Direct Detection Prospects for the Cosmic Neutrino Background
(and other Cosmic Relics)

Martin Spinrath
National Center for Theoretical Sciences, Hsinchu, Taiwan

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Mostly based on:
collaborations with V. Domcke [arXiv:1703.08629]; L. Tancredi and J. Zurita [arXiv:1807.?????], PTOLEMY proposal [arXiv:1307.4738], A.J. Long, C. Lunardini, E. Sabancilar [arXiv:1405.7654]

Outline

- Introduction
- Resonant Absorption
- Mechanical Forces
- Inverse β-Decay Processes
- Summary and Conclusions

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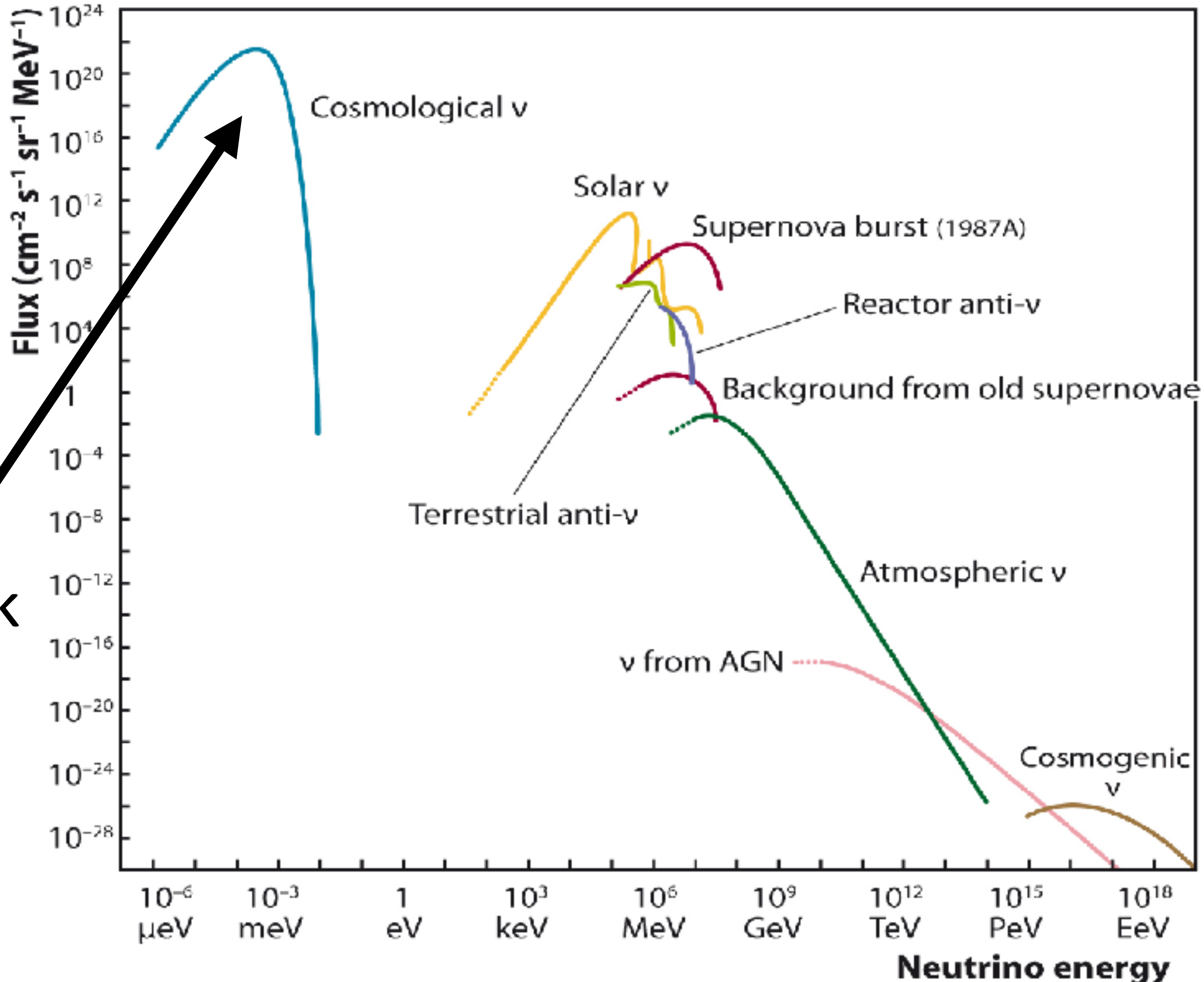
The Cosmic Neutrino Background

- Produced 1 s after Big Bang (CMB: 379k years)
- Number density: 330 cm^{-3}
- Temperature: 1.9 K
- Energy: 0.16 meV
- Velocity: 10^{-3} c - 1 c
- CNB cross section to neutrons: 10^{-27} pb

Flux Comparison

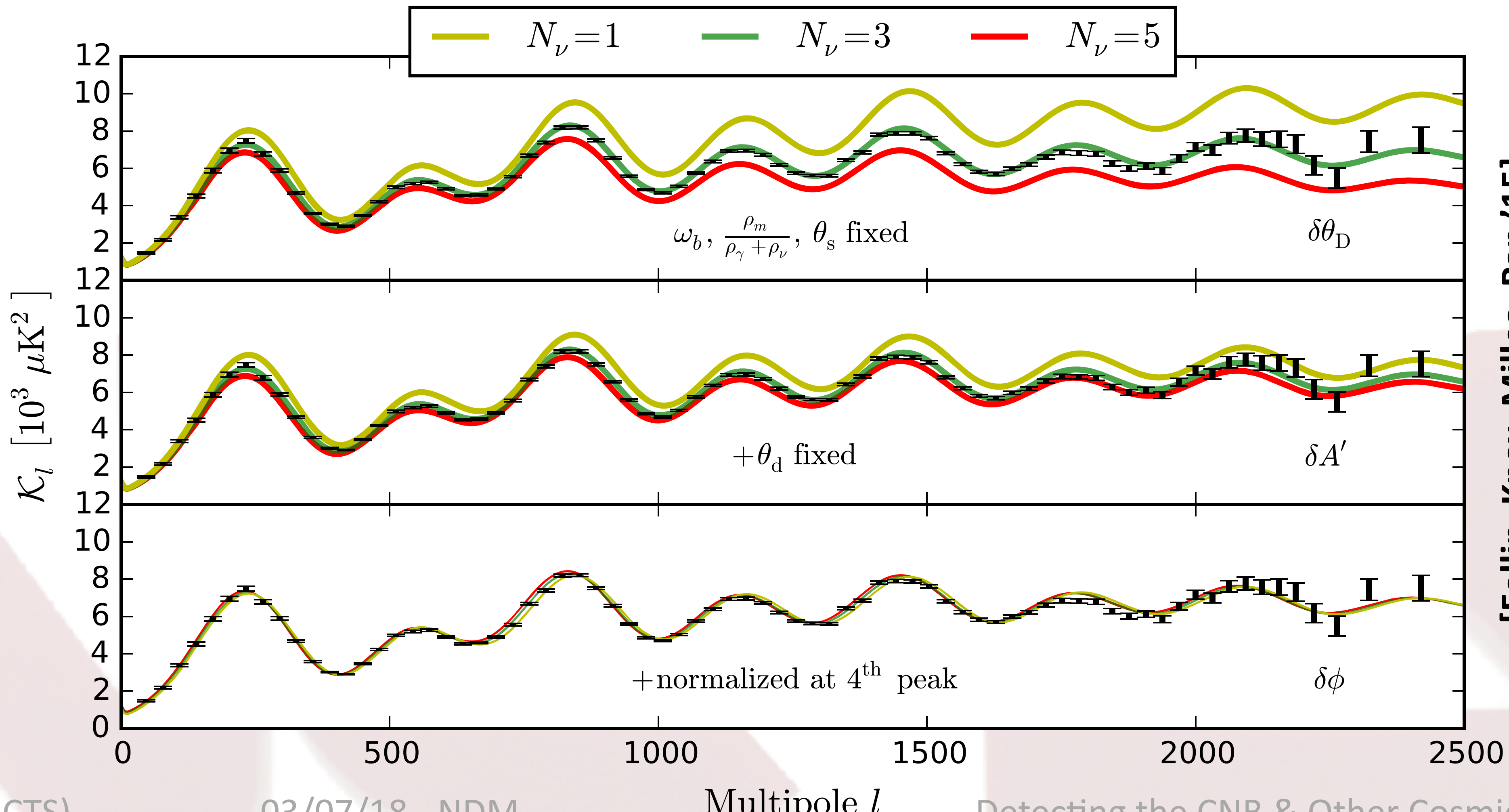


This talk

[Katz, Spiering 2011]

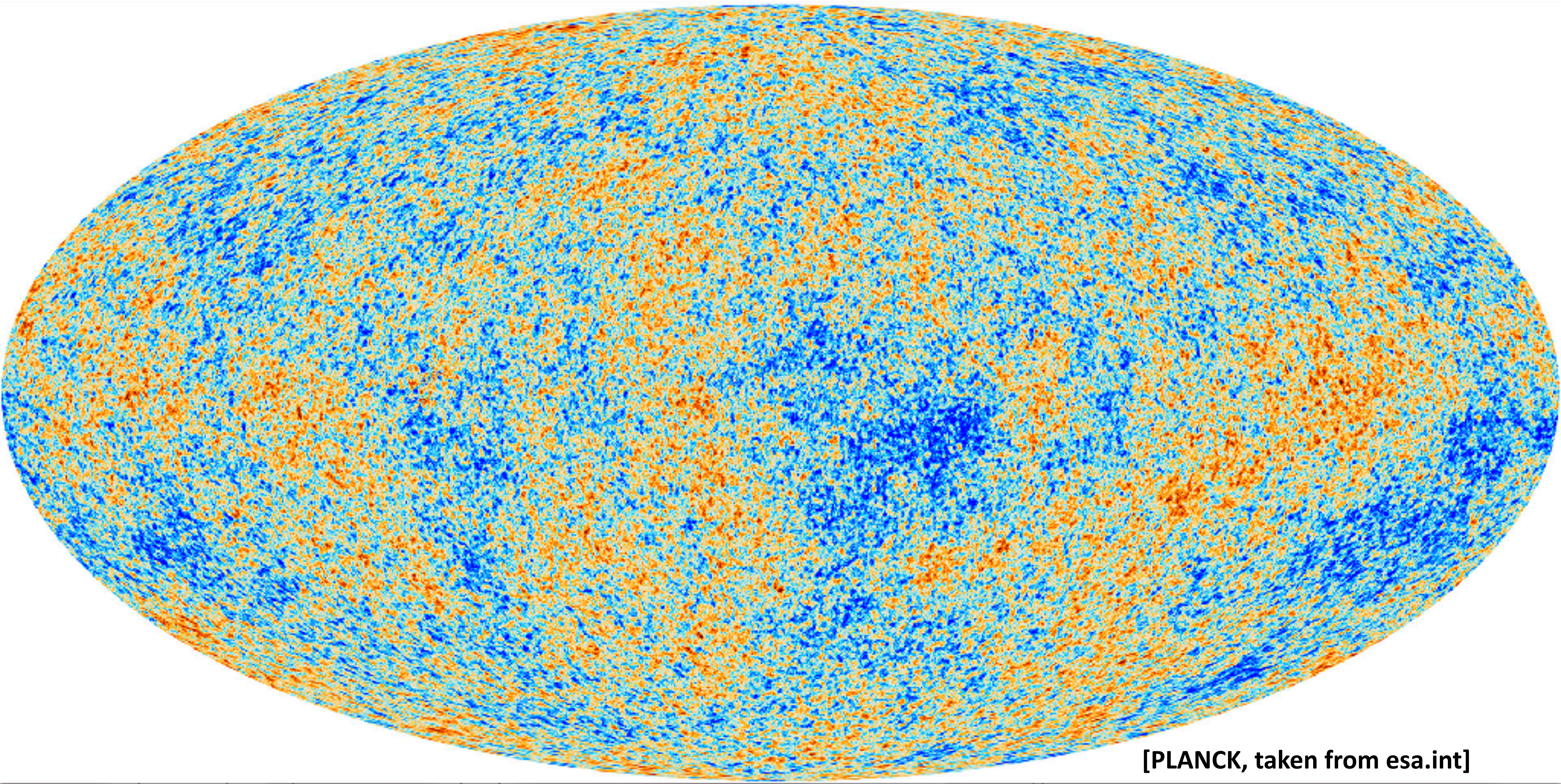
Indirect Evidence

- Big Bang Nucleosynthesis
- Imprint on Baryon Acoustic Oscillations



[Follin, Knox, Millea, Pan '15]

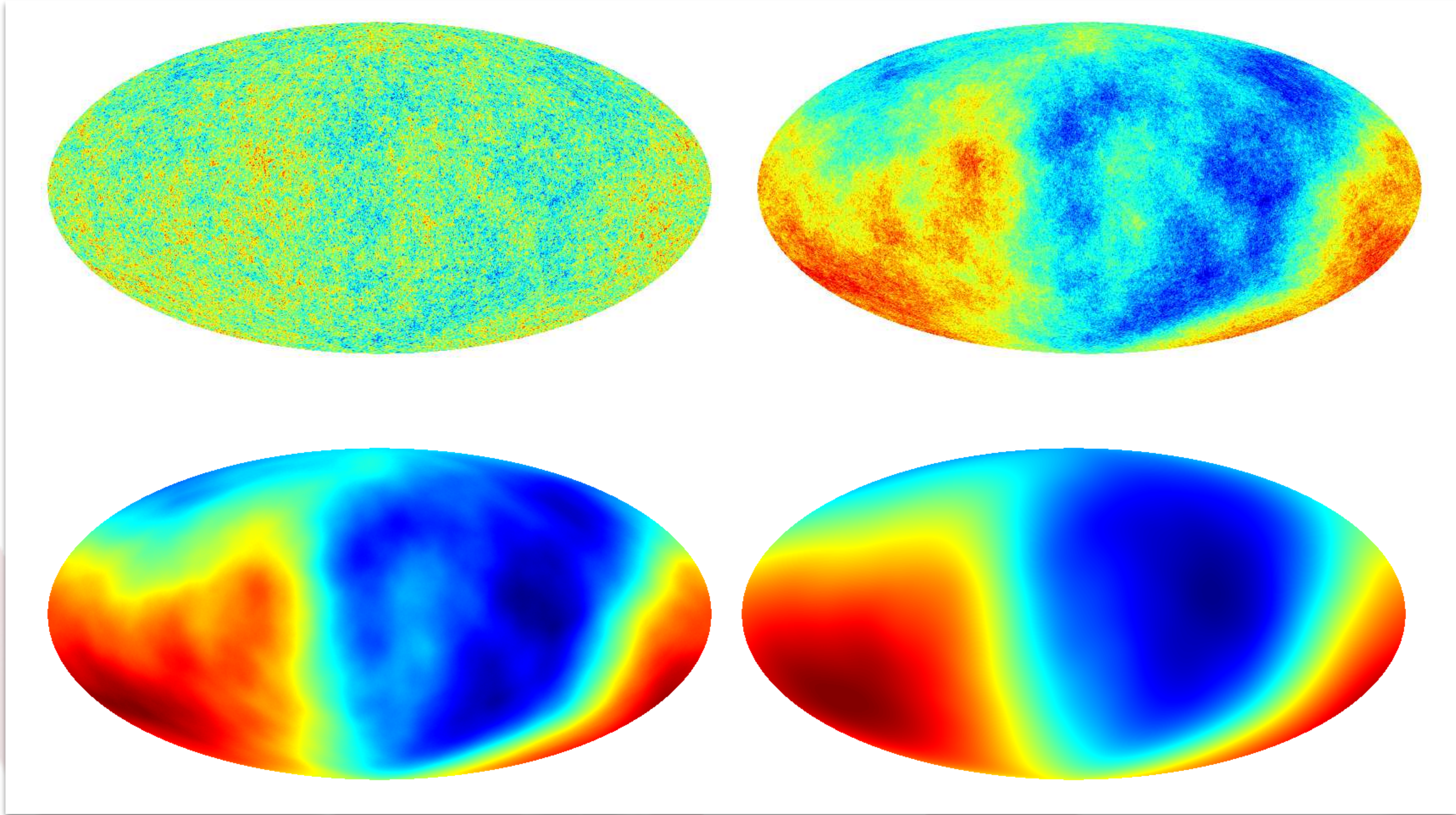
The Oldest Picture of the Universe (so far)



[PLANCK, taken from esa.int]

The Oldest Picture of the Universe in the future?

[Hannestad & Brandbyge '06]



m_ν = (10^{-5} eV, 10^{-3} eV, 10^{-2} eV, 10^{-1} eV) from upper left to lower right

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Resonant Absorption

[Weiler '82]

- Similar to GZK cutoff for charged cosmic rays
- Resonant scattering

$$\nu_{\mathrm{UHE}}\,\bar{\nu}_{\mathrm{CNB}} \to Z$$

[In Z' models dip at lower energies possible, see, e.g., talk by Ayuki Kamada]

- Dip in energy spectrum at about 10^{11} GeV
  - Highest energetic neutrinos observed have 10^3 GeV
- High energetic Z bursts (not seen so far)

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The Experiment

[Domcke, MS '17]

- Pendulum in neutrino wind

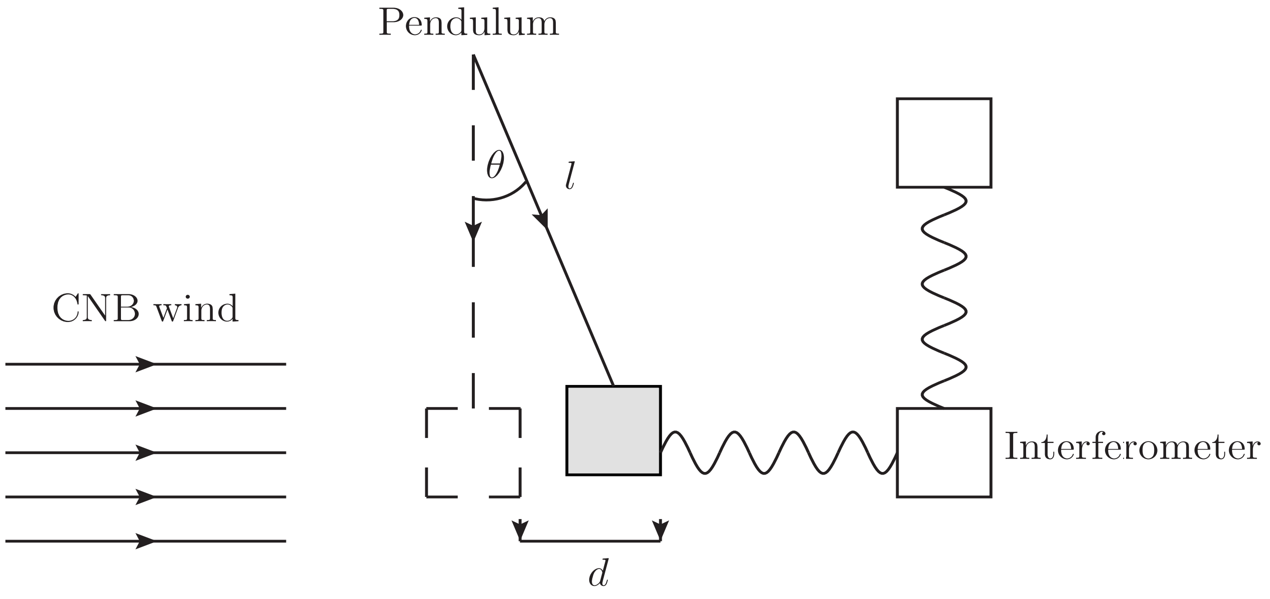
$$a_\nu \gtrsim \frac{g}{l} d$$

- LIGO-like interferometers

$$a_\nu \gtrsim 10^{-16} \mathrm{cm/s}^2$$

- Einstein telescope maybe

$$a_\nu \gtrsim 3 \cdot 10^{-18} \mathrm{cm/s}^2$$



Theory: Scattering I

[Domcke, MS ’17; see also Duda *et al.* '01, ..., orginal idea goes back to Opher '74]

- The basic formula

$$a_{G_F^2} = \Phi_\nu \, \frac{N_{AV}}{A\, m_{AV}} \, N_c \, \sigma_{\nu-A} \, \langle \Delta p \rangle$$

- Incoming flux: Φ_ν
- #nuclei in 1 g test material: $N_{AV}/(A m_A V)$
- ν-nucleus cross-section: $\sigma_{\nu-A} \approx 10^{-27}\ \mathrm{pb} = 10^{-63}\ \mathrm{cm}^2$
- Coherence factor: $N_c = \frac{N_{AV}}{A\, m_{AV}} \, \rho \, \lambda_\nu^3 \sim 10^{20}$
- Average momentum transfer: $\langle \Delta p \rangle$

Theory: Scattering II

[Domcke, MS ’17; see also Duda *et al.* '01]

- Neutrinos can come in three kinematics
  - relativistic (R)
  - non-relativistic non-clustered (NR-NC)
  - non-relativistic clustered (NR-C)
- Different typical momenta and momenta transfers

Theory: Scattering III

[Domcke, MS '17; see also Duda *et al.* '01]

- Results assuming lead target

$$a_{G_F^2} = \frac{n_\nu}{2\,\bar{n}_\nu} \begin{cases} 3 \cdot 10^{-33}\,\mathrm{cm/s}^2 & \text{for (R)} \\ 5 \cdot 10^{-31}\,(m_\nu/0.1\ \mathrm{eV}/c^2)\,\mathrm{cm/s}^2 & \text{for (NR-NC)} \\ 2 \cdot 10^{-27}\,(10^{-3}/\beta_{\mathrm{vir}})\,\mathrm{cm/s}^2 & \text{for (NR-C)} \end{cases}$$

- Current theoretical experimental sensitivity

$$a_\nu \gtrsim 10^{-16}\mathrm{cm/s}^2$$

Other "Winds"

[Domcke, MS ’17; see also Duda *et al.* '01]

- Solar neutrinos

$$a_{\text{solar}-\nu} \approx 3 \cdot 10^{-26}\,\text{cm/s}^2$$

- Vanilla WIMP Dark Matter (m_X > 1 GeV)

$$a_{\text{DM}} = \mathcal{O}(10^{-30})\ \text{cm/s}^2$$

- Light WIMP Dark Matter (m_X = 3.3 keV)

$$a_{\text{light DM}} \approx N_c\, a_{\text{DM}} \approx 10^9\, a_{\text{DM}}$$

[See also Graham *et al.* '15]

Wind vs. Nudges

[Domcke, MS '17]

- The scattering rate for the CNB

$$R = \frac{a_{G_F^2}}{\langle \Delta p \rangle} \sim \mathcal{O}(10^{-4} - 0.1)\ \mathrm{g}^{-1}\ \mathrm{s}^{-1}$$

- Compared to solar neutrinos

$$R_{\mathrm{solar}-\nu} \approx 2 \cdot 10^{-9}\,\mathrm{g}^{-1}\,\mathrm{s}^{-1}$$

- And DM

$$R \sim \mathcal{O}(10^{-12} - 10^{5})\ \mathrm{g}^{-1}\ \mathrm{s}^{-1}$$

Improvements

[Domcke, MS '17]

- Sensitivity proportional to g factor
  - Suspension
  - Space
- Give up on pendulum setup
  - free falling masses and wait

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  - **PTOLEMY**
  - Muon Beam
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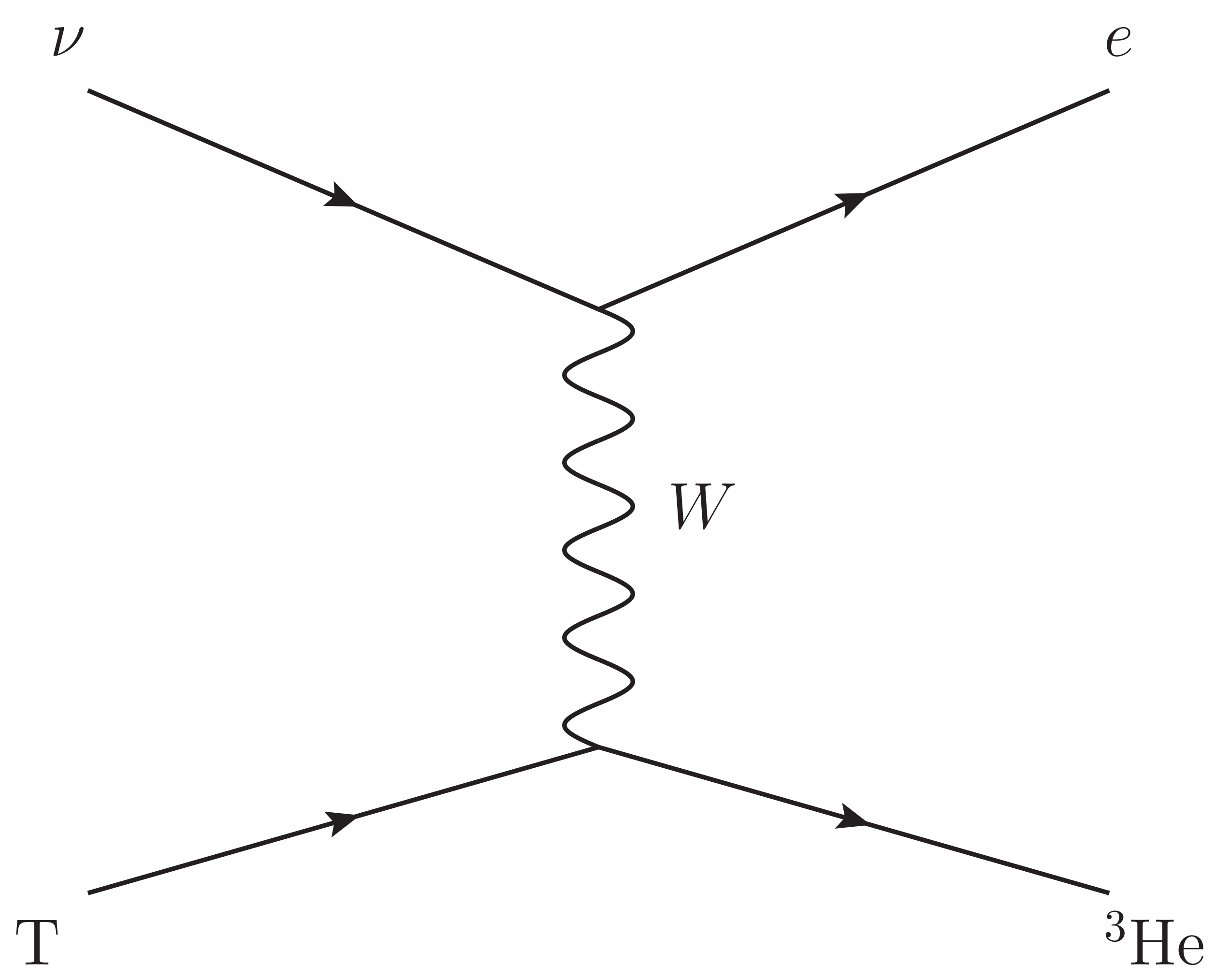
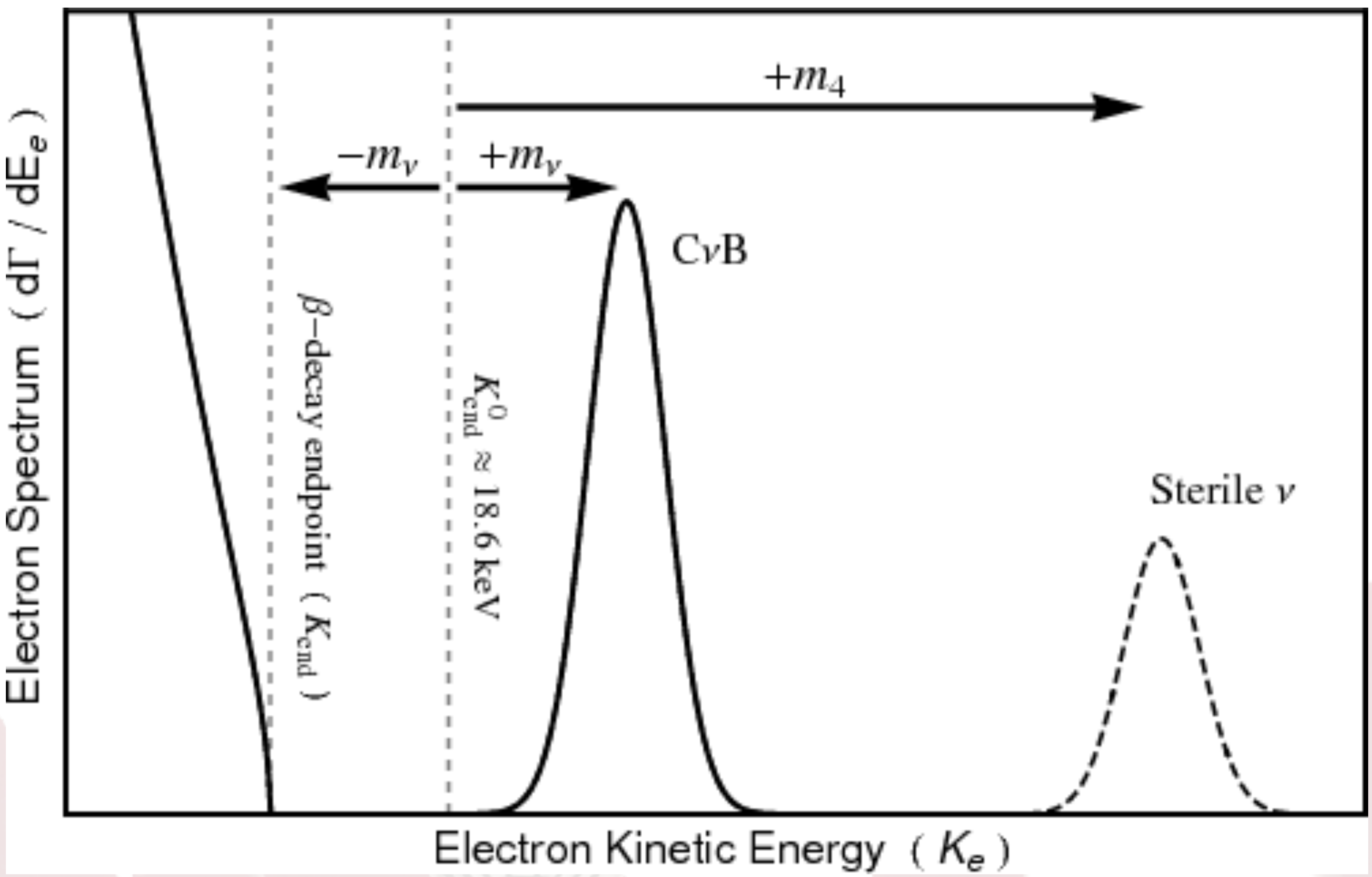
Inverse Beta Decay

- Huge CNB flux
- Take radioactive nuclei, e.g. tritium
- Wait for neutrino captures
- Goes back to Weinberg

[Weinberg ’62]



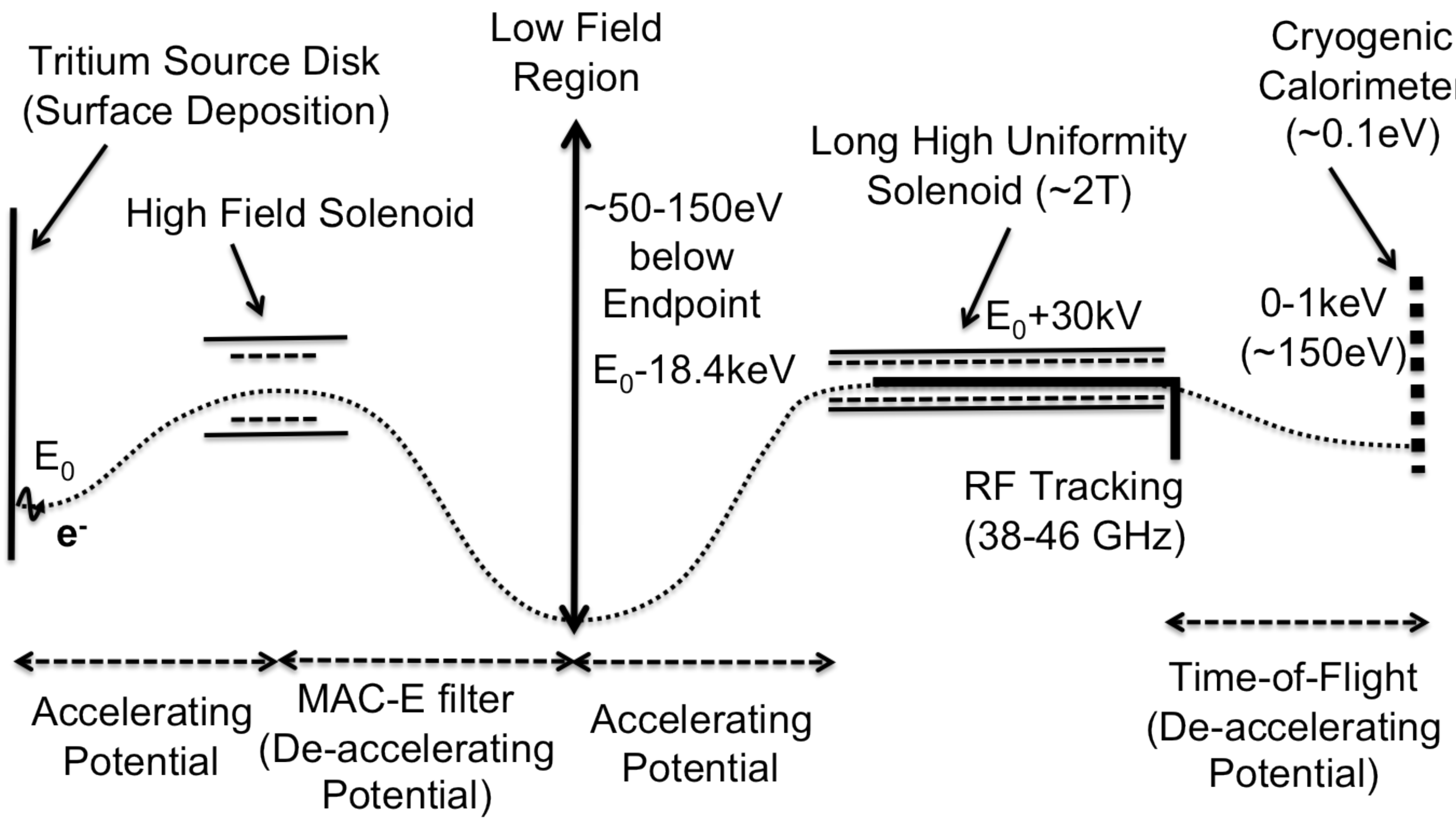
Energy Spectrum



[Long, Lunardini, Sabancilar '14]

Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

[PTOLEMY '13]



Expectations

[Long, Lunardini, Sabancilar ’14]

- Number of target nuclei: 2×10^{25} (100 g)
- Rate for Dirac particles (no right-helical neutrinos today):

$$\Gamma^{\mathrm{D}}_{\mathrm{CNB}} = \bar{\sigma}\, c\, n_0\, N_T \approx 4.06 \ \mathrm{yr}^{-1}$$

- Rate for Majorana particles (both helicities equally present):

$$\Gamma^{\mathrm{M}}_{\mathrm{CNB}} = 2\, \Gamma^{\mathrm{D}}_{\mathrm{CNB}} \approx 8.12 \ \mathrm{yr}^{-1}$$

Event Rates

[PTOLEMY '13]

- β-decay electrons from 100 g tritium: 10^{16} /s
- Fraction within 100 eV of endpoint: ~2 x 10^{-7}
- Fraction within 0.1 eV of endpoint: ~2 x 10^{-16}
- Expected event rate in signal region: 2 Hz
- Expected CNB events: O(1) /yr

From Princeton Tritium to PonTecorvo

and it is long-lived [529, 533–536]. The proposal for an experiment chasing this purpose was made in [529]. Currently, efforts are put for such experiment, the PonTecorvo Observatory for Light Early-Universe Massive-Neutrino Yield (PTOLEMY) [370, 371], to be built. The experiment has recently been approved by the Scientific Committee of the Italian National Laboratories of Gran Sasso and, in the following months, the existing prototypes for various components are expected to be moved from Princeton, where the R&D has been performed up to now, to Gran Sasso. The idea is to implant the tritium source on graphene layers, to avoid the problems related to a gaseous source, then collect and measure the energy of the emitted electrons using a combination of MAC-E filter, radio-frequency tracking and micro-calorimetry to obtain a determination of the β-decay and neutrino capture spectrum of tritium with an energy resolution of the order $\Delta \simeq 0.05 - 0.1$ eV.

[Taken from de Salas, Gariazzo, Mena, Ternes, Tórtola arXiv:1806.11501]

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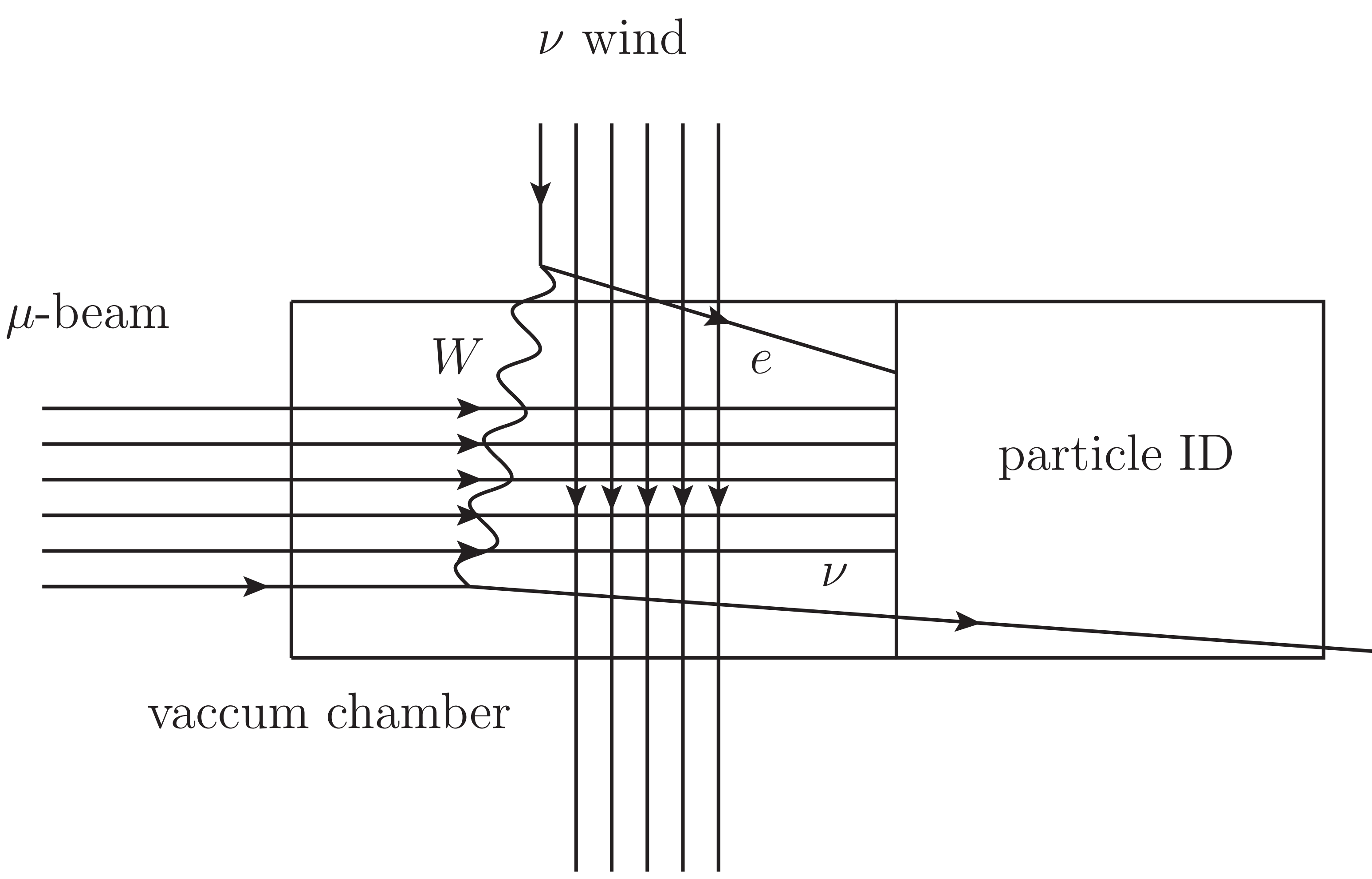
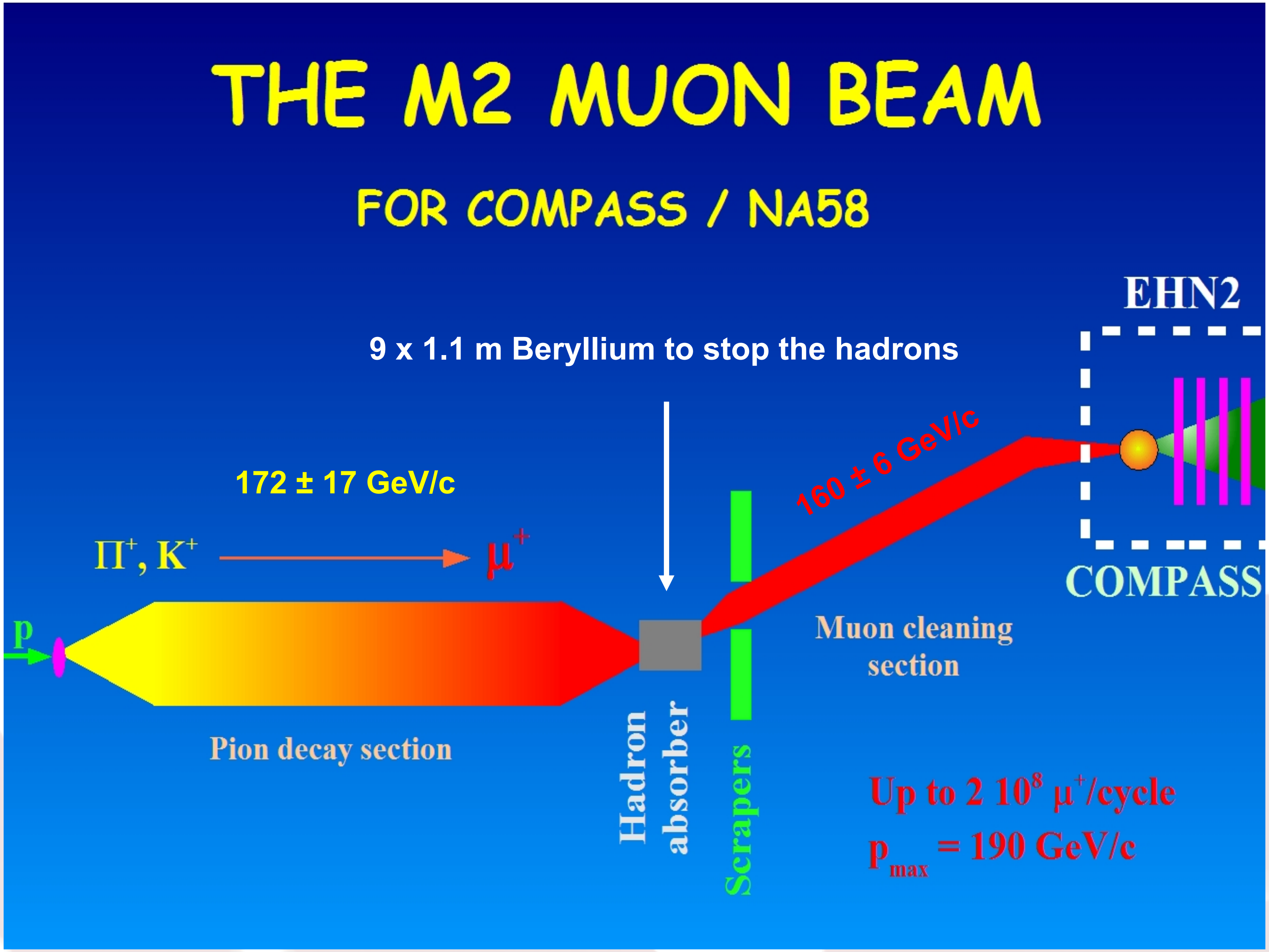
Dumping Muons on Cosmic Relics

[MS, Tancredi, Zurita WIP]

- Increase the cross section (~E^2) by using a beam
- High energy/intensity muon beams available
- Look for electrons in final state



CERN M2 Beam Line



[taken from sba.web.cern.ch/sba/BeamsAndAreas/M2/M2-OperatorCourse.pdf]

CERN M2 Beam Line

- Beam energy: 150 GeV
- Muon rate: 1.3×10^7 /s
- Beam "length": 100 cm
- Beam tube acts as fixed target
- Event rate:

$$R = 1.3 \times 10^9 \, n_{\mathrm{CR}} \, \sigma \, \frac{\mathrm{cm}}{\mathrm{s}}$$

Physics Cases (Preliminary)

[MS, Tancredi, Zurita WIP]

Physics Case	Estimated Rate R
CNB	10^{-21}/year
Solar ν	10^{-22}/year
Atmospheric ν	10^{-27}/year
Sterile ν DM	10^{-28}/year
Vanilla WIMP	10^{-33}/year

Other Ideas?

Why are we so much worse than PTOLEMY?

[MS, Tancredi, Zurita WIP]

- Reminder:

$$\Gamma \sim n_\nu \bar{\sigma} N$$

  - CNB number density the same
  - Cross sections:

$$\bar{\sigma}_{\rm STZ}/\bar{\sigma}_{\rm PT} \sim 10^5$$

  - Amount of muons/tritium:

$$N_\mu/N_T \sim 10^{-27}$$

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Summary and Conclusions

- The CNB is one of the earliest pictures of the universe
- Overwhelming indirect evidence
- But no direct observation so far
- Maybe possible via inverse β-decay (PTOLEMY)
- CNB searches can be DM searches as well