The Future of High-Energy Astrophysical Neutrino Measurements: Standard Model and beyond

Ningqiang Song

Institute of Theoretical Physics, Chinese Academy of Sciences

July 4, 2023

WiN2023 ZHUHAI CHINA

Sun Yat-sen University Zhuhai Campus

Outline

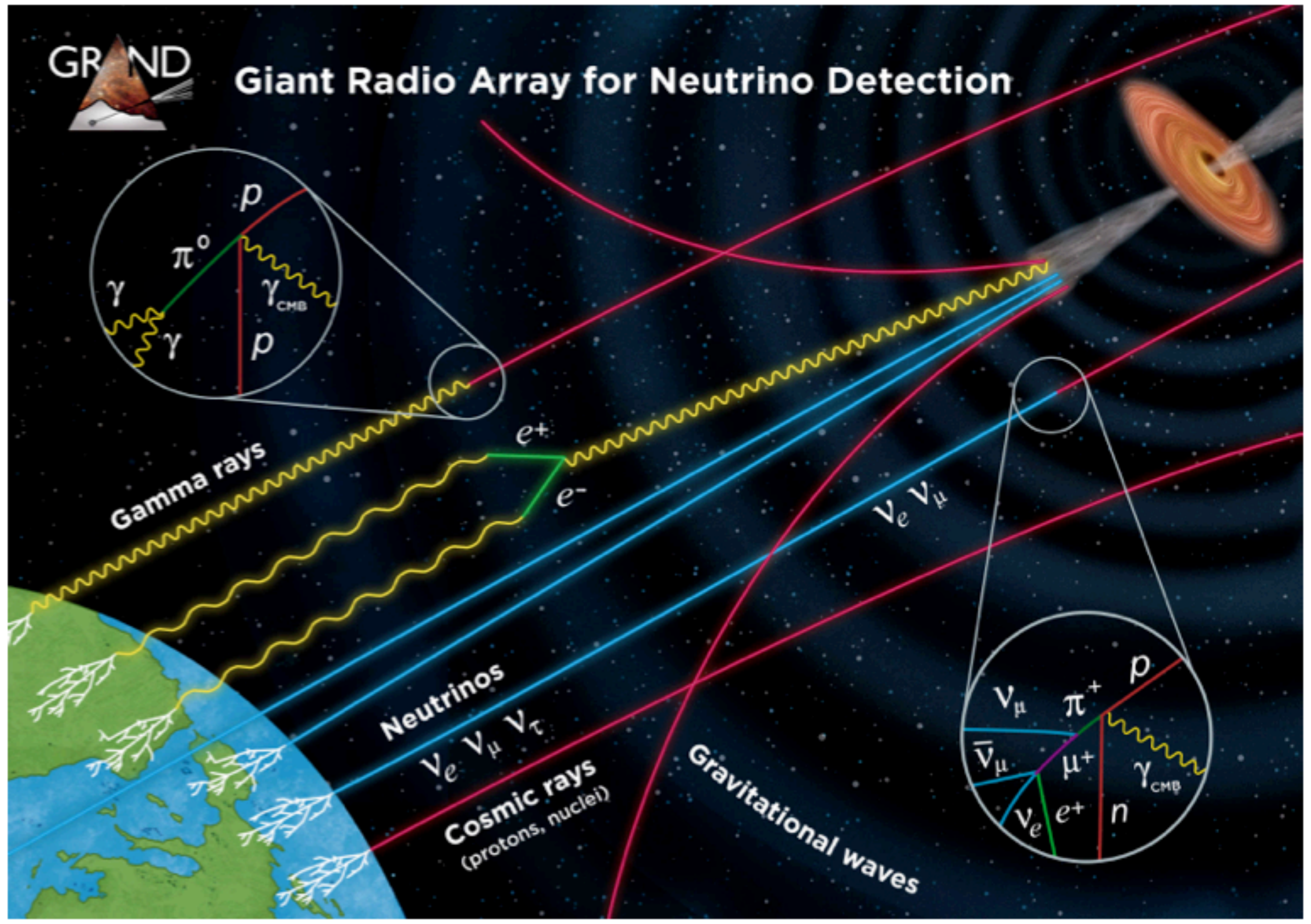
- ❖ Determining neutrino flavour composition at the source
- ❖ Breaking the degeneracy with Glashow resonance
- ❖ Probing new physics with future measurements

Outline

- ❖ Determining neutrino flavour composition at the source
- ❖ Breaking the degeneracy with Glashow resonance
- ❖ Probing new physics with future measurements

High Energy Astrophysical Neutrinos

GRAND , 1810.09994



- Pion decay $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0)$

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$$

- Muon-damped $(\nu_e : \nu_\mu : \nu_\tau) = (0 : 1 : 0)$

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\not{\mu^+} \to e^+ + \nu_\mu + \bar{\nu}_e$$

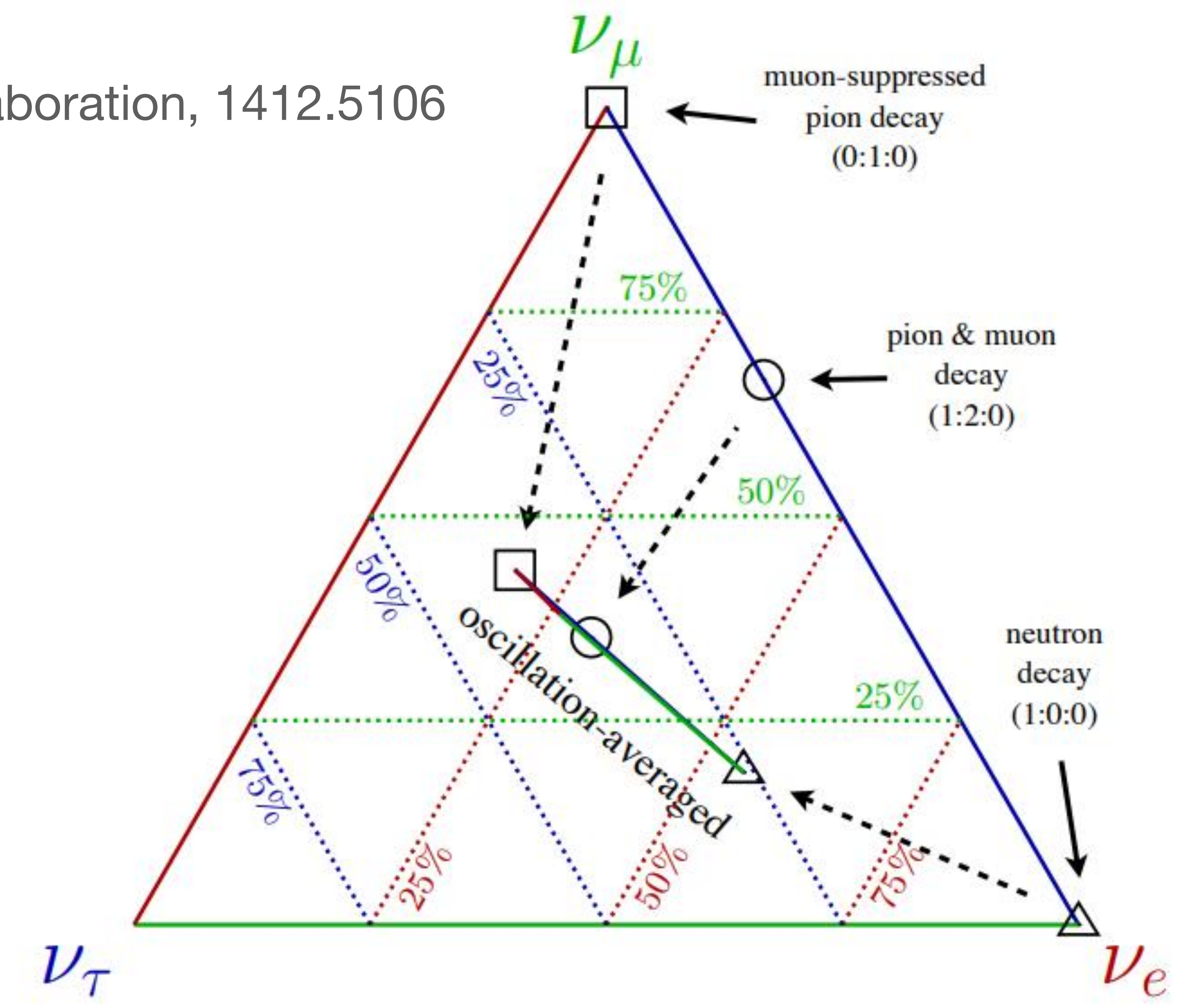
- Neutron decay $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 0 : 0)$

$$n \to p + e^- + \bar{\nu}_e$$

Shiqi Yu's talk

Neutrino Flavor at IceCube

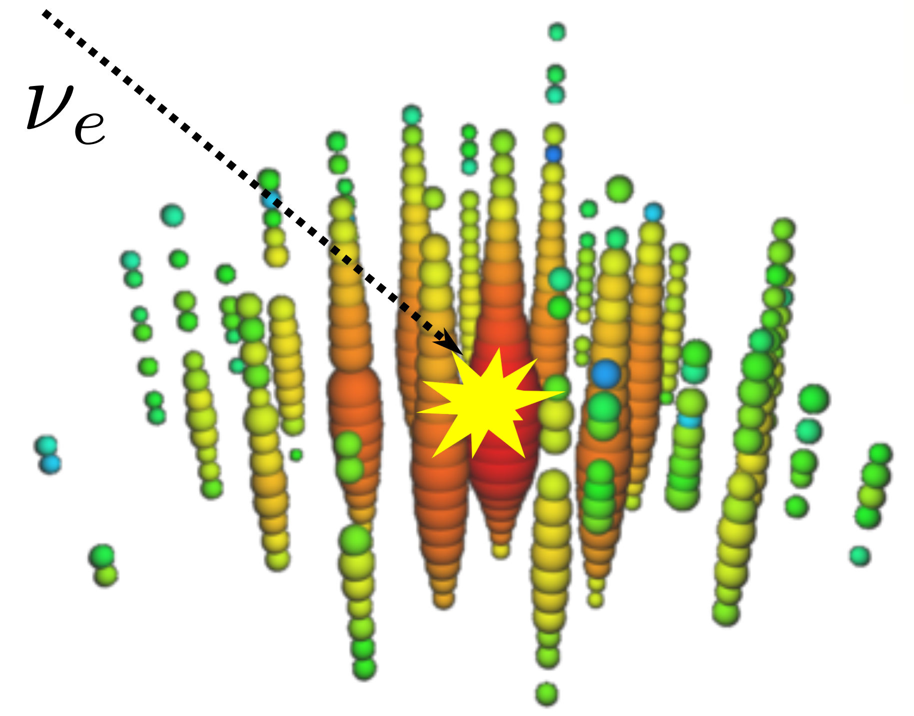
Gen2 collaboration, 1412.5106



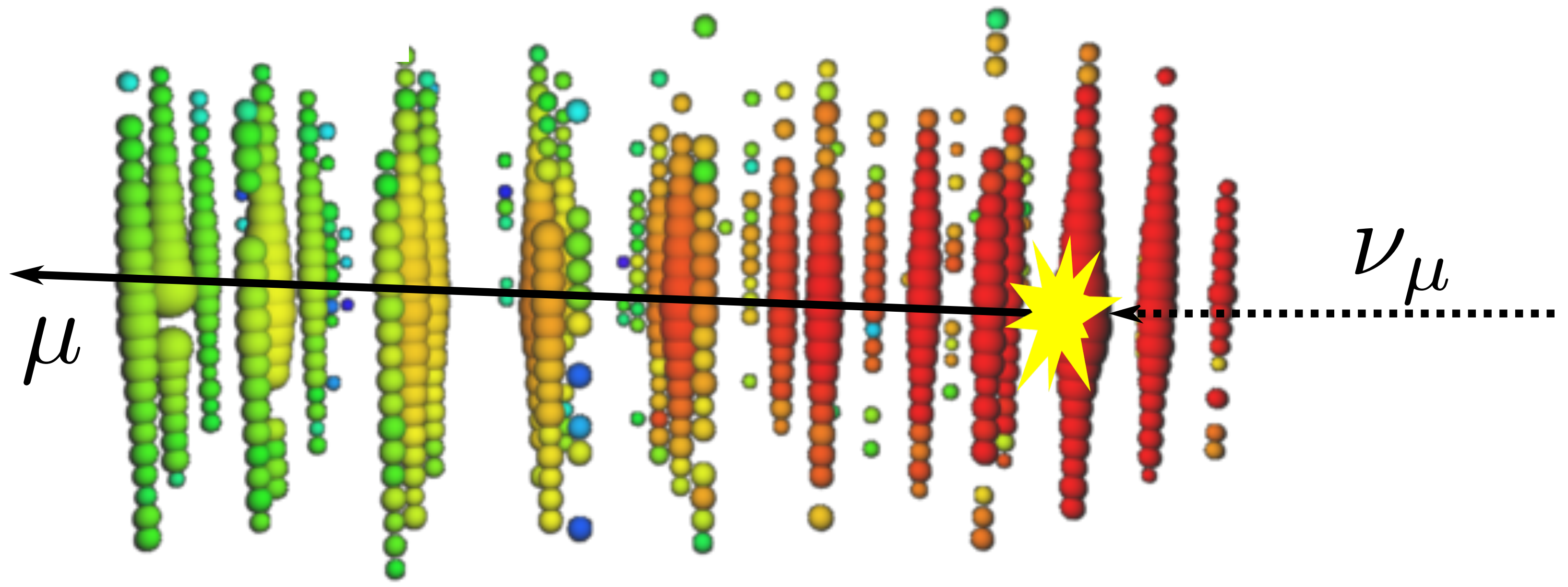
- Neutrinos oscillate from source to Earth

$$P^{s\to\oplus}_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

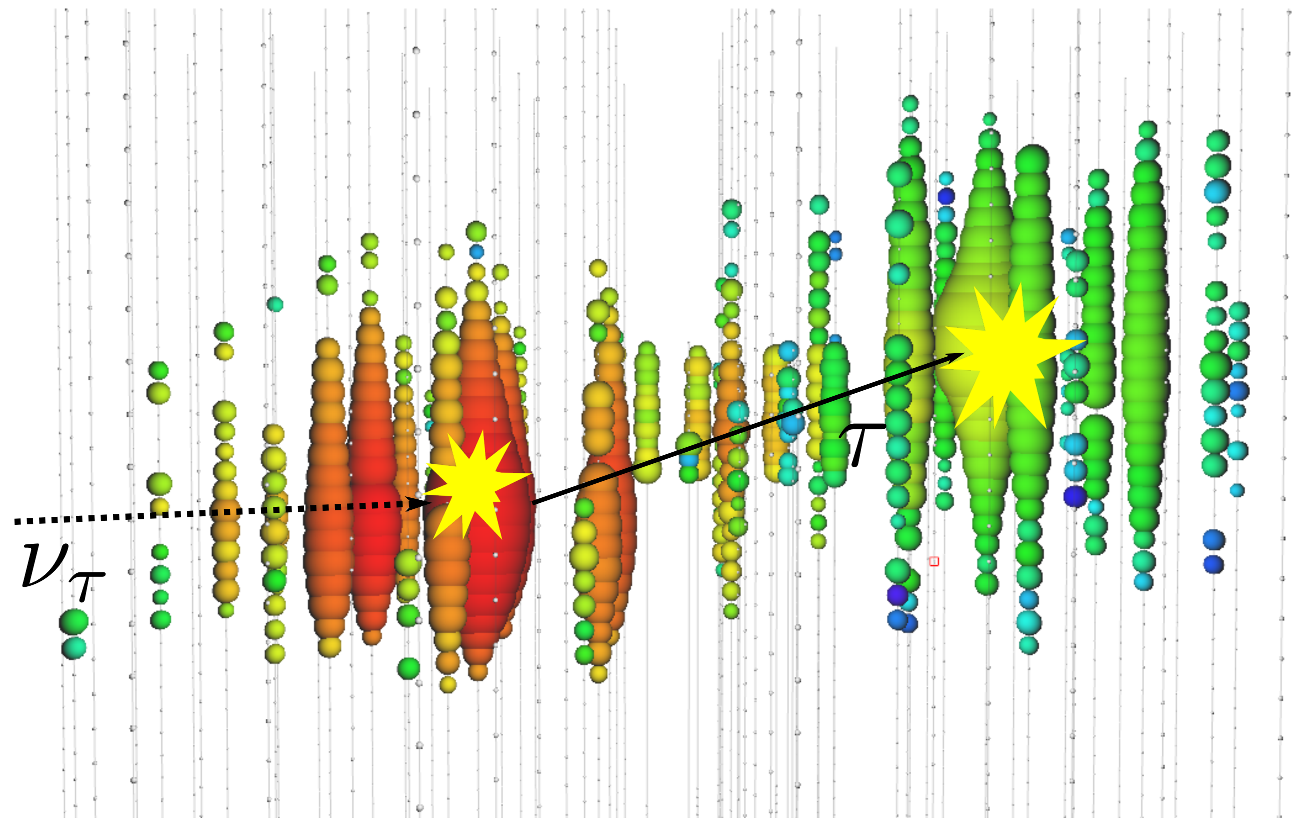
- $f_S = (1/3,\ 2/3,\ 0) \to f_\oplus = (0.3,\ 0.36,\ 0.34)$



Showers/Cascades



Tracks



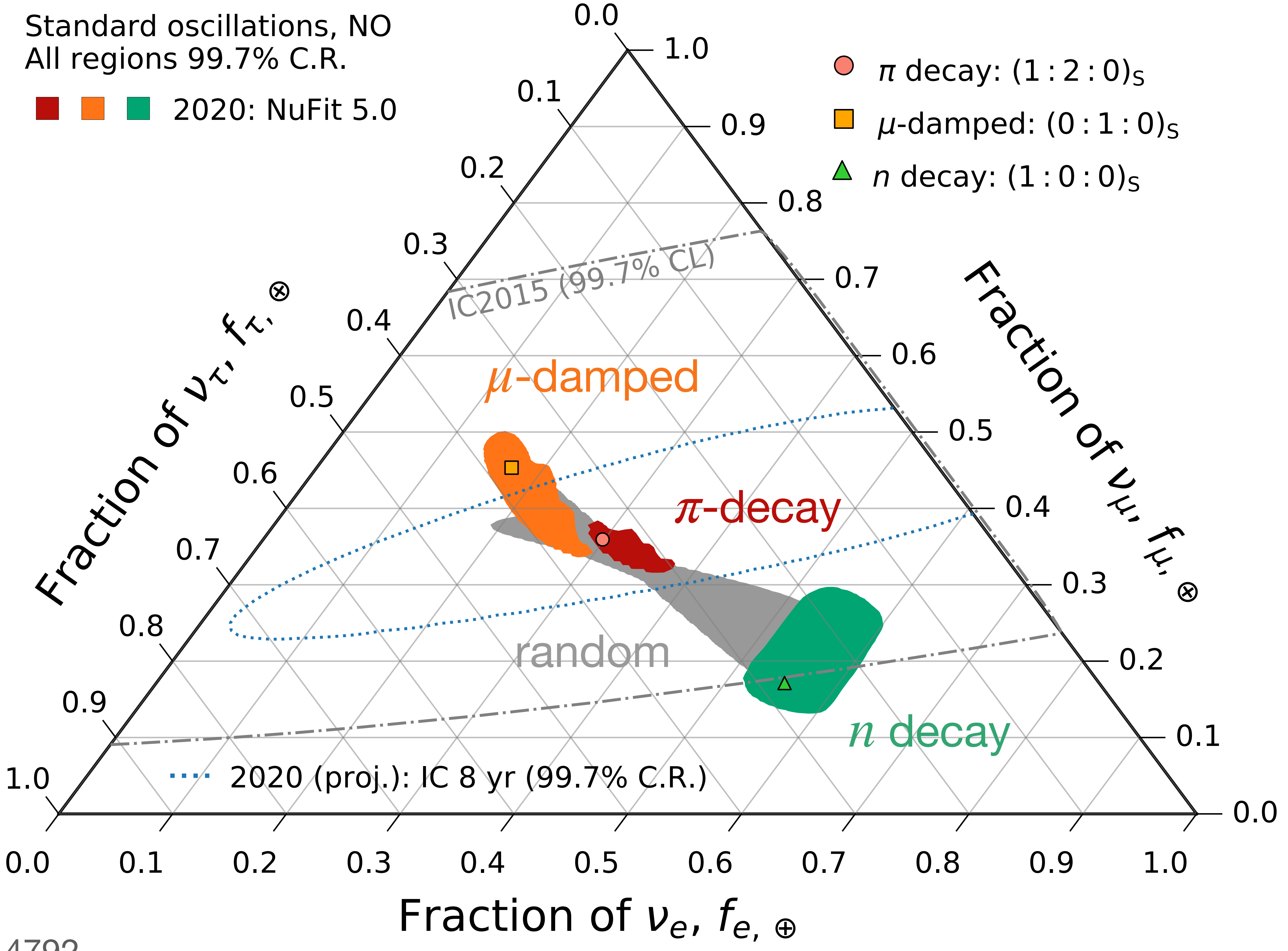
Double bangs

Source Discrimination? **Hard!**

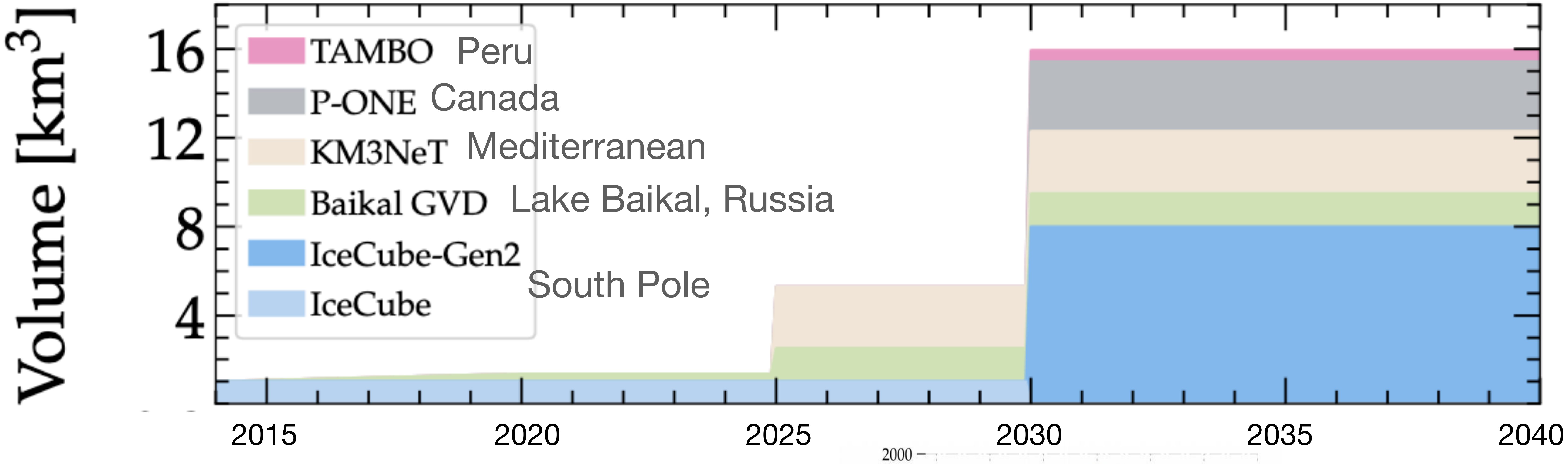
- Limitations
  - Statistical: flux measurement
  - Systematical: precise oscillation parameters

Parameter	Normal ordering	Inverted ordering
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.304^{+0.013}_{-0.012}$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.575^{+0.016}_{-0.019}$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02238^{+0.00063}_{-0.00062}$
δ_{CP} (°)	197^{+27}_{-24}	282^{+26}_{-30}

NuFit 5.0 global fit, Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792

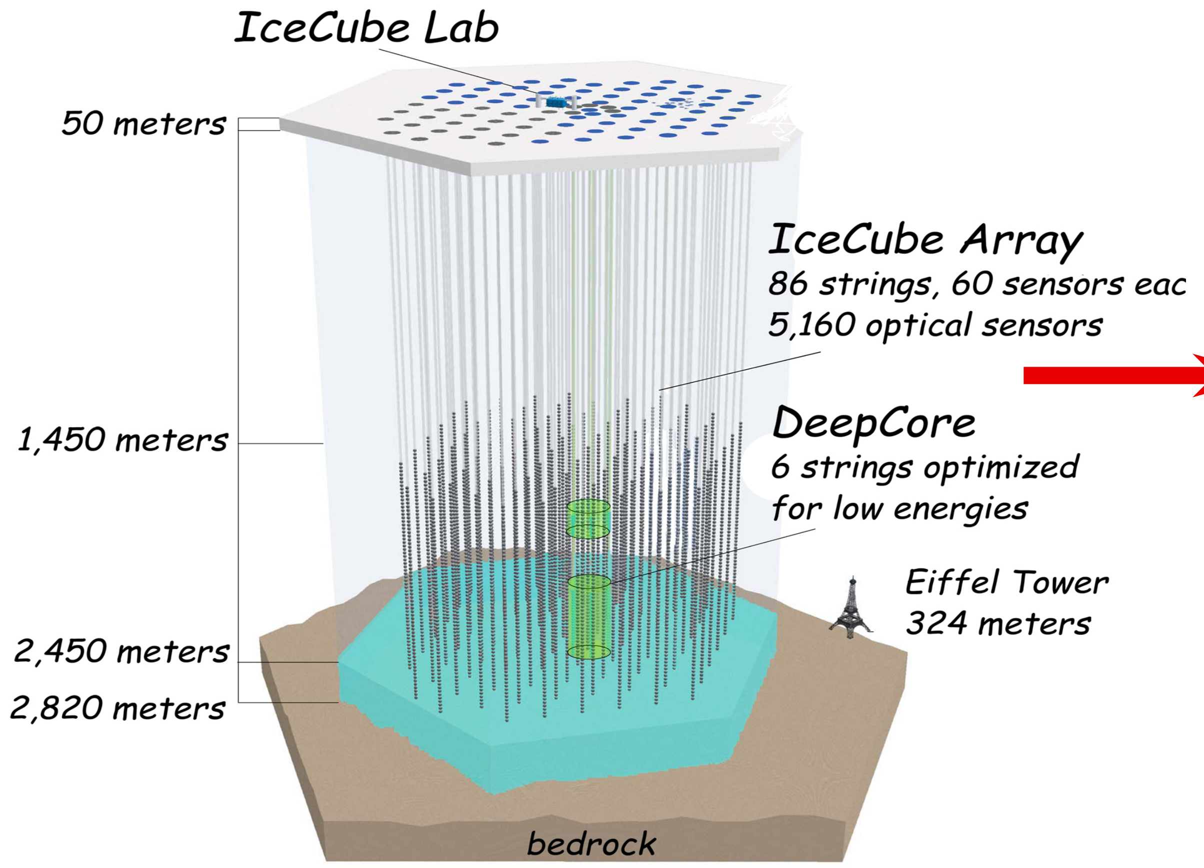


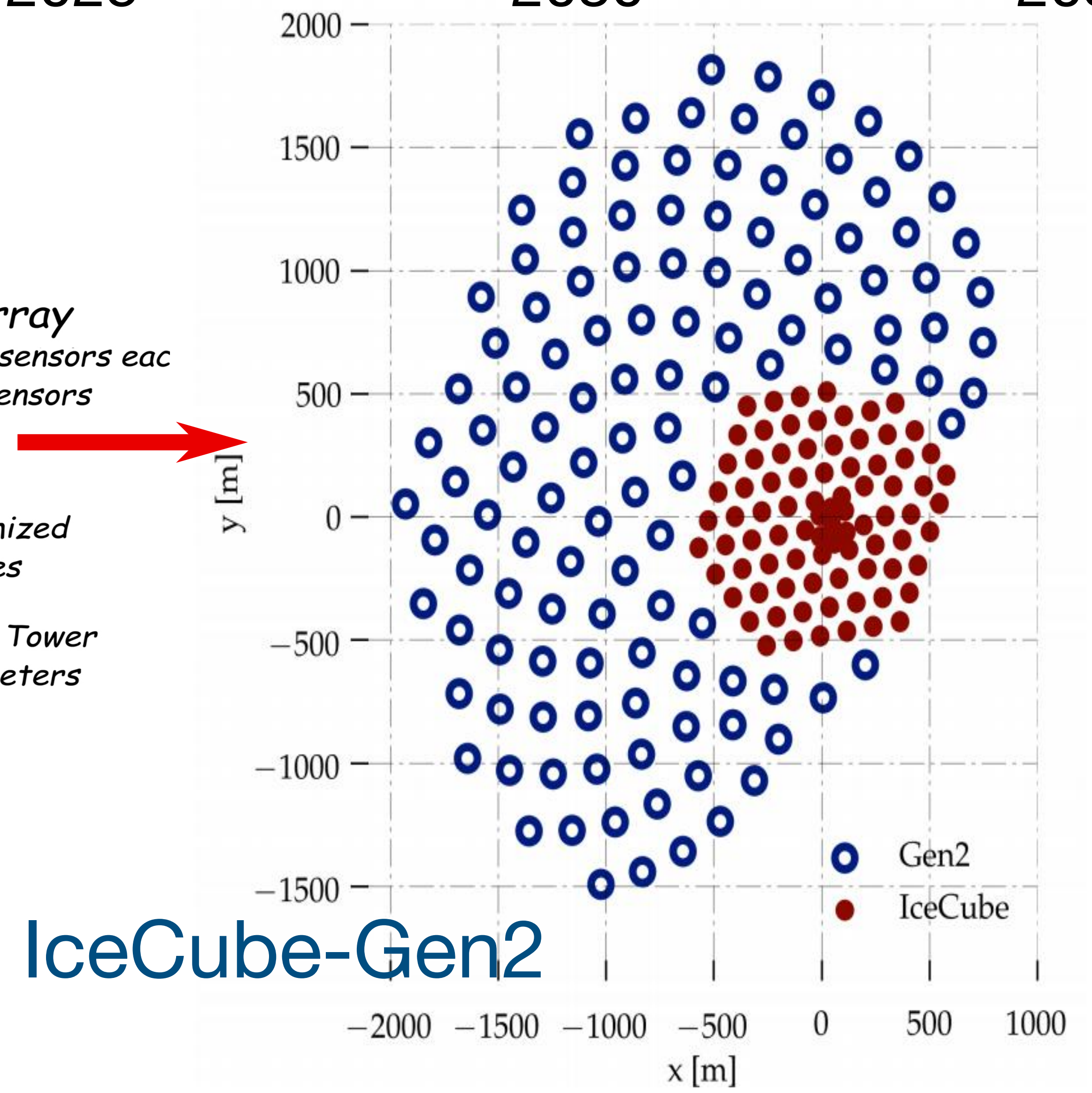
Future Neutrino Telescopes

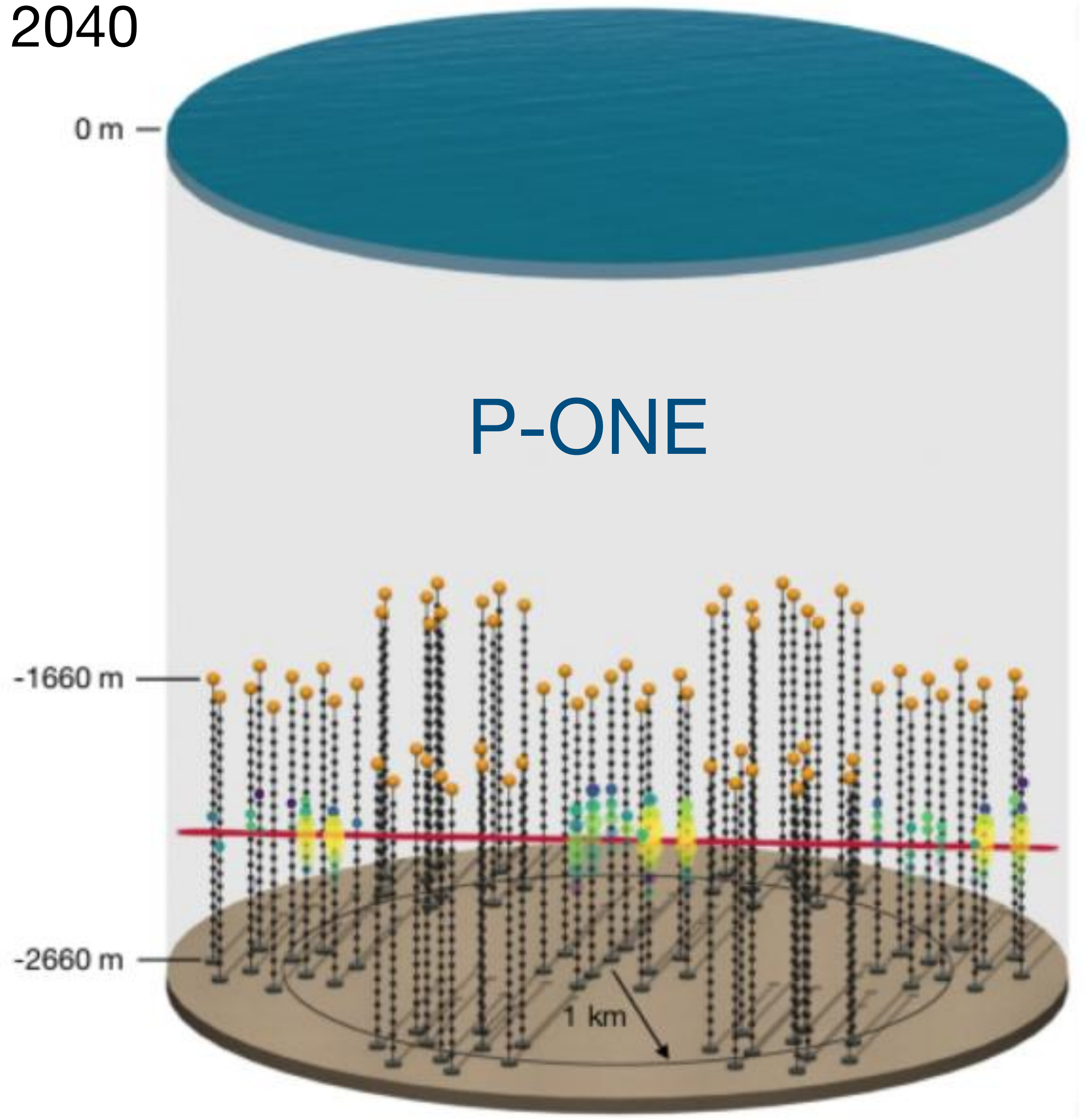


Combination of IC-Gen2, P-ONE, KM3NeT, GVD, TAMBO offers ~20 times more exposure by 2040 than IceCube

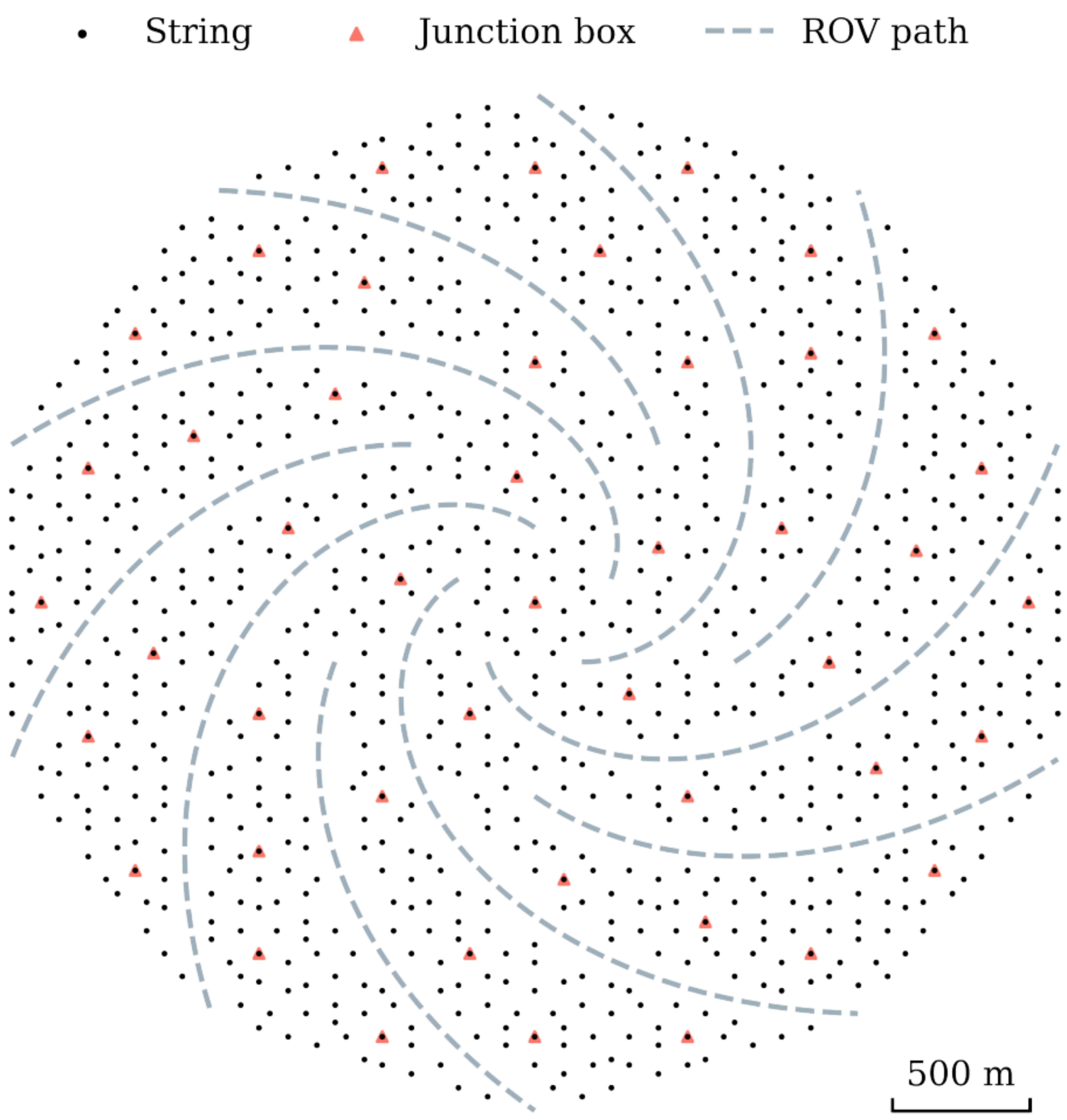
+more (Trident)

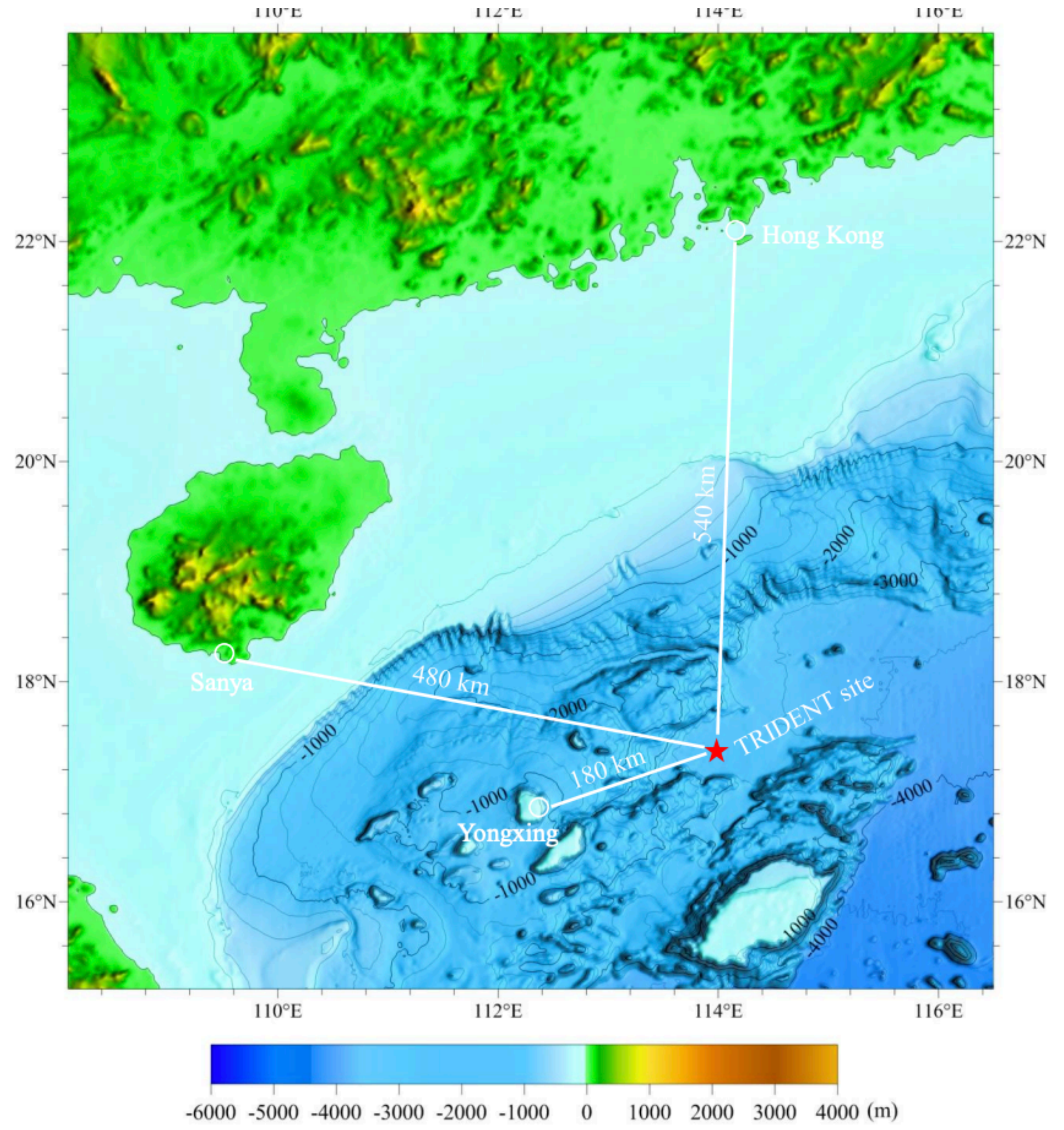






Trident

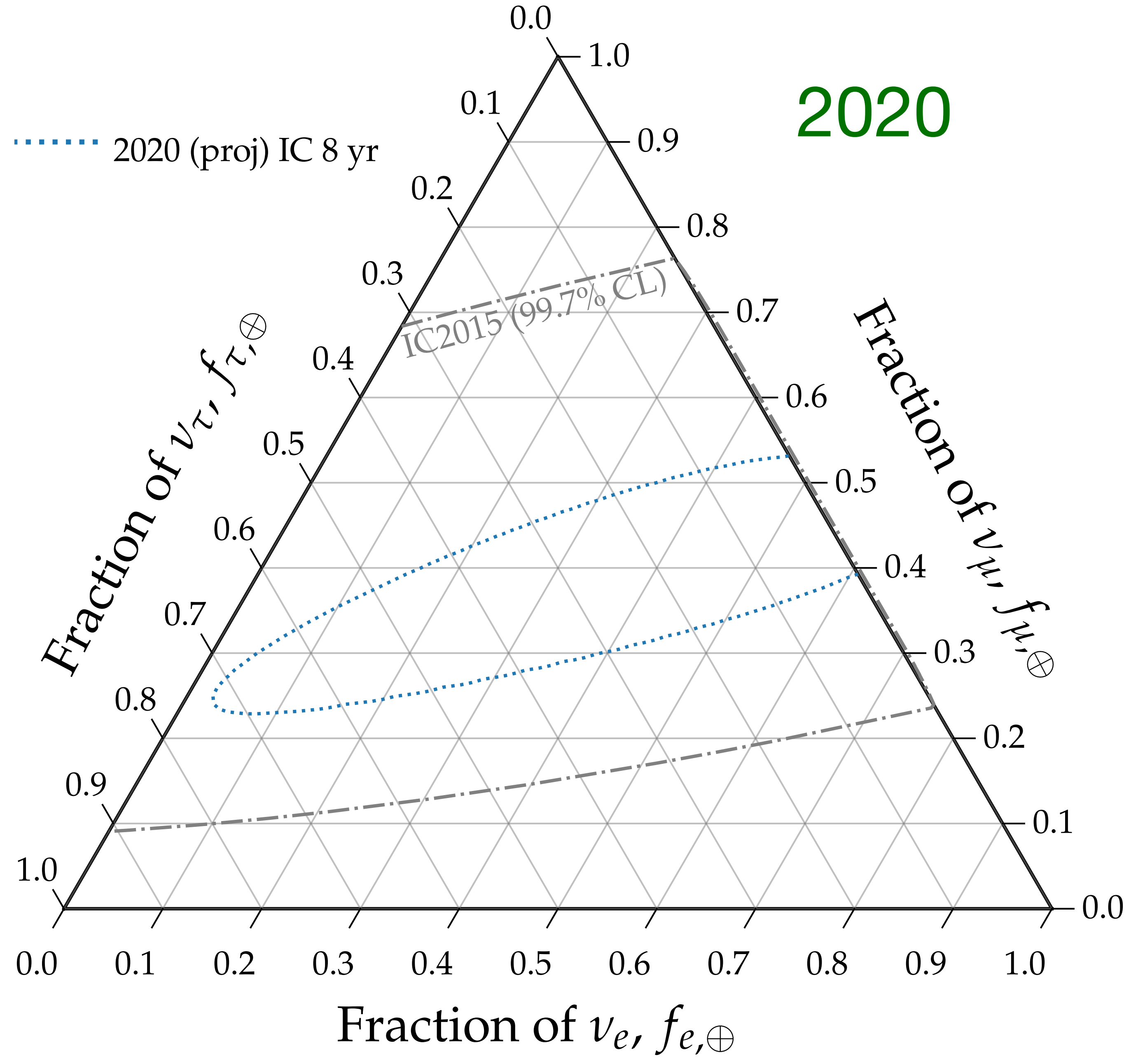


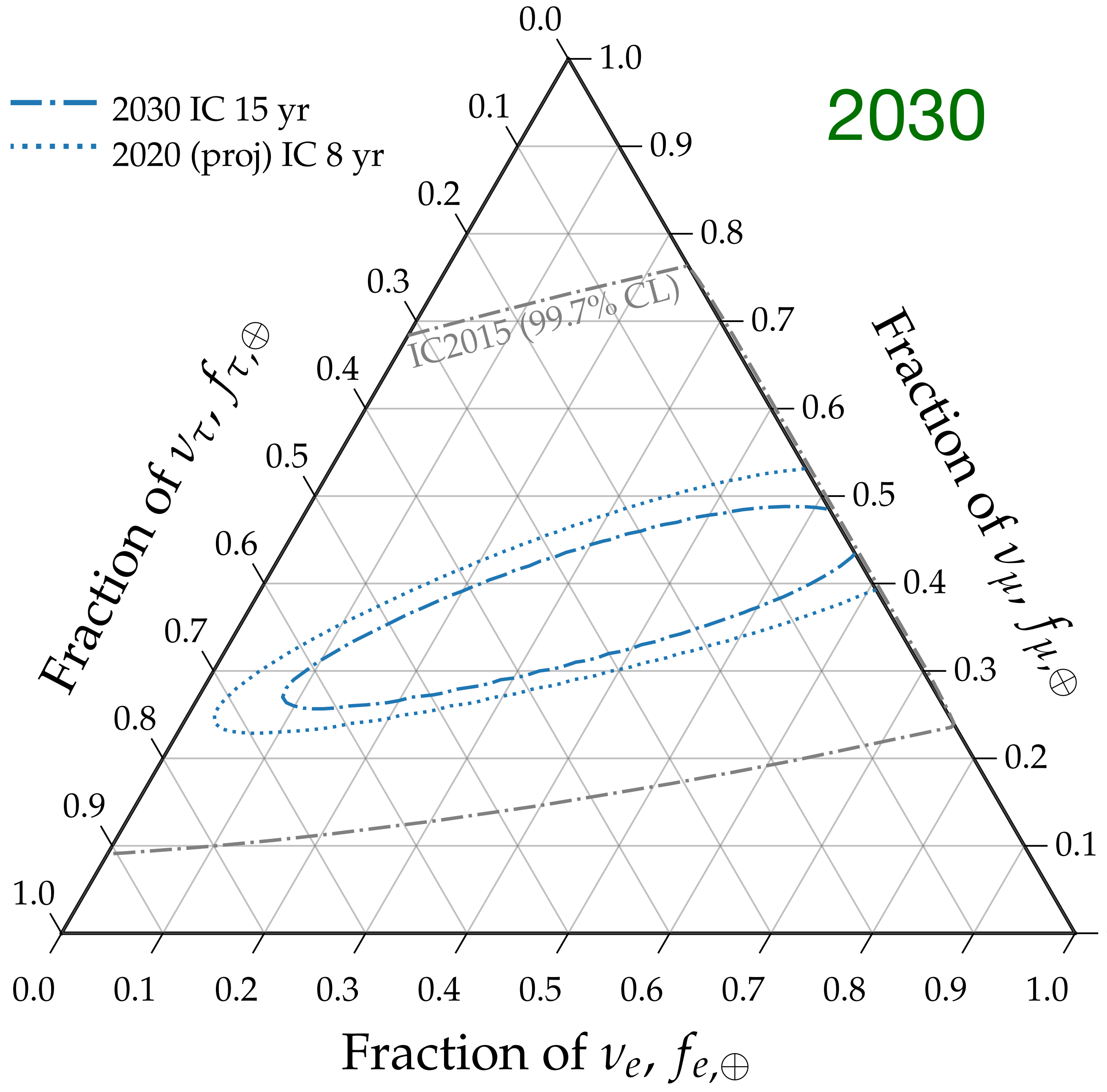


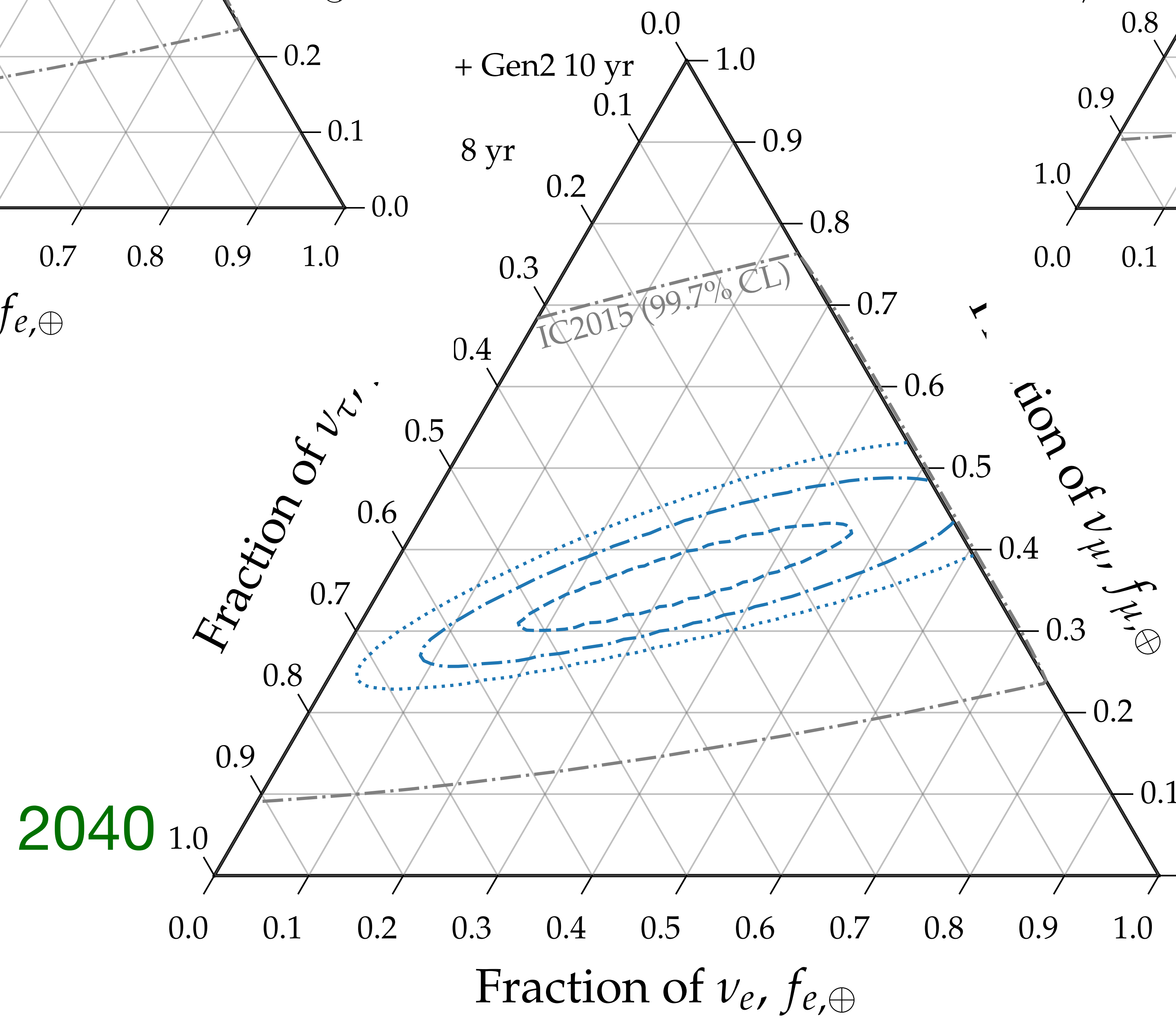
1211 strings, 20 hDOMs, ~7.5 km^3 total

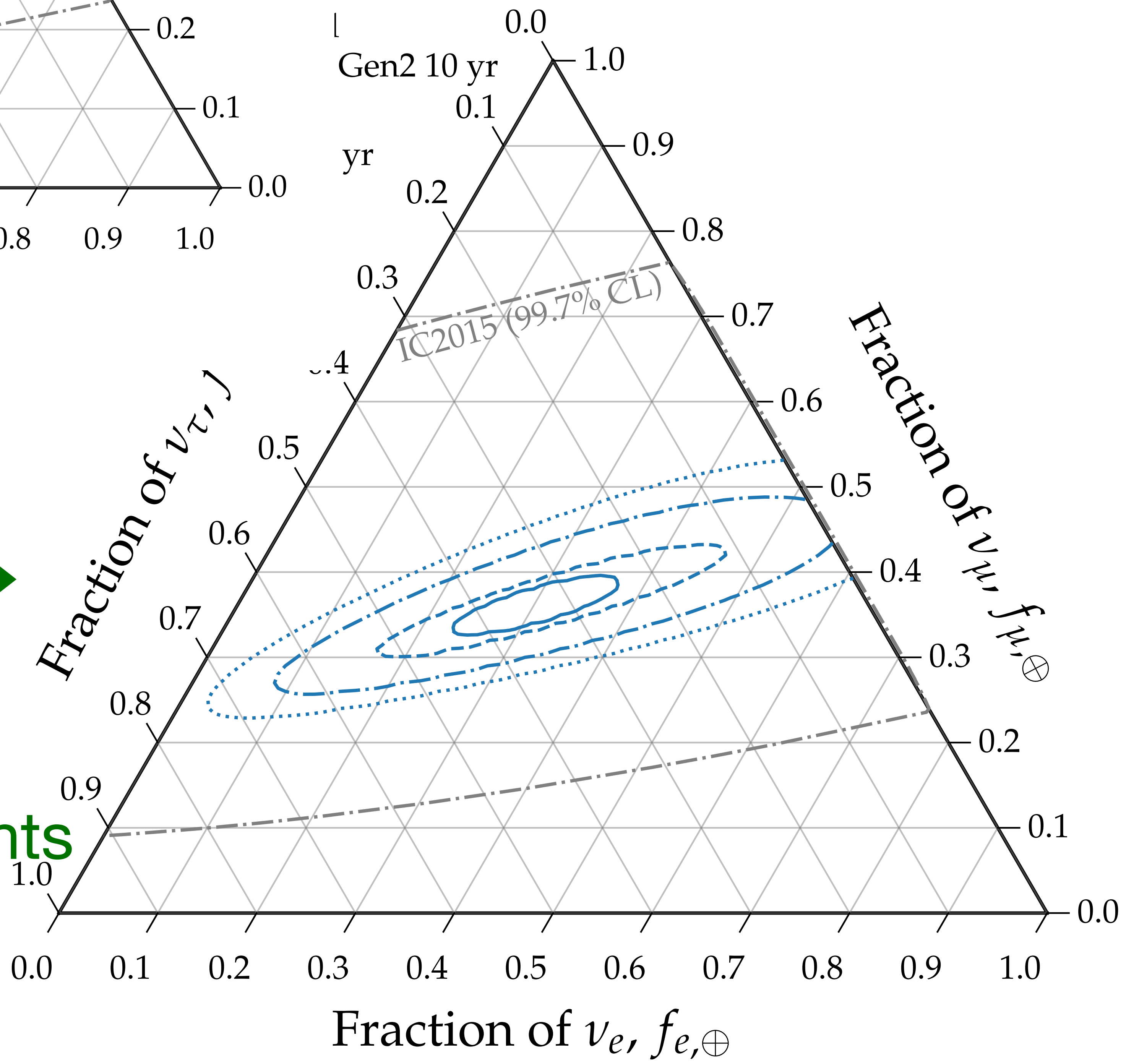
Ningqiang Song (songnq@itp.ac.cn)

Neutrino Flavor Measurements: Future





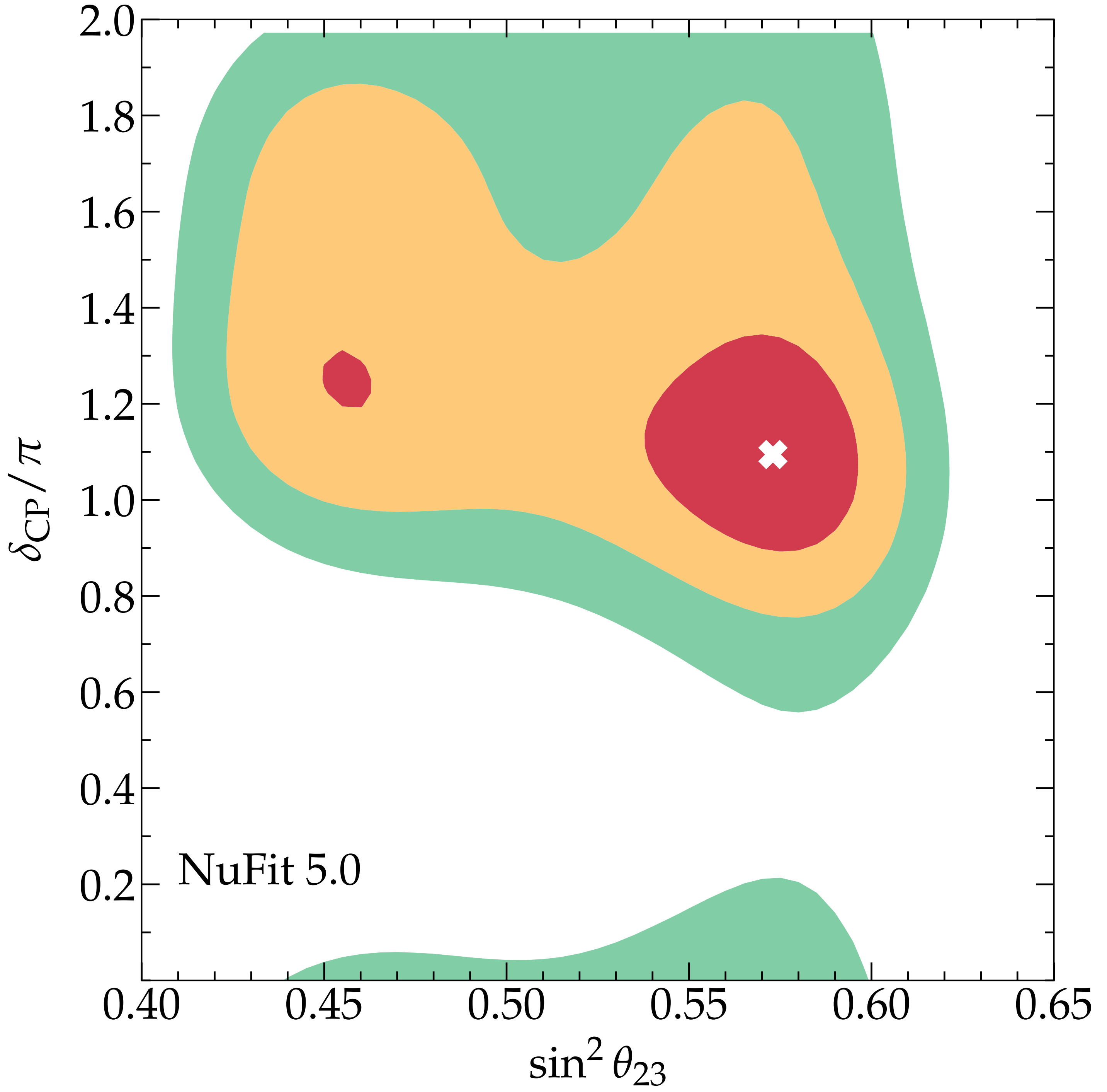


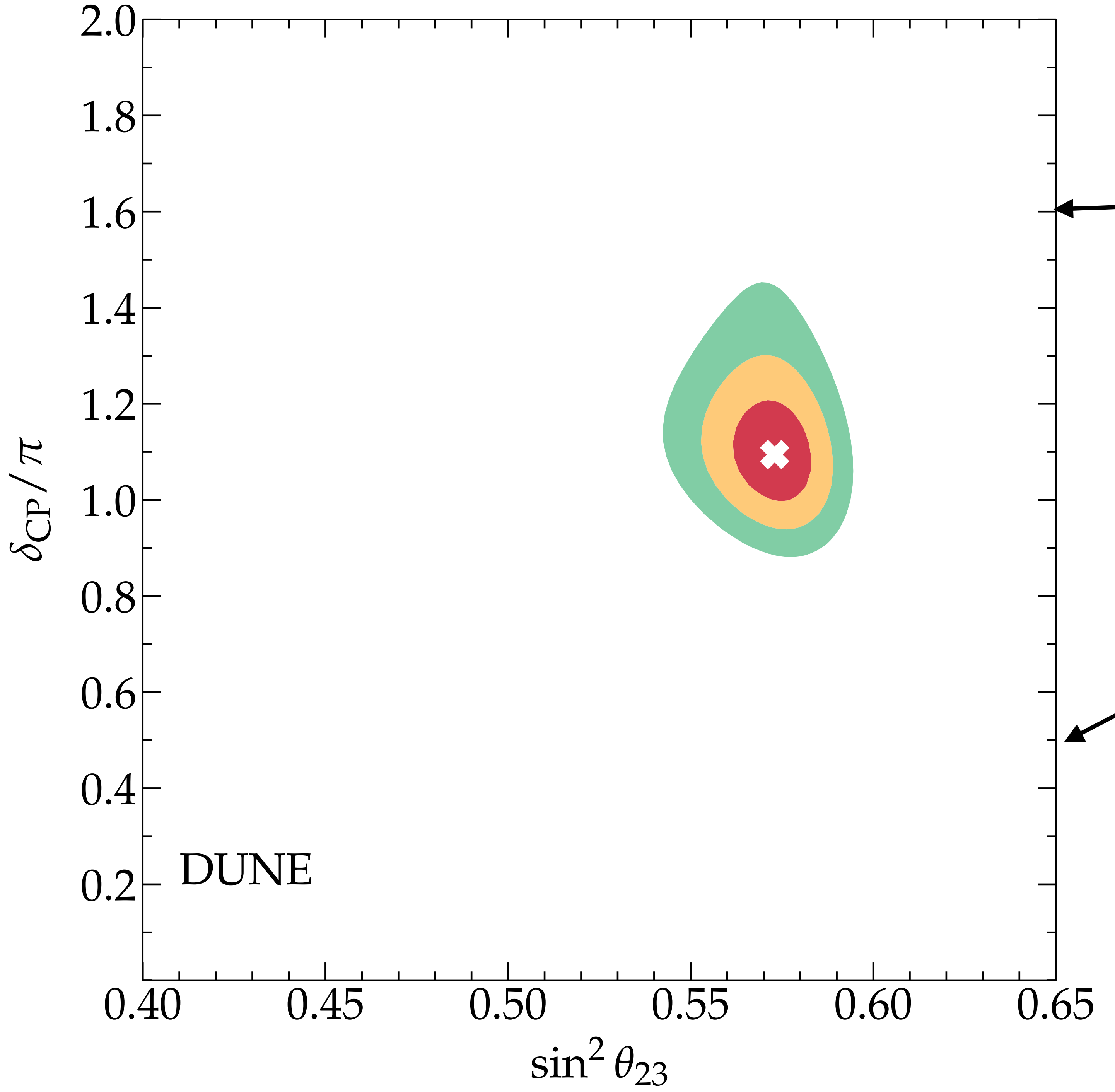


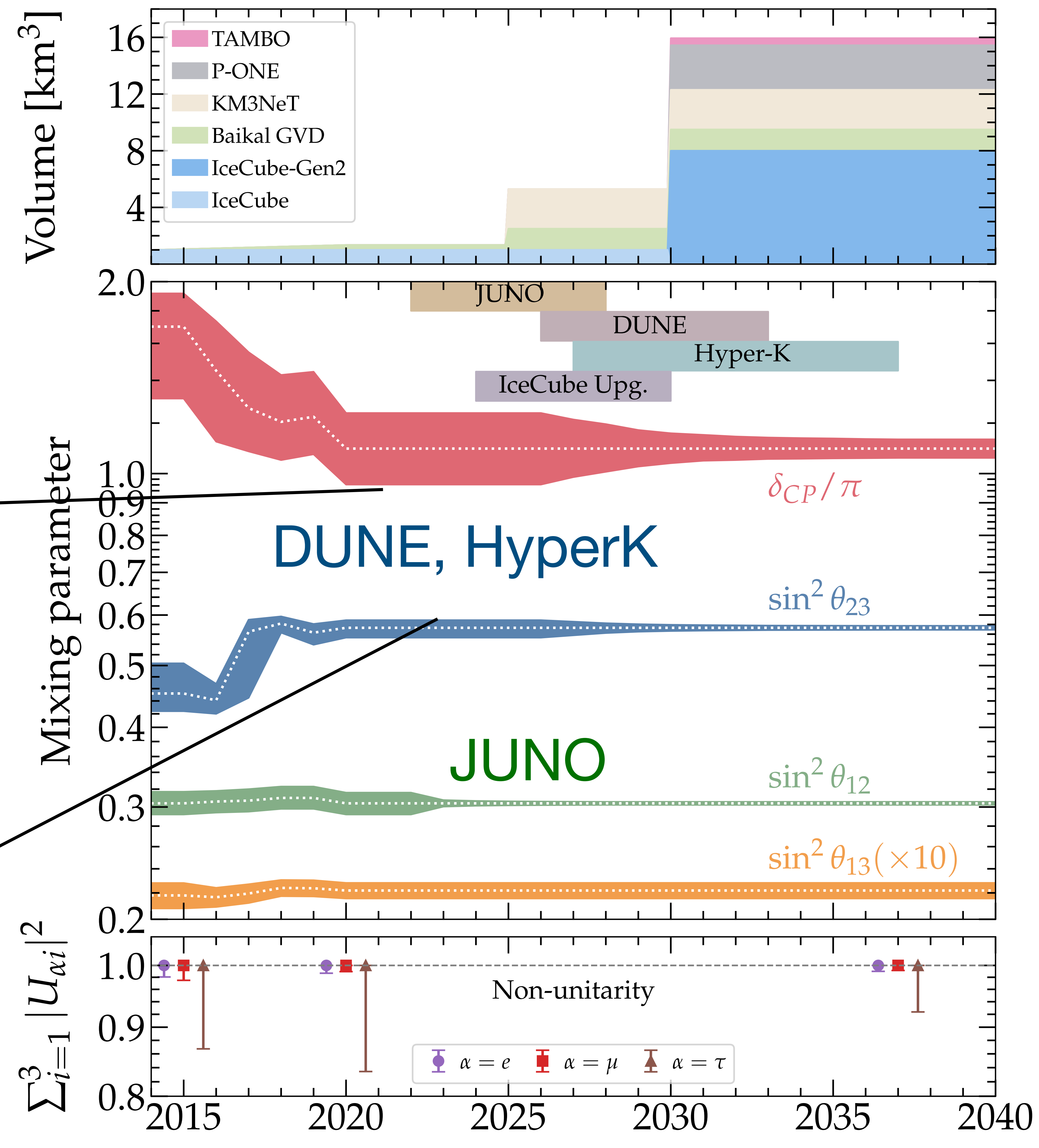
	Flavor ratios at Earth		
	$f_{e,\oplus}$	$f_{\mu,\oplus}$	$f_{\tau,\oplus}$
2020	$0.30^{+0.13}_{-0.11}$	$0.36^{+0.059}_{-0.053}$	$0.34^{+0.16}_{-0.18}$
2040	$0.30^{+0.039}_{-0.037}$	$0.36^{+0.017}_{-0.016}$	$0.34^{+0.049}_{-0.050}$
2040 all	$0.30^{+0.030}_{-0.027}$	$0.36^{+0.011}_{-0.011}$	$0.34^{+0.037}_{-0.039}$

Neutrino Oscillation Measurements

More precise oscillation parameters:
JUNO, DUNE, Hyper-K







Non-Unitarity

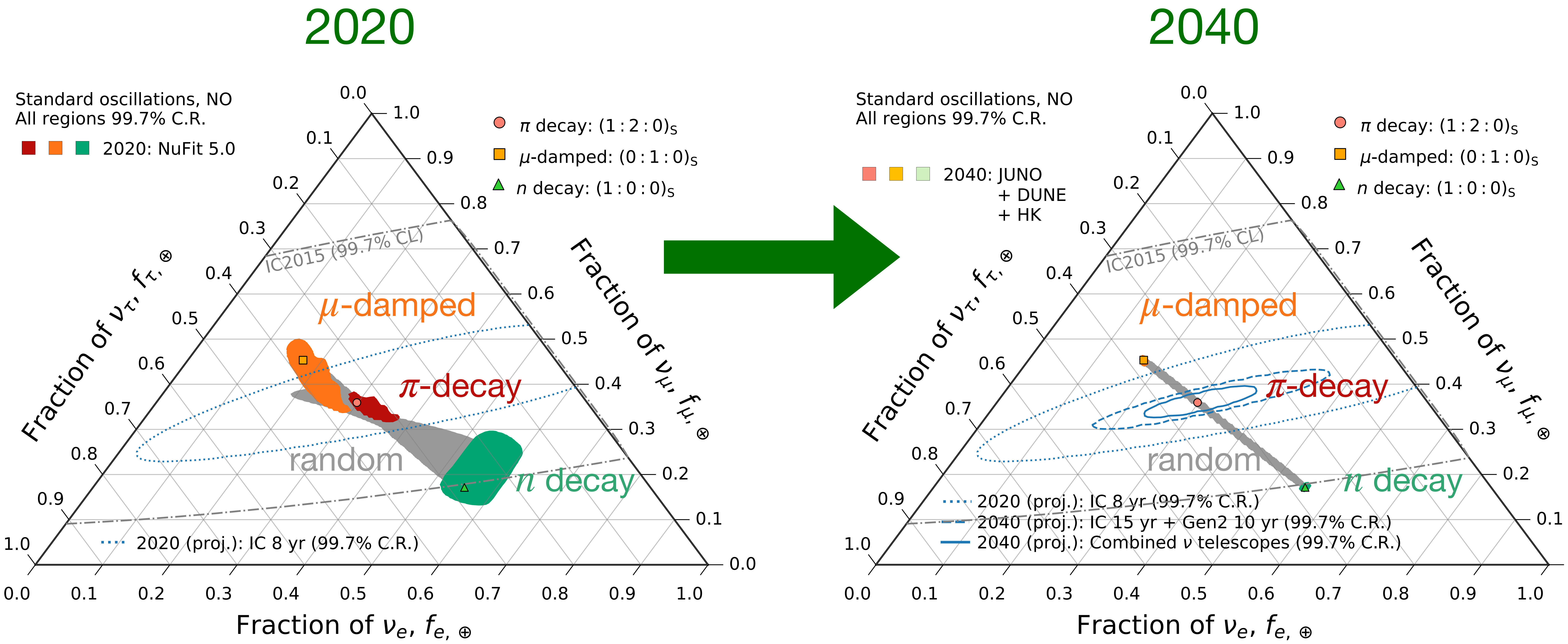
$$P_{\alpha\beta}^{s\to\oplus} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Source Discrimination? **Yes!**

$$f_{\beta,\oplus} = \sum_{\alpha=e,\mu,\tau} P^{s\to\oplus}_{\alpha\beta} f_{\alpha,S}$$

$$P^{s\to\oplus}_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Pion decay well separated from muon damped by 2040



NS, Li, Argüelles, Bustamante, Vincent, JCAP/2012.12893

Outline

- Determining neutrino flavour composition at the source
- Breaking the degeneracy with Glashow resonance
- Probing new physics with future measurements

Ningqiang Song (songnq@itp.ac.cn)

Degeneracies at the high energy neutrino sources

Production	Source flavor ratio	Earth flavor ratio $\nu+\bar{\nu}$	Earth flavor ratio	$f_{\bar{\nu}_e}$
pp	$\{1,1\}:\{2,2\}:\{0,0\}$	$0.33:0.34:0.33$	$\{0.17,0.17\}:\{0.17,0.17\}:\{0.16,0.16\}$	0.17
$pp\,\mu$ damped	$\{0,0\}:\{1,1\}:\{0,0\}$	$0.23:0.39:0.38$	$\{0.11,0.11\}:\{0.20,0.20\}:\{0.19,0.19\}$	0.11
$p\gamma$	$\{1,0\}:\{1,1\}:\{0,0\}$	$0.33:0.34:0.33$	$\{0.26,0.08\}:\{0.21,0.13\}:\{0.20,0.13\}$	0.08
$p\gamma\,\mu$ damped	$\{0,0\}:\{1,0\}:\{0,0\}$	$0.23:0.39:0.38$	$\{0.23,0.00\}:\{0.39,0.00\}:\{0.38,0.00\}$	0

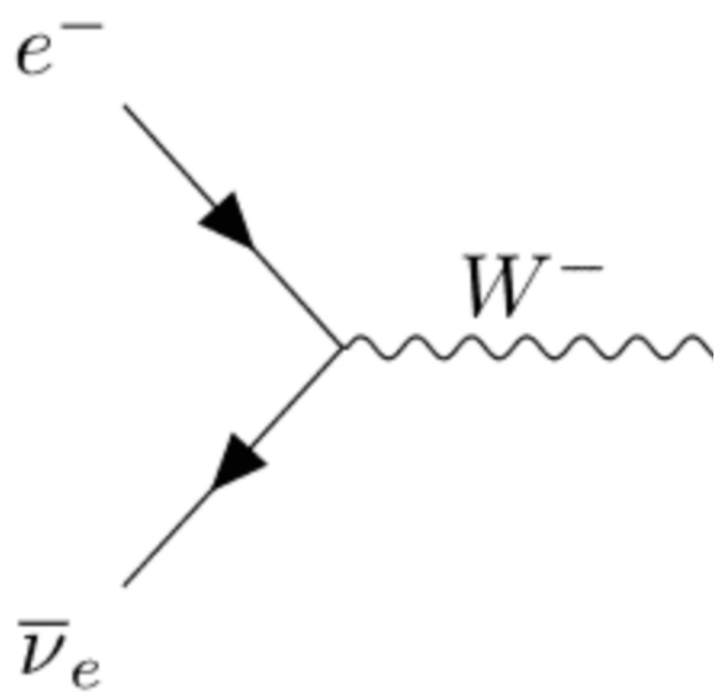
- $p\gamma$ produces more neutrinos than antineutrinos $p+\gamma\to\Delta^+\to\pi^++n$, if μ damped, no antineutrinos are produced
- pp produces equal amount of neutrinos and antineutrinos $p+p\to n_\pi\,[\pi^0+\pi^++\pi^-]$, which holds even if μ damped
- pp is indistinguishable from $p\gamma$ if only $\nu+\bar{\nu}$ is analyzed

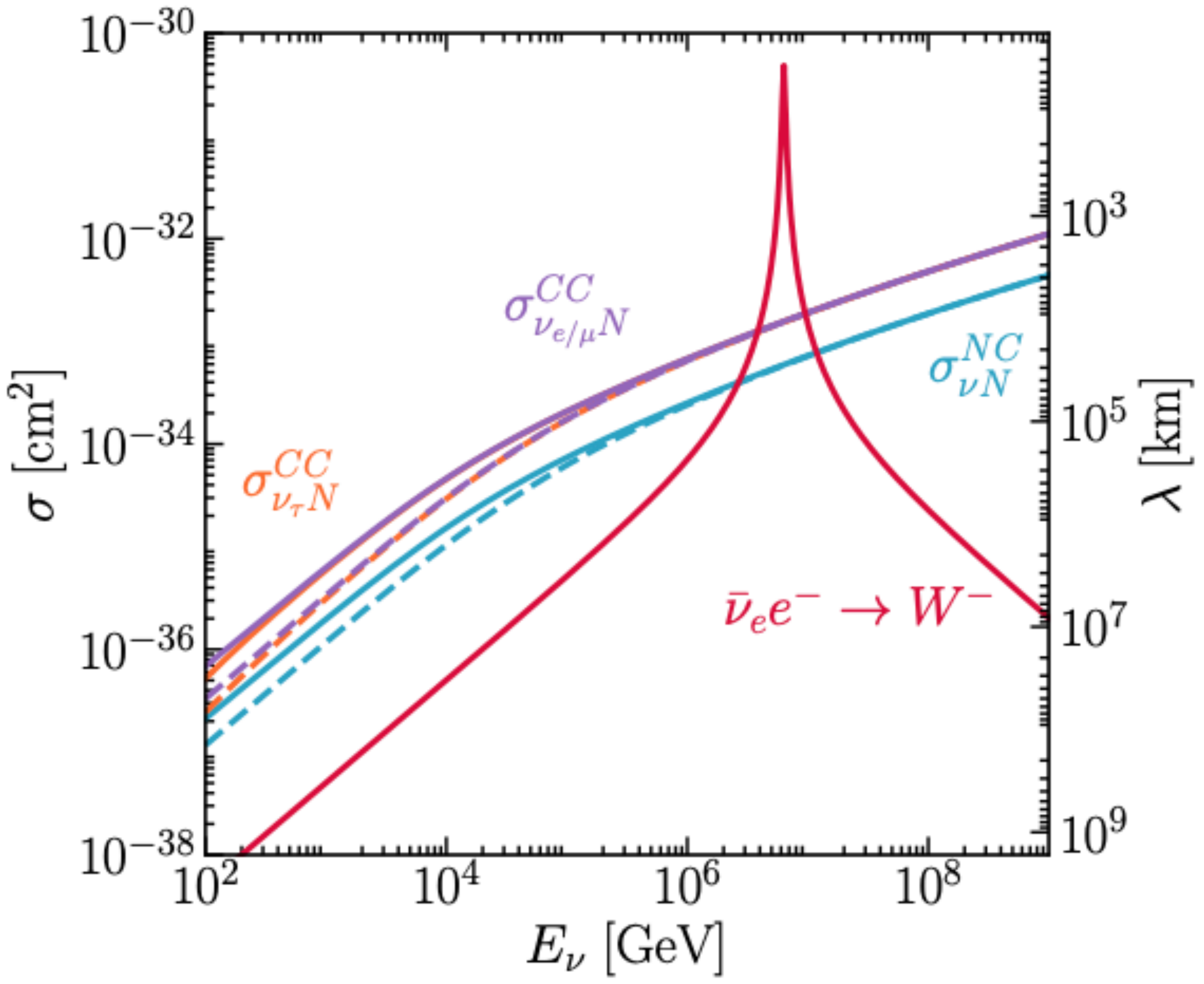
Glashow Resonance (GR)

Huang, Liu , 1912.02976

When the centre of mass energy is close to W boson mass, $\bar{\nu}_e$-electron interaction is enhanced by the resonant production of W

$$\sigma_{\overline{\nu}_e e}(s) = 24\pi\,\Gamma_W^2\,\mathrm{Br}(W^- \to \overline{\nu}_e + e^-) \times \frac{s/M_W^2}{(s - M_W^2)^2 + (M_W\Gamma_W)^2},$$





Glashow Resonance at IceCube

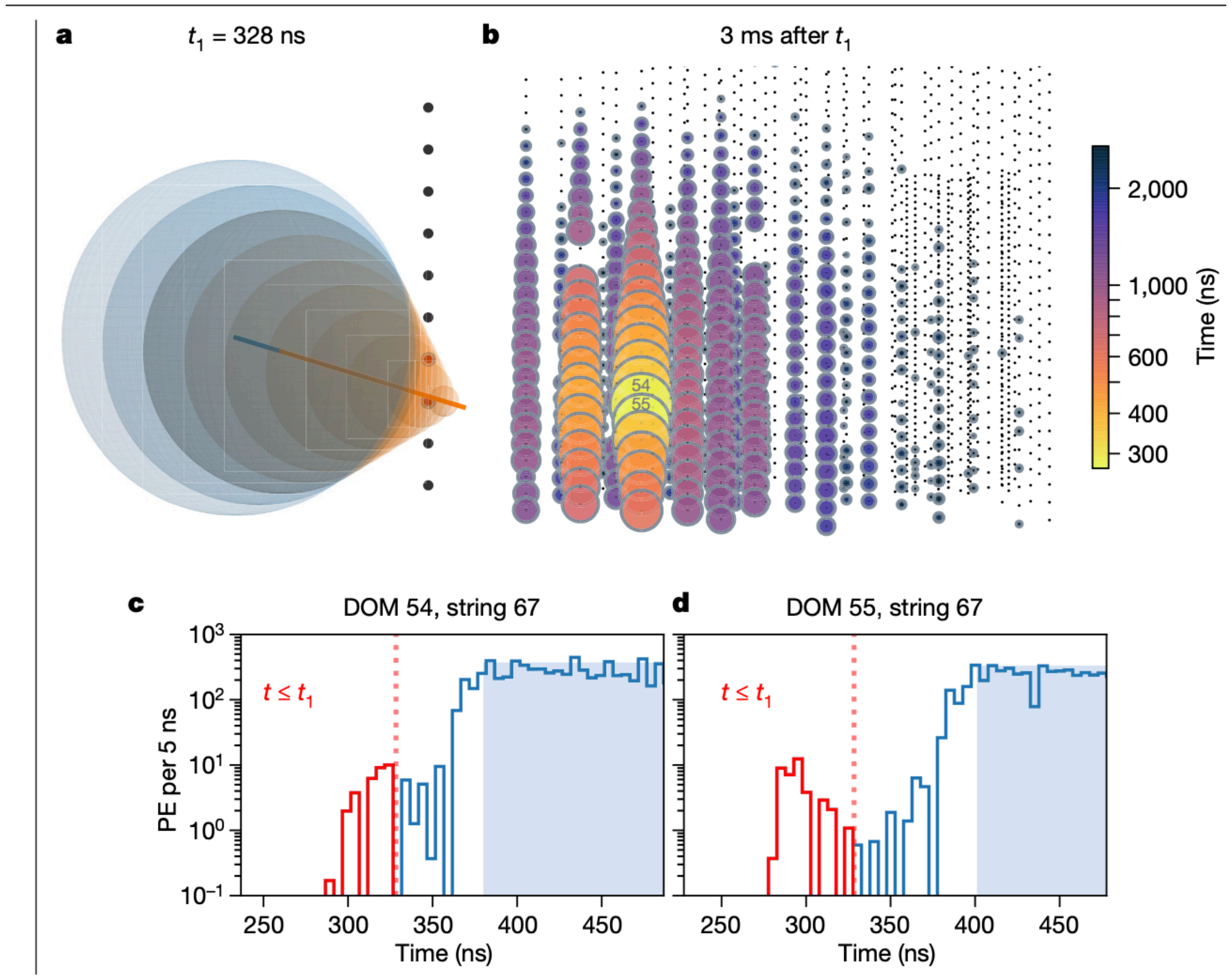
Article | Published: 10 March 2021

Detection of a particle shower at the Glashow resonance with IceCube

The IceCube Collaboration

Nature **591**, 220–224 (2021) | Cite this article

16k Accesses | **63** Citations | **507** Altmetric | Metrics



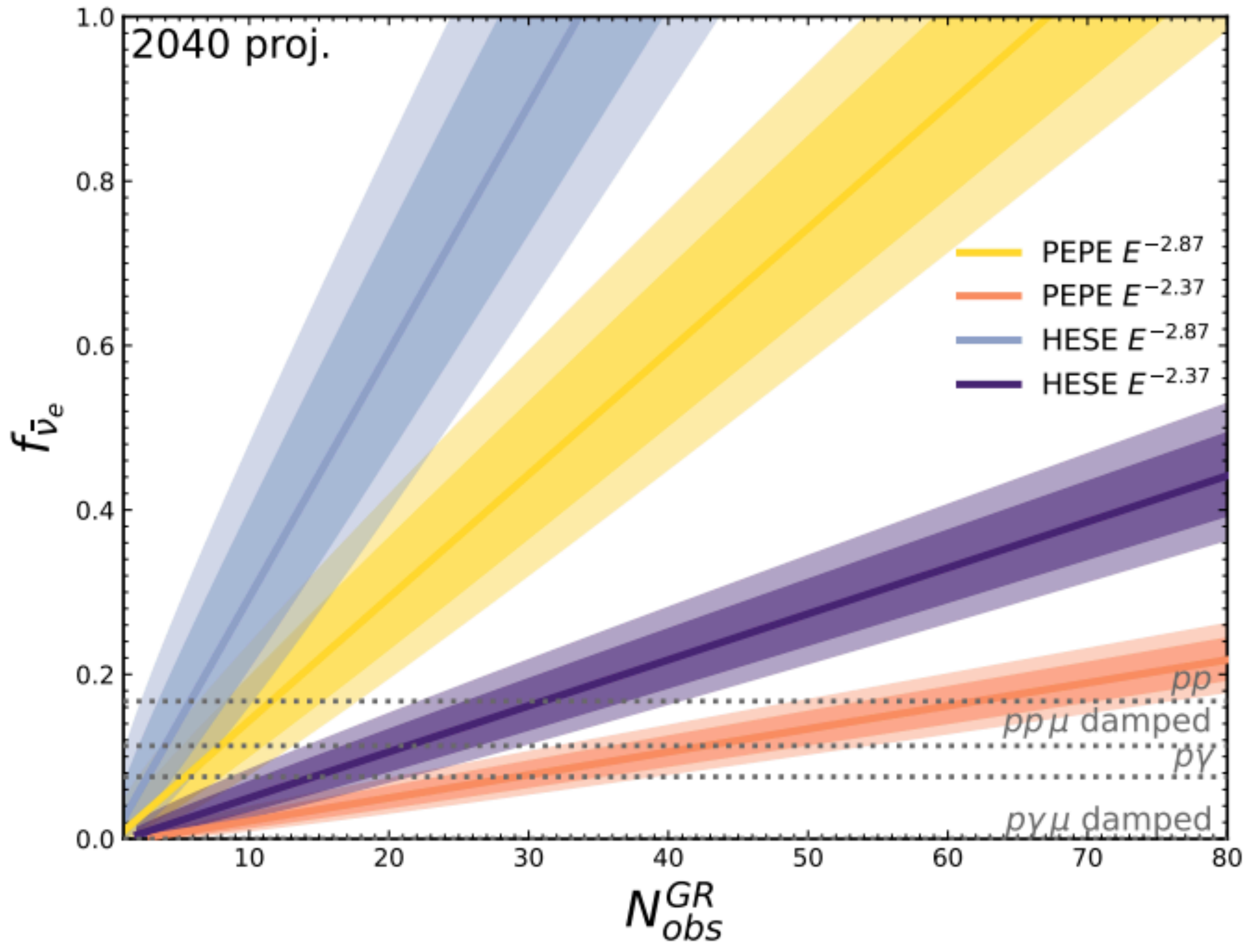
- Glashow resonance candidate was identified with 2.3 σ significance assuming $E^{-2.5}$ spectrum
- The cascade is partially contained (PEPE), with muon early pulses consistent with W decay

Event-wise Glashow Resonance Identification

- GR cascade (W hadronic decay, e, τ leptonic decay) indistinguishable from NC DIS. However, NC cascades are less energetic
- GR track without cascade at interaction vertex distinguishable from ν_μ CC
- $2\,\% \leq f_{\bar{\nu}_e} \leq 72\,\%$ with 4.6 years of PEPE, $f_{\bar{\nu}_e} \leq 51\,\%$ with 7.5 years of HESE, assuming hard spectrum
- pp separated from $p\gamma$ at more than 2 σ significance regardless of flux assumption

See also 2303.13706

All future ν telescopes

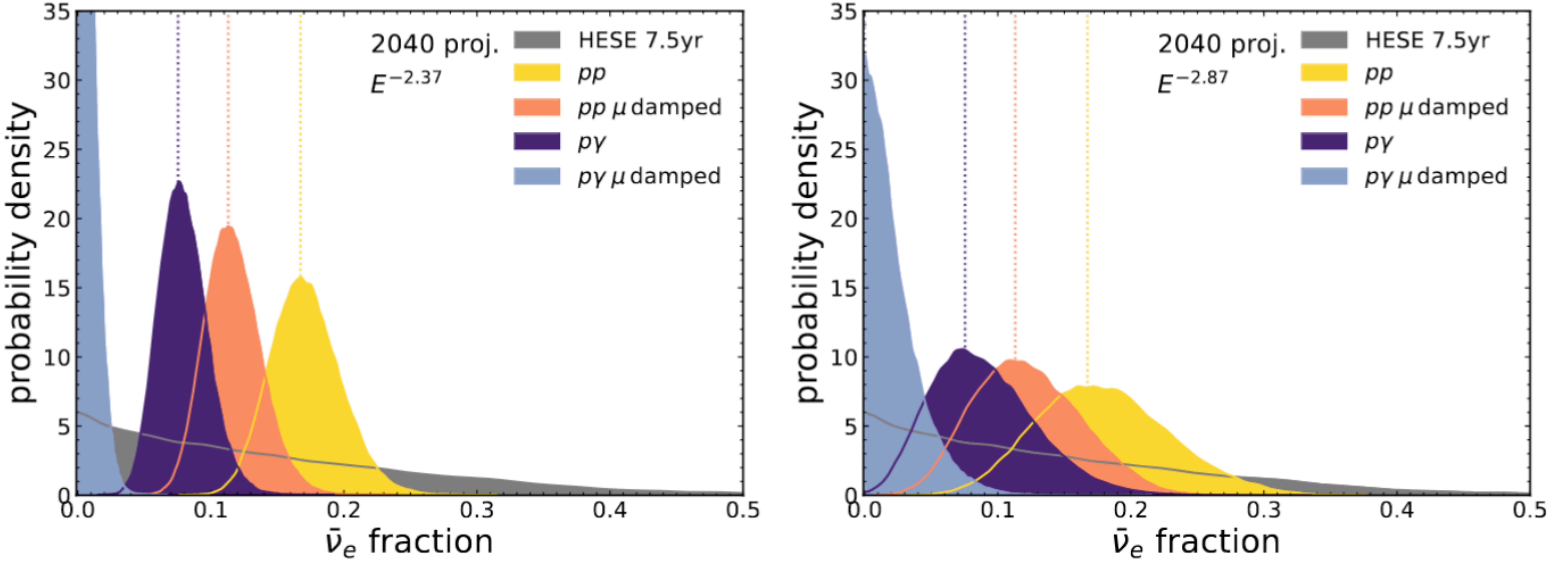


Liu, **NS**, Vincent, 2304.06068

Ningqiang Song (songnq@itp.ac.cn)

Statistical Analysis of GR

Assuming event-wise identification not possible, consider only contained events

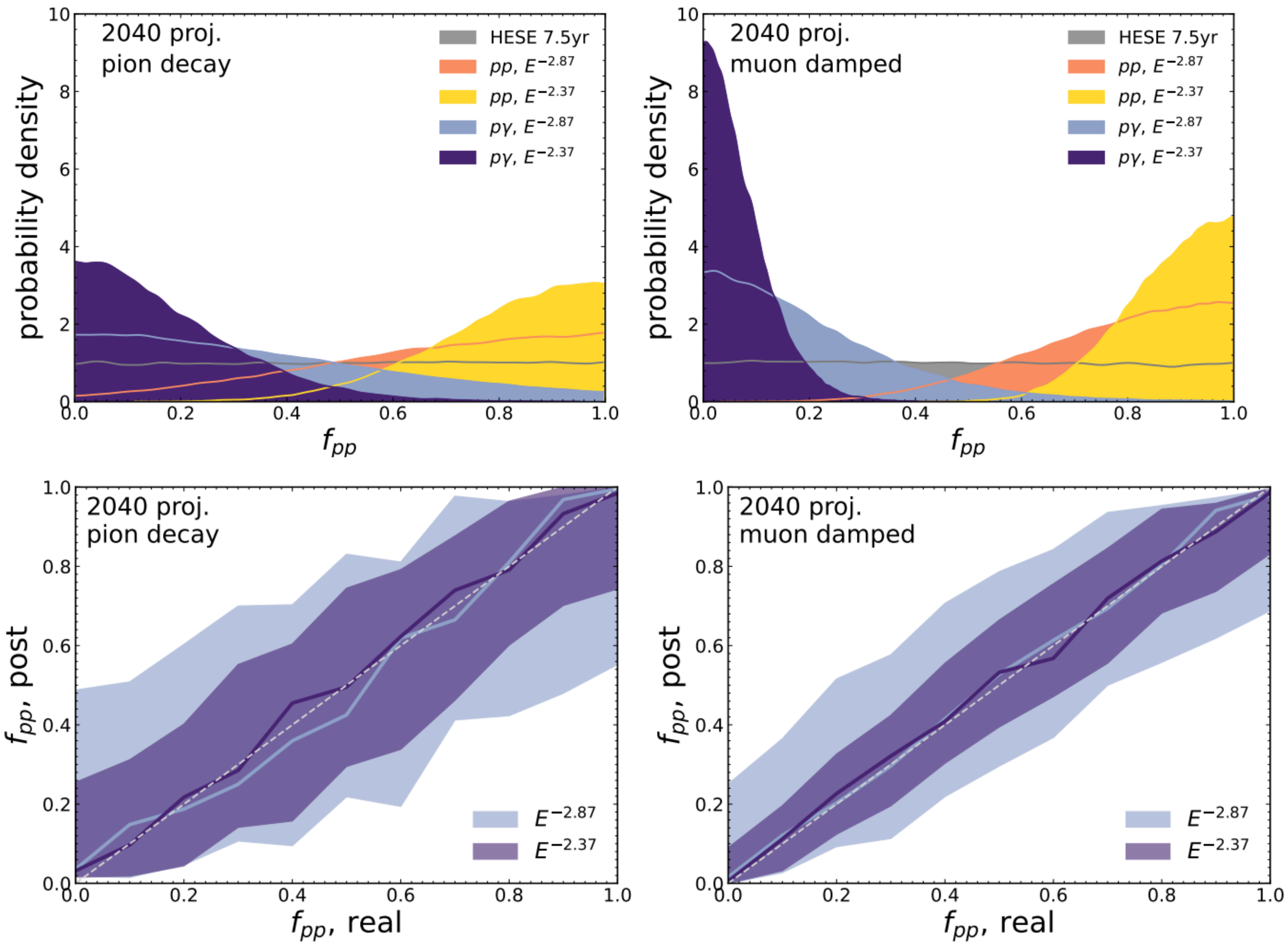


Analysis	Spectrum	pp from $p\gamma$ π decay	$p\gamma$ from pp π decay	pp from $p\gamma$ μ damped	$p\gamma$ from pp μ damped
HESE event-wise	soft	1.6σ	1.4σ	$> 5\sigma$	0.7σ
	hard	3.8σ	3.3σ	$> 5\sigma$	6.0σ
PEPE event-wise	soft	2.3σ	2.0σ	$> 5\sigma$	1.4σ
	hard	5.3σ	4.7σ	$> 5\sigma$	6.9σ
HESE Bayesian	soft	2.6σ	2.1σ	3.5σ	3.1σ
	hard	4.4σ	3.9σ	6.3σ	6.5σ

Liu, **NS**, Vincent, 2304.06068

Mixture sources

Assuming sources are mixture of pp and $p\gamma$



Outline

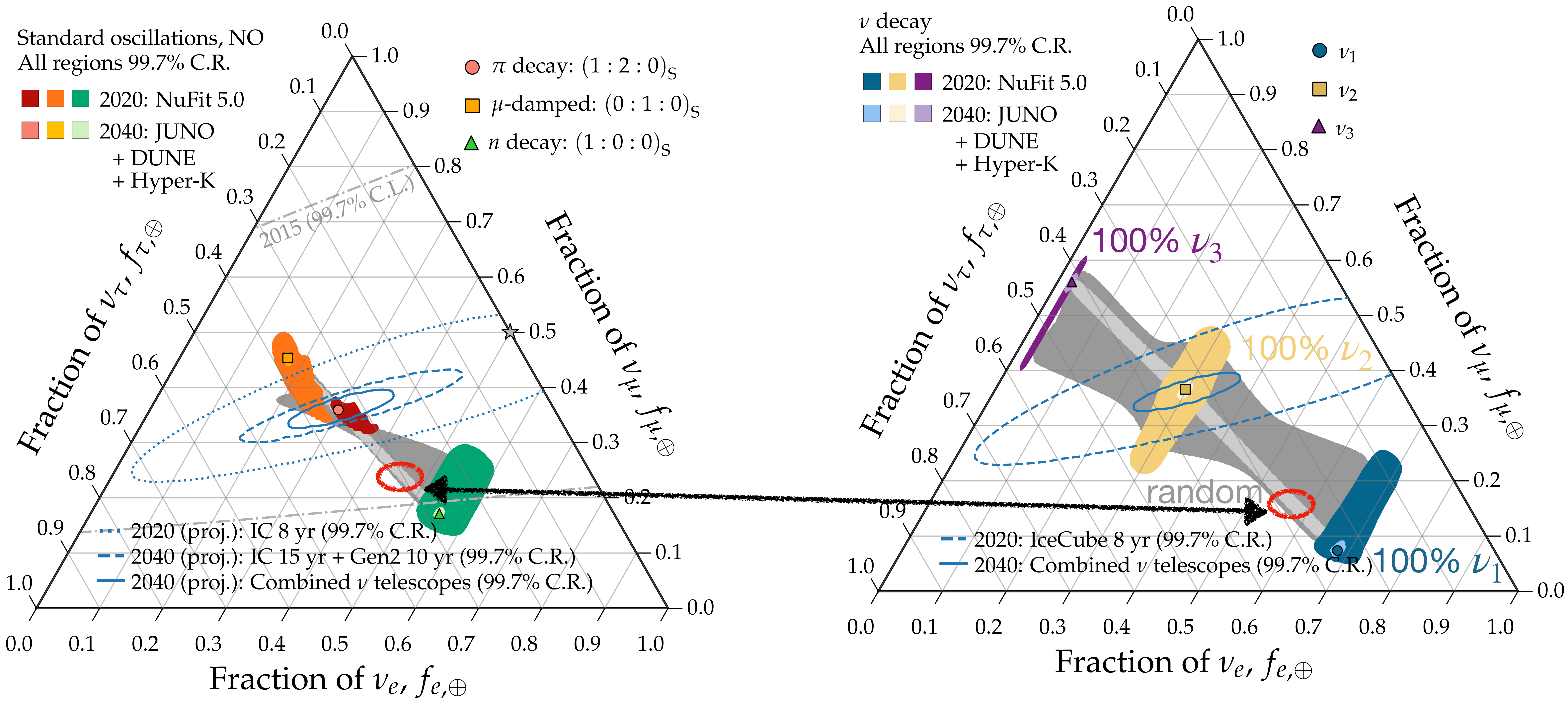
- ❖ Determining neutrino flavour composition at the source
- ❖ Breaking the degeneracy with Glashow resonance
- ❖ Probing new physics with future measurements

Neutrino Decay

Decay to a combination of mass states $f_{\beta,\oplus} = \sum_{i=1}^{3} |U_{\beta i}|^2 f_{i,\oplus}$

Standard Oscillation

Neutrino Decay



Code available at https://github.com/songningqiang/FANFIC

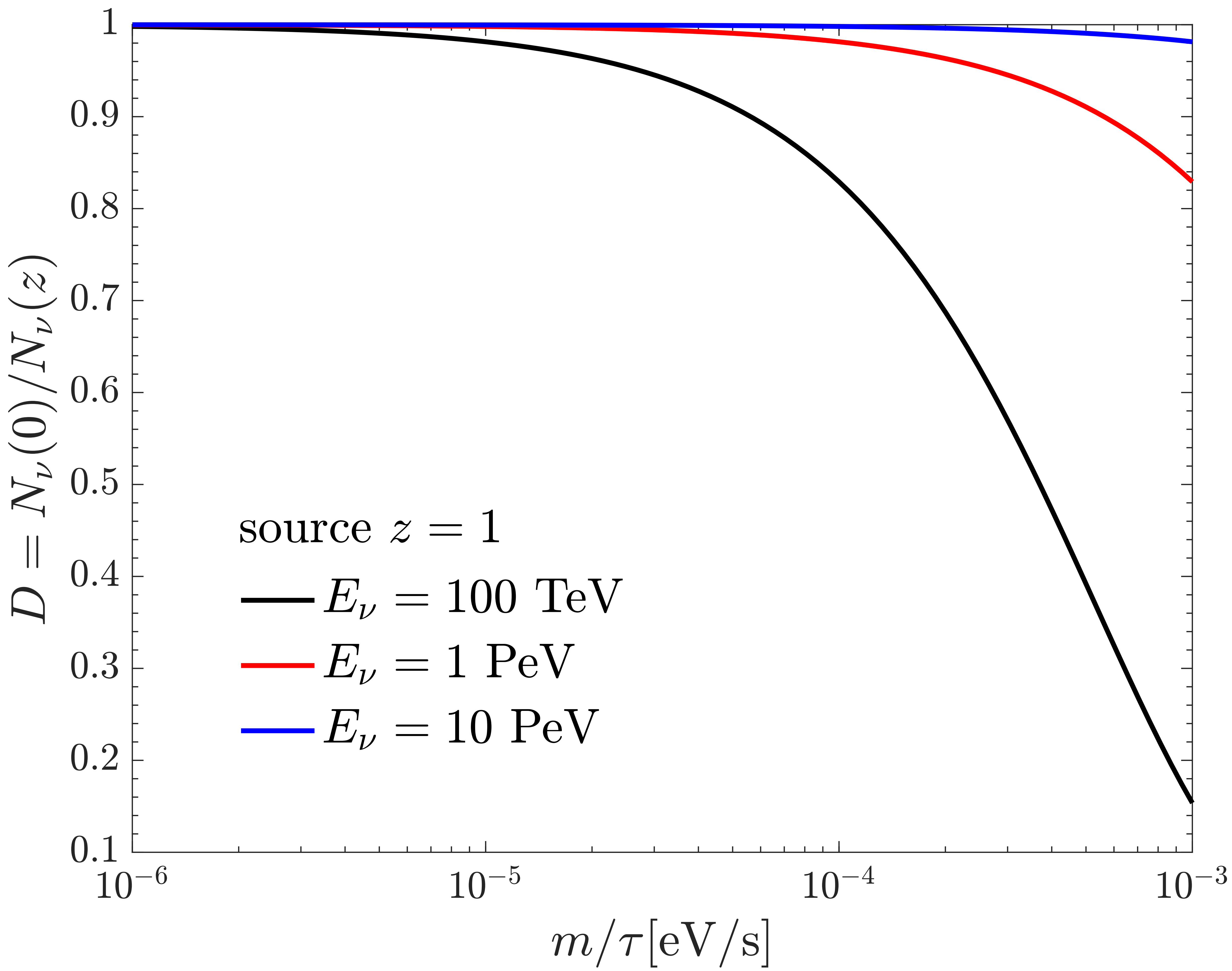
NS, Li, Argüelles, Bustamante, Vincent, JCAP/2012.12893

Neutrino Decay

- Assume ν_2, ν_3 decay invisibly, ν_1 stable
- Assume pion decay at source $(f_e : f_\mu : f_\tau)_S = (1/3,\ 2/3,\ 0)$
- Sum up neutrinos sources at different redshifts

$$D_i = \frac{N_i(E,0)}{N_i(E,z)} = Z(z)^{-\frac{m_i}{\tau_i}\frac{1}{H_0 E}}$$

See also 1208.4600, 1610.02096 for details



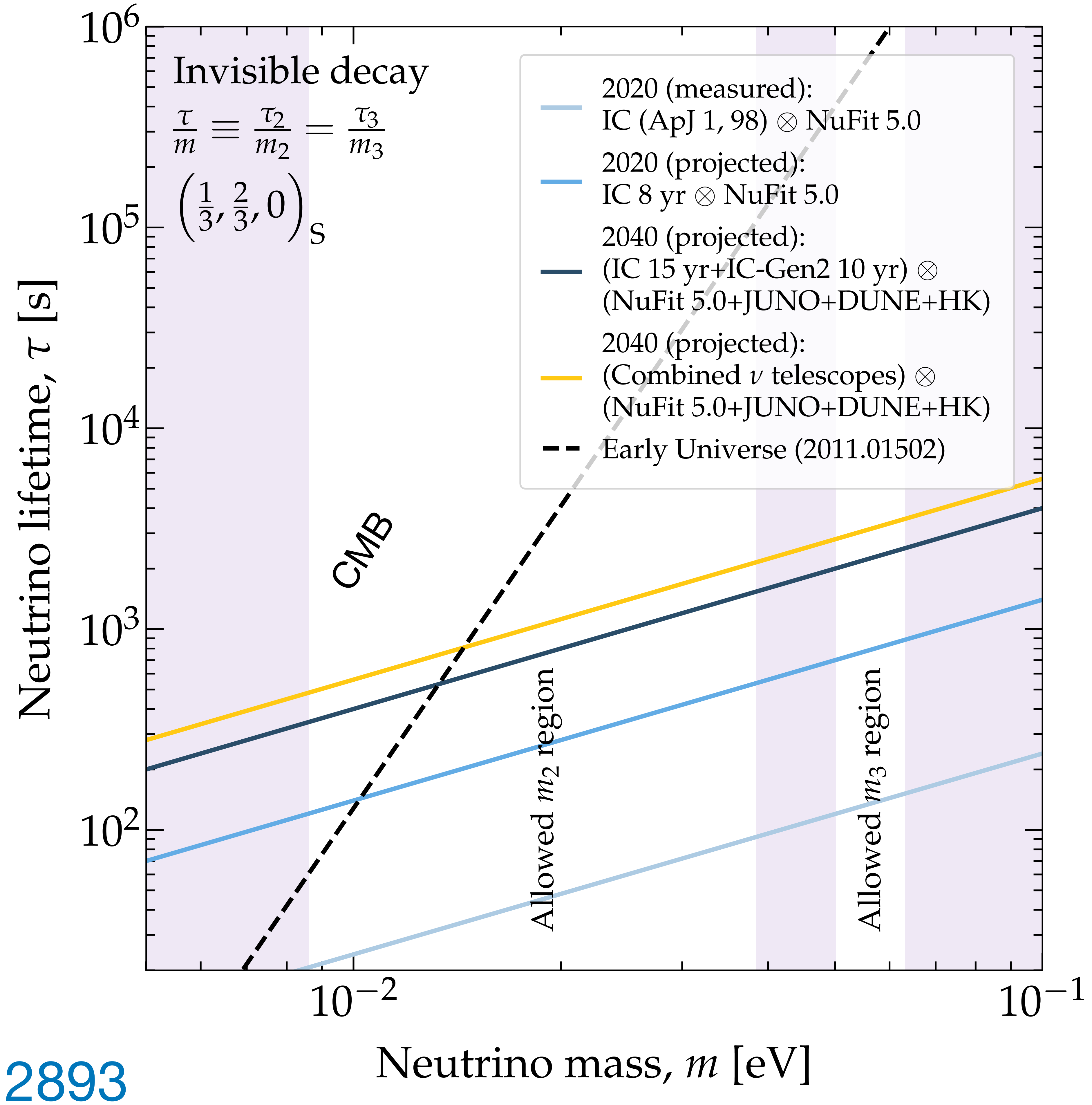
Ningqiang Song (songnq@itp.ac.cn)

Neutrino Decay

ν telescopes $\otimes$ oscillation experiments	m_ν/τ_ν (eV s^{-1})
2015 (measured): IC $\otimes$ NuFit 5.0	4.1×10^{-4}
2020 (projected): IC 8 yr $\otimes$ NuFit 5.0	7.4×10^{-5}
2040 (projected): IC 15 yr + IC-Gen2 10 yr $\otimes$ (NuFit 5.0 + JUNO + DUNE + HK)	2.5×10^{-5}
2040 (projected): All ν telescopes $\otimes$ (NuFit 5.0 + JUNO + DUNE + HK)	1.8×10^{-5}

- Assume ν_2, ν_3 decay invisibly, ν_1 stable
- Assume pion decay at source $(f_e : f_\mu : f_\tau)_S = (1/3,\ 2/3,\ 0)$
- Sum up neutrinos sources at different redshifts

$$D_i = \frac{N_i(E,0)}{N_i(E,z)} = Z(z)^{-\frac{m_i}{\tau_i}\frac{1}{H_0 E}}$$



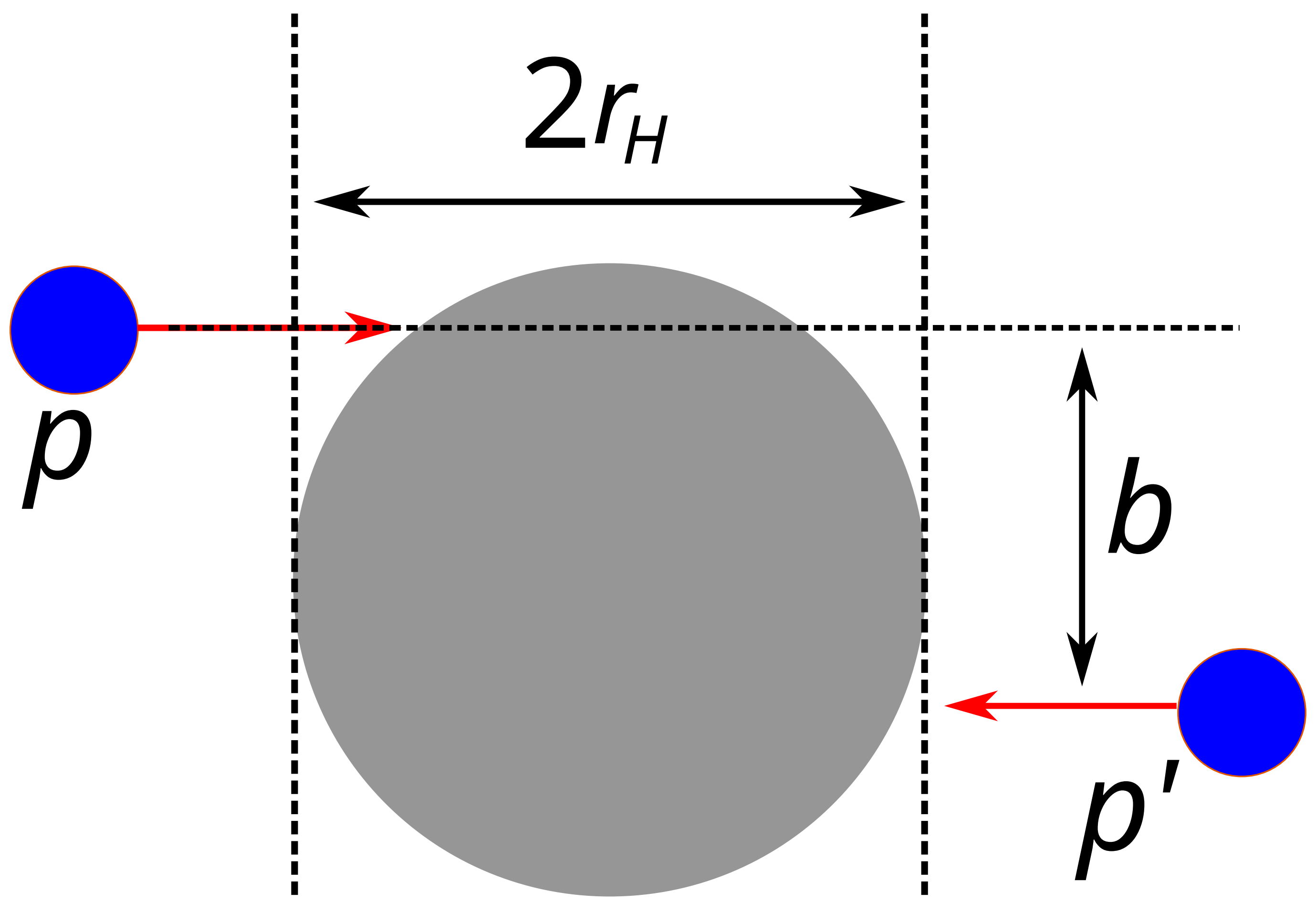
NS, Li, Argüelles, Bustamante, Vincent, JCAP/2012.12893

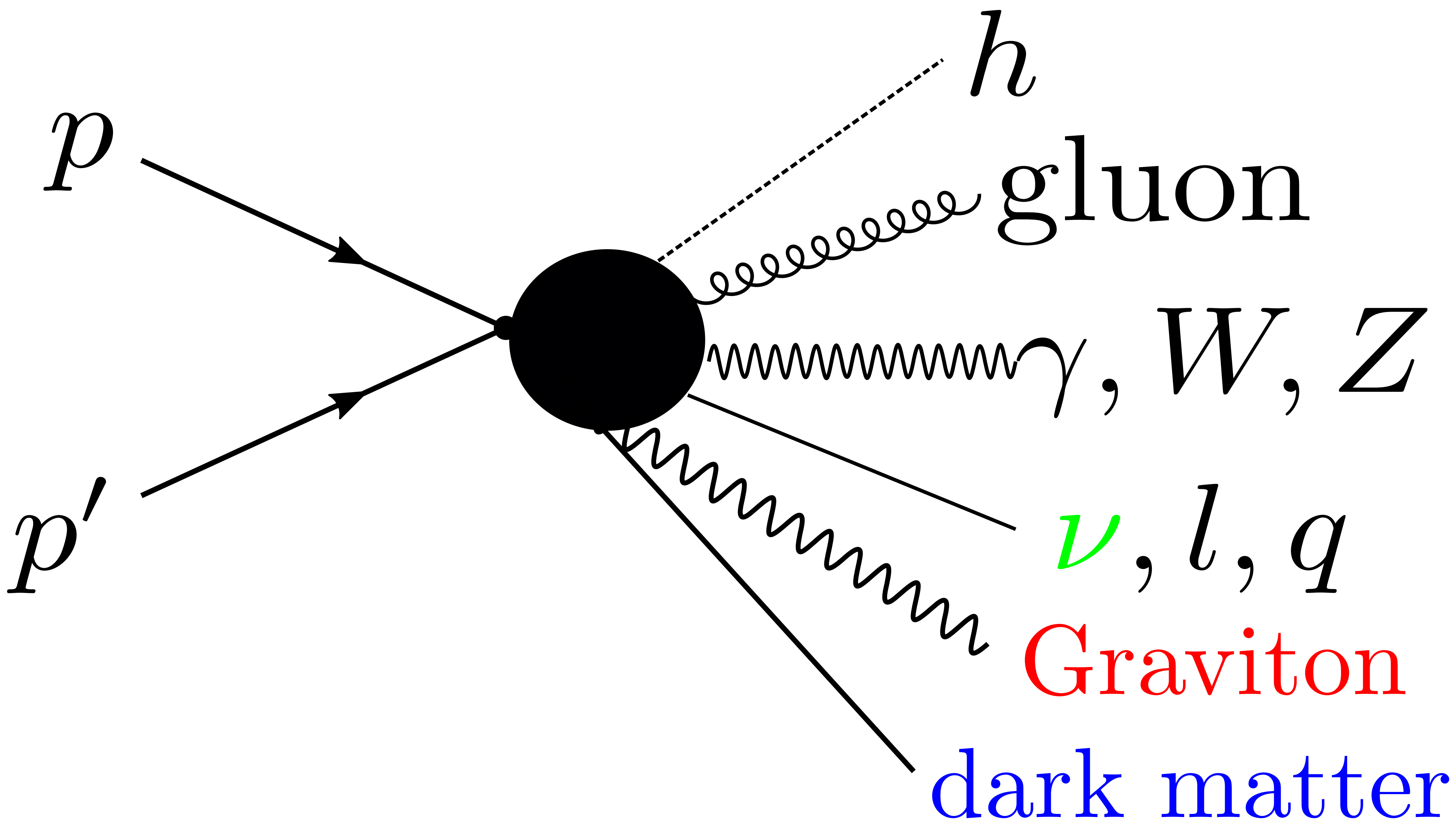
Y³ Wong's talk

Quantum Gravity at a Glance

- Micro BH production allowed if $b < b_{\max}$ or $E_{CM} \gtrsim M_{\star}$
- BHs can be produced in high energy particle collisions

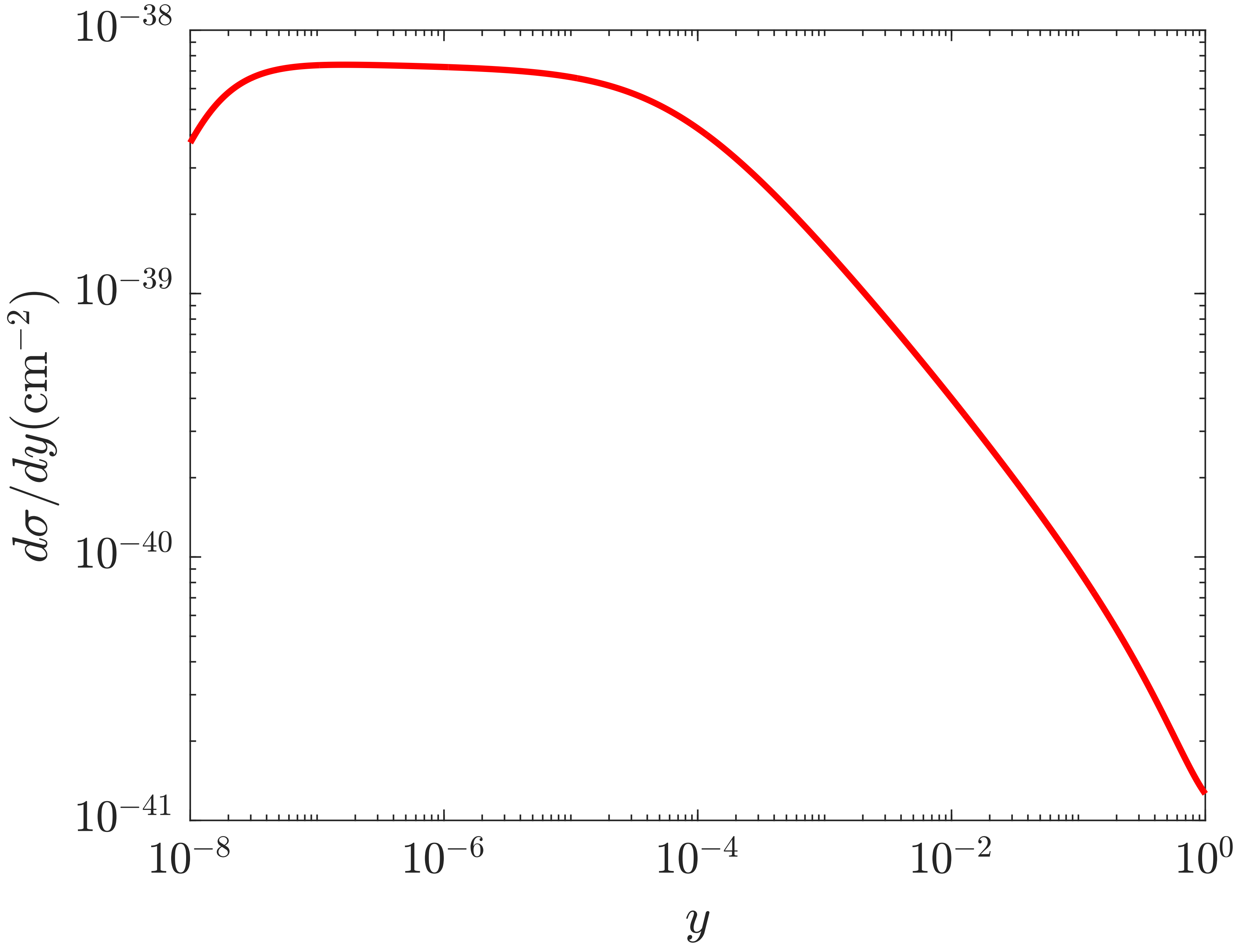
Large Extra Dimensions
Arkani-Hamed, Dimopoulos, Dvali, PRD 1998

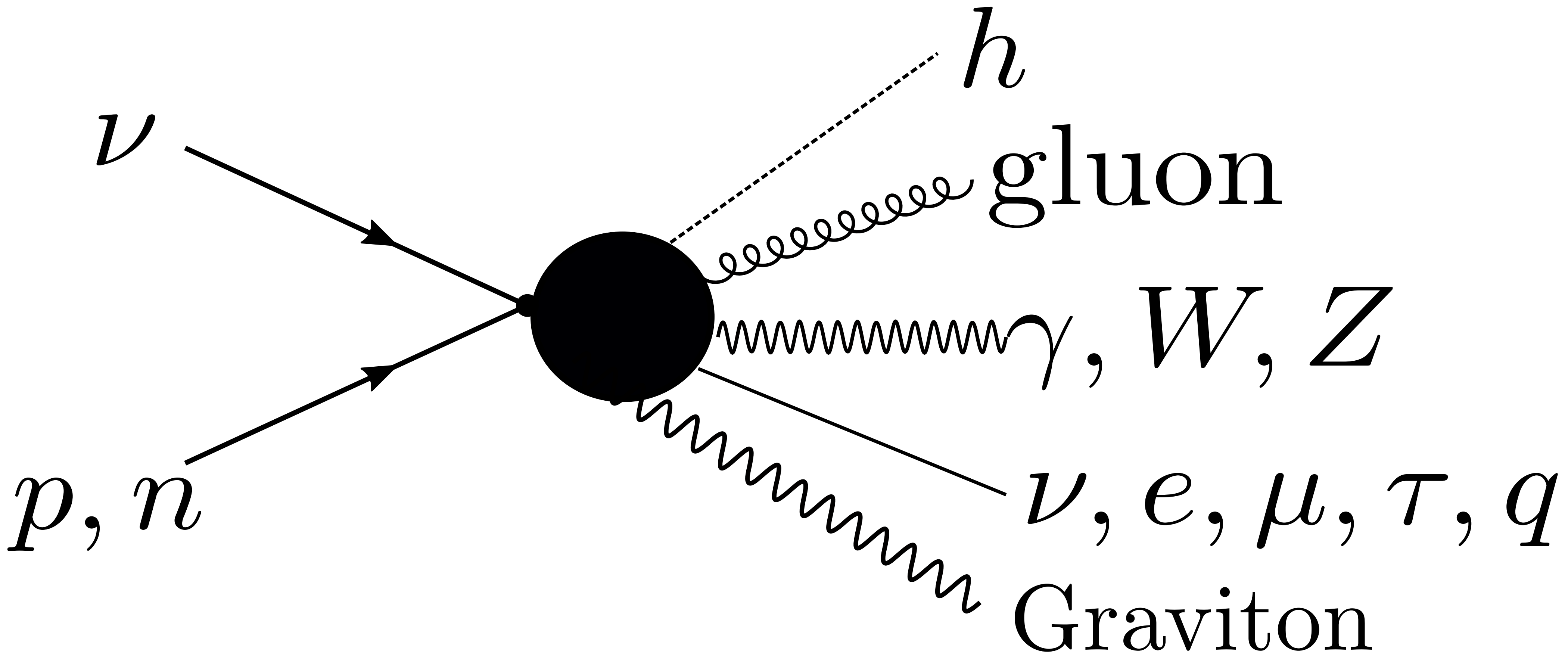




Ningqiang Song (songnq@itp.ac.cn)

Standard Model Events vs Black Holes





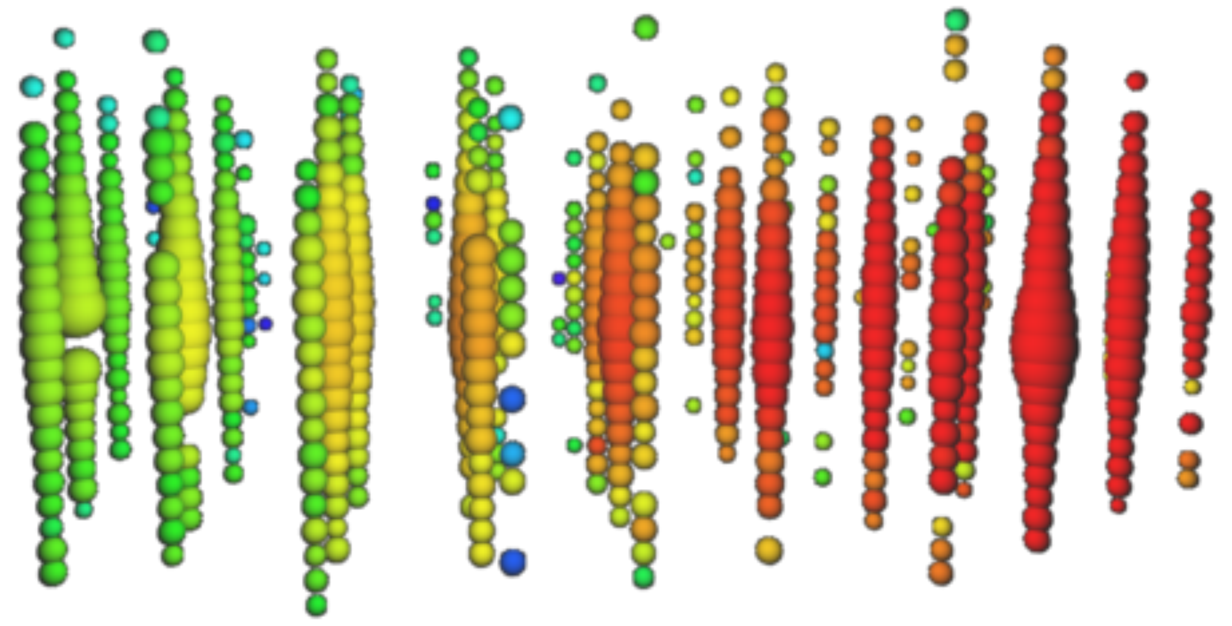
- SM
  - $y = 1 - E_l/E_\nu$
  - $E_l \sim E_\nu$

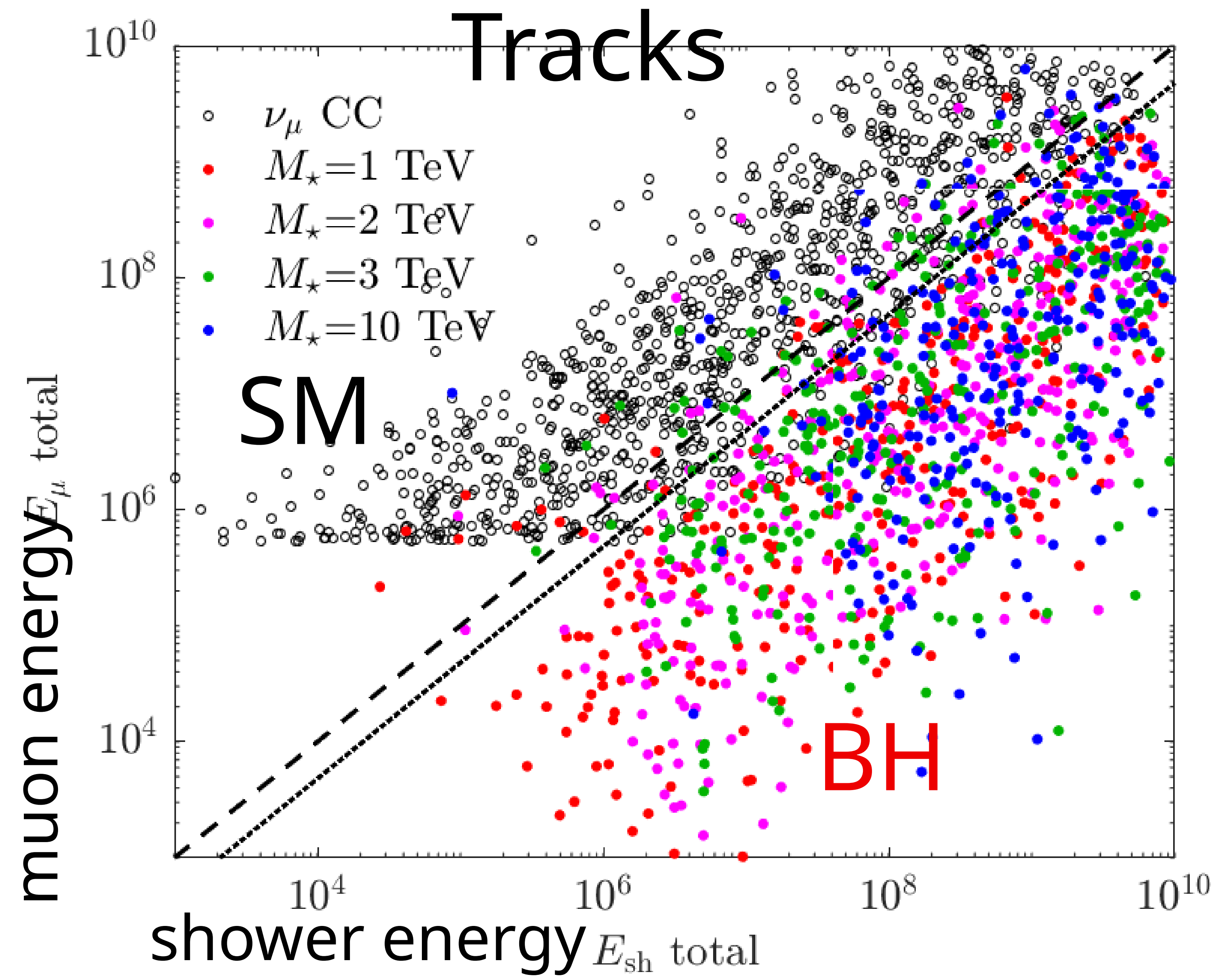
BHs

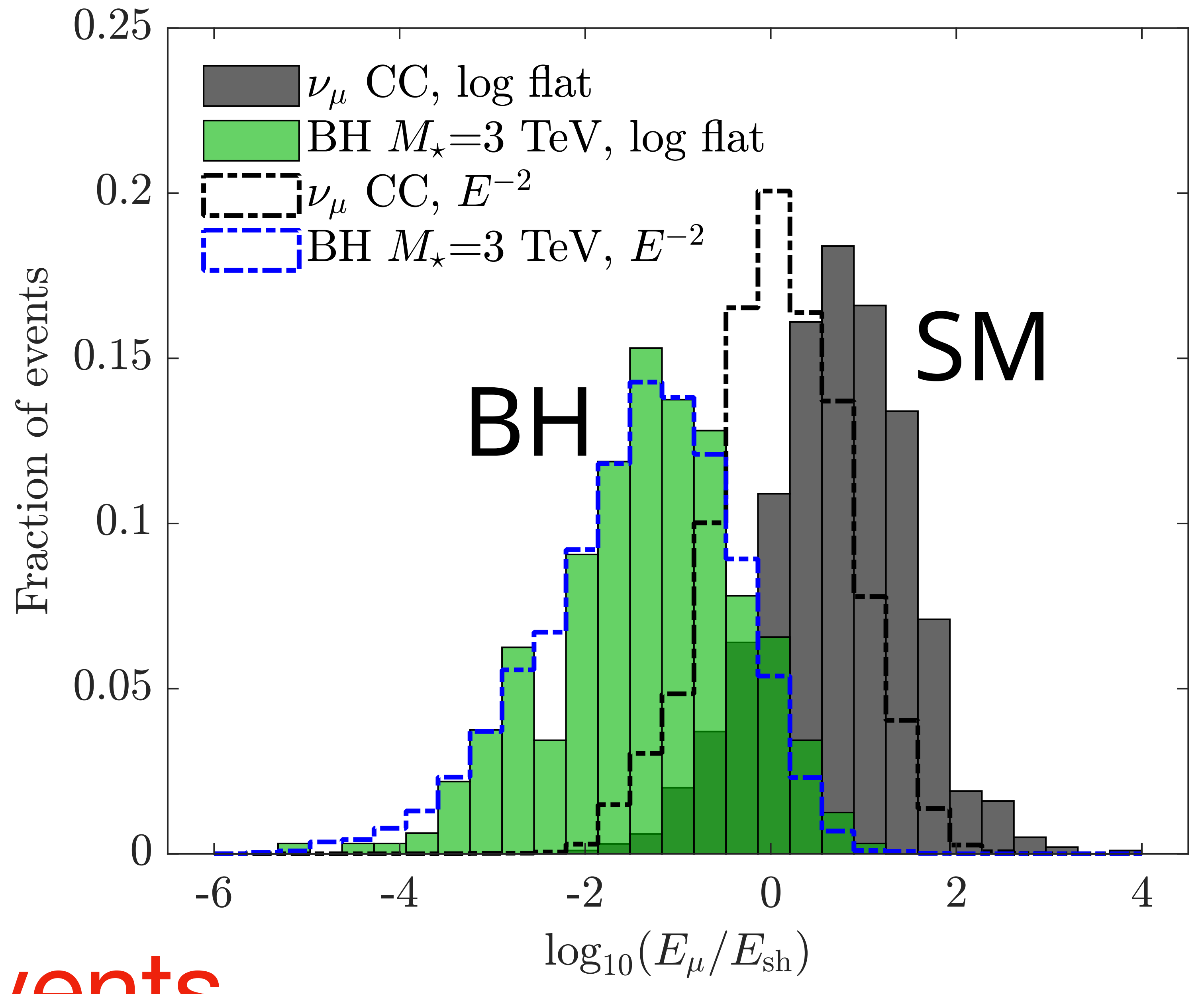
- $N \sim 6 - 20$ primary decay particles
- $E_l \sim E_\nu/N$

Lepton energy in black holes tends to be smaller than in SM!

Muon Energy Ratio in BH Tracks





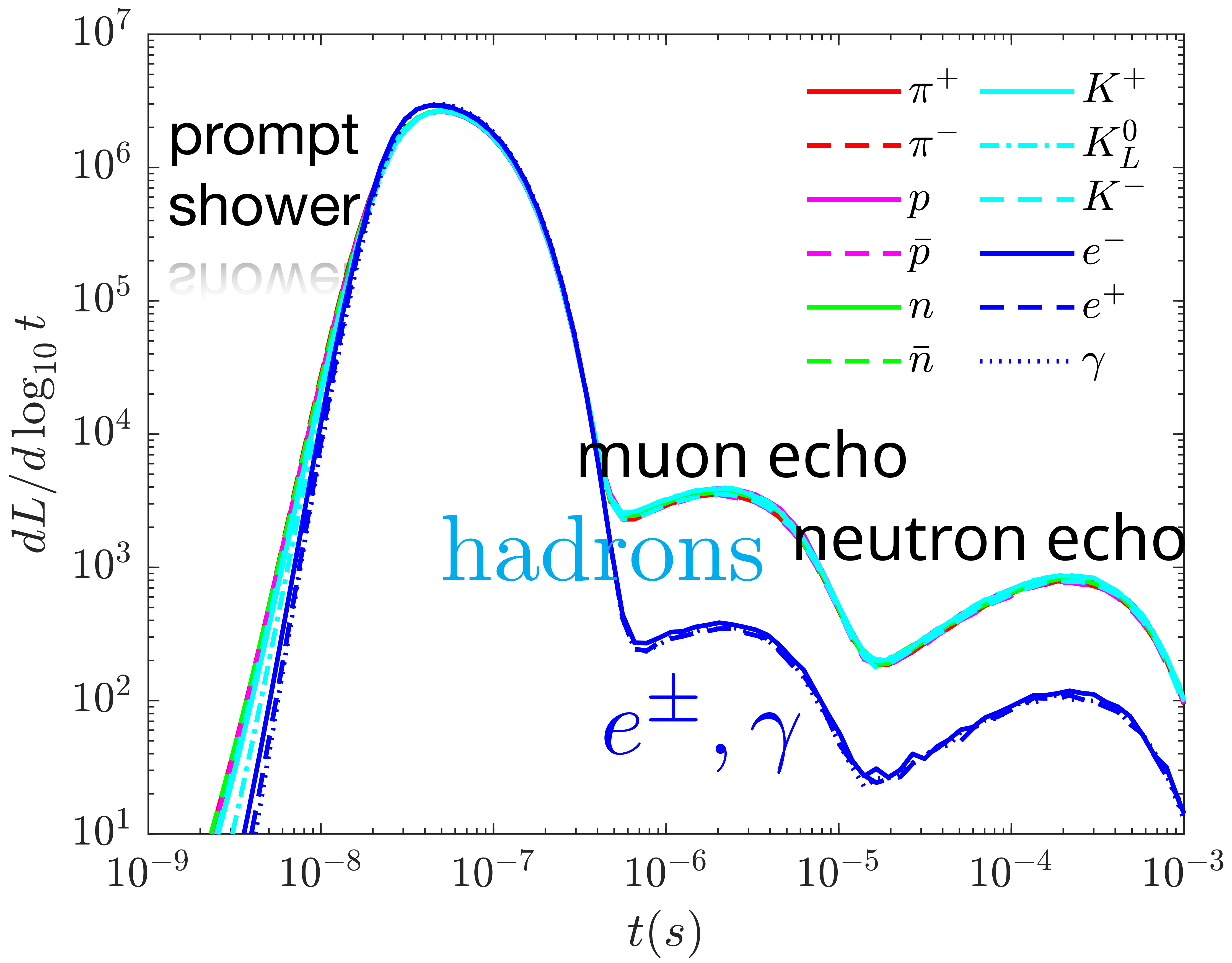


- Tracks produced in $\nu_{\mu,\tau}$ CC
  - SM $E_\mu > E_{hadron}$
  - BH $E_{hadron} > E_\mu$

Lower track energy/shower energy ratio in BH events

Neutrino Telescope - Cherenkov Light Echos

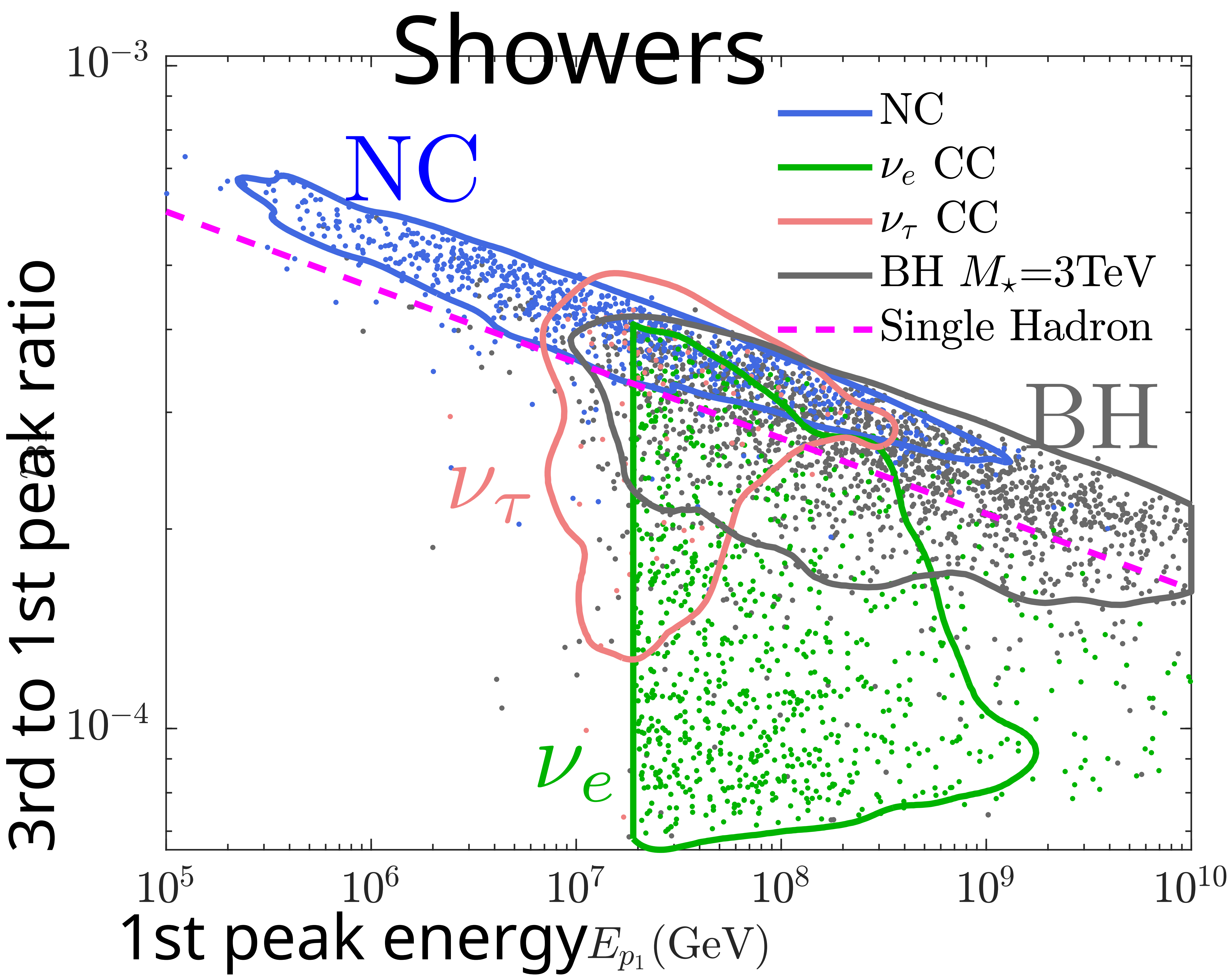
- Particles from neutrino-nucleon interaction deposit their energy promptly within 10^{-7} s, secondary muons decay at $\sim 1 - 10\ \mu$s, and neutrons are captured at $\sim 200\ \mu$s
- Hadronic showers featured with larger muon echo and neutron echo than electromagnetic shower



See also Li, Bustamante, Beacom, 1606.06290

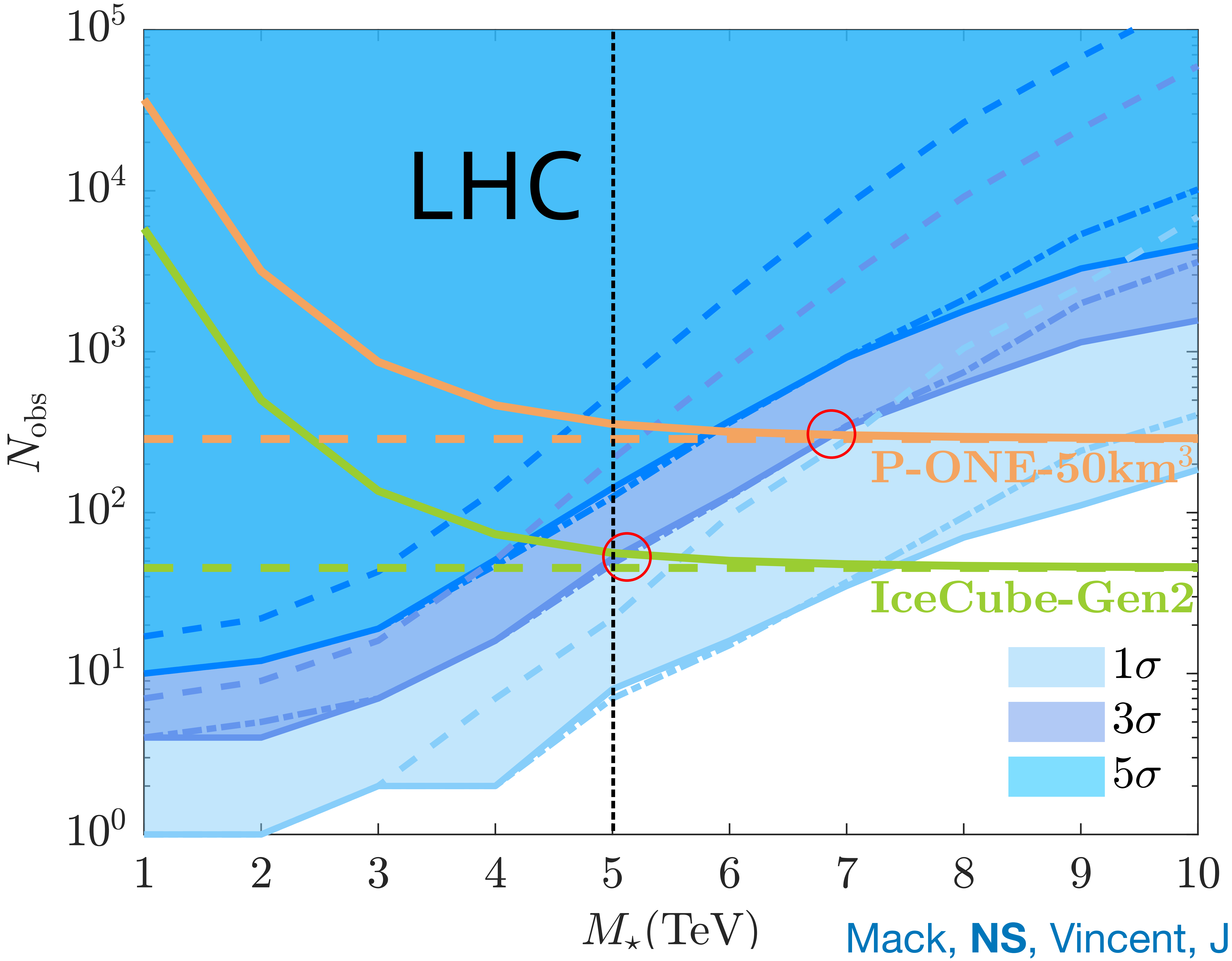
Micro Black Holes at Neutrino Telescopes

- ν_e CC: Energetic EM shower with less energetic hadronic shower
- NC: Energetic hadronic shower
- ν_τ CC: EM shower or hadronic shower depending on decay product
- Black holes: Energetic hadronic shower with less energetic EM shower



Mack, **NS**, Vincent, JHEP 2019/1912.06656

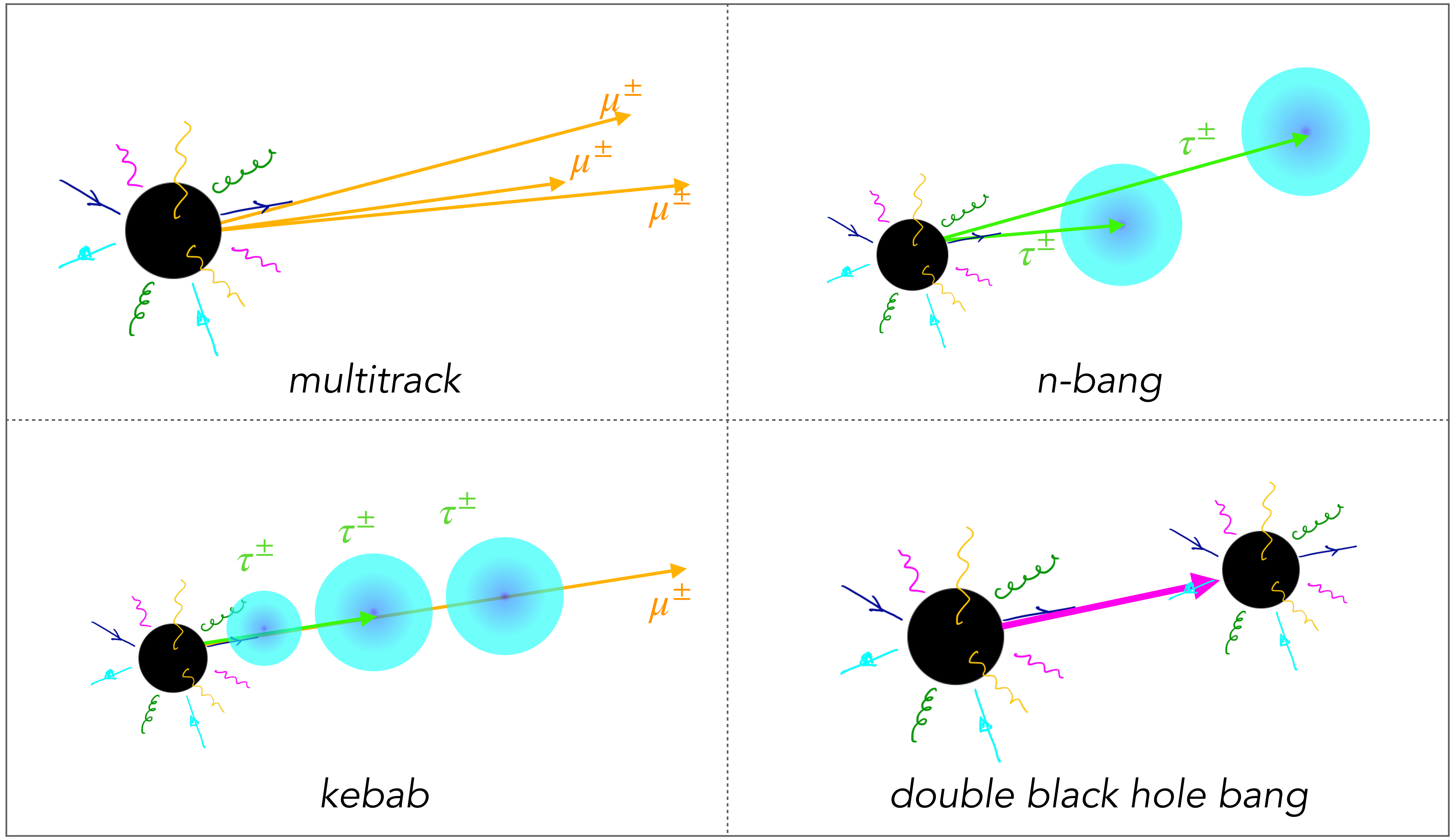
Black Hole Discovery Limit



Mack, **NS**, Vincent, JHEP 2019/1912.06656

Micro Black Holes at IceCube and beyond

- Mutitrack: BHs produce multiple muons or taus
- N-bang: Multiple taus decay
- Kebab: Multiple taus decay along with a track
- Double BH bang: BH decay product produces another BH



Rare but smoking-gun evidence of BHs!

Mack, **NS**, Vincent, JHEP 2019/1912.06656

Summary

❖ Determining neutrino flavour composition at the source

❖ Breaking the degeneracy with Glashow resonance

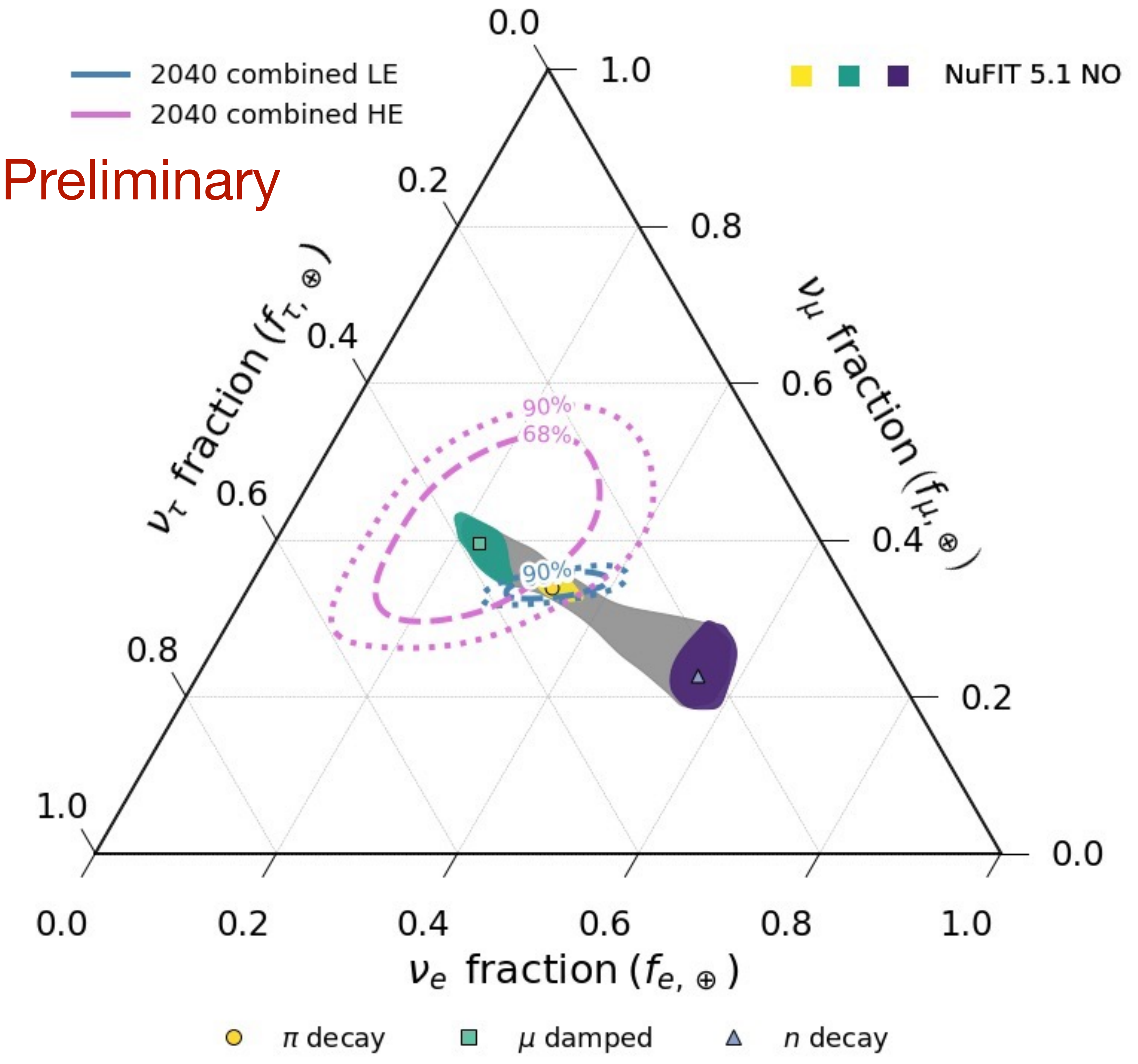
❖ Probing new physics with future measurements

Ningqiang Song (songnq@itp.ac.cn)

Thank you!

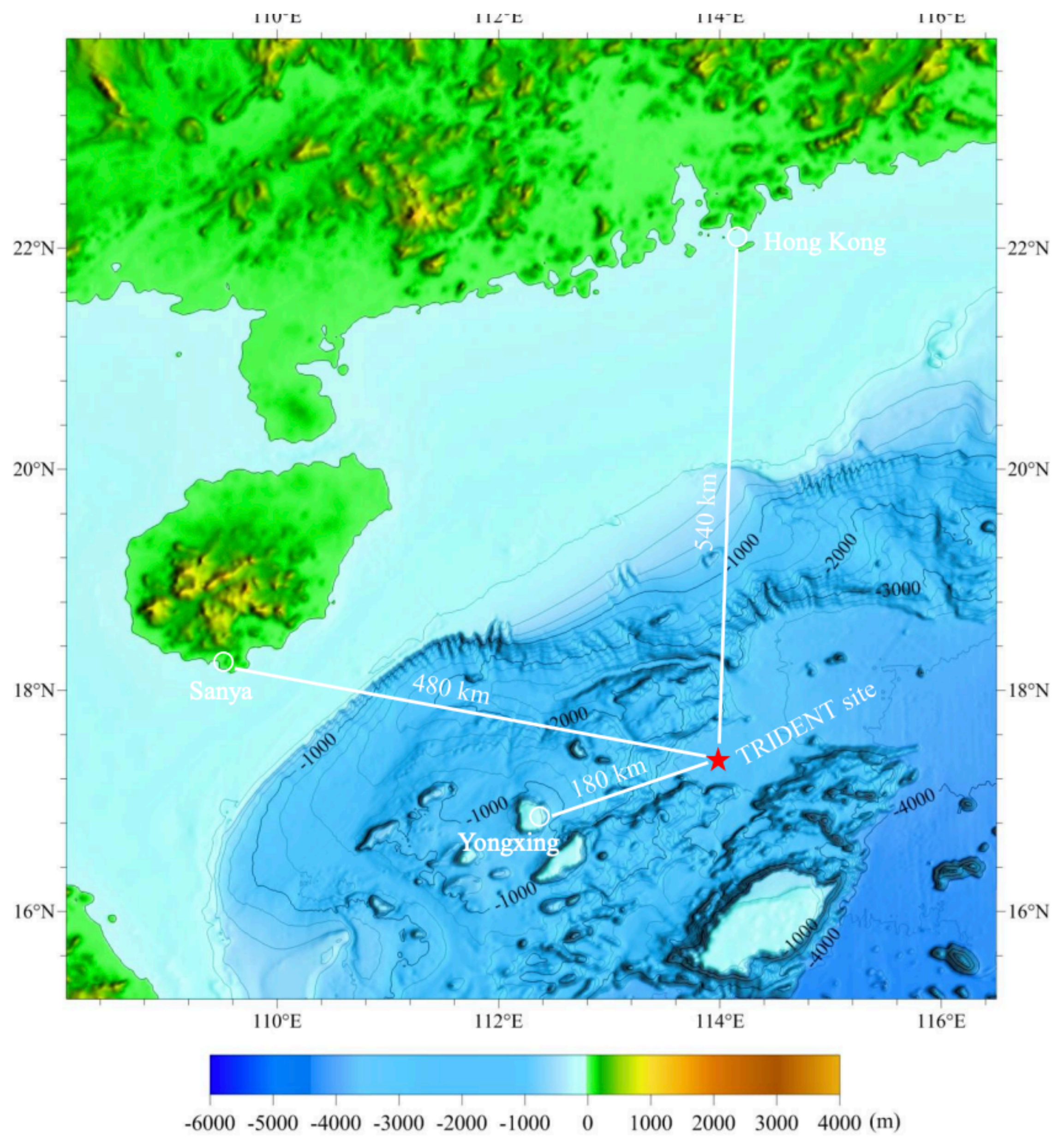
Back up

Spectral Analysis



What future neutrino observations tell us about the neutrino flavours at high and low energies?

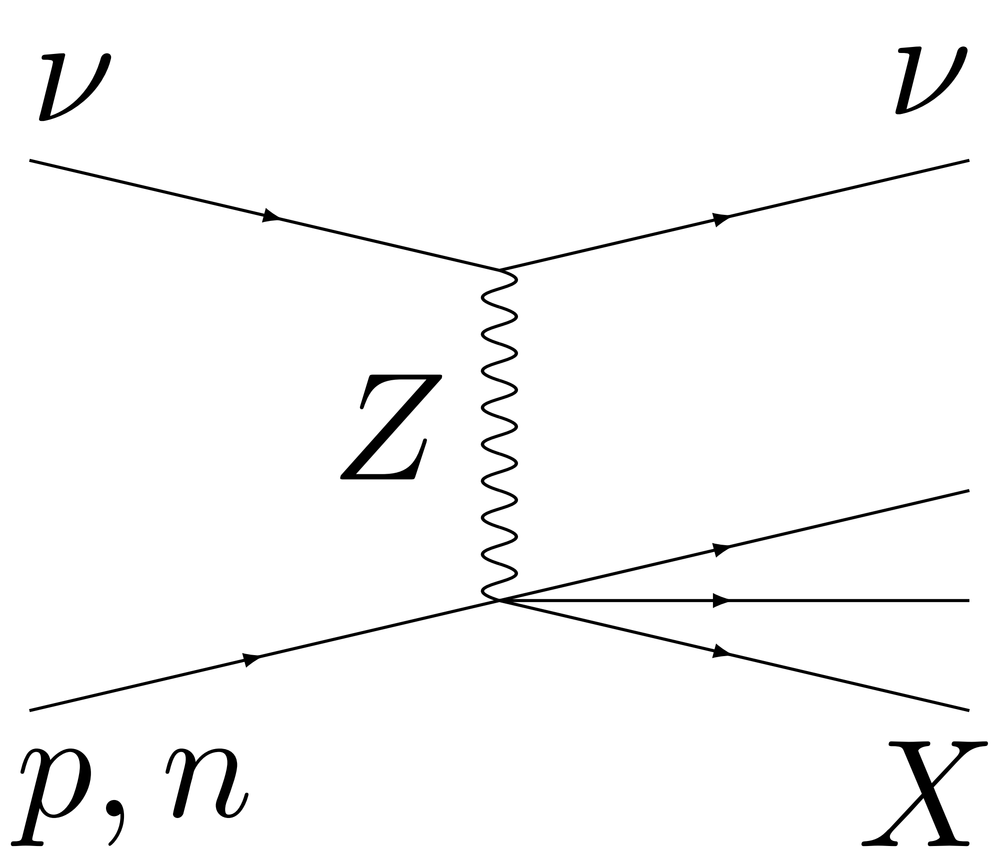
Combination of future neutrino telescopes, including Trident

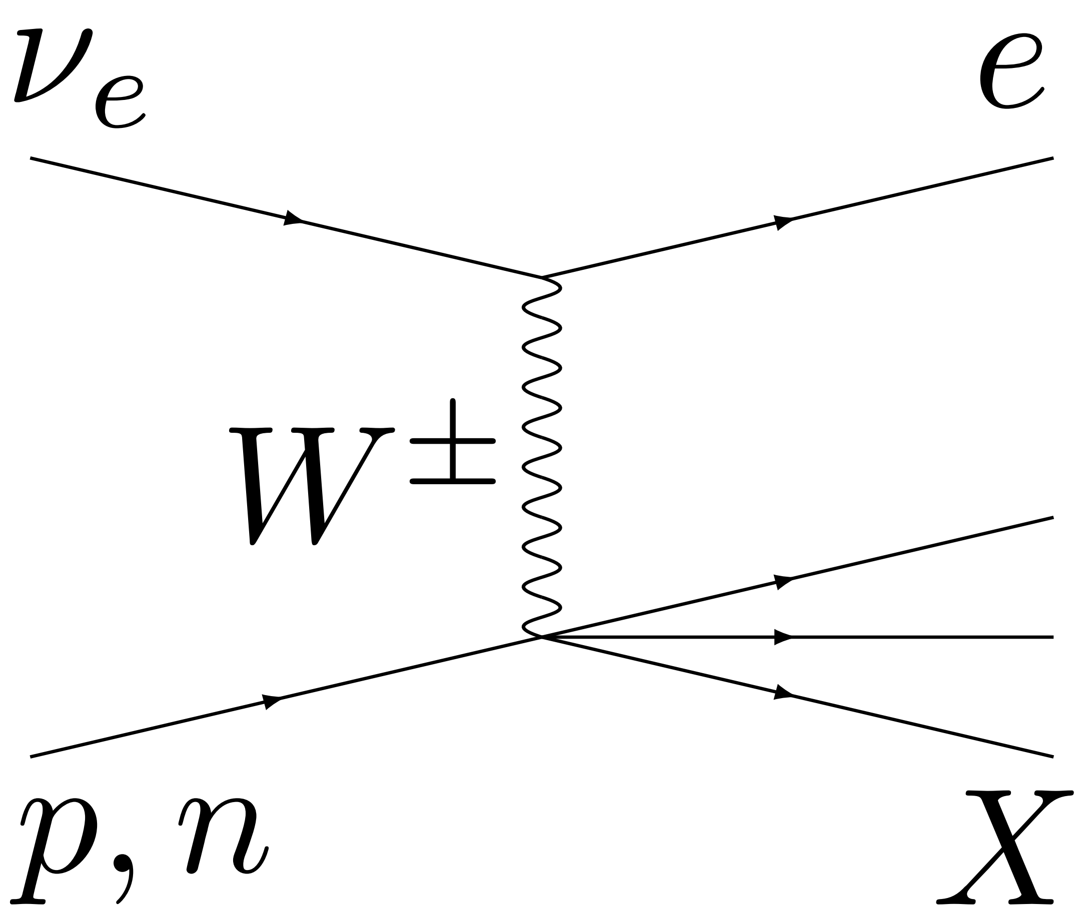


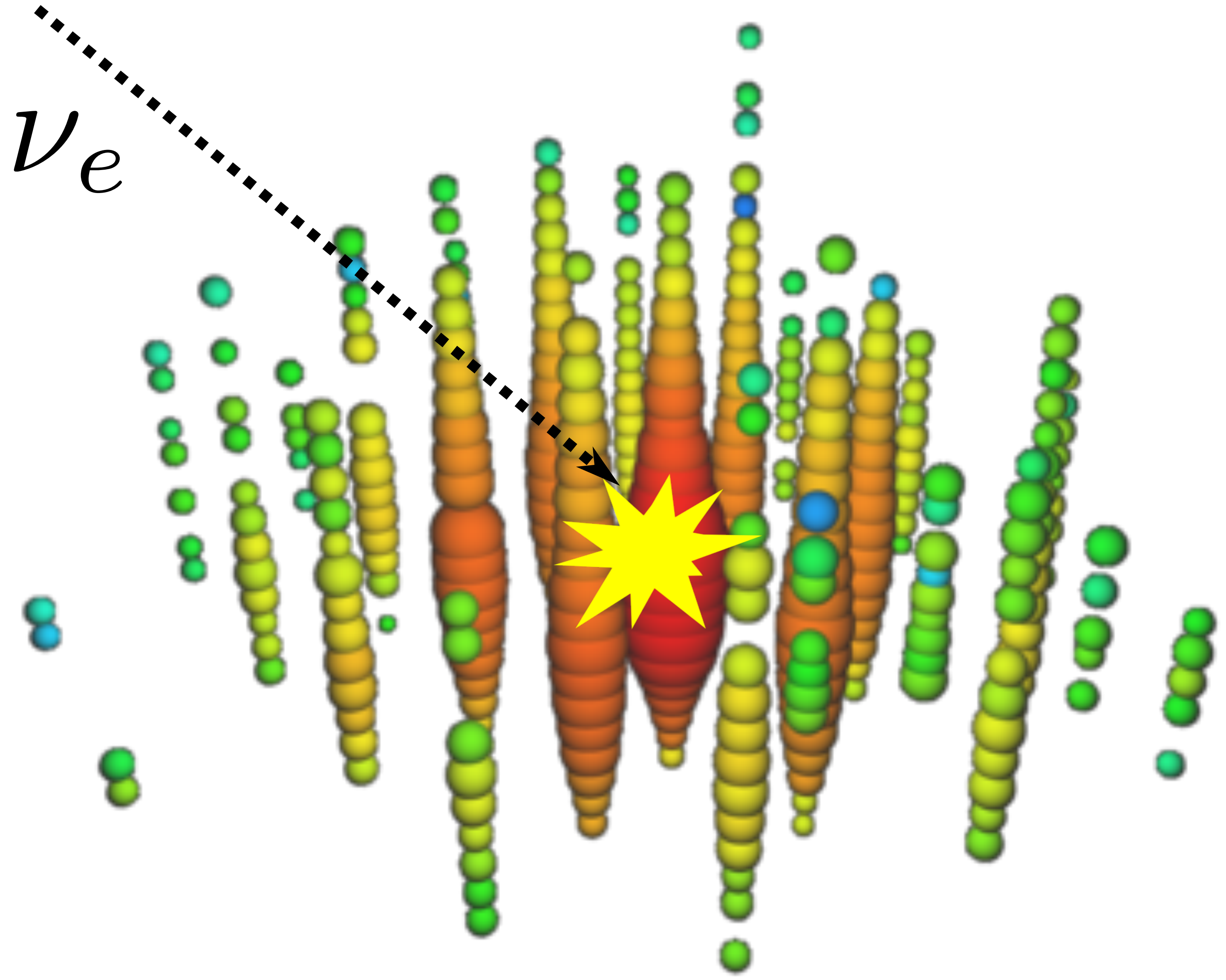
Argüelles, Bustamante, Fiorillo, Liu, **NS**, Vincent, 2303.xxxxx

Shower

- Neutral current (NC) & ν_e charged current (CC) (low-E ν_τ CC)



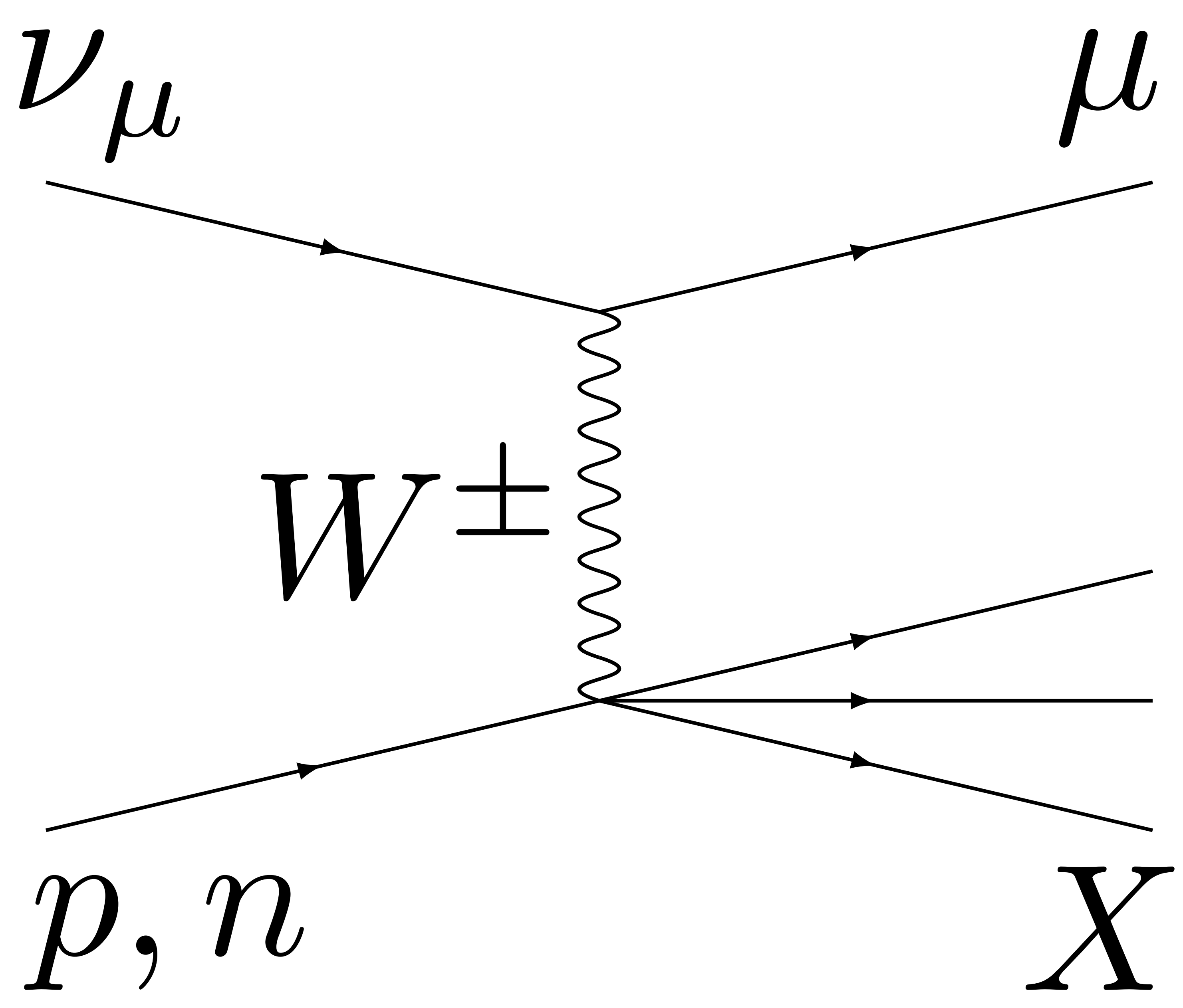


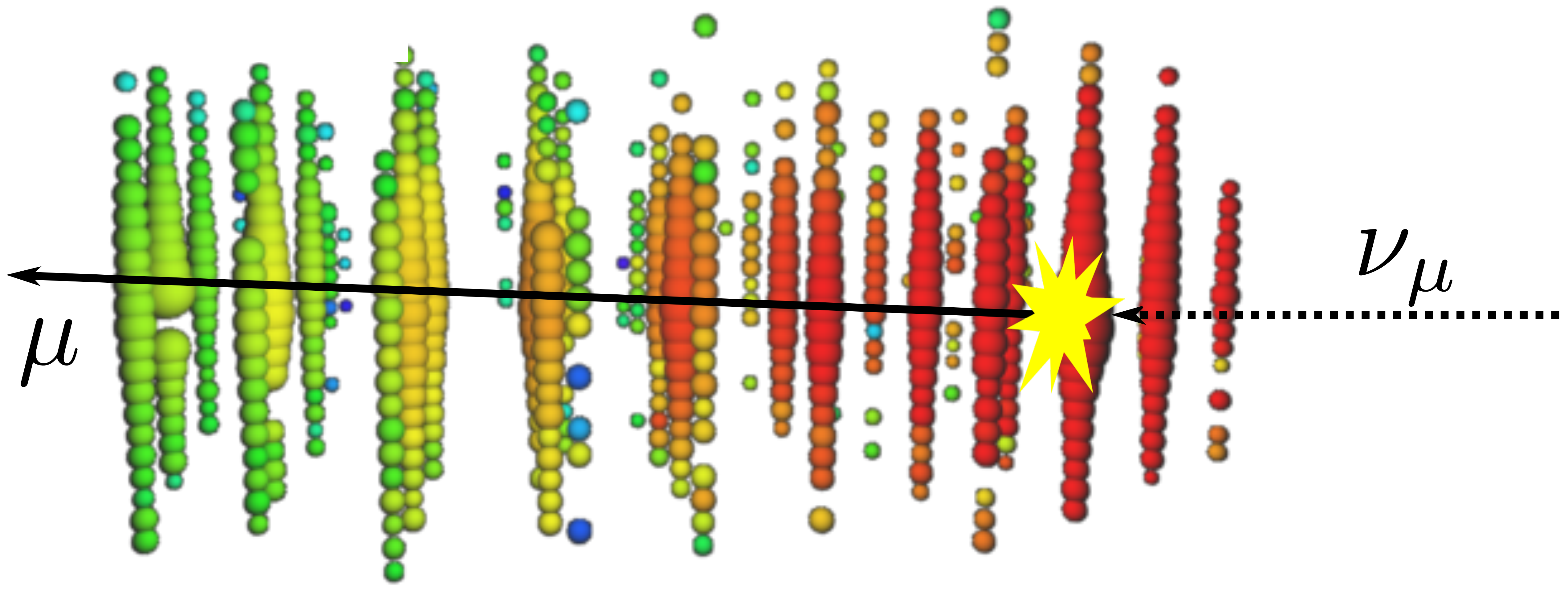


icecube.wisc.edu

Track

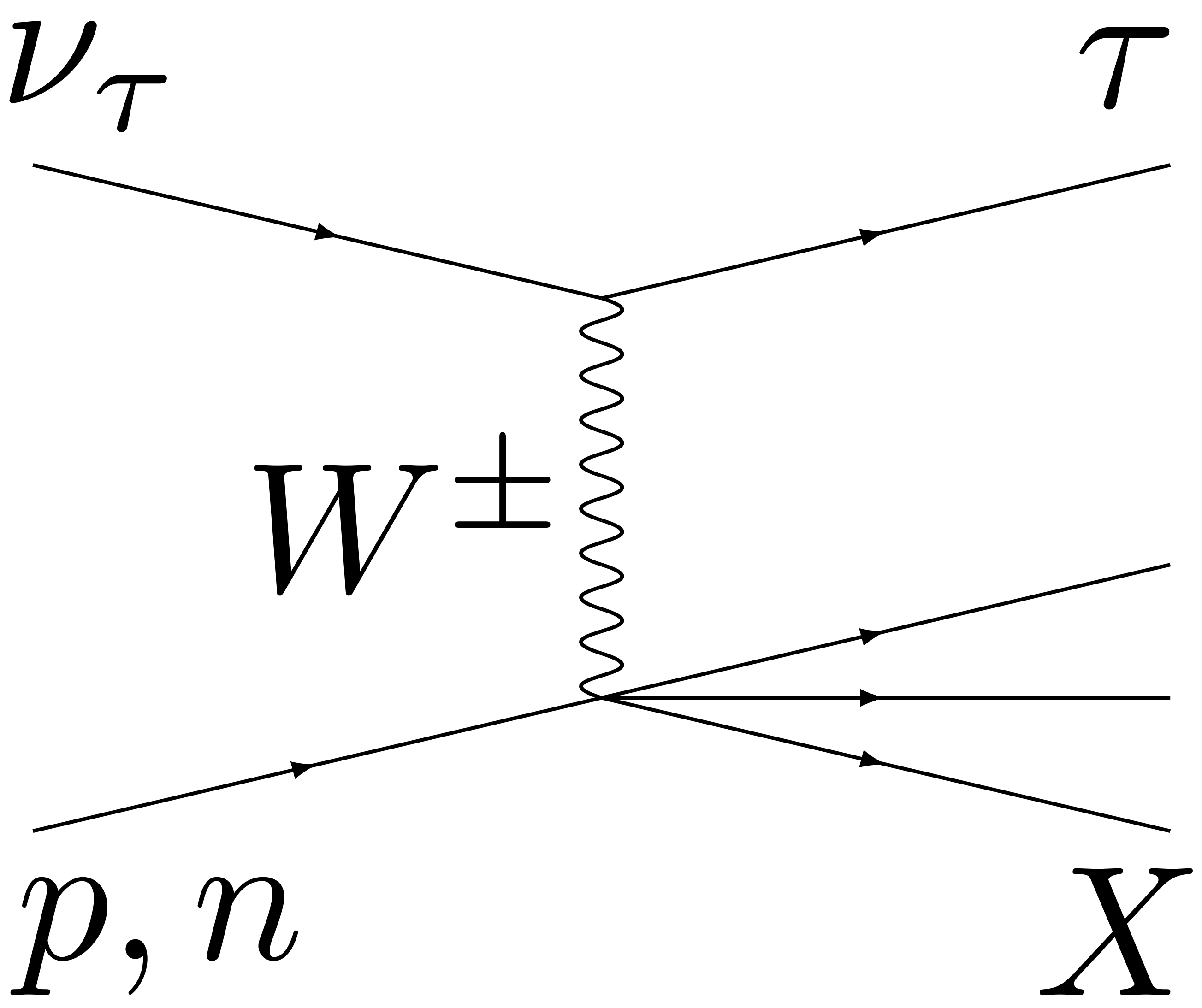
- ν_μ charged current (CC) (ν_τ CC)

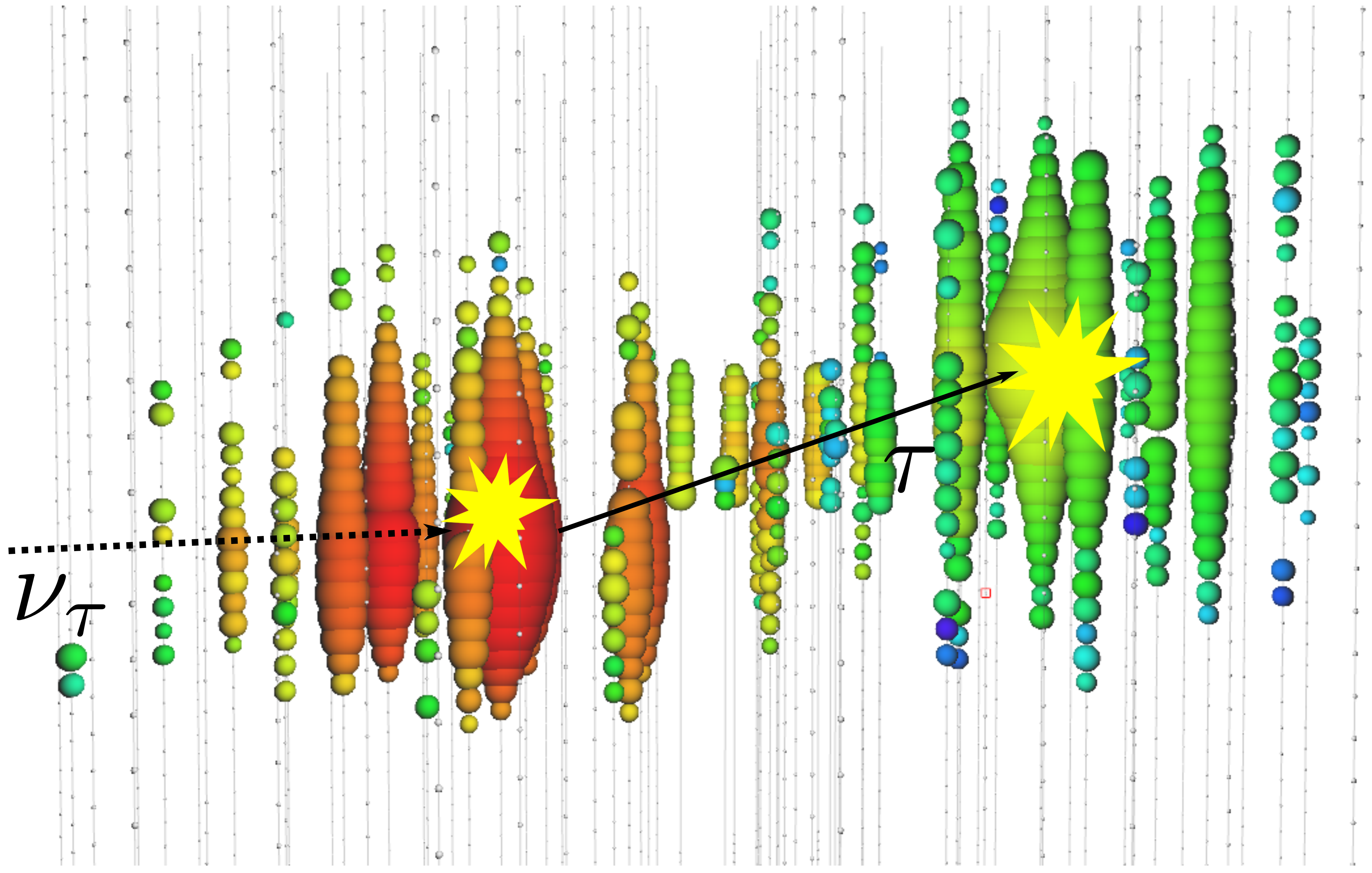




Double bang

- High-E ν_τ charged current (CC)

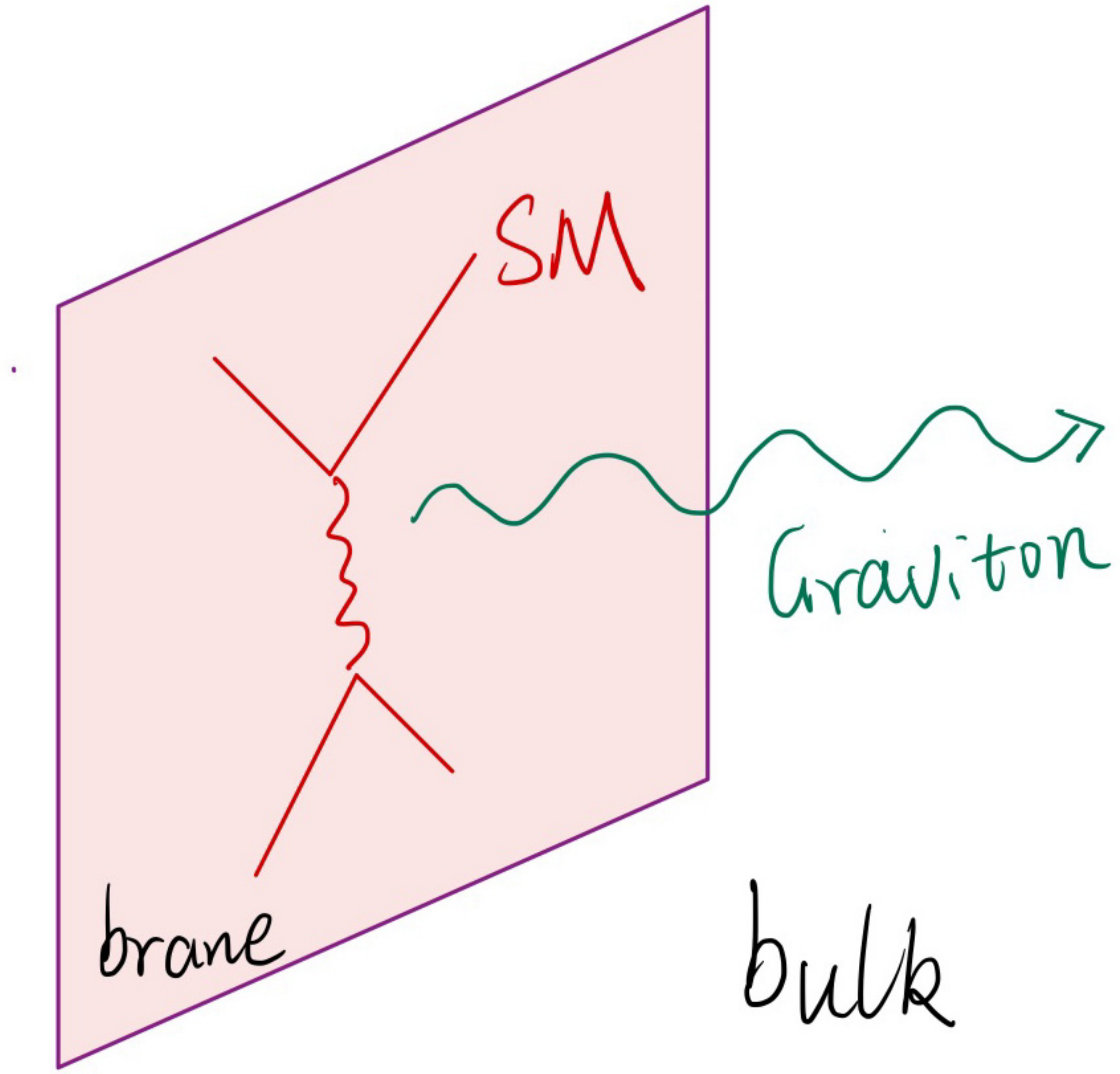




icecube.wisc.edu

Large Extra Dimensions (LEDs)

- SM particles are confined to the 3D "brane"
- Gravitons can propagate in the 3+n D "bulk"



extra dimensions

Arkani-Hamed, Dimopoulos, Dvali, PRD 1998

Large Extra Dimensions (LEDs)

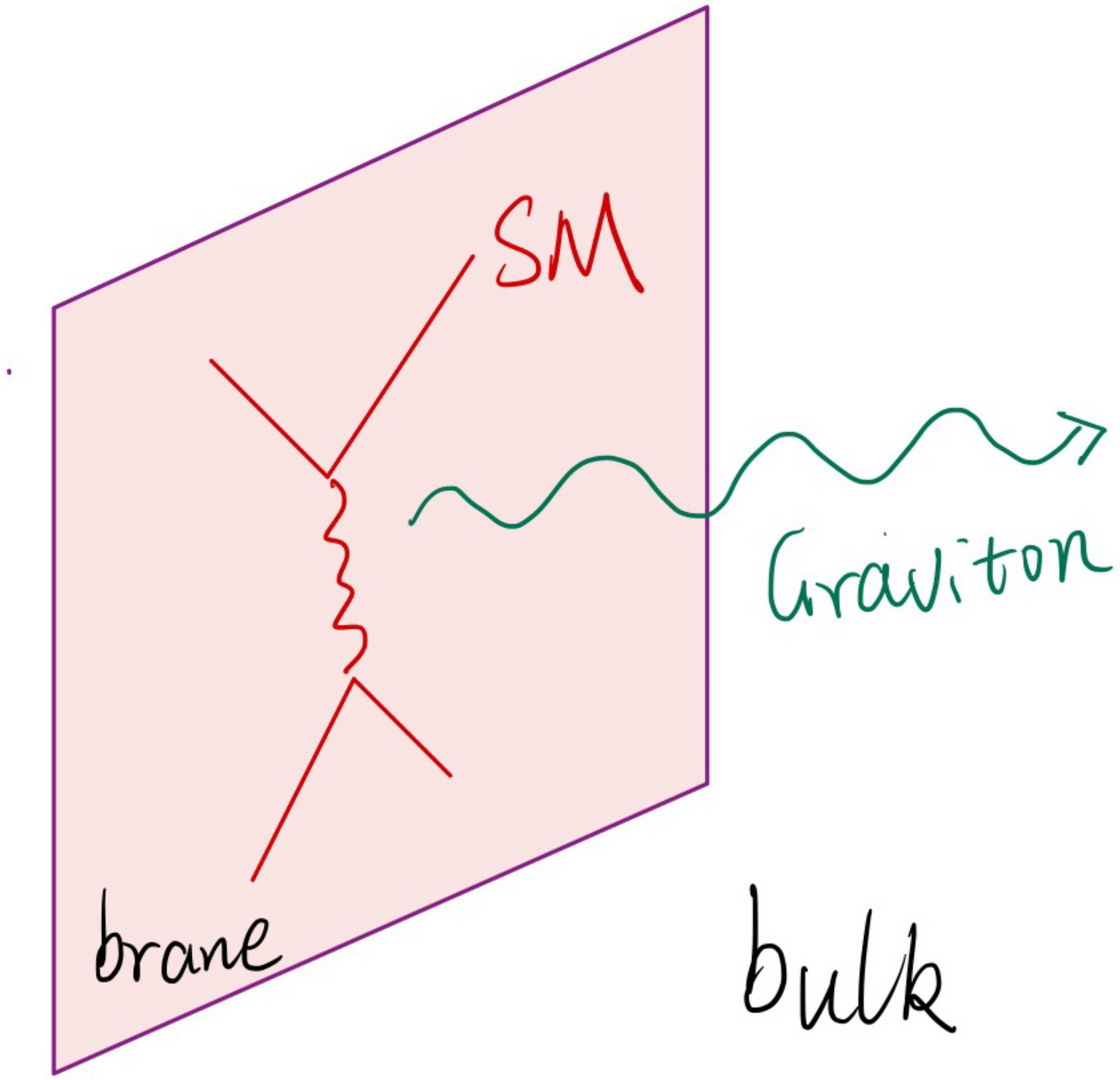
- SM particles are confined to the 3D "brane"
- Gravitons can propagate in the 3+n D "bulk"

Gravitational potential

$$V(r) \sim \frac{m_1 m_2}{M_\star^{n+2}} \frac{1}{r^{n+1}} (r \ll R) \Leftrightarrow V(r) \sim \frac{m_1 m_2}{M_\star^{n+2} R^n} \frac{1}{r} (r \gg R)$$

Match two conditions at $r \sim R$

$$M_{pl}^2 \sim M_\star^{2+n} R^n$$



extra dimensions

Arkani-Hamed, Dimopoulos, Dvali, PRD 1998

Large Extra Dimensions (LEDs)

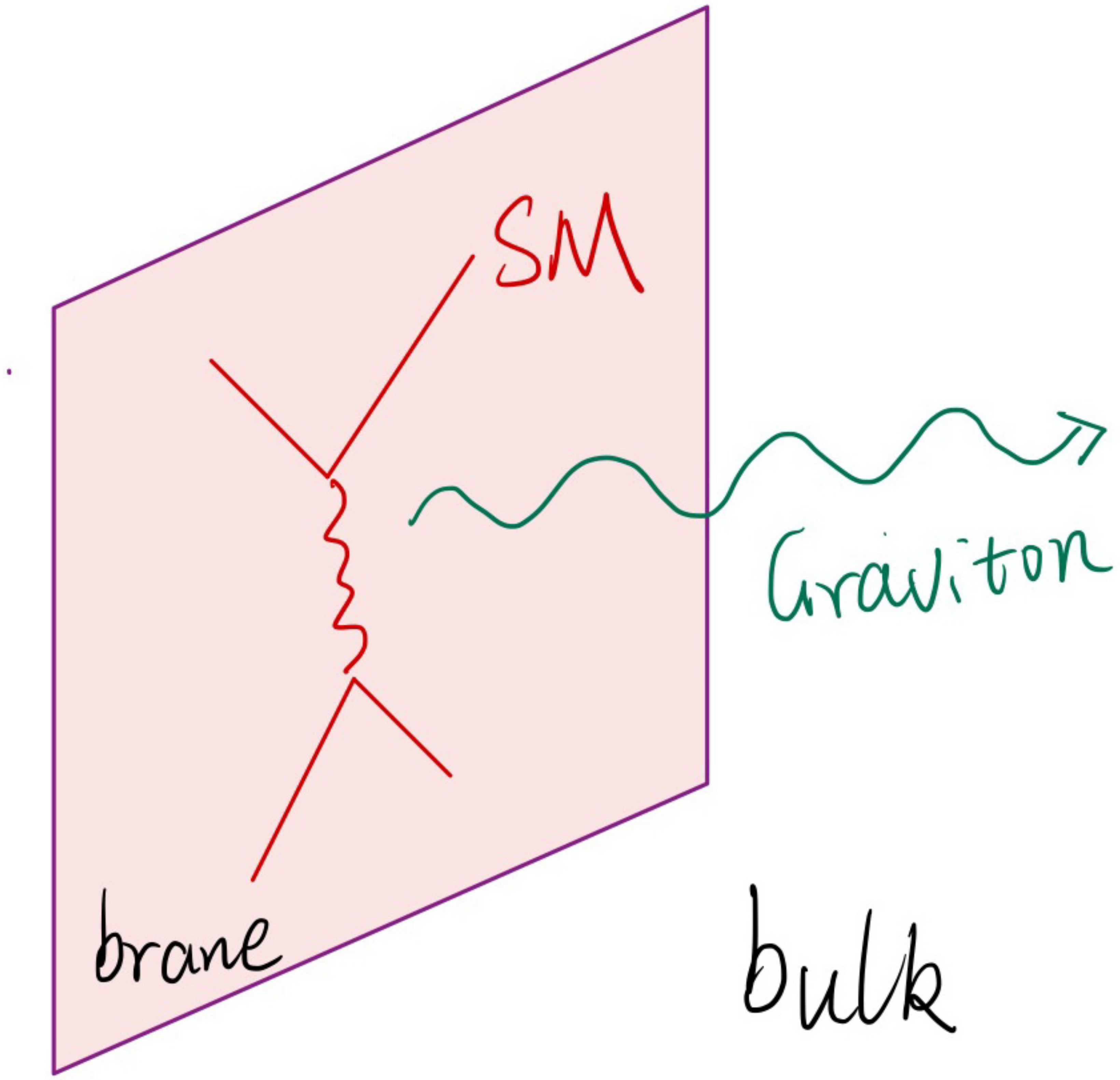
Gravitational potential

$$V(r) \sim \frac{m_1 m_2}{M_\star^{n+2}} \frac{1}{r^{n+1}} (r \ll R) \Leftrightarrow V(r) \sim \frac{m_1 m_2}{M_\star^{n+2} R^n} \frac{1}{r} (r \gg R)$$

Match two conditions at $r \sim R$

$$\boxed{M_{pl}^2 \sim M_\star^{2+n} R^n}$$

- The bulk Planck scale $M_\star \sim \mathrm{TeV} \ll M_{pl}$
- Solve the hierarchy problem



extra dimensions

Arkani-Hamed, Dimopoulos, Dvali, PRD 1998