Solar Atmospheric Neutrinos: A Simulation-Based Flux Calculation with Solar Magnetic Field and Neutrino Propagation

MA Ho Lung[1], Prof. NG Chun Yu[1], Chingam Fong[1], Zhe Li[2]
[1]The Chinese University of Hong Kong
[2]Institute of High Energy Physics, Chinese Academy of Sciences

Background & Motivation

Solar atmospheric neutrino (SAv):
Neutrinos produced by cosmic ray air shower in solar atmosphere.

Motivation:

1. WIMPs accumulated in the solar core can self-annihilate into neutrinos. For indirect dark matter search by neutrino, SAv becomes a background needed to be studied. [1]
2. Solar physics via SAv (if possible?)

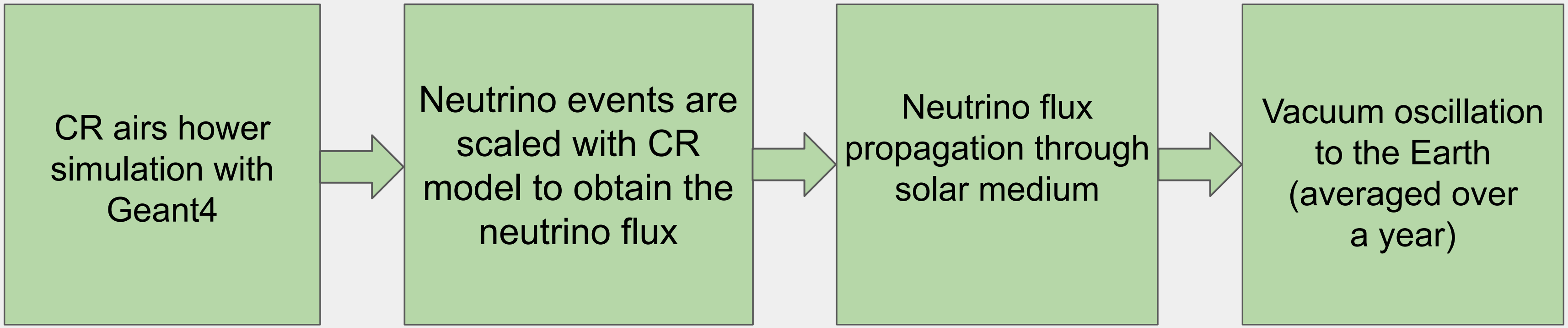
Previous Studies

- C.A. Argüelles, et al. (2017) [2] and J. Edsjö, et al. (2017) [3]
- Both includes neutrino propagation
- Neutrino yield : MECq, without solar magnetic field

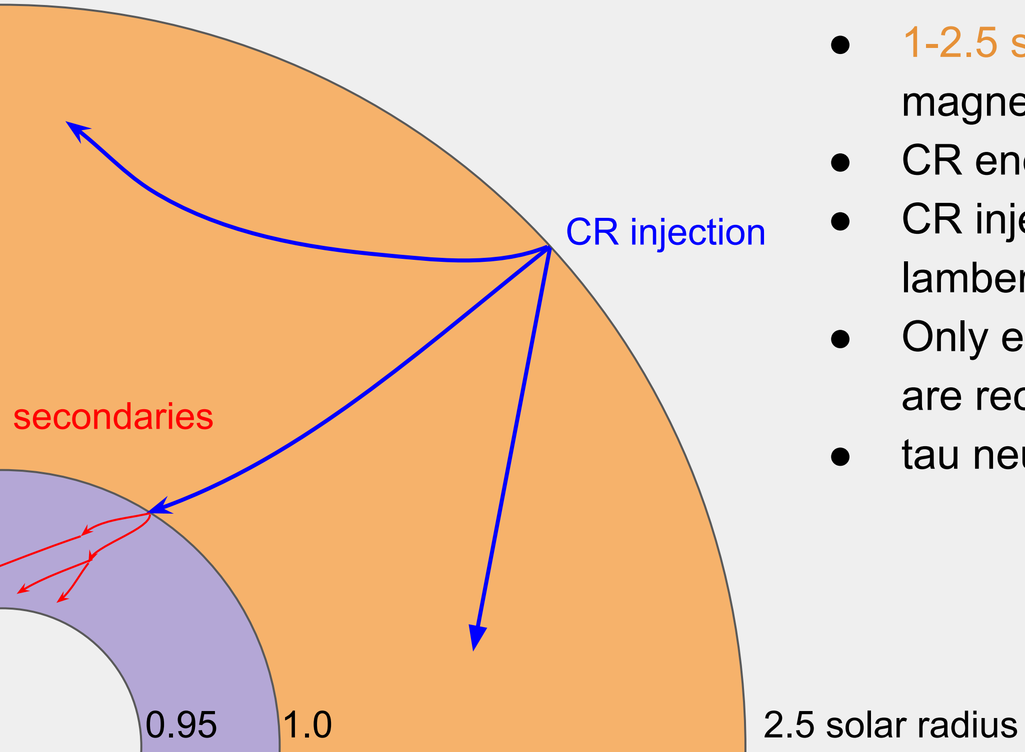
- IceCube Collaboration (R. Abbasi, et al.) (2025) [4]
- IceCube limit of SAν flux via C.A. Argüelles, et al.

- M. N. Mazziotta, et al. (2020) [5]
- No neutrino propagation effects
- Neutrino yield : FLUKA, with solar magnetic field

Analysis Pipeline



CR Air Shower Simulation



- 0.95-1 solar radius: dense solar material, interaction region
- 1-2.5 solar radius: low density, with coronal magnetic field
- CR energy range: 10GeV-10PeV
- CR injected into the volume isotropically + lambert's cosine law correction
- Only e and mu neutrinos between 10GeV-100TeV are recorded
- tau neutrinos are orders of magnitude lower

CR Simulation (Details)

CR Composition: proton (10GeV-10PeV), alpha (10GeV-100TeV)

Hadronic models: below 100TeV, Geant4 default (FTFP-BERT)

100TeV-10PeV, EPOS1.99 via the crmc interface [5,6]

Both cannot produce prompt neutrino

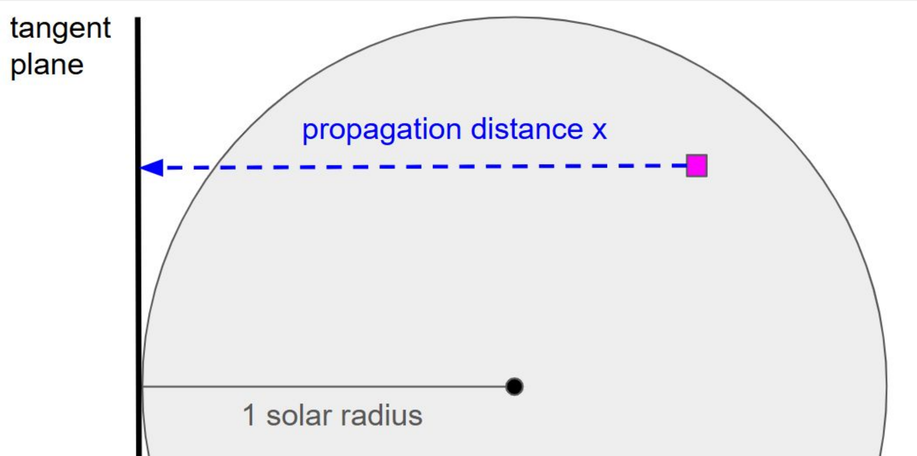
Solar model: the B16 Standard Solar Models (from 0.95-1.0 solar radius)

CR model: HillasGaisser2012

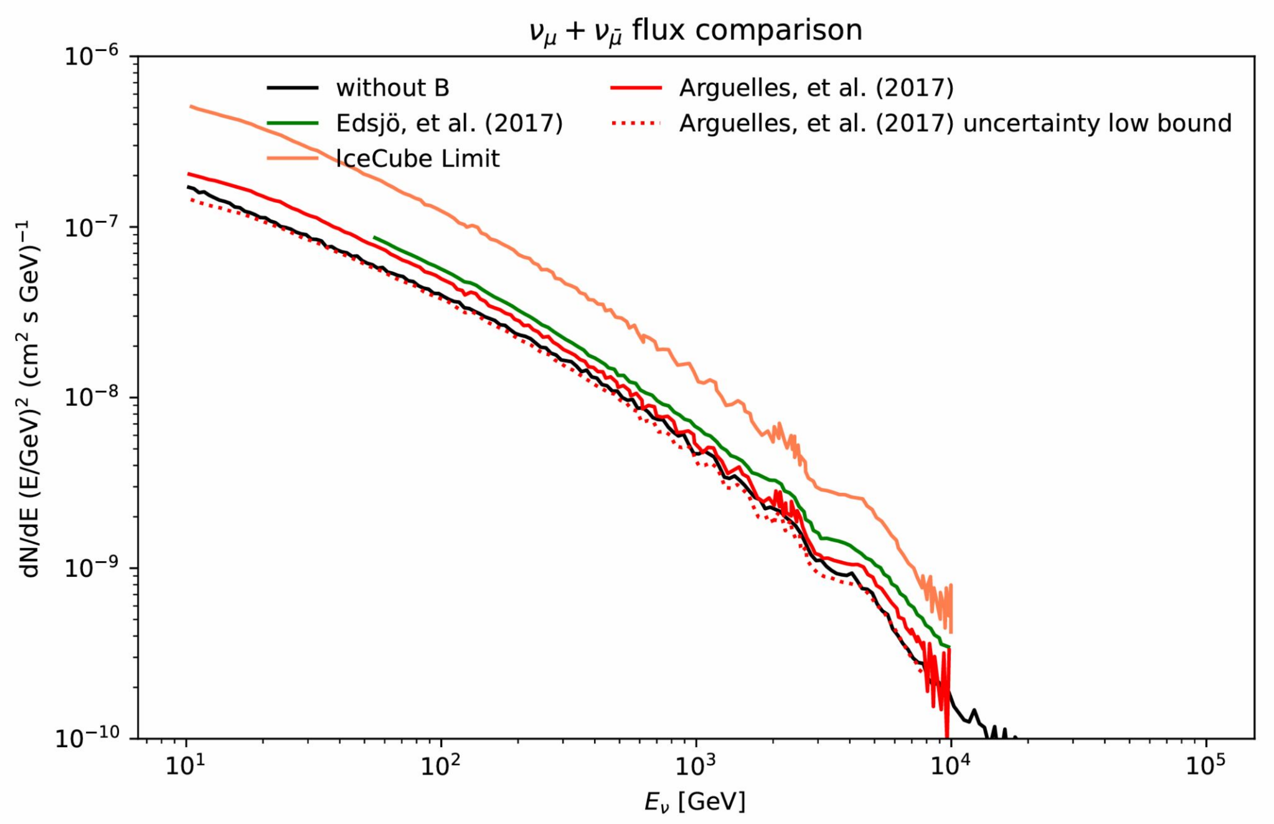
Geant4 code for simulation first developed by Zhe Li (2009.03888), followed by Chingam Fong

Neutrino Propagation

- SAv flux are binned according to position and propagated to the tangent plane at the opposite side of the sun
- Propagation are done by numerical computation via nuSQuIDS [7], with oscillation in material and interaction included
- The flux are summed and oscillate through the vacuum to the Earth
- Time averaged over the varying Earth-Sun distance



SAv flux: Without B



Roughly less than previous studies (by a factor of 1.3)

Within the uncertainty bound by Argüelles though

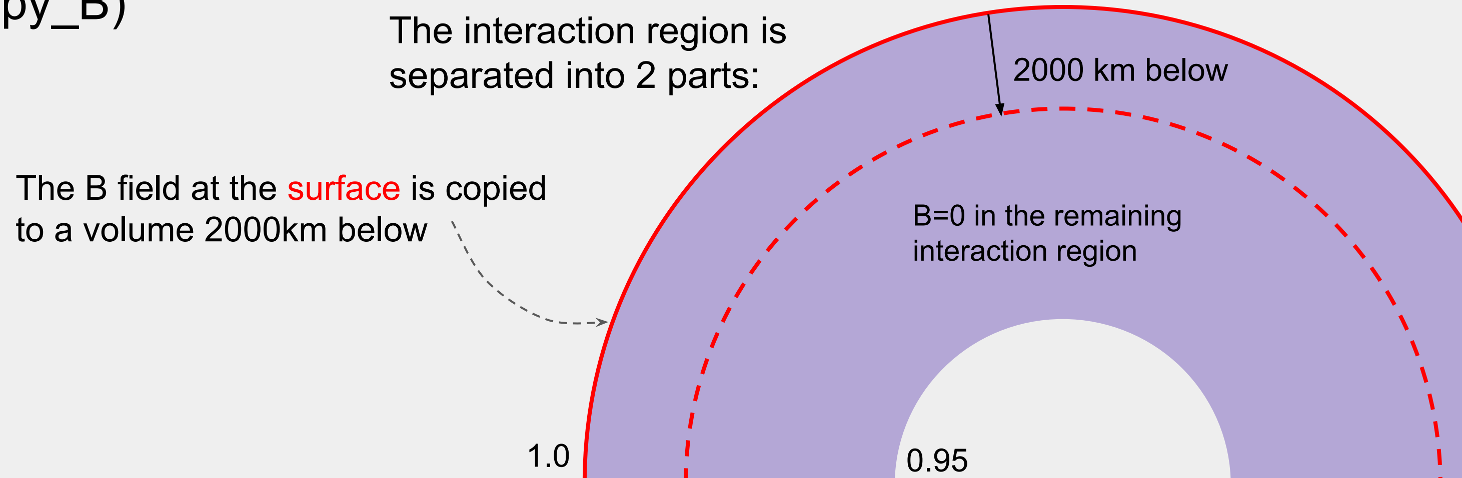
Possible reasons:

1. Different solar, CR and hadronic models
2. Lack of He between 100TeV - 10PeV

Including Solar Magnetic Field

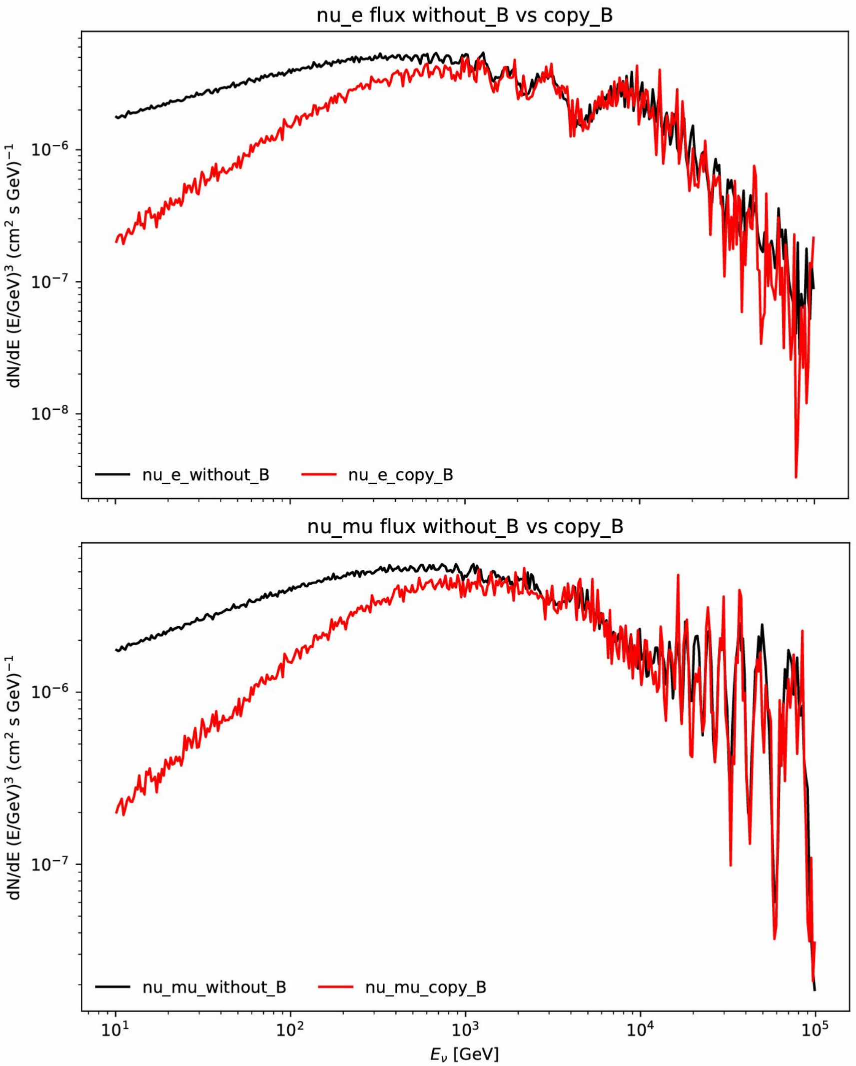
- For the coronal field between 1-2.5 solar radius, we applied PFSS (Potential Field Source Surface) model to the simulation volume.
- However, the detail configuration of the magnetic field below 1 solar radius is unclear. Three testing cases are proposed:

1st case: Assuming the magnetic field inside is similar to the surface value. (Label in plots: copy_B)



Comparison: without B vs copy B

- < 1 TeV, there is a deficit of the flux
- CR tends to be deflected away from the sun by the coronal field
- The difference vanishes gradually at ~1 TeV
- But the magnetic field inside the sun should be stronger than the surface value



Including Solar Magnetic Field

2nd case: Randomizing the direction of the neutrino produced (isotropic).

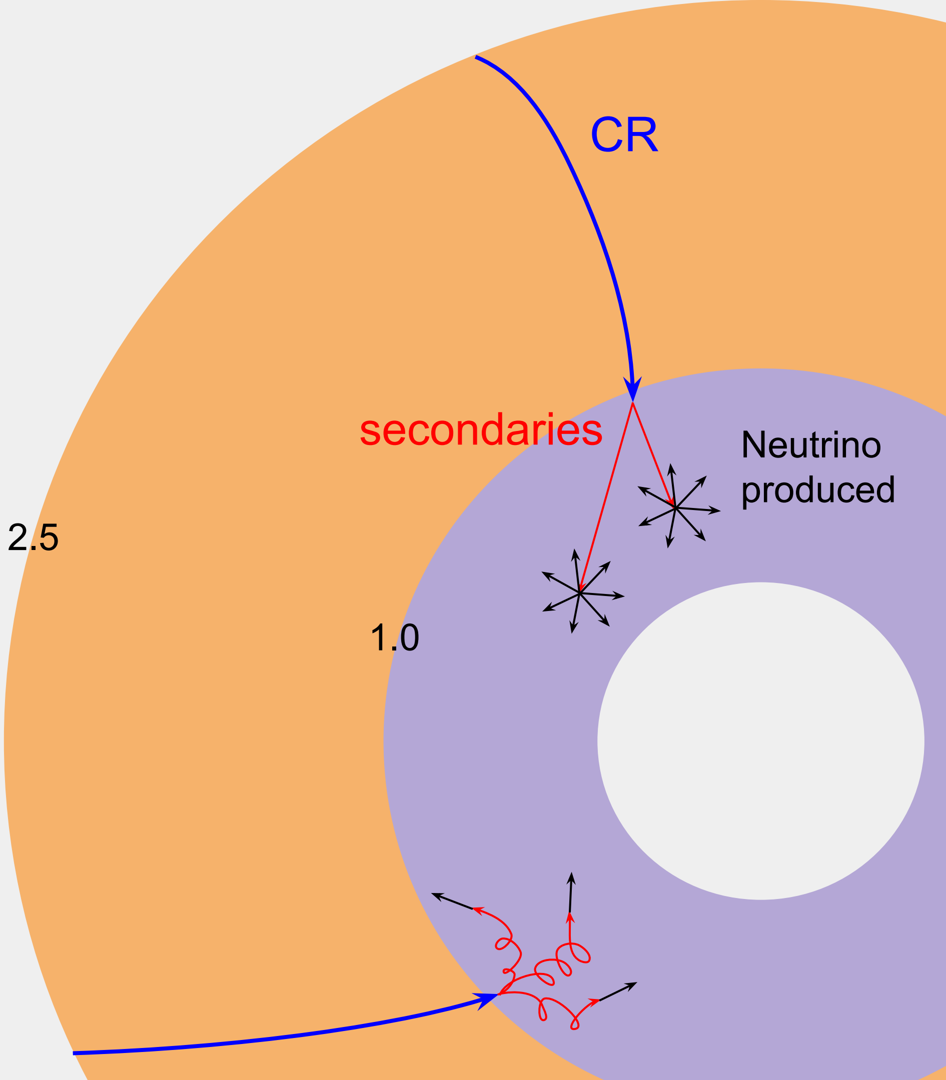
Label in plots: iso

This the large magnetic field limit.

coronal field region:

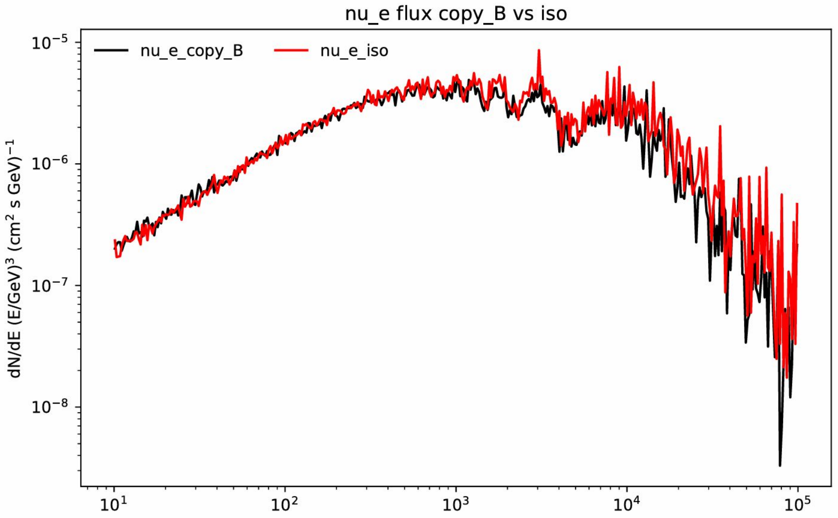
interaction region: (without magnetic field)

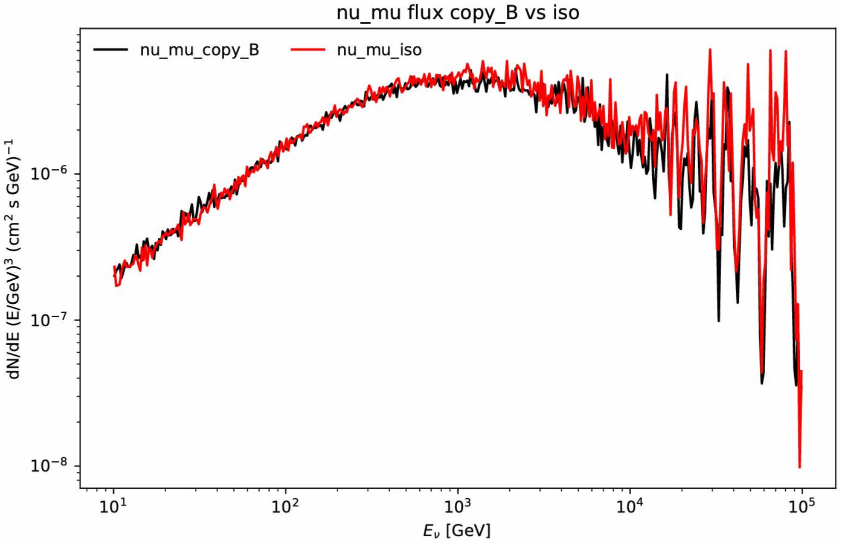
With large magnetic field, direction of neutrinos are mostly isotropic:



Comparison: copy B vs iso

- They are basically the same
- As expected at low energy, but turns out at high energy, the flux of the iso case is not amplified much
- Conclusion: A high magnetic field in the interaction region is hardly probed by SAv.
- Can there exist some specific magnetic field configuration that changes the flux greatly?

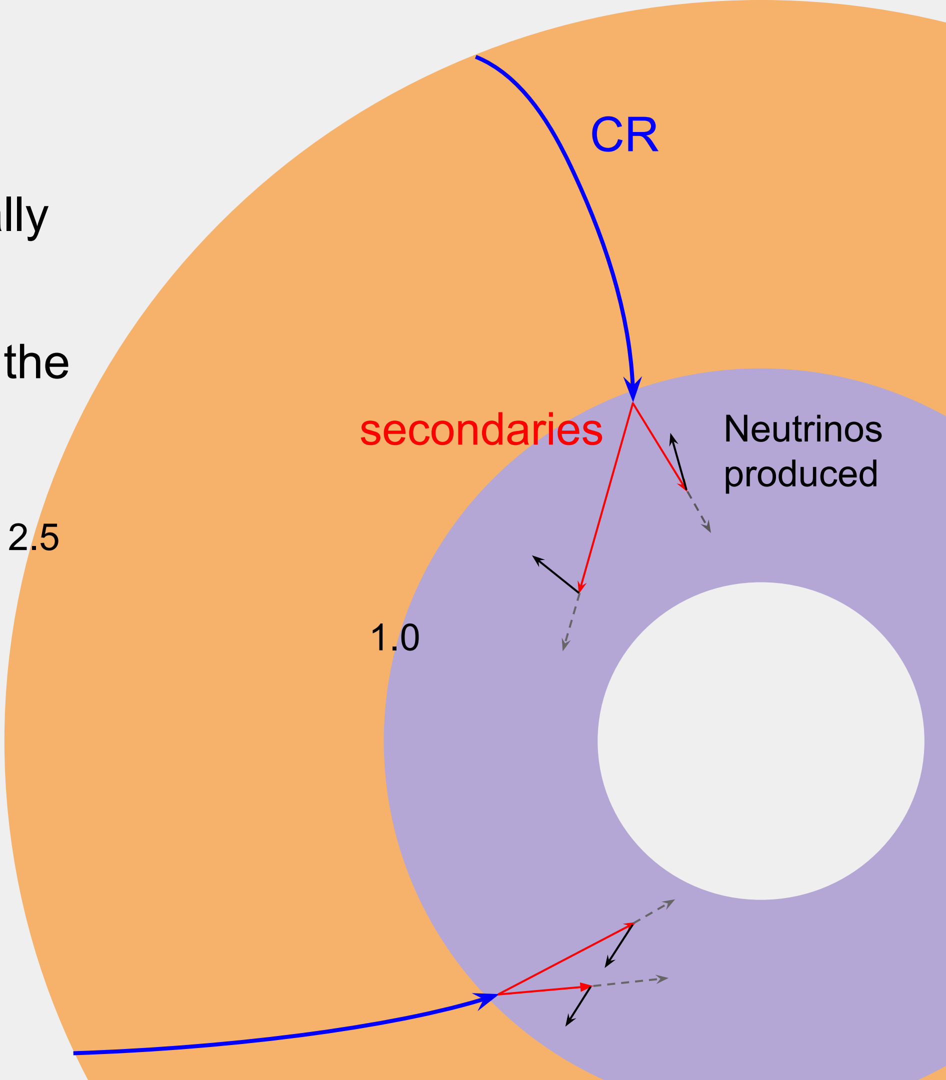




Including Solar Magnetic Field

3rd case: Forcing all neutrino heading radially outwards (Label in plots: rad_out)

This serves at a theoretical upper bound to the flux.

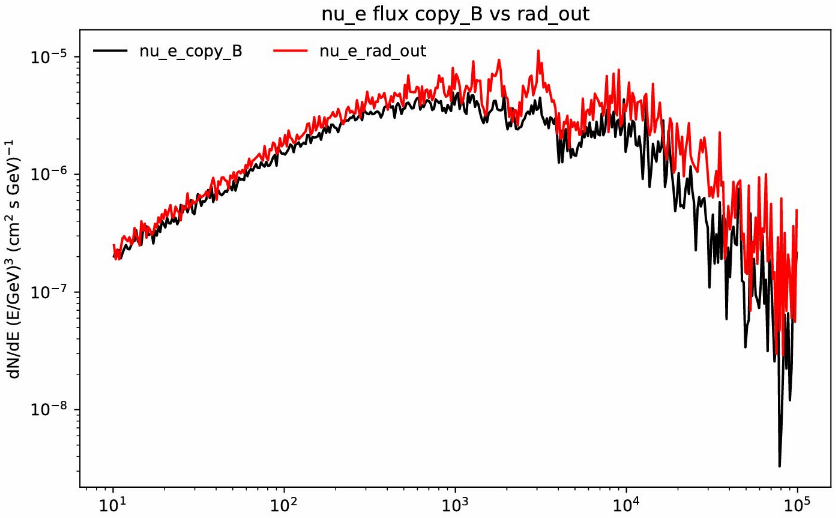


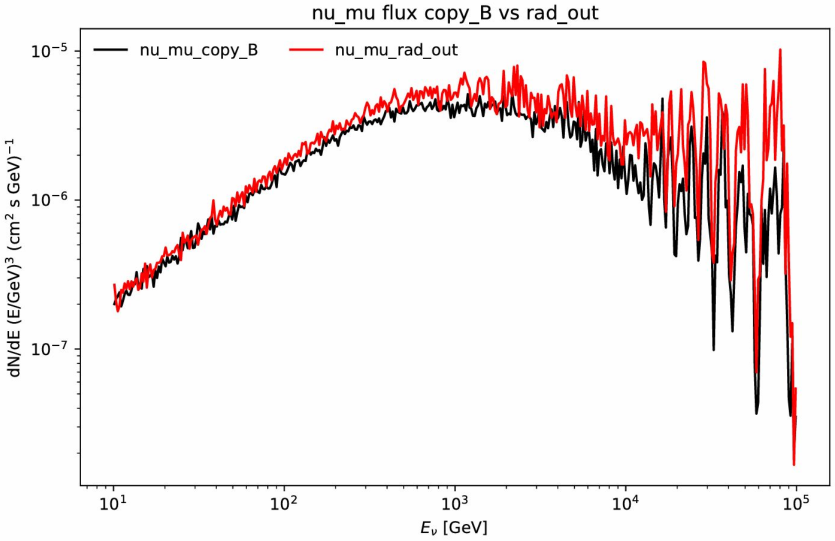
coronal field region:

interaction region: (without magnetic field)

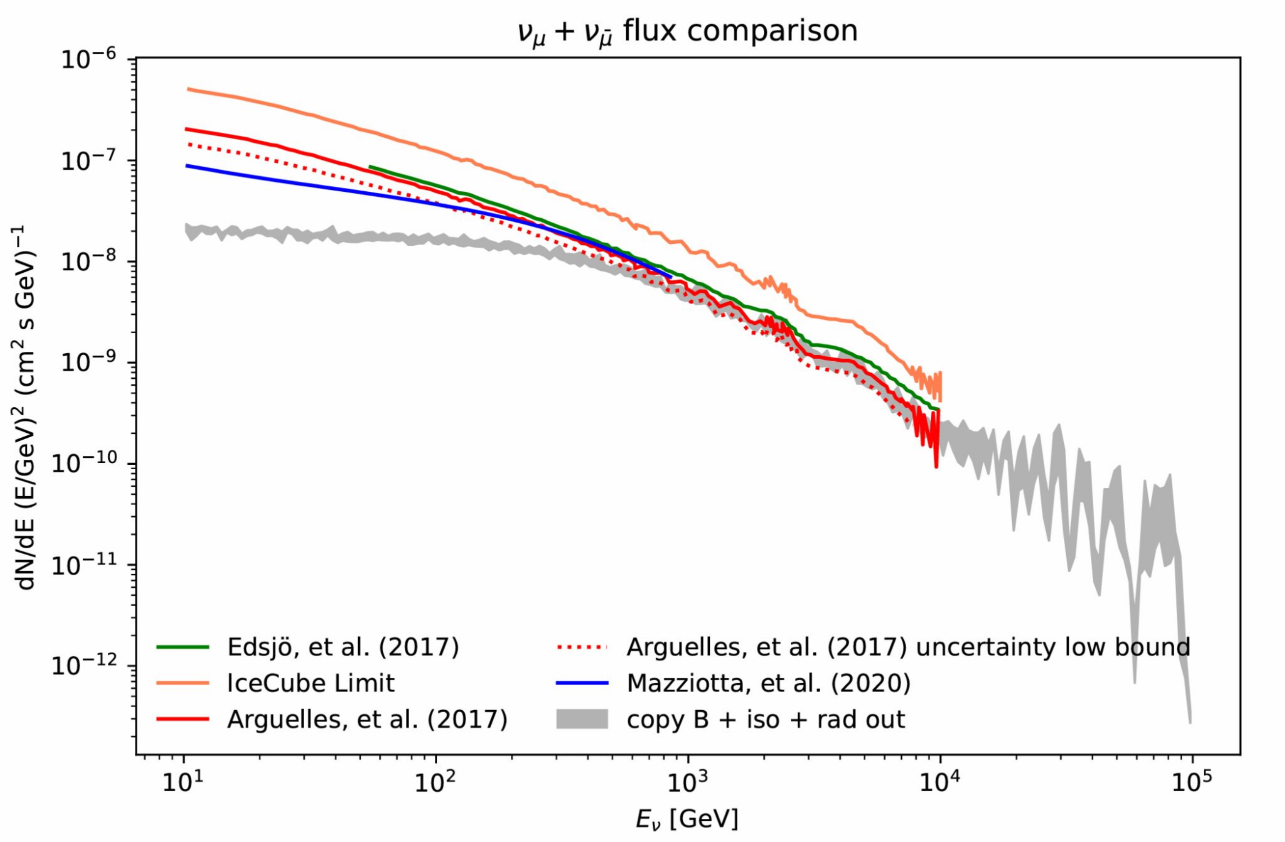
Comparison: rad out vs copy B

- At TeV level, the flux intensity is similar
- Turns out SAv is insensitive to the magnetic field configuration inside the sun
- Maybe not a tool for solar magnetic field studies, but robust as TeV neutrino source





Comparison with Existing SAν Calculation



At TeV level, similar flux intensity

A narrow band: Magnetic field in the interaction region has limited effect on SAν

The band width is comparable with the model uncertainty

Future work: Try different CR & hadronic models, look into the offset with other studies

Thanks for Listening

Any Questions

References and Acknowledgement

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