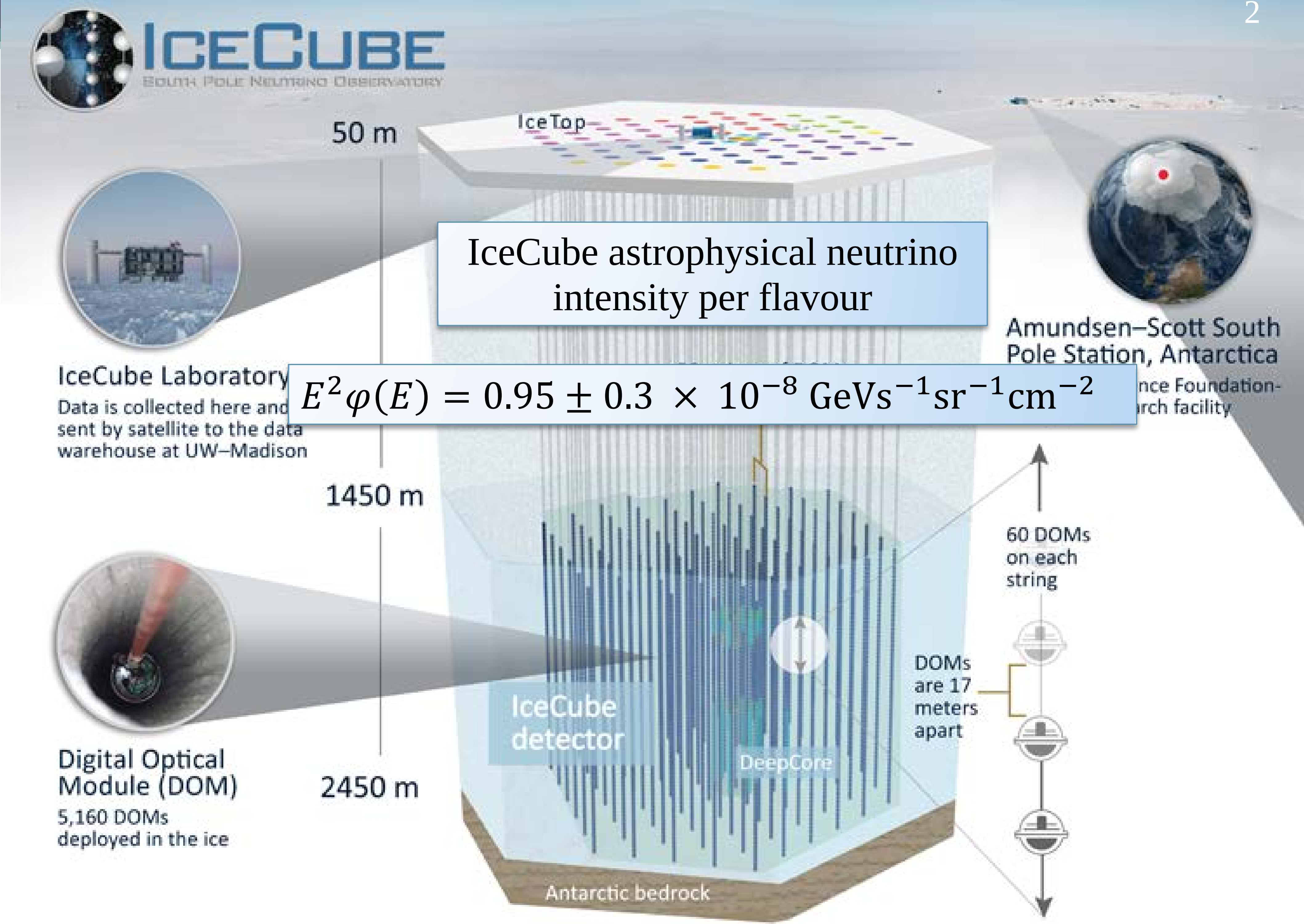
THE UNIVERSITY *of* ADELAIDE

IceCube's Neutrinos: Can they all be Galactic?

IPA 8/5/17

Natasha Atkins
University of Adelaide

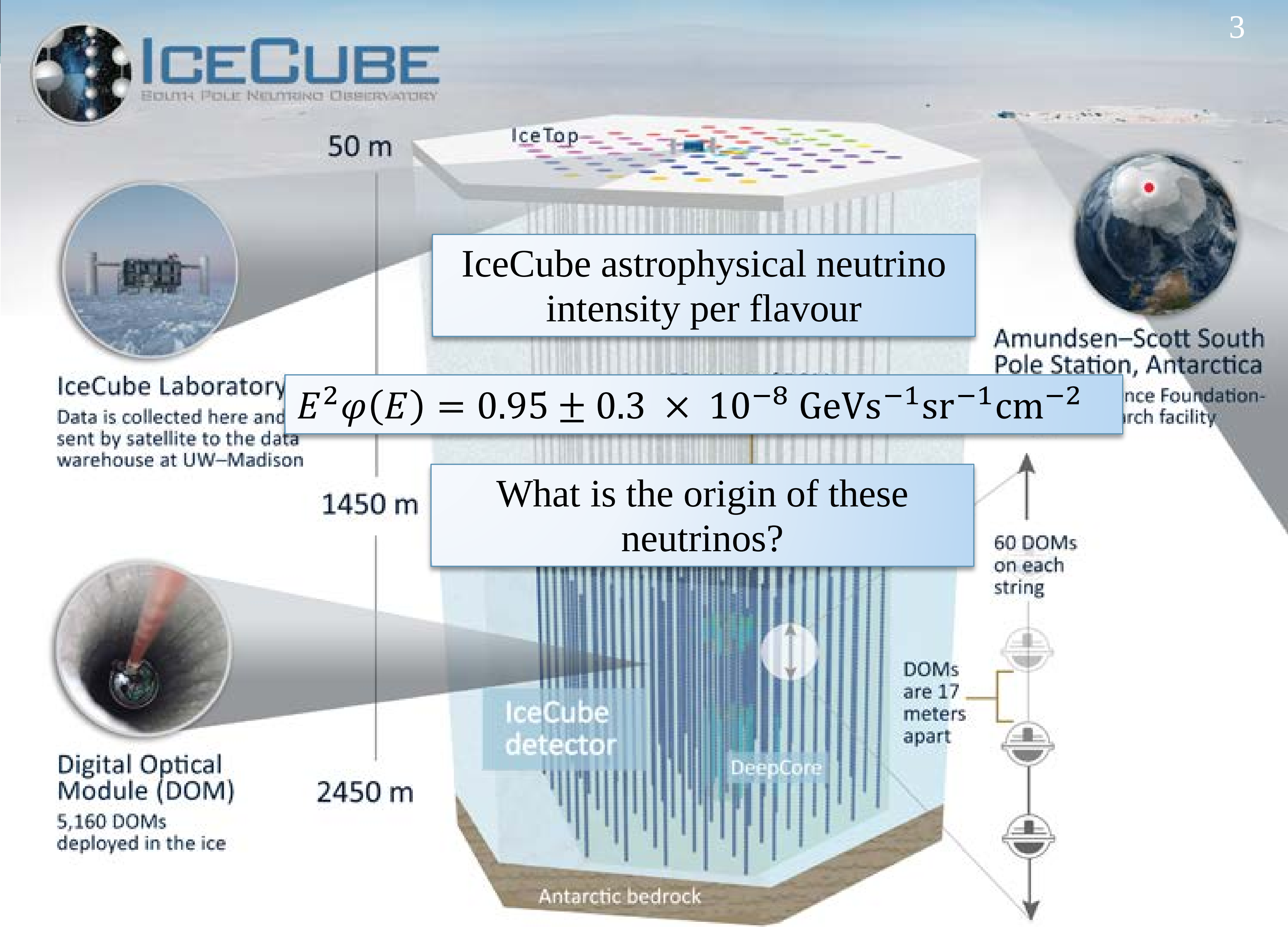
Gary Hill, Ben Whelan, Roland Crocker



IceCube astrophysical neutrino intensity per flavour

$$E^2\varphi(E) = 0.95 \pm 0.3 \times 10^{-8}\ \mathrm{GeV s^{-1} sr^{-1} cm^{-2}}$$

IceCube Collaboration, 2017



IceCube astrophysical neutrino intensity per flavour

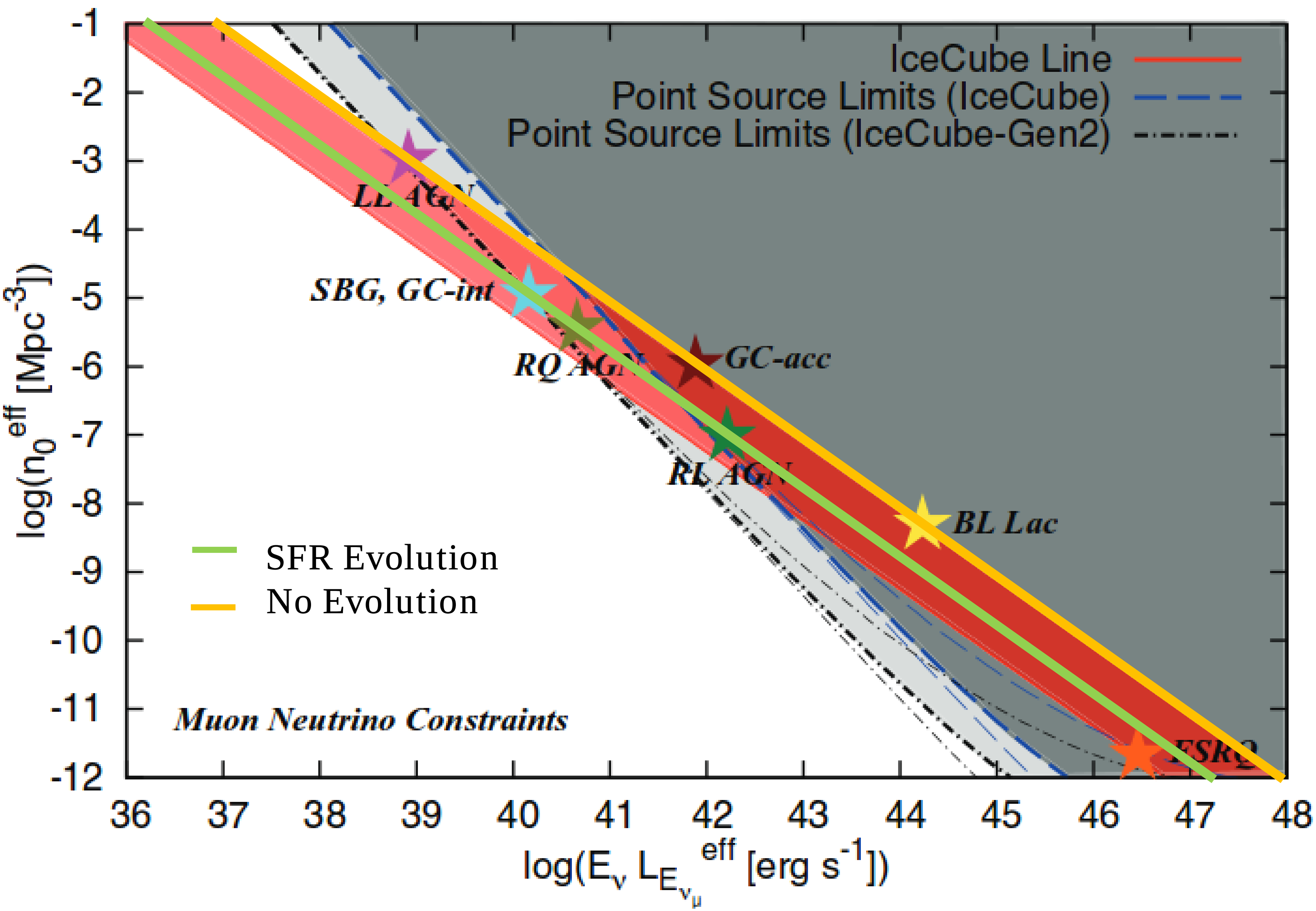
$$E^2\varphi(E) = 0.95 \pm 0.3 \times 10^{-8}\ \mathrm{GeV s^{-1} sr^{-1} cm^{-2}}$$

What is the origin of these neutrinos?

IceCube Collaboration, 2017

Murase & Waxman, 2015

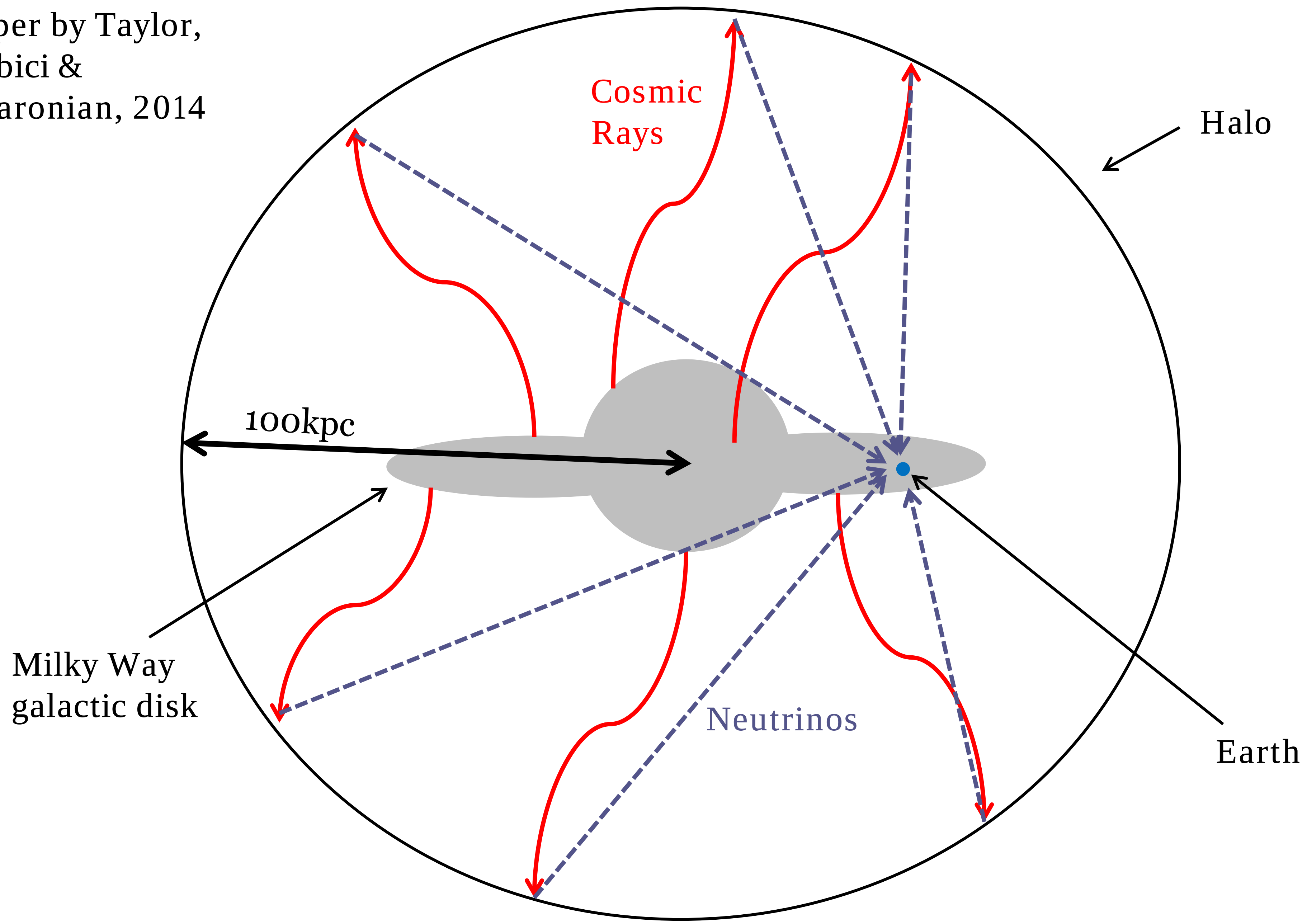
Local source density



Muon neutrino luminosity, defined as the luminosity per logarithmic neutrino energy bin.

A Galactic Origin?

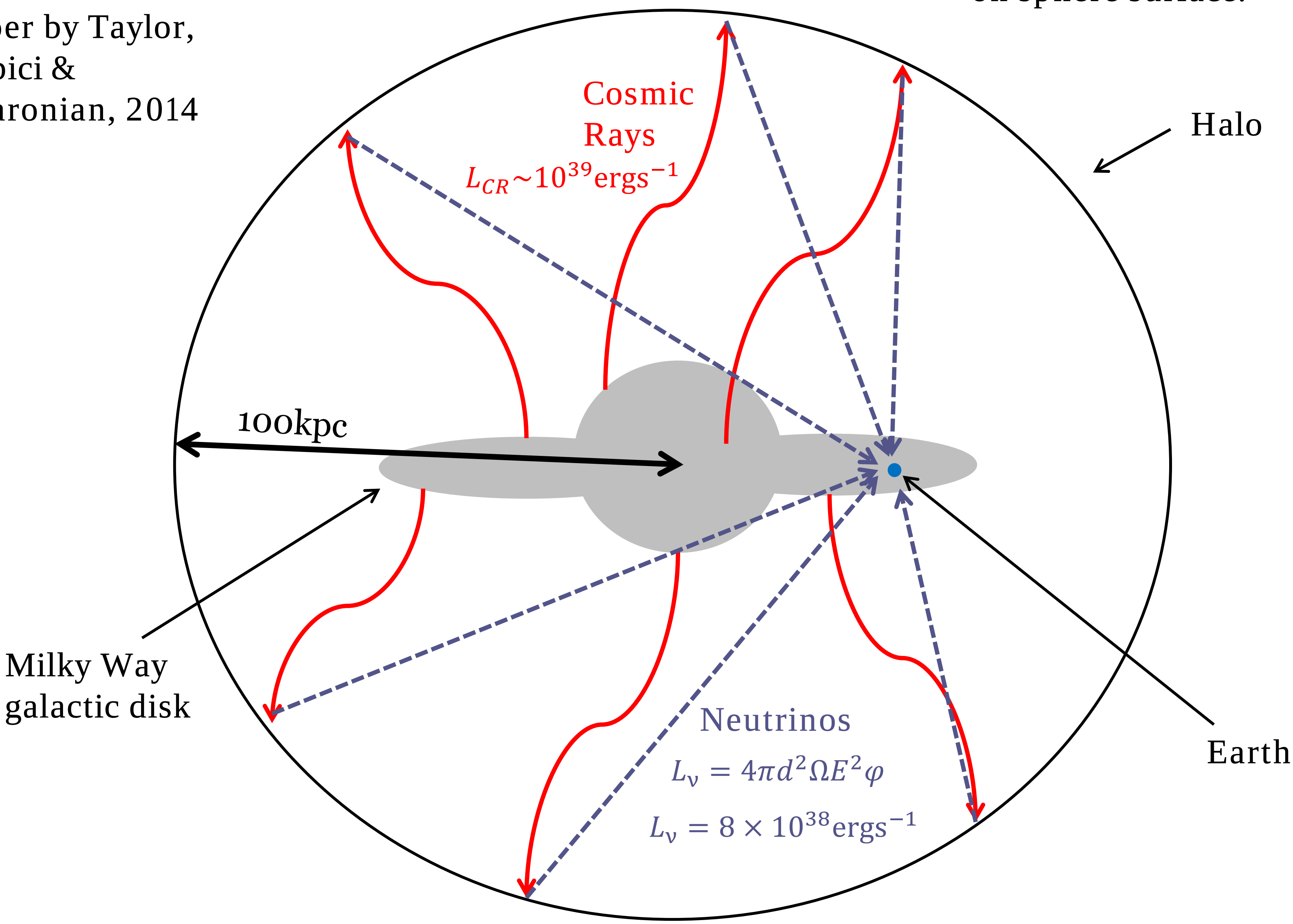
Paper by Taylor, Gabici & Aharonian, 2014



A Galactic Origin?

Paper by Taylor, Gabici & Aharonian, 2014

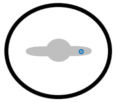
Assume neutrino sources on sphere surface.



Model

IceCube has observed 350,000 neutrinos in the Northern sky in six years of data, approximately 500 of which are astrophysical-weighted. (*IceCube Collaboration*, 2017)

If we assume all 500 neutrinos are coming from our galaxy, then statistically there is an upper limit of 2.3 neutrinos from outside our galaxy from the 90% confidence level.

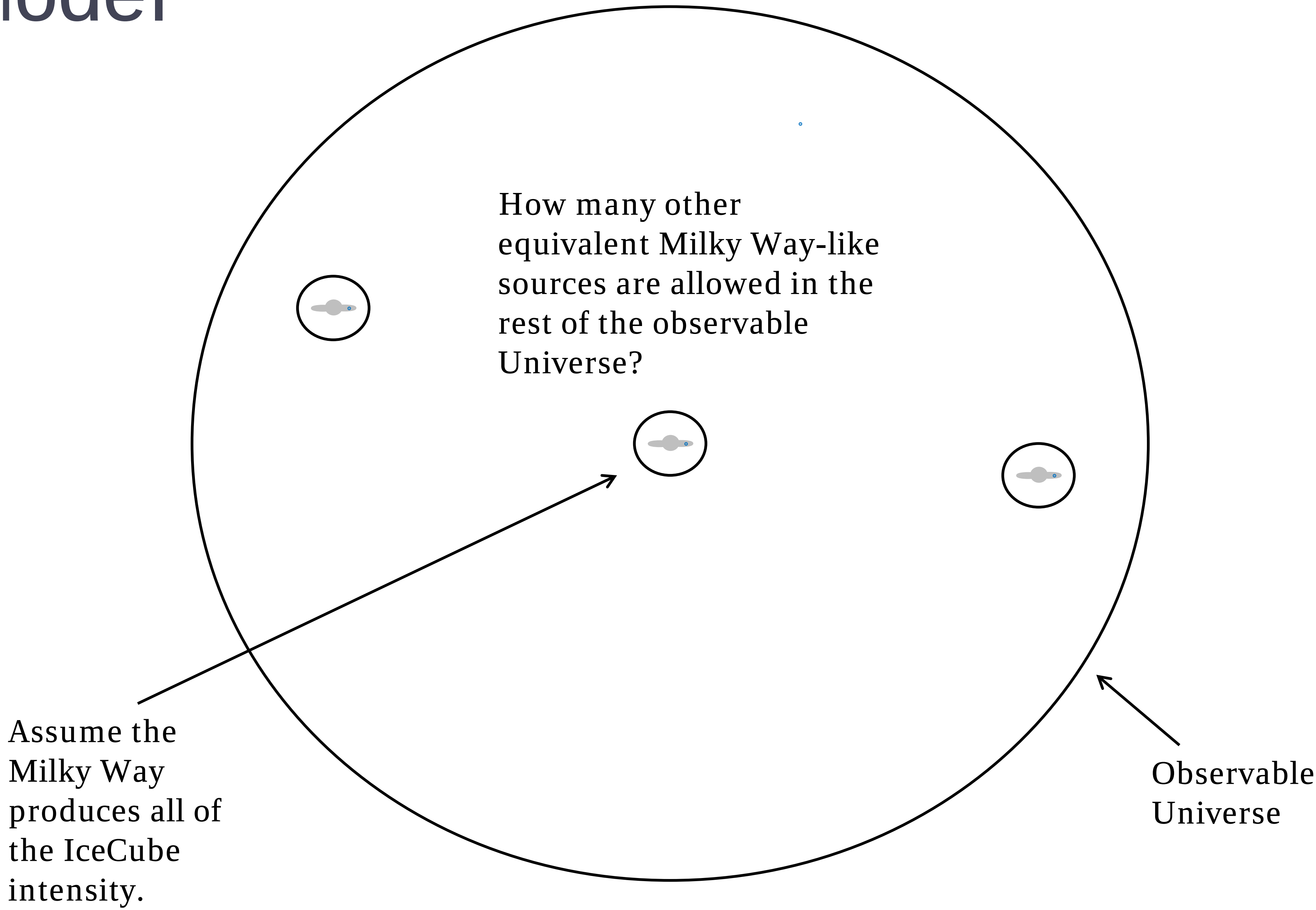


Assume the Milky Way produces all of the IceCube intensity.

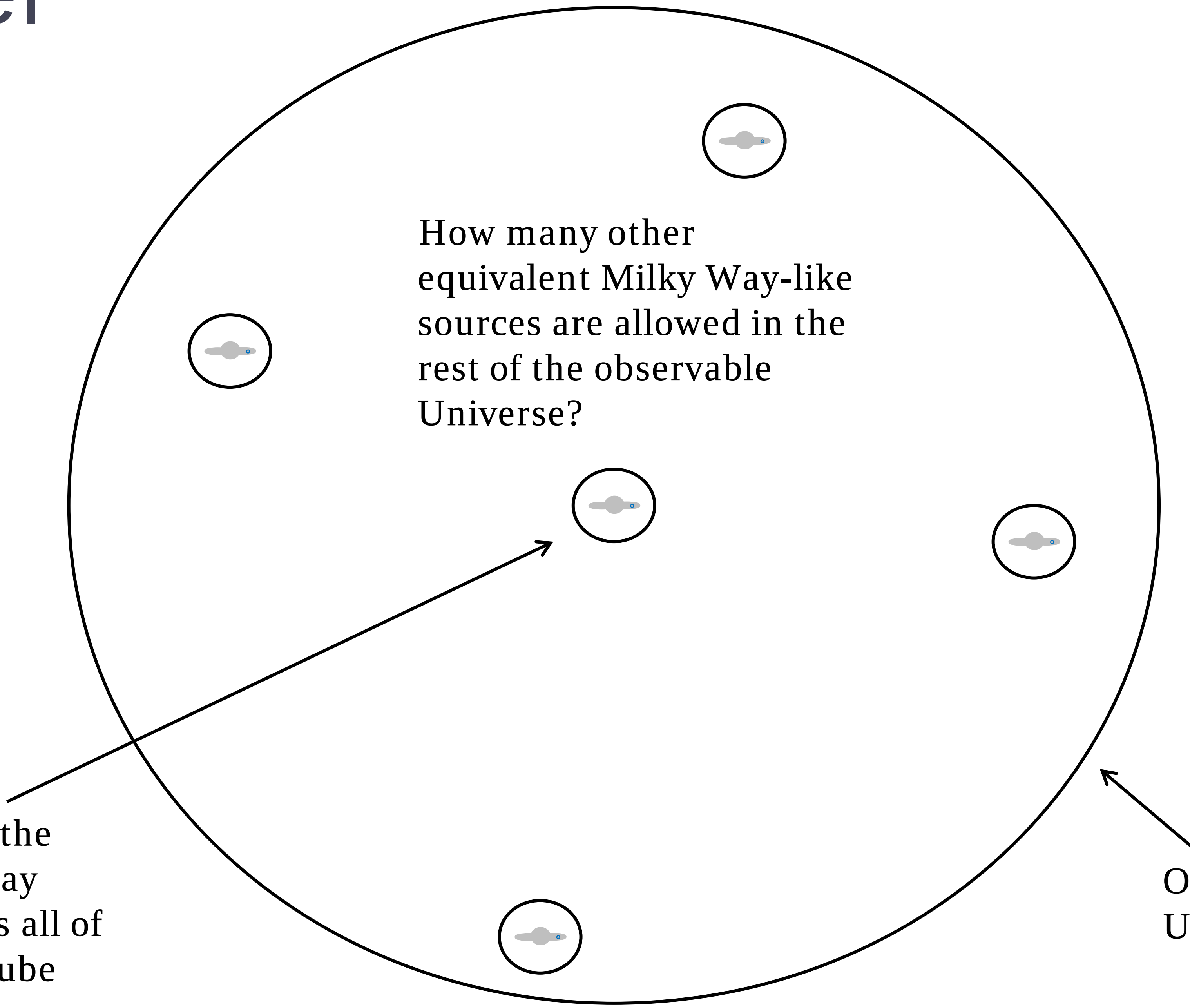
Hence the rest of the Universe is only allowed to produce an upper limit of 0.4% of the IceCube intensity.

Observable Universe

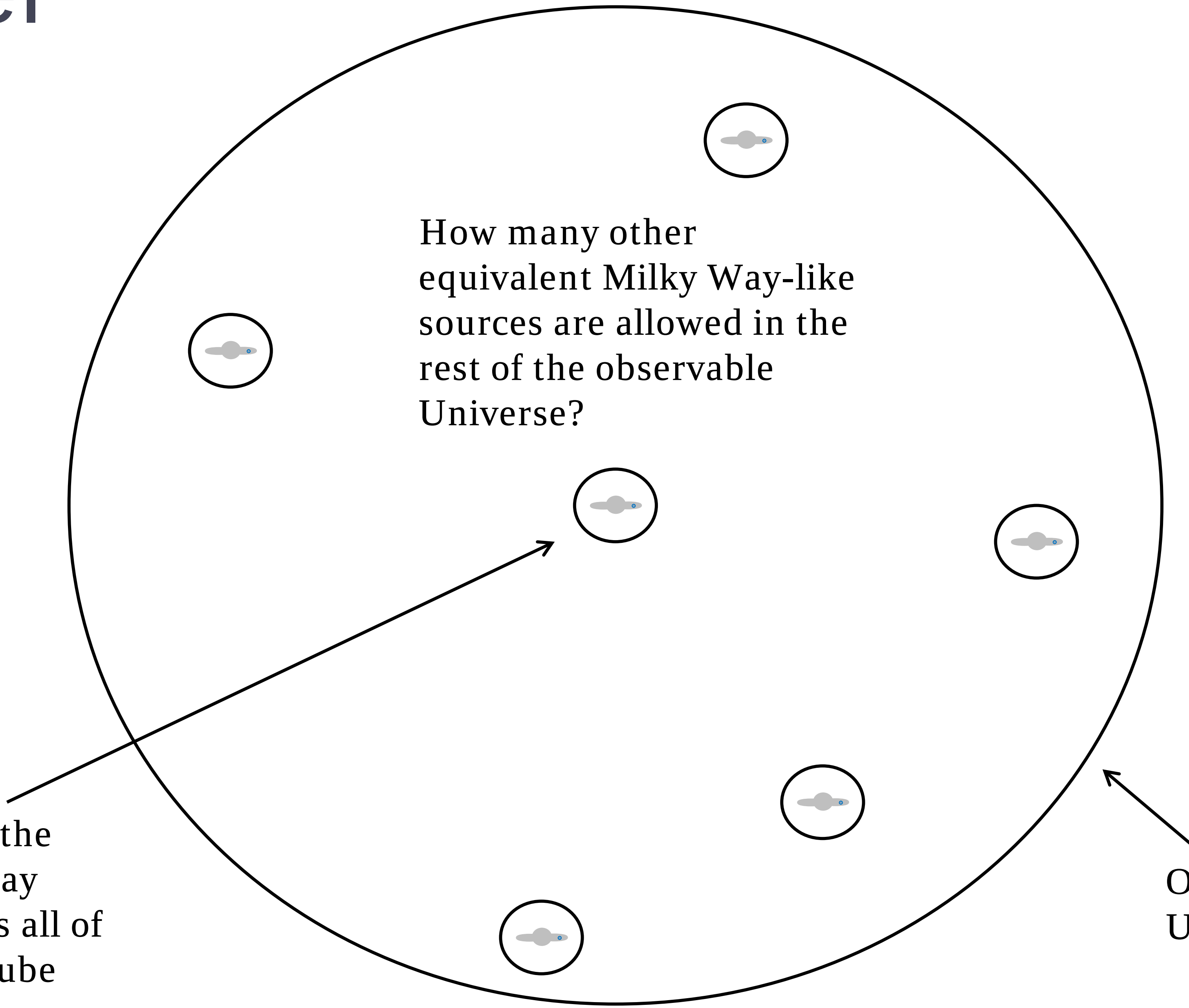
Model


How many other equivalent Milky Way-like sources are allowed in the rest of the observable Universe?
Assume the Milky Way produces all of the IceCube intensity.
Observable Universe

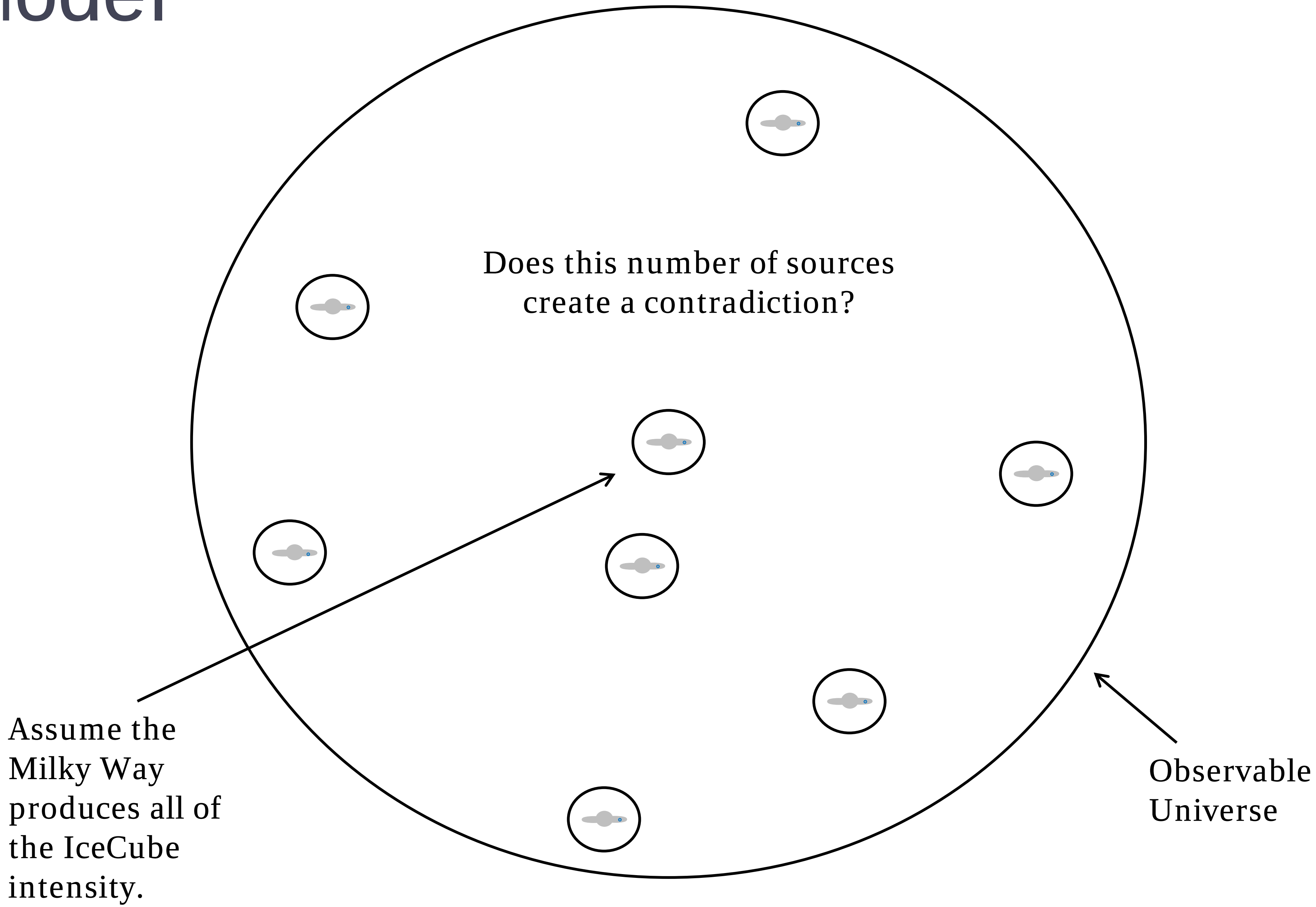
Model


How many other equivalent Milky Way-like sources are allowed in the rest of the observable Universe?
Assume the Milky Way produces all of the IceCube intensity.
Observable Universe

Model

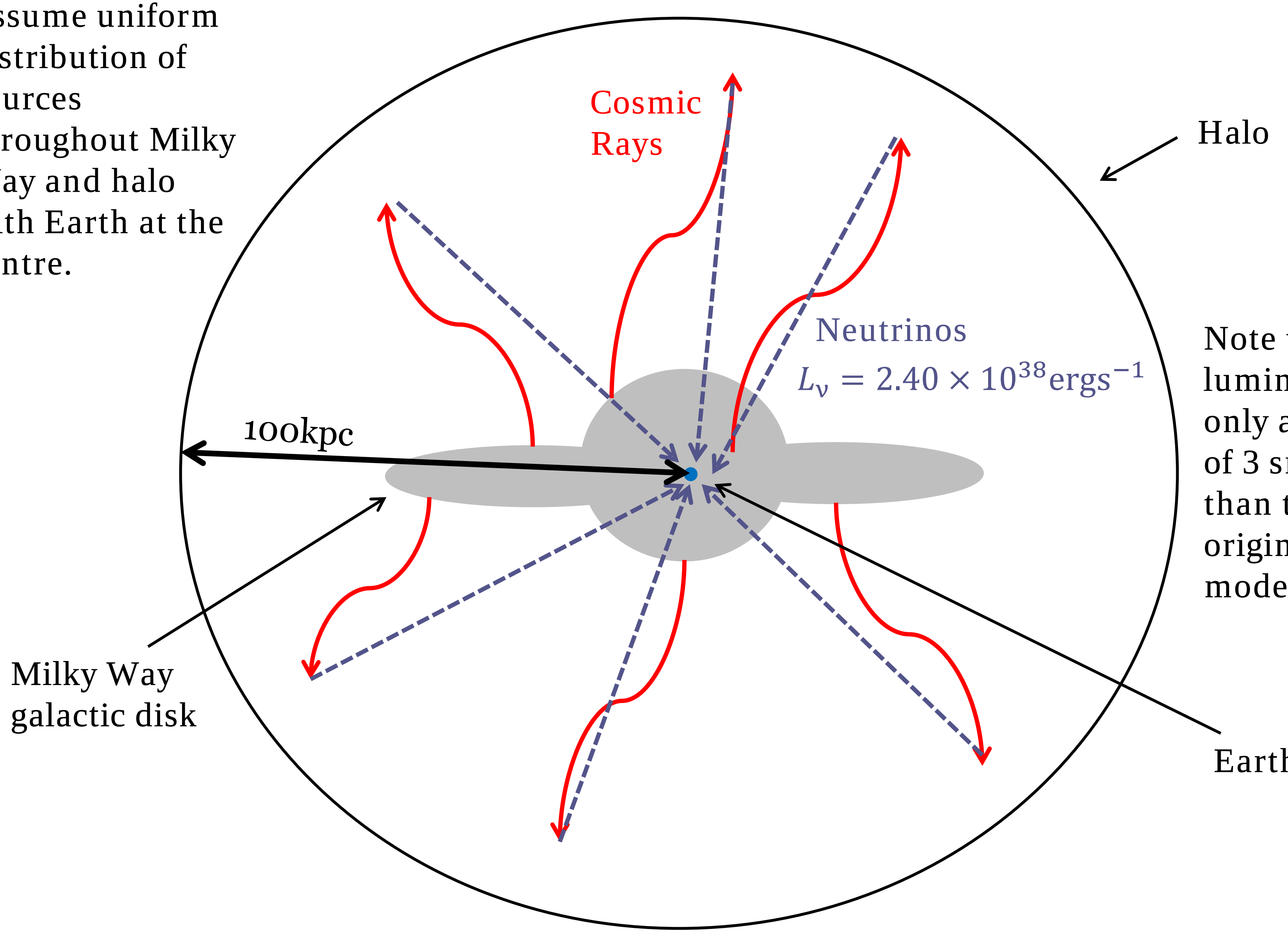

How many other equivalent Milky Way-like sources are allowed in the rest of the observable Universe?
Assume the Milky Way produces all of the IceCube intensity.
Observable Universe

Model


Does this number of sources create a contradiction?
Assume the Milky Way produces all of the IceCube intensity.
Observable Universe

Distribution of Sources

Assume uniform distribution of sources throughout Milky Way and halo with Earth at the centre.



Note that our luminosity is only a factor of 3 smaller than the original model.

Volume Integral

Produce an integral that calculates the volume of the Universe (assuming it's spherical in shape, $V = \frac{4}{3}\pi d_{cm}^{3}$) with respect to redshift.

$$V = \int_{-4}^{1} \frac{z}{E(z)} \frac{c}{H_0} \ln(10) 4\pi d_{cm}^{2} \mathrm{d}log\mathrm{z}$$

$$= 1.06 \times 10^{86} \mathrm{cm}^3$$

$$= 3.61 \times 10^{12} \mathrm{Mpc}^3$$

This will be the basis of all other integrals.

Intensity and Luminosity

Incorporate some function, L(z) [$\mathrm{GeVs}^{-1}\mathrm{cm}^{-3}$] a luminosity per volume, to calculate the luminosity of some arbitrary Universe.

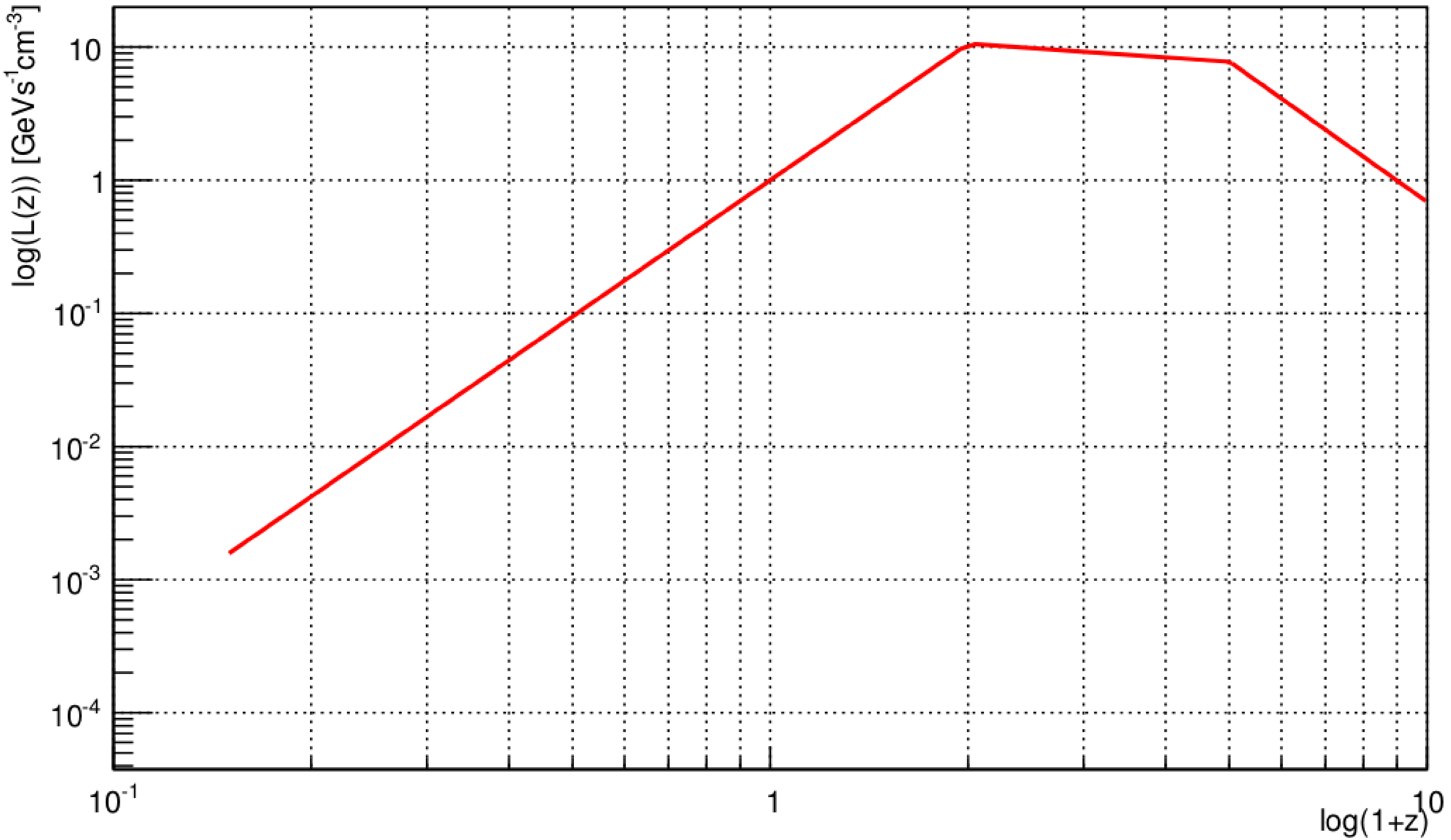
$$L_{tot} = \int_{-4}^{1} L(z) \frac{z}{E(z)} \frac{c}{H_0} \ln(10) 4\pi d_{cm}^2 \mathrm{d}log z$$

To calculate the intensity of some arbitrary Universe, add the factors for spreading out onto a sphere and cosmological redshift.

$$I_{tot} = \int_{-4}^{1} L(z) \frac{z}{E(z)} \frac{c}{H_0} \ln(10) \frac{1}{4\pi} \frac{1}{(1+z)^2} \mathrm{d}log z$$

To make this the luminosity of the rest of the Universe, normalise L(z) to some portion of the IceCube diffuse intensity.

Star Formation Rate

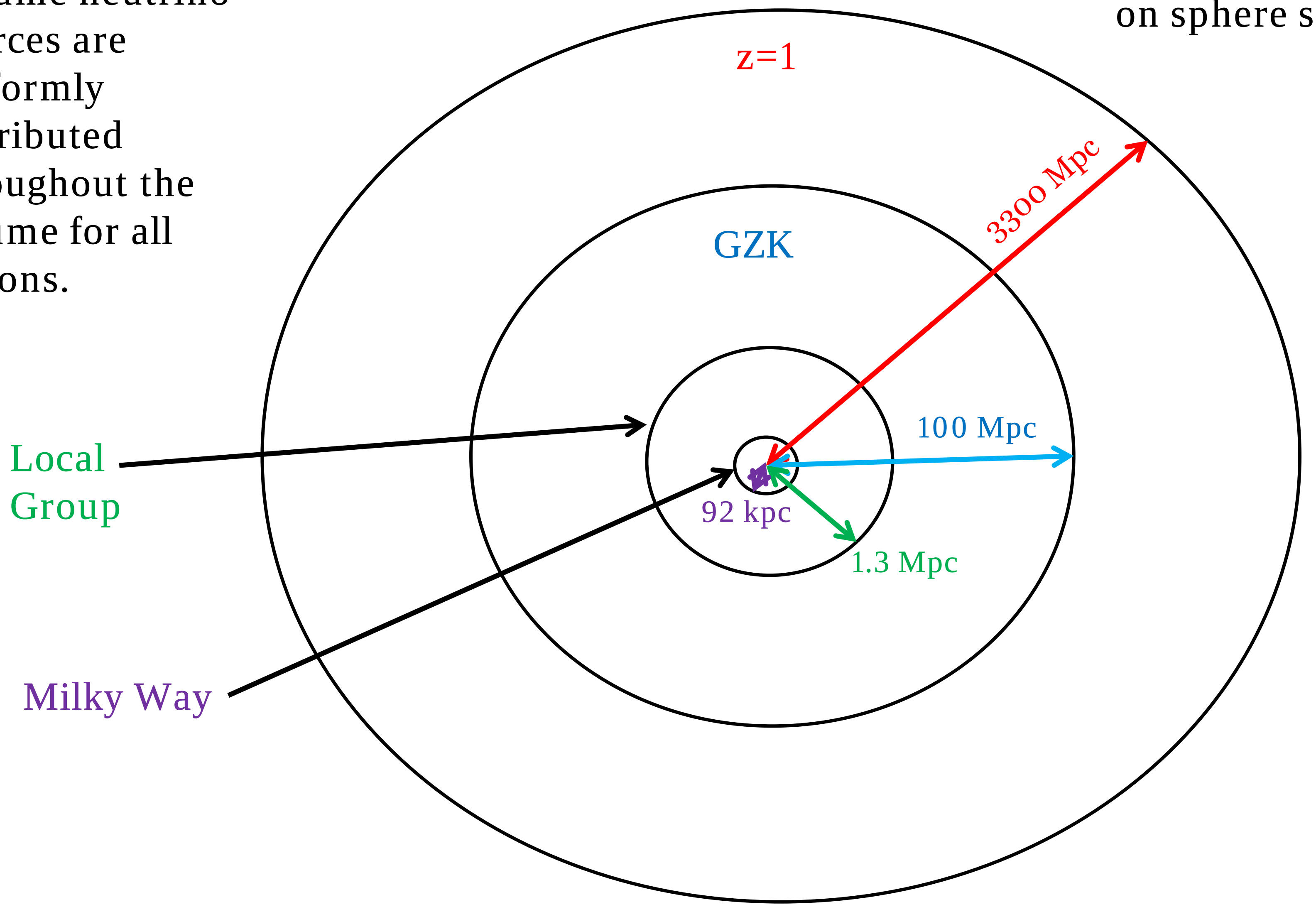


Hopkins & Beacom, 2006

Larger Volumes

For the Local Group, also consider neutrino sources on sphere surface.

Assume neutrino sources are uniformly distributed throughout the volume for all regions.



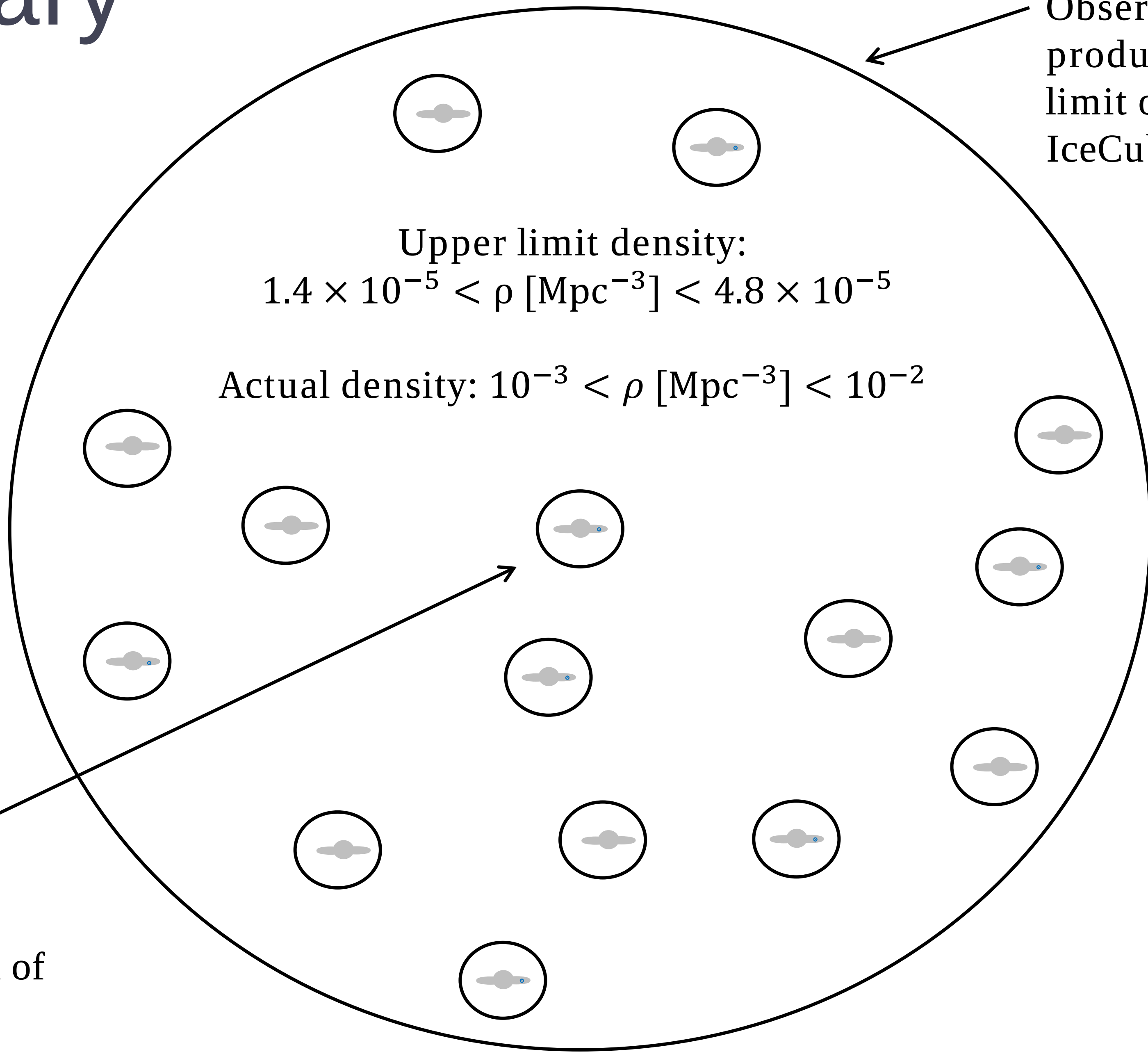
Number Density

We calculate the number of sources allowed in the rest of the observable Universe if the Milky Way produced all of the IceCube intensity while the rest of the Universe was responsible for only an upper limit of 0.4% of the IceCube intensity. We also calculate the average density of allowed sources in the rest of the Universe.

Source	Distance [kpc]	Number of Sources (SFR)	Average Density (SFR) [Mpc^{-3}]	Number of Sources (No Evolution)	Average Density (No Evolution) [Mpc^{-3}]
Milky Way (throughout volume)	≤ 100	1.8×10^{8}	4.8×10^{-5}	1.5×10^{8}	4.2×10^{-5}
Milky Way (sphere surface)	100	5.8×10^{7}	1.6×10^{-5}	5.1×10^{7}	1.4×10^{-5}

Compare with number densities of Milky Way-like galaxies from Crocker & Clay (arXiv:0710.4990v1) of $5 \times 10^{-3}\mathrm{Mpc}^{-3}$ and from Ahlers *et. al.* (arXiv:1505.03156v2) of $10^{-3} - 10^{-2}\mathrm{Mpc}^{-3}$.

Summary


Observable Universe producing an upper limit of 0.4% of the IceCube intensity.
Upper limit density:
$1.4 \times 10^{-5} < \rho\ [\mathrm{Mpc}^{-3}] < 4.8 \times 10^{-5}$
Actual density: $10^{-3} < \rho\ [\mathrm{Mpc}^{-3}] < 10^{-2}$
Assume the Milky Way produces all of the IceCube intensity.

Future Work

We have considered one specific combination of galactic and extra-galactic contributions to the IceCube intensity in which the Milky Way can account for all of the IceCube intensity while the rest of the Universe only produces an upper limit.

We are currently working on looking at number densities of sources in the rest of the Universe for all combinations to be able to put a limit on the fraction of the IceCube intensity that could come from the Milky Way.

Thank you!

Backup

Number Densities

Source	Distance [kpc]	Number of Sources (SFR)	Average Density (SFR) [Mpc^{-3}]	Number of Sources (No Evolution)	Average Density (No Evolution) [Mpc^{-3}]
Milky Way (throughout volume)	≤ 100	1.8×10^{8}	4.8×10^{-5}	1.5×10^{8}	4.2×10^{-5}
Milky Way (sphere surface)	100	5.8×10^{7}	1.6×10^{-5}	5.1×10^{7}	1.4×10^{-6}
Local Group (throughout volume)	≤ 1530	742912	2.1×10^{-7}	646707	1.8×10^{-7}
Local Group (sphere surface)	1530	247637	6.9×10^{-8}	215569	6.0×10^{-8}
GZK	100	178	5.1×10^{-11}	159	4.4×10^{-11}
z=1	3.3×10^{6}	0.33	9.7×10^{-14}	0.58	1.7×10^{-13}

Number of Sources - Murase and Waxman

TABLE I: Densities of various classes of steady sources suggested to produce the flux of high-energy neutrinos observed in IceCube.

Source class	$E_\nu L^{\rm eff}_{E_{\nu_\mu}}$ [erg s^{-1}]	$L^{\rm eff}_{\rm ph}$ [erg s^{-1}]	$n_0^{\rm eff}$ [Mpc^{-3}]	$n_0^{\rm tot}$ [Mpc^{-3}]
FSRQ[a]	$\sim 3 \times 10^{46}$	$L_\gamma \sim 5 \times 10^{47}$	$\sim 2 \times 10^{-12}$	$\sim 10^{-9}$
BL Lac[b]	$\sim 2 \times 10^{44}$	$L_\gamma \sim 5 \times 10^{45}$	$\sim 5 \times 10^{-9}$	$\sim 10^{-7}$
SBG[c]	$\sim 2 \times 10^{40}$	$L_\gamma \sim 10^{41}$	$\sim 10^{-5}$	$\sim 3 \times 10^{-5}$
GC/GG-acc[d]	$\sim 1 \times 10^{42}$	$L_X \sim 8 \times 10^{44}$	$\sim 10^{-6}$	$\sim 2 \times 10^{-6}$
GC/GG-int[e]	$\sim 2 \times 10^{40}$	$L_X \sim 6 \times 10^{43}$	$\sim 10^{-5}$	$\sim 5 \times 10^{-5}$
RL AGN[f]	$\sim 2 \times 10^{42}$	$L_\gamma \sim 10^{43}$	$\sim 10^{-7}$	$\sim 10^{-4}$
RQ AGN[g]	$\sim 7 \times 10^{40}$	$L_X \sim 10^{44}$	$\sim 3 \times 10^{-6}$	$\sim 10^{-4}$
LL AGN[h]	$\sim 1 \times 10^{39}$	$L_{\rm H\alpha} \sim 10^{40}$	$\sim 10^{-3}$	$\gtrsim 10^{-2}$

A minimum number of sources can be calculated using the n_0^{tot} values from Table 1 and compared to the number of sources allowed in the Universe on the previous slide.

Chosen Region	**Number of Sources in Rest of Universe**
Local Group	3.70×10^{10}
GZK	3.54×10^{10}
z=1	3.50×10^{10}