Neutrinos which we will detect soon: diffuse supernova neutrino background and GZK/ BZ/ cosmogenic neutrinos

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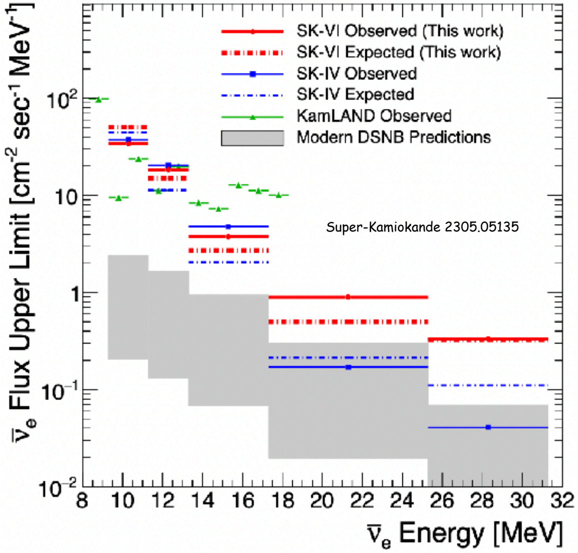
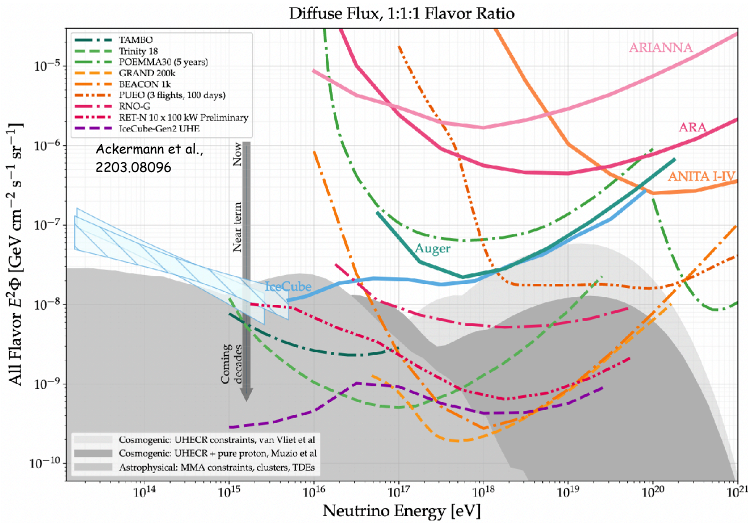
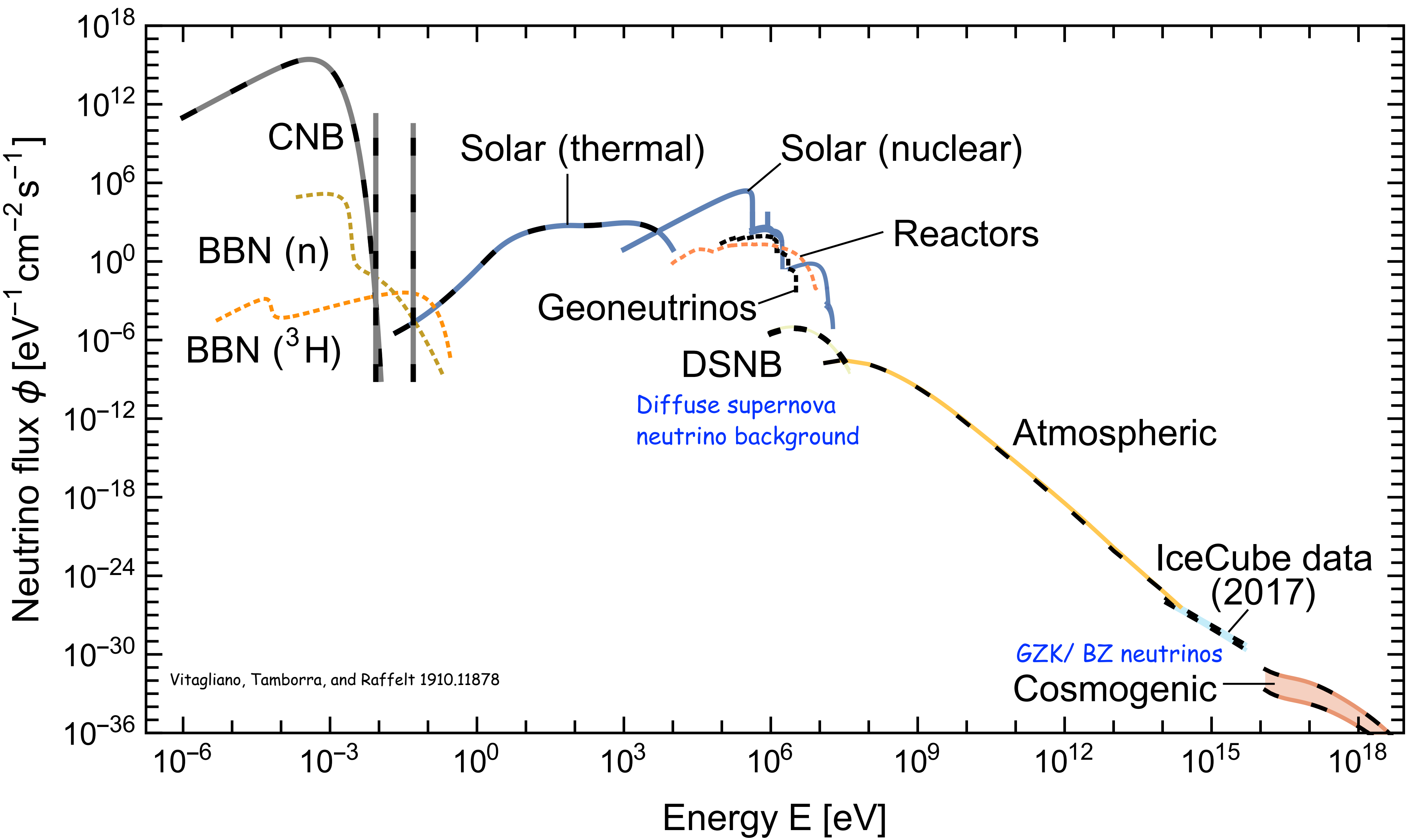
- Diffuse supernova neutrino background



- GZK/ BZ/ cosmogenic neutrinos

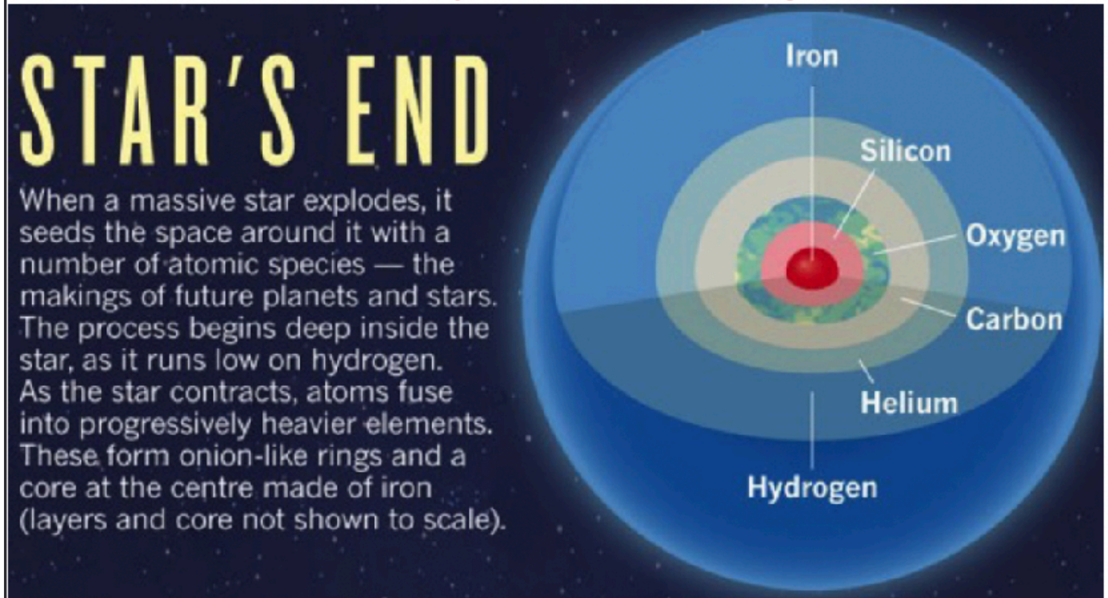


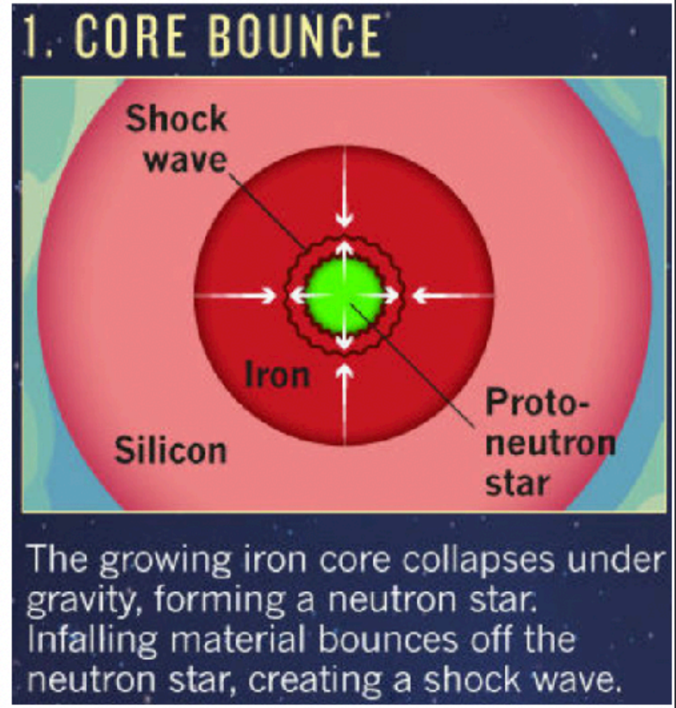
Astrophysical neutrino spectrum

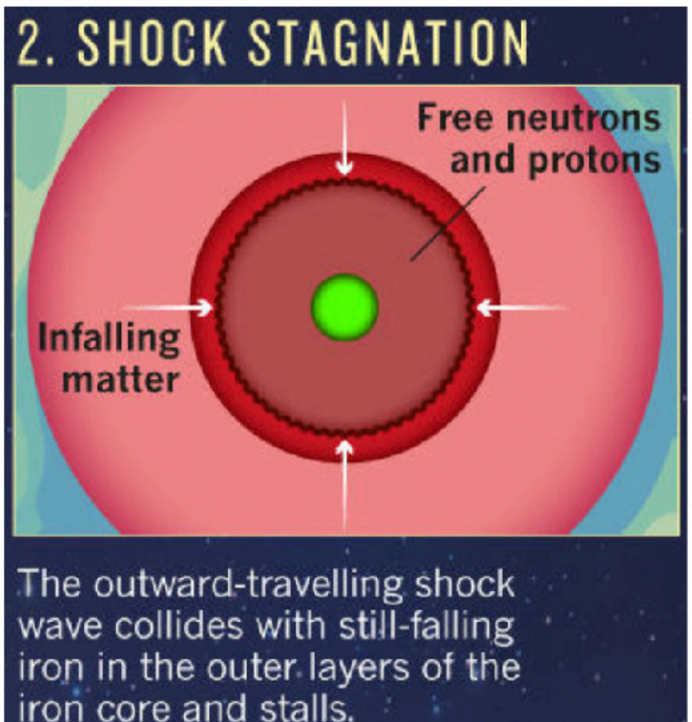


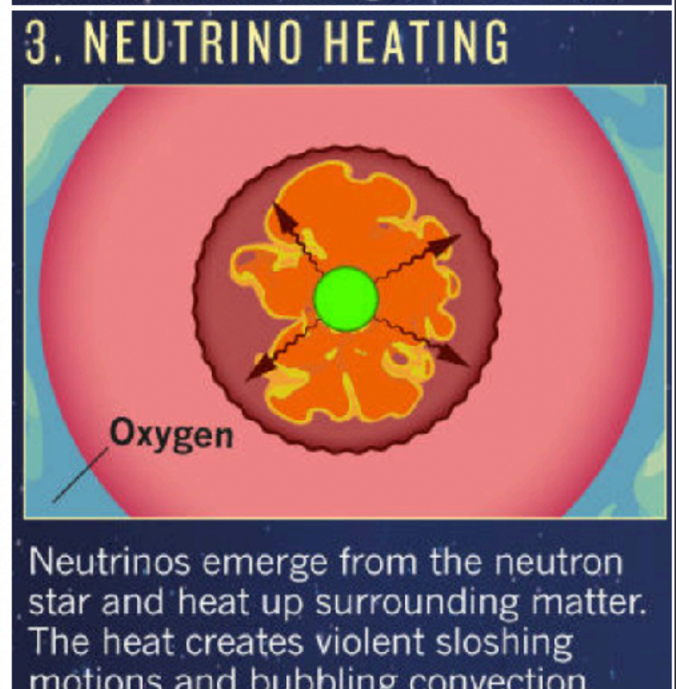
Diffuse supernova neutrino background (DSNB)

Supernova explosion





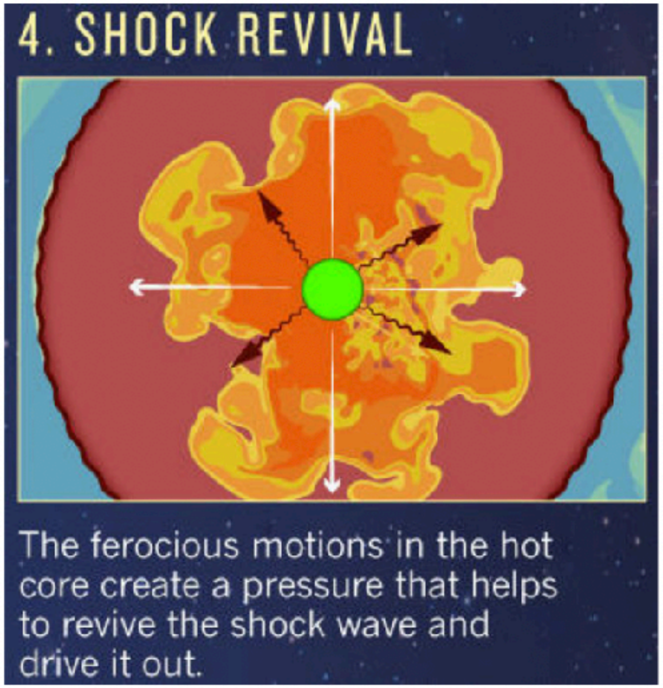




https://www.nature.com/articles/d41586-018-04601-7

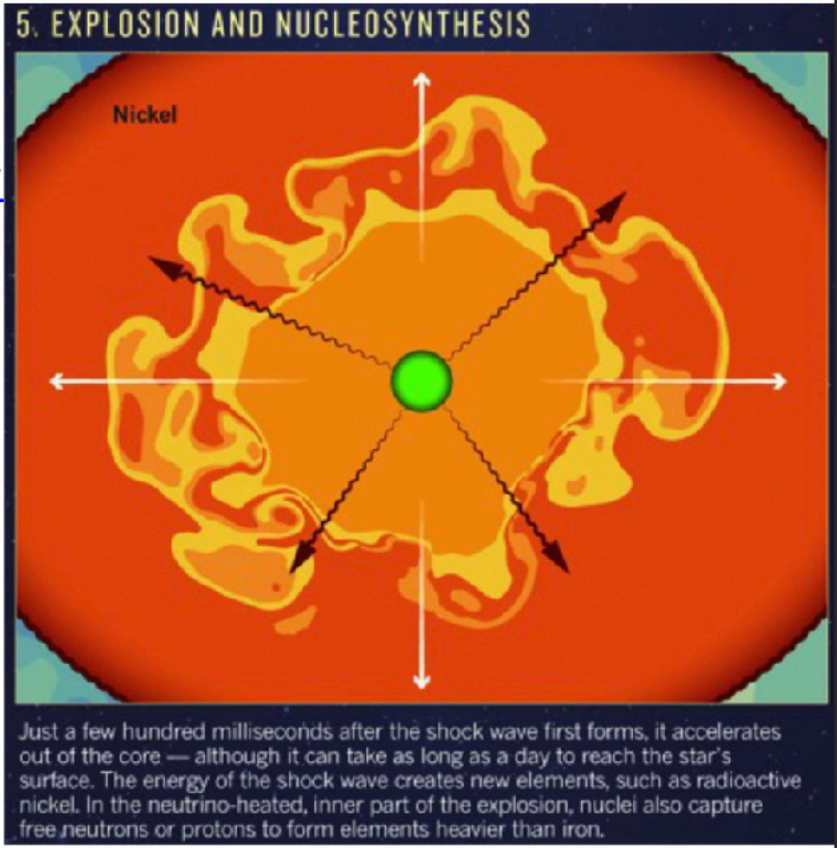
Janka 1702.08825

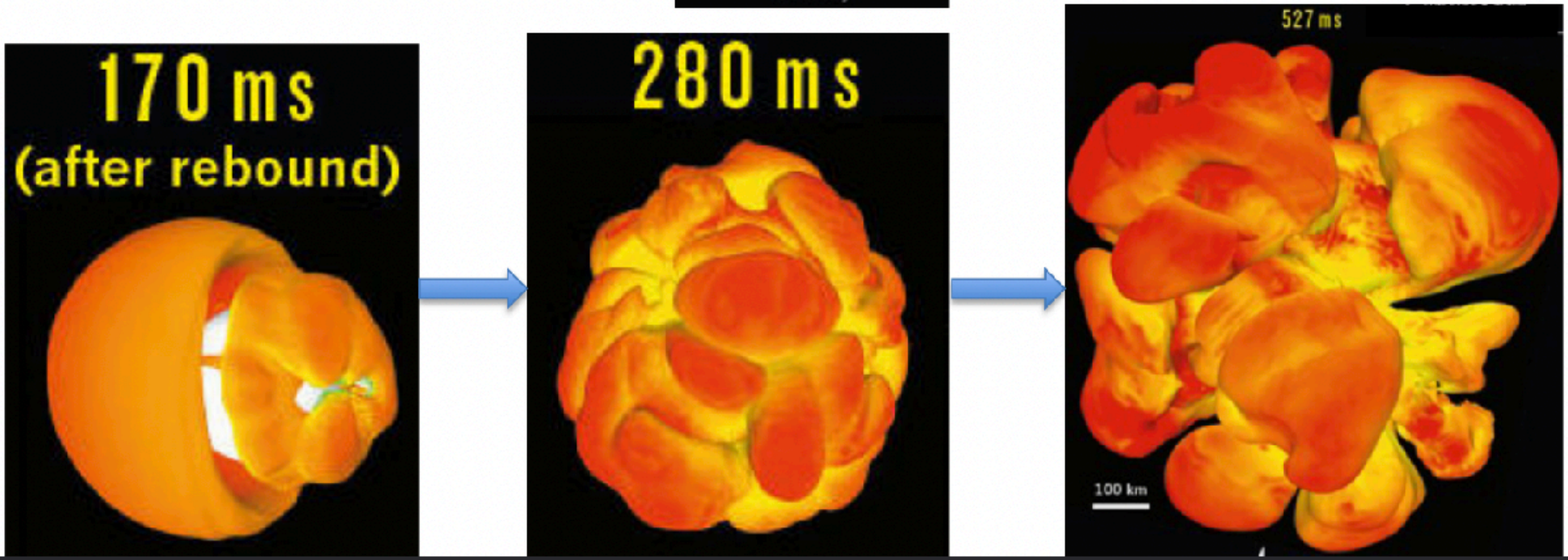
Supernova explosion (contd.)



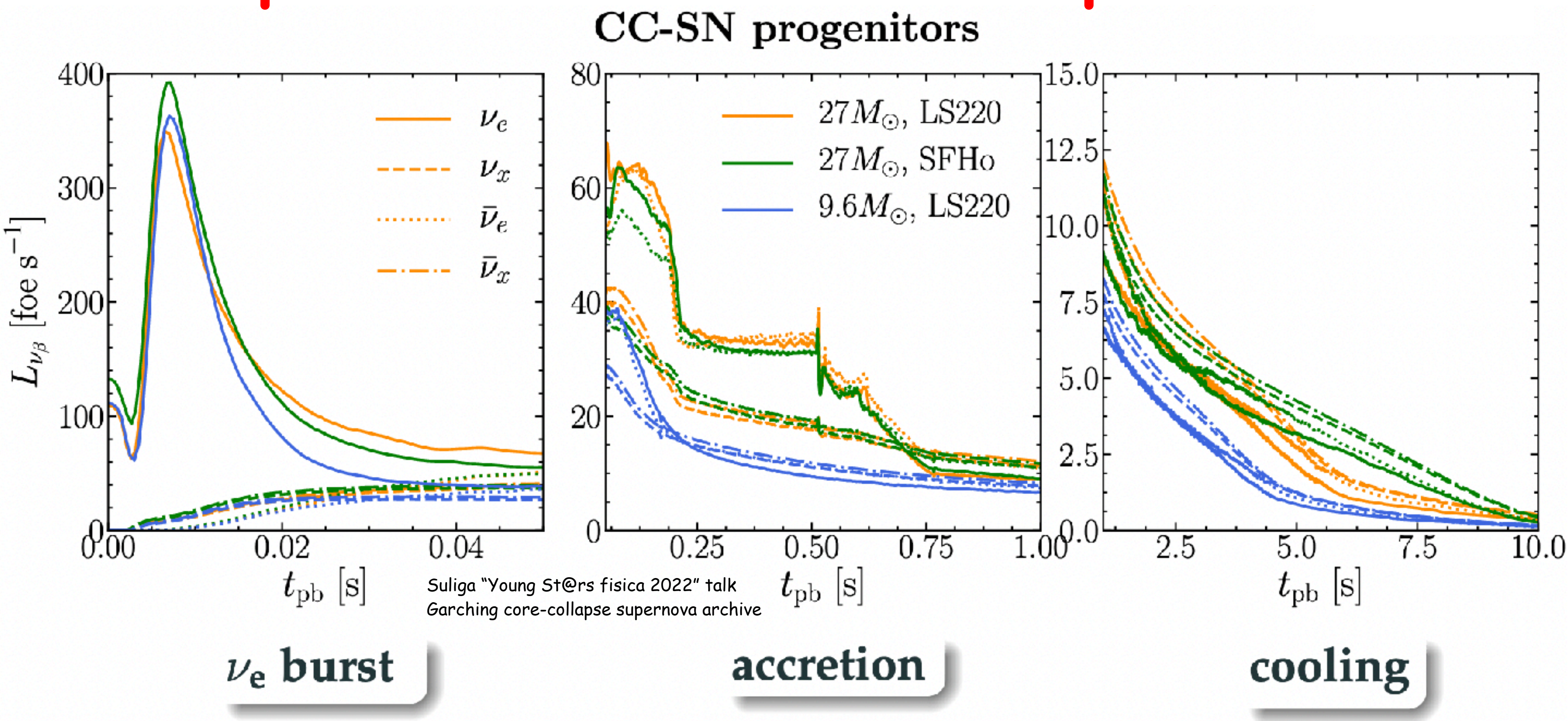
https://www.nature.com/articles/d41586-018-04601-7

Janka 1702.08825





Supernova neutrino spectrum



Suliga "Young St@rs fisica 2022" talk
Garching core-collapse supernova archive

- Neutrino burst of all flavours — lasting for ~ 10 seconds
- Neutrinos can be detected from Galactic supernova in large numbers
- Neutrino energies up to ~ 50 MeV

Diffuse supernova neutrino background

- Galactic supernova is rare; the rate is ~ 1 per century

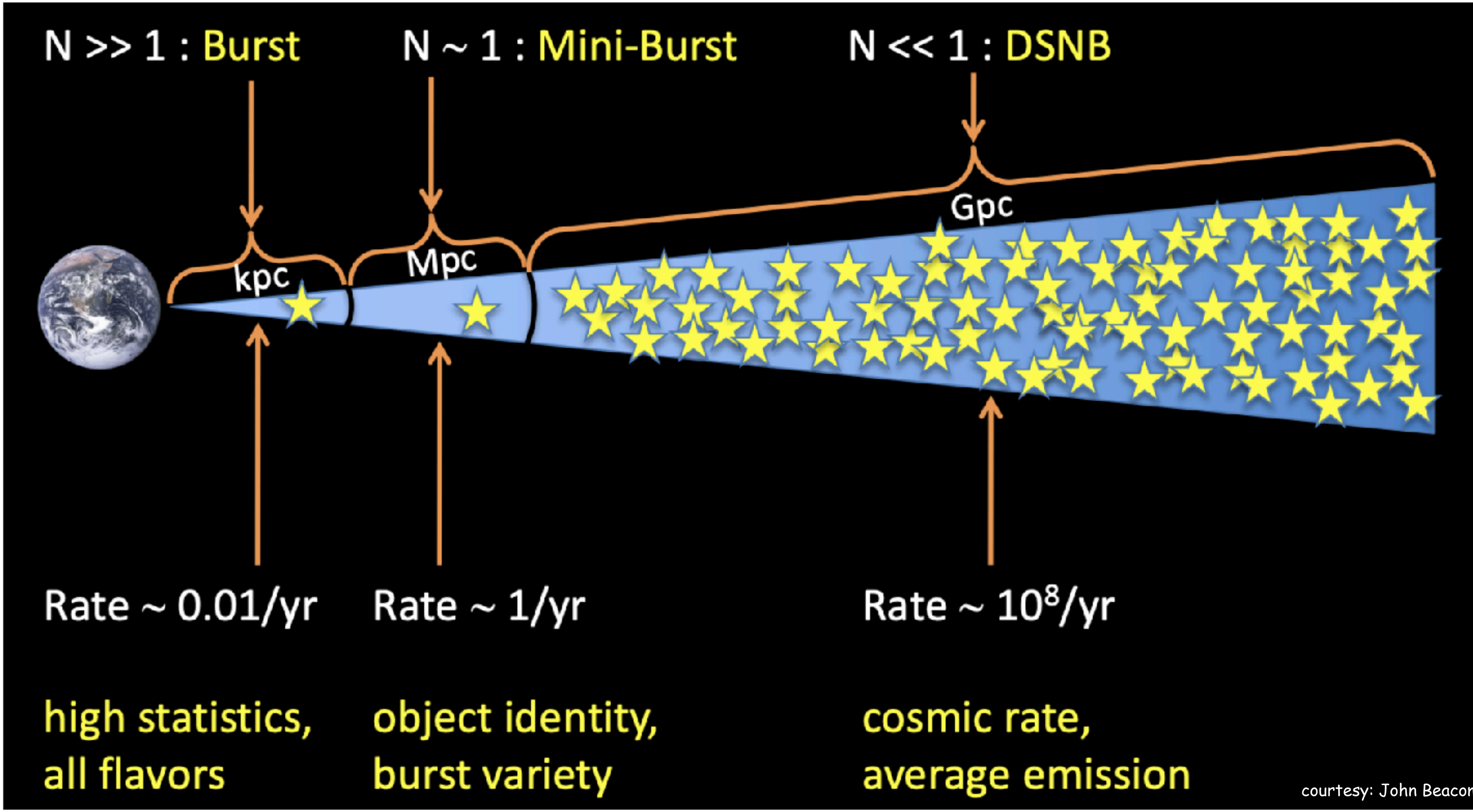
- We will detect ~ 1 or 2 neutrinos from a core-collapse supernova in Andromeda

- The probability of detecting a neutrino from a core-collapse supernova from galaxies farther away is $\ll 1$

- However, the rate of supernova in the entire Universe is large; the rate is ~ 10 per second

- Can we detect the combined flux of neutrinos from all core-collapse supernova in the Universe?

Diffuse supernova neutrino background



Diffuse supernova neutrino background

- An order of magnitude estimate of the DSNB flux using the scaling from SN 1987A data Beacom 1004.3311, Lunardini 1007.3252, Mathews et al. 1907.10088, Suliga 2207.09632, Ando et al. 2306.16076

$$\left[\frac{dN_\nu}{dt}\right]_{\rm DSNB} \approx \left[\frac{dN_\nu}{dt}\right]_{\rm 1987A} \left[\frac{N_{\rm SN} M_{\rm det}}{4\pi D^2}\right]^{-1}_{\rm 1987A} \left[\frac{N_{\rm SN} M_{\rm det}}{4\pi D^2}\right]_{\rm DSNB}$$

- For SN 1987A detection in Kamiokande-II: $[dN_\nu/dt]_{\rm 1987A} \approx 1\,{\rm s}^{-1}$

- Super-Kamiokande is 10 times larger than Kamiokande-II:

$$[M_{\rm det}]_{\rm DSNB}/[M_{\rm det}]_{\rm 1987A} \approx 10$$

- Distance to SN 1987A $\approx\ 50\,{\rm kpc}$

- Most of the supernova are at $z \approx 1$, which is $c/H_0 \approx 4\,{\rm Gpc}$

$$\left[\frac{dN_\nu}{dt}\right]_{\rm DSNB} \approx 1\,{\rm s}^{-1} \times 100 \times 10 \times 10^{-10} \approx 3\,{\rm yr}^{-1}$$

Diffuse supernova neutrino background

$$\frac{d\phi}{dE_\nu}(E_\nu) = \int_0^{z_{\rm max}} \left[(1+z)\,\varphi[E_\nu(1+z)]\right] \left[R_{\rm SN}(z)\right] \left[\left|\frac{cdt}{dz}\right|dz\right]$$

DSNB flux spectrum on Earth as a function of the neutrino energy E_ν

Neutrino emission per supernova

Core-collapse supernova rate

Beacom 1004.3311, Lunardini 1007.3252, Mathews et al. 1907.10088, Suliga 2207.09632, Ando et al. 2306.16076

$\varphi(E_\nu)$ includes neutrino emission from supernova forming both neutron stars and black holes

$(1+z)$ accounts for the redshift factor

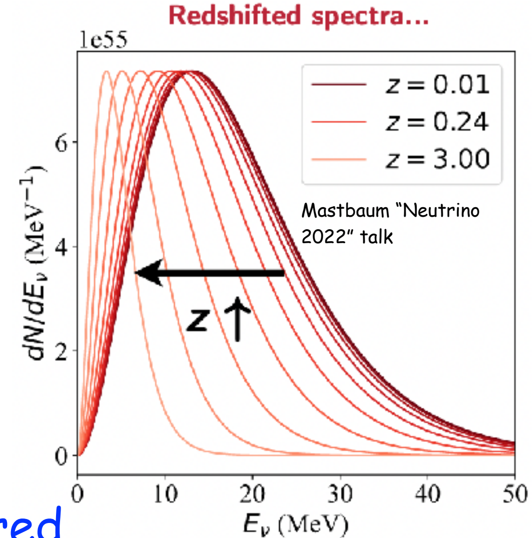
$$|dt/dz|^{-1} = H_0(1+z)\left[\Omega_\Lambda + \Omega_m(1+z)^3\right]^{1/2}$$

- Most of the emission comes from $z \lesssim 3$, $z_{\rm max}$ is restricted by the formation of first massive stars (Riya and Rentala 2007.02951, Moller et al. 1804.03157, Ekanger et al., 2310.15254)

- DSNB flux spectrum computation demonstrates line-of-sight integral (individual contribution drops as $\frac{1}{r^2}$, the volume increases as r^2, thus the integral is only over distance)

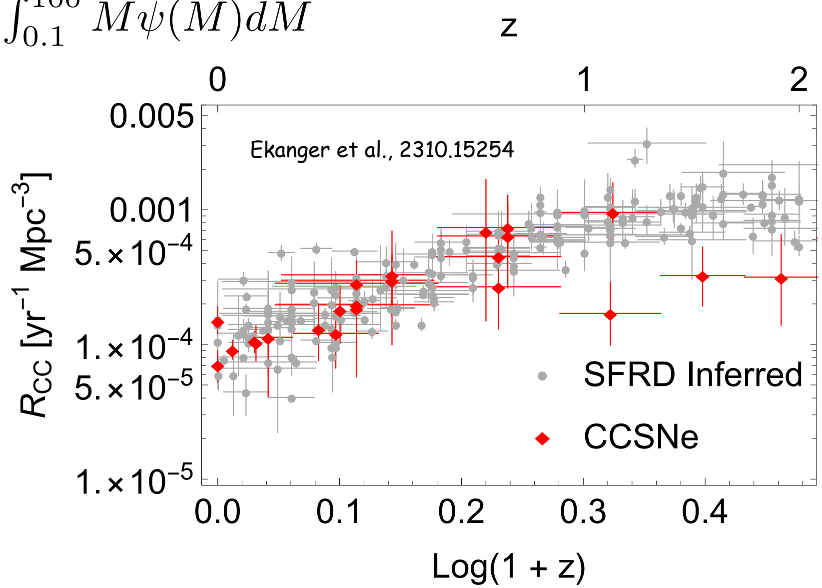
Diffuse supernova neutrino background

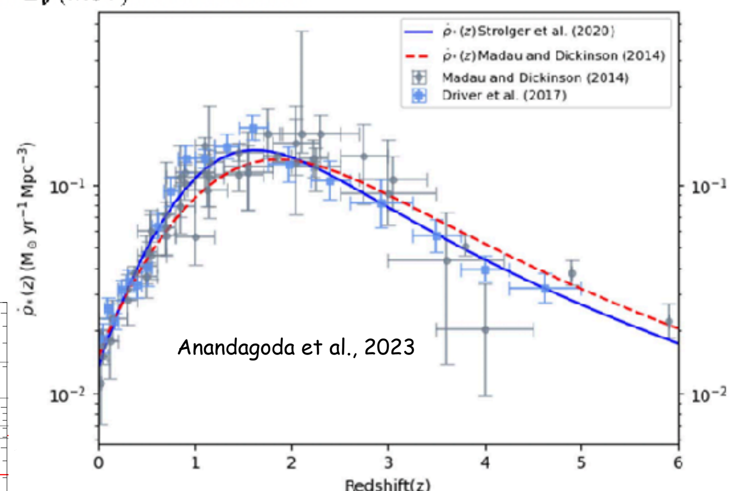
- The spectrum of neutrinos from distant supernova gets redshifted



- The supernova rate can either be measured or inferred from star formation rate

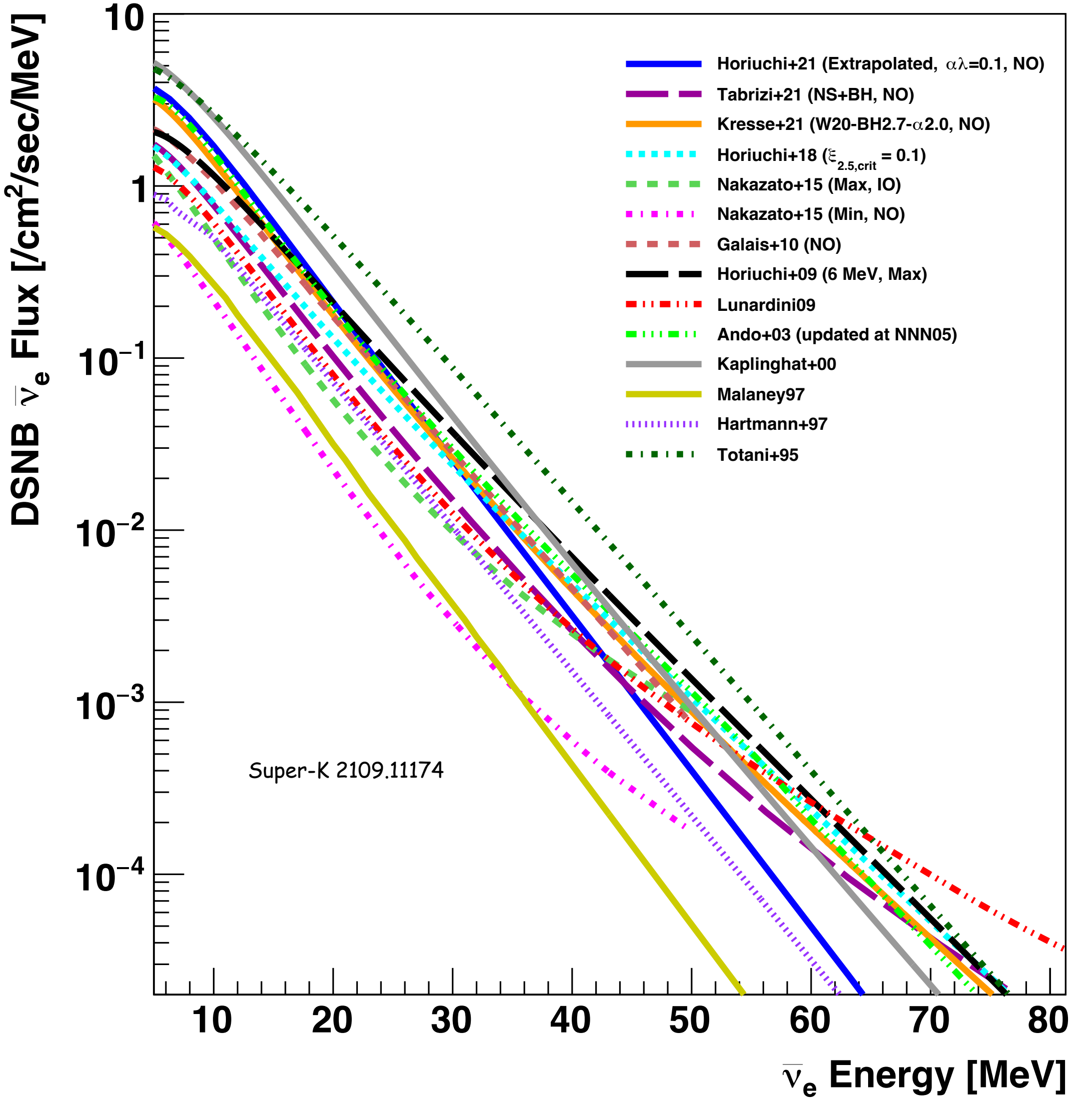
$$R_{\rm SN}(z) = R_{\rm SF}(z)\,\frac{\int_8^{50} M\psi(M)dM}{\int_{0.1}^{100} M\psi(M)dM}$$





Diffuse supernova neutrino background

- A compilation of various calculations of the diffuse supernova neutrino background flux



- A large number of calculations of the DSNB flux has been performed over the last three decades: the calculations broadly agree even after including a wide variety of uncertainties

- Most of the flux calculations concentrate on the $\bar{\nu}_e$ flux, as that is the most easily detectable neutrino flavour. We expect other neutrino flavours to have a similar flux

Diffuse supernova neutrino background

- The main interaction that is used to detect DSNB is the inverse beta interaction

$$\bar{\nu}_e + p \to e^+ + n$$

e^+: detected either via Cherenkov or scintillation emission

n: detected either via capture on proton or Gadolinium

$$\sigma(\bar{\nu}_e p) \approx 10^{-43}\,\mathrm{cm}^2\, p_e E_e E_\nu^{-0.07056+0.02018\ln E_\nu - 0.001953 \ln^3 E_\nu}$$

Vogel & Beacom hep-ph/9903554; Strumia & Vissani astro-ph/0302055; Ricciardi, Vignaroli & Vissani 2206.05567

- Threshold of interaction $E_\nu > 1.8\,\mathrm{MeV}$

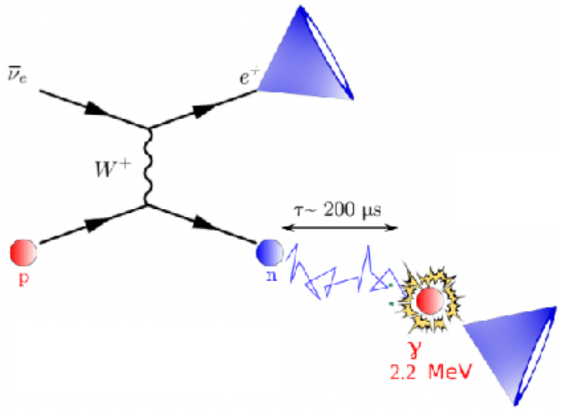
$T_e \approx E_\nu - 1.8\,\mathrm{MeV}$ $\quad$ T_e : kinetic energy of the positron

- Largest cross section at the relevant energies (~ MeV - 50 MeV)

- Other neutrino interactions have also been used to search for DSNB; however, these interactions have much smaller cross-sections

Diffuse supernova neutrino background

- Neutron capture on free proton produces 2.2 MeV photon --- delay time ~ 200 μsec --- capture cross section 0.3 barns



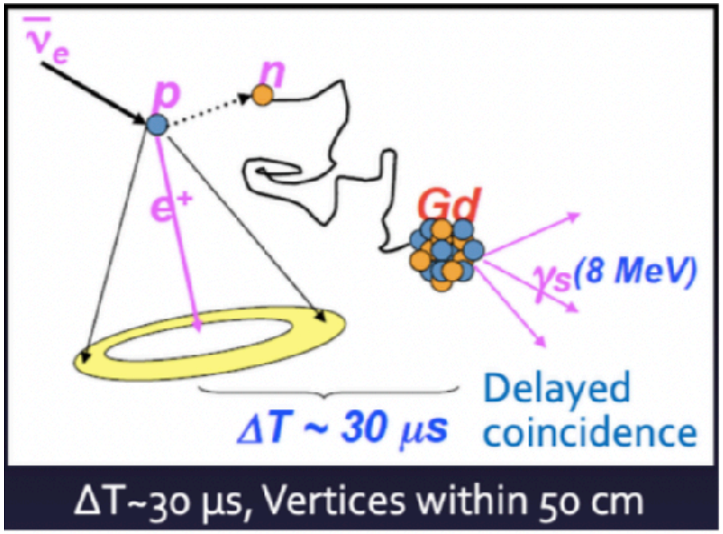
Mastbaum "Neutrino 2022" talk

technique used in Super-K 2021 search 2109.11174

- Neutron capture on Gadolinium produces ~ 8 MeV photons --- delay time ~ 20 μsec --- capture cross section 49000 barns

Perez-Gonzalez "CERN Neutrino platform 2023" talk

technique used in Super-K 2023 search 2305.05135



Beacom and Vagins hep-ph/0309300

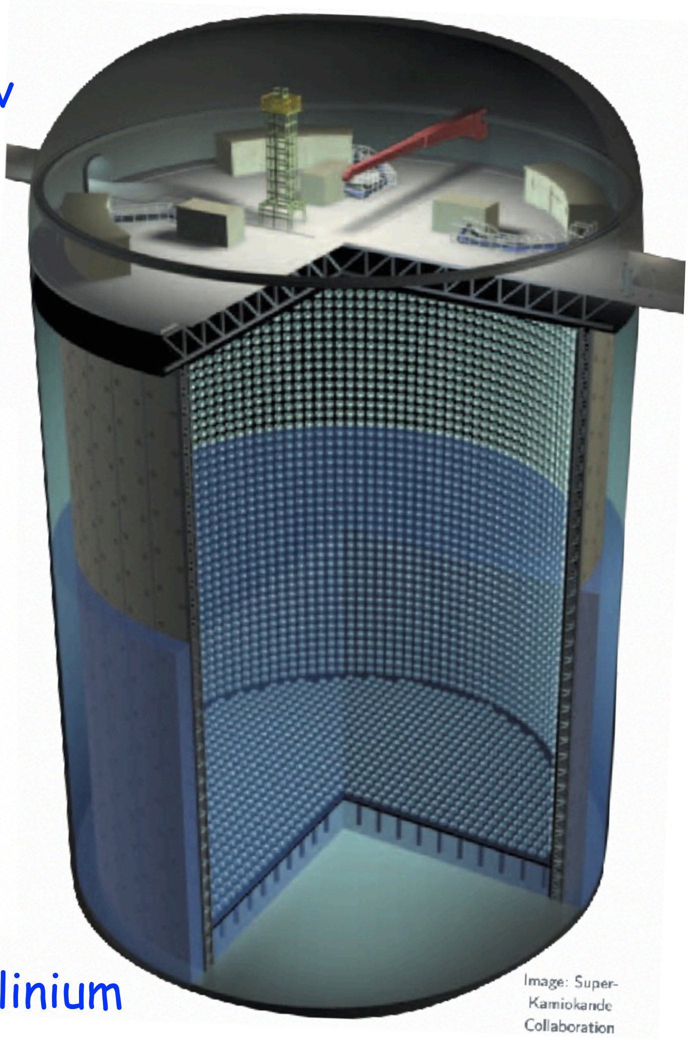
Super-Kamiokande detector

- Super-Kamiokande is a 50 kilo-ton water Cherenkov detector

- The fiducial volume for DSNB search is 22.5 kilo-ton

Super-K 2311.05105

Phase	Dates	Livetime (Days)	Photo-coverage (%)	Neutron tagging
SK I	1996–2001	1489.2	40	–
SK II	2002–2005	798.6	19	–
SK III	2006–2008	518.1	40	–
SK IV	2008–2018	3244.4	40	H
SK V	2019–2020	461.0	40	H
SK Gd	2020–Present	–	40	H+Gd



- Some physics analyses already published with gadolinium loading (2305.05135, 2403.06760,2403.07796)

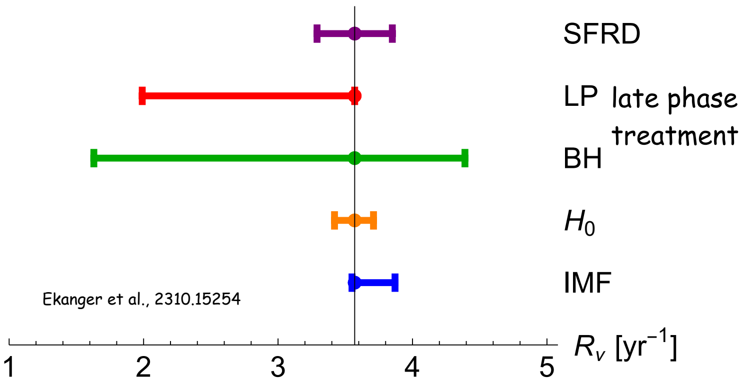
Diffuse supernova neutrino background

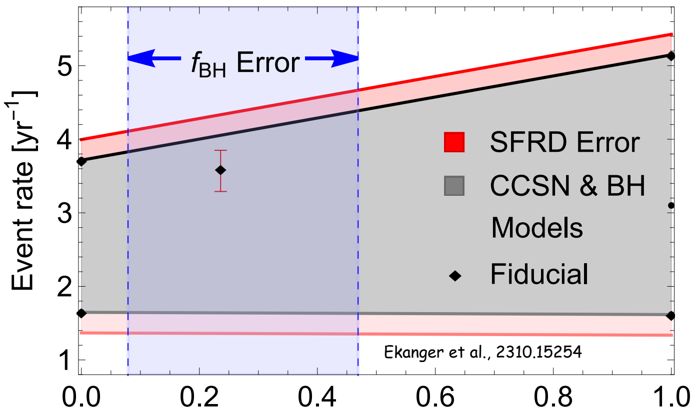
$$\frac{dN_e}{dE_e}(E_e) = N_p\,\sigma(E_\nu) \int_0^\infty \left[(1+z)\,\varphi[E_\nu(1+z)]\right]\left[R_{\rm SN}(z)\right]\left[\left|\frac{cdt}{dz}\right|dz\right]$$

number of free protons

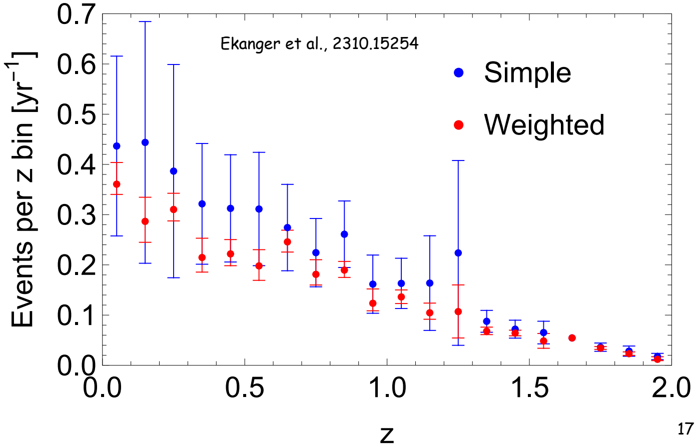
- Latest predictions take into account various astrophysical uncertainties and predict ~ 4 events per year in SuperK-Gd

Ekanger et al., 2310.15254

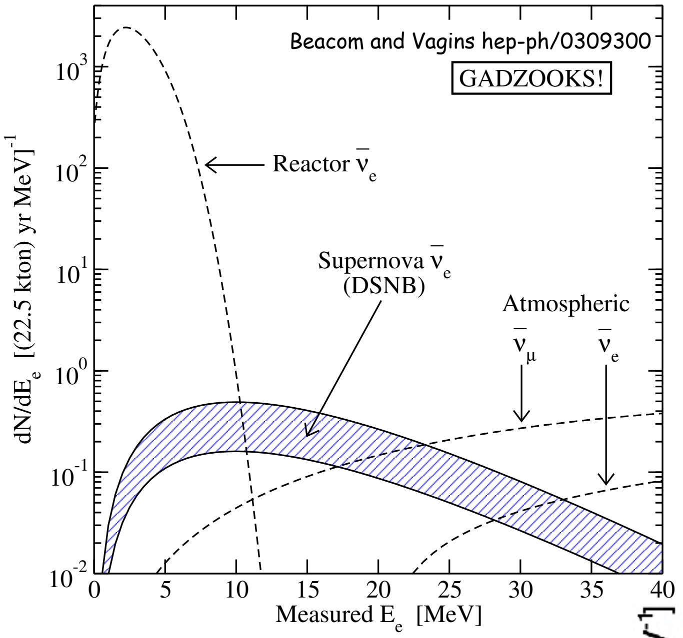


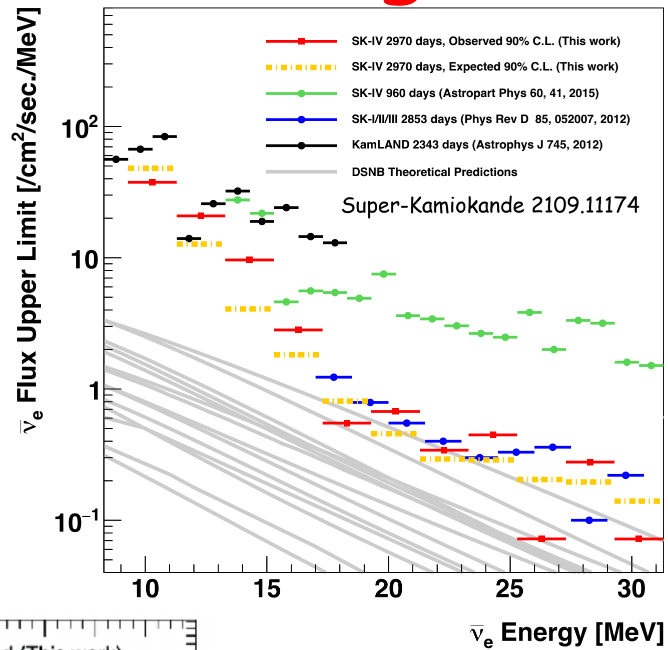


- The number of events can vary between ~ 0.5 to 5 per year

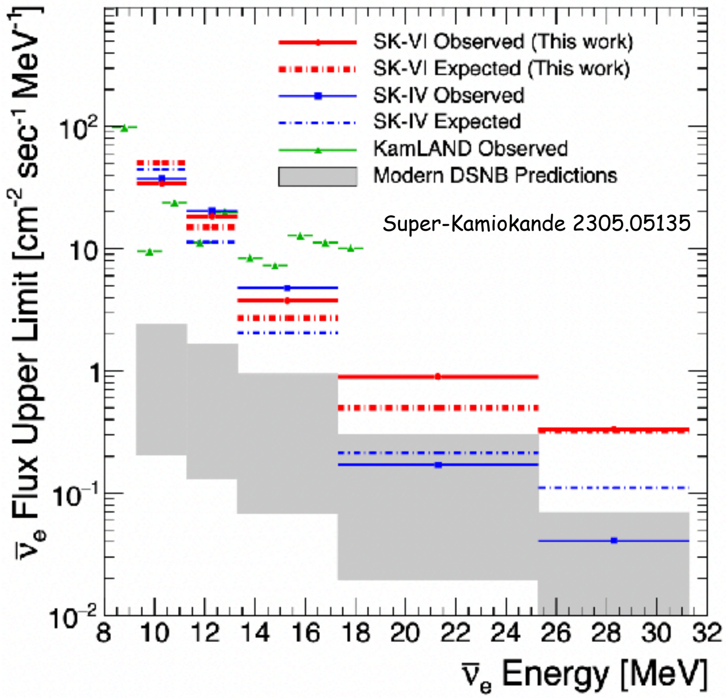


Diffuse supernova neutrino background





- Sensitivity of Super-K Gd (0.01%) is similar to that of Super-K IV search inspite of the fact that the live-time is five times smaller



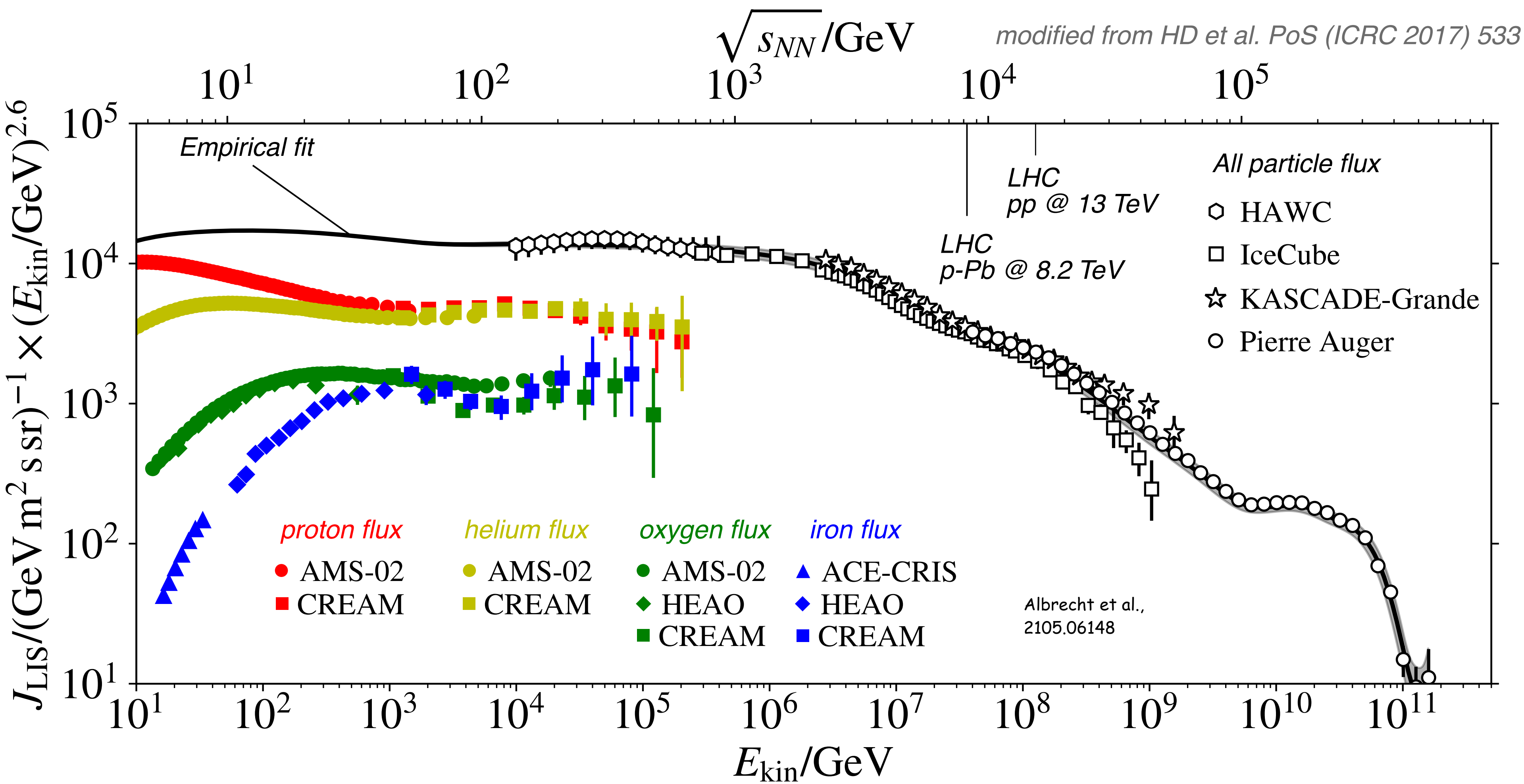
Diffuse supernova neutrino background

- A large number of neutrino experiments are being built/ planned which can detect DSNB

- A variety of astrophysical and new physics studies can be conducted with this upcoming detection

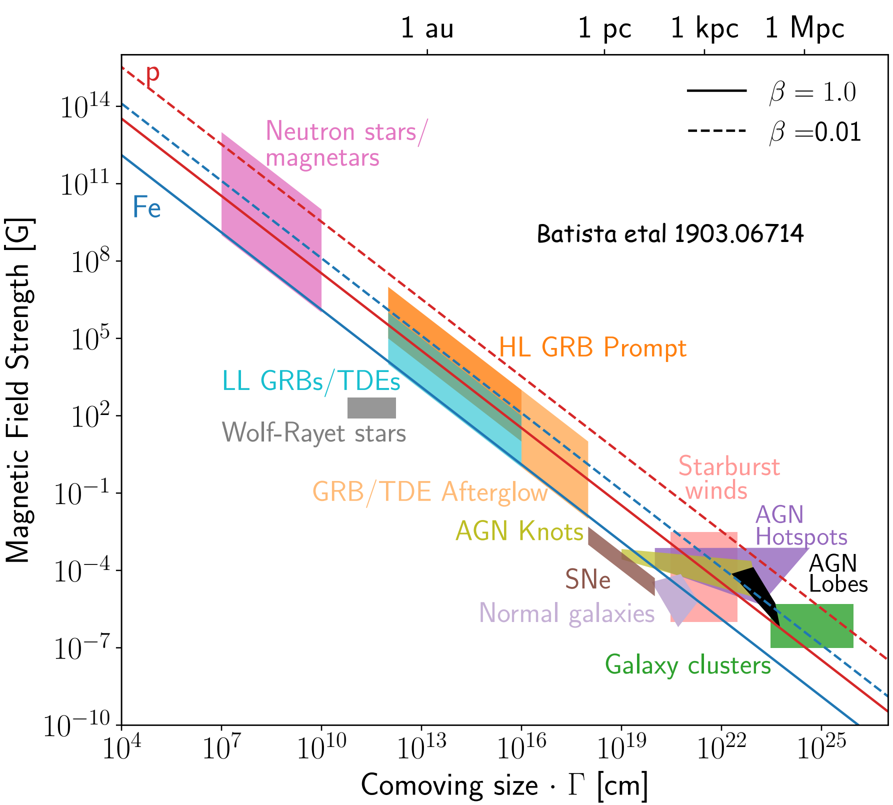
GZK (Greisen-Zatsepin-Kuzmin)/ BZ (Berezinsky-Zatsepin)/ cosmogenic neutrinos

Ultra-high energy cosmic rays



Ultra-high energy cosmic rays

- Cosmic rays are the highest energy particles that we have detected
- The cosmic-ray flux is suppressed beyond ~ 10^{20} eV
- Why is the flux suppressed? (i) intrinsic astrophysical source properties or (ii) due to something else?
- Hillas plot $E_{\rm max} = \eta^{-1}\beta_{\rm sh} e B R \Gamma$



$E_{\rm max}$ = maximum achievable energy in a source with characteristic size R and magnetic field strength B

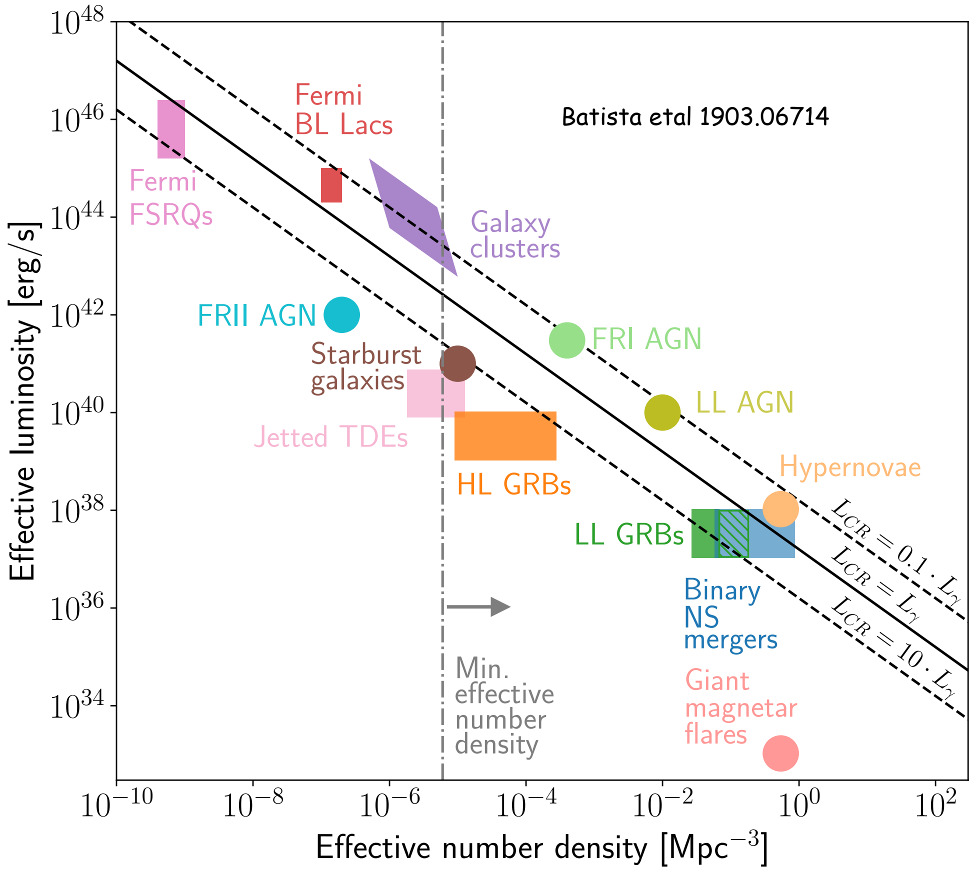
$\beta_{\rm sh}$ = velocity of the shock

η = efficiency of the shock acceleration

Γ = Lorentz factor of the motion

The diagonal lines show the minimum product of BR required to accelerate protons (red) or iron nuclei (blue) to 10^{20} eV for a fast shock assuming some value of $\beta_{\rm sh}$

Ultra-high energy cosmic rays



- Luminosity in ultra-high energy cosmic rays versus their number density for a number of astrophysical sources
- The suppression in the flux of ultra-high energy cosmic rays is probably due to propagation effects

Ultra-high energy neutrinos

- As ultra-high energy cosmic rays are propagating through the Universe, they will interact with the underlying photon background (primarily cosmic microwave background, however, extra-galactic radio background and extragalactic background light is also important)

$$p + \gamma_{\mathrm{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, \mathrm{BR} = 2/3 \\ n + \pi^+, \mathrm{BR} = 1/3 \end{cases}$$

Greisen PRL 1966
Zatsepin and Kuz'min JTEP Lett. 1966

GZK process

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

Berezinsky and Zatsepin PLB 1969
Berezinsky and Zatsepin Sov. J. Nucl. Phys. (1970)

$$n \rightarrow p + e^- + \bar{\nu}_e$$

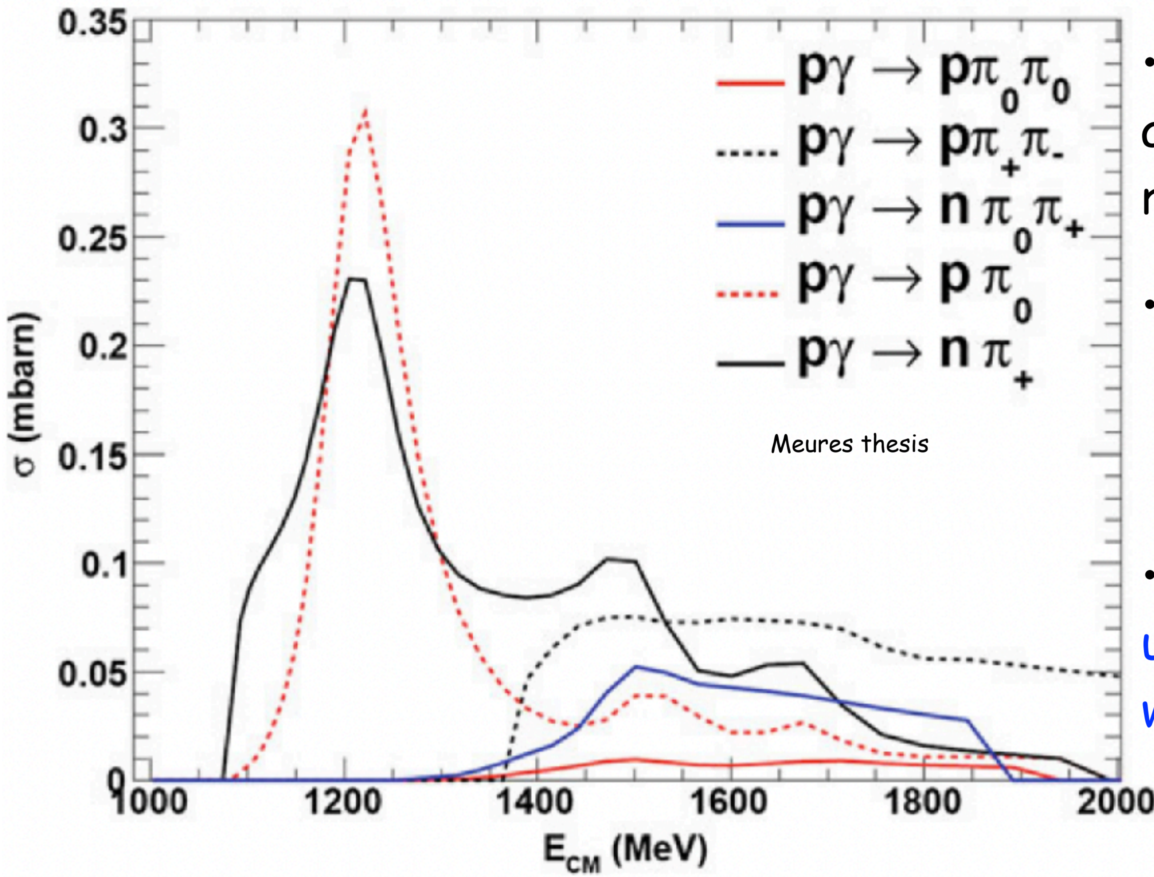
BZ neutrinos
cosmogenic neutrinos

$$p + \gamma \rightarrow e^+ + e^- + p$$ pair-production

$$A + \gamma \rightarrow (A - nN) + nN$$ photo-disintegration

Ultra-high energy neutrinos

The threshold for GZK process: $E_{\mathrm{th}} \approx \frac{6.8 \times 10^{16}}{(E_\gamma/\mathrm{eV})}\,\mathrm{eV}$



- Peak cross-section is approximately $500\,\mu\mathrm{b}$ at the Δ^+ resonance

- The mean free path of the proton at this peak cross-section is approximately 10 Mpc

- In general, sources of ultra-high energy cosmic rays are within 100 Mpc from the Earth

- We do not know sources of ultra-high energy cosmic rays, neutrinos will help us discover these sources

Ultra-high energy neutrinos

- The neutrino flux on Earth due to the interaction of ultra-high energy cosmic rays during propagation over cosmological distances is an integral over redshift and the proton energy E_p^s where s denotes the source Engel, Seckel and Stanev astro-ph/0101216

$$\mathcal{F}_i(E_{\nu_i}) = \frac{c}{4\pi E_{\nu_i}} \int\int \mathcal{L}(z, E_p^s) Y(E_p^s, E_{\nu_i}, z) \frac{dE_p^s}{E_p^s} dz$$

- The neutrino yield function $Y(E_p^s, E_{\nu_i}, z) = E_{\nu_i} \frac{dN_{\nu_i}}{dN_p dE_{\nu_i}}$

- Source function per unit redshift $\mathcal{L}(z, E_p^s) = \mathcal{L}_0(E_p^s)\, \eta(z)\, \mathcal{H}(z)$

where $\eta(z) = \frac{dt}{dz} \approx \frac{1}{H_0(1+z)} [\Omega_m (1+z)^3 + \Omega_\Lambda]^{-1/2}$

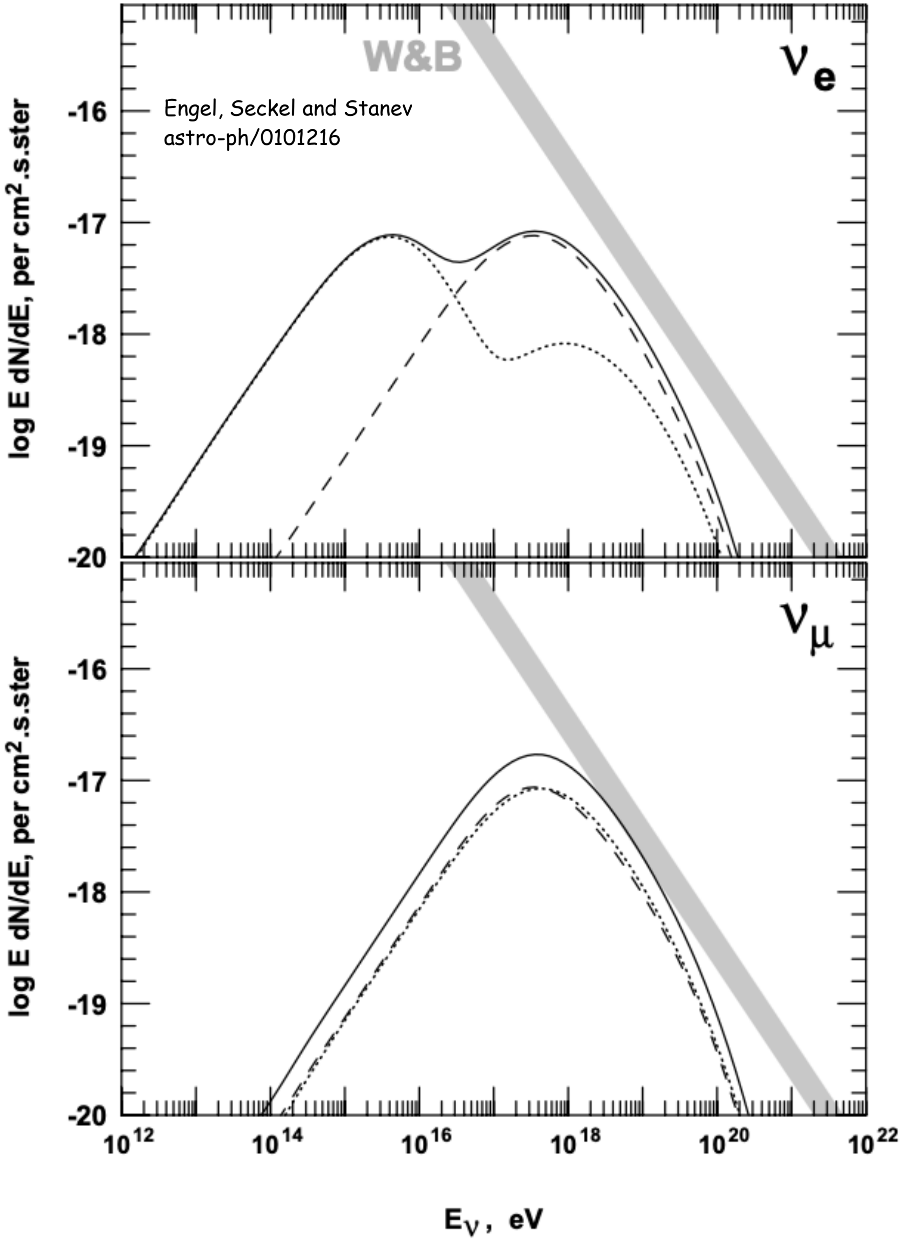
$\mathcal{H}(z)$ is the cosmological source evolution function

- Modern calculations mostly involve CRPropa

https://crpropa.github.io/CRPropa3/

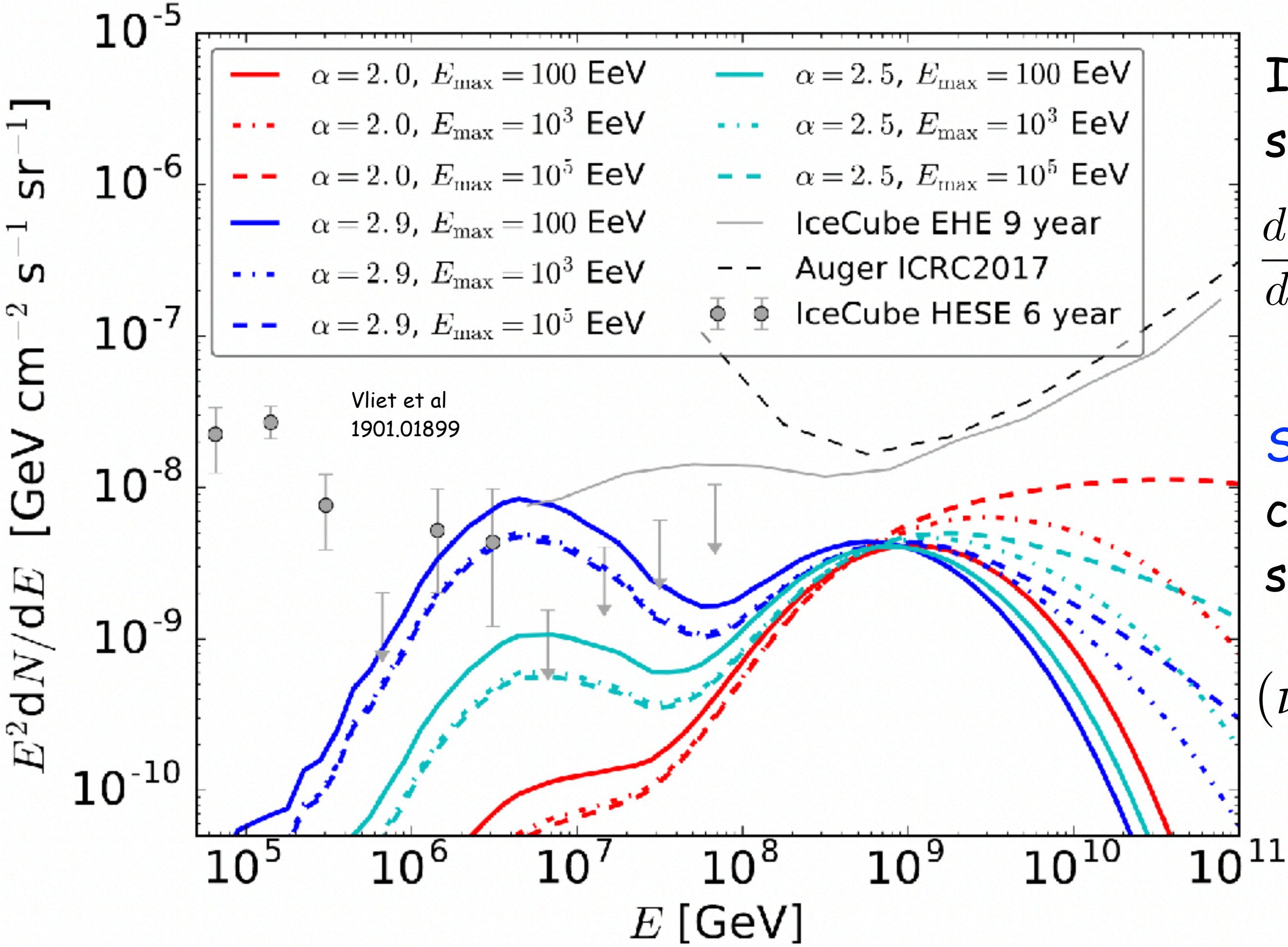
Batista et al., 2208.00107

Ultra-high energy neutrinos



- Neutrinos are denoted by dashed lines
- Anti-neutrinos are denoted by dotted lines
- Total neutrino + anti-neutrinos are denoted by solid lines
- W&B is the Waxmann-Bahcall bound
- The muon neutrino flux peaks at a neutrino energy corresponding to the resonance energy of the interaction.
- The electron neutrino spectrum will have two peaks, one corresponding to the resonance and one additional low energy component from the decaying neutron

Ultra-high energy neutrinos



Injection energy spectrum of protons

$$\frac{dN}{dE} \propto E^{-\alpha} \exp\left(-\frac{E}{E_{\max}}\right)$$

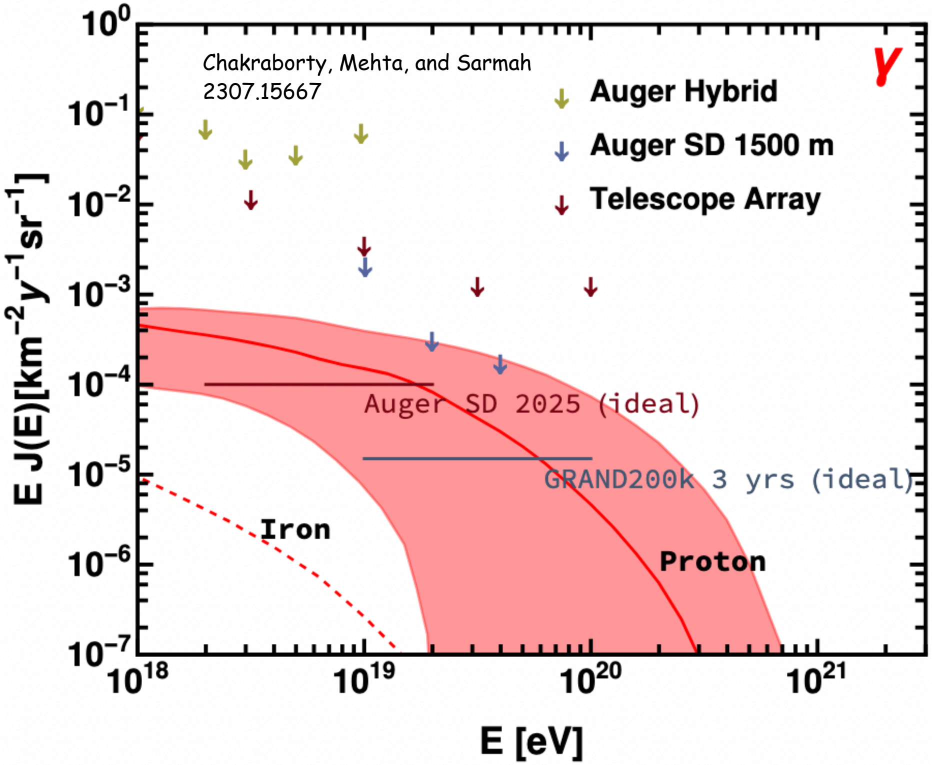
Single flavour cosmogenic neutrino spectrum

$$(\nu_e : \nu_\mu : \nu_\tau) = (1:1:1)$$

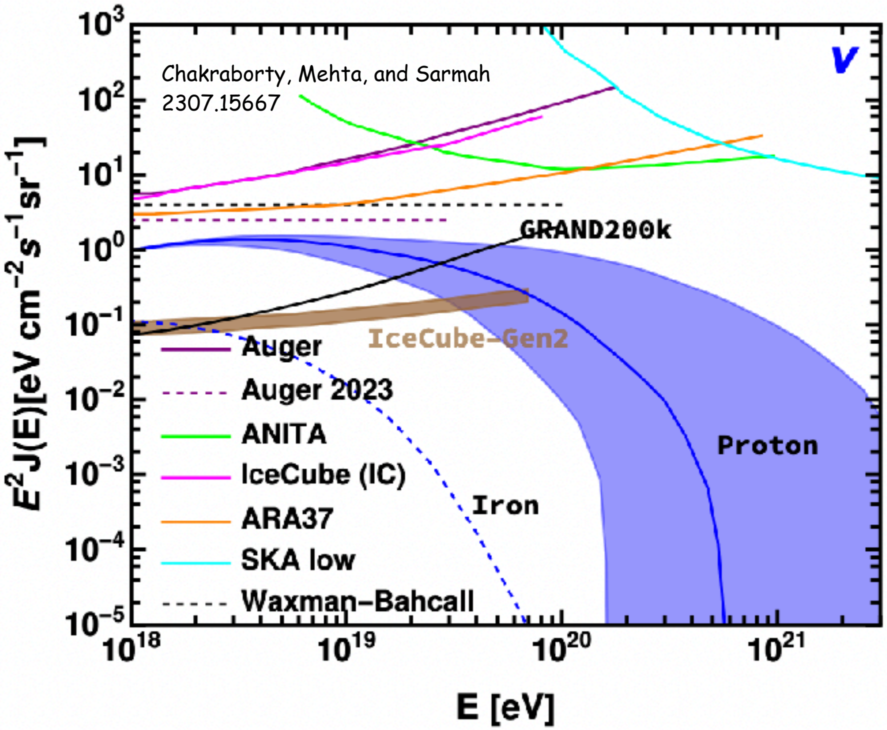
- Assuming a pure proton injection spectrum and a certain source redshift evolution
- Neutrinos will be important to discriminate between various models

Ultra-high energy neutrinos and gamma-rays

- Ultra-high energy photons (along with neutrinos) are also important to understand these sources

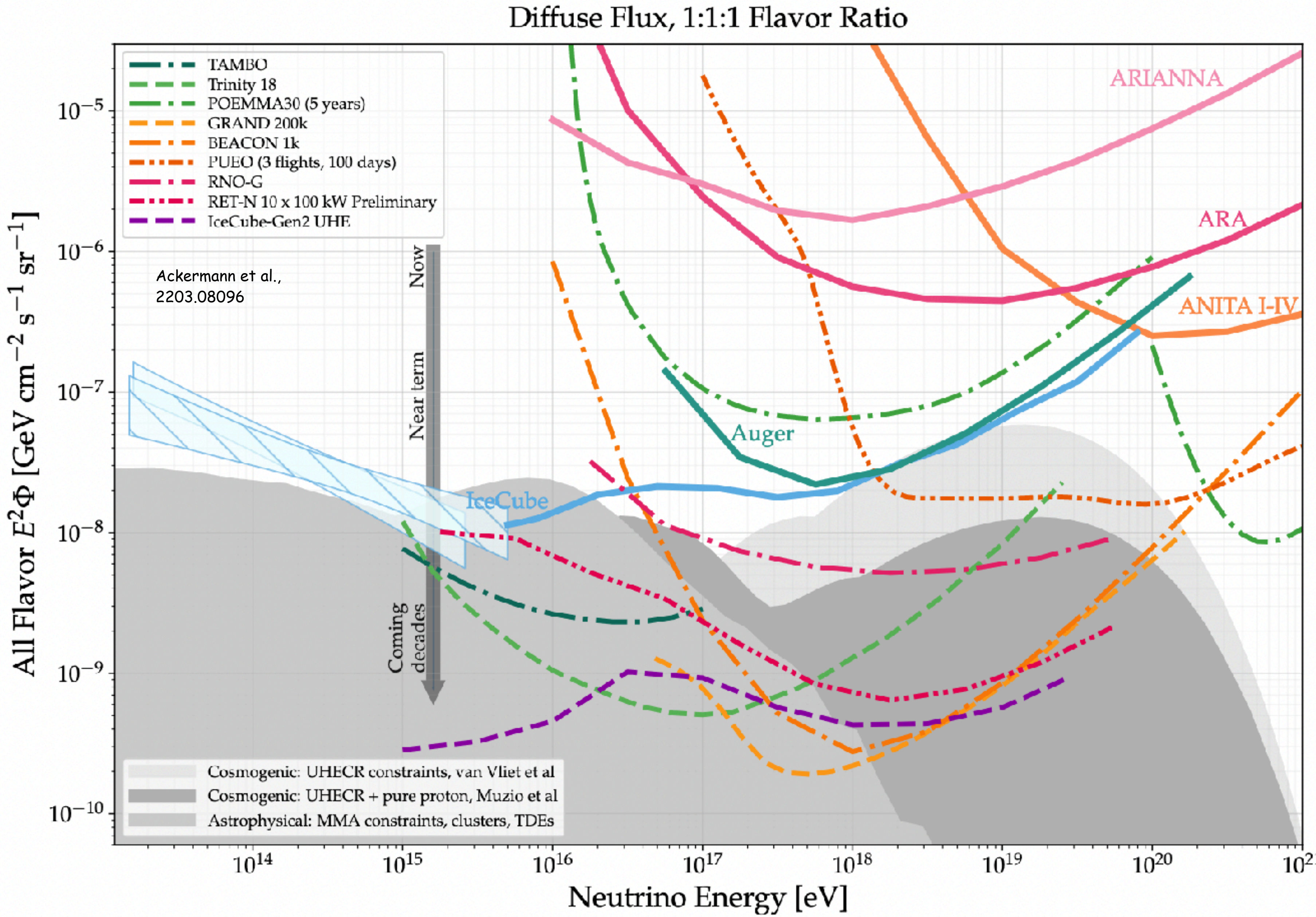


- Latest calculations study the importance of taking into account all the astrophysical parameters in the calculation

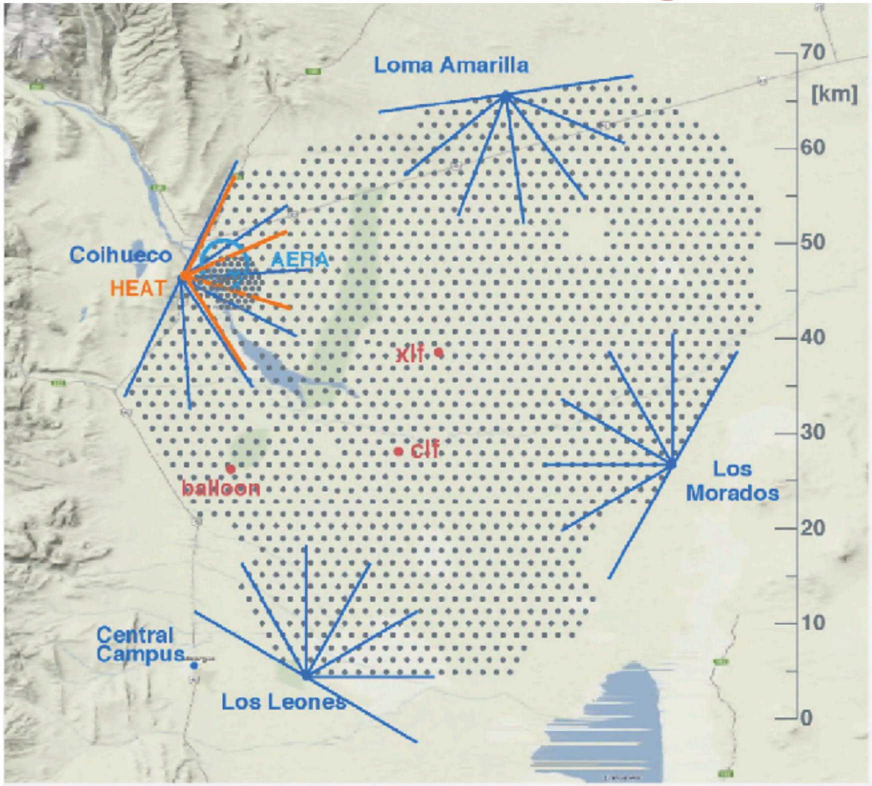


- The gamma-ray spectrum is also guaranteed along with the neutrinos; however, gamma-rays cannot travel for very long distances

Ultra-high energy neutrinos

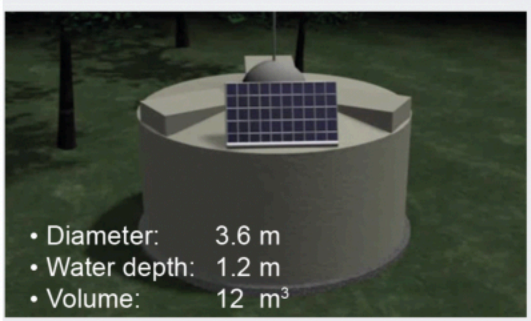


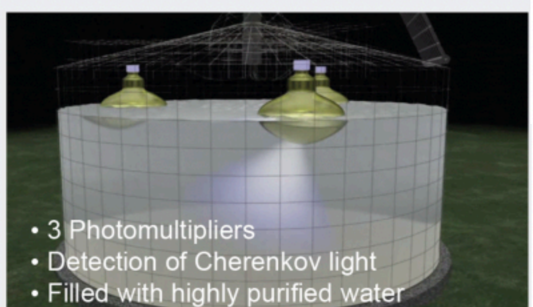
Ultra-high energy neutrinos



Ebr talk "Ultra-high energy neutrinos at the Pierre Auger Observatory"

Surface Detector
1,660 surface detector stations
(1,500 m apart from each other)

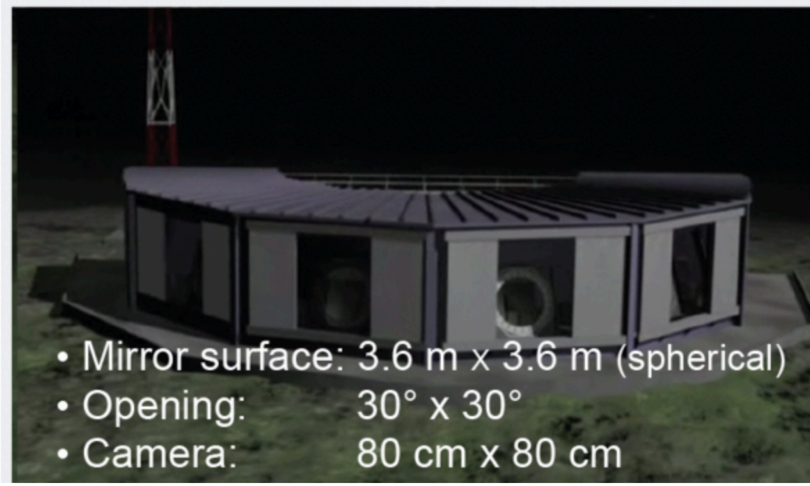




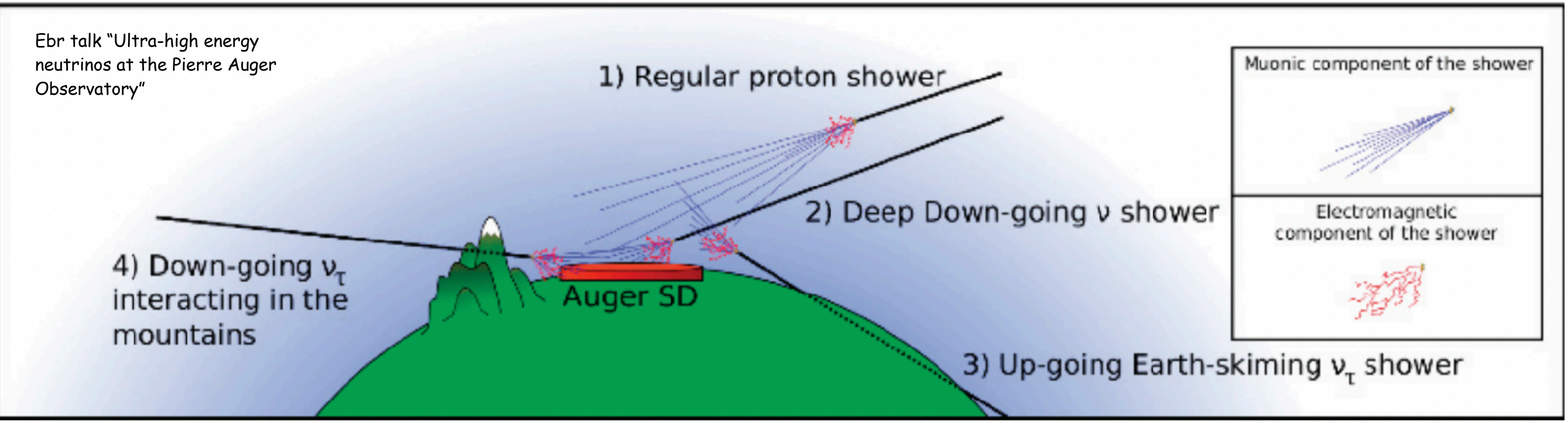
Pierre Auger Observatory

- Designed for detecting ultra-high energy cosmic-rays, neutrinos, and gamma-rays

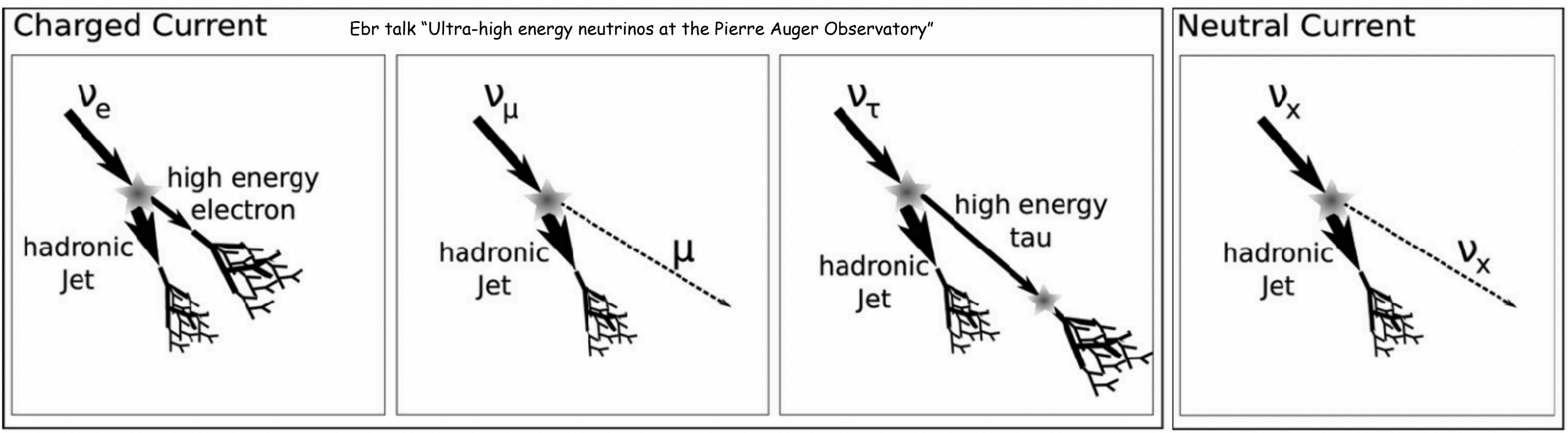
Fluorescence Detector
27 fluorescence telescopes
(in 4 different places)



Ultra-high energy neutrinos



A variety of neutrino detection techniques



Ultra-high energy neutrinos

- Neutrinos can pass through a lot of matter, thus, one can use this to distinguish it from cosmic-rays

- Search for down-going neutrinos:

- Protons, nuclei, and photons will interact higher in the atmosphere, whereas neutrinos will interact much lower in the atmosphere

- At large zenith angles, one can discriminate between neutrinos and other cosmic-rays by using the "shower age"

- All flavours of neutrinos can be detected using this technique, for both charged current and neutral current interactions

Ultra-high energy neutrinos

- Search for Earth-skimming neutrinos:

- For Earth-skimming (i.e., up-going neutrinos, typically for neutrinos within 5^0 of the horizon), ν_τ can interact via charged-current interaction to produce τ, and then the τ decays after traveling some distance; only decays to electrons and hadrons are observable

- Such a technique cannot be used to search for ν_e or ν_μ

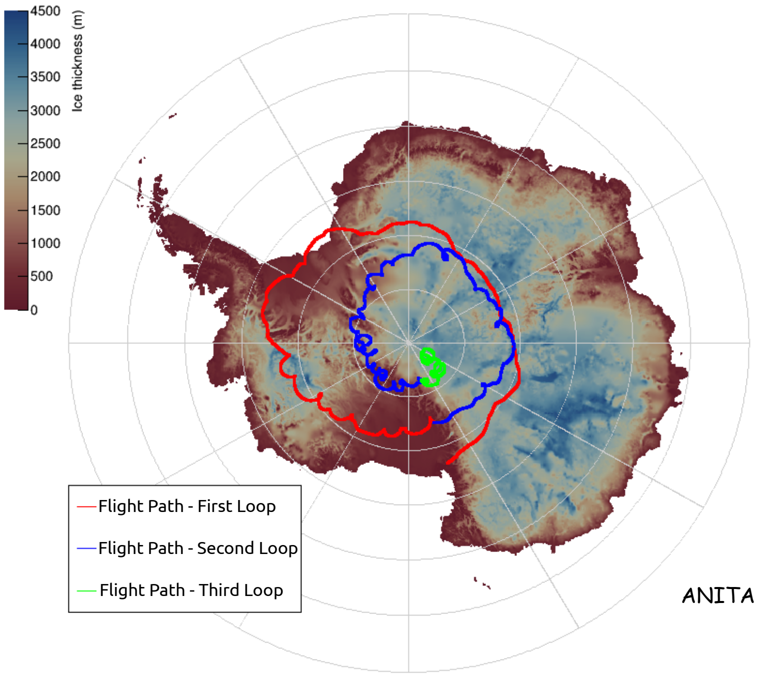
  ν_e does not produce a shower which will escape the Earth

  ν_μ does not produce a shower

- Such search techniques are also used to search for ultra-high energy neutrinos in the Telescope Array Observatory arXiv: 1905.03738

Ultra-high energy neutrinos

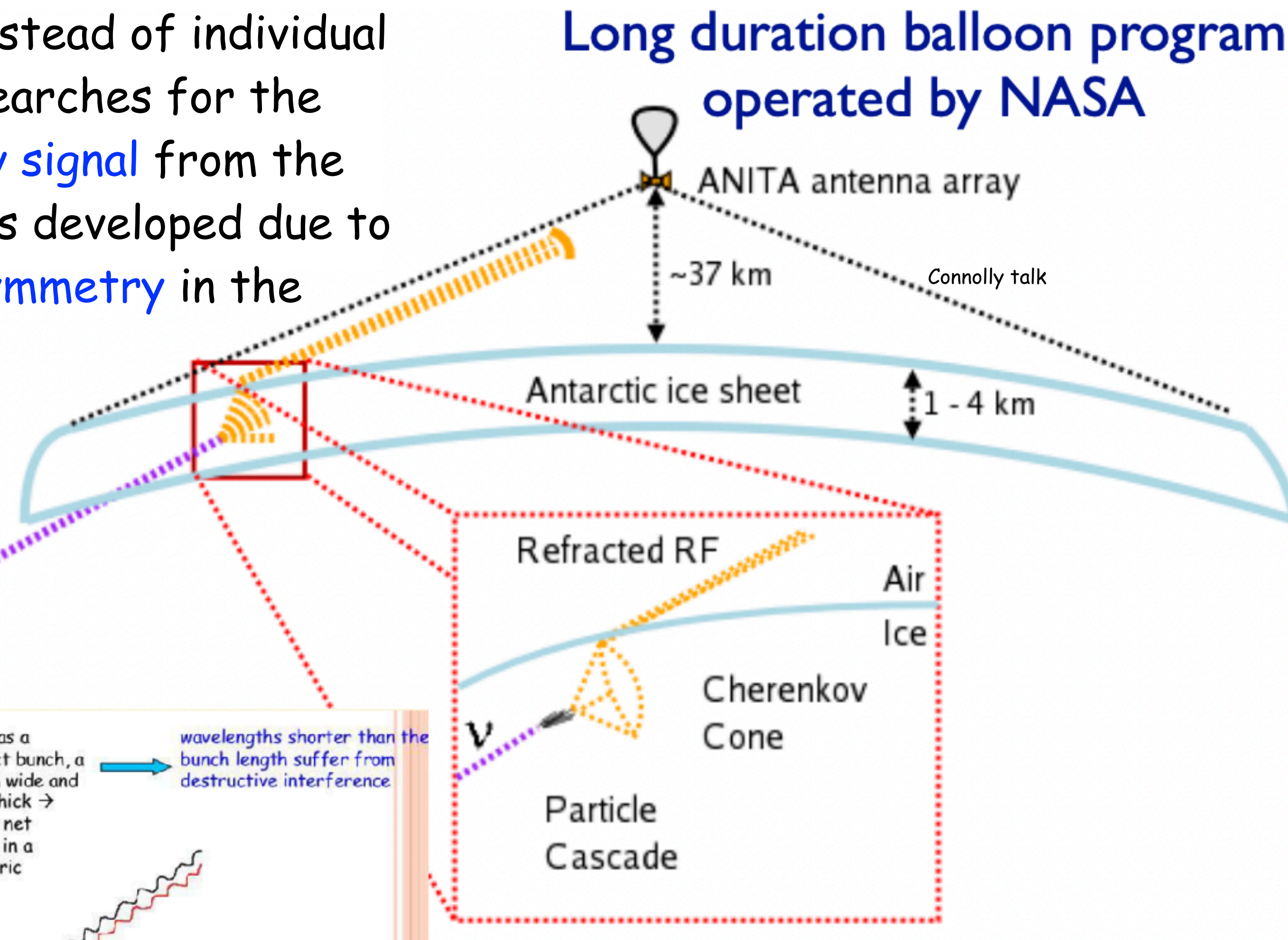
- Antarctic Impulsive Transient Antenna (ANITA)
- An array of radio antennas suspended from a balloon flying at ~ 37 km above Antartica
- 4 flights: ANITA-I, ANITA-II, ANITA-III, and ANITA-IV

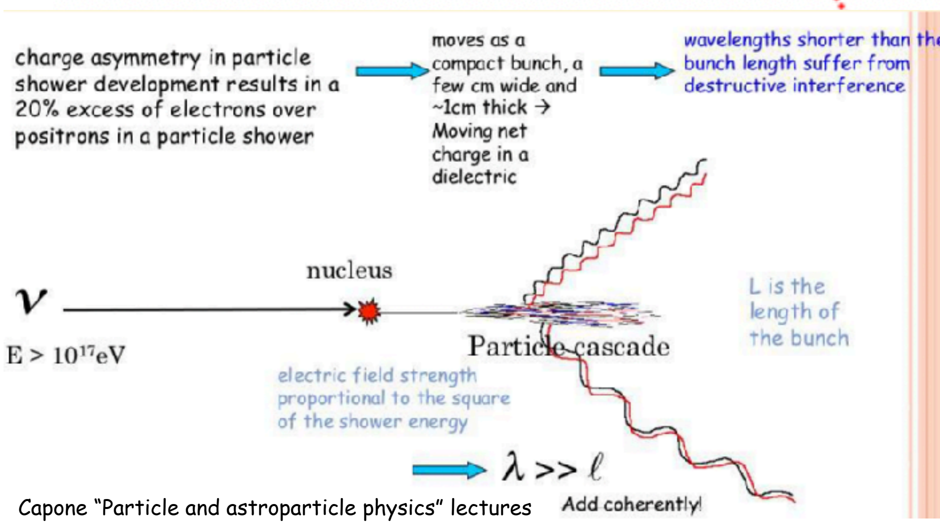


ANITA 1902.04005

Ultra-high energy neutrinos

- Askaryan effect: instead of individual track events, one searches for the coherent Cherenkov signal from the net "current" that is developed due to the 20% charge asymmetry in the shower
- ANITA observes Earth-skimming neutrinos





Capone "Particle and astroparticle physics" lectures

Ultra-high energy neutrinos

https://icecube-gen2.wisc.edu

https://ara.wipac.wisc.edu/home

https://radio.uchicago.edu

https://grand.cnrs.fr

https://trinity.physics.gatech.edu

- A large number of neutrino experiments are being built/ planned which can detect GZK/ BZ/ cosmogenic neutrino flux

- A variety of astrophysical and new physics studies can be conducted with this upcoming detection

Conclusions

- We will detect two new astrophysical neutrinos fluxes soon: diffuse supernova neutrinos and GZK/ BZ/ cosmogenic neutrinos, which will help us understand the Universe even better

- Diffuse supernova neutrino background is produced by all unresolved core-collapse supernova in the Universe

- GZK/ BZ/ cosmogenic neutrinos is produced due to the attenuation of ultra-high energy cosmic rays on the underlying cosmological photon background

- Near-future guaranteed data set from various different neutrino telescopes (either currently running or under construction) have the potential to discover these neutrino fluxes

- We will be able to better understand particle physics and astrophysics from these upcoming discoveries

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