$\boxed{\text{Neutrino Cosmology}}$

SSI 2010

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First Day: Macrophysics of the hot Big Bang

Second Day: Microphysics of the hot Big Bang

Third Day: New views with neutrinos

Third Day

A. Testing Cosmology with Detected Neutrinos

B. Line of Sight Integral for Radiation Intensity

C. Living Large with Logarithms

D. Estimating the DSNB Neutrino Signal

A. Testing Cosmology with Detected Neutrinos

In cosmology and astrophysics, it is usually assumed that neutrinos are undetectable. Besides the Sun and Supernova 1987A, no other astrophysical sources have been detected.

But, thanks to the hard work of experimentalists, the sensitivity of neutrino detectors has improved by orders of magnitude. This allows new opportunities in cosmology; these are surprising, sometimes even to neutrino physicists.

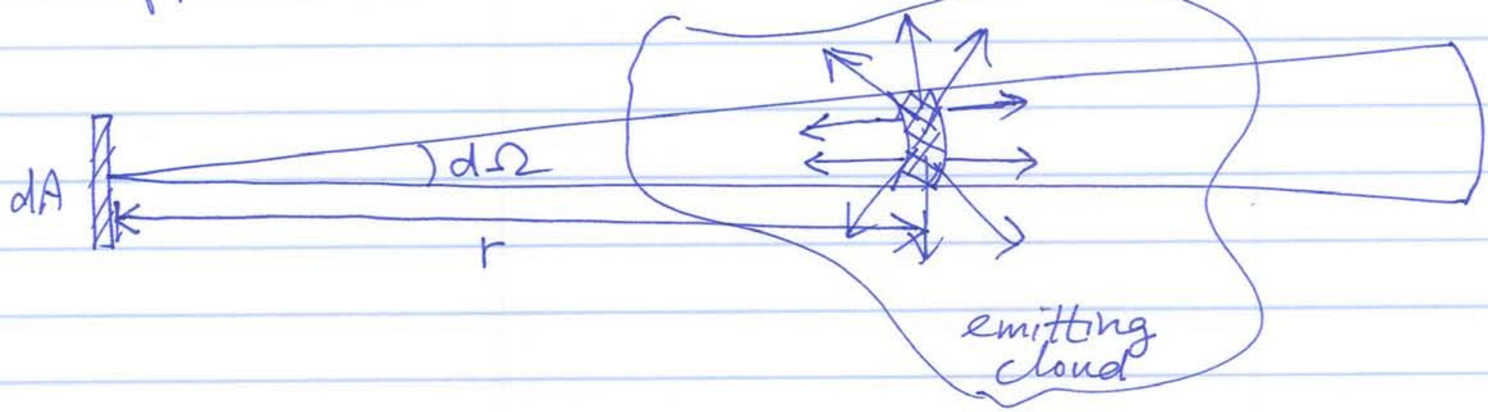
The three established frontiers are:

- MeV scale — neutrinos from supernovae, either in individual bursts or in the cosmic background from distant supernovae.
- TeV scale — neutrinos from hadronic cosmic-ray sources, either discrete sources (SNR, AGN, GRBs) or their cosmic backgrounds.
- EeV scale — neutrinos from the cosmic flux of UHE cosmic rays, through their energy losses on the CMB.

An example of a surprising new topic is using neutrinos to probe dark matter annihilation in the Milky Way and the cosmos; this was pointed out by my collaborators and me.

B. Line of Sight Integral for Radiation Intensity

This is the simplest derivation, ignoring angular variations within the beam size $d\Omega$, attenuation of the flux, redshift effects, etc.



The idea is that every differential volume element of the cloud is emitting radiation isotropically. This is characterized by the emissivity $q = q(\vec{r})$, which varies throughout the cloud, and has units [volume^{-1} time^{-1}].

$$dF(\vec{r}) = \frac{1}{4\pi r^2} q(\vec{r})\, dV$$ flux from volume element

$$= \frac{1}{4\pi \cancel{r^2}} q(\vec{r}) \cdot d\Omega \cancel{r^2} dr$$ volume element grows like r^2; flux falls like r^{-2}

$$dI(\vec{r}) = \frac{dF}{d\Omega}(\vec{r}) = \frac{q(\vec{r})\, dr}{4\pi}$$

flux has units [cm^{-2} s^{-1}] ; intensity has units [cm^{-2} s^{-1} sr^{-1}].

$$\boxed{I = \underbrace{\frac{1}{4\pi}}_{\text{hidden }[sr^{-1}]} \int_{LOS} \overbrace{dr}^{[cm]}\; \underbrace{q(\vec{r})}_{[cm^{-3}\, s^{-1}]}} \qquad [cm^{-2}\, s^{-1}\, sr^{-1}]$$

Some examples of emissivity functions:

- Cosmic ray collisions with gas, producing pions and subsequent γ, ν

$$q(\vec{r}) \simeq c\, n_{CR}(\vec{r}) \cdot n_{gas}(\vec{r}) \cdot \sigma_{pp}$$

- particle decay at rest

$$q(\vec{r}) \simeq \frac{n_{parent}(\vec{r})}{\tau} \underbrace{e^{-t/\tau}}_{\simeq 1 \text{ for long lifetime}}$$

- dark matter annihilation

$$q(\vec{r}) \simeq \frac{1}{2} n_{DM}^2(\vec{r}) \langle \sigma_A v \rangle$$

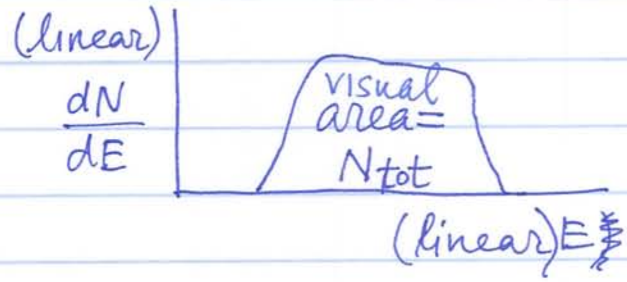
$$\simeq \frac{1}{2} \left[\frac{\rho_{DM}(\vec{r})}{M_{DM}} \right]^2 \langle \sigma_A v \rangle$$

C. Living Large with Logarithms

Logarithms are at the heart of order-of-magnitude estimation, timescale analyses, and effective use of log plots.

Suppose we have

$$\underbrace{N_{tot}}_{[\text{dim.less}]} = \underbrace{\int dE}_{[\text{GeV}]}\ \underbrace{\frac{dN}{dE}}_{[\text{GeV}^{-1}]}$$

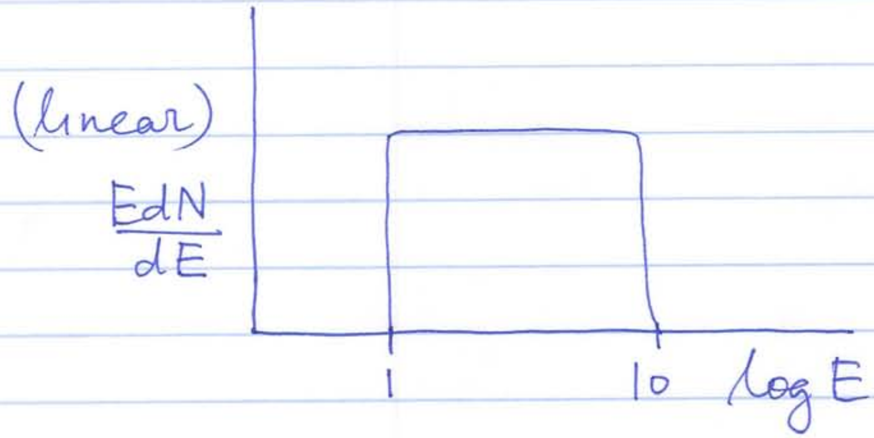


The dimensionless area $\simeq$ height x width is invariant under $E \to E + E_0$ transformations.

All easy — now compare to the same kind of thing where $\log E$ is the variable on the x-axis.

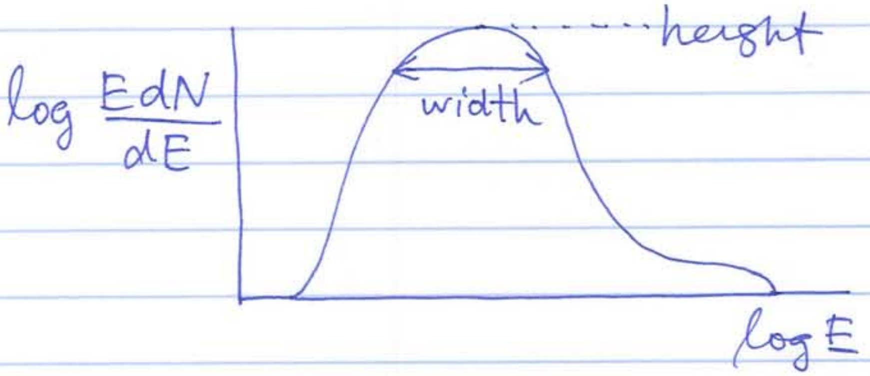
$$\underbrace{N_{tot}}_{[\text{dim.less}]} = \int \underbrace{\frac{dE}{E}}_{[\text{dim.less}]} \cdot \underbrace{\frac{E\,dN}{dE}}_{[\text{dim.less}]} = \int d\ln E \cdot \frac{dN}{d\ln E}$$

The dimensionless area $\simeq$ height x lnwidth is invariant under $E \to E/\alpha$ transformations, i.e. changes of units or scale.



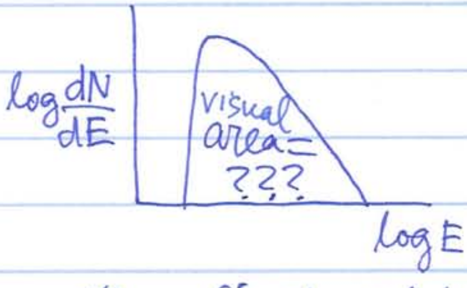
(means that $\frac{dN}{dE} \sim \frac{1}{E}$)

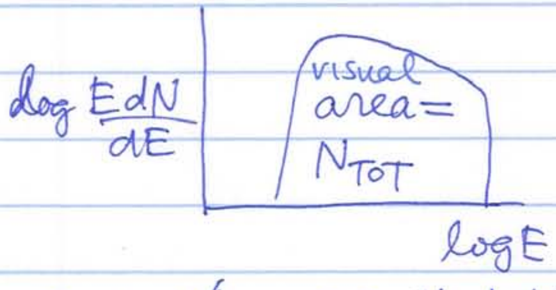
Easy to read height off plot. The width is <u>not</u> 10. It is $1 \cdot 2.3 = 2.3$; the 1 is for one unit in log E and the 2.3 is for the number of units in ln E per unit in log E.

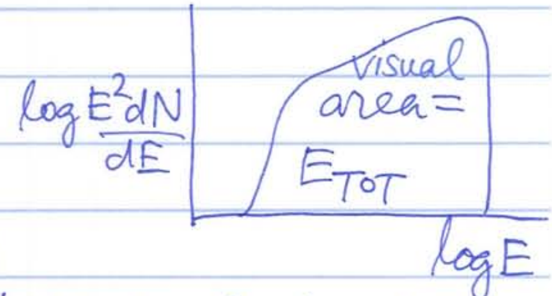


(By the way, note that using EdN/dE makes it easy to get $E \to E/\alpha$ changes right in spectrum.)

The area is $\simeq$ height $\times$ ln width, but chose the width such that the height decreases by only a factor ~few, as this dominates the integral.







The first plot is a sin, as it hides real physics information — never use it!

D. Estimating the DSNB Neutrino Signal

I will approximate like crazy here. See my review article on "The Diffuse Supernova Neutrino Background" for details.

$$\underbrace{I}_{[\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}]} \sim \frac{1}{4\pi}\underbrace{\int_{\text{LOS}}^{\sim 4000\,\text{Mpc}} dr}_{[\cancel{\text{cm}}\ \text{Mpc}]} \left[\underbrace{\overset{\sim 10^{58}}{N_{\nu/SN}}}_{[\text{dim.less}]} \cdot \underbrace{\overset{\sim 10^{-2}\,\text{yr}^{-1}}{R_{SN/gal}}}_{[\text{yr}^{-1}]} \cdot \underbrace{\overset{\sim 10^{-2}\,\text{Mpc}^{-3}}{n_{gal/vol.}}}_{[\text{Mpc}^{-3}]}\right]$$

Need a factor ~10 for evolution of supernova rate per galaxy in past (i.e., over LOS).

Need a factor ~1/6 to isolate just $\bar{\nu}_e$ flavor.

Can show flux $F = 4\pi I \sim 10\ \text{cm}^{-2}\,\text{s}^{-1}$ for the $\bar{\nu}_e$ flavor. (at all energies; less at high energies).

Can also show that this leads to ~few events per year in Super-Kamiokande.

Many other estimates of intermediate steps, some done in lecture, are left for the reader.