Neutrinos and gamma rays from long-lived mediator decays in the Sun

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Outline

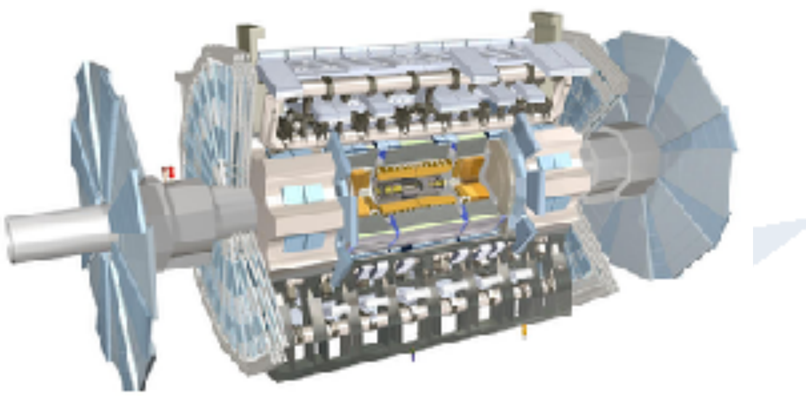
- Dark matter searches from the Sun – WIMP scenario (for review)
- Neutrinos and gamma rays from long-lived mediator decays
- Backgrounds

Ways to search for dark matter

Ways to search for dark matter

Accelerator searches

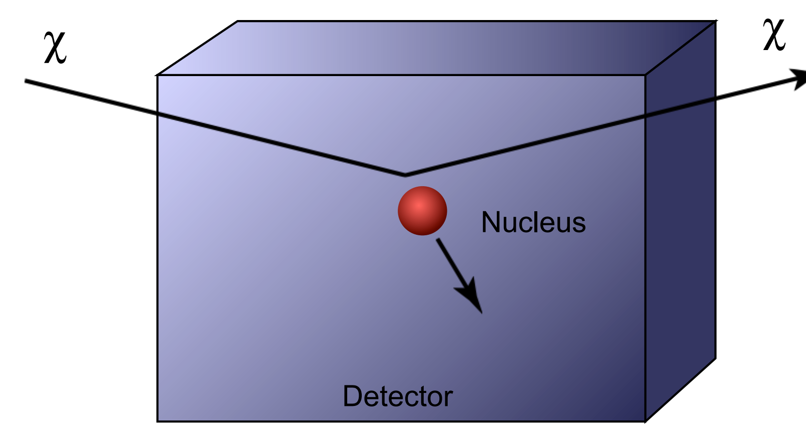
- LHC (ATLAS, CMS...)
- Rare decays
- ...



We

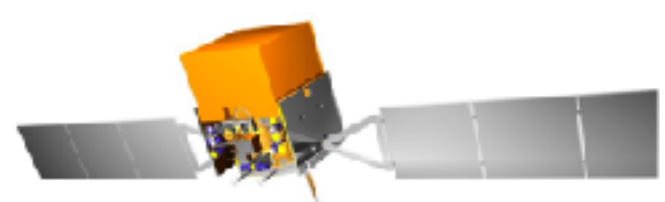
Direct searches

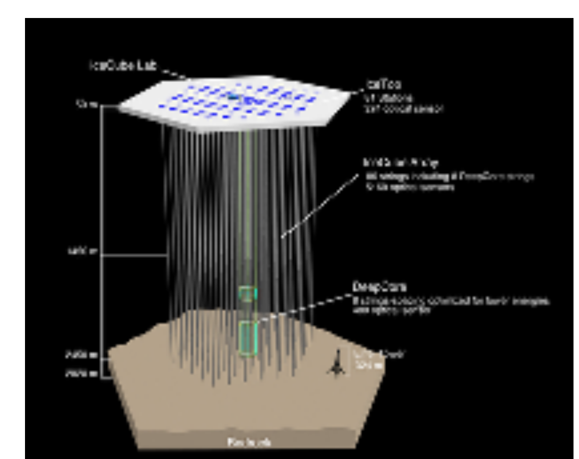
- Spin-independent scattering
- Spin-dependent scattering



Indirect searches

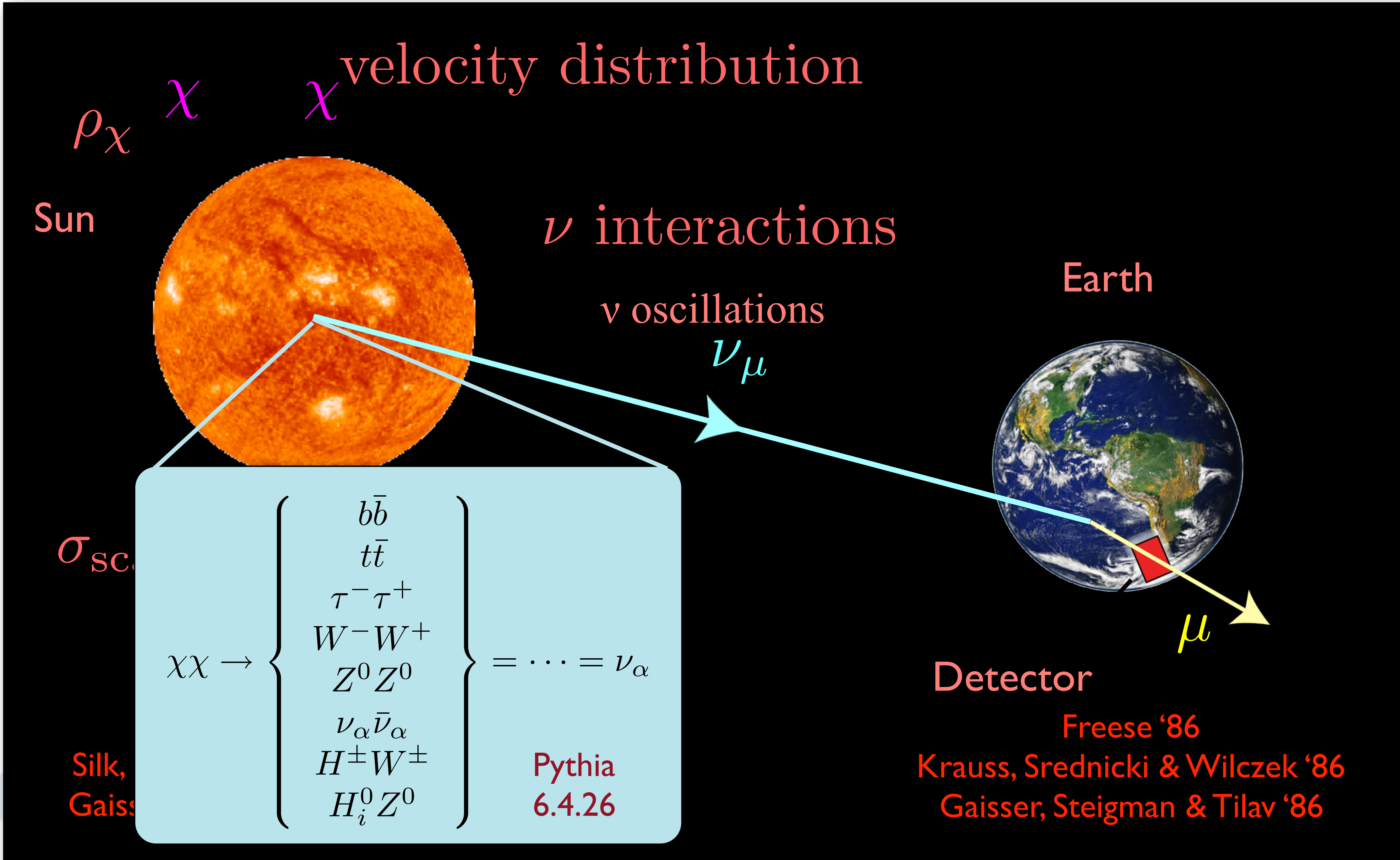
- Gamma rays from the galaxy
- Neutrinos from the Earth/Sun
- Antiprotons from the galactic halo
- Antideuterons from the galactic halo
- Positrons from the galactic halo
- Dark Stars
- ...





Neutrinos from the Sun and the Earth

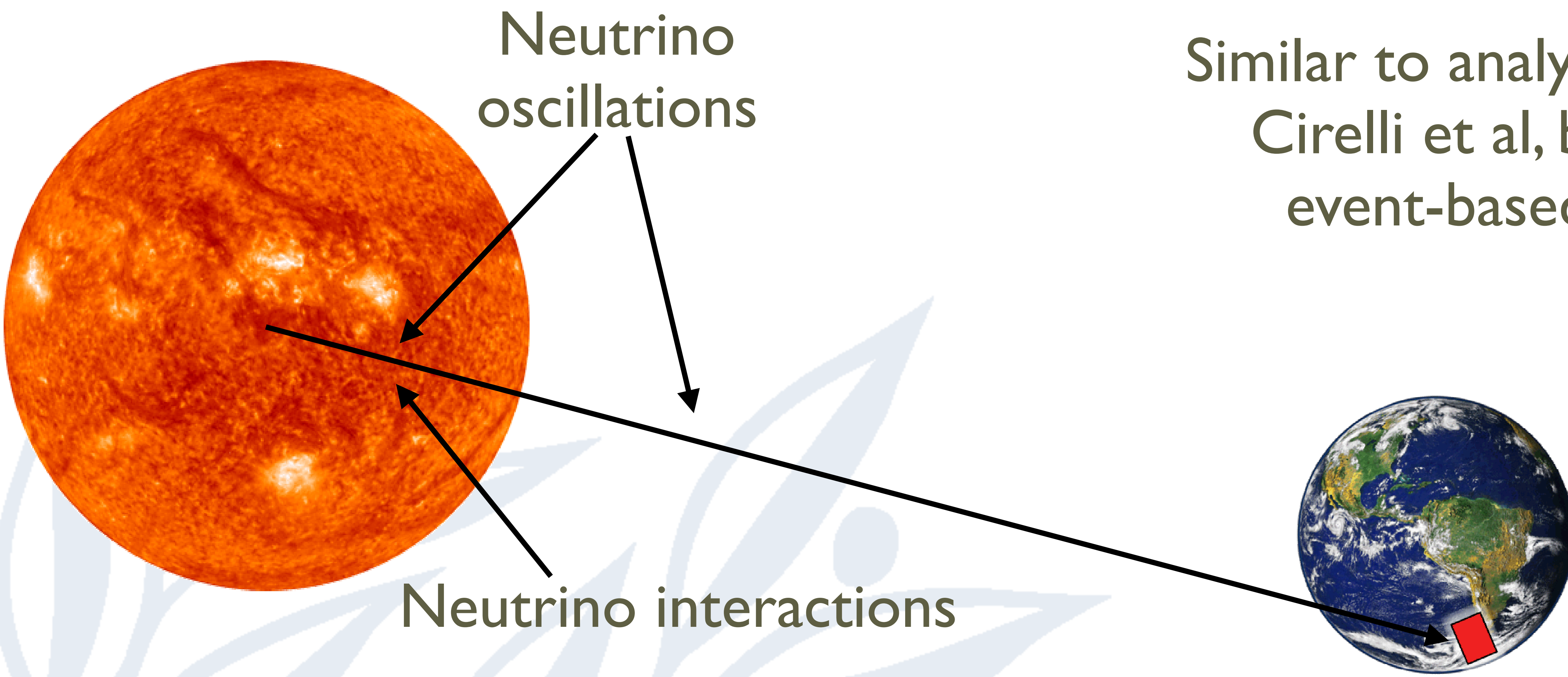
WIMP Capture



Public WimpSim code available that treats the annihilation and neutrino propagation/oscillations.

M. Blennow, J. Edsjö and
T. Ohlsson, JCAP01 (2008) 021

WimpSim



Similar to analysis of Cirelli et al, but event-based.

- Numerical calculation of interactions and oscillations in a fully three-flavour scenario. Regeneration from tau leptons also included.
- **Publicly available code:** wimpsim.astroparticle.se
- Main results are included in DarkSUSY.

General search setup

Pick model $\Rightarrow$ $\sigma_{\mathrm{SI}}, \sigma_{\mathrm{SD}}, \sigma_{\mathrm{ann}}, m_\chi, \ldots$

Calculate: $\Gamma_{\mathrm{cap}}, \Gamma_A, \Phi_\nu, \Gamma_{\nu\to\mu}, \Phi_\mu, \ldots$

Compare with data

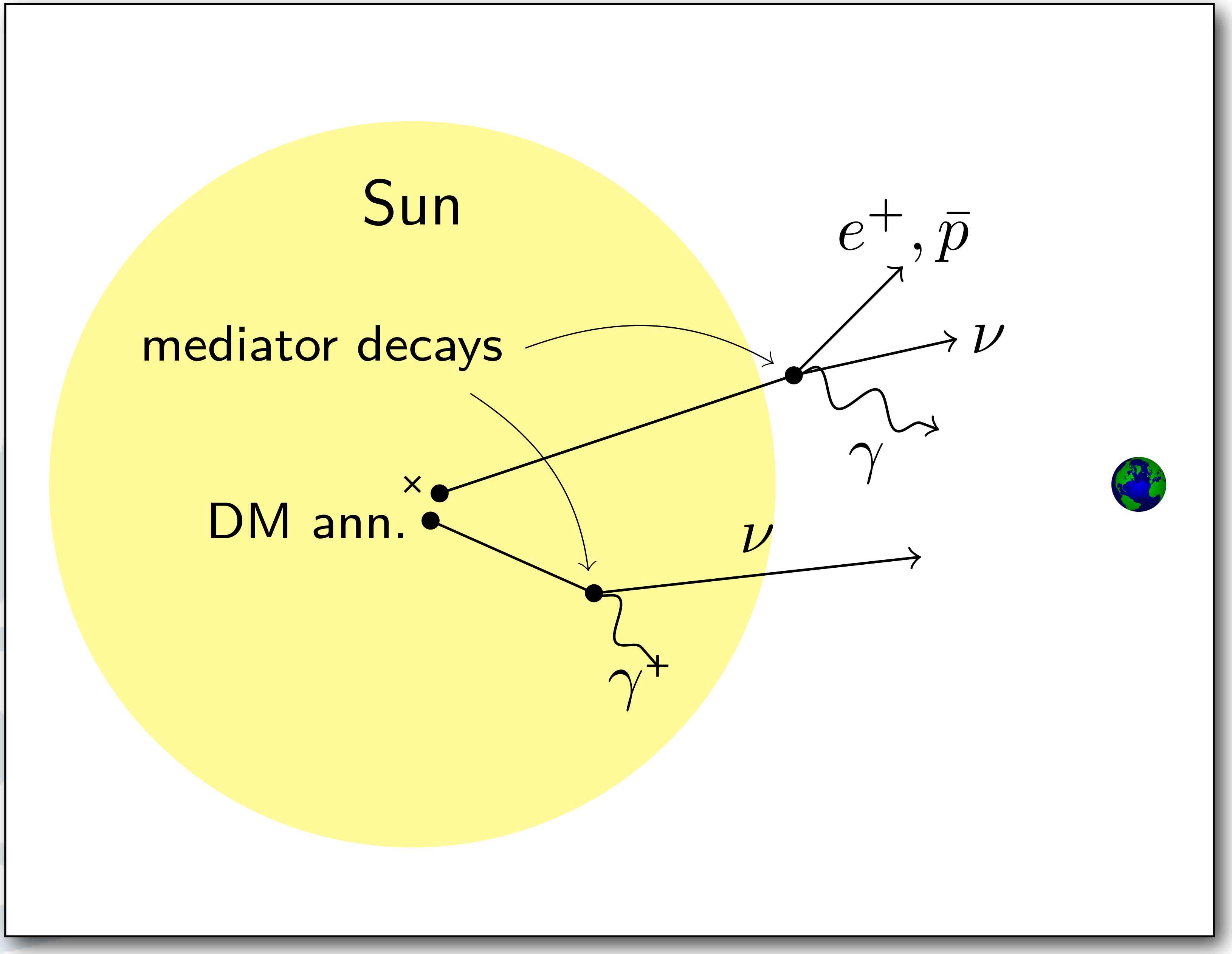
Constrain: $\Gamma_{\mathrm{cap}}, \Gamma_A, \Phi_\nu, \Gamma_{\nu\to\mu}, \Phi_\mu, \ldots$
(or model-specific parameters)

Long-lived mediators

Long lived mediators

Niblaeus, Beniwal and Edsjö, arXiv:1903.11363, JCAP, in press

- What happens if the DM does not annihilate directly to standard model particles in the core of the Sun?



Analysis choice

Specific models, like specific secluded dark matter models, dark photons, etc

or

Phenomenological models

Some of the earlier studies:

- Batell et al, '10 - gamma rays from Sun in secluded models
- Bell and Petraki, '11, neutrinos from Sun in mediator models (enhancements as core is avoided)
- Arina et al, '17, gamma rays from the Sun in models with long-lived mediator
- Leane, Ng and Beacom, '17, solar signatures of long-lived mediators, neutrinos and gammas, focus on one decay length
- Albert et al (HAWC), '18, constraints on models from gamma rays from the Sun
- Adrian-Martinez (ANTARES), '16, Secluded dark matter searches with Antares
- Ardid et al, '17, Secluded dark matter searches with IceCube data, muon and pion channels

In this study we try to be more general and provide a public tool that can be used by others

Model parameters

Parameters	Description
m_χ	Dark Matter (DM) mass
m_Y	Mediator mass
γL	Boosted mediator decay length
–	Mediator decay channel
Γ_A	DM annihilation rate in the Sun

$$\gamma L = \gamma c\tau_0 = \frac{m_\chi}{m_Y} c\tau_0$$

- We assume that the DM scatters and accumulate in the Sun (via some process) and then annihilate to the mediator which later decays

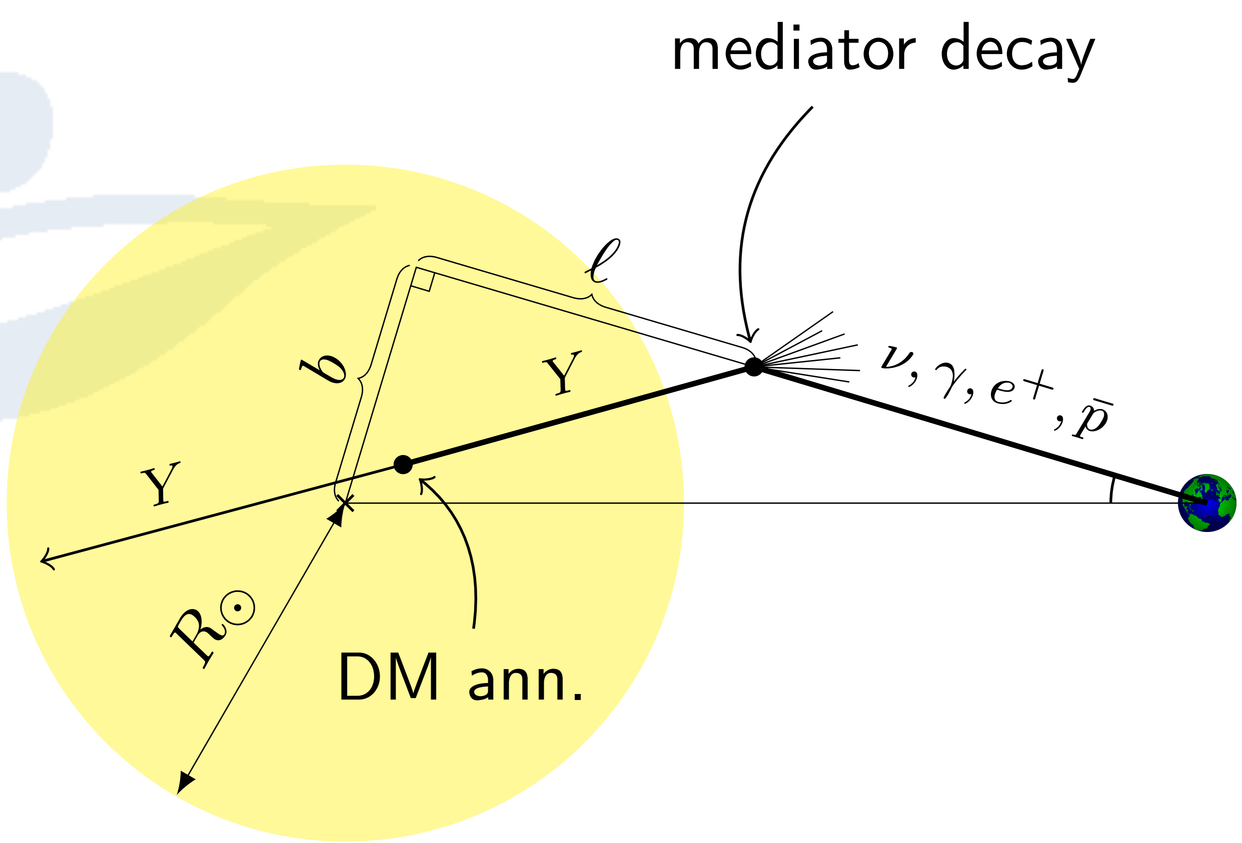
$$\chi\chi \to YY, \quad Y \to \ldots$$

Constraints on model

- The mediator decay can give observable fluxes of other particles, focus on
  - neutrinos (constraints from e.g. IceCube and Super-Kamiokande), and
  - gamma rays (constraints from e.g. Fermi-LAT and HAWC)
- Also constraints from BBN (too long lifetime can lead to energy injection in the thermal plasma)

Methodology

- Use public code WimpSim and add the possibility of mediator decays
- Simulate decays with Pythia, and keep track of gamma rays, neutrinos (and charged particles)



Note

- For neutrinos,
  - we include interactions (charged and neutral current) and oscillations (matter and vacuum)
  - we include annihilation channels/decay products that produce neutrinos outside of the Sun, but not inside (e.g. kaons, pions and muons)
- For gamma rays,
  - we include absorption in the Sun if mediator decays inside of the Sun (but include the decay tail that happens outside of the Sun)
- For both,
  - we discard mediator decays further away than the Earth

Simulation scenarios

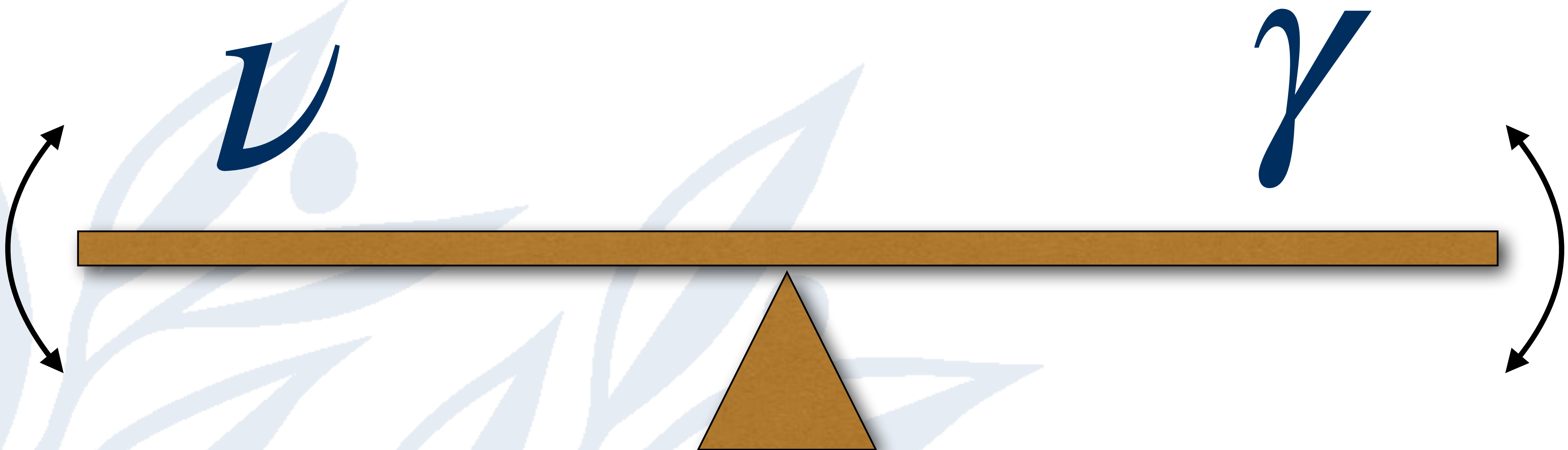
Scenario	Decay channel	m_χ (GeV)	m_Y (GeV)	$\gamma L/R_\odot$
A) Varying $\gamma L/R_\odot$	$Y \to b\bar{b}$	1000	20	[0.01, 10]
	$Y \to \tau^+\tau^-$	1000	20	[0.01, 10]
B) Varying m_Y	$Y \to b\bar{b}$	5000	{20, 200, 2000}	1
	$Y \to \tau^+\tau^-$	5000	{20, 200, 2000}	1
C) 3D treatment	$Y \to \tau^+\tau^-$	5000	4900	0.3
D) γ-ν comparison	$Y \to \tau^+\tau^-$	$[100,\ 10^4]$	20	[0.01, 10]
	$Y \to b\bar{b}$	$[100,\ 10^4]$	20	[0.01, 10]
	$Y \to \tau^+\tau^-$	$[10,\ 10^4]$	4	[0.01, 10]
E) Muon channel	$Y \to \mu^+\mu^-$	$[10,\ 10^4]$	1	$[0.01,\ 10^6]$

Sensitivity study

- For each model point, we calculate the (approximate) limit on the annihilation rate Γ_A from
  - the neutrino limits from IceCube and Super-Kamiokande, Γ_A^ν
  - the gamma ray limits from Fermi-LAT, HAWC and ARGO, Γ_A^γ
- We then define $$\eta \equiv \Gamma_A^\nu / \Gamma_A^\gamma$$

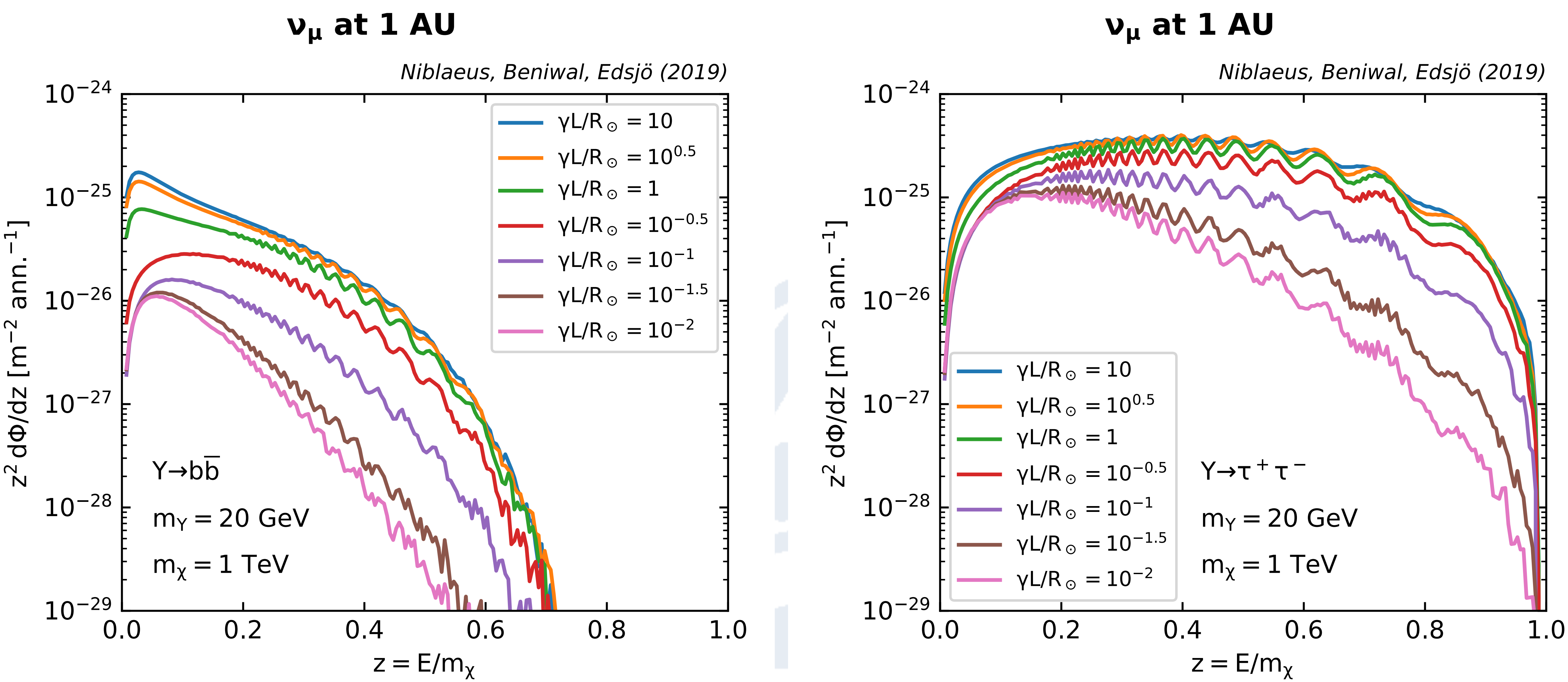
$\eta > 1$	$\Rightarrow$	γ more sensitive
$\eta < 1$	$\Rightarrow$	ν more sensitive

Main question



Which signal is most sensitive to constrain the model?

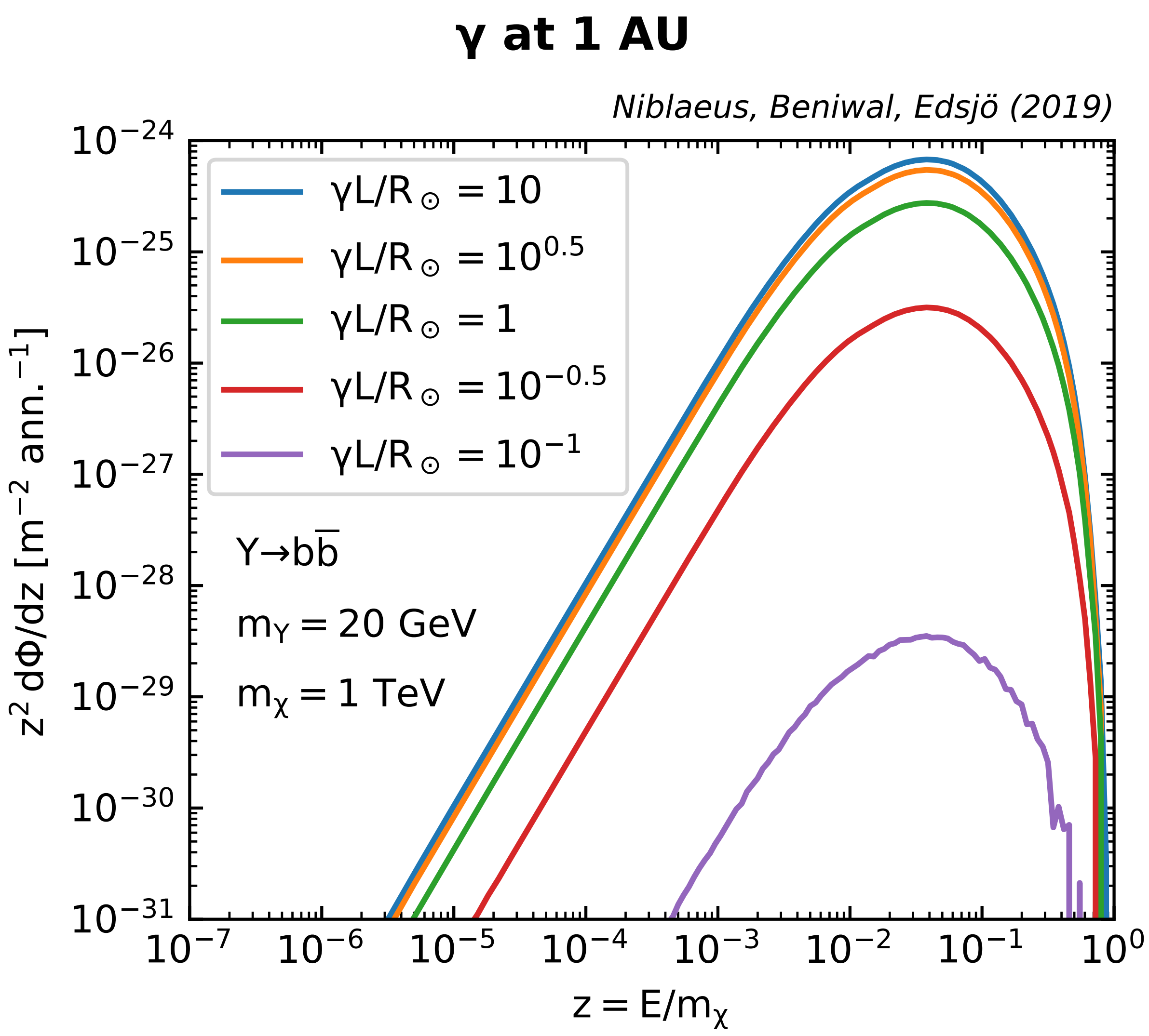
Dependence on γL – neutrinos

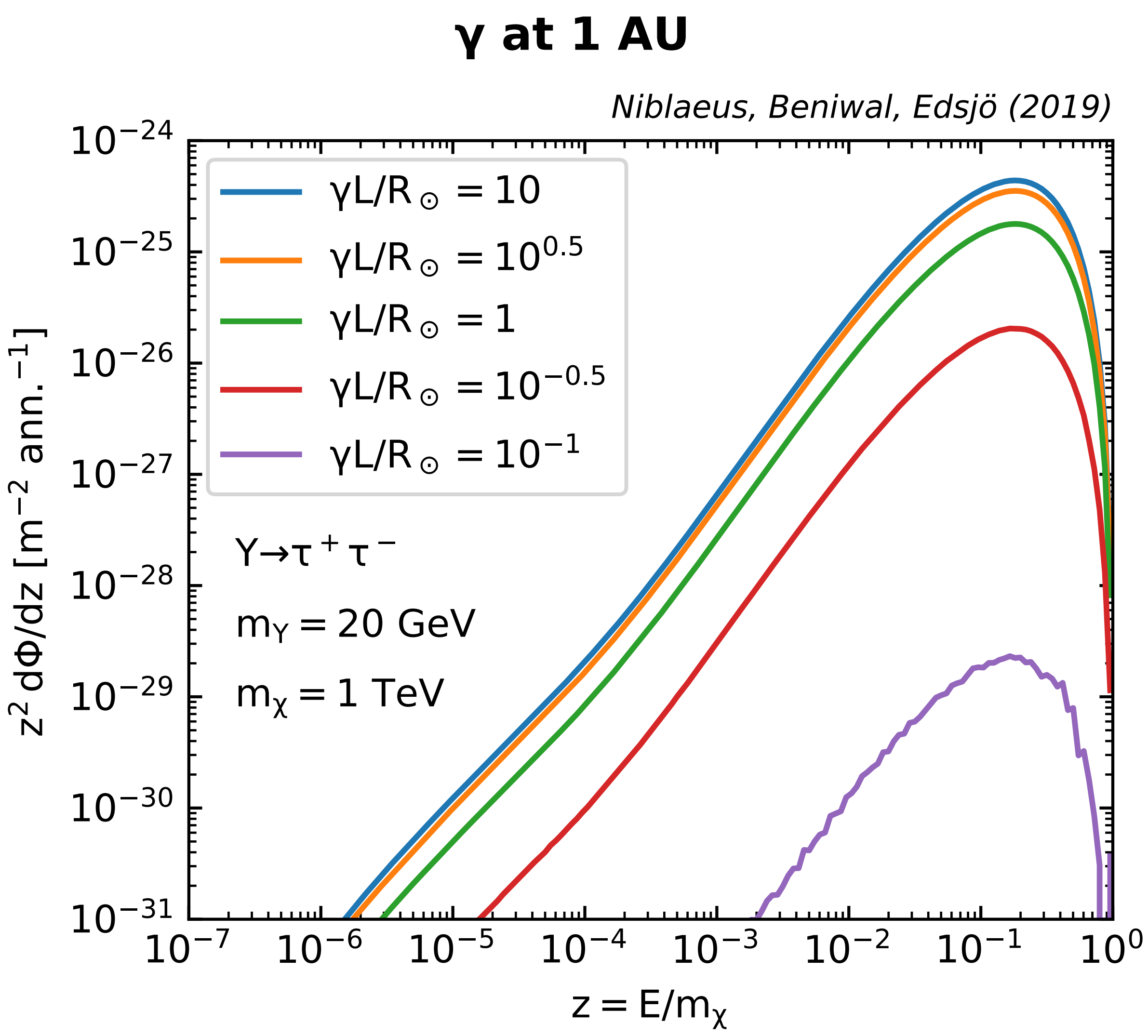


Increase for large γL:

- less absorption in Sun's core
- contribution from decay products usually stopped in the Sun (mainly pions, kaons and muons)

Dependence on γL – gammas

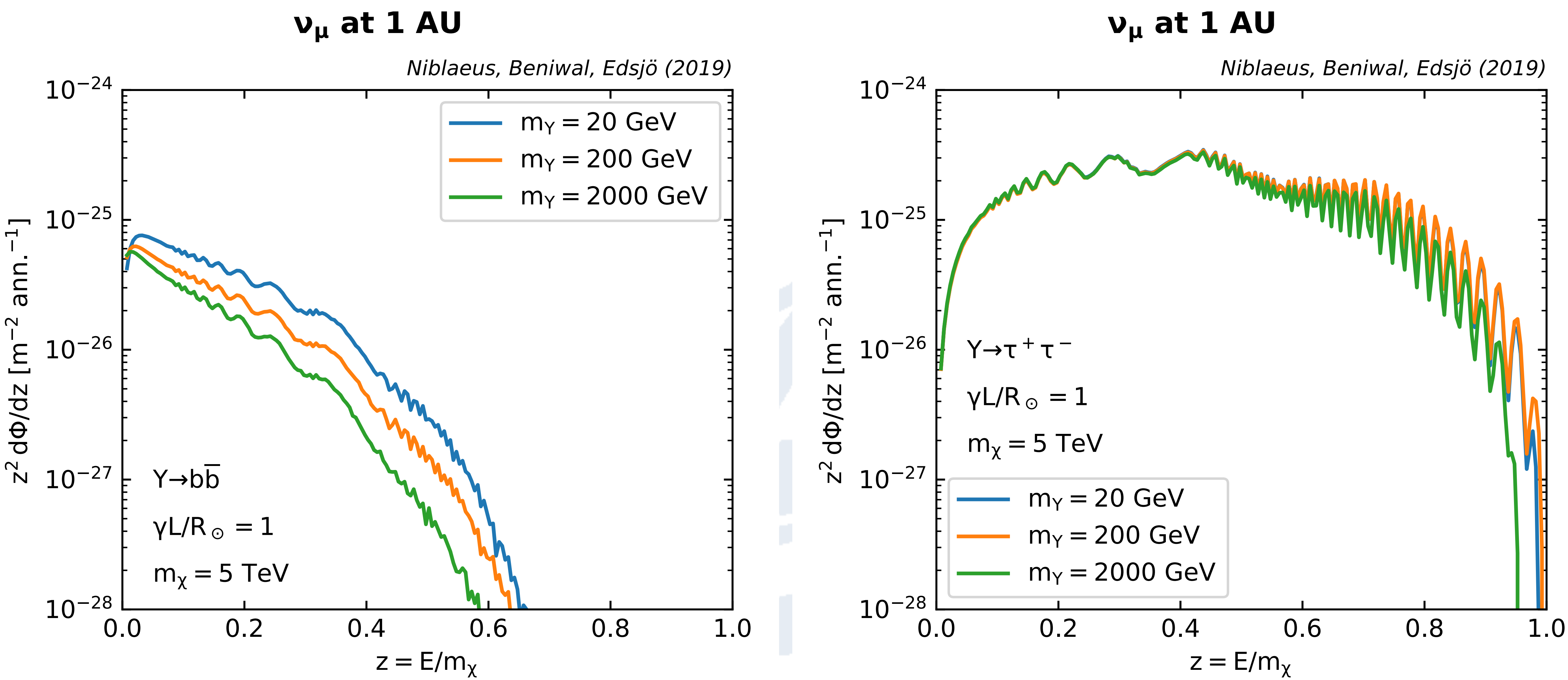




Increase for large γL:

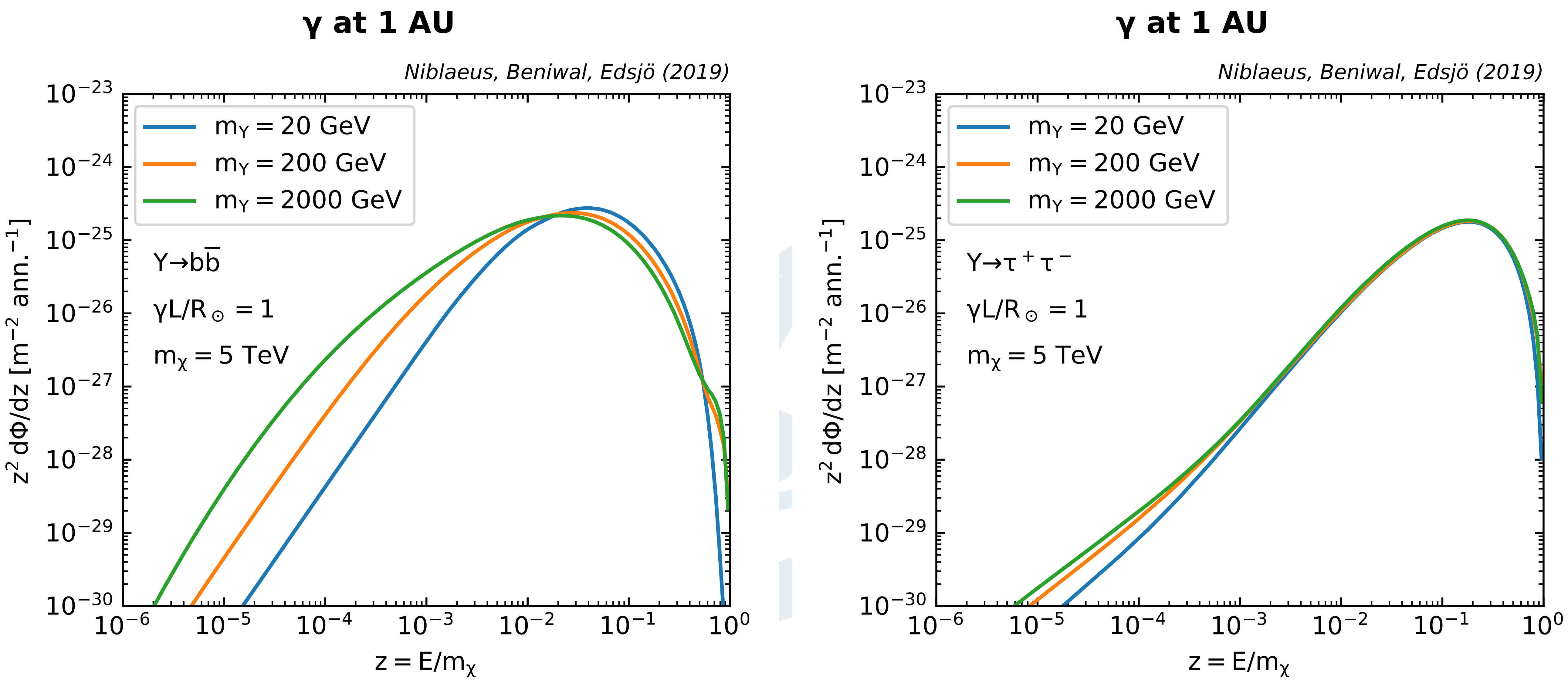
- more decays happen outside of the Sun

Dependence on m_Y – neutrinos



- For $b\bar{b}$: some mediator mass dependence, higher $m_Y \Rightarrow$ more energy in the hadronic jets
- Fro $\tau^+\tau^-$: very small mediator mass dependence

Dependence on m_Y – gammas



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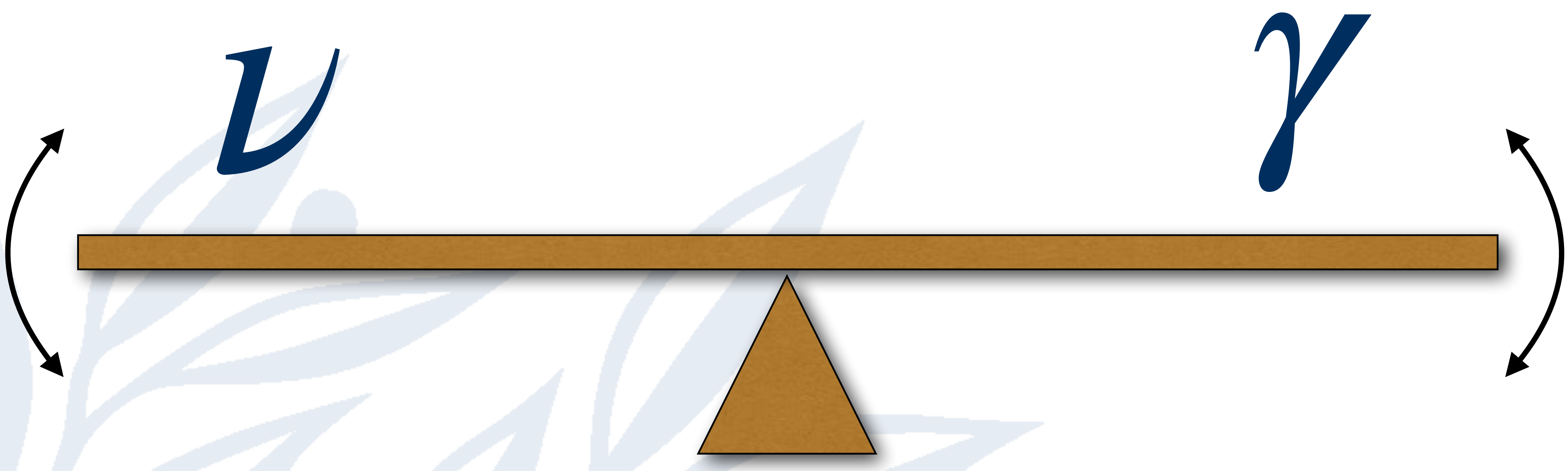
Main question

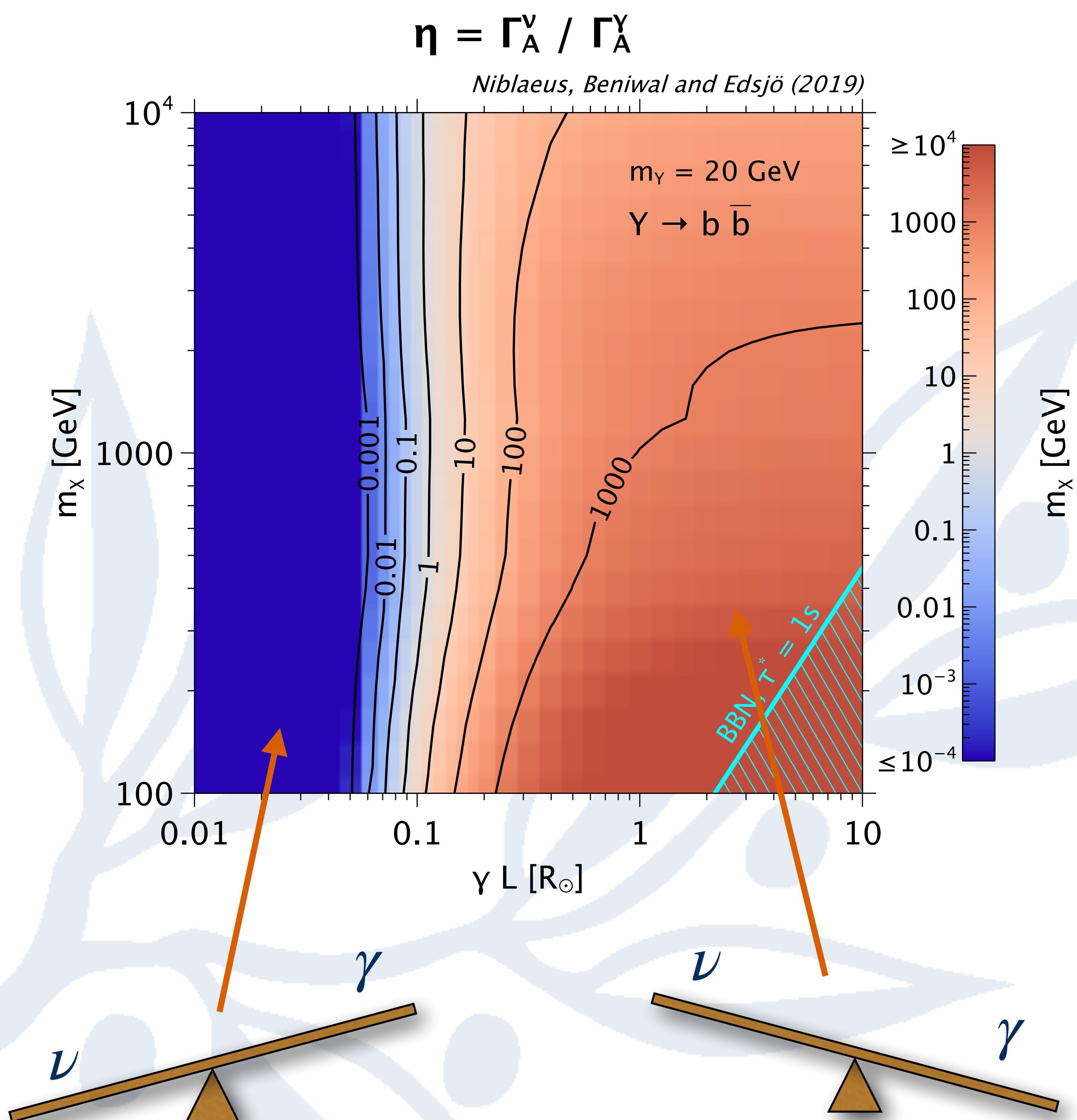


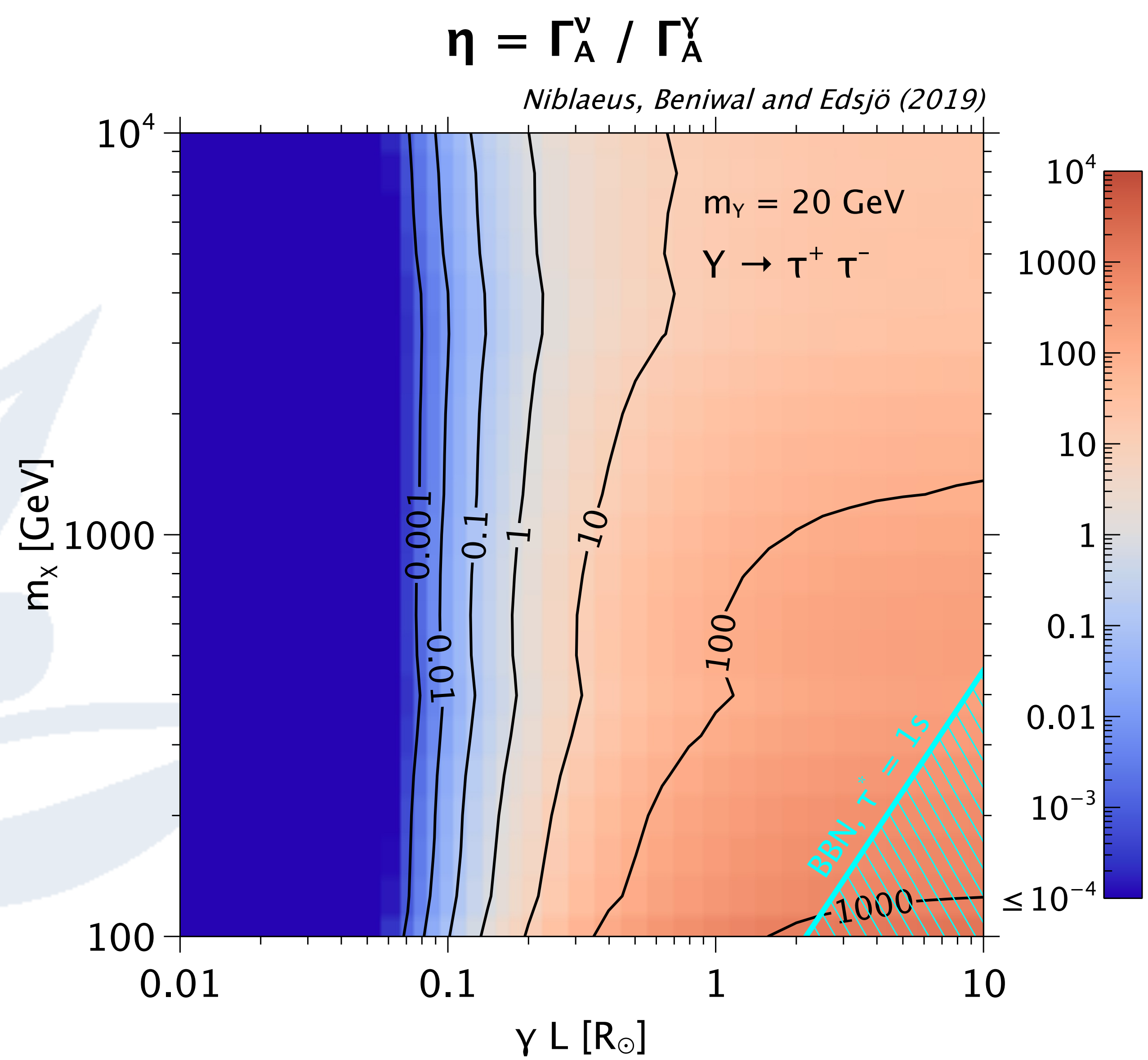
$$\eta \equiv \Gamma_A^{\nu}/\Gamma_A^{\gamma}$$

$\eta > 1 \quad \Rightarrow \quad \gamma$ more sensitive

$\eta < 1 \quad \Rightarrow \quad \nu$ more sensitive

Complementarity ν/γ





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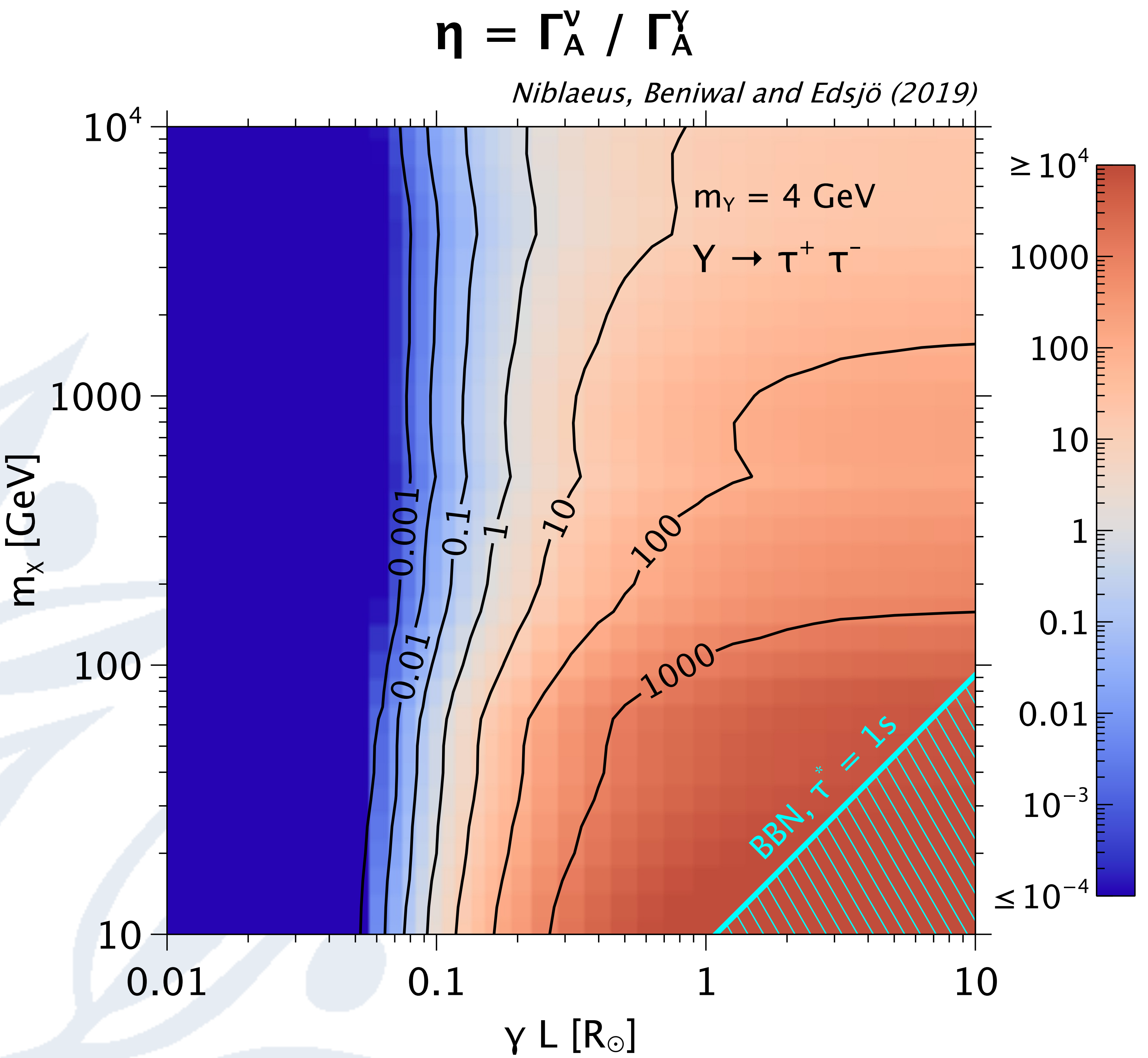
Complementarity ν/γ

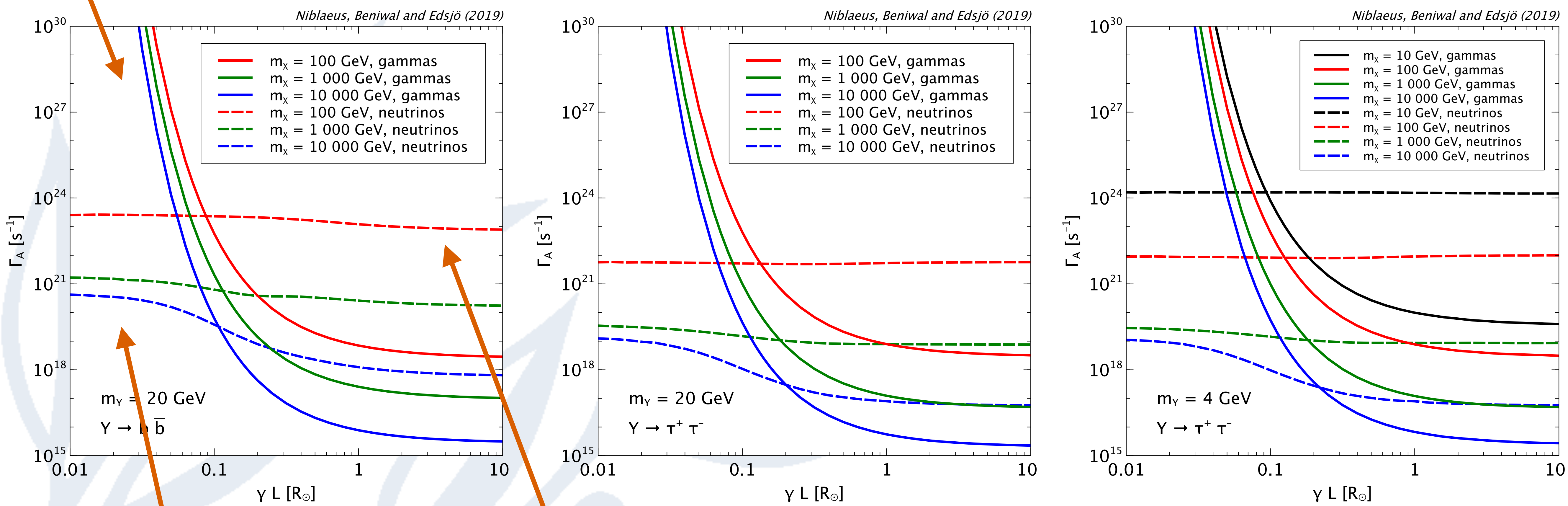


$\eta > 1 \quad \Rightarrow \quad \gamma$ more sensitive

$\eta < 1 \quad \Rightarrow \quad \nu$ more sensitive

Complementarity ν/γ

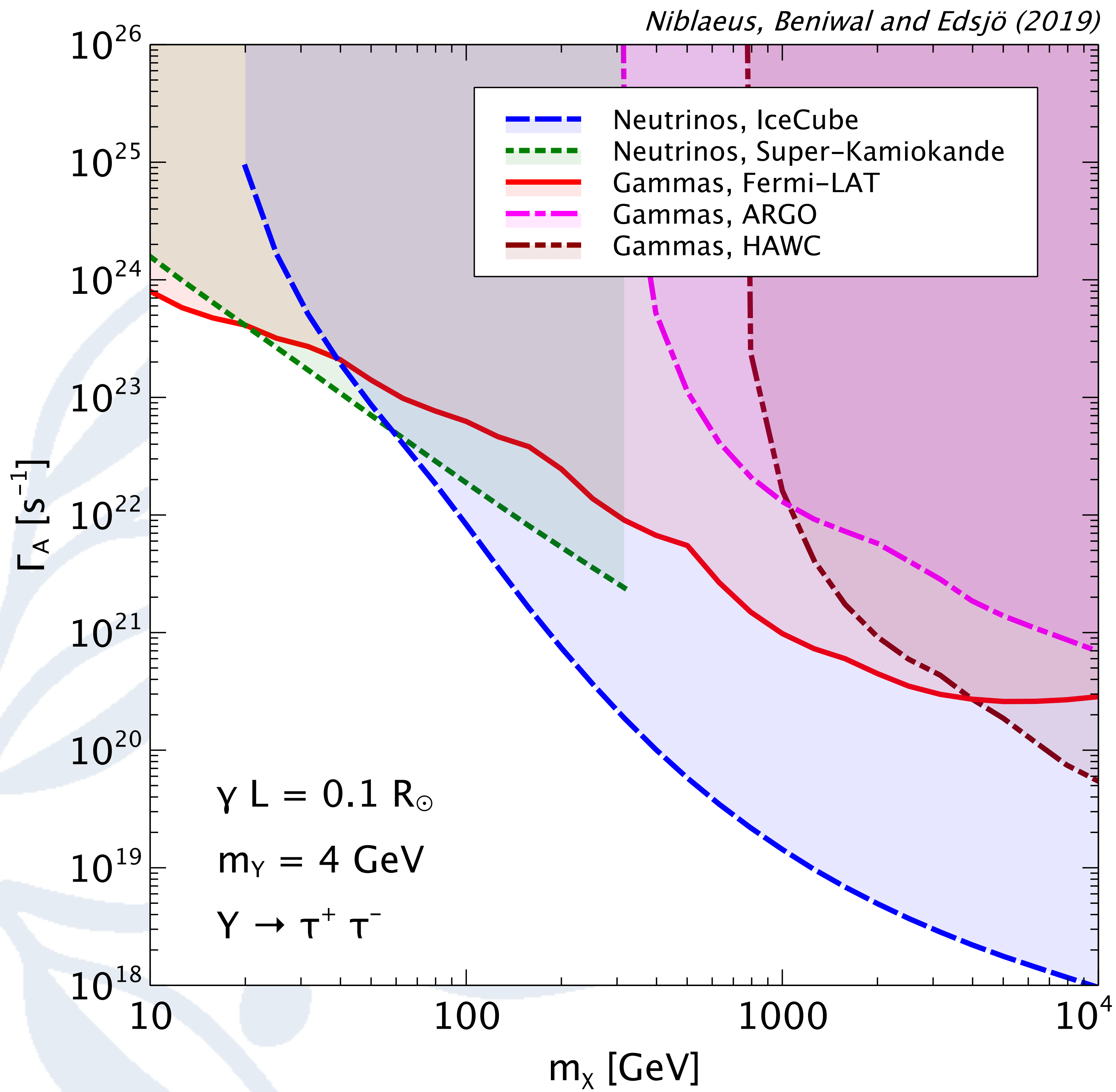
Few mediator decays outside of the Sun



Neutrino absorption in Sun's core

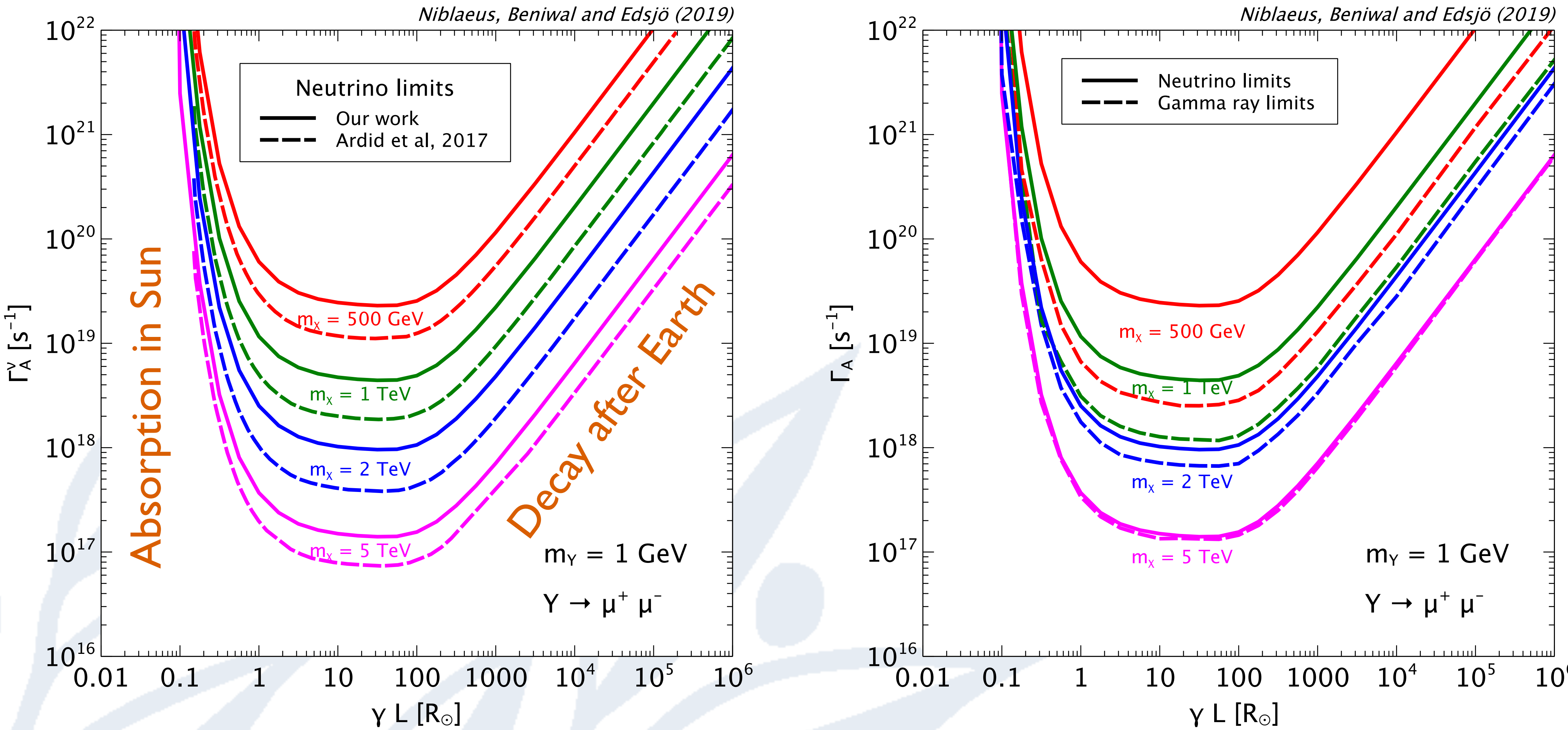
Contribution from decay products usually stopped in the Sun (mainly pions, kaons and muons)

Which limits dominate?



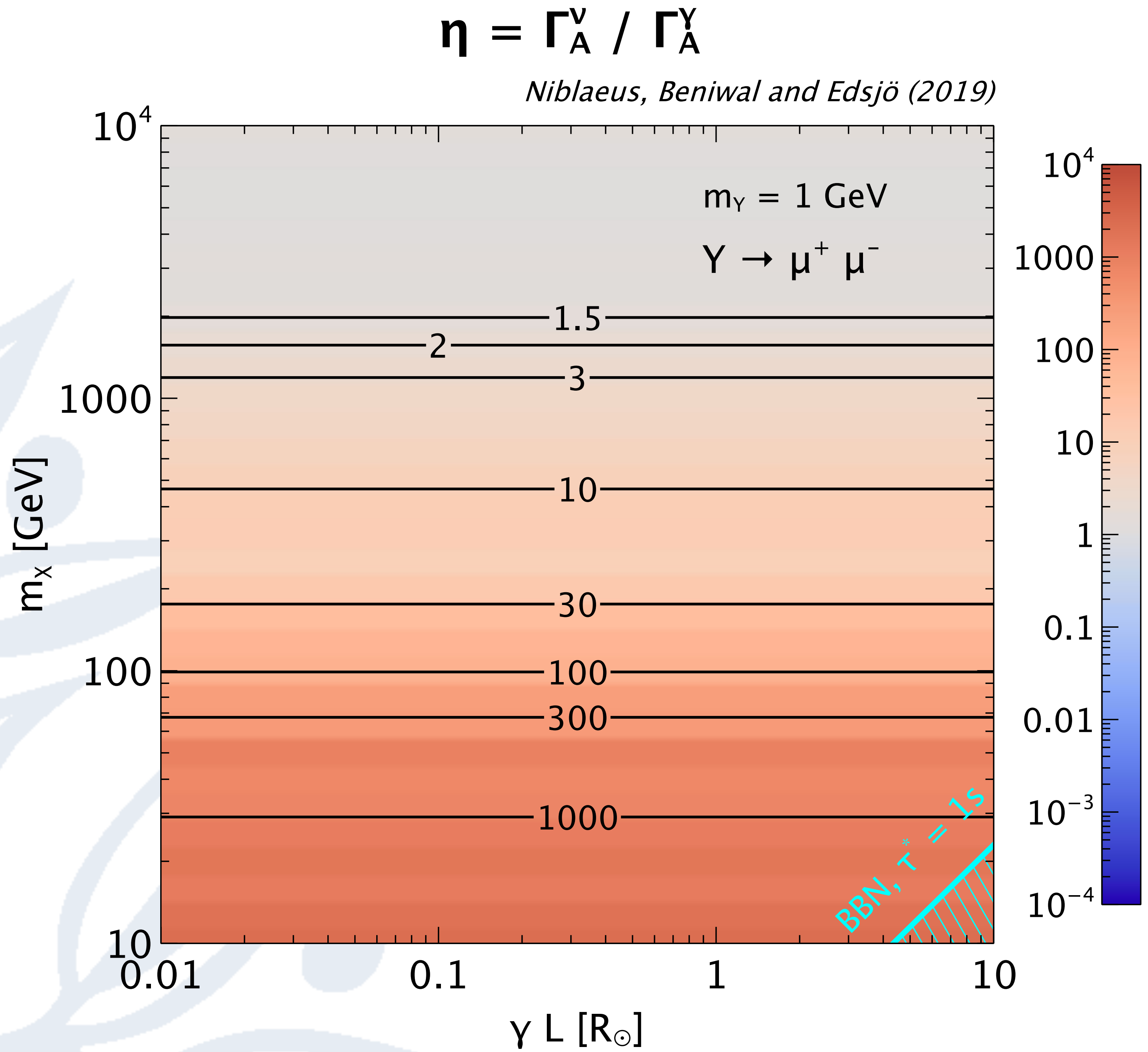
For larger γL, the main effect is that gamma limits shift down (more sensitive)

Comparisons with recent earlier study (muon channel)



- Qualitatively, we get very similar results, but quantitatively, there is a difference of a factor of a few
- Still unsure why this difference is there (we use different methods and different data though)
- We have validated our results in the limit where mediator decay mimics WIMP models

Complementarity ν/γ – muon channel



$\eta > 1 \quad \Rightarrow \quad \gamma$ more sensitive

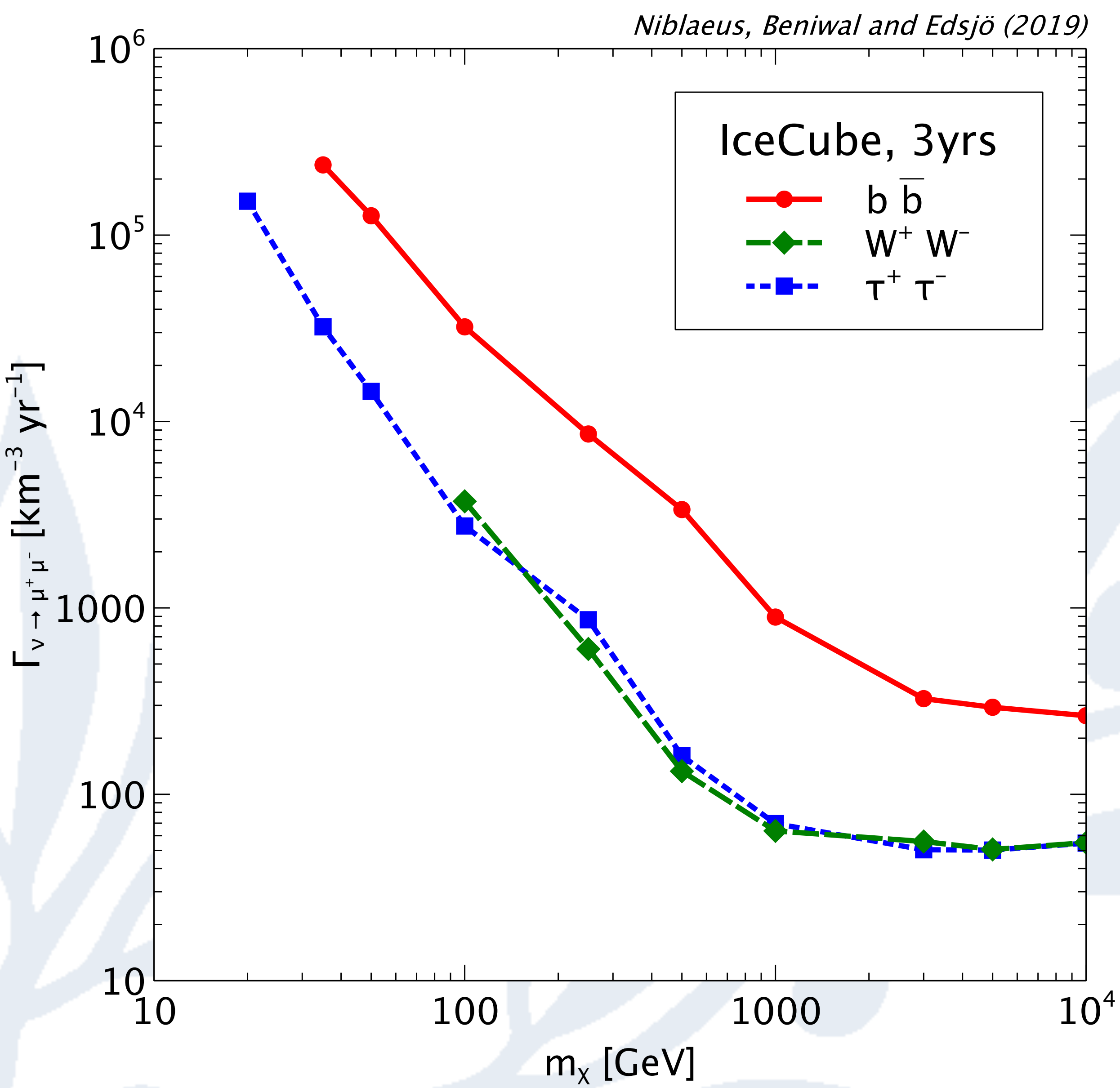
$\eta < 1 \quad \Rightarrow \quad \nu$ more sensitive

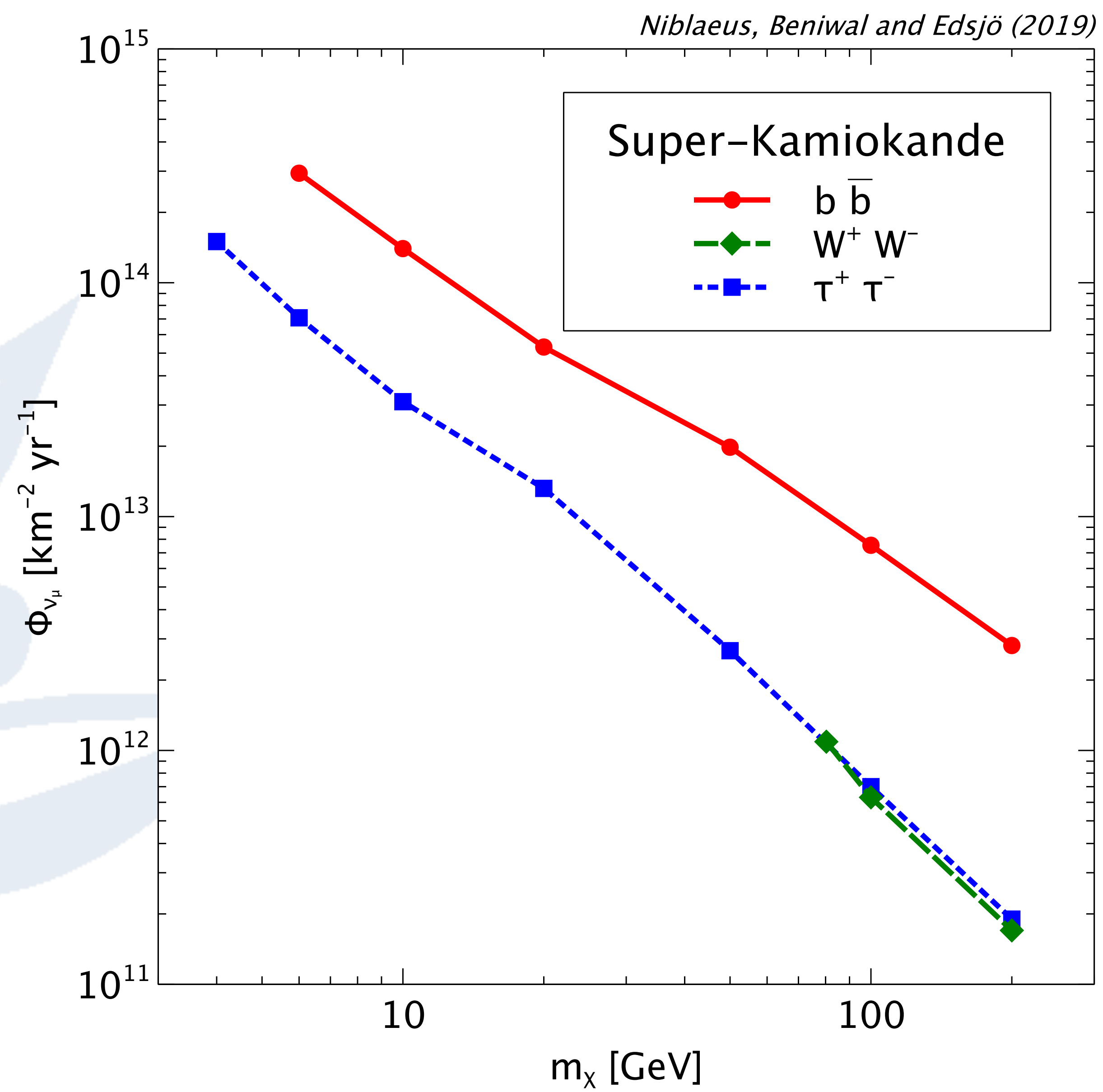
Neutrino limits

A note on neutrino limits

- We have used published limits on WIMPs from IceCube and Super-Kamiokande to set limits on our mediator models
- How can we do that when the models, and hence the neutrino spectra, are different?

Published limits





Note the large differences for hard/soft channels

What is the problem with different channels?

- Different channels have different spectra, their *shapes* differs.
- Can we include this in some way and use a different quantity than DM mass and annihilation channel to specify the DM model?

Normalizing quantities

- Define

$$\langle E^2_{\nu_\mu} \rangle \equiv \frac{\int_{E_{\rm min}}^{m_\chi} E^2_{\nu_\mu} \left(d\Phi_{\nu_\mu}/dE \right) \, dE}{\int_{E_{\rm min}}^{m_\chi} \left(d\Phi_{\nu_\mu}/dE \right) \, dE}$$

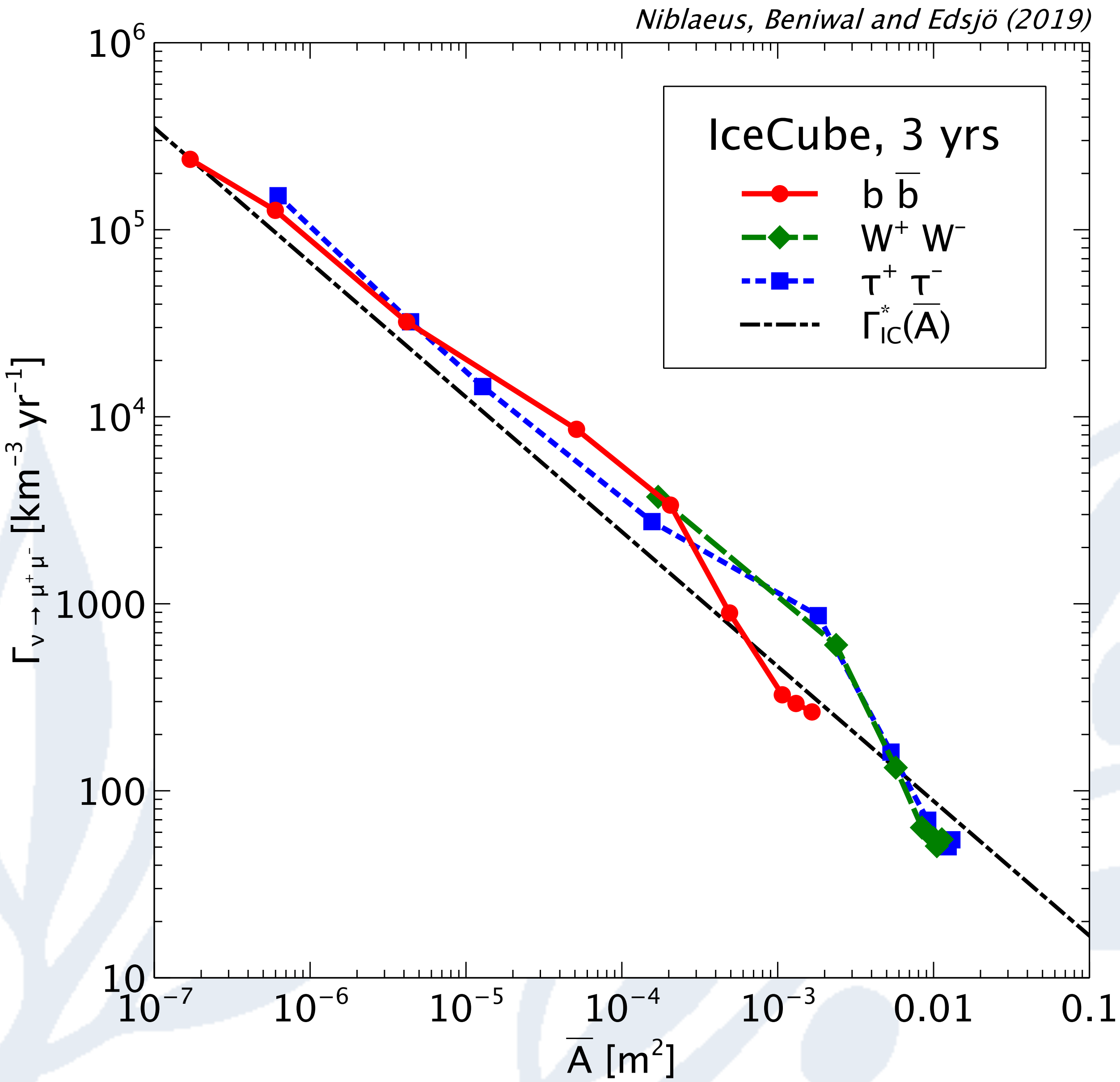
S-K

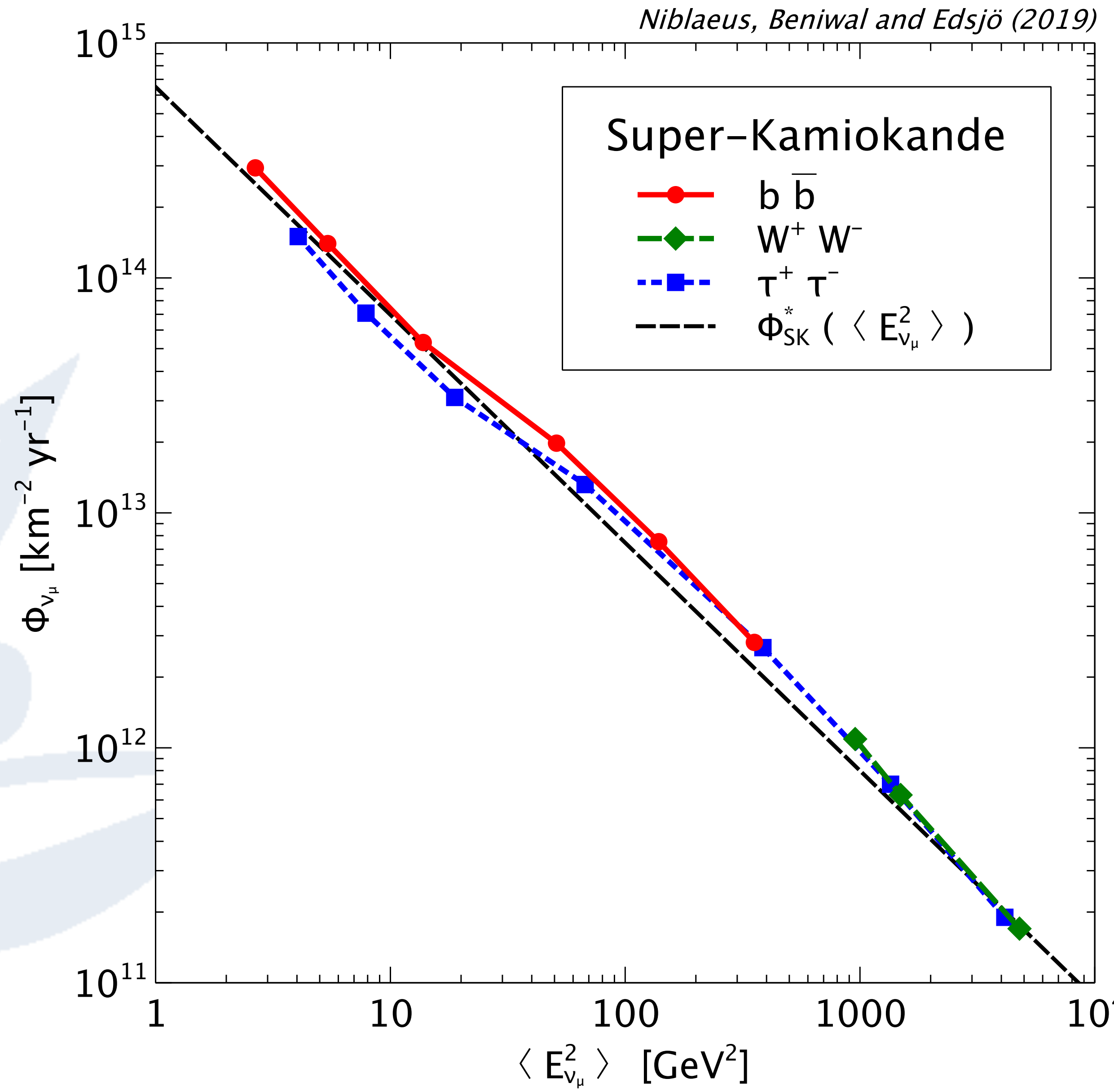
$$\bar{A} \equiv \frac{\int_{E_{\rm min}}^{m_\chi} A_{\rm eff}(E) \left(d\Phi_{\nu_\mu}/dE + d\Phi_{\overline{\nu}_\mu}/dE \right) \, dE}{\int_{E_{\rm min}}^{m_\chi} \left(d\Phi_{\nu_\mu}/dE + d\Phi_{\overline{\nu}_\mu}/dE \right) \, dE}$$

IceCube

- These essentially contain information on the number of events *per neutrino flux*

Limits as function of $\langle E^2_{\nu_\mu} \rangle$ and $\bar{A}$

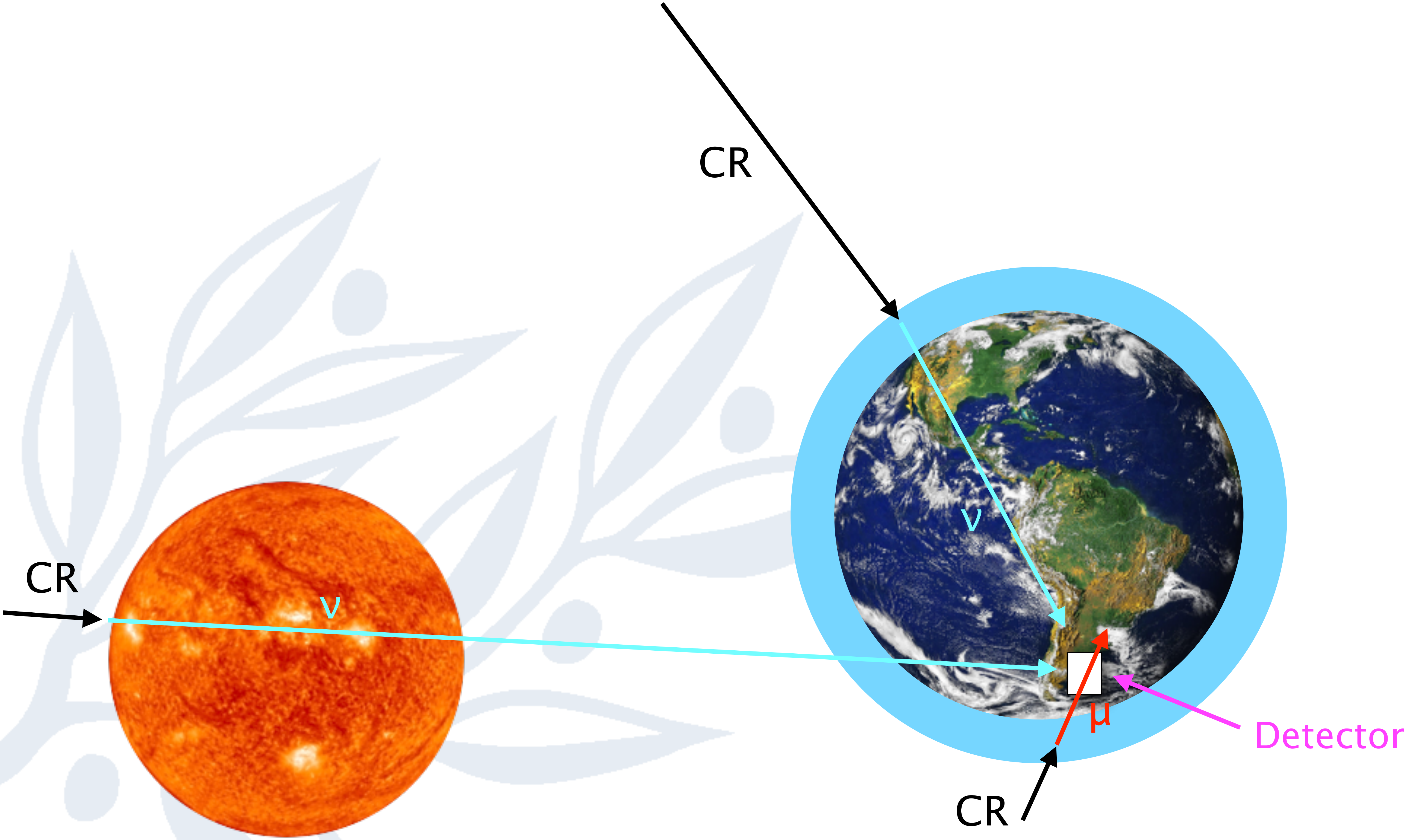




- Use the fitted functions to get approximate limits for *any* dark matter model

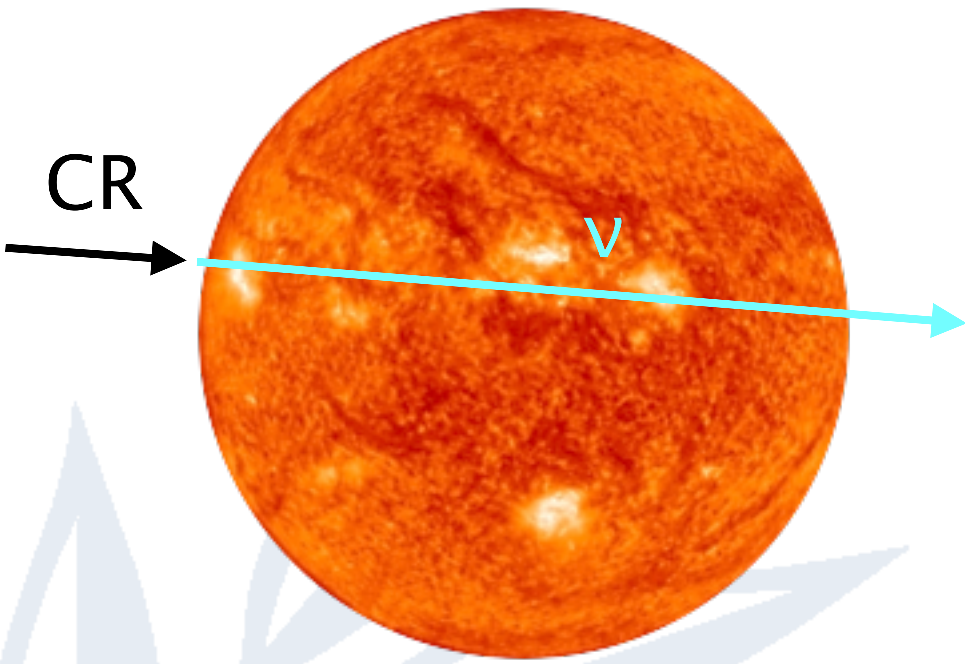
Backgrounds

Backgrounds



Solar atmospheric neutrinos, SAν

Edsjö, Elevant, Enberg and Niblaeus, JCAP 06 (2017) 033, arXiv:1704.02892



- CR-solar atmosphere interactions simulated with public code MCEq

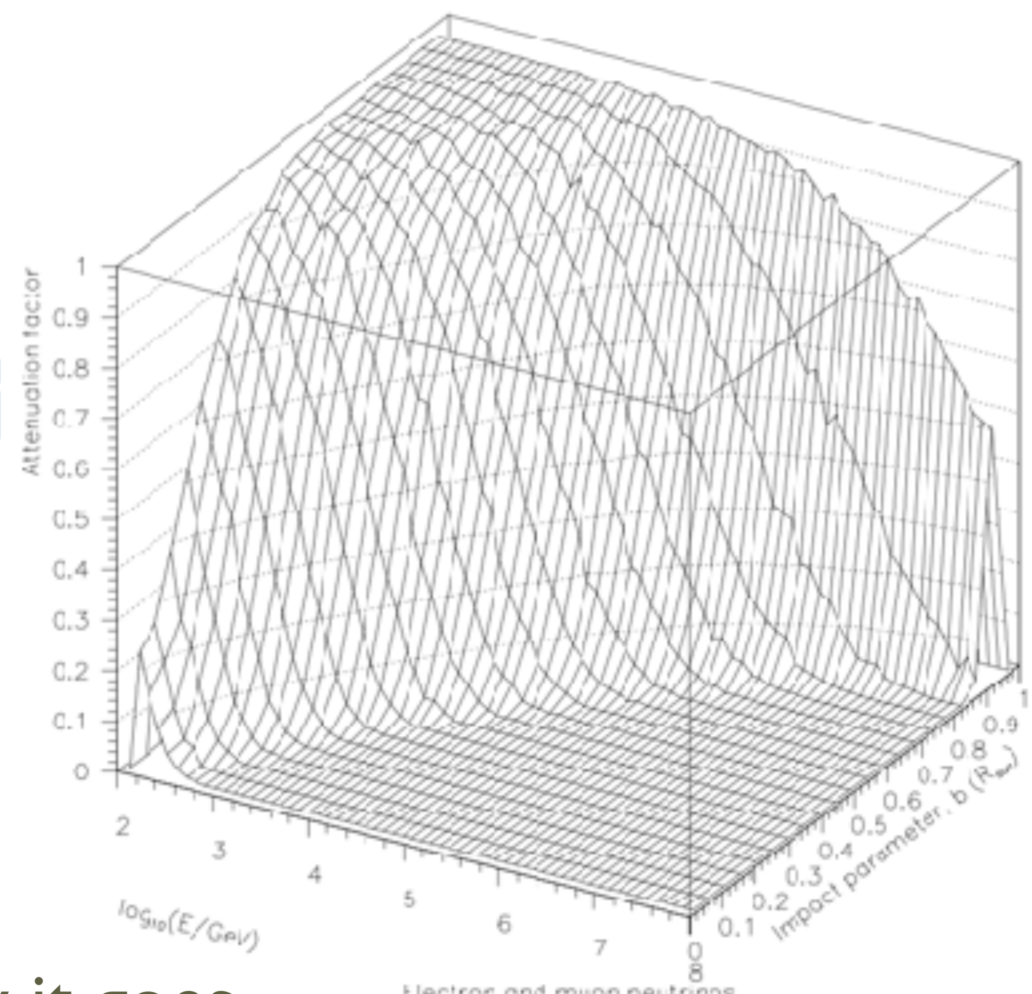
- Propagation and oscillation through the Sun and to the Earth with public code WimpSim

- Interactions at the detector with WimpSim

First studied by Moskalenko et al & Seckel et al in 1991, but we now have better CR understanding, better solar models and know that neutrinos oscillate. We can also make the calculation more carefully as we have better tools.

Compared to Earth atmospheric neutrinos

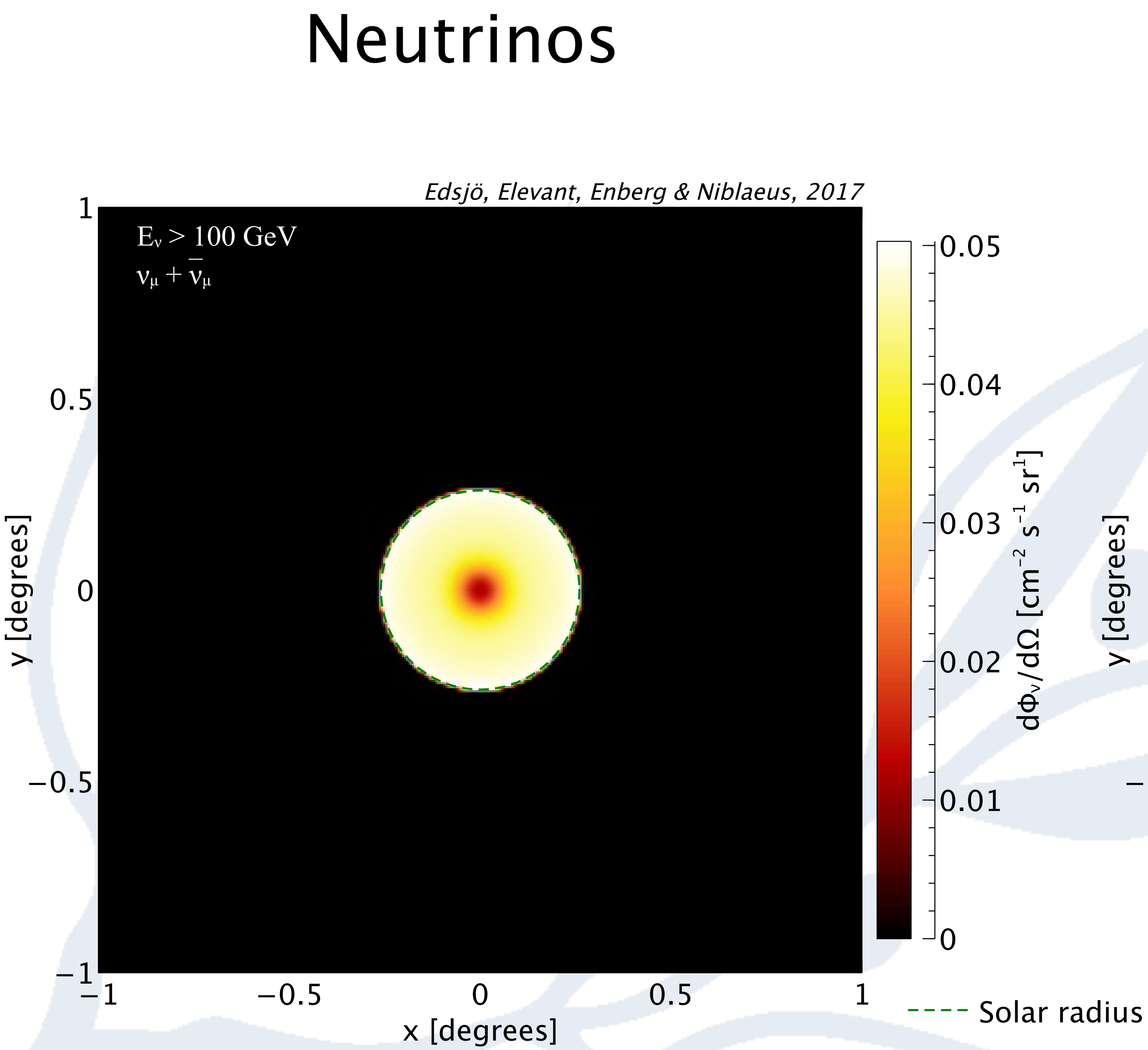
- The Sun blocks CR:s and reduce the Earth atmospheric neutrino flux in the Sun's direction
- But, we instead get neutrinos from CR interactions in the Sun. Is it higher or lower?
  - the Sun has lower density where interactions take place, more particles decay before they lose energy
    ⇒ higher flux
  - the produced neutrinos pass through the Sun which is opaque to high energy neutrinos ($\gtrsim$ 100 GeV)
    ⇒ lower flux

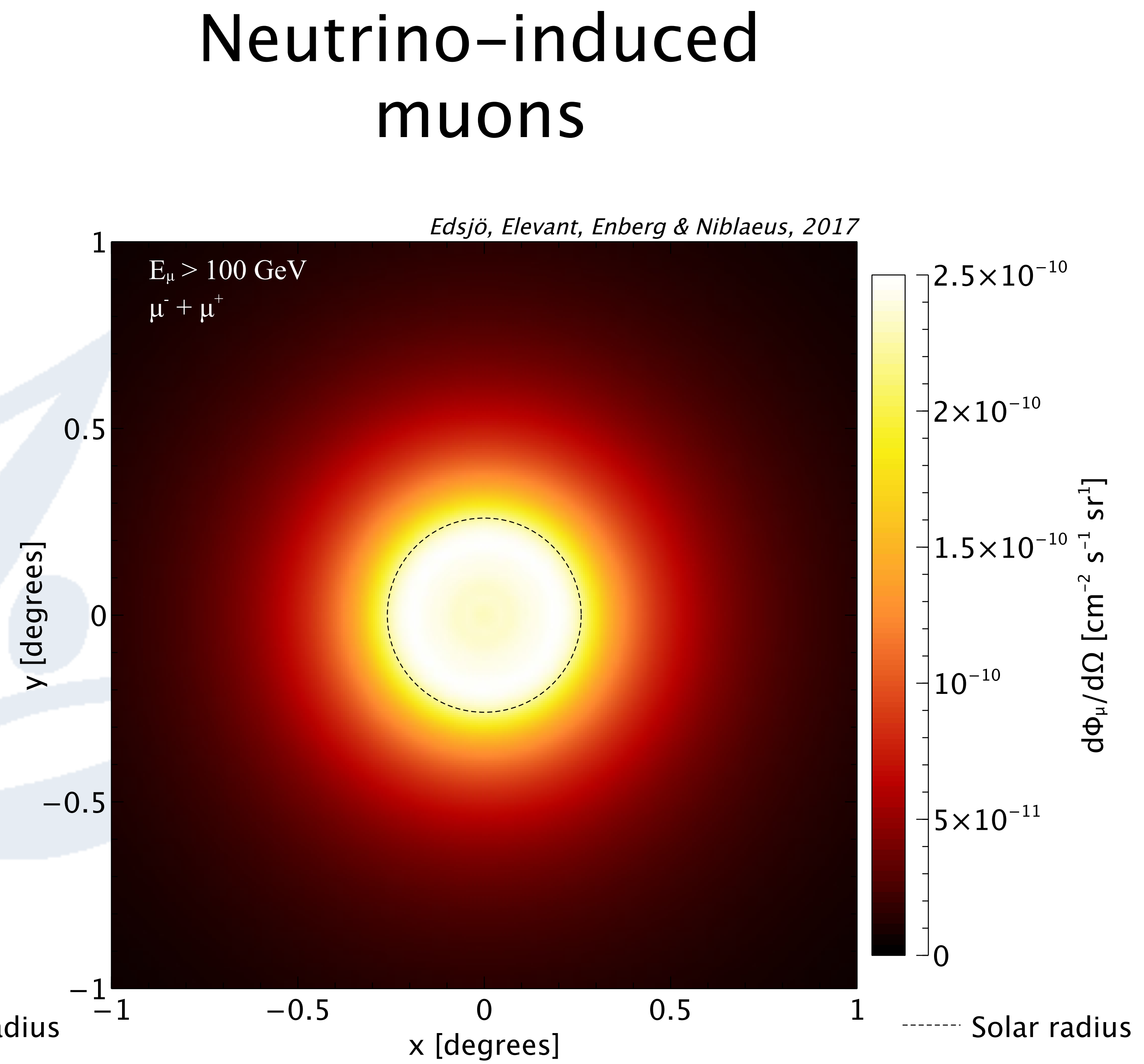


- Need a more careful calculation to see how it goes

Note: Magnetic fields complicate things further…

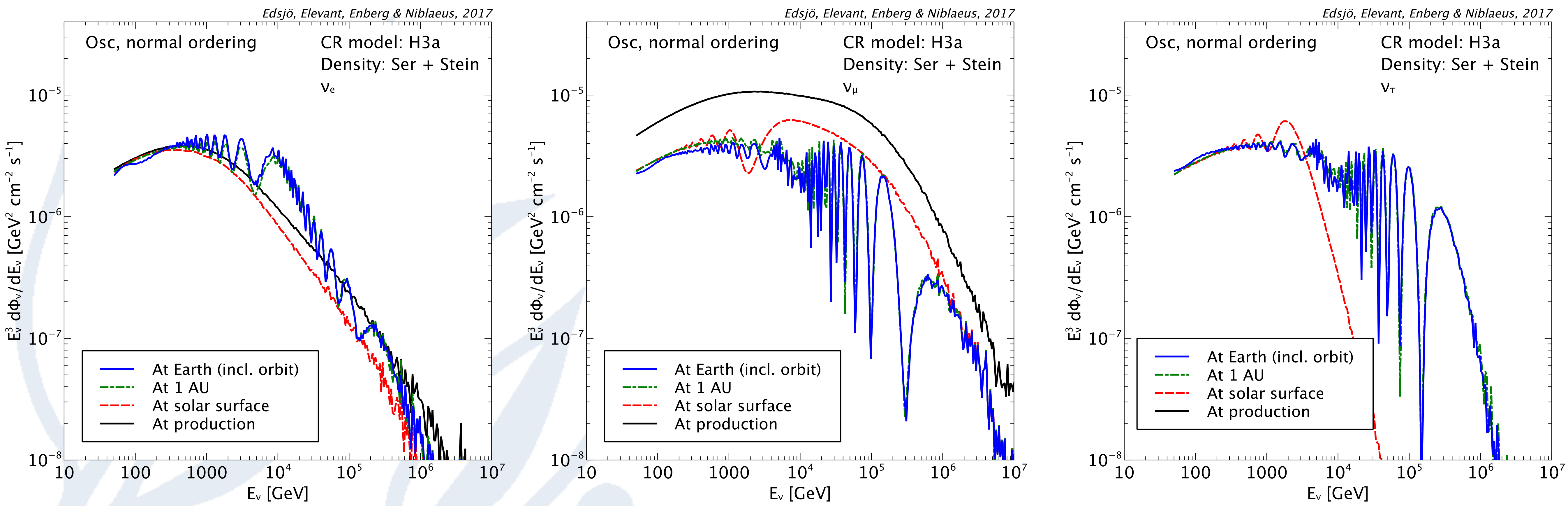
The Sun in neutrinos and neutrino-induced muons





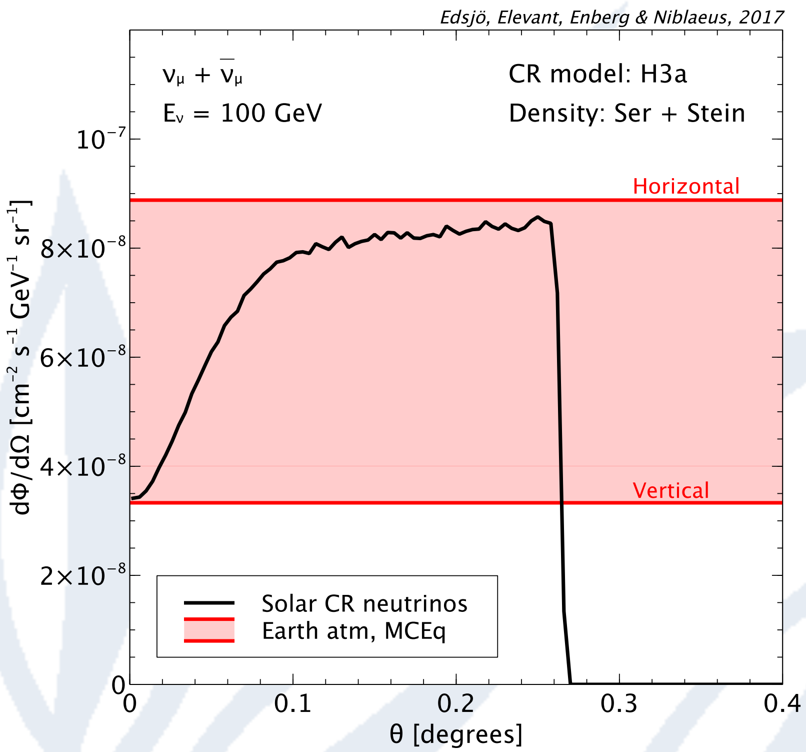
Neutrino fluxes

ν_e ν_μ ν_τ

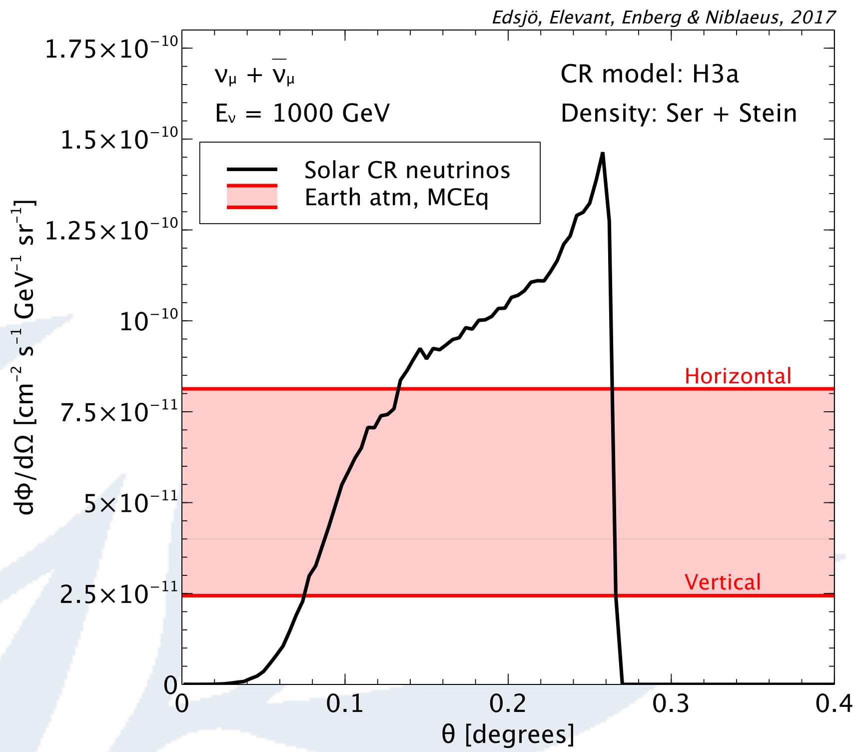


Compared to Earth atmospheric neutrinos

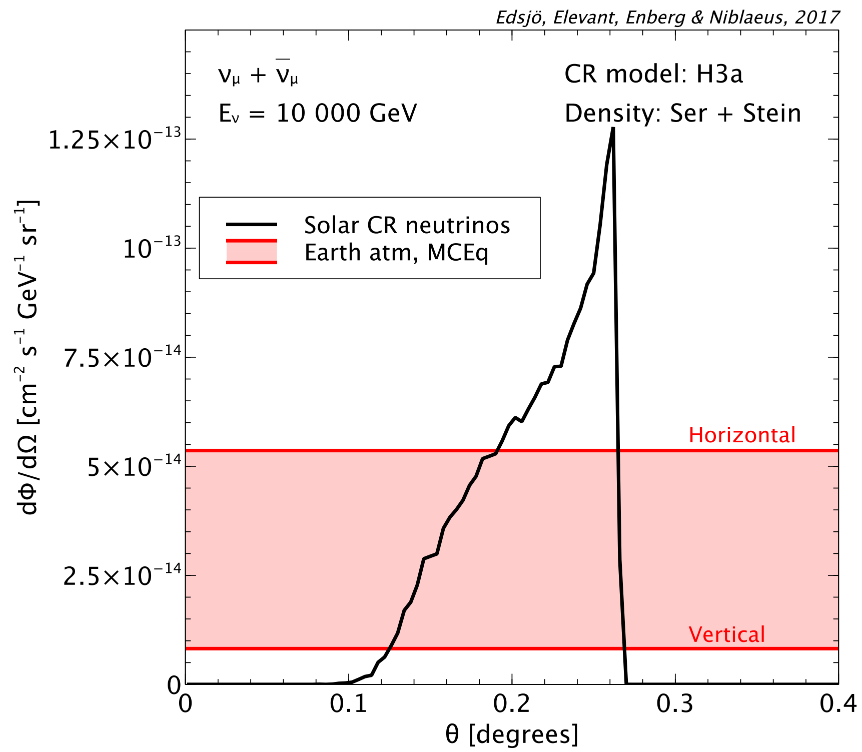
100 GeV



1 000 GeV



10 000 GeV



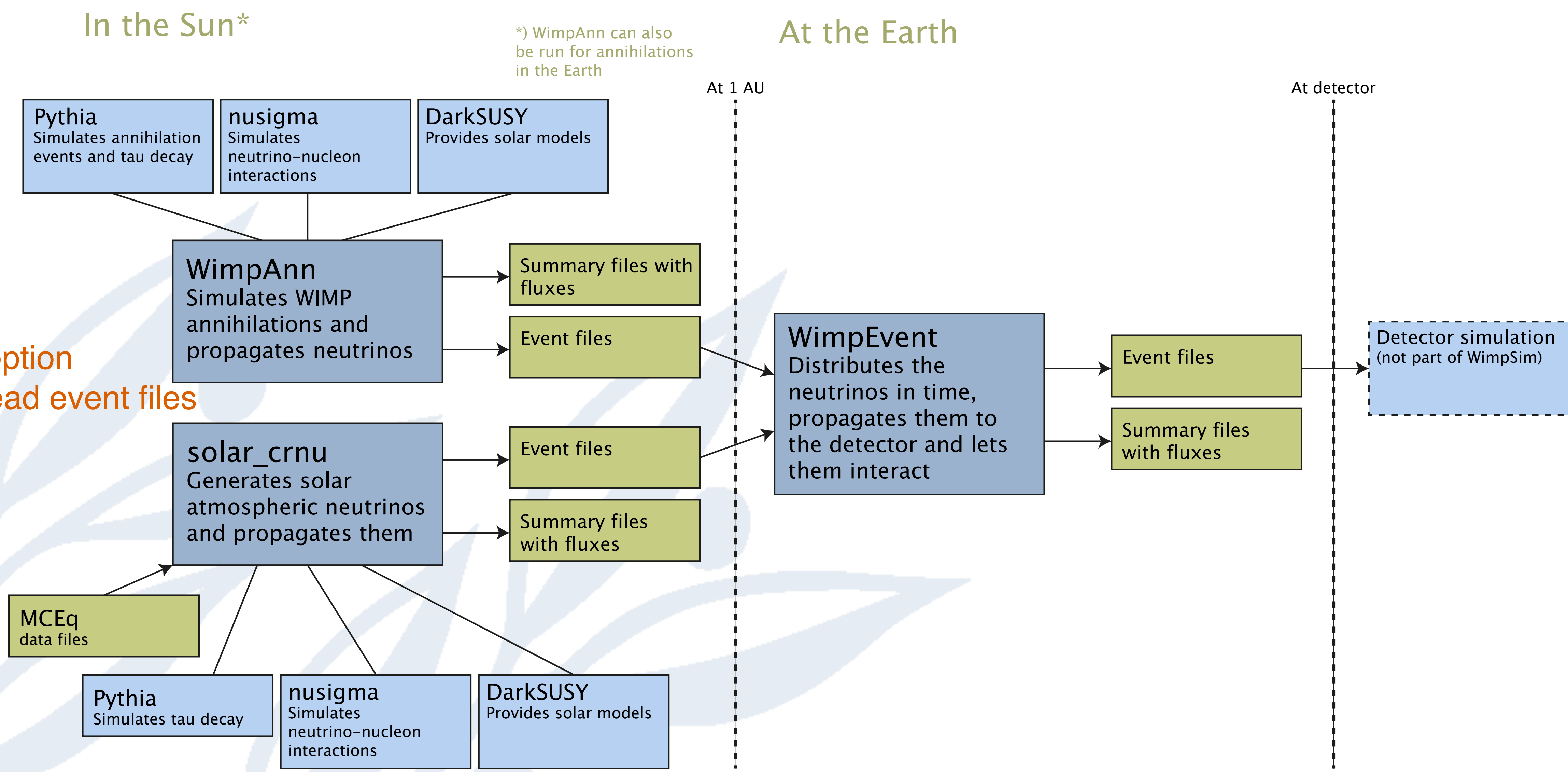
Event rates

$$\int A_{\text{eff}}(E)\frac{d\Phi}{dE}(E)\;dE$$

	Events per year	
Oscillation scenario	*IC-79*	*IC3*
Normal ordering	1.17	2.26
Inverted ordering	1.40	2.70

New WimpSim 4

WimpSim code layout



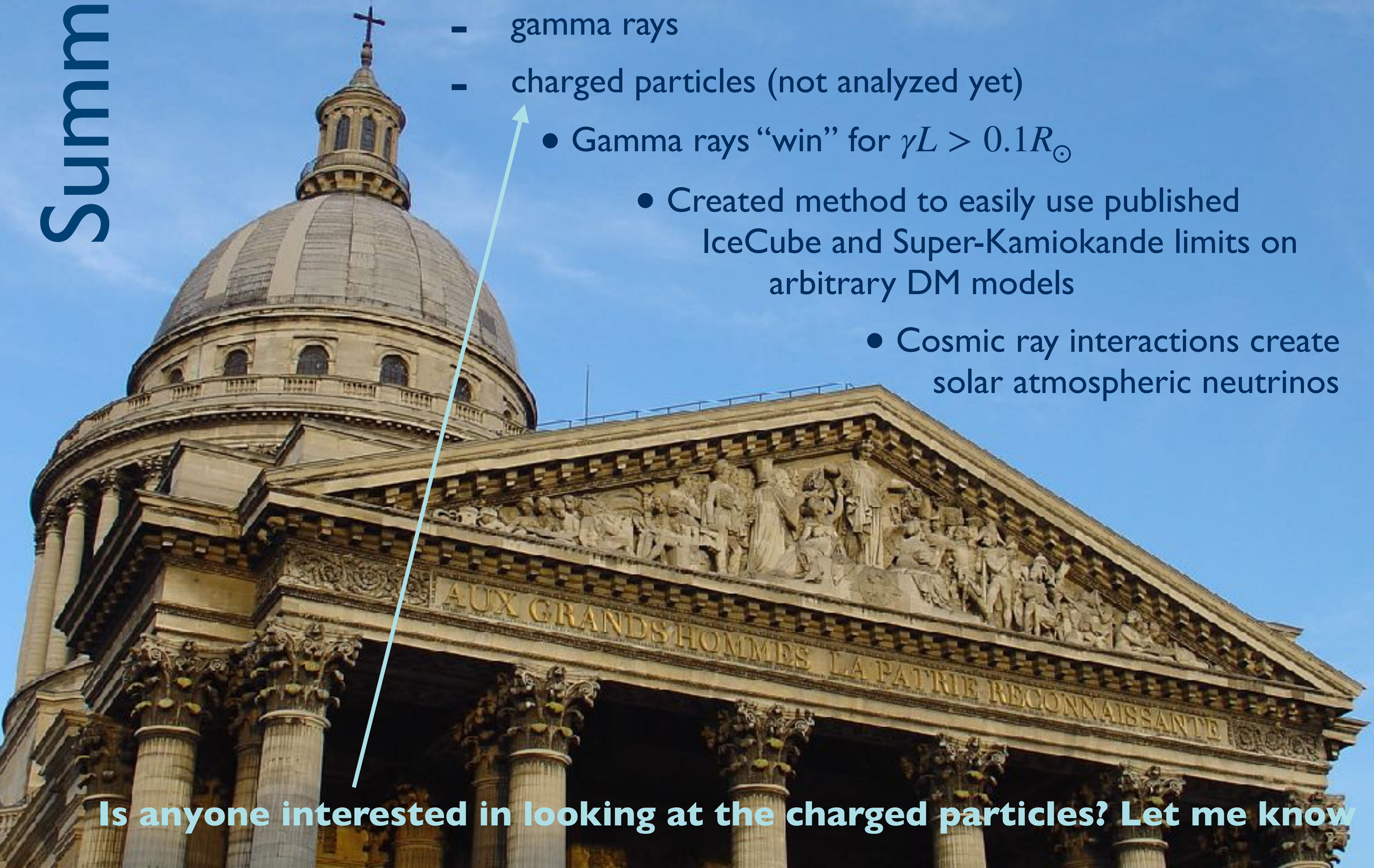
+ med_dec option
+ option to read event files

Publicly available code: wimpsim.astroparticle.se

M. Blennow, J. Edsjö and T. Ohlsson, [arXiv: 0709.3898] for the original WIMP annihilation calculation
J. Edsjö J. Elevant, R. Enberg and C. Niblaeus, [arXiv: 1704.02892] for the new version including the solar_crnu addition
C. Niblaeus, A. Beniwal and J.Edsjö, [arXiv: 1903.11363] for the new version including the mediator decay addition

Summary

- Compared to the regular WIMP scenario, the long-lived mediator scenario can lead to
  - higher neutrino fluxes
  - gamma rays
  - charged particles (not analyzed yet)
- Gamma rays “win” for $\gamma L > 0.1 R_\odot$
- Created method to easily use published IceCube and Super-Kamiokande limits on arbitrary DM models
- Cosmic ray interactions create solar atmospheric neutrinos



Is anyone interested in looking at the charged particles? Let me know

EXTRA

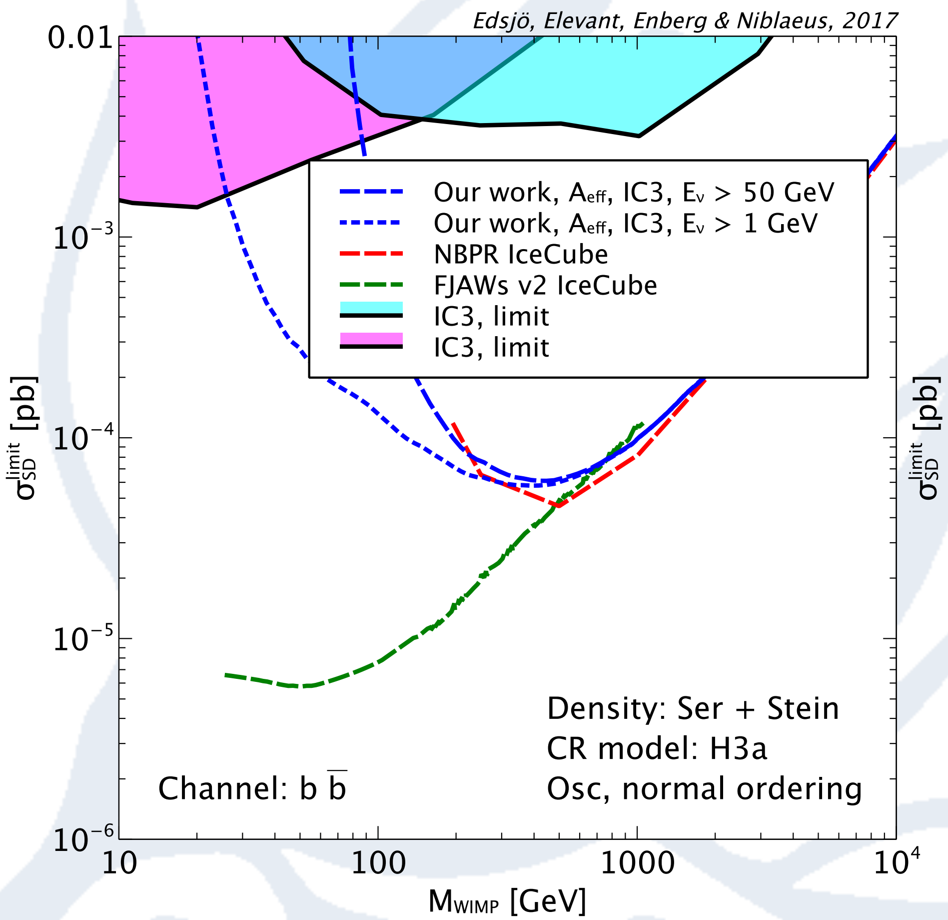
Stockholm University

Neutrino sensitivity floor

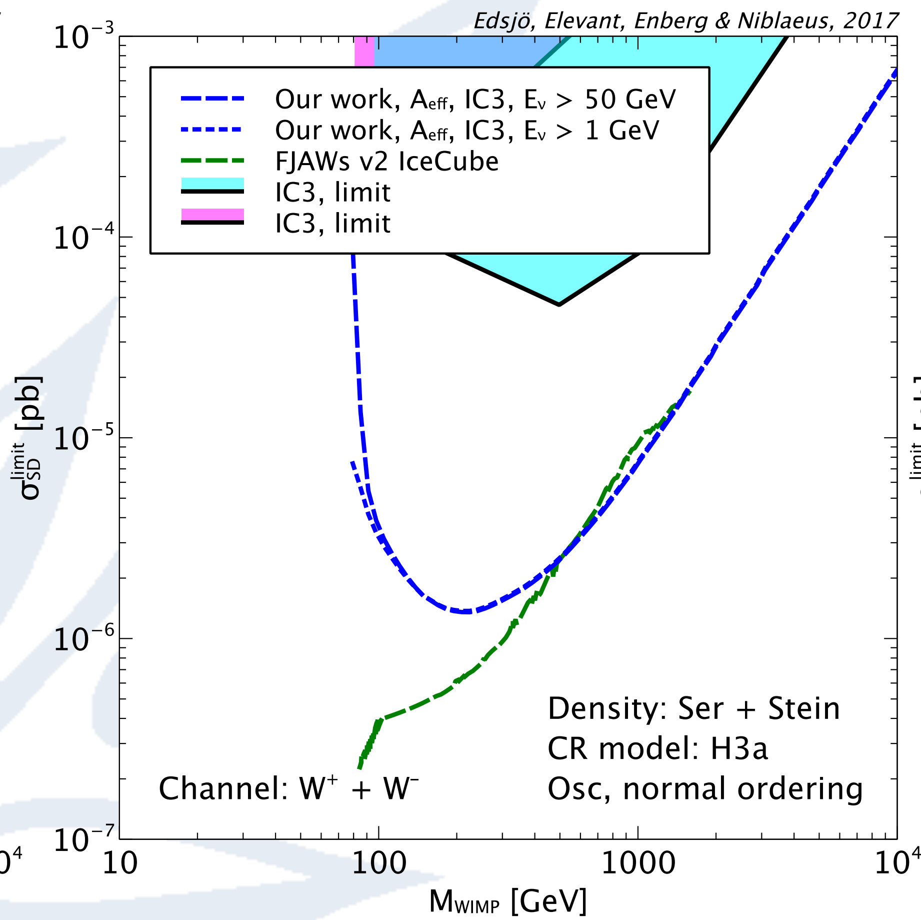
We can adjust the spin-dependent scattering cross section so that the number of events from WIMPs and SAν matches

$$N_{WIMP} = N_{SA\nu}$$

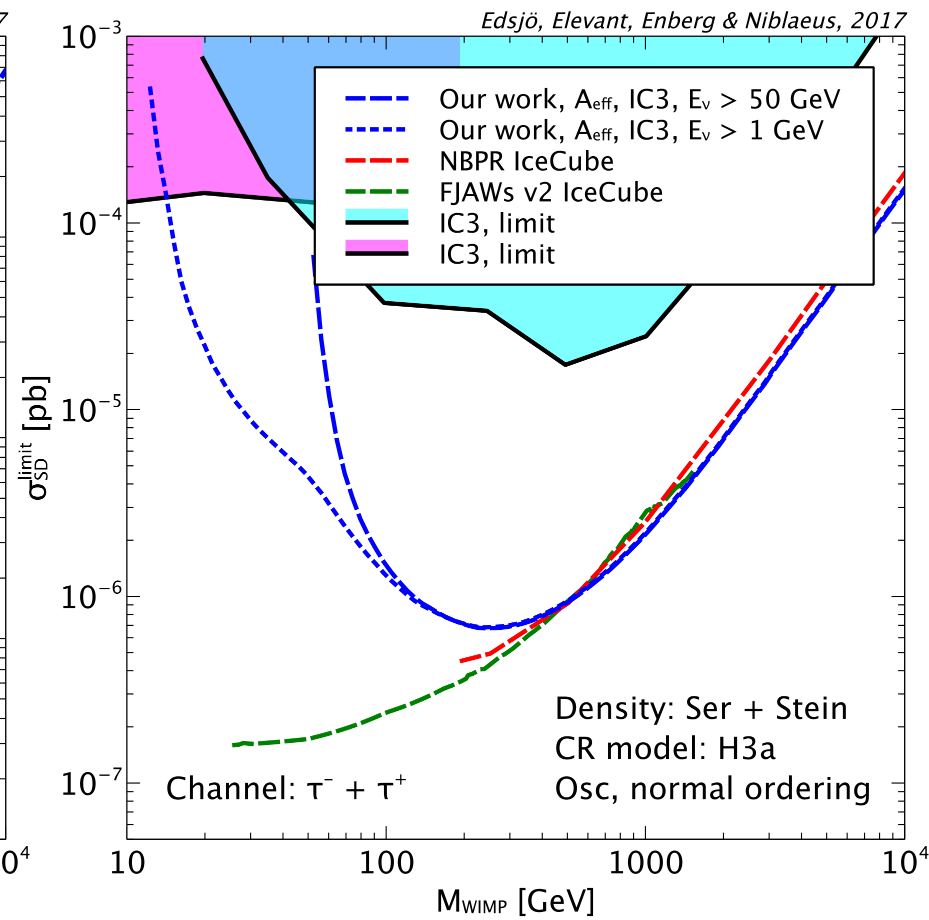
b b-bar



W+ W−



τ+ τ−



The actual floor depends quite a lot on assumptions on background rejection