High-energy and ultra-high-energy tau neutrinos and BSM

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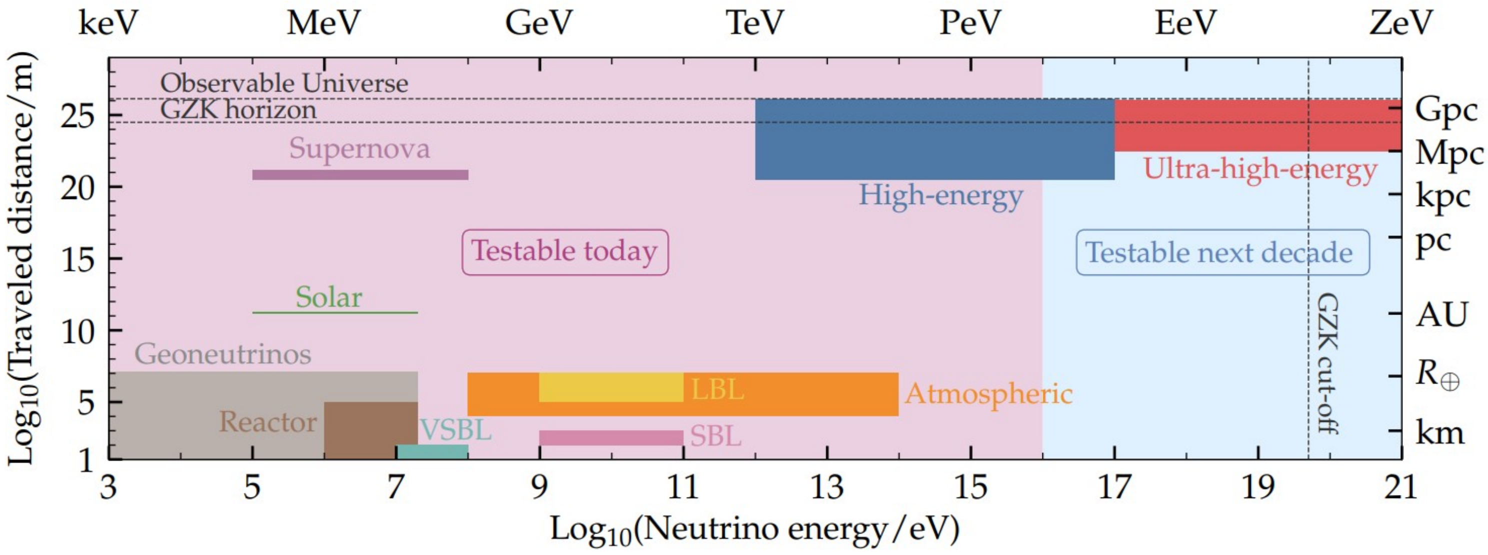
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

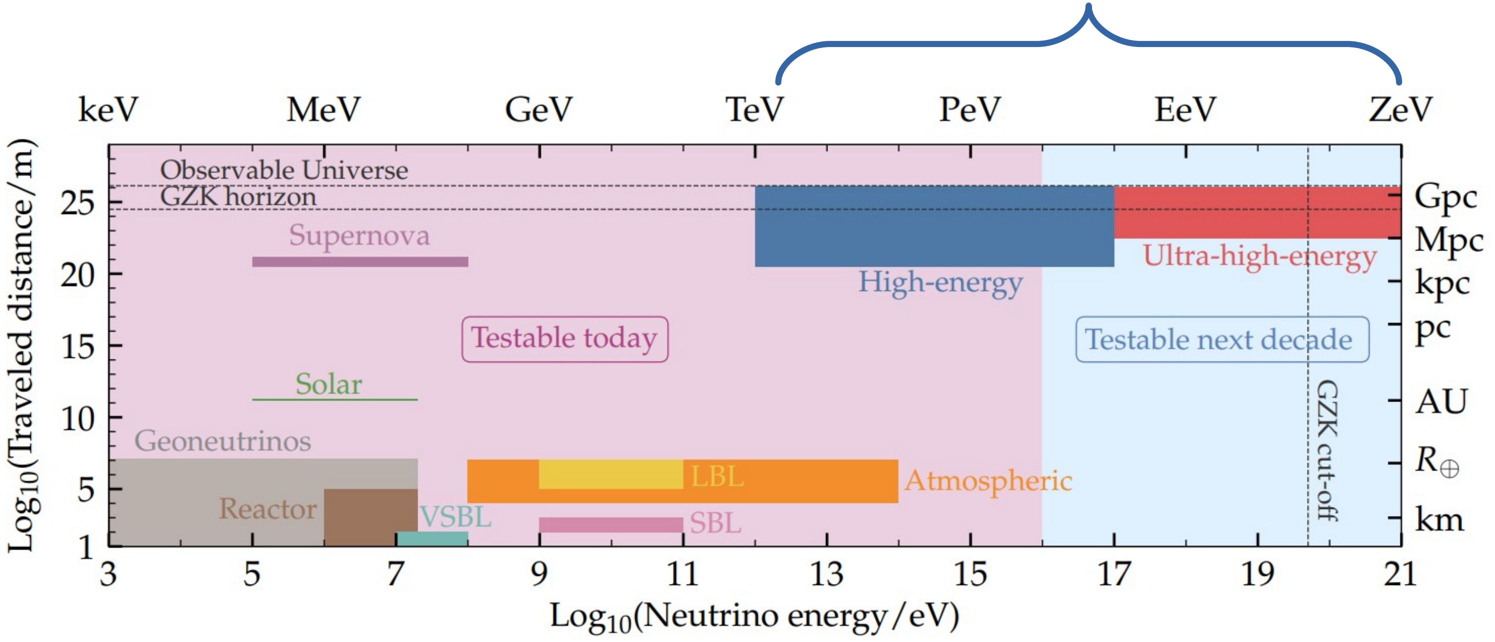
What makes high-energy cosmic ν exciting?



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

What makes high-energy cosmic ν exciting?

They have the highest energies



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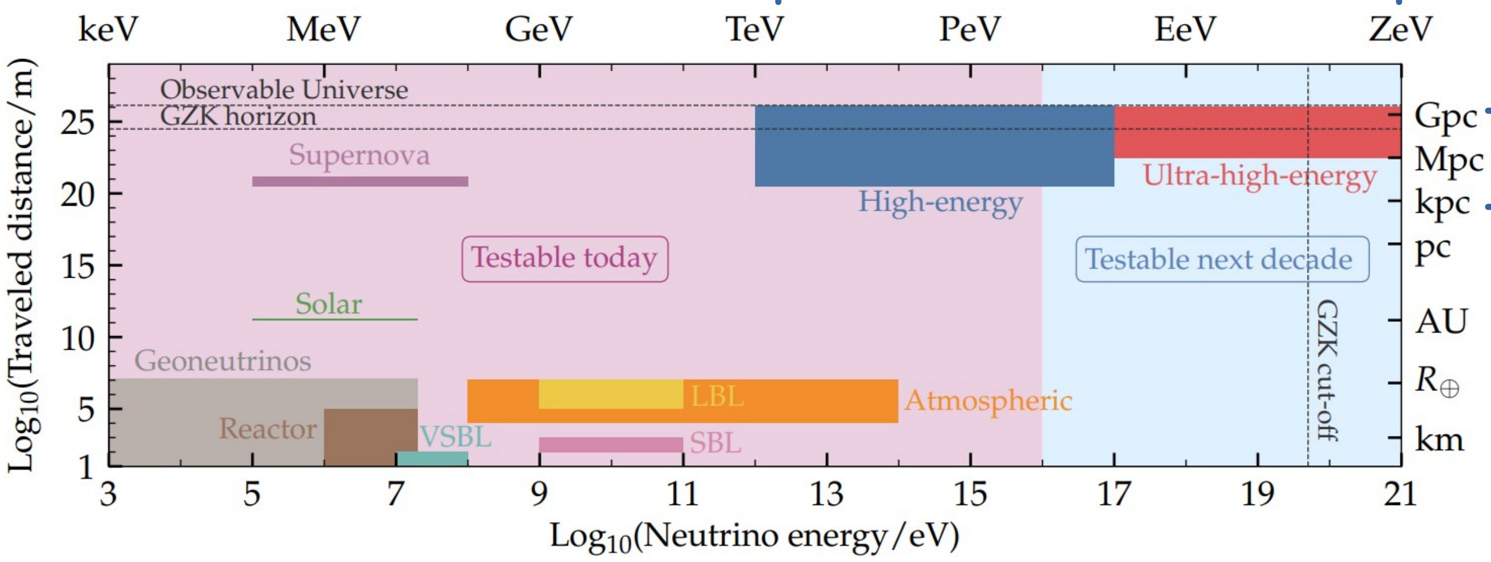
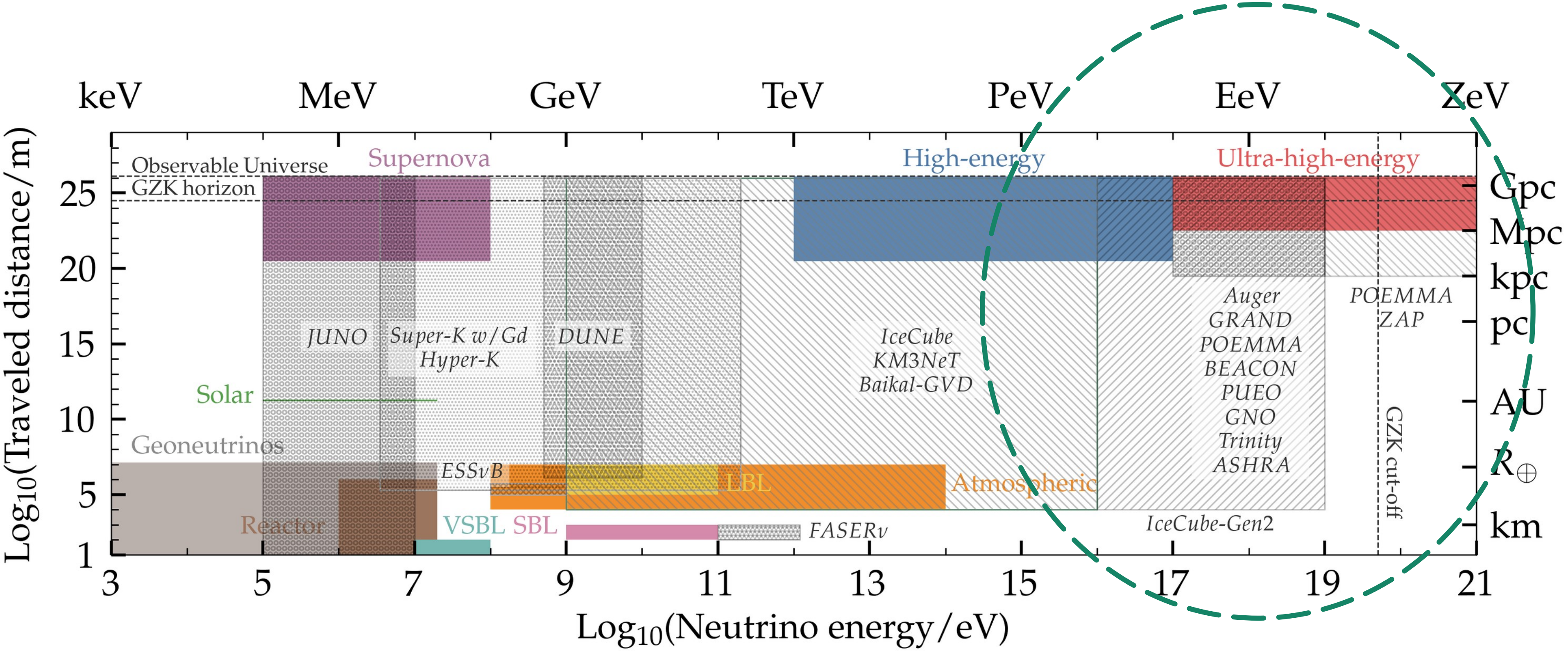


They travel the longest distances

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

Next decade: a host of planned neutrino detectors



Synergies with lower energies

Increase TeV–PeV
ν statistics

Discover > EeV ν

MB *et al.*, Snowmass 20201 Letter of interest

High-energy neutrinos: TeV–PeV

(*Detected*)

Ultra-high-energy neutrinos: $>$ 100 PeV

(*Predicted but undiscovered*)

Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\, (E/\mathrm{PeV})^{-n}\, (L/\mathrm{Gpc})^{-1}\, \mathrm{PeV}^{1-n}$

- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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n = 0: CPT-odd Lorentz violation
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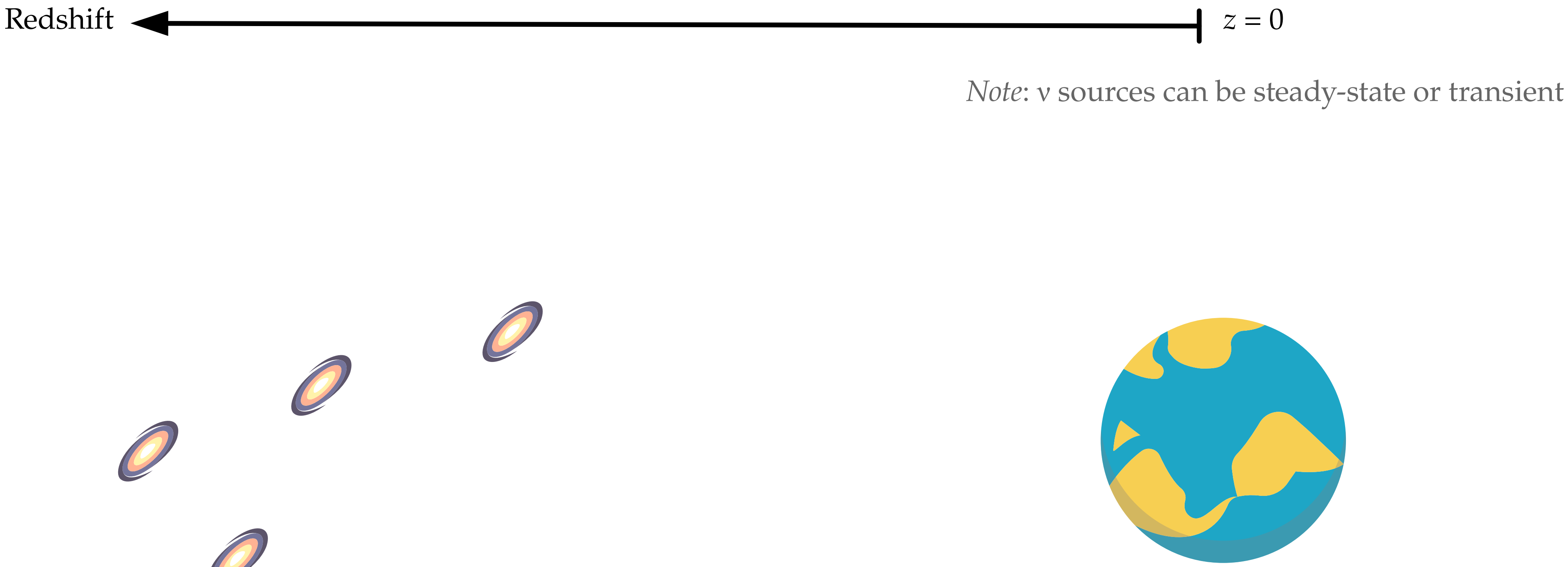
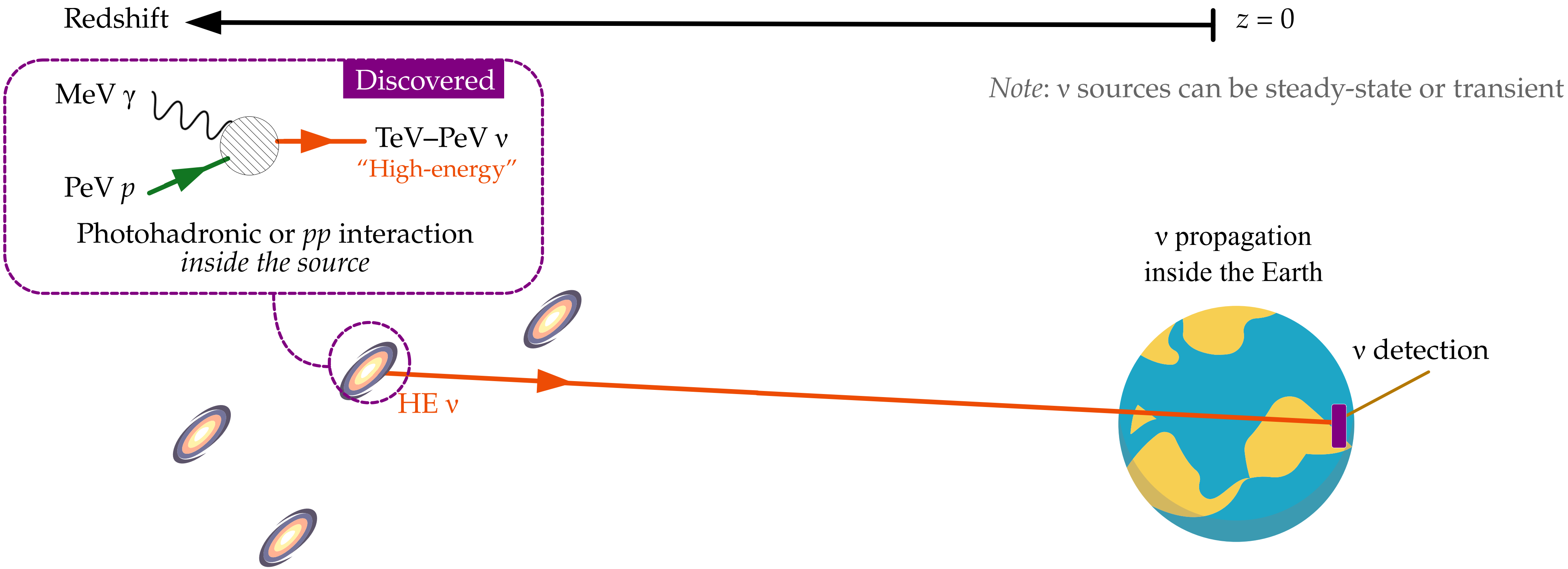
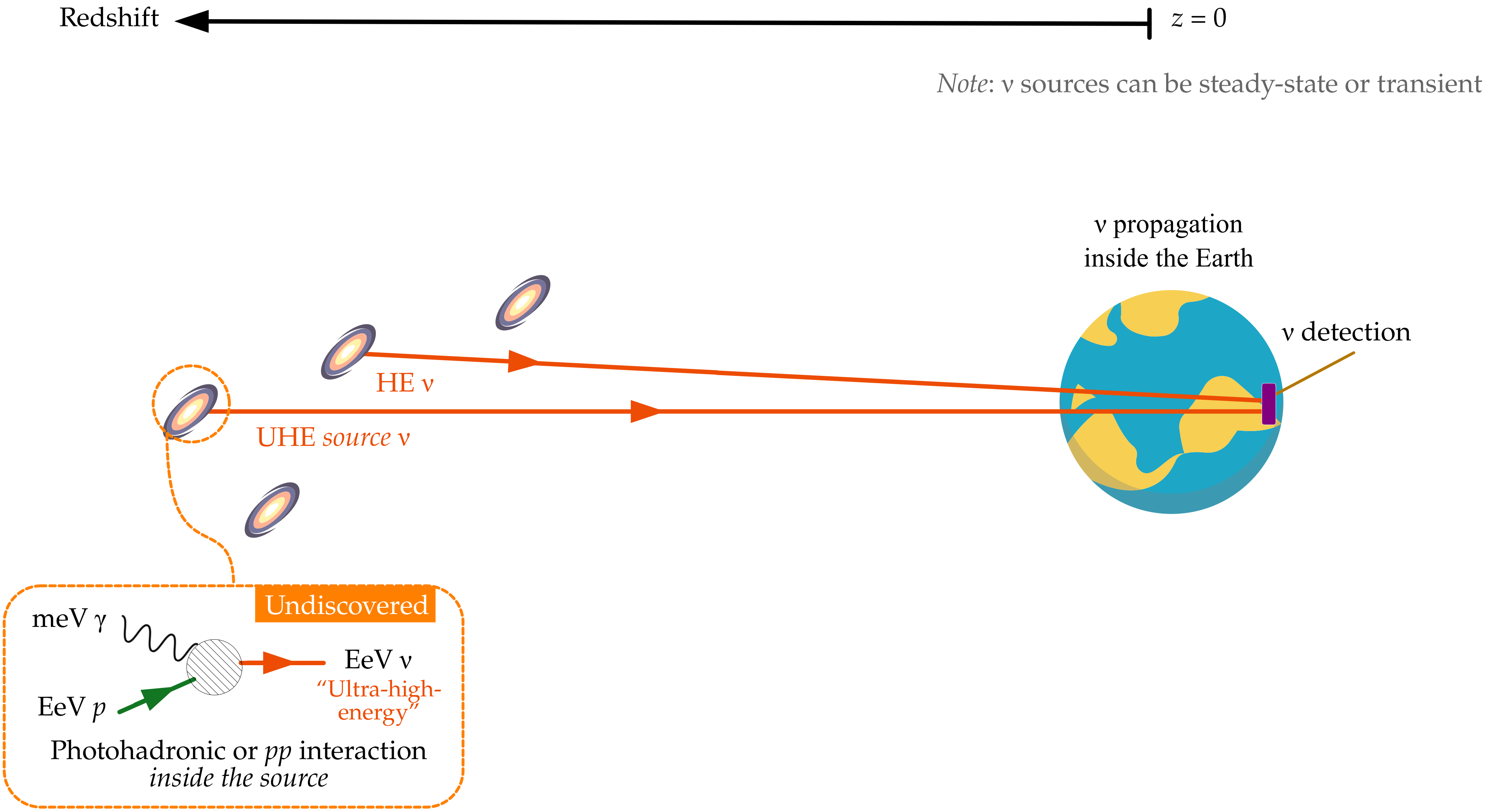
  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns


Redshift
$z = 0$
Note: ν sources can be steady-state or transient



Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or *pp* interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν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ν detection
HE ν
UHE *source* ν
Undiscovered
meV γ
EeV ν
"Ultra-high-
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EeV *p*
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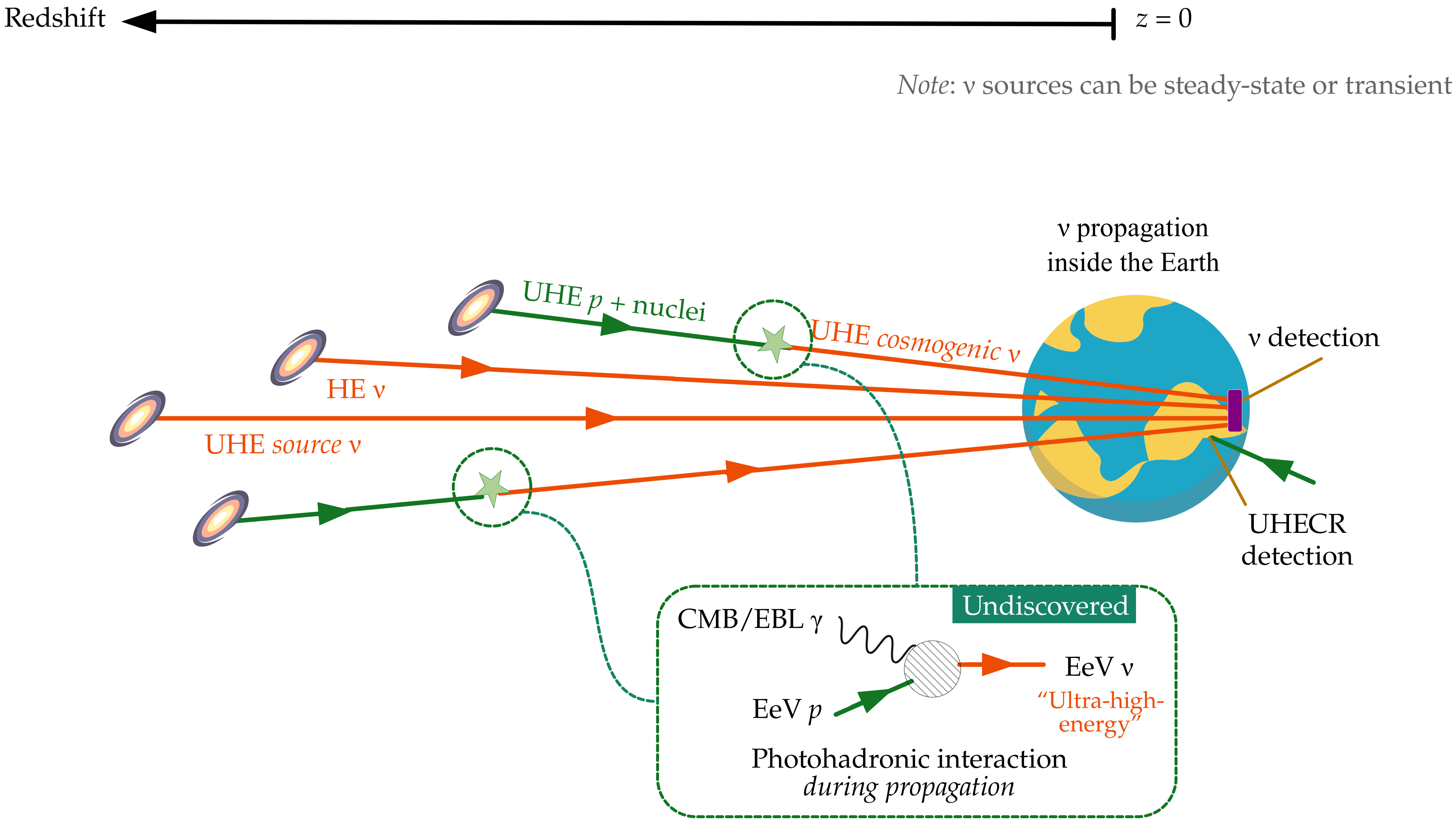
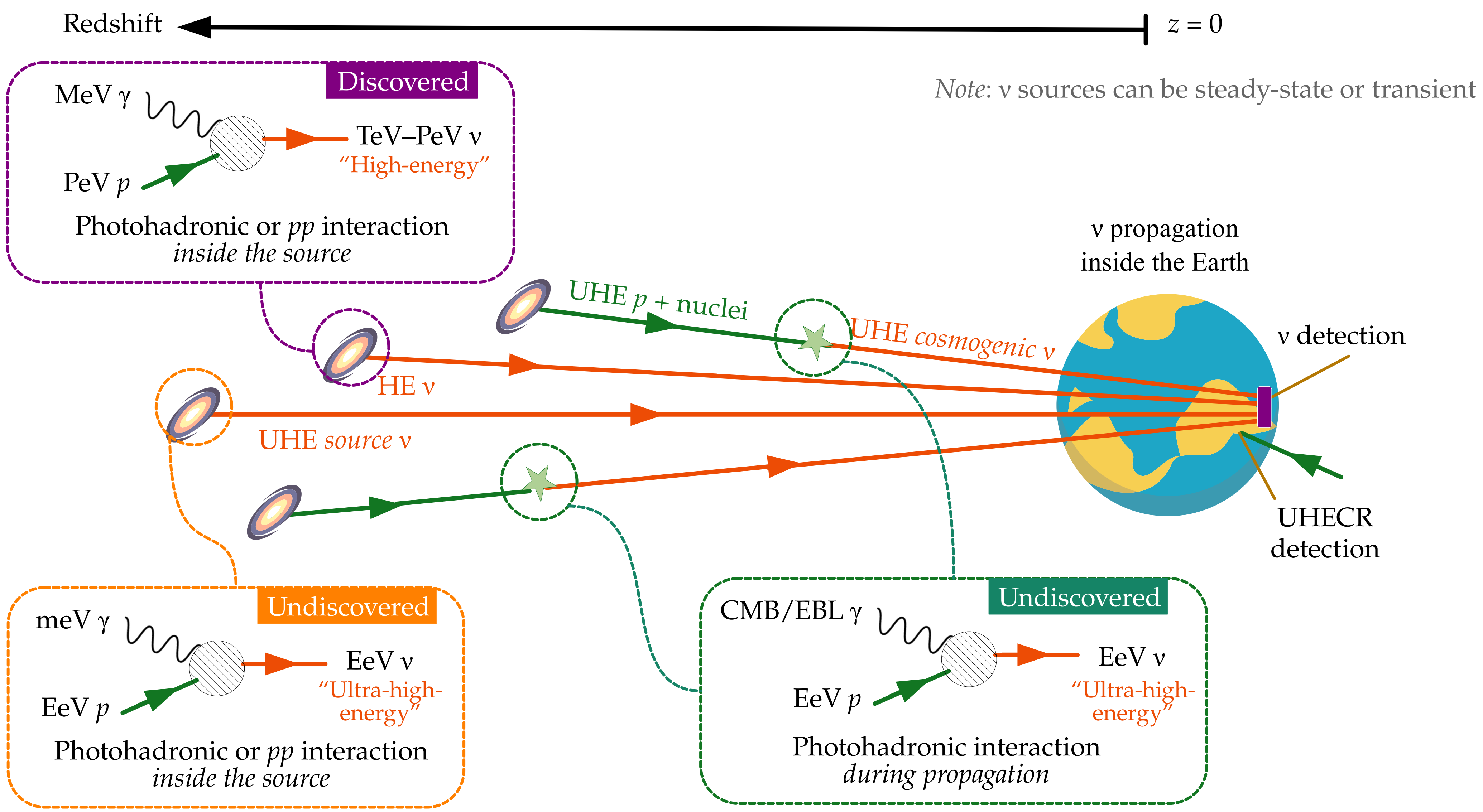


Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
HE ν
UHE *source* ν
UHECR detection
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic interaction *during propagation*



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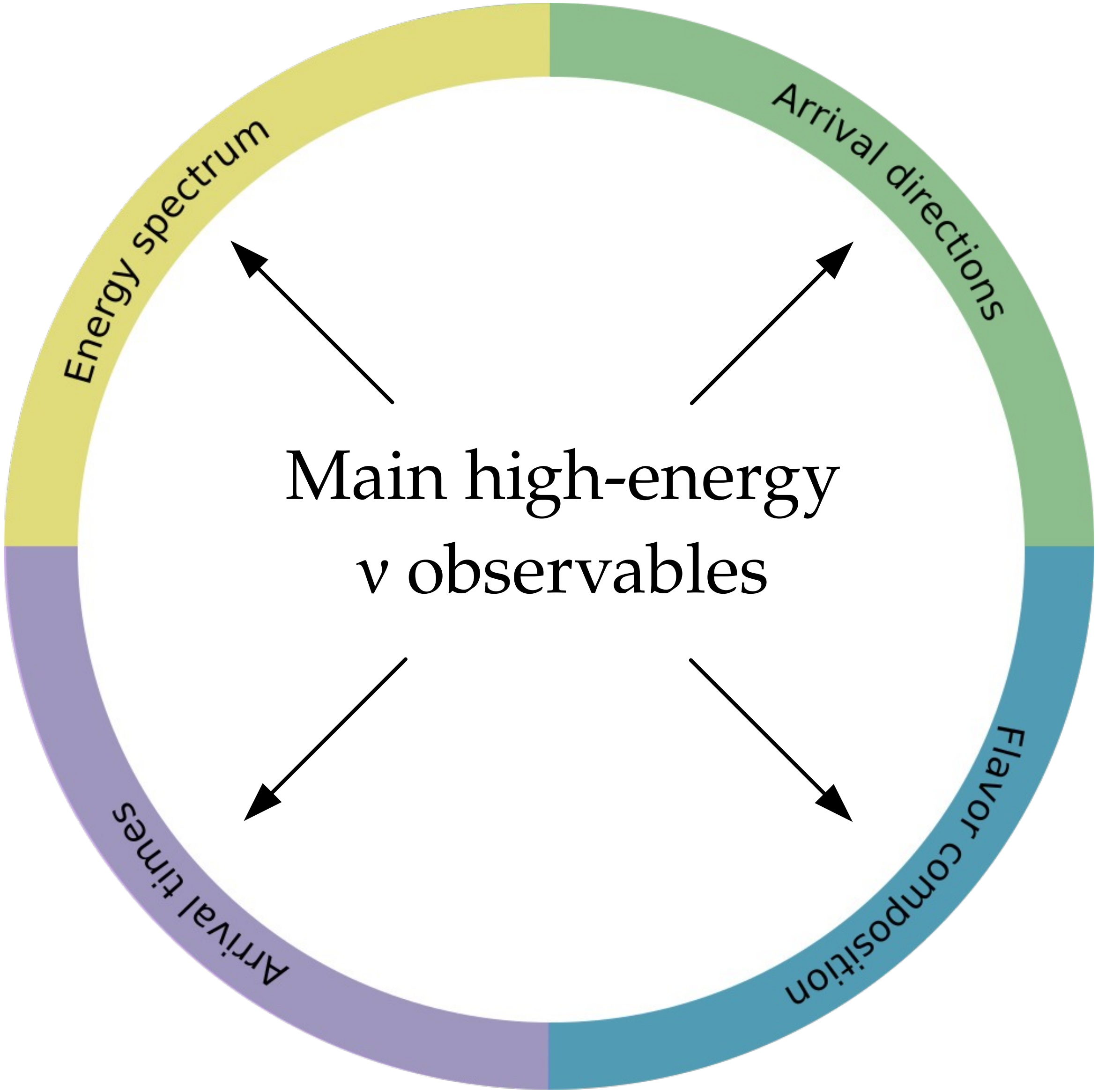
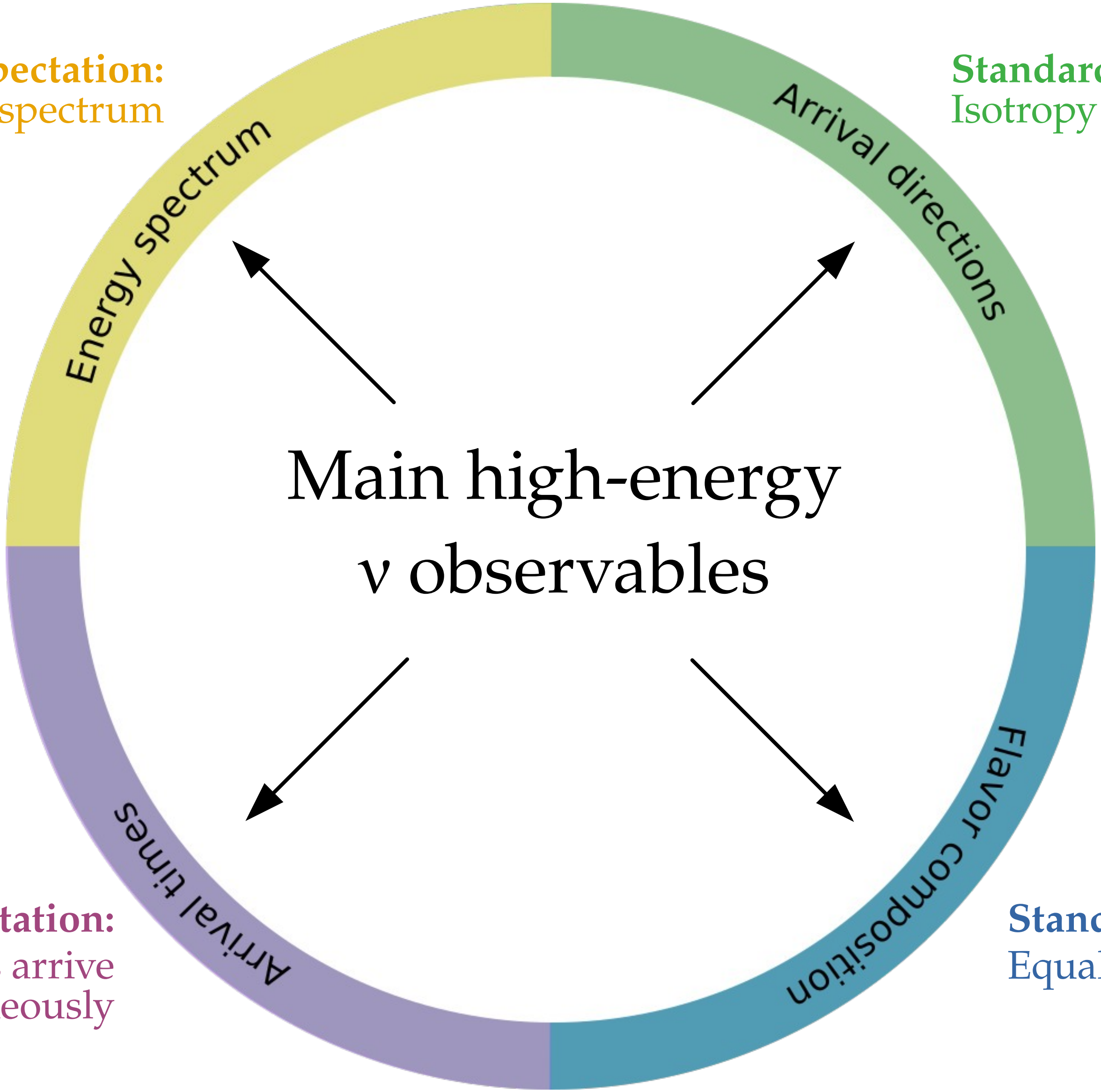

Main high-energy
ν observables
Energy spectrum
Arrival directions
Arrival times
Flavor composition

Standard expectation:
Power-law energy spectrum

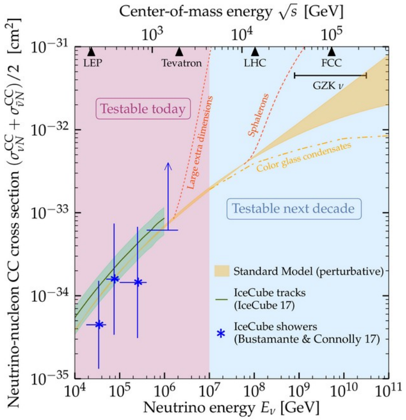
Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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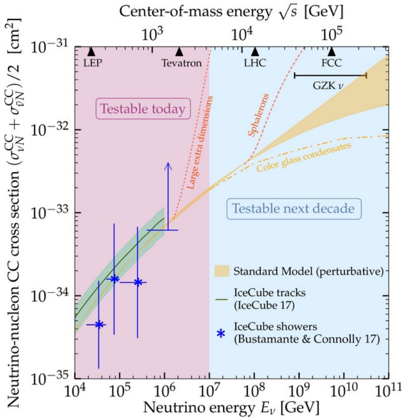
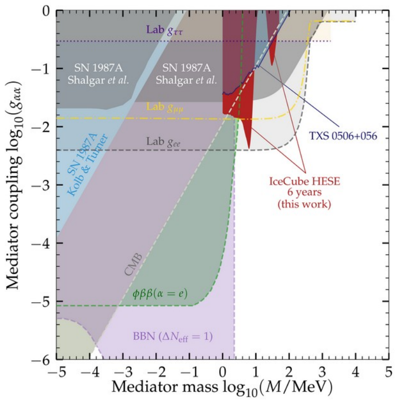


MB & Connolly, *PRL* 2019

ν self-interactions



MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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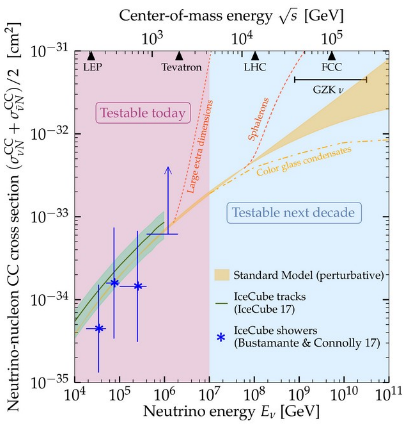

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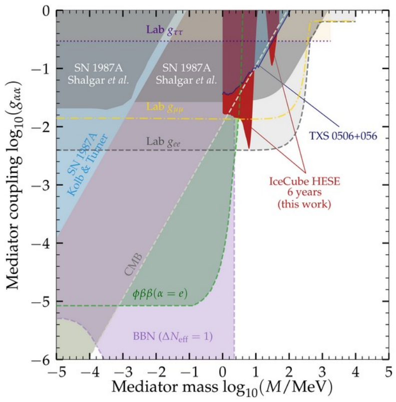

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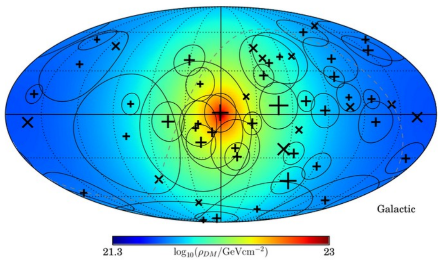
ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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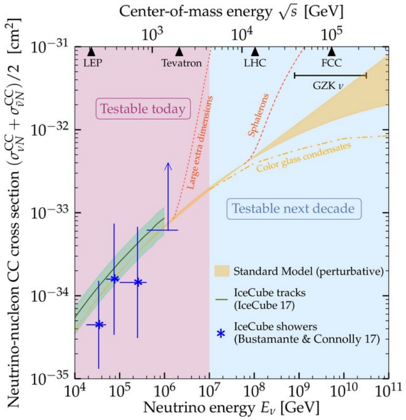

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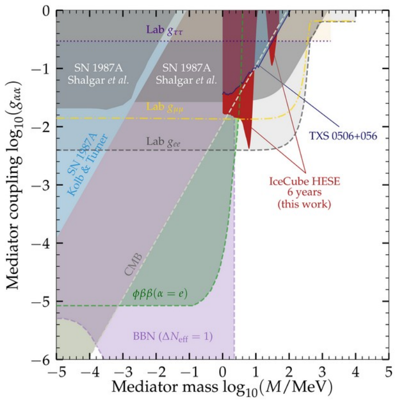

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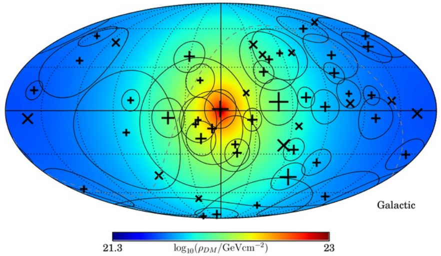
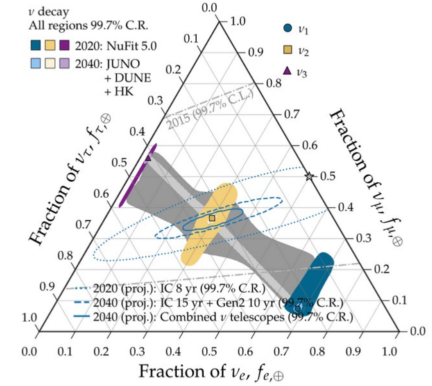


Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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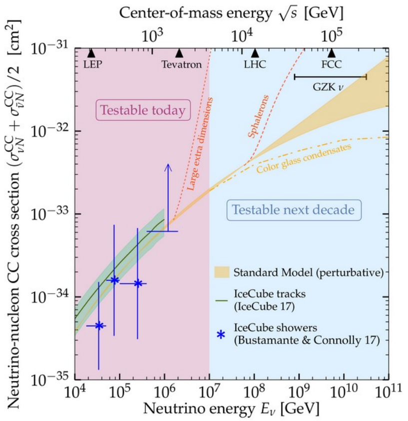

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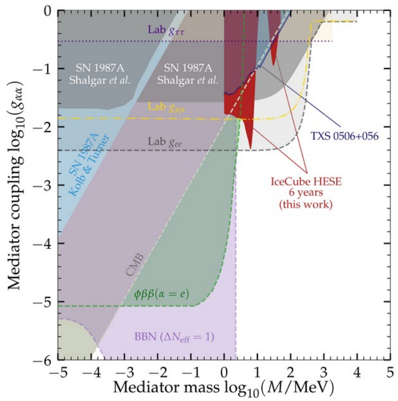

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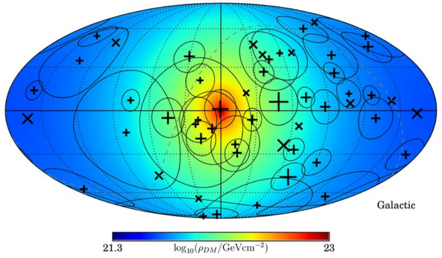

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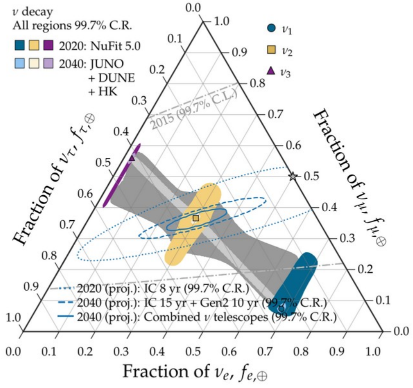
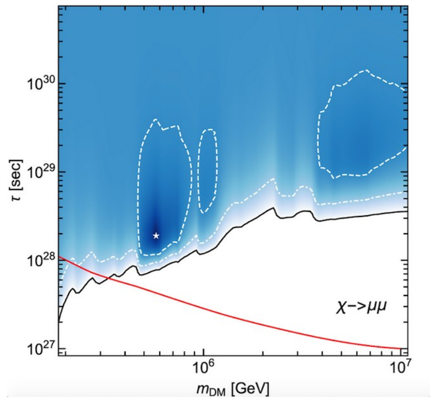


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

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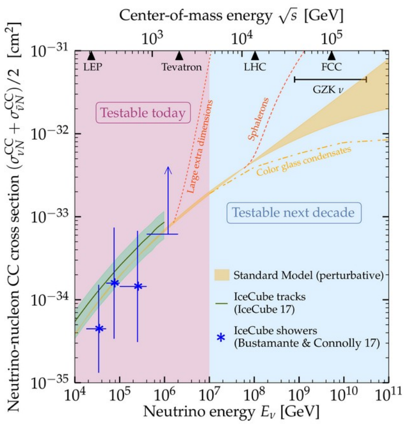

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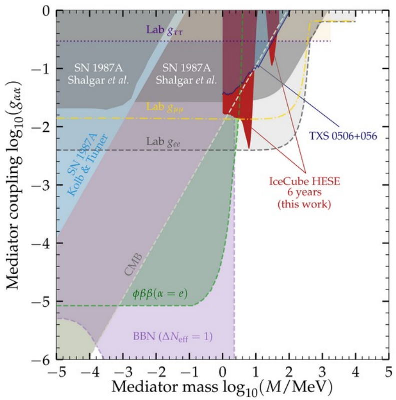

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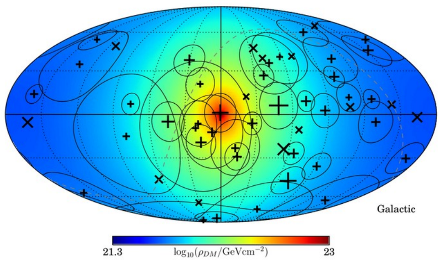

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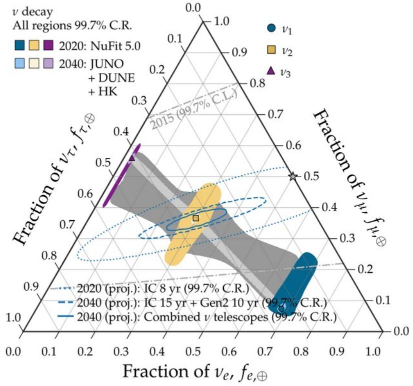

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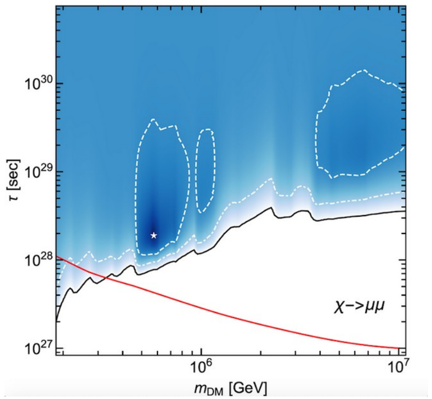
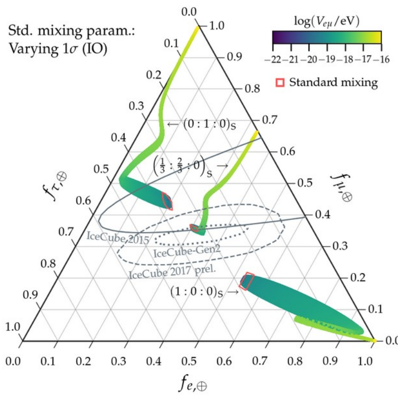


Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



MB & Agarwalla, *PRL* 2019

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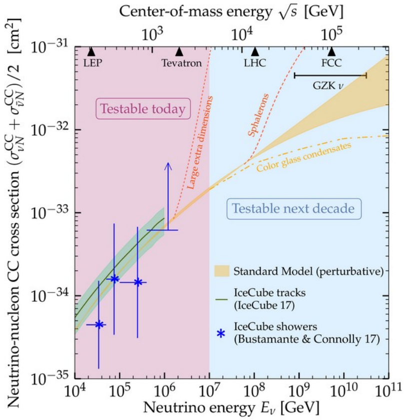

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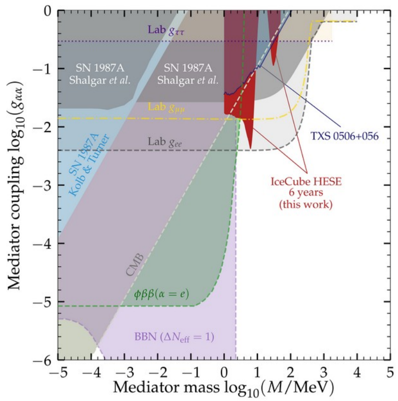

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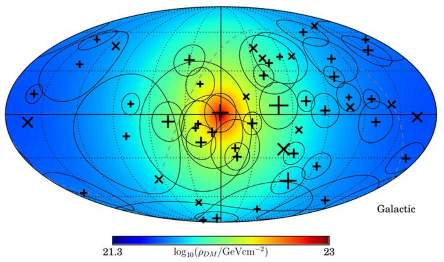

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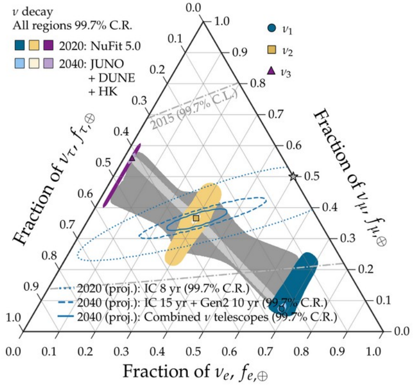

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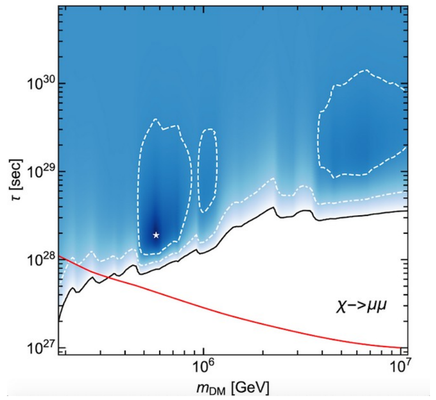

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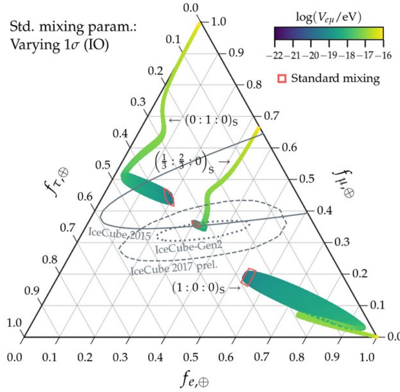
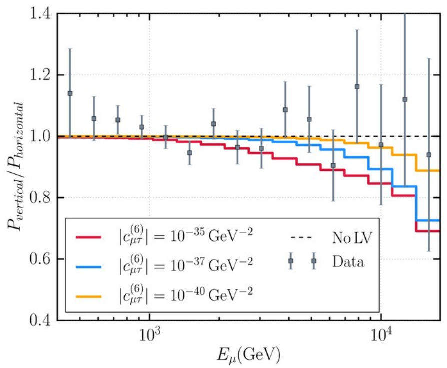


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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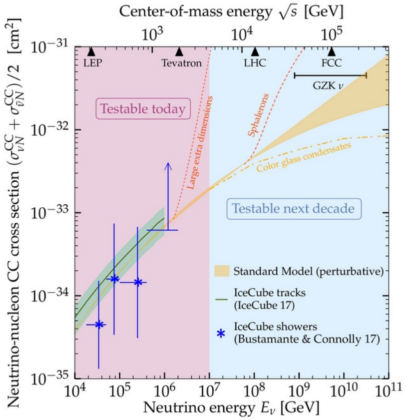

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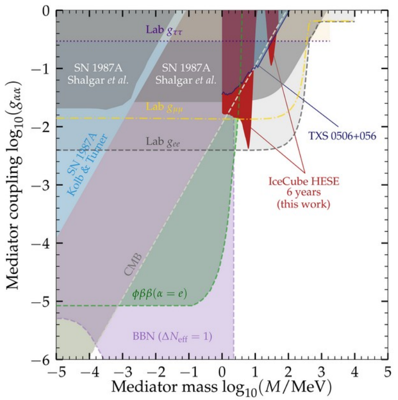

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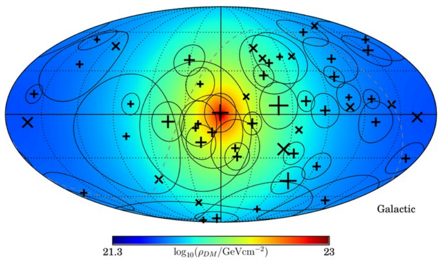

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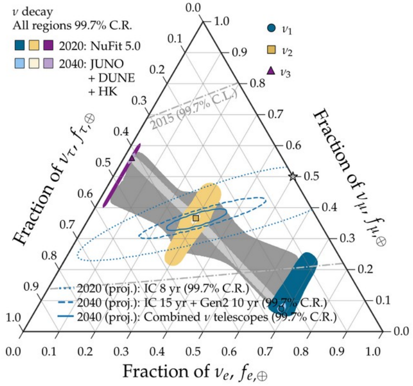

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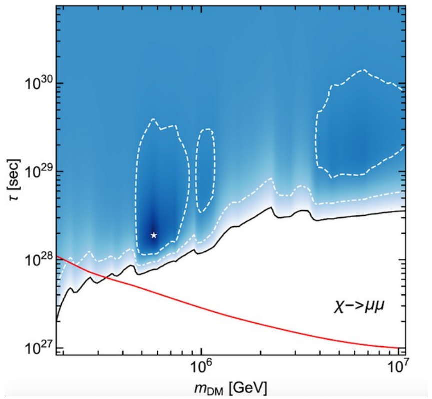

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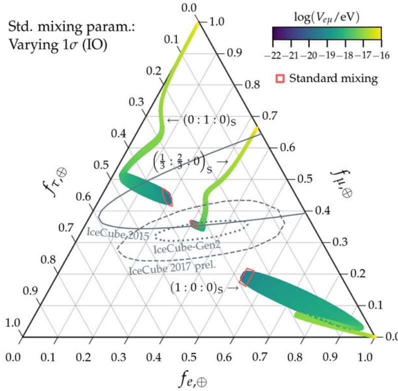

MB & Agarwalla, *PRL* 2019

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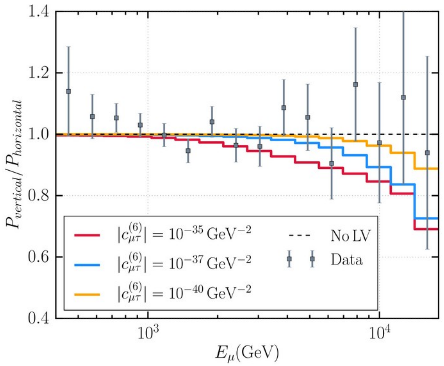
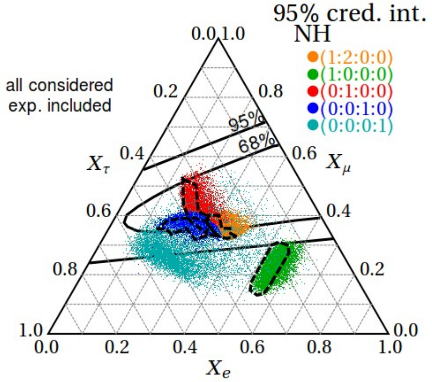


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

Note: Not an exhaustive list

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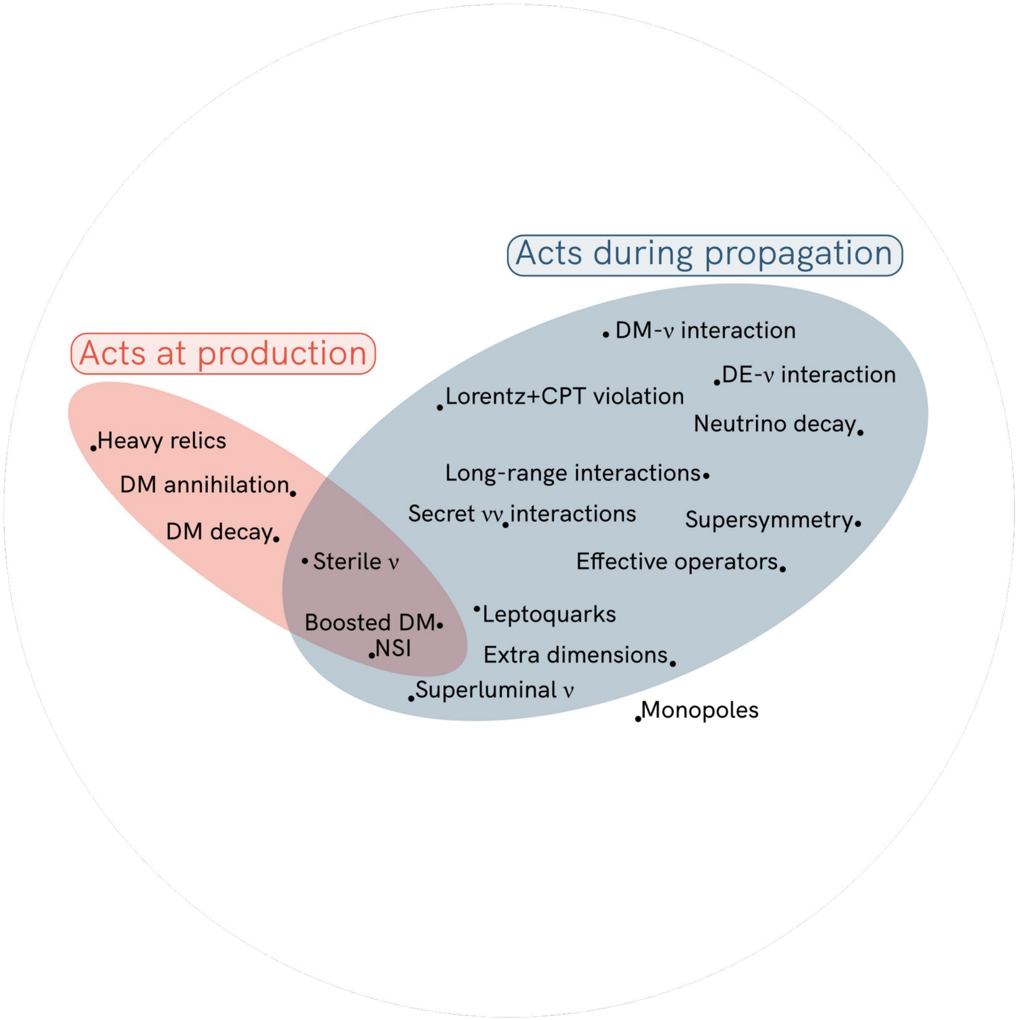

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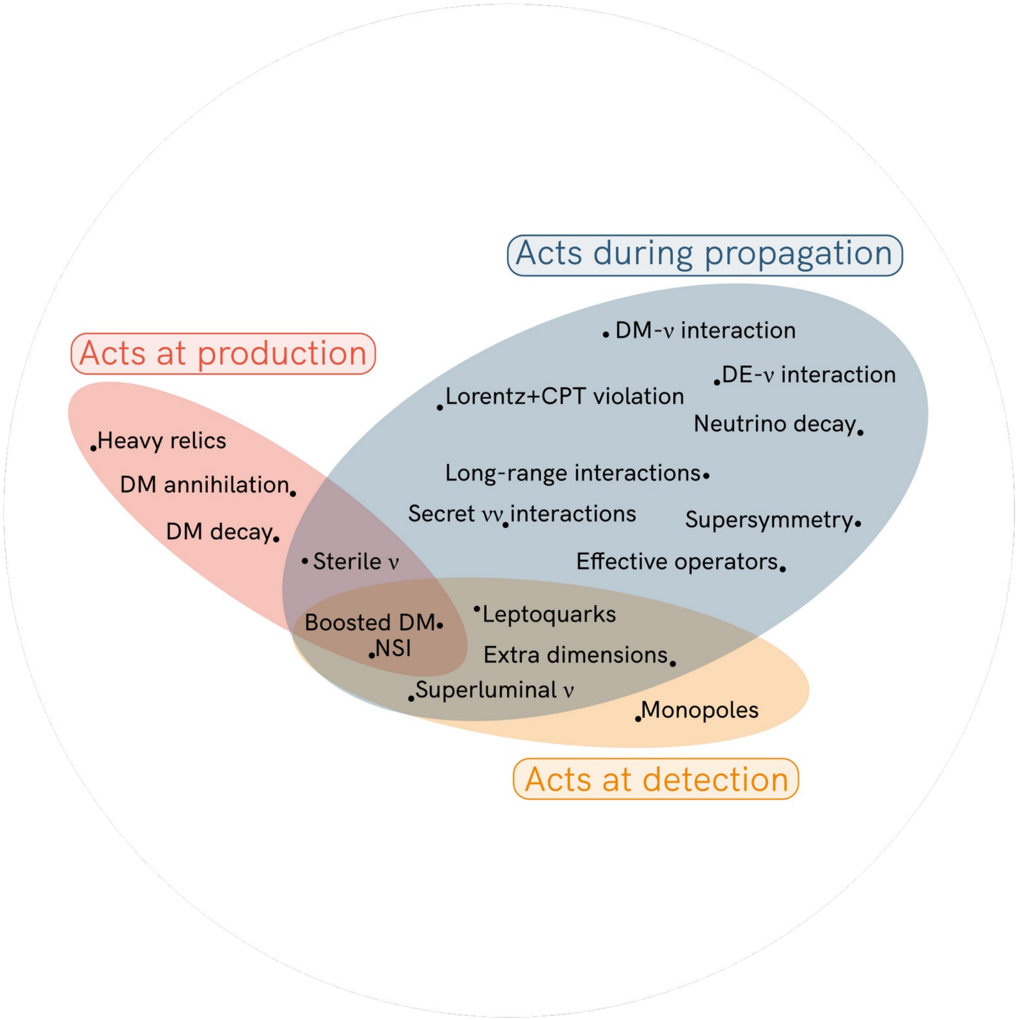

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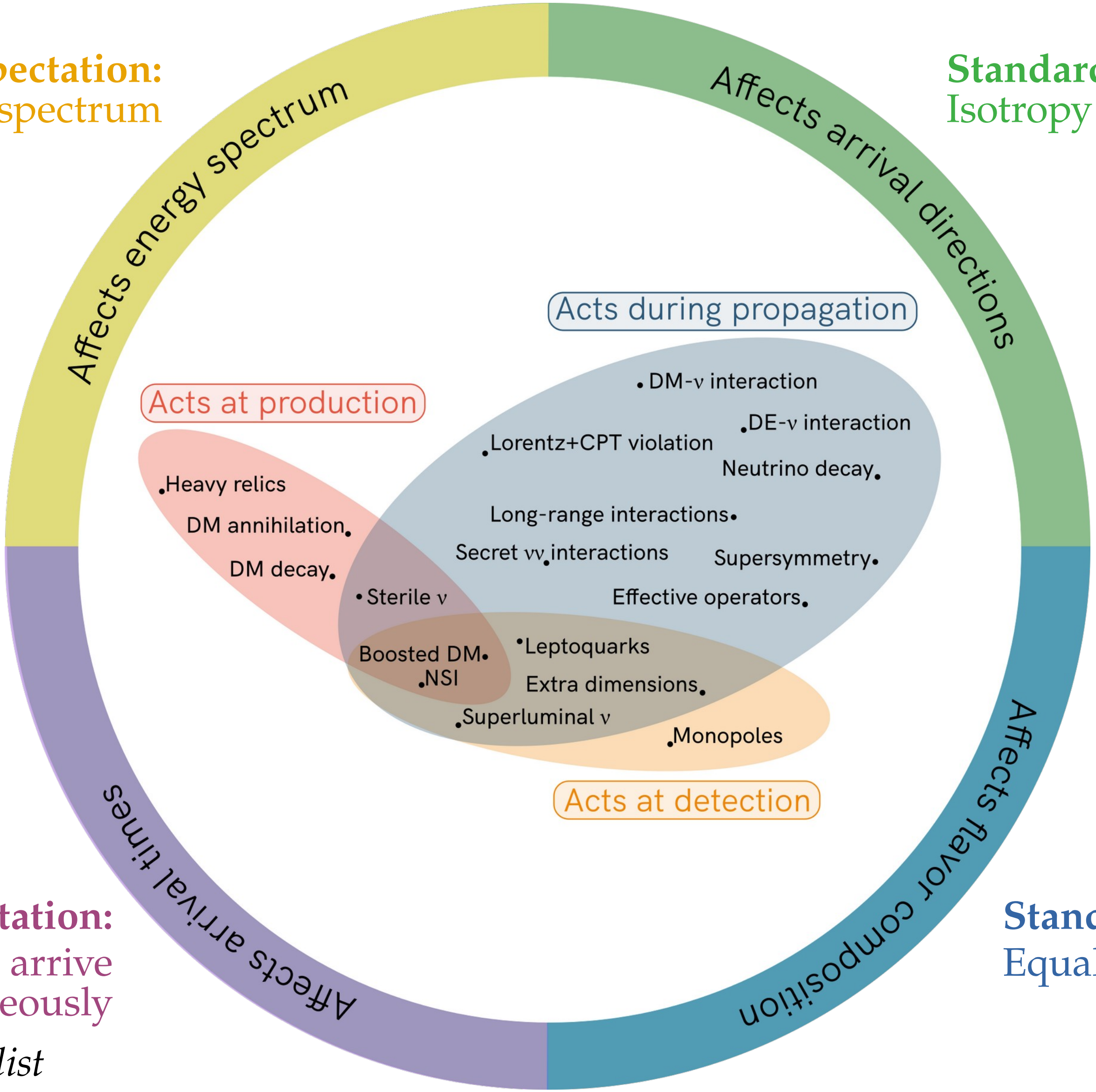
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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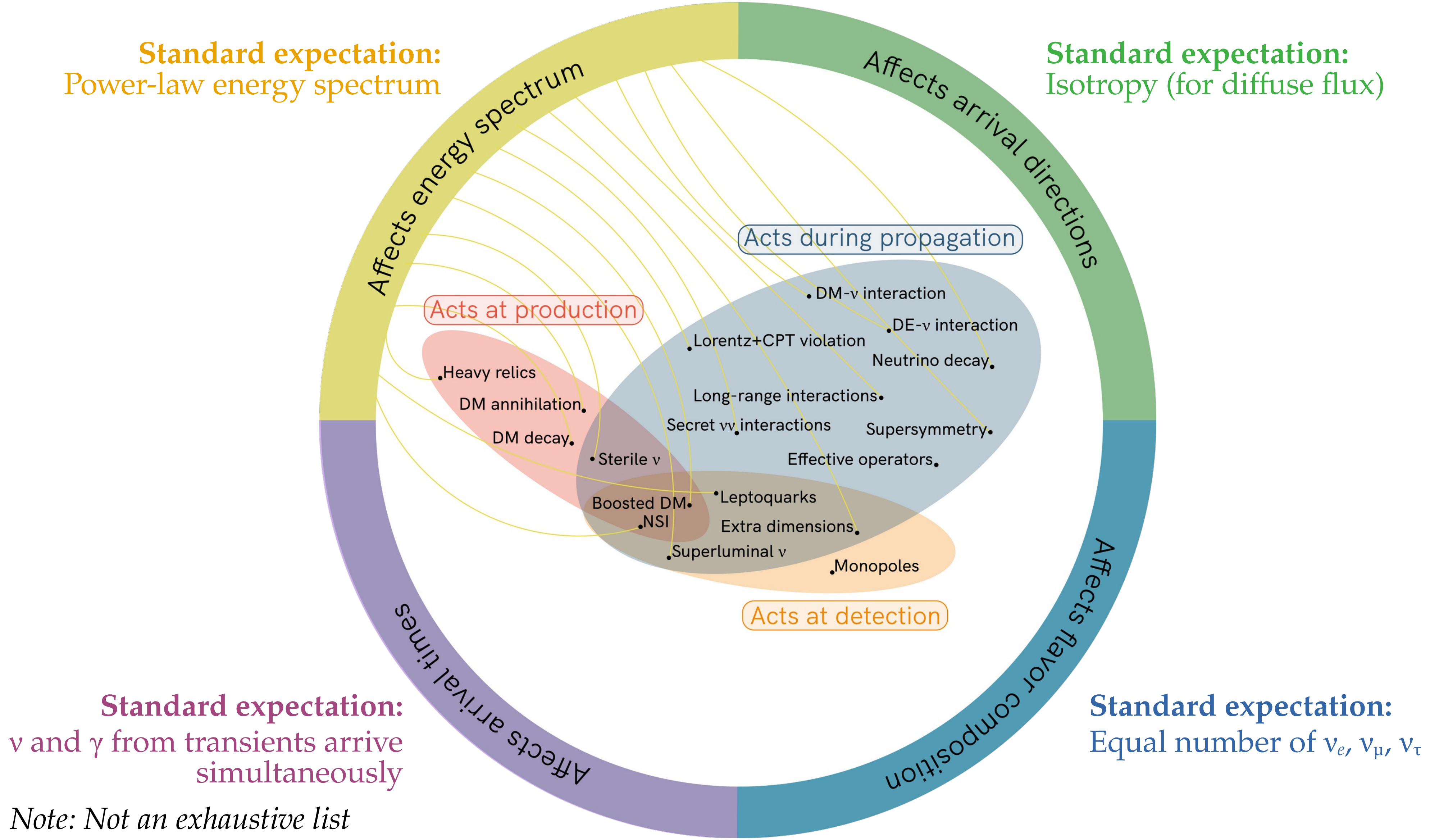
Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects arrival times
Affects flavor composition
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Long-range interactions
Secret νν interactions
Supersymmetry
Effective operators
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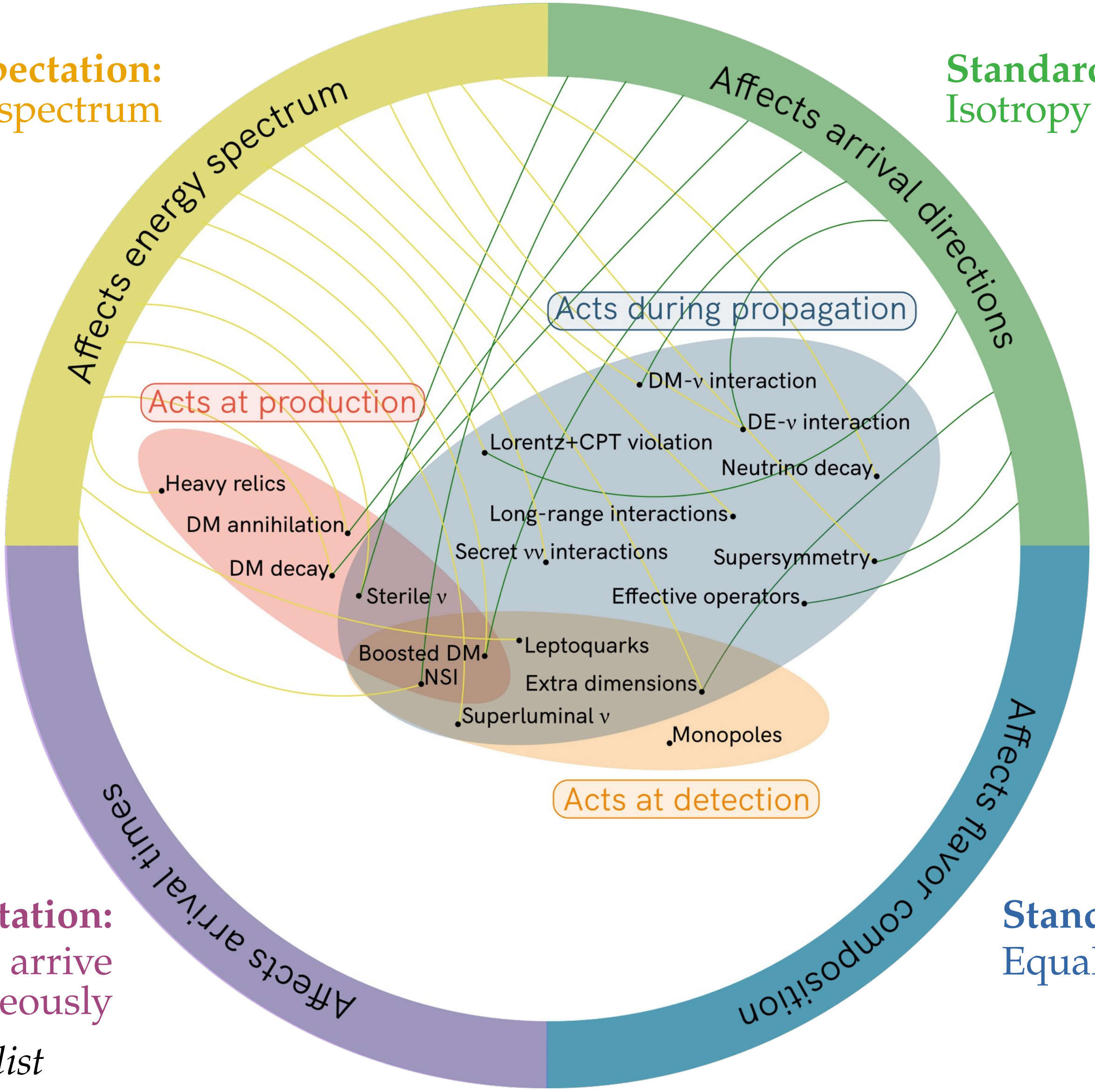

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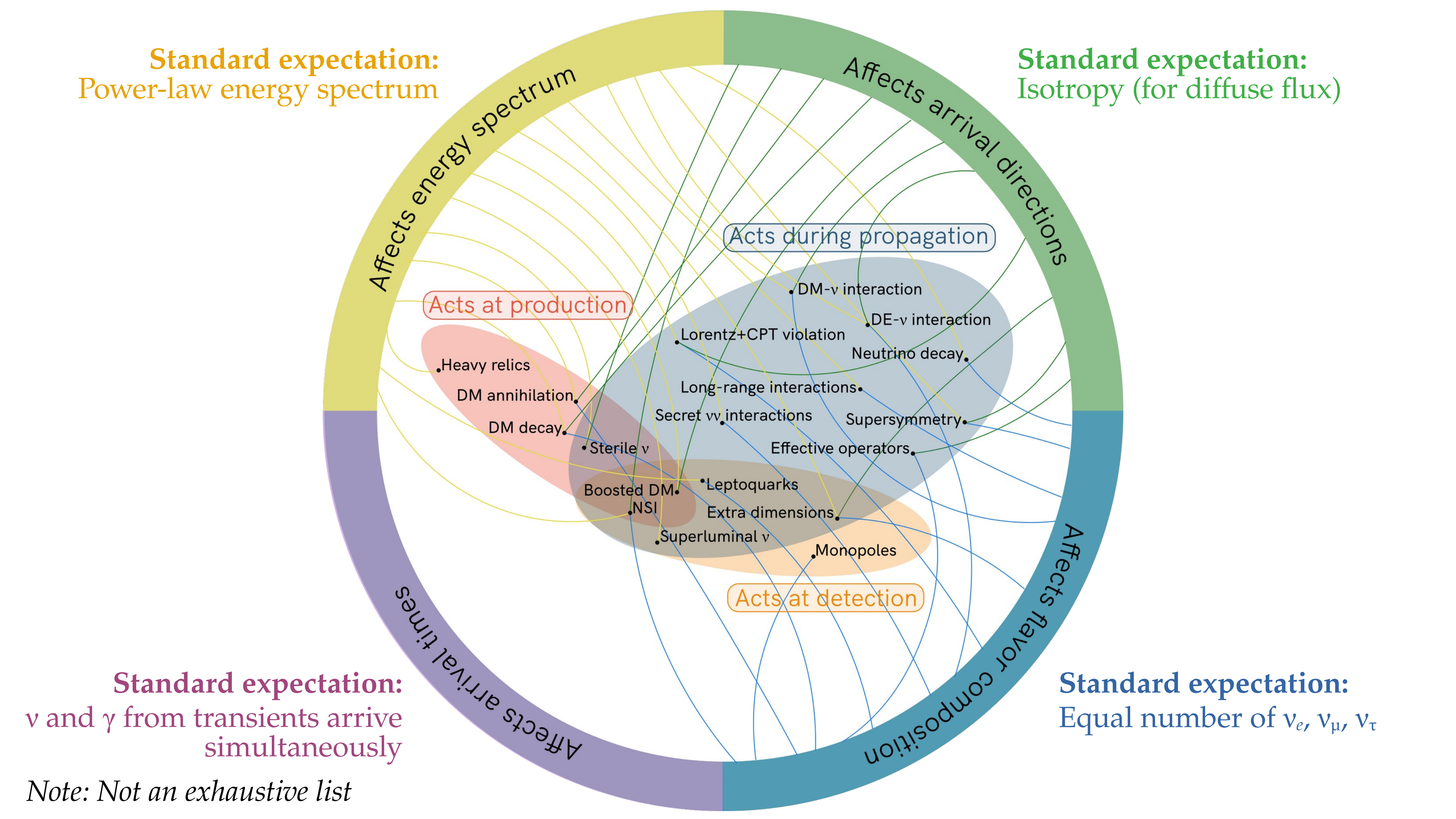

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
Long-range interactions
Secret νν interactions
Supersymmetry
DM decay
Sterile ν
Effective operators
Leptoquarks
Boosted DM
NSI
Extra dimensions
Superluminal ν
Monopoles
Standard expectation:
ν and γ from transients arrive simultaneously
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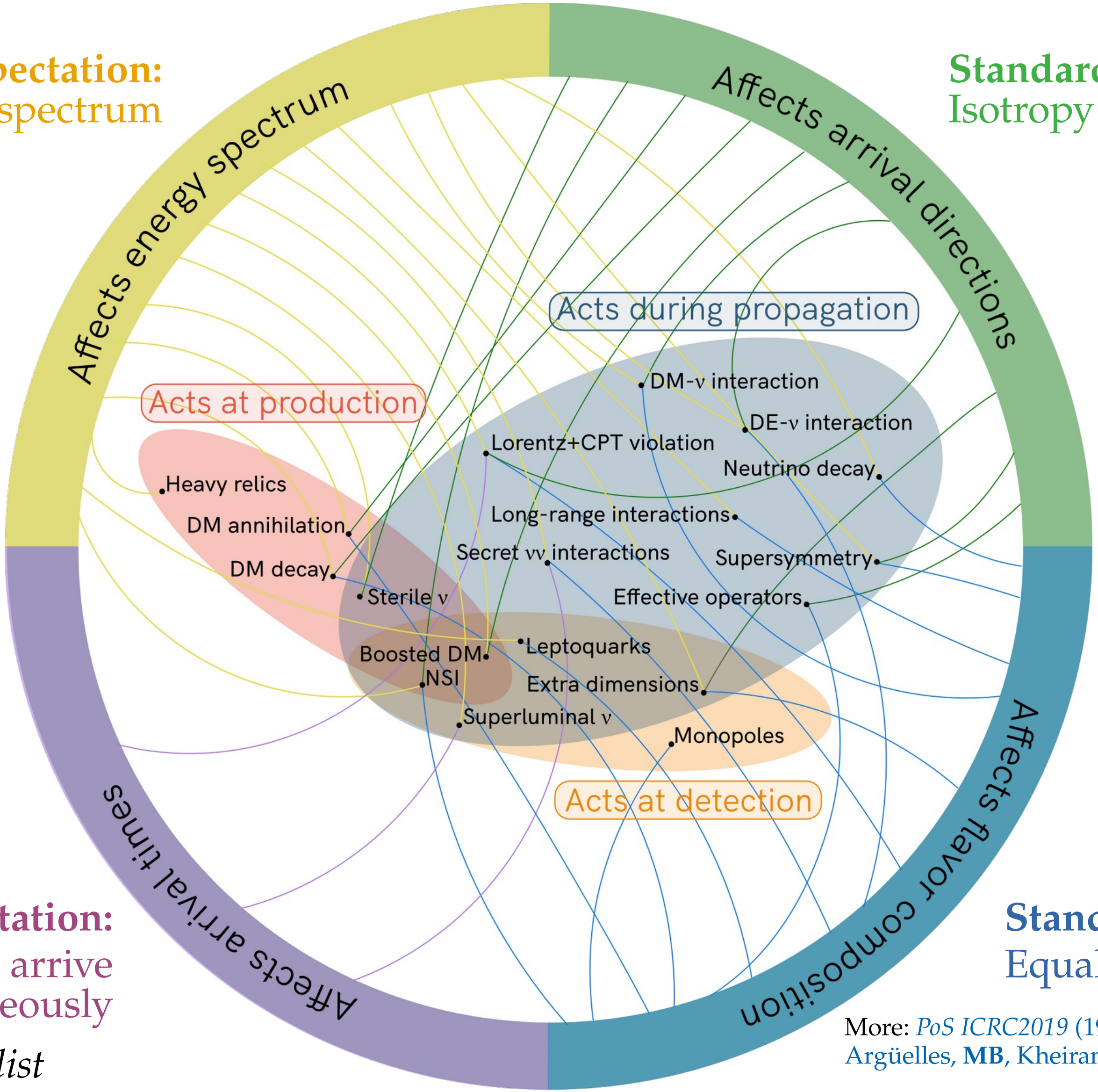

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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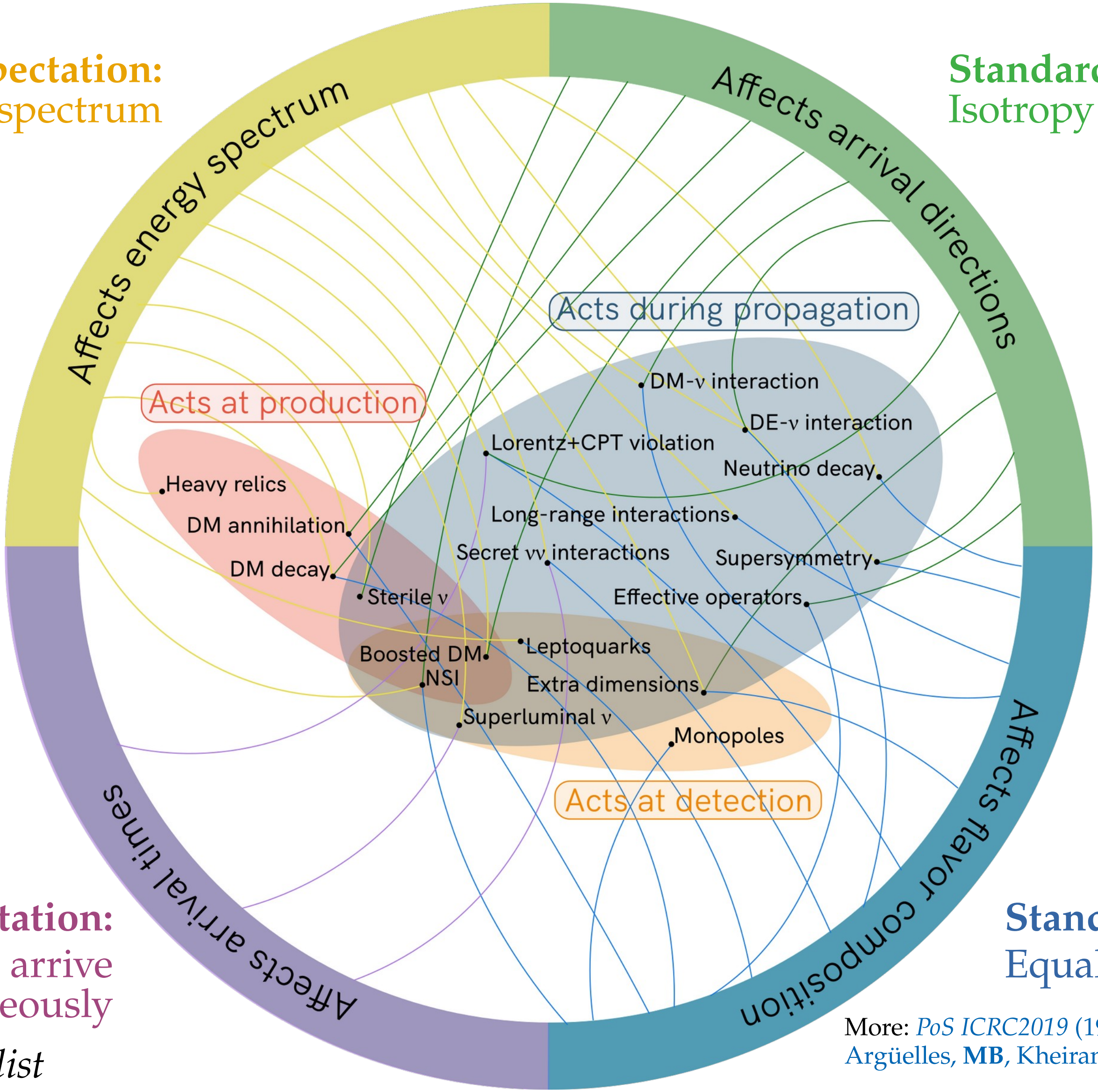

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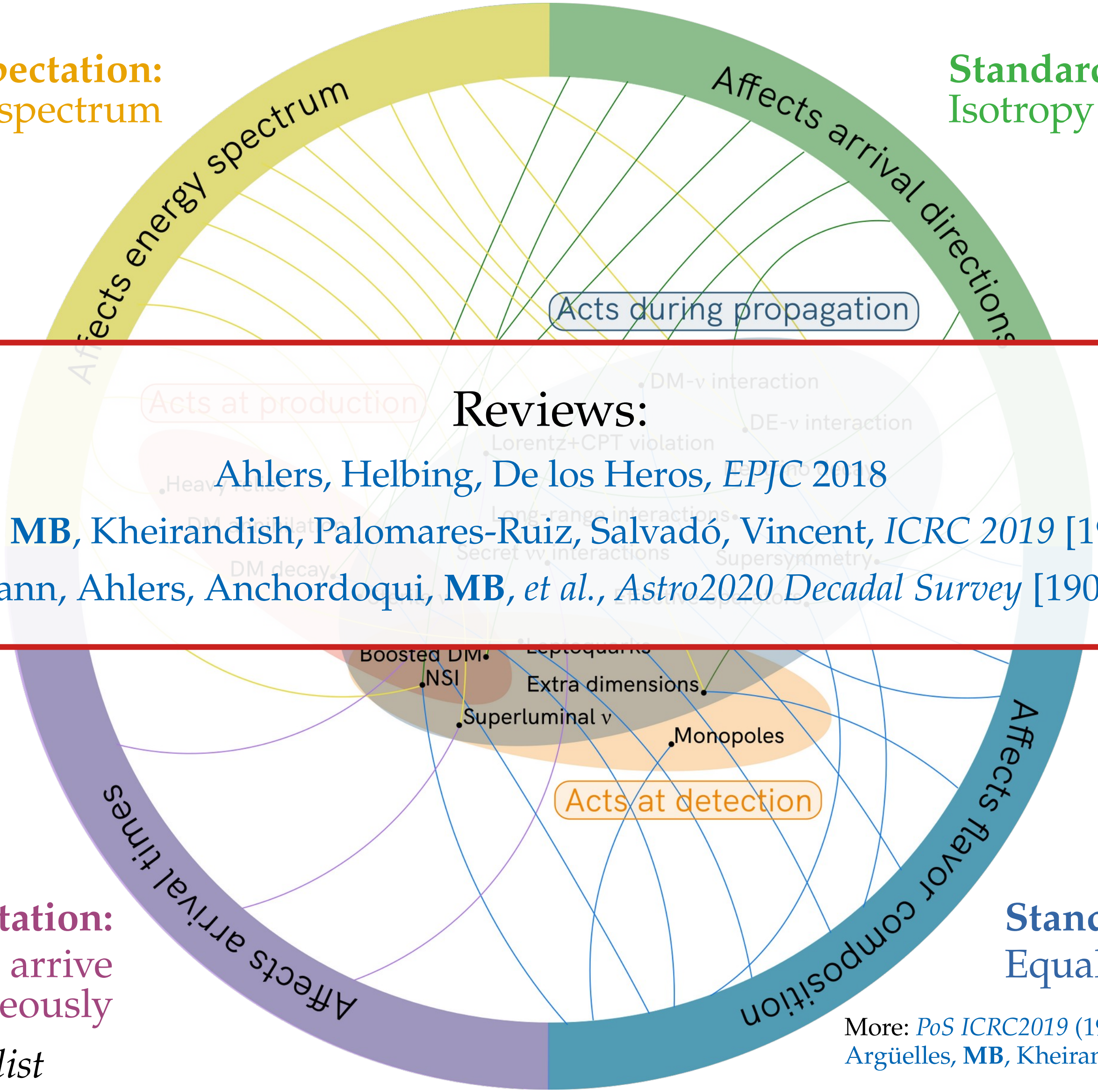

Reviews:

Ahlers, Helbing, De los Heros, *EPJC* 2018

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC 2019* [1907.08690]

Ackermann, Ahlers, Anchordoqui, **MB**, *et al.*, *Astro2020 Decadal Survey* [1903.04333]

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Today

TeV–PeV ν

Next decade

> 100-PeV ν

Today

TeV–PeV ν

Turn BSM predictions into data-driven tests

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Key developments:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

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Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

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Next decade

$>$ 100-PeV ν

Make predictions for BSM
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Key developments:
Discovery
New detection techniques
Better UHE ν flux predictions

Similar to the evolution of cosmology to a high-precision field in the 1990s

Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties


Not knowing the sources
Not knowing the ν production mechanism
(Us)
BSM using TeV– EeV ν
Low statistics / limited reconstruction


(Also us)
(*If* we factor in all the uncertainties)

What is unique about BSM with HE and UHE ν_τ?

From experiment

<u>High energies (TeV–PeV)</u>

<u>Ultra-high energies ($\geq$ 100 PeV)</u>

The also make up ~1/3 of the flux

Detectors sensitive to ν_τ only or especially

From theory

Test the three-flavor oscillation paradigm at large L and E

Sensitivity to six flavor-transition probabilities: $\nu_e \to \nu_\beta$, $\nu_\mu \to \nu_\beta$

Test flavor universality in νN interactions up to $s^{1/2} \sim 100$ TeV

What is unique about BSM with HE and UHE ν_τ?

From experiment

<u>High energies (TeV–PeV)</u>

The make up ~1/3 of the flux

Needed for precision flavor studies

<u>Ultra-high energies ($\geq$ 100 PeV)</u>

The also make up ~1/3 of the flux

Detectors sensitive to ν_τ only or especially

From theory

τ-sector BSM couplings are the least constrained

Test the three-flavor oscillation paradigm at large L and E

Sensitivity to six flavor-transition probabilities: $\nu_e \to \nu_\beta$, $\nu_\mu \to \nu_\beta$

Test flavor universality in νN interactions up to $s^{1/2} \sim 100$ TeV

What BSM effects do we focus on?

1. Flavor stuff
2. Cross-section stuff
3. Energy-spectrum stuff

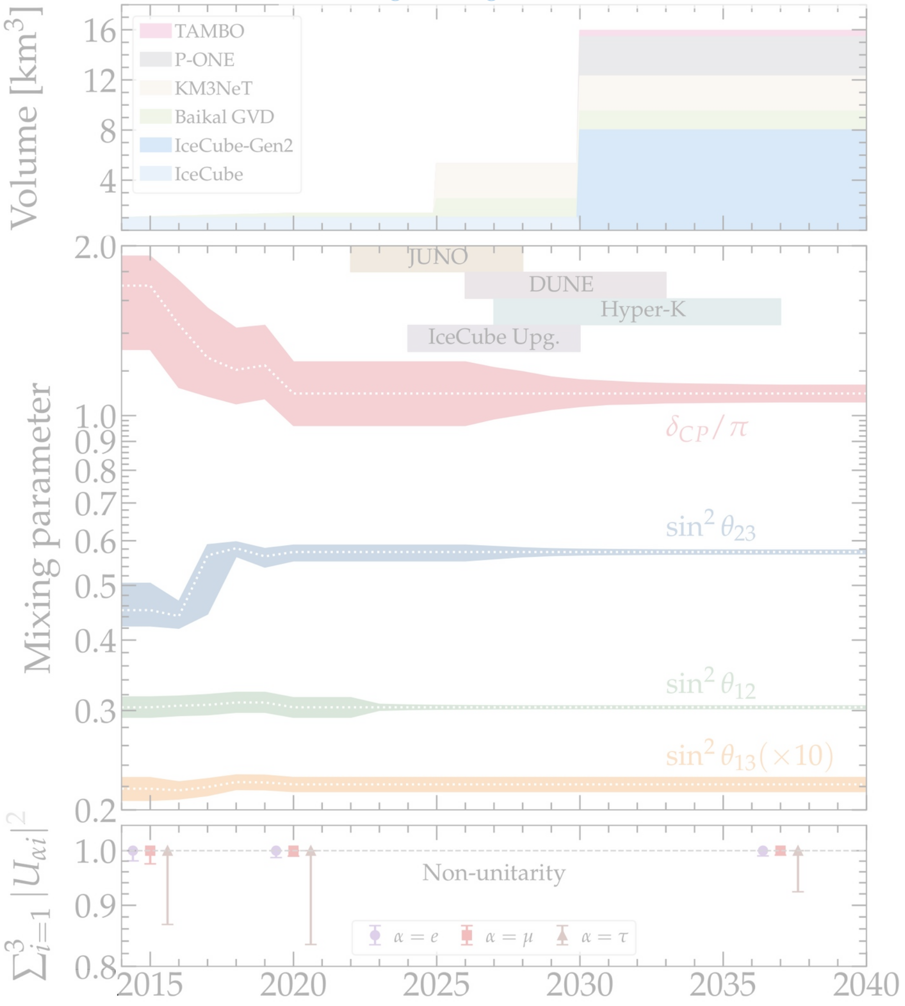
Good chances of discovery or setting strong bounds

Keep ourselves grounded by accounting for all relevant particle and astrophysics unknowns

Flavor:
Towards precision

Three reasons to be excited

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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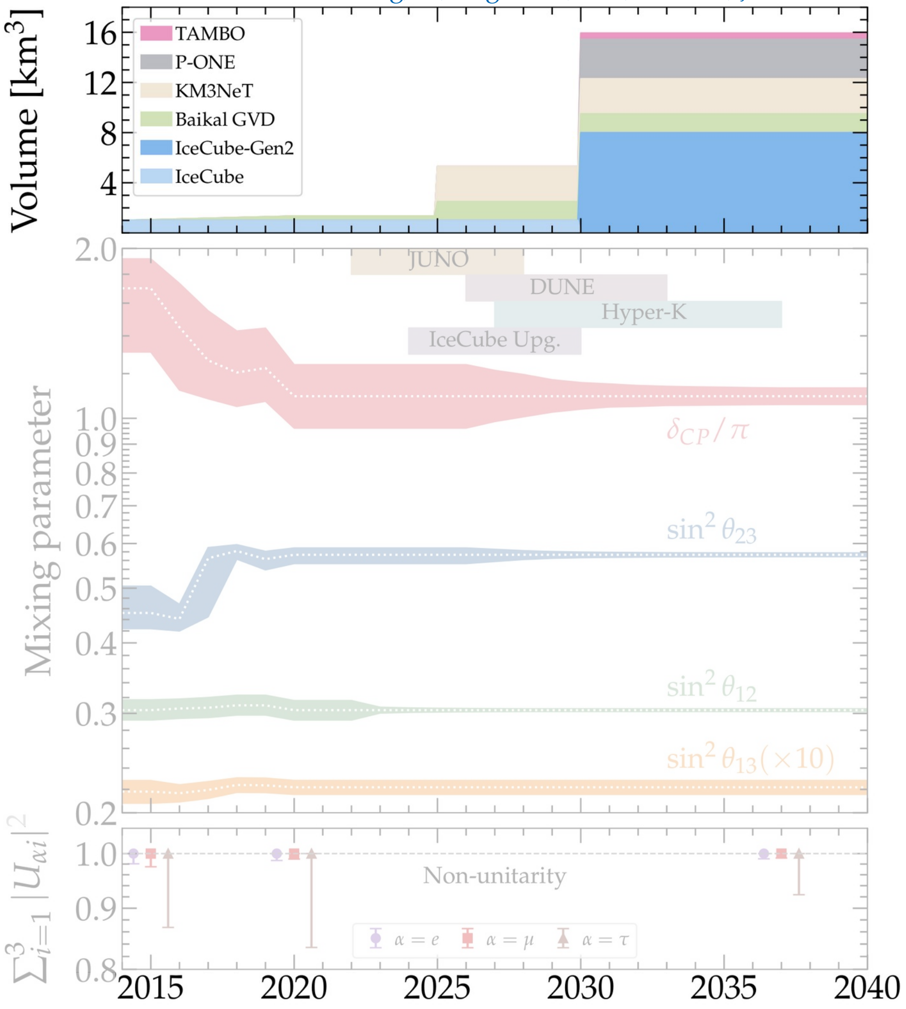

Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

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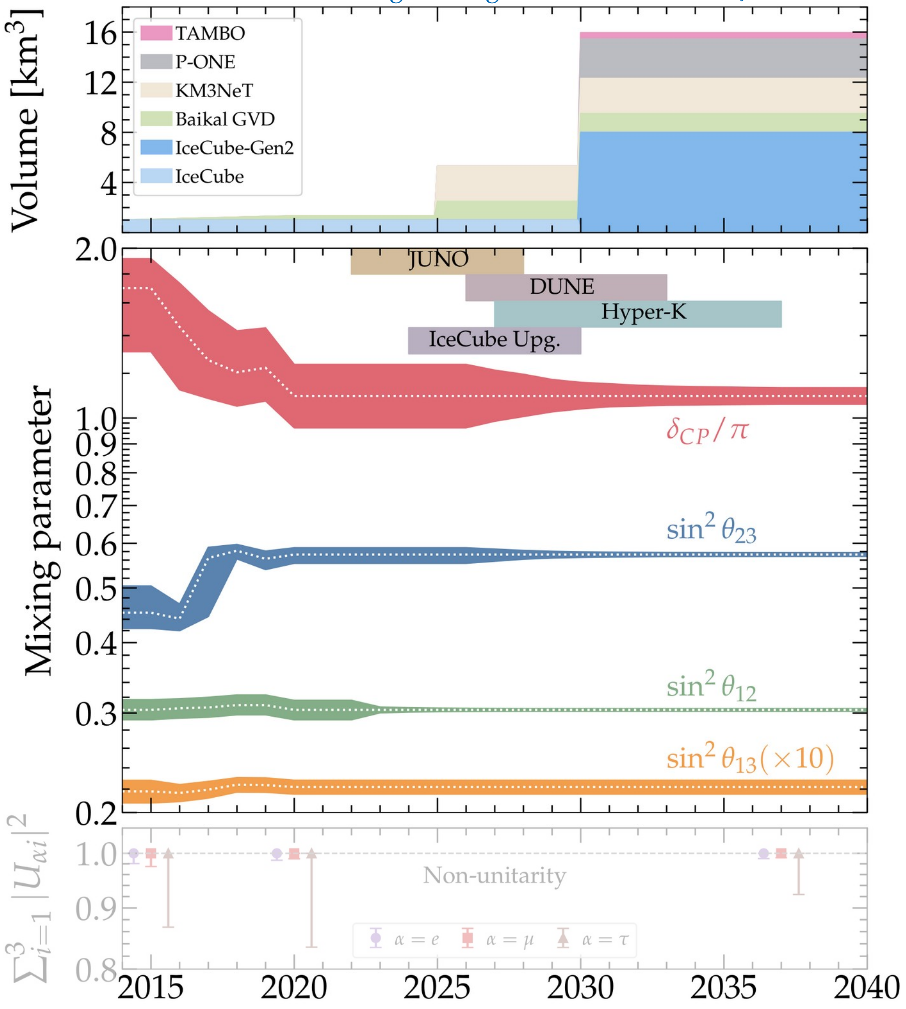

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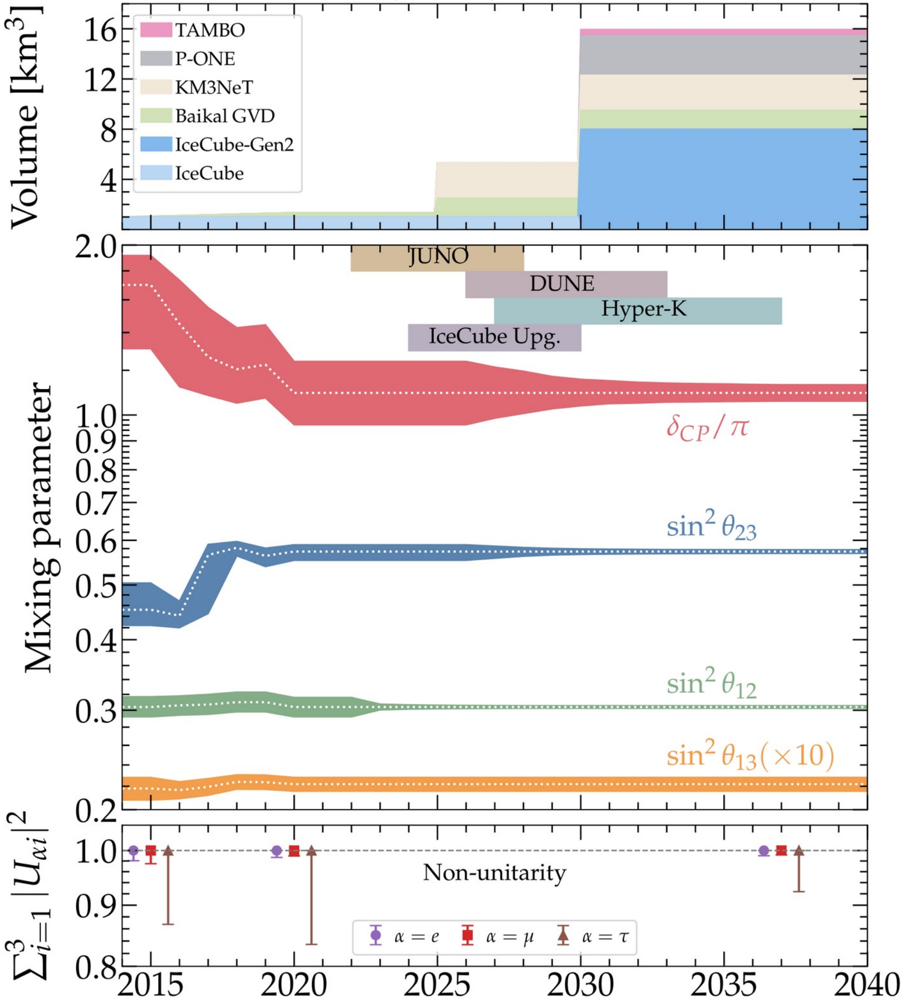

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Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

Test of the oscillation framework:
We will be able to do what we want even if oscillations are non-unitary

One likely TeV–PeV ν production scenario:

$$p + \gamma \to \pi^+ \to \mu^+ + \nu_\mu \quad \text{followed by} \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Full π decay chain

$(1/3:2/3:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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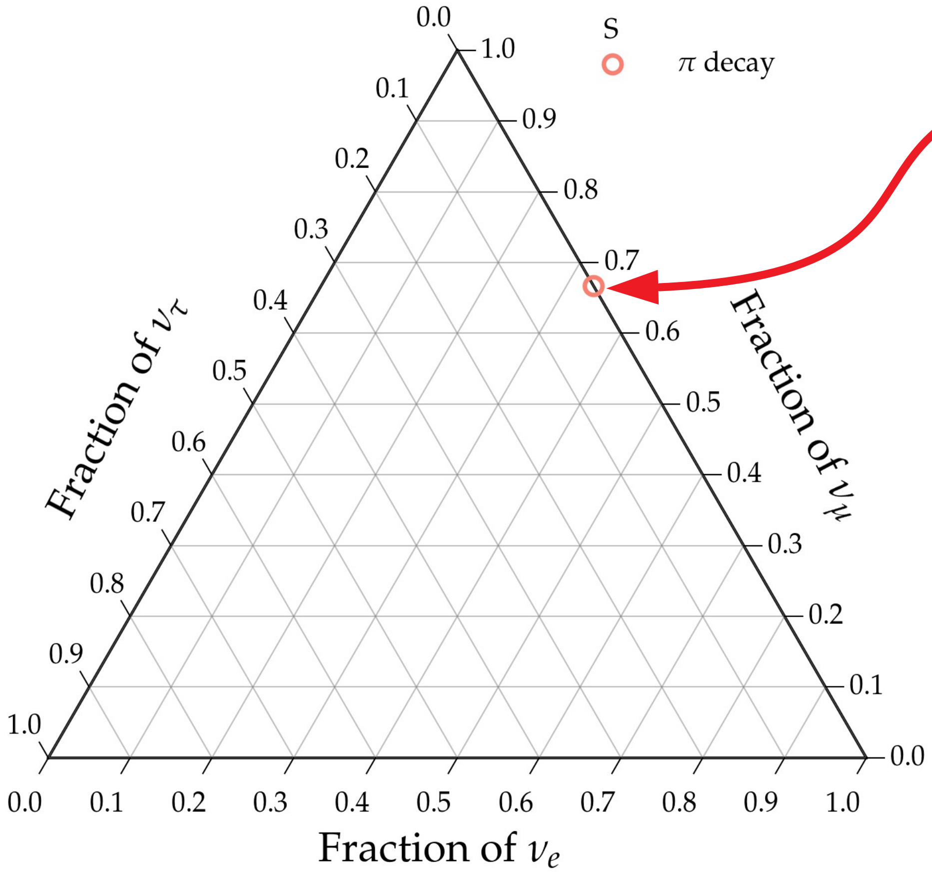

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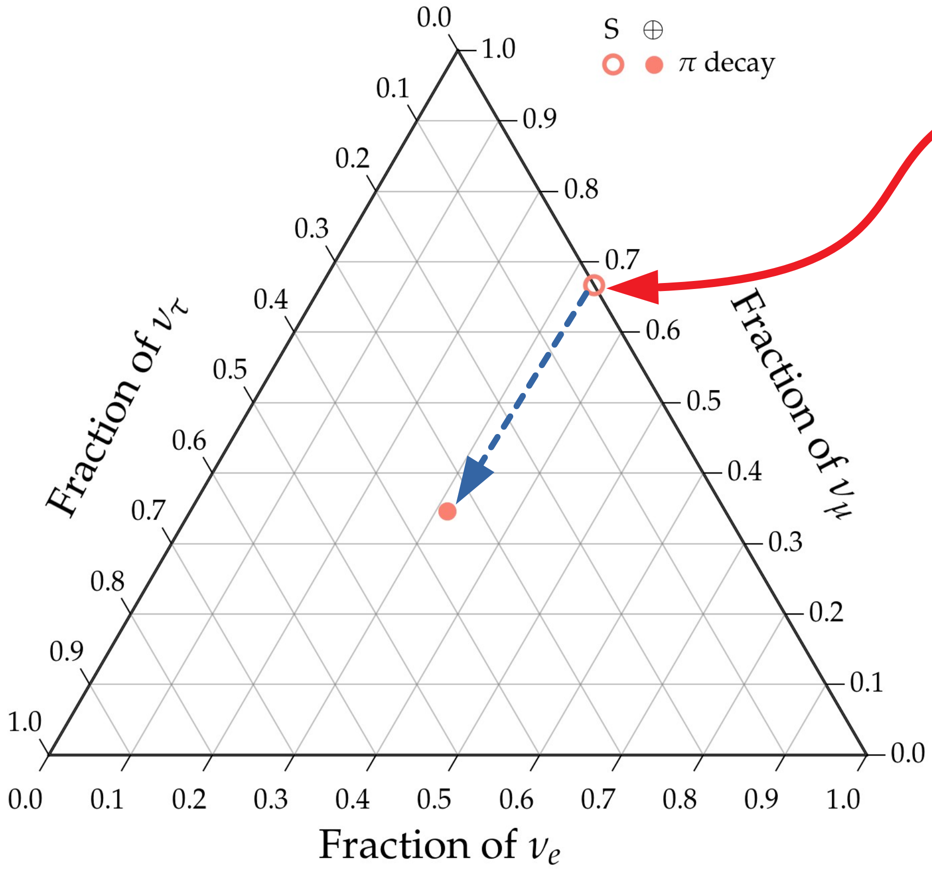

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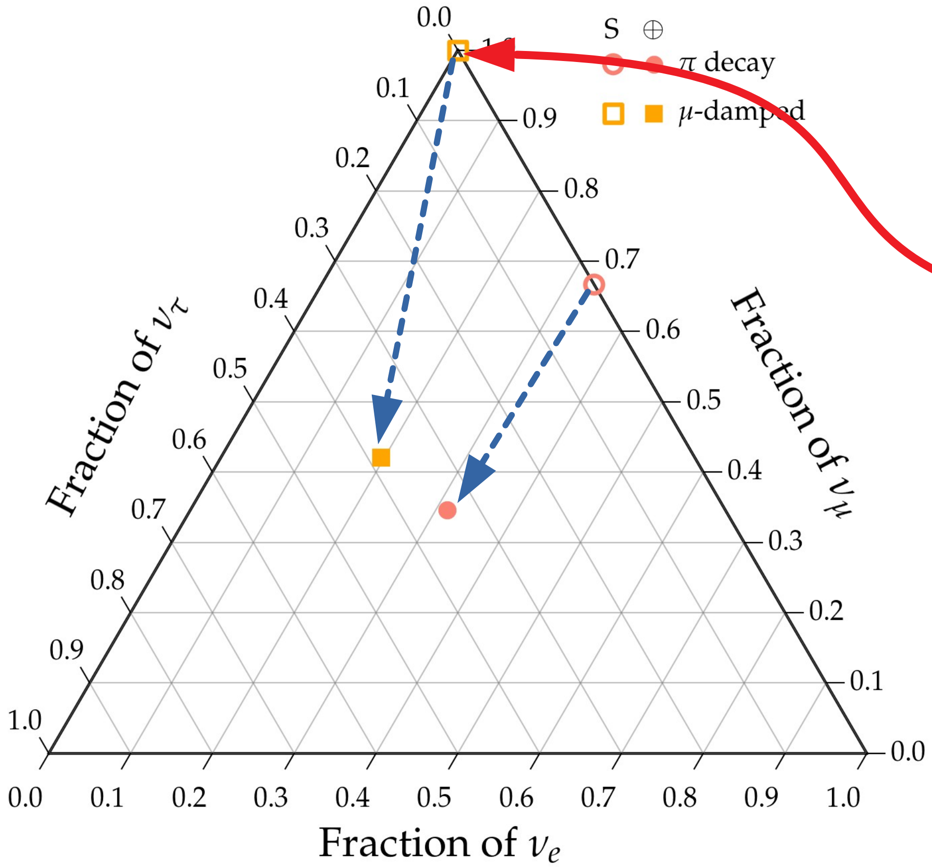

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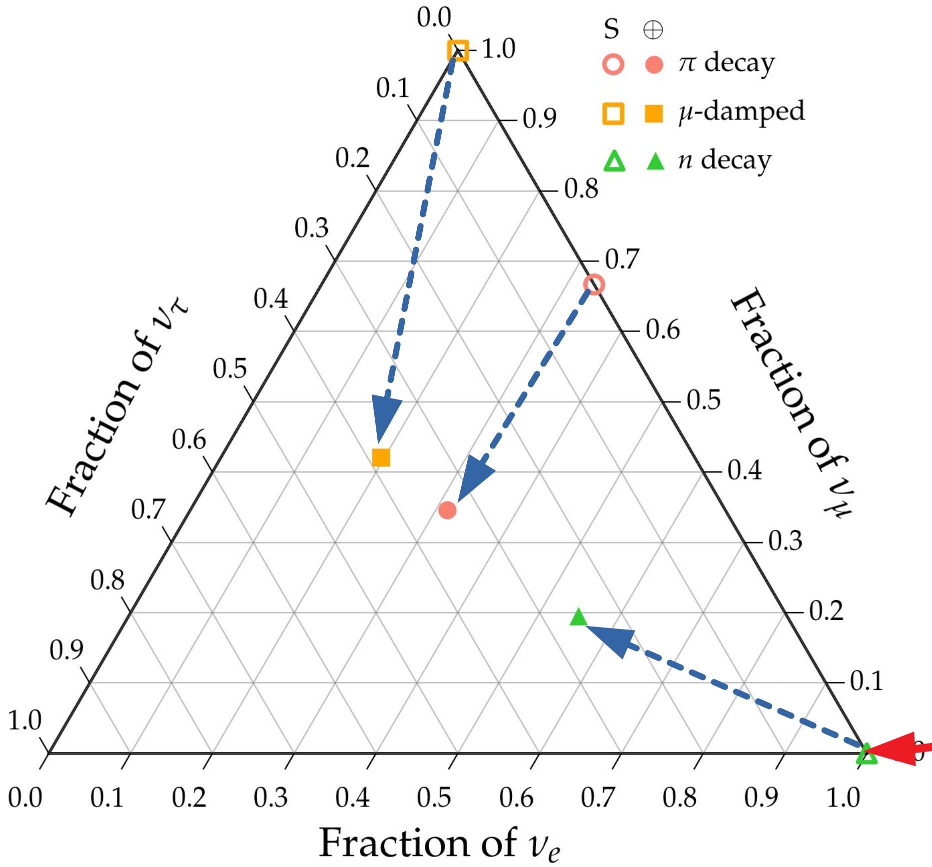

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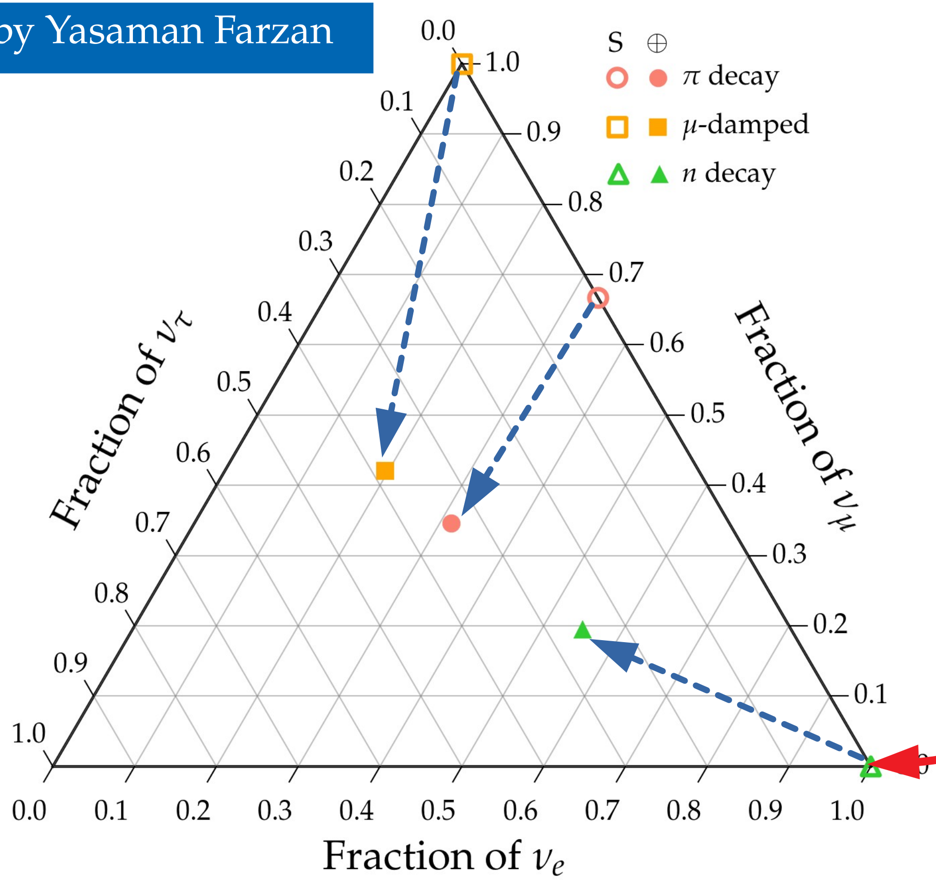
See talk by Yasaman Farzan



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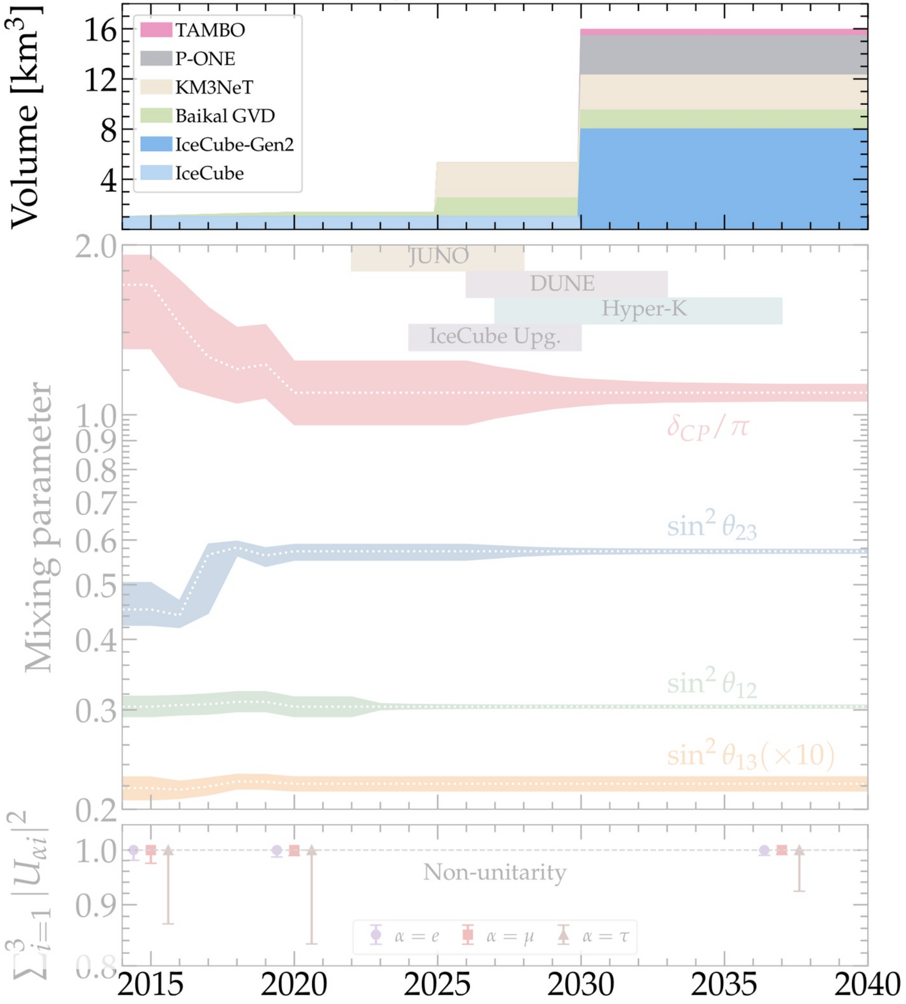
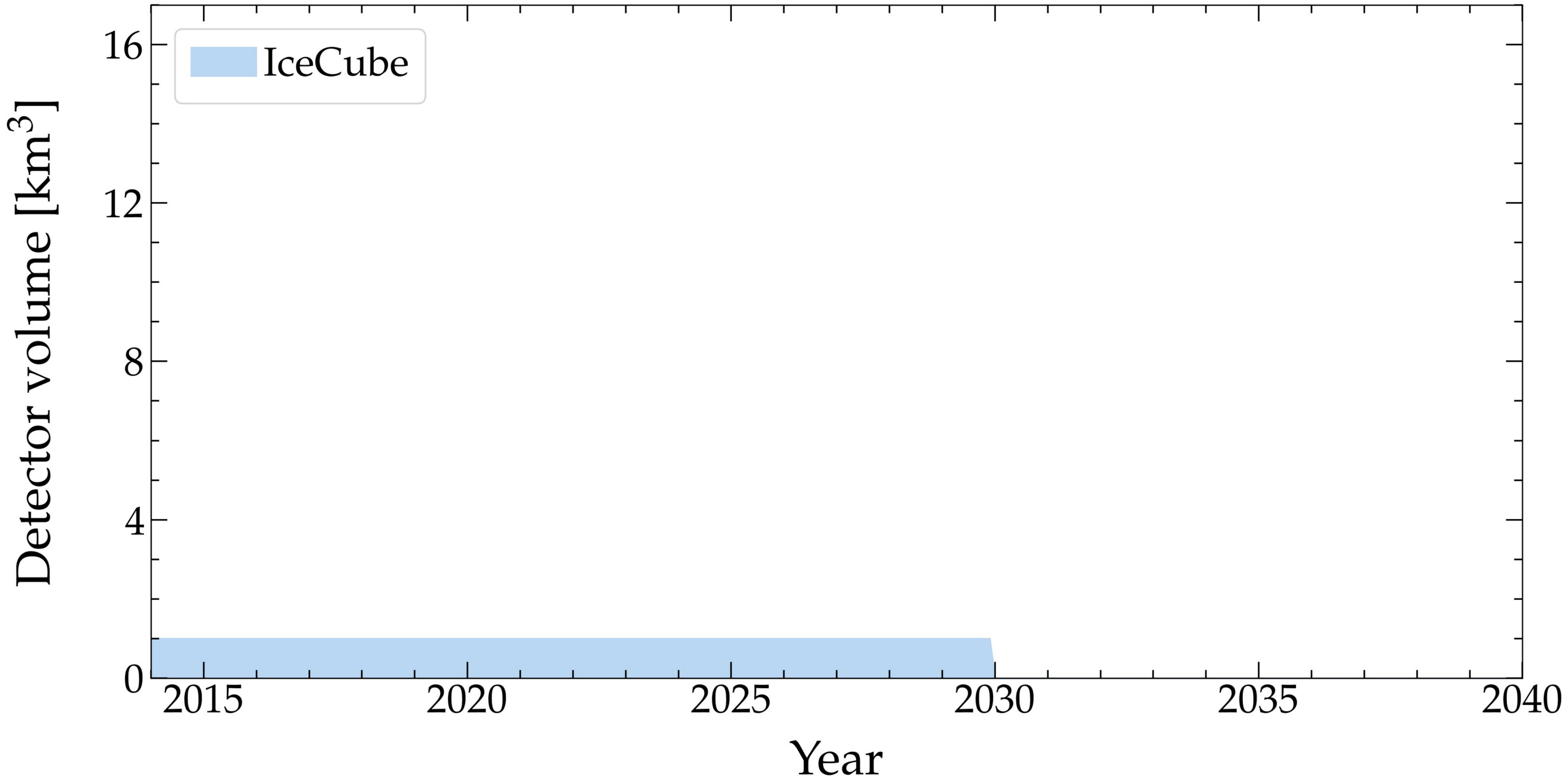
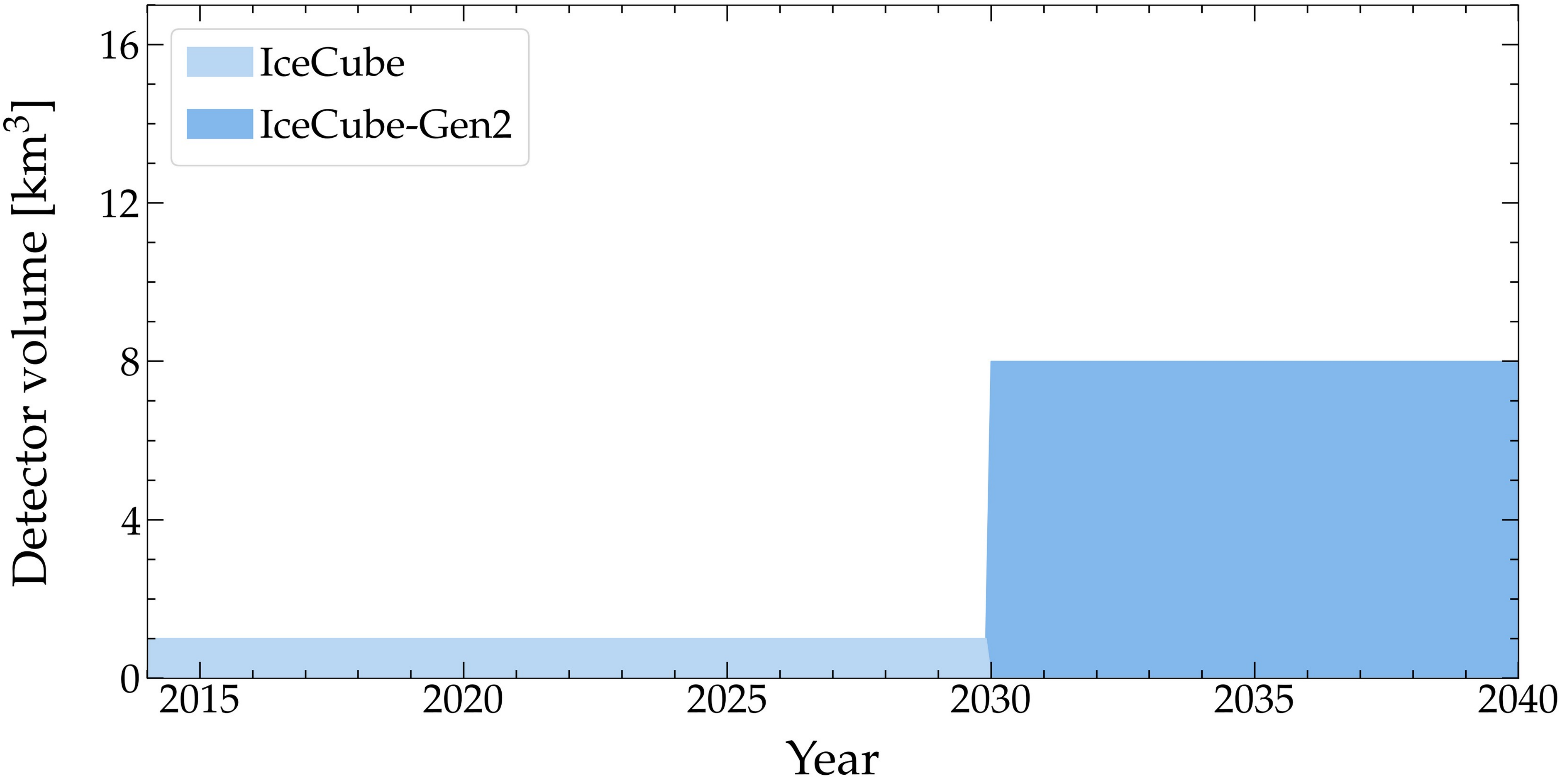
Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021





Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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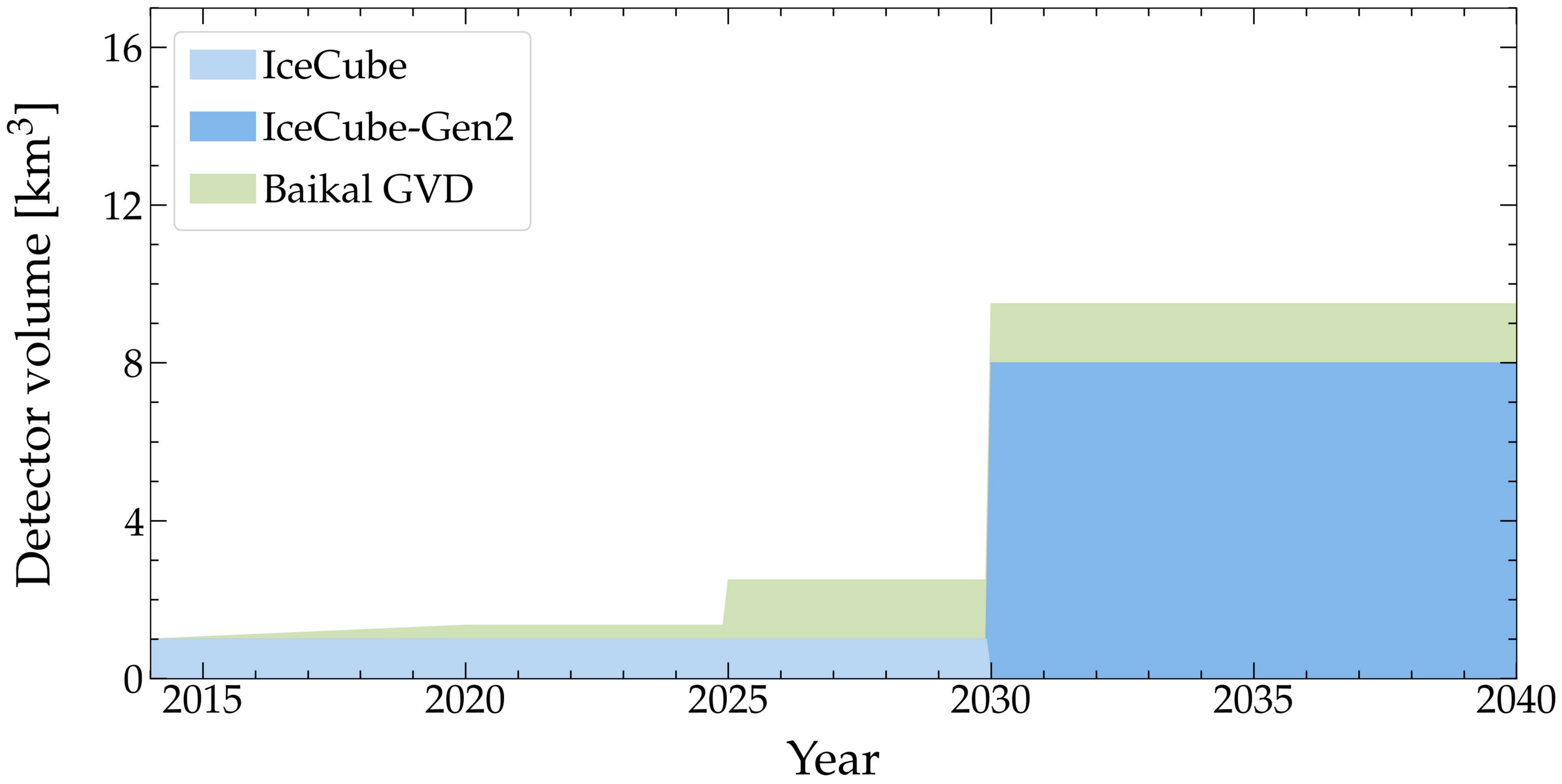

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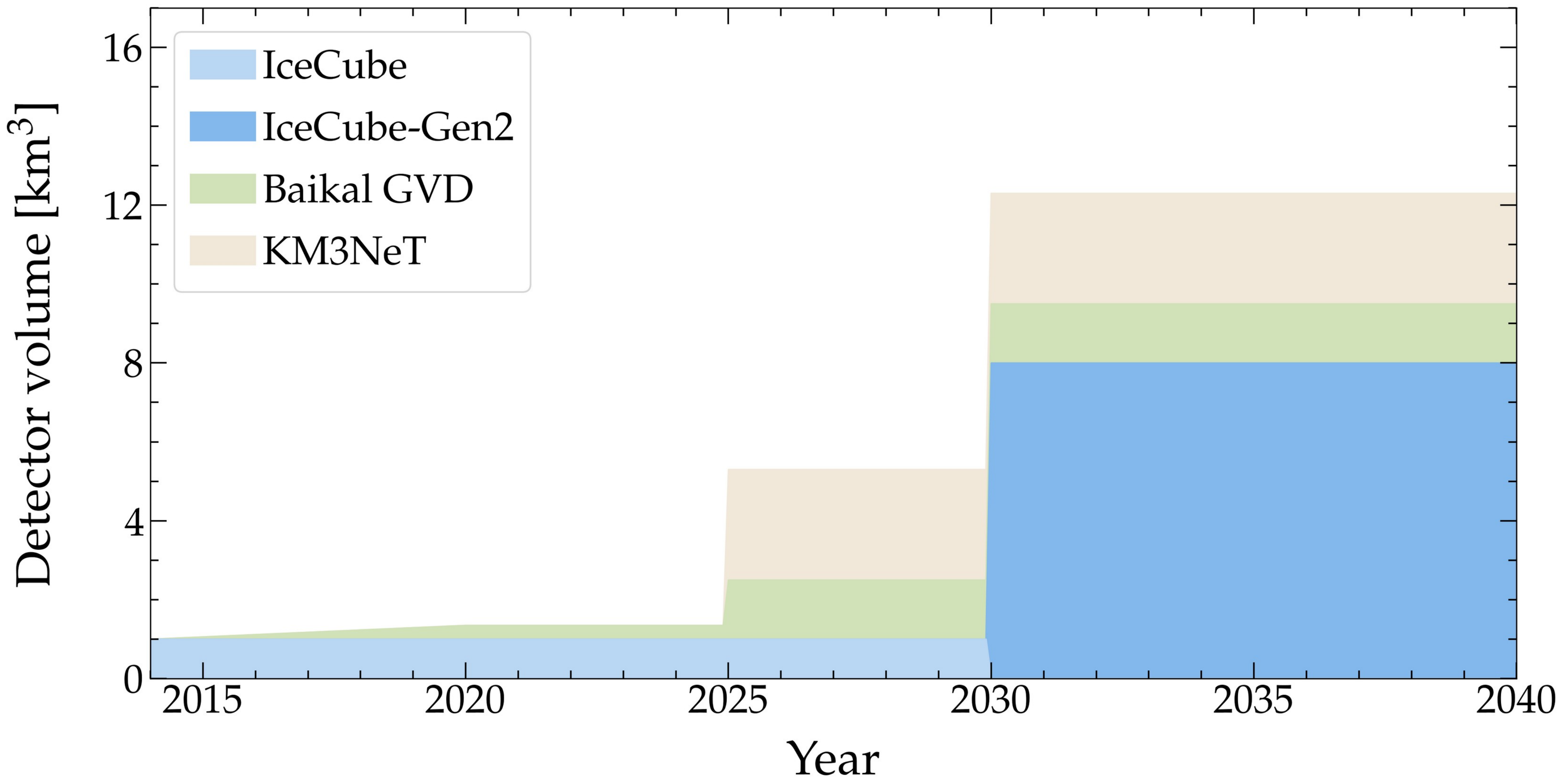

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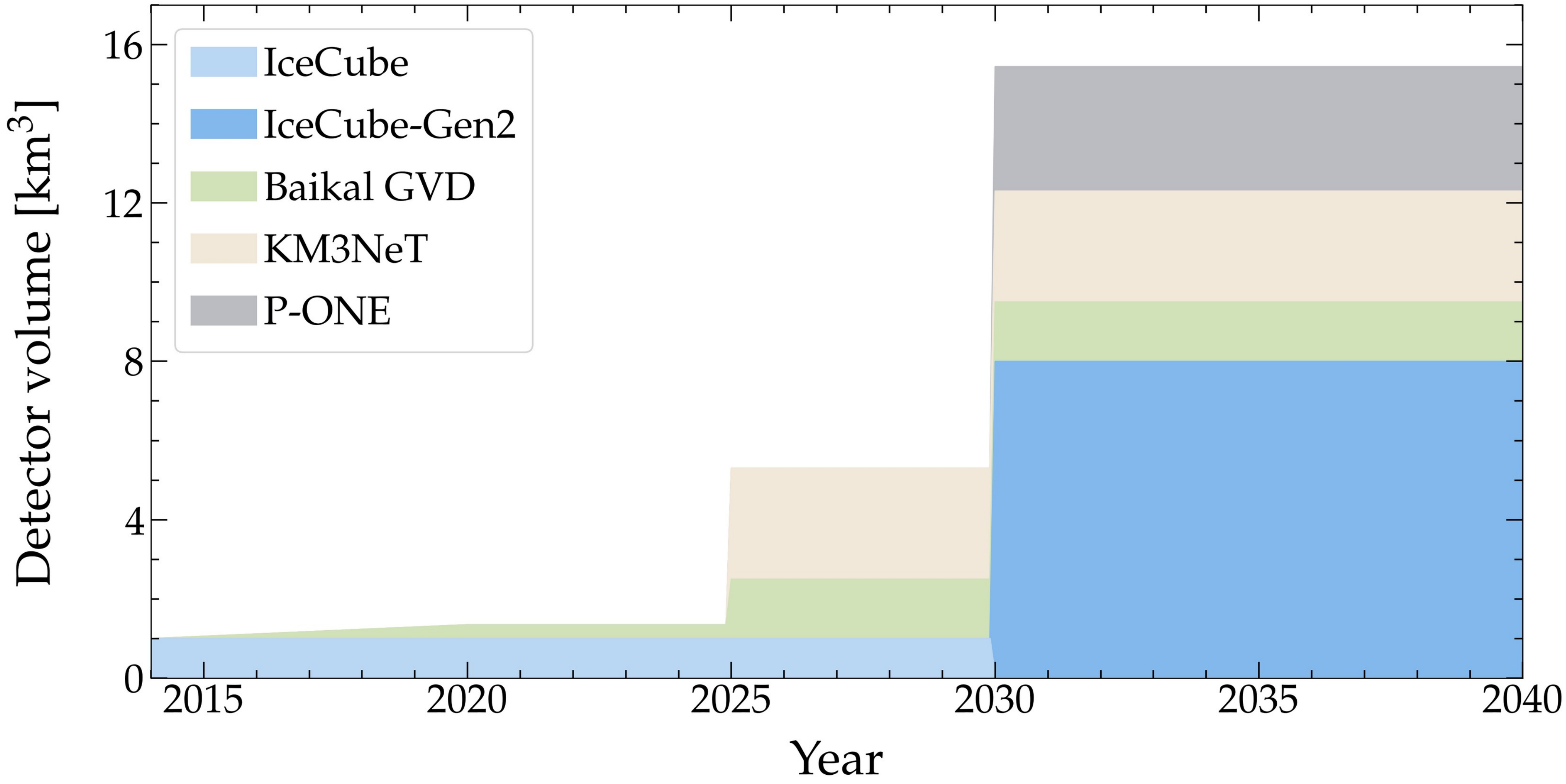

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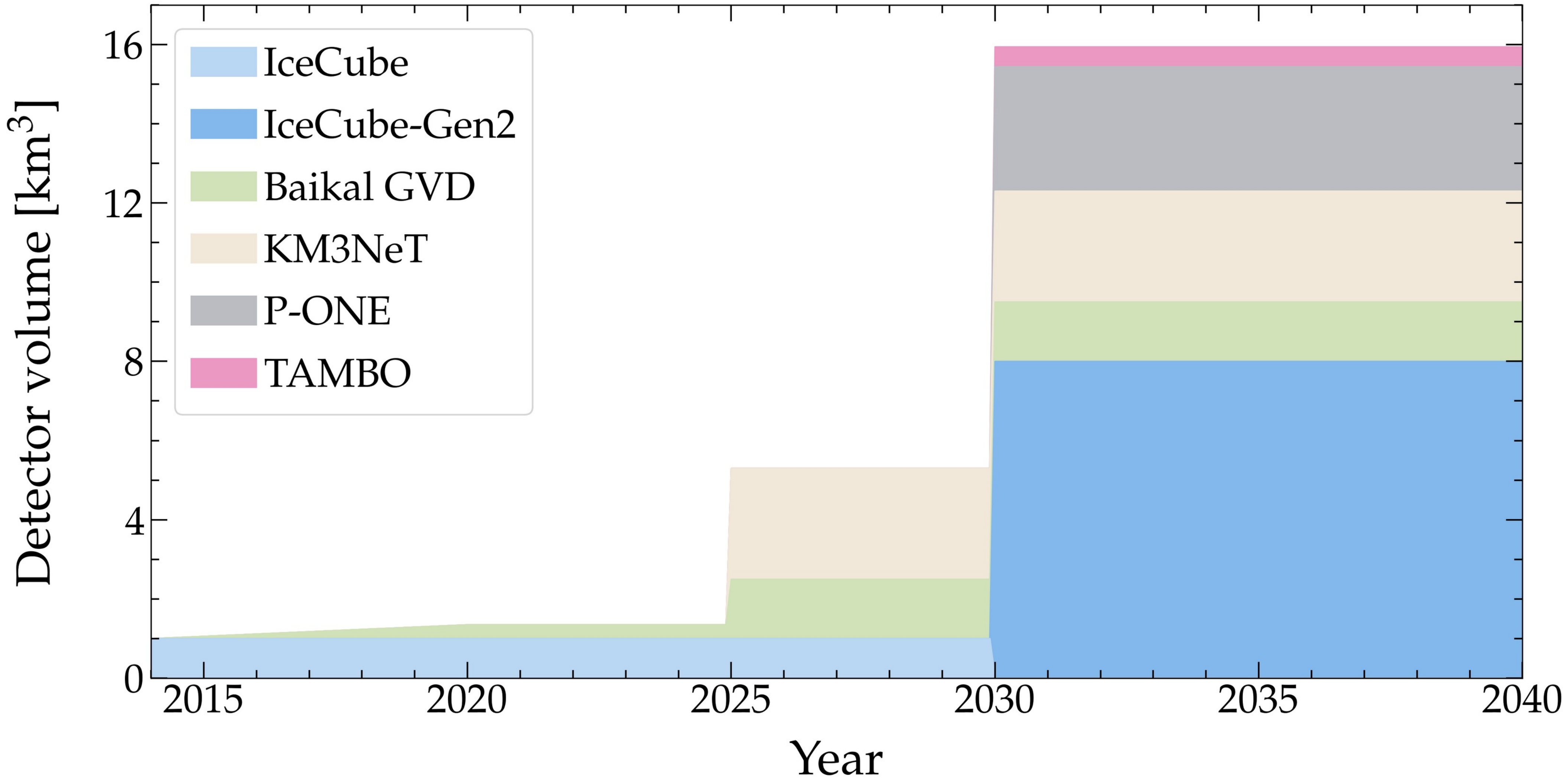

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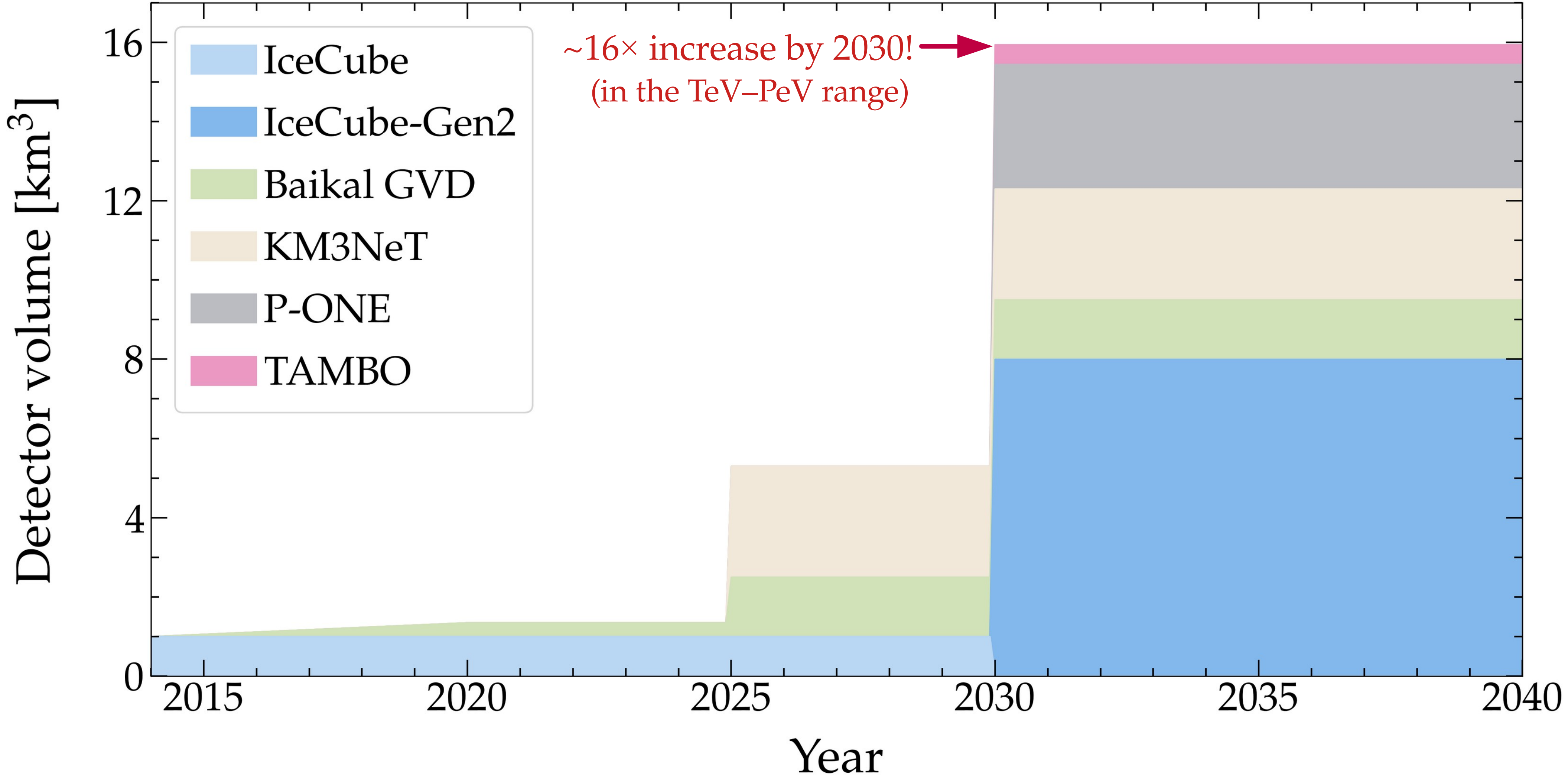
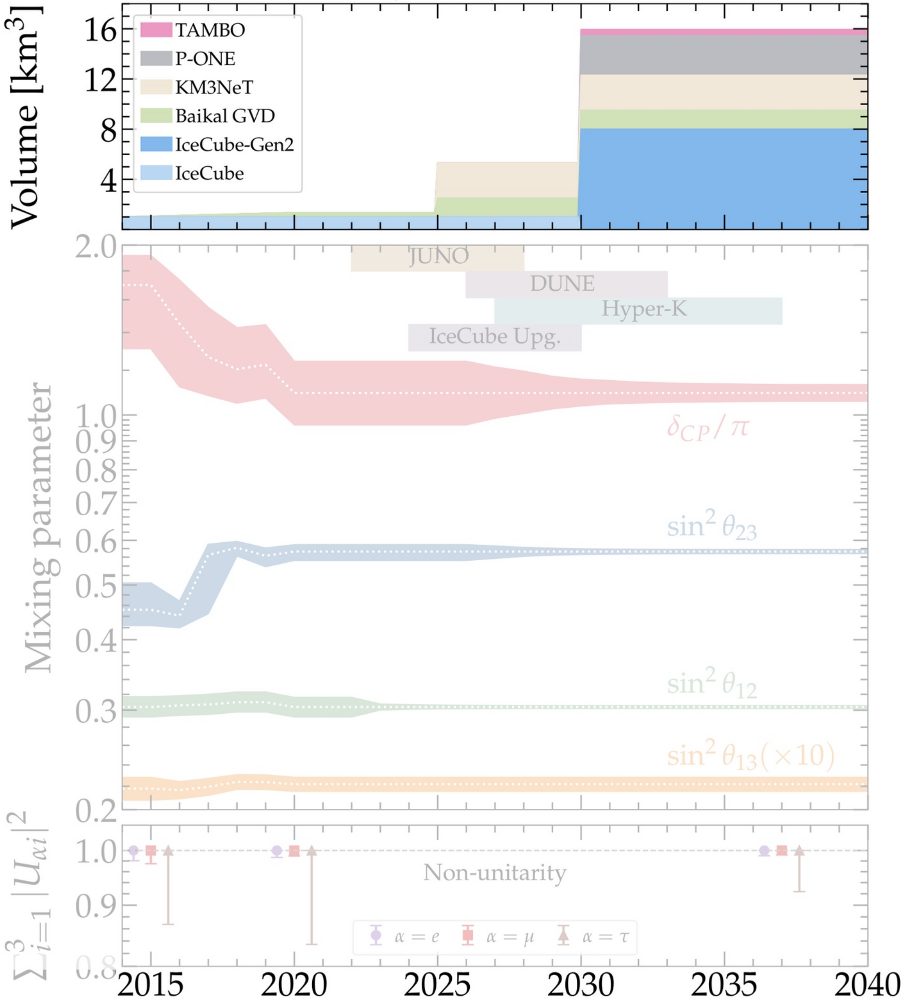


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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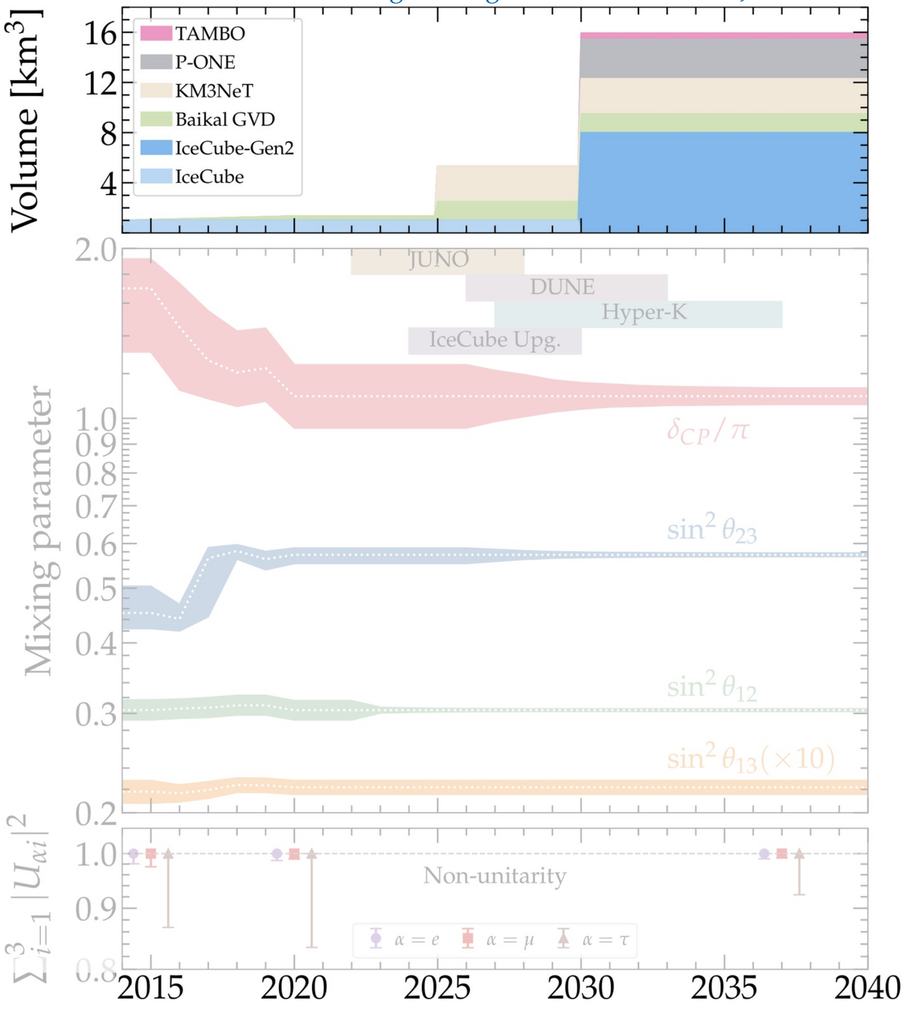

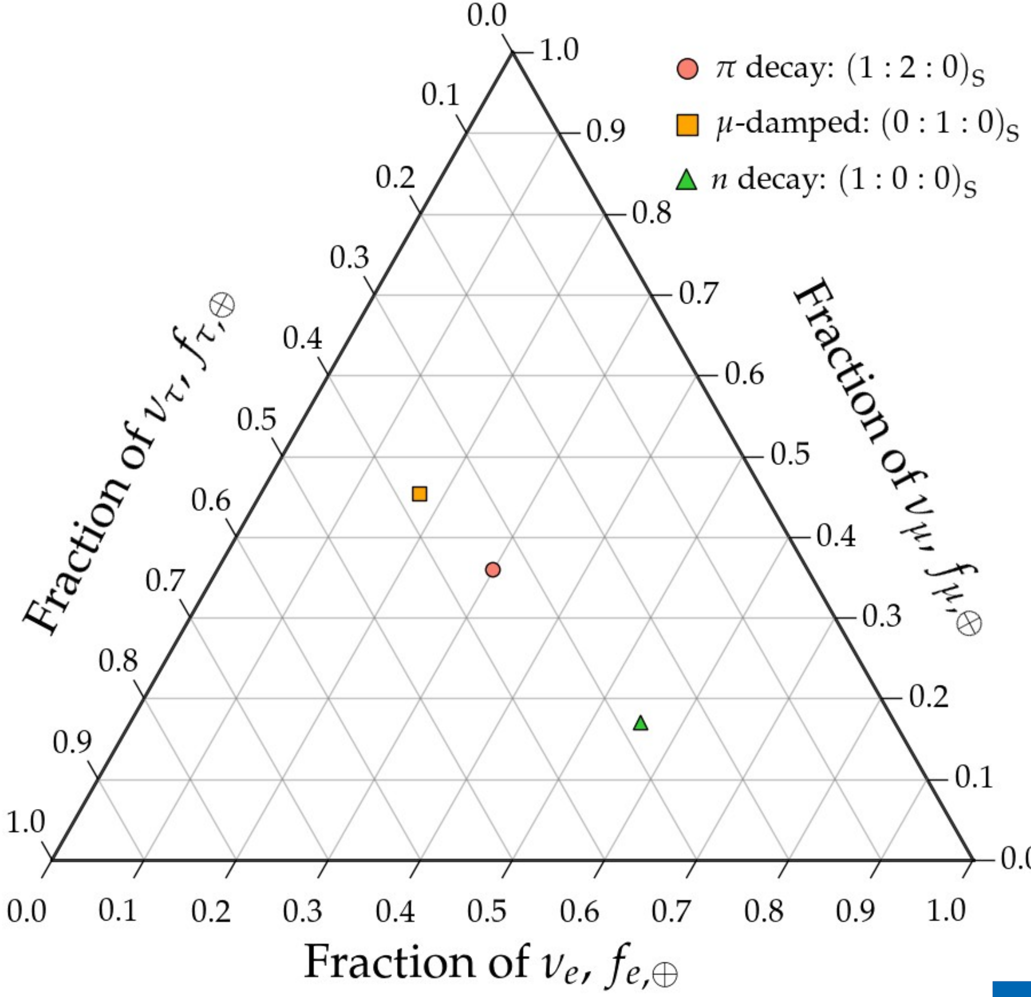

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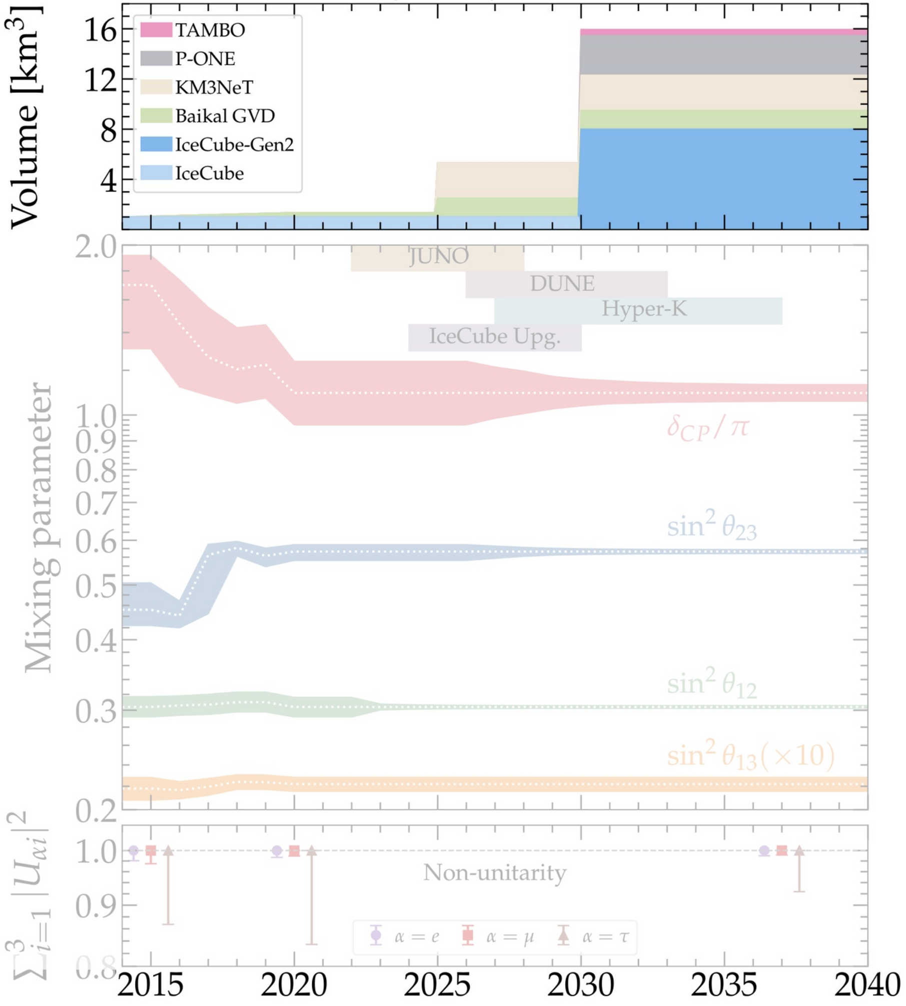

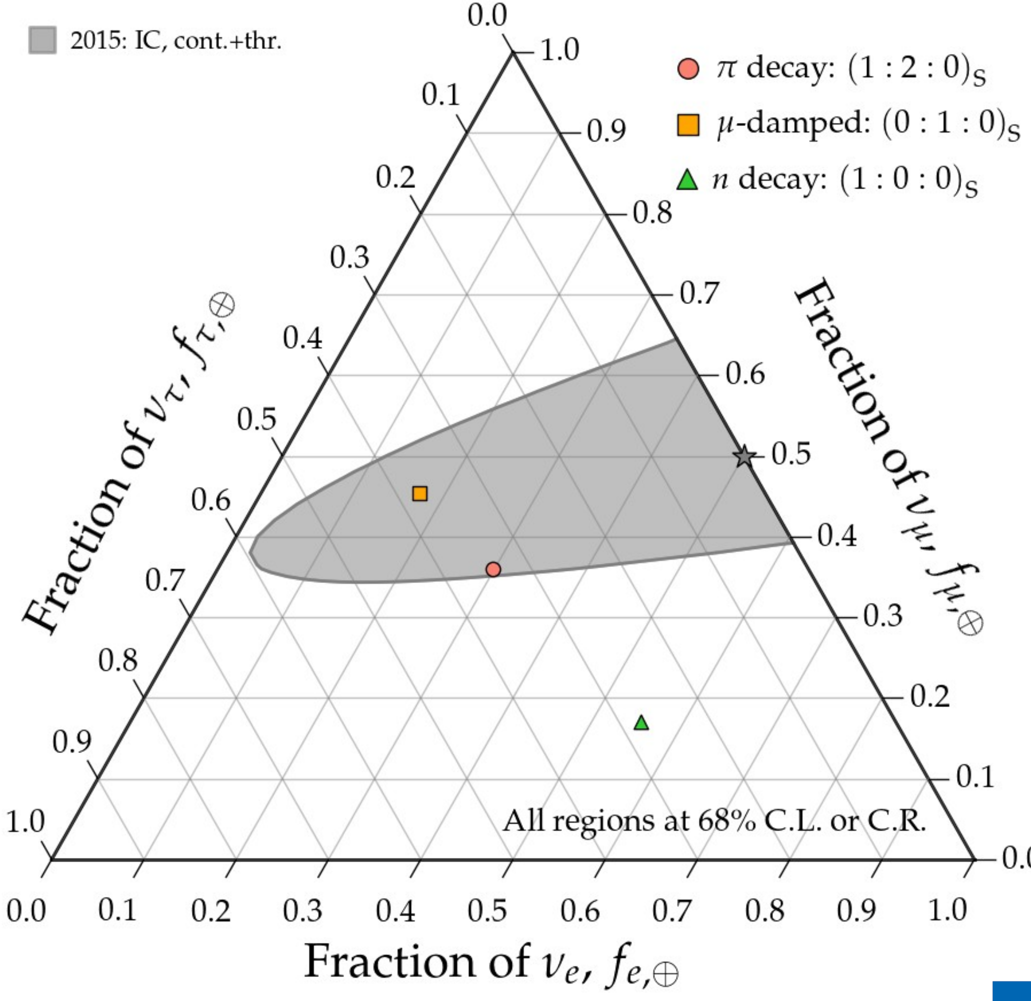

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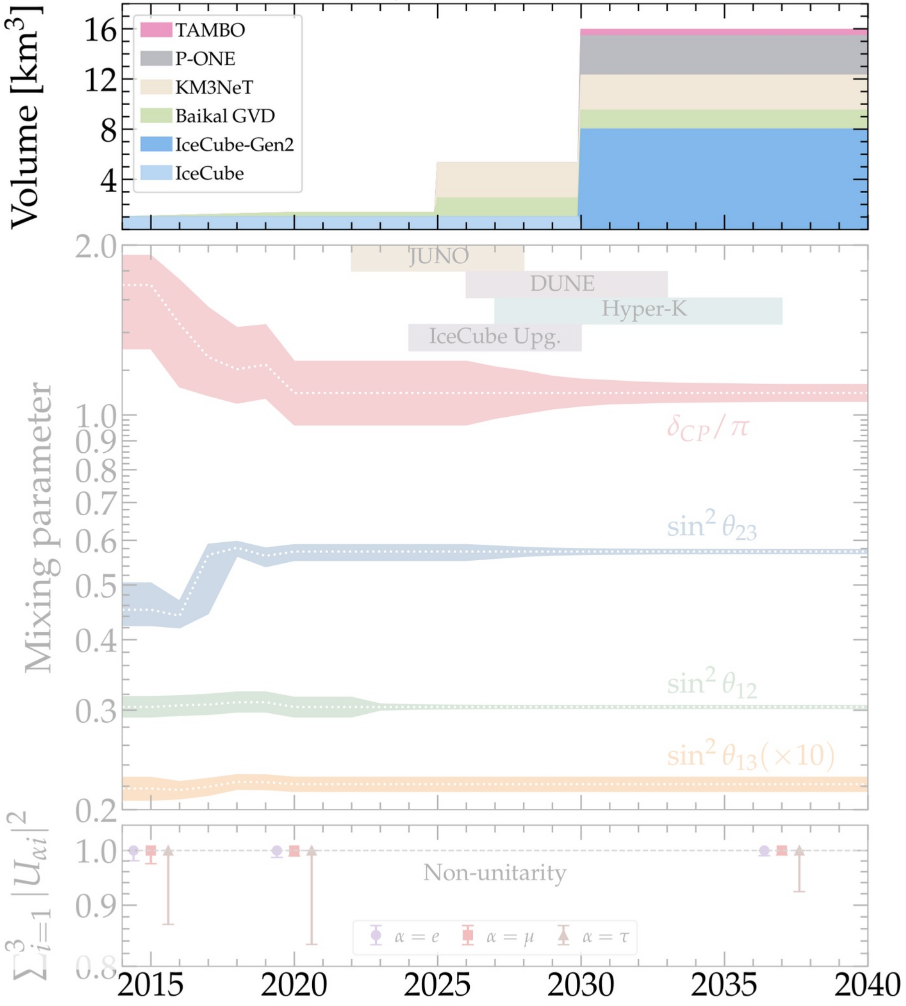

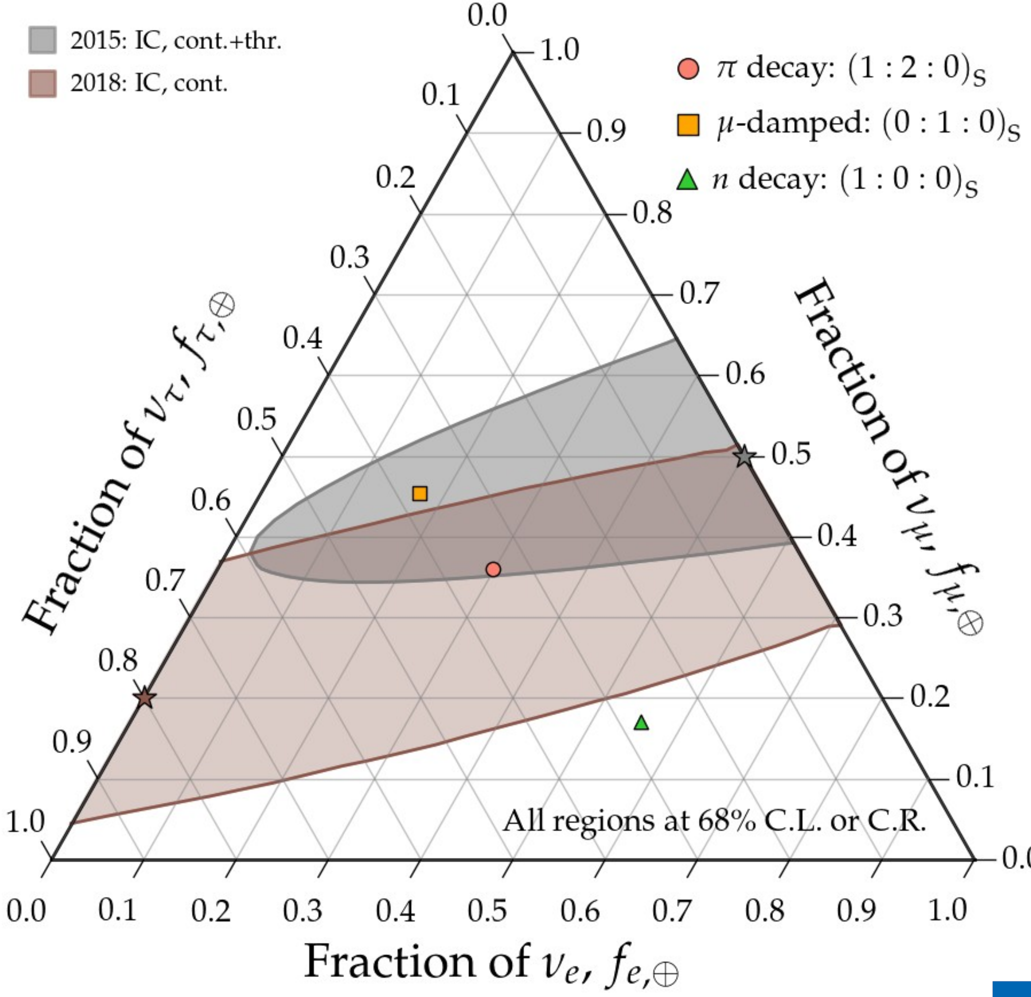

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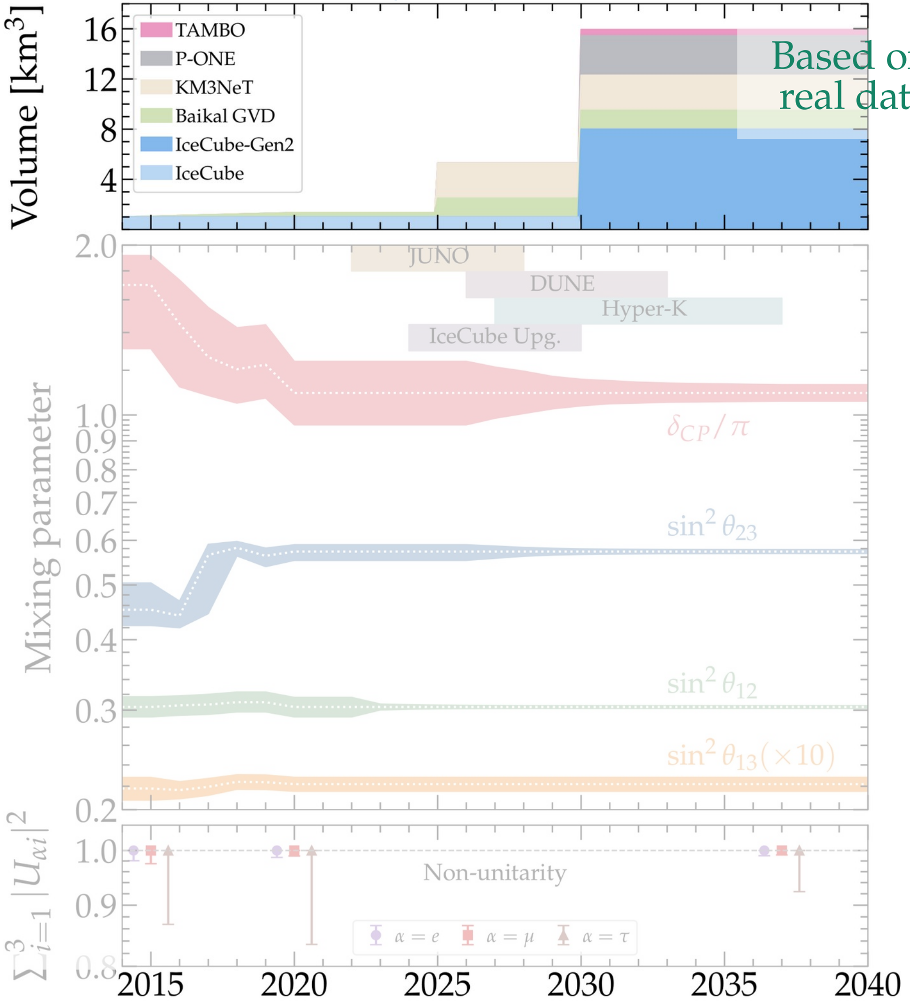

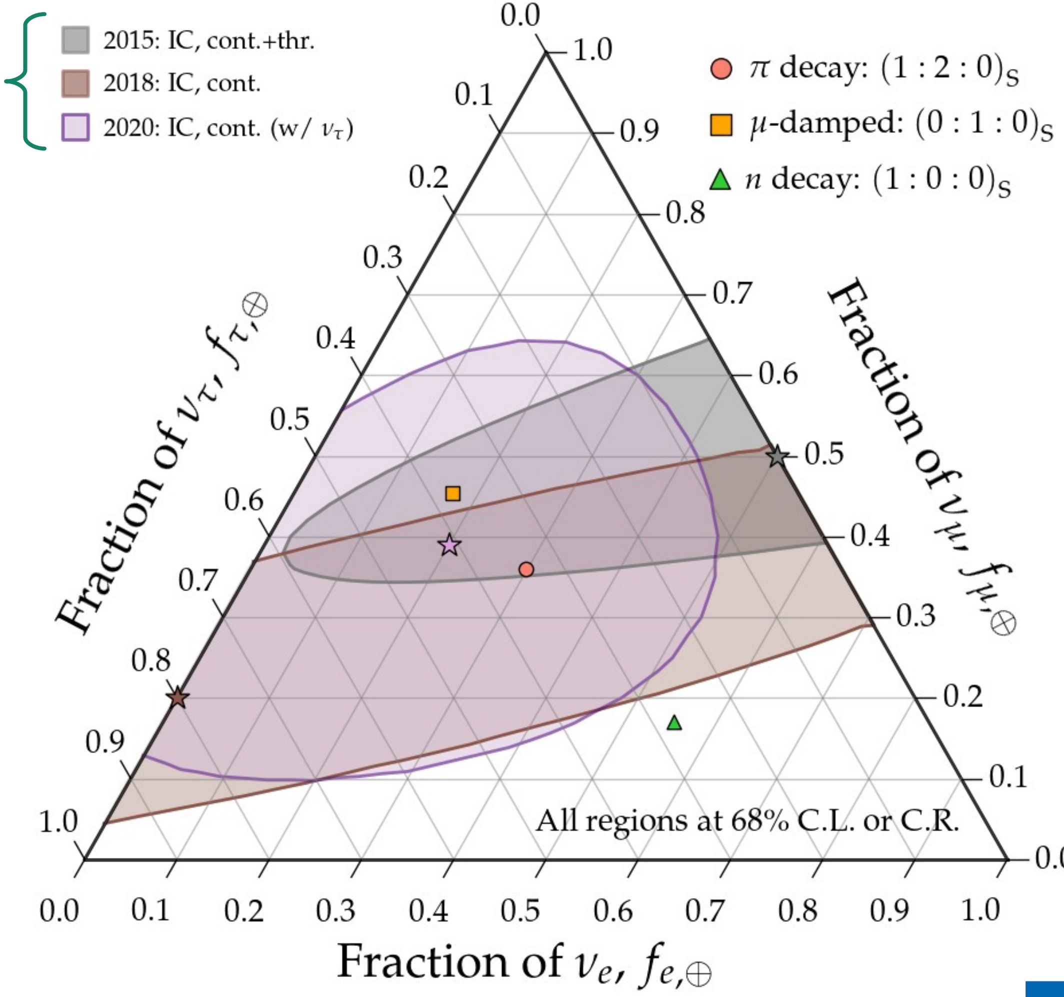

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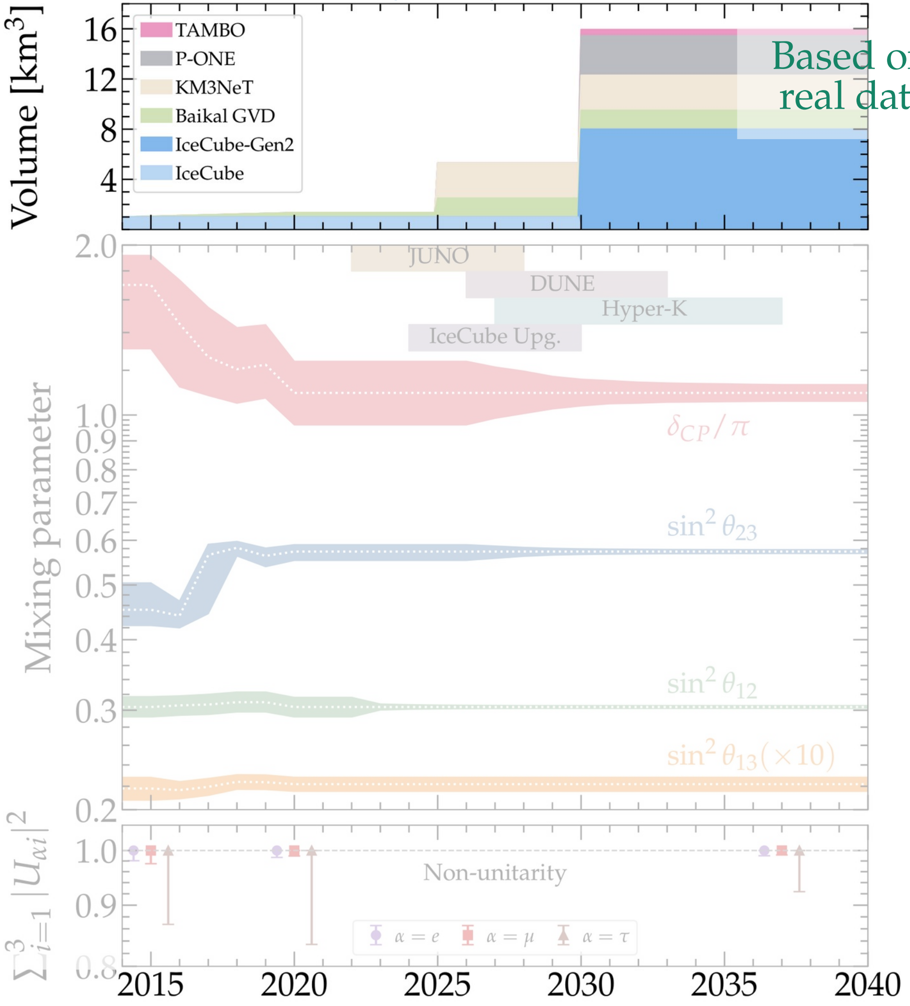

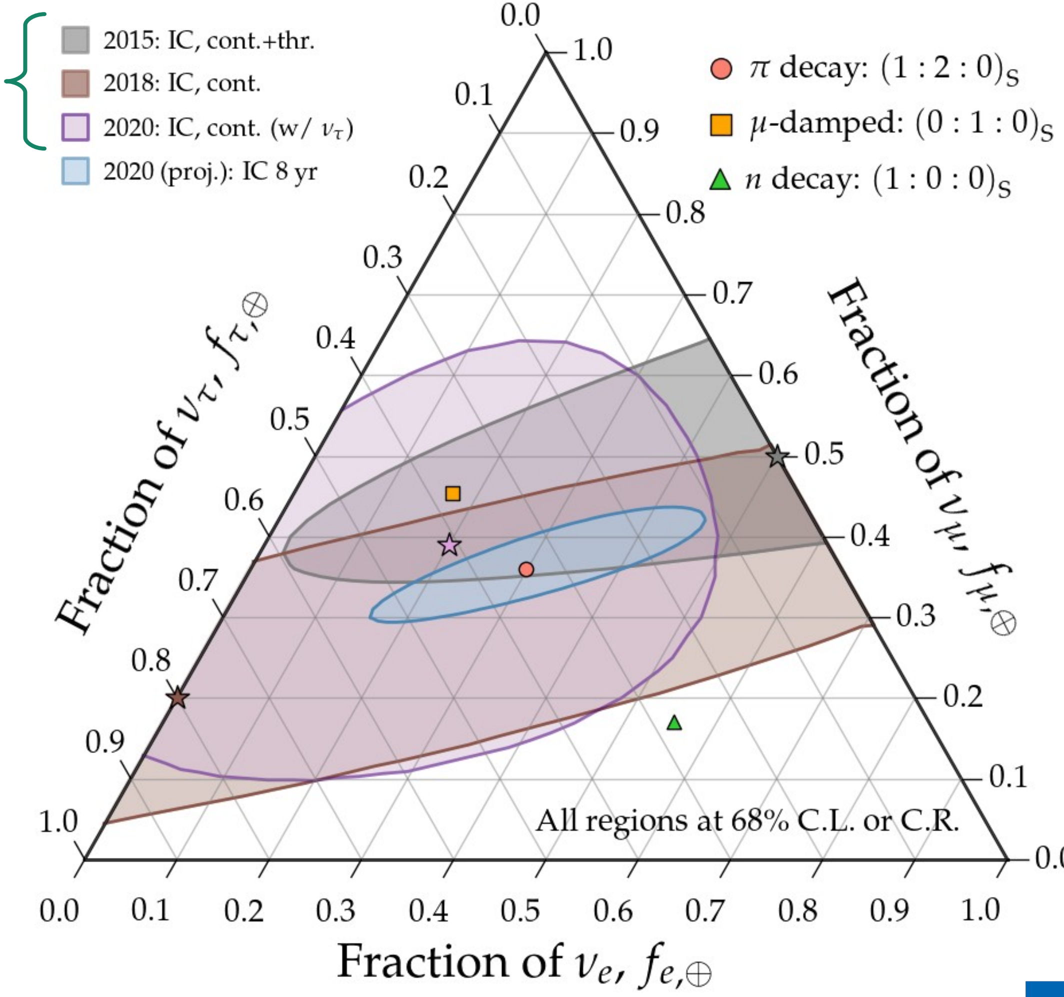

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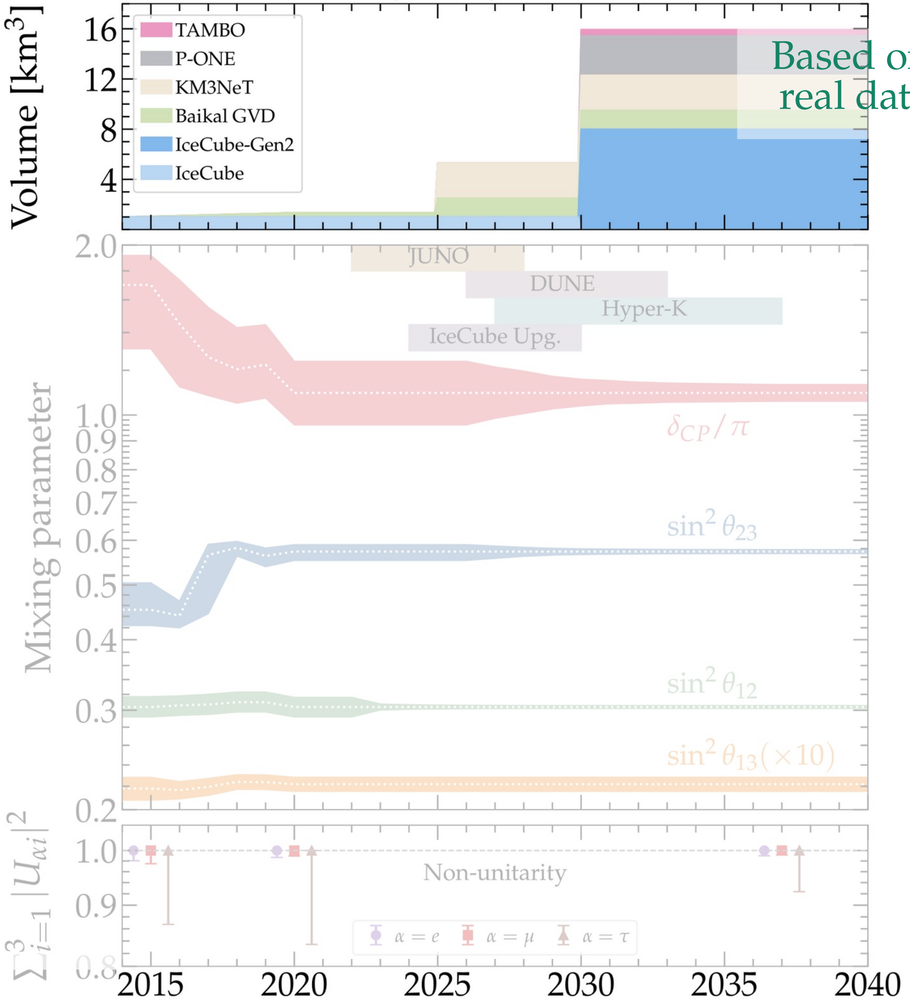
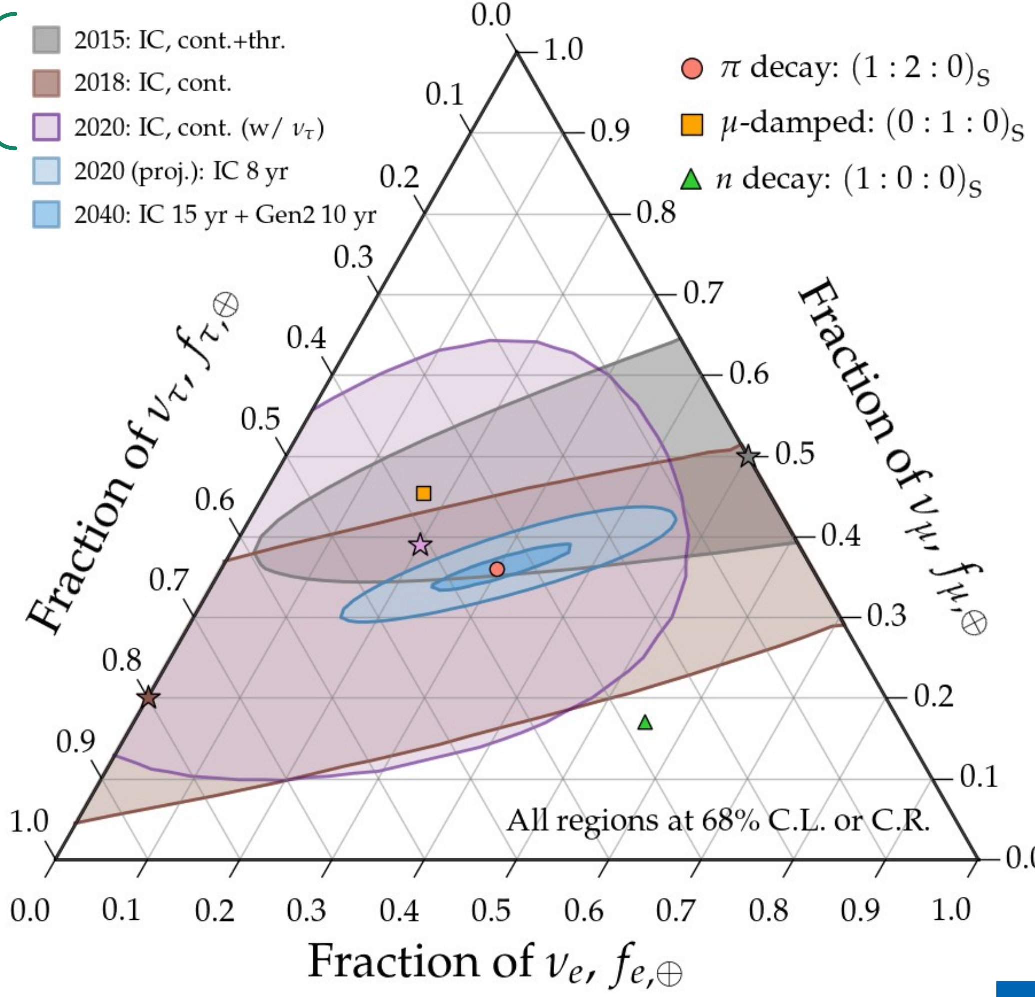


Based on real data



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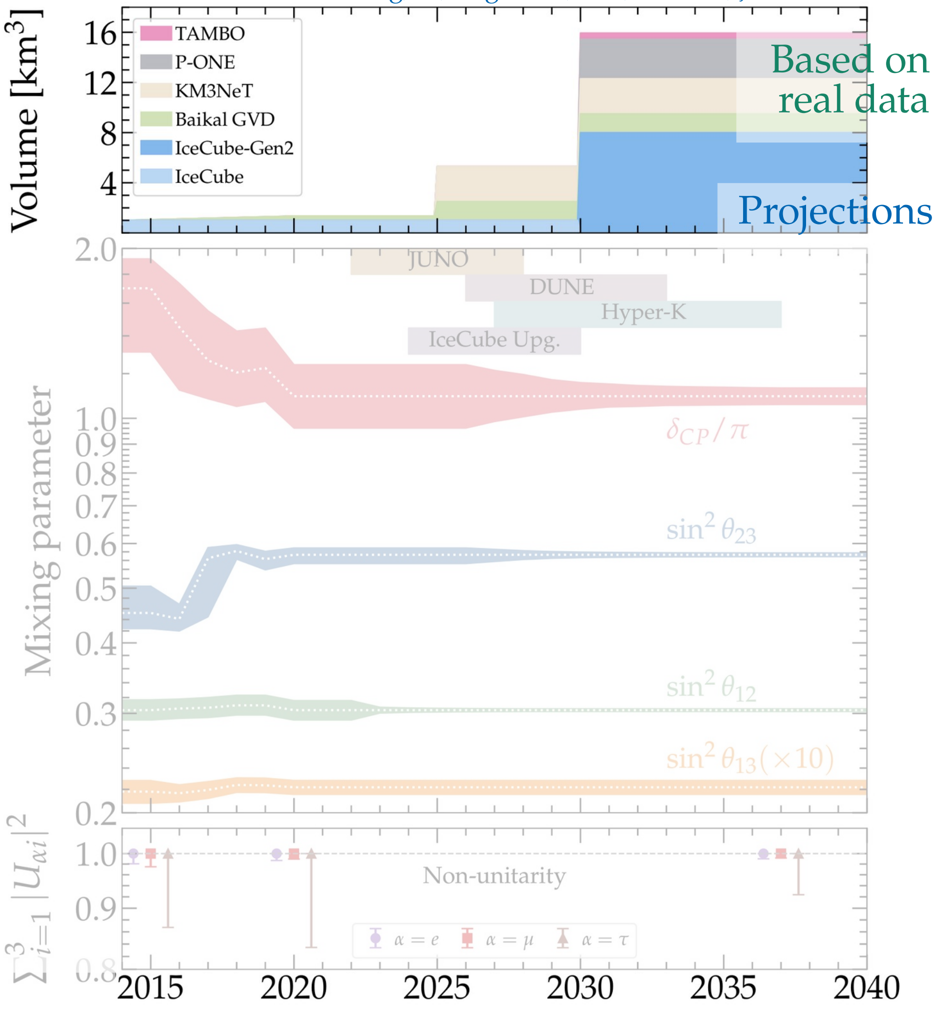
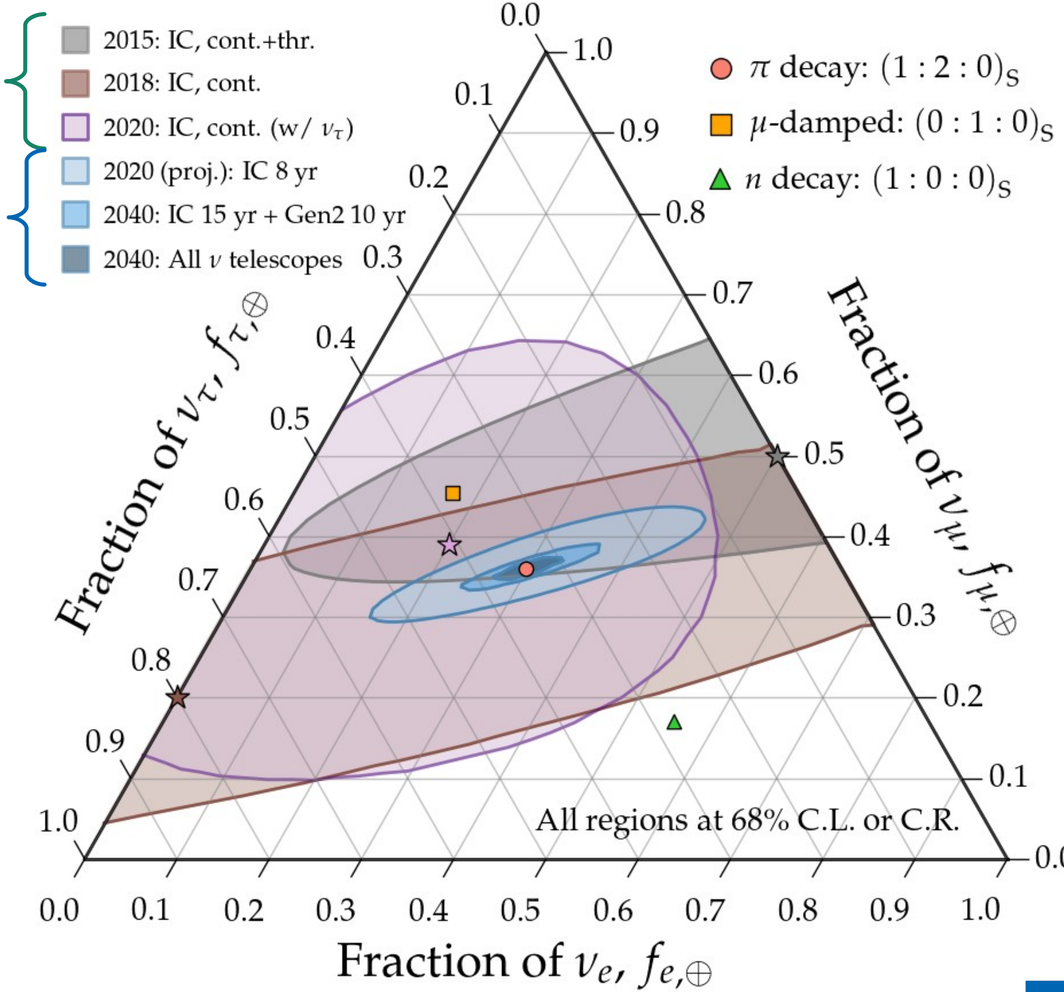
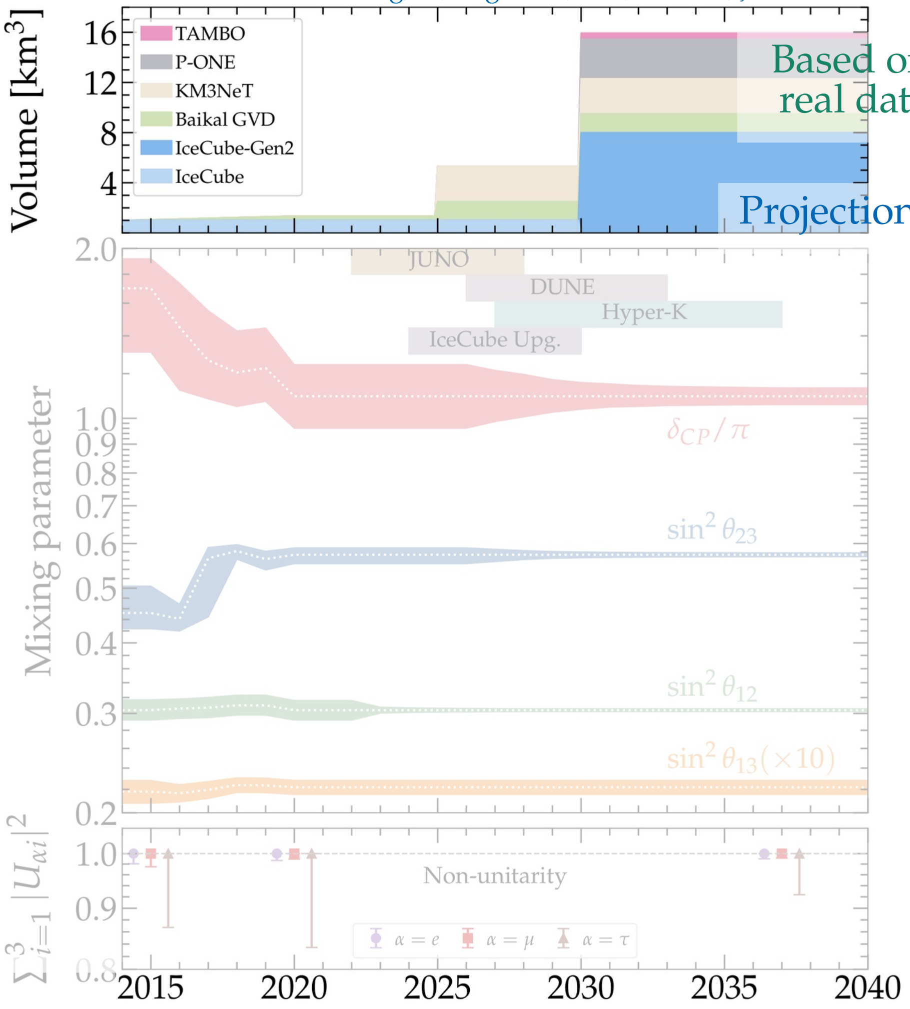




Measuring flavor composition: 2015–2040

See talk by Juliana Stachurska

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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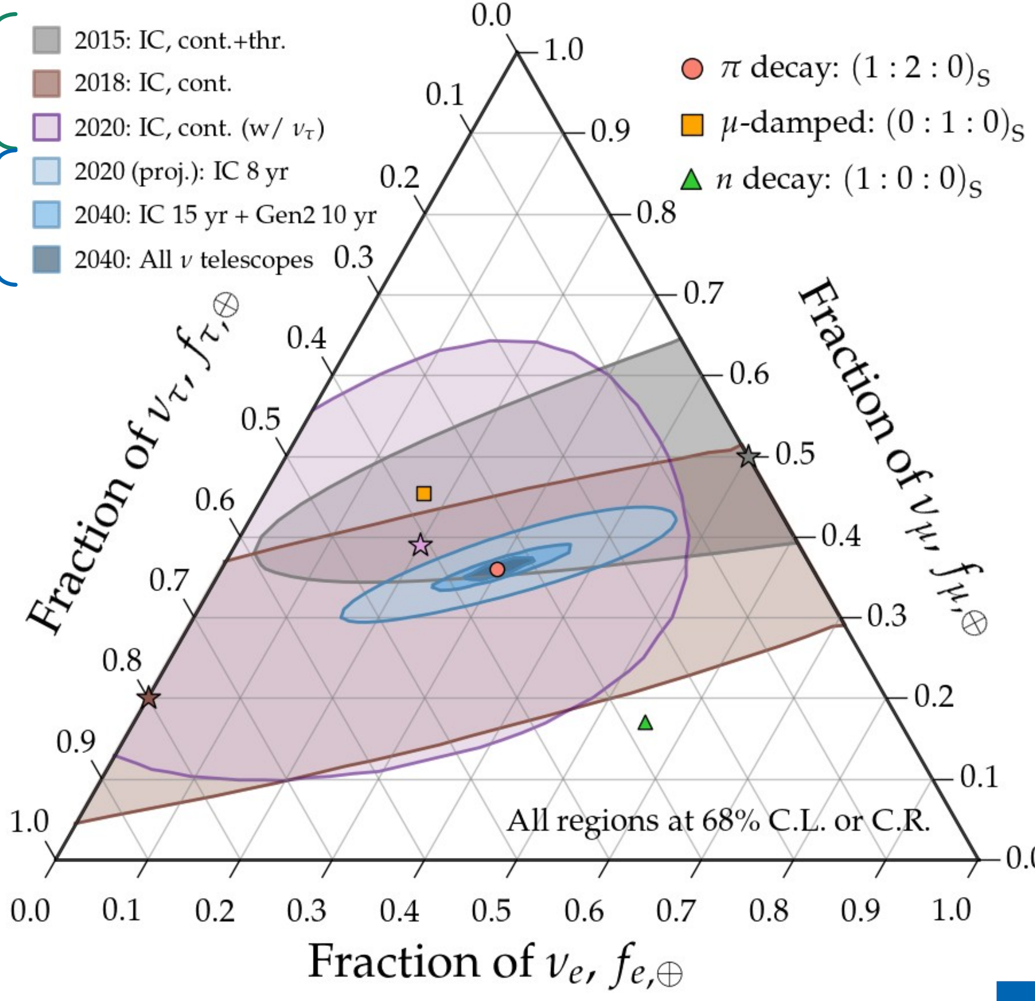
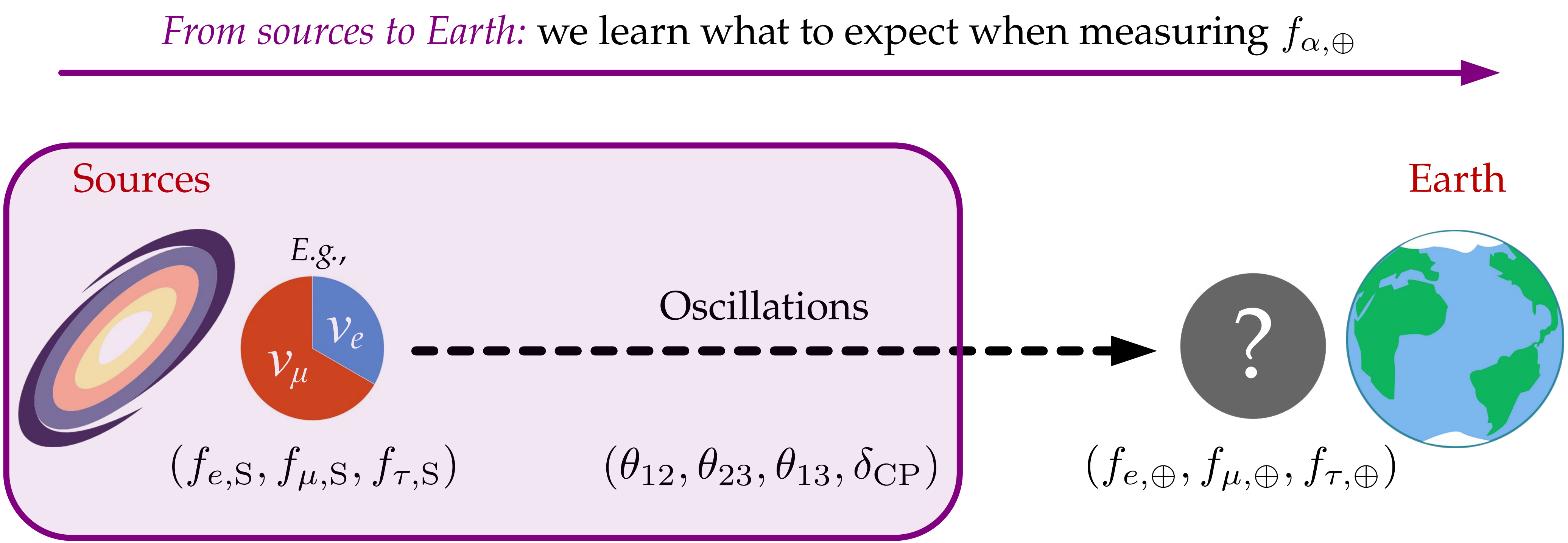
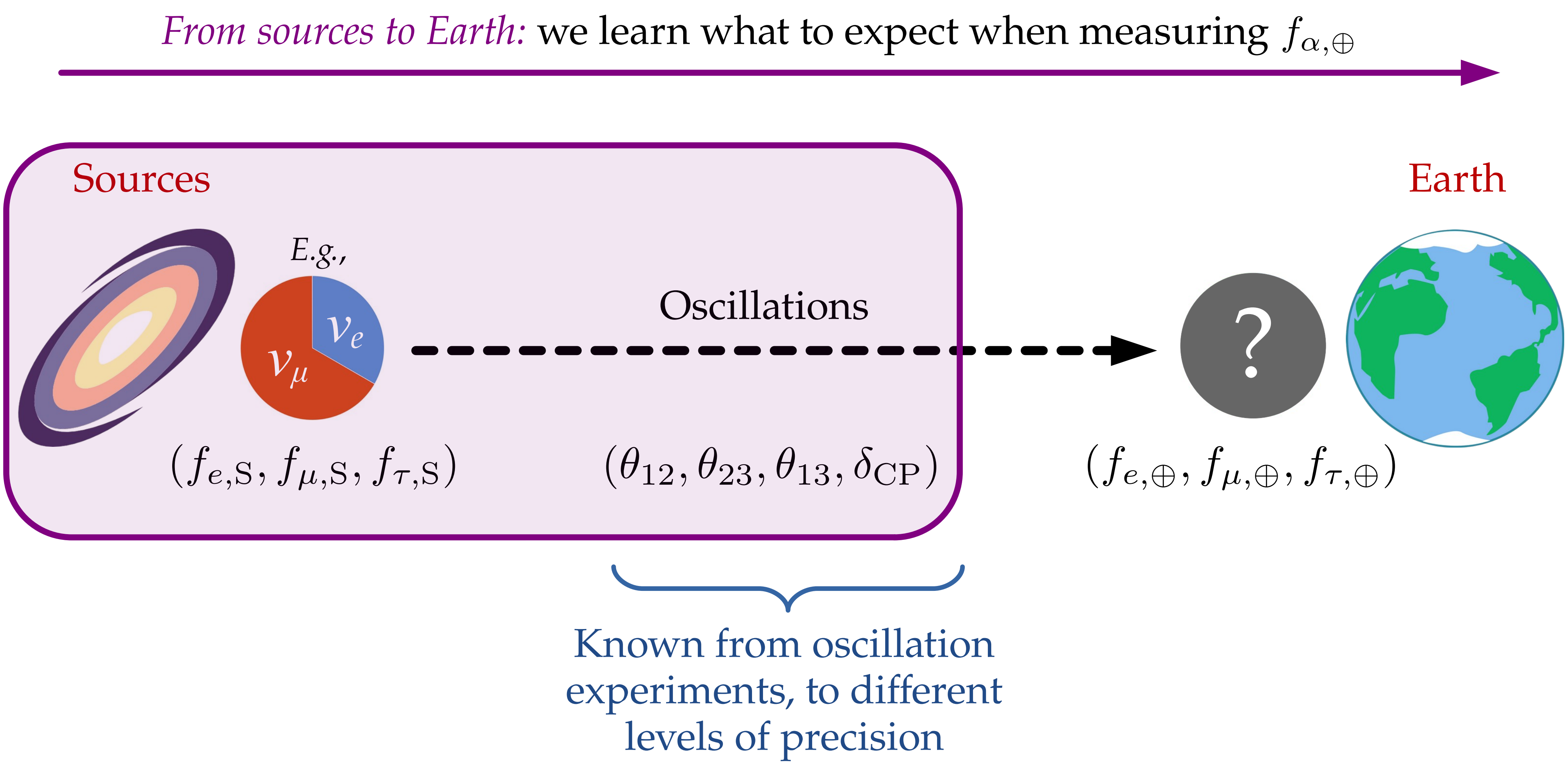
Projections





From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$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E.g.,
ν_e
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Oscillations
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
Earth
?
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
Known from oscillation experiments, to different levels of precision

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Note:
The original palatable regions were frequentist [**MB**, Beacom, Winter, *PRL* 2015]; the new ones are Bayesian

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Ingredient #1:

Flavor ratios at the source,

$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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Ingredient #2:
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

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the new ones are Bayesian

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:
Flavor ratios at the source,
$(f_{e,S}, f_{\mu,S}, f_{\tau,S})$

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

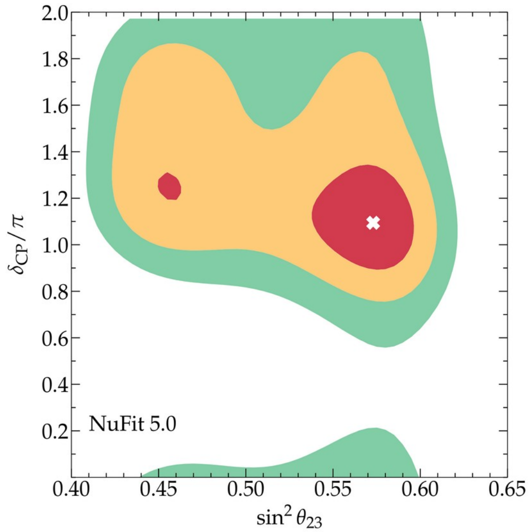
or

Explore all possible combinations

Ingredient #2:
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



Note:
The original palatable regions were frequentist [**MB**, Beacom, Winter, *PRL* 2015]; the new ones are Bayesian

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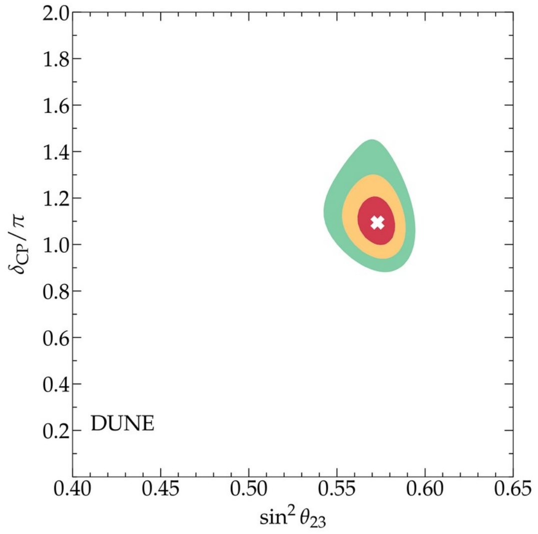
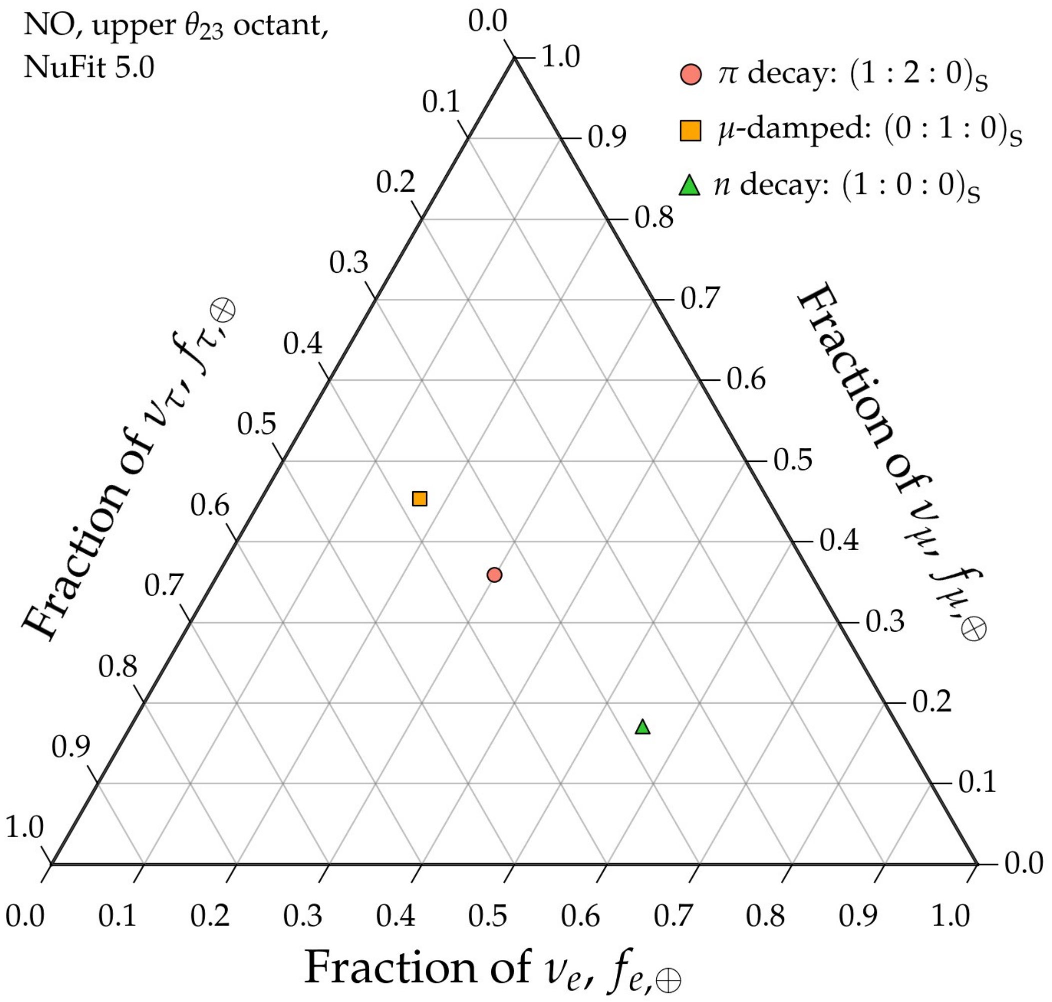
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005
Huber, Lindner, Winter, *Nucl. Phys. B* 2002



Theoretically palatable regions: today (2021)



Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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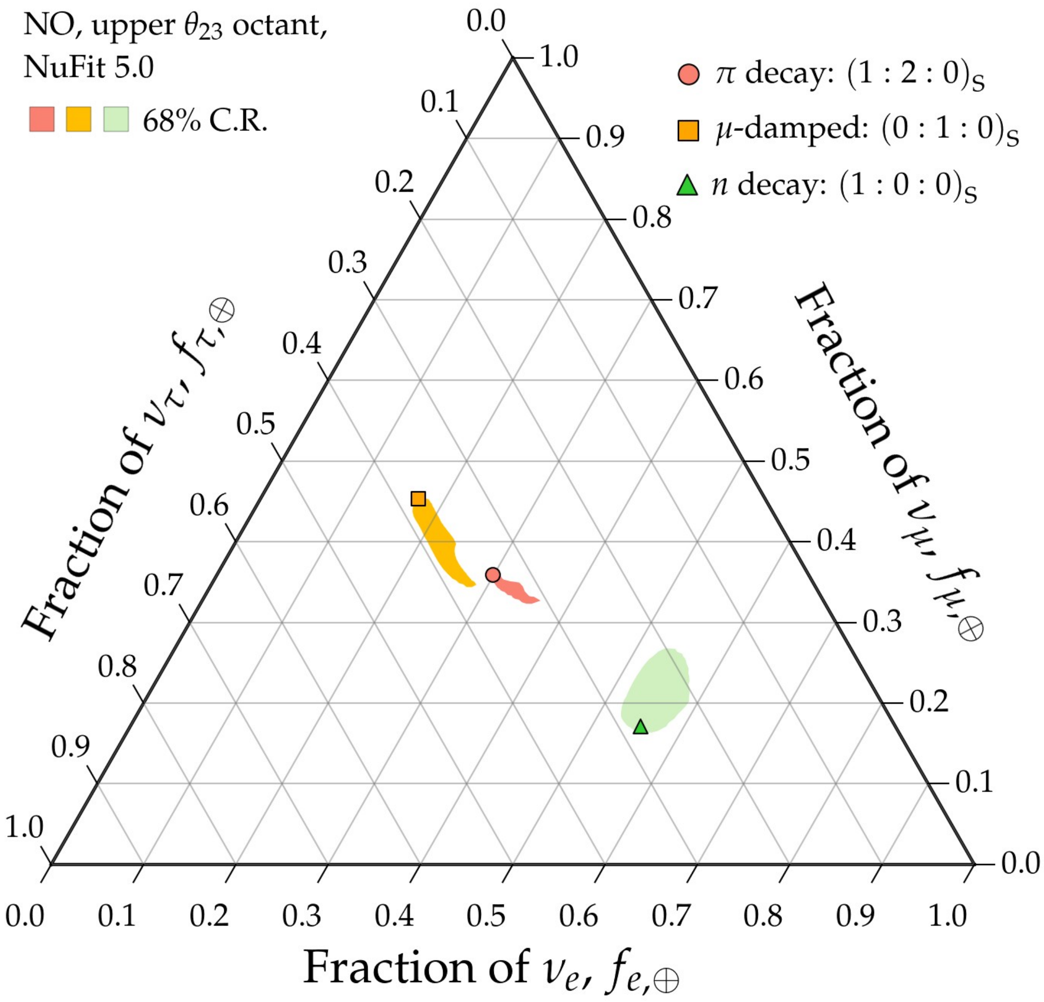

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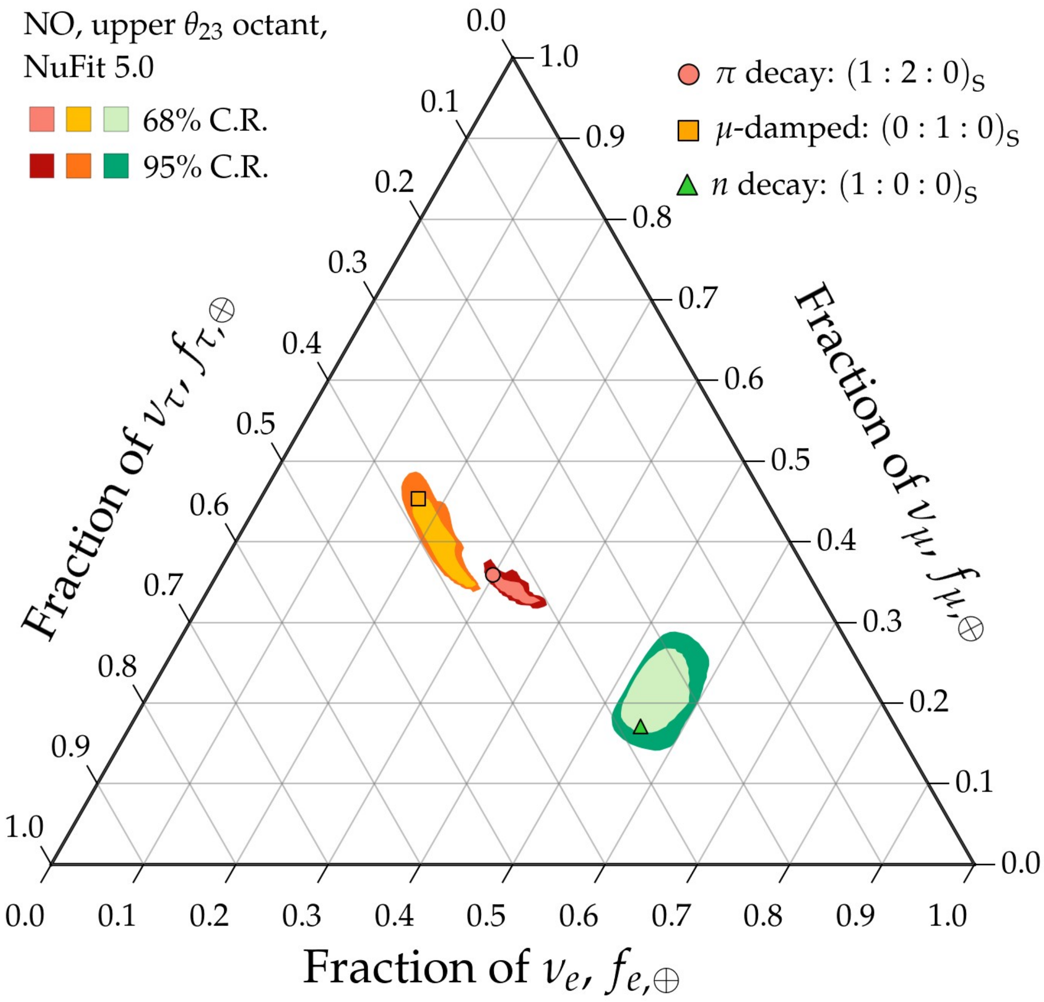

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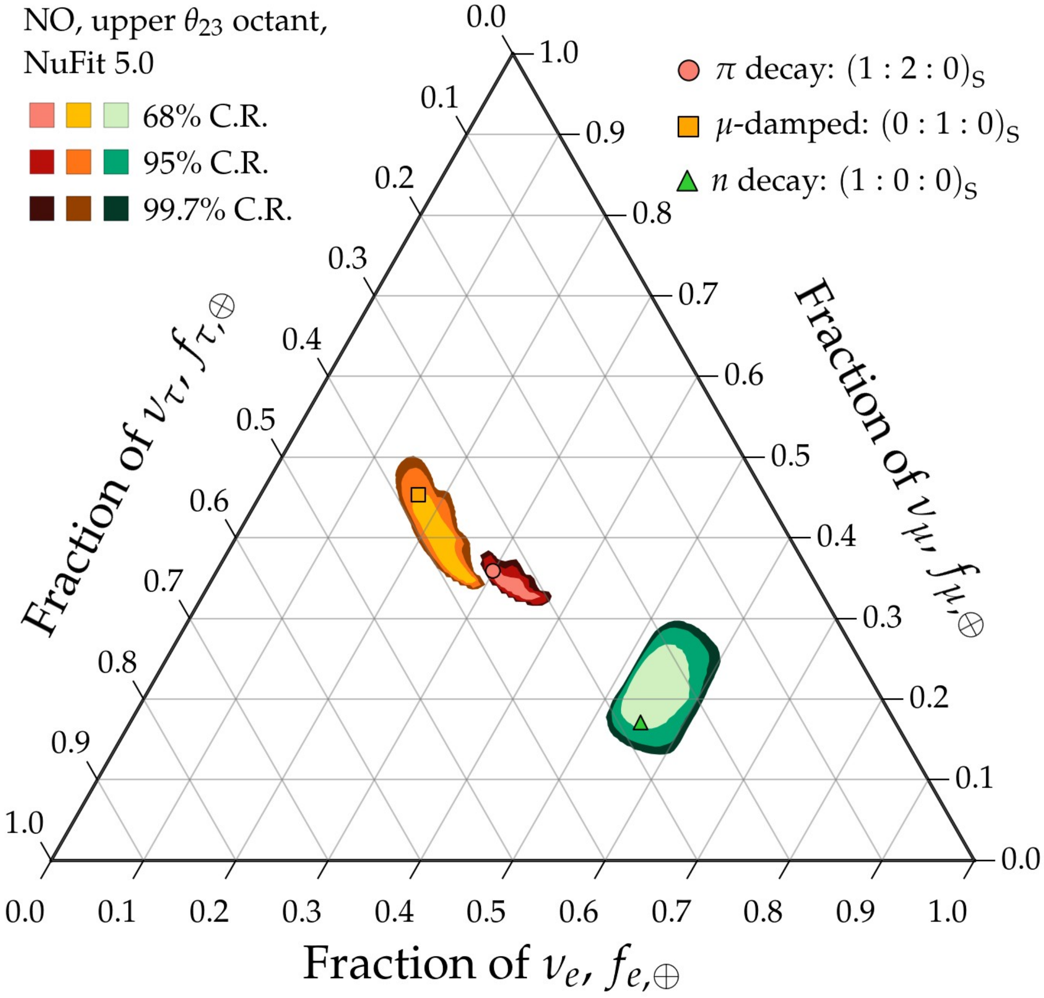

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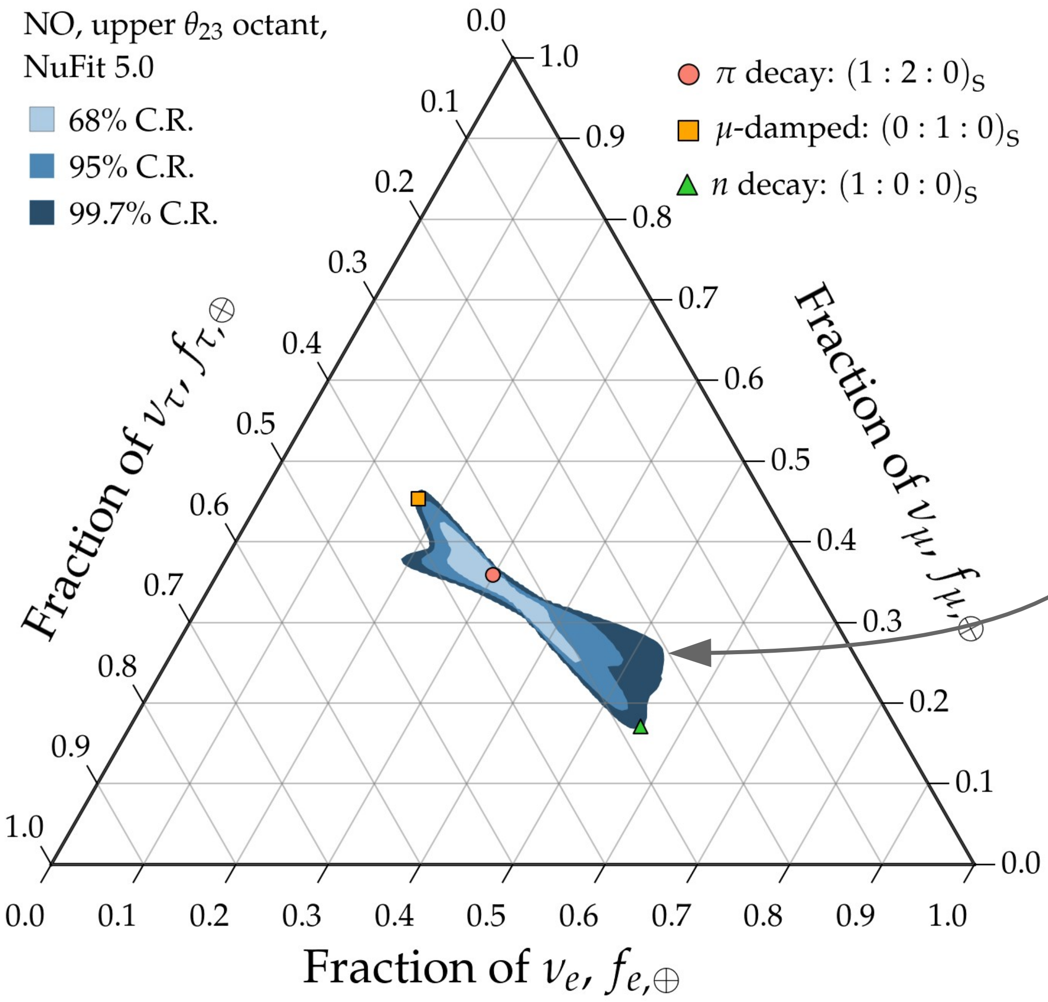

Varying over all possible flavor ratios at the source

Note:
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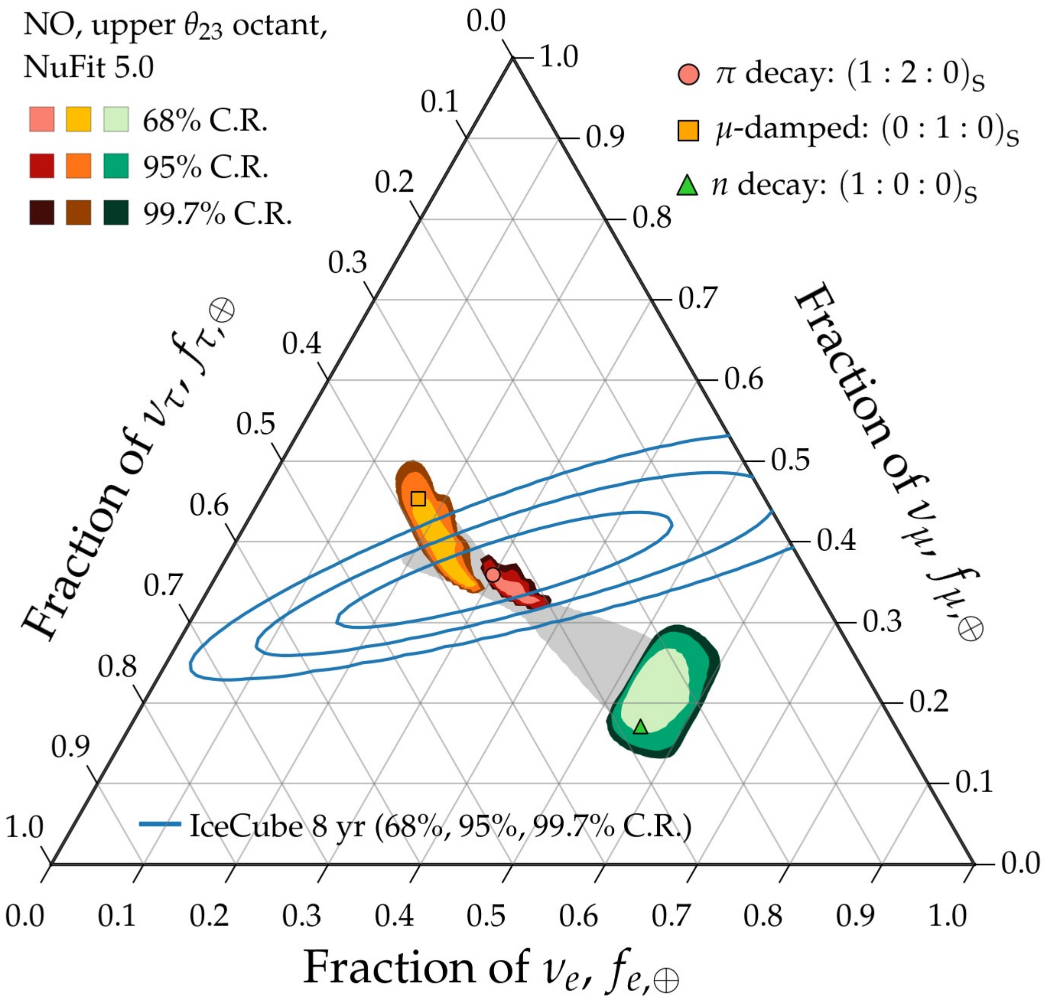
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



Note:
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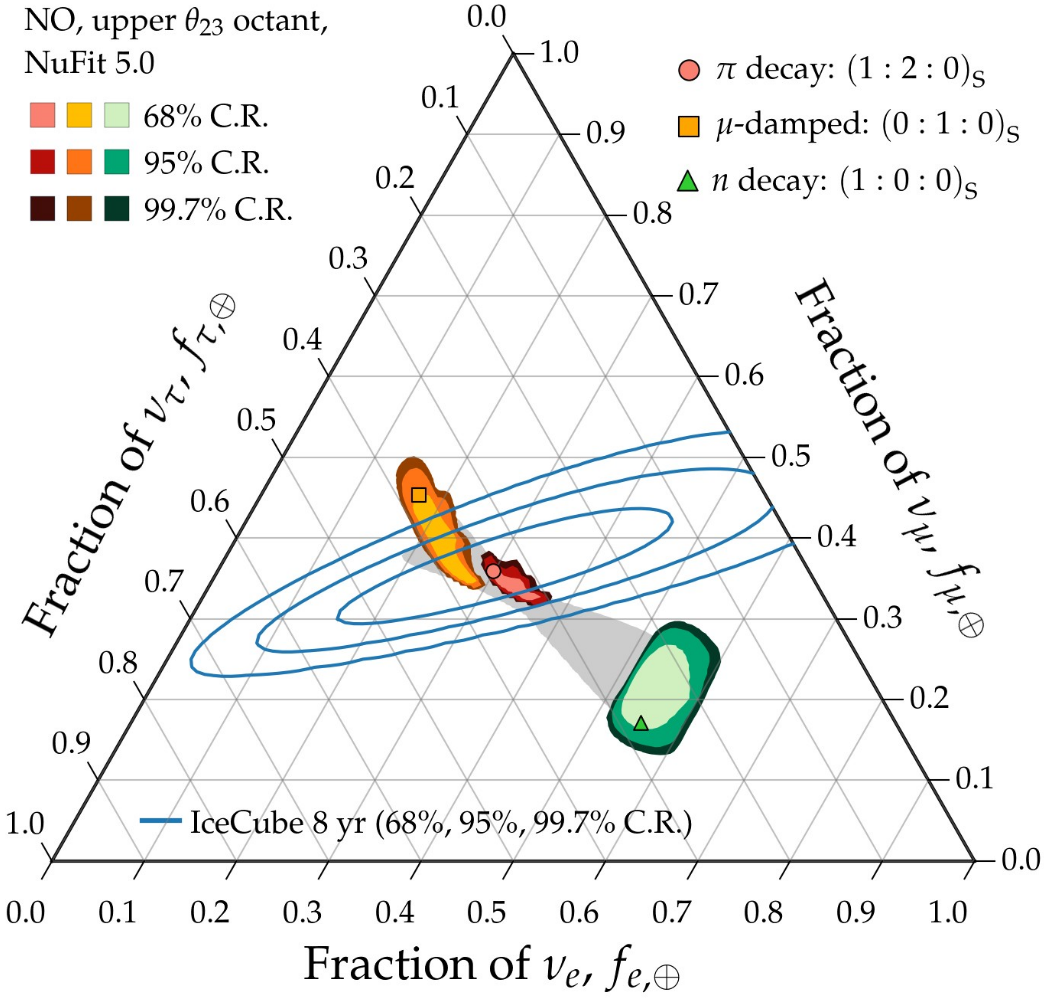
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



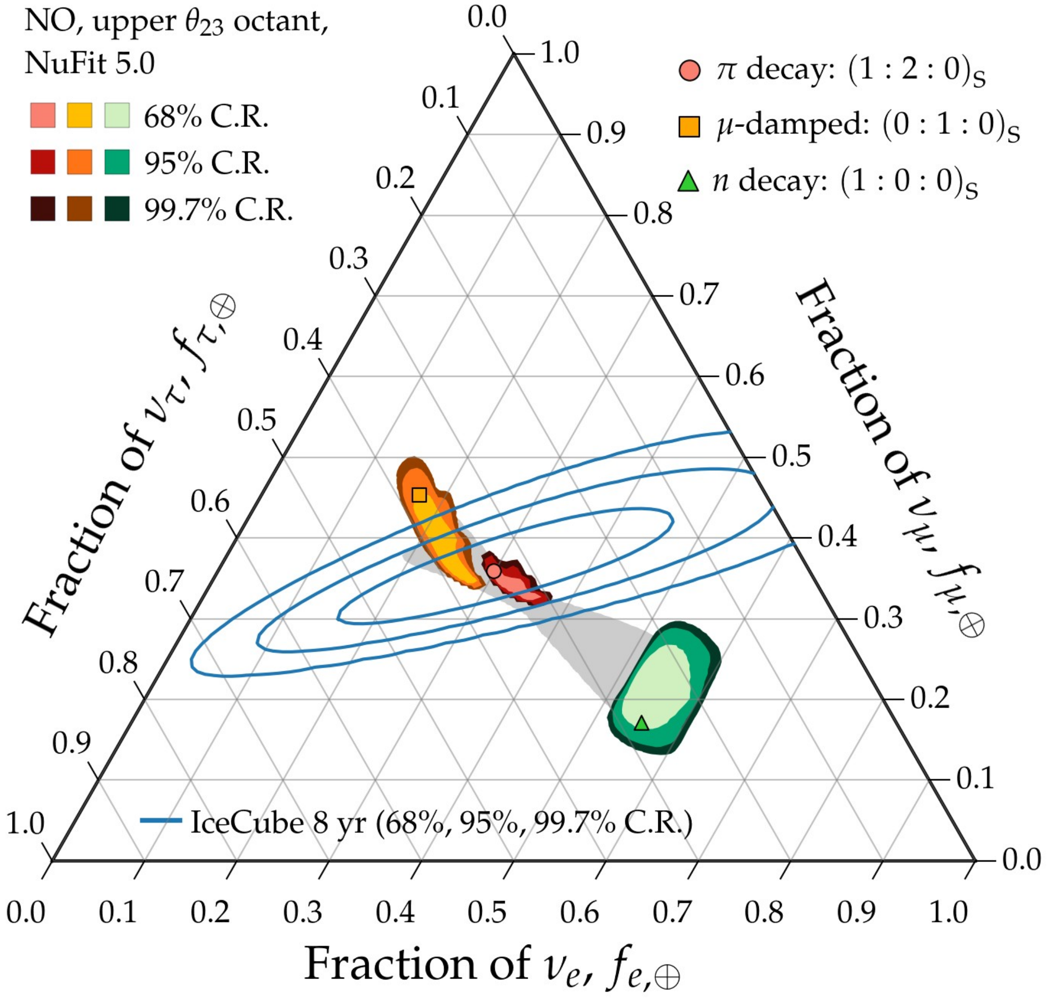
Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



Two limitations:

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Will be overcome by 2030

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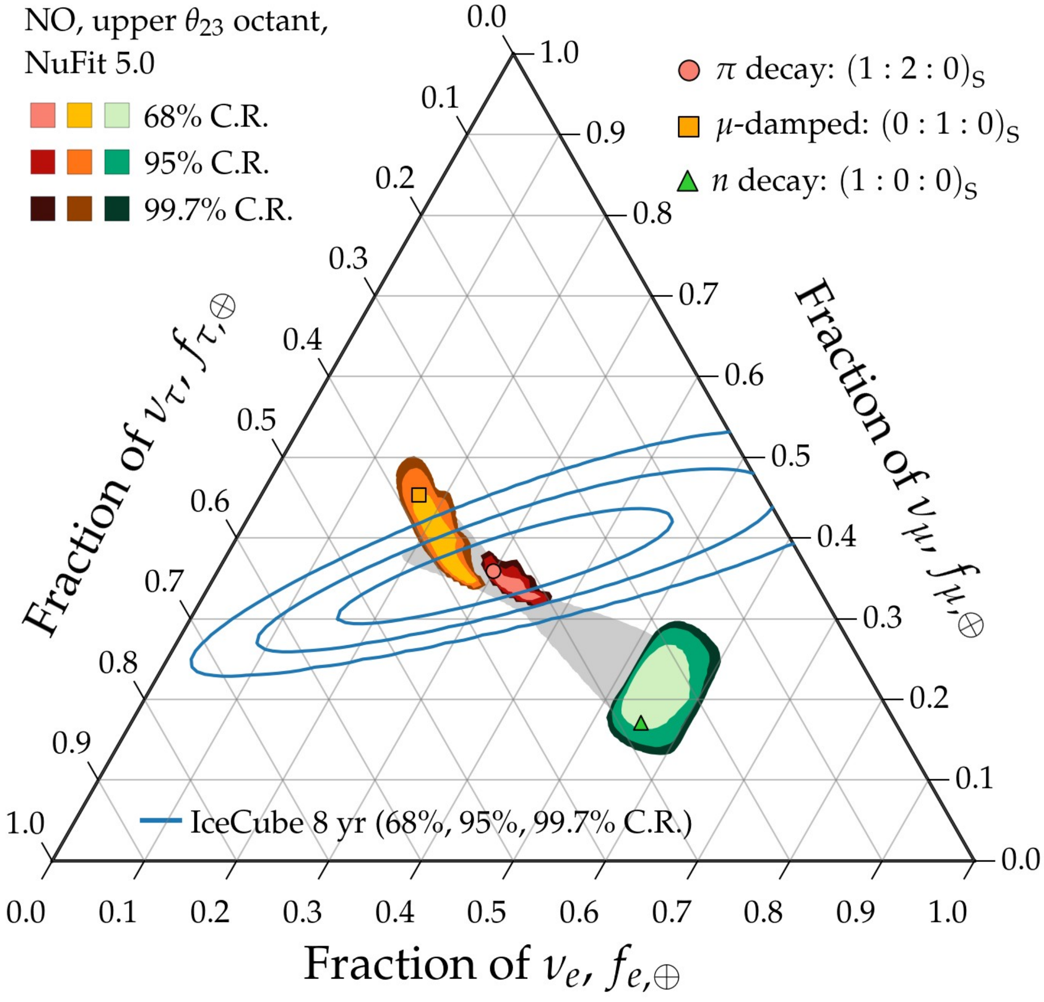
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



Two limitations:

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Will be overcome by 2030

Measurement of flavor ratios –
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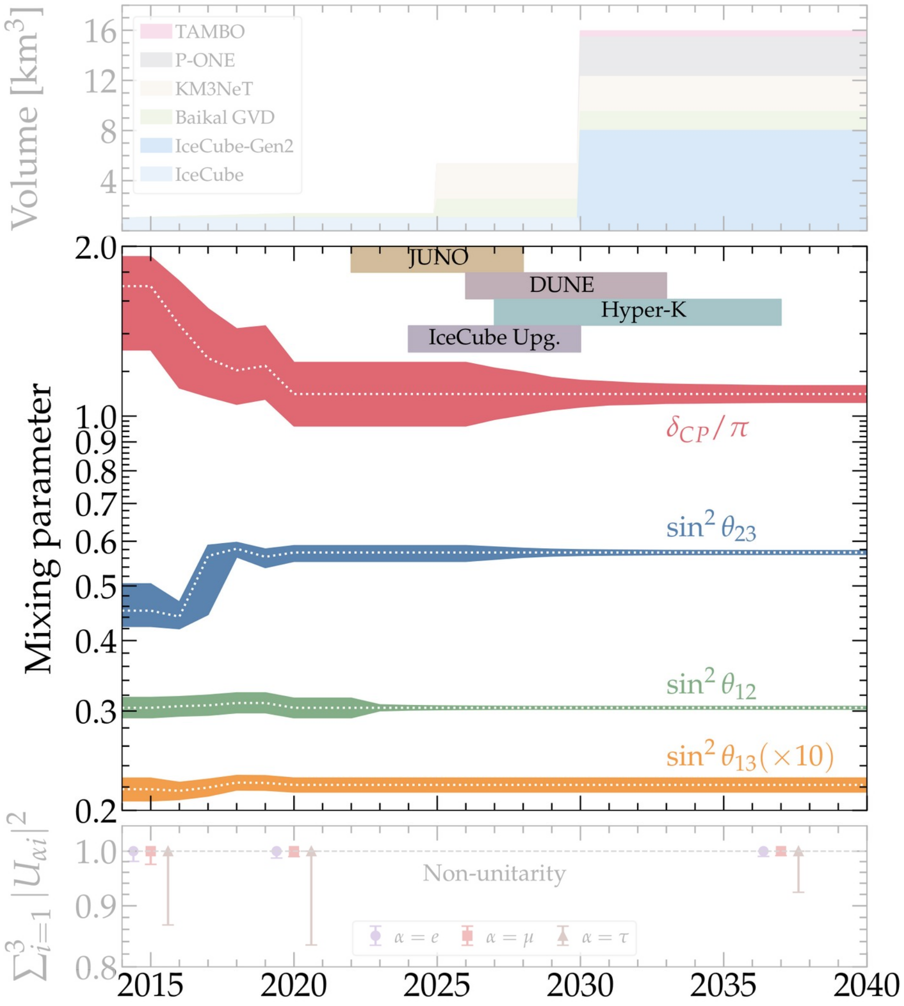
Will be overcome by 2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

How knowing the mixing parameters better helps

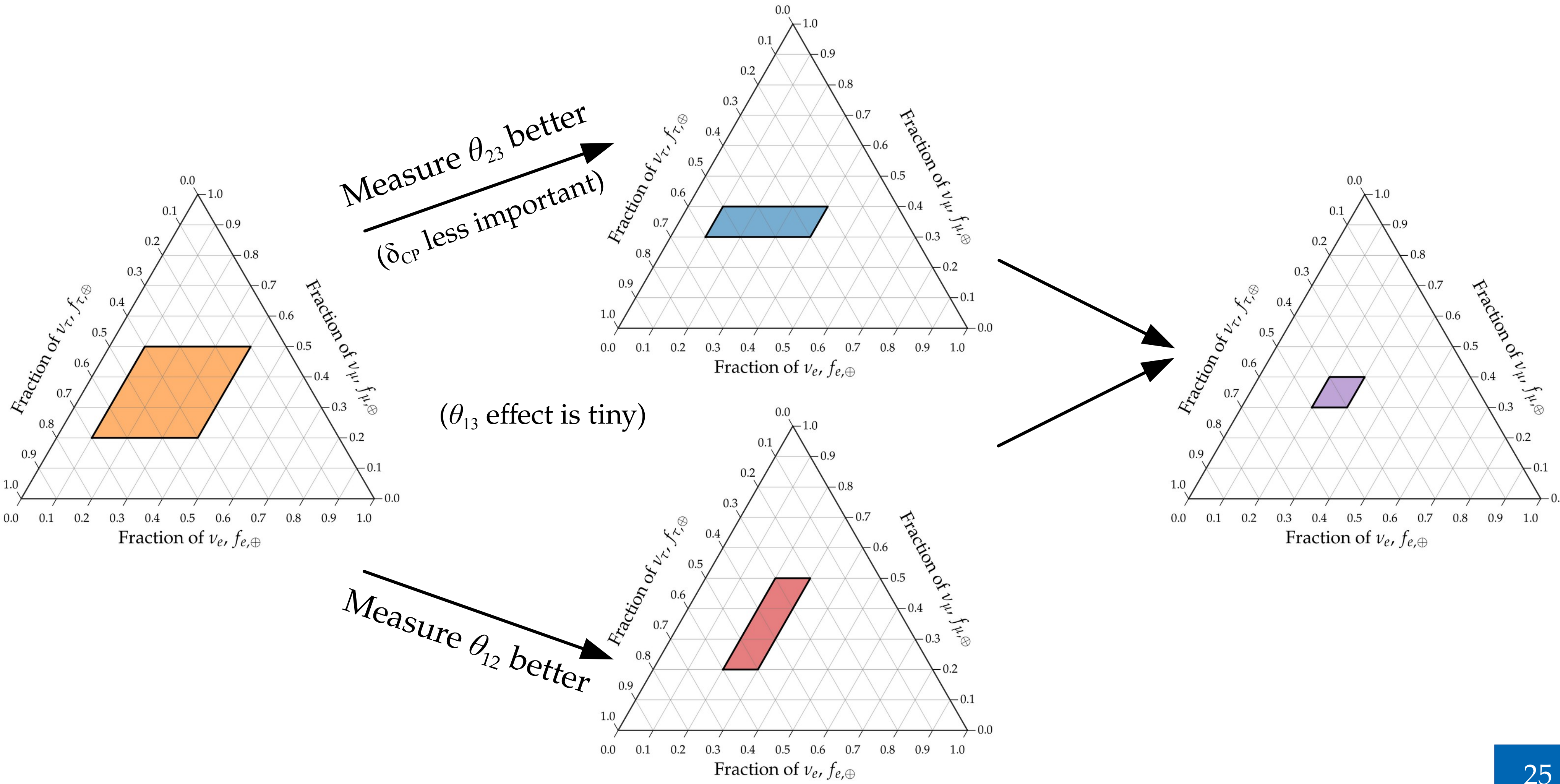


We can compute the oscillation probability more precisely:

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\beta\alpha} f_{\beta,\mathrm{S}}$$

So we can convert back and forth between source and Earth more precisely

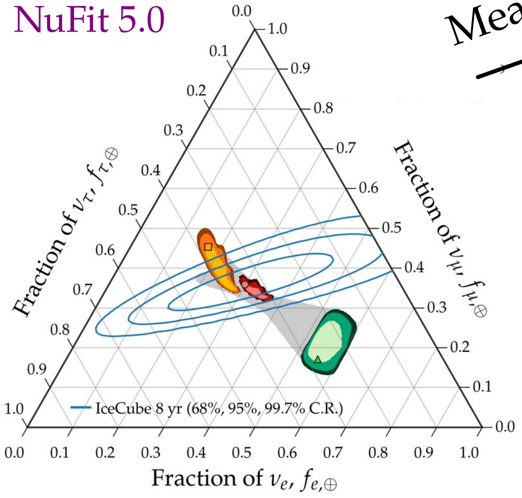
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

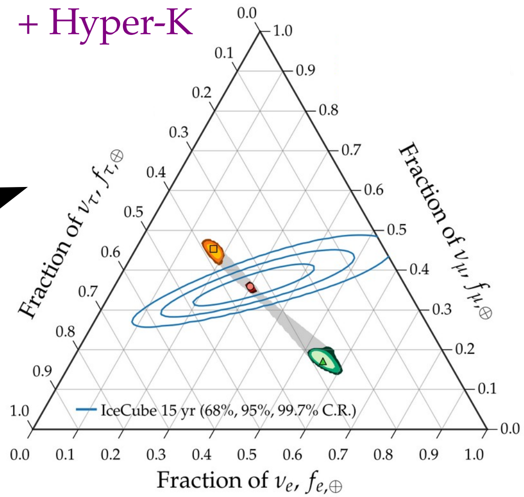
2020

NuFit 5.0



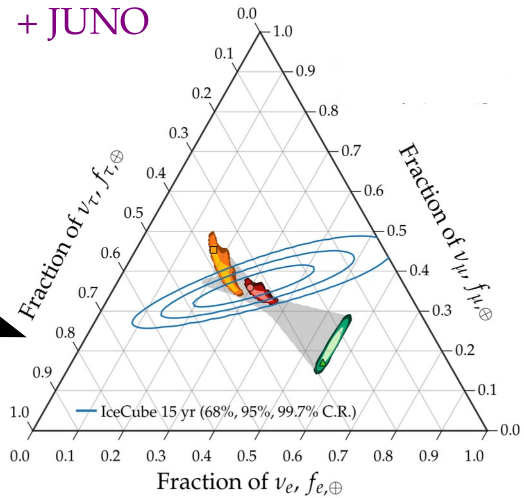
Measure θ_{23} better

+ Hyper-K



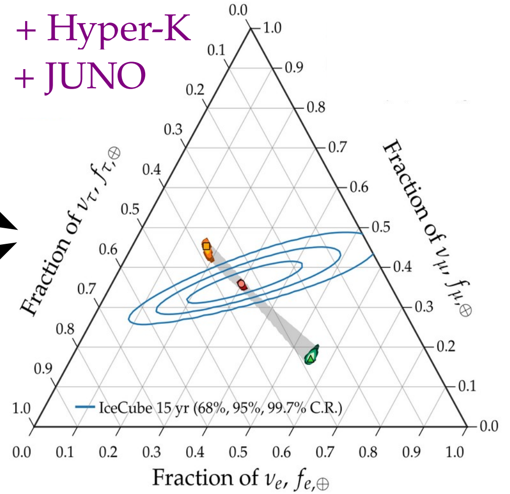
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

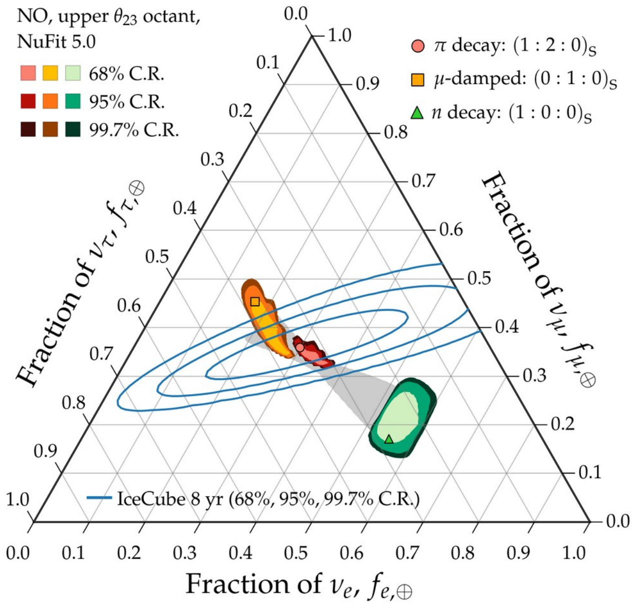
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

2020



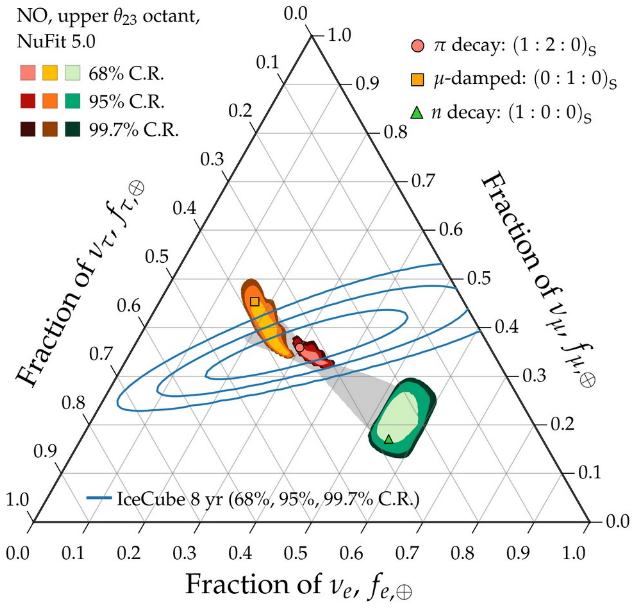
Allowed regions: overlapping

Measurement: imprecise

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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Measurement: imprecise

Not ideal

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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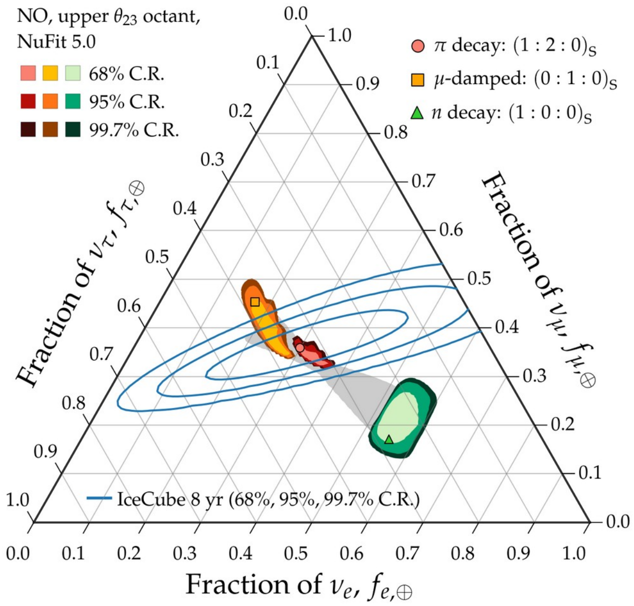
2020



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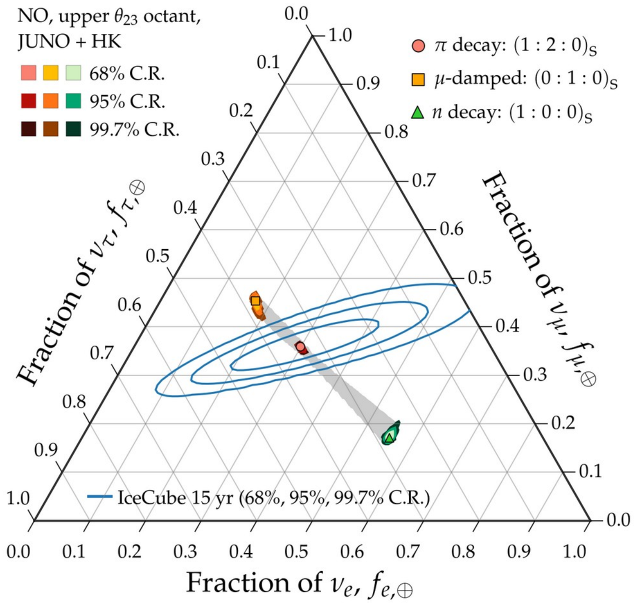
Measurement: imprecise

Not ideal

2030



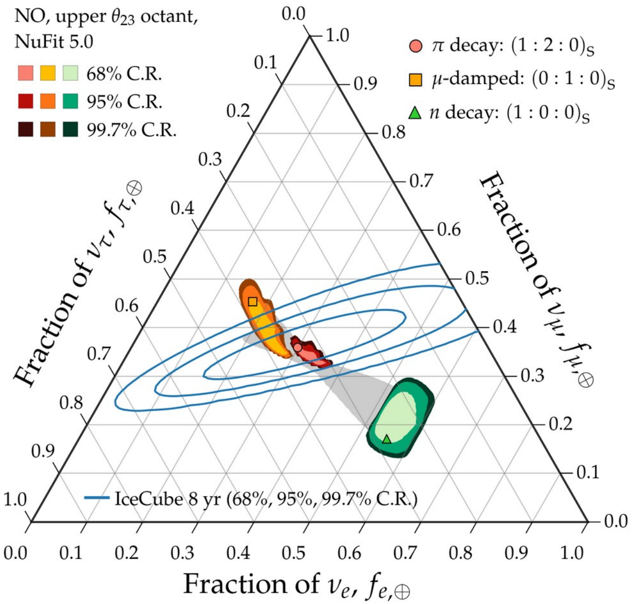
Allowed regions: well separated

Measurement: improving

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

2020

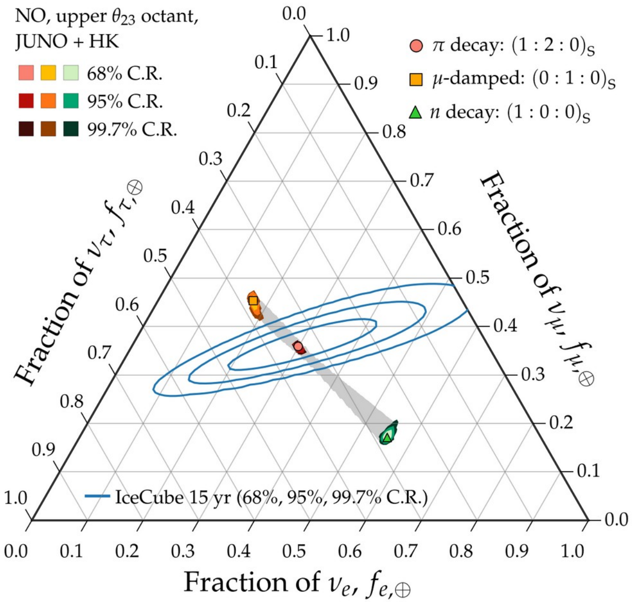


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

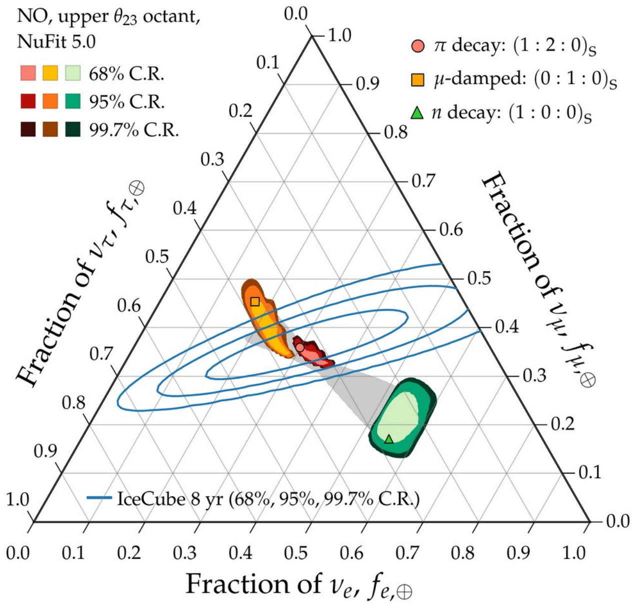
Measurement: improving

Nice

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

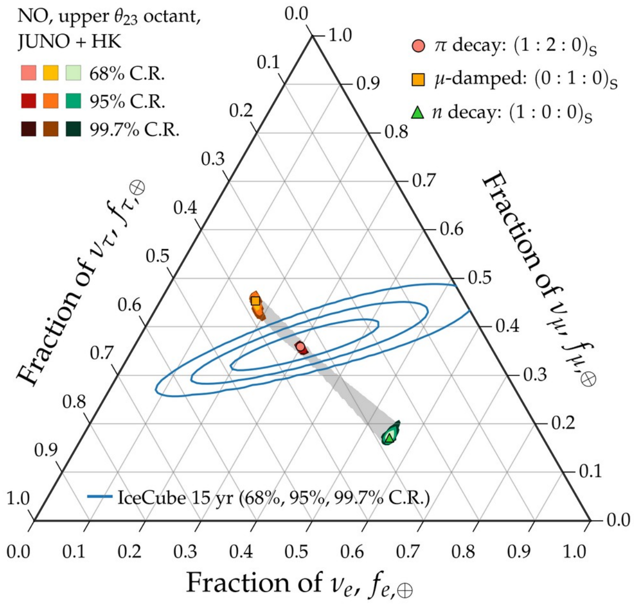
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

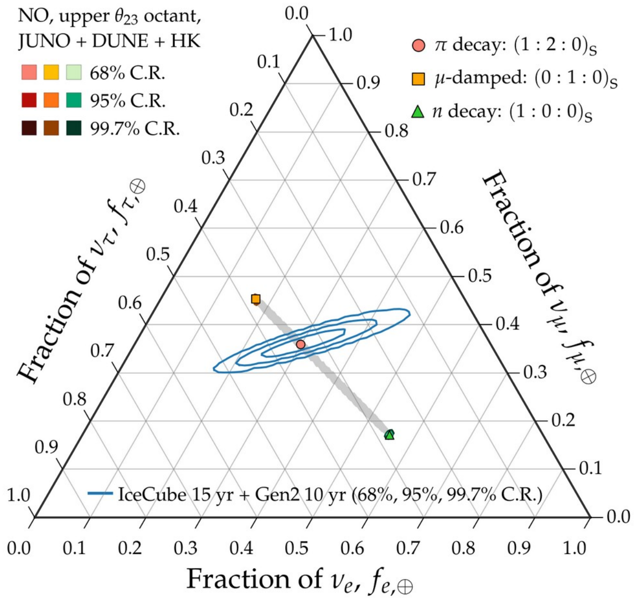
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

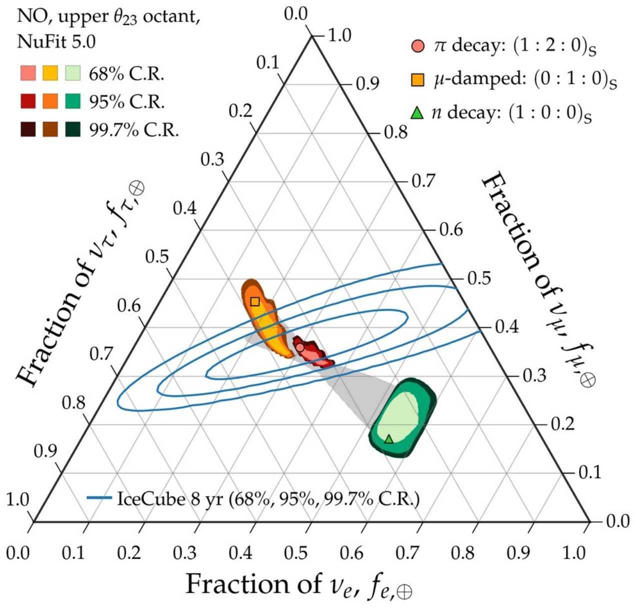


Allowed regions: well separated
Measurement: precise

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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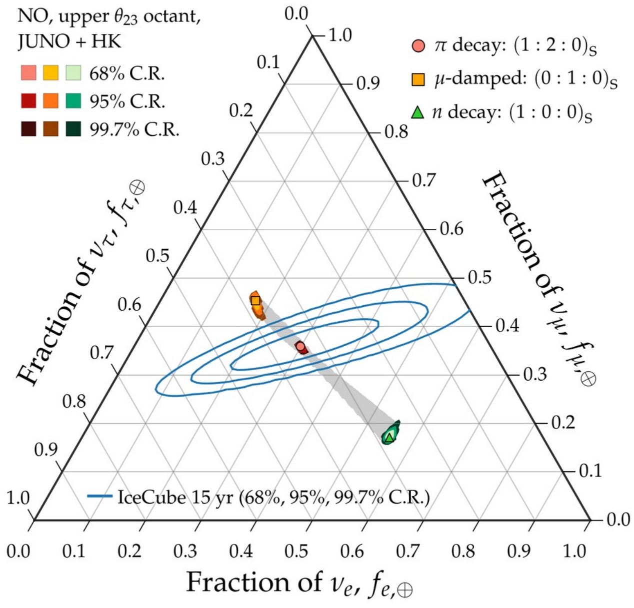
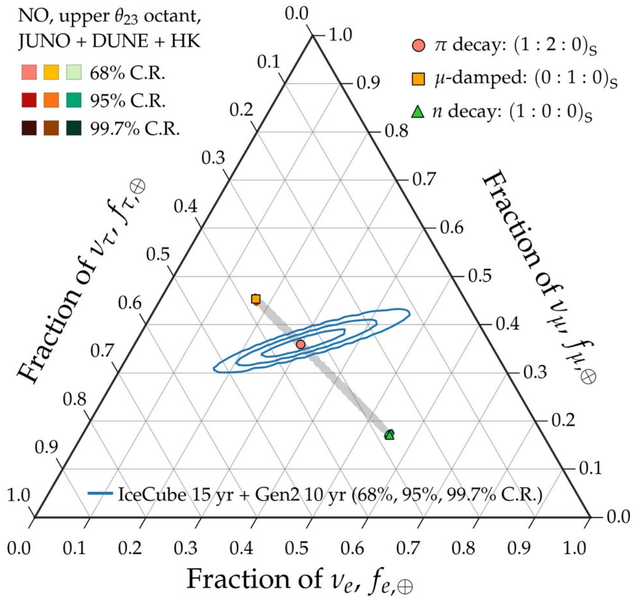
2030



Allowed regions: well separated
Measurement: improving

Nice

2040



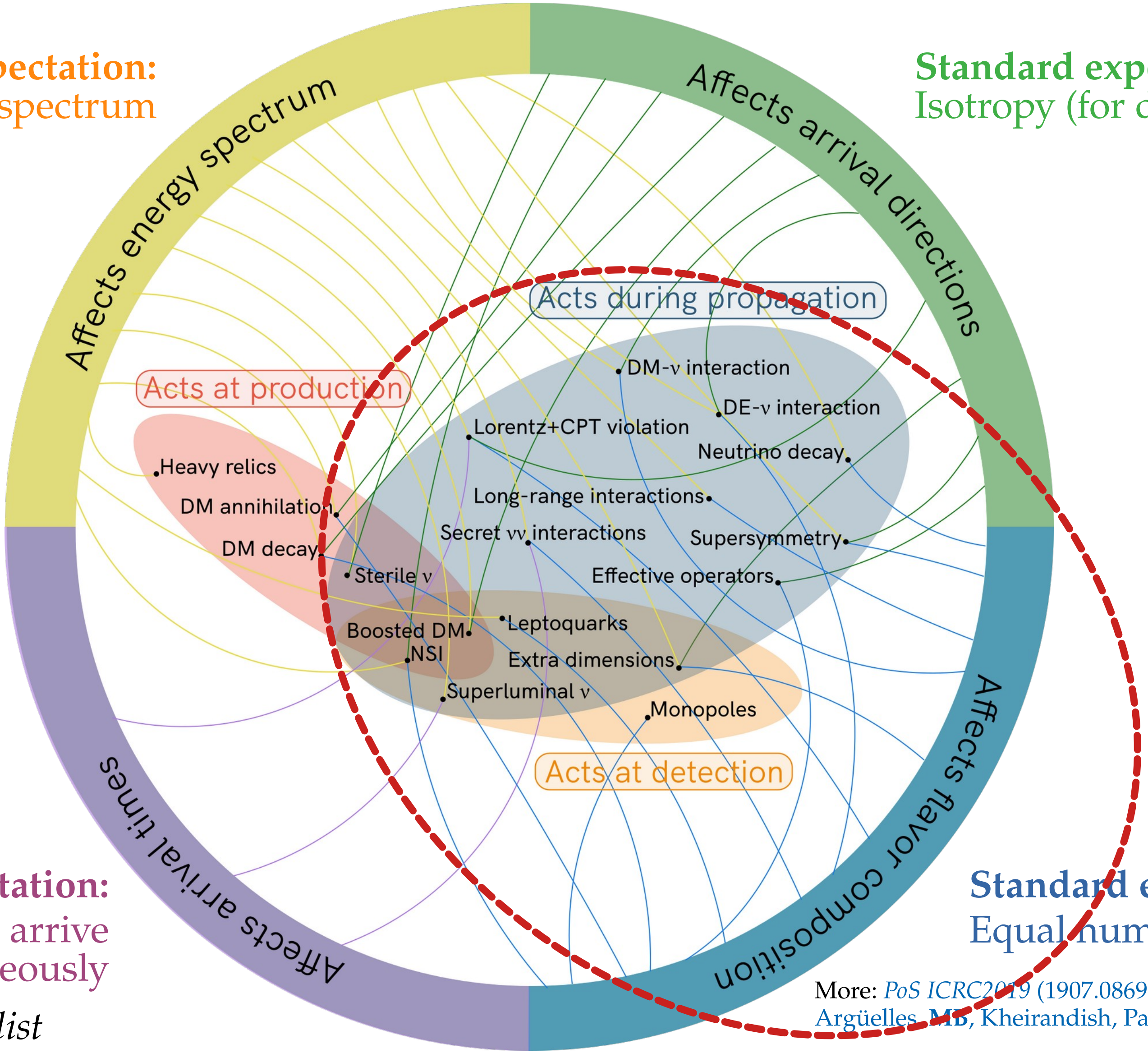
Allowed regions: well separated
Measurement: precise

Success

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

More: *PoS ICRC2019* (1907.08690)
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

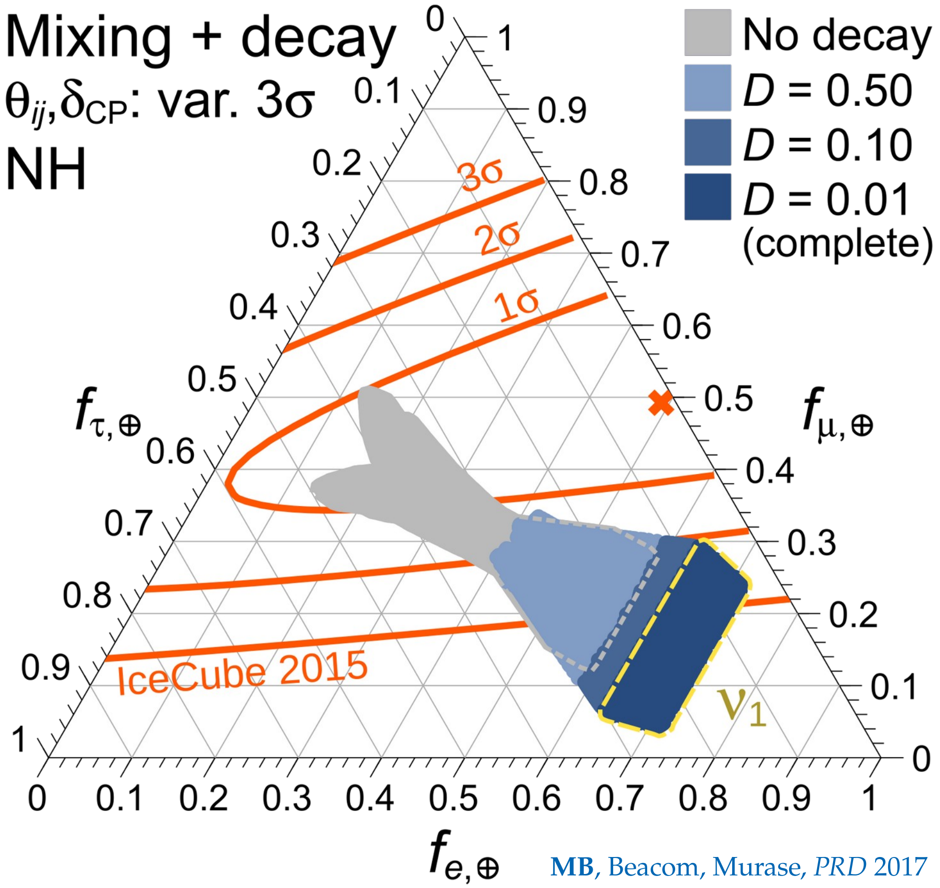
Repurpose the flavor sensitivity to test new physics:

Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010; **MB**, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]



MB, Beacom, Murase, *PRD* 2017

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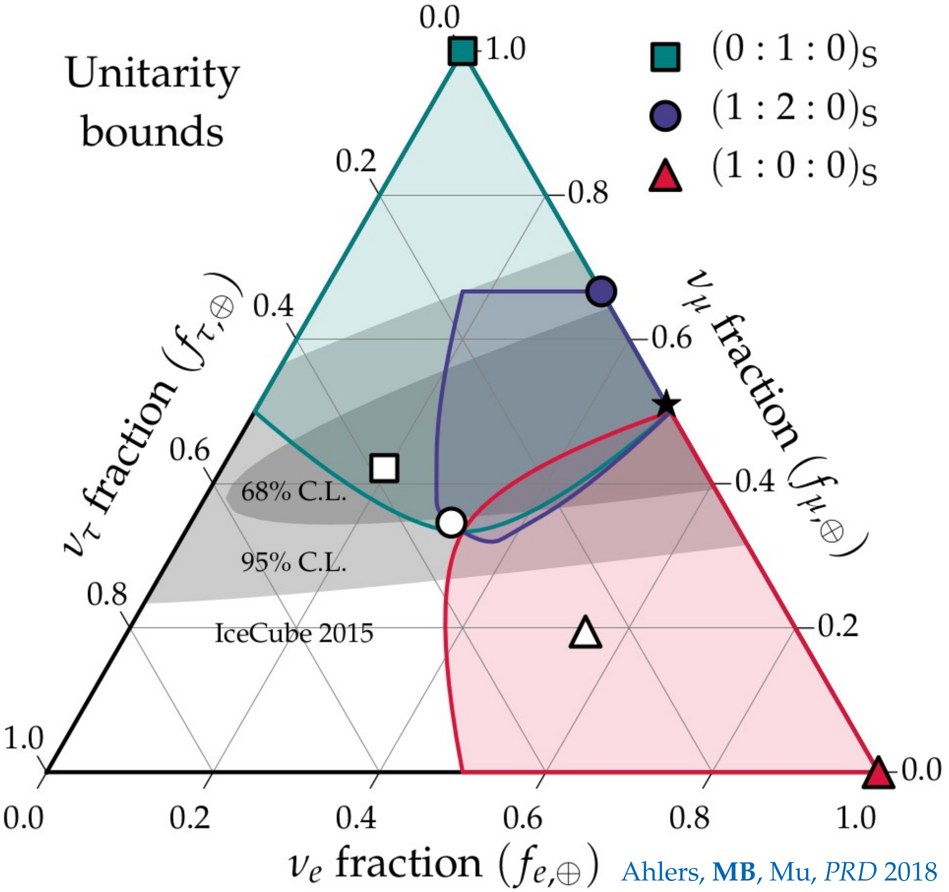

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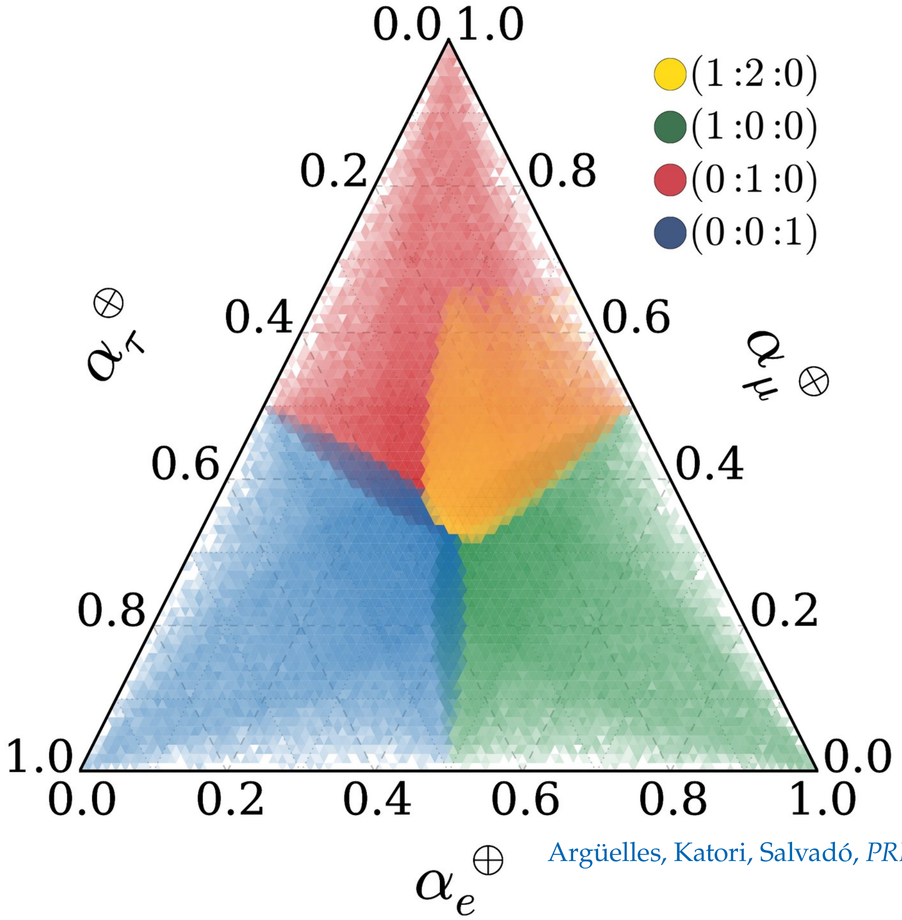

Argüelles, Katori, Salvadó, *PRL* 2015

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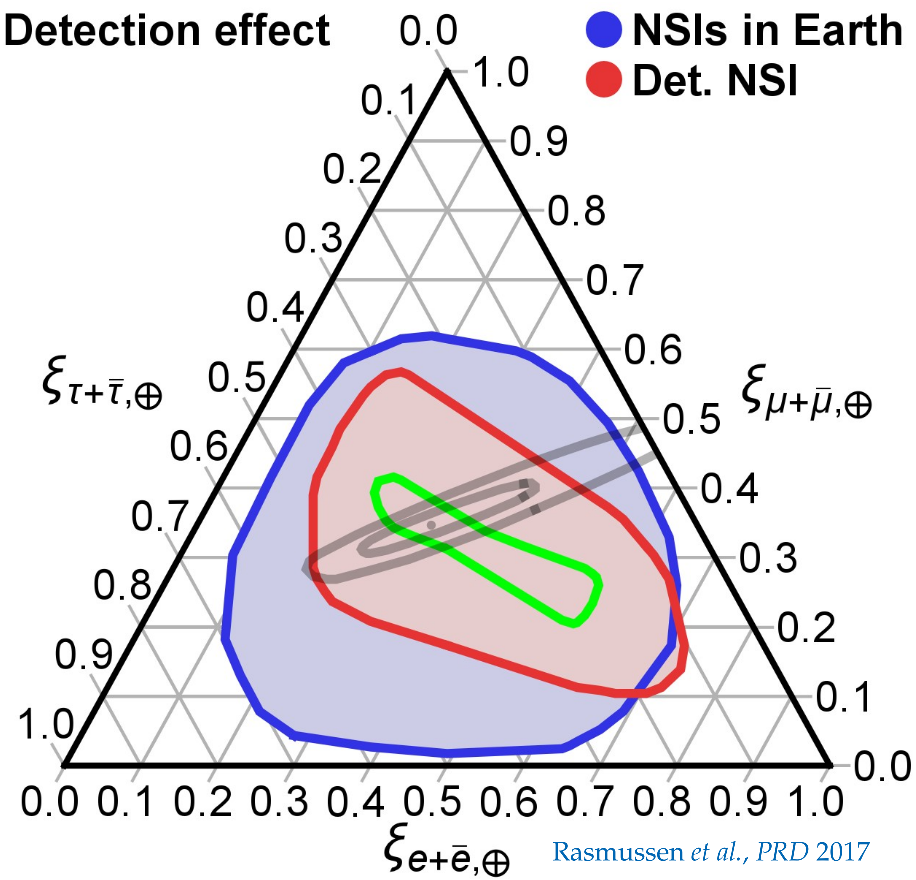

Rasmussen *et al.*, *PRD* 2017

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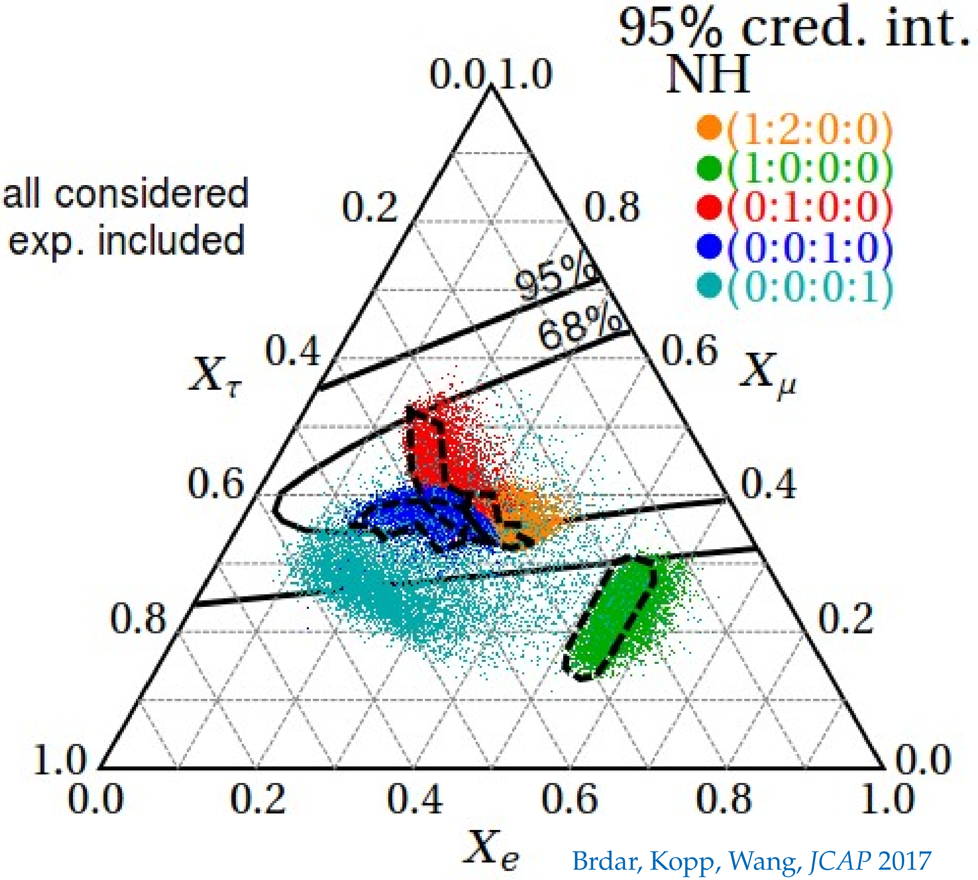

Brdar, Kopp, Wang, *JCAP* 2017

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- ▶ Long-range *e*ν interactions
  [**MB** & Agarwalla, *PRL* 2019]

Reviews:
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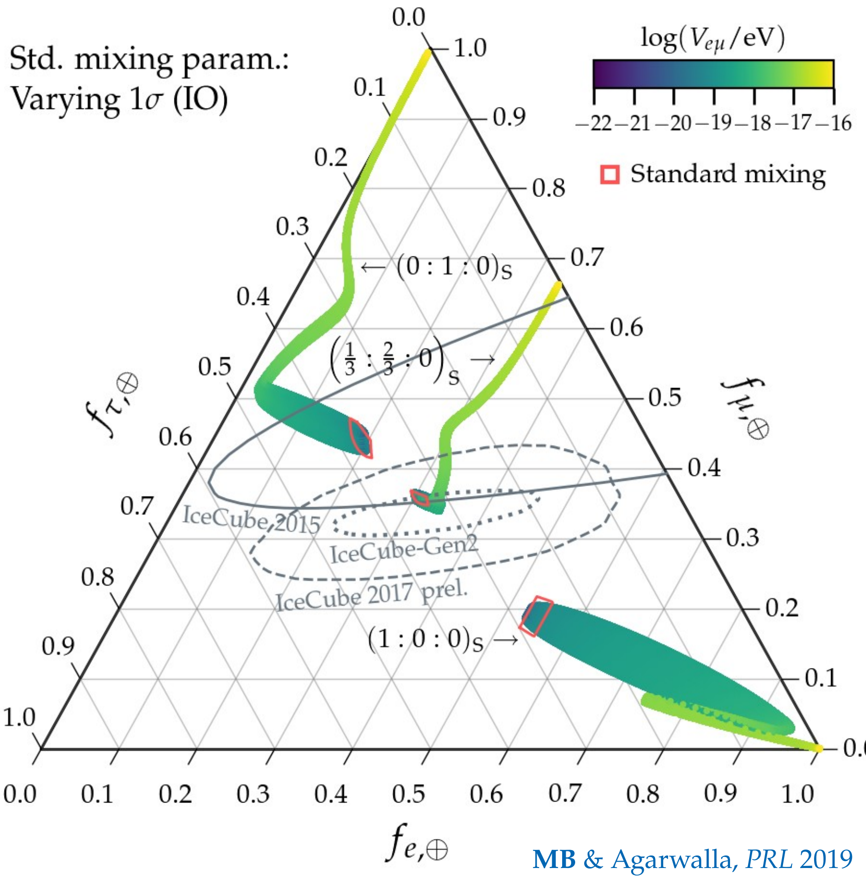
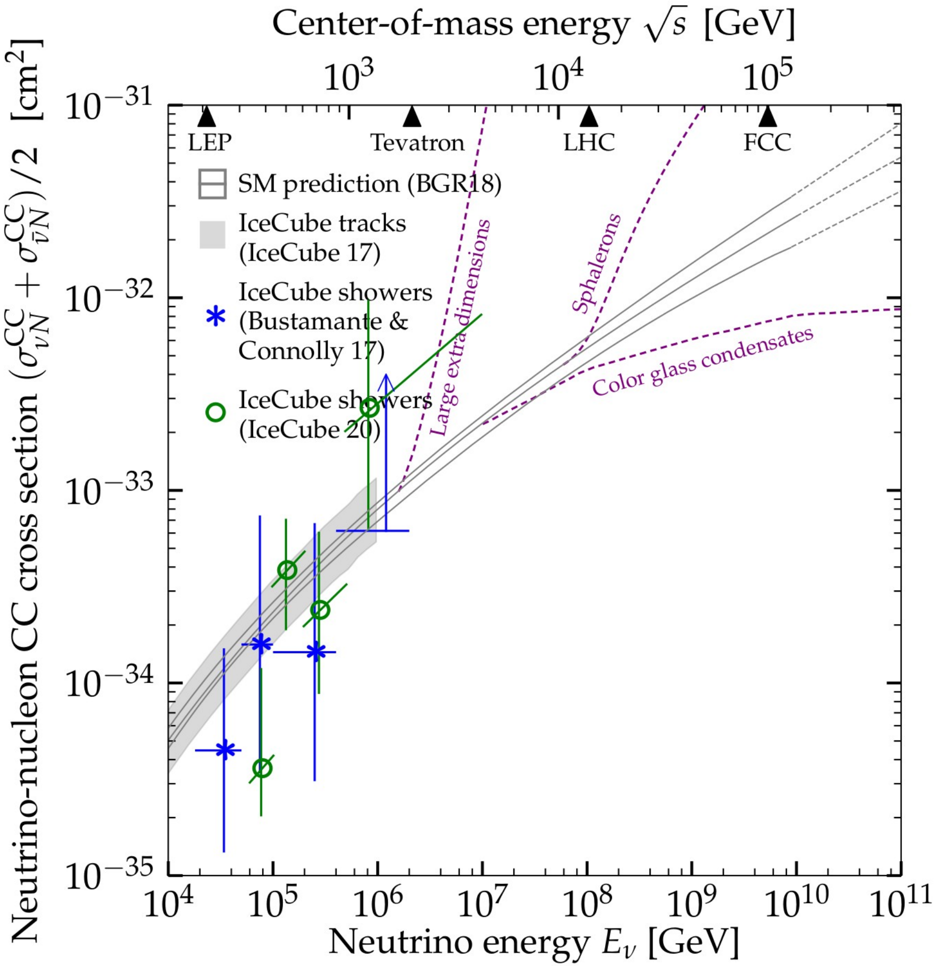


MB & Agarwalla, *PRL* 2019

Neutrino-nucleon cross section: Towards ultra-high energies

(with the help of ν_τ)

High-energy neutrino-nucleon cross section: *today*



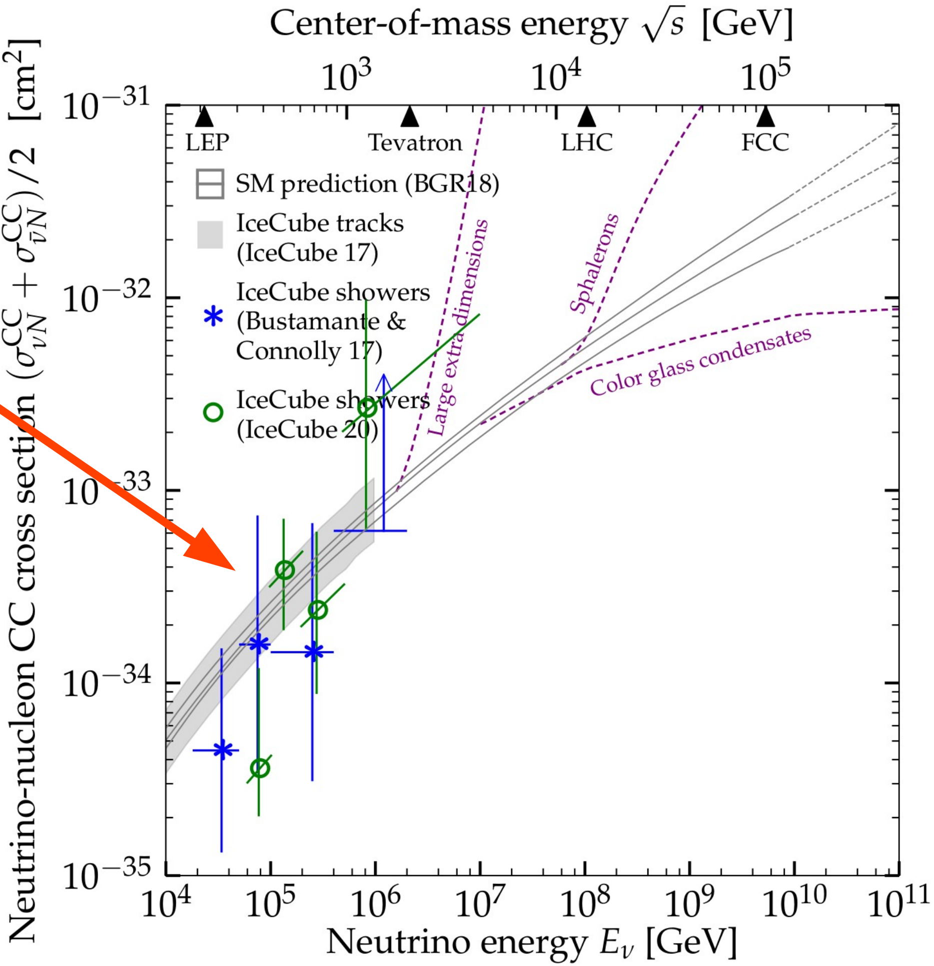
BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy neutrino-nucleon cross section: *today*

Measured:
TeV – PeV
cross section



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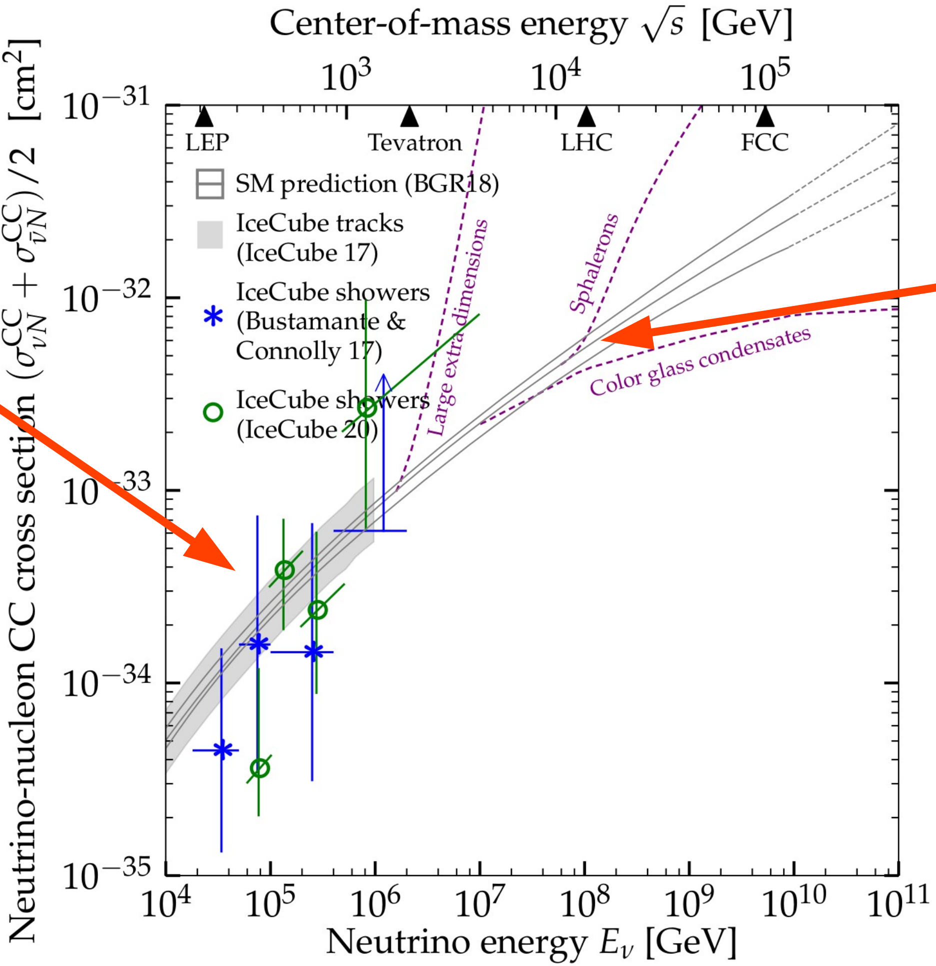


Not measured:
> 10-PeV
cross section

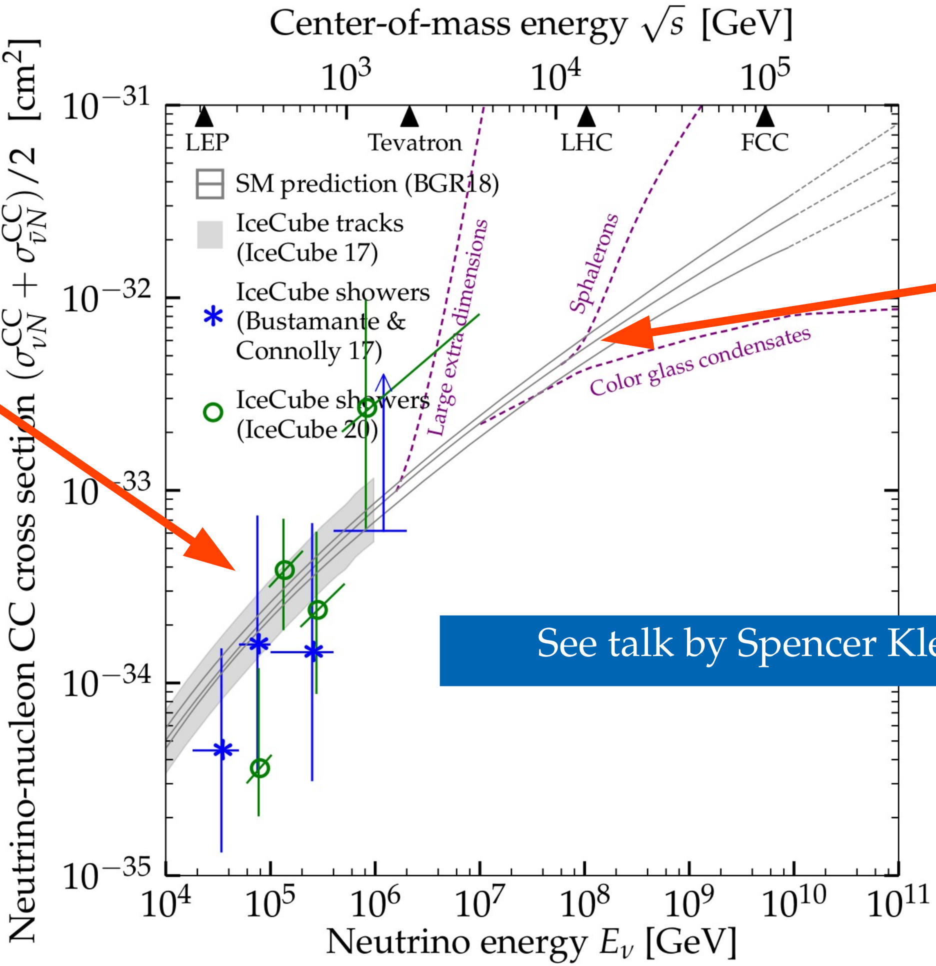
BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy neutrino-nucleon cross section: *today*

Measured:
TeV – PeV
cross section



Not measured:
> 10-PeV
cross section

See talk by Spencer Klein

BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

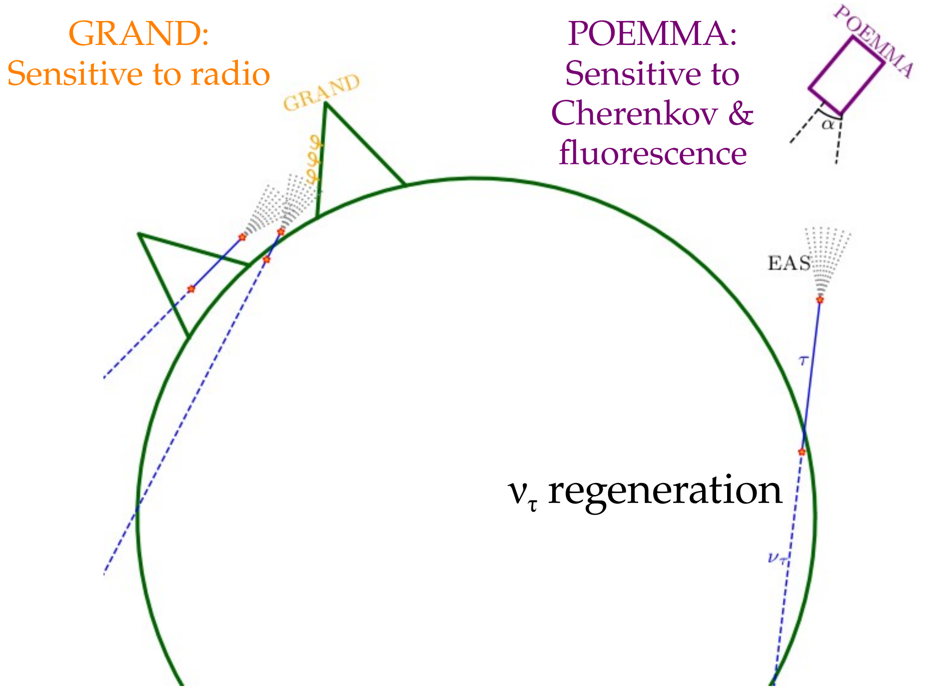
Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

GRAND & POEMMA

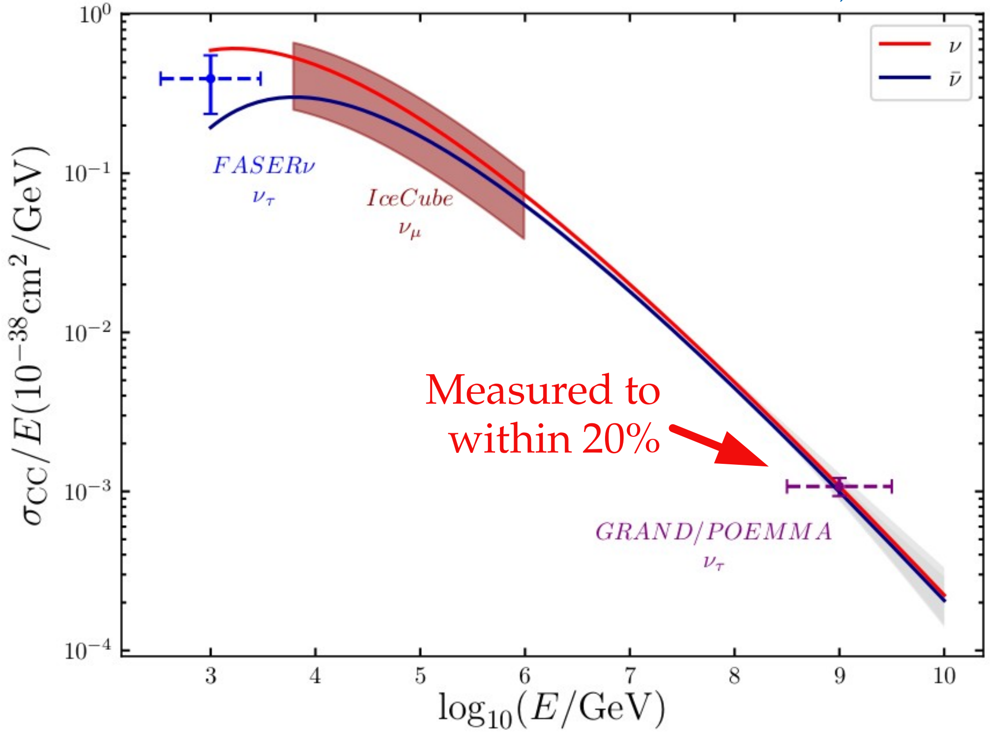
See talks by Lech Piotrowski & John Krizmanic

Both sensitive to extensive air showers induced by Earth-skimming UHE ν_τ

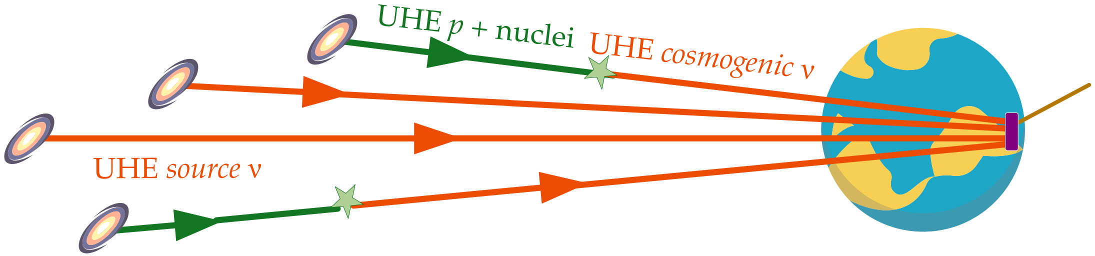
If they see 100 events from ν_τ with initial energy of 10^9 GeV (pre-attenuation):



Denton & Kini, *PRD* 2020

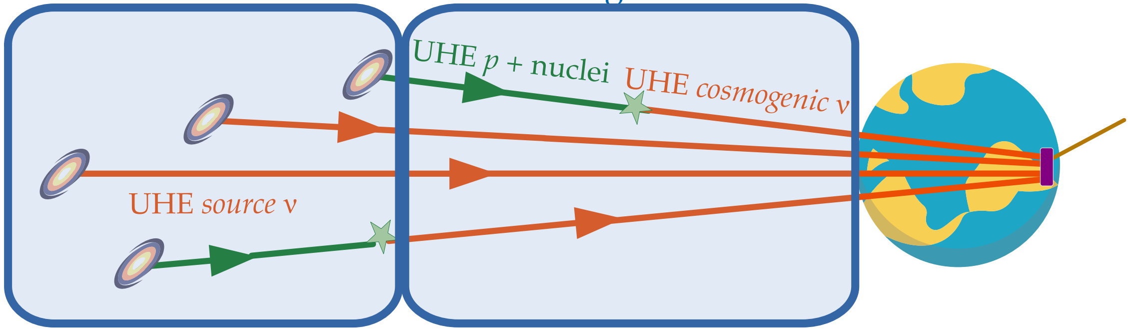


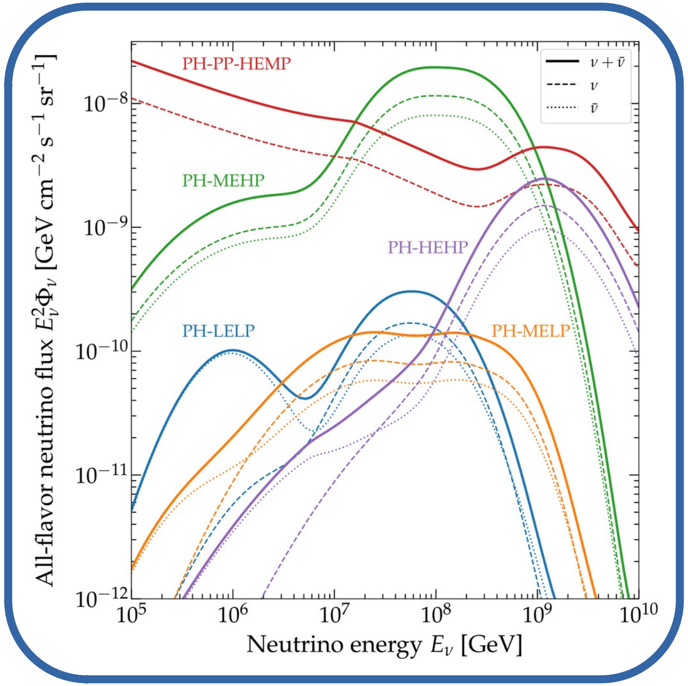
IceCube-Gen2 Radio


UHE p + nuclei
UHE cosmogenic ν
UHE source ν

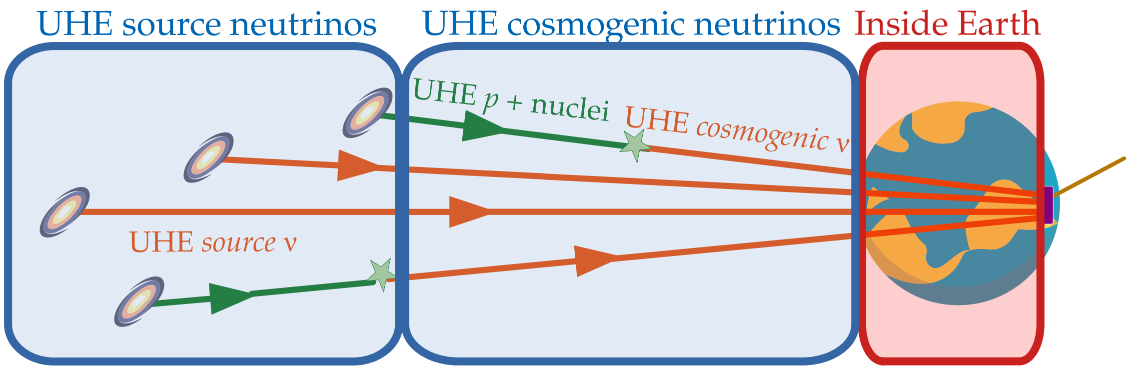
UHE source neutrinos

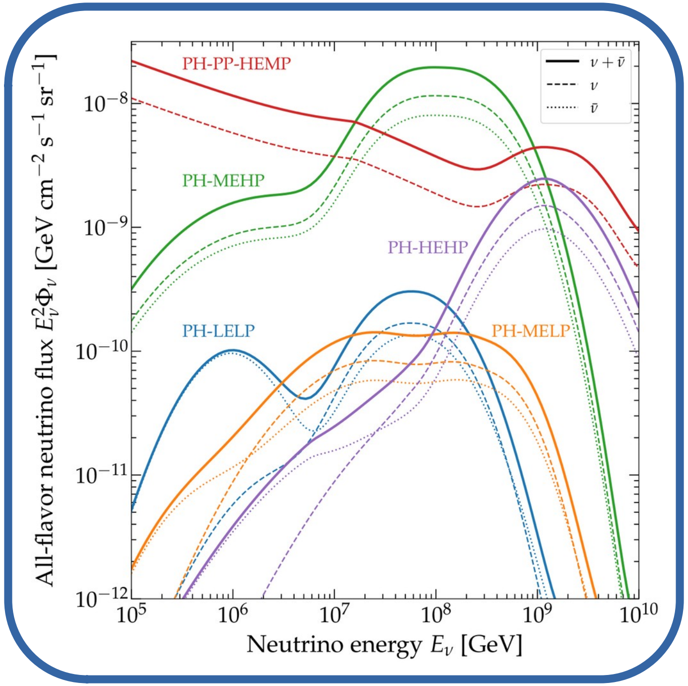
UHE cosmogenic neutrinos



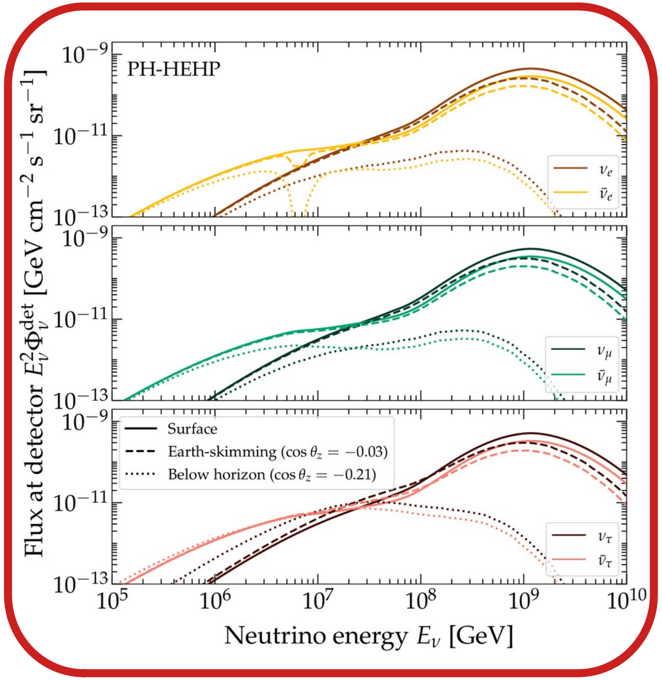


UHE ν from *pp* and *pγ* interactions, account for cosmic-ray spectrum & mass composition, source properties

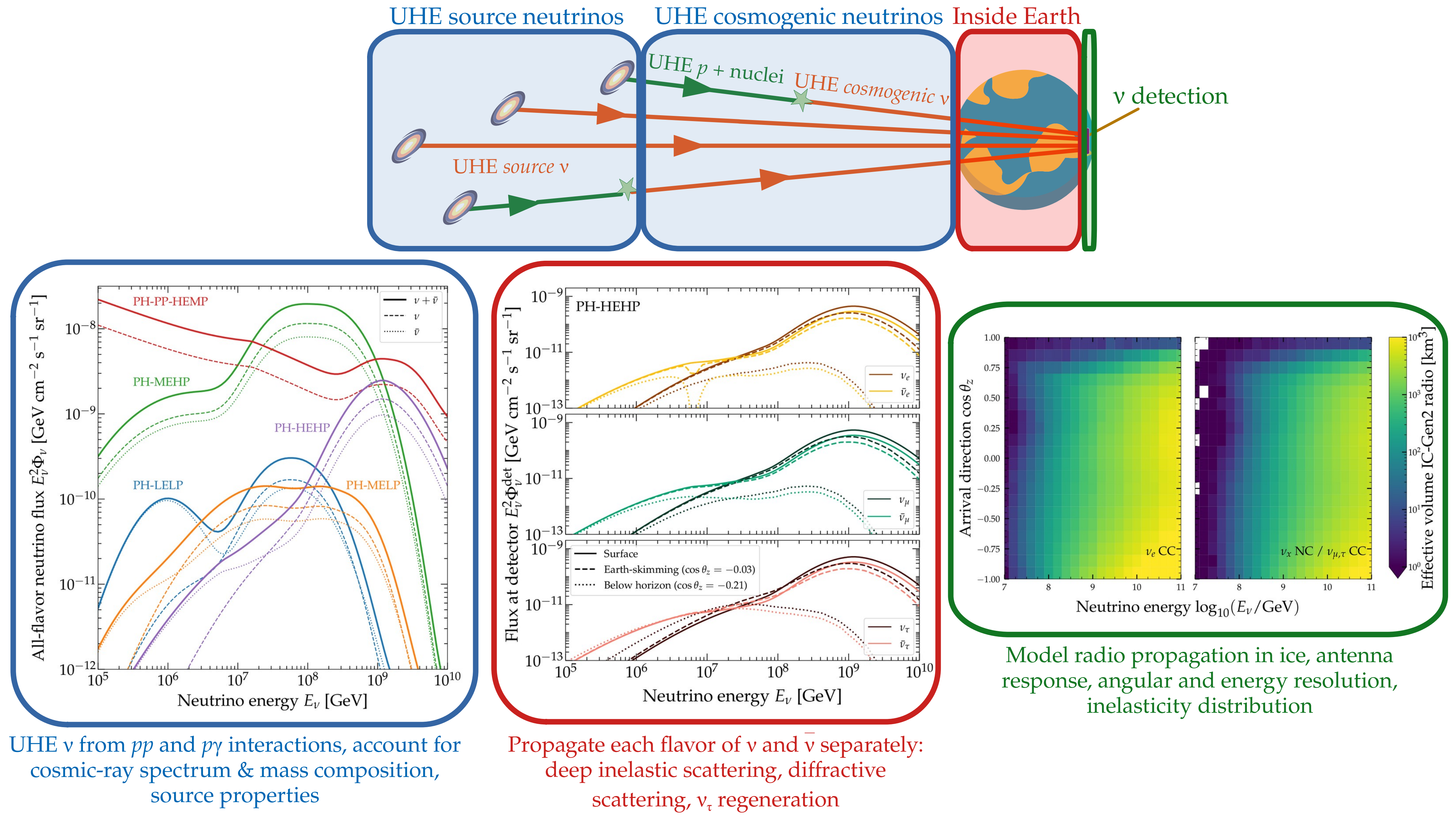


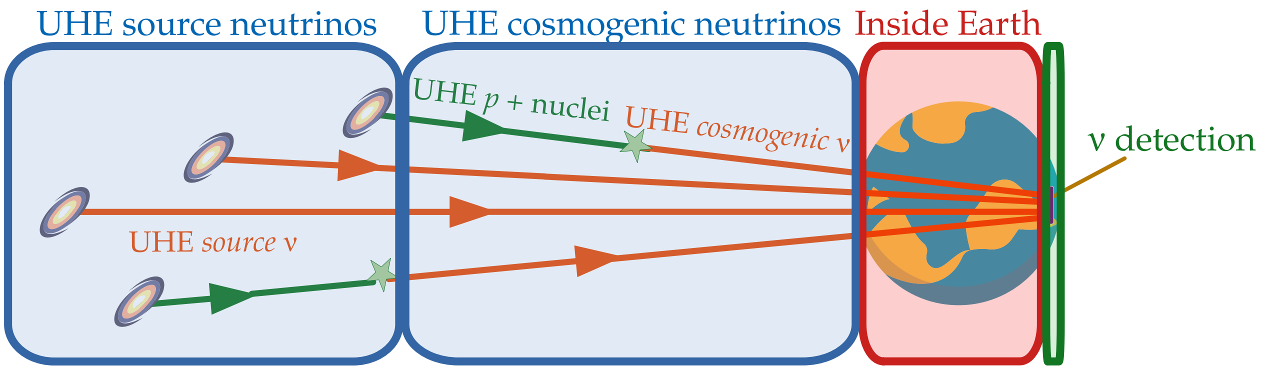


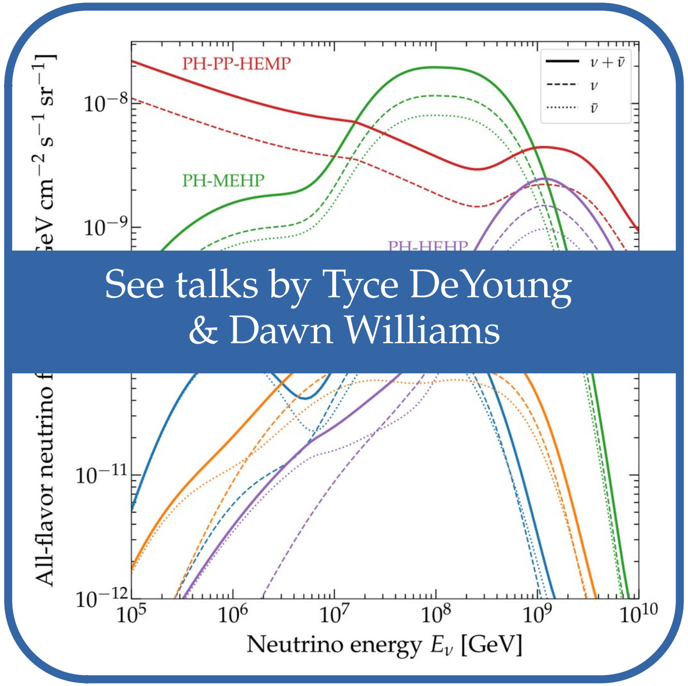
UHE ν from pp and $p\gamma$ interactions, account for cosmic-ray spectrum & mass composition, source properties



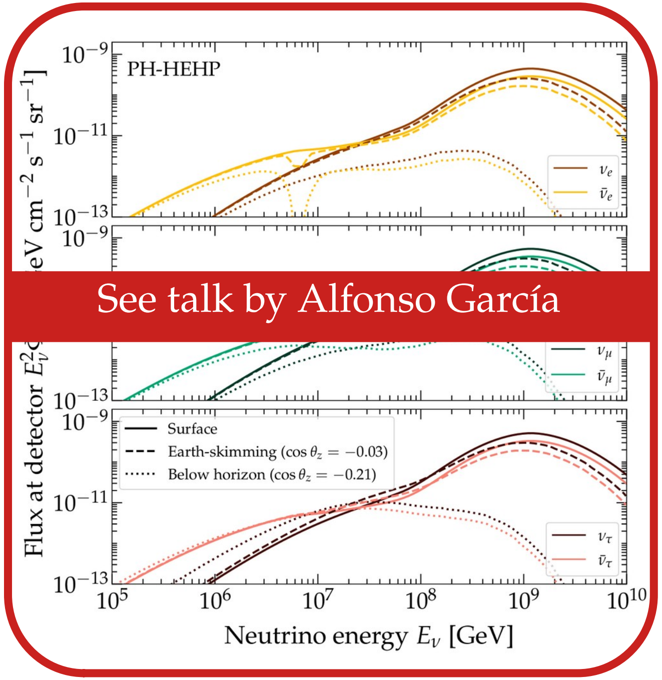
Propagate each flavor of ν and $\bar{\nu}$ separately: deep inelastic scattering, diffractive scattering, ν_τ regeneration


UHE source neutrinos
UHE cosmogenic neutrinos
Inside Earth
UHE p + nuclei
UHE cosmogenic ν
UHE source ν
ν detection
PH-PP-HEMP
PH-MEHP
PH-HEHP
PH-LELP
PH-MELP
ν + ν̄
ν
ν̄
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
UHE ν from pp and pγ interactions, account for cosmic-ray spectrum & mass composition, source properties
PH-HEHP
ν_e
$\bar{\nu}_e$
ν_μ
$\bar{\nu}_\mu$
ν_τ
$\bar{\nu}_\tau$
Surface
Earth-skimming ($\cos\theta_z = -0.03$)
Below horizon ($\cos\theta_z = -0.21$)
Flux at detector $E_\nu^2 \Phi_\nu^{\rm det}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
Propagate each flavor of ν and ν̄ separately: deep inelastic scattering, diffractive scattering, ν_τ regeneration
Arrival direction $\cos\theta_z$
ν_e CC
ν_x NC / $\nu_{\mu,\tau}$ CC
Effective volume IC-Gen2 radio [km^3]
Neutrino energy $\log_{10}(E_\nu/\text{GeV})$
Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution





UHE ν from *pp* and *pγ* interactions, account for cosmic-ray spectrum & mass composition, source properties



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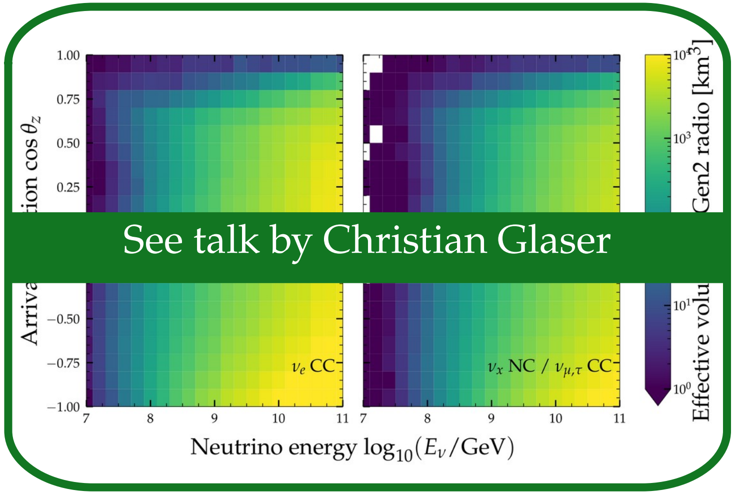
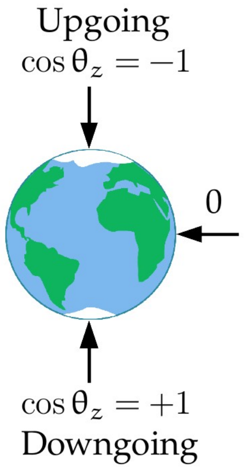
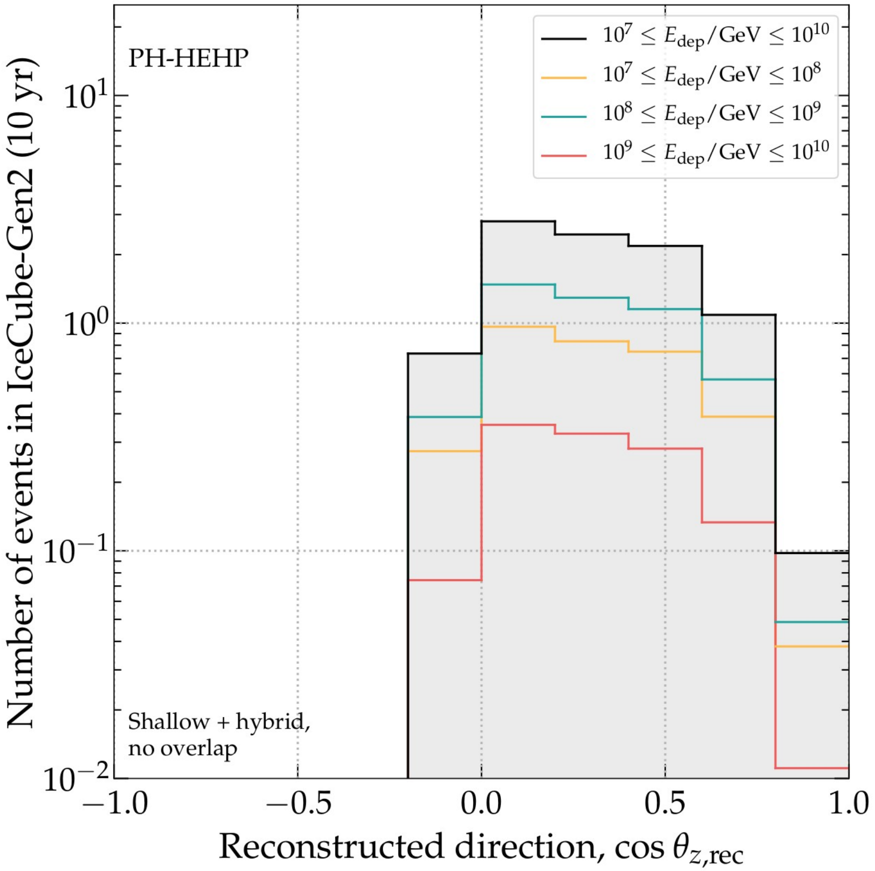
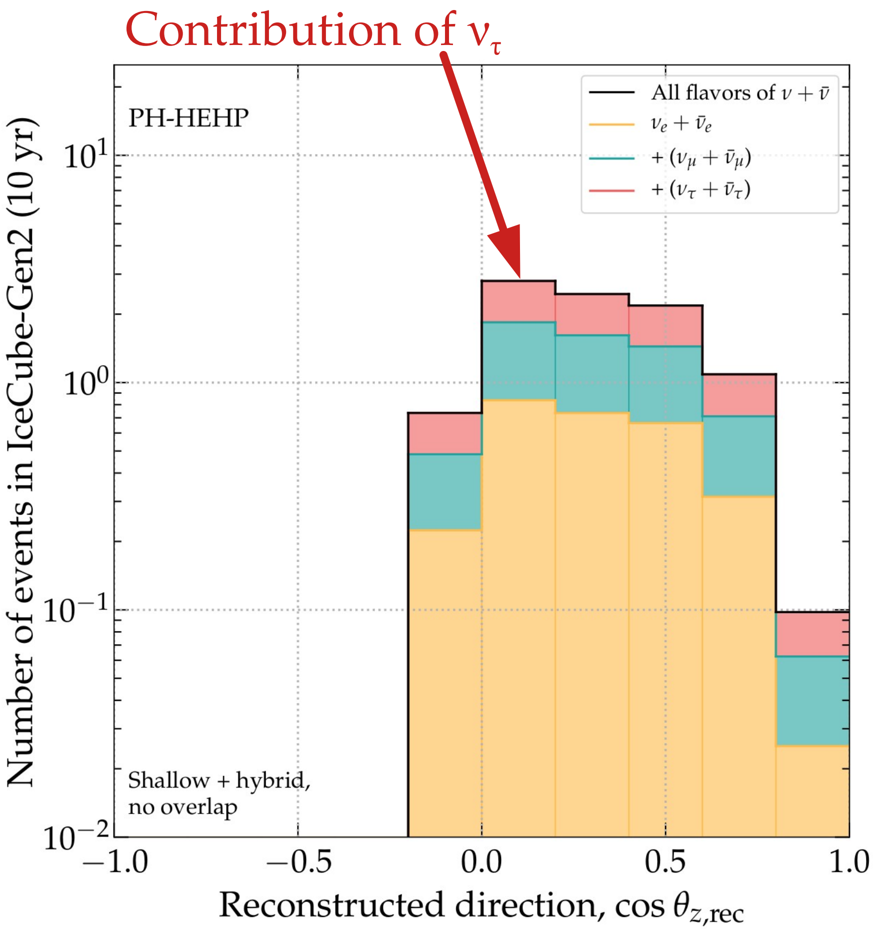


Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution

IceCube-Gen2 Radio



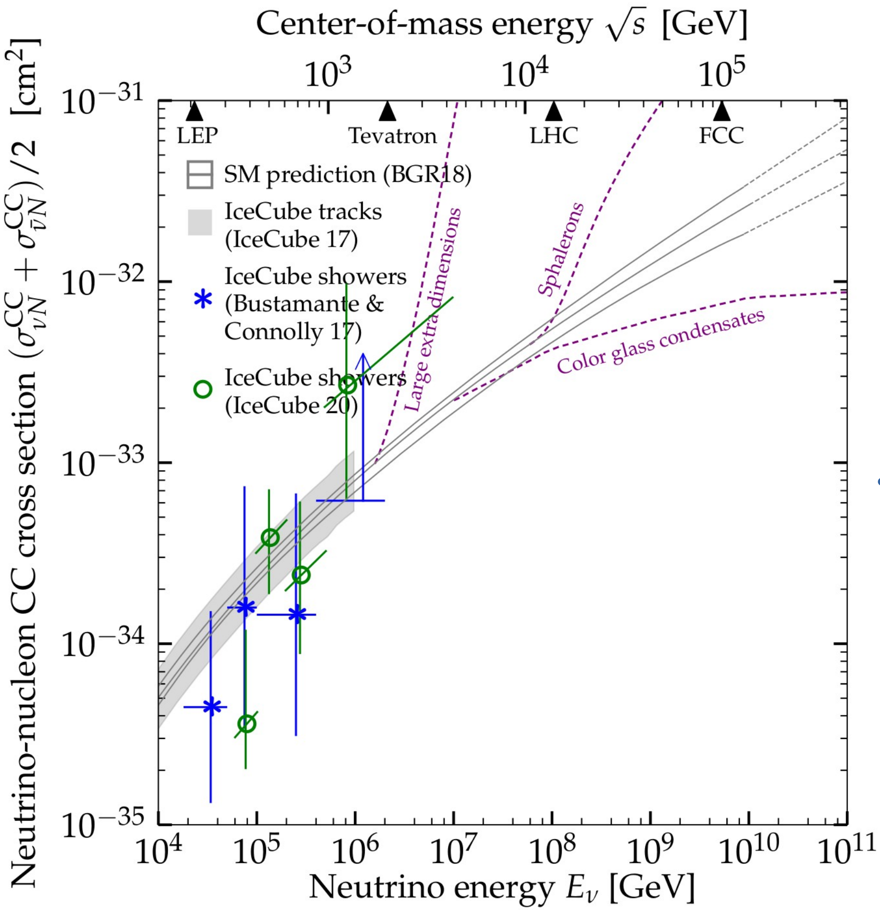


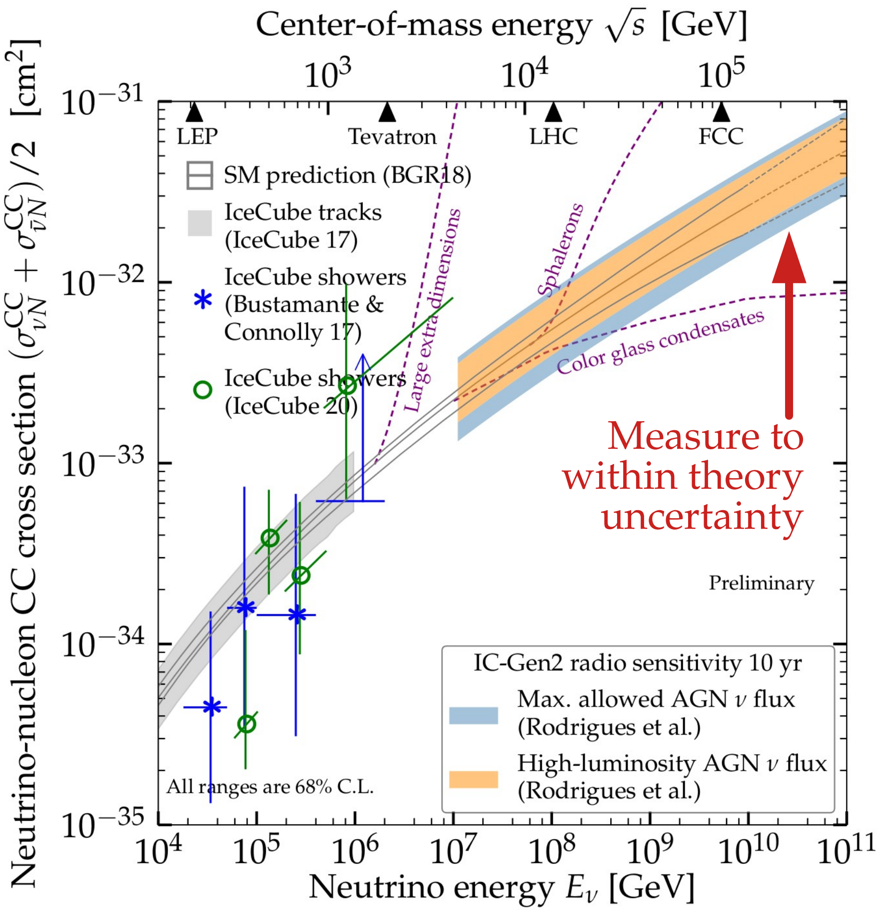


(Angular resolution in $\theta_{z,\rm rec}$: 2°
Energy resolution in $\log_{10}(E_{\rm dep}/\mathrm{GeV})$: 0.1)

Valera, **MB**, Glaser, *In preparation*

2021 → ~2040





(Including 40% uncertainty normalization of the UHE ν flux)

Valera, **MB**, Glaser, *In preparation*

Spectral shape:
Looking for new ν interactions

Astrophysical neutrino sources

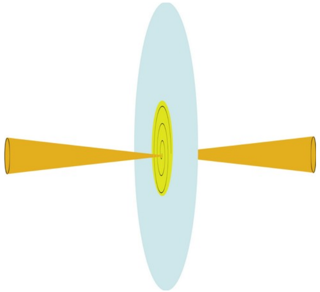
Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Astrophysical neutrino sources

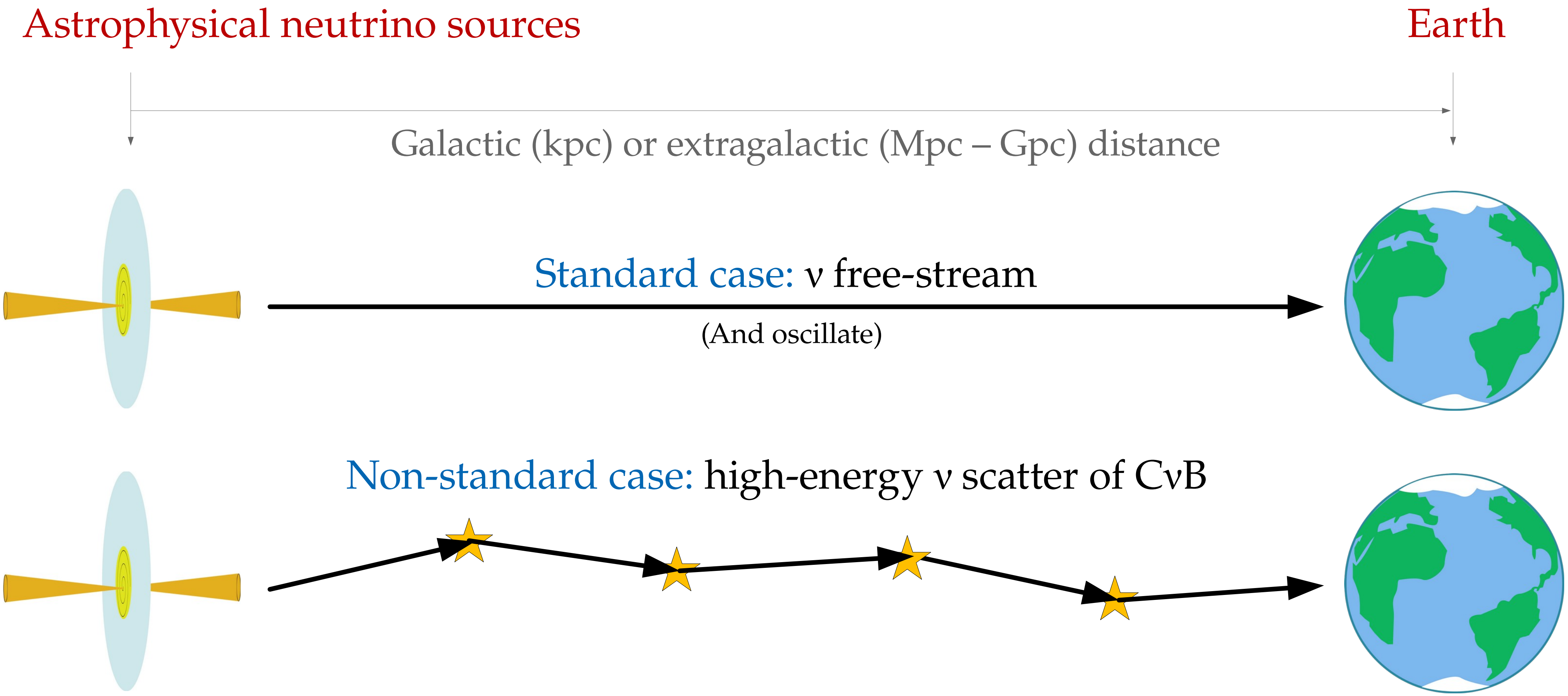
Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Standard case: ν free-stream

(And oscillate)


Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
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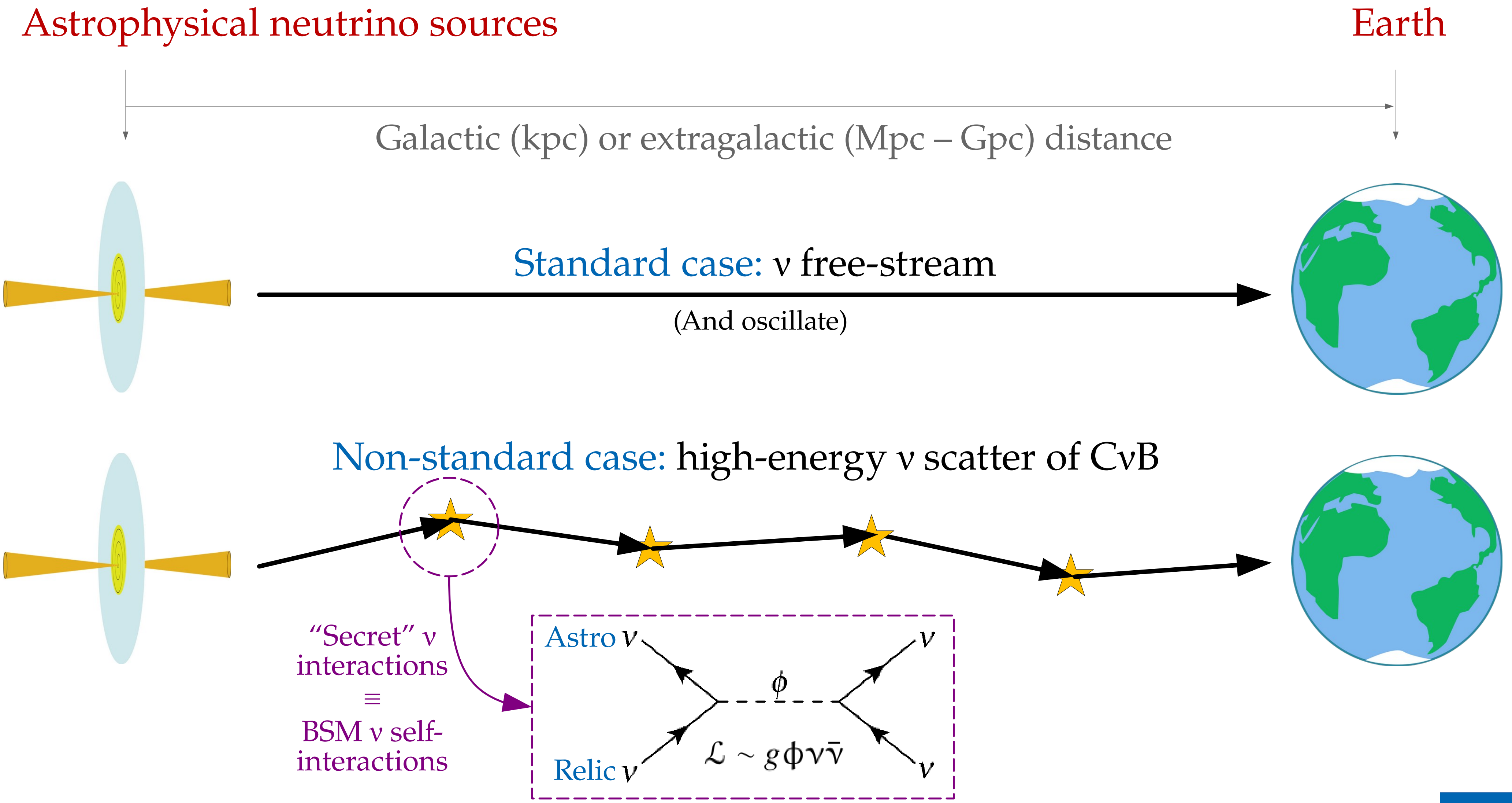
Non-standard case: high-energy ν scatter of CνB



Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
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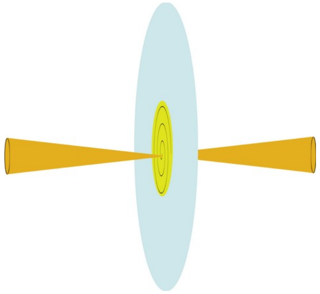
“Secret” ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$

Astrophysical neutrino sources   Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance



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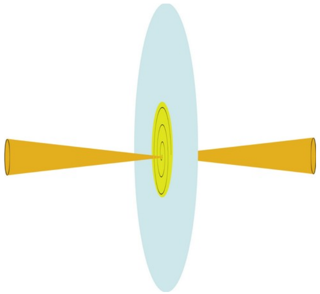
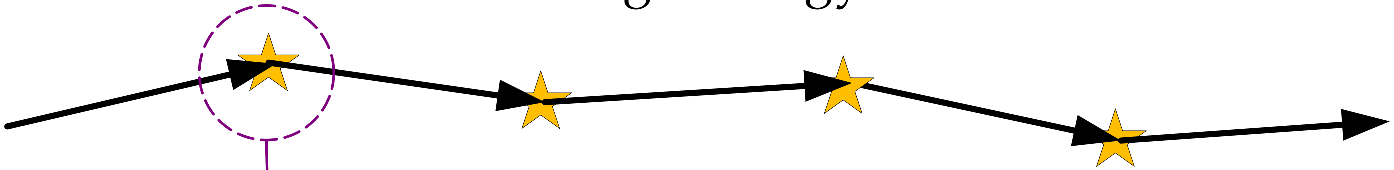
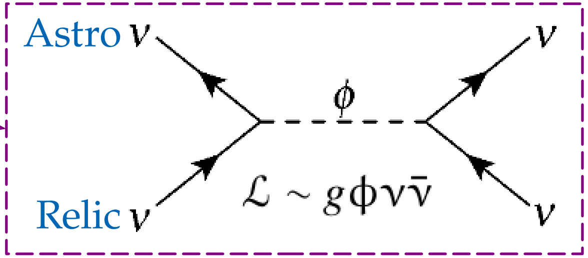
(And oscillate)

Non-standard case: high-energy ν scatter of CνB

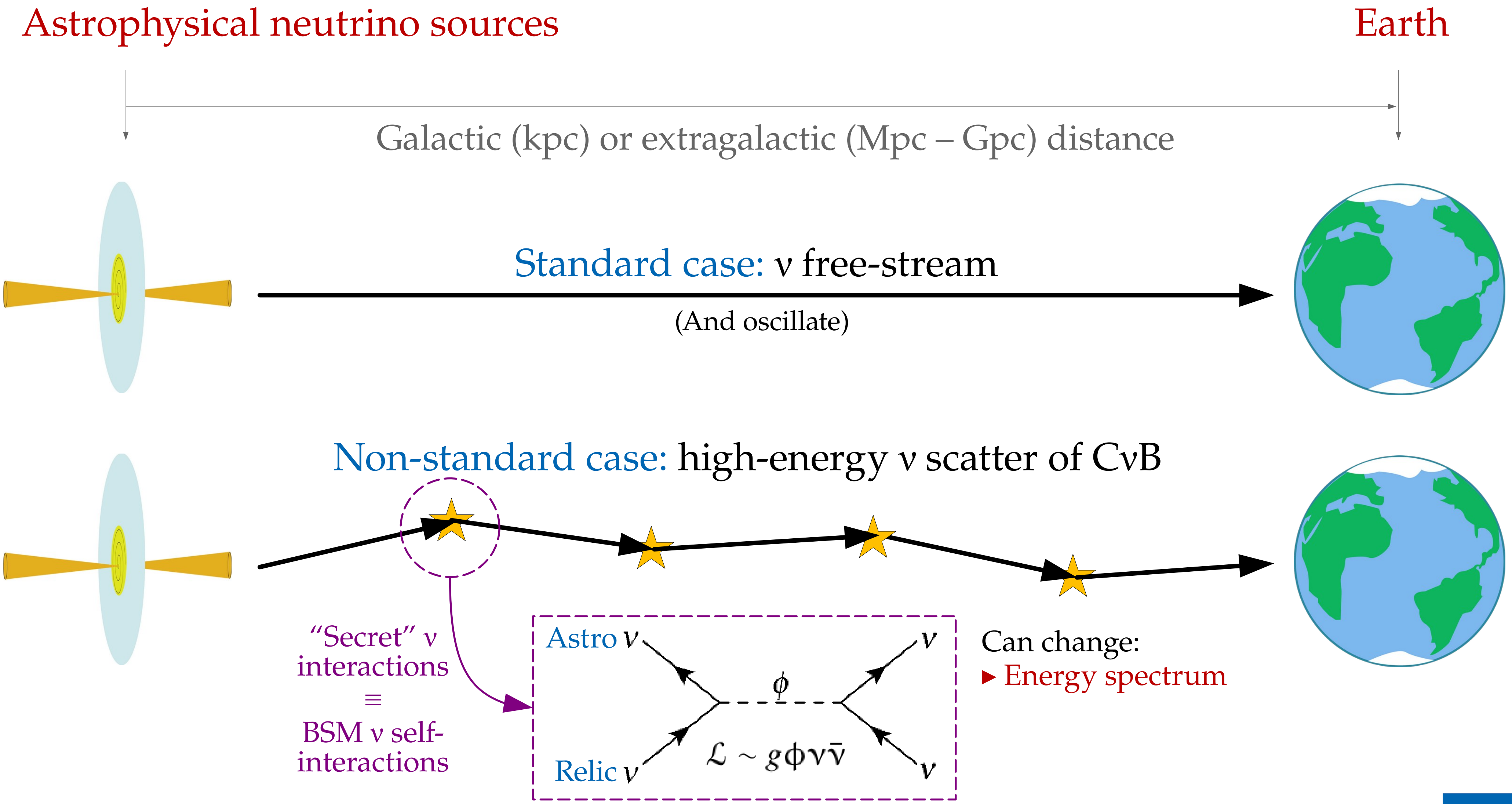




"Secret" ν interactions
≡
BSM ν self-interactions



Can change: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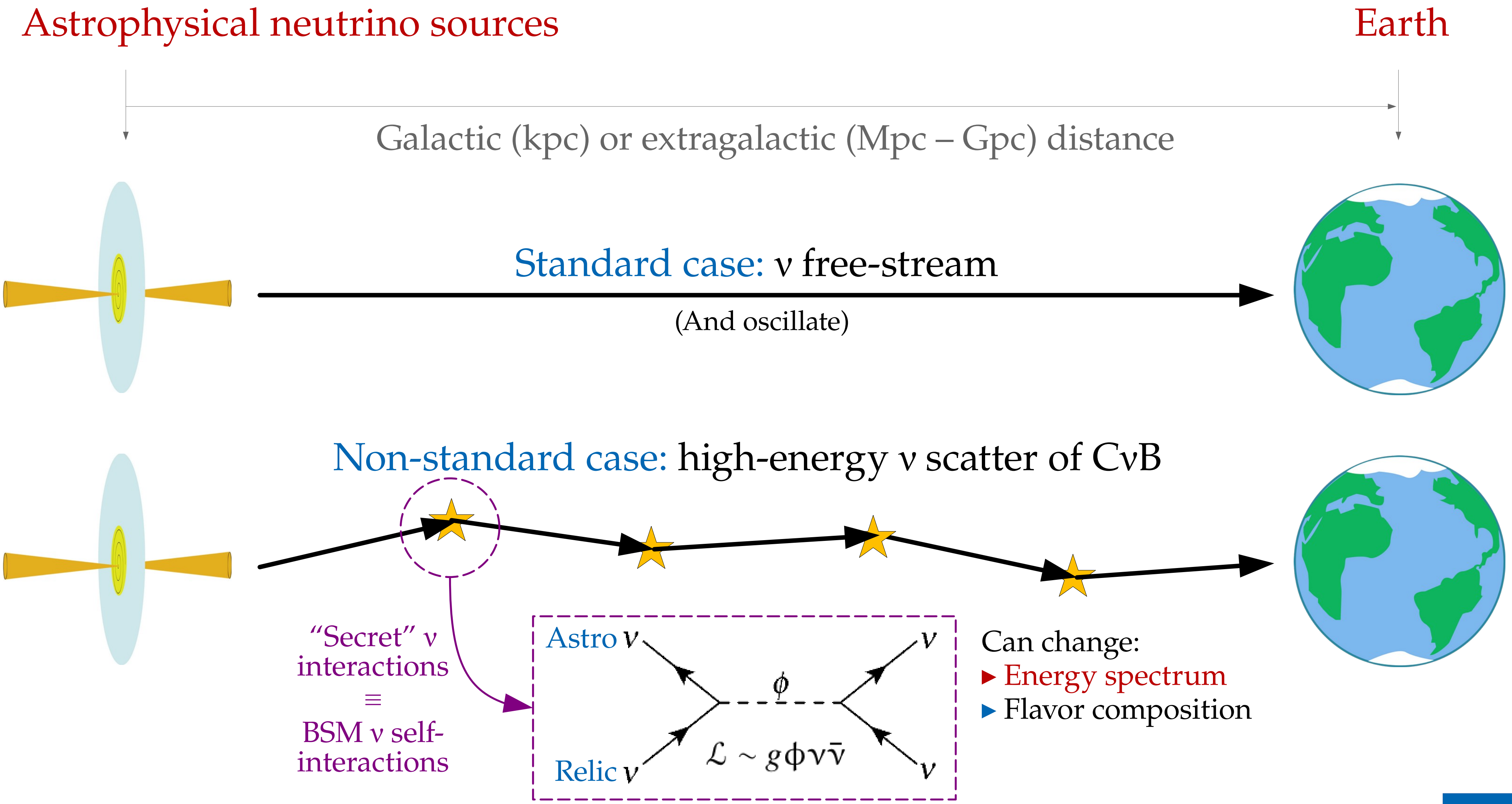
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum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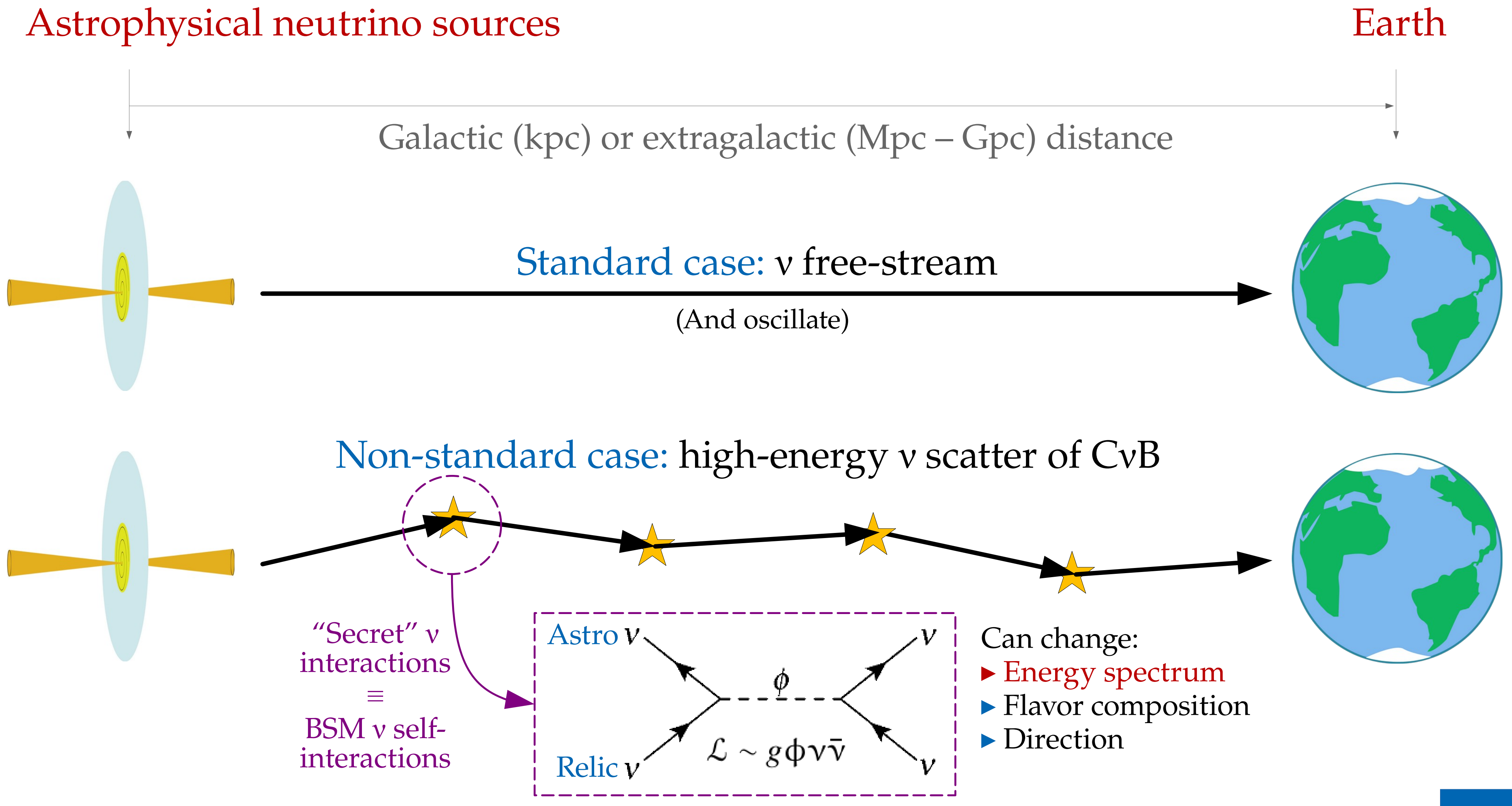
Can change:
▸ Energy spectrum
▸ Flavor composition



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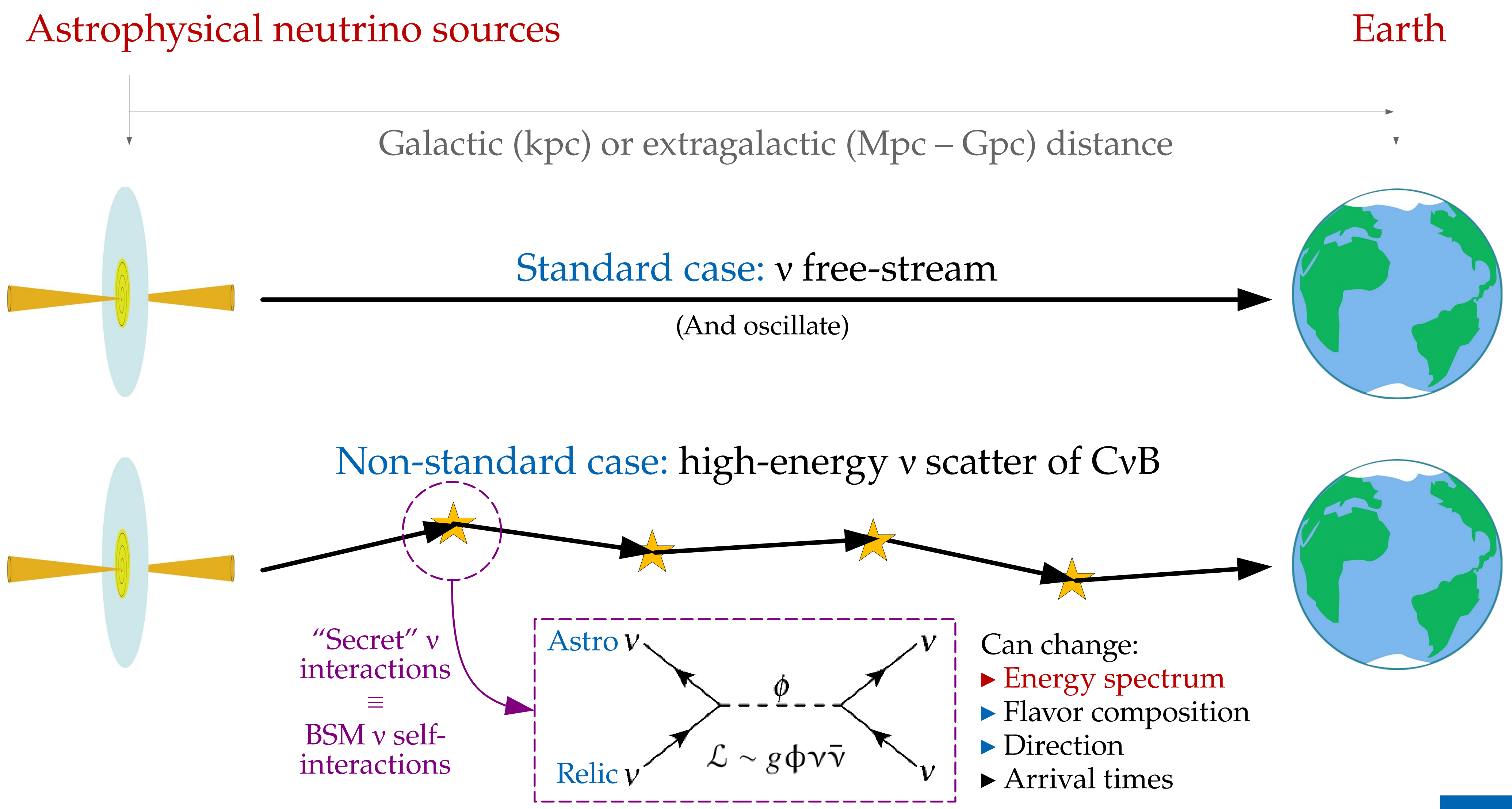
Can change:
Energy spectrum
Flavor composition
Direction



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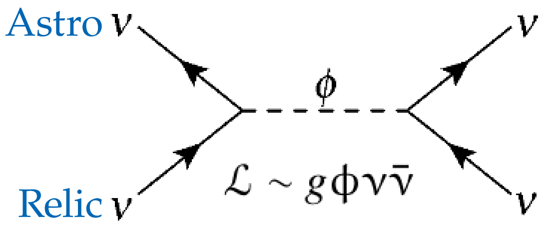
Astro ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Relic ν
ν
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction
▸ Arrival times

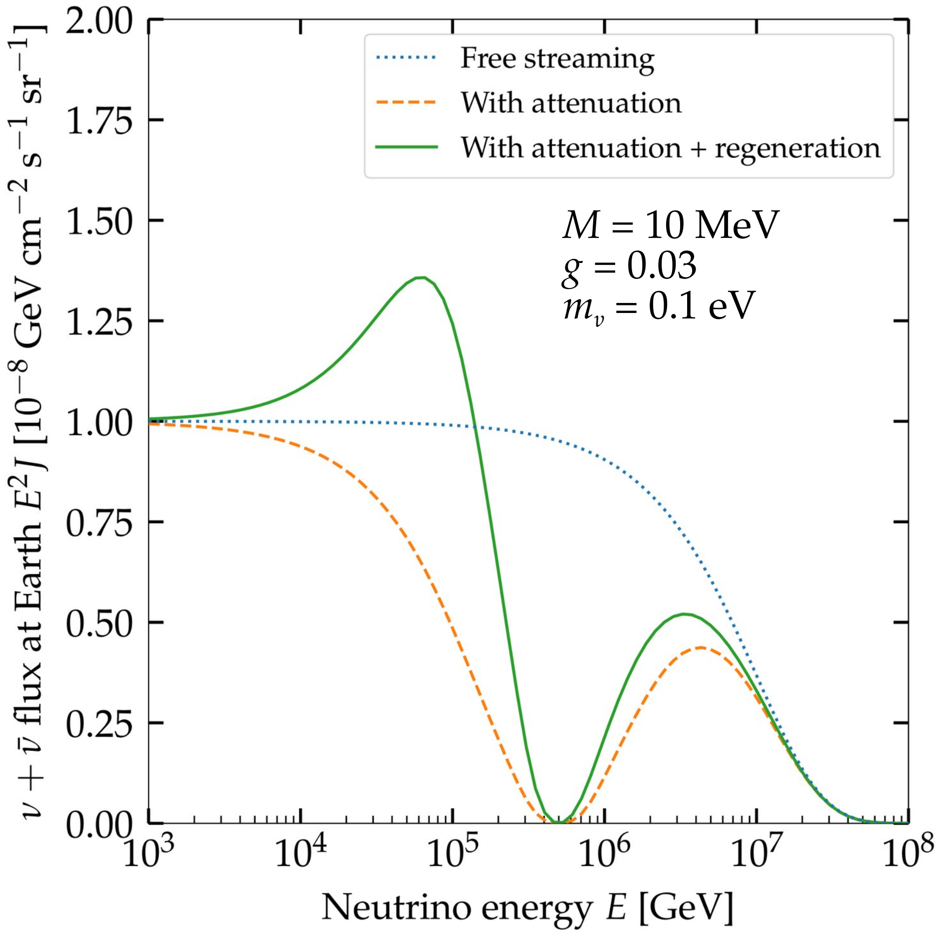
Secret interactions of high-energy astrophysical neutrinos

"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section: $$\sigma = \frac{g^4}{4\pi}\frac{s}{(s-M^2)^2+M^2\Gamma^2}$$

Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
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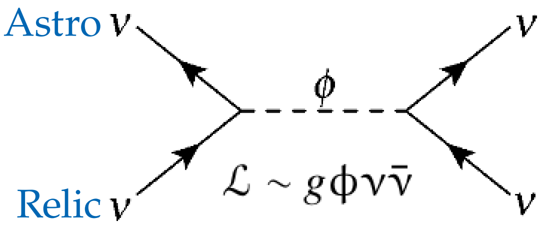
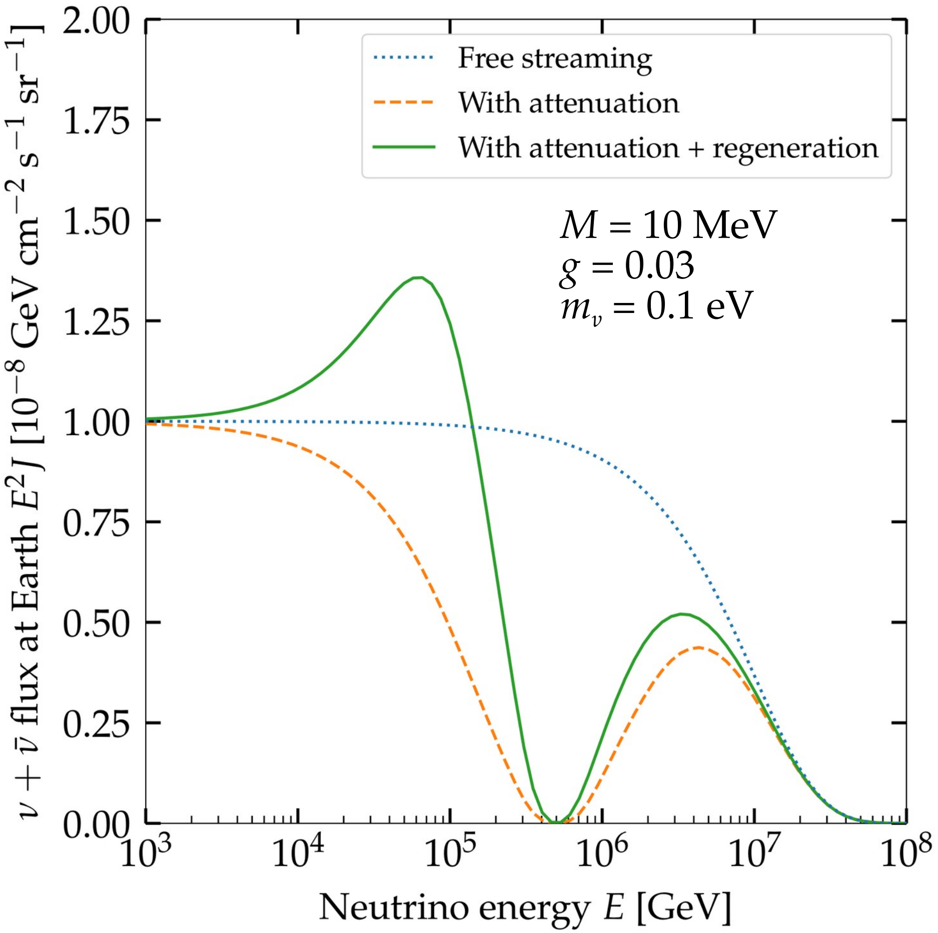


New coupling

Cross section: $$\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

Mediator mass

Resonance energy: $$E_{\mathrm{res}} = \frac{M^2}{2m_\nu}$$



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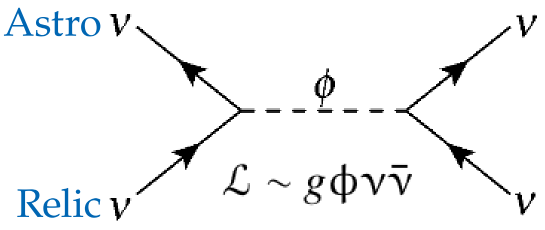

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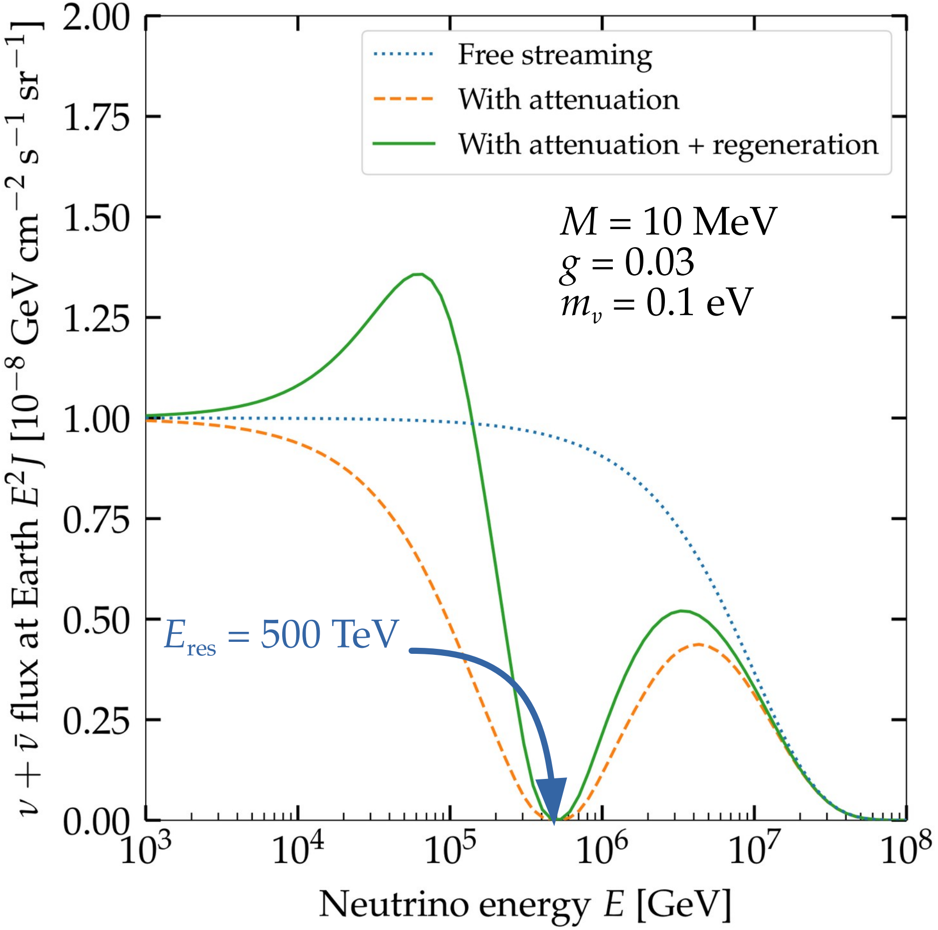

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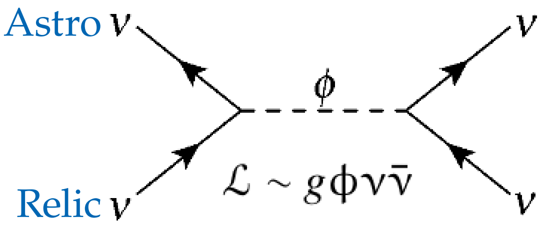

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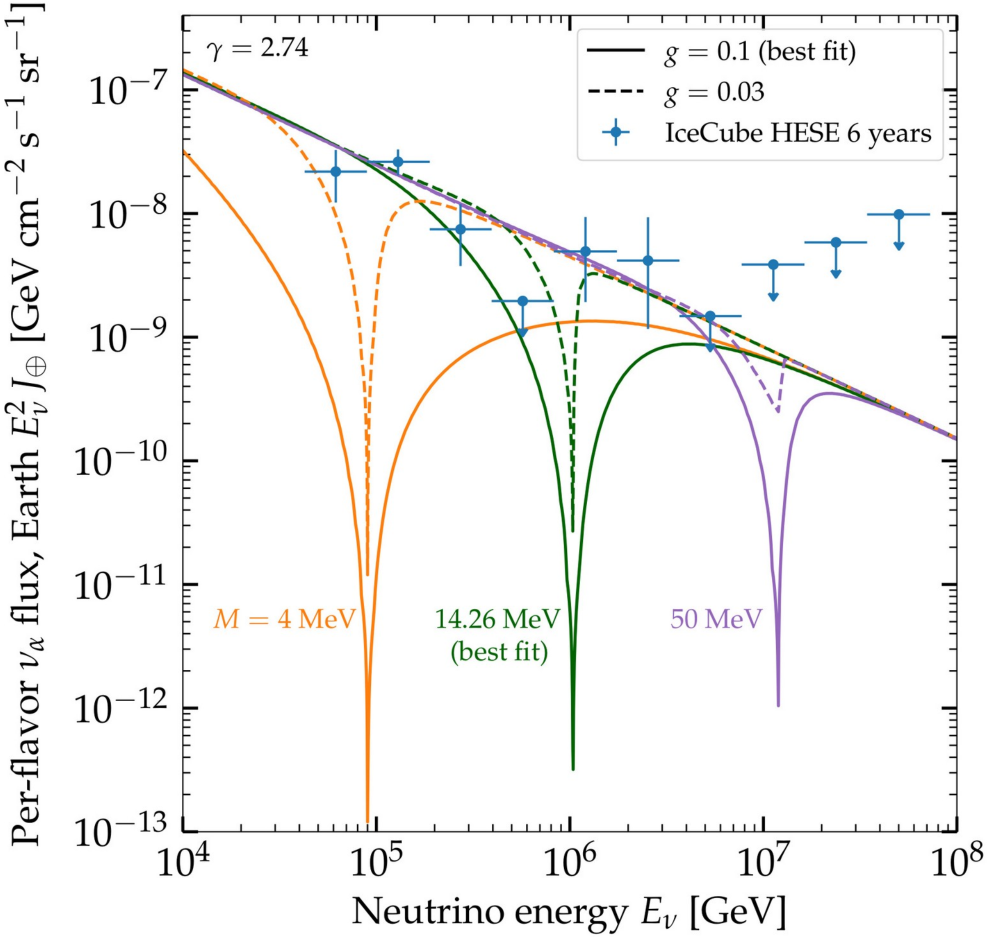

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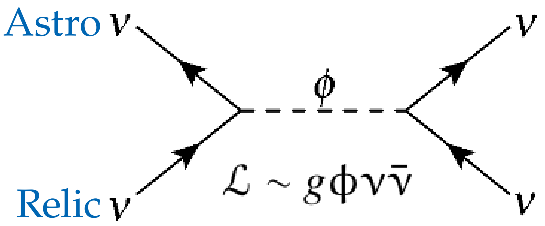

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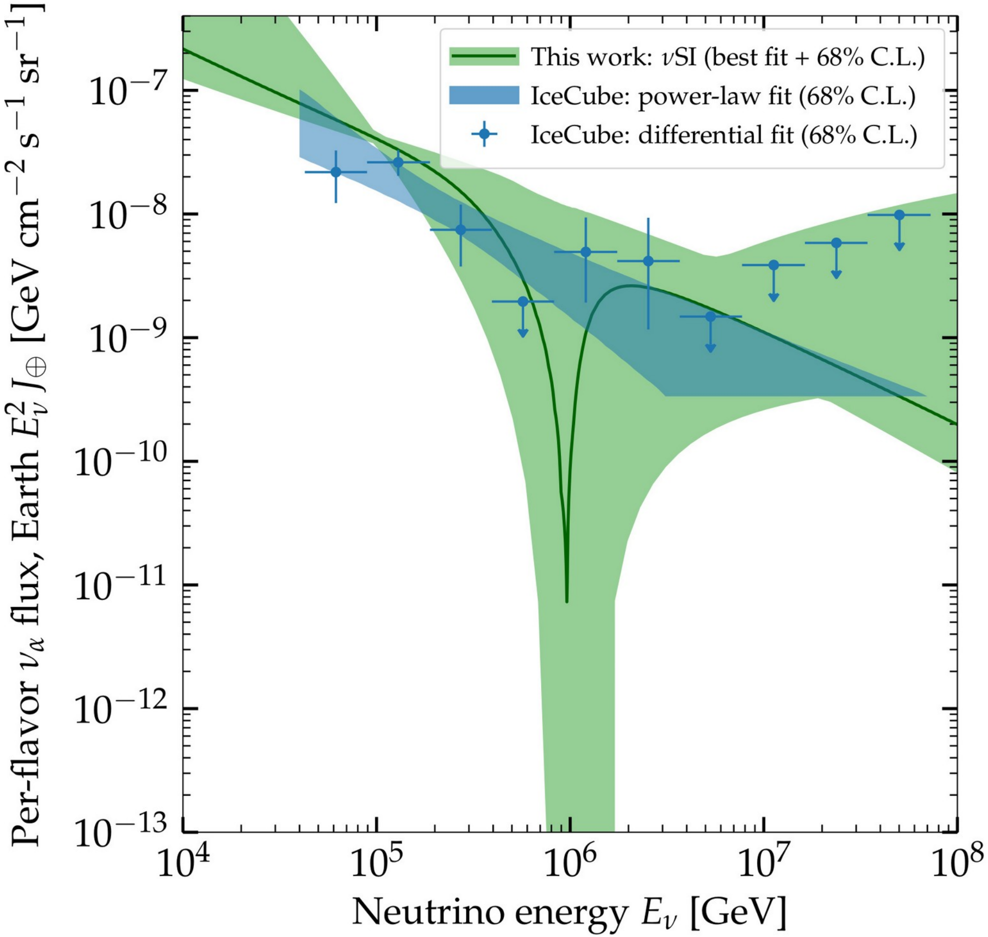
Looking for evidence of νSI

- Look for dips in 6 years of public IceCube data (HESE)
- 80 events, 18 TeV–2 PeV
- Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g\,\delta_{\alpha\alpha}$
- Bayesian analysis varying M, g, shape of emitted flux (γ)
- Account for atmospheric ν, in-Earth propagation, detector uncertainties

No significant (> 3σ) evidence for a spectral dip …



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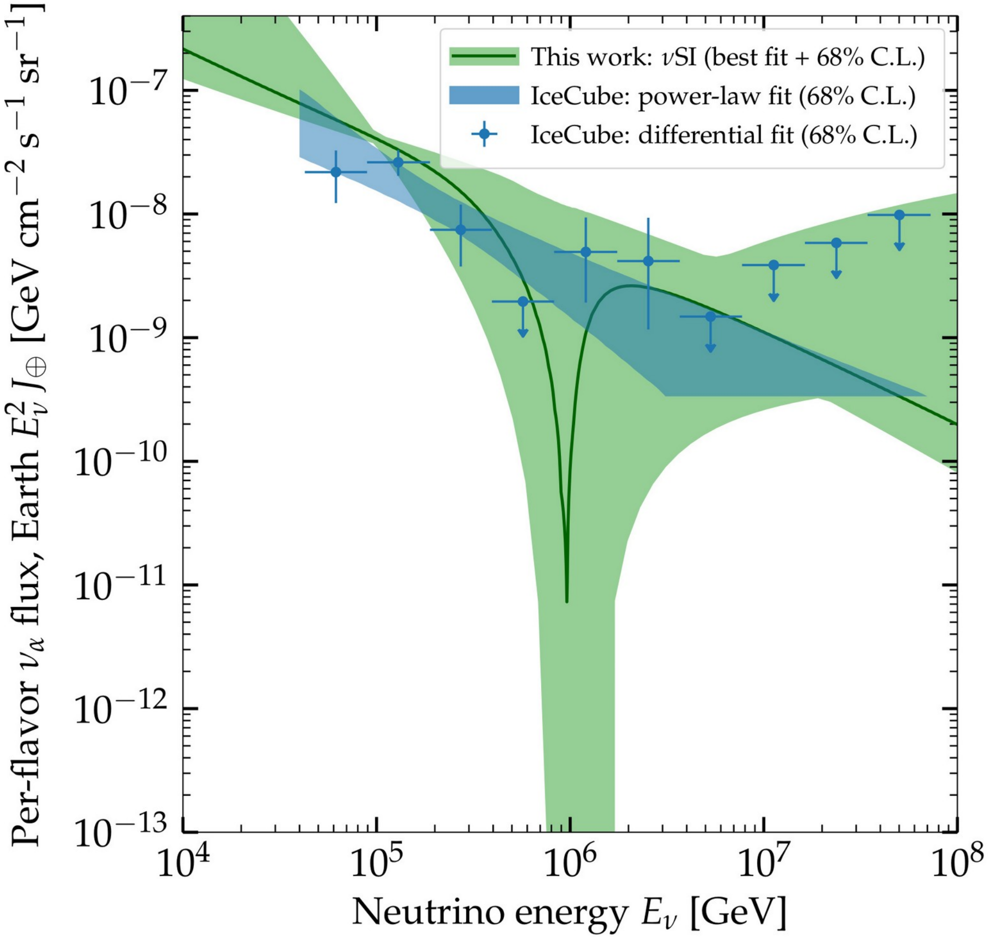
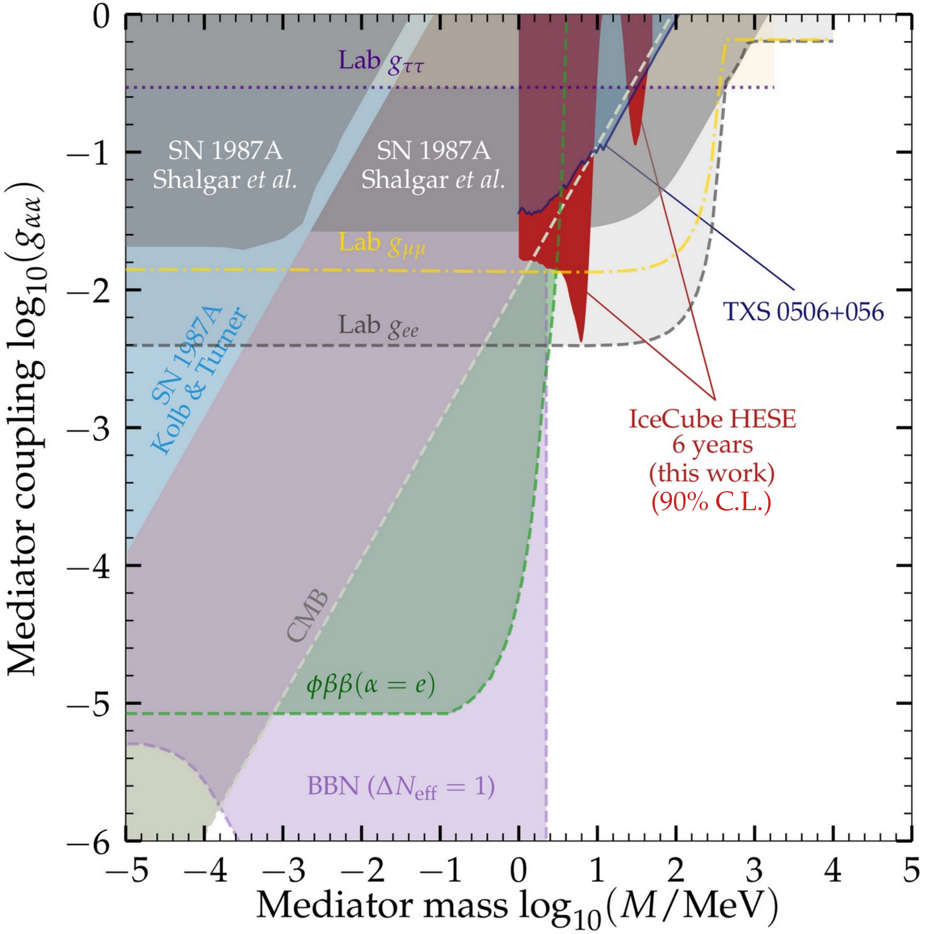
No significant (> 3σ) evidence for a spectral dip … … so we set upper limits on the coupling g





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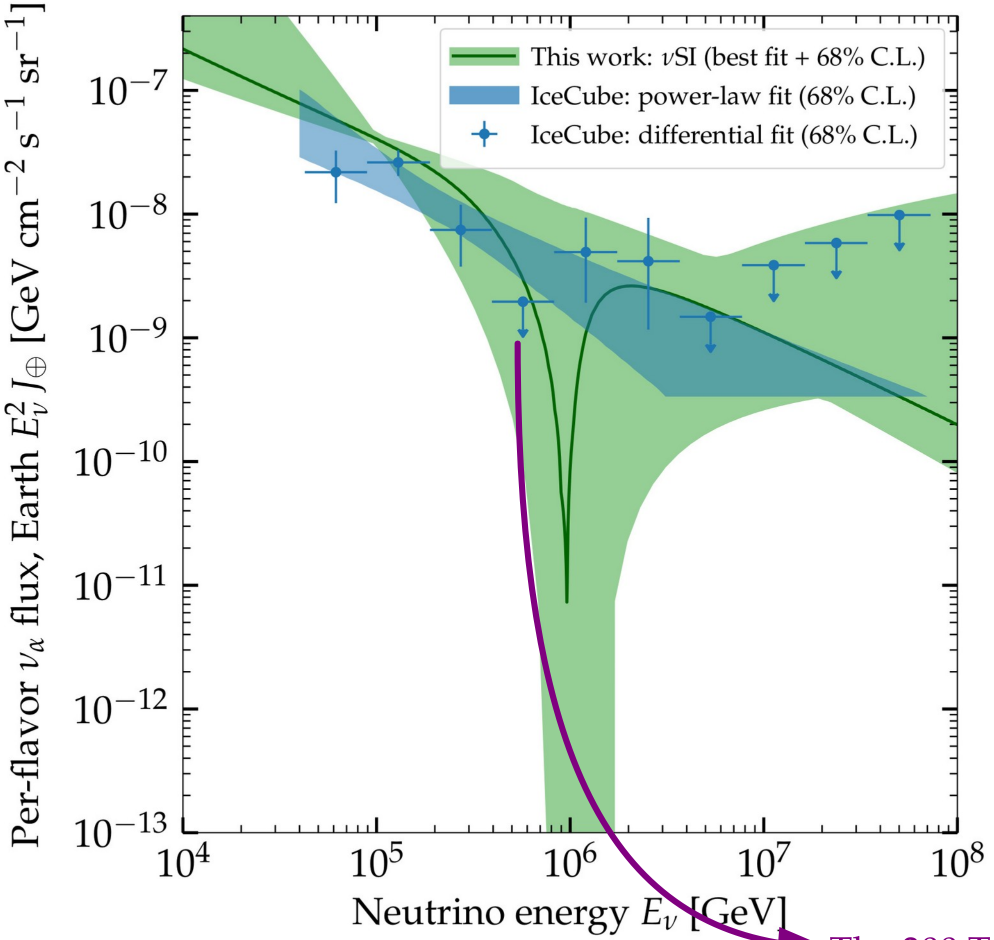
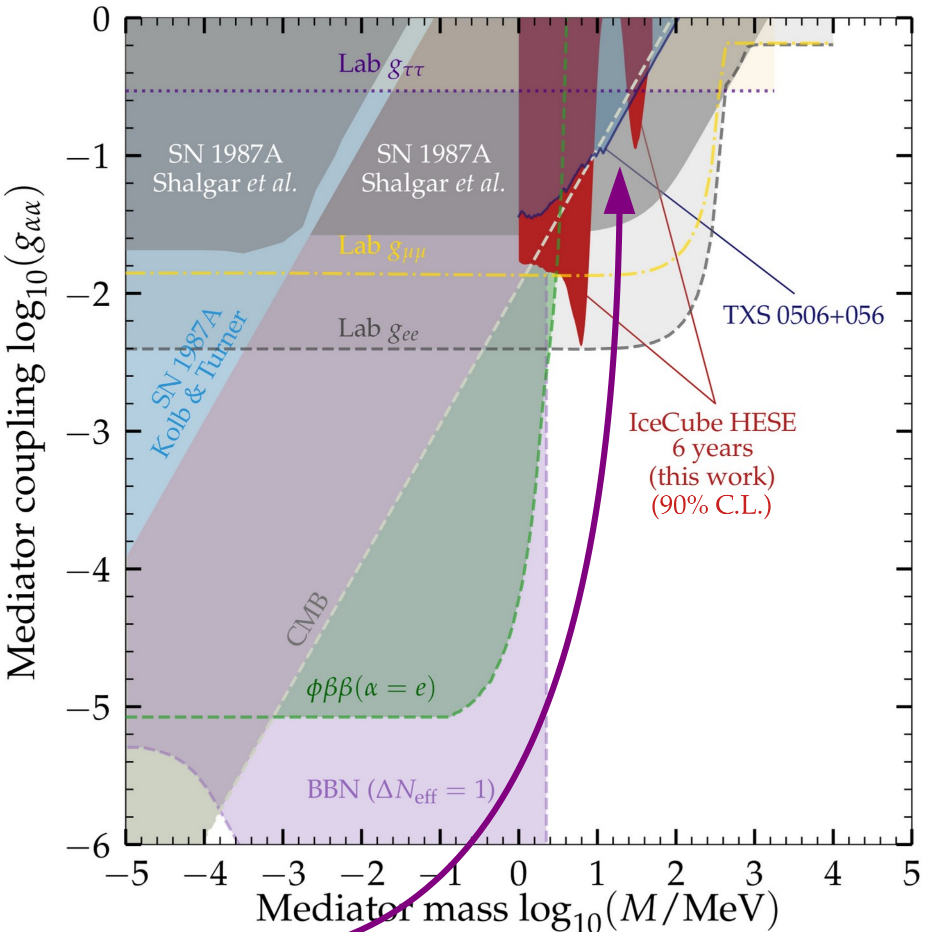
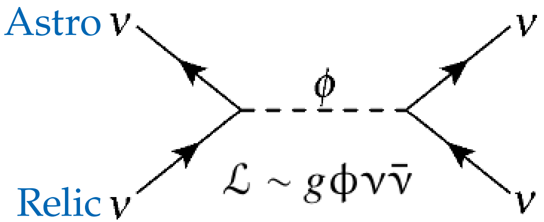




The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, *PRD* 2020

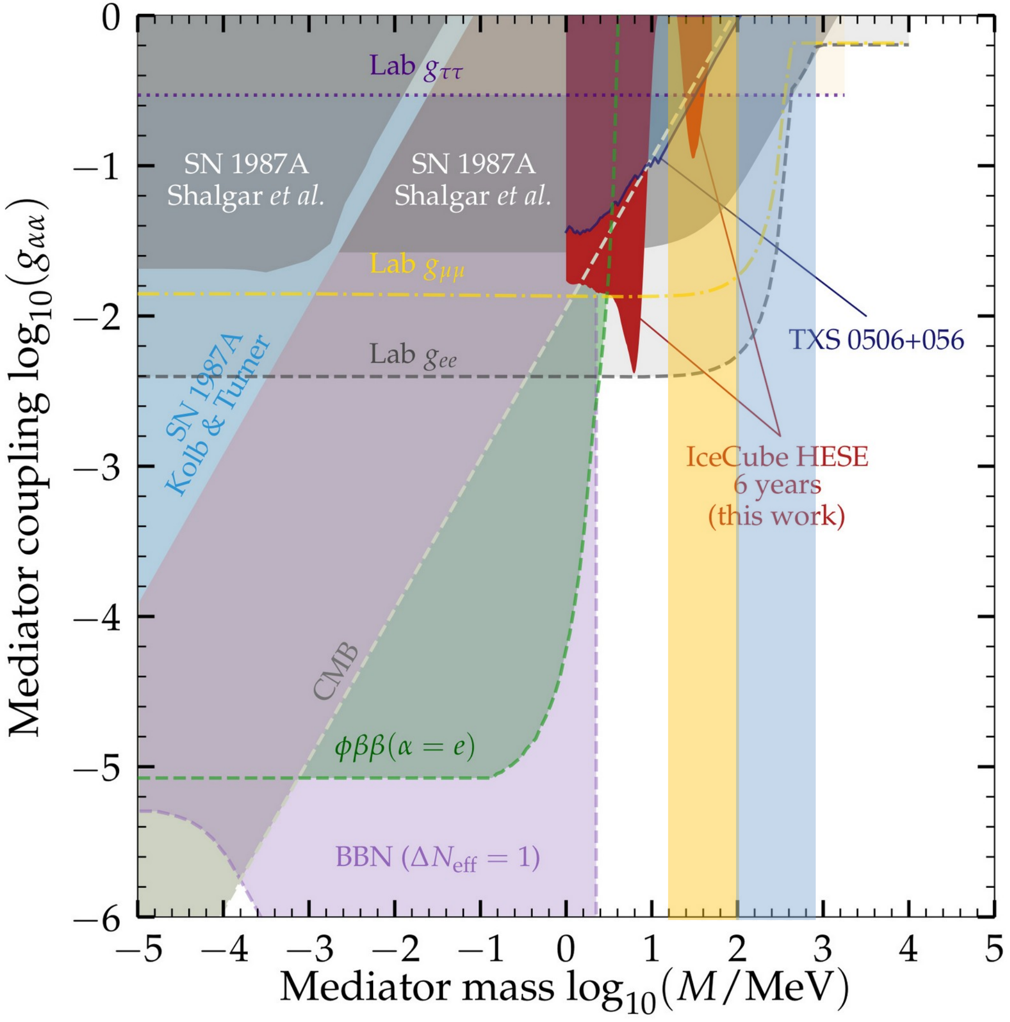


Flavor-dependent coupling matrix:

$$\mathbf{G} \equiv \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{e\mu} & g_{\mu\mu} & g_{\mu\tau} \\ g_{e\tau} & g_{\mu\tau} & g_{\tau\tau} \end{pmatrix}$$

Least-constrained couplings

We can use the large flux of HE and UHE ν_τ to constrain them



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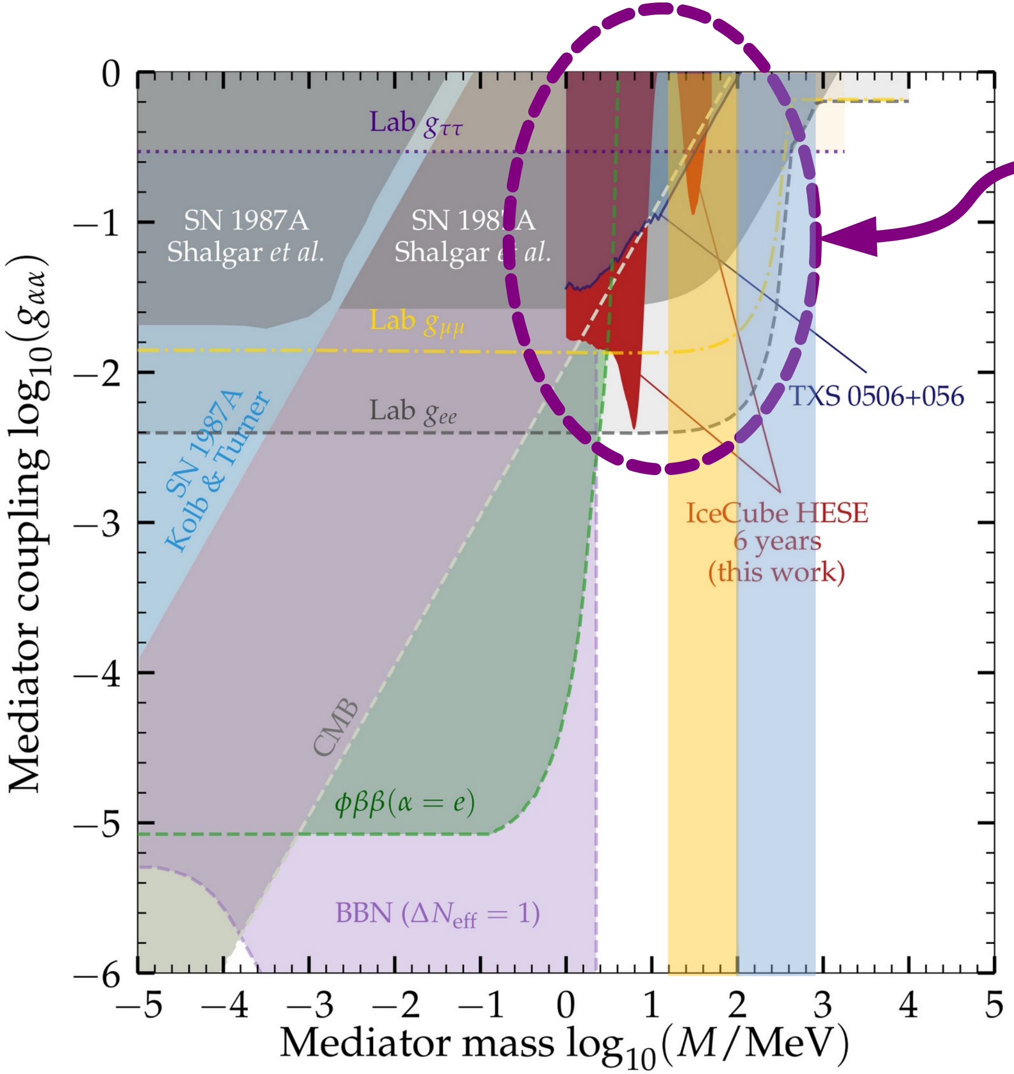
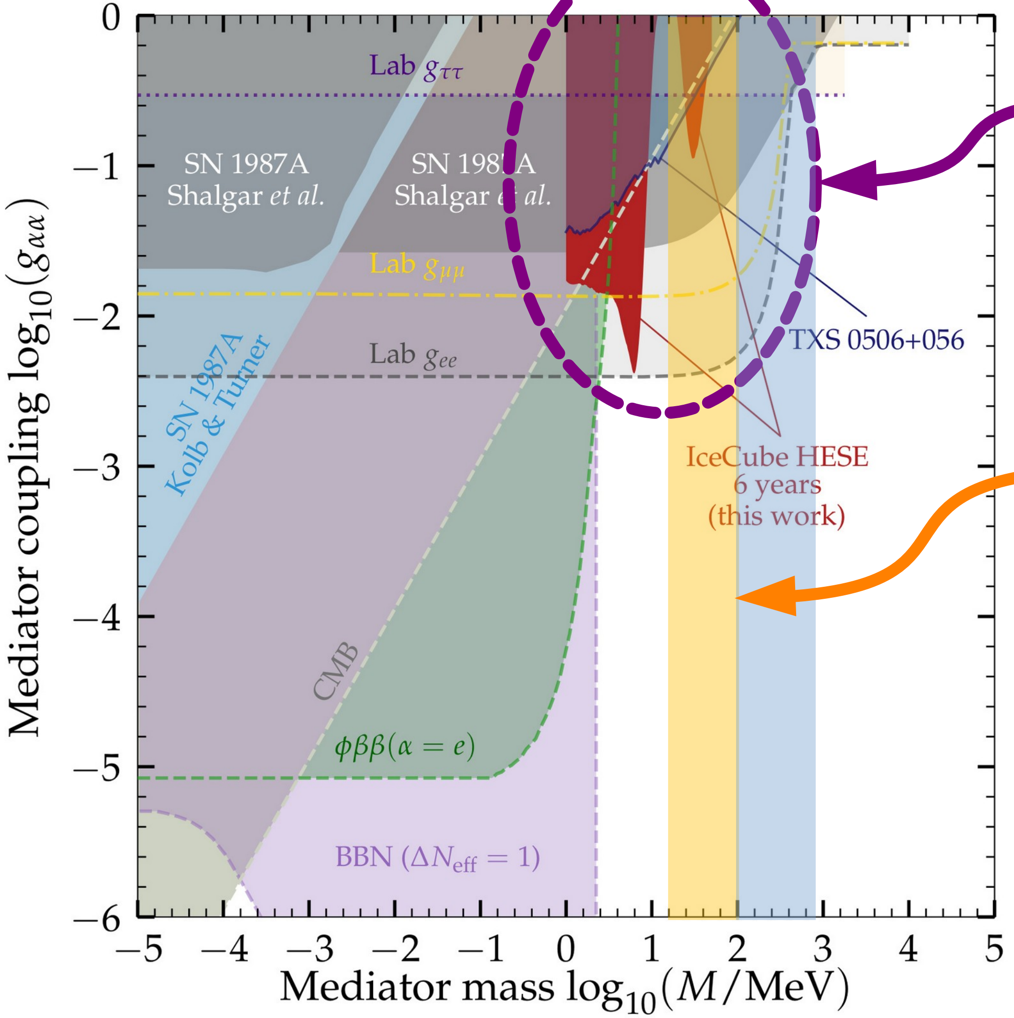


Today: Constraints from IceCube TeV–PeV ν observations

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

See also: Shalgar, **MB**, Tamborra, *PRD* 2020



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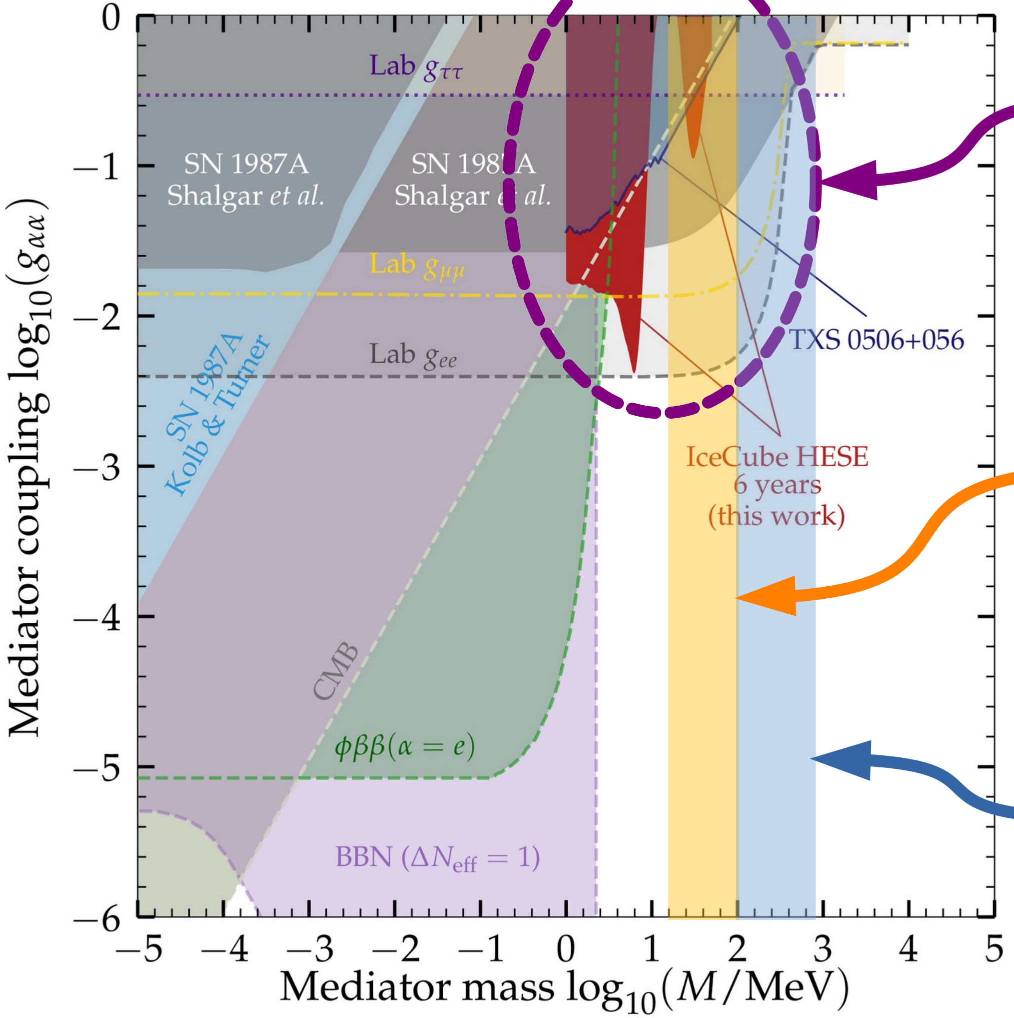

Today: Constraints from IceCube TeV–PeV ν observations

Future: High-statistics TeV–PeV ν in IceCube-Gen2 (optical)

See talk by Iván Esteban

Future: UHE ν in IceCube-Gen2 (radio)

MB, Másson, Valera, *In preparation*

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, *PRD* 2020

Food for thought

Measure flavor ratios better in water-based Cherenkov ν telescopes?

Neutron and muon echoes separate better showers from ν_e and ν_τ [Li, **MB**, Beacom, *PRL* 2019]

Might also help distinguish e.m. *vs.* hadronic showers

Can we measure the flavor composition of ultra-high-energy neutrinos?

Using in-ice radio (RNO-G, IceCube-Gen2): promising! [García-Fernández, Nelles, Glaser, *PRD* 2020]

Other techniques (atmospheric radio, fluorescence, *etc.*): remains to be seen

BSM from transient emission of UHE ν_τ?

Some UHE n detectors are especially sensitive to neutrino flares (*e.g.*, POEMMA)

Make it easier for people outside experimental collaborations

Provide detailed detector effective volumes, efficiency, *etc.* in useful forms

Big picture: the UHE BSM ν program is underdeveloped

Act now to inform the design and funding of detectors currently in planning

End