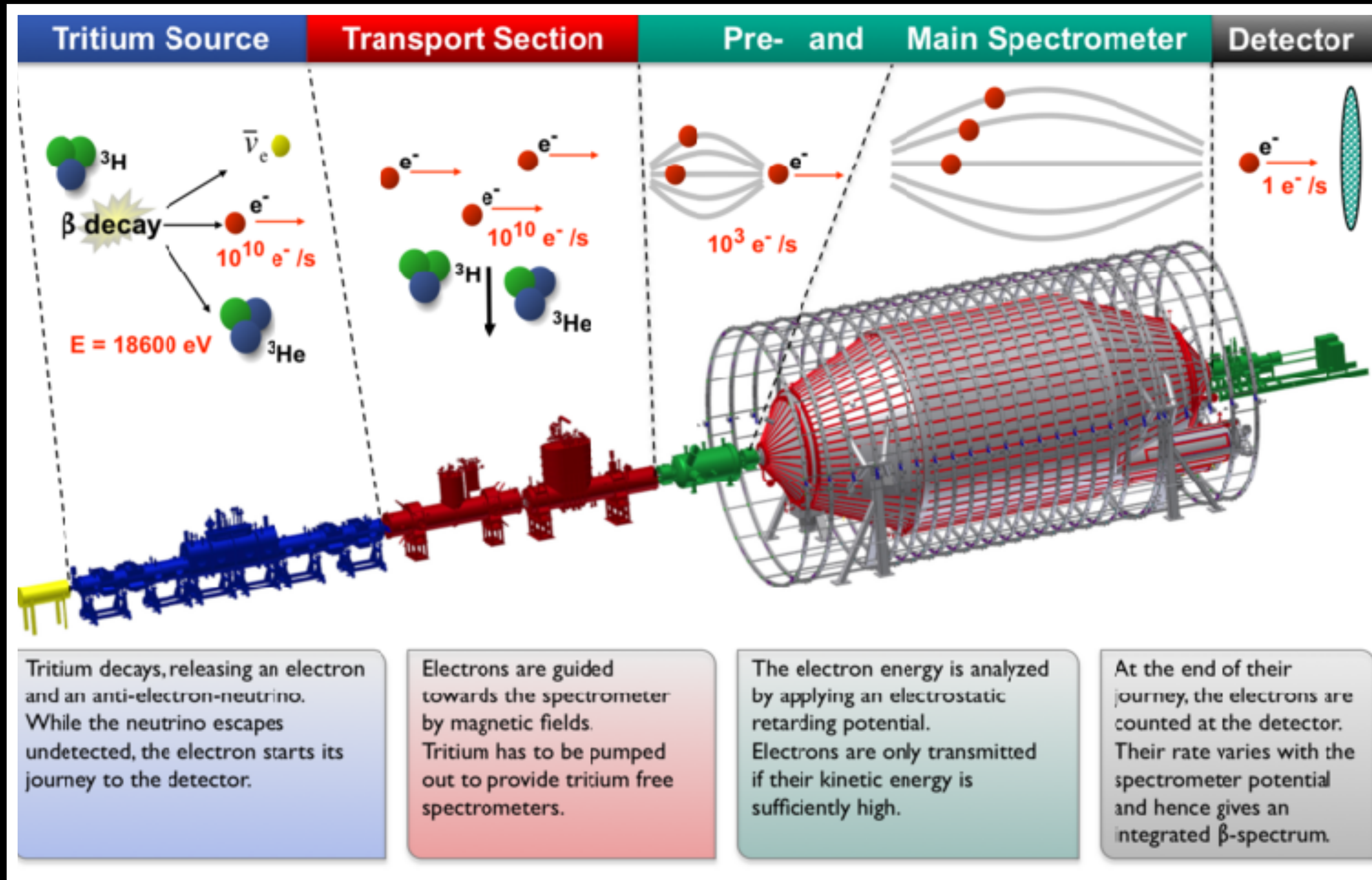
Beyond SM Sensitivity with KATRIN

Nicholas Steinbrink

RTG 2149 Retreat 2016, Körbecke

KATRIN

Because Size Does Matter



http://katrin.kit.edu

- Worlds strongest Tritium source (10^{11} Bq)
- Worlds sharpest MAC-E-Filter (1 eV)
- **Worlds best neutrino mass sensitivity (0.2 eV)**

Neutrino Mass

- Seesaw (1 generation):

$$\mathcal{L}_{\mathrm{mass},\nu} = -\frac{1}{2}(\bar{\nu}_L, (\bar{\nu}_R)^C) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ \nu_R \end{pmatrix}$$

- Set $m_L = 0$ (Seesaw Type I), diagonalisation

$$m_l = \frac{m_D^2}{m_R} \qquad m_h = m_R$$

- In reality more complex…

The truth is out there…

- Increase neutrino mass sensitivity
- Find keV sterile neutrinos
- Find right-handed currents and eV sterile neutrinos

The truth is out there...

- Increase neutrino mass sensitivity
- Find keV sterile neutrinos
- Find right-handed currents and eV sterile neutrinos

My job: simulate!

Pars Prima

❦

Increase Neutrino Mass Sensitivity

Increase Neutrino Mass Sensitivity

- Seesaw (1 generation):

$$\mathcal{L}_{\mathrm{mass},\nu} = -\frac{1}{2}(\bar{\nu}_L, (\bar{\nu}_R)^C) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ \nu_R \end{pmatrix}$$

- Set $m_L = 0$ (Seesaw Type I), diagonalisation

$$m_l = \frac{m_D^2}{m_R} \qquad m_h = m_R$$

- In reality more complex…

Increase Neutrino Mass Sensitivity

- Seesaw (1 generation):

$$\mathcal{L}_{\mathrm{mass},\nu} = -\frac{1}{2}(\bar{\nu}_L, (\bar{\nu}_R)^C) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ \nu_R \end{pmatrix}$$

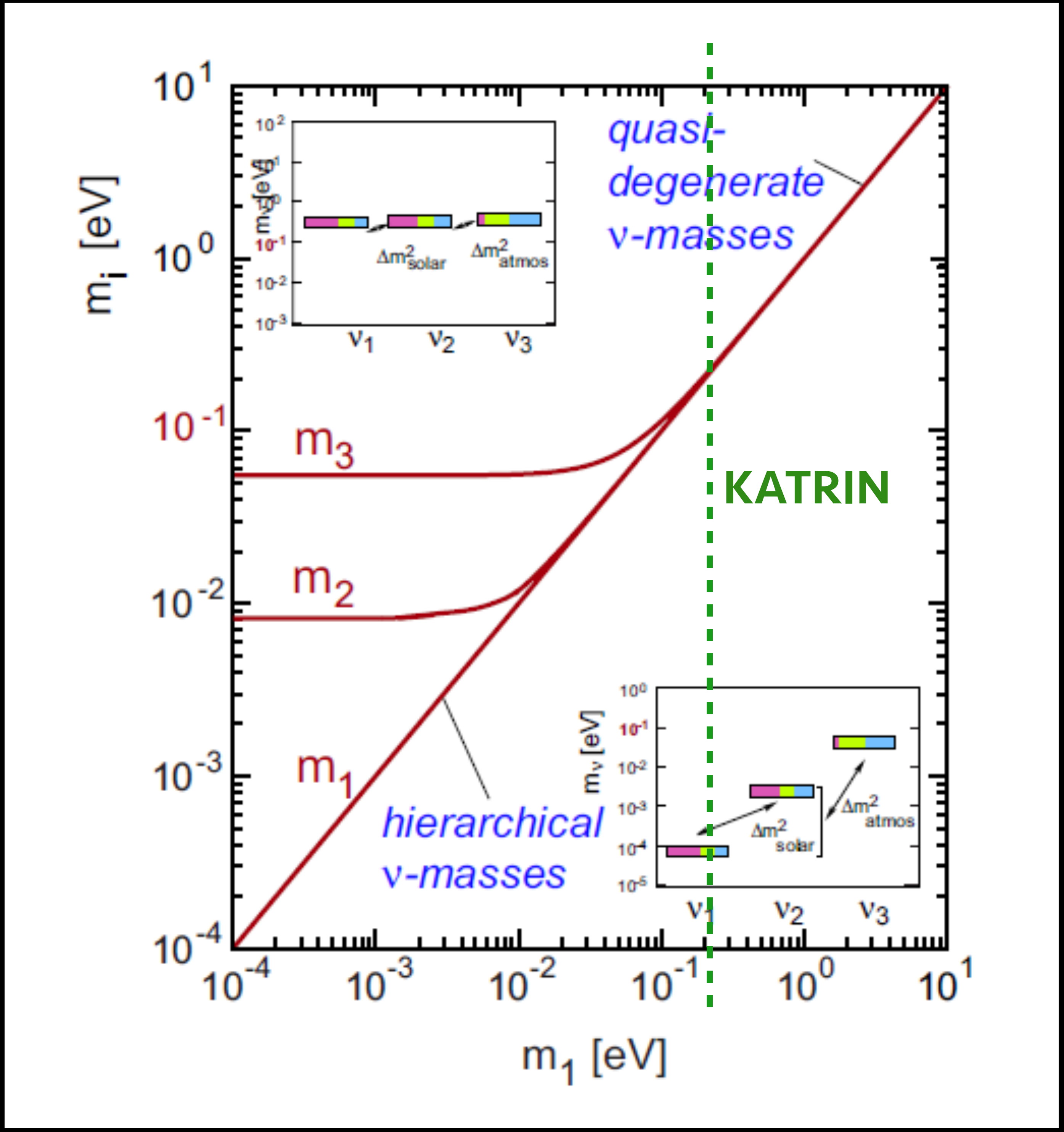
- Set $m_L = 0$ (Seesaw Type I), diagonalisation

$$m_l = \frac{m_D^2}{m_R} \qquad m_h = m_R$$

- In reality more complex…

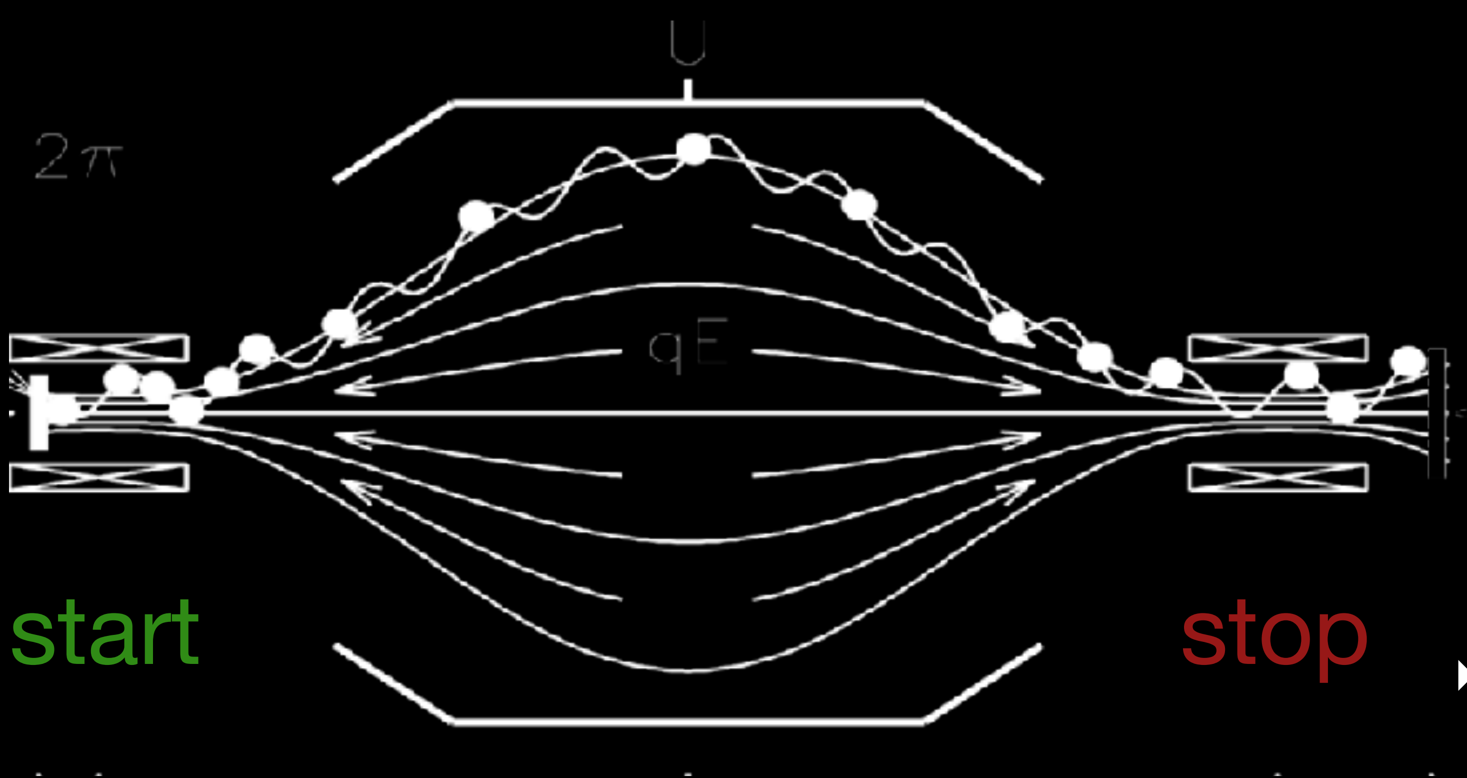
Increase Neutrino Mass Sensitivity

- Cosmologists: no way, KATRIN!
  - Planck + BAO: $m_1 + m_2 + m_3 < 0.23$ eV
- Descend into hierarchical region
- Idea: TOF spectroscopy



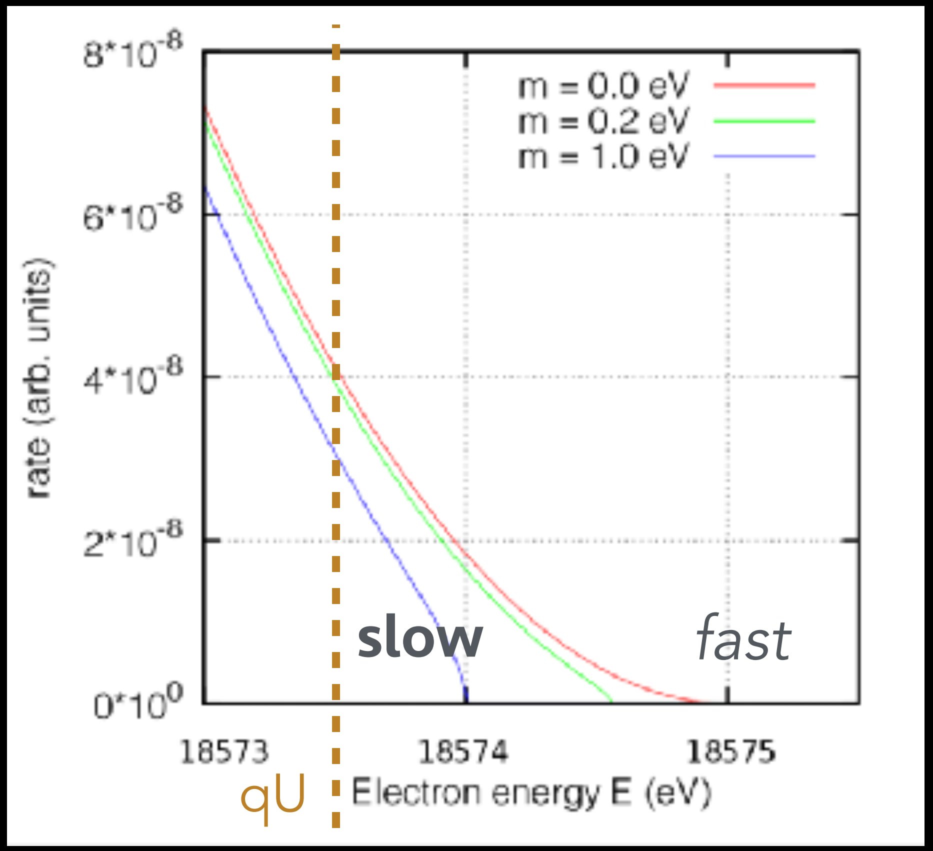
KATRIN Design Report (2004)

TOF Spectroscopy



$$TOF = \int_{start}^{stop} 1/v_{\parallel} = \mathrm{f}(\mathrm{E}, \theta)$$

M. Zacher, Diploma Thesis



- Classic mode: **integral**
  - MAC-E-Filter = high-pass filter, transmits e⁻ above threshold *qU* ("integrates")
- TOF mode: **differential**
  - Given *qU*, e⁻ TOF spectrum ~ isomorphic to energy spectrum above *qU*

New Journal of Physics
The open access journal for physics

Neutrino mass sensitivity by MAC-E-Filter based time-of-flight spectroscopy with the example of KATRIN

Nicholas Steinbrink[1,3], Volker Hannen[1], Eric L Martin[2], R G Hamish Robertson[2], Michael Zacher[1] and Christian Weinheimer[1]

[1] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Wilhelm Klemm-Strasse 9, D-48149 Münster, Germany

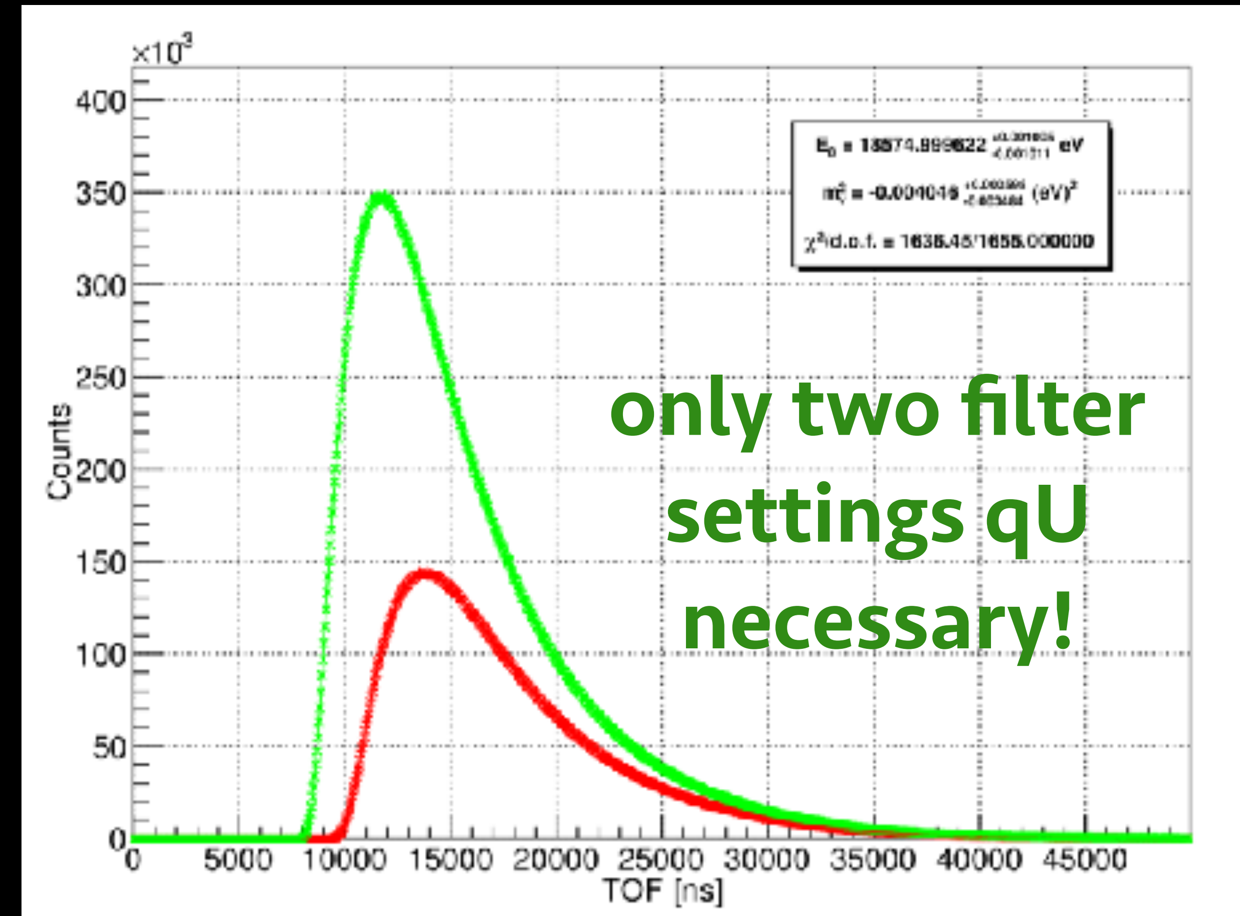
[2] Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA, USA

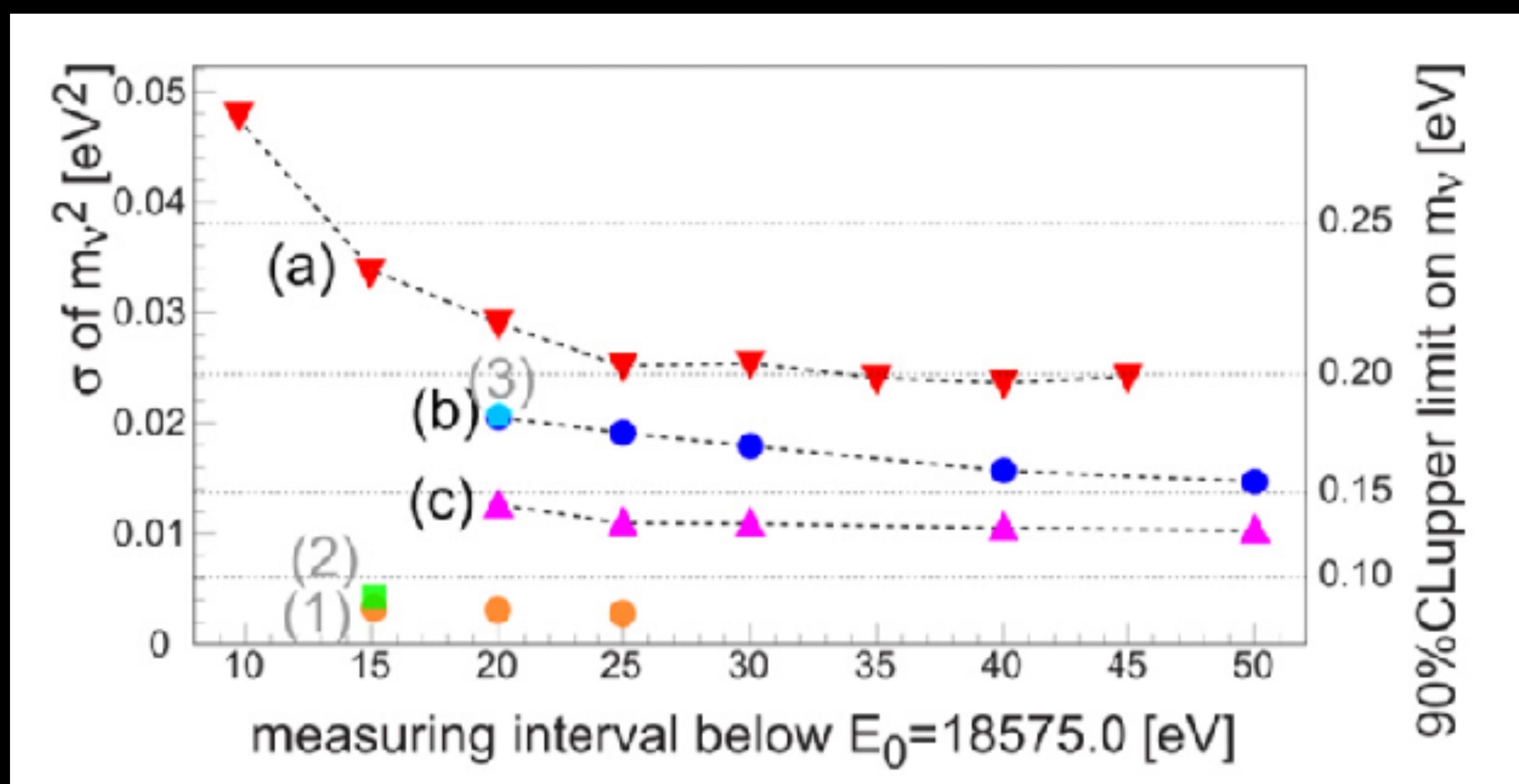
E-mail: n.steinbrink@uni-muenster.de

New Journal of Physics **15** (2013) 113020 (29pp)
Received 6 August 2013
Published 11 November 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/11/113020

Results

- Ideal TOF mode (tagger): Improvement of statistical sensitivity up to a factor 2!
- Background almost no deal





a) KATRIN old design
b) KATRIN current design
c) KATRIN w reduced background

1) ideal TOF
2) ideal TOF w. bg & time res.
3) Gated Filter TOF (pulsed pre-spec)

Pars Secunda

❦ ❦

Find keV Sterile Neutrinos

Find keV sterile neutrinos

- Seesaw (1 generation):

$$\mathcal{L}_{\text{mass},\nu} = -\frac{1}{2}(\bar{\nu}_L, (\bar{\nu}_R)^C) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ \nu_R \end{pmatrix}$$

- Set $m_L = 0$ (Seesaw Type I), diagonalisation

$$m_l = \frac{m_D^2}{m_R} \qquad m_h = m_R$$

- In reality more complex…

Find keV sterile neutrinos

- Seesaw (1 generation):

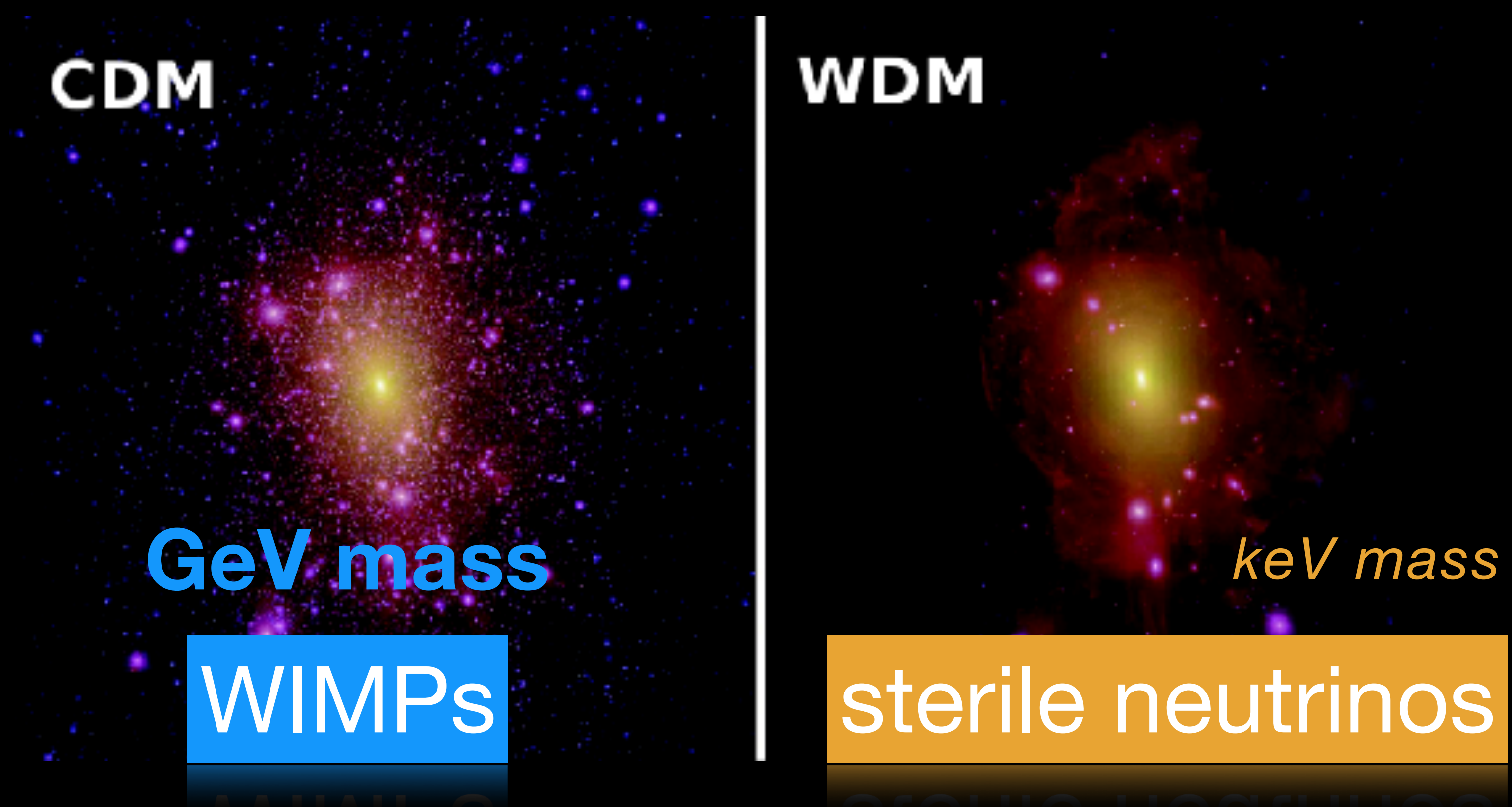
$$\mathcal{L}_{\text{mass},\nu} = -\frac{1}{2}(\bar{\nu}_L, (\bar{\nu}_R)^C) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ \nu_R \end{pmatrix}$$

- Set $m_L = 0$ (Seesaw Type I), diagonalisation

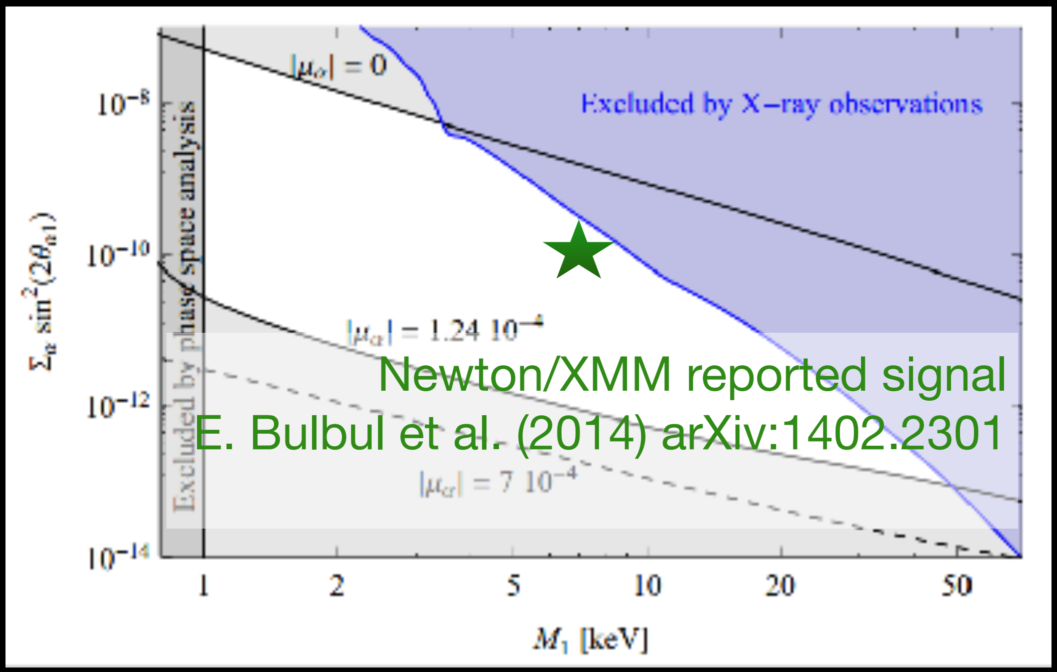
$$m_l = \frac{m_D^2}{m_R} \qquad m_h = m_R$$

- In reality more complex…

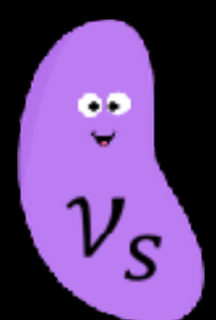
Find keV sterile neutrinos



Simulation, Lovell et al. (2012), CIAS Meudon Workshop 2012



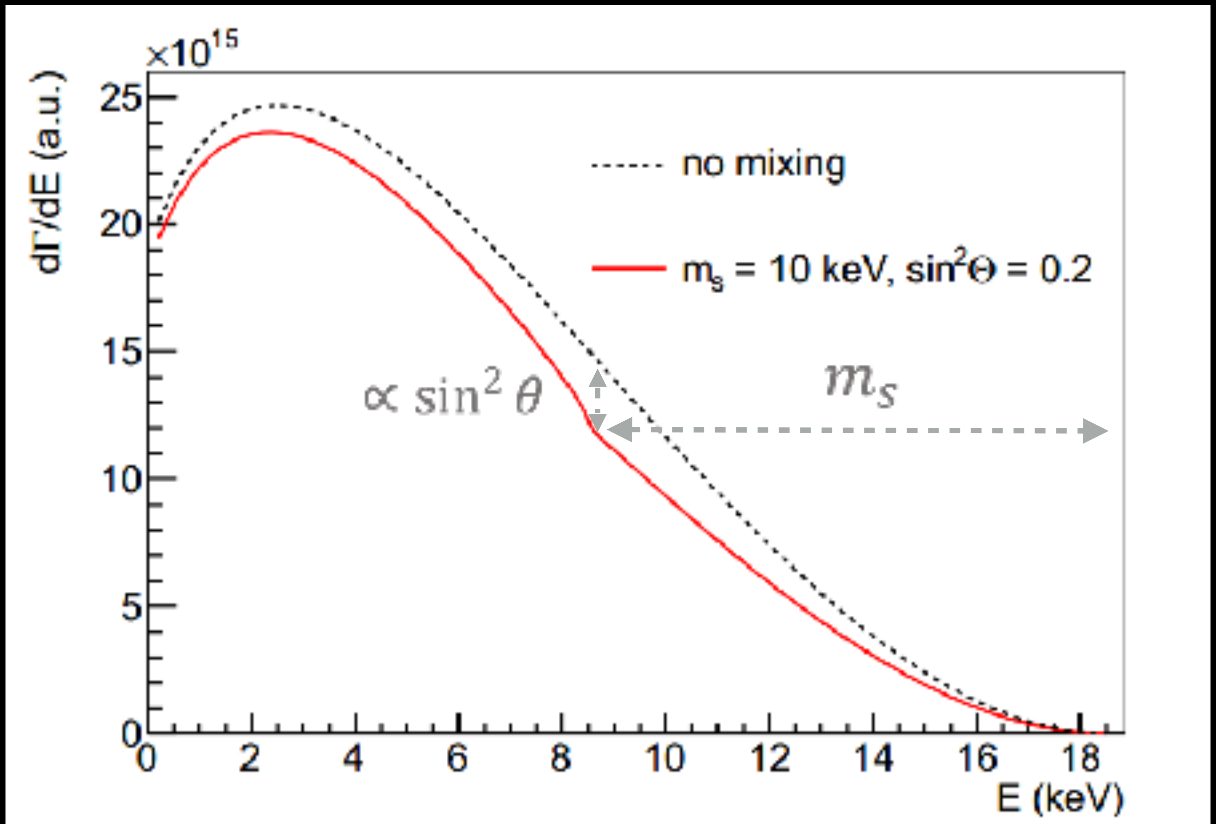
Canetti et al, Phys. Rev. D87 (2013) 093006



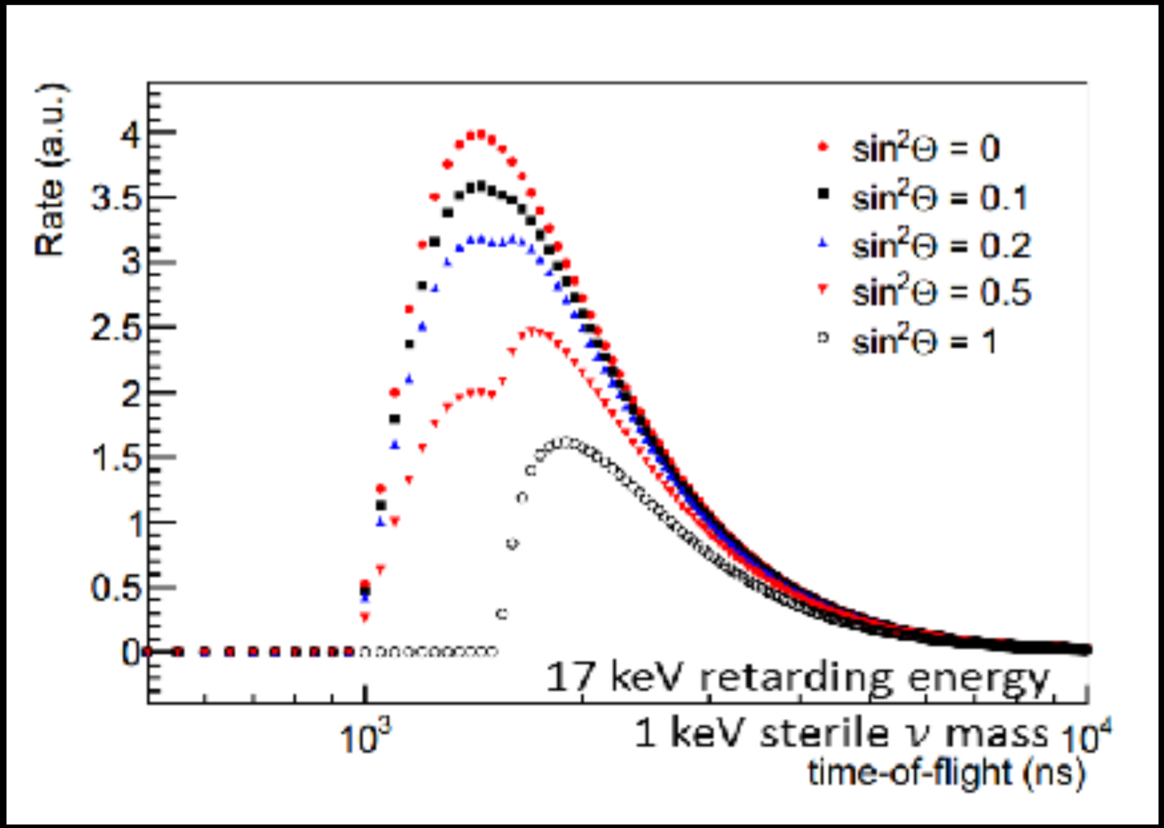
$$\sin^2\theta \leq 10^{-8}$$

Sterile ν in KATRIN - searching for the *kink*

Energy



TOF



S. Mertens et al. JCAP02(2015)020

$$R_{tot} = \cos^2\theta R(m_l) + \sin^2\theta R(m_h)$$

High rate, tiny signal, many systematics

Approaches:

- Differential detector (S. Mertens et al.)
- TOF (NS)

Sensitivity estimation method

- **~10^{18} events expected!** Now try classic Monte Carlo…
- Alternative simulation strategy: divide et impera (or some other name)
- Approximate model Φ by splitting

$$\Phi' = c_S \Phi_S + c_B \Phi'_B$$

Signal
Realistic

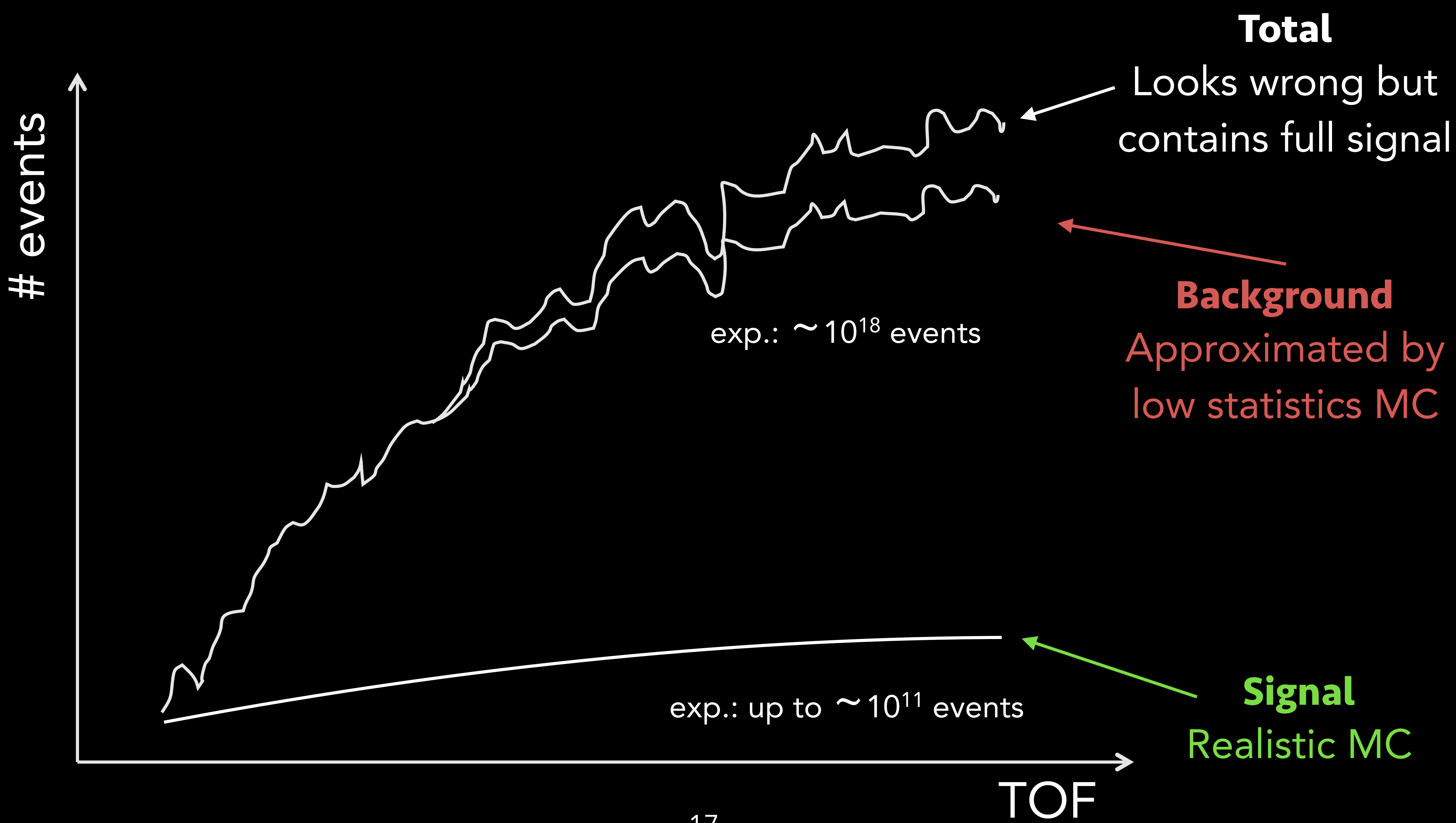
Background
Approximated

- Natural solution for sterile neutrinos
  - linear combination
  - coefficient $c_S = \sin^2\theta$ very small

Trick 1: different model but result correct!

Importance sampling, ya know?

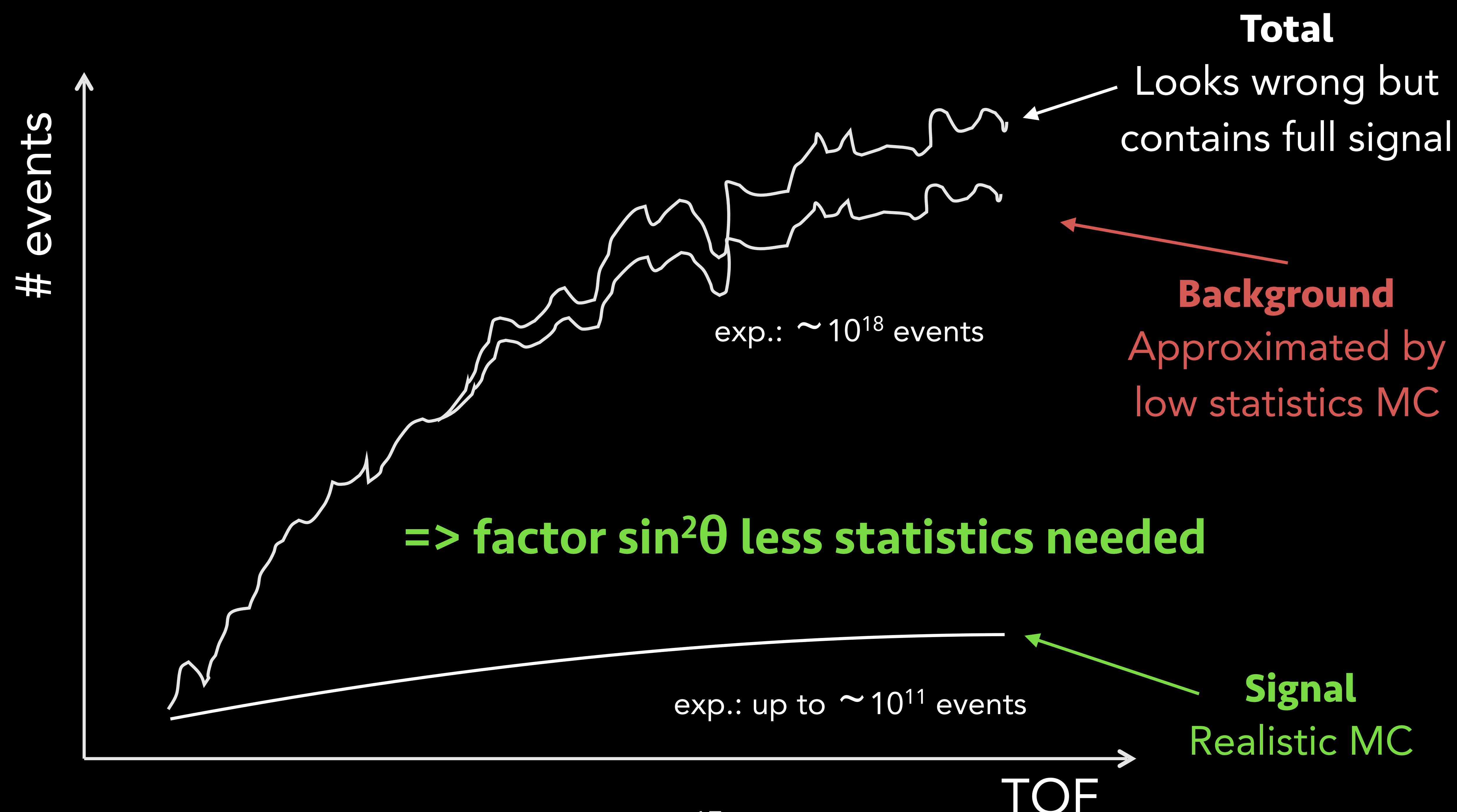
- Reason: χ^2 width for $\sin^2\theta$ only depends on signal :)



Trick 1: different model but result correct!

Importance sampling, ya know?

- Reason: χ^2 width for $\sin^2\theta$ only depends on signal :)



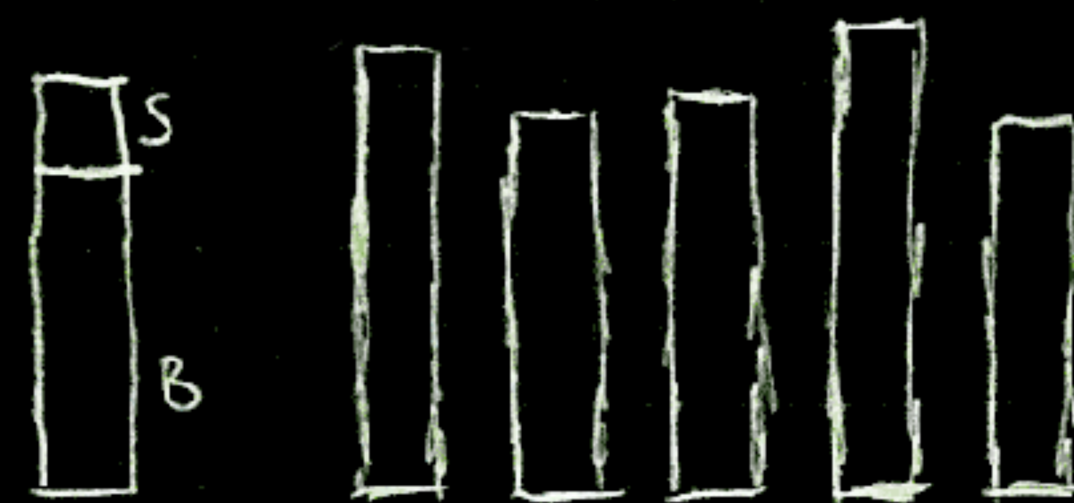
Trick 2: relative variance reduction

Remember: max. 10^{11} signal events expected. Do we need > 10^{11} MC samples?

- No. And here's why.

Background

- Always signal PLUS background measured
- Theor. signal variance only needs to be smaller than total variance



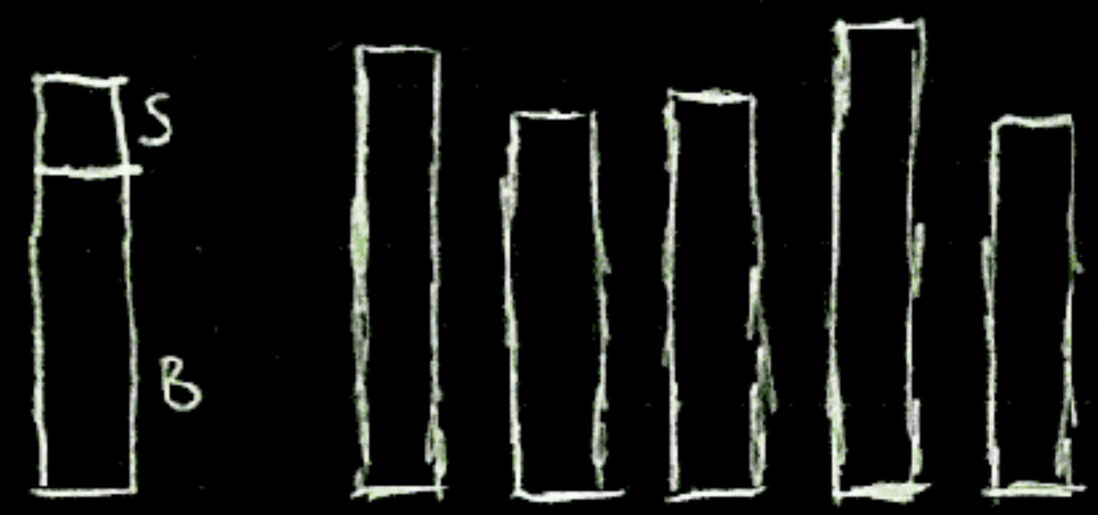
Trick 2: relative variance reduction

Remember: max. 10^{11} signal events expected. Do we need > 10^{11} MC samples?

- No. And here's why.

Background

- Always signal PLUS background measured
- Theor. signal variance only needs to be smaller than total variance



=> yet another factor $\sin^2\theta$ less statistics needed

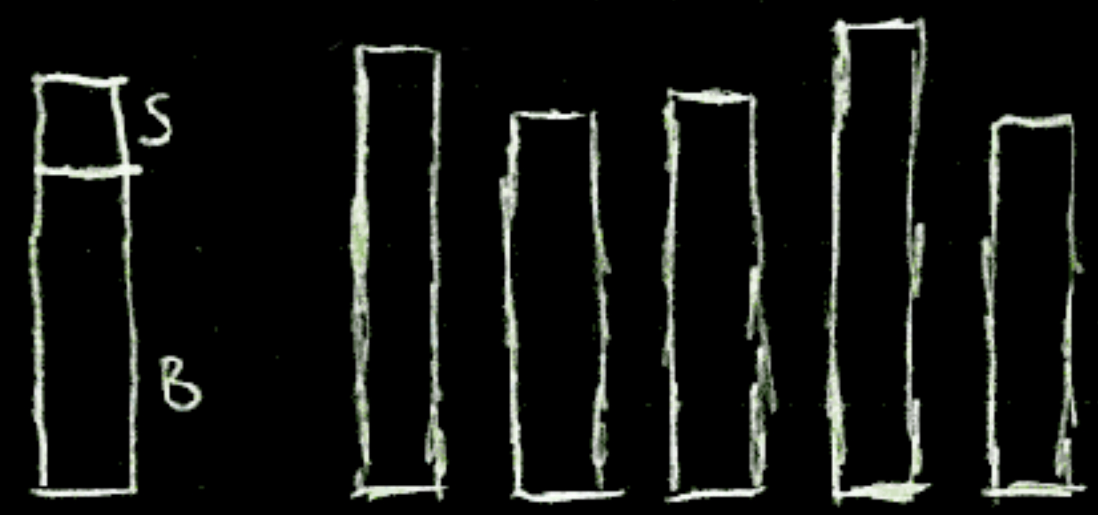
Trick 2: relative variance reduction

Remember: max. 10^{11} signal events expected. Do we need > 10^{11} MC samples?

- No. And here's why.

Background

- Always signal PLUS background measured
- Theor. signal variance only needs to be smaller than total variance

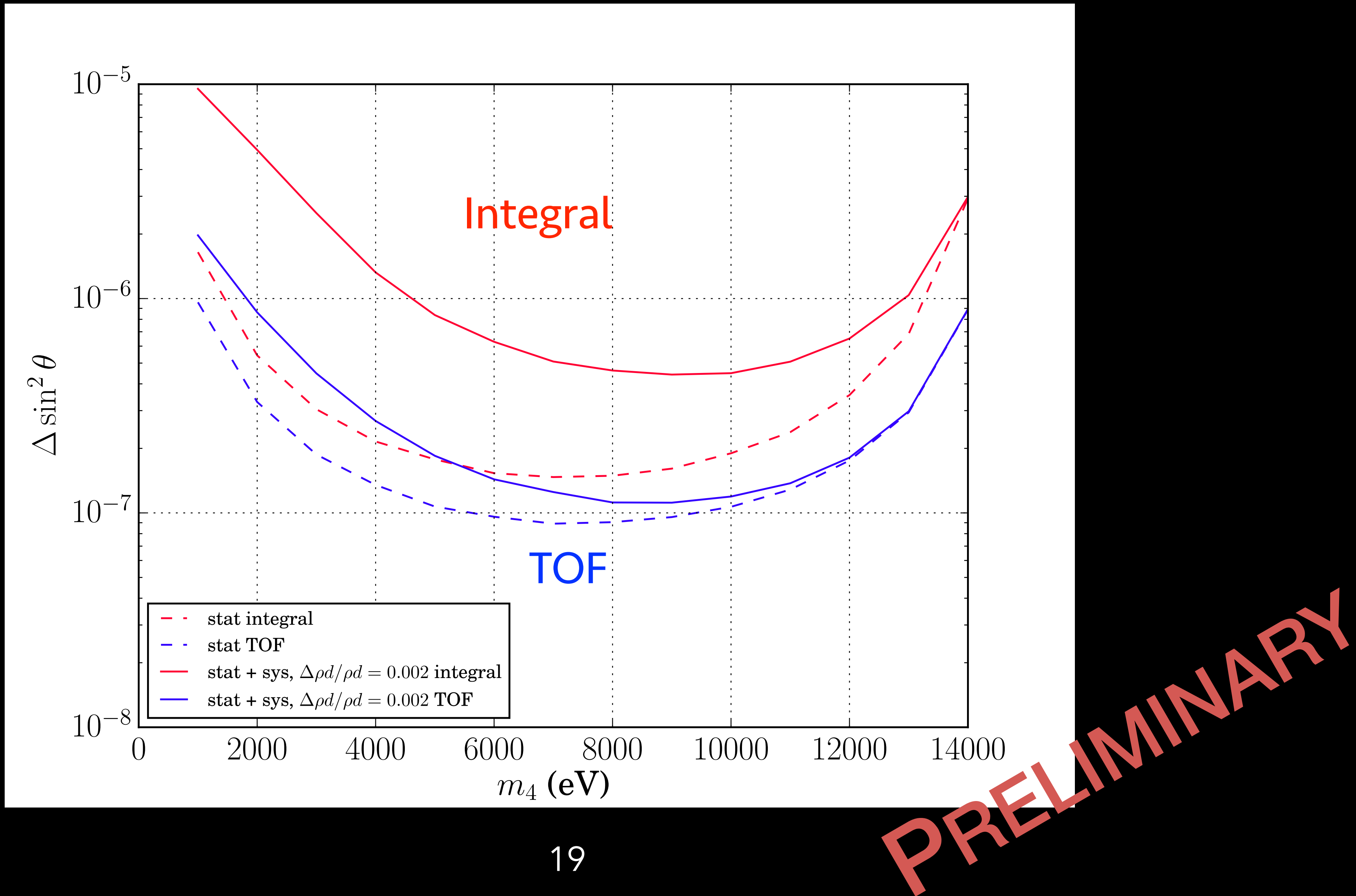


=> yet another factor $\sin^2\theta$ less statistics needed

==> total reduction: $\sin^4\theta$!!!

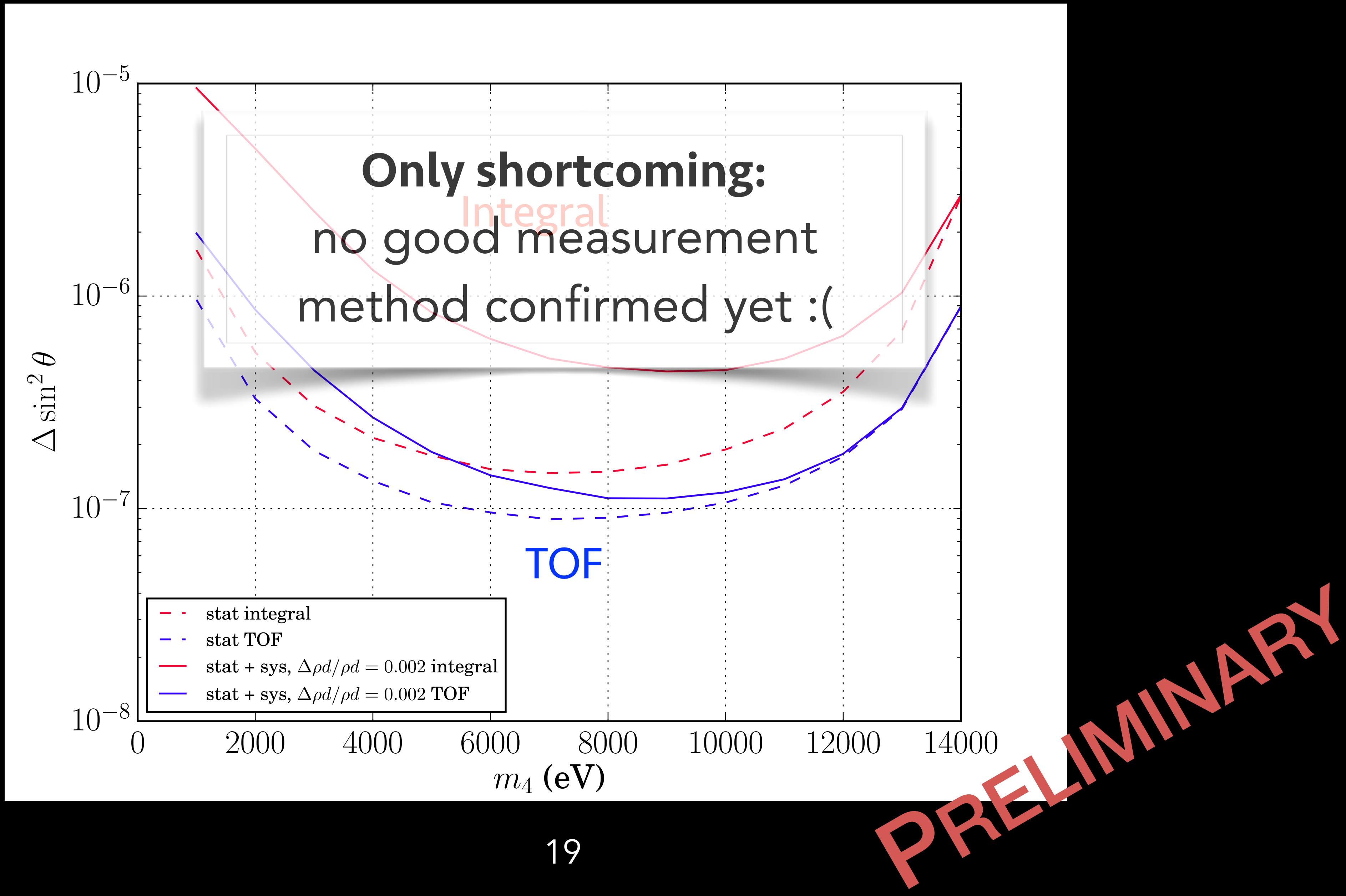
Sensitivity for ideal TOF mode

- Stat + exemplary systematics (inelastic scattering cross section)
- **Overall sensitivity improvement by ~ factor 5** (≙ 25 x more measurement time)
- **Significant systematics reduction**



Sensitivity for ideal TOF mode

- Stat + exemplary systematics (inelastic scattering cross section)
- **Overall sensitivity improvement by ~ factor 5** (≙ 25 x more measurement time)
- **Significant systematics reduction**



Pars Tertia

❦ ❦ ❦

Find right-handed currents and eV sterile neutrinos

Aarhus, DK

Find right-handed currents and eV scale sterile neutrinos

- Seesaw (1 generation):

$$\mathcal{L}_{\mathrm{mass},\nu} = -\frac{1}{2}(\bar{\nu}_L, (\bar{\nu}_R)^C) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ \nu_R \end{pmatrix}$$

- Set m_L = 0 (Seesaw Type I), diagonalisation

$$m_l = \frac{m_D^2}{m_R} \qquad m_h = m_R$$

- In reality more complex...

Find right-handed currents and eV scale sterile neutrinos

just a little hint…

- Seesaw (1 generation):

$$\mathcal{L}_{\mathrm{mass},\nu} = -\frac{1}{2}(\bar{\nu}_L, (\bar{\nu}_R)^C) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_L)^C \\ \nu_R \end{pmatrix}$$

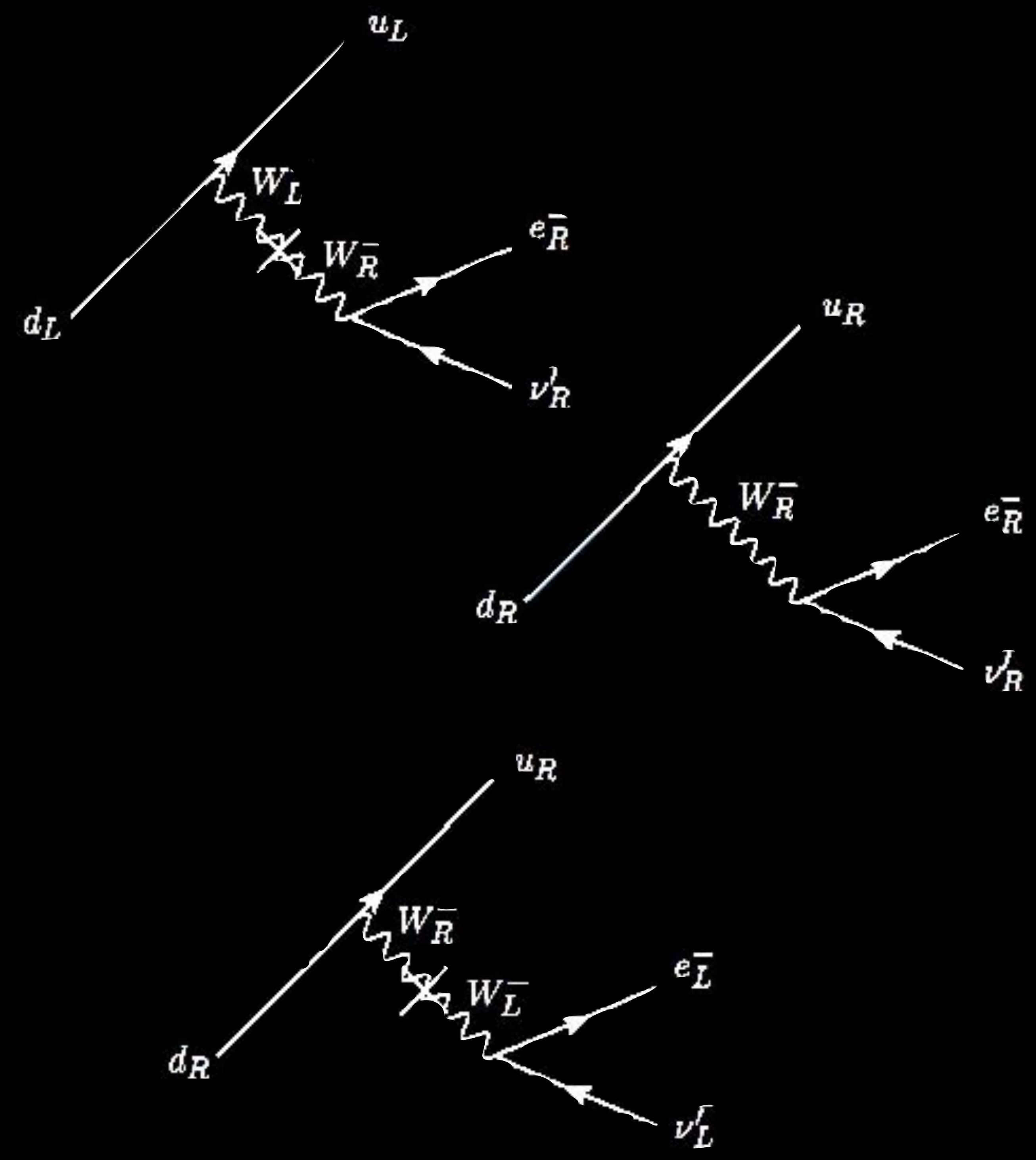
- Set m_L = 0 (Seesaw Type I), diagonalisation

$$m_l = \frac{m_D^2}{m_R} \qquad m_h = m_R$$

- In reality more complex…

Right handed currents

- Occur e.g. in **left-right-symmetric models** $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Couple to right handed particles.
- Possible mixing/oscillation between W_L and W_R bosons



Beta spectrum in LR symmetric theory

Derived from
Barry, Rodejohann et al., JHEP07(2014)081

$$
\begin{aligned}
\frac{\mathrm{d}\Gamma}{\mathrm{d}E} &= \frac{\mathrm{d}\Gamma_h}{\mathrm{d}E}\cdot\left(a_{LL}\ \sin^2\theta + a_{RR}\ \cos^2\theta\right) \\
&+ \frac{\mathrm{d}\Gamma_l}{\mathrm{d}E}\cdot\left(a_{LL}\ \cos^2\theta + a_{RR}\ \sin^2\theta\right) \\
&+ \frac{\mathrm{d}\Gamma_h}{\mathrm{d}E}\cdot\frac{m_h}{E_0 - E}\ a_{LR}\ \cos\theta\sin\theta \\
&+ \frac{\mathrm{d}\Gamma_l}{\mathrm{d}E}\cdot\frac{m_l}{E_0 - E}\ a_{LR}\ \cos\theta\sin\theta
\end{aligned}
$$

$$a_{LL} = 1 + 2C\tan\xi\cos\alpha\ ,$$

$$a_{RR} = \frac{m_{W_L}^4}{m_{W_R}^4} + \tan^2\xi + 2C\frac{m_{W_L}^2}{m_{W_R}^2}\tan\xi\cos\alpha\ ,$$

$$a_{LR} = \frac{m_{W_L}^2}{m_{W_R}^2} + C\tan\xi\cos\alpha$$

$$C = \frac{g_V^2 - 3g_A^2}{g_V^2 + 3g_A} \simeq -0.65$$

- θ: active sterile mixing angle
- $m_{h/l}$: sterile/active ν mass
- $d\Gamma_{h/l}/dE$: raw β spectrum with neutrino mass $m_{h/l}$, respectively

- ξ: W_L/W_R mixing angle
- α: CP violating phase

Model-independent reparametrization

- Effective mixing $\sin^2\theta_{\text{eff}}$

$$(a_{LL} + a_{RR}) \sin^2 \theta_{\text{eff}} = a_{LL} \sin^2 \theta + a_{RR} \cos^2 \theta$$

- Effective right handed coupling strength c_{RH}

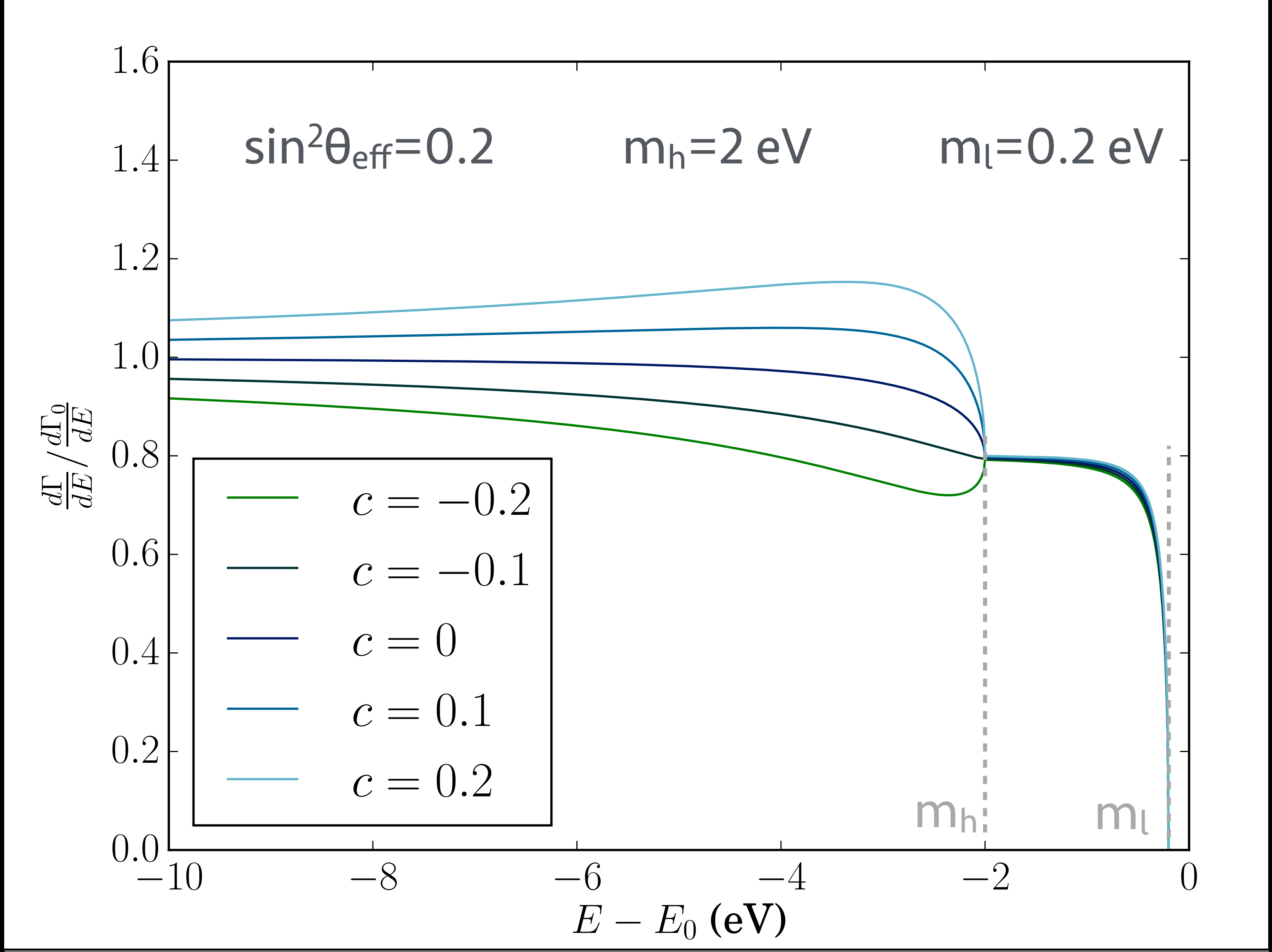
$$c_{\text{RH}} = \frac{a_{LR}}{a_{LL} + a_{RR}} \cos\theta \sin\theta$$

- Model-independent feature: right-handed terms $\propto m_\nu/E\text{-}E_0$

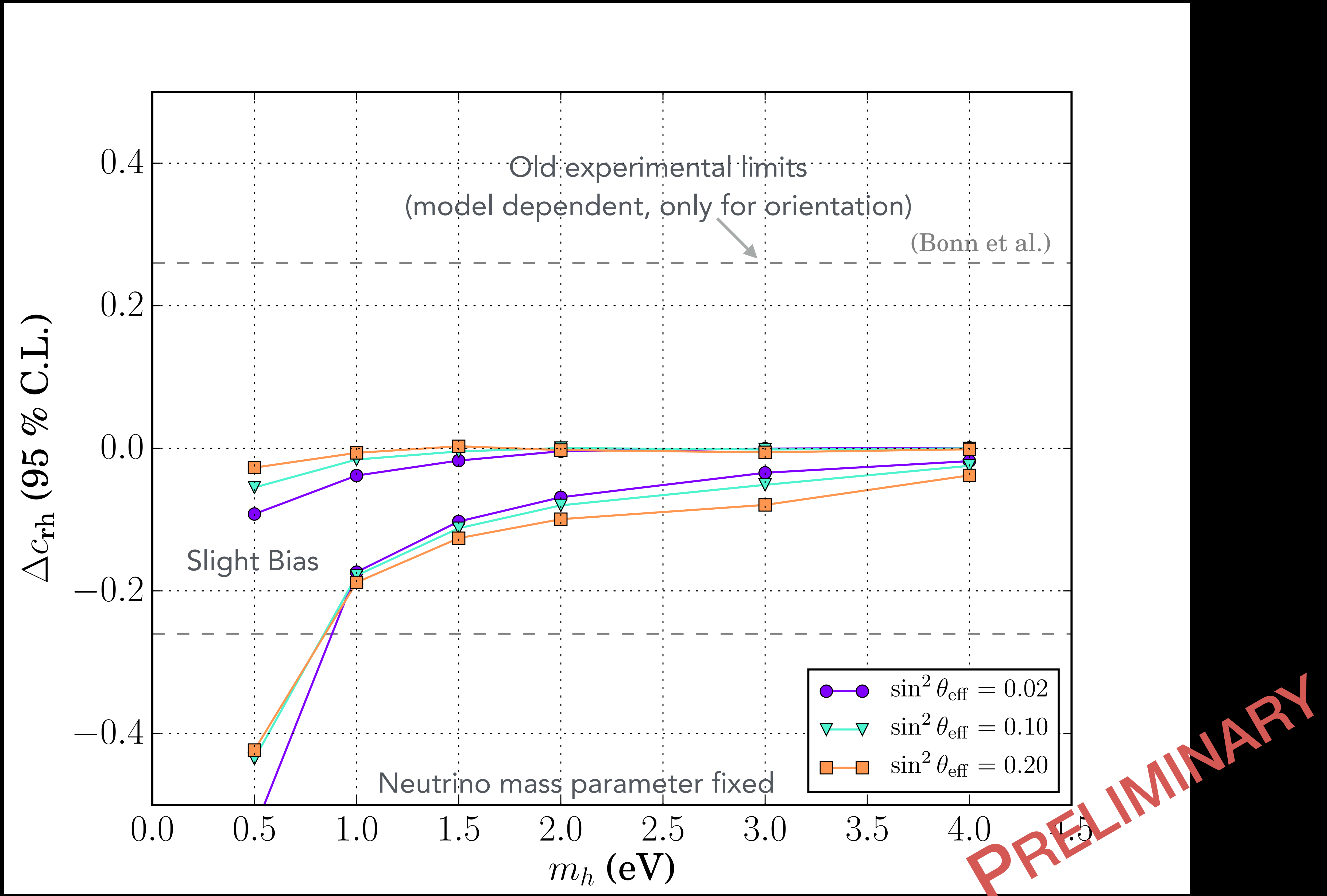
$$\frac{d\Gamma}{dE} = \frac{d\Gamma'_h}{dE} \cdot \sin^2 \theta_{\text{eff}} + \frac{d\Gamma'_l}{dE} \cdot \cos^2 \theta_{\text{eff}} + c_{\text{RH}} \cdot \left(\frac{d\Gamma'_h}{dE} \cdot \frac{m_h}{E_0 - E} + \frac{d\Gamma'_l}{dE} \cdot \frac{m_l}{E_0 - E} \right)$$

eff. RH coupling strength

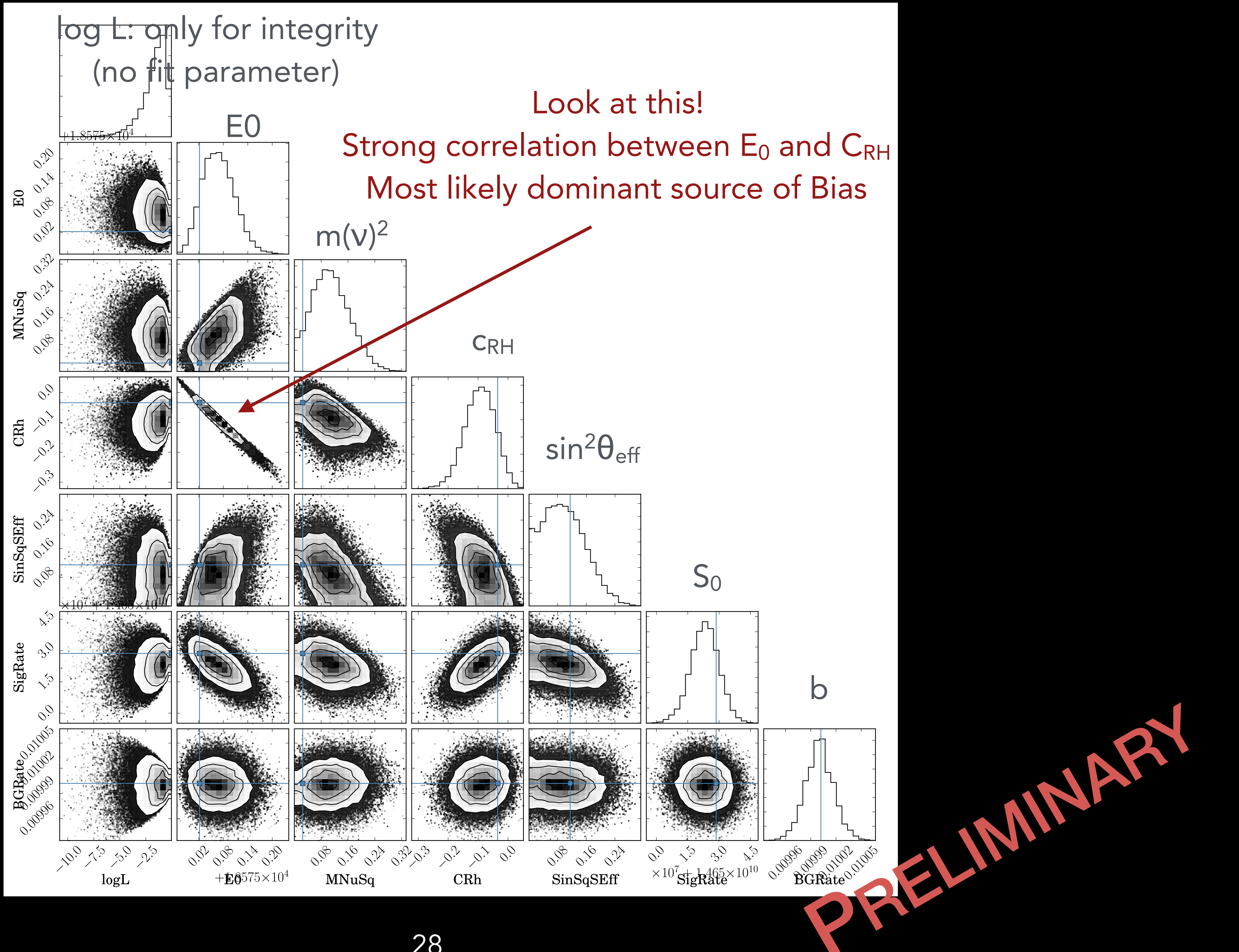
- Endpoint of β spectrum normalized to β spectrum without ν
- RH currents boost or lower region close to endpoint
- Effect much stronger on sterile ν



MCMC credible intervals for $c_{RH} = 0$



Corner plot - shows posterior parameter distribution



Summary

- Increase neutrino mass sensitivity
  - **factor 2** (stat) ideal improvement (≙ 15 x more measurement time)
  - tagger?
- Find keV sterile neutrinos
  - **factor 5** (stat + exemplary sys) ideal improvement (≙ 25 x more measurement time)
  - new estimation method for high background + low signal scenarios
  - measurement method?
- Find right-handed currents and eV sterile neutrinos
  - mass-dependent sensitivity of C_{RH} ~ 0.2 - 0.05
  - constraining endpoint?