Modelling High-Energy Neutrino Emission from Star-Forming Activity using the SIMBA Cosmological Simulation

Alyssa Debot[a], Krijn de Vries[a], Nick van Eijndhoven[a], Yarno Merckx[a], Else Magnus[a], Romeel Davé[b], George Privon[c]

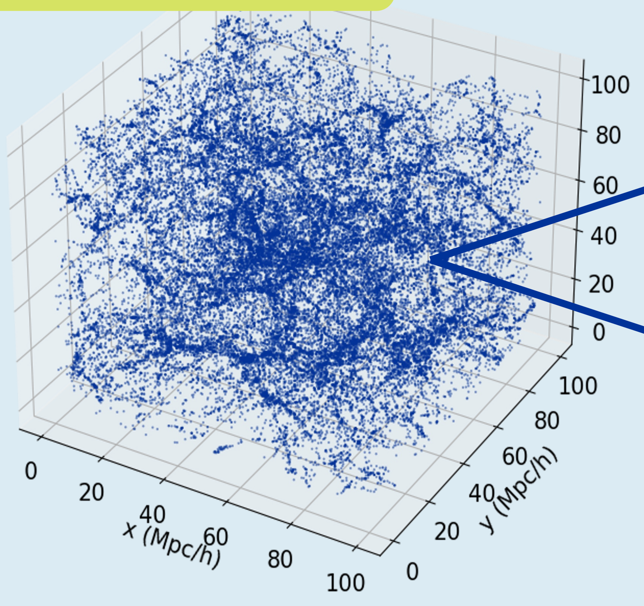
[a] Vrije Universiteit Brussel (VUB) [b] University of Edinburgh, University of the Western Cape [c] University of Florida, University of Virginia

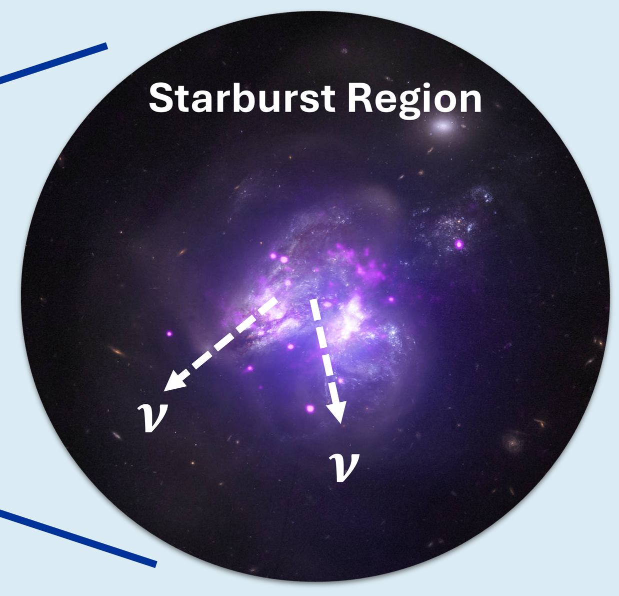
INTRODUCTION

- The IceCube observatory observed a diffuse astrophysical neutrino flux for the first time in 2013 [1]. However, its origin largely remains a mystery.
- Different source classes are believed to contribute to this diffuse flux, among them: starburst galaxies are strong contenders.
- To estimate contribution of starbursts to diffuse flux, we introduce a novel approach by using a time-integrated method across redshift with large-scale hydrodynamical simulations.

Aim: Predict a diffuse high-energy neutrino flux using large-scale hydrodynamical simulation of the cosmos.

METHODOLOGY





SIMBA simulation

Large-scale **hydrodynamical cosmological simulation** [2] . It models formation and evolution of galaxies from z=20 till z=0. Use galaxy properties from simulation to model neutrino emission.

Starburst-driven neutrino emission

Predict high-energy neutrino emission from starburst regions using a **phenomenological model** [3].

COMBINING SIMBA WITH NEUTRINO EMISSION

Neutrino flux from neutrino emission model depends on many starburst parameters.
→ Use SIMBA simulation to obtain these parameters.

Neutrino flux: $$\Phi_{\nu_j} = \Phi_{\nu_j}\left(\mathcal{R}_{\mathrm{SN}}, \gamma_{\mathrm{SN}}, p_{\max}, H_{\mathrm{SBR}}, v_{\mathrm{adv}}, n, B, D_L\right)$$

Fixed parameters:
- γ_{SN} : spectral index proton spectrum
- p_{max}: max. proton momentum
- H_{SBR}: scale height starburst region (SBR)
- B: magnetic field strength

$$\left(\frac{\mathcal{R}_{\mathrm{SN}}}{\mathrm{yr}^{-1}}\right) = A_{\mathrm{SFR}} \cdot \left(\frac{\boxed{\mathrm{SFR}}}{M_\odot\ \mathrm{yr}^{-1}}\right)$$

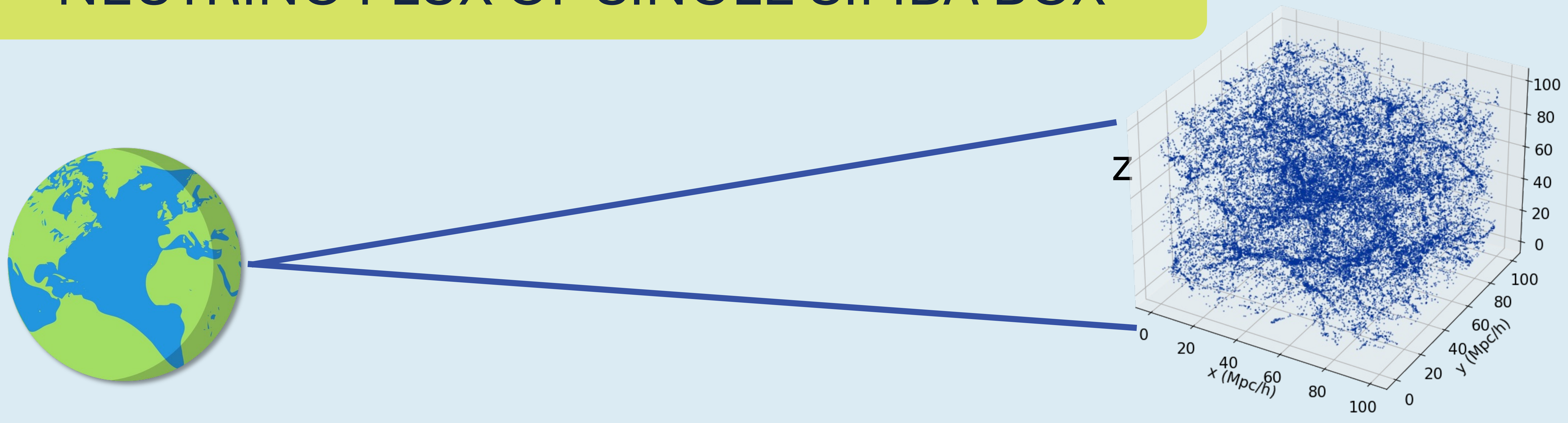
Luminosity distance D_L from redshift z of SIMBA simulation box.

Supernova rate R_{SN}
- Injects the cosmic rays in the starburst region
- Obtained from **scaling relation with the star formation rate (SFR),** that can be extracted with SIMBA for each galaxy

Galactic-scale outflows v_{adv}
- Carry CRs away from interaction region
- Modelled in SIMBA, driven by star formation
- Obtained in post-processing from **scaling with galaxy's baryonic mass** and halo properties

Proton density of central starburst region n
- Probability of pp-interactions and hence neutrino production
- Described by fixed values and a **scaling relation with SFR** based on Kennicutt-Schmidt relation [5]

NEUTRINO FLUX OF SINGLE SIMBA BOX



Assumption: each simulation box is treated as if it represents a population of galaxies located at the corresponding redshift as seen from Earth

Single galaxy flux:

$$\Phi_\nu(E_\nu, z) = \frac{V_{\mathrm{SBR}}}{4\pi D_L^2} \cdot (1+z)^2 \cdot q_\nu(E_\nu(1+z))$$

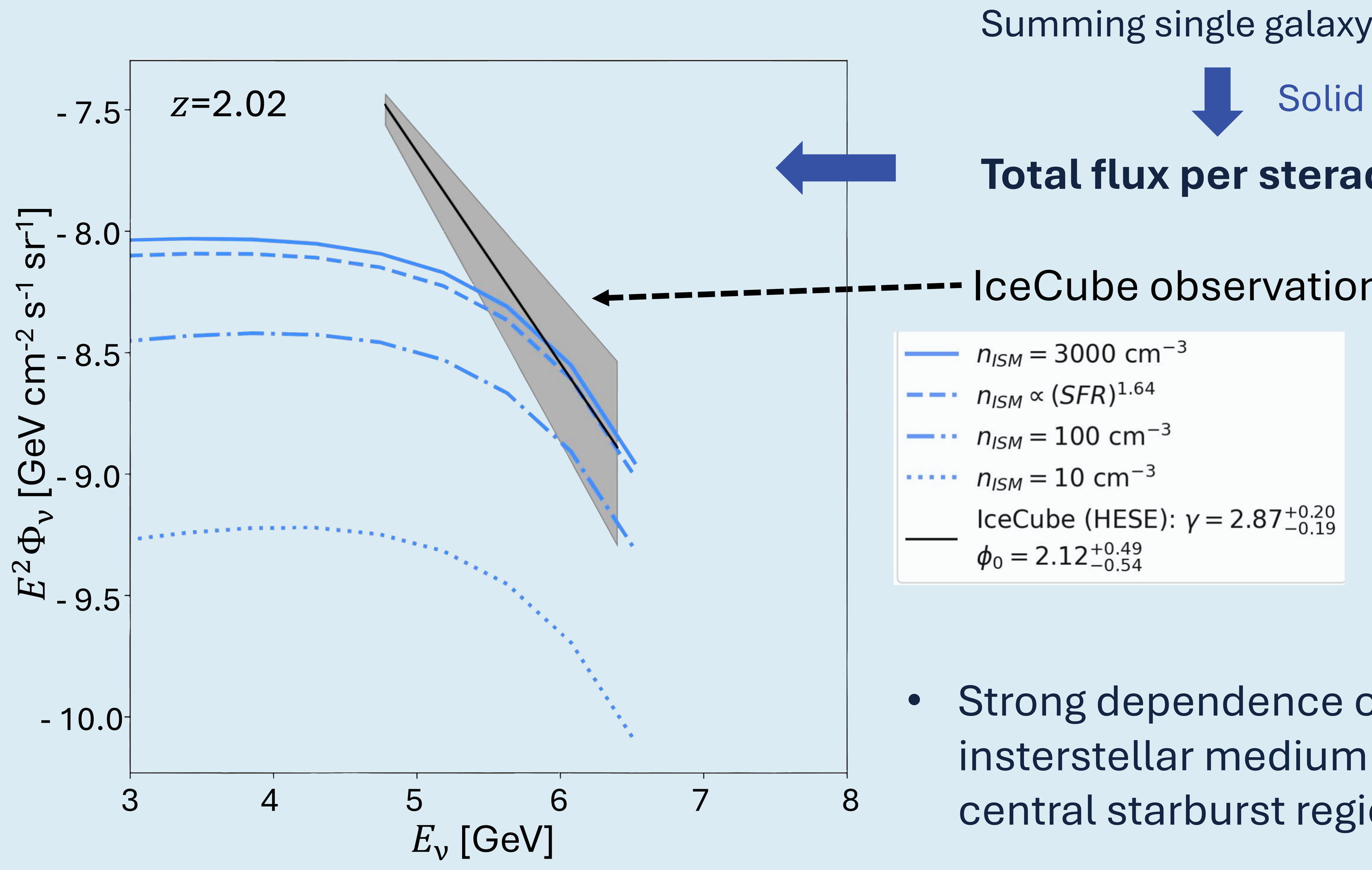
Total flux of box:

$$\Phi_{\nu,tot}(E_\nu, z) = \sum_i \Phi_{\nu,i}(E_\nu, z)$$

Summing single galaxy fluxes

Solid angle box

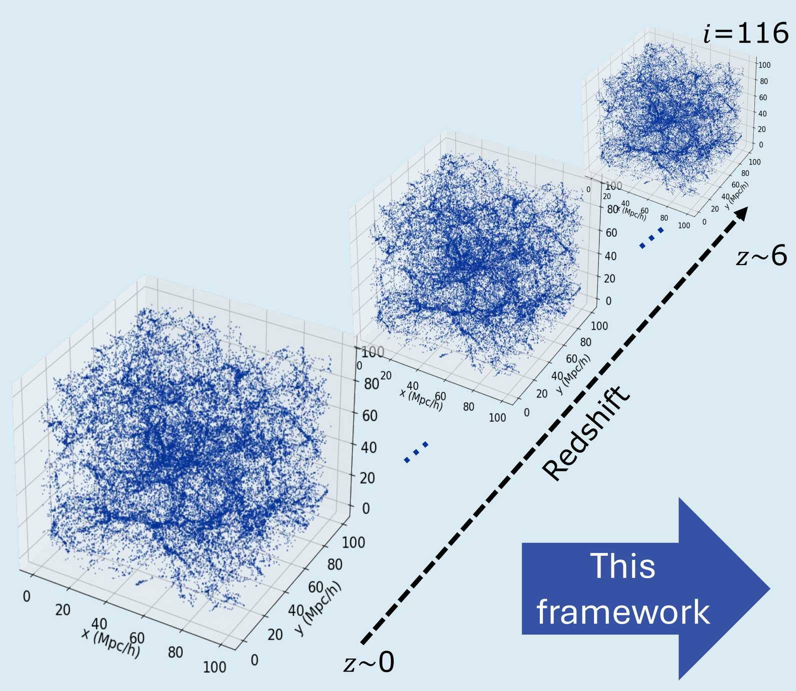
Total flux per steradian

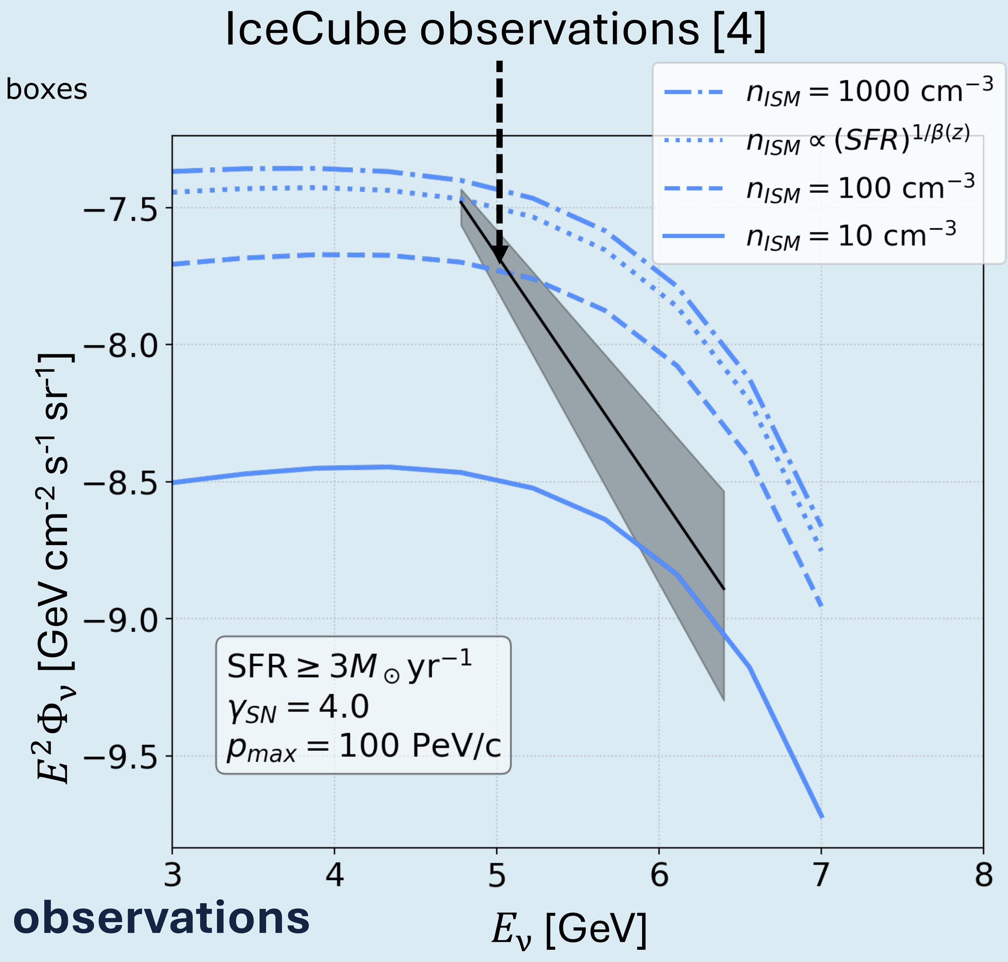


- Strong dependence on density insterstellar medium n_{ISM} of central starburst region

DIFFUSE NEUTRINO FLUX ACROSS COSMIC HISTORY

- **First implementation** of predicting the diffuse neutrino flux using larg-scale hydodynamical simulations.
- **Estimated by summing the contribution of SIMBA boxes across redshift.**





- Result **overshoots IceCube observations** except for low n_{ISM} assumption
- No galaxy evolution considered, can lead to overcounting the galaxy contributions

CONCLUSION AND OUTLOOK

- Made first time-integrated prediction of the diffuse high-energy neutrino flux from starburst regions using the SIMBA simulation
- The result overshoots the IceCube observations, except for low densities. This can be used to constrain the parameters of the neutrino emission model in future work.

Outlook:
- Obtain proton density of central region of galaxy directly from SIMBA simulation, instead of an approximate scaling relation with SFR.
- Consider galaxy evolution by tracking the galaxies across snapshots.

[1] IceCubeCollaboration and M. G. Aartsen.Science 342 (2013) 1242856.
[2] R.Davé et al. Mon. Not. R. Astron. Soc. 486 (2019) 2827.
[3] Y.Merckx et al. Phys. Rev. D 108 (2023) 023015.
[4] R.Abbasi et al. Phys. Rev. D 104 (2021) 022002.
[5] R.C. Kennicutt and M. A.C.De Los Reyes. ApJ 908 (2021) 61.