Multi-messenger Astrophysics

IceCube Summer School
1 June 2026

Keith Bechtol
UW-Madison

Multi-messenger Astrophysics Defined

Multi-messenger Astrophysics is the scientific discipline of combining astronomical observations using multiple "messengers" — particle species (e.g., photons, nuclei, electrons, neutrinos) and gravitational waves — to advance physical understanding of objects in the cosmos and the fundamental laws of nature

Particle Physics Basis for Multi-messenger Astrophysics

Interactions of relativistic cosmic ray nuclei intrinsically involve multiple particle species

At high energies, **proton-proton collisions** produce three pion states in roughly equal ratios $\pi^0 : \pi^+ : \pi^- \approx 1 : 1 : 1$

$$p + p \rightarrow p + p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$ branching ratio 0.99

$$p + p \rightarrow p + p + \pi^+ + \pi^-$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

branching ratio 0.9999

Subsequent pion decays produce both photons (gamma rays) AND neutrinos

Particle Physics Basis for Multi-messenger Astrophysics

Interactions of relativistic cosmic ray nuclei intrinsically involve multiple particle species

Next, consider **photo-hadronic interactions** of cosmic ray nuclei with radiation fields

Near the energy threshold for pion production, single-pion production from baryon resonance decay dominates, followed by direction production

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

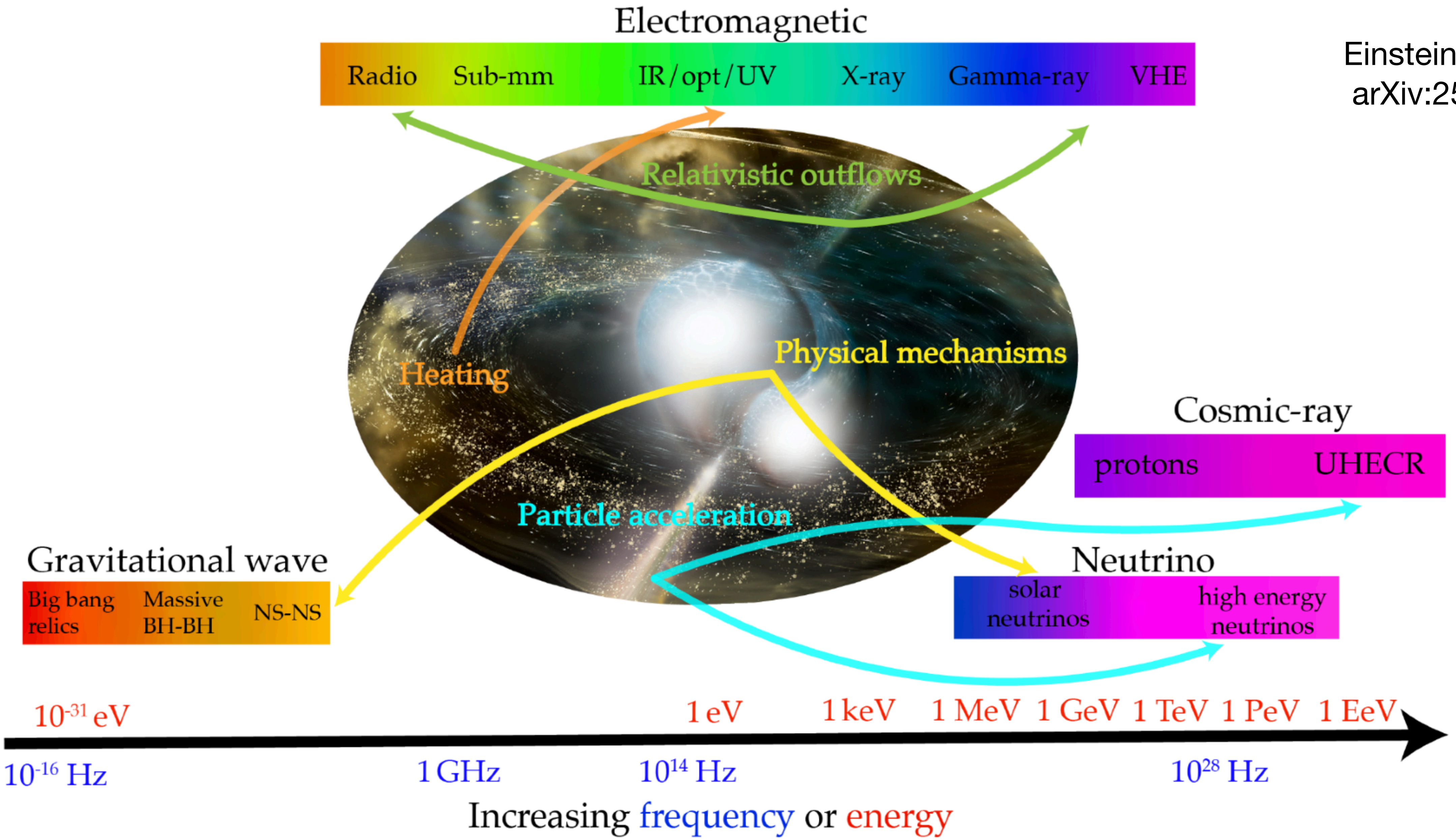
At higher energies, multi-pion production dominates, with pion multiplicities increasing as a function of incoming proton energy, producing π^+ , π^0, and π^-

$$\pi^0 \rightarrow \gamma + \gamma \qquad \pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

In both cases, pion decays produce both photons (gamma rays) AND neutrinos

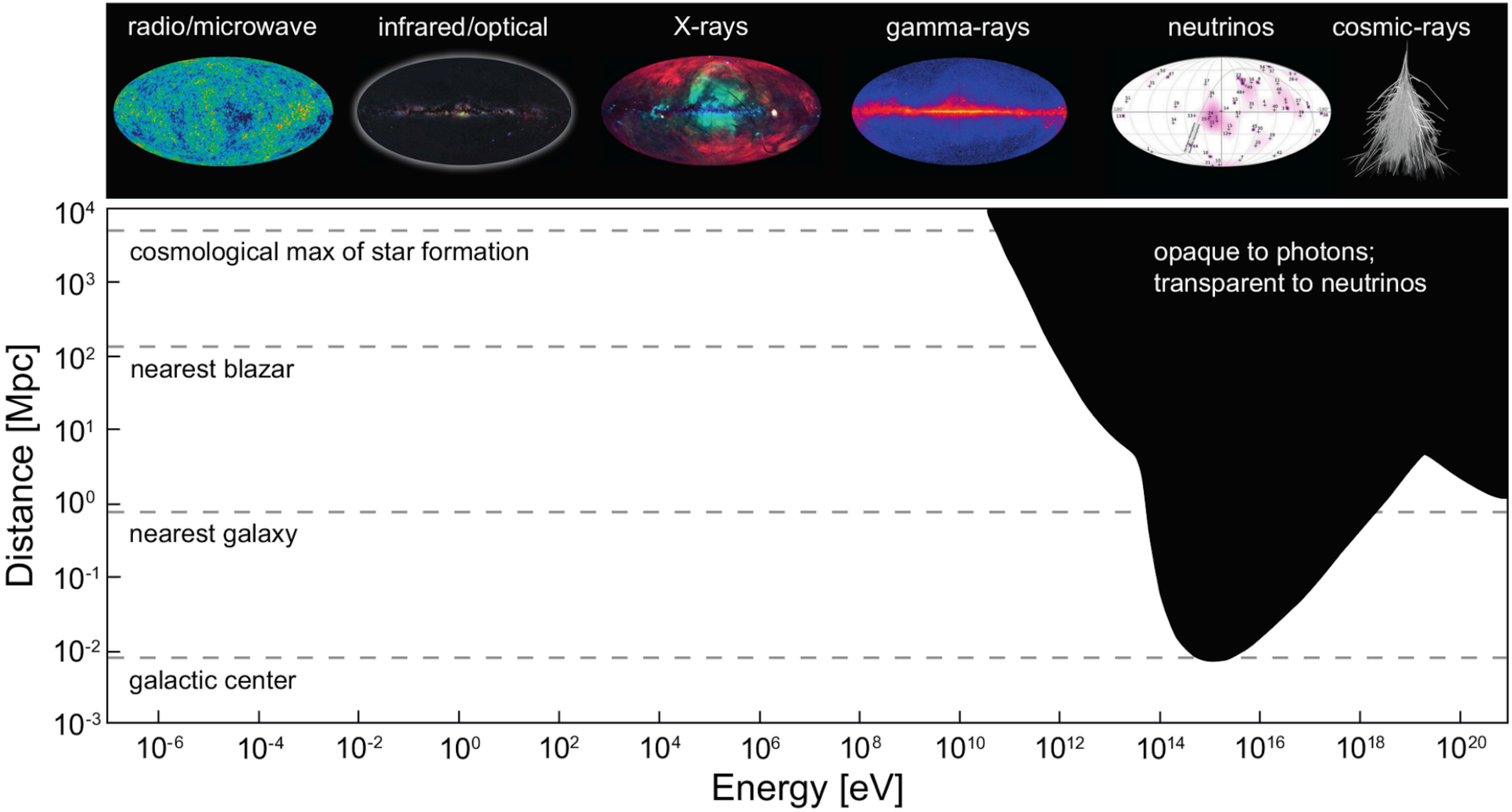
“Common Environment” Basis for Multi-messenger Astrophysics

Einstein Telescope
arXiv:2503.12263



Extreme densities, magnetic field strengths, bulk relativistic outflows, inspiraling and/or rapidly rotating massive compact objects, …

Use Neutrinos and Gravitational Waves to see “Hidden” Sources across the Universe



https://icecube-gen2.wisc.edu/science/publications/tdr/

Universe is opaque to the highest energy photons and cosmic rays

pair production

$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

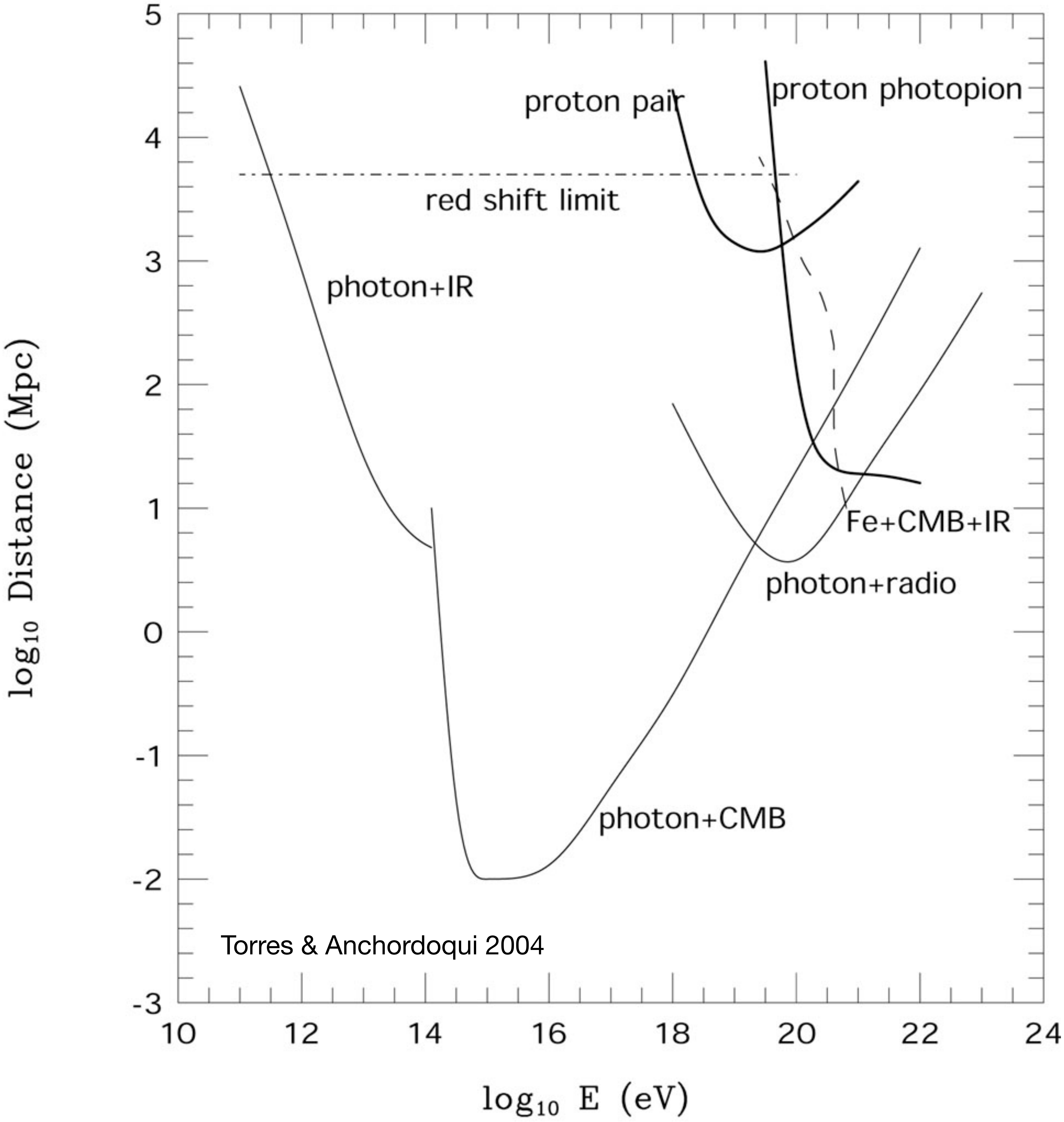
Bethe-Heitler pair production

$$p + \gamma \rightarrow p + e^{+} + e^{-}$$

photo-pion production

$$p + \gamma \rightarrow \Delta \rightarrow p + \text{pions}$$

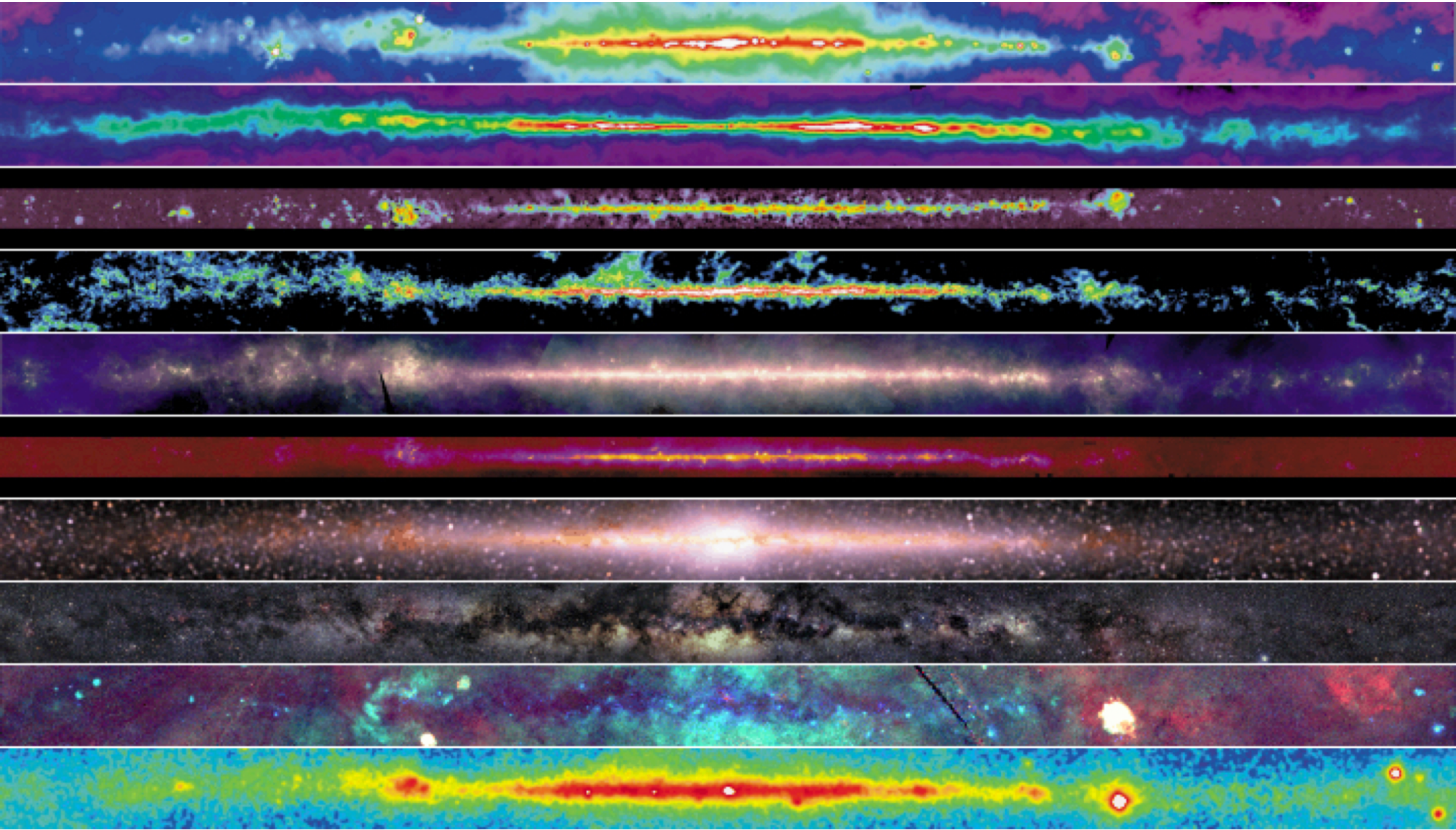
Universe is transparent to neutrinos and gravitational waves



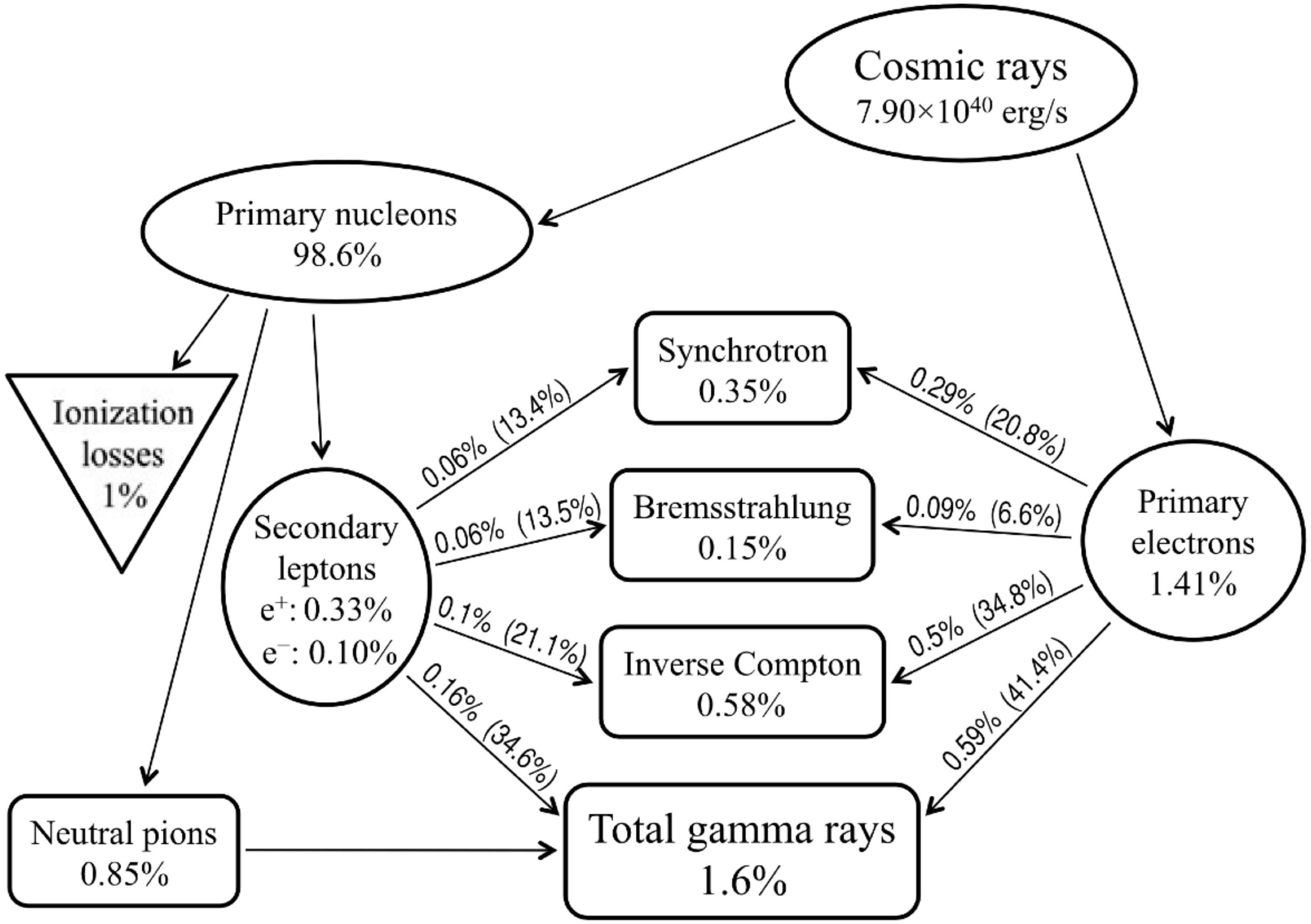
Torres & Anchordoqui 2004

Multi-messenger view of the Milky Way

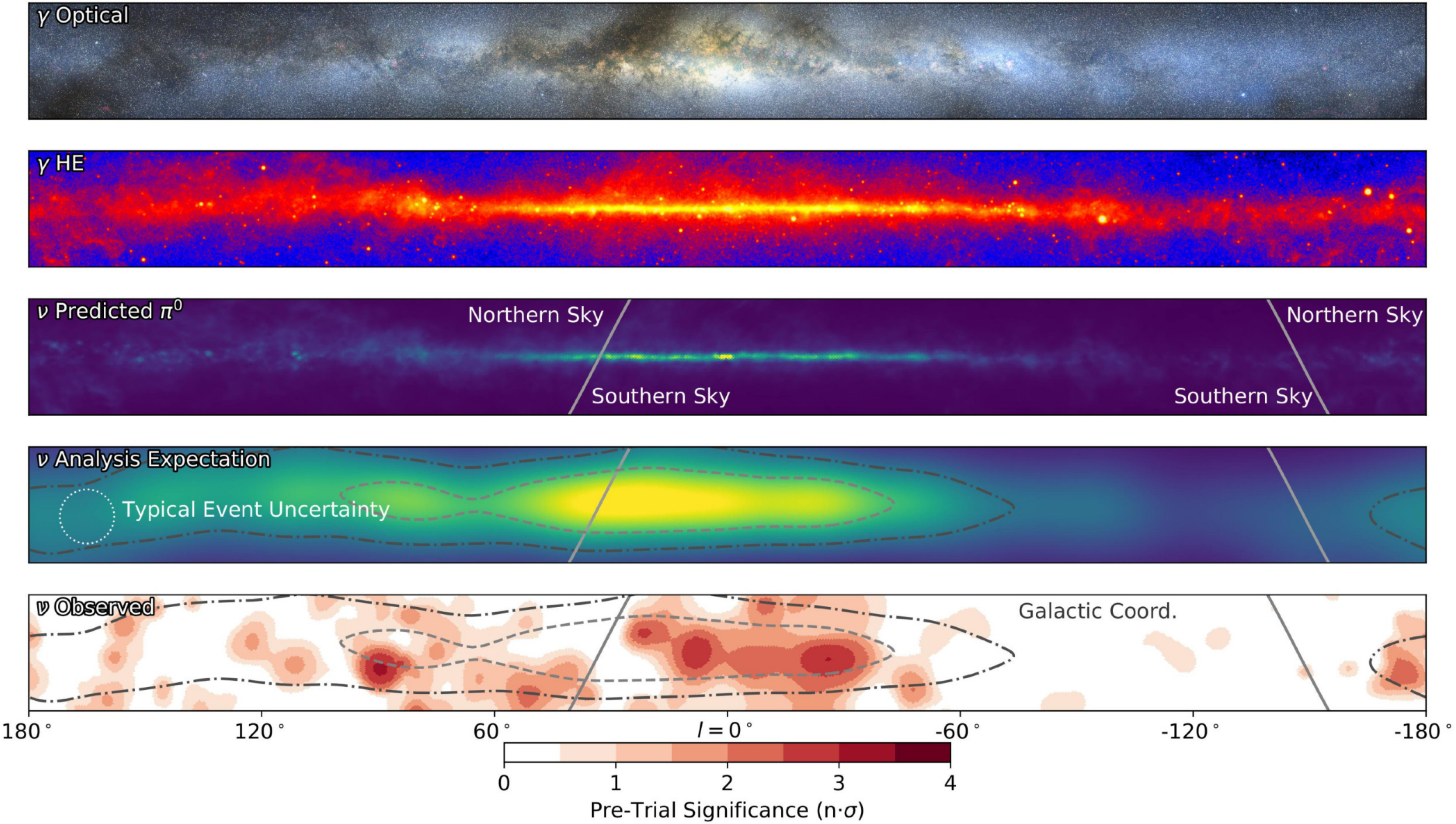
Multi-messenger view of the Milky Way



Multi-messenger view of the Milky Way

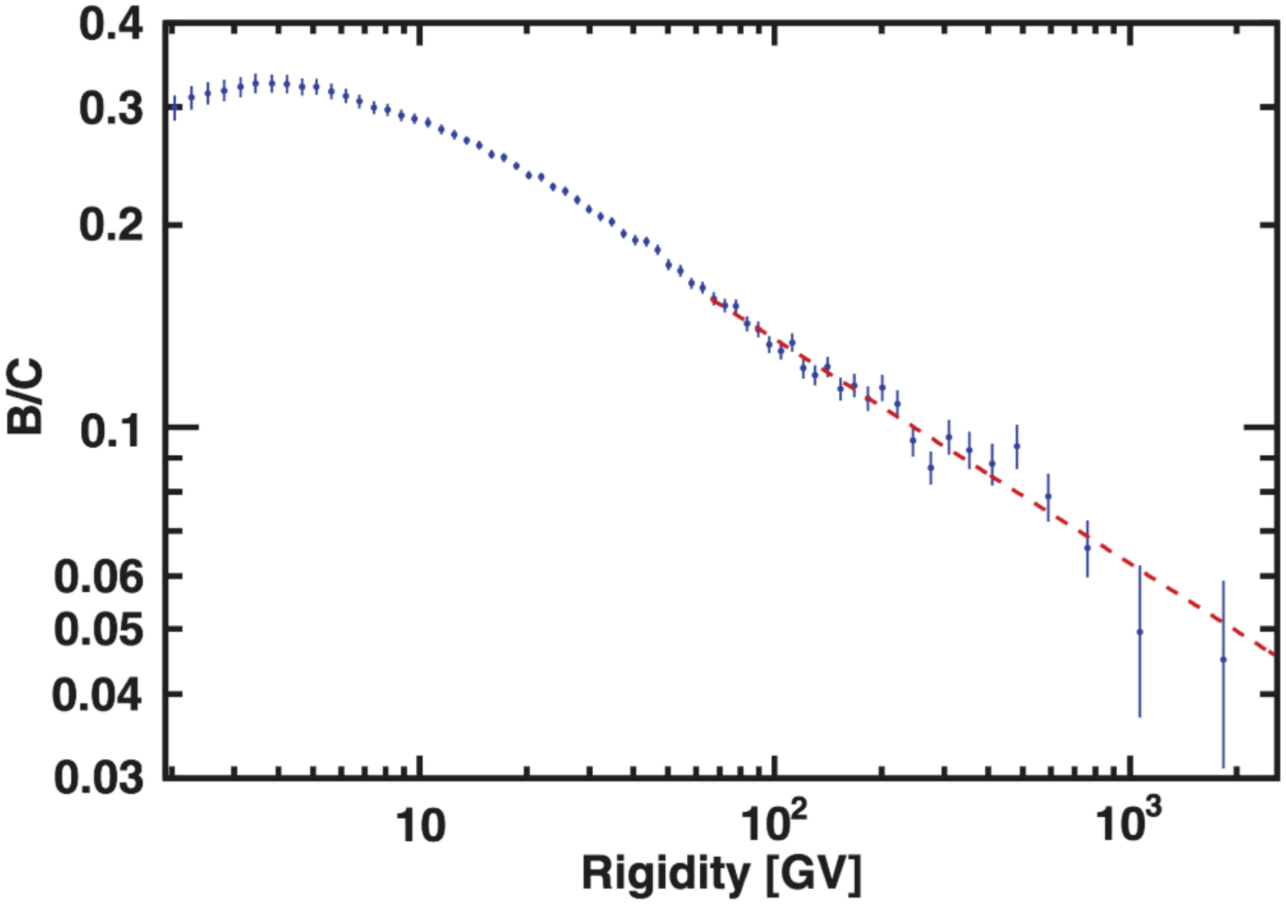


Strong et al. 2010


γ Optical
γ HE
ν Predicted π^0
Northern Sky
Southern Sky
Northern Sky
Southern Sky
ν Analysis Expectation
Typical Event Uncertainty
ν Observed
Galactic Coord.
180°
120°
60°
l = 0°
-60°
-120°
-180°
0
1
2
3
4
Pre-Trial Significance (n·σ)

Insights from Measurements of Multiple Cosmic-ray Species

Carbon nuclei in cosmic rays are thought to be mainly produced and accelerated in astrophysical sources, while boron nuclei are entirely produced by the collision of heavier nuclei, such as carbon and oxygen, with nuclei of the interstellar matter. Therefore, the boron to carbon flux ratio (B=C) directly measures the average amount of interstellar material traversed by cosmic rays

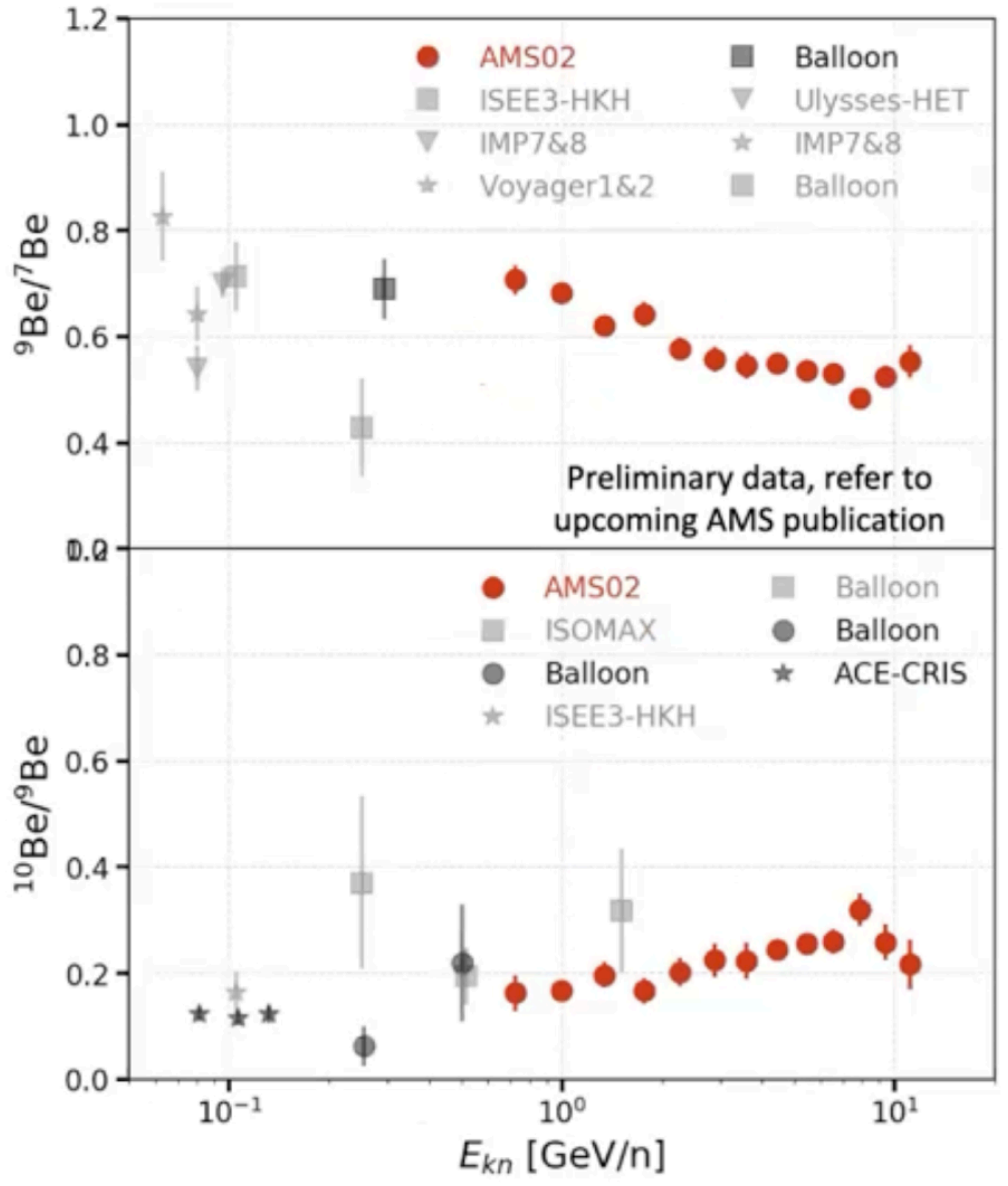


AMS Collaboration 2016

Normalization: Grammage around 10 g cm–2 for particles with an energy of about 10 GeV per nucleon

Energy dependence: cosmic rays diffusing on magnetized plasma of the Milky Way dependence of -1/3 in excellent agreement w/ prediction from Kolmogorov
theory of interstellar turbulence

Insights from Measurements of Multiple Cosmic-ray Species



AMS Collaboration 2021 ICRC

^{10}Be is the highest isotope with half-life comparable to the residence time of Milky Way cosmic rays

^{10}Be is radioactive nucleus with half-life tau = 1.39 x 10^6 yr

^{9}Be is stable

Beryllium are expected to be mainly produced by the fragmentation of primary cosmic rays (CR) during their propagation

“Breakthrough” Science Opportunities in Multi-messenger Astrophysics
(10-20 year timeframe)

What is the nature of hidden cosmic ray accelerators?

What is the physics of stellar core collapse and central engine of supernova explosions?

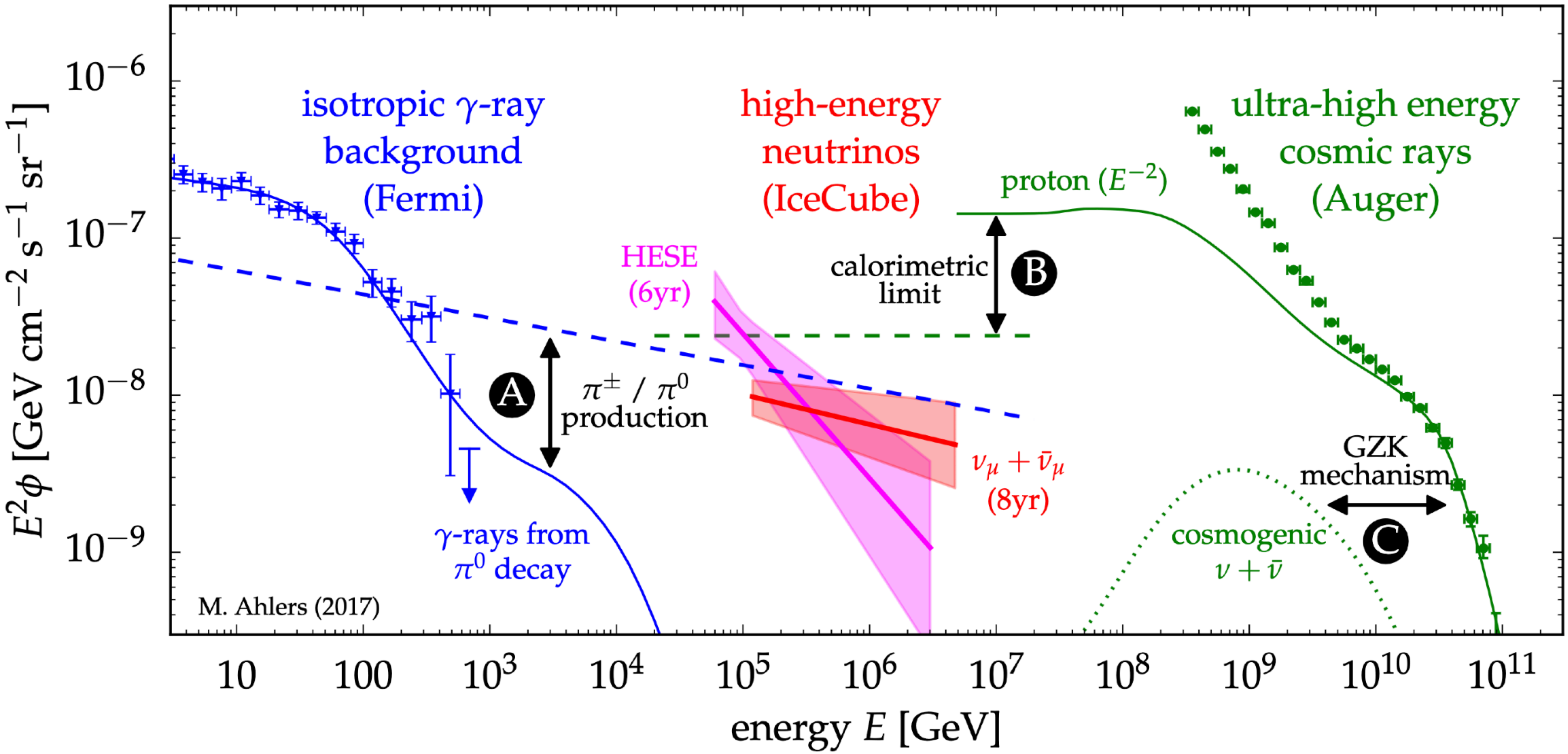
What is the physics of matter at extreme densities? How are heavy elements synthesized in nature?

How did supermassive black holes form?

Can we use gravitational wave “standard sirens” to constrain the cosmic expansion history?

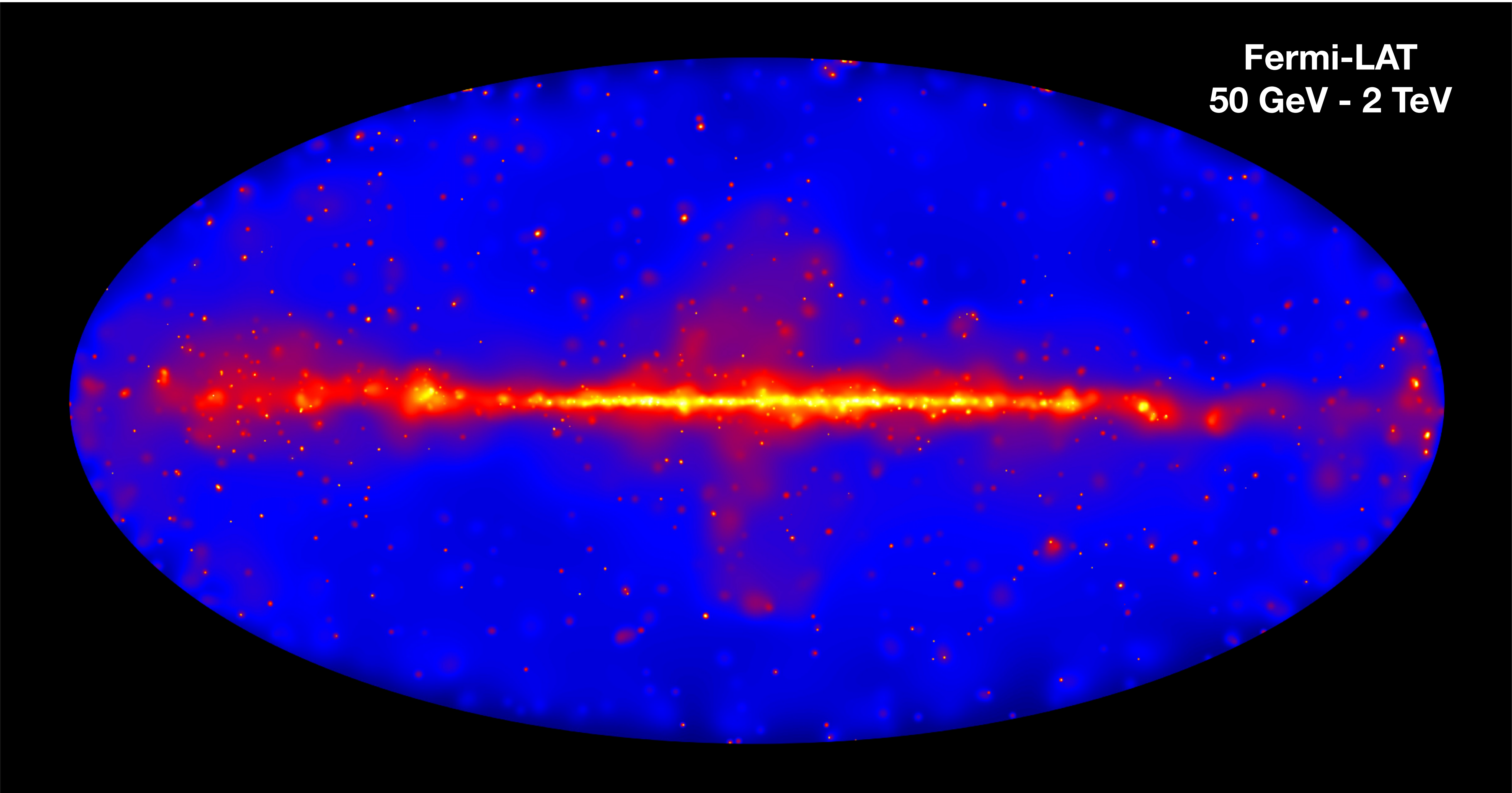
Uncovering Hidden Cosmic Ray Accelerators

Energy Density in Gamma Rays, Neutrinos, and Cosmic Rays



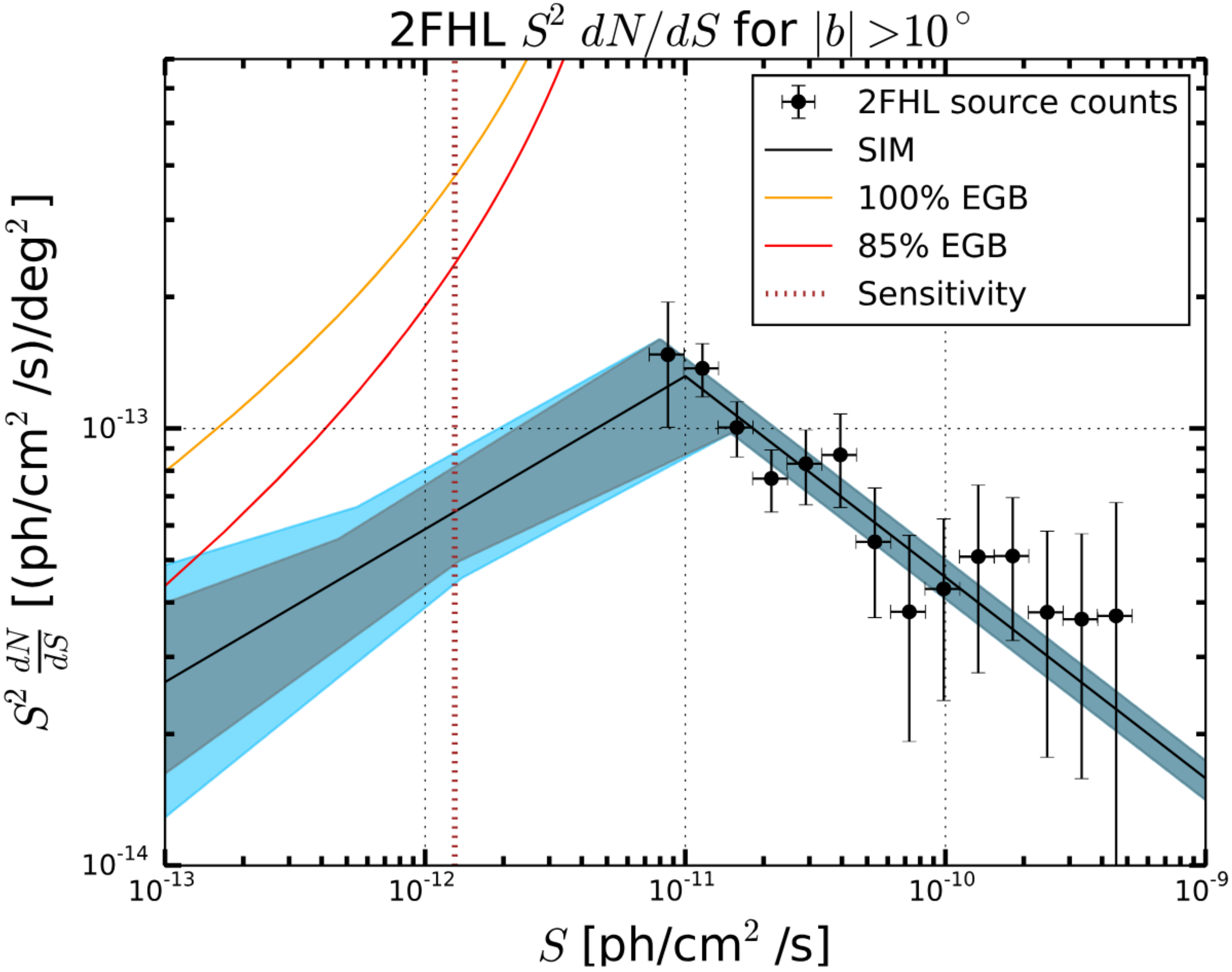
arXiv:1805.11112

Resolving the High-Energy Extragalactic Gamma-ray Sky



Resolving the High-Energy Extragalactic Gamma-ray Sky

Individually detected sources + photon counting statistics accounts for ~85% of the total intensity, dominated by blazars

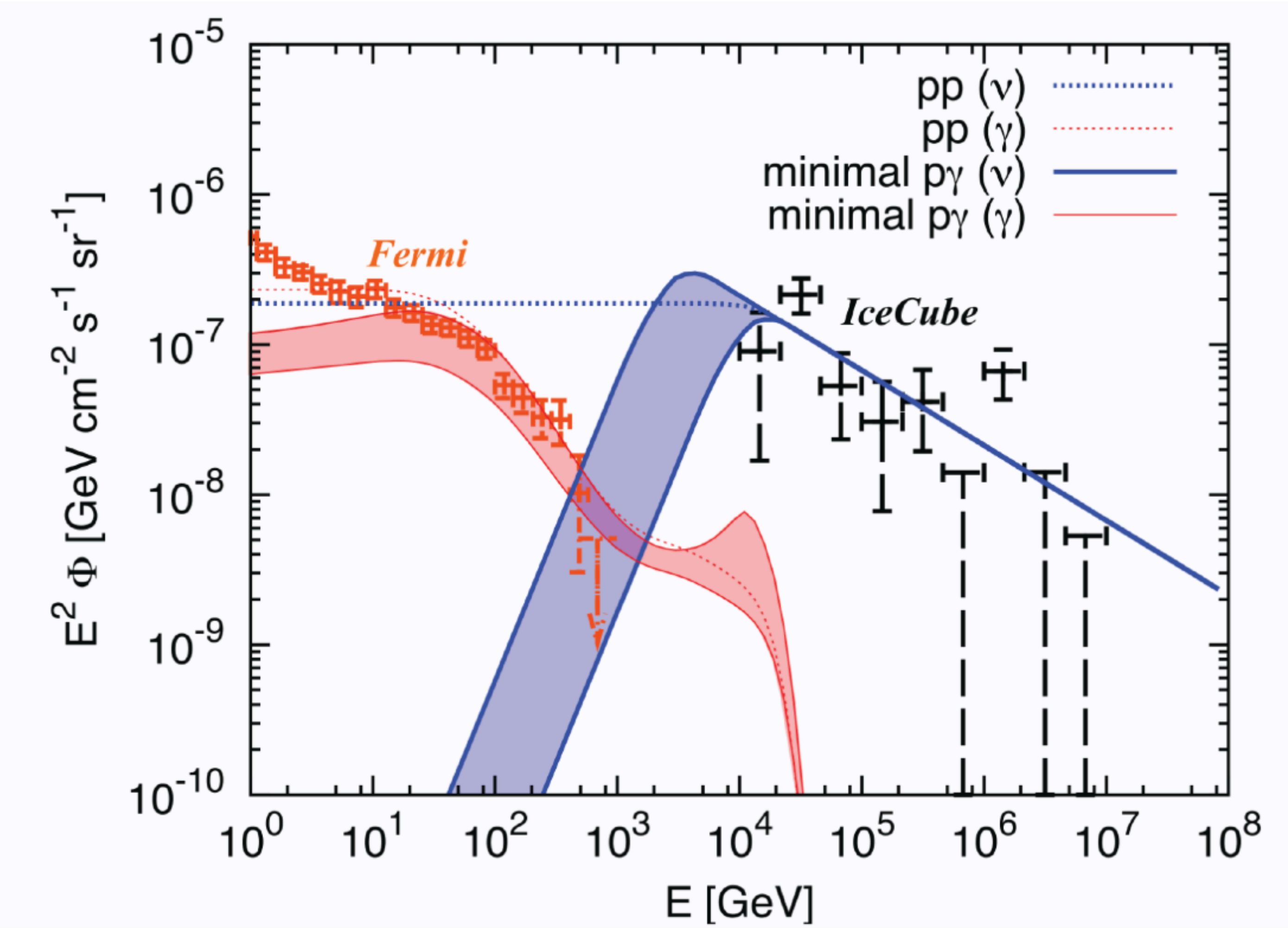


Fermi 2FHL
arXiv:1508.04449

Fermi-LAT
arXiv:1511.00693

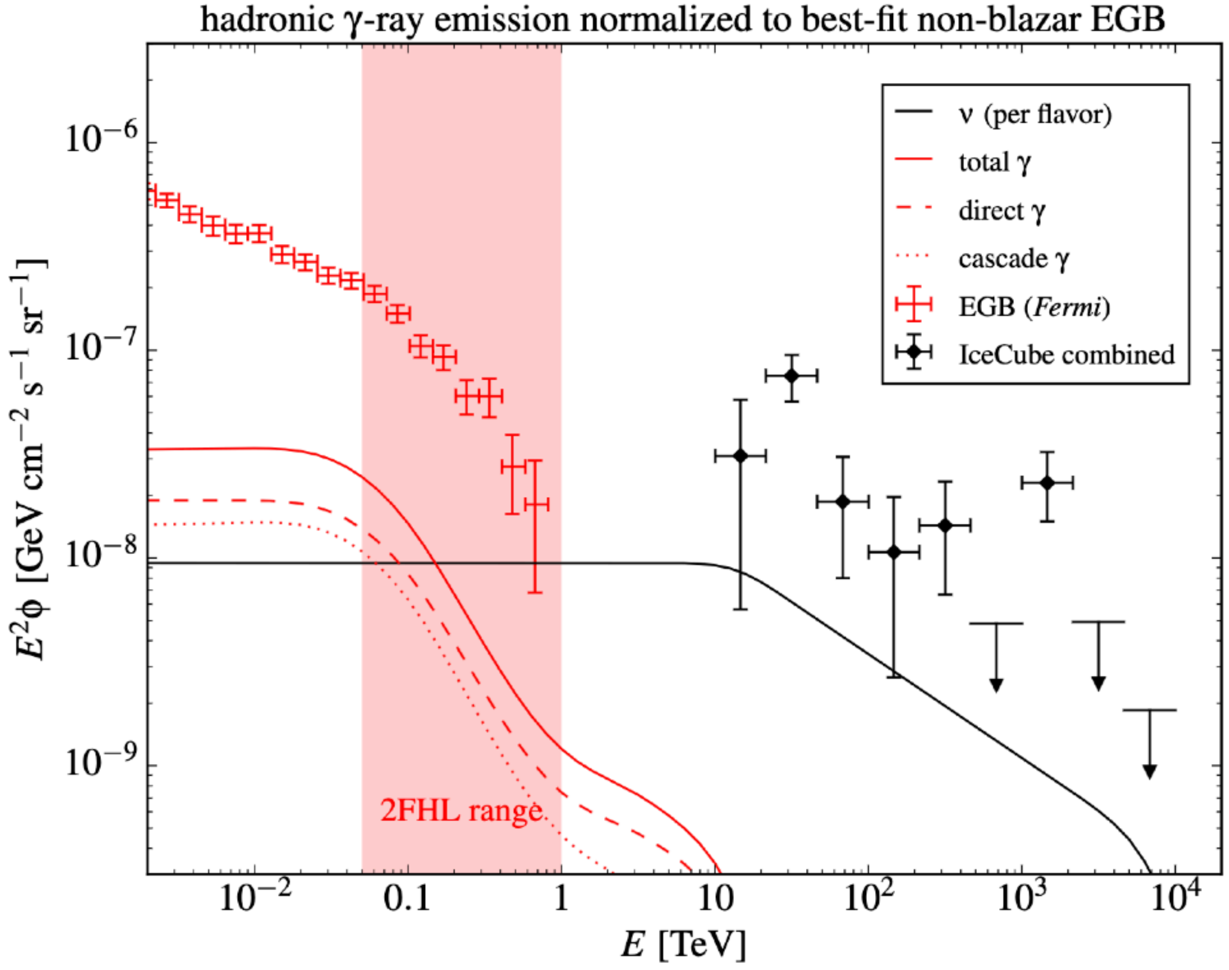
Evidence for Hidden Neutrino Sources: Extragalactic Gamma-ray Background

Photo-hadronic Interactions



Murase, Guetta, & Ahlers 2016
arXiv:1509.00805

Proton-Proton Interactions

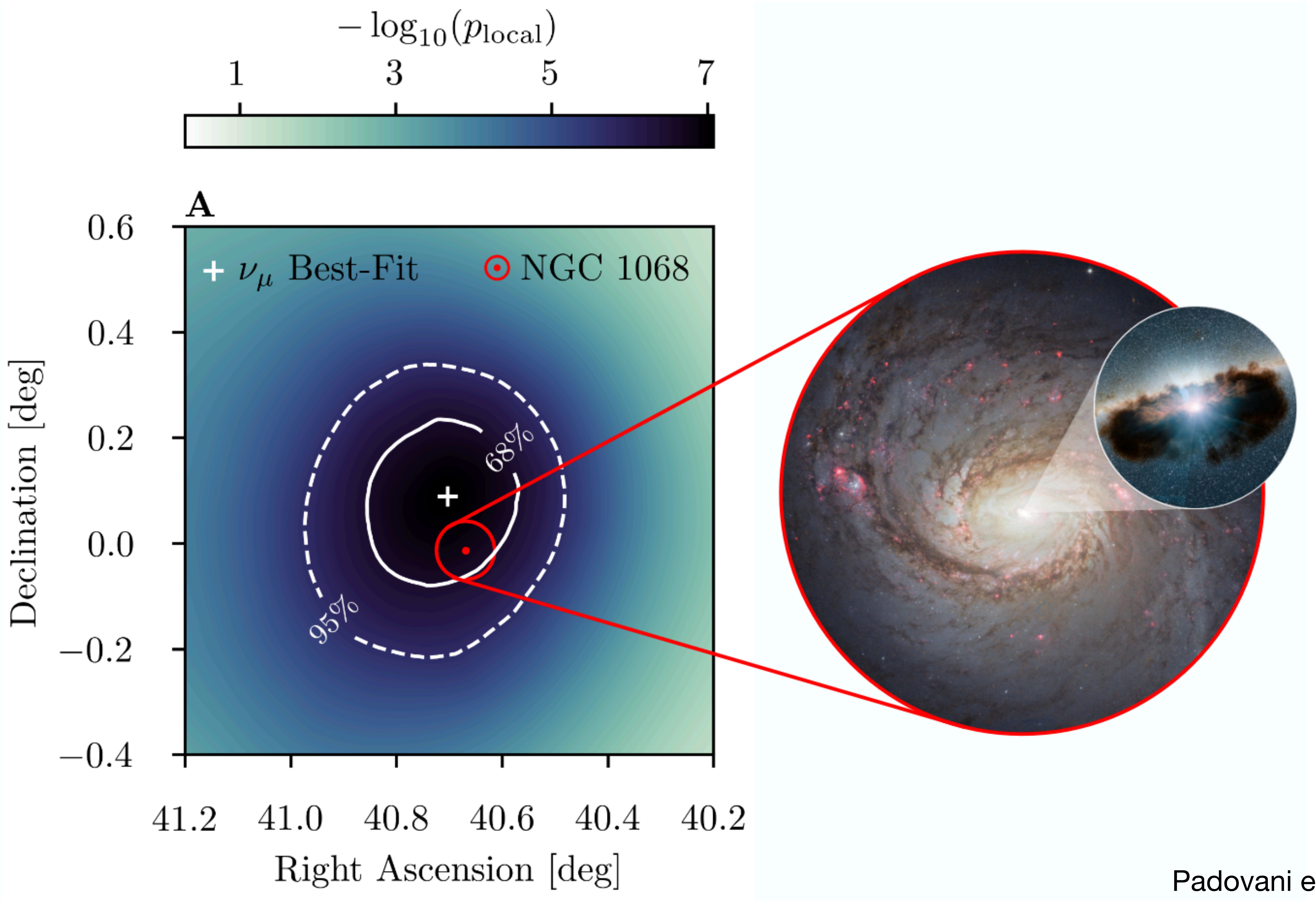


Bechtol et al. 2017
arXiv:1511.00688

Implies population of TeV-PeV neutrino sources that are opaque to GeV-TeV gamma-rays

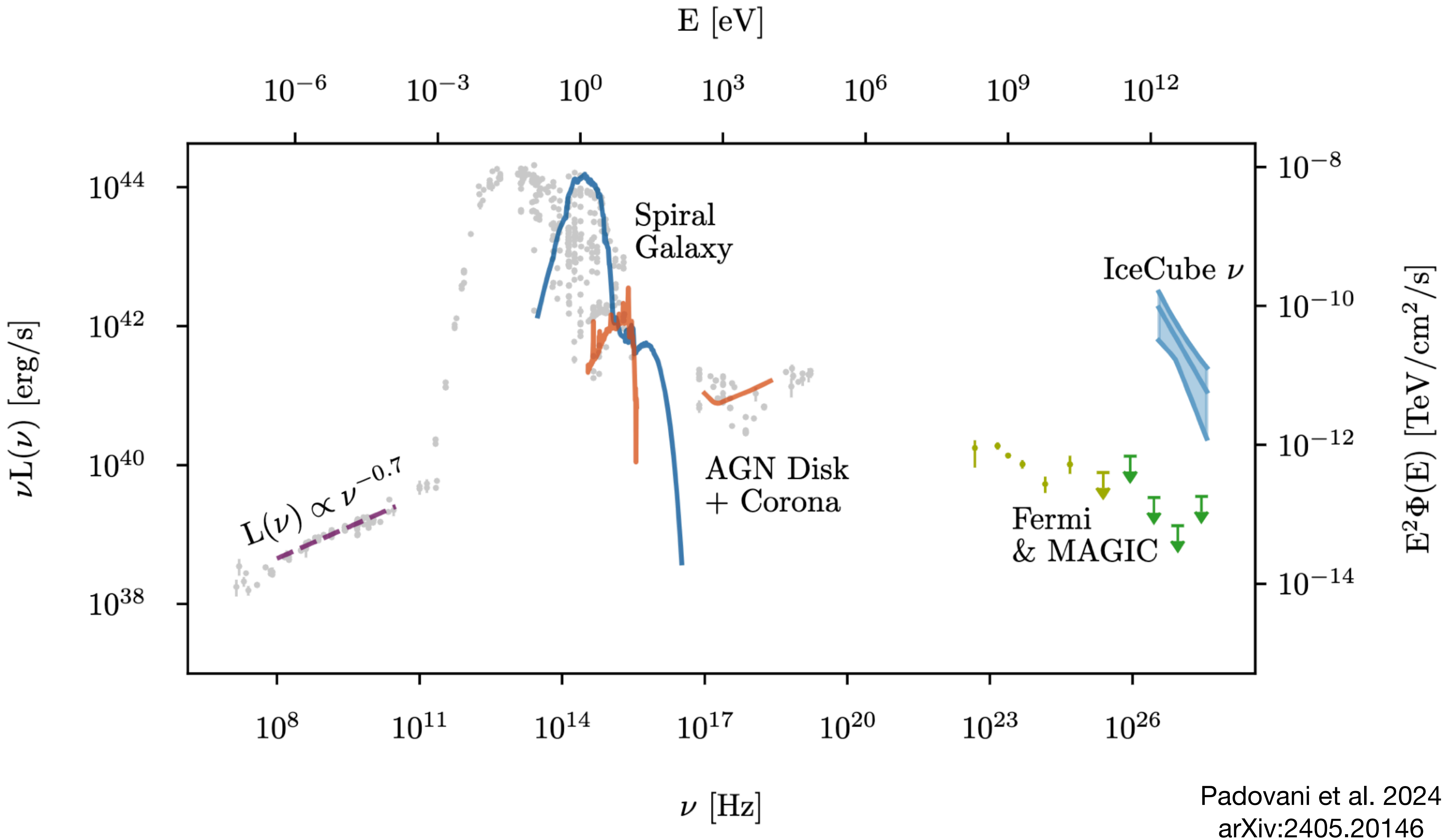
—> high column density of matter and/or intense radiation fields

Evidence for Hidden Neutrino Sources: Case study of NGC 1068 Active Nucleus



Padovani et al. 2024
arXiv:2405.20146

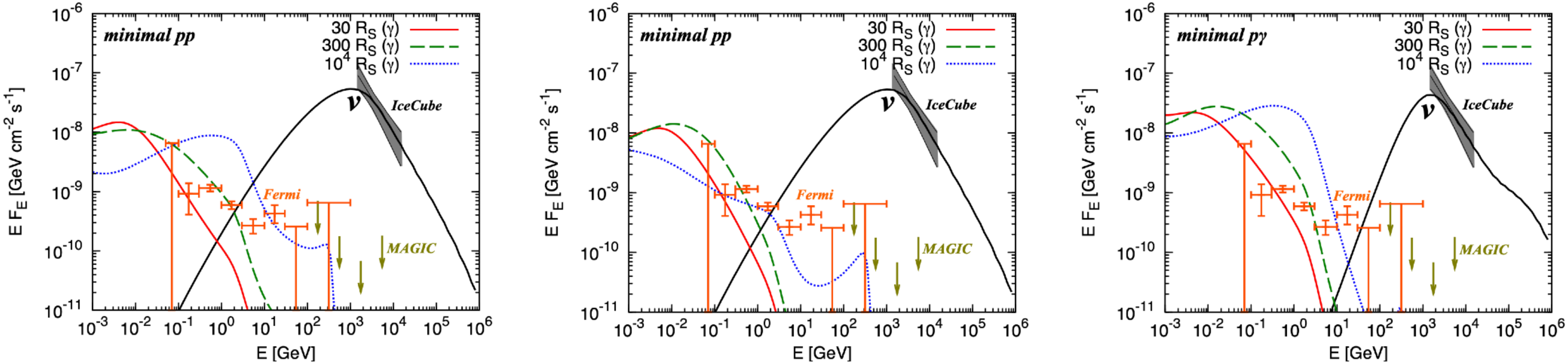
Evidence for Hidden Neutrino Sources: Case study of NGC 1068 Active Nucleus



Padovani et al. 2024
arXiv:2405.20146

Evidence for Hidden Neutrino Sources: Case study of NGC 1068 Active Nucleus

“Comprehensive analysis of the multi-messenger characteristics … ultimately points to the ***region near the black hole*** *as the sole environment where both proton acceleration and photon interactions can occur at the required intensity”* — Padovani et al. 2024



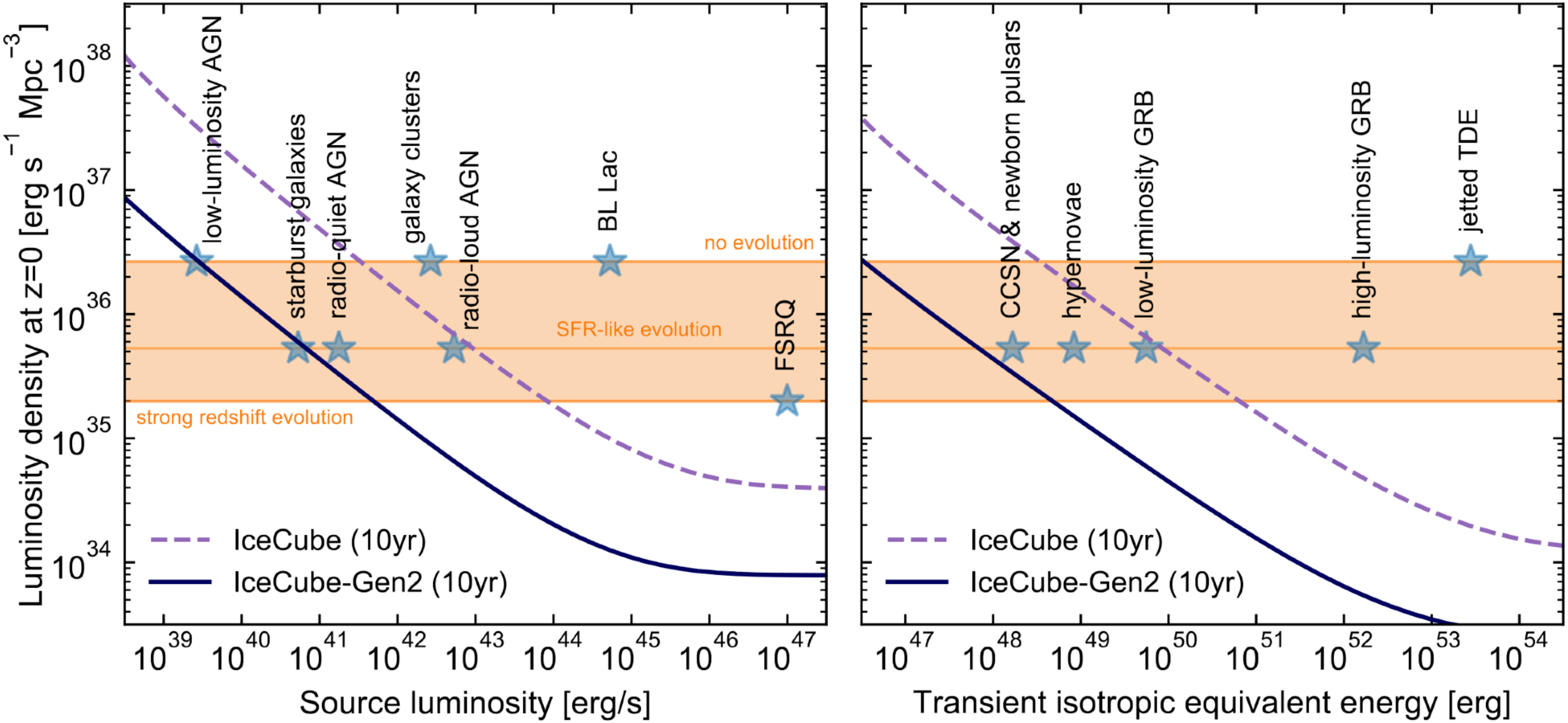
Murase 2022
arXiv:2211.04460

“neutrinos most likely come from regions within ***~30 – 100 Schwarzschild radii****”* — *Murase 2022*

see also
Fang et al. 2023
arXiv:2307.07121

IceCube has shown that astrophysical neutrino sources at TeV to PeV energies are individually faint and numerous rather than individually bright and rare

Need larger integrated exposure, improved angular resolution, and multi-messenger approaches to recognize “hidden” neutrino sources



https://icecube-gen2.wisc.edu/science/publications/tdr/

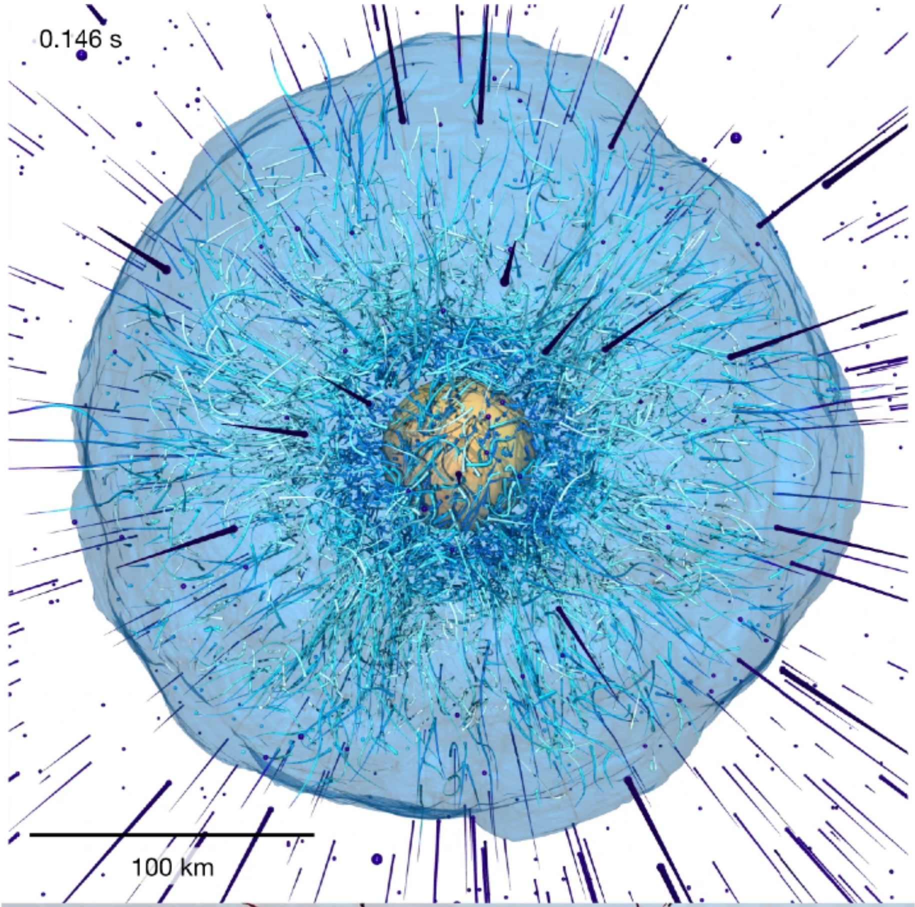
Physics of
Stellar Core Collapse
and Supernovae

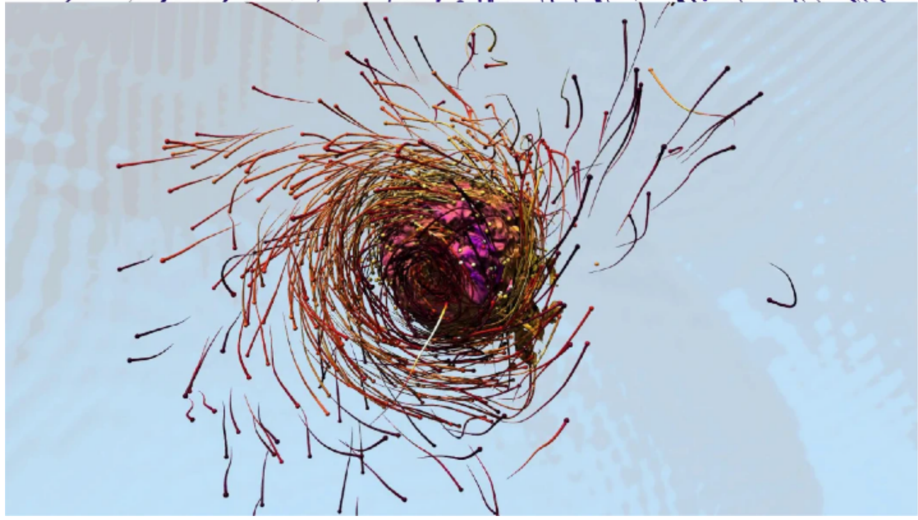
Physics of Stellar Core Collapse

Every ~second, a massive star somewhere in the observable universe undergoes stellar core collapse, and emits 10^{58} neutrinos and antineutrinos in all lepton flavors in ~1 minute that carry ~99% of the gravitational energy of the star away in kinetic energy, and leaves behind a compact remnant — neutron star or black hole

In the extreme density environment of the proto-neutron star, neutrino-neutrino and neutrino-matter interactions a frequent enough to thermalize the neutrinos, and the neutrinos undergo flavor oscillations

Physics of
Stellar Core Collapse



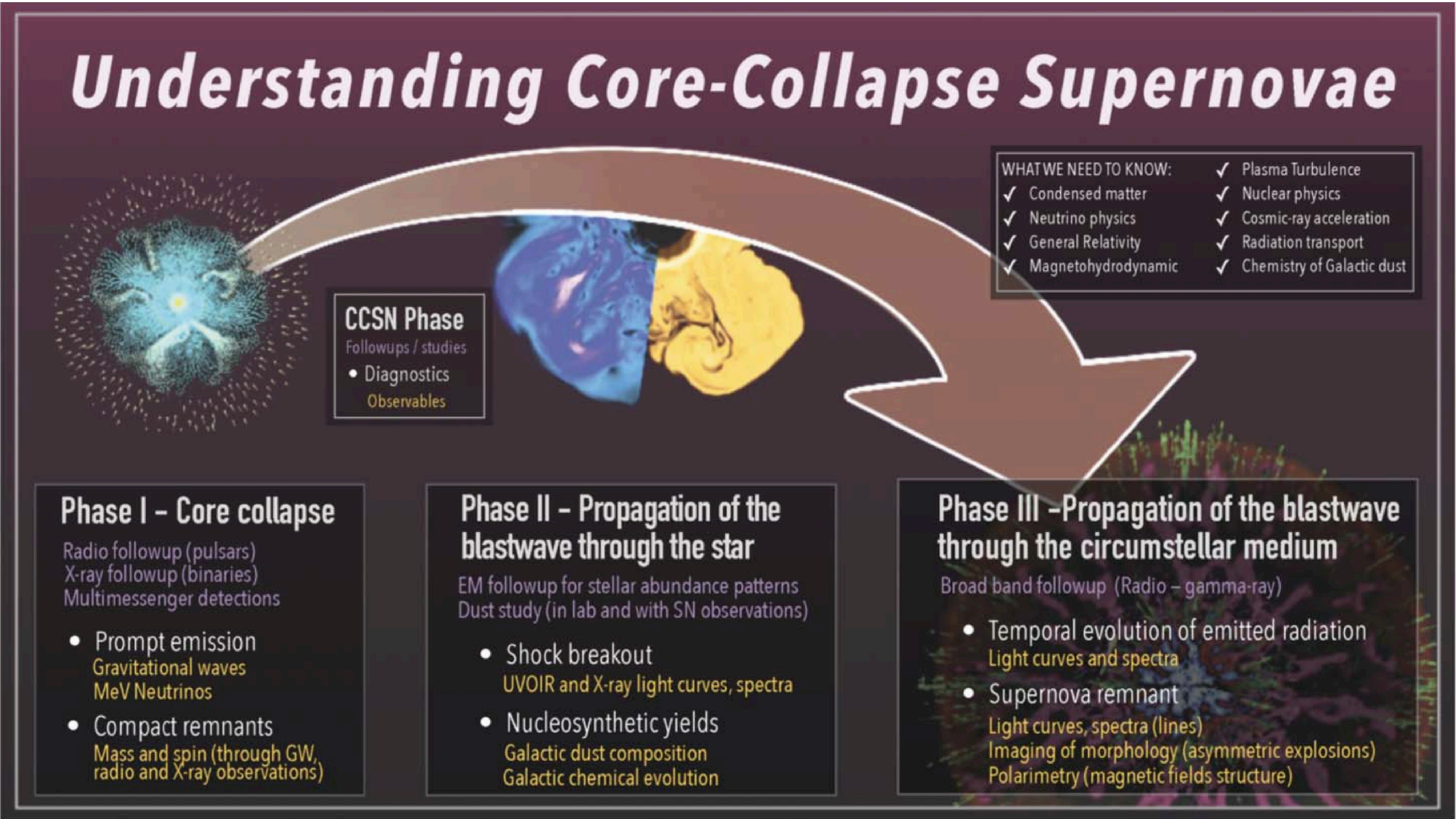


"The core is so dense and the neutrino particle energies are so high (tens to hundreds of MeV), that the structure interior to about (~10^{11} g cm^{-3}) is opaque to neutrinos of all species; the structure is a 'neutrino star', and the 'neutrinosphere' radius is initially about 30–60 km"
— Burrows & Vartanyan 2021

Neutrino-matter interactions are essential to understanding the how a supernova is launched and the dispersal of heavy chemical elements

Physics of Stellar Core Collapse

Fryer et al. 2023



Understanding Core-Collapse Supernovae

WHAT WE NEED TO KNOW:
- ✓ Condensed matter
- ✓ Neutrino physics
- ✓ General Relativity
- ✓ Magnetohydrodynamic
- ✓ Plasma Turbulence
- ✓ Nuclear physics
- ✓ Cosmic-ray acceleration
- ✓ Radiation transport
- ✓ Chemistry of Galactic dust

CCSN Phase
Followups / studies
- Diagnostics
  Observables

Phase I - Core collapse

Radio followup (pulsars)
X-ray followup (binaries)
Multimessenger detections

- Prompt emission
  Gravitational waves
  MeV Neutrinos
- Compact remnants
  Mass and spin (through GW, radio and X-ray observations)

Phase II - Propagation of the blastwave through the star

EM followup for stellar abundance patterns
Dust study (in lab and with SN observations)

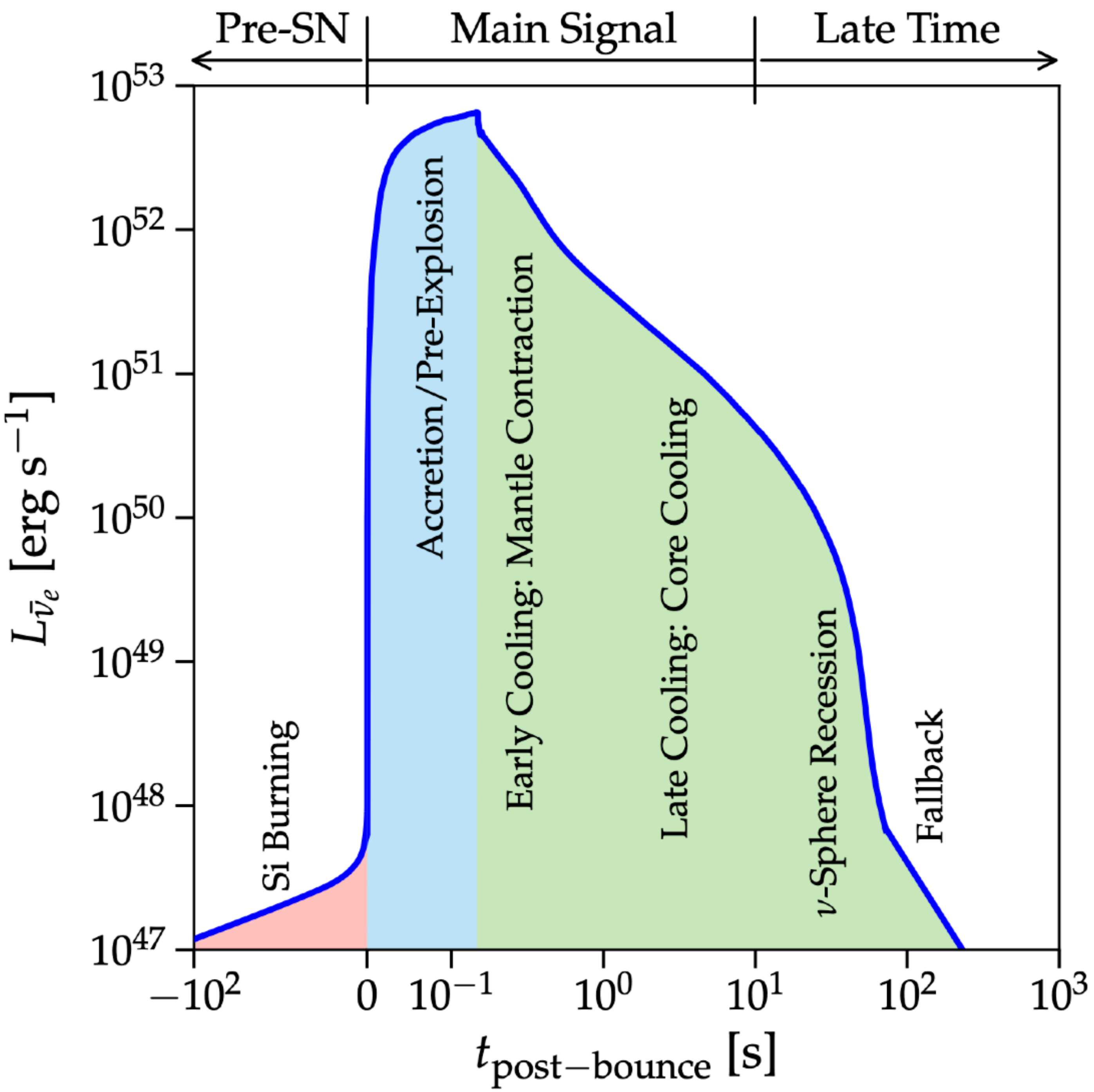
- Shock breakout
  UVOIR and X-ray light curves, spectra
- Nucleosynthetic yields
  Galactic dust composition
  Galactic chemical evolution

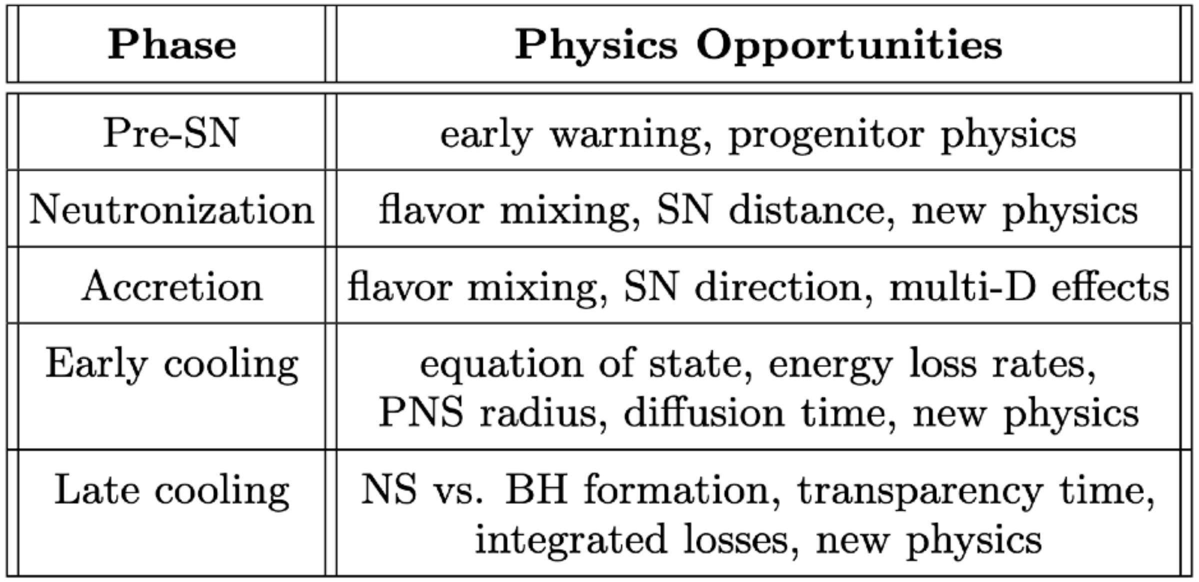
Phase III -Propagation of the blastwave through the circumstellar medium

Broad band followup (Radio – gamma-ray)

- Temporal evolution of emitted radiation
  Light curves and spectra
- Supernova remnant
  Light curves, spectra (lines)
  Imaging of morphology (asymmetric explosions)
  Polarimetry (magnetic fields structure)

Galactic Supernova Neutrinos

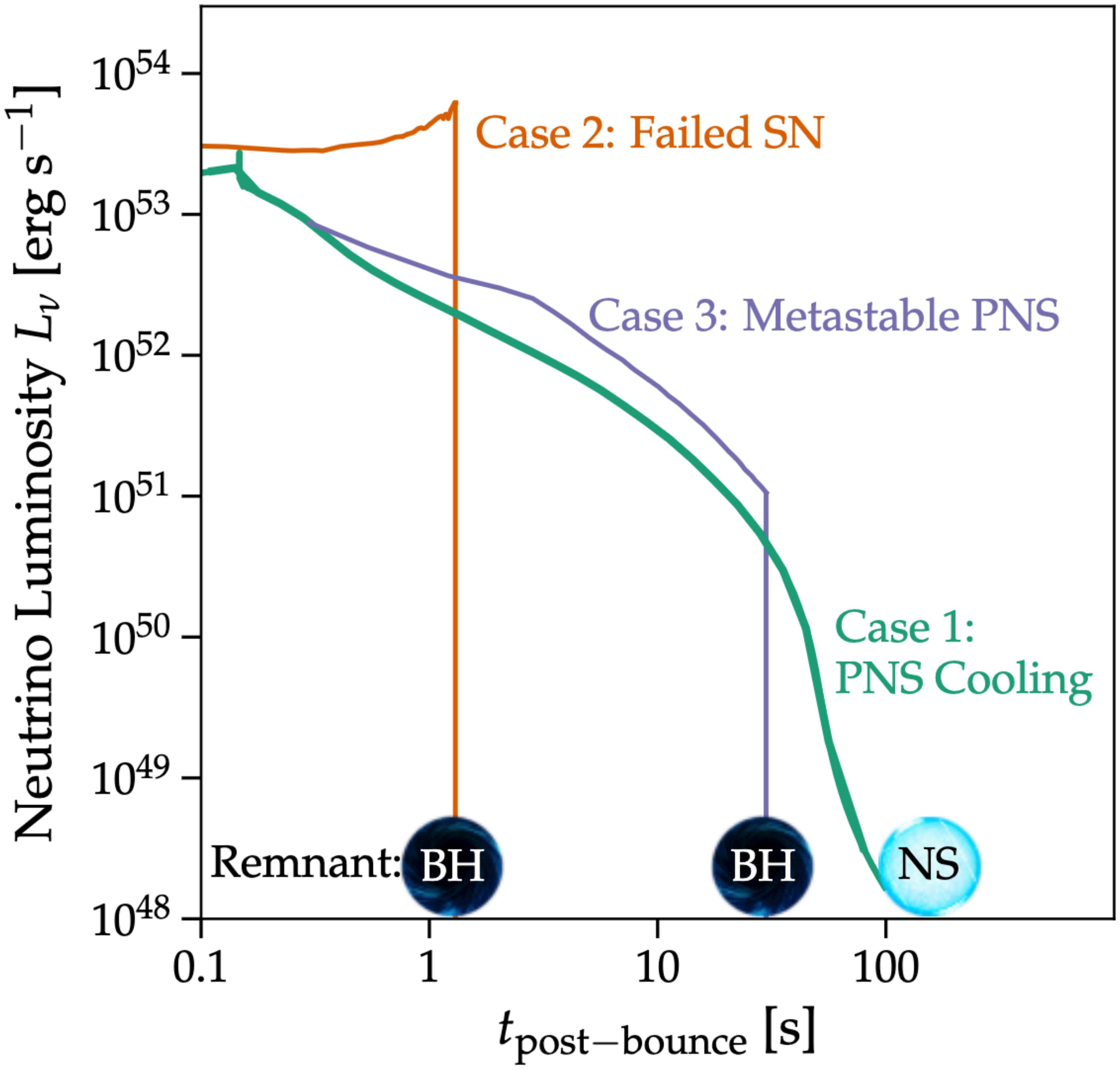




Phase	**Physics Opportunities**
Pre-SN	early warning, progenitor physics
Neutronization	flavor mixing, SN distance, new physics
Accretion	flavor mixing, SN direction, multi-D effects
Early cooling	equation of state, energy loss rates, PNS radius, diffusion time, new physics
Late cooling	NS vs. BH formation, transparency time, integrated losses, new physics

Li, Roberts, & Beacom
2021

Galactic Supernova Neutrinos

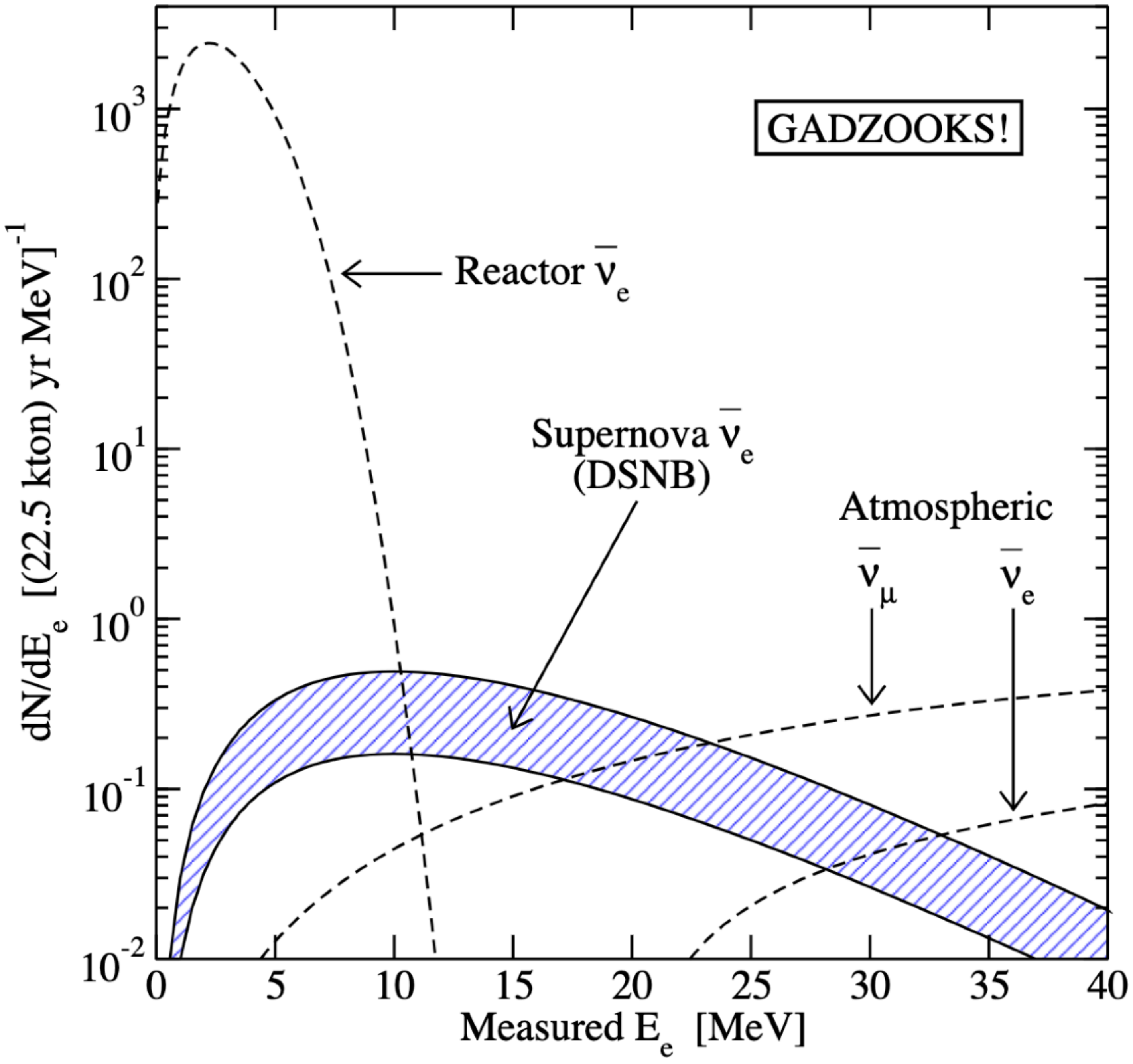


Li, Roberts, & Beacom
2021

Diffuse Supernova Neutrino Background

The predicted **diffuse supernova neutrino background** (DSNB) is a “guaranteed signal” that arises from the collective emission of supernovae across cosmic time

DSNB is sensitive to
- neutrino emission from individual stellar core collapse event
- cosmic core collapse event rates (compare with rates of “successful” supernovae)



Beacom et al. 2010
arXiv:1004.3311

Connections with Neutrino Physics

- Sensitivity to neutrino mass ordering through neutrino-matter interactions

- Neutrino-neutrino interactions and collective oscillation phenomena

- Details of neutrino oscillations (including neutrino mass hierarchy) could affect isotopic ratios and nucleosynthesis in supernovae

- New neutrino physics inferred from energy loss (total energy and cooling rate of proto-neutron star)

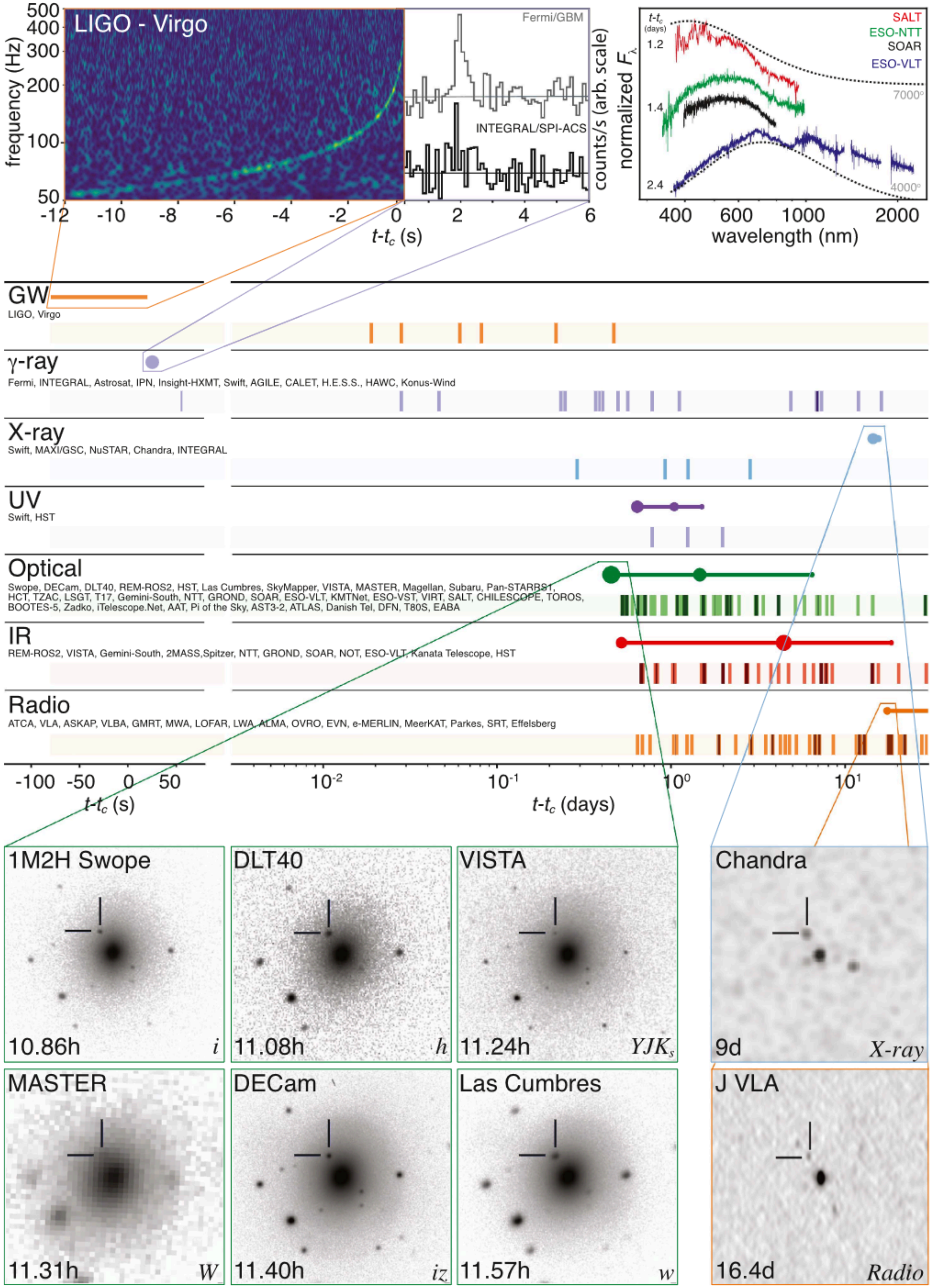
Physics of Matter at Extreme Density and Heavy Element Nucleosynthesis

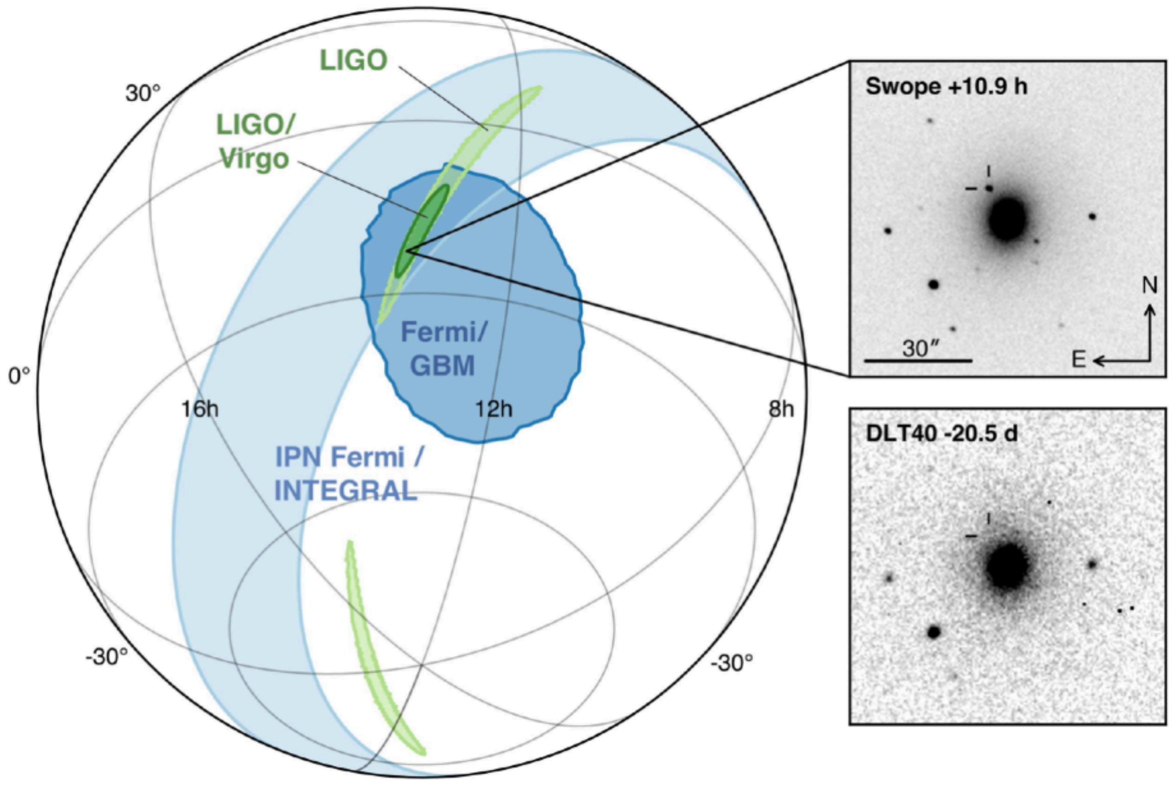
Multimessenger Observations of a Binary Neutron Star Merger

Compact Binary Coalescence: GW170817

Gamma-ray Burst: GRB 170817A

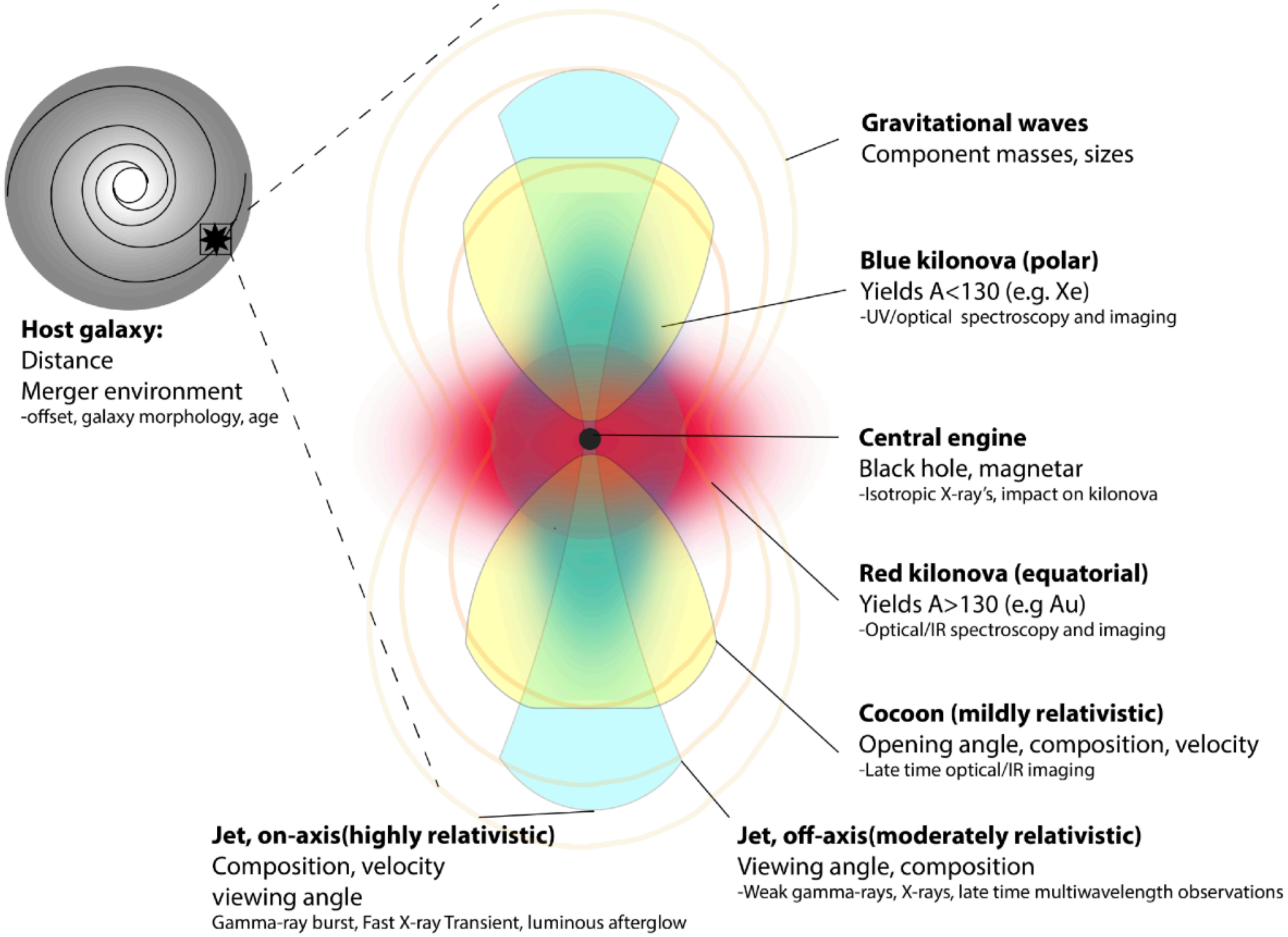
Kilonovae: AT 2017gfo





arXiv:1710.05833

Multi-messenger Signals from Binary Neutron Star Coalescence



Gravitational waves
Component masses, sizes

Blue kilonova (polar)
Yields A<130 (e.g. Xe)
-UV/optical spectroscopy and imaging

Host galaxy:
Distance
Merger environment
-offset, galaxy morphology, age

Central engine
Black hole, magnetar
-Isotropic X-ray's, impact on kilonova

Red kilonova (equatorial)
Yields A>130 (e.g Au)
-Optical/IR spectroscopy and imaging

Cocoon (mildly relativistic)
Opening angle, composition, velocity
-Late time optical/IR imaging

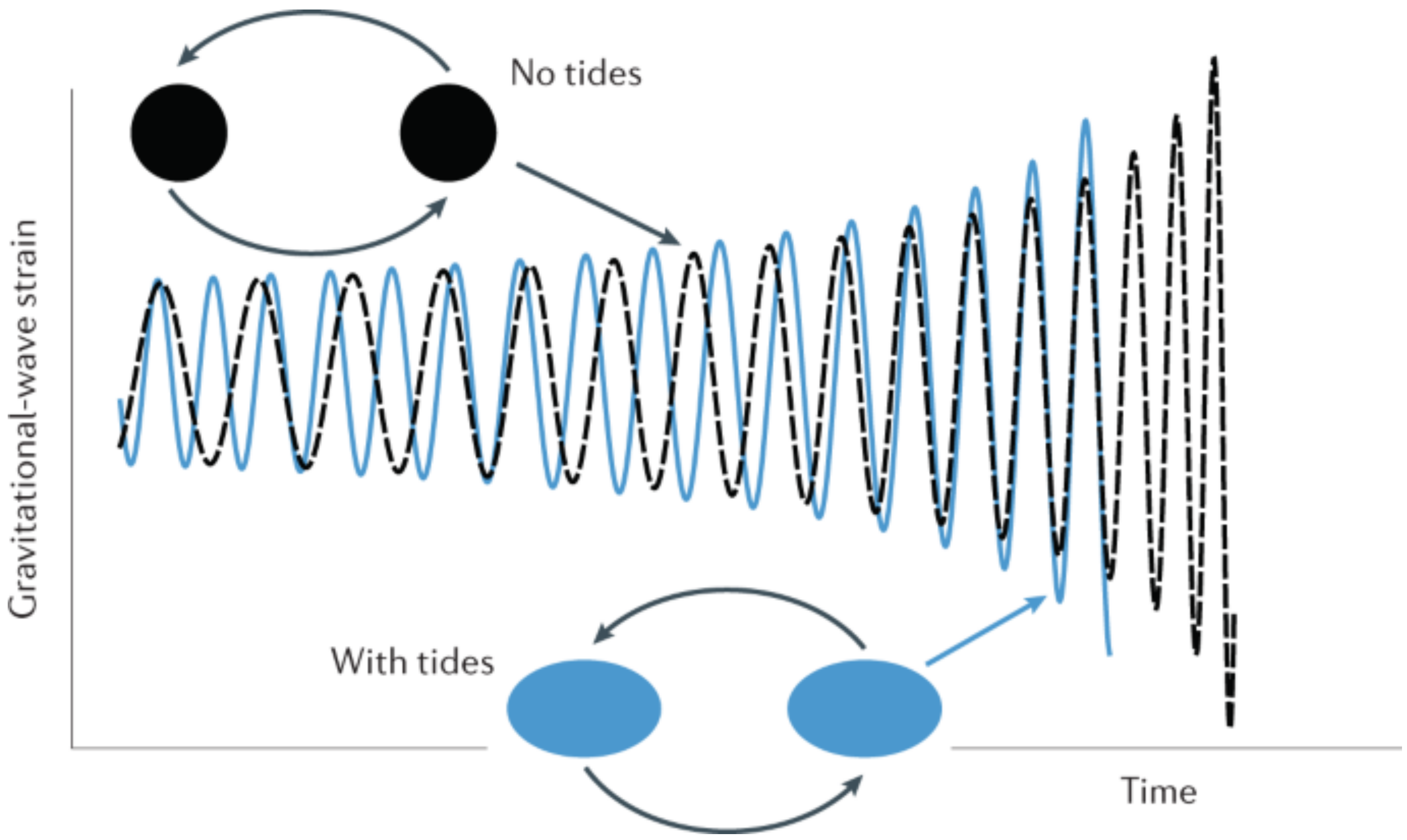
Jet, on-axis(highly relativistic)
Composition, velocity
viewing angle
Gamma-ray burst, Fast X-ray Transient, luminous afterglow

Jet, off-axis(moderately relativistic)
Viewing angle, composition
-Weak gamma-rays, X-rays, late time multiwavelength observations

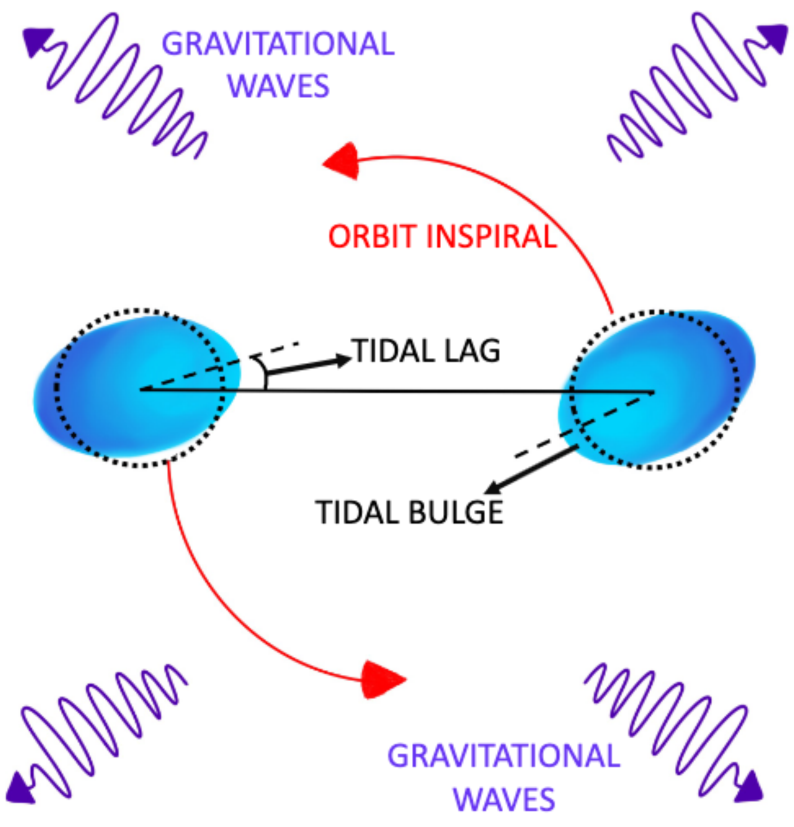
GW170807 demonstrated the diversity of multi messenger signals associated with binary neutron star (BNS) coalescence
— gravitational waves, gamma-ray burst, nucleosynthesis, moderately relativistic outflows

Network of third-generation ground-based gravitational wave detectors (Cosmic Explorer, Einstein Telescope) will localize many BNS to better than 1 deg^2, linking properties of compact objects to outflows and host galaxies, and in some cases, provide advance notice of merger events

Tidal Deformation during Binary Neutron Star Coalescence



Yunes, Miller, Yagi 2022
arXiv:2202.04117

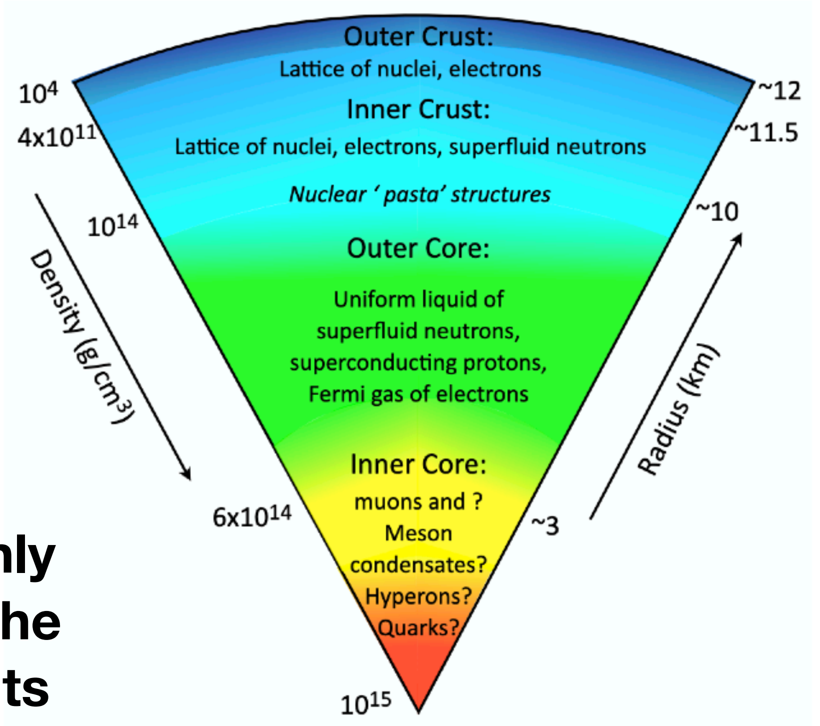


Ripley et al. 2024
arXiv:2312.11659

Exploring Properties of Dense Matter during Binary Neutron Star Coalescence

Third-generation ground-based gravitational wave detectors (Cosmic Explorer, Einstein Telescope) are expected to use neutron star tides to constrain the radius of individual neutron stars at ~100m level (1%) and a ~10m level (0.1%) for the neutron star population

Might also be possible to constrain the formation of post-merger remnant and electromagnetic counterparts



Access to states of matter that only exist in neutron stars and during the formation of their merger remnants

Cosmic Explorer
arXiv:2306.13745
Einstein Telescope
arXiv:2503.12263

Heavy Element Nucleosynthesis

Roughly half of the chemical elements heavy than iron are produced via rapid neutron capture (r-process). Astrophysical production sites are thought to be core collapse supernovae and neutron star merger events.

Optical emission of kilonovae is powered by radioactive decay of newly formed heavy nuclei. Spectral analysis of GW170817 / GRB 170817A / AT 2017gfo revealed r-process elements. To what extent was this event representative of the population?

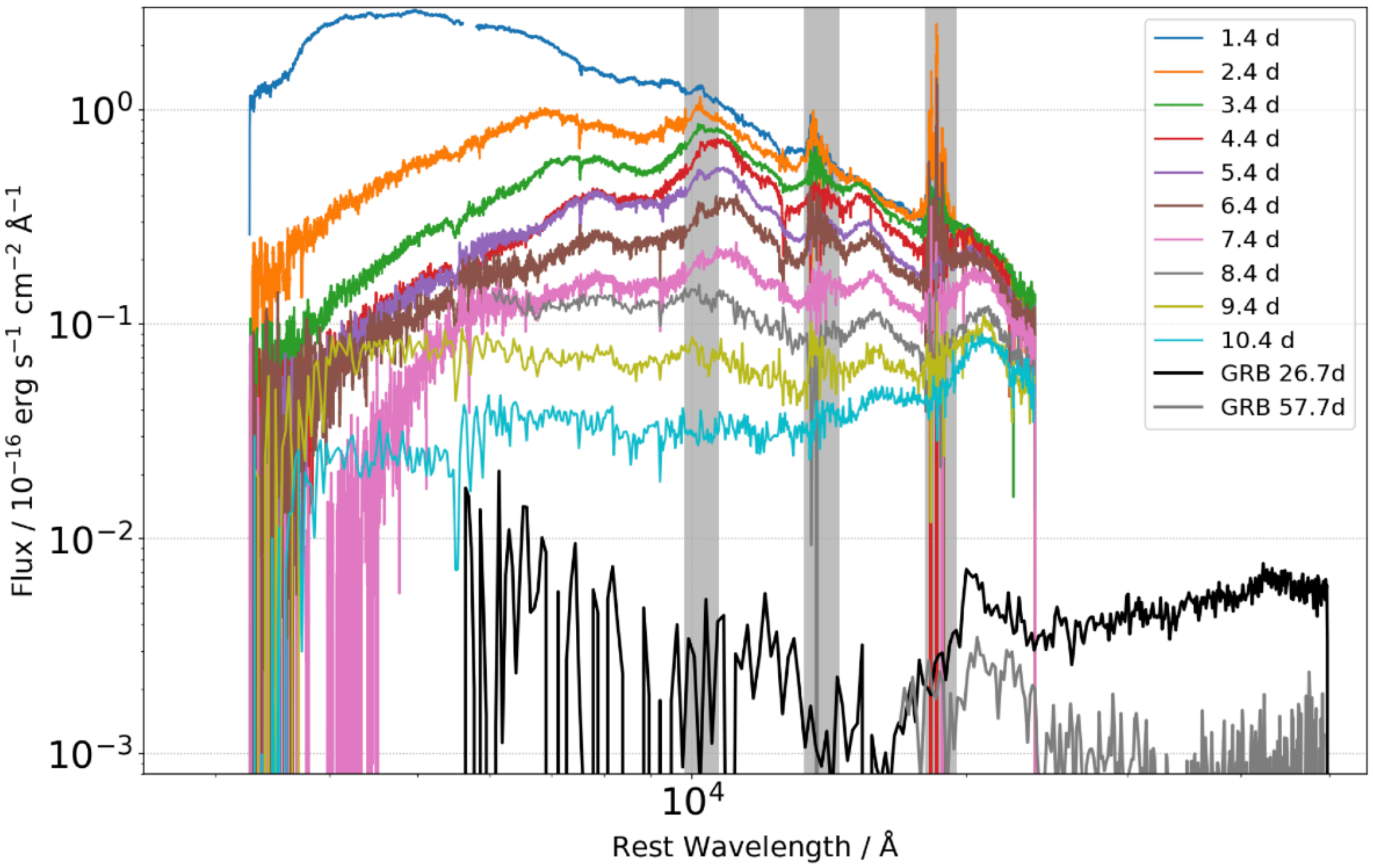


Figure from
Einstein Telescope
arXiv:2503.12263
adapted from Pian et al. 2017
arXiv:1710.05858

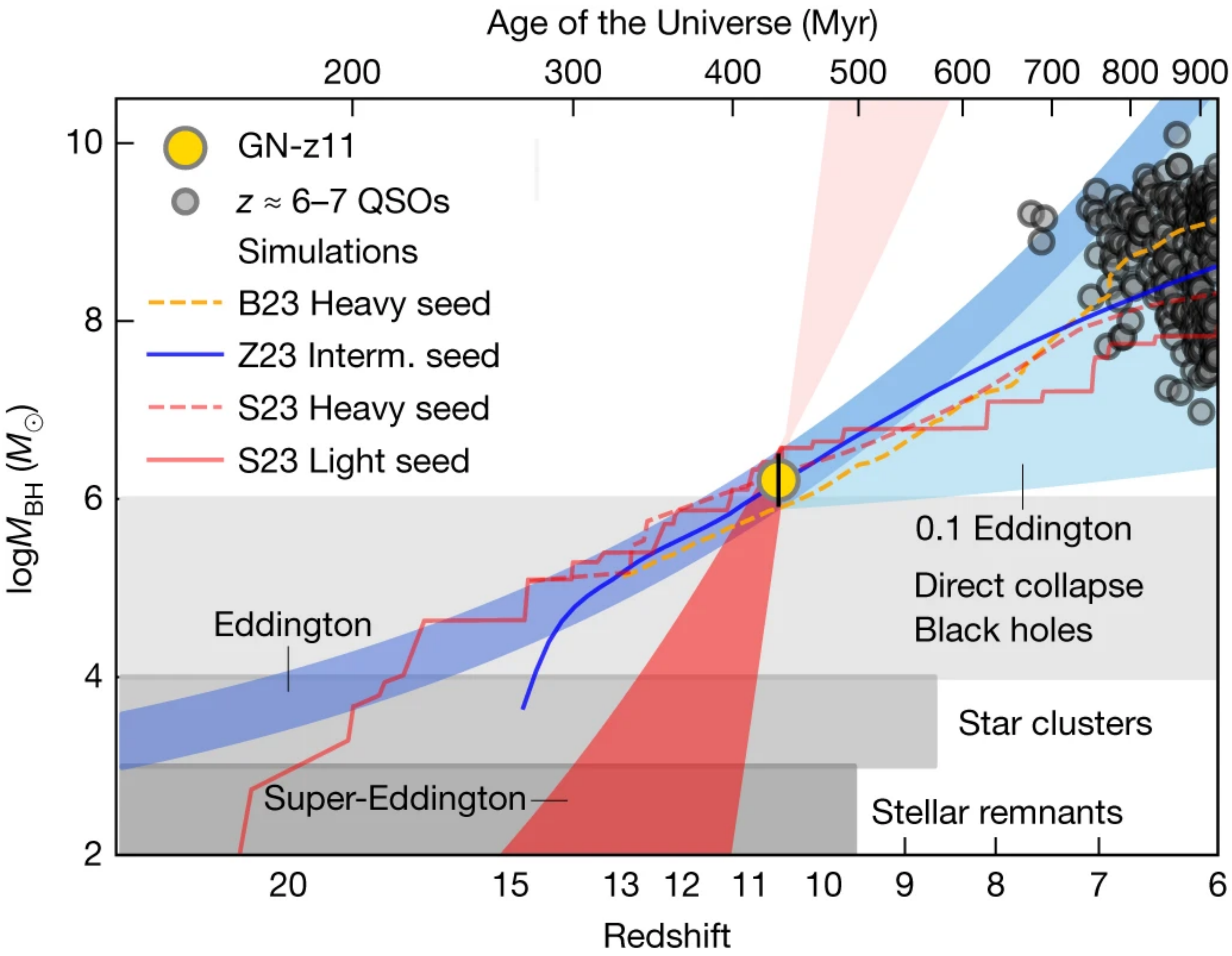
Formation of Supermassive Black Holes

How did supermassive black holes form?

Massive black holes were already in place within the first billion years of cosmic history, as evidenced by

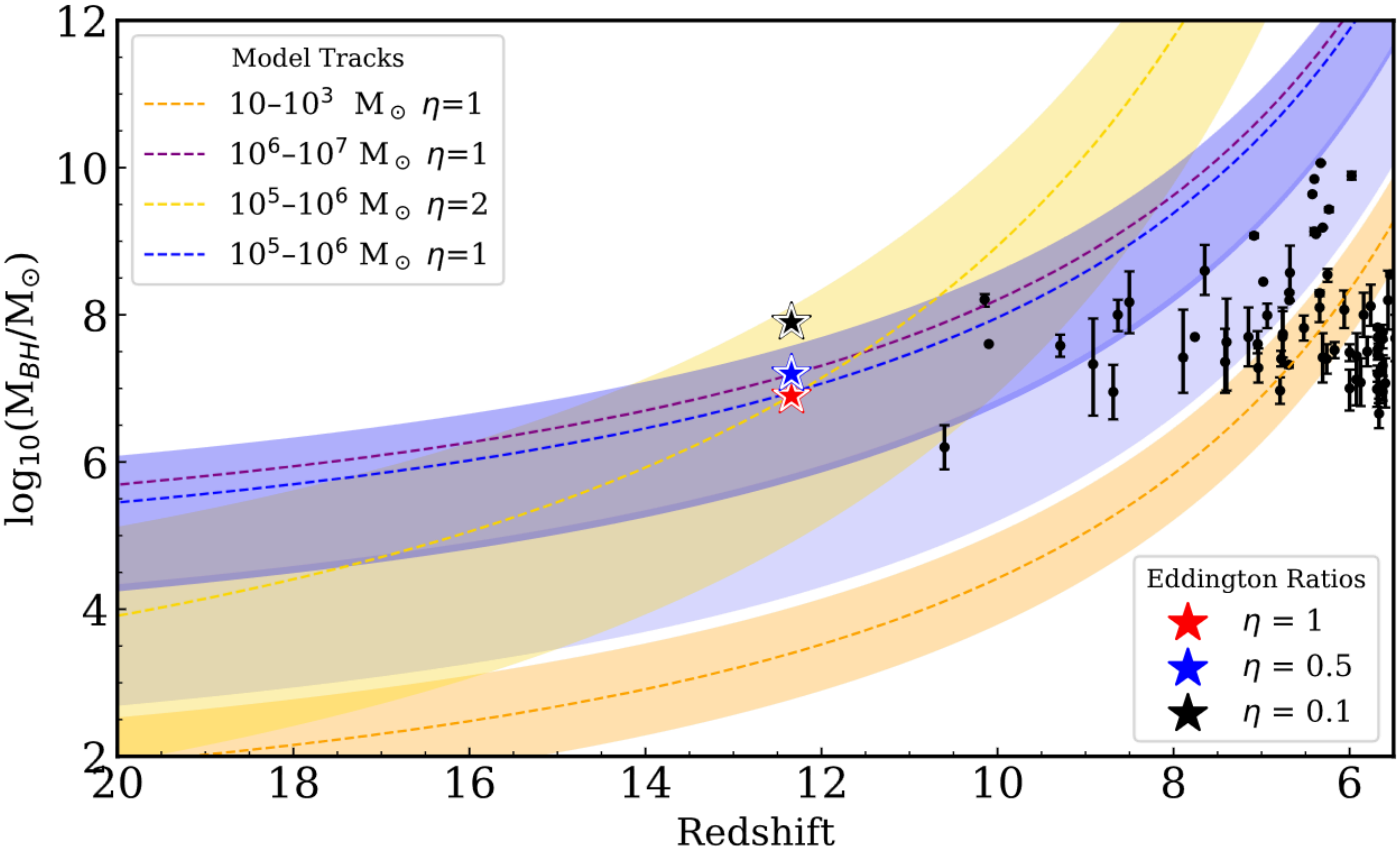
- Luminous quasars at $z > 6$ powered by $M > 10^9\ M_{\mathrm{Solar}}$ black holes
- Detections of AGN at $z > 8$ with inferred black hole masses of 10^6–$10^8\ M_{\mathrm{Solar}}$

Evidence for Early Massive Black Hole Formation



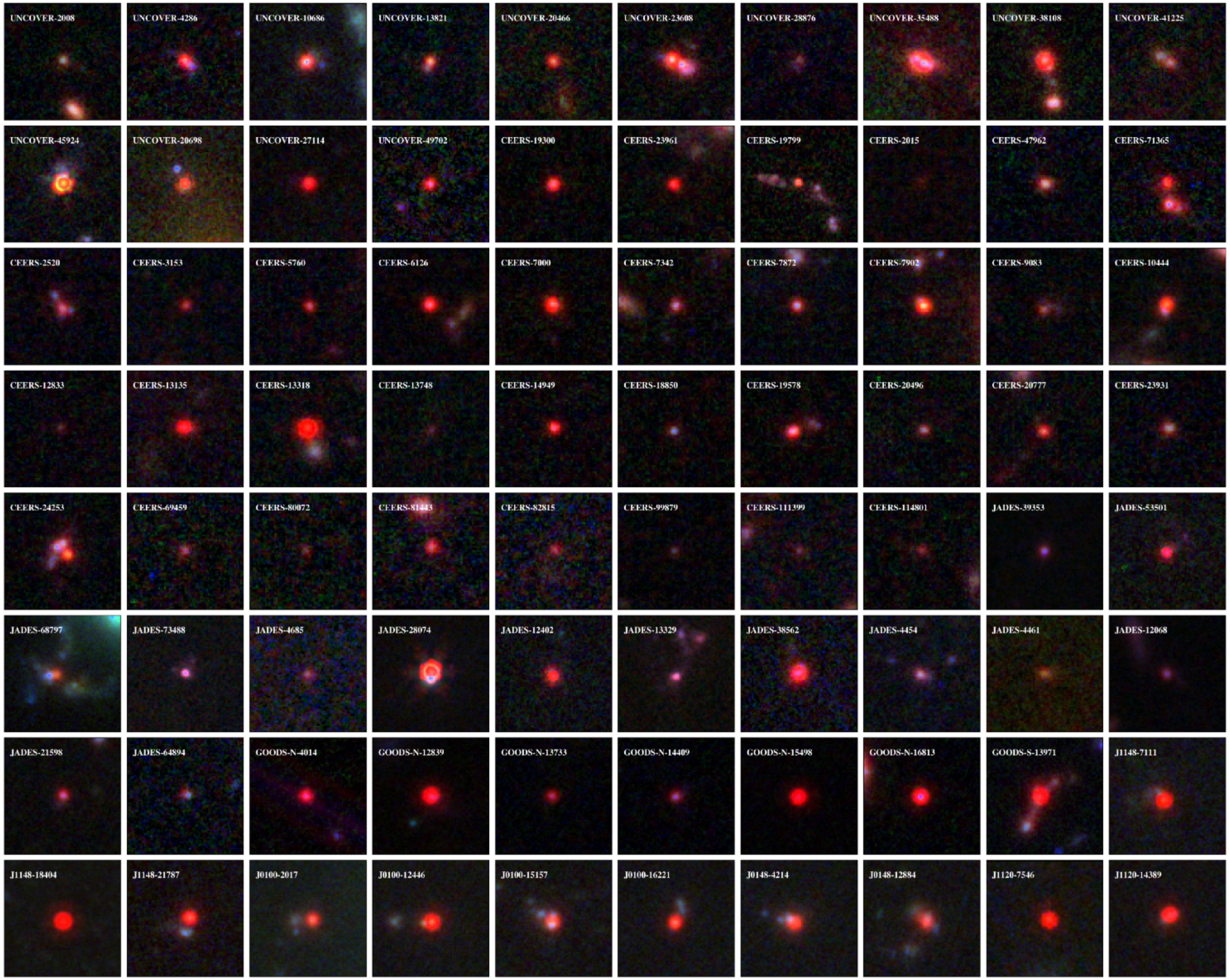
Maiolino et al. 2024

Evidence for Early Massive Black Hole Formation



Chavez Ortiz et al. 2025
arXiv:2511.03035

Evidence for Early Massive Black Hole Formation



Population of red and compact infrared sources with unusual spectra seen in JWST data

Many have a UV-bright companion that could plausible supply enough radiation to suppresses molecular hydrogen cooling

Baggen et al. 2026

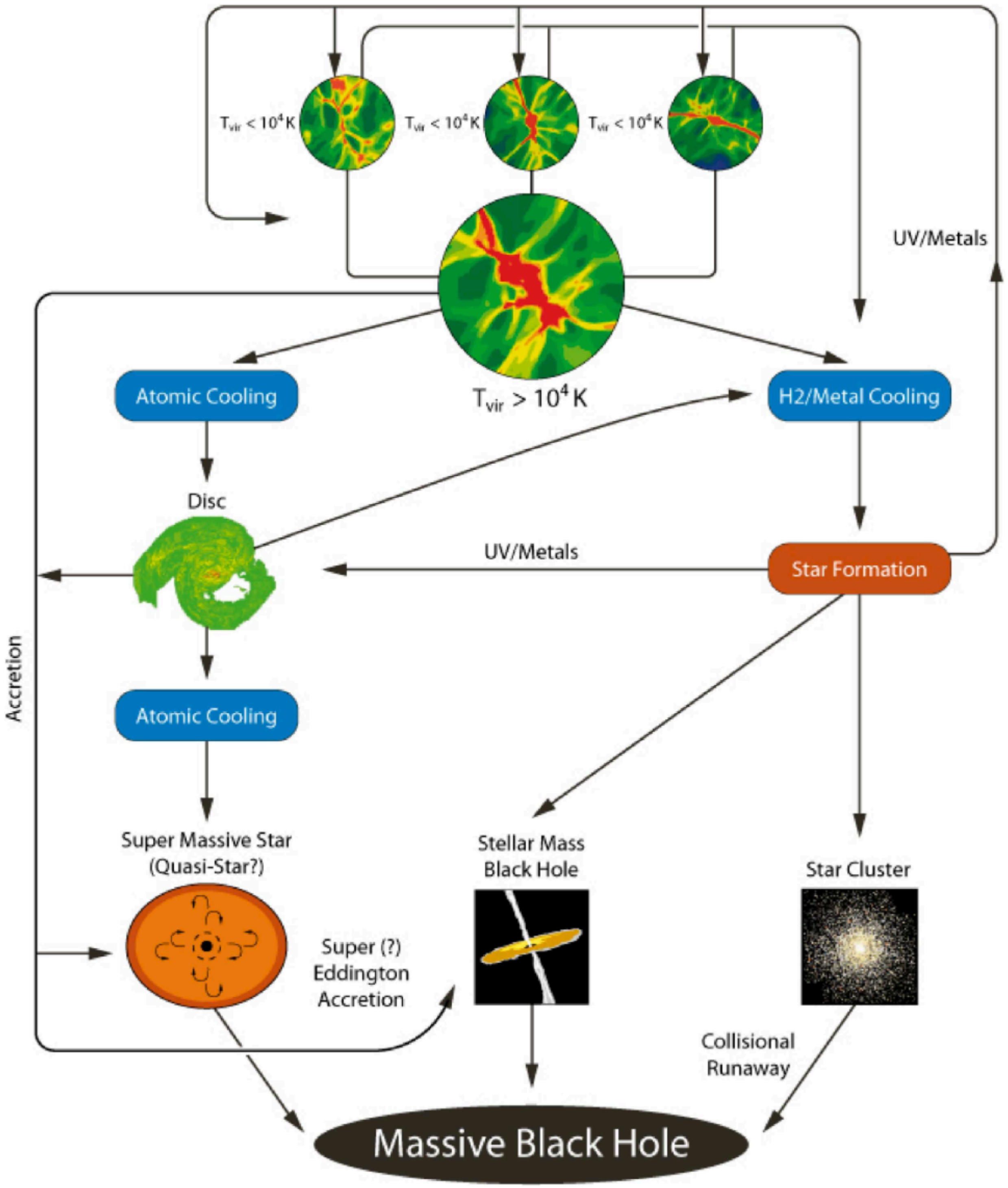
How did supermassive black holes form?

Light seeds — remnants of Pop III stars w/ initial masses of 10^2 M_{Solar}

Heavy seeds —direct collapse of metal poor atomic cooling halos exposed to weak Lyman–Werner (LW) radiation fields, w/ initial masses of 10^4 to 10^6 M_{Solar}

"In nearly metal-free gas, molecular hydrogen provides the dominant cooling channel, but far-UV photons in the Lyman–Werner (LW) band can dissociate H2 via the Solomon process. If the local LW radiation field is sufficiently intense, molecular hydrogen is dissociated, and cooling is suppressed, allowing gas clouds to bypass normal star formation and collapse rapidly at the atomic-cooling threshold, avoiding fragmentation and ultimately leading to a massive black hole"

How did supermassive black holes form?

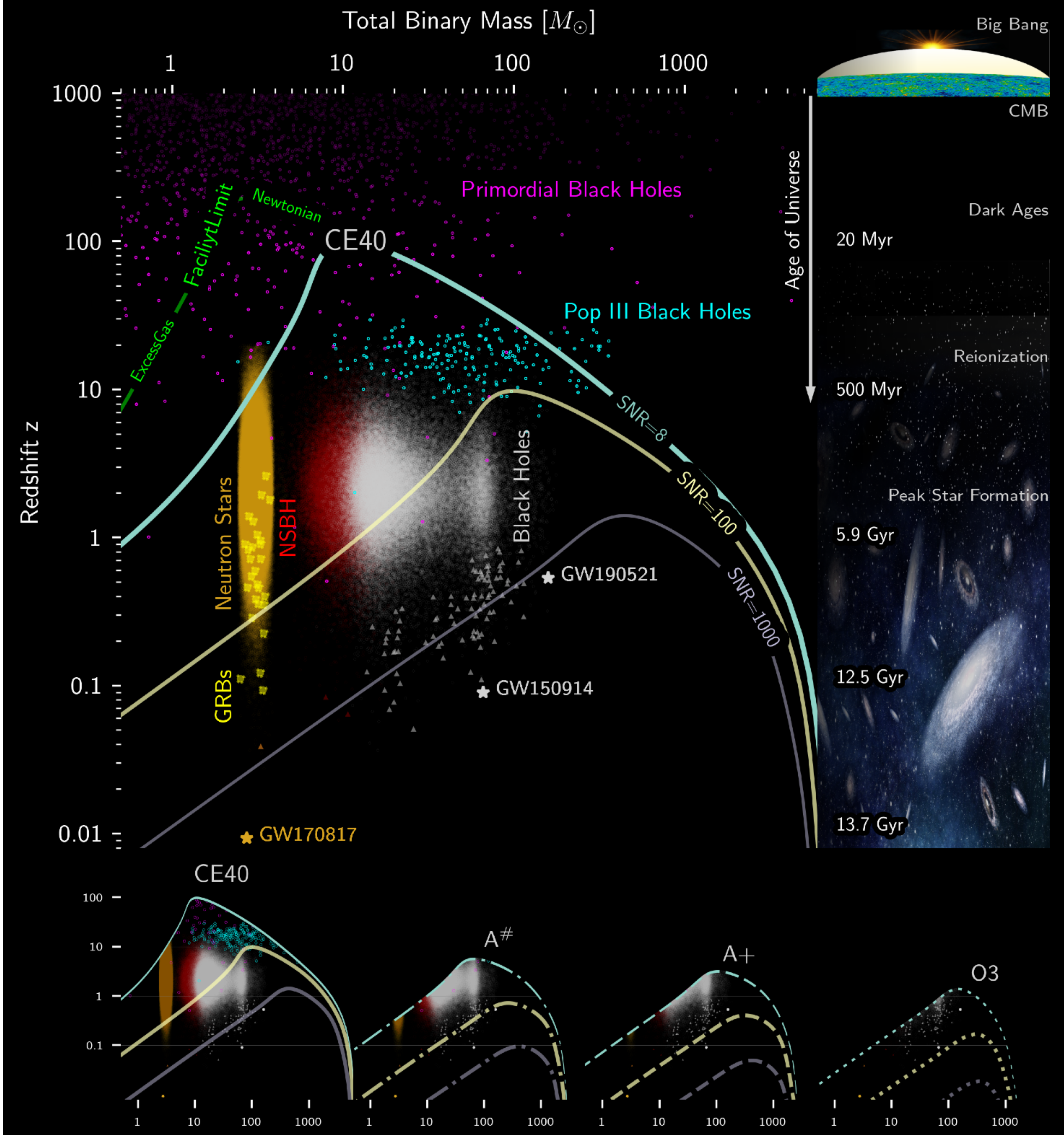


Regan & Haehnelt 2009

Third generation ground-based gravitational wave detectors with see stellar black hole mergers to redshifts z>10

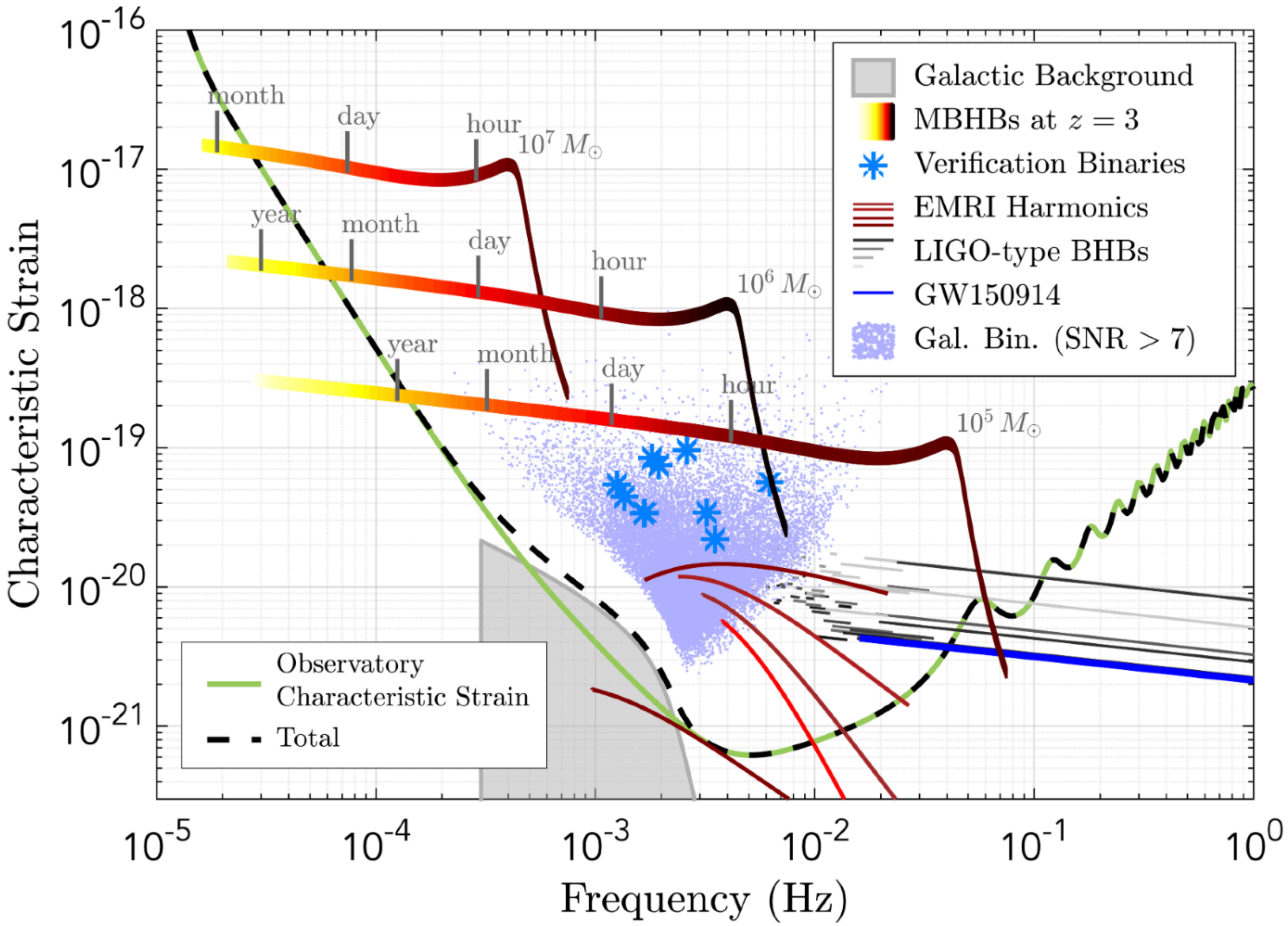
Expect 10^5 and 10^6 Binary Black Hole (BBH) mergers per year (roughly one every 30 seconds)

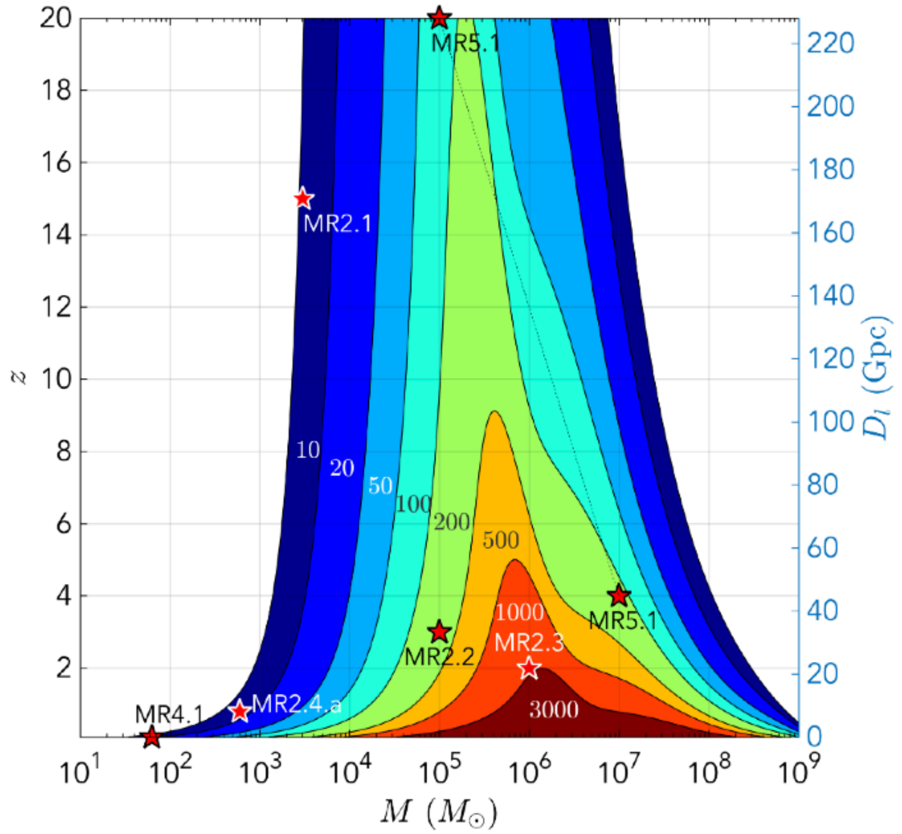
Expect 10^4 and 10^5 Binary Neutron Star (BNS) mergers per year



Cosmic Explorer
arXiv:2306.13745
Einstein Telescope
arXiv:2503.12263

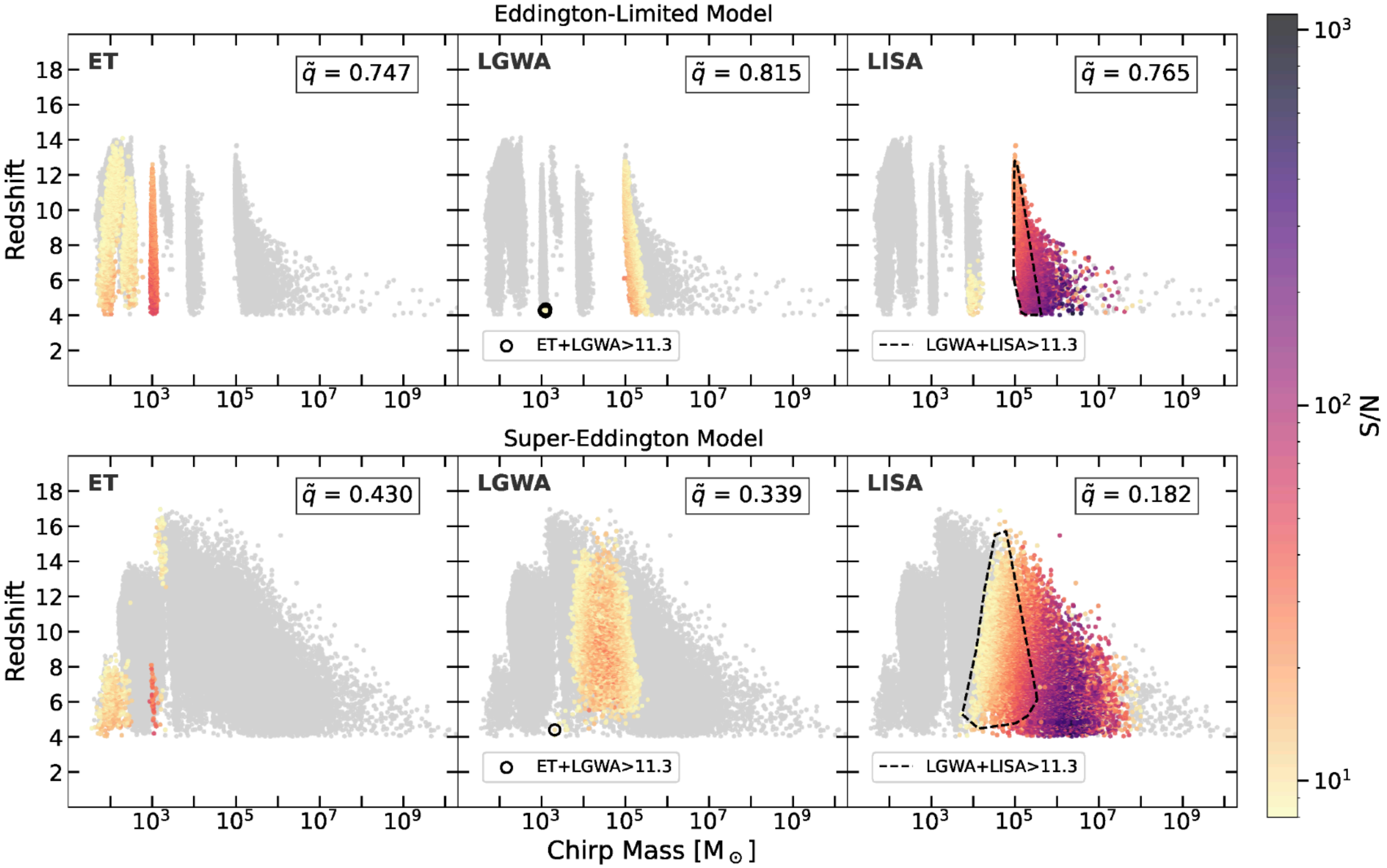
Space-based Gravitational Wave Detectors



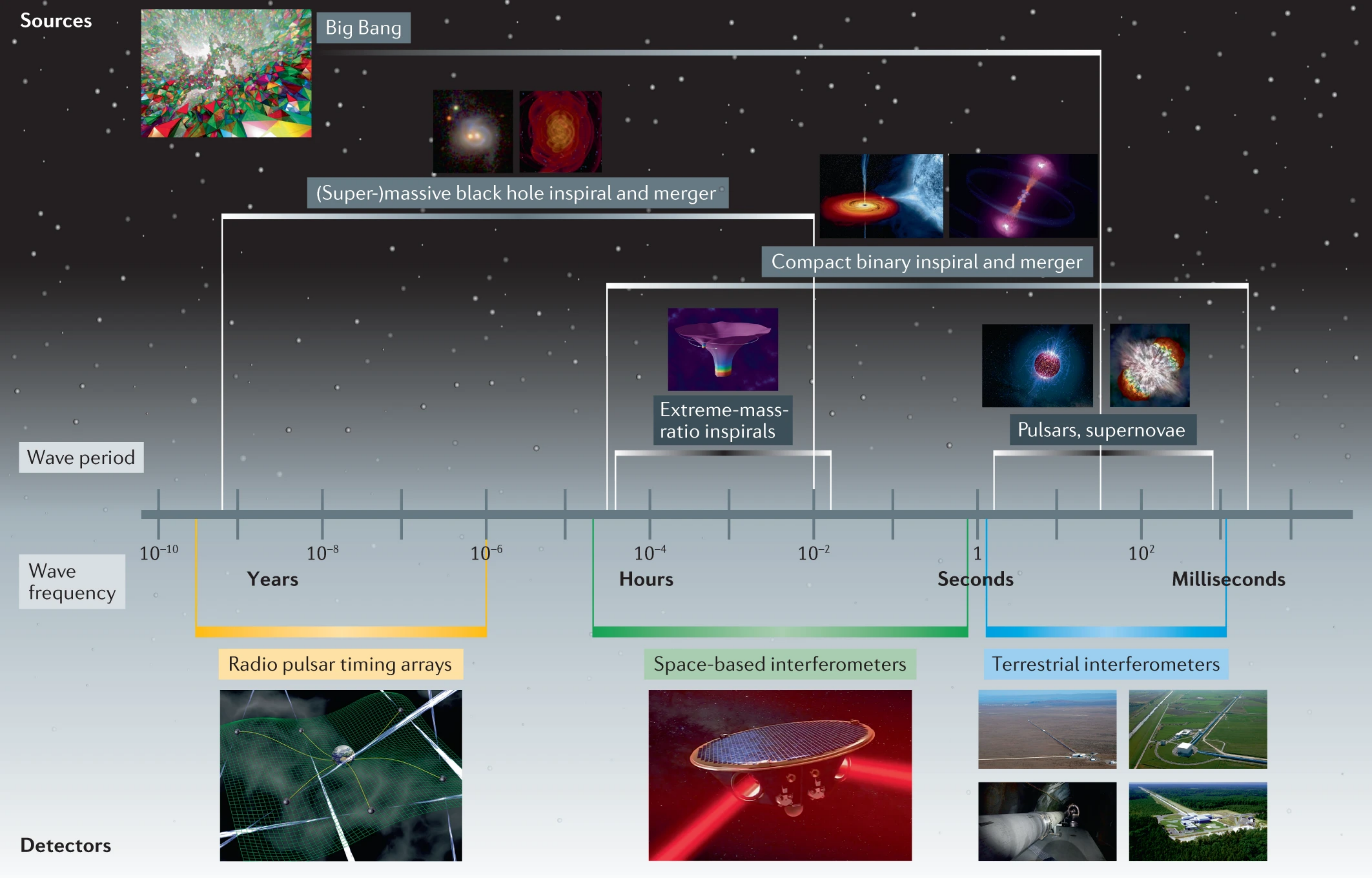


LISA
arXiv:1702.00786

Black Hole Binaries from Combination of Ground- and Space-based Detectors



Davani et al. 2026
arXiv:2604.18173



Sources

Big Bang

(Super-)massive black hole inspiral and merger

Compact binary inspiral and merger

Extreme-mass-ratio inspirals

Pulsars, supernovae

Wave period

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

Years **Hours** **Seconds** **Milliseconds**

Wave frequency

Radio pulsar timing arrays

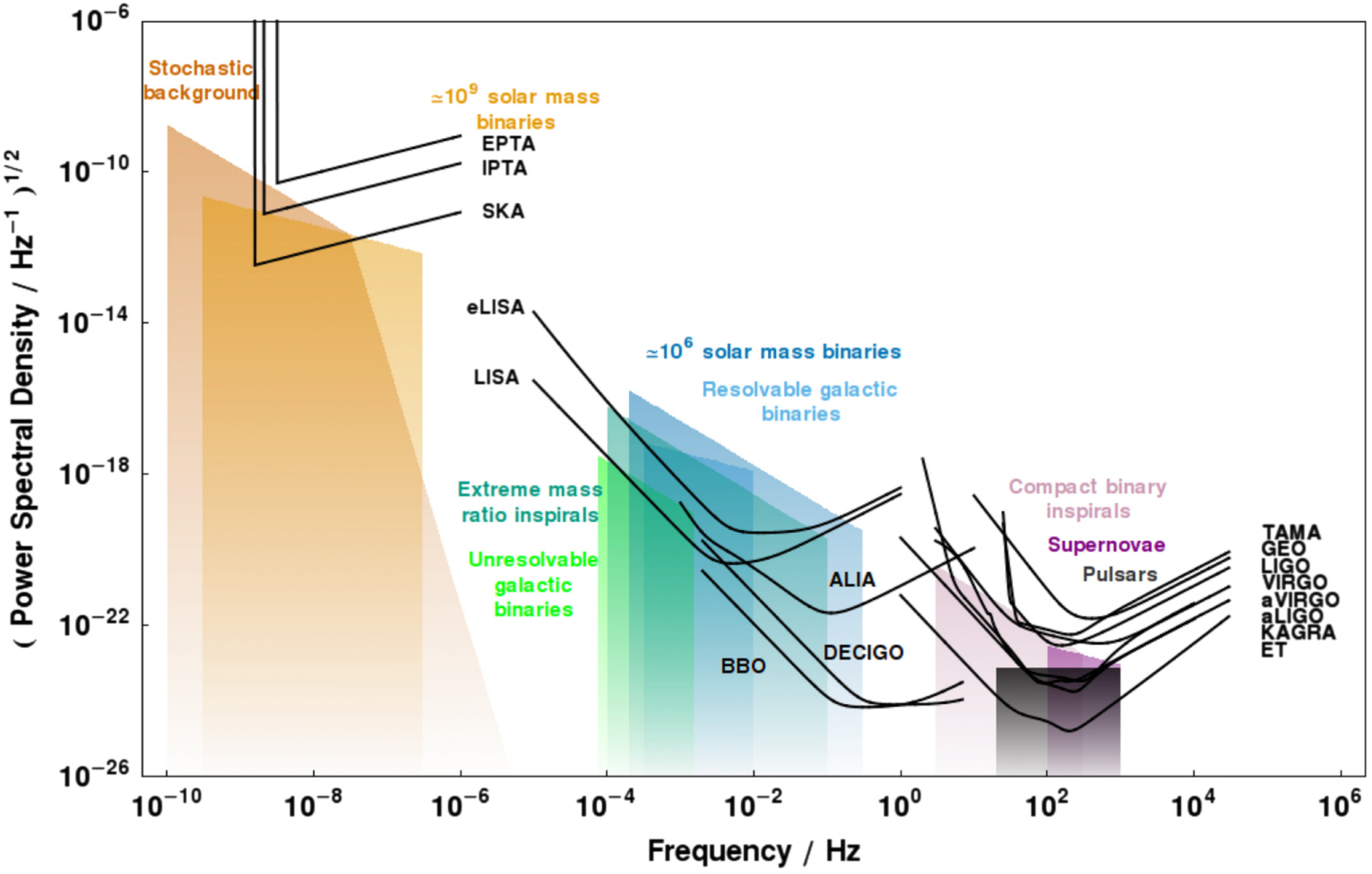
Space-based interferometers

Terrestrial interferometers

Detectors

Bailes et al. 2021

Collective Gravitational Wave Emission of Supermassive Black Holes



Moore, Cole, Berry 2015

Collective Gravitational Wave Emission of Supermassive Black Holes

Since ~2020, global network of Pulsar Timing Array (PTA) observatories have found increasing evidence for isotropic unpolarised stochastic gravitational wave background with observed characteristic Hellings & Downs inter-pulsar correlations

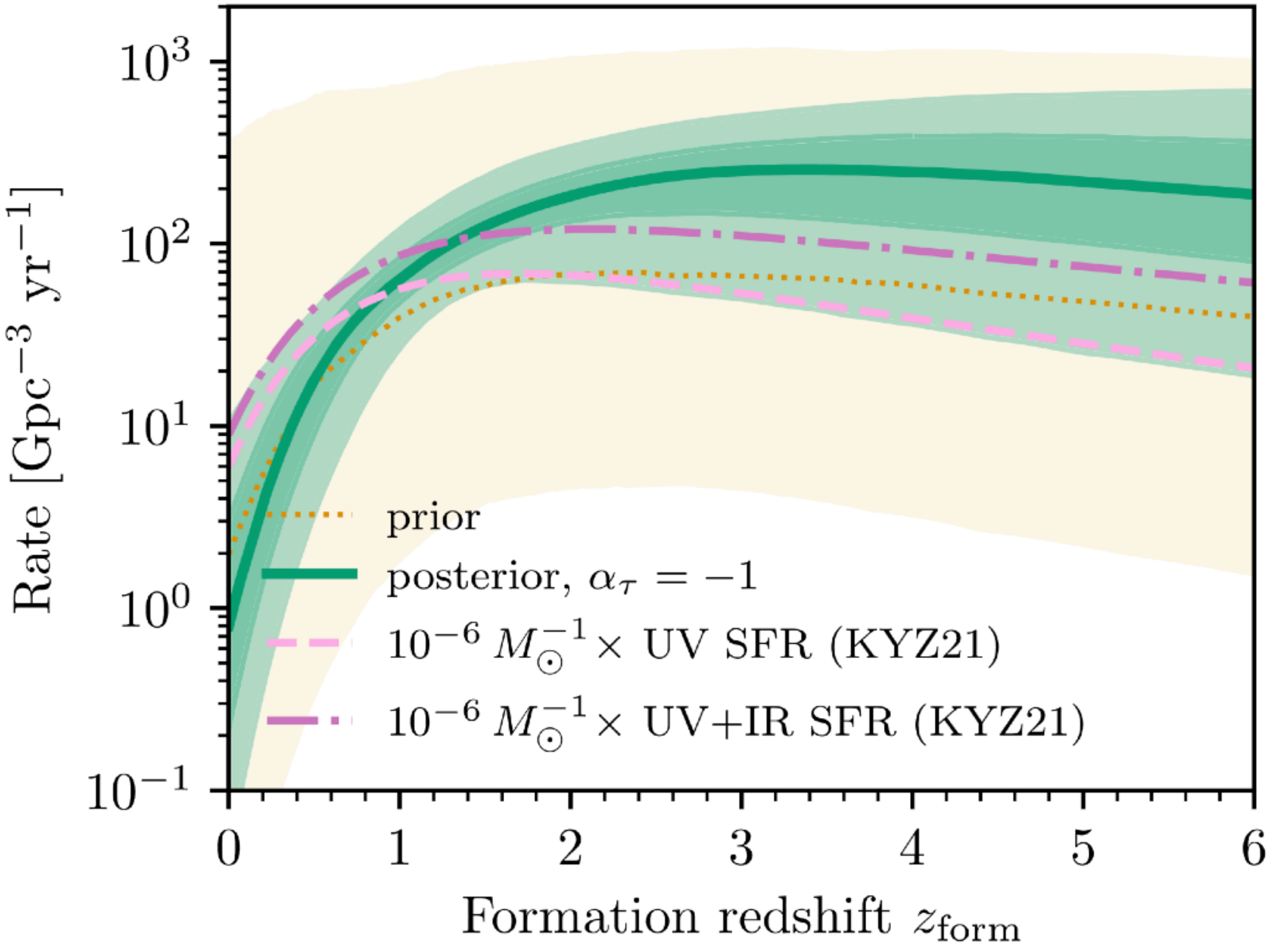
Cosmic population of supermassive black hole binaries at sub-parsec separations across the universe are expected to be a dominant source of the stochastic gravitational wave background at nanohertz frequencies

Next major observational milestone will be detection of contribution from individual super-massive black holes (first likely ~10^9 M_{Solar} roughly equal-mass binary at $z < 1$) and identification of electromagnetic counterpart

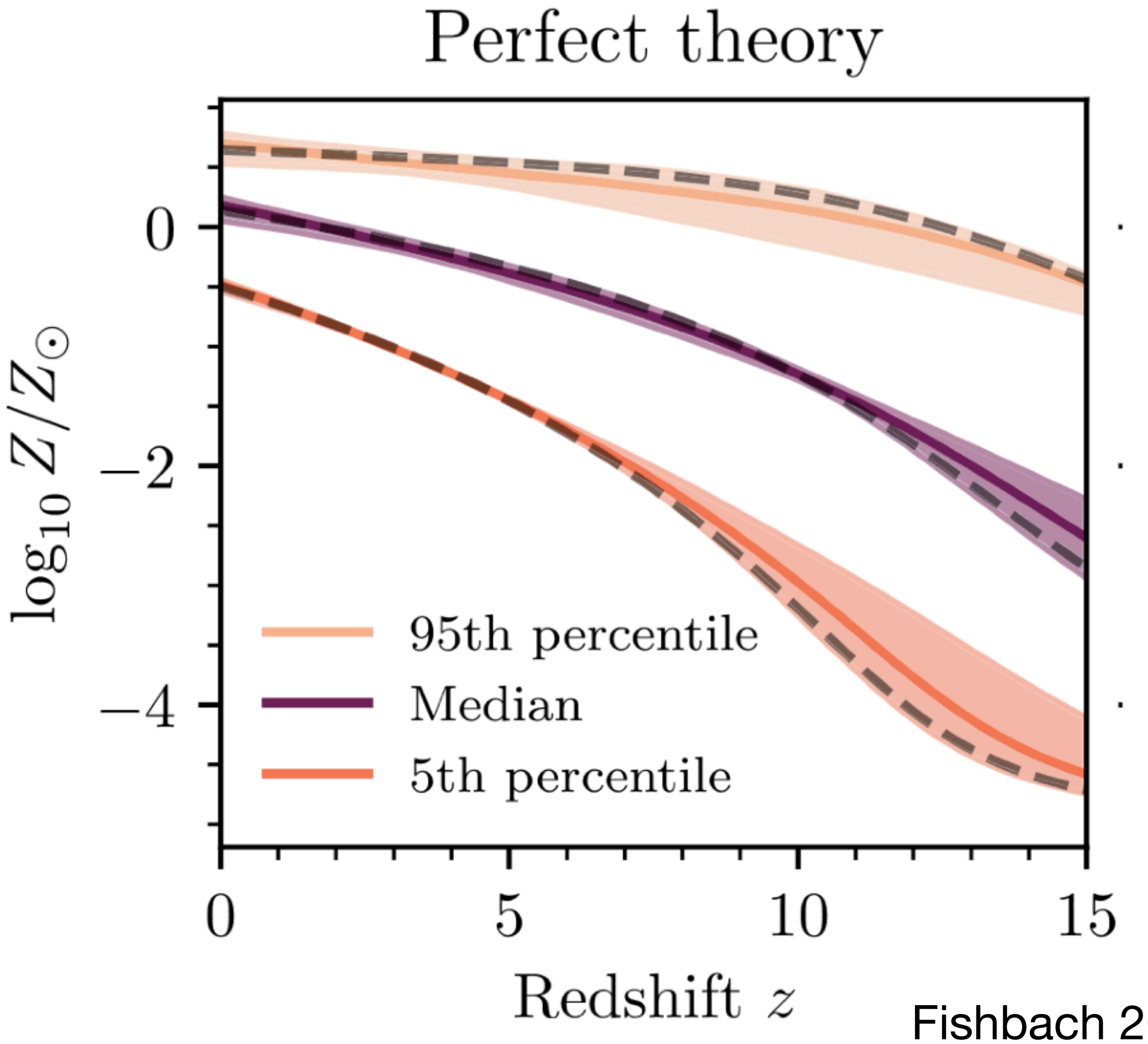
Taylor et al. 2025
arXiv:2511.08966
Mingarelli et al. 2025
arXiv:2501.08956
Goncharov et al. 2025

Inferences on Cosmic Star Formation Rate and Chemical Enrichment

Third-generation GW detectors will make direct measurement of the BBH merger rate over the entire history of the Universe, from the very first mergers to the present day



Fishbach & van Son 2023



Fishbach 2025

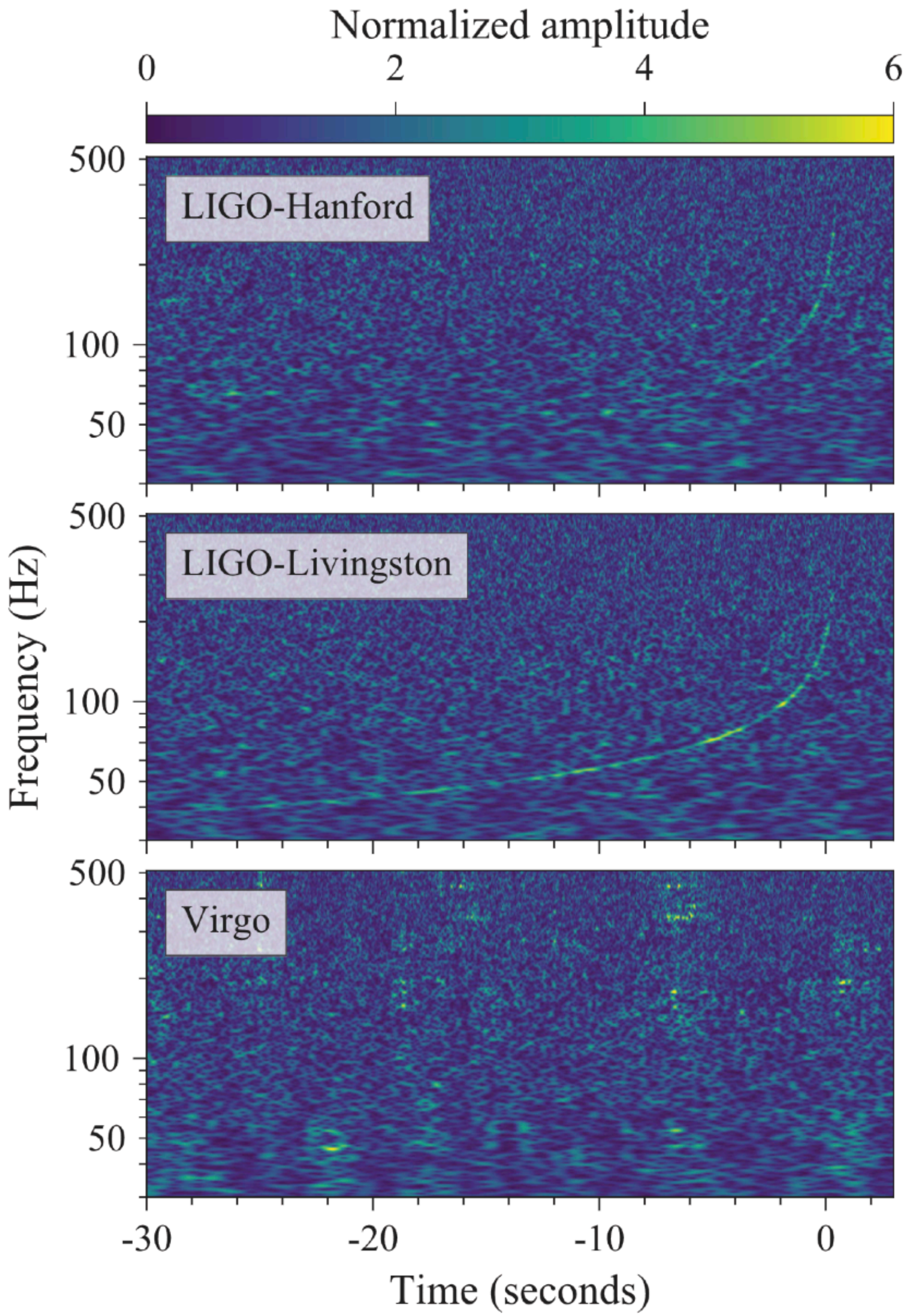
Star formation rate across cosmic time inferred from stellar mass BBH mergers (considering delay time from formation to merger event)

Formation of merging BBH systems is thought to be more efficient at low metallicities compared to high metallicities

See also Churślińska 2024

Using Gravitational Wave “Standard Sirens” to Constrain the Cosmic Expansion History

Gravitational Wave Standard Sirens: Absolute Distance Indicators



arXiv:1710.05832

Gravitational waves from compact binary inspirals are “self-calibrated” distance indicators

Absolute gravitational wave luminosity (and hence luminosity distance) can be determined directly from observed gravitational strain waveform

$$\frac{dE}{dt} = \frac{32c^5}{5G} \times \left(\frac{G\mathscr{M}}{c^3} \times \omega_r \right)^{10/3}$$

Chirp mass can be determined by gravitational wave frequency and frequency derivative

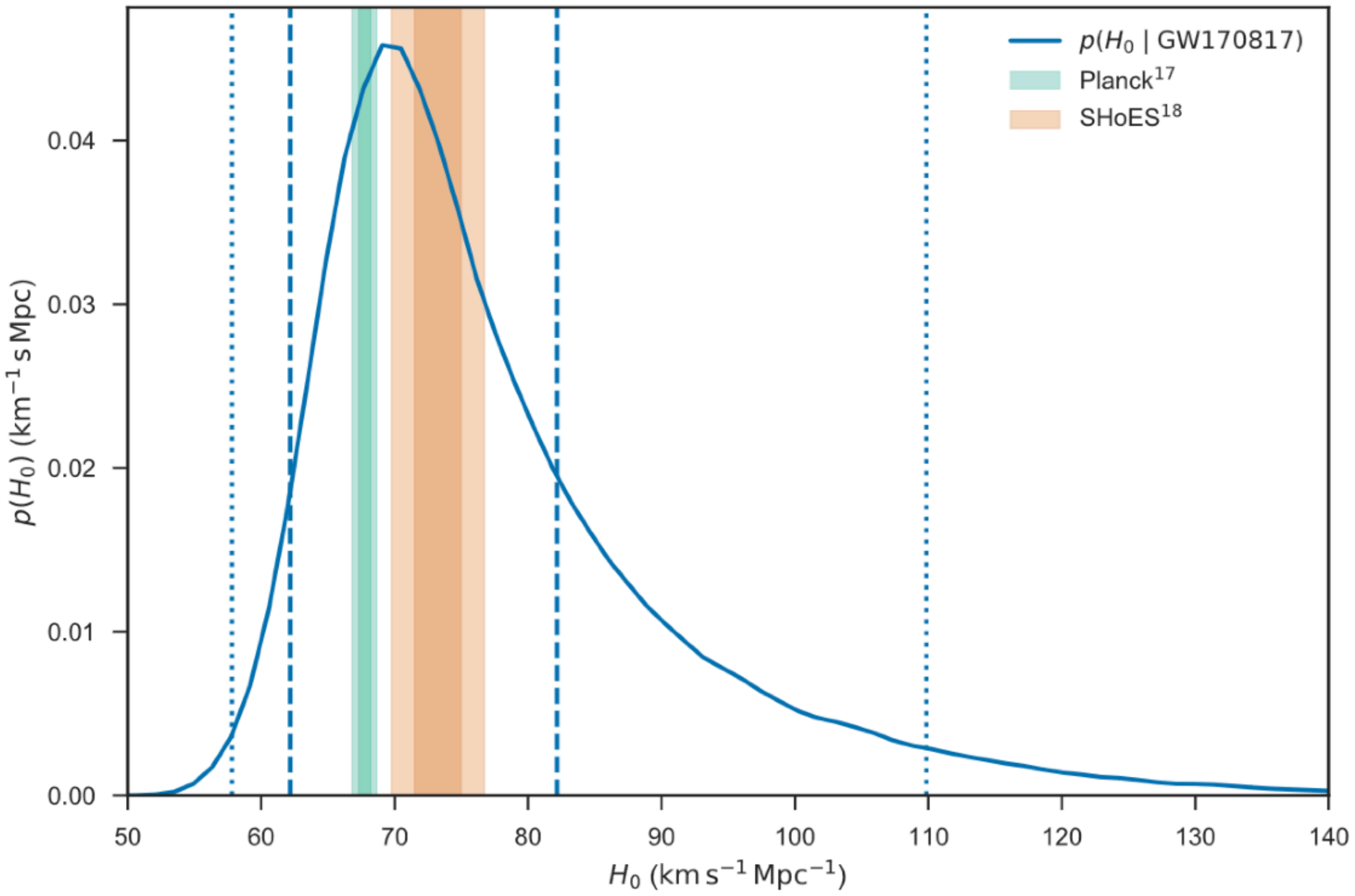
$$\mathscr{M} = \frac{c^3}{G} \left(\frac{5}{96} \pi^{-8/3} f_{GW}^{-11/3} \dot{f}_{GW} \right)^{3/5} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$f_{GW} = \frac{\omega_{GW}}{2\pi} = \frac{\omega_r}{\pi}$$

Hubble Diagram from Gravitational Wave Standard Sirens

A standard siren luminosity distance (gravitational waves) + redshift (electromagnetic counterpart) constraints the cosmic expansion history

Standard siren approach is *completely independent* from both low-z distance ladder and high-z cosmic microwave background (CMB)

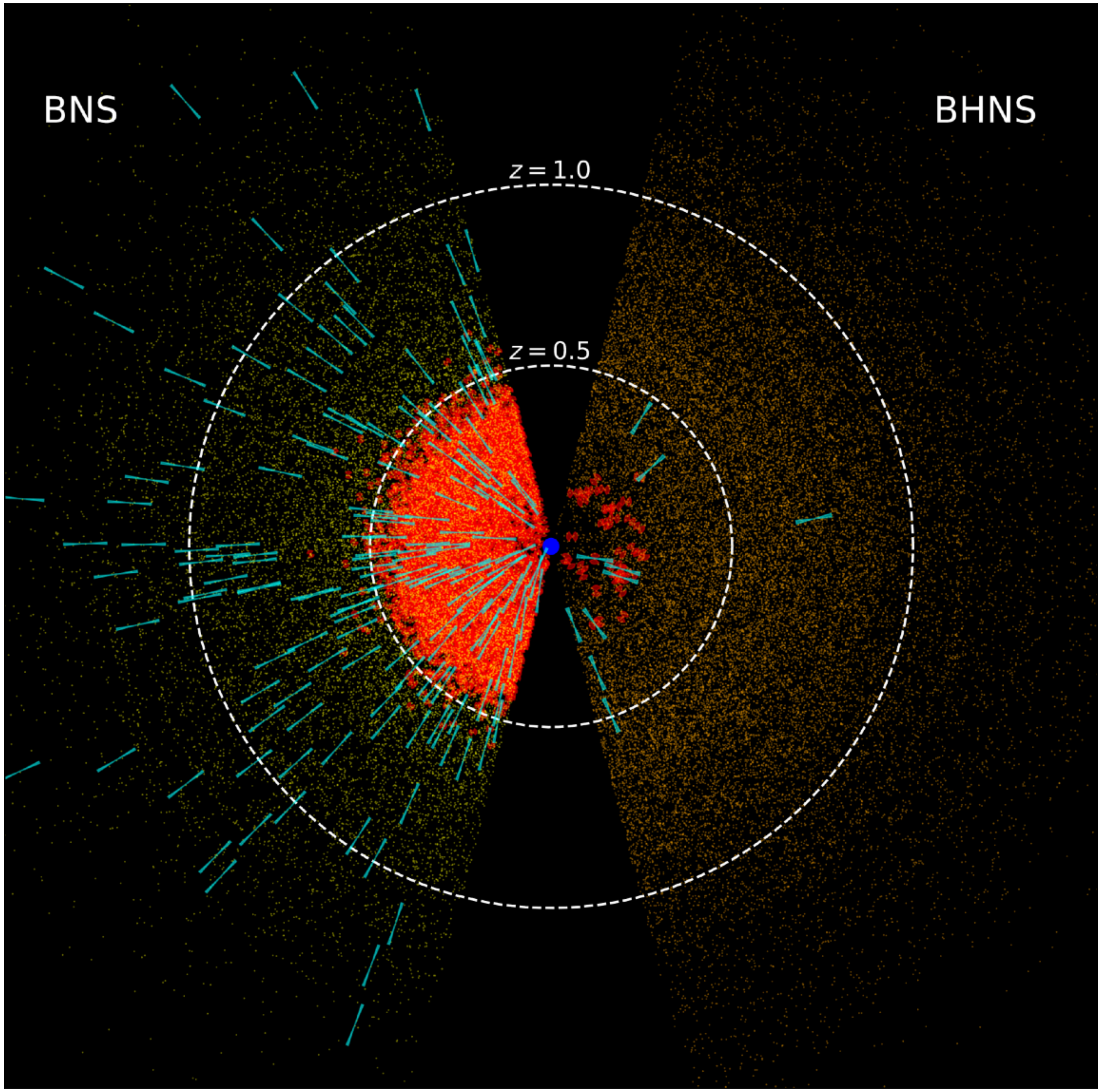


GW170817
arXiv:1710.05835

Multi-messenger Signals from Binary Neutron Star Coalescence

Thousands of BNS mergers detected every year by a network containing two Cosmic Explorer observatories will have distance uncertainties less than 10%

A network containing the two Cosmic Explorer observatories will allow for precise localization of the binary mergers and achieve sub-1% precision on Hubble constant in under a year



Cosmic Explorer
arXiv:2306.13745
Einstein Telescope
arXiv:2503.12263

Two Types of Standard Siren Analysis Methods

“Bright sirens” with an individually identified electromagnetic counterpart for each gravitational wave event to determine redshift

“Dark sirens” without an individual electromagnetic counterpart — redshift is instead estimated through statistical approaches such as cross correlation with tracers of galaxies and/or large scale structure

Summary

Summary

Multi-messenger astrophysics is intrinsically interdisciplinary, bringing together many detector technologies, coordinated observation strategies, and theory/modeling approaches

Next 10-20 years of multi-messenger astrophysics has the potential for breakthrough discoveries across diverse subfields of physics and astronomy

Providing access to extreme physical environments that cannot be re-created in terrestrial laboratories and that are hidden from electromagnetic observations alone — across the universe and deep within sources, close to the central engine