Probing ν_τ Disappearance in SHiP Experiment

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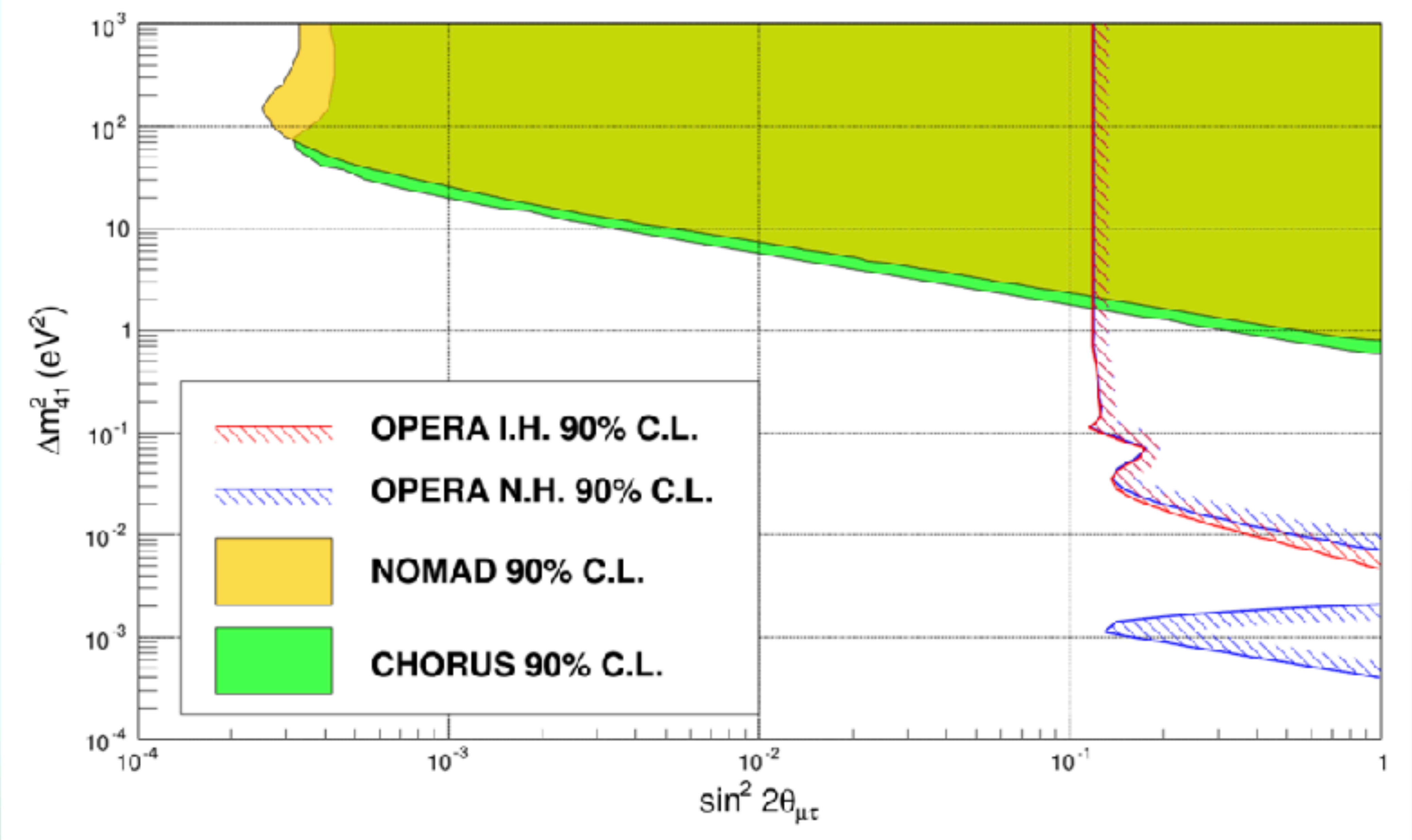
Bound on $4|U_{\mu 4}|^2|U_{\tau 4}|^2 = \sin^2 2\theta_{\mu\tau}$



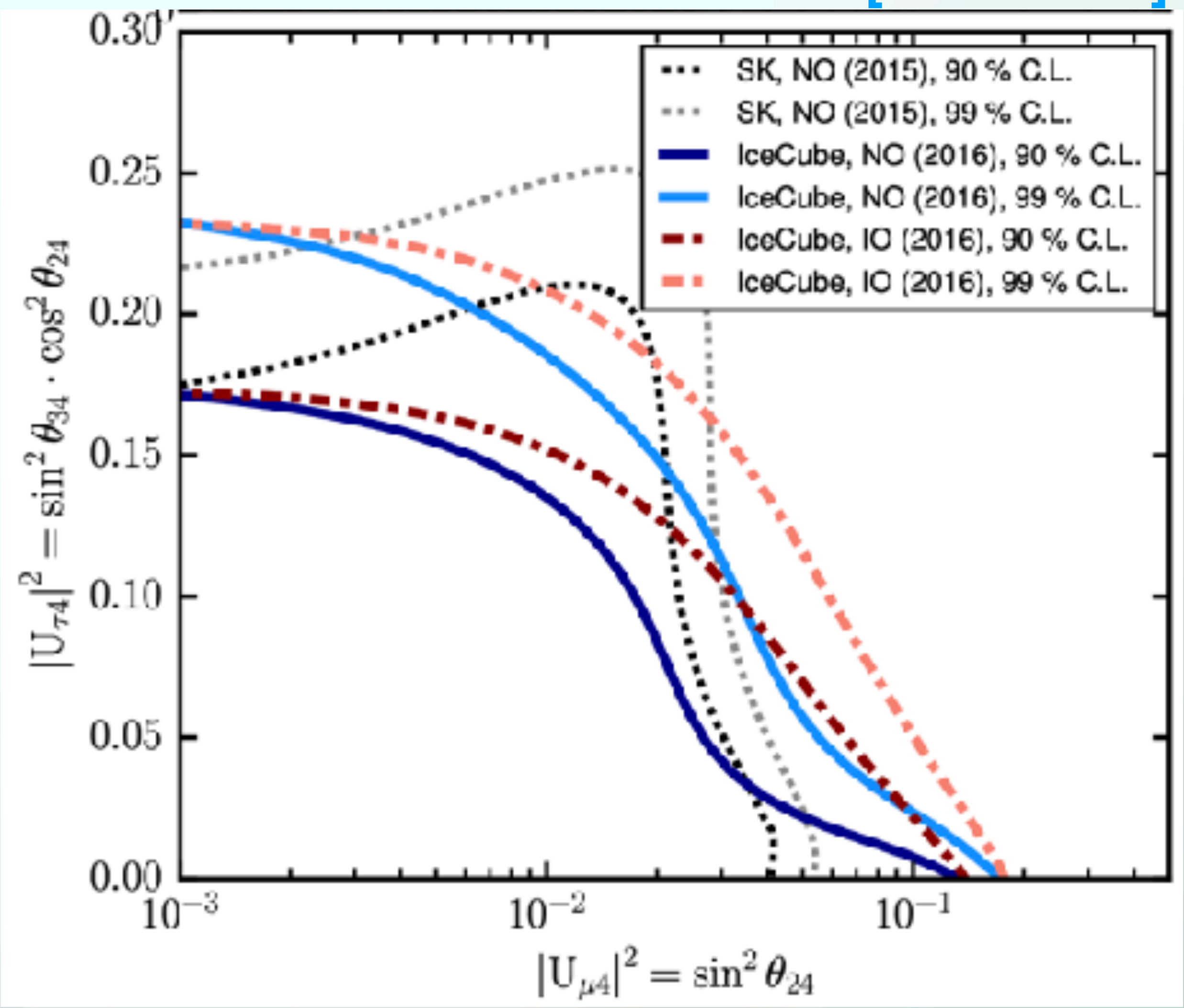
CHORUS & NOMAD:
$\sin^2 2\theta_{\mu\tau} \lesssim 3 \times 10^{-4}$

OPERA:
$\sin^2 2\theta_{\mu\tau} \lesssim 0.1$

Bound on $|U_{\tau 4}|^2$

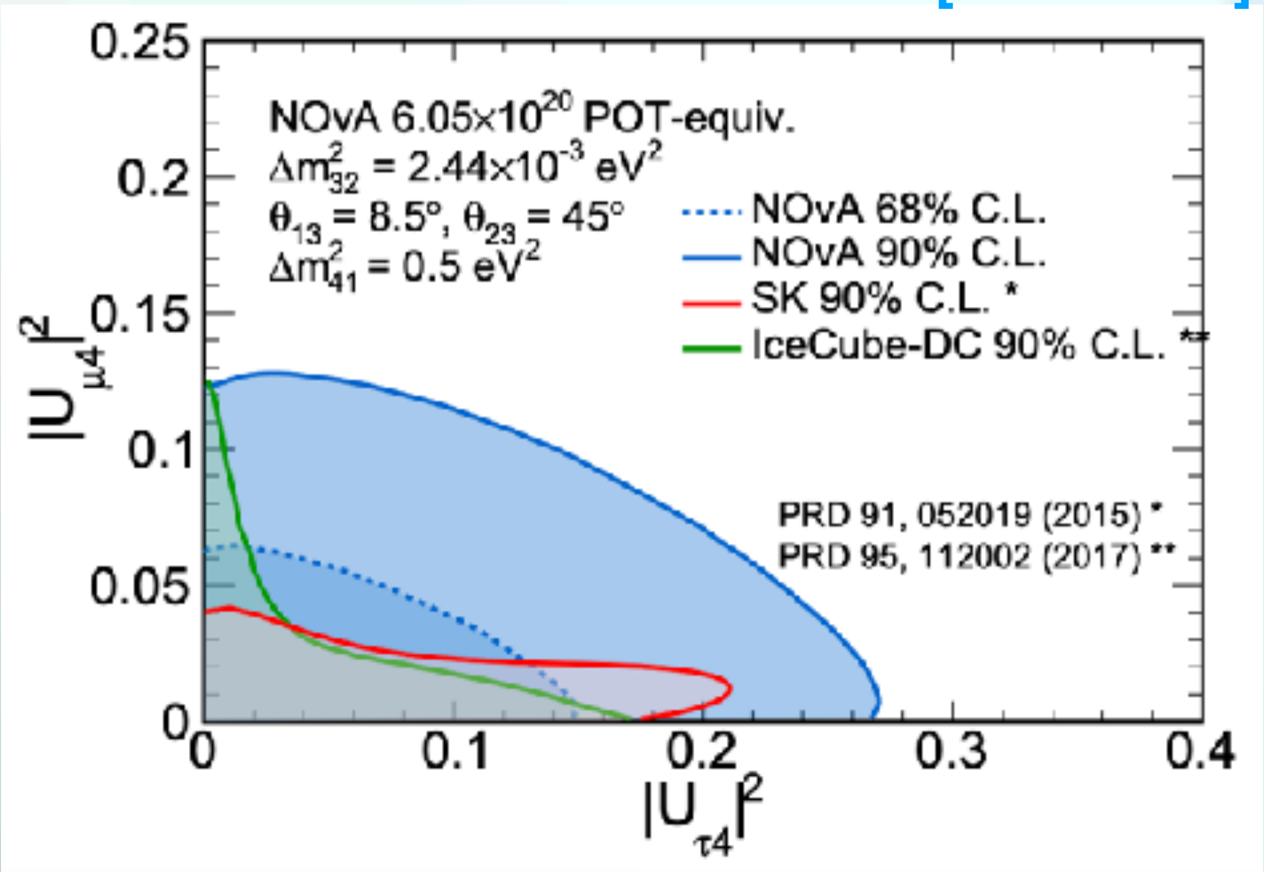
Atmospheric neutrinos

[1702.05160]



Accelerator based,
Neutral current

[1706.04592]



$$|U_{\tau 4}|^2 \lesssim 0.15$$

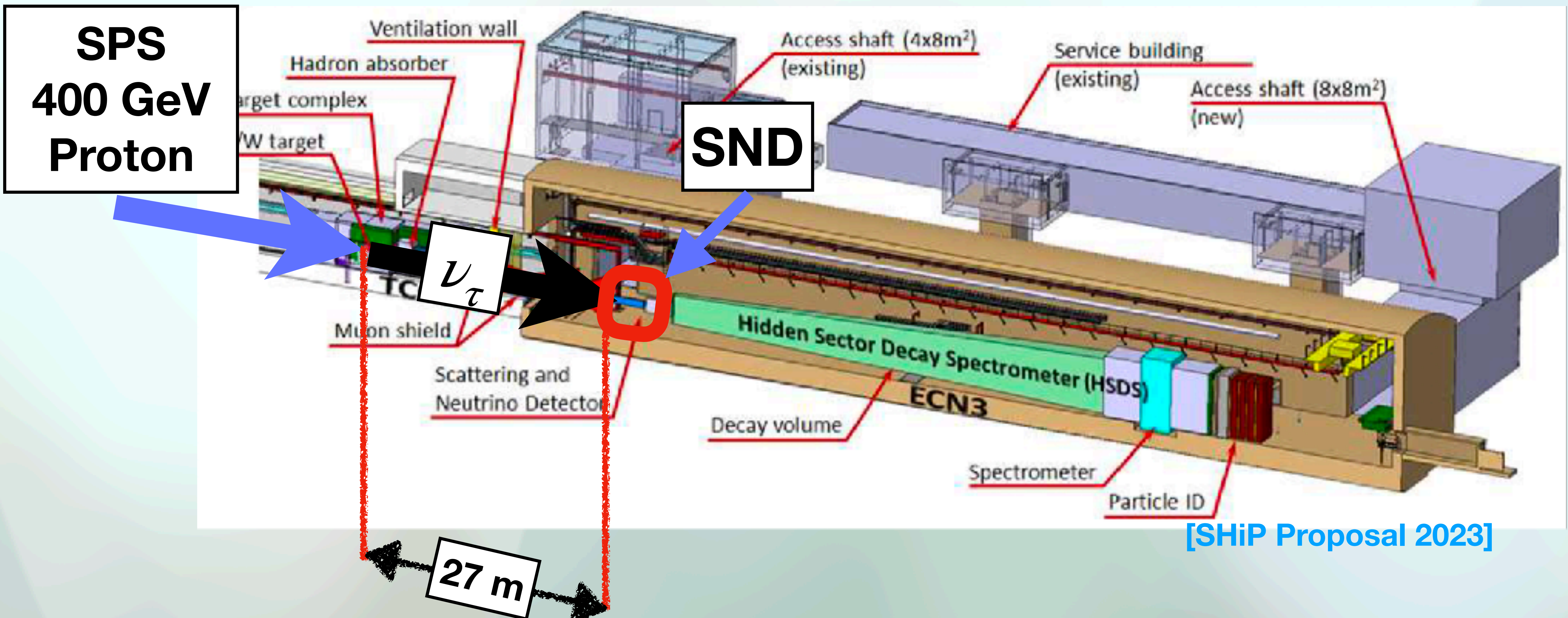
ν_τ Disappearance?

- # of ν_τ CC events from CHORUS/NOMAD/DONUT/OPERA is in total 19, which is not enough to detect ν_τ disappearance.

- However in SHiP experiment, $\sim 10^4$ tau neutrino CC events are expected to be seen.

➡Enough to measure ν_τ disappearance.

SHiP as $\nu_\tau - \nu_s$ Mixing Prober

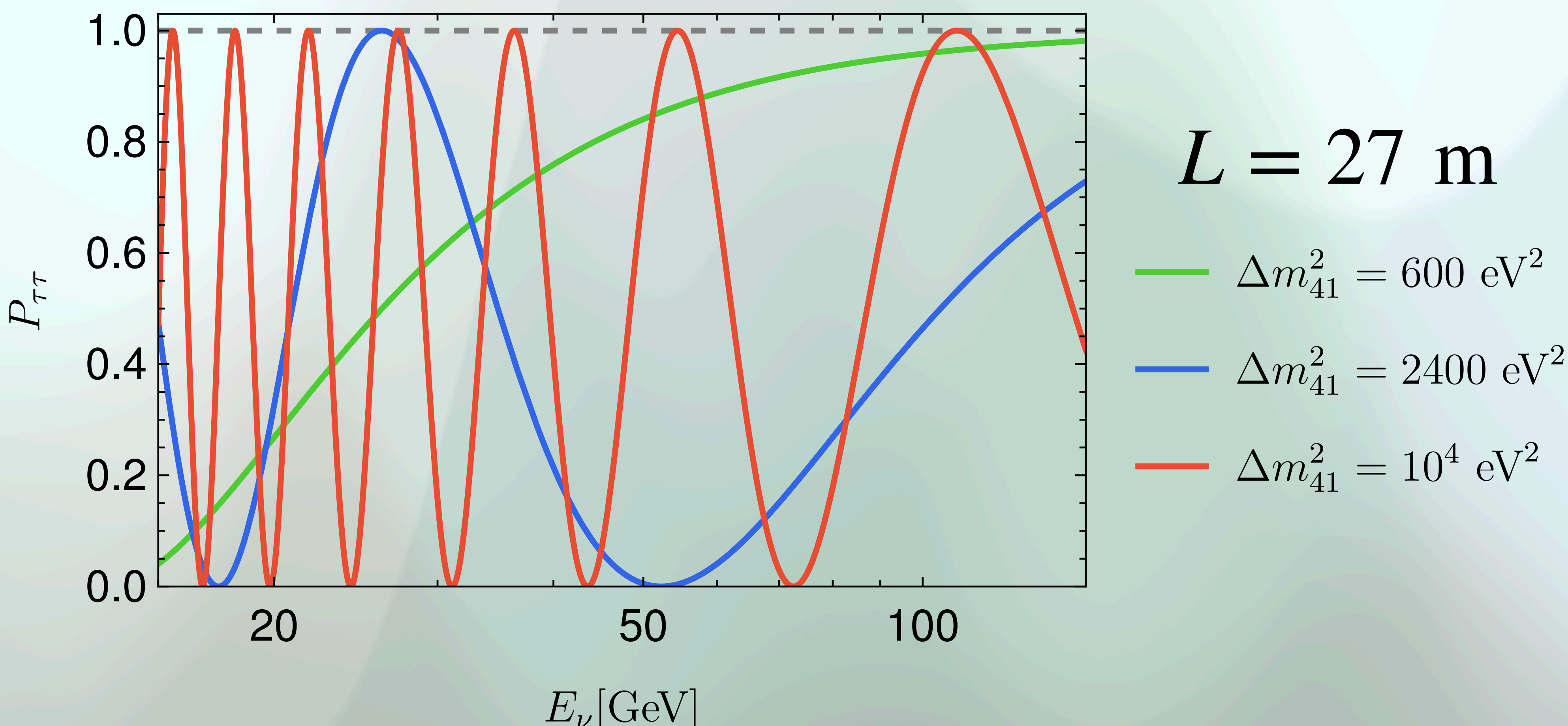


[SHiP Proposal 2023]

ν Oscillation in SHiP Experiment

- For the survival probability of tau neutrinos $P_{\tau\tau}$,

$$P_{\tau\tau} = 1 - 4(|U_{\tau 4}|^2 - |U_{\tau 4}|^4)\sin^2 \frac{\Delta m_{41}^2 L}{4E_\nu}.$$



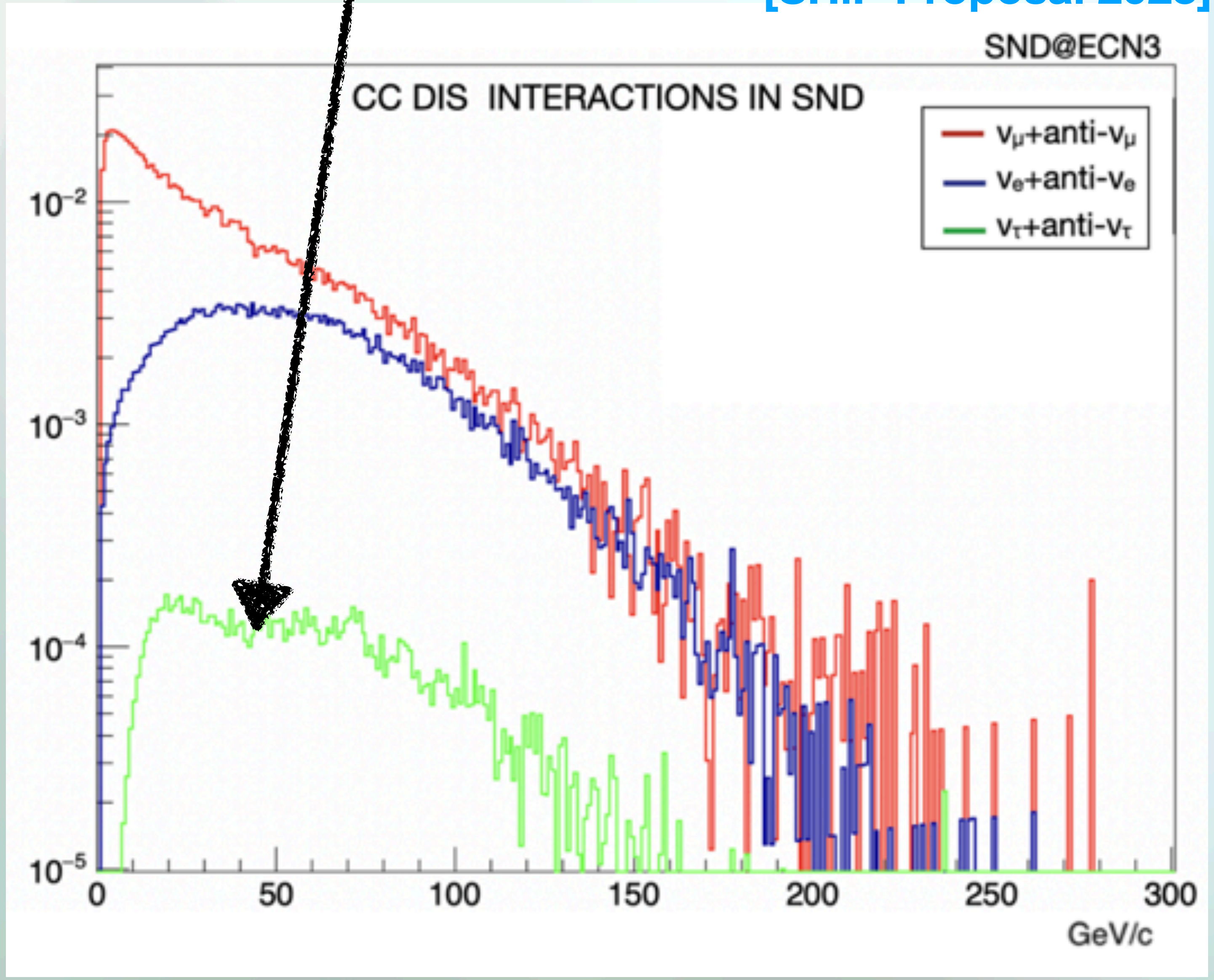
How to Estimate the # of Event

- $$\frac{d^2N}{dE_\nu dl} = P_{\tau\tau}(E_\nu, l)\boxed{\epsilon_{\rm eff}}\boxed{n_{\rm W}\frac{L_{\rm W}}{L_{\rm SND}}\left(\phi_{\nu_\tau}\sigma_{\nu_\tau A} + \phi_{\bar{\nu}_\tau}\sigma_{\bar{\nu}_\tau A}\right)}$$

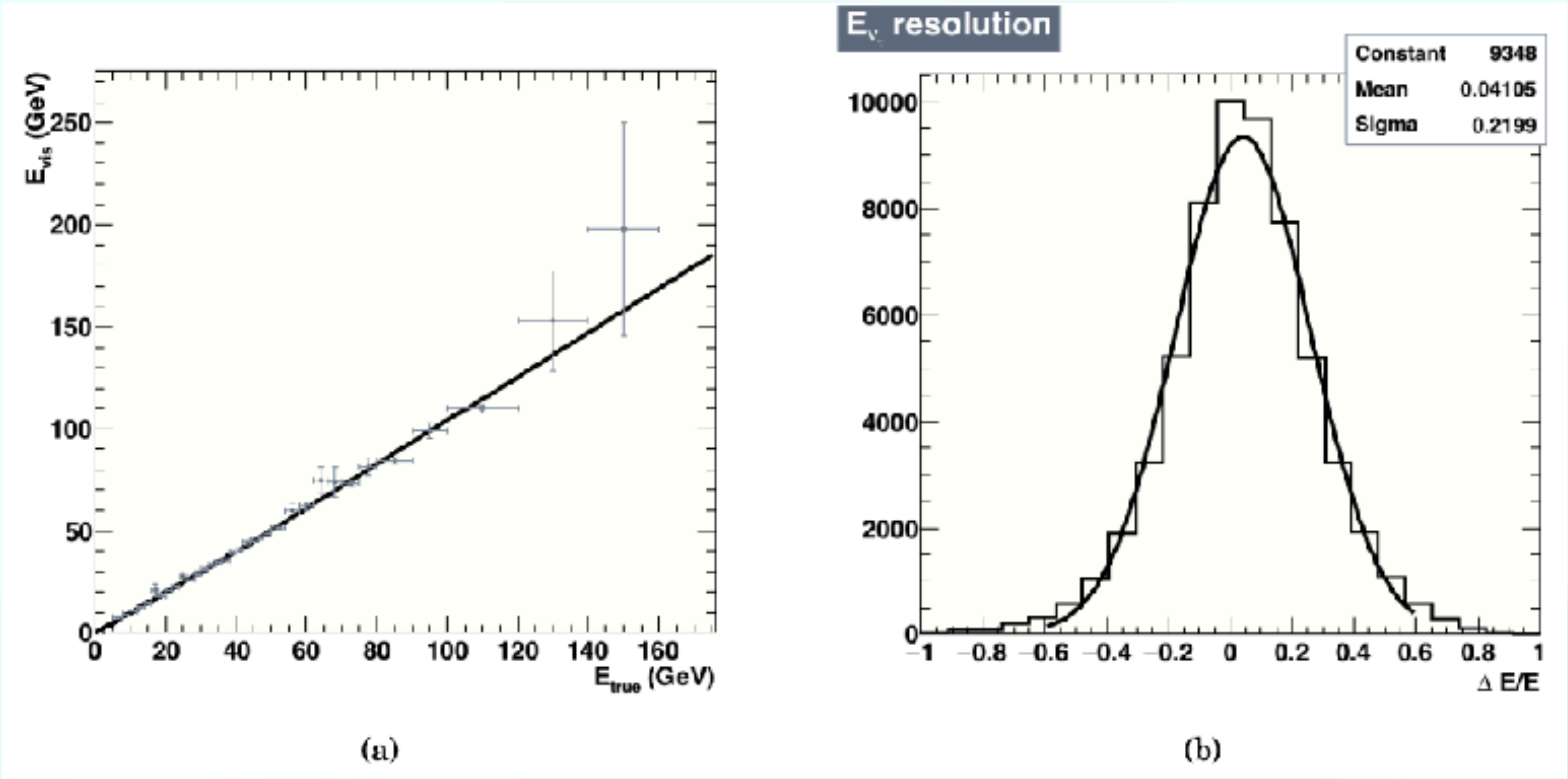
$15\,\%$, Flat

In the recent proposal,
$\epsilon_{\rm eff}$ is proposed as 30%.

[SHiP Proposal 2023]



Uncertainty of Reconstructed E



[CERN-THESIS-2017-064]

$$\frac{dN}{dE_{\mathrm{rec}}} = \int \boxed{P(E_{\mathrm{rec}} \mid E_\nu)} \frac{dN}{dE_\nu} dE_\nu$$

Gaussian response function, ~20% resolution

Uncertainties of ν_τ CC Events

- # of events at bin i:

$$\mu_i = (1 + A + \alpha_i)s_i + (1 + B + \beta_i)b_i,$$

(Signal) (Background)

$$s_i \equiv \int_{E_i^{\min}}^{E_i^{\max}} \frac{dN}{dE_{\rm rec}} dE_{\rm rec}.$$

- Signal-to-background ratio $R_{s/b}$ is assumed to be the constant over E_ν. $\Rightarrow$ $b_i = s_i(|U_{\tau 4}|^2 = 0)/R_{s/b}$

- In this study, we chose $R_{s/b} = 10$ or 1.

Uncertainties of ν_τ CC Events

- # of events at bin i:

$$\mu_i = (1 + A + \alpha_i)s_i + (1 + B + \beta_i)b_i$$

(Signal) (Background)

- Distributions of nuisance parameters follow a normal distribution.

- A, B, α_i, β_i mimics the uncertainty from parton distributions, scale factors, and other experimental uncertainties.

- $\sigma_A = \sigma_B = \sigma_{\alpha_i} = \sigma_{\beta_i} = \sigma_{\mathrm{norm}}$

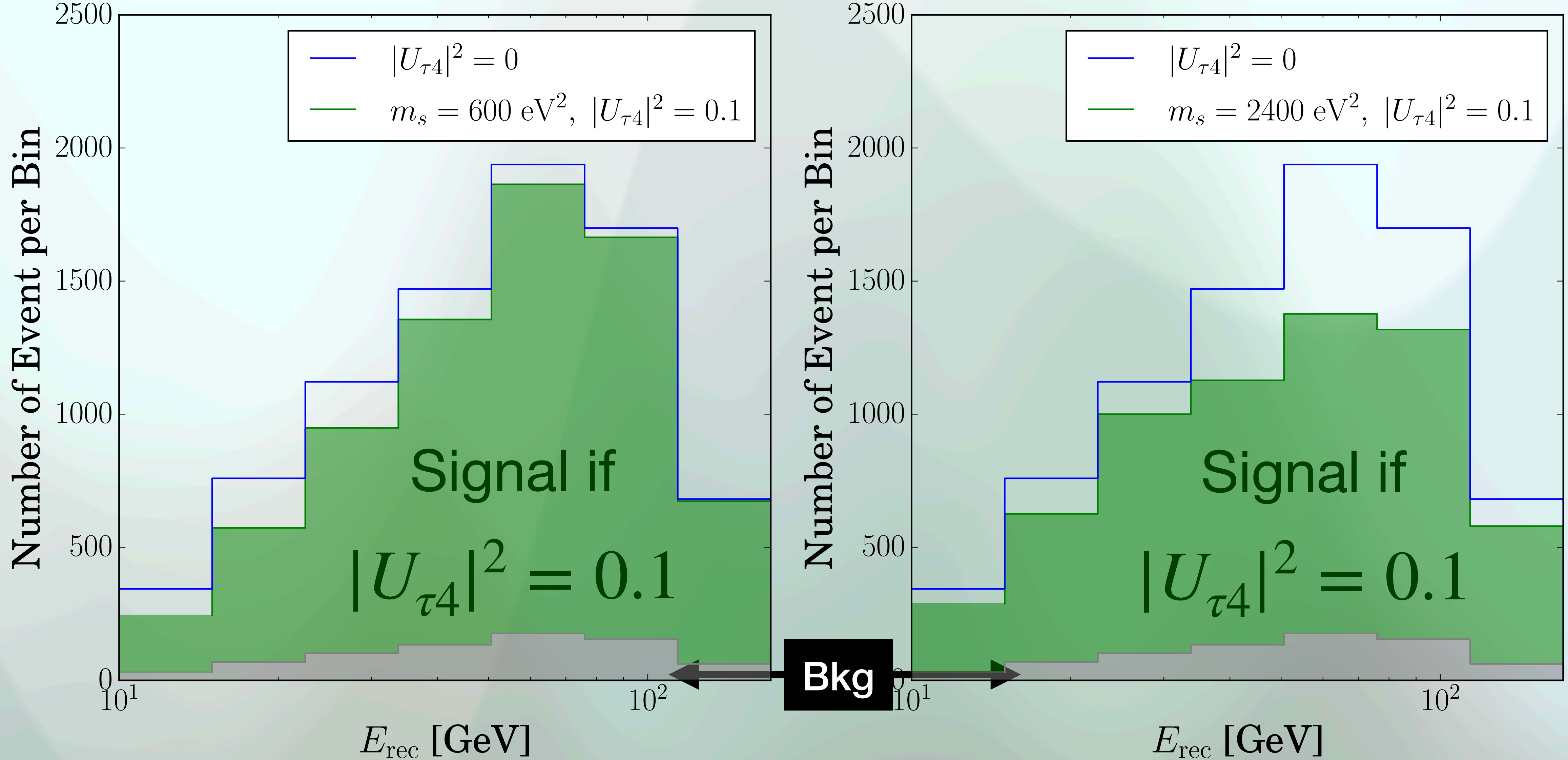
- Estimated sensitivities are shown with $\sigma_{\mathrm{norm}} = 20\,\%$ and $\sigma_{\mathrm{norm}} = 10\,\%$ cases.

Choice of Energy Bin

Total # of events: ~7300 events in 5 years w/o bkg.

$$R_{s/b} = 10,\ A = B = \alpha_i = \beta_i = 0$$

$\Delta m^2_{41} = 600\ \mathrm{eV}^2$ $\Delta m^2_{41} = 2400\ \mathrm{eV}^2$



Profiled FC Method [2207.14353]

$$\Delta\chi^2(O) = -2\log\frac{\max_{\phi}[L(\theta,\phi \mid O)]}{\max_{\theta,\phi}[L(\theta,\phi \mid O)]}$$

1. Generate MC data on each point of θ, assuming $\hat{\hat{\phi}}$.

$$\hat{\hat{\phi}} \equiv \mathrm{argmin}_{\phi}[L(\theta,\phi \mid O_{\mathrm{data}})]$$

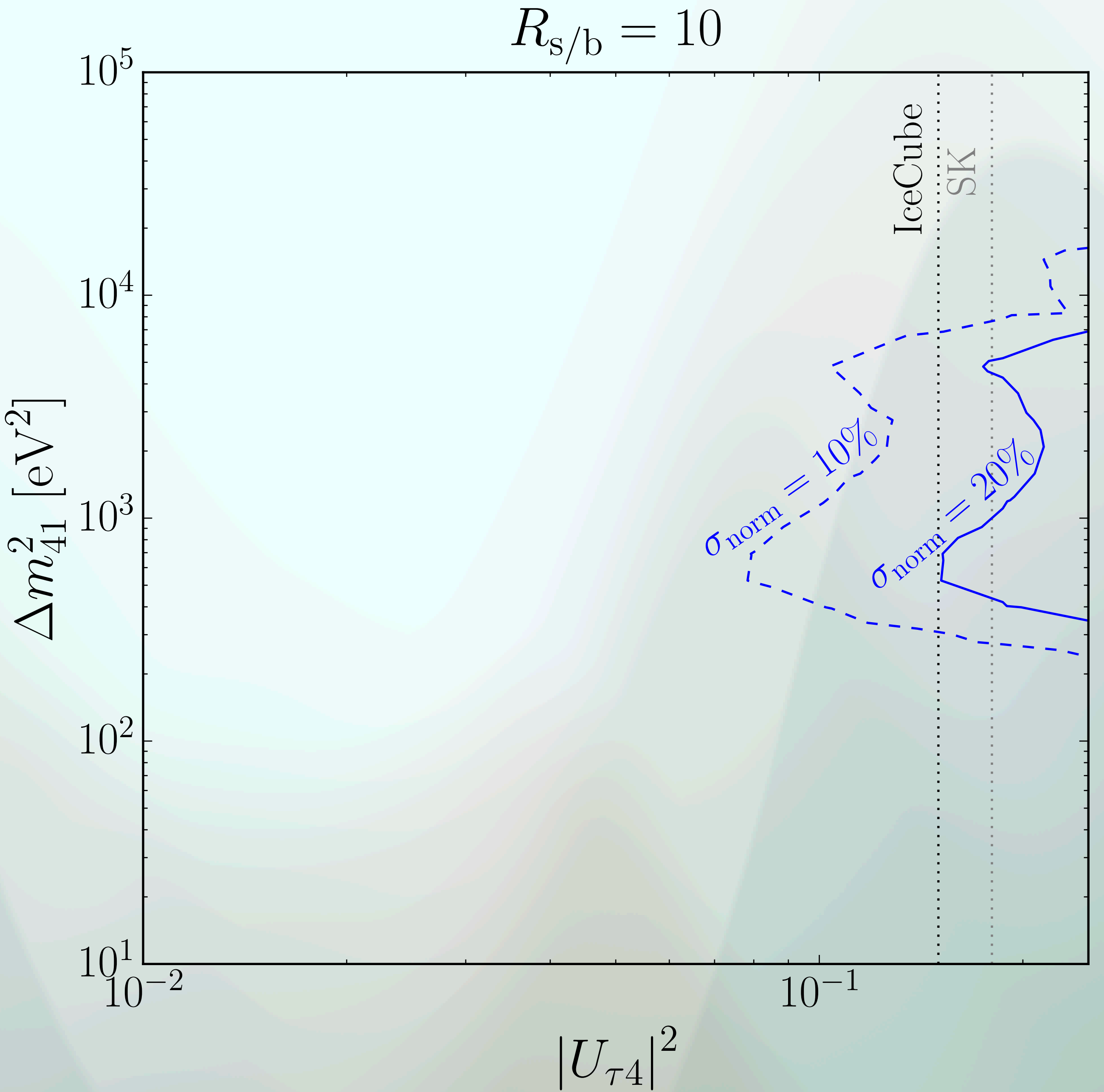
2. On a given MC data, find the distribution of $\Delta\chi^2$.

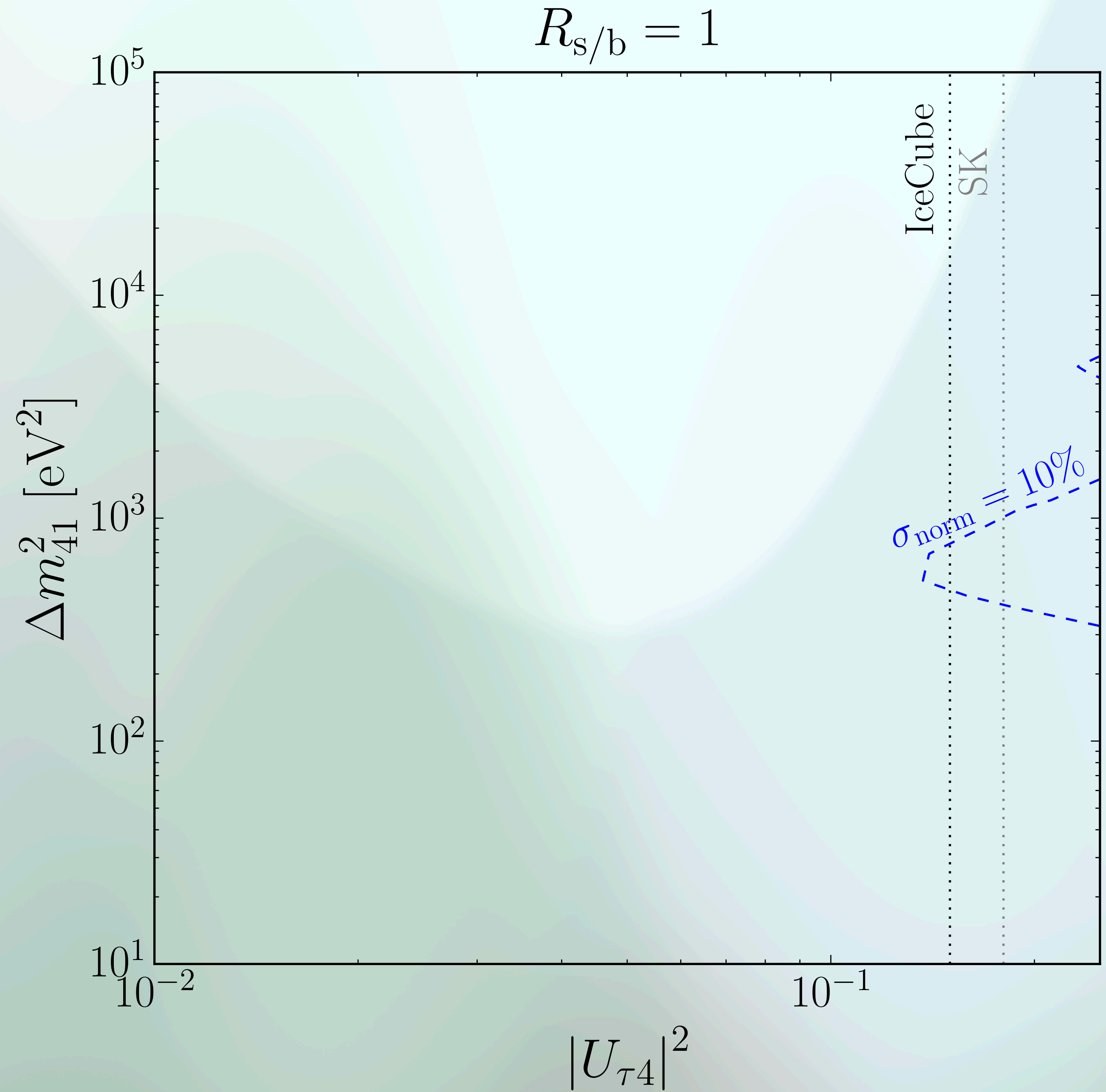
3. Find the PDF of $\Delta\chi^2$, *i.e.* $f(x)$.

$$\mathrm{CL} = \int_0^{\Delta\chi^2(O_{\mathrm{data}})} f(x)dx$$

90% Confidence Level of SHiP

O_{data} is assumed as the most-probable case, $O_{3\nu}$.



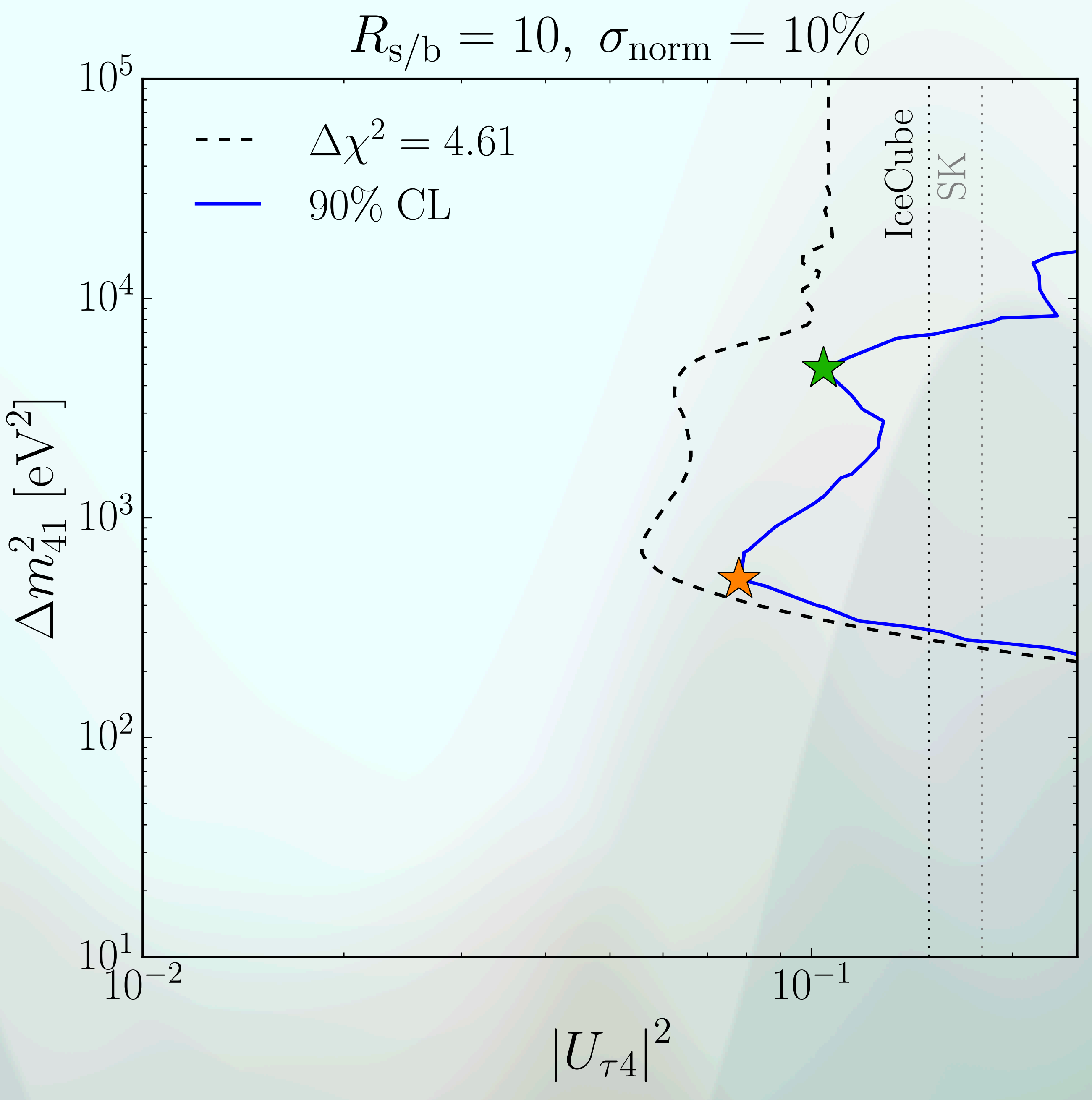


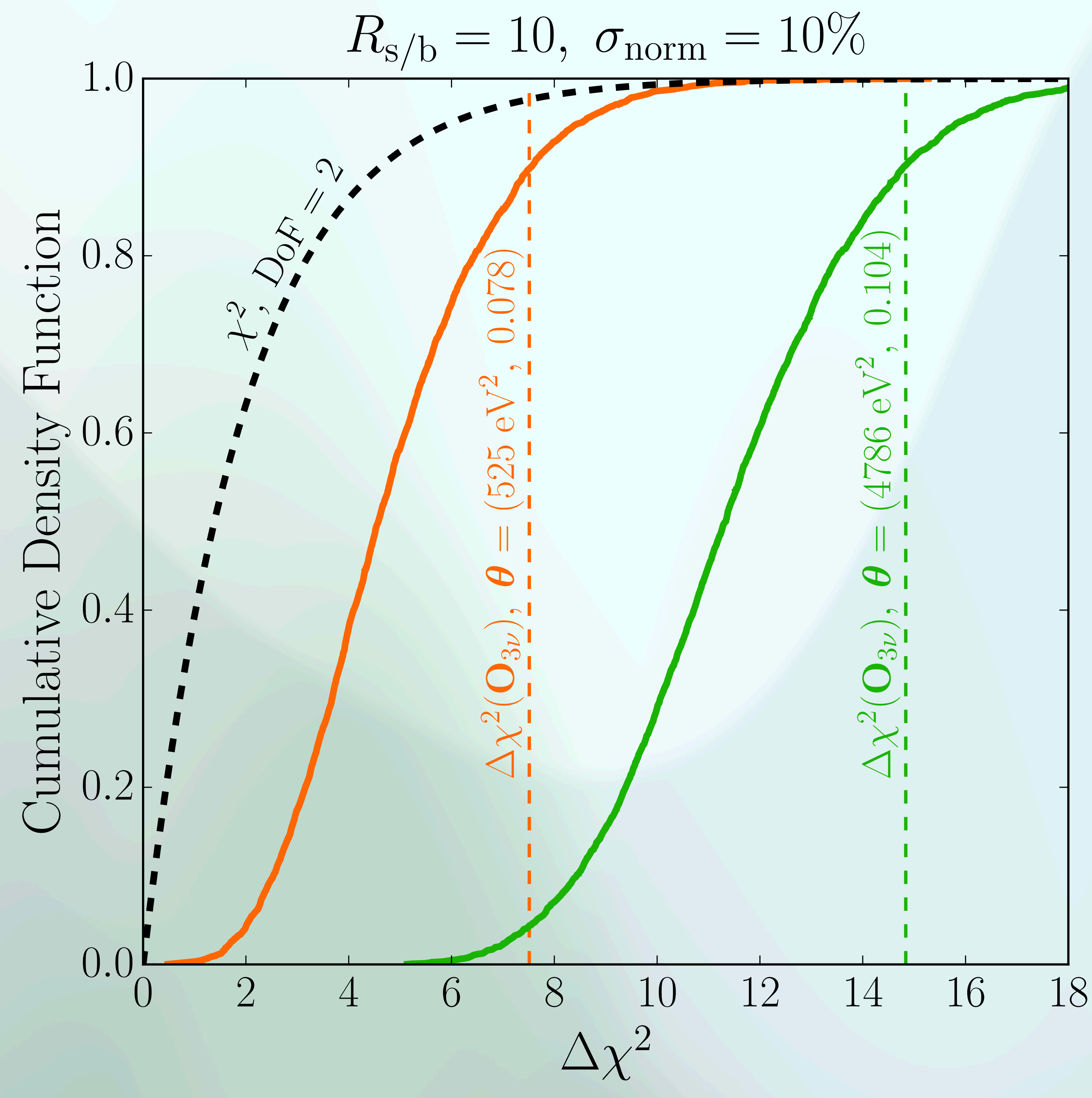
Wilks' Theorem

$$\Delta\chi^2(O) = -2\log\frac{\max_{\phi}[L(\theta,\phi\mid O)]}{\max_{\theta,\phi}[L(\theta,\phi\mid O)]}$$

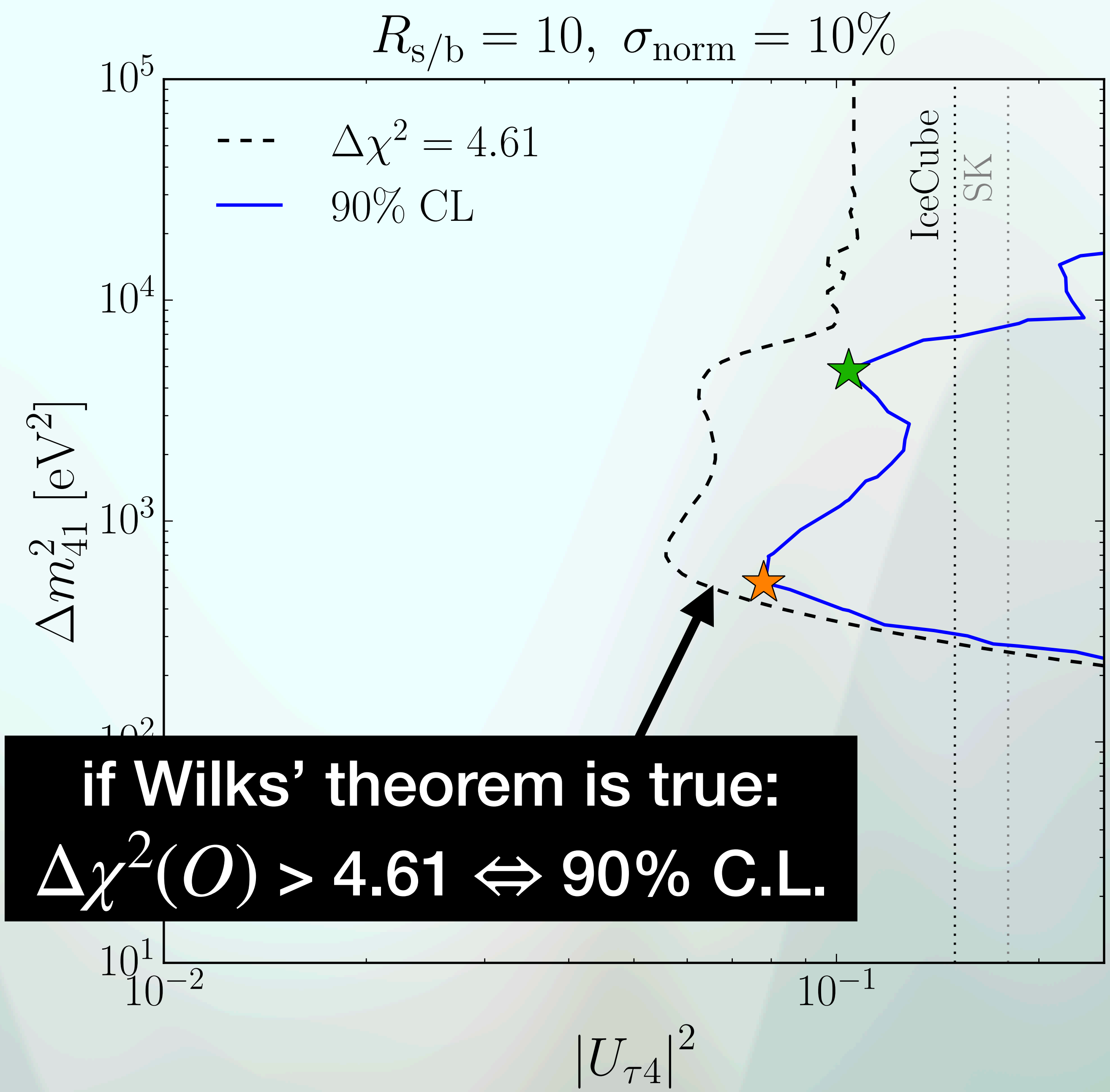
- The Wilks' theorem states that $\Delta\chi^2(O)$ follows the χ^2 distributions on n DoF if…
  - Null hypothesis is the special case of alternative hypothesis, with less DoF,
  - and $\Delta\chi^2(O)$ follows a ellipsoidal distribution under additional DoF (in the case above, additional freedom is θ).

Validity of Wilks' Theorem

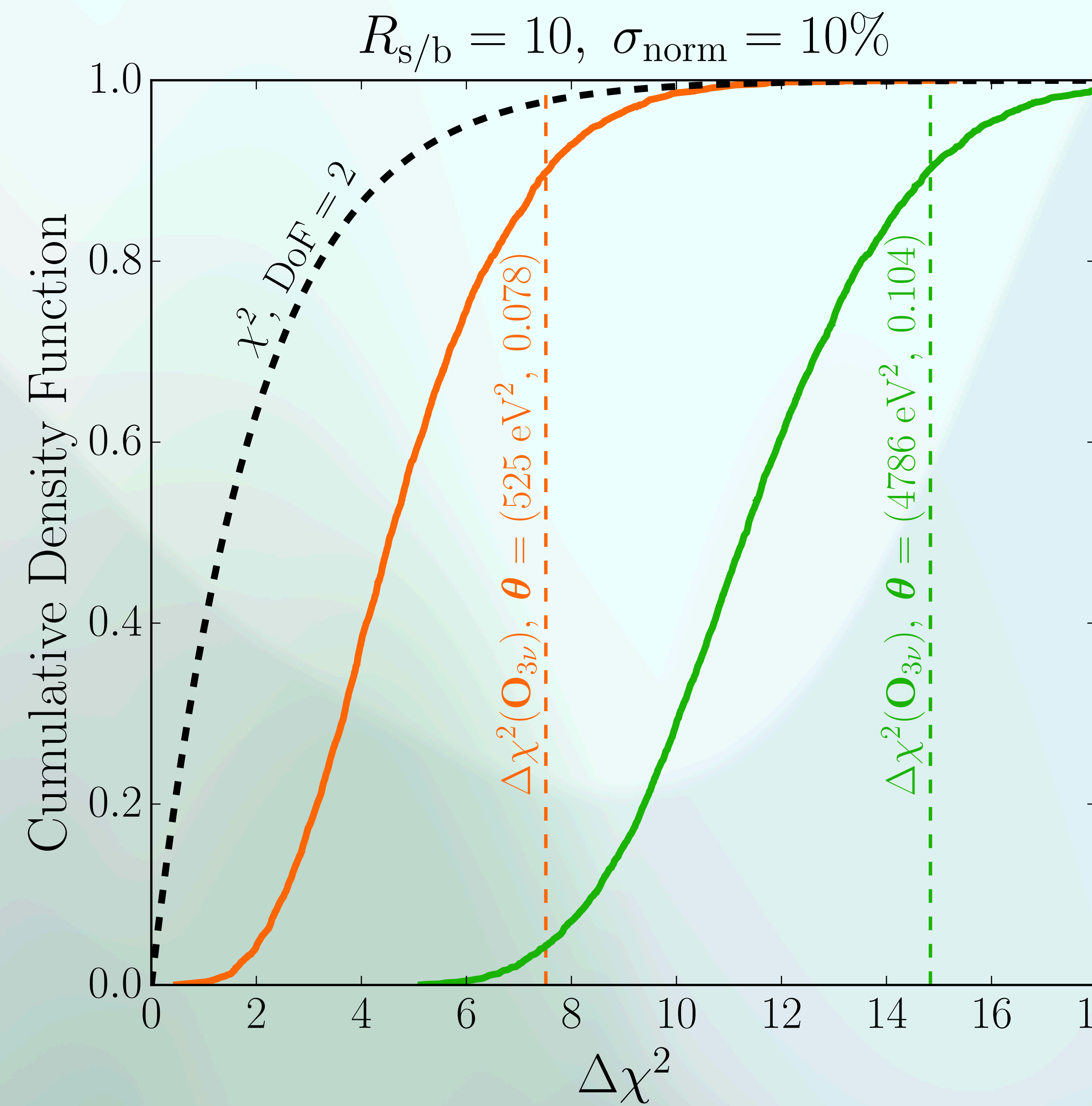




Validity of Wilks' Theorem



if Wilks' theorem is true:
$\Delta\chi^2(O)$ > 4.61 ⇔ 90% C.L.



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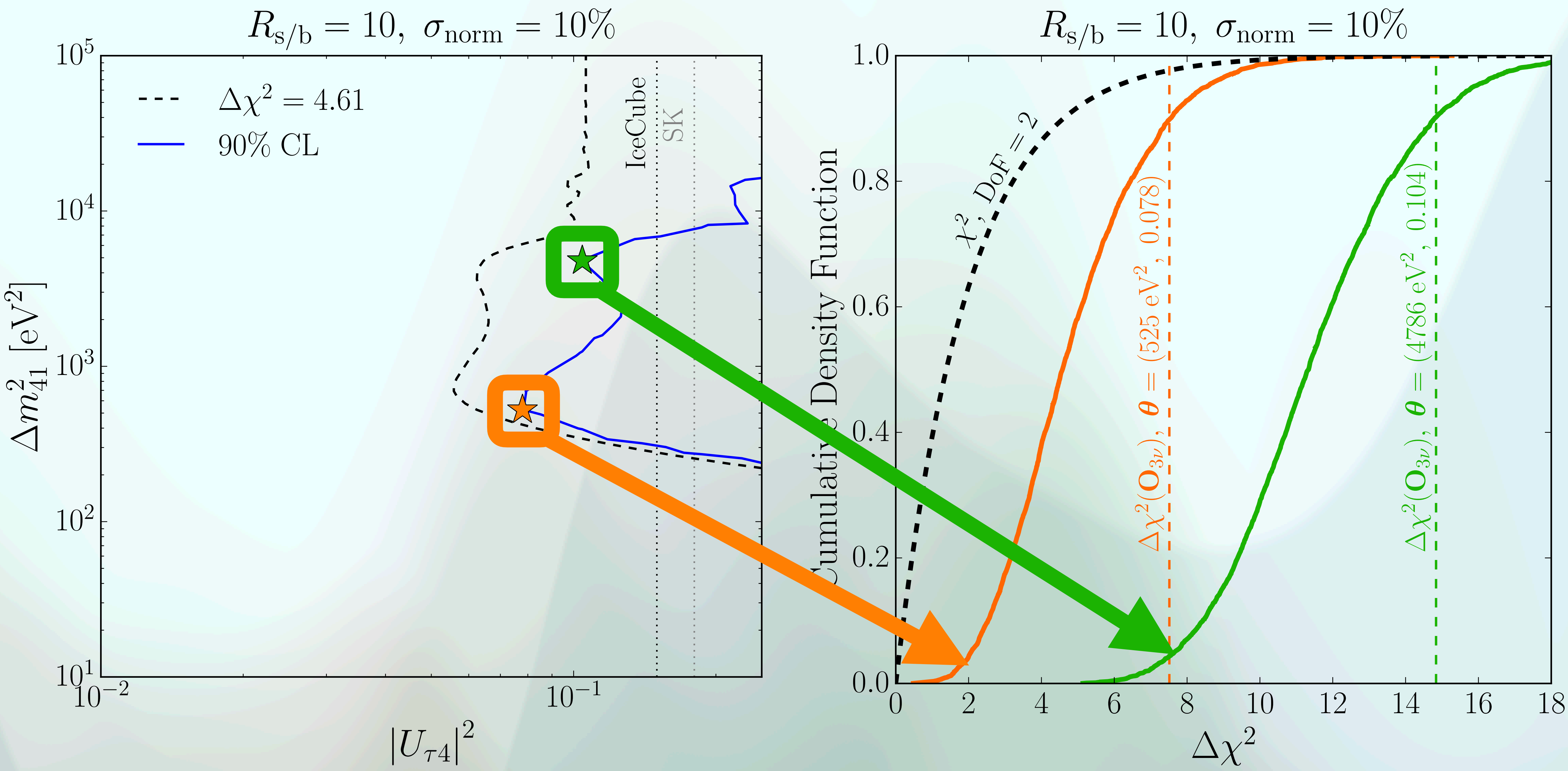
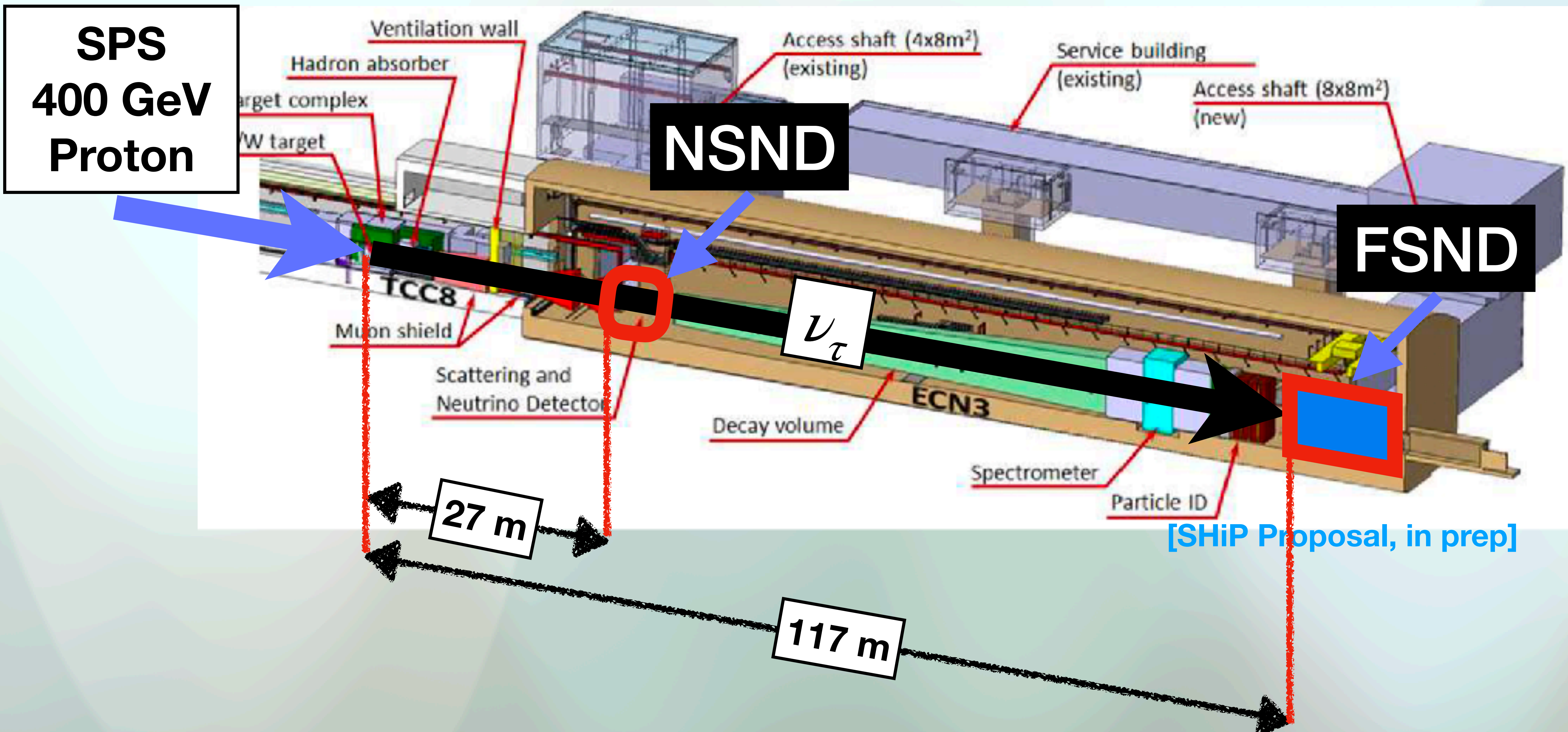


Far SND(FSND) after HSDS



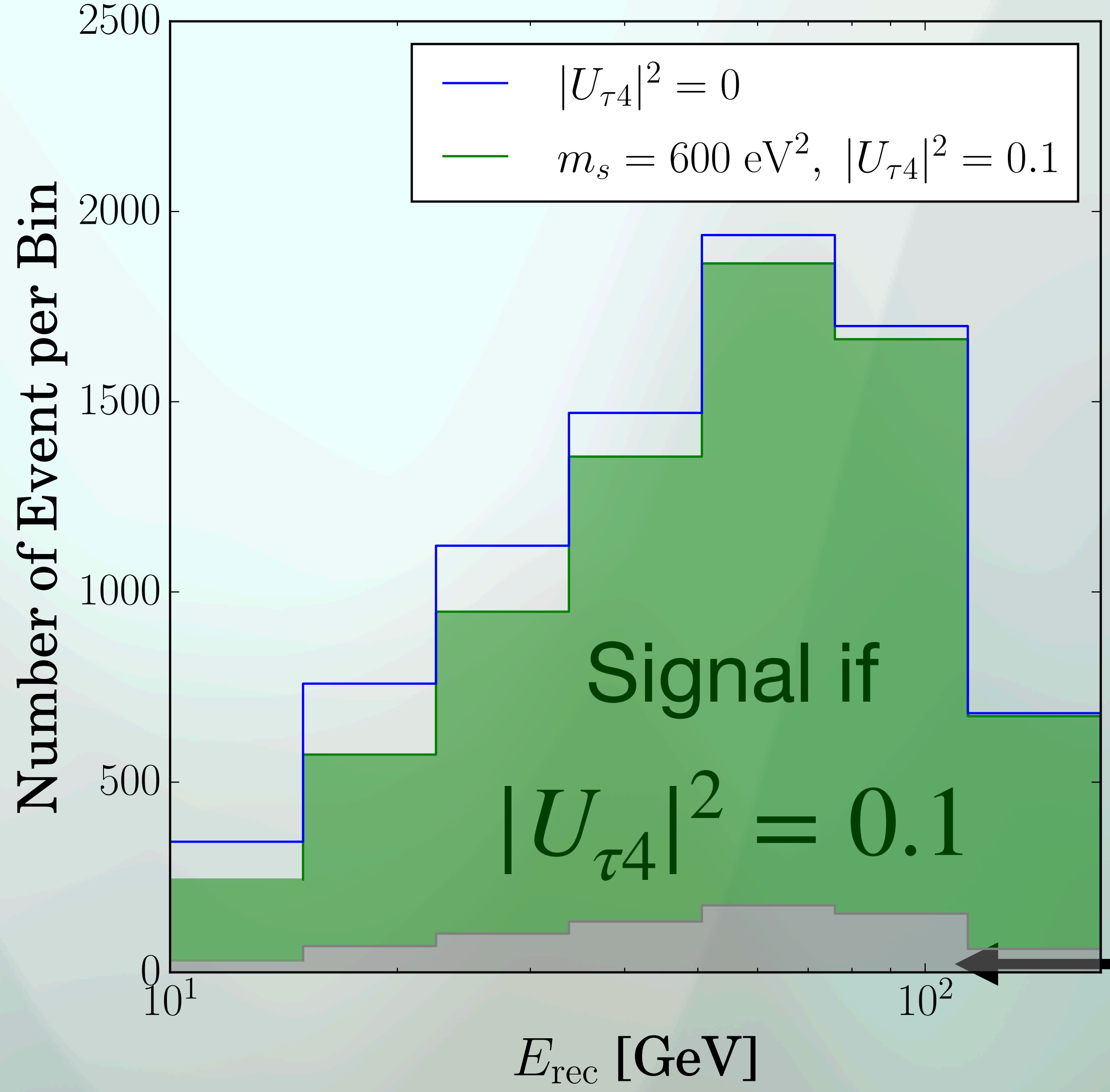
[SHiP Proposal, in prep]

Event Rate at FSND

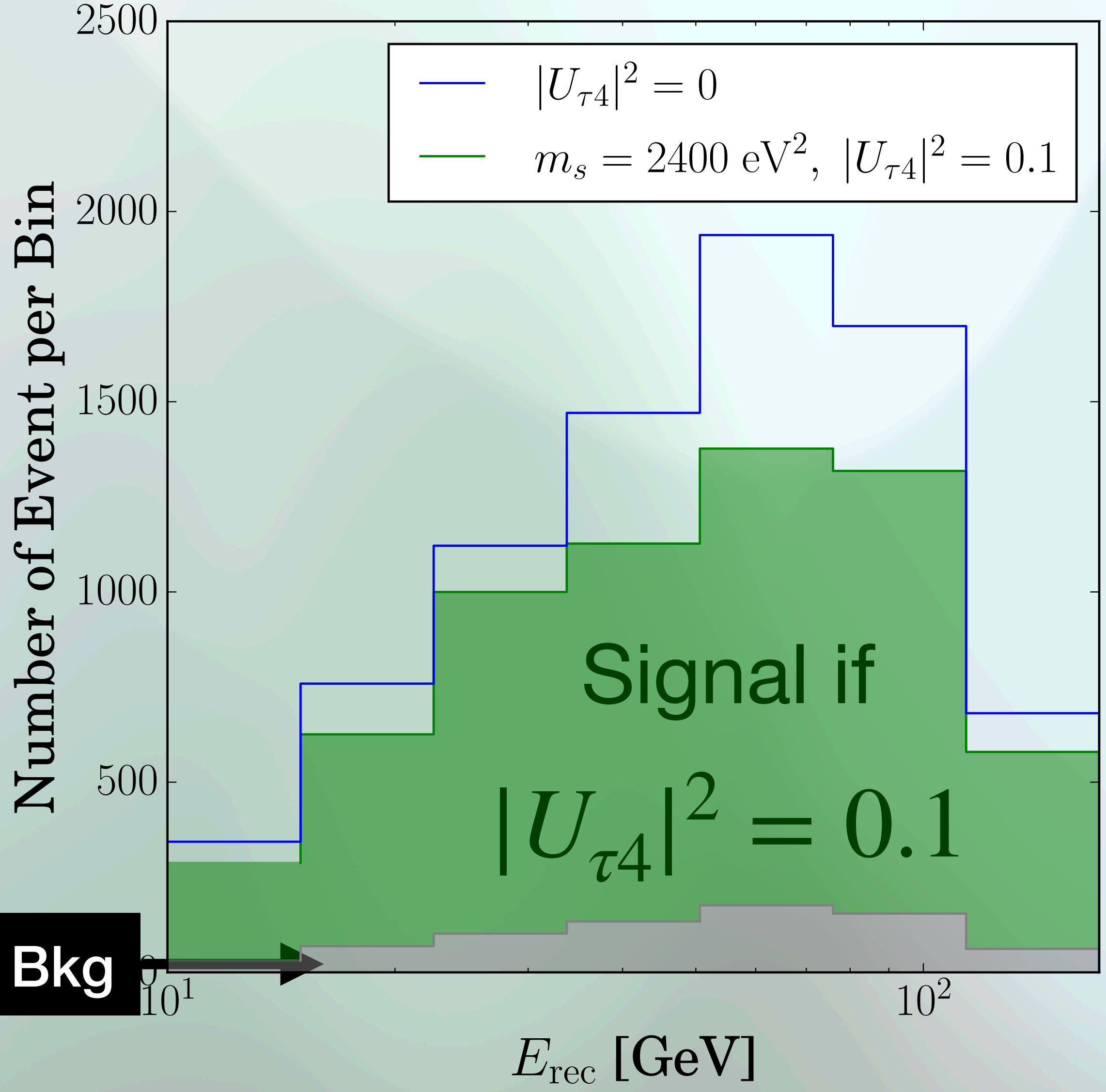
Total # of events: ~7300 events in 5 years w/o bkg.

$$R_{s/b} = 10,\ A = B = \alpha_i = \beta_i = 0$$

$\Delta m^2_{41} = 600\ \mathrm{eV}^2$



$\Delta m^2_{41} = 2400\ \mathrm{eV}^2$



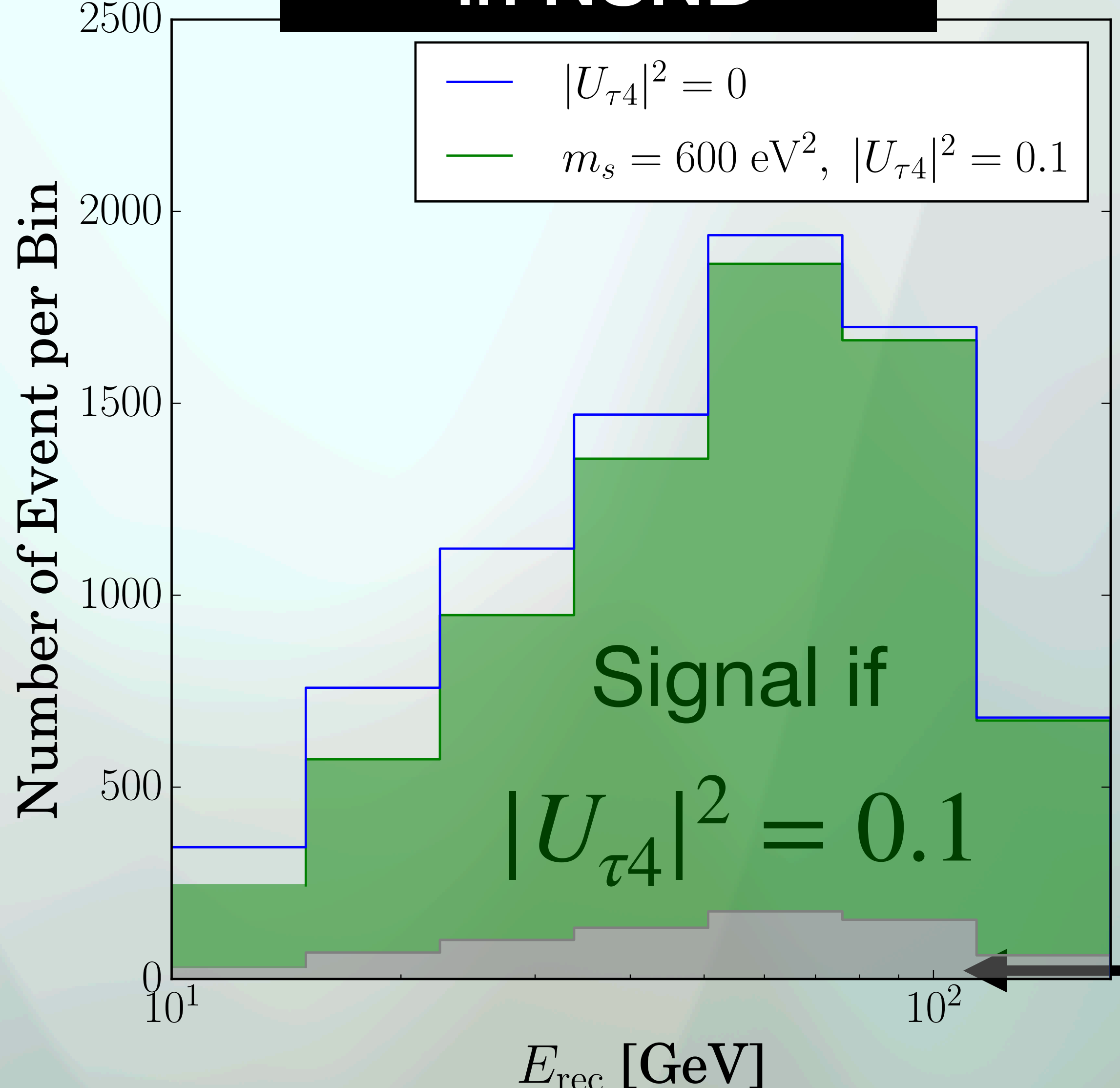
Bkg

Event Rate at FSND

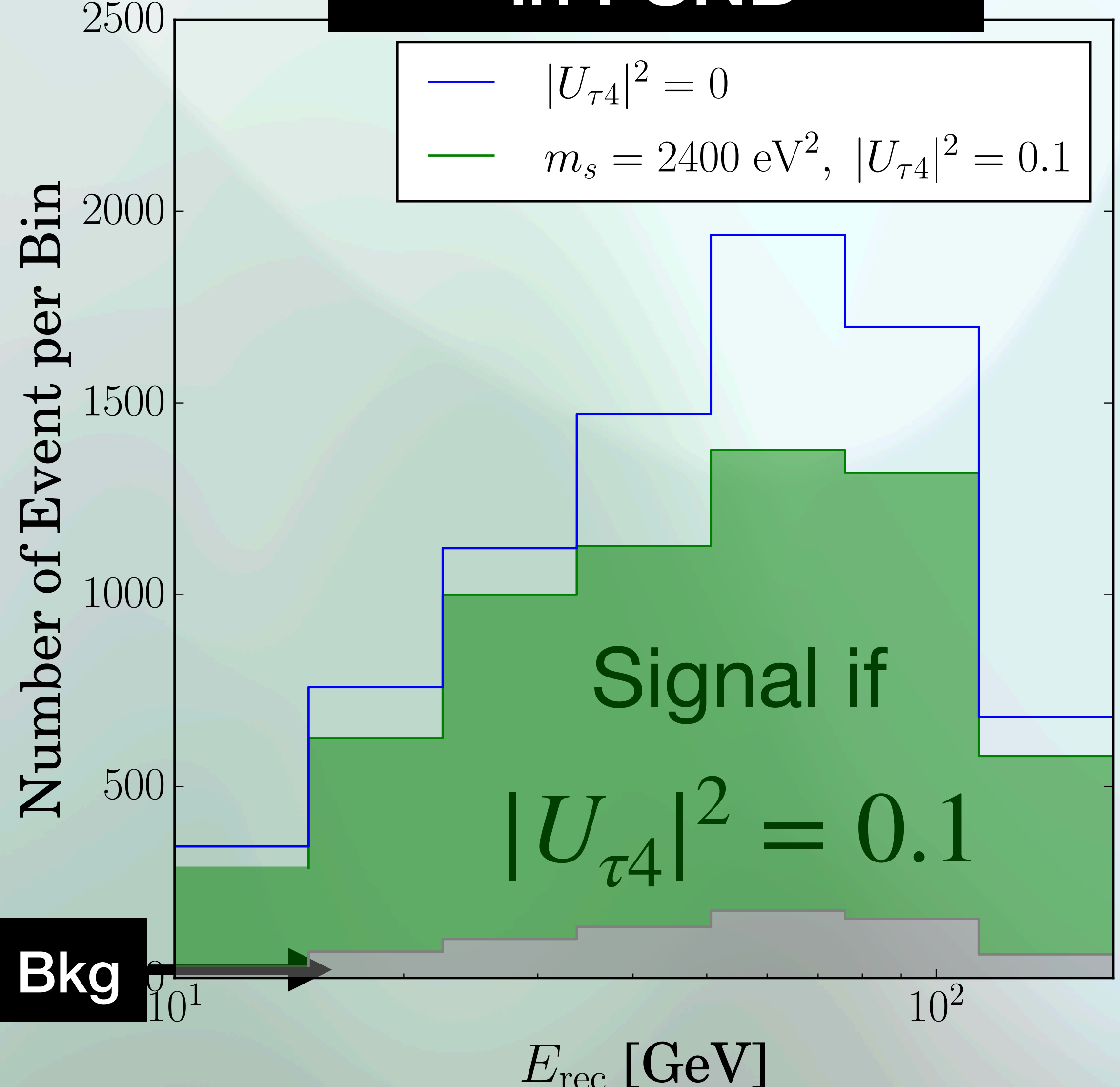
Total # of events: ~7300 events in 5 years w/o bkg.

$$R_{s/b} = 10,\ A = B = \alpha_i = \beta_i = 0$$

$\Delta m^2_{41} = 600\ \mathrm{eV}^2$
in NSND



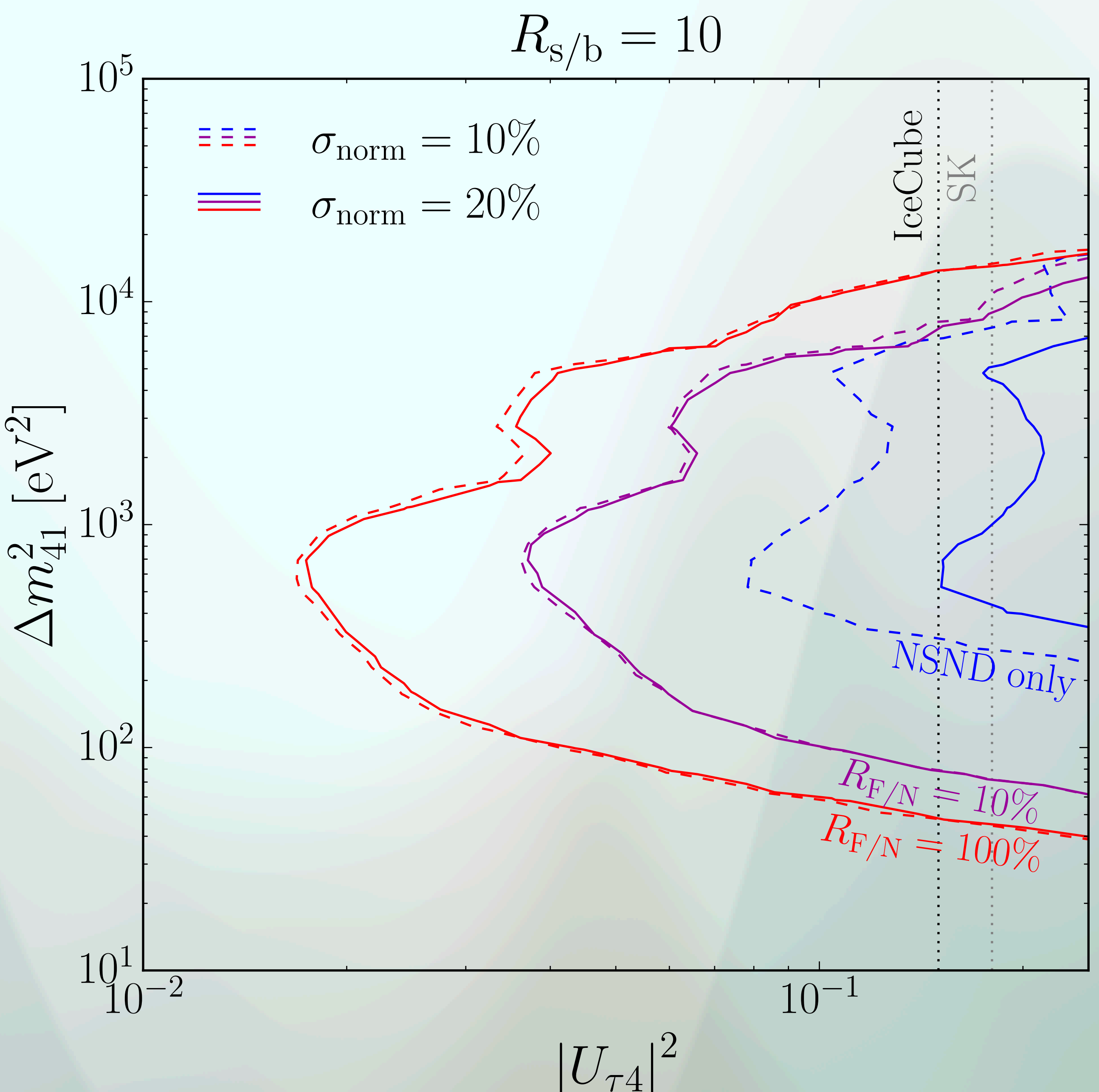
$\Delta m^2_{41} = 600\ \mathrm{eV}^2$
in FSND

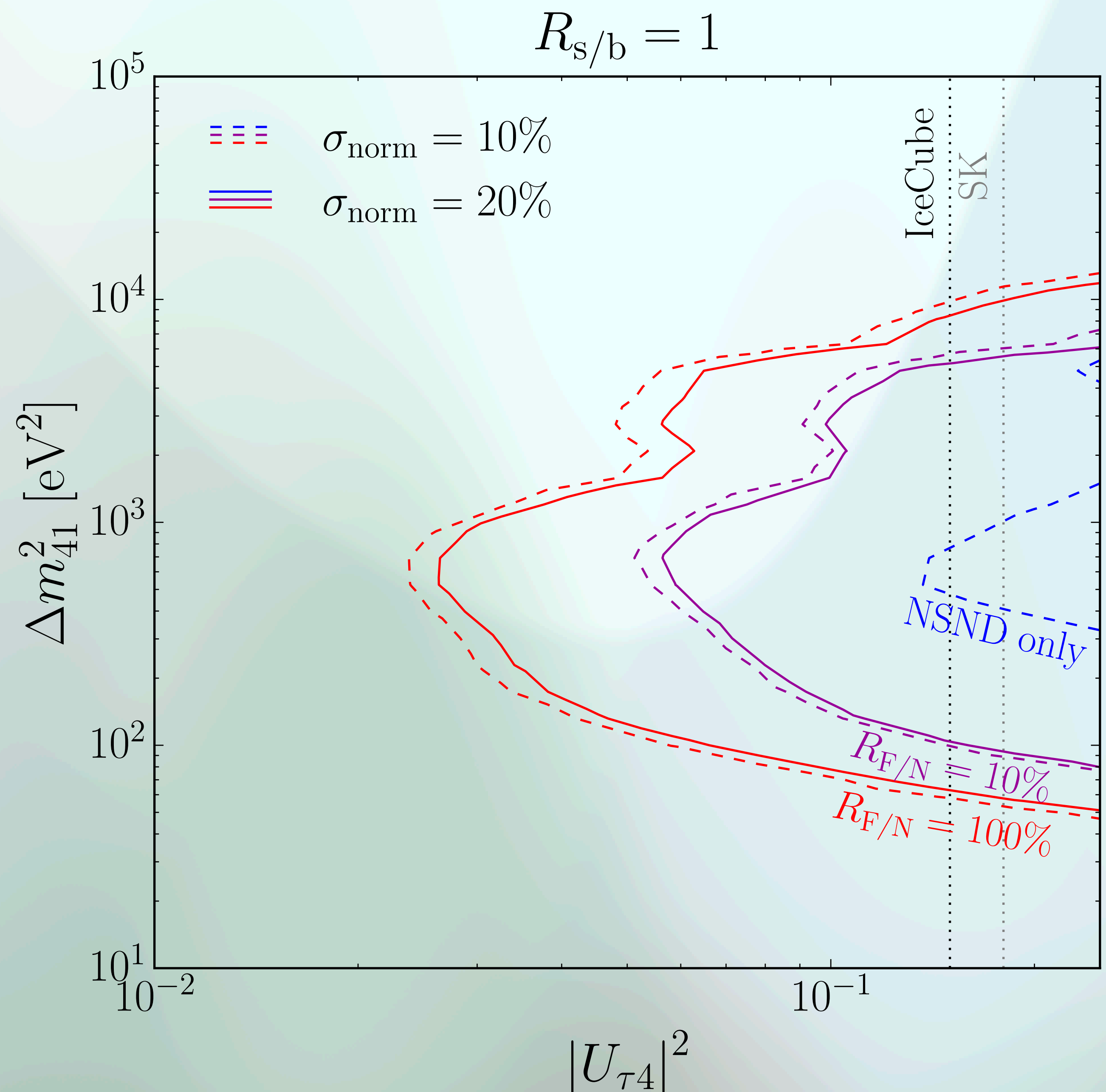


Bkg

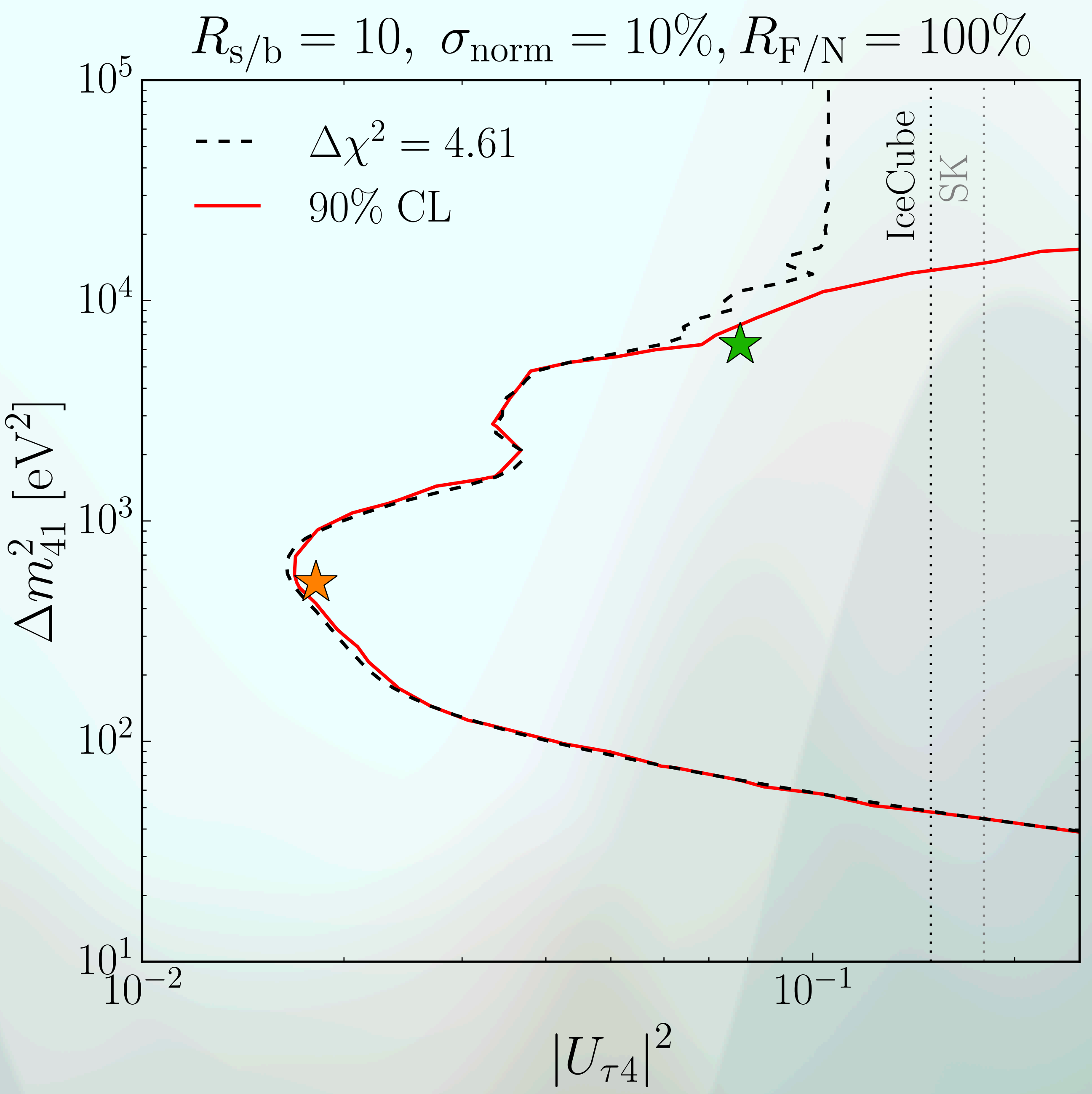
Sensitivity of NSND + FSND

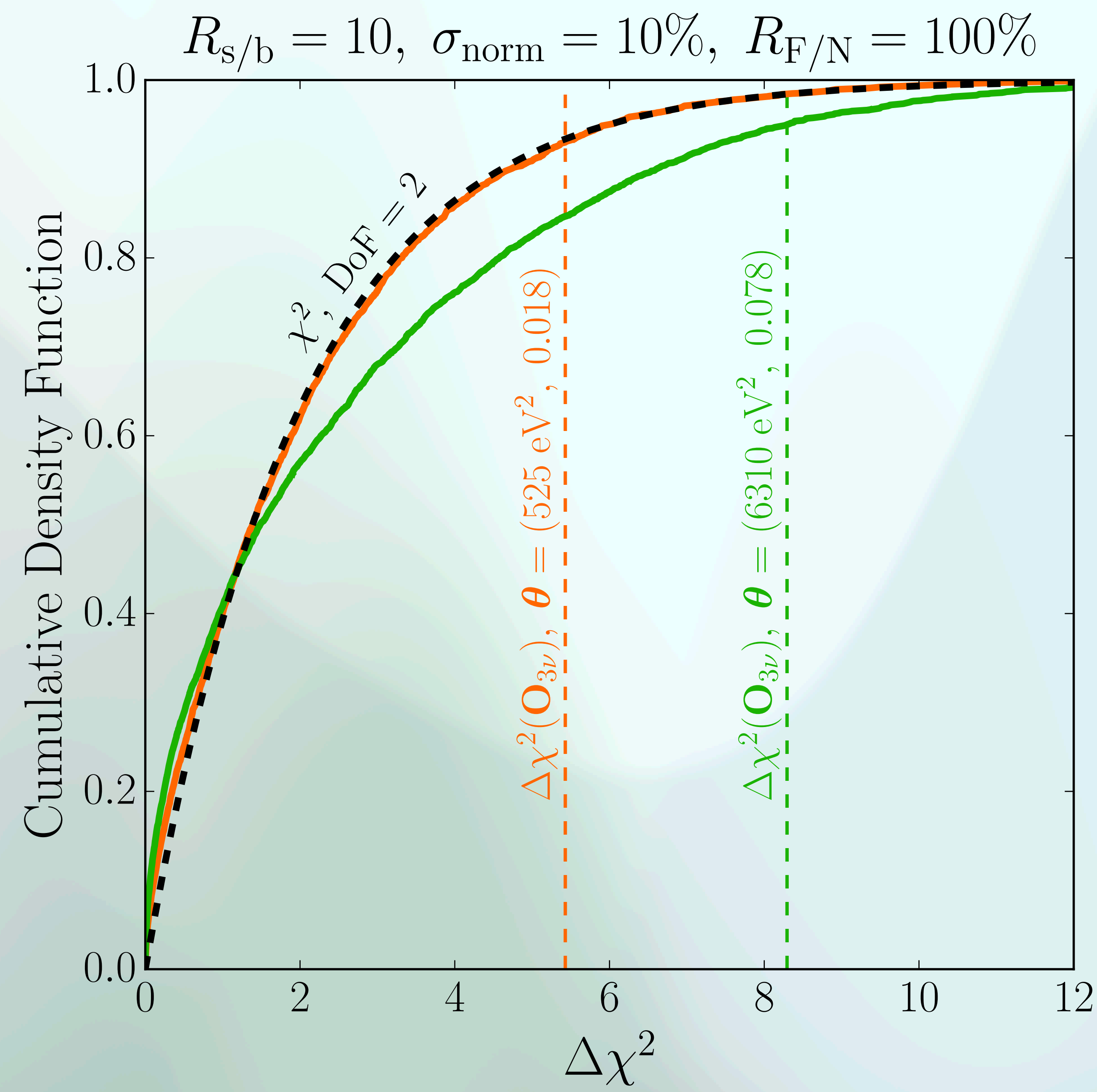
$R_{\mathrm{F/N}} \equiv$ (# of event at FSND) / (# of event at NSND)





Validity of Wilks' Theorem





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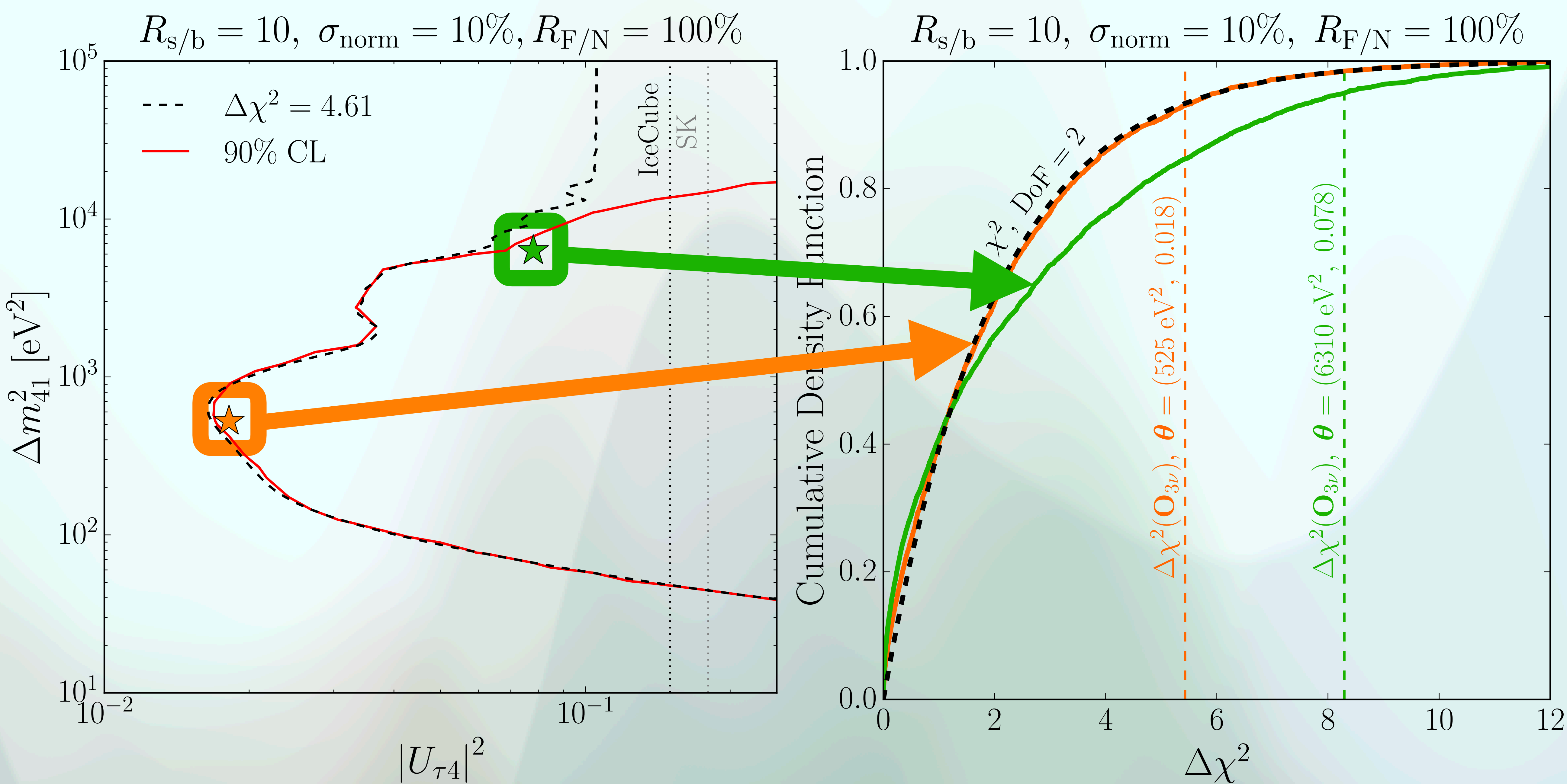

Conclusion

- Using the profiled FC method, we have shown that Wilks' theorem does not hold in the NSND-only case.

- The sensitivity of NSND+FSND case changes little by varying $\sigma_{\rm norm}$.

- NSND+FSND could constrain $10^2~\mathrm{eV}^2 \lesssim \Delta m_{41}^2 \lesssim 10^4~\mathrm{eV}^2$ region,
  from $|U_{\tau 4}|^2 \lesssim 0.02$ for $R_{s/b} = 10,~R_{\rm F/N} = 100\,\%$
  to $|U_{\tau 4}|^2 \lesssim 0.06$ for $R_{s/b} = 1,~R_{\rm F/N} = 10\,\%$.

- What about $\sin^2 2\theta_{\mu\tau}$? What if we use CL_s method?