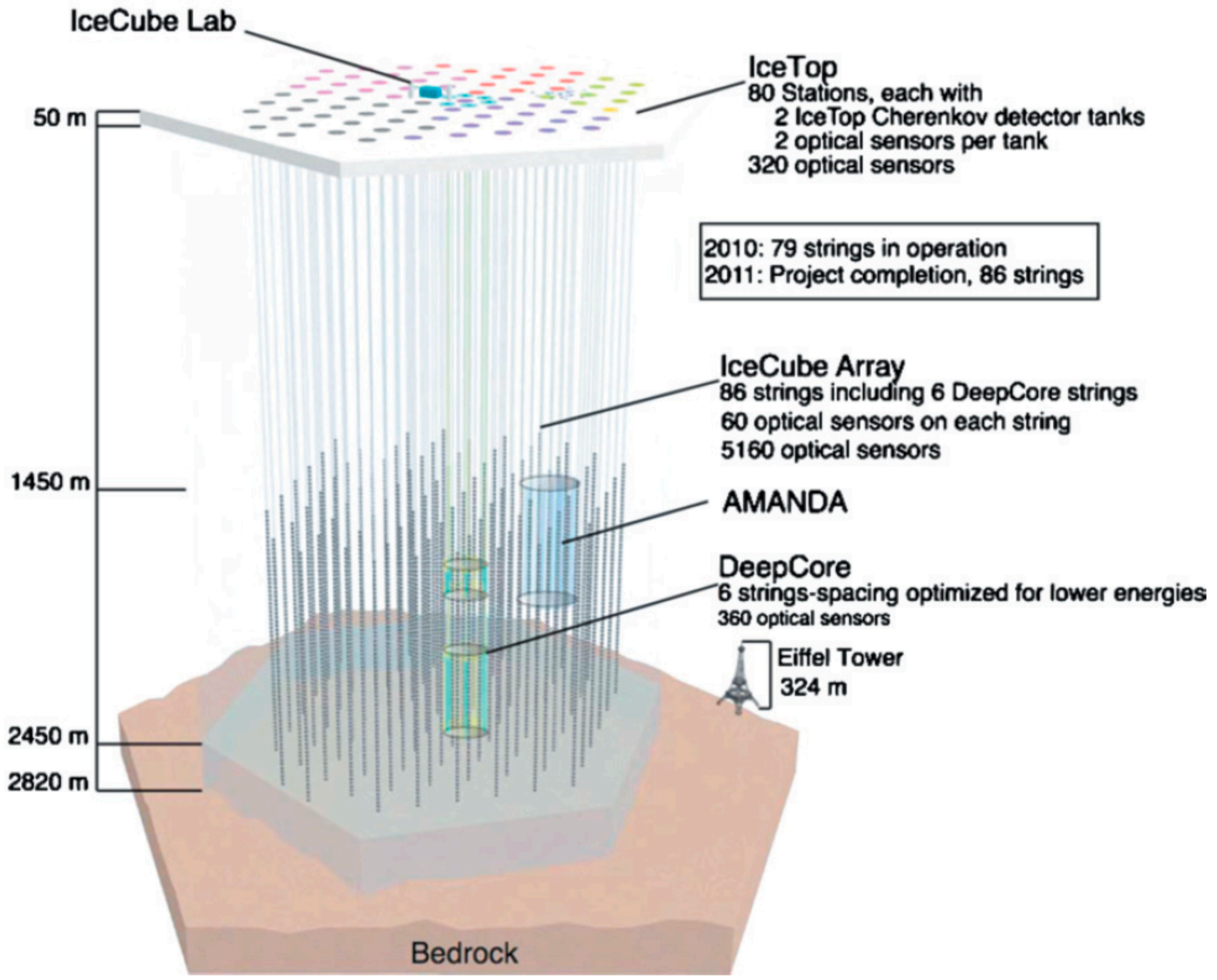
Optical Transients (Rubin Obs)

X-rays (Einstein Probe)

Neutrinos

- Weak couplings => produced in thermal abundance in high lepton/baryon number environments. Can also be produced in non-thermal processes (e.g. high energy scatterings).

- Many production mechanisms: p-p scattering, leptogenesis, beta decay etc.



IceCube

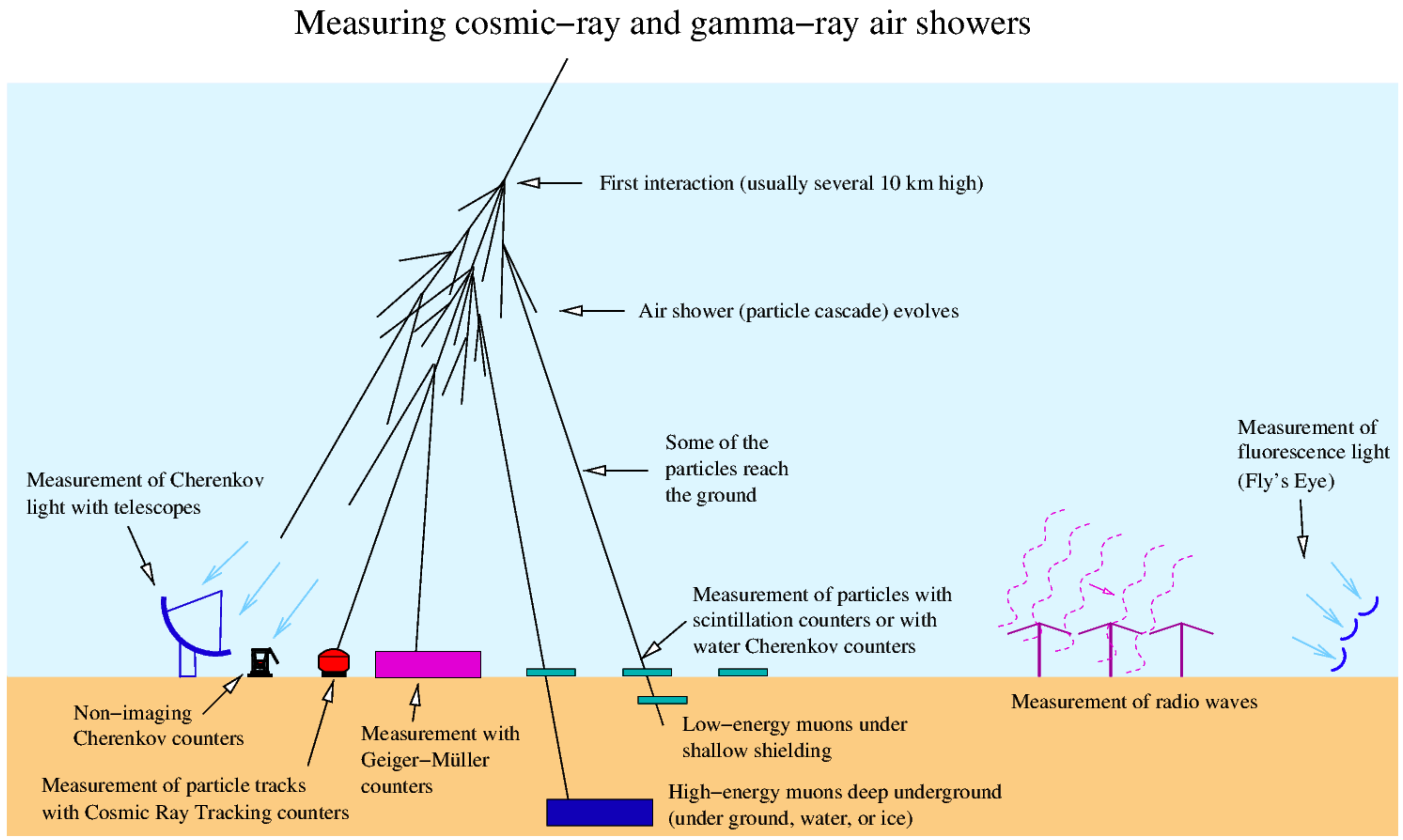
- Detected diffused neutrino background $E_\nu^2 \Phi_\nu \sim 3 \times 10^{-8} \mathrm{GeV\ cm^{-2} s^{-1} sr^{-1}}$

- Weak couplings => Need huge detectors!

Cosmic Rays

- High energy (charged) protons/nuclei — collisions with atmosphere generate air showers.

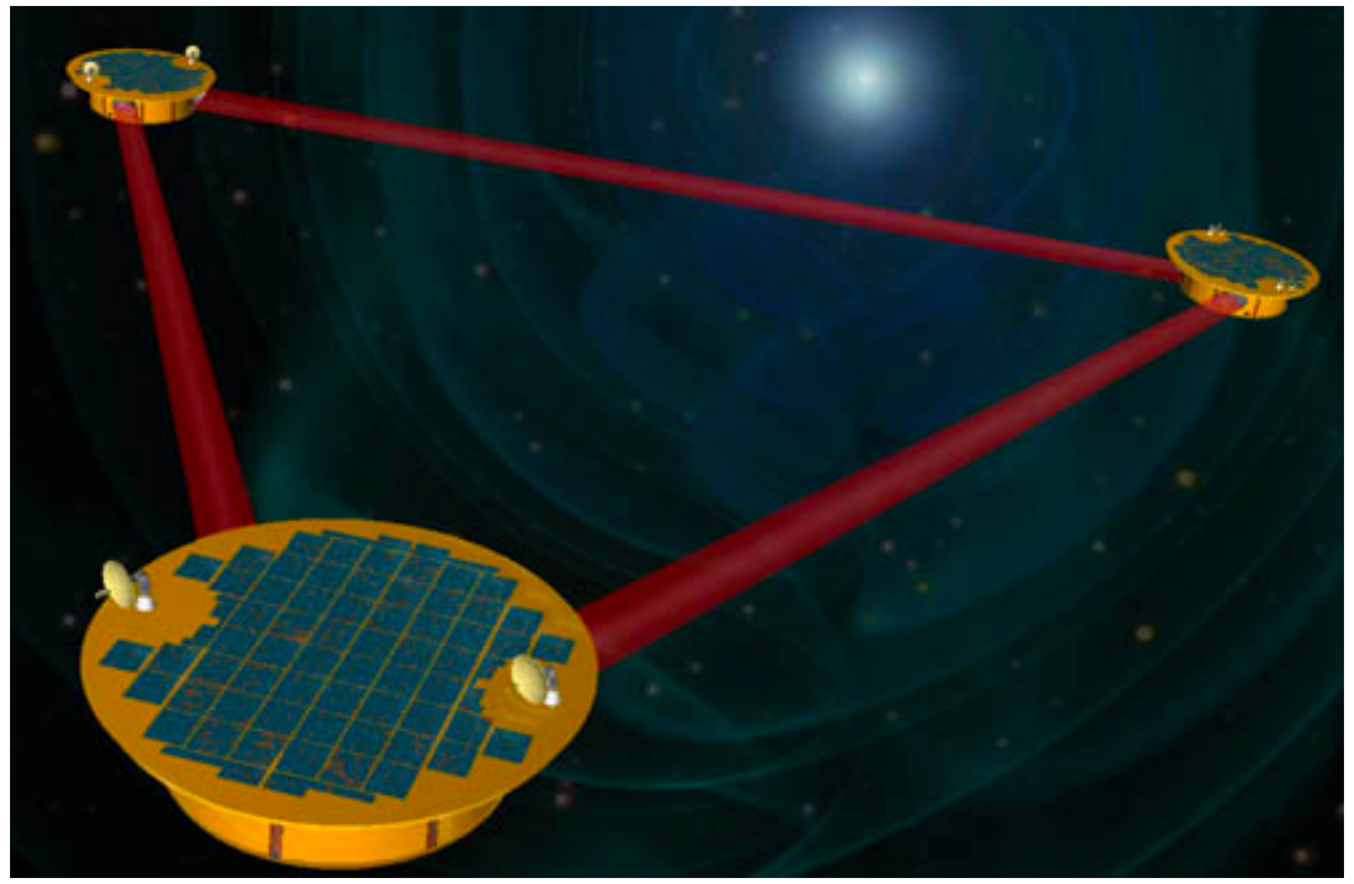
- GZK cut-off energy 5×10^{19} eV for intergalactic protons.



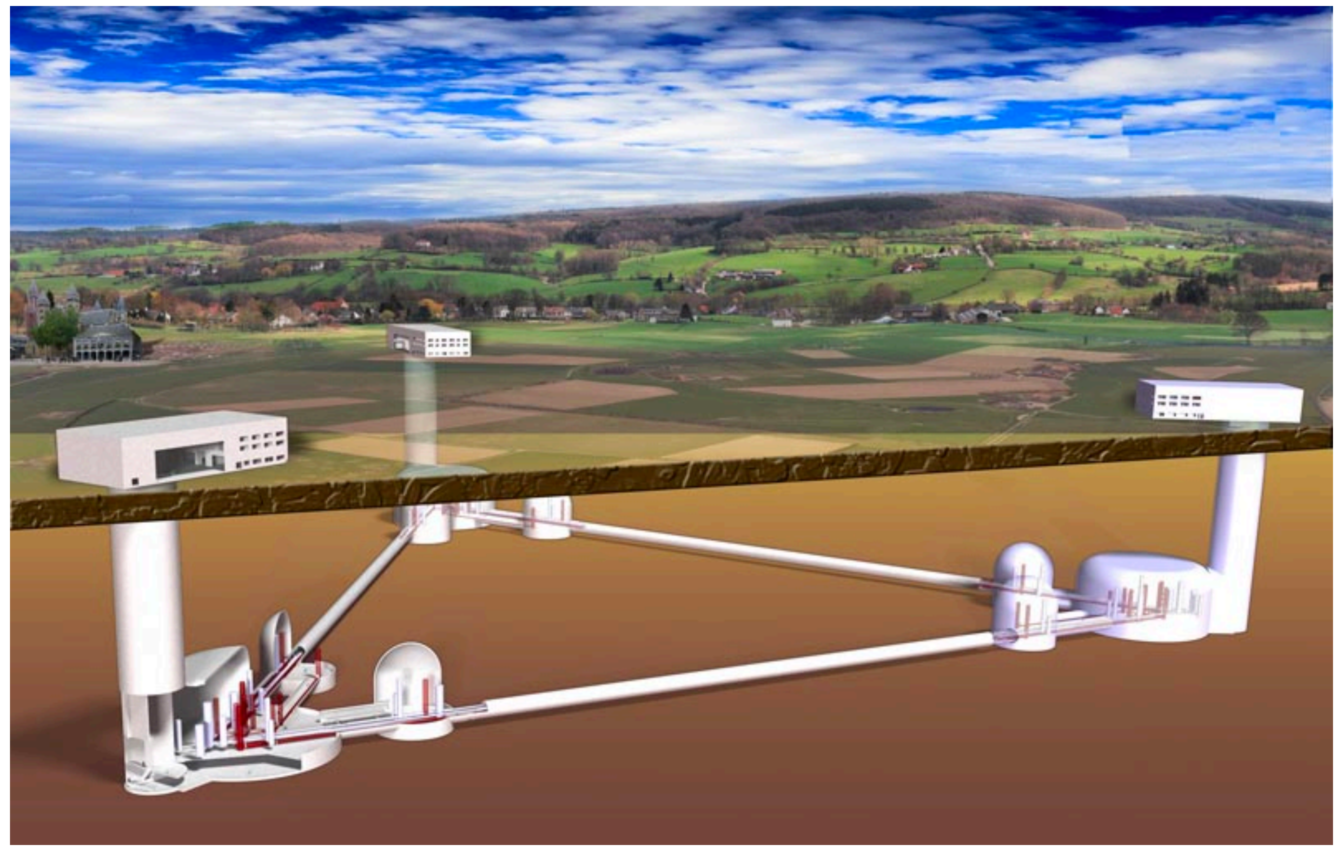
Gravitational Waves

- Interferometers to look for characteristic deformation of spacetime caused by a passing GW.
- Spacetime is very rigid : need very energetic events to generate detectable signals.

LIGO



LISA

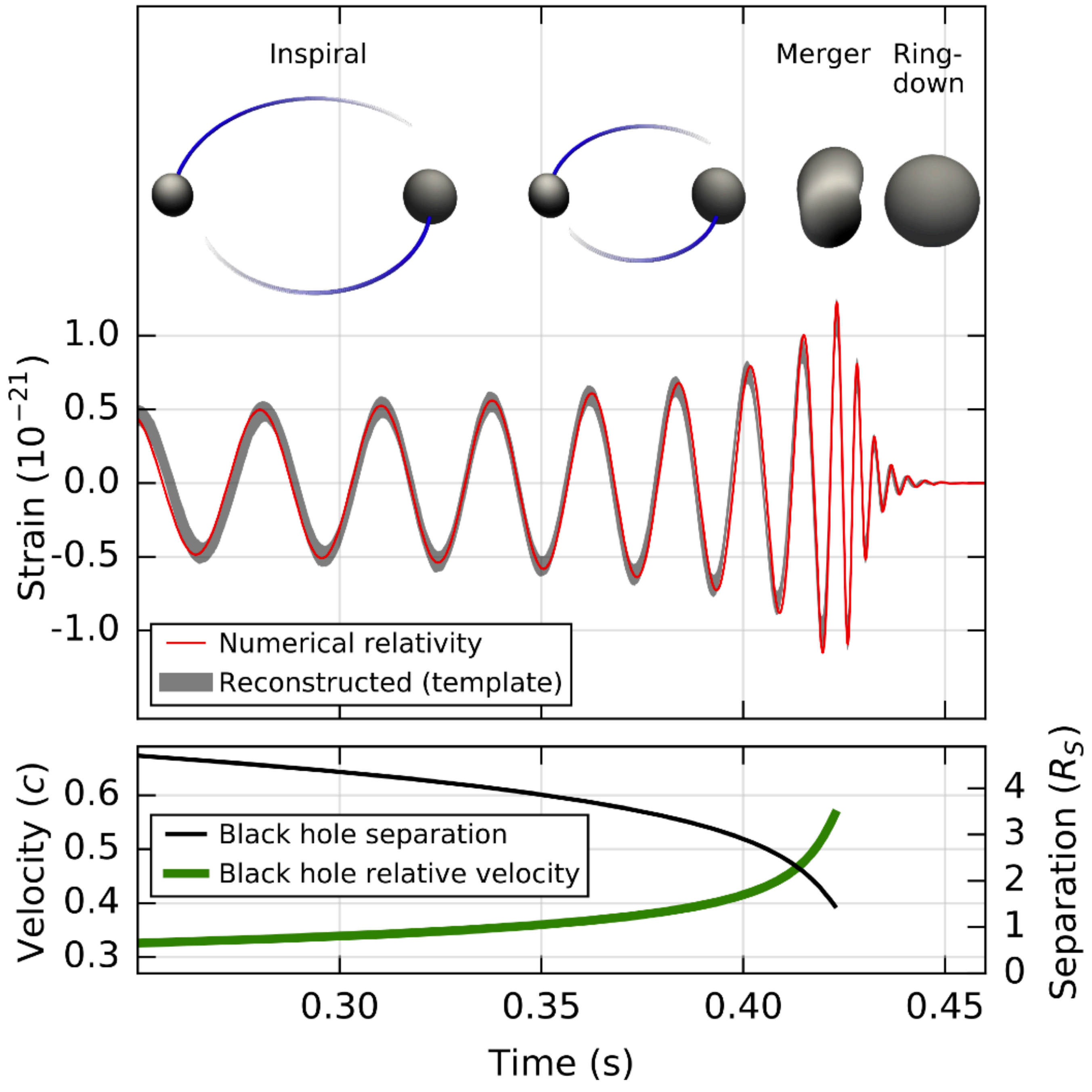


Einstein Telescope

Gravitational Waves

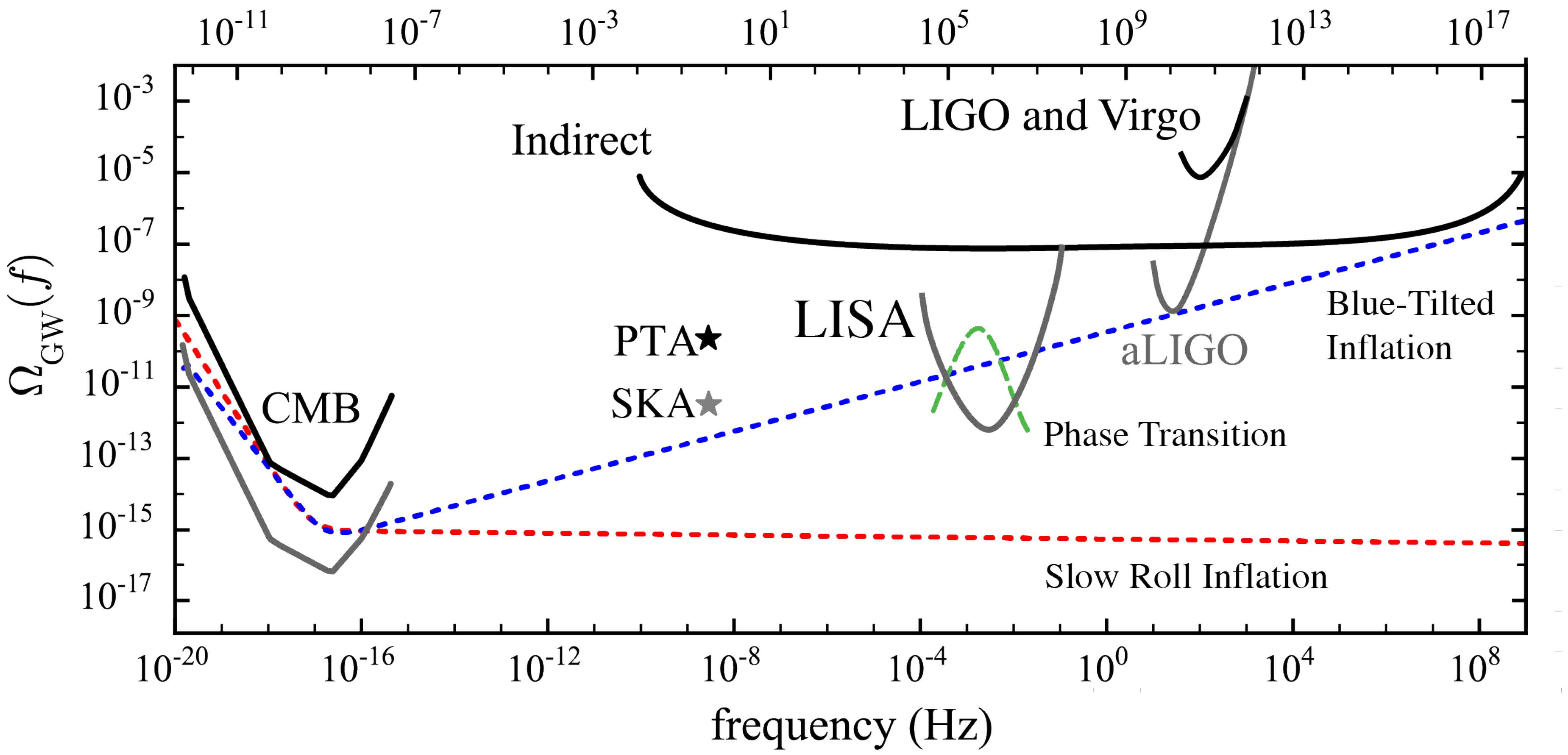
- First detected in 2015 (GW150914) binary black hole merger. Latest count : 90 events including 2 confirmed NS-BH mergers.

- No detection of stochastic (i.e. unresolved) background signal yet.



Coherent source event

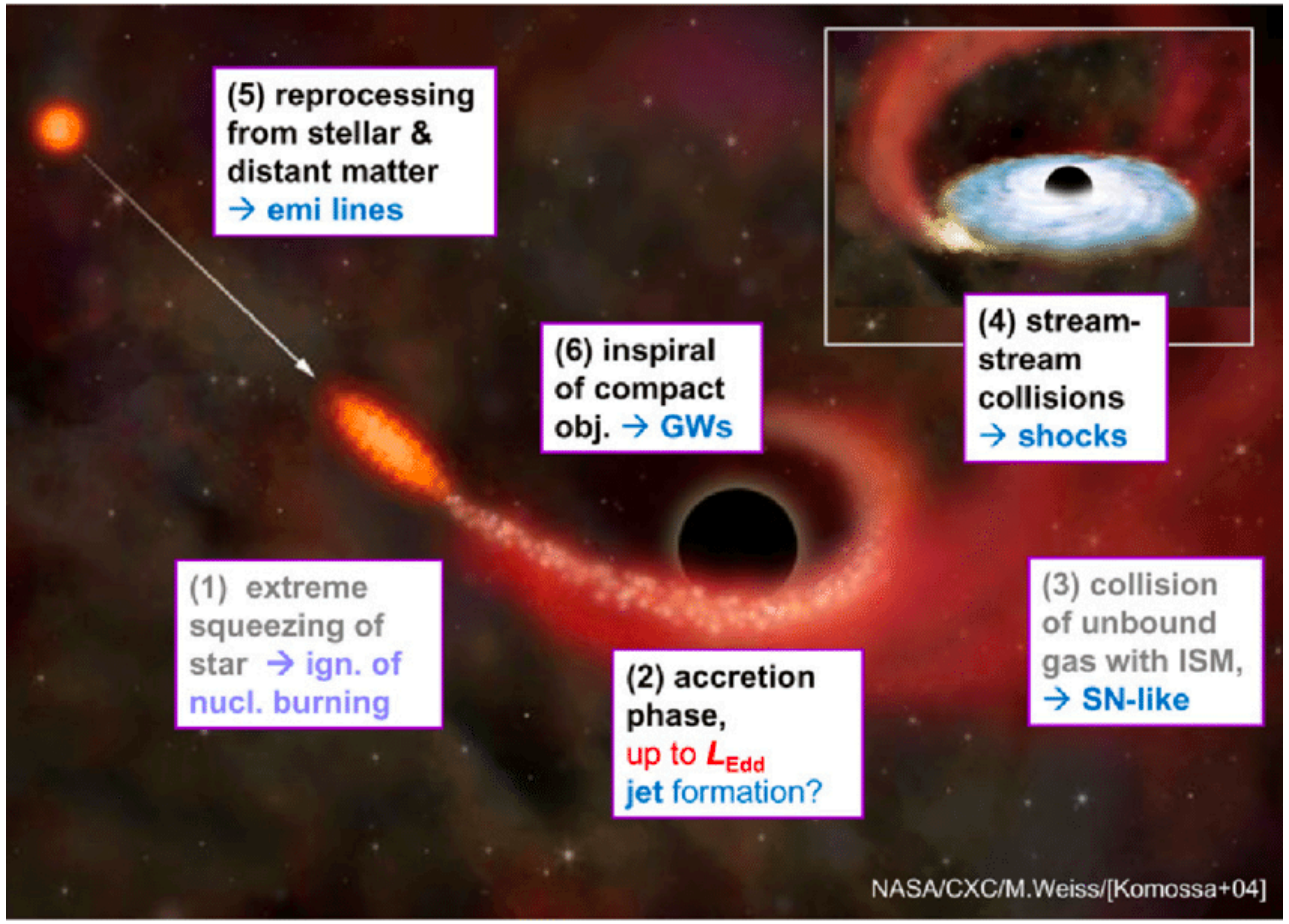
Astro2020 White Paper (Caldwell et al)



Stochastic (unresolved) background limits

Why Multi-messenger?

Sources often emit multiple signatures in multiple energies/wavelengths : the more you see, the more you learn.



Tidal Disruption Event

- Multi-wavelength Electromagnetic spectra
- GW from eventual inspiral merger
- Possible high energy neutrinos (Stein et al. 2020)

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- Charged cosmic rays easy to detect, but are deflected by galactic magnetic field, loses directional info.

- Neutrinos are hard to detect: need big expensive detectors. But they propagate freely with little interactions.

- GW also hard to detect, but is universally coupled so everything makes them.

Earliest paper on MM*…

* as far as I could search

University of Wisconsin - Madison

MADPH-03-1320
January 2003

MULTI-MESSENGER ASTRONOMY: COSMIC RAYS, GAMMA-RAYS AND NEUTRINOS

FRANCIS HALZEN

Department of Physics, University of Wisconsin, Madison, WI 53706, USA

Although cosmic rays were discovered a century ago, we do not know where or how they are accelerated. There is a realistic hope that the oldest problem in astronomy will be solved soon by ambitious experimentation: air shower arrays of 10,000 kilometer-square area, arrays of air Cerenkov telescopes and kilometer-scale neutrino observatories. Their predecessors are producing science. We will review the highlights:

- Cosmic rays: the highest energy particles and the GZK cutoff, the search for cosmic accelerators and the the Cygnus region, top-down mechanisms: photons versus protons?
- TeV-energy gamma rays: blazars, how molecular clouds may have revealed proton beams, first hints of the diffuse infrared background?
- Neutrinos: first results and proof of concept for technologies to construct kilometer-scale observatories.

7 citations only….!!?!

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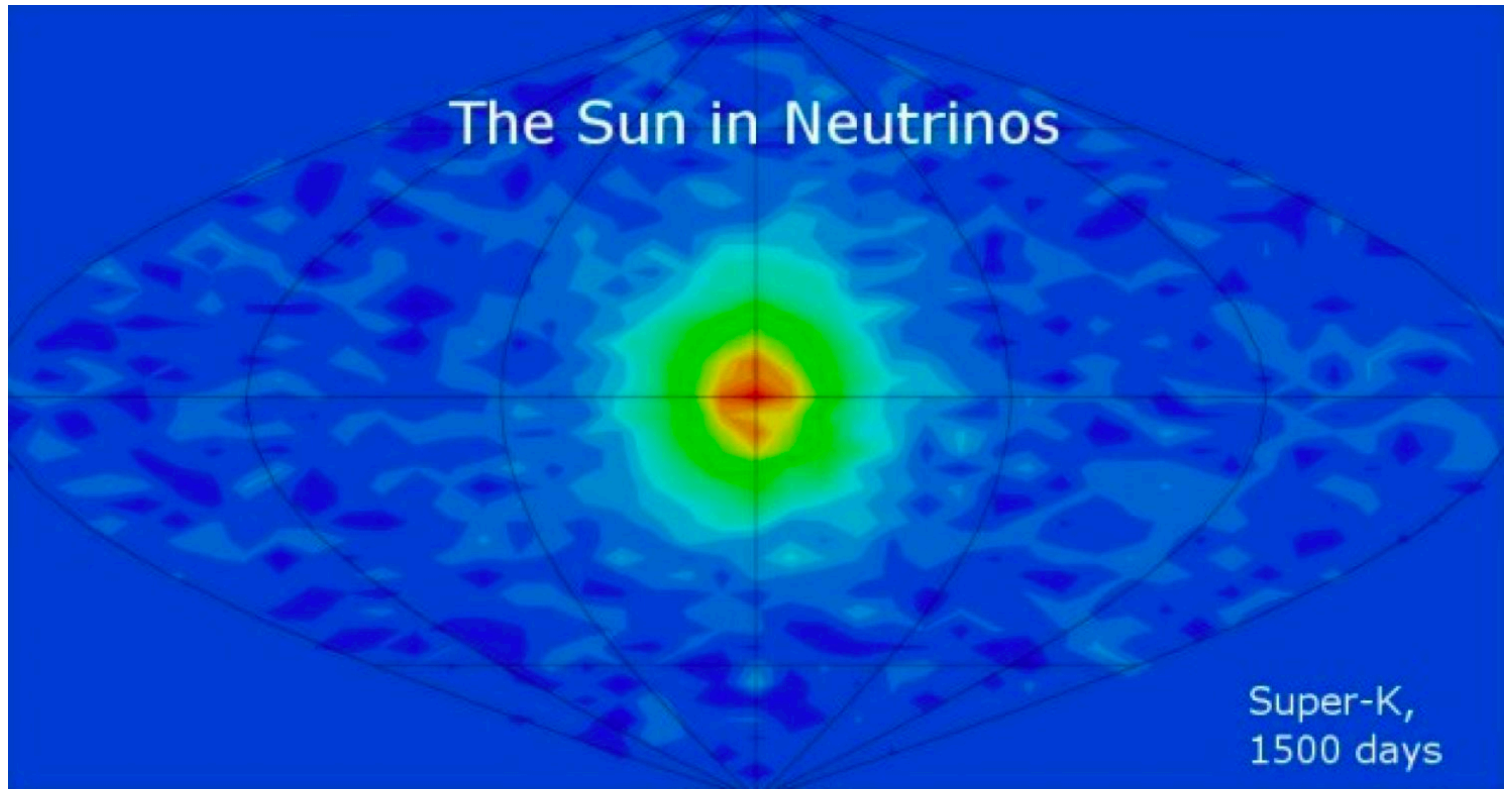
It stood the test of time :

- Protons are relatively abundant, but their arrival directions have been scrambled by magnetic fields.
- γ-rays do point back to their sources, but are absorbed on extra-galactic backgrounds at TeV- energy and above.
- neutrinos propagate unabsorbed and without deflection throughout the universe but are difficult to detect.

(Cut and paste from Halzen 2003)

Early MM Events

- Solar neutrinos + photons : neutrino oscillations



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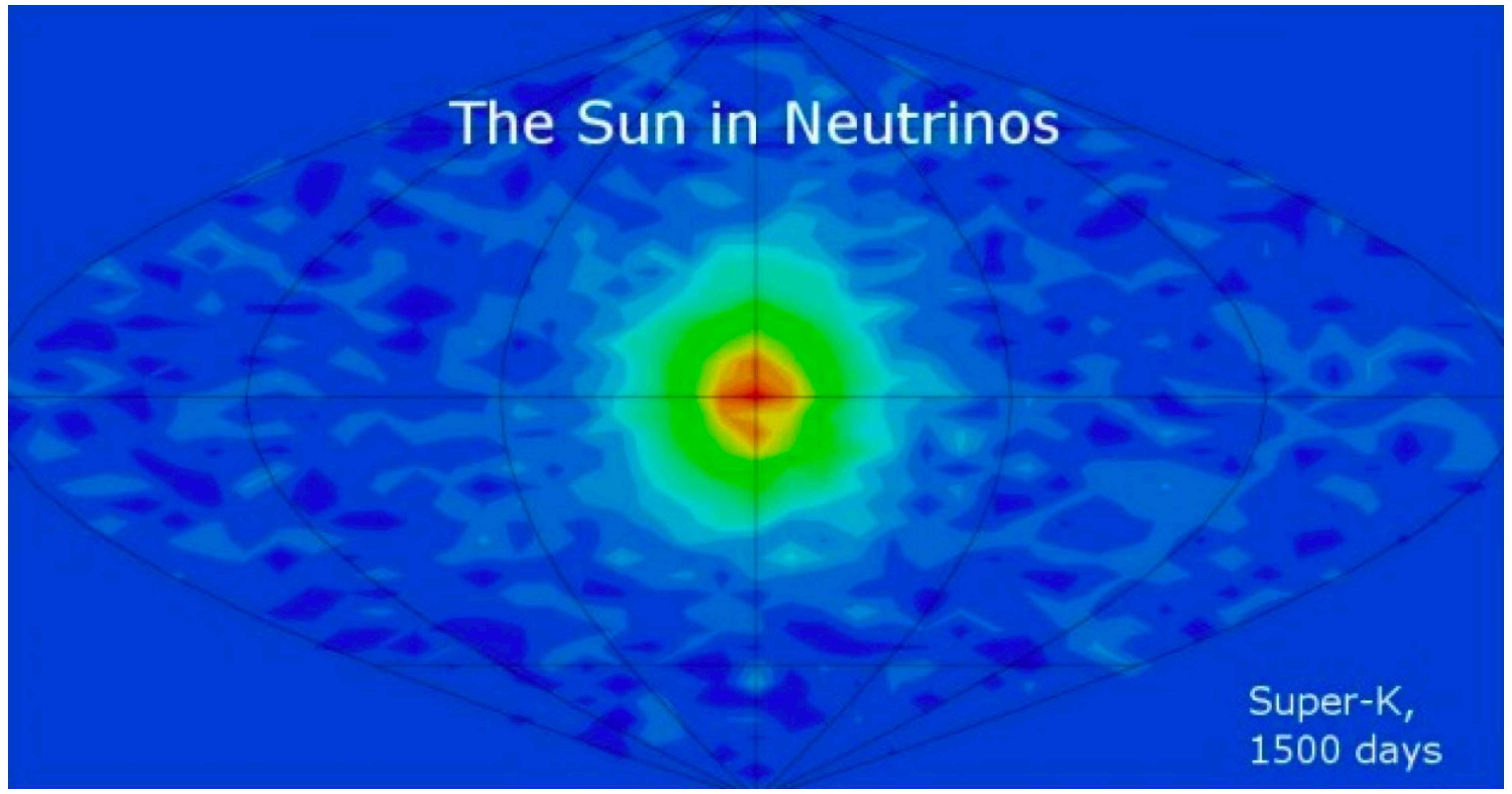
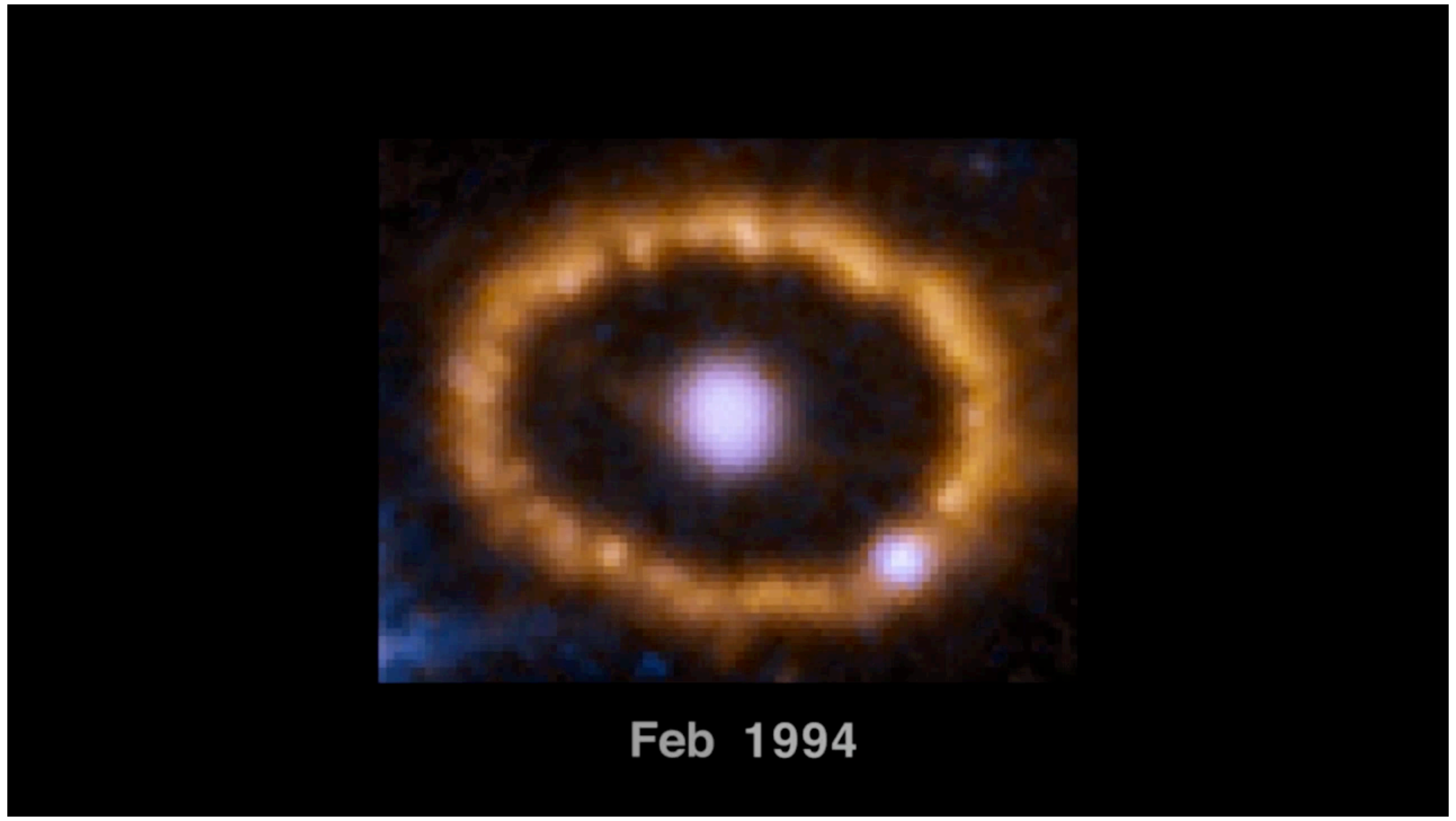


Chandra X-ray time-lapse of SN1987A

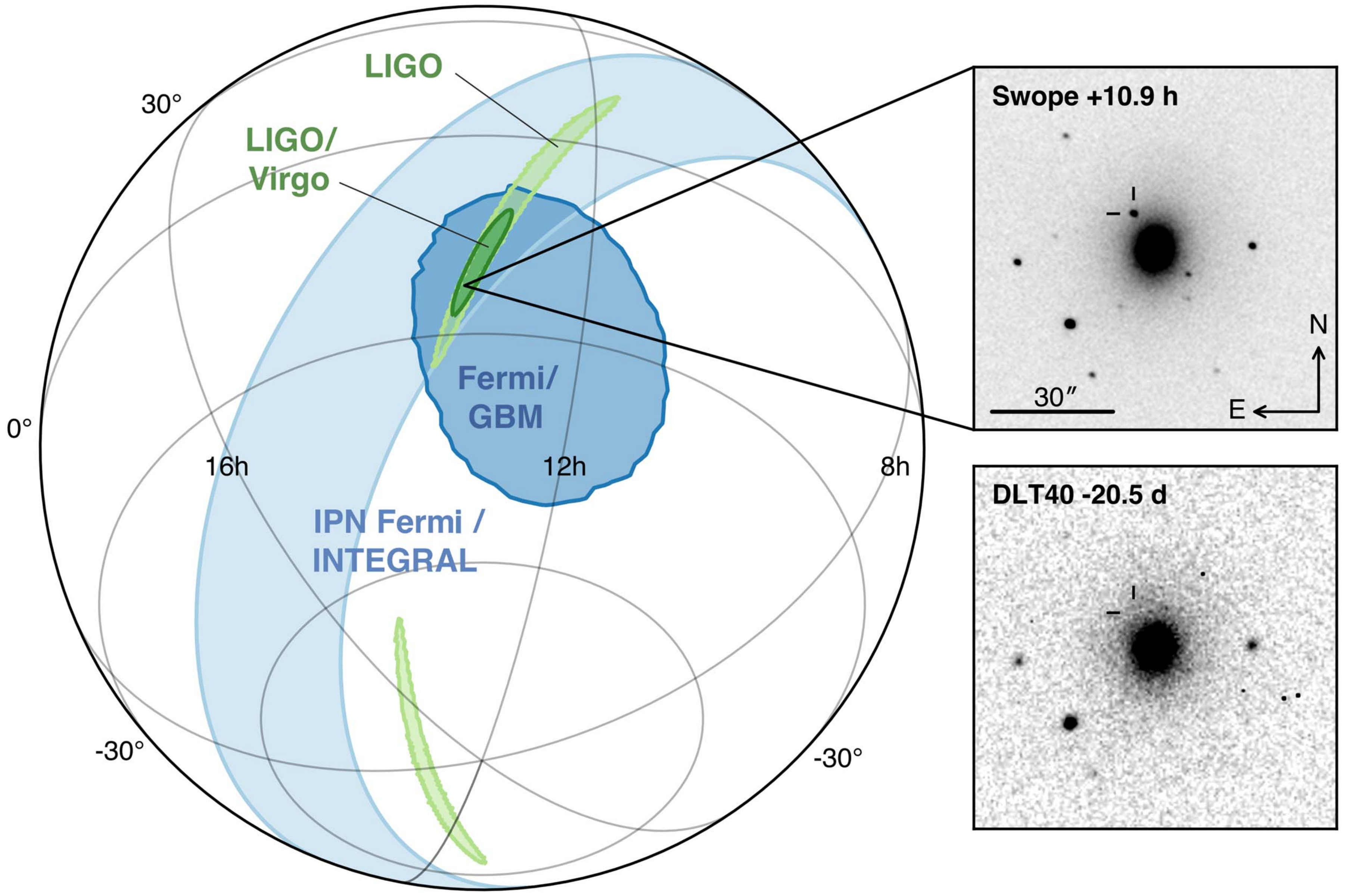


- Supernova 1987A : optical (our eyes!) and neutrino detection by Super-Kamiokande/Baksan/IMS detectors

MM Poster Child : GW170817

- GW from the inspiral Merger of 2 Neutron Stars, triggers LIGO/VIRGO detector alert. Independently detected by *Fermi* gamma-ray observatory 1.7s later.

Image Credit : LIGO



- Worldwide effort to make follow up observations from radio to gamma rays, and neutrinos.

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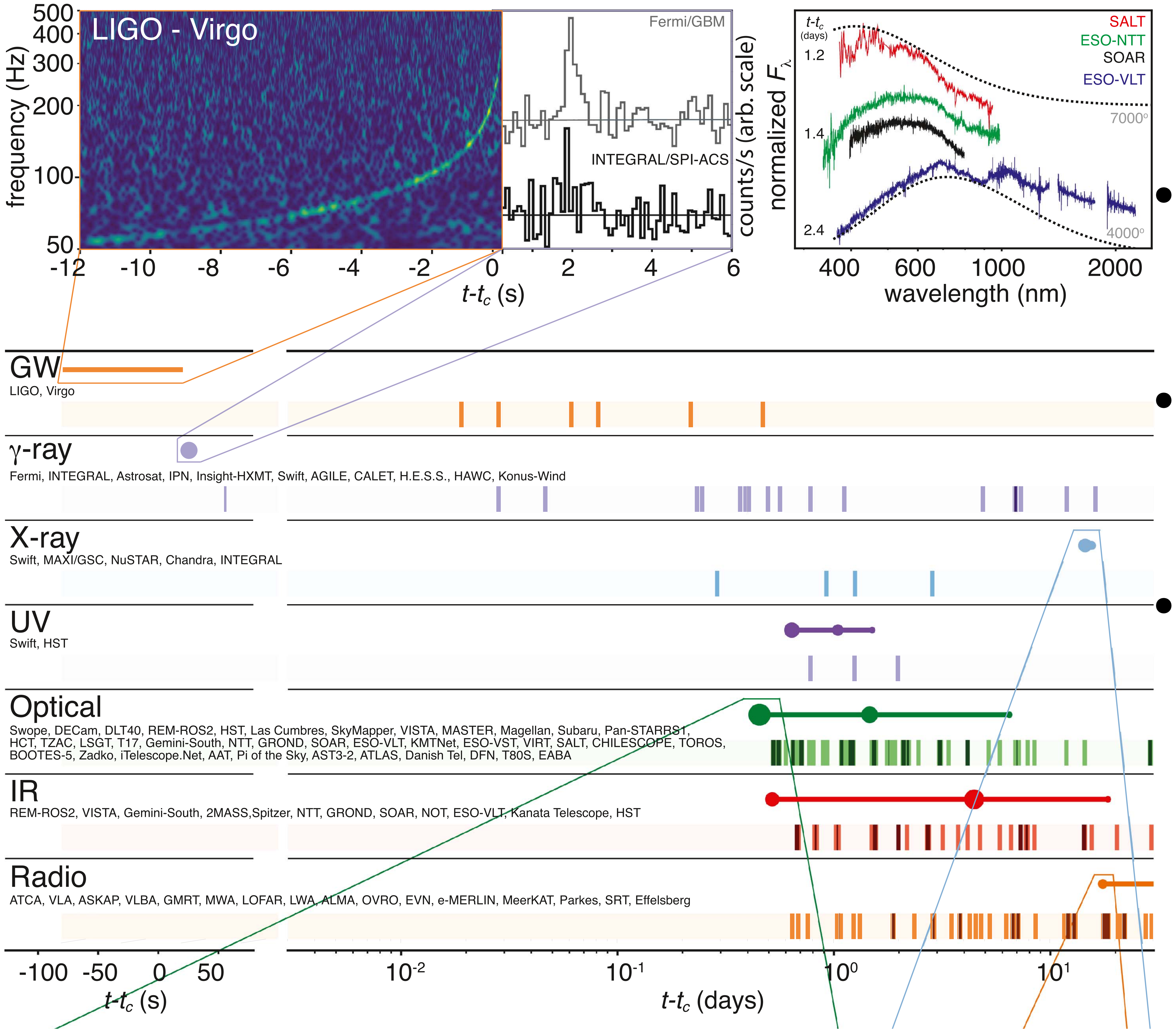


- Multi-wavelength EM detection from Radio to gamma-ray frequencies.
- Merger mass $M = 0.86 - 2.66 M_\odot$ at a distance of $40\ \mathrm{Mpc}$
- No neutrinos (off-axis, unlucky?) or cosmic rays (not expected) detected.

Blazar TXS0506-056 event

- Less well known Sept 22 2017: $3 - 4\sigma$ coincident detection of high energy neutrinos, radio, optical and gamma rays. **First detection of cosmic neutrino source!**

- IceCube detection of 290 TeV high energy neutrino, from direction consistent with (known) flaring blazer TXS0506-056 at redshift *z*=0.3365.

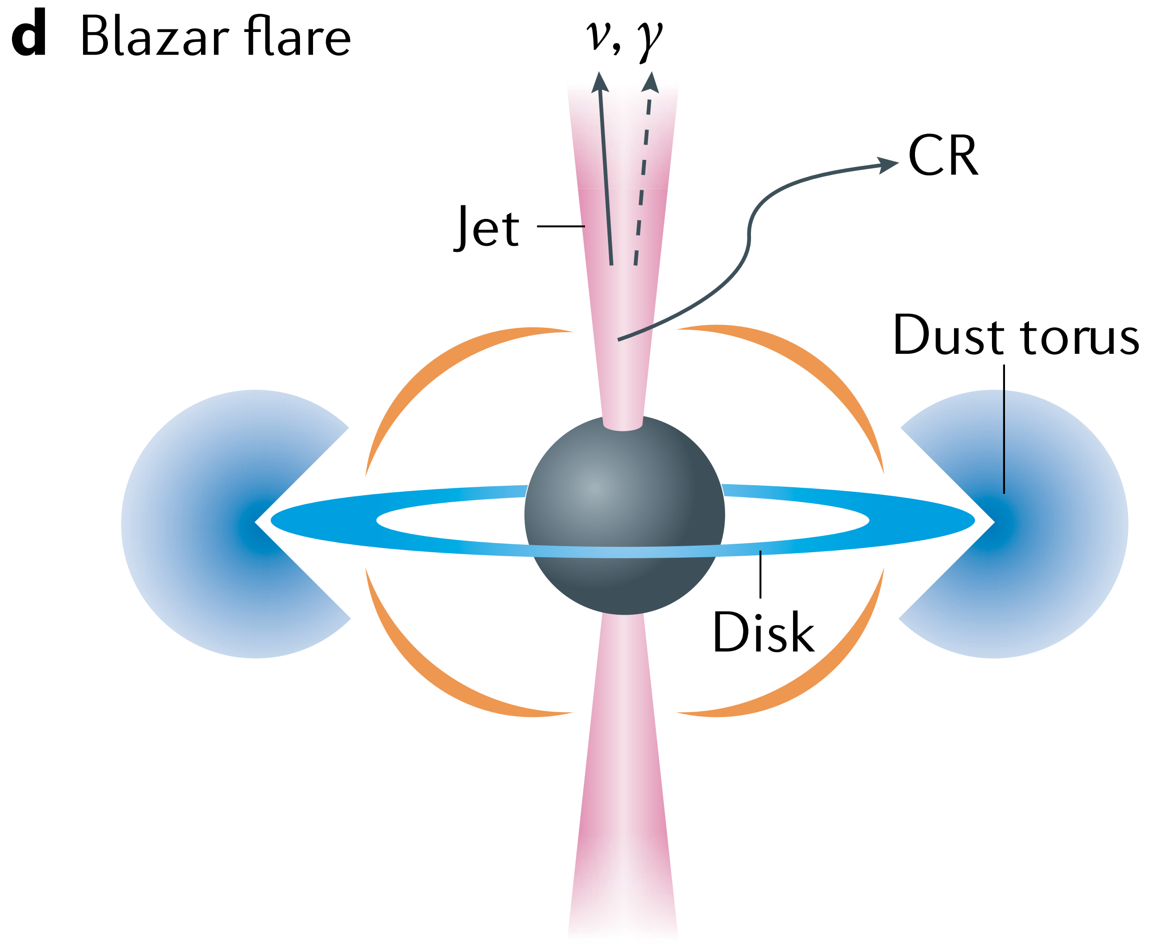
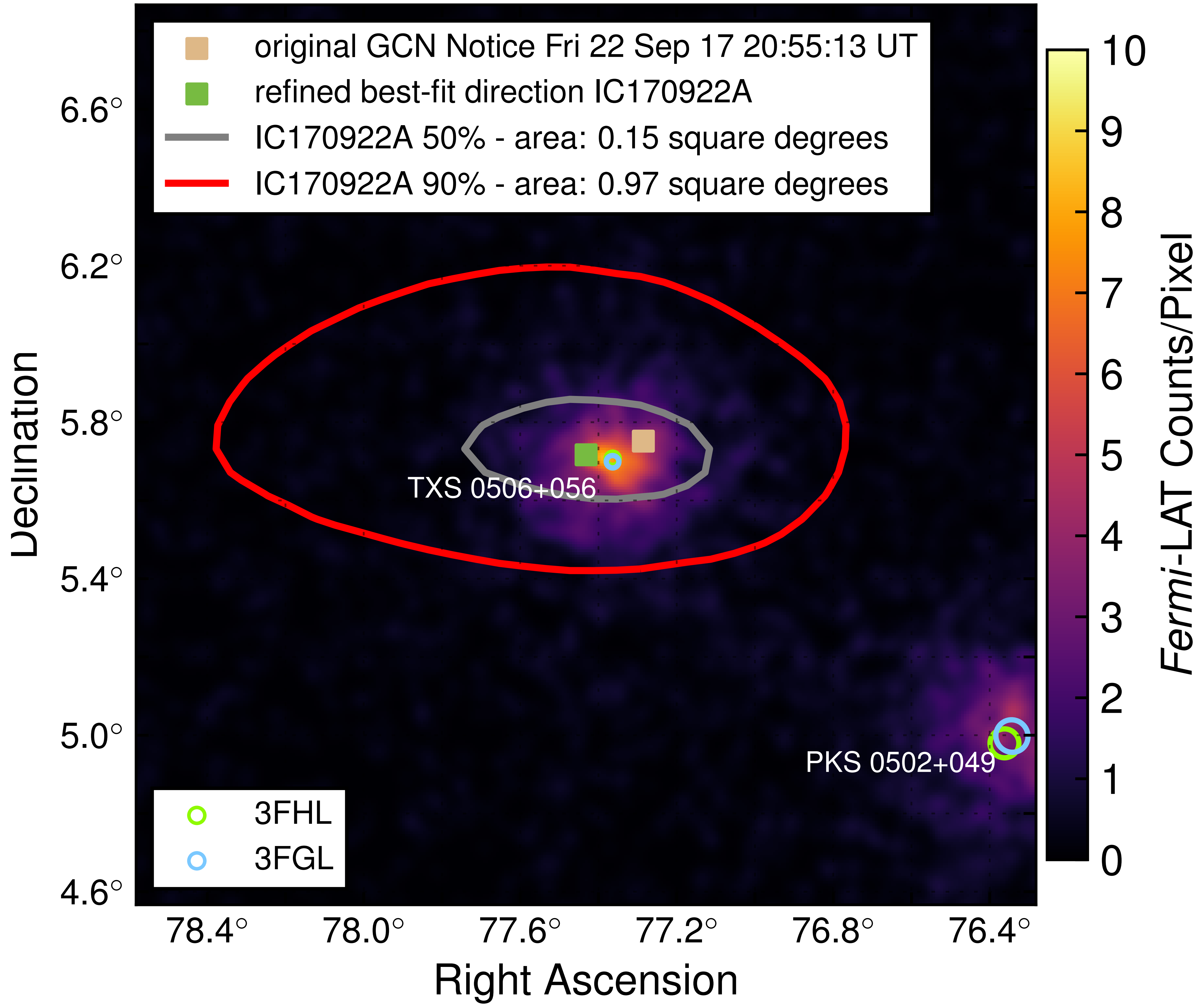


Image : Mészáros et al 2019

Blazar TXS0506-056 event

- Fermi-LAT gamma ray photon count map.

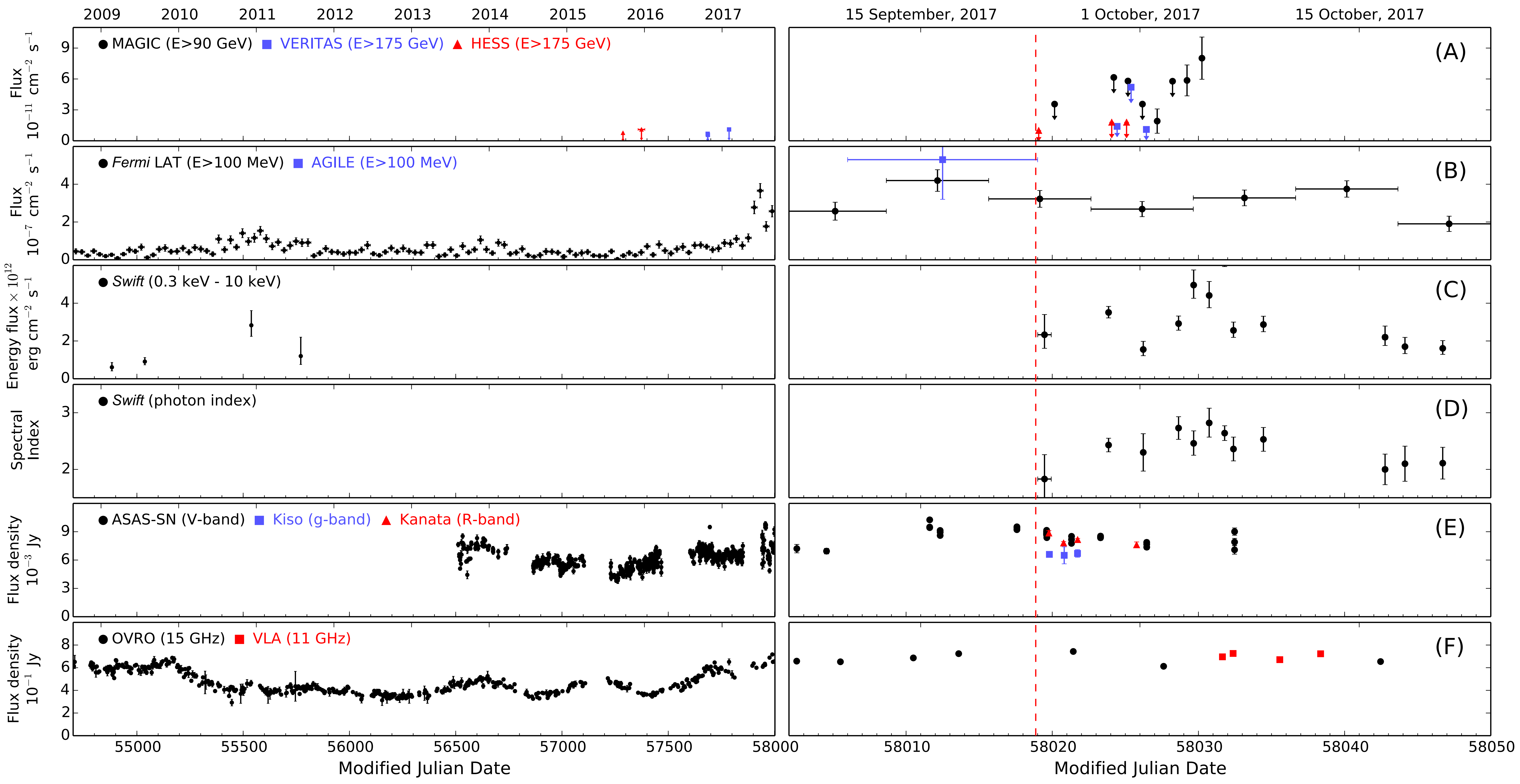
(A)



IceCube et al 2018

Blazar TXS0506-056 event

(Source : IceCube et al 2018)



- Increase in activity of emissions across all EM observed frequencies during event.

All good, what about Multi-messenger *Cosmology*?

Cosmologists' view of MM Cosmology

EuCAPT White Paper (endorsed by 400+)

"…entering an age of "multi-messenger cosmology", with multiple cosmological probes (CMB, Large Scale Structure, GWs)…"

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"Multi-frequency EM and GW signals are two independent avenues to explore the universe…"

Mostly excited about GW + EM combo.
Not much love for neutrinos and cosmic rays.

Applications of MM Cosmology

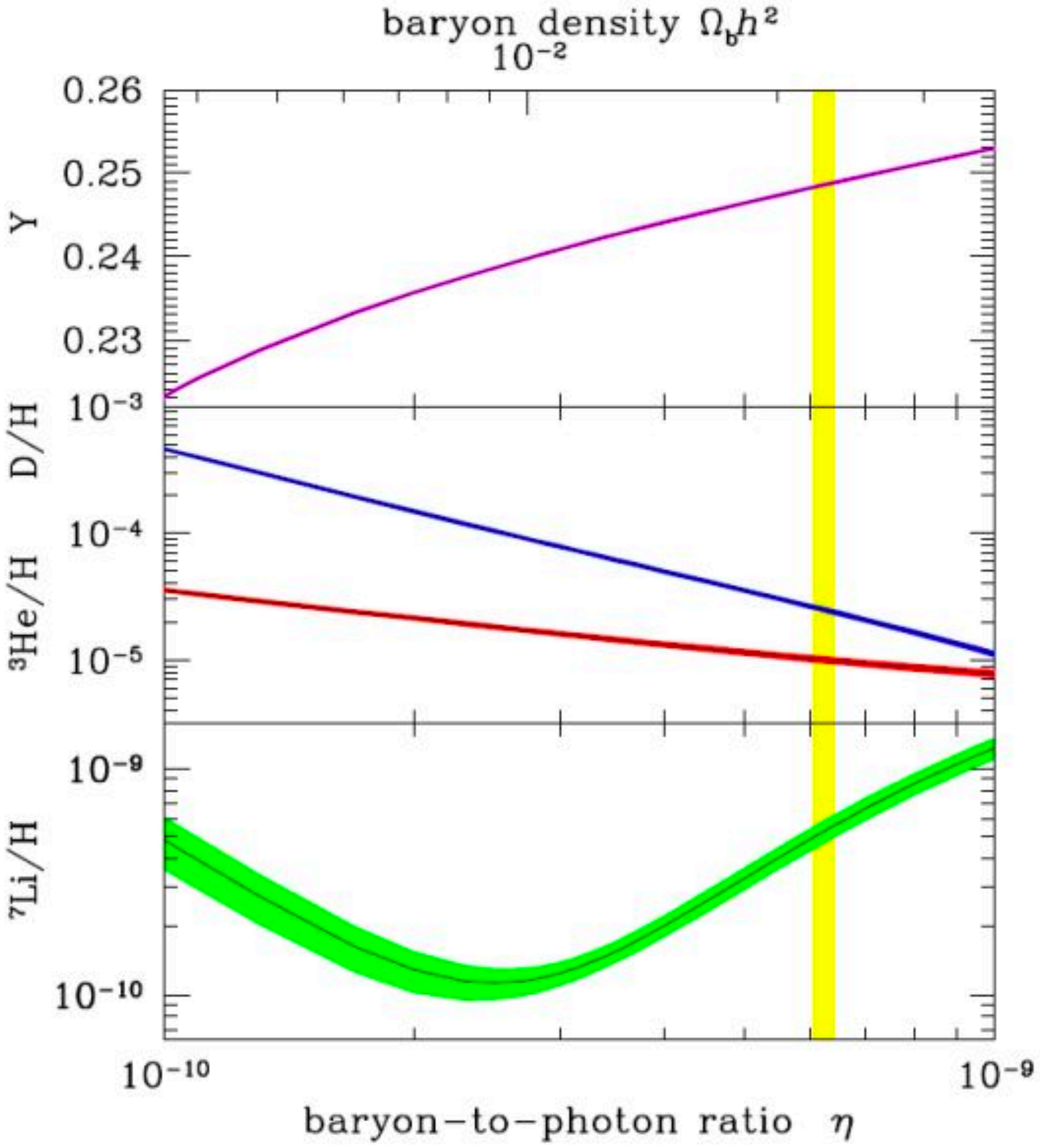
In order of speculativeness…..

- Actual observed multi-messenger signals
- Single messenger so far : Cosmological Backgrounds from Inflation
- No messenger yet : Multi-messenger search for Axion Dark Matter

Actual Observed Multi-messenger signals

Big Bang Nucleosynthesis

- The first multi-messenger cosmology observation!!!
- At temperature $T \sim 1 \ \mathrm{MeV}$, nucleosynthesis of H into light elements He, D, and Li. These primordial abundances are our (strong force) messengers!
- Abundances depends strongly on baryon/photon ratio : measured precisely by CMB observations.



(credit : Ned Wright)

Standard Sirens

Schulz 86, Holz+Hughes 2005, Nissanke et al 2010 + many

- Inspiral GWs encode **luminosity distance *D***, orientation and some combination of mass/spin information. ***D*** is strongly correlated with **chirp mass *M*.** Schematically:

$$\text{strain} \propto \frac{M^{5/3}}{D} f^{2/3} \cos\Phi(t) \ , \ M = \frac{(1+z)(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

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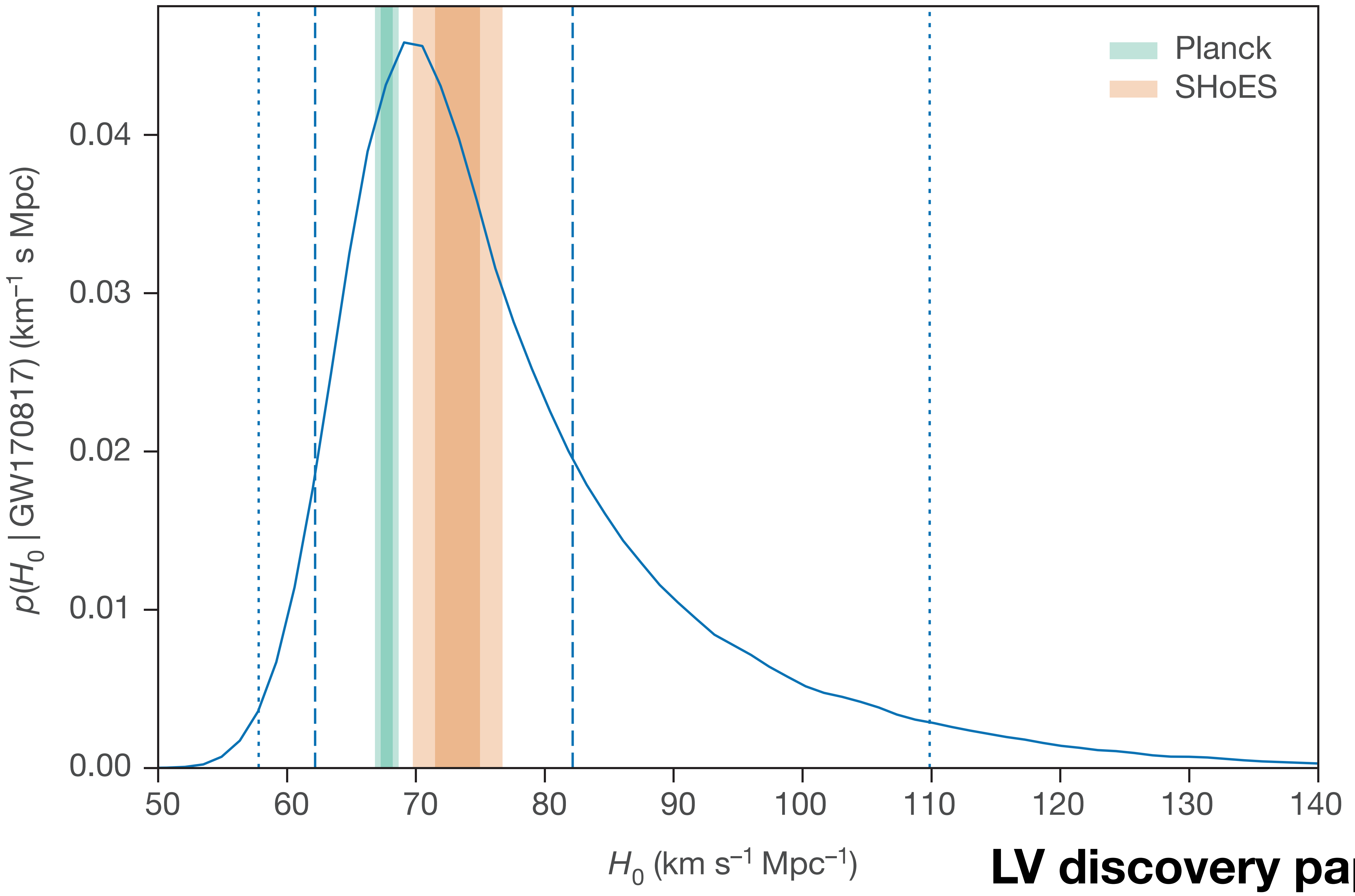
- To probe Hubble parameter, need both ***D*** and ***z*** : independent measurement of redshift is required.

Standard Sirens

- We can get ***z*** if we can identify the host galaxy of the progenitor : find optical counterpart! **Schulz 86**

- GW170817 NS merger our only known case!



LV discovery paper (2018)

$$D = 43.8^{+2.9}_{-6.9}\ \mathrm{Mpc}$$

$$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

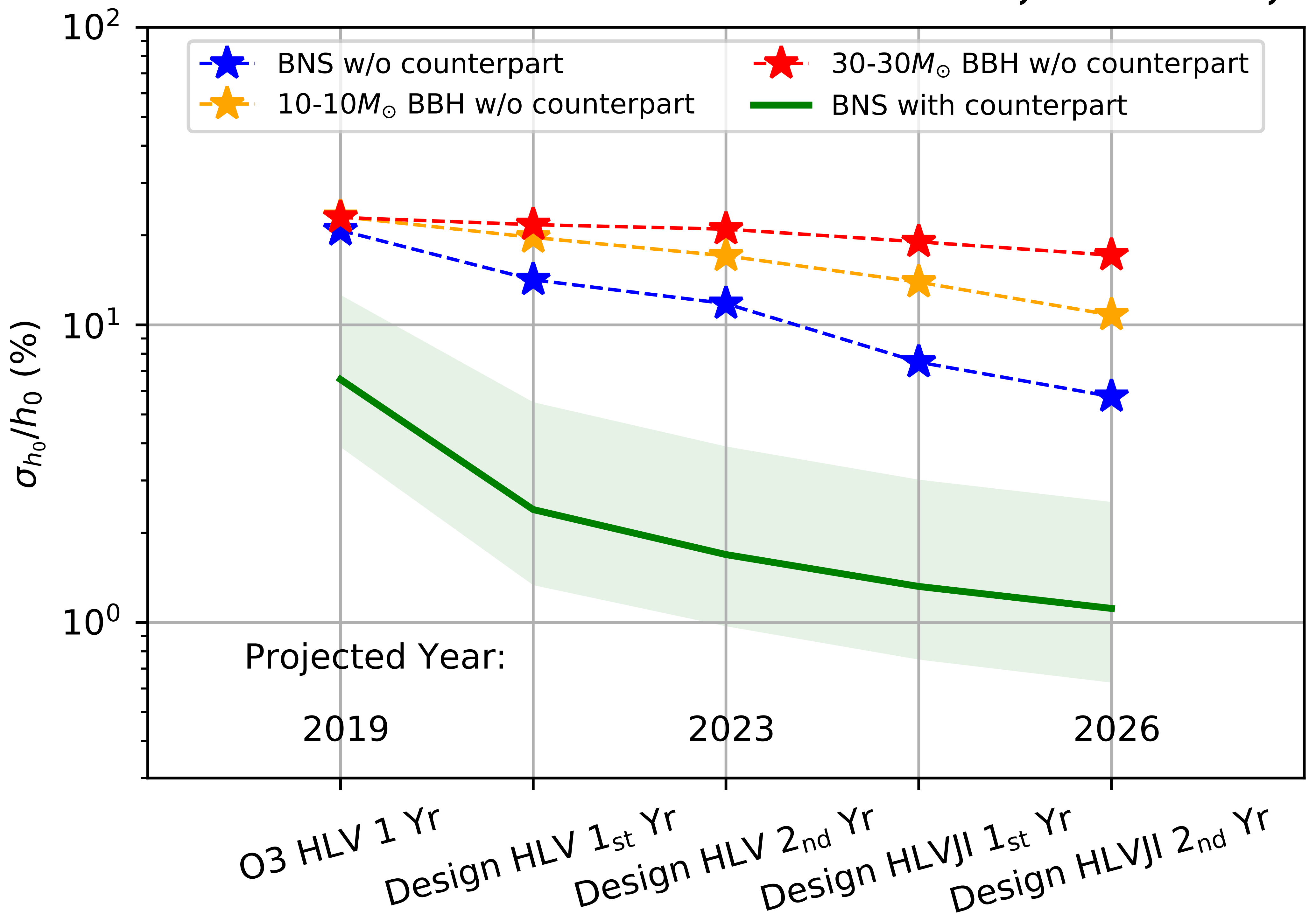
Big error bars, consistent with both SHoEs and Planck results.

Need ~50 measurements for 2% accuracy (Chen et al 2018)

Standard Sirens

- For no counterpart BBH/BNS mergers, guess its host using existing galaxy catalogs.

Chen, Fishbach, Holz (2018)



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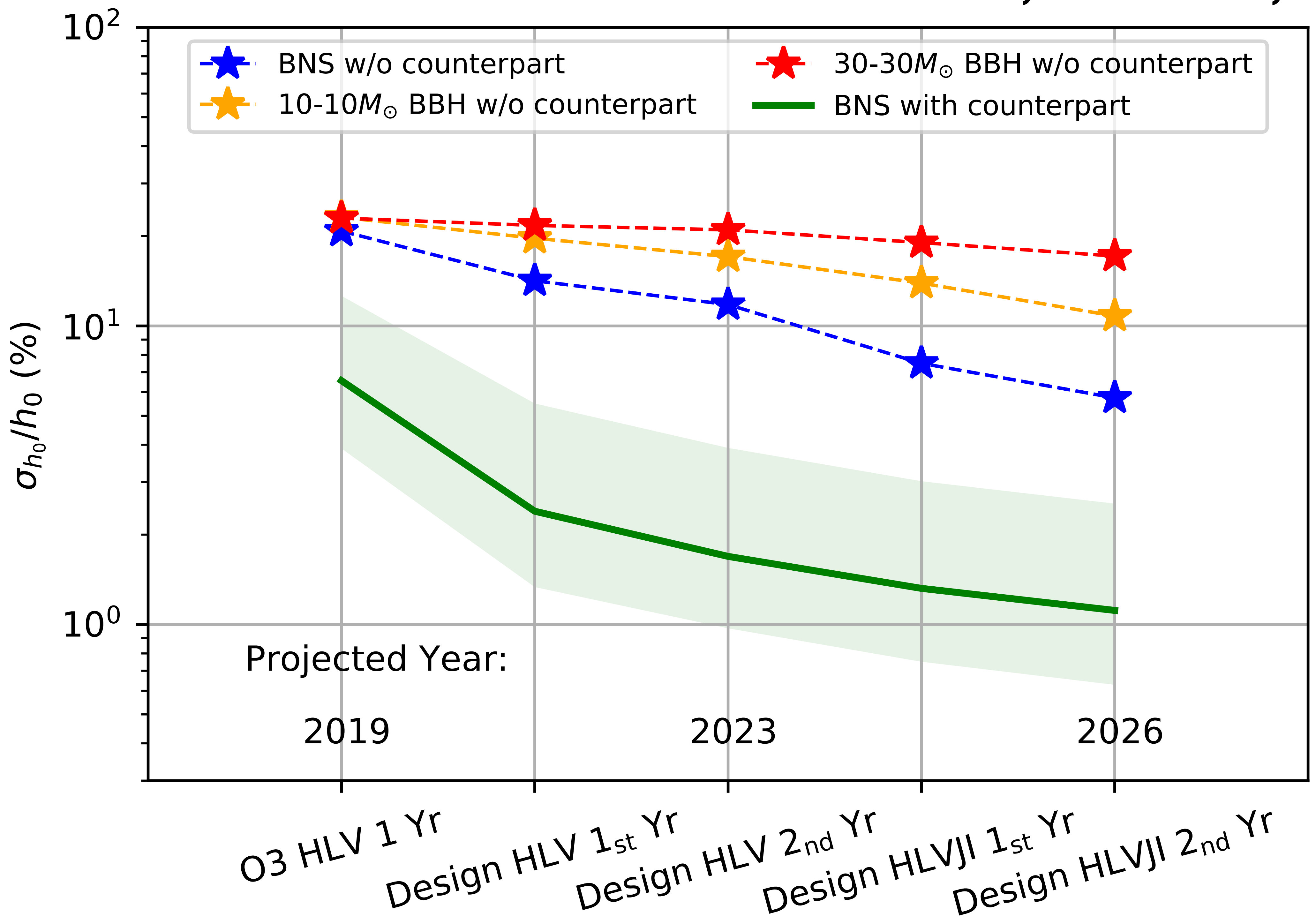

- Or statistically cross-correlate clustering of BBH sources with clustering of galaxies up to ***z=0.5*** : ~2.5% accuracy.

(Mukherjee, Wandelt 2018
Mukherjee, Wandelt, Nissanke, Silvestri 2020)

The speed of gravity and Modified Gravity

- In GW170817, the GW signal and EM counterpart was detected around 1.7s from each other : impose a speed limit on gravity.

$$c_g^2 - 1 < 10^{-15}$$

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- Kills most Hordenski-type theories, placed strong constraints on vector-tensor (e.g. Einstein-Aether and Horava-type) theories, and biometric theories. **(Baker, Nollini, Ferreira, Lagos, Noller 2017)**

Multi-messenger Cosmic Backgrounds

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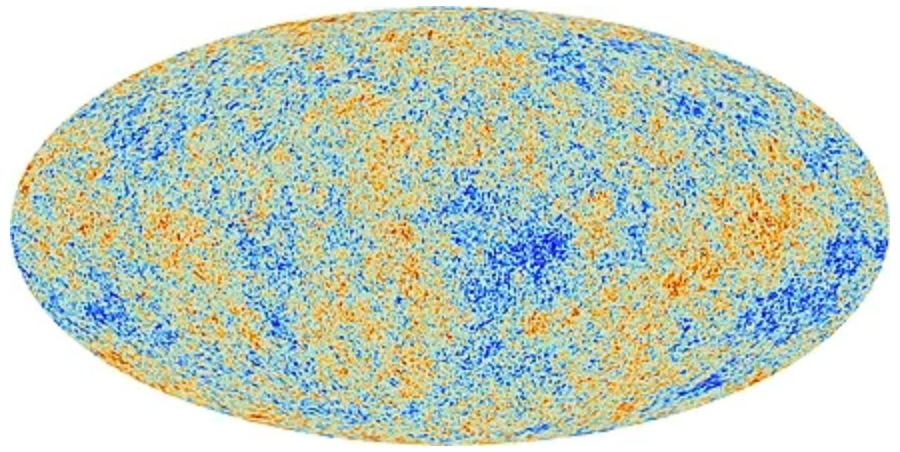
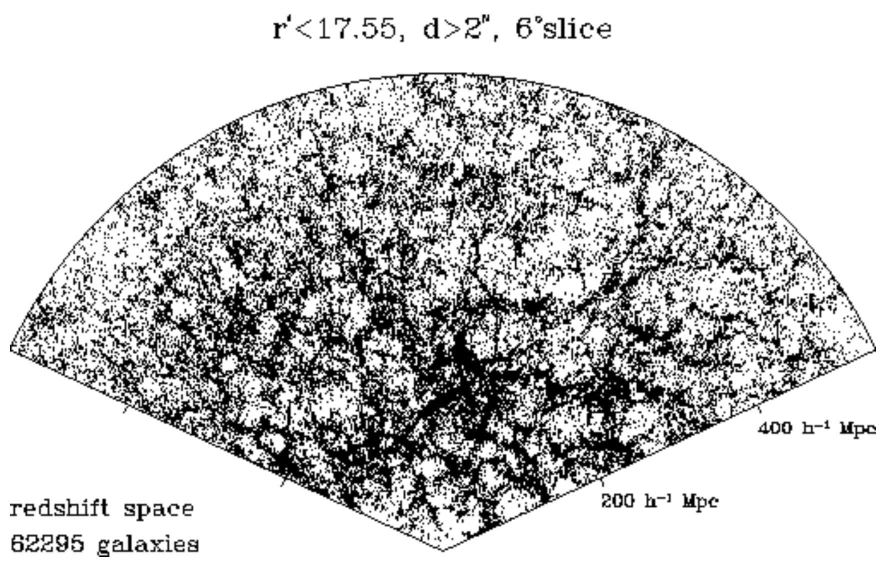
$$P_\zeta = A_S \left(\frac{k}{k_*}\right)^{n_s - 1}$$

Scalar

CMB Temp Anisotropies
Large Scale Structure





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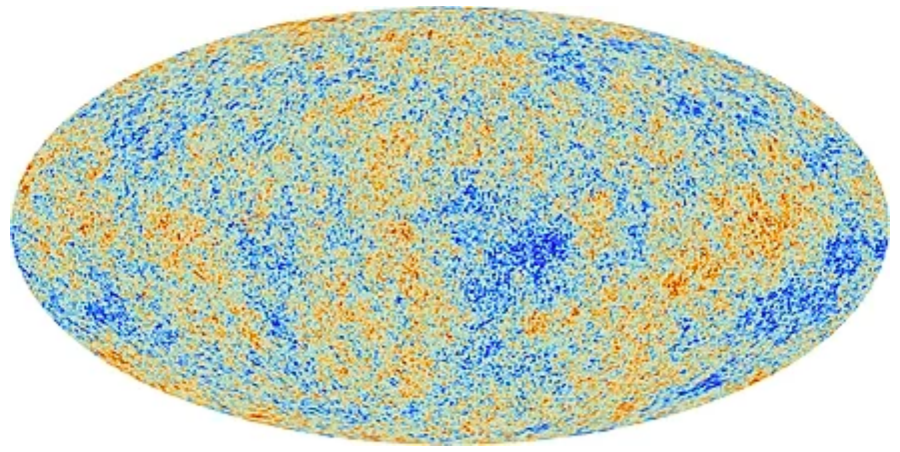
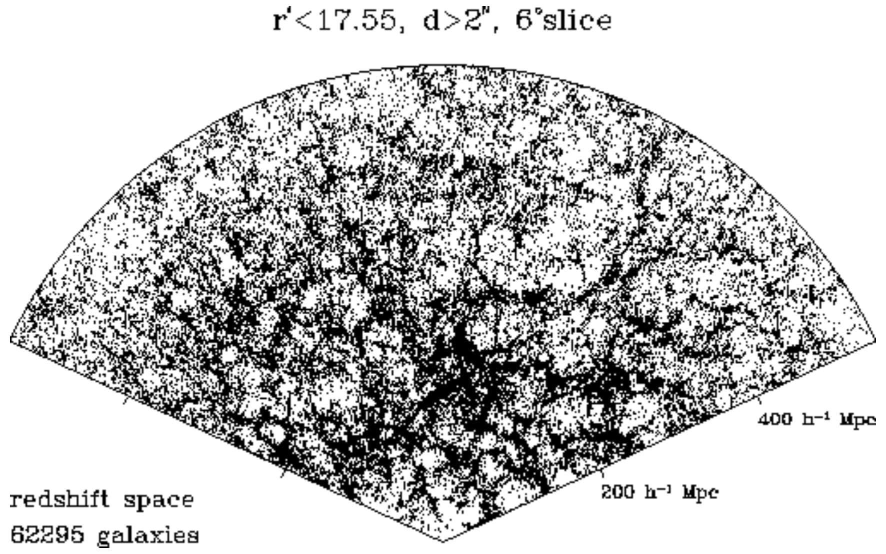
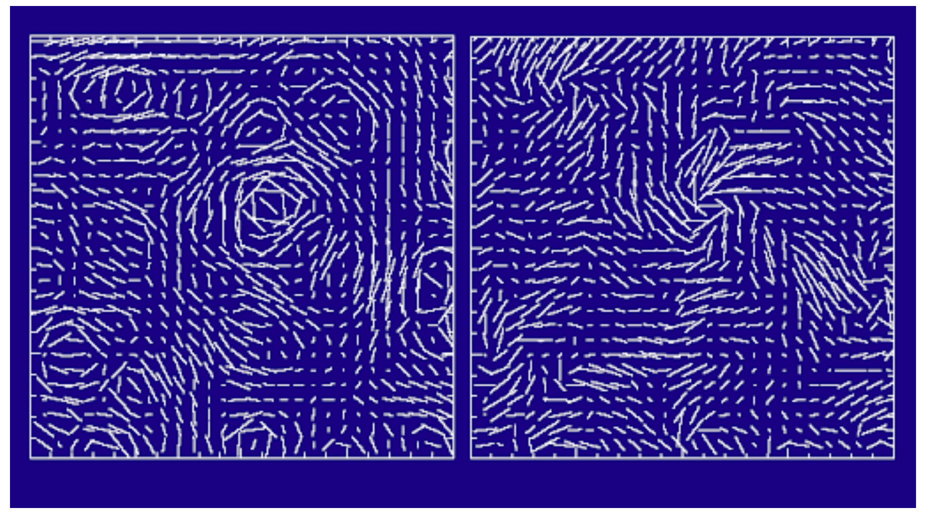
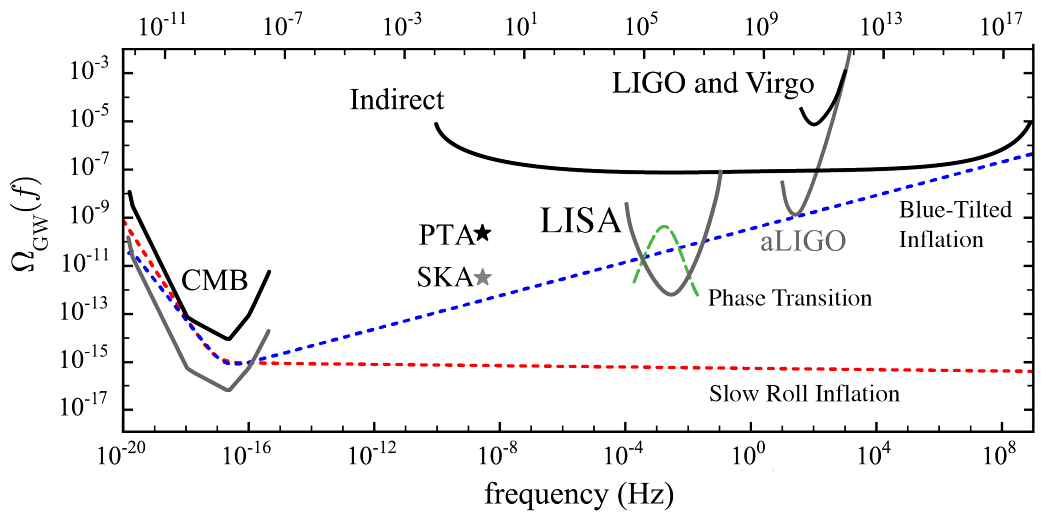
$$P_\zeta = A_S \left(\frac{k}{k_*}\right)^{n_s - 1} \qquad\qquad P_T = A_T \left(\frac{k}{k_*}\right)^{n_T}$$

Scalar	Tensor (GW)
CMB Temp Anisotropies	CMB B-mode polarizations
Large Scale Structure	Stochastic GW background









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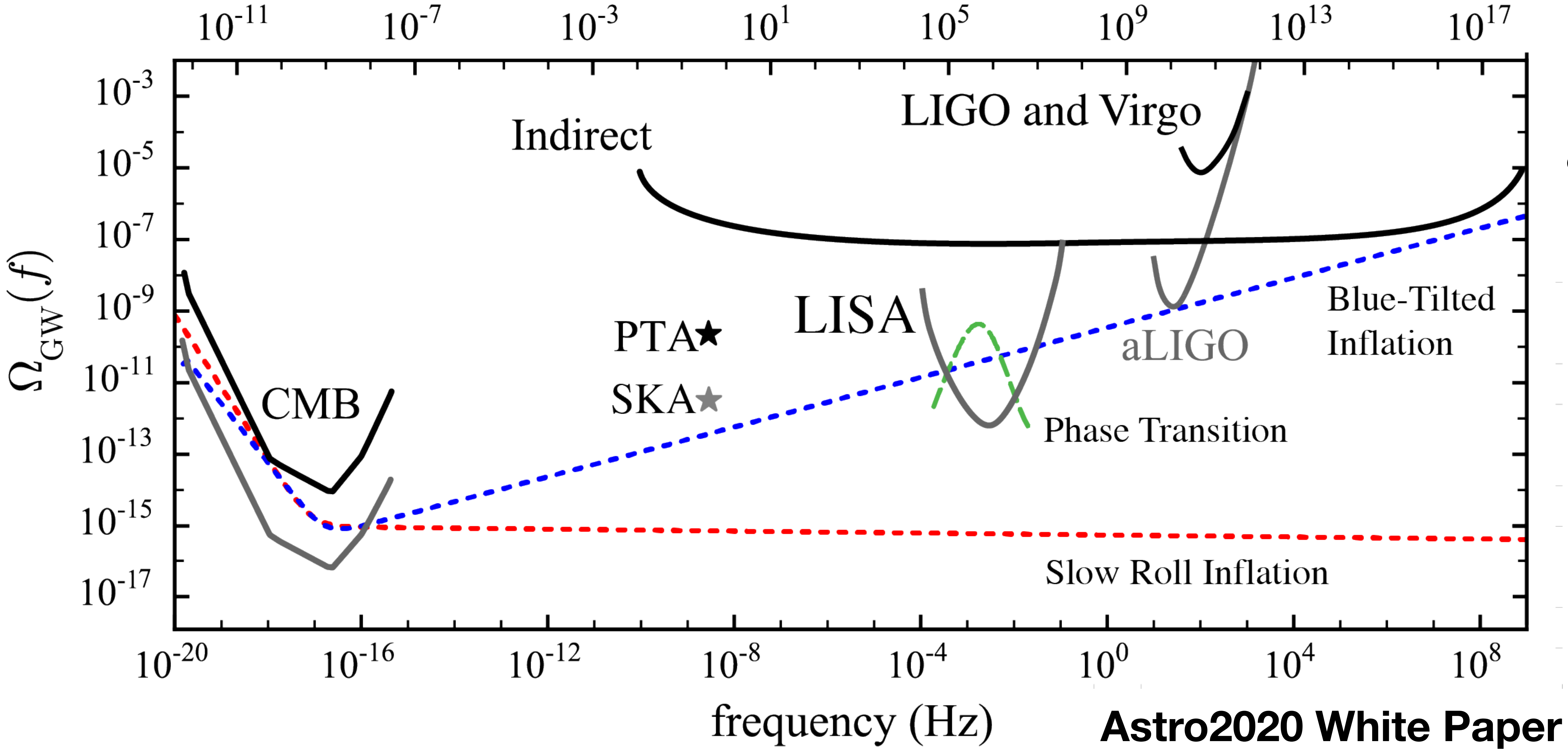


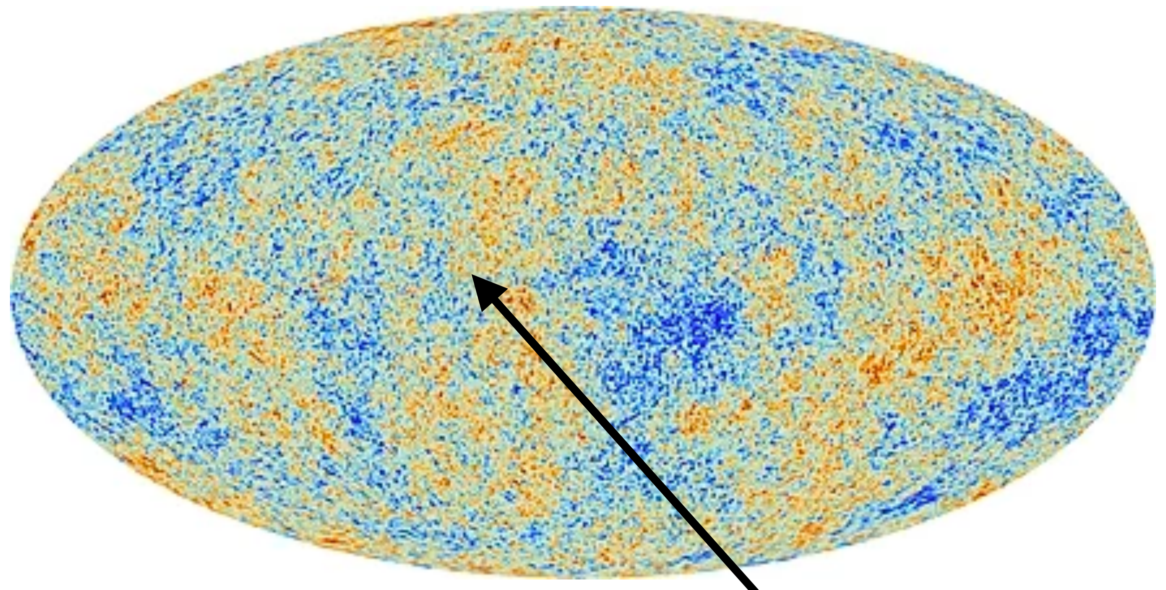
Astro2020 White Paper (Caldwell et al)

- Still ways off for direct GW detection, but not impossible.

Cross-correlation of CMB and GW backgrounds

Adshead, Afshordi, Dimastrogiovanni, Fasiello, Lim, Tasitano (2020)

- Gravity is non-linear, so tensor and scalar modes must couple (“non-gaussianities).
- Probe this by correlating CMB temperature with GW anisotropies:



$$\frac{\Delta T}{T}(\hat{\mathbf{n}})$$

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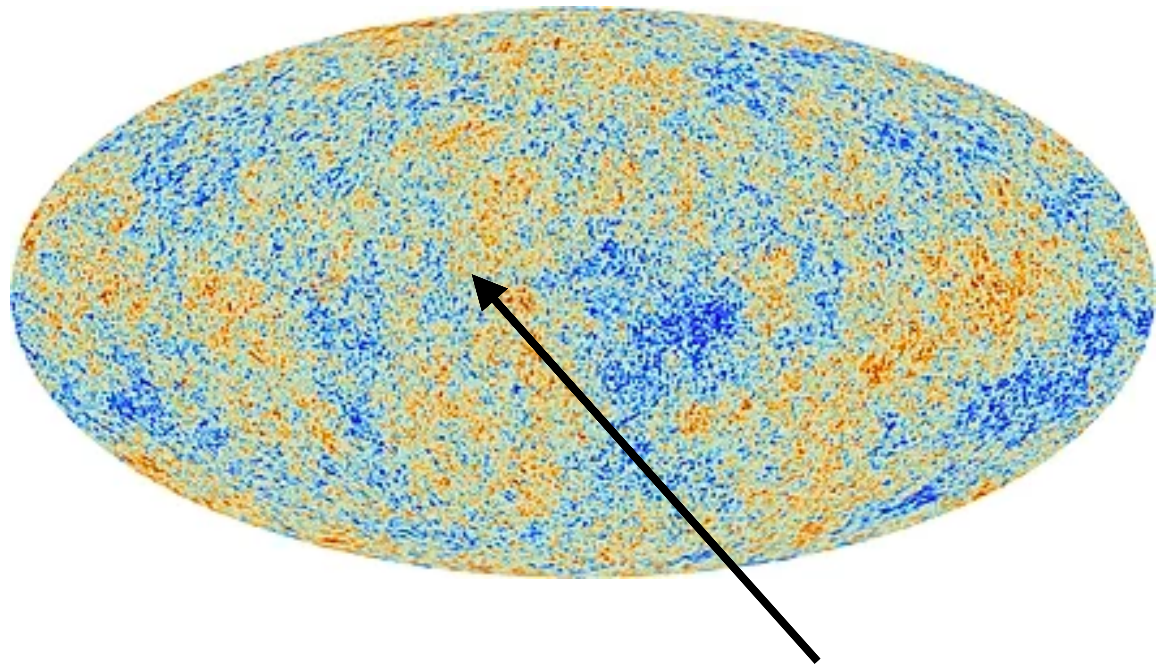

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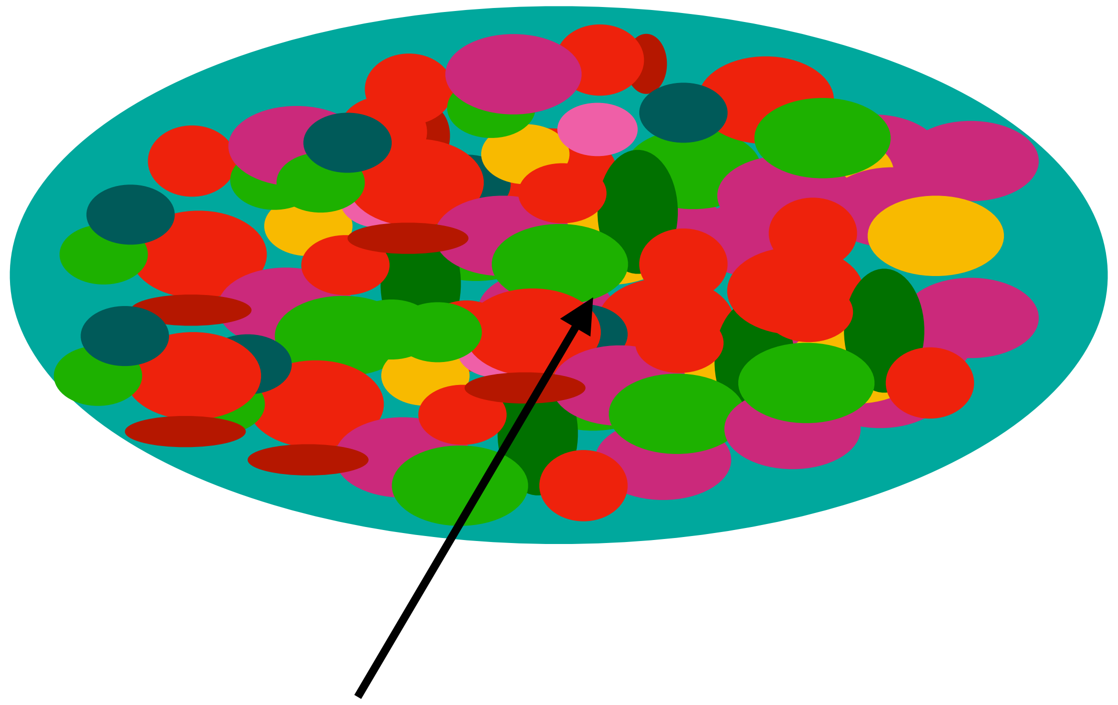

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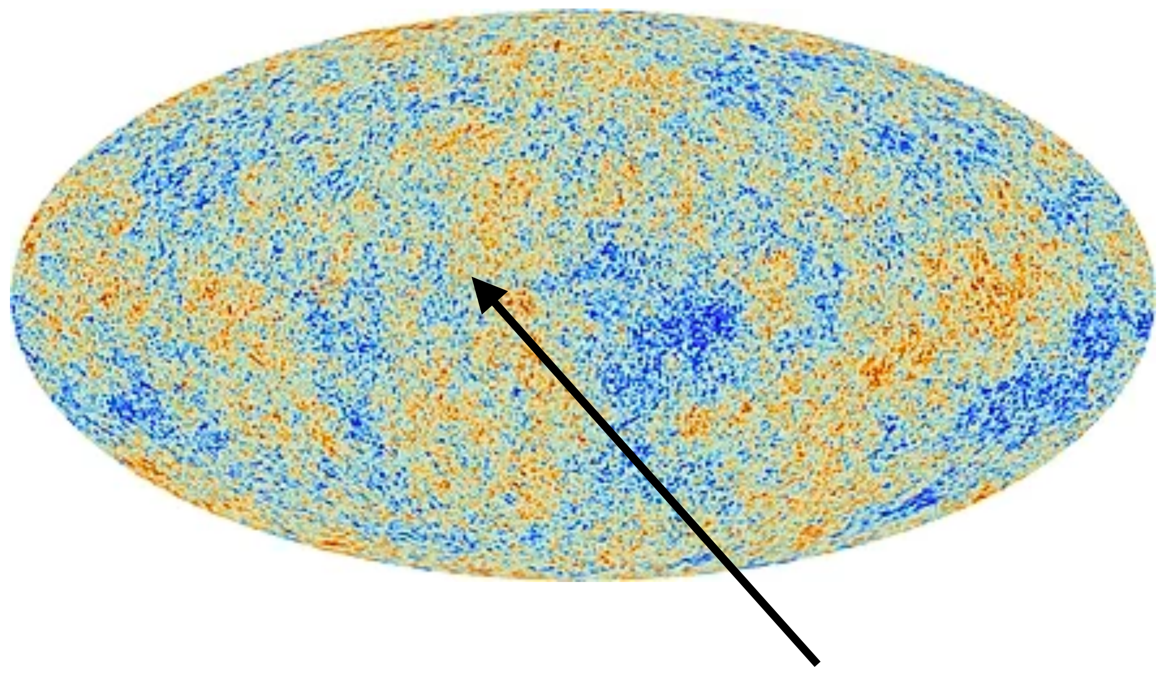

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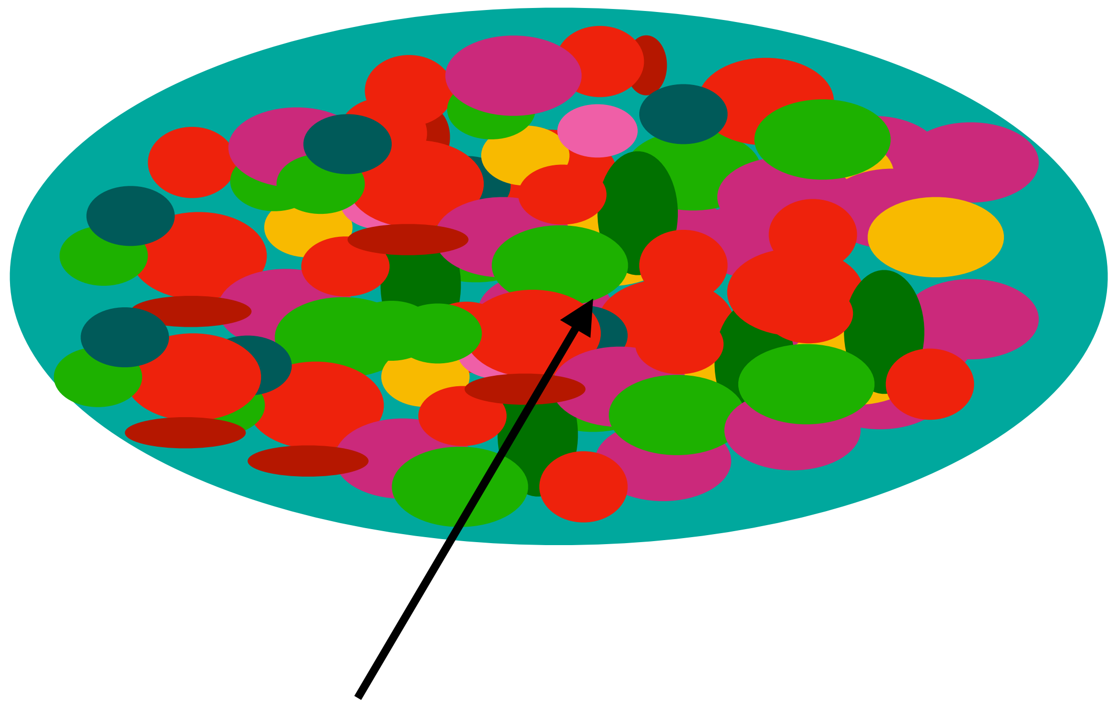

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Non-linear coupling

Correlate them to construct a 3pt Correlation $\left\langle \frac{\Delta T}{T} \langle hh \rangle \right\rangle \sim F_{NL} P_\zeta$

Cross-correlation of CMB and GW backgrounds

Adshead, Afshordi, Dimastrogiovanni, Fasiello, Lim, Tasitano (2020)

- Two possible sources of non-zero F_{NL} :

- **Induced** : Post-inflationary evolution generates a tiny amount $F_{NL} \sim 1$ — long wavelength scalar modes modulate GW power anisotropy (Sach-Wolfe).

Cross-correlation of CMB and GW backgrounds

Adshead, Afshordi, Dimastrogiovanni, Fasiello, Lim, Tasitano (2020)

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- **Induced** : Post-inflationary evolution generates a tiny amount $F_{NL} \sim 1$ — long wavelength scalar modes modulate GW power anisotropy (Sach-Wolfe).

- **Primordial** : set down during inflation (depends on inflationary models), e.g. extra massless spin-2 field generates $F_{NL} \gg 1$

Cross-correlation of CMB and GW backgrounds

Adshead, Afshordi, Dimastrogiovanni, Fasiello, Lim, Tasitano (2020)

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- Observability : BBO/DECIGO type space-based detector can possibly detect $F_{NL} \sim 10^3$, $n_T = 0.25$, difficult, but not completely crazy.

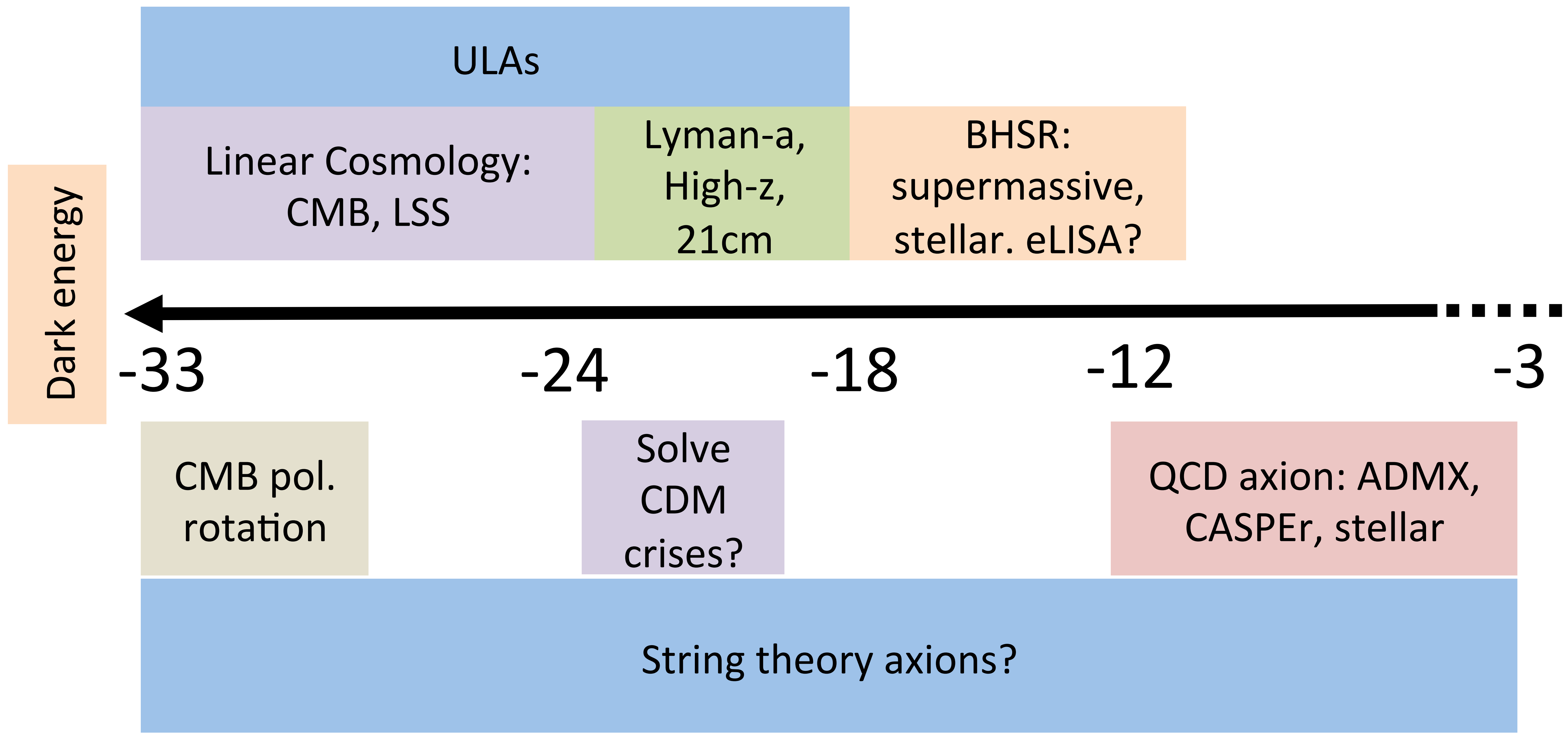
Multi-messenger search for cosmological Axion Dark Matter

Axion Dark Matter

- Axions and “Axion-Like Particles” are ultra light bosons ϕ

$$V(\phi) = \frac{m_a^2}{2}\phi^2 - \frac{m_a^2}{4! f_a^2}\phi^4 + \ldots$$

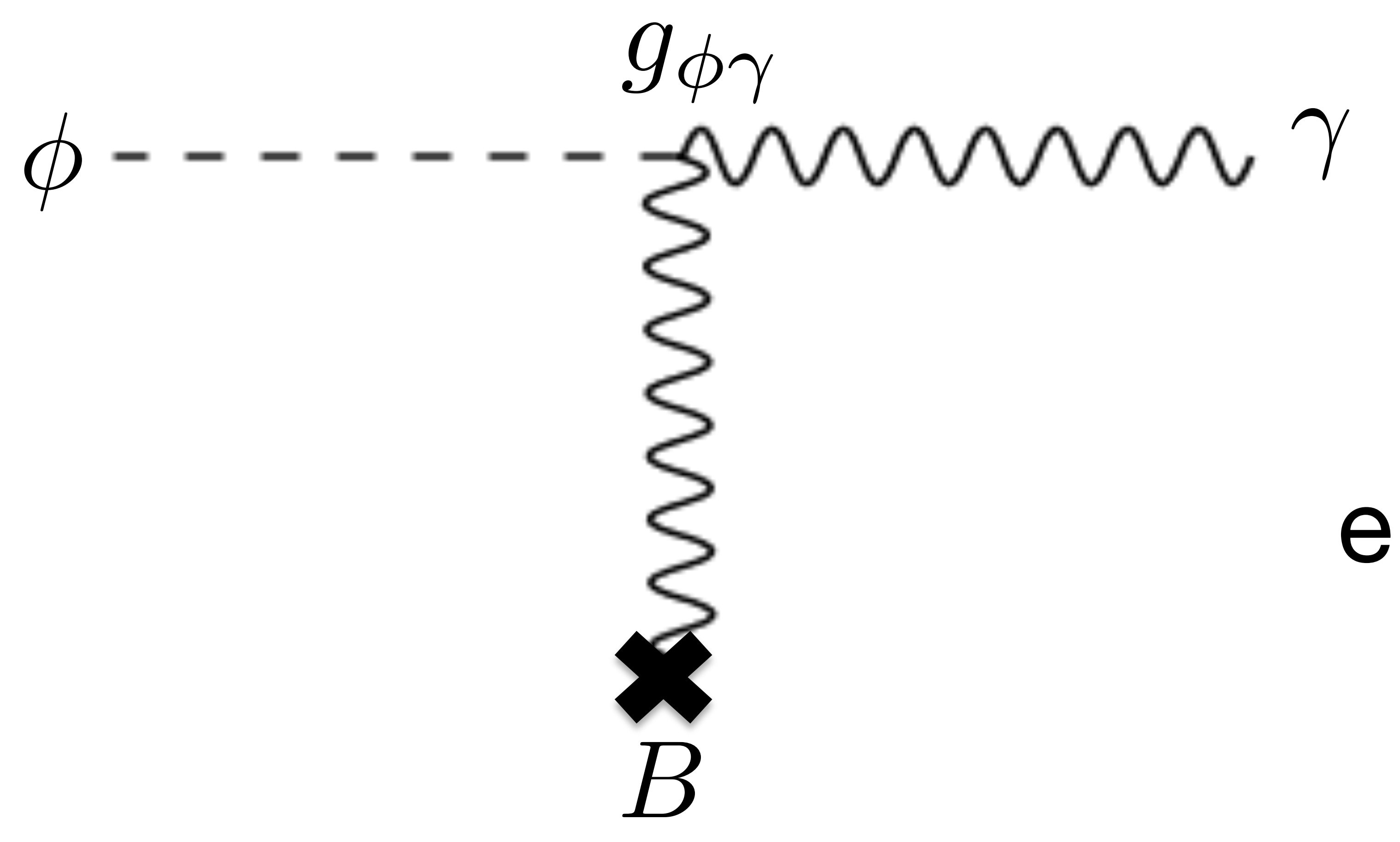
f_a decay constant



$\log_{10}(m_a/\mathrm{eV})$ **Marsh (2015)**

Axion Dark Matter

- Generic weak axion-photon coupling $L_{\phi\gamma\gamma} = g_{\phi\gamma\gamma}\phi F^{\mu\nu}\tilde{F}_{\mu\nu}$ => axion-photon conversion.

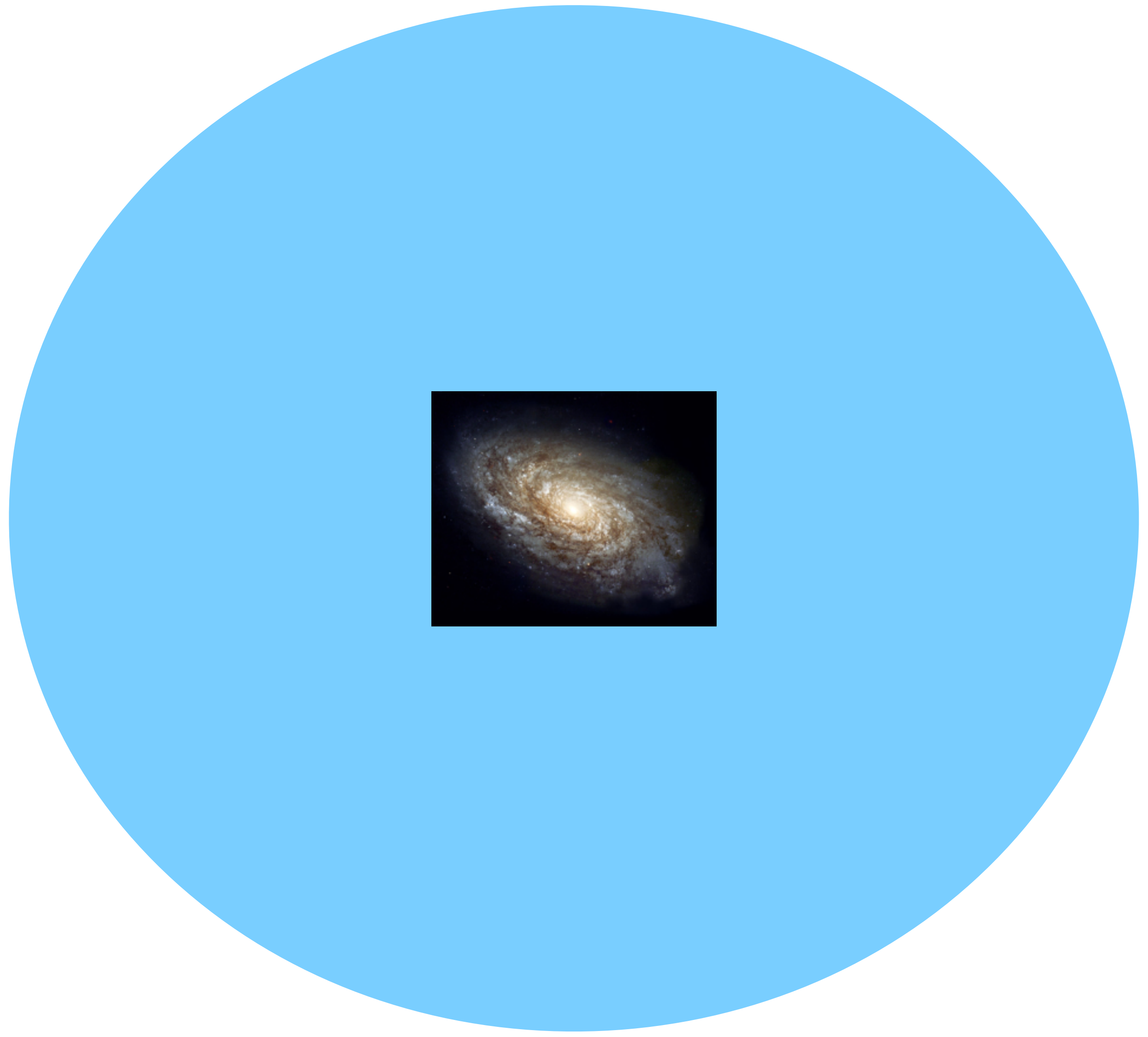


e.g. Primakoff Process

- Multi-messenger search : GW/gravity effects + photons. Usually requires presence of strong **B** fields.

Axion Dark Matter

- 2 possible behaviours as Dark Matter:



diffuse “ambient” non-relativistic halo

Axion Dark Matter

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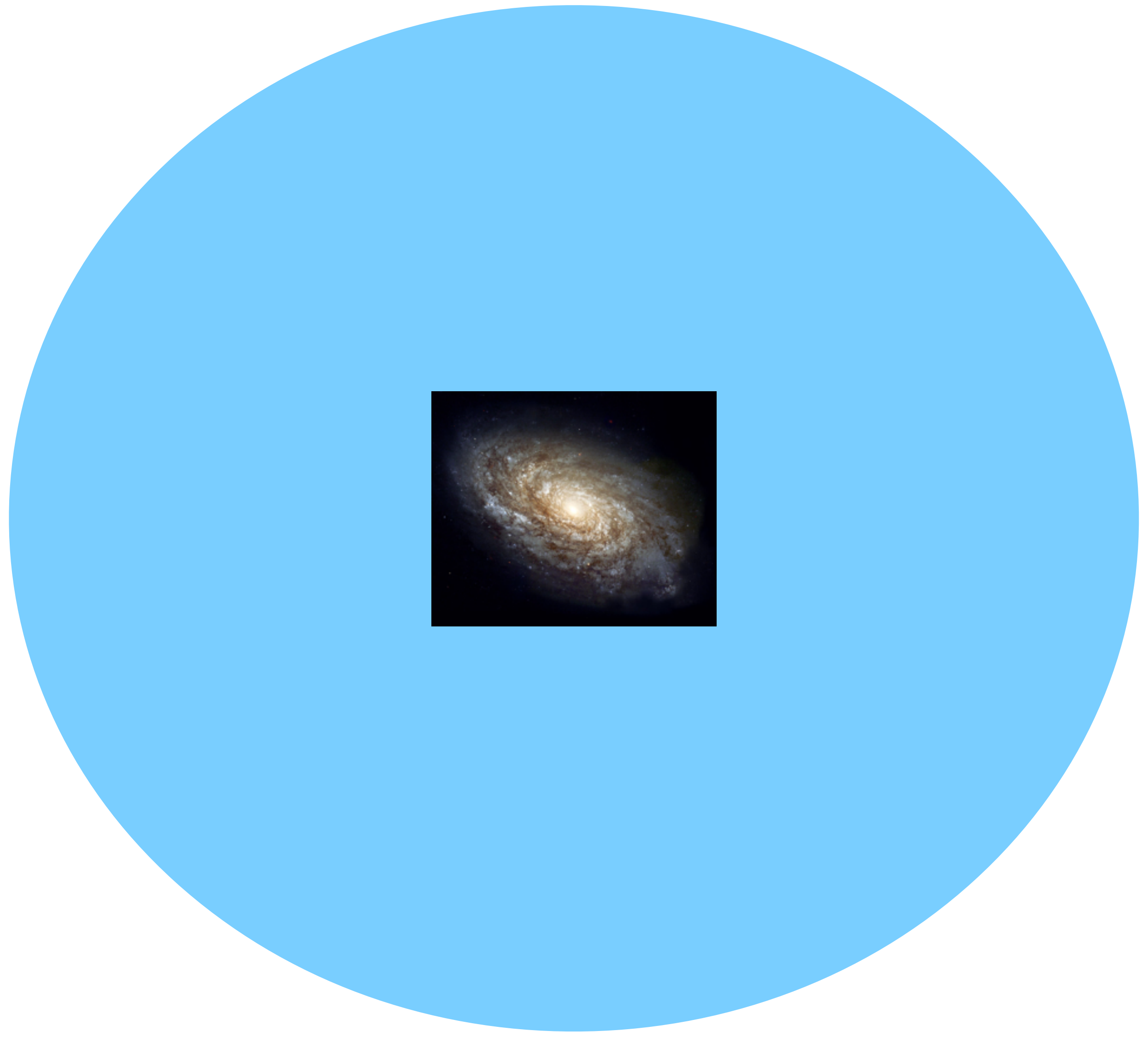
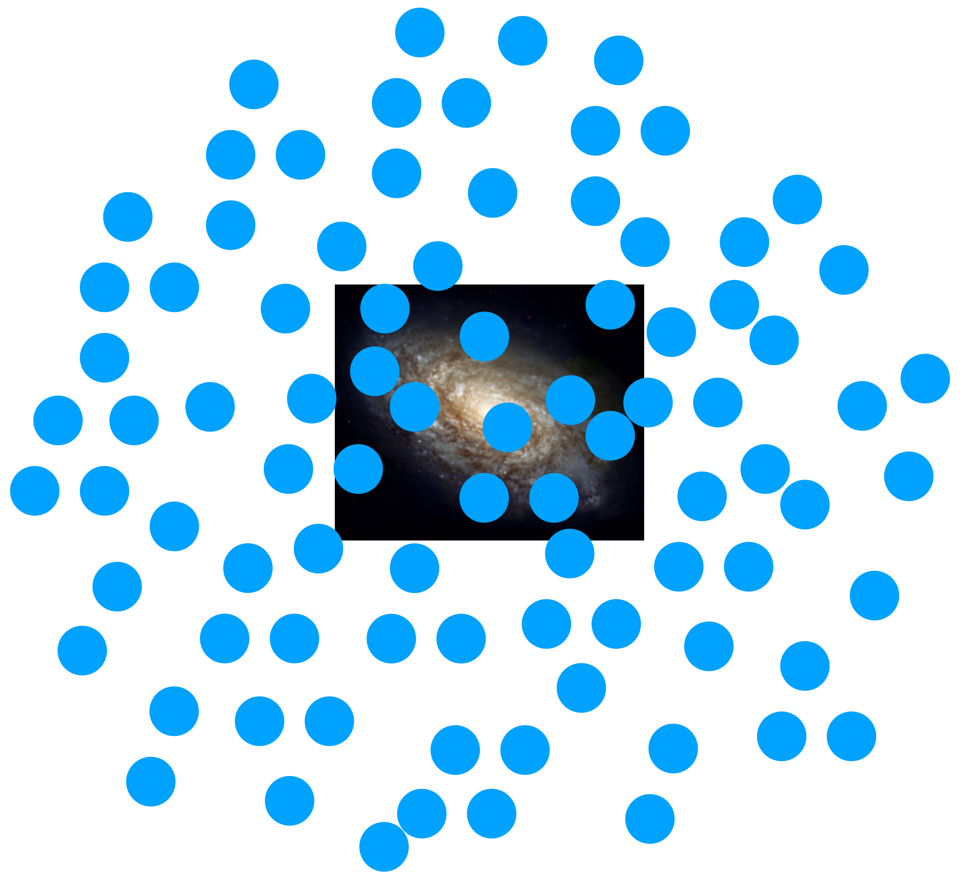


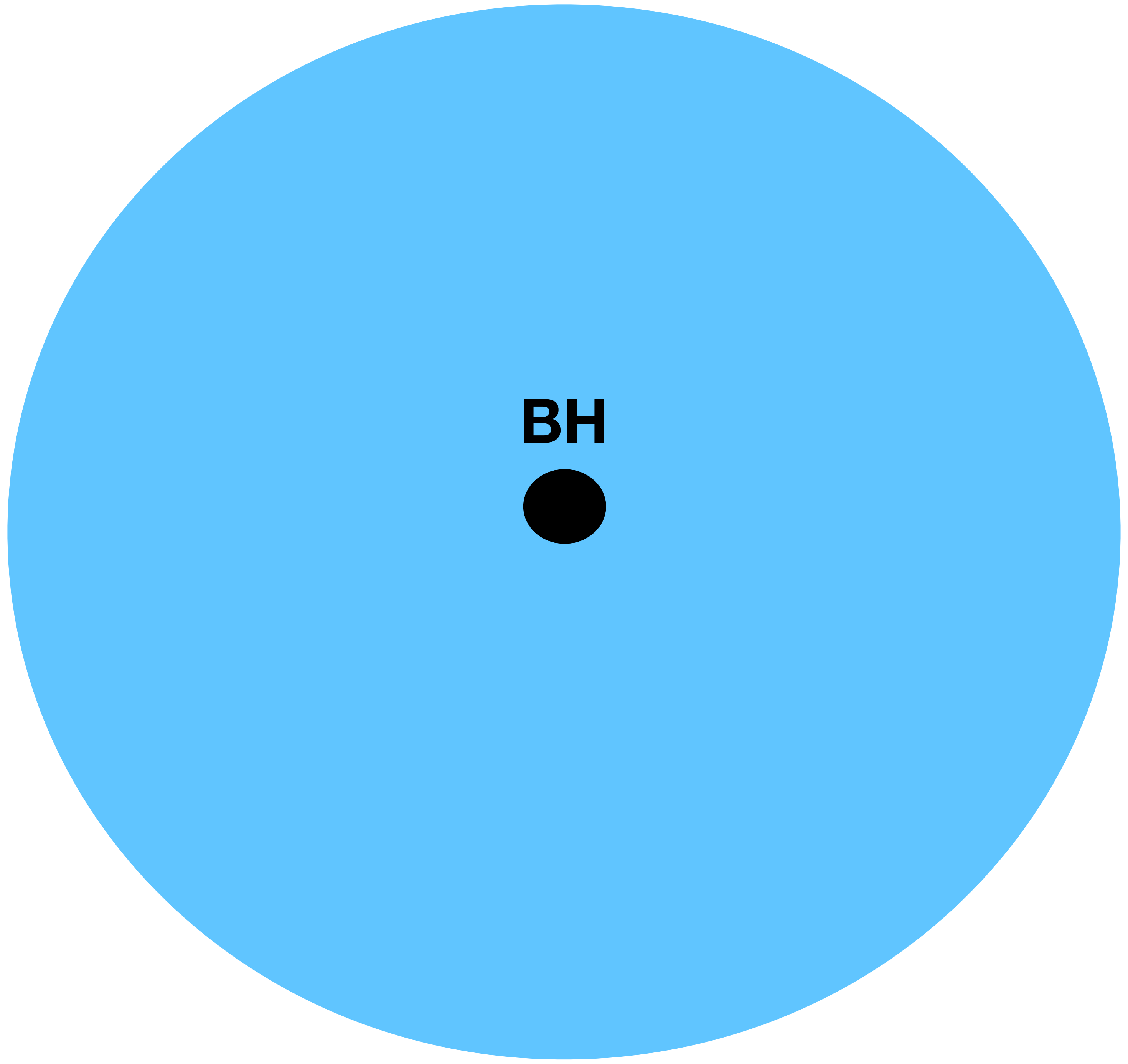
diffuse “ambient” non-relativistic halo



Halo of highly compact
relativistic “axion stars”

Radio + GW from BH-NS-Axions

Edwards, Chianese, Kavanaugh, Nissanke, Weniger (2020)



- Axions accrete around Intermediate Mass BH

$$M_{BH} = 10^3 \sim 10^4 \ M_\odot$$

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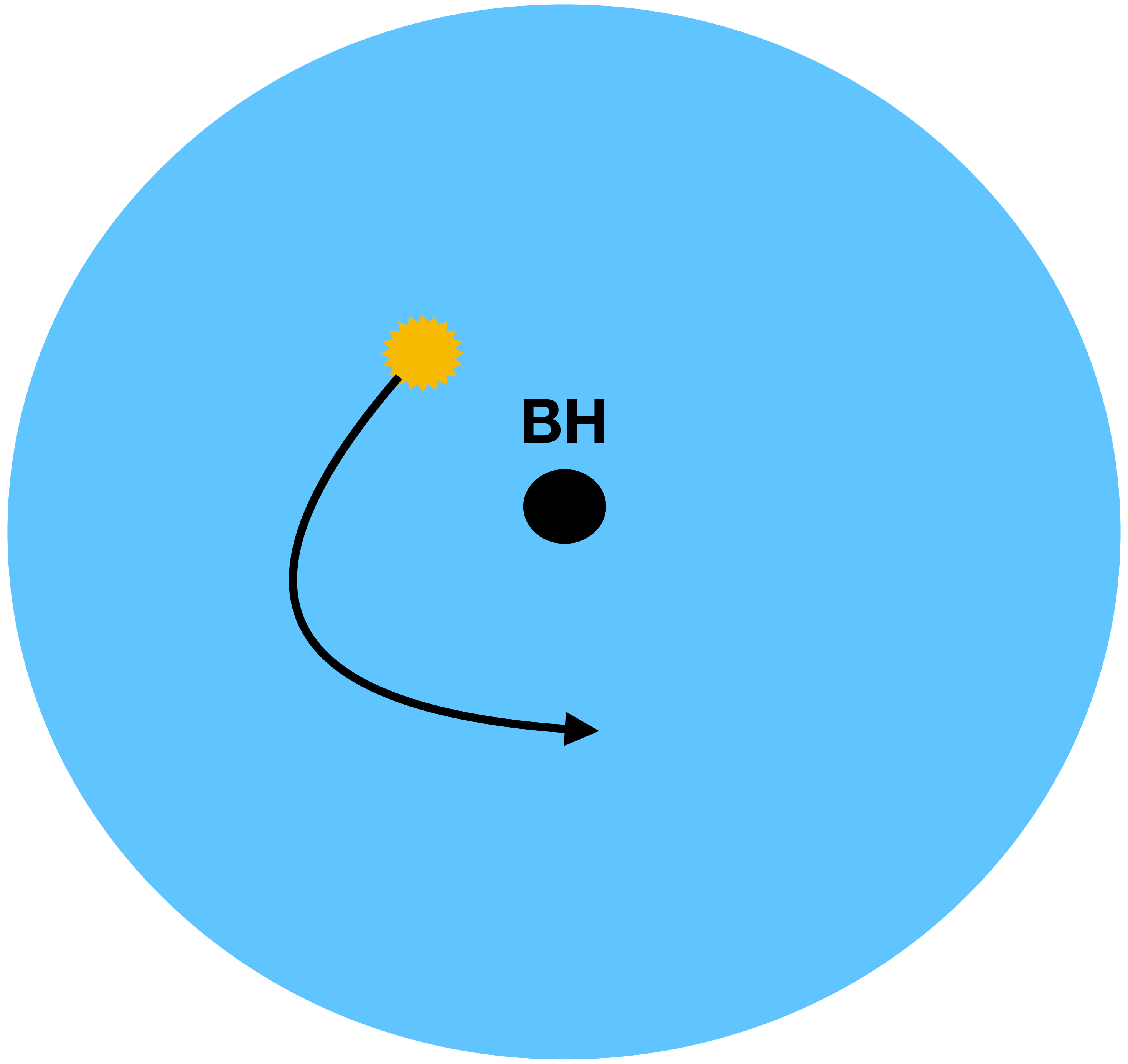

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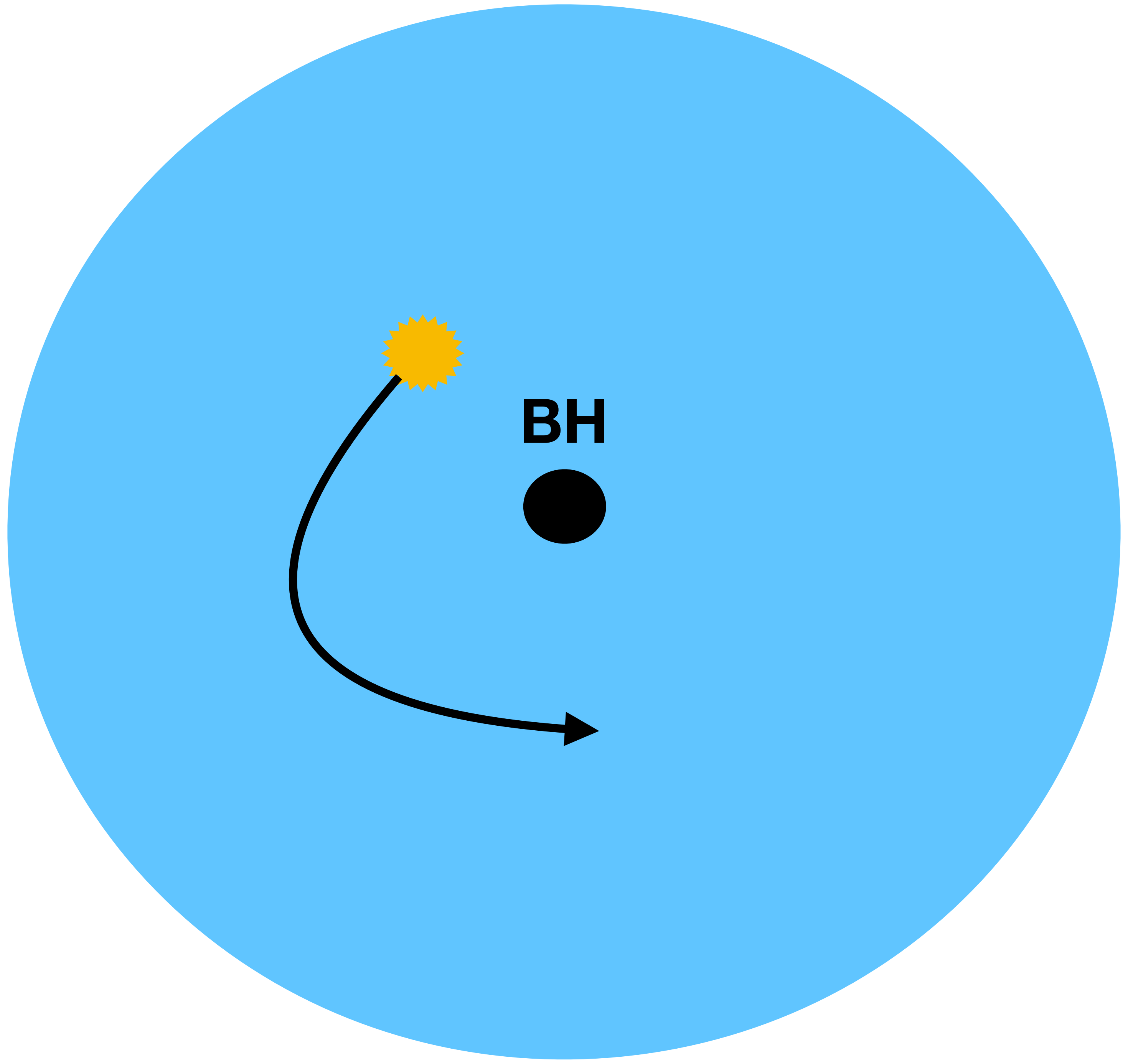

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- Due to dynamical friction with ambient axion field, NS orbit slows => change in phase of inspiral GW!

- Measuring phase change => probe Axion DM density.

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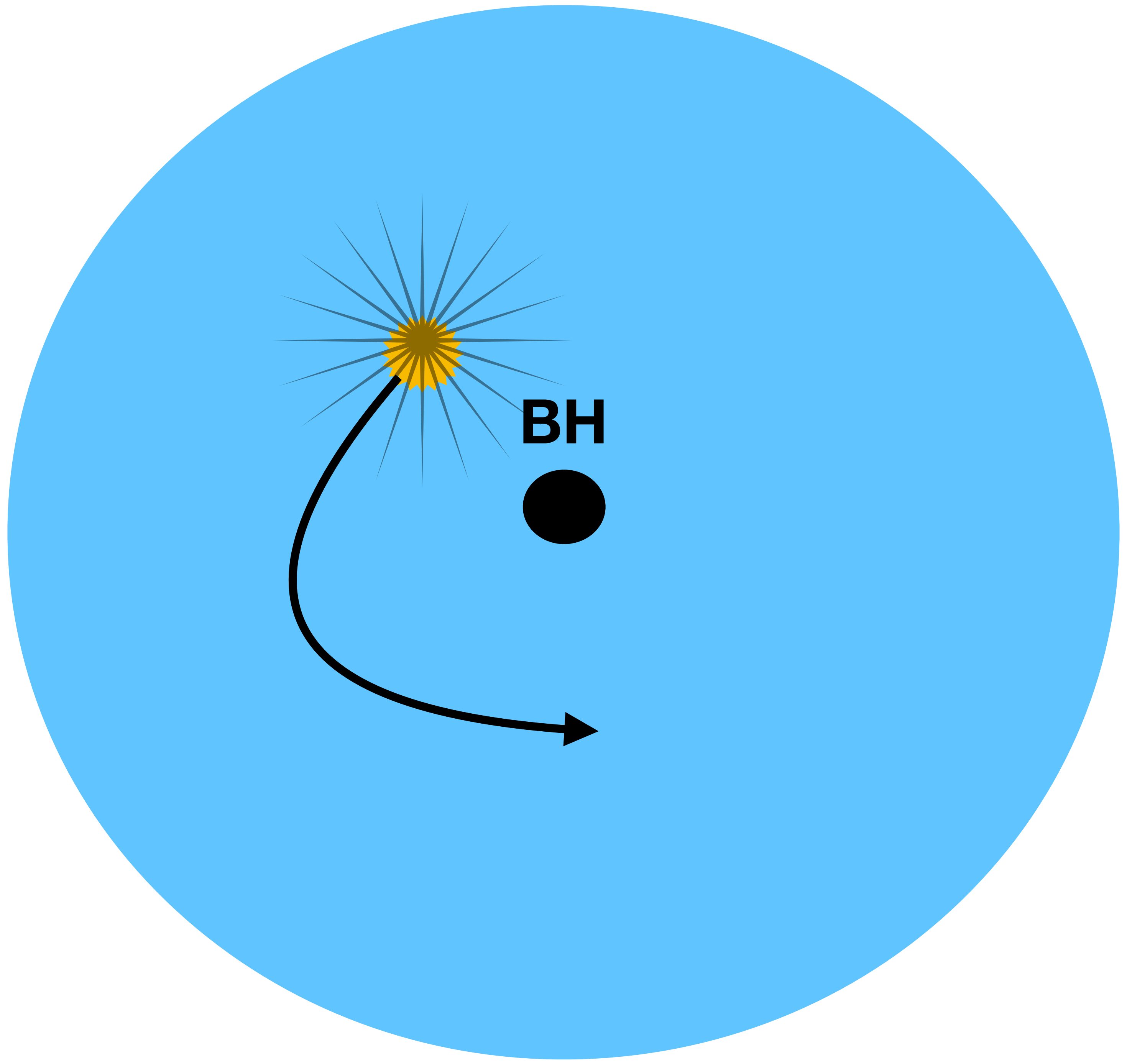

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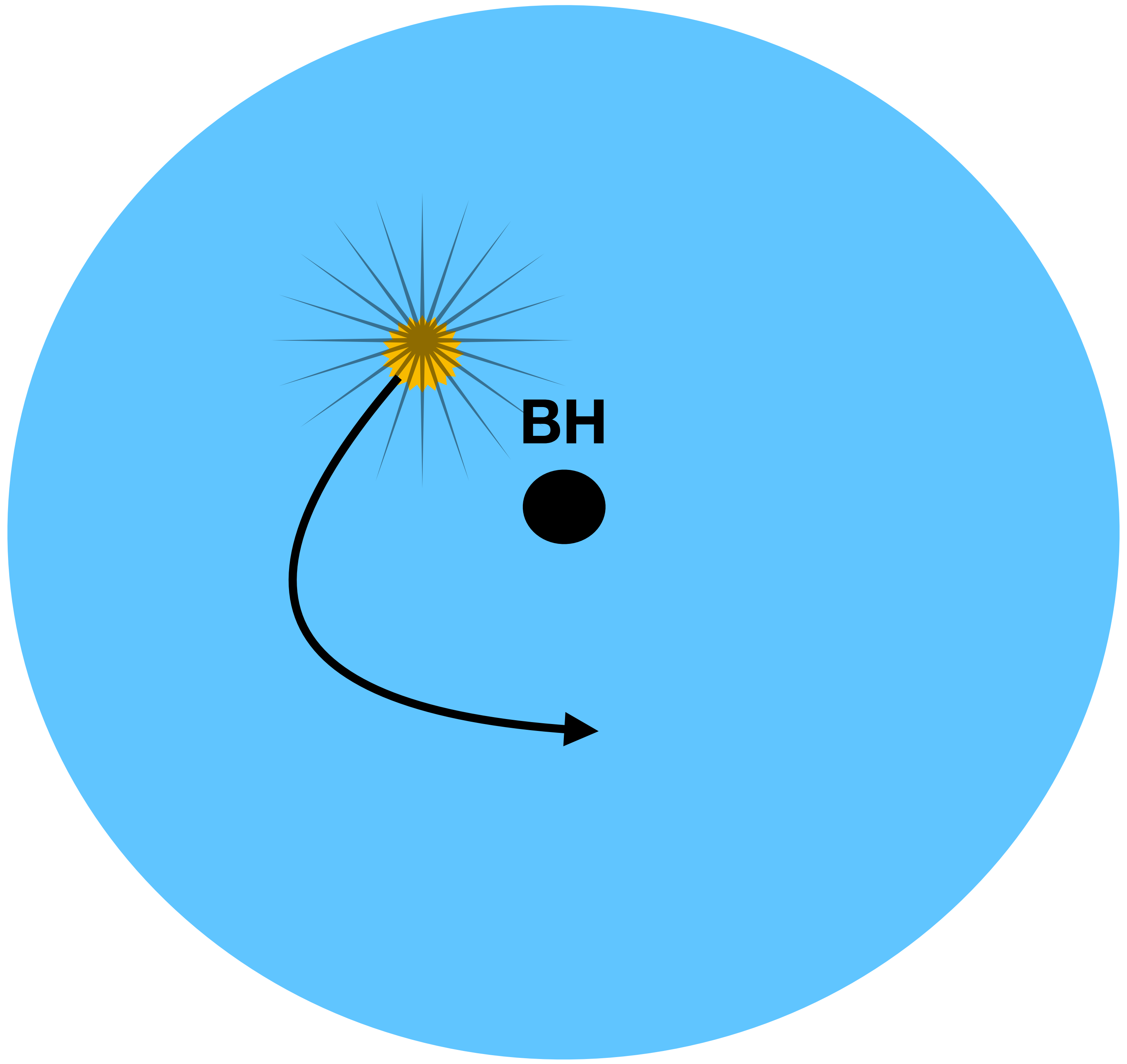

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Correlate : MM!

Radio + GW from BH-NS-Axions

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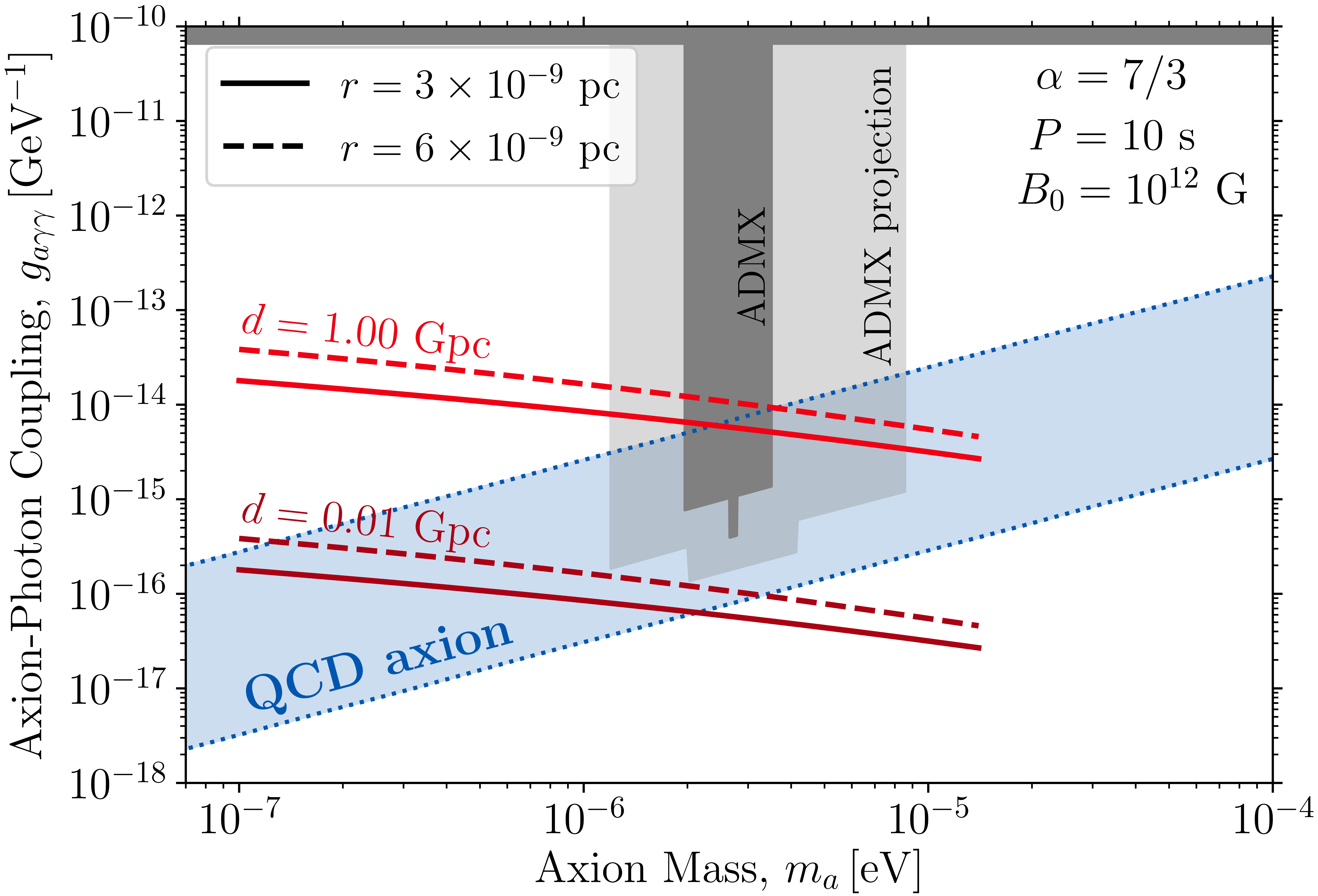
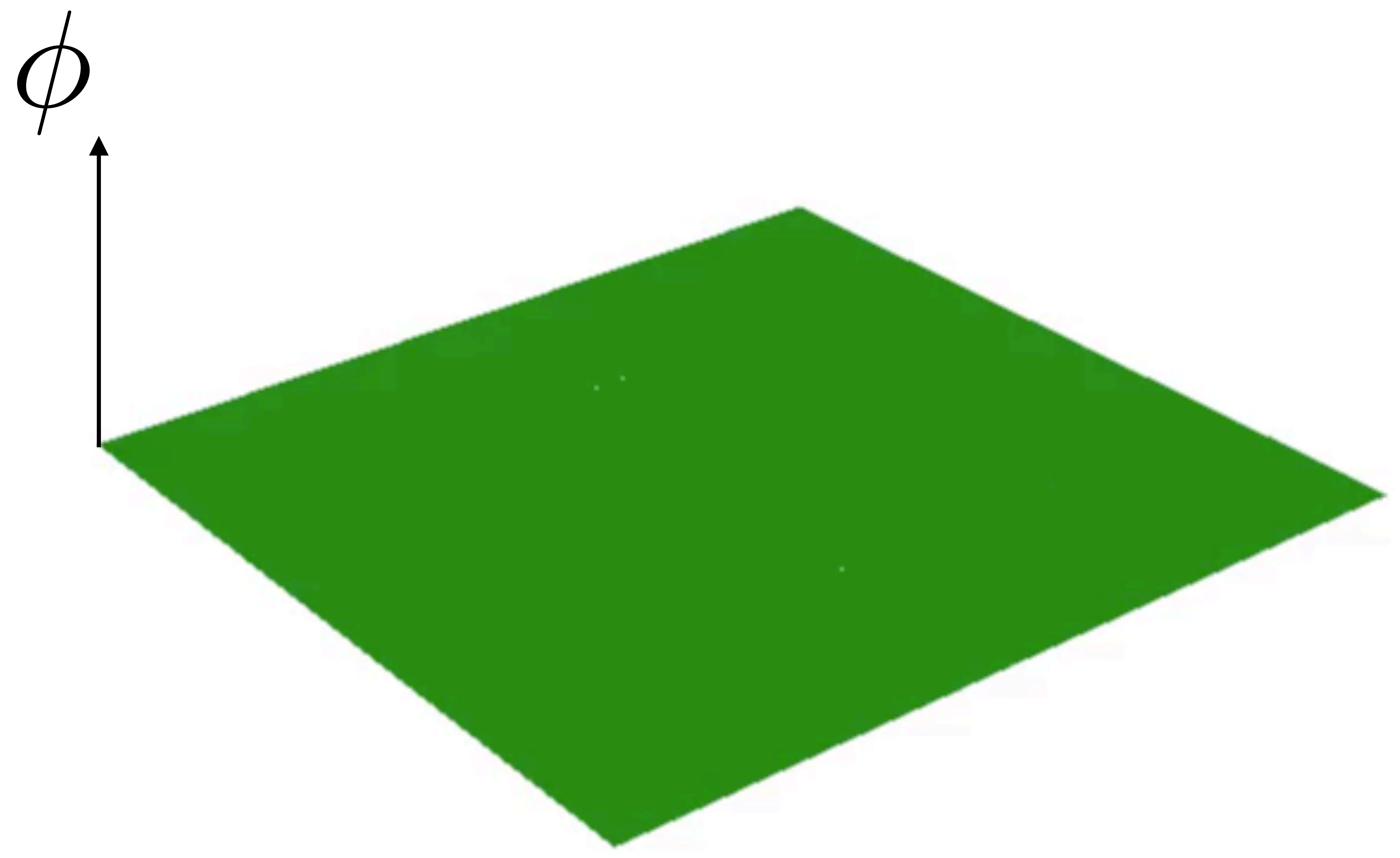
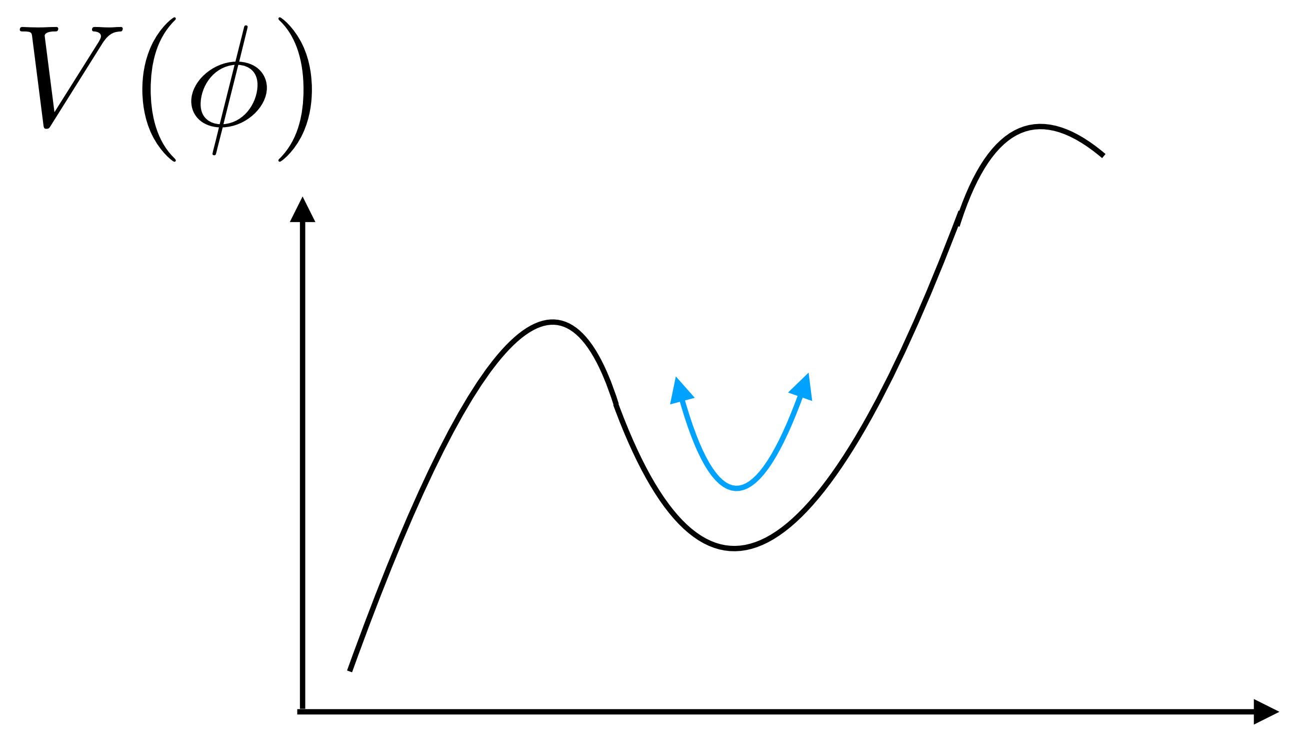


Axion Stars/ECOs

- Relativistic axions can *dynamically* form self-gravitating highly compact (~NS densities) “Axion Stars” or more generally **Exotic Compact Objects** (ECOs).





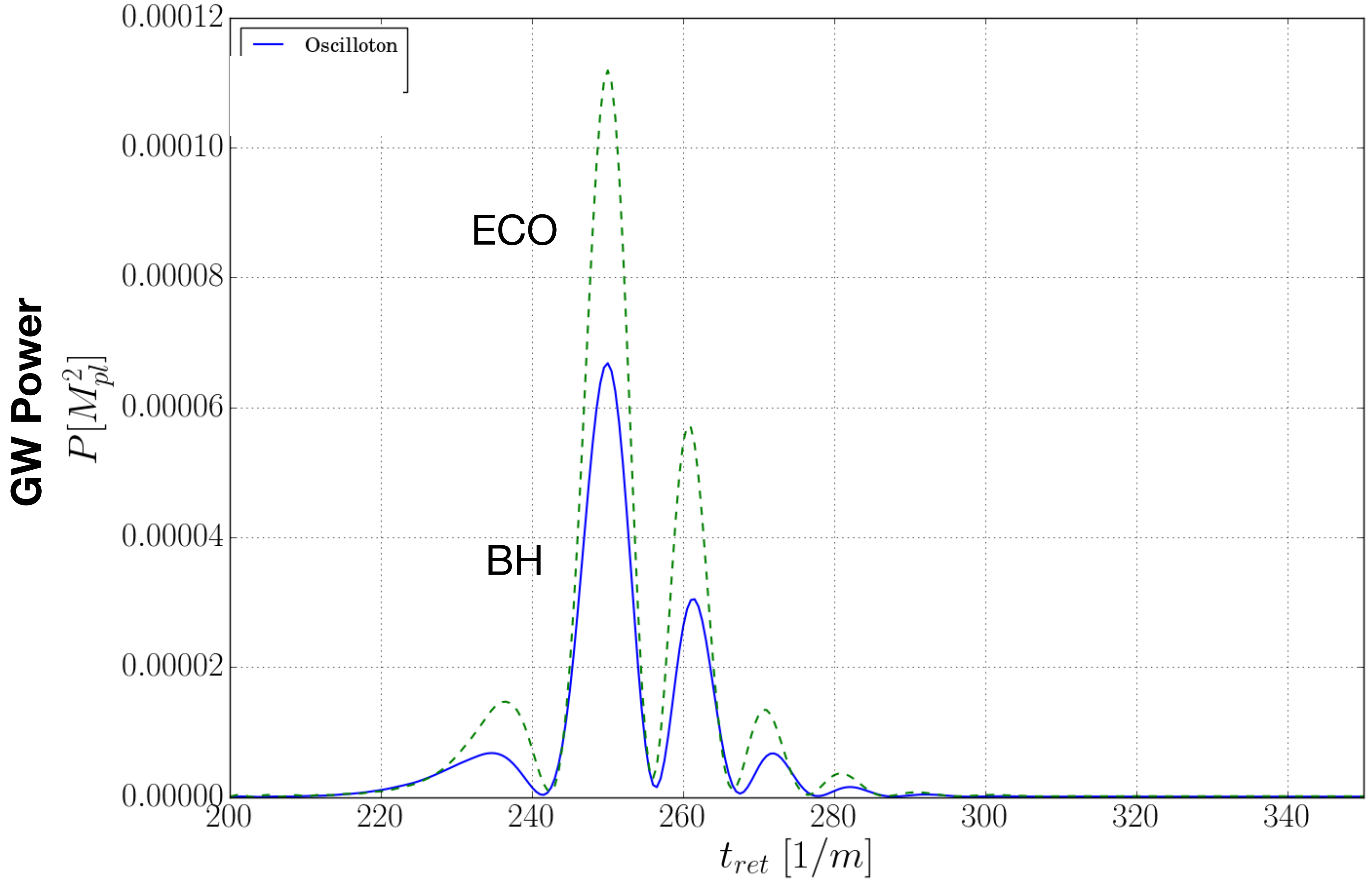
Helfer, Marsh, Clough, Fairbairn, Lim, Becceril (2016)
Widdicoombe, Helfer, Marsh, Lim (2018)

- aka Boson stars, oscillatons, solitons etc (nobody agrees on nomenclature!)

GW from Axion Star mergers

- Highly compact => merger generate GW. Solve using numerical relativity.
- Since Axion stars are "squishy", makes even more GW than equivalent BH-BH mergers!

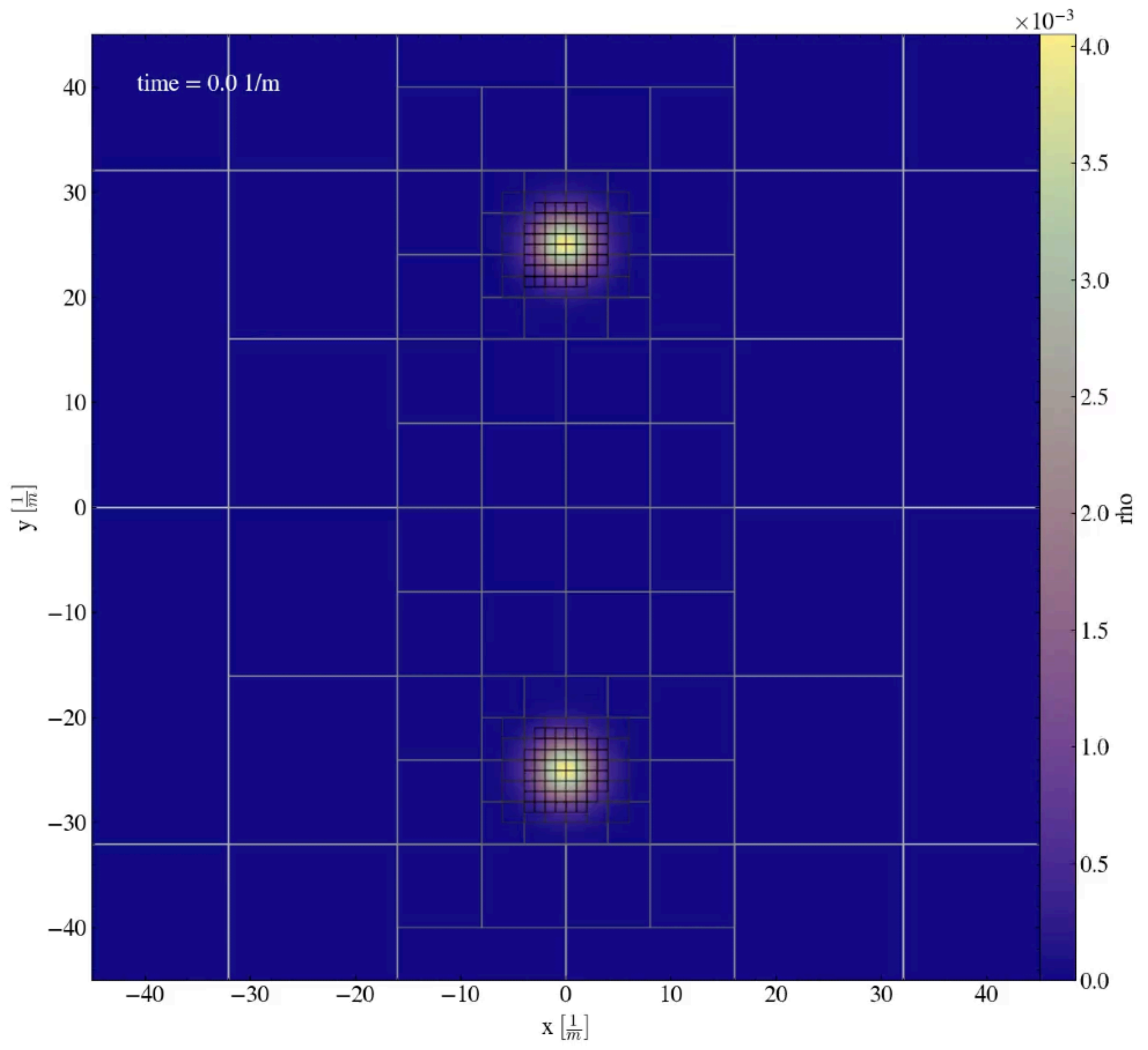
Helfer, Lim, Amin, Garcia (2018)

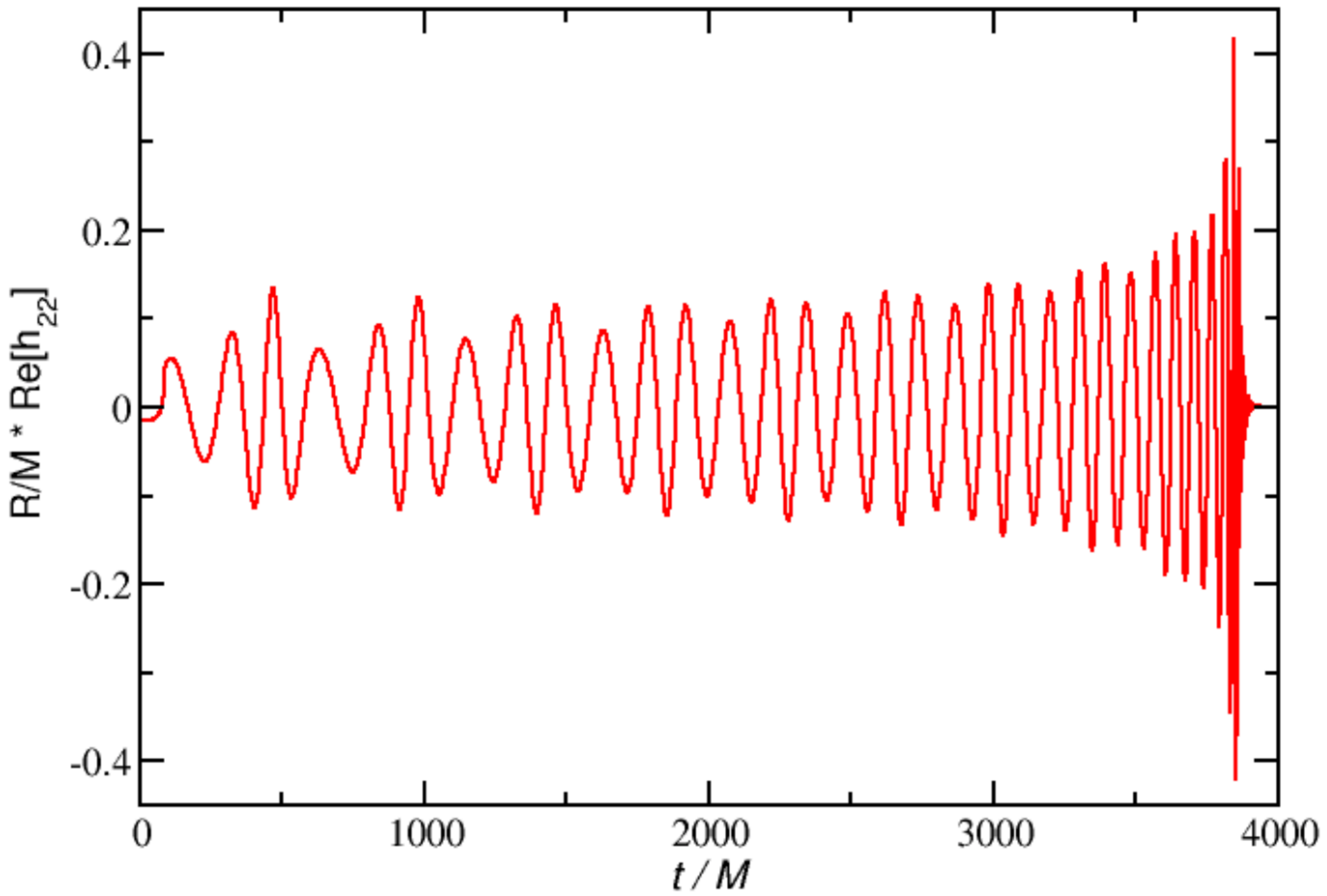


Head-on merger

GW from Axion Star mergers

- Stable axion star inspiral simulations is an unsolved problem (!), but recent big progress!





Helfer, Sperhake, Croft, Radia, Ge, Lim (2021 + WIP)

Radio emission from Axion Star

Levkov, Panin, Tkachev (2020)

- The axion field oscillate at characteristic frequency $\omega \sim m_a$

$$\partial_\mu \left(F^{\mu\nu} + g_{\phi\gamma\gamma} \phi \tilde{F}^{\mu\nu} \right) = \partial_\mu \left(F^{\mu\nu} + \boxed{g_{\phi\gamma\gamma} \phi_0 \cos(m_a t) \tilde{F}^{\mu\nu}} \right) = 0$$

parametric pumping

$$\text{Photon Flux } F_\gamma \propto \exp[\mu t] \qquad \mu = f_a m_a g_{\phi\gamma\gamma} |\phi_0|$$

Floquet const.

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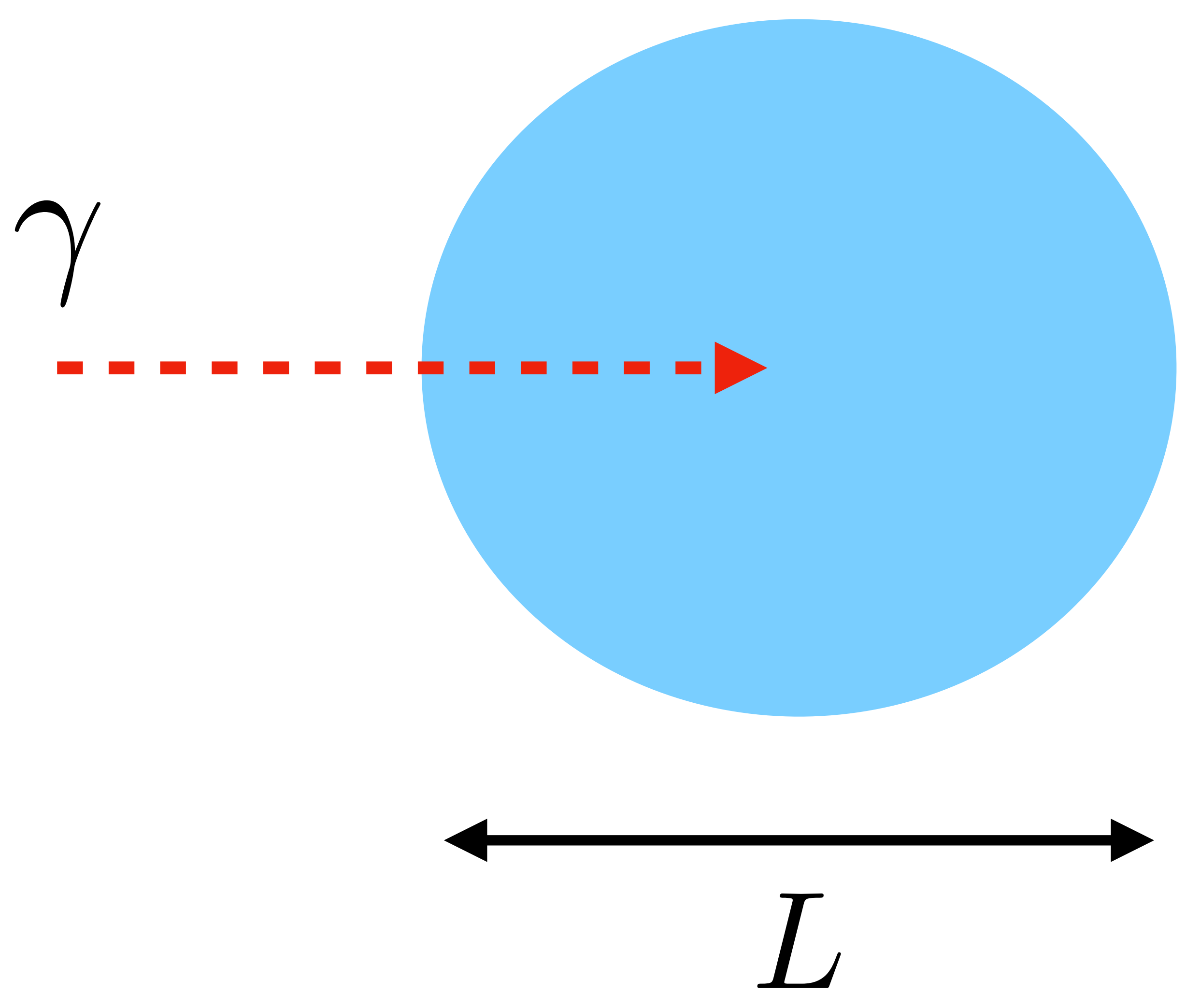


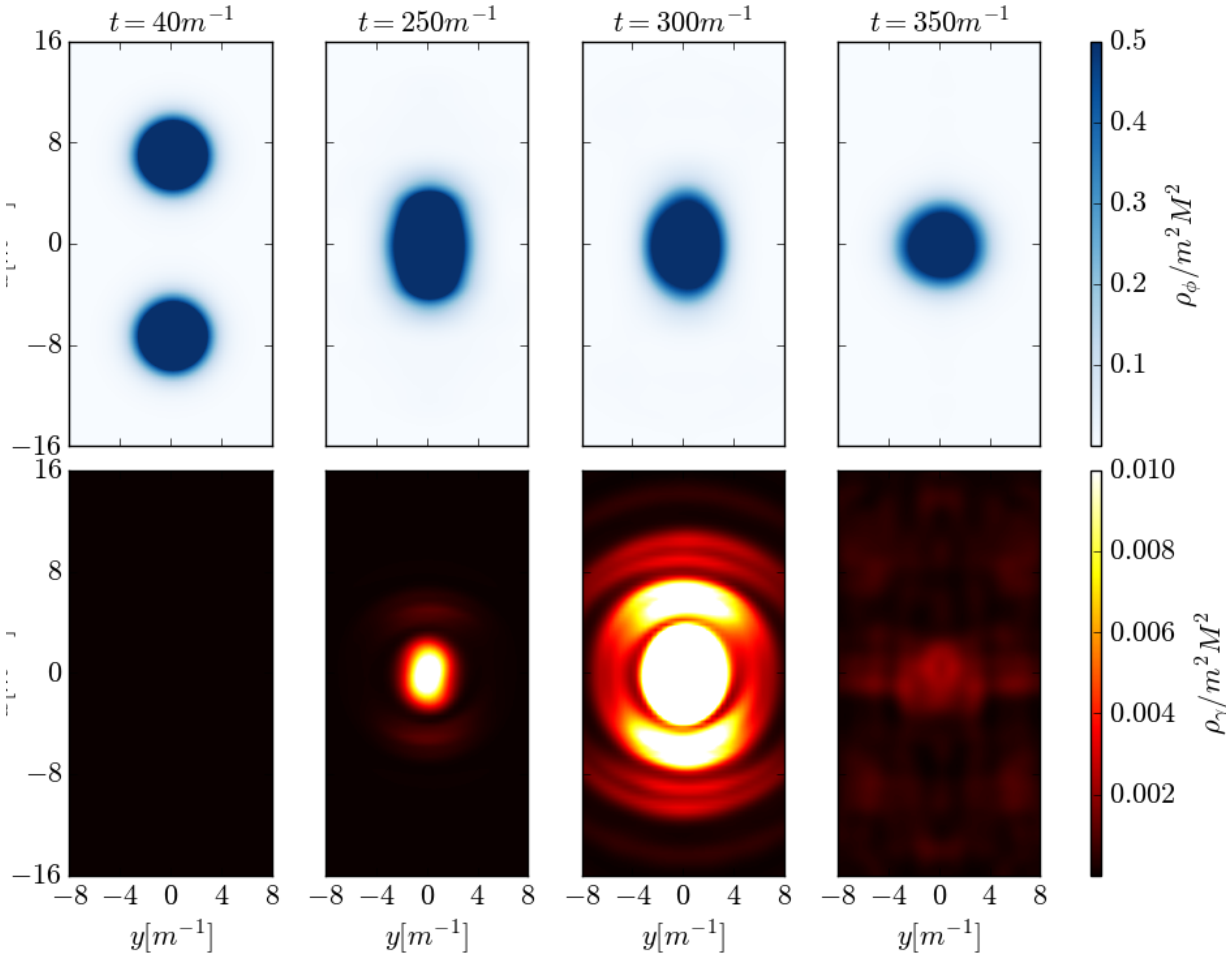
- So pumping occurs if photon stays in Star long enough to trigger a single $\phi \to \gamma\gamma$

$$\mu L > 1$$

Radio bursts from Axion Star mergers

Amin + Zong (2020)

- Mergers of two axion stars can also trigger resonance ‘bursts’



- Only computed for non-relativistic stars. GW needs relativistic stars => **stay tuned!**

Other MM Possibilities?

- Cosmic Strings : GW and EM emissions?
- Stochastic GW + Relics from Electroweak phase transitions?
- SGW from primordial black hole mergers and microlensing of MACHOs?
- Cosmological Neutrino Background to go with CMB and CGWB?
- Many others — I am 100% sure I have missed a lot!

Final thoughts

- Presently focused on EM and GW messengers
- Cosmological neutrinos may be on the cusp of being useful (TXS0506-056).
- Strong force messengers are under-developed (it can be useful : BBN!)

Multimessenger Cosmology is very new and mostly undefined : we have a chance to decide what it is!

A message from Drake

Thank you!