

Solar Neutrinos at ESSnuSB

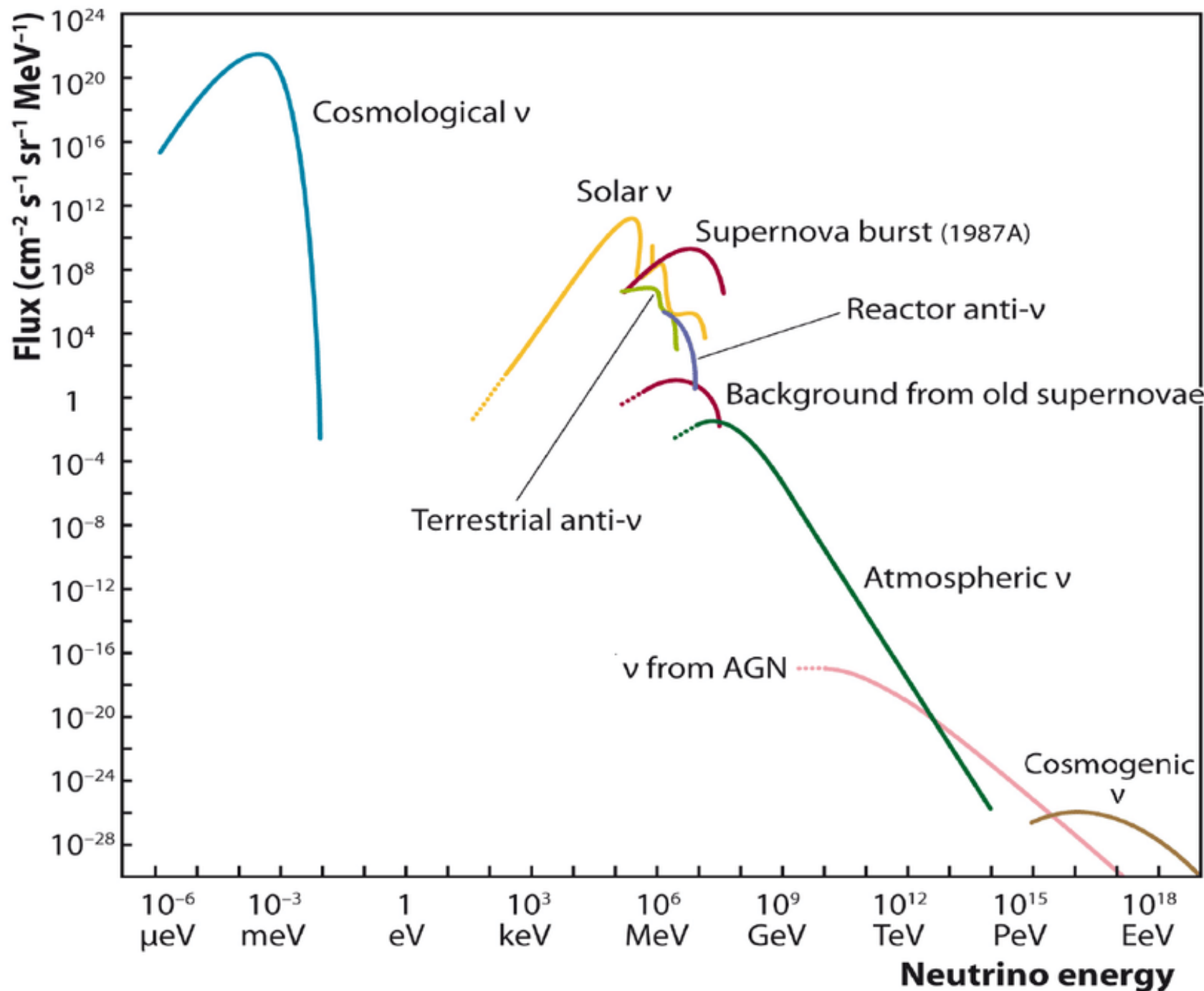
Alessio Giarnetti, WP5



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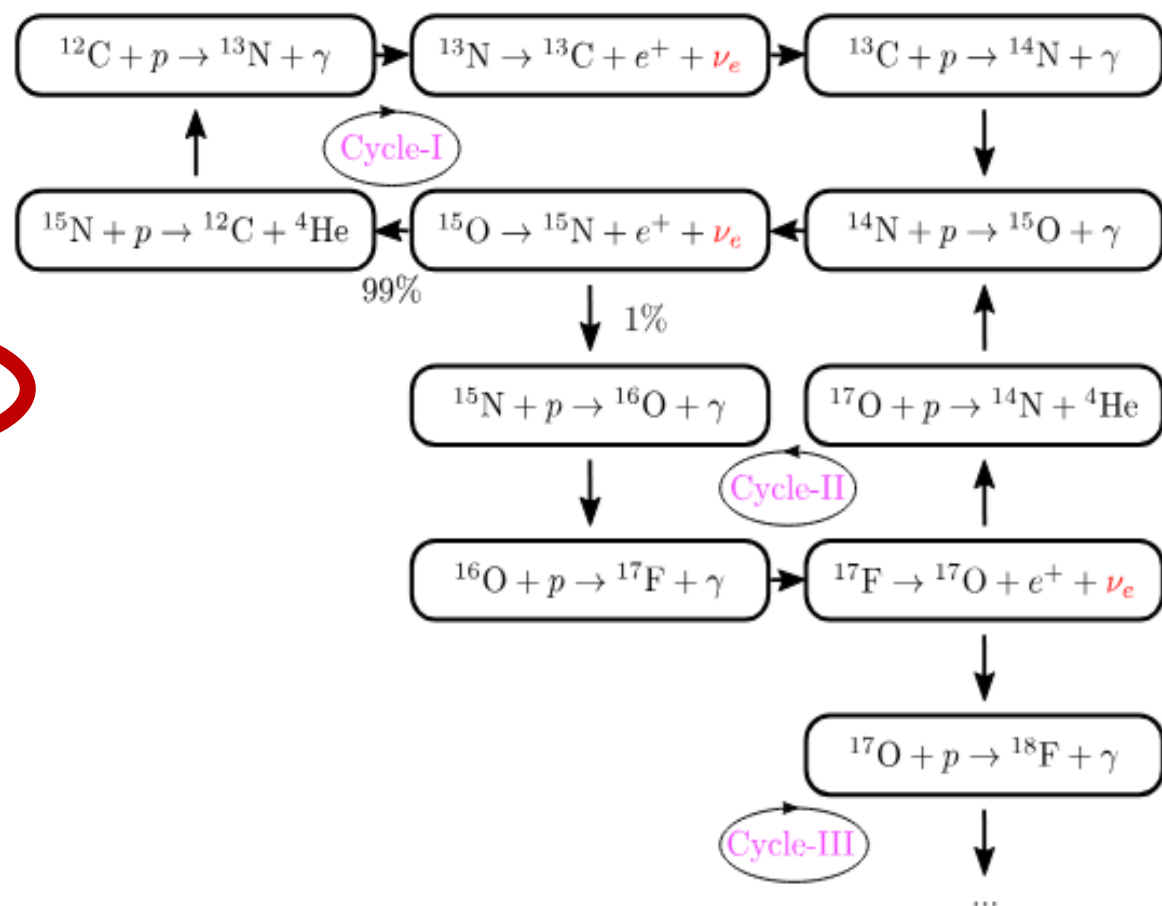
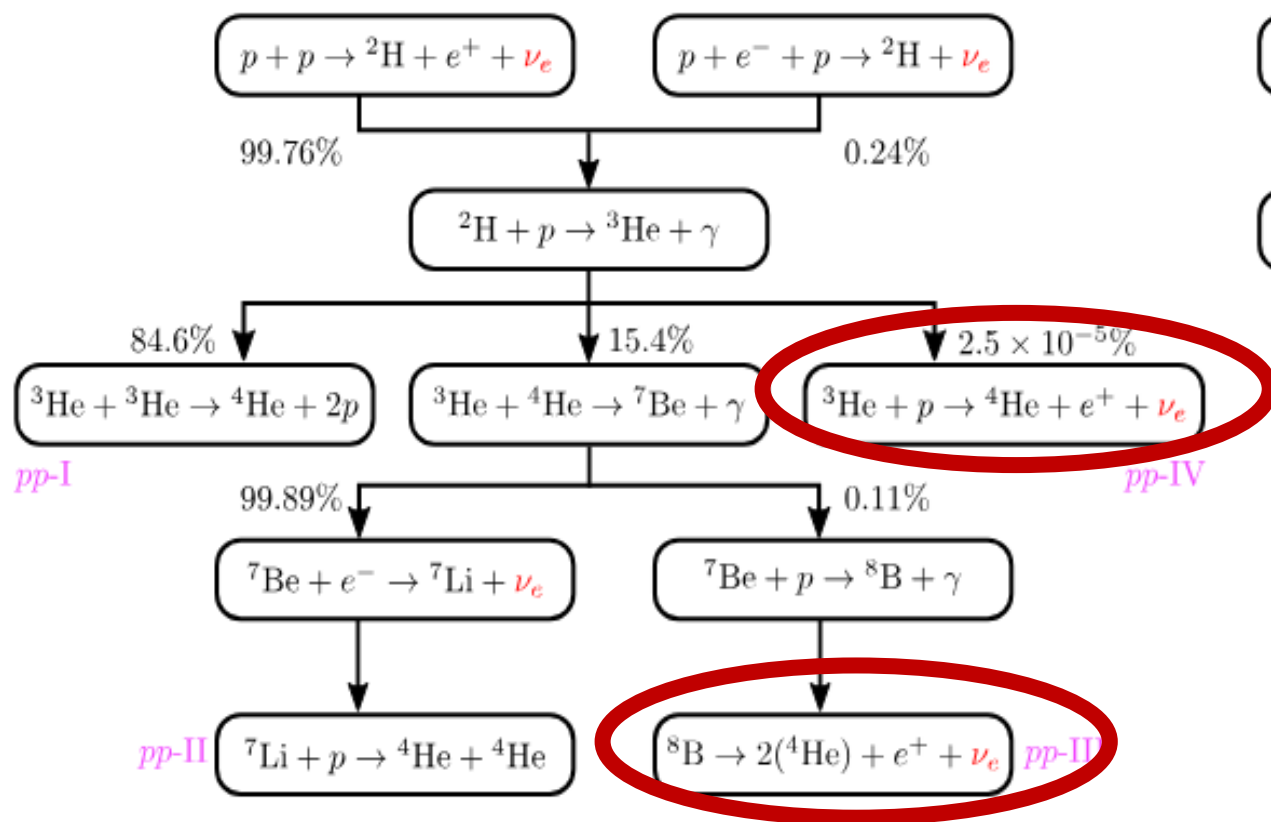


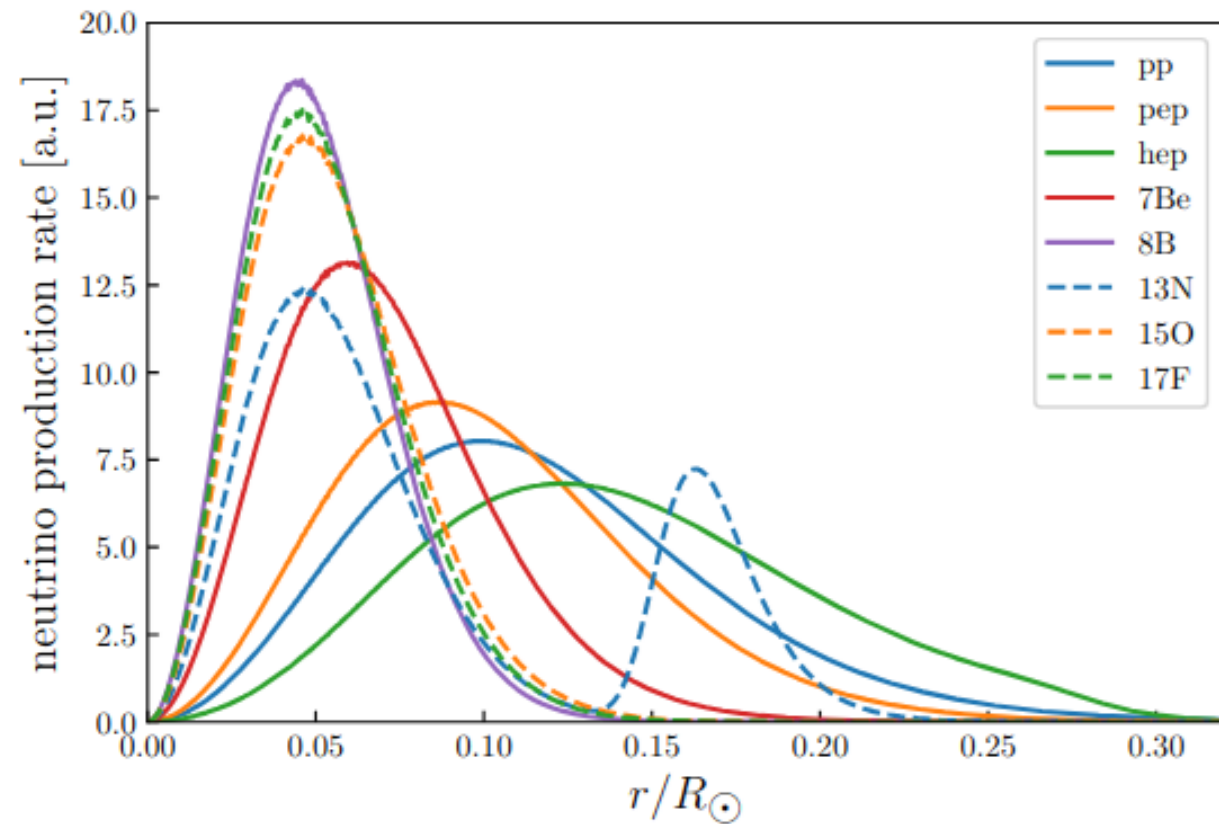
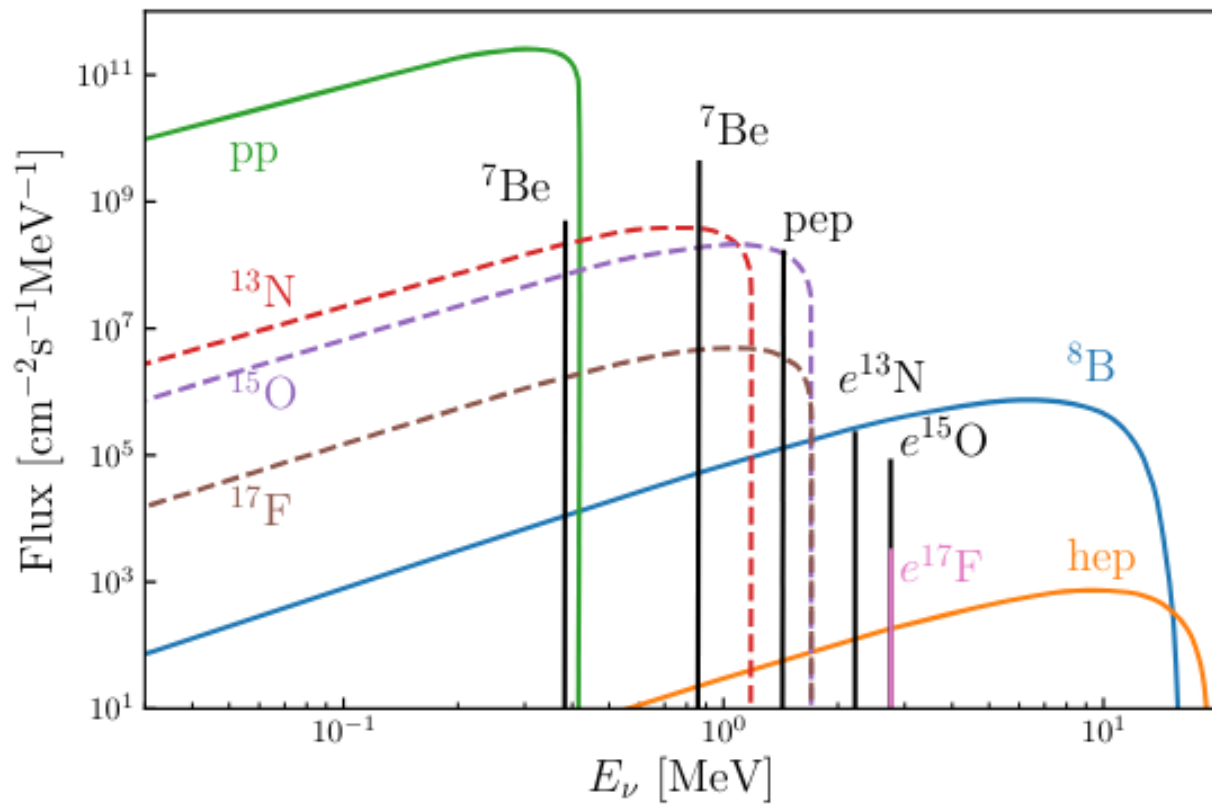
Uppsala, 6/10/2026



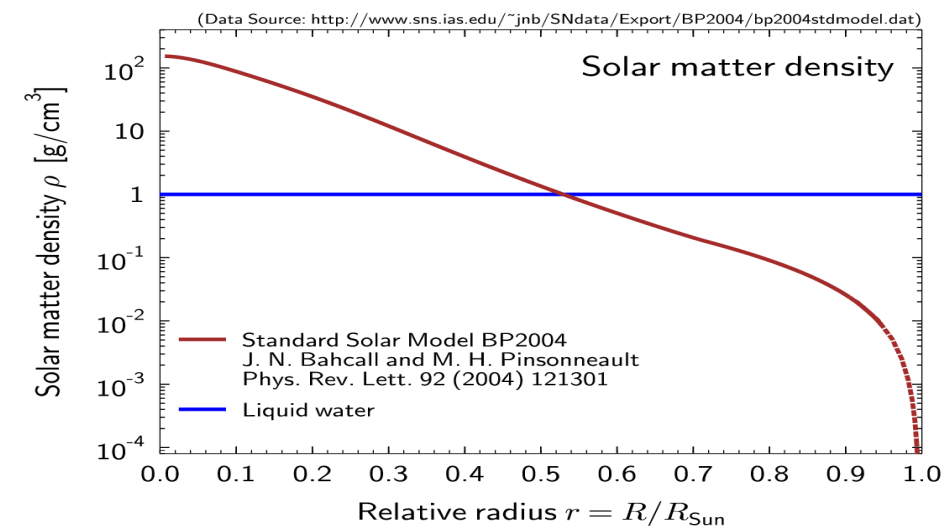
Solar neutrinos:

- Only electron neutrinos
- From hundreds of keV to a few MeV
- Highest observable neutrino flux at the Earth



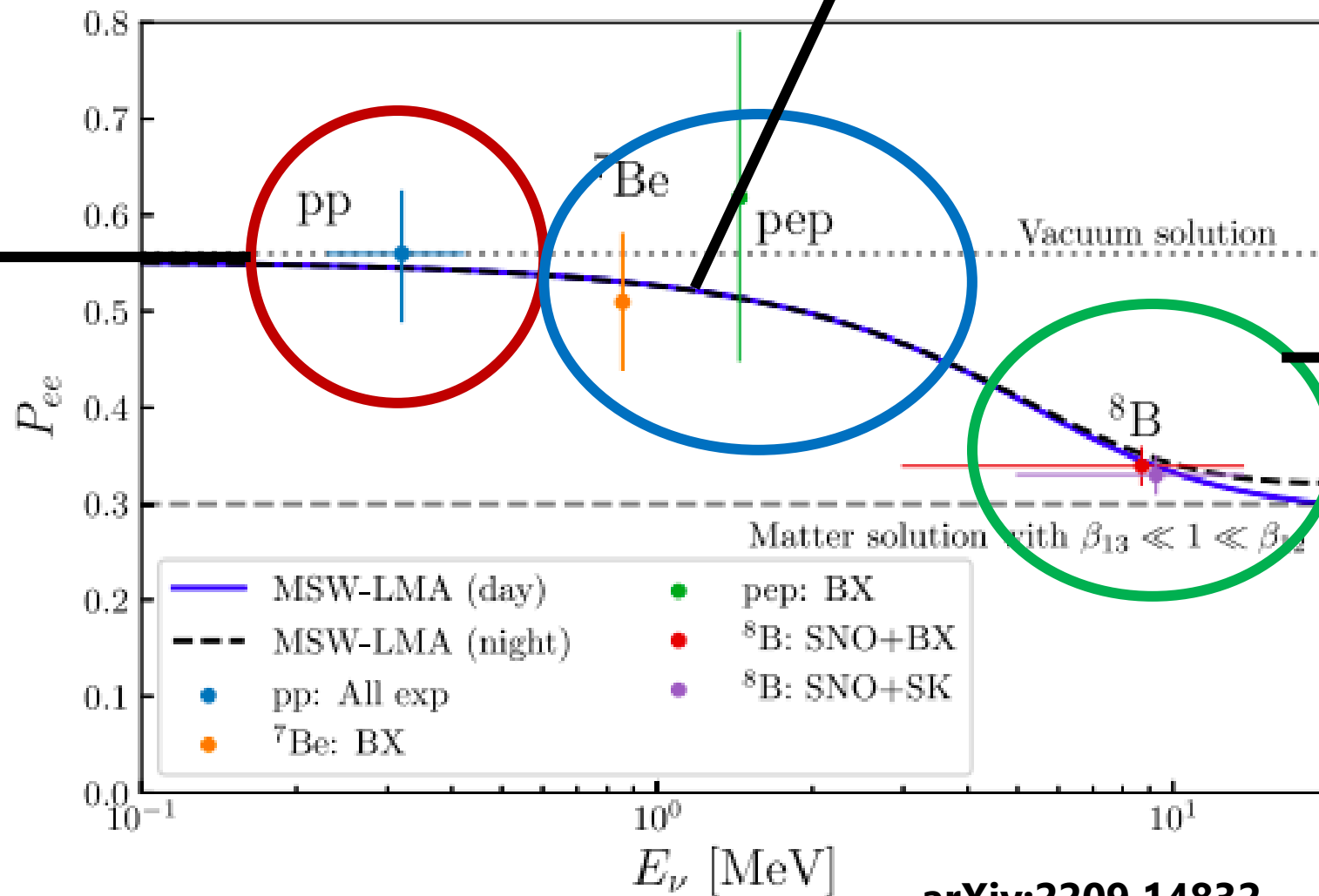


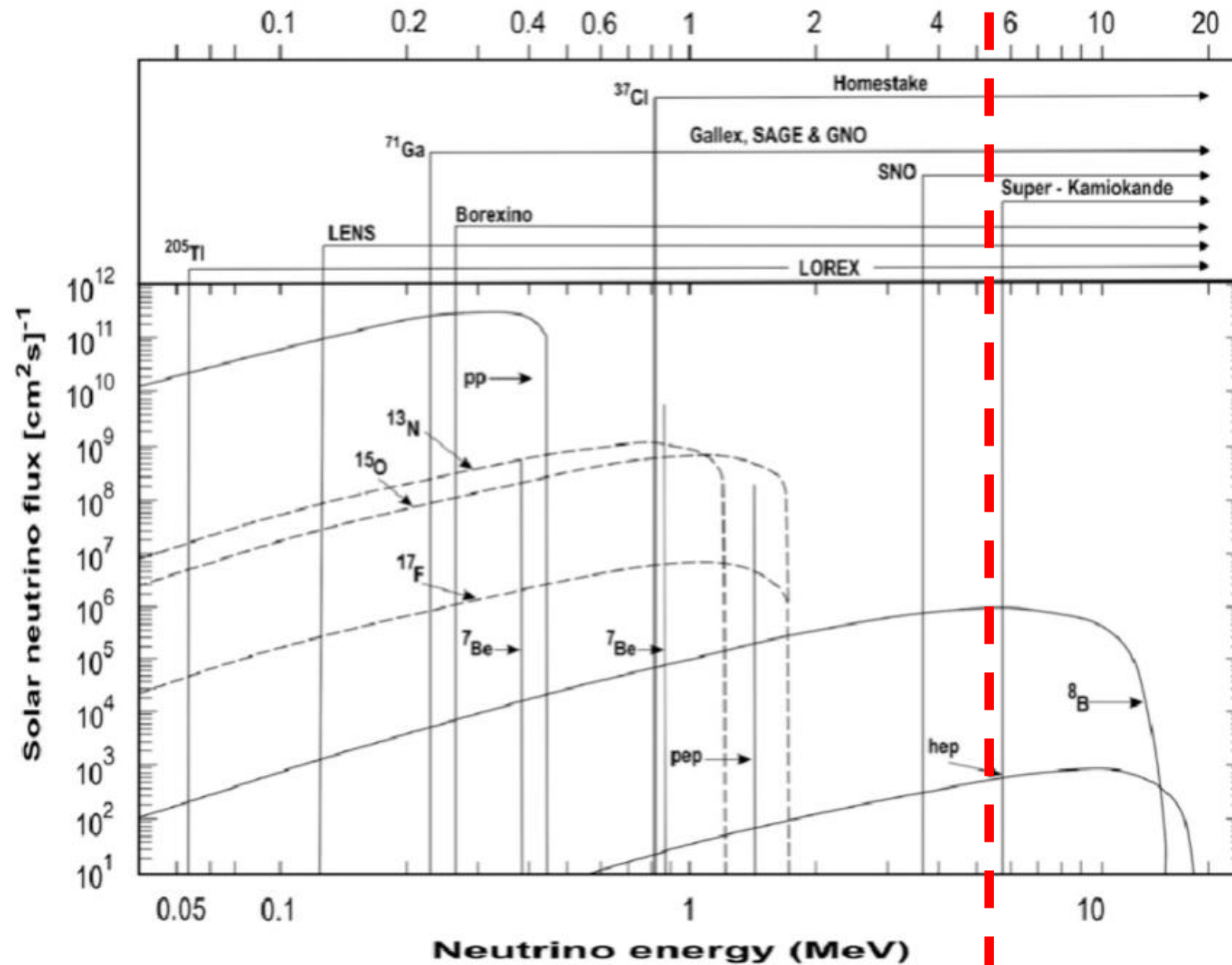
All neutrinos are produced in the core, where the matter density is of about 100 g/cm^3 . While pp are produced in all the core, high energetic neutrinos (B8) need higher temperature and are produced in the inner part of the core.



$$P_{ee}(E) = \int dr \, \phi(E) \, \varphi(r) \sum_{i=1}^3 |U_{ei}^\nu|^2 |U_{ei}^m(r, E)|^2,$$

Low energy region:
- Measure of mixing angle





Two unresolved solar-neutrino signatures

^8B spectral upturn

MSW-LMA predicts that the electron-neutrino survival probability rises as the energy falls through the transition region near a few MeV.

Current data favor the transition, but the upturn has not yet been isolated with high significance in the ^8B spectrum alone. Its shape can test the standard matter effect and possible subleading new physics.

hep neutrinos

The reaction $^3\text{He} + \text{p} \rightarrow ^4\text{He} + \text{e}^+ + \nu_{\text{e}}$ produces the highest-energy neutrinos of the solar pp chain, with an endpoint near 18.8 MeV.

The Standard Solar Model flux is more than two orders of magnitude below the ^8B flux. Experiments have set upper limits, but no direct observation has yet mapped this final pp-chain component.

ESSvSB analysis details

- Fiducial mass of 540 kt in total, 1 km underground
- Detection channel: ν -e elastic scattering, 90% signal efficiency

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{2G_F^2 m_e}{\pi} \left[g_L^2 + g_R^2 \left(1 - \frac{T}{E_\nu} \right)^2 - g_L g_R \frac{m_e T}{E_\nu^2} \right]$$

Recoil T from threshold (nominal 5 MeV) to maximum

- 1 MeV reconstructed-energy bins
- Analysis window: [6.5-15] MeV for upturn and [14-25] MeV for hep
- Energy resolution: Gaussian 10% for upturn, 5% for hep

$$\mu_k = N_e t \Delta \bar{E} \int dE_\nu 0.9 \phi(E_\nu) P_{ee}(E_\nu) \sigma(E_\nu) R(E_\nu, E_{\text{rec}}),$$

Radon background model

Source and spectral shape

The β decay of ^{214}Bi in the ^{222}Rn chain has $Q = 3.27$ MeV. A Gaussian tail models reconstructed events above the endpoint, reaching close to 5 MeV.

SK-IV normalization

9.53 events $\text{day}^{-1} \text{kt}^{-1}$ after radon cuts in the 3.5-5.0 MeV interval

Adaptation in ESSvSB

Photocathode coverage

30% at ESSvSB compared with 40% at Super-Kamiokande

Position-leakage scaling

$$1/\sqrt{N_Y} \Rightarrow \sqrt{(0.40/0.30)} \approx 1.15$$

The radon contribution is negligible above 6.5 MeV and throughout the hep window. It matters when the recoil threshold scan approaches 3.5 MeV.

Spallation extrapolation to Zinkgruvan

Reference measurement

The model starts from isotope-resolved production rates measured by Super-Kamiokande in water.

Depth-intensity relation

$$I(h) = 67.97 \times 10^{-6} e^{-h/0.285} + 2.071 \times 10^{-6} e^{-h/0.698} \quad [\text{cm}^{-2}\text{s}^{-1}]$$

$h = 2.7$ km water equivalent

$$I_{\text{sk}} = 1.49 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$$

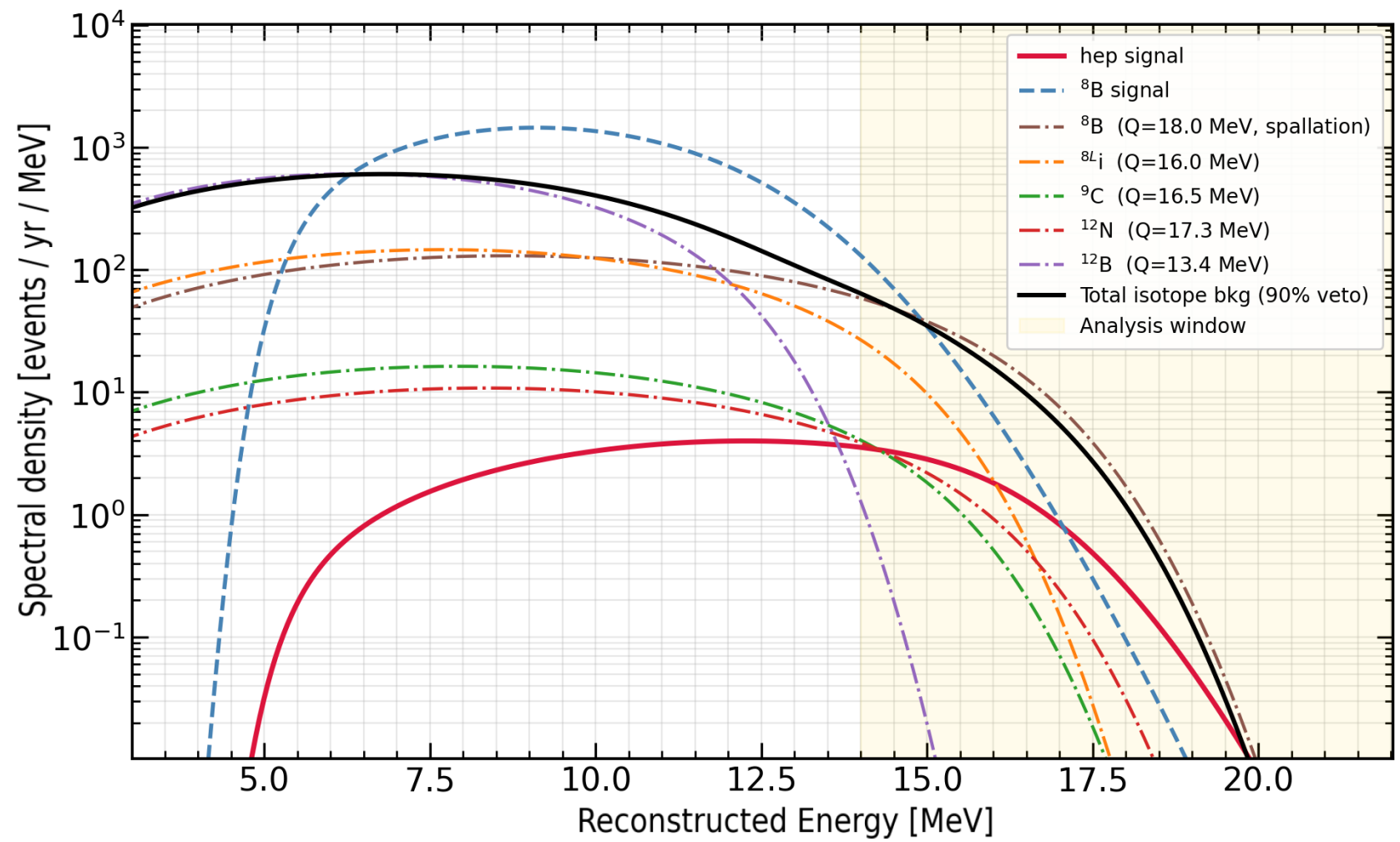
Adaptation in ESSvSB

$$R(\text{ESS/SK}) = I(h_{\text{ess}}) / I_{\text{sk}} \approx 0.33$$

predicted Zinkgruvan/SK muon-intensity ratio
from the adopted relation

In our case, the flatter overburden let less muons to pass with respect to the mountain over SK.

Isotope-resolved spallation spectrum



Residual-background scenarios

Ideal

0%

residual environmental
background

This limit isolates the intrinsic
statistics and detector-
response systematics.

Realistic benchmark

10%

of the spallation spectrum remains
after 90% rejection

The benchmark follows Super-
Kamiokande performance and
recent JUNO solar-neutrino
studies.

Pessimistic

100%

of the modeled spallation
spectrum remains

No veto is applied. The
signal-shape differences
become nearly invisible.

Spectral-shape fits with floating normalization

Upturn

MSW-LMA spectrum
versus constant P_{ee}



Upturn hypotheses

H₁ Full energy-dependent MSW-LMA prediction

H₀ Energy-independent $P_{ee} = P_{flat}$, profiled within 0.294-0.553

hep

^8B + hep spectrum
versus ^8B alone



hep hypotheses

H₁ Solar ^8B plus the Standard Solar Model hep flux

H₀ Solar ^8B alone, with its normalization free

Both analyses use spectral shape after profiling the overall normalization.

Statistical test and nuisance parameters

Discovery test

The data vector n is set to the H_1 expectation.
The fit minimizes the H_0 prediction $\mu(\theta)$, giving the median expected discovery sensitivity without statistical fluctuations.

$$\chi^2(\theta) = (n - \mu)^T V^{-1}(\mu) (n - \mu)$$

$$V = \text{diag}(\mu) + \alpha^2 \mu \mu^T$$

Poisson covariance

10% normalization
(i.e. on flux or mass)



Systematics

Overall normalization

Free in the shape comparison

Energy resolution

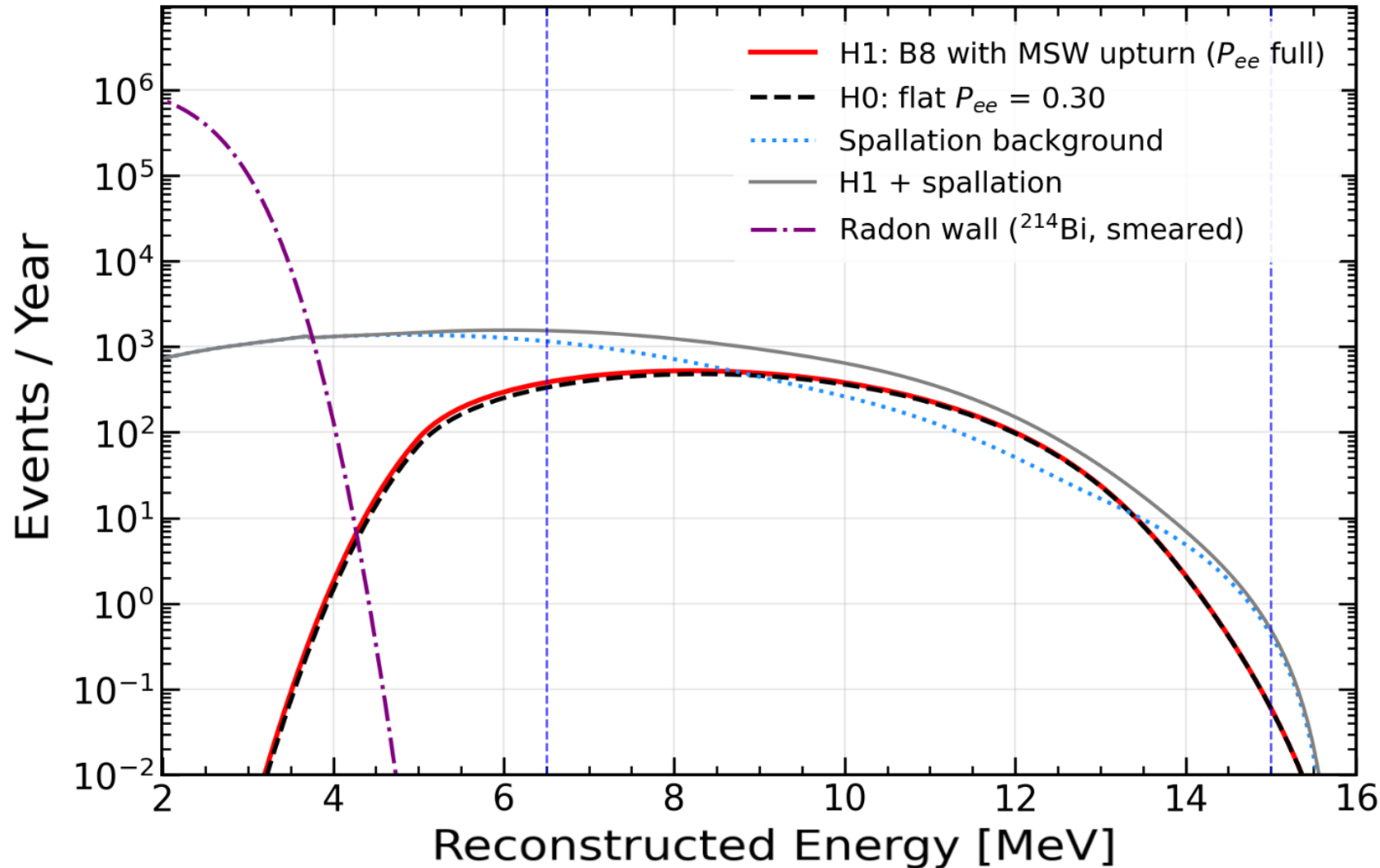
Gaussian penalty around the nominal response

Background normalization

Included where the environmental model enters

The upturn discovery

Reconstructed spectra for the upturn test



Analysis window

6.5-15 MeV

Signal hypotheses

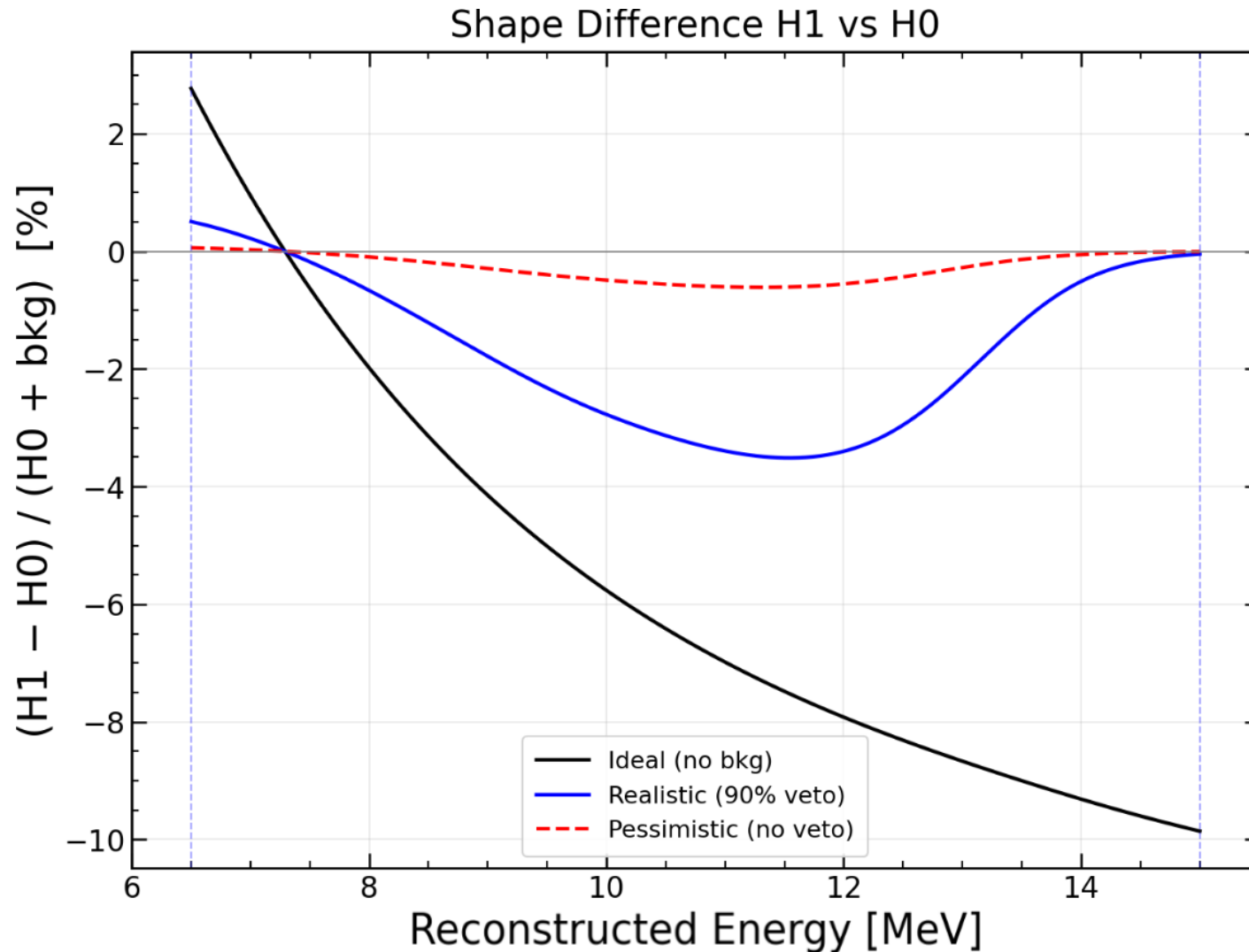
MSW upturn

Flat P_{ee}

Background hierarchy

Spallation exceeds the solar signal near the lower edge. Radon falls below the selected fit window.

Spallation dilutes the upturn distortion



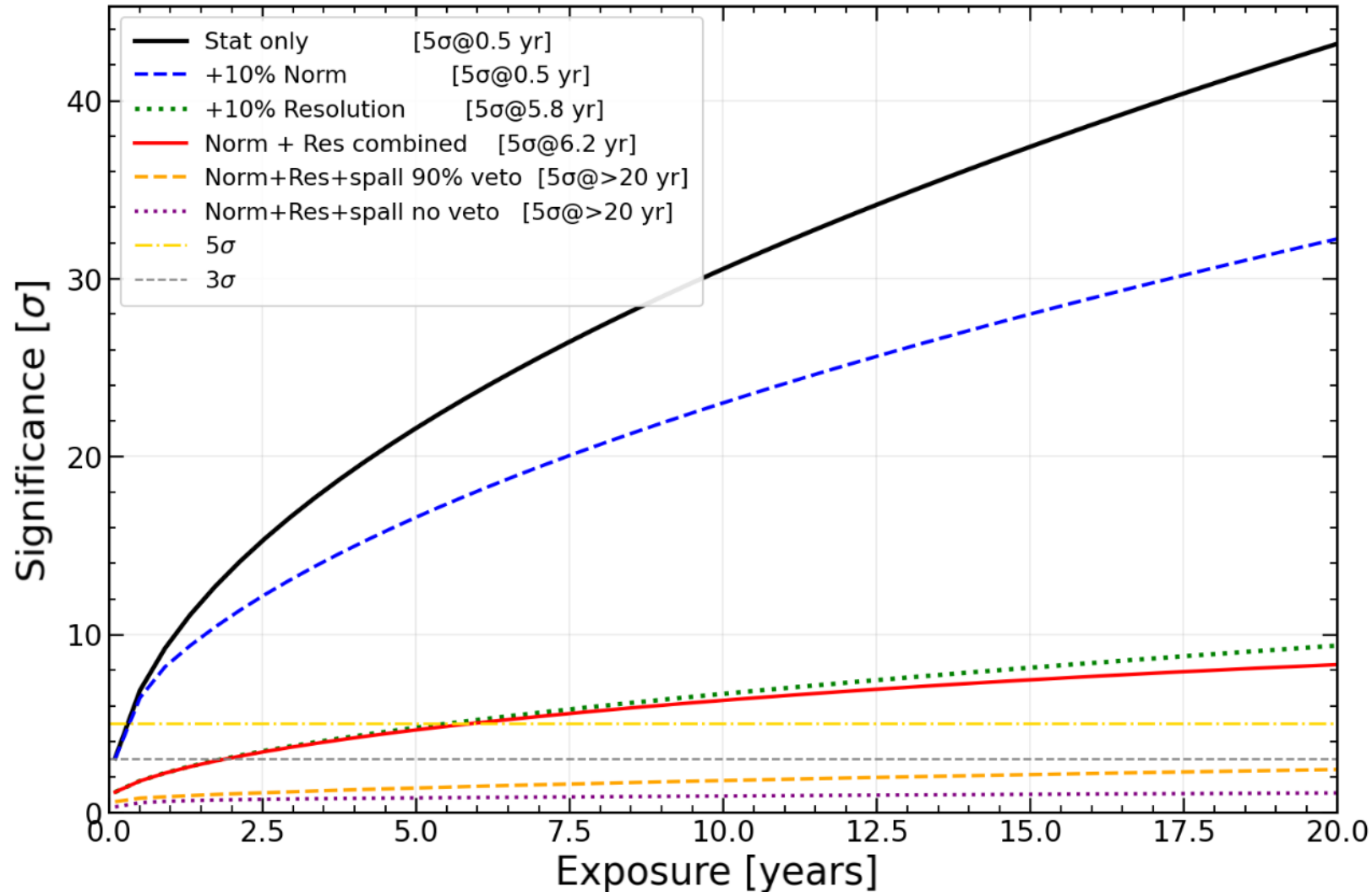
$\approx 3.5\%$

maximum distortion with
90% spallation rejection

$< 0.6\%$

distortion with no veto

Upturn sensitivity versus exposure



0.5 year

5 σ with statistics only

5.8 years

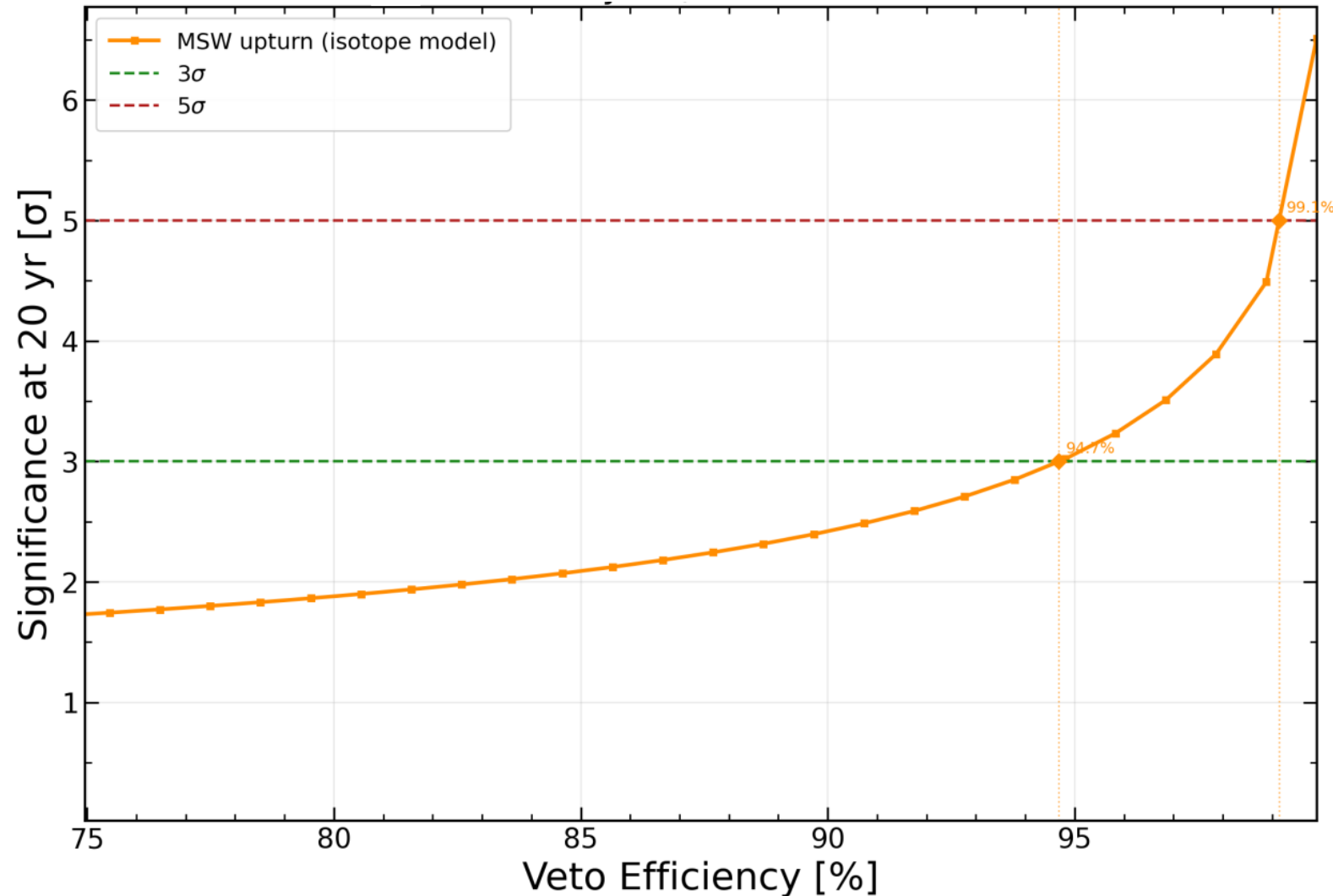
5 σ with the resolution nuisance only

6.2 years

5 σ with normalization and resolution systematics

A 90% veto remains below 3 σ after 20 years.

Spallation rejection for the upturn



94.7%

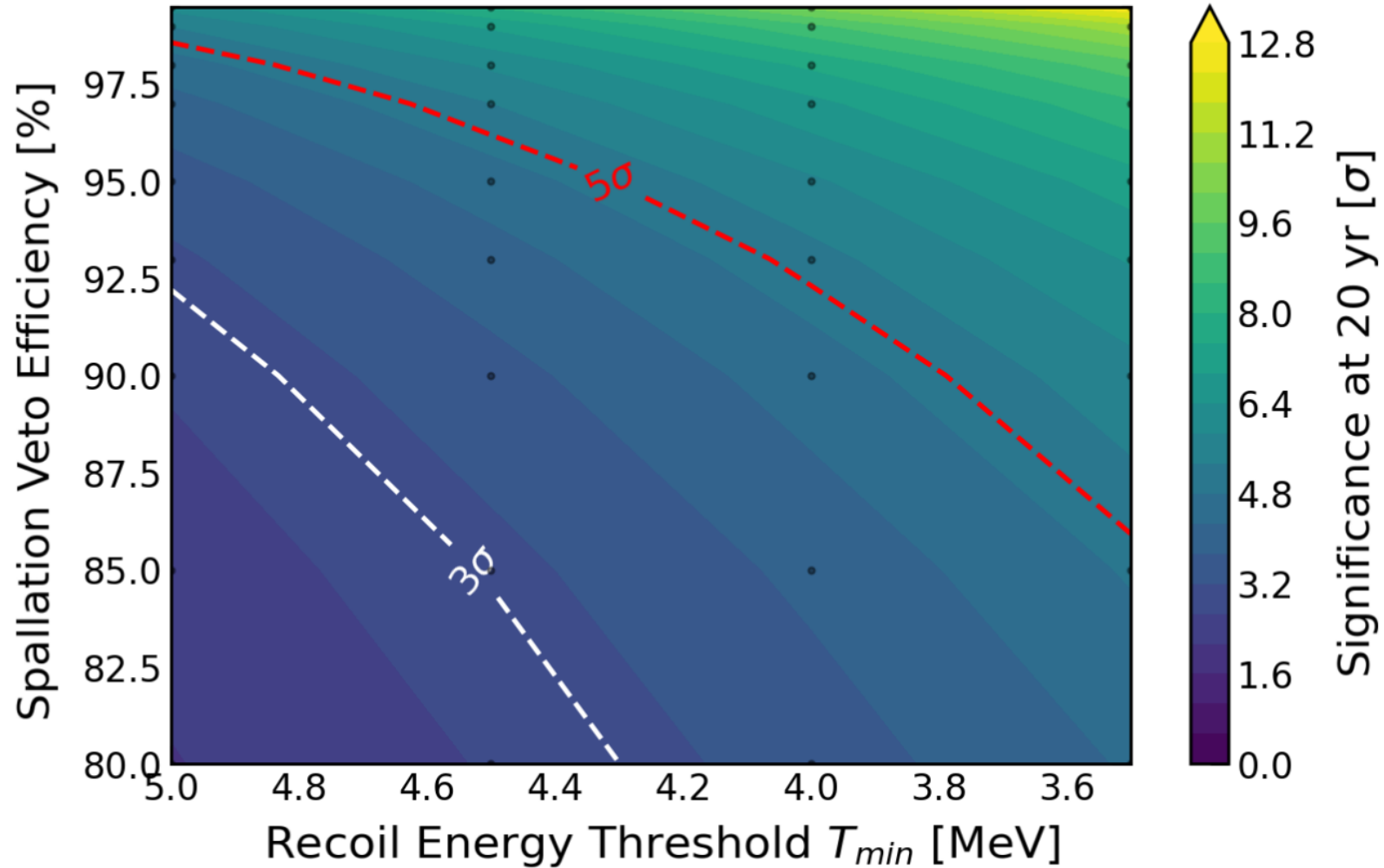
rejection for 3 σ
after 20 years

99.1%

rejection for 5 σ
after 20 years

**At 90% rejection the
expected significance
is only about 2.3 σ .**

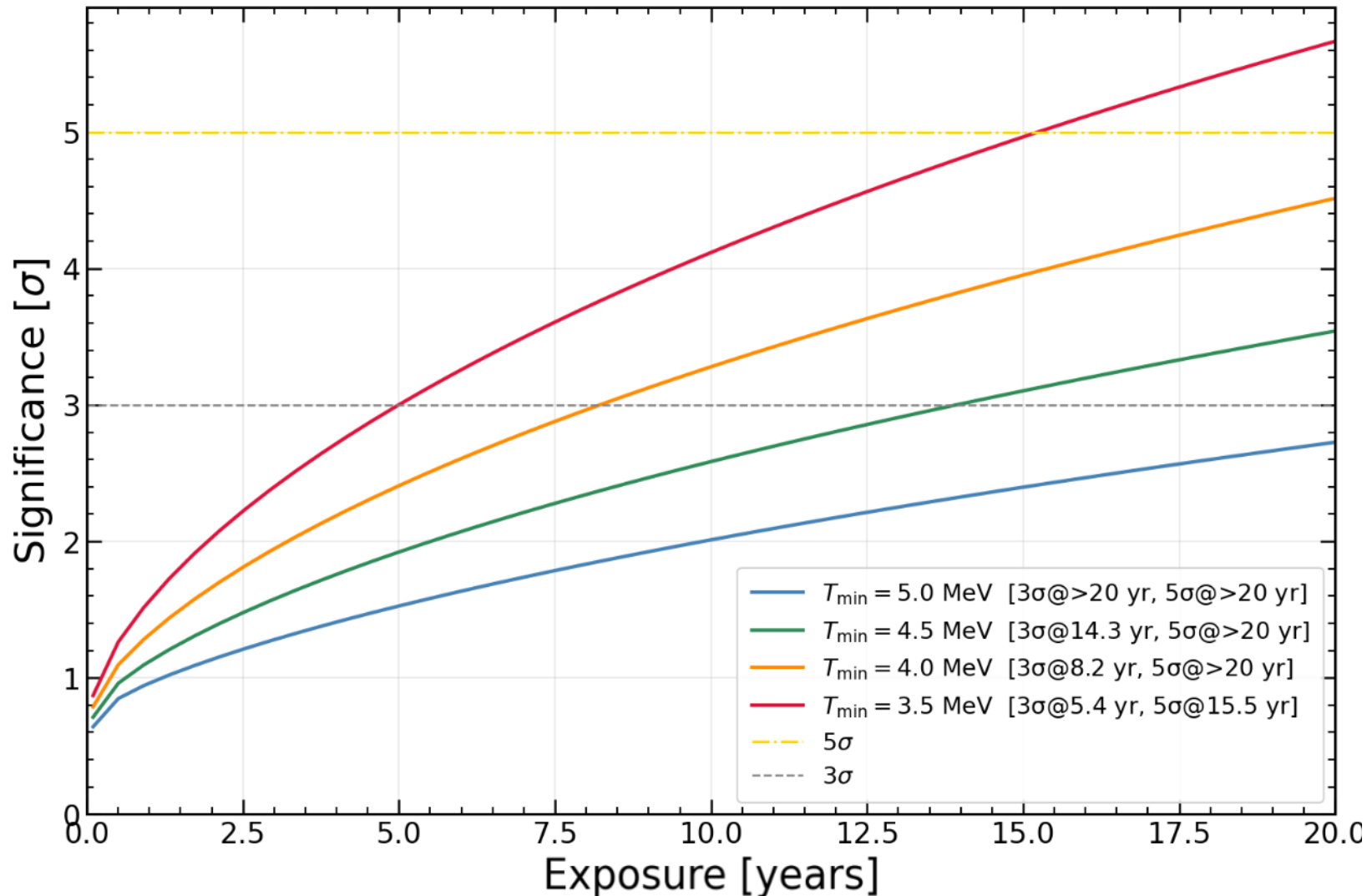
Lower thresholds improve the upturn reach



Lower T_{min}

opens a wider 3σ and 5σ region

Threshold dependence of the exposure



5.4 years

3σ for $T_{\min} = 3.5$ MeV

8.2 years

3σ for $T_{\min} = 4.0$ MeV

14.3 years

3σ for $T_{\min} = 4.5$ MeV

Only the 3.5 MeV case reaches 5σ within 20 years, at about 15.5 years.

The hep discovery

The hep component at the solar endpoint

Reaction



The spectrum extends to about 18.8 MeV, above the solar ${}^8\text{B}$ endpoint near 15 MeV. The final few MeV provide the cleanest spectral distinction from solar ${}^8\text{B}$.

A measurement would complete the experimental map of the pp chain and probe the ${}^3\text{He}$ distribution in the solar core.

$$4.21 \times 10^6$$

${}^8\text{B}$ flux [$\text{cm}^{-2} \text{s}^{-1}$]

$$7.88 \times 10^3$$

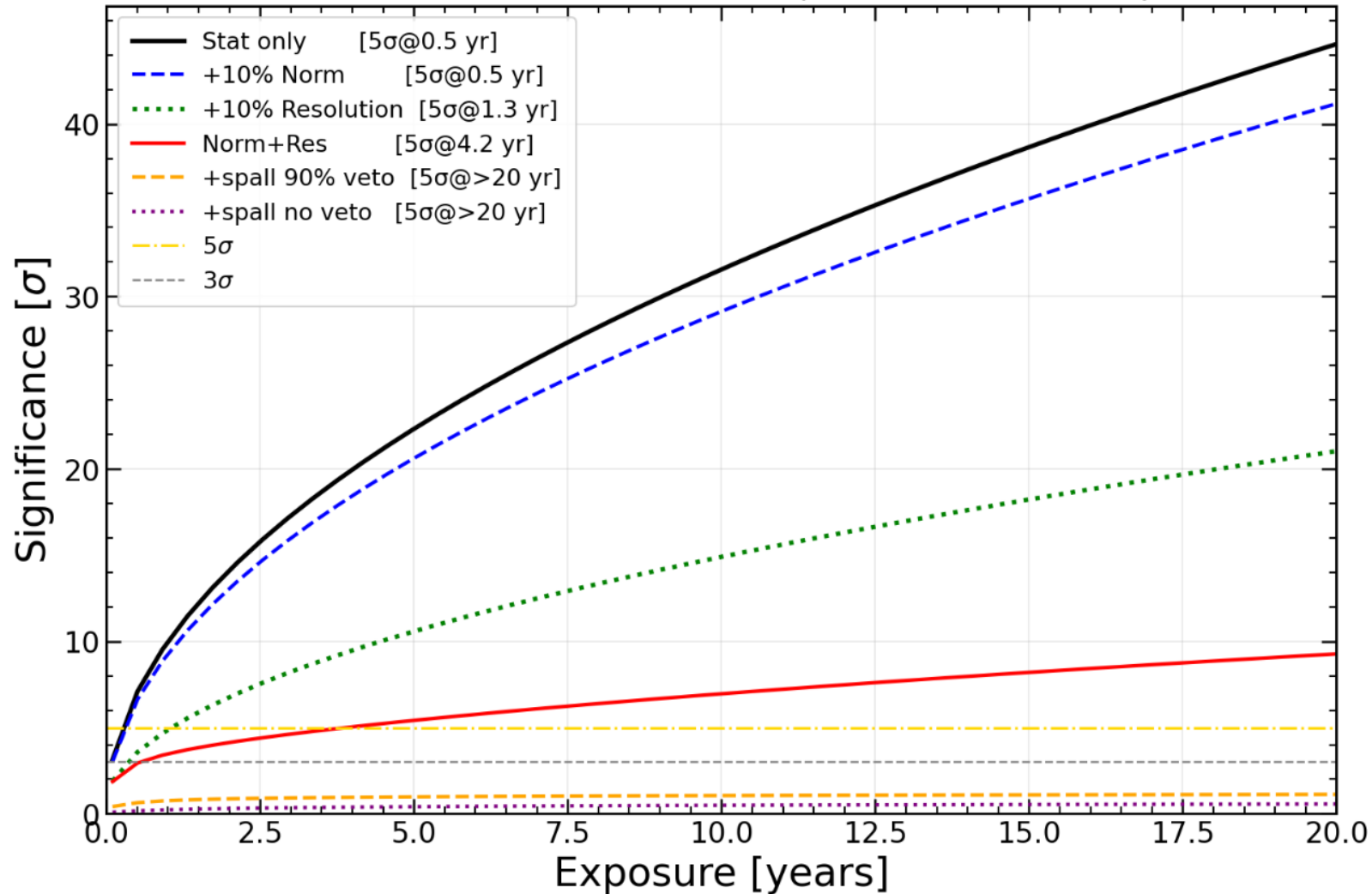
hep flux [$\text{cm}^{-2} \text{s}^{-1}$]

Expected in 14-25 MeV

$\approx 1,077$ solar ${}^8\text{B}$ events/year

≈ 126 hep events/year

Spallation dominates the hep sensitivity



4.2 years

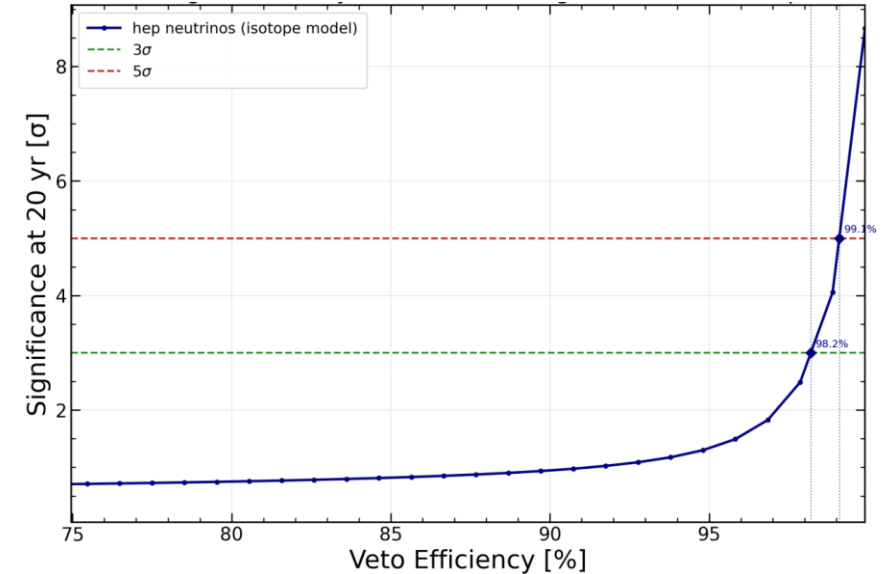
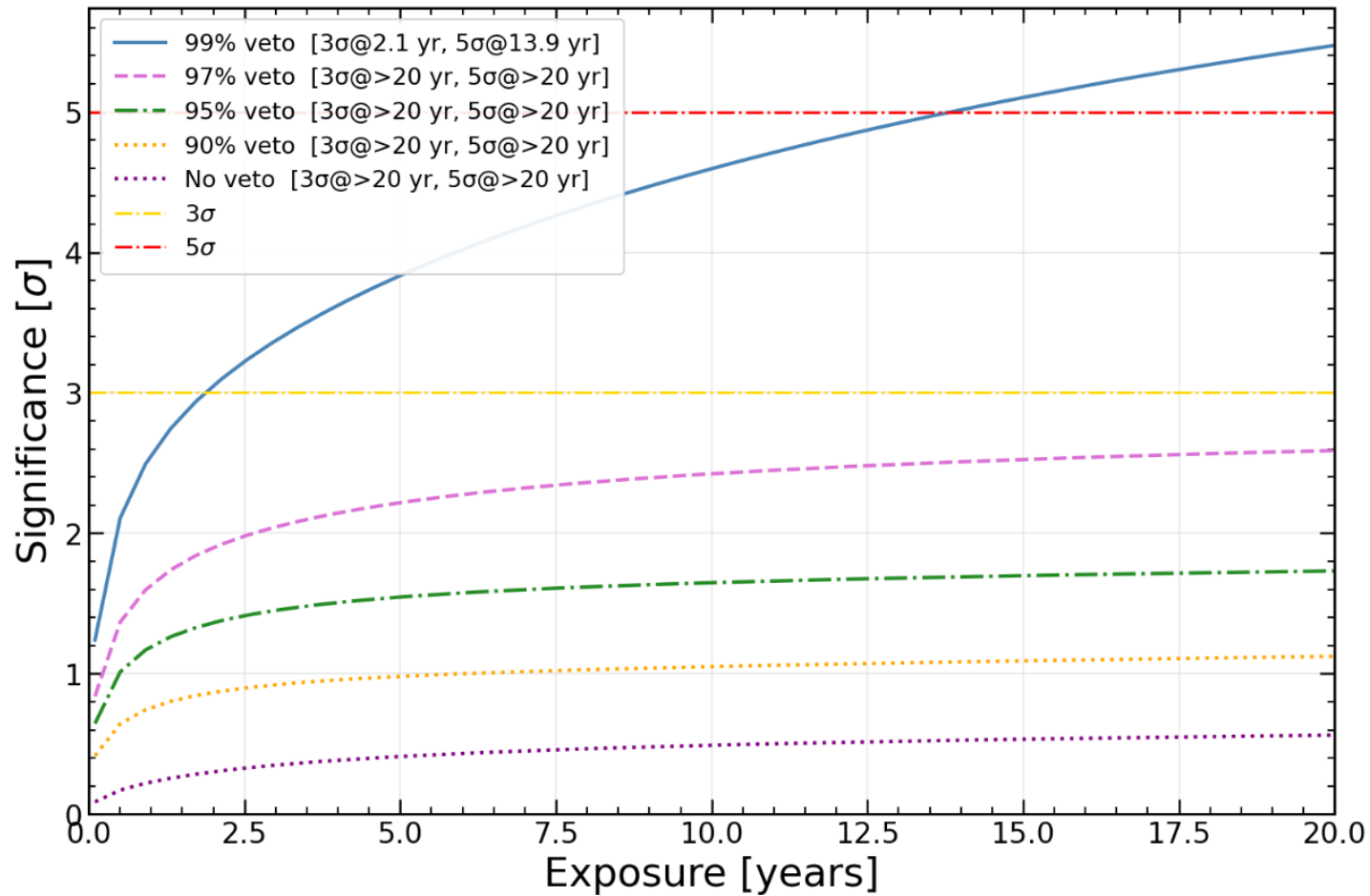
5 σ with normalization and resolution systematics only

$\approx 1.2\sigma$

after 20 years
with a 90% veto

**Environmental background
dominates the result**

hep discovery requires about 99% rejection

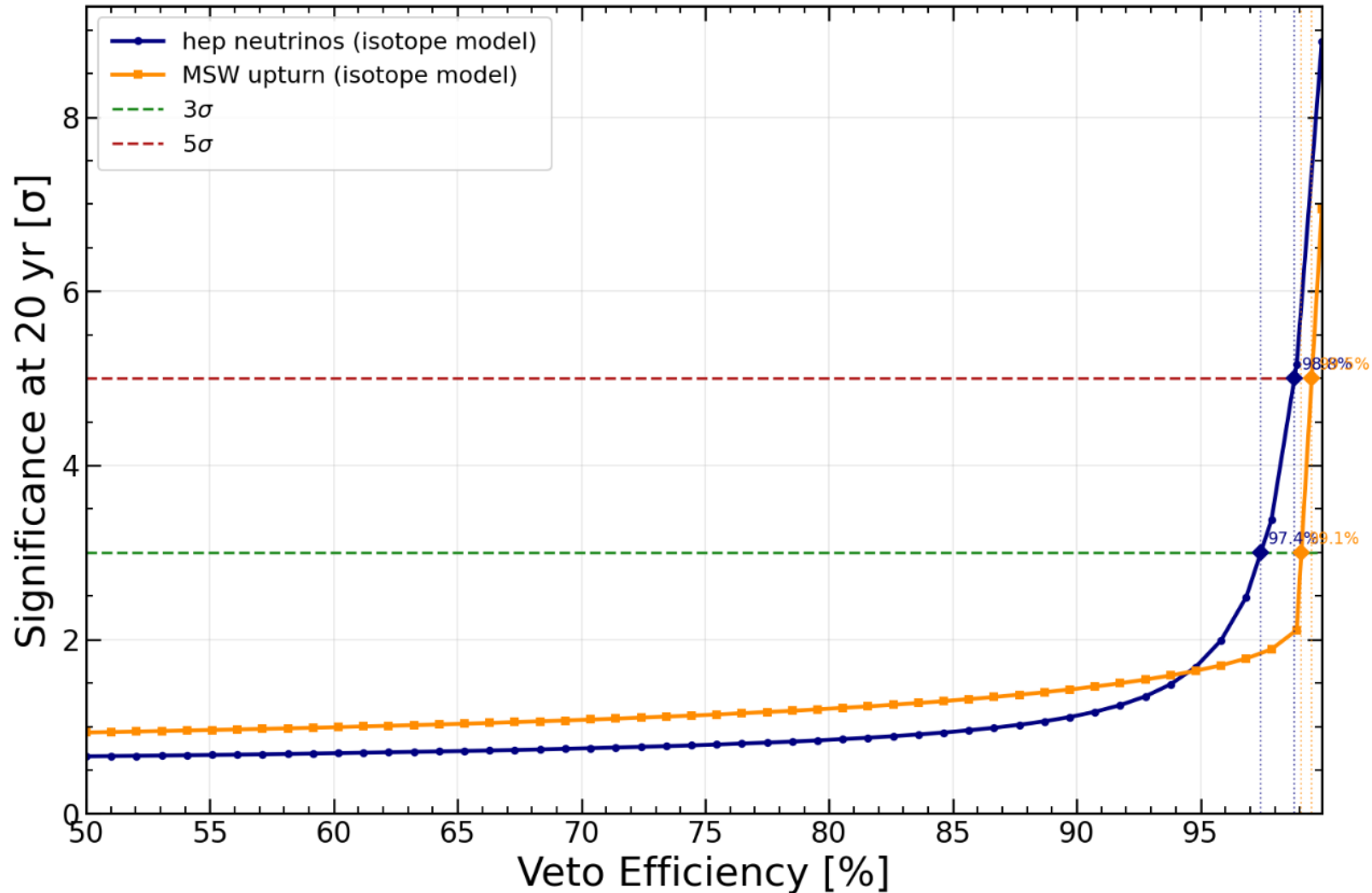


99% veto

3σ in 2.1 years
 5σ in 13.9 years

At 20 years: 3σ at 98.2%, 5σ at 99.1%

Both searches enter discovery near 99% rejection



98.2%

hep rejection for 3 σ

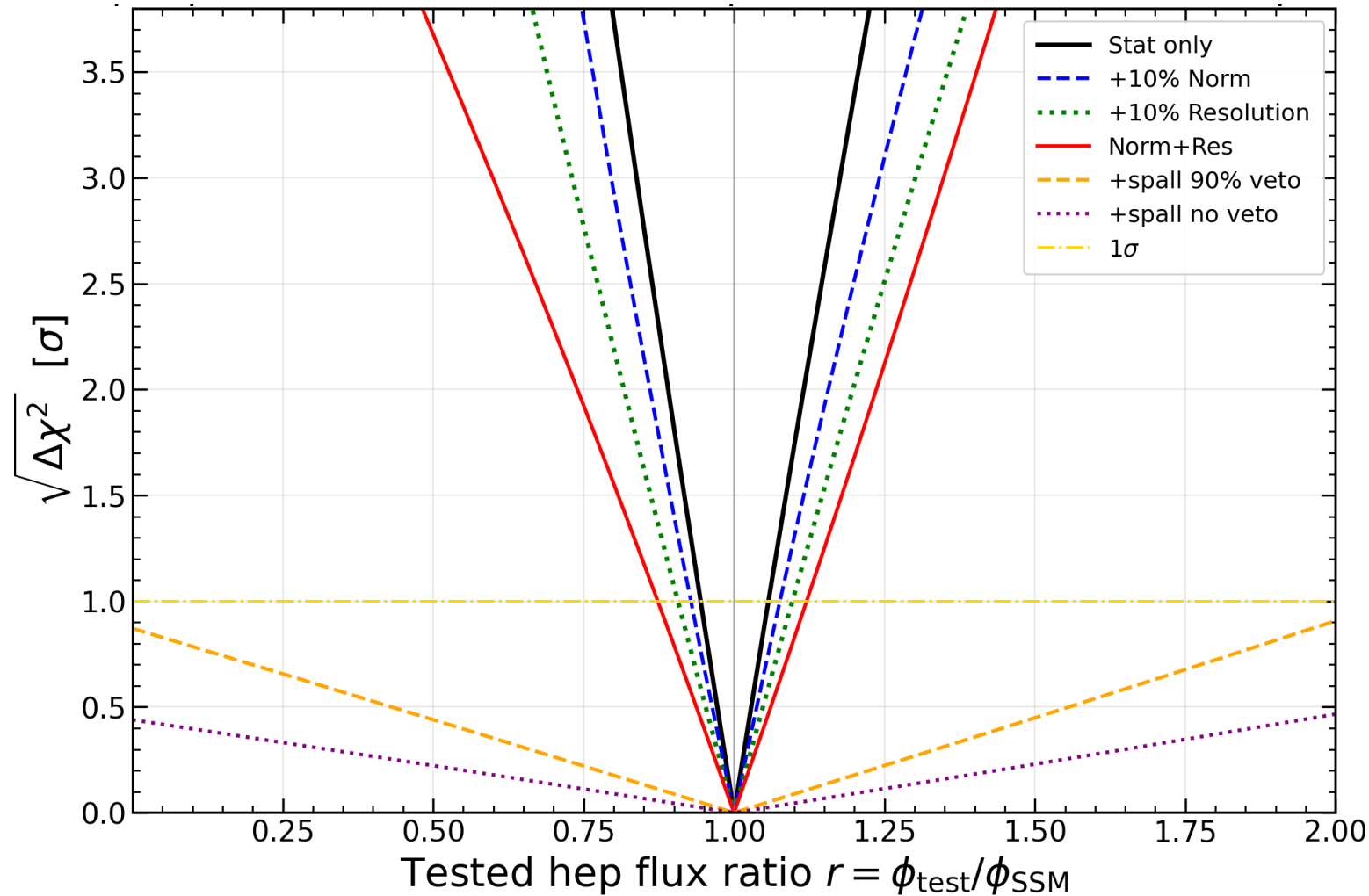
94.7%

upturn rejection for 3 σ

99.1%

rejection for 5 σ
for either target

Spallation also erases useful hep-flux precision



10-year exposure

6%

statistical only

12%

normalization and
resolution systematics

> factor 2

with 90%
spallation rejection

Conclusions

- ESSvSB's 540 kt fiducial mass may provide intrinsic sensitivity to both the ^8B MSW upturn and hep neutrinos.
- In the ideal-background case, 5σ requires about 6.2 years for the upturn and 4.2 years for hep once normalization and resolution systematics are included.
- Cosmogenic spallation controls the realistic reach; a 90% veto remains background dominated even after 20 years.
- Lower recoil thresholds can improve the upturn search
- A detector-specific simulation must validate isotope rates, veto performance, radon leakage, and the assumed energy response.
- Dedicated strategies to reduce drastically the spallation background is needed to improve the performances

$\approx 99\%$

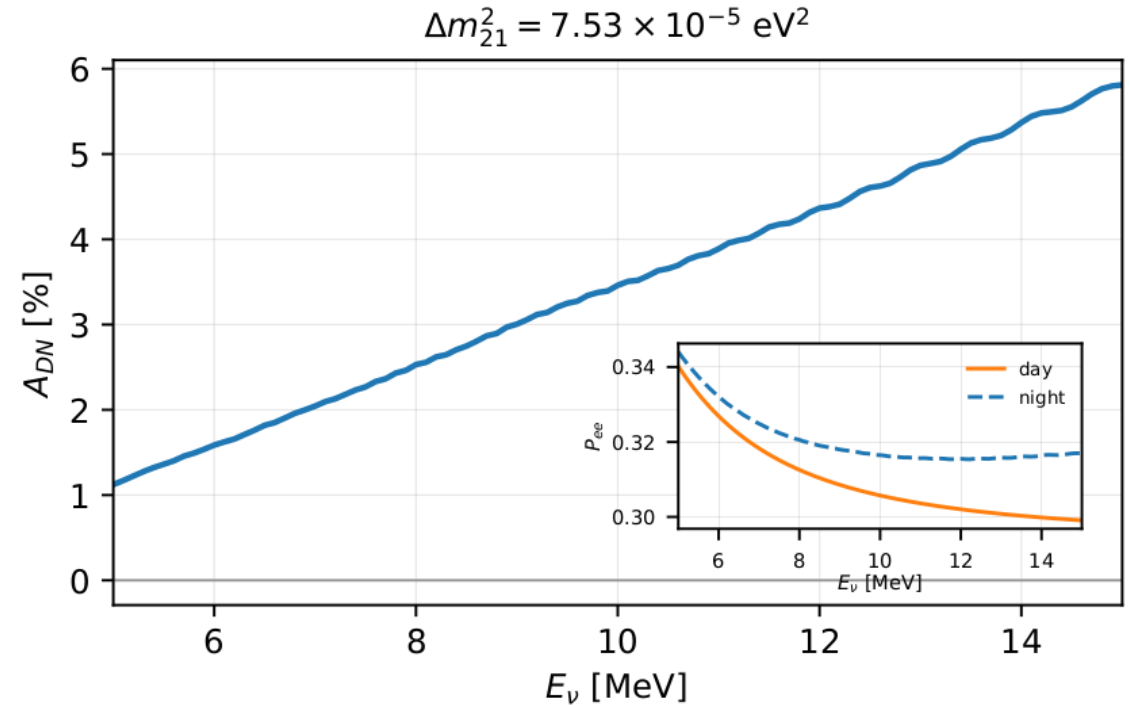
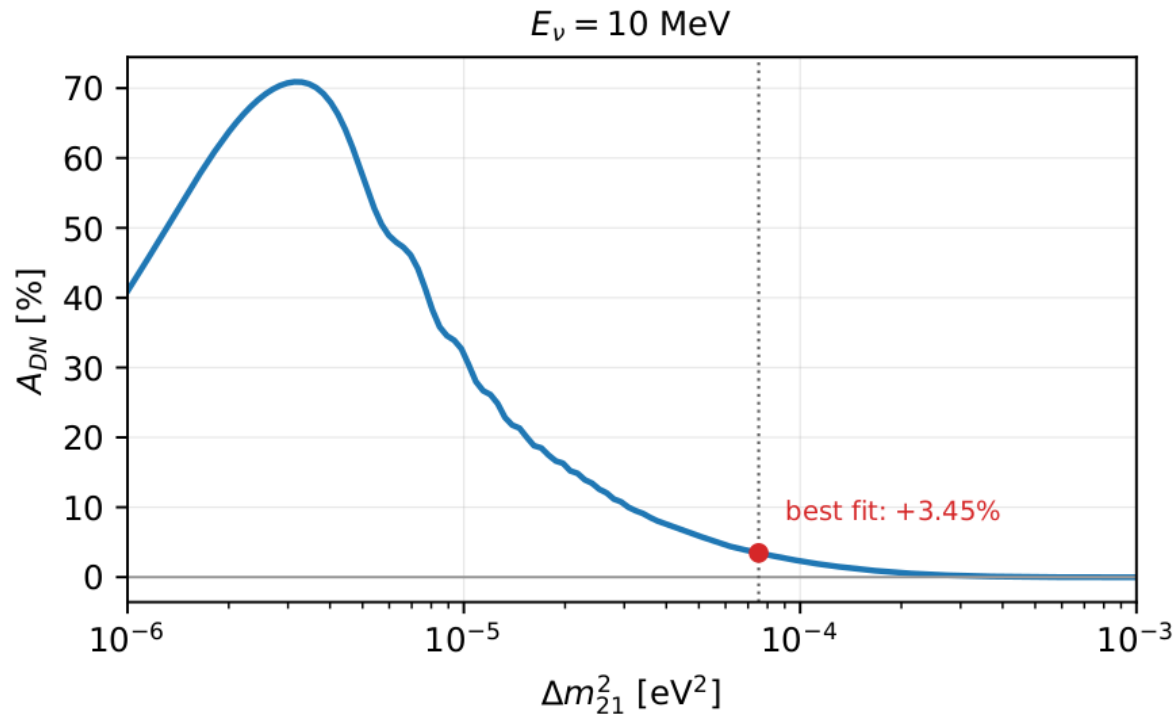
spallation rejection
needed for 5σ after 20
years in either target

90% veto

$\approx 2.3\sigma$ upturn
 $\approx 1.2\sigma$ hep after 20
years

A further analysis: a complementary day-night signal

$$A_{DN} = 2 \frac{R_N - R_D}{R_N + R_D},$$



$\approx 3.4\%$

at $E_\nu = 10 \text{ MeV}$

59° N

Zinkgruvan latitude

Annual average

Seasonal structure may carry additional information.