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

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Cosmology Frontier in Particle Physics - 27/09/2018

Mostly based on:
collaborations with V. Domcke [arXiv:1703.08629], with L. Tancredi and J. Zurita [arXiv:18??.?????];
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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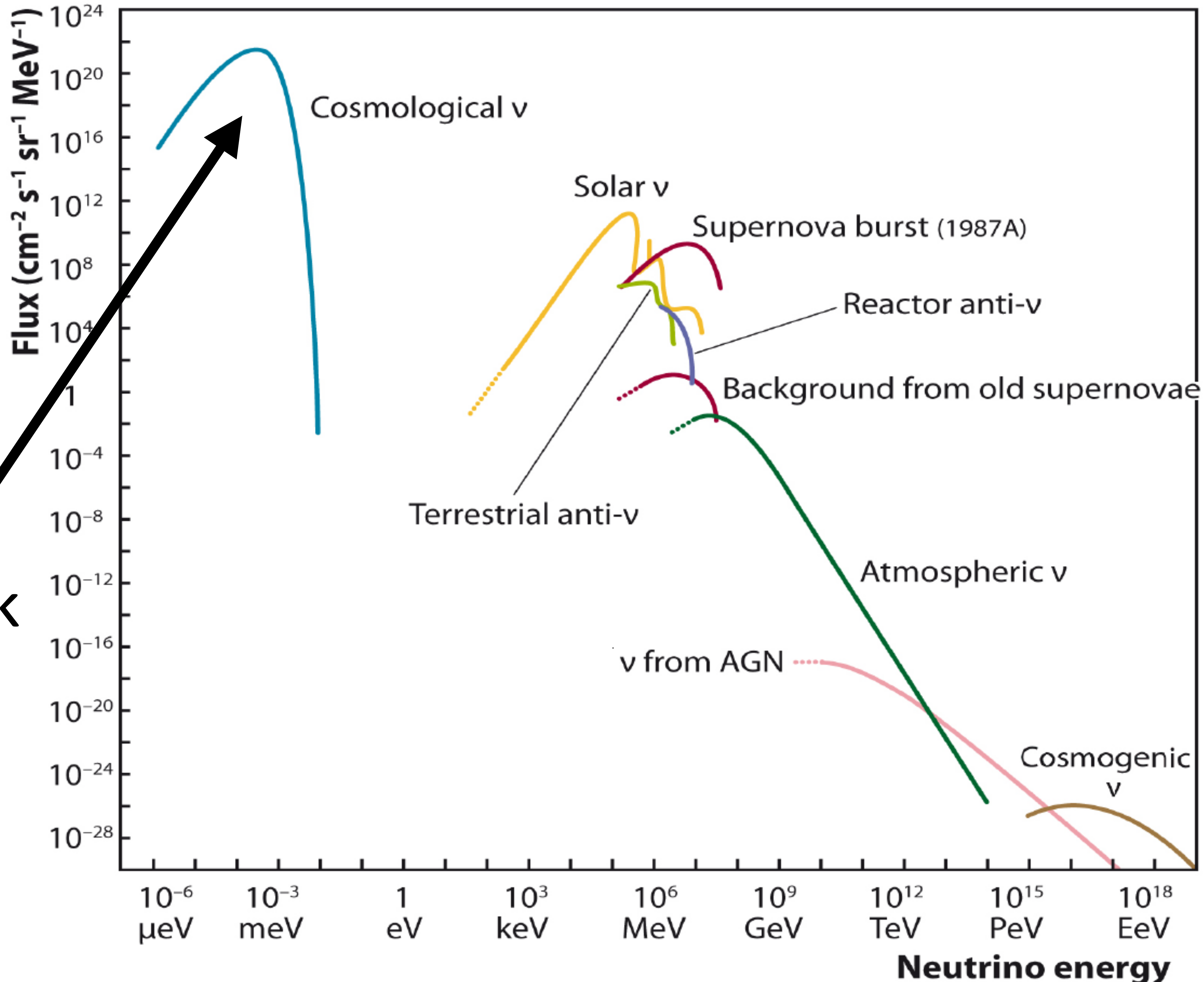
The Cosmic Neutrino Background

- Produced 1 s after Big Bang (CMB: 379k years)
- Number density: 330 cm^{-3} = 6 n_0
- Temperature: 1.9 K
- Energy: 0.16 meV
- Velocity: 10^{-3} - 1 c
- CNB cross section to neutrons: 10^{-27} pb

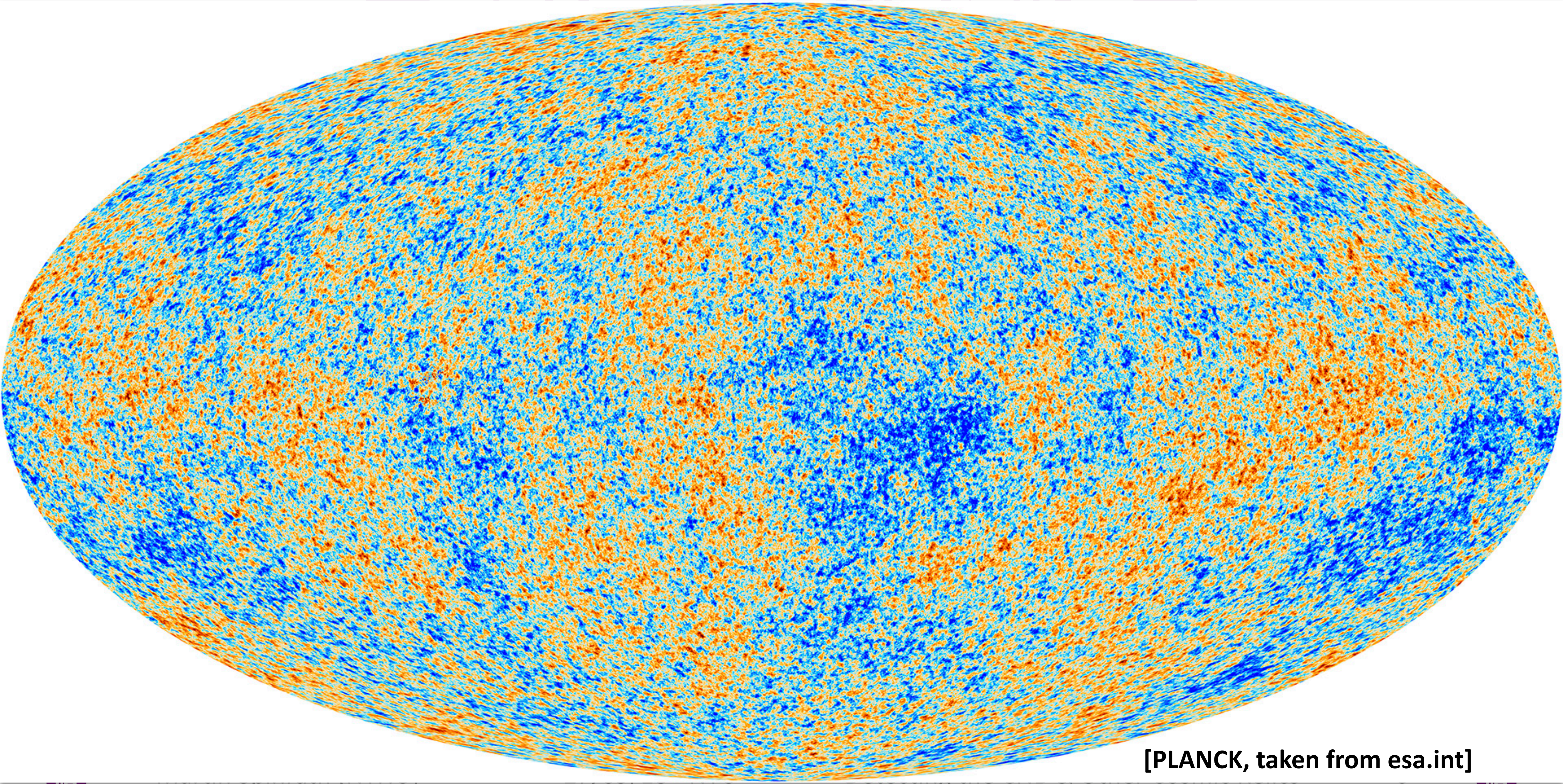
Neutrino Flux Comparison



This talk

[Katz, Spiering 2011]

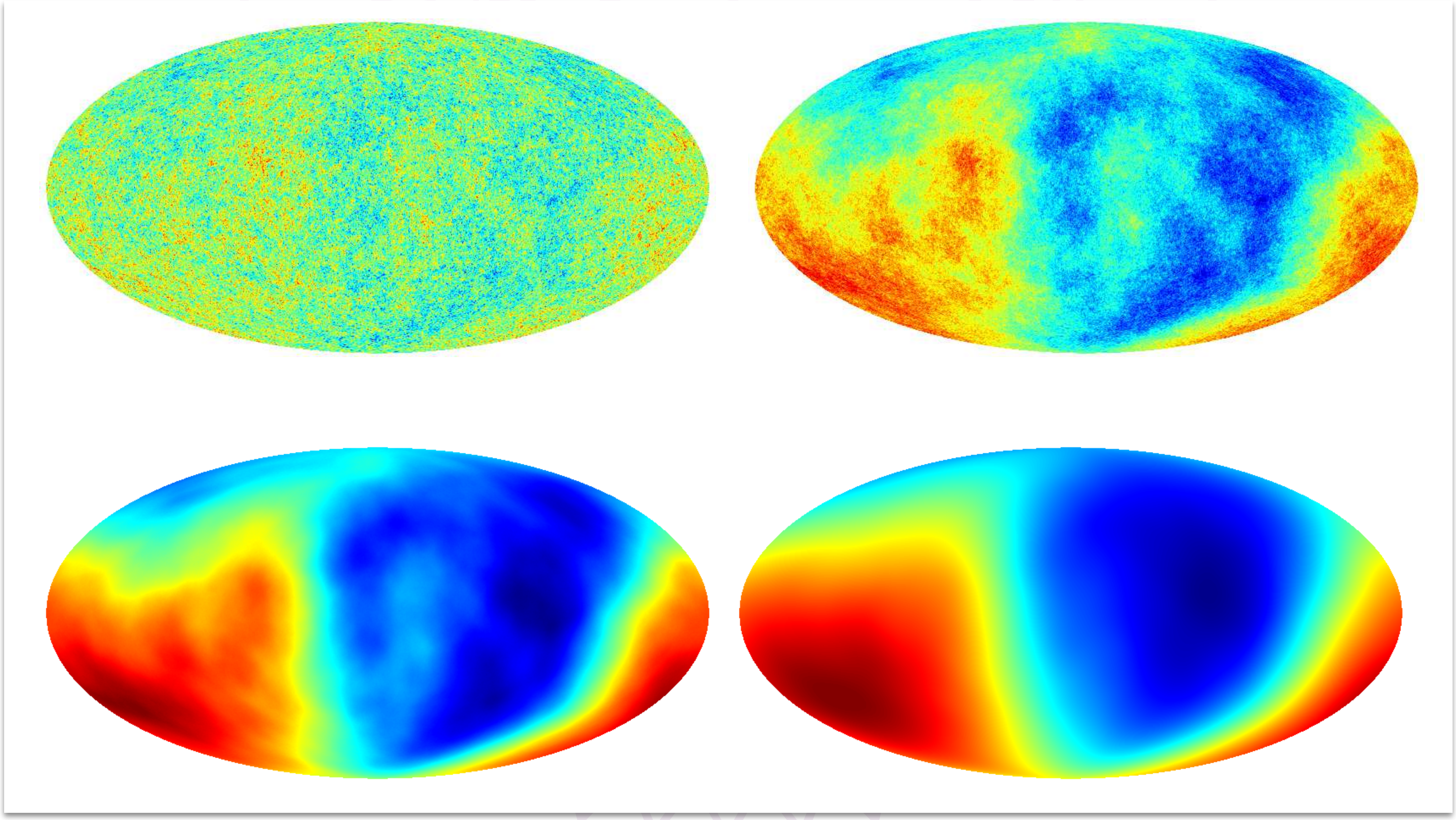
The Oldest Picture of the Universe (so far)



[PLANCK, taken from esa.int]

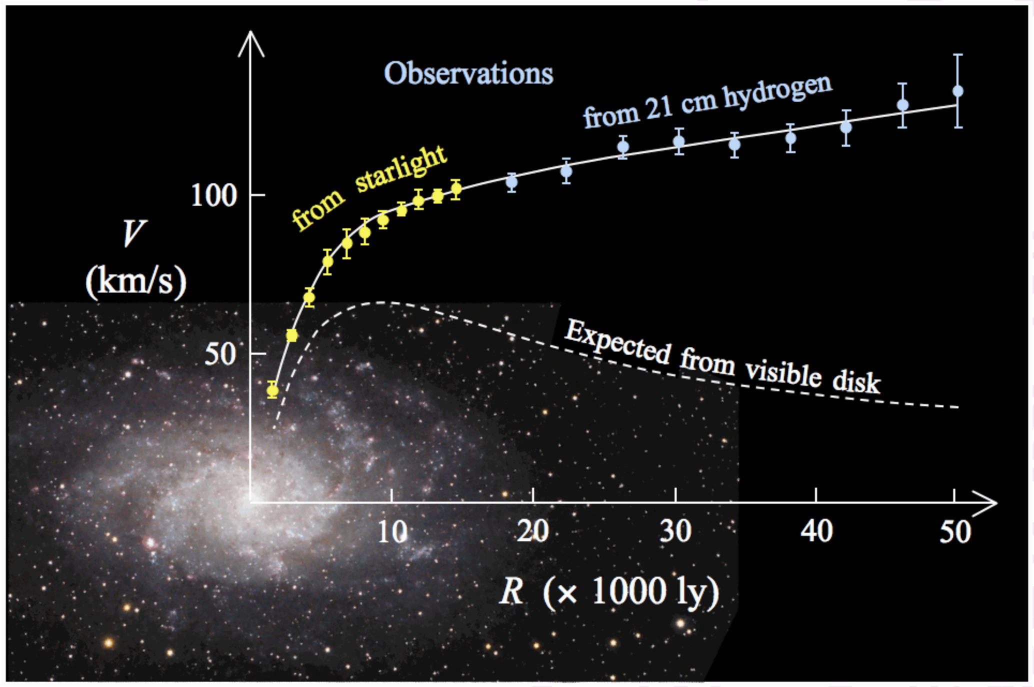
The Oldest Picture of the Universe in the future?

[Hannestad & Brandbyge '06]



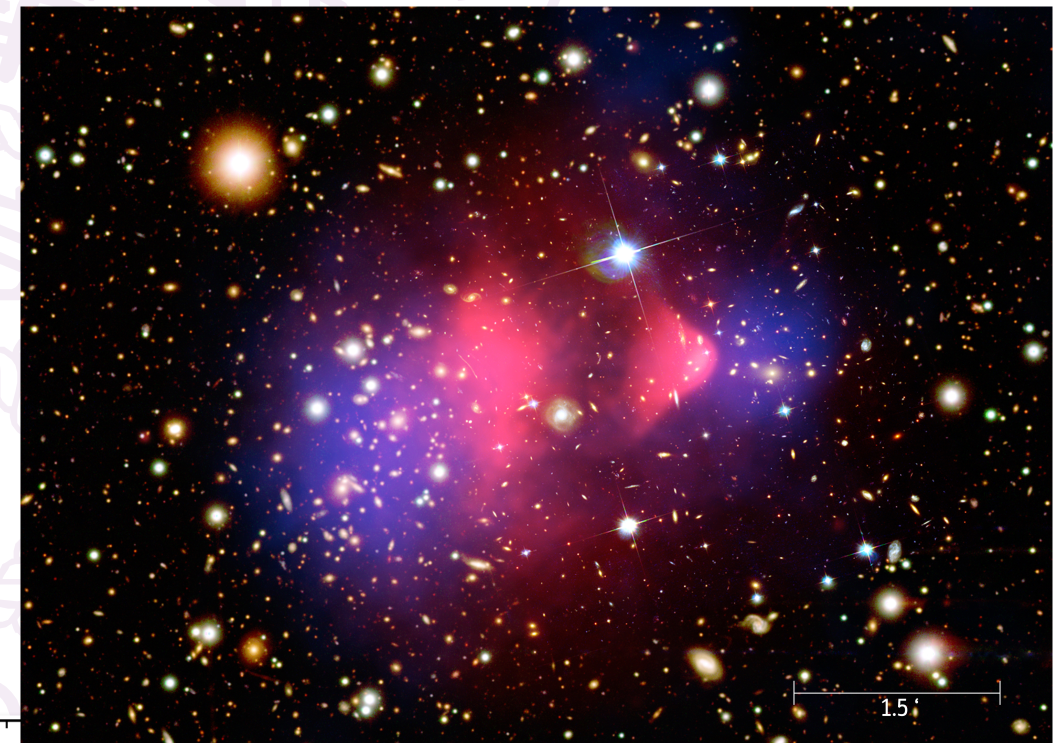
m_ν = (10^{-5} eV, 10^{-3} eV, 10^{-2} eV, 10^{-1} eV) from upper left to lower right

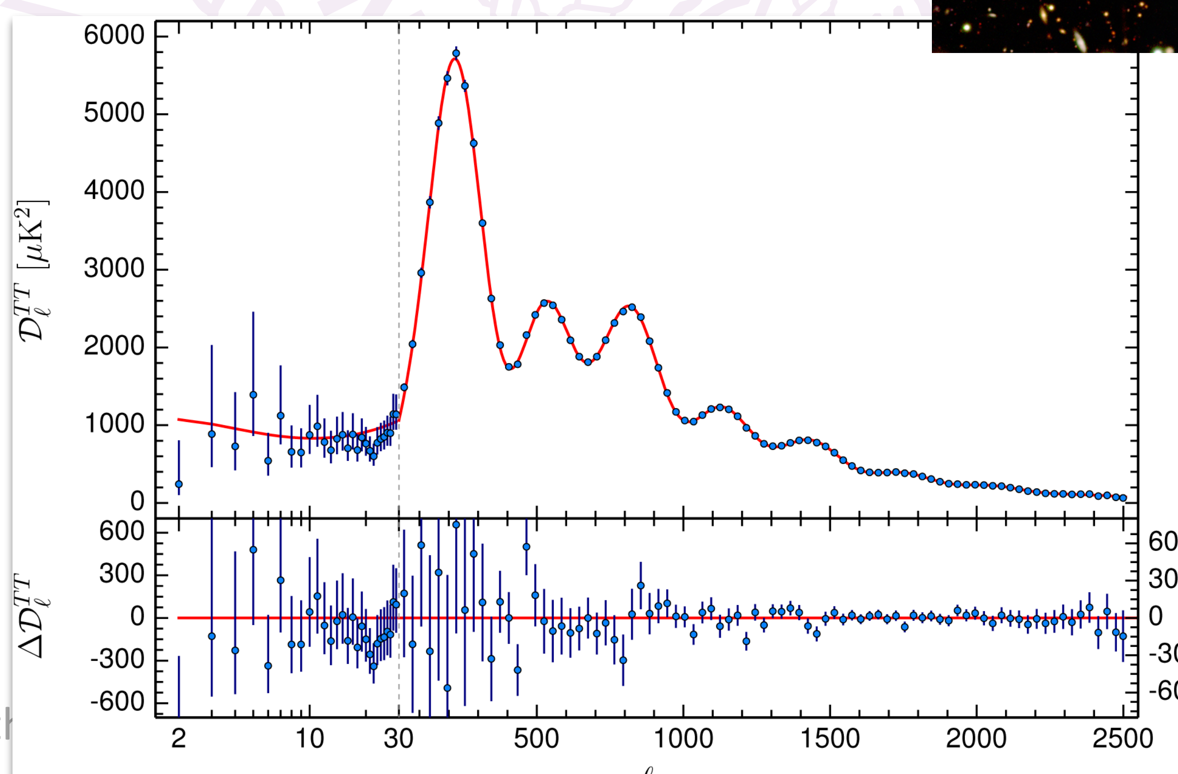
The Other Relics



[M33 rot. curve, Source: Wikipedia]

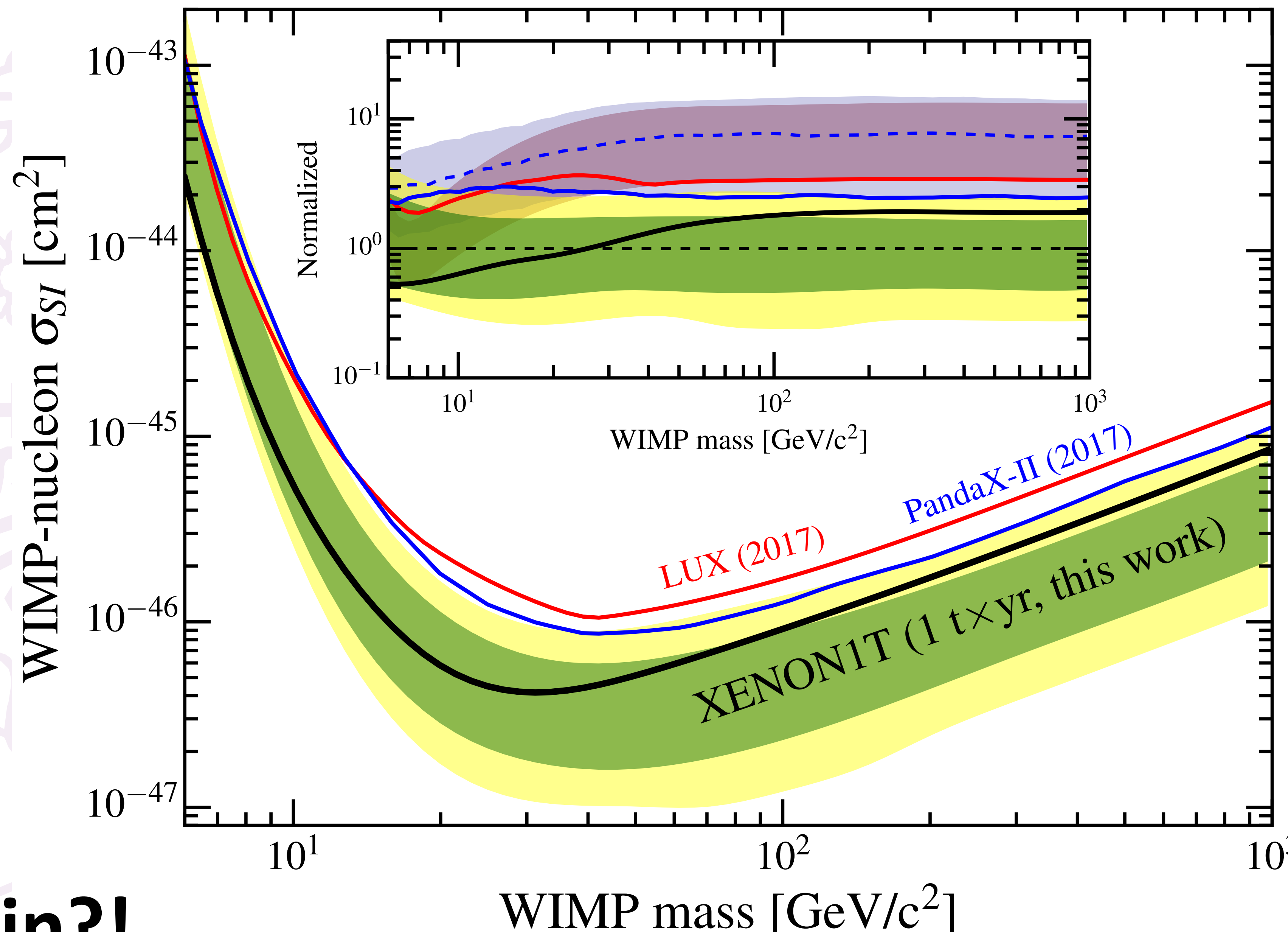
[Chandra picture of the bullet cluster]





[https://wiki.cosmos.esa.int/planckpla2015/images/2/2f/A15_TT.png]

Fake(?) WIMP Miracle



[XENON1T result '18]

Time to think again?!

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Resonant Absorption

[Weiler '82]

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

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

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

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The Experiment

[Domcke, MS '17]

- Pendulum in neutrino wind

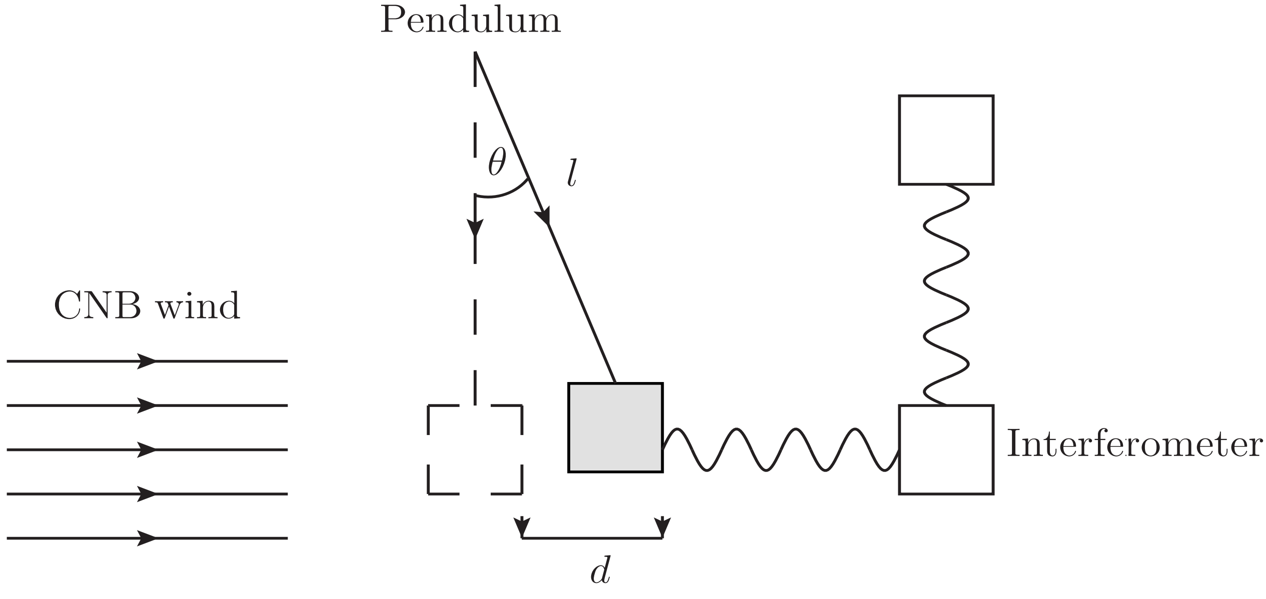
$$a_\nu \gtrsim \frac{g}{l} d$$

- 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

[Domcke, MS ’17; see also Duda *et al.* '01, ..., Opher '74]

- Results for three kinematical cases:

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

- Compare to experimental sensitivity:

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

Other Winds

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

- Solar neutrinos

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

- Cold WIMP Dark Matter (m$_X$ > 1 GeV)

$$a_{\mathrm{DM}} \approx 4 \cdot 10^{-30} \left(\frac{(A-Z)^2}{76\, A}\right) \left(\frac{\sigma_{X-N}}{10^{-46}\, \mathrm{cm}^2}\right) \left(\frac{\rho_{\mathrm{dark(local)}}}{10^{-24}\, \mathrm{g/cm}^3}\right) \left(\frac{\beta_X}{10^{-3}}\right)^2 \mathrm{cm/s}^2$$

- Light WIMP Dark Matter (m$_X$ = 3.3 keV)

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

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

Improvements and Alternatives

[Domcke, MS '17]

- Sensitivity proportional to g factor
  - Suspension
  - Space
- Give up on pendulum setup
  - free falling masses and wait
- Alternatives to mechanical force experiment
  - Resonant Absorption
  - Inverse beta decay (PTOLEMY)

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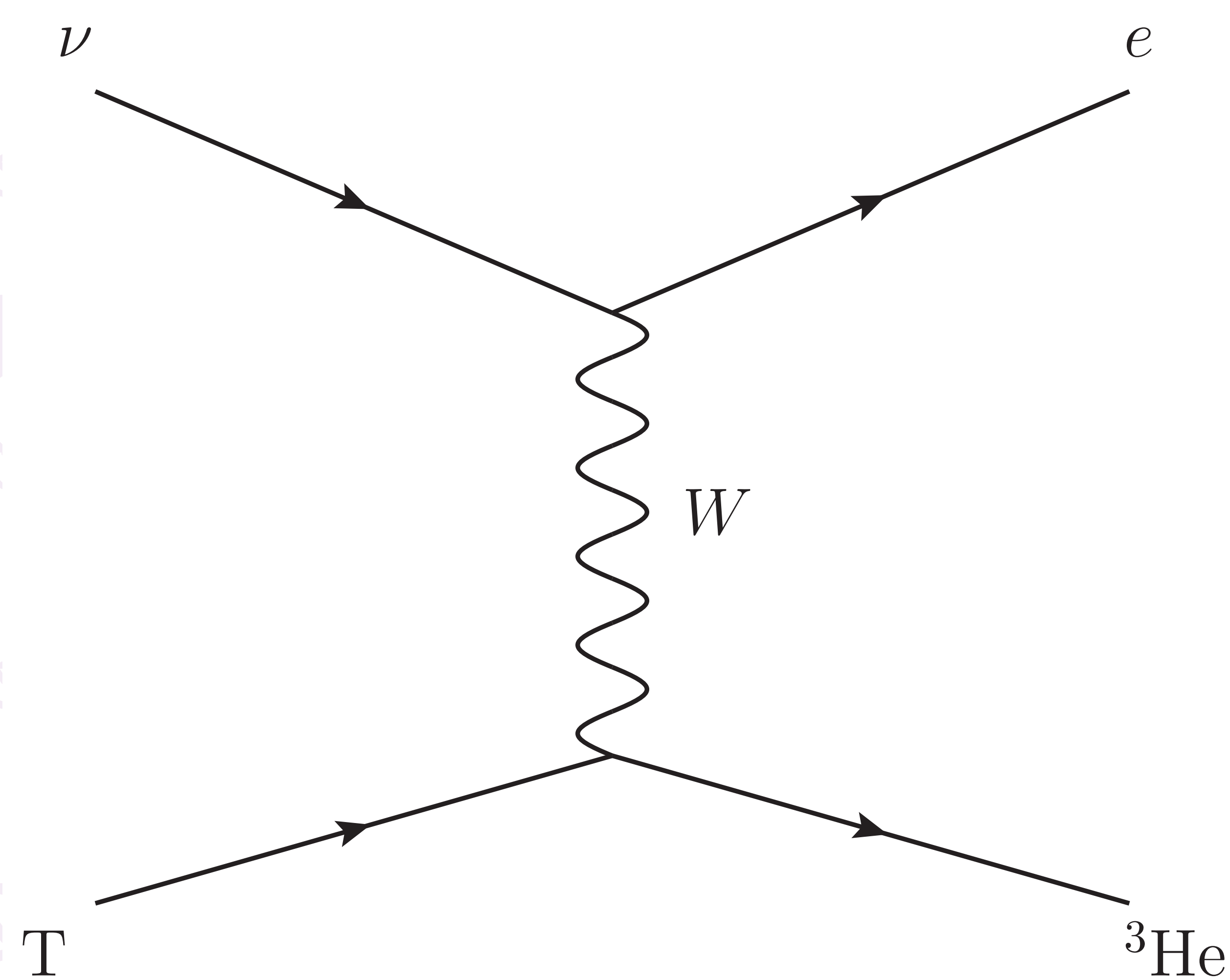
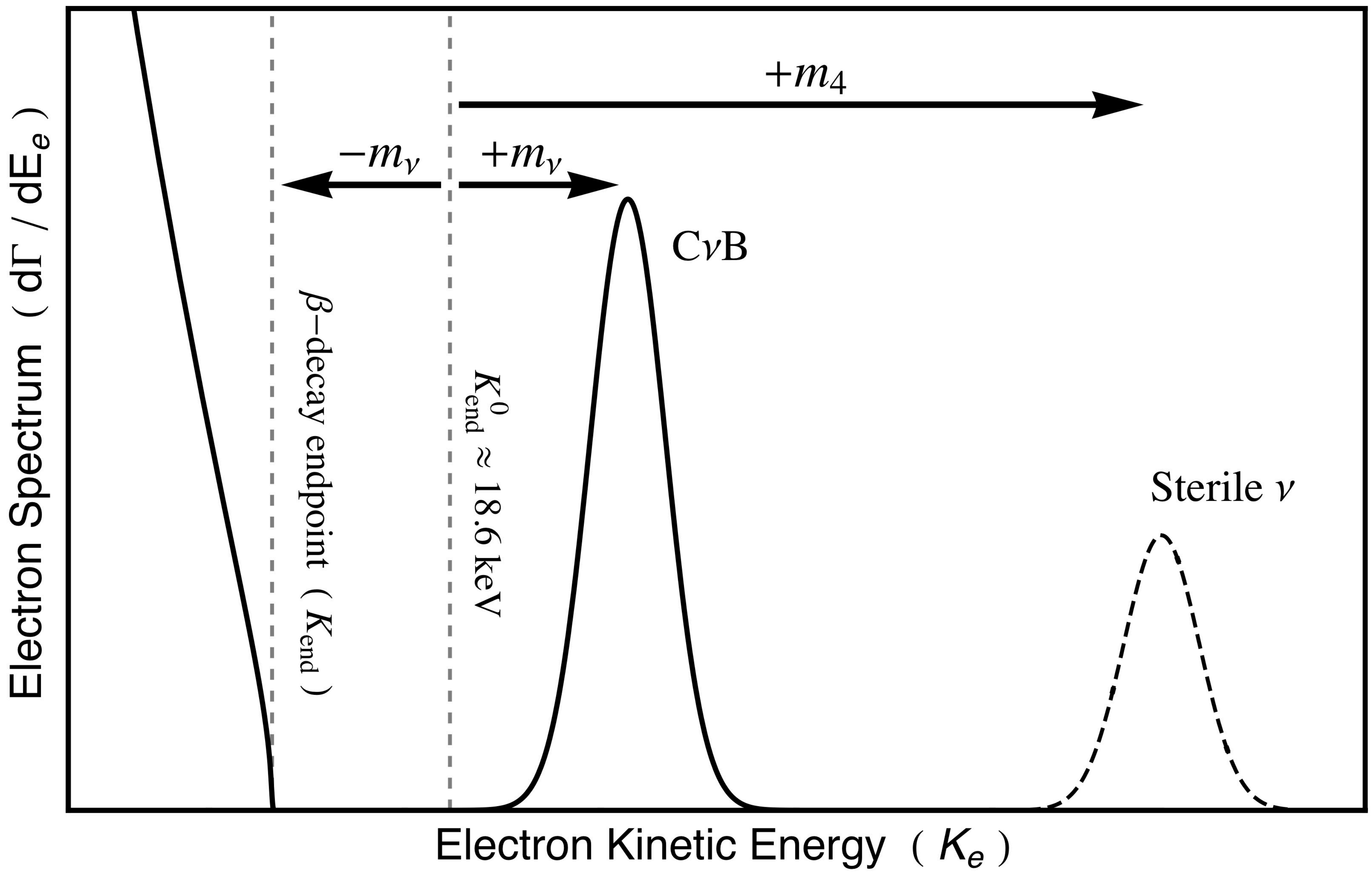
- **Inverse β-Decay Processes**
  - **PTOLEMY**
  - Muon Beam
- Summary and Conclusions

Inverse Beta Decay

- Lots of Neutrinos around
- Radioactive nuclei, e.g. tritium
- Wait for a neutrino capture
- Goes back to Weinberg **[Weinberg '62]**



Energy Spectrum



[Long, Lunardini, Sabancilar '14]

Numbers

[Long, Lunardini, Sabancilar '14]

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

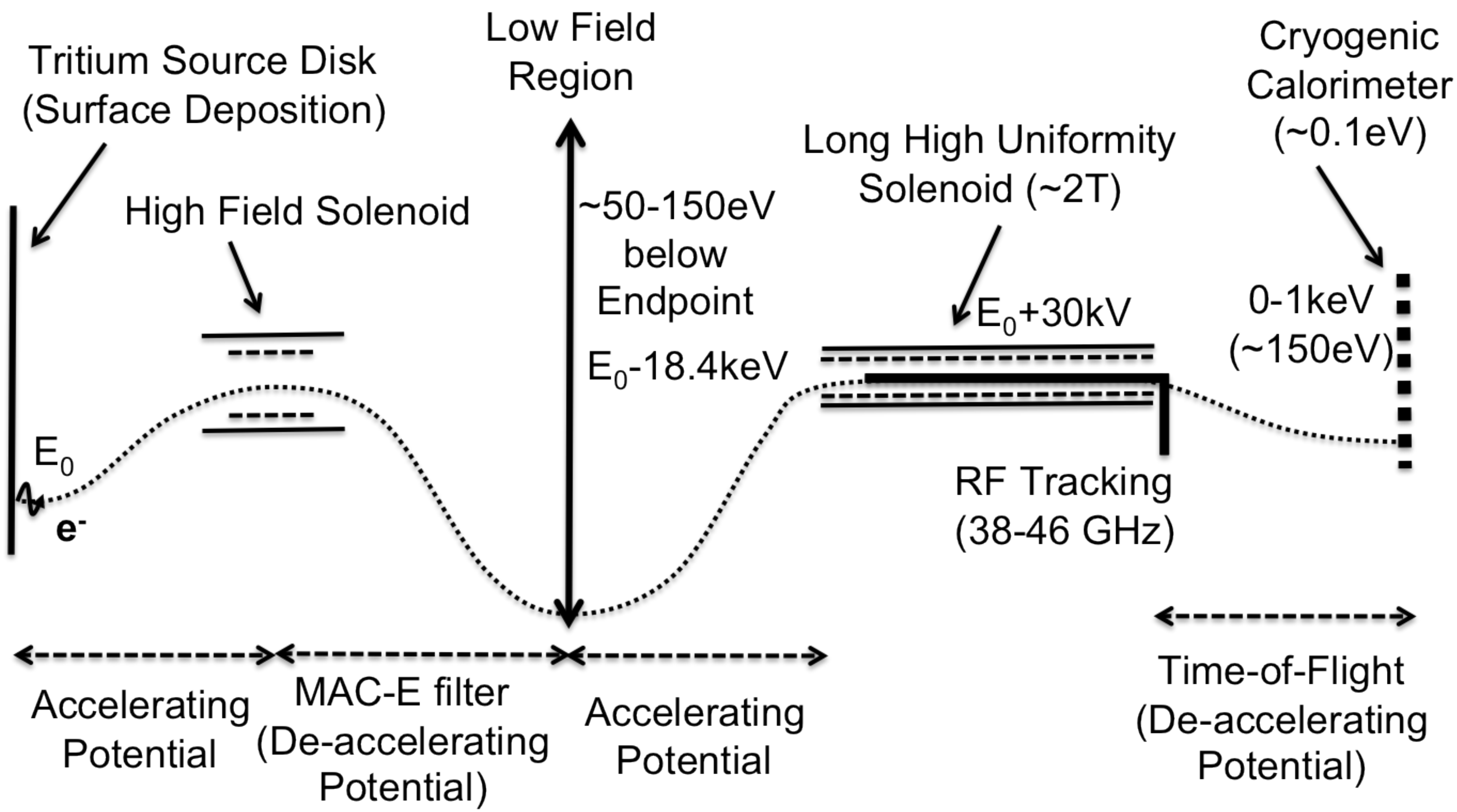
$$\Gamma^{\mathrm{D}}_{\mathrm{CNB}} = \bar{\sigma}\, c\, n_0\, N_T \approx 4.06\ \mathrm{yr}^{-1}$$

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

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

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

[PTOLEMY '13]



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

Current Status

[PTOLEMY '18]

PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

E. Baracchini[3], M.G. Betti[11], M. Biasotti[5], A. Boscá[16], F. Calle[16], J. Carabe-Lopez[14], G. Cavoto[10,11], C. Chang[22,23], A.G. Cocco[7], A.P. Colijn[13], J. Conrad[18], N. D'Ambrosio[2], P.F. de Salas[17], M. Faverzani[6], A. Ferella[18], E. Ferri[6], P. Garcia-Abia[14], G. Garcia Gomez-Tejedor[15], S. Gariazzo[17], F. Gatti[5], C. Gentile[25], A. Giachero[6], J. Gudmundsson[18], Y. Hochberg[1], Y. Kahn[26], M. Lisanti[26], C. Mancini-Terracciano[10], G. Mangano[7], L.E. Marcucci[9], C. Mariani[11], J. Martínez[16], G. Mazzitelli[4], M. Messina[20], A. Molinero-Vela[14], E. Monticone[12], A. Nucciotti[6], F. Pandolfi[10], S. Pastor[17], J. Pedrós[16], C. Pérez de los Heros[19], O. Pisanti[7,8], A. Polosa[10,11], A. Puiu[6], M. Rajteri[12], R. Santorelli[14], K. Schaeffner[3], C.G. Tully[26], Y. Raitses[25], N. Rossi[10], F. Zhao[26], K.M. Zurek[21,22]

Submitted to the LNGS Scientific Committee on March 19$^{\text{th}}$, 2018

Abstract

We propose to achieve the proof-of-principle of the PTOLEMY project to directly detect the Cosmic Neutrino Background (CNB). Each of the technological challenges described in [1, 2] will be targeted and hopefully solved by the use of the latest experimental developments and profiting from the low background environment provided by the LNGS underground site. The

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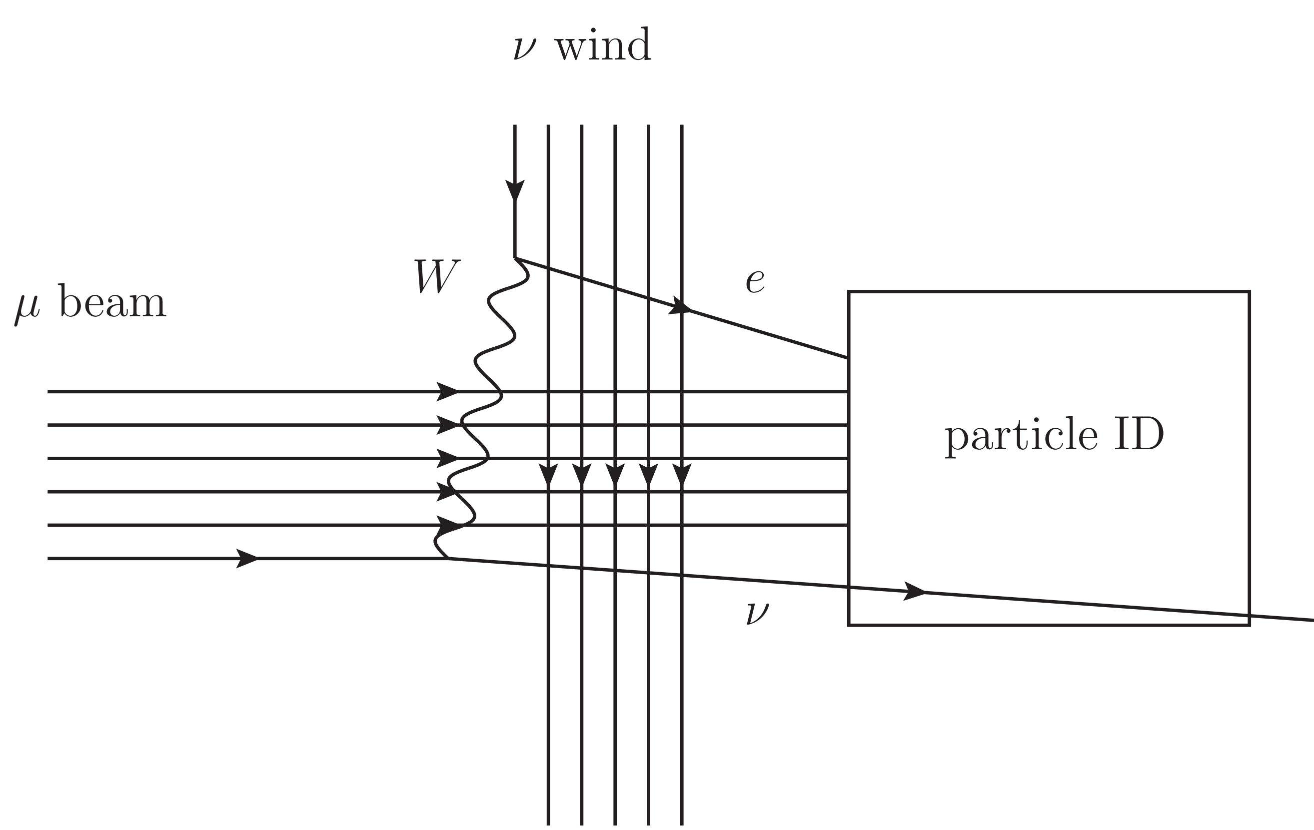
- Mechanical Forces
- **Inverse β-Decay Processes**
  - PTOLEMY
  - **Muon Beam**
- Summary and Conclusions

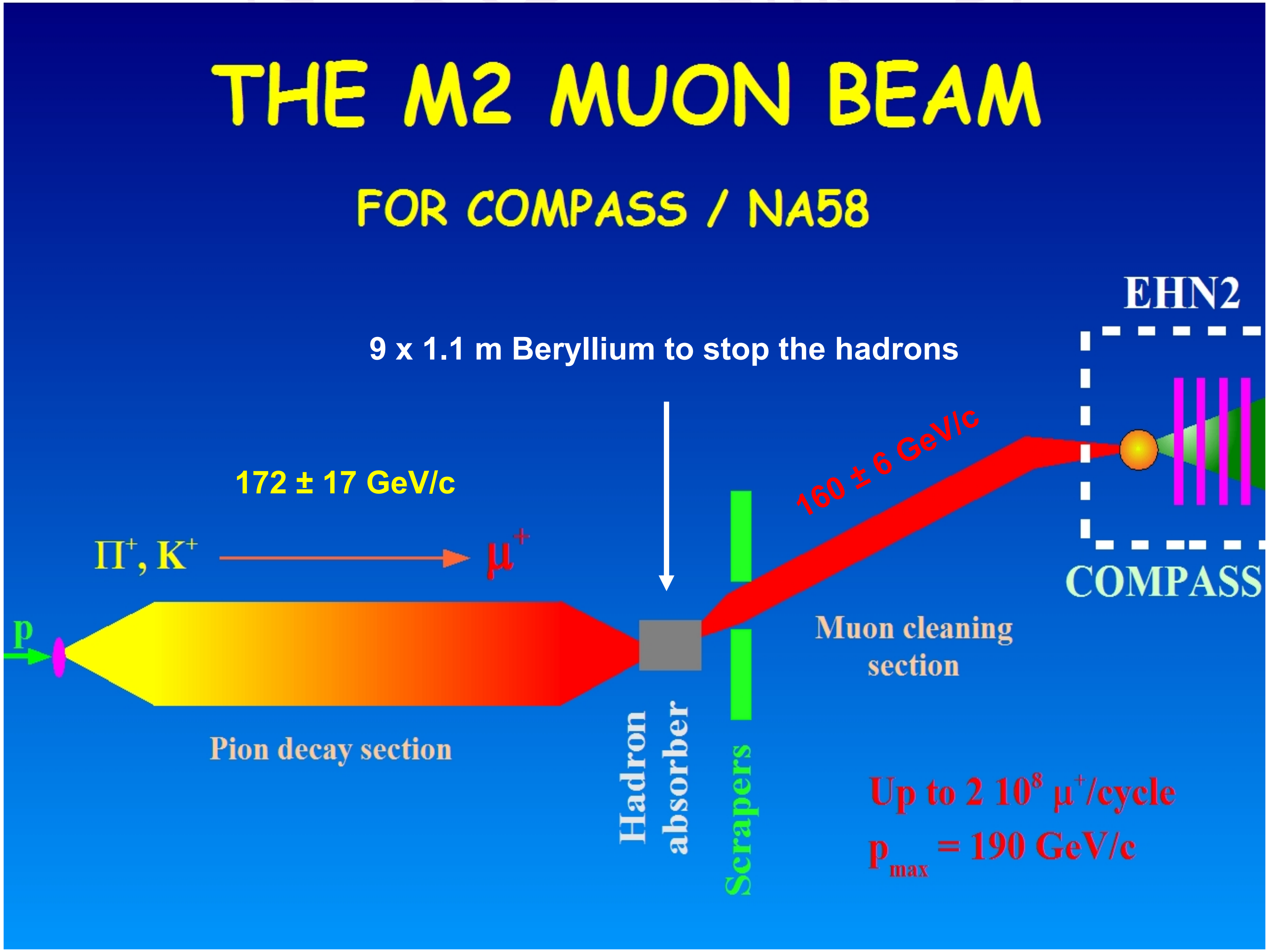
Another Idea

[MS, Tancredi, Zurita WIP; see also Weiler '01, Mellissinos '99, Müller '87]

- 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 x 10^7 /s
- Beam "length": 100 cm
- Treating the beam as fixed target, event rate:

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

Physics Cases (Preliminary)

[MS, Tancredi, Zurita WIP]

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

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:

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

  - Amount of muons/tritium:

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

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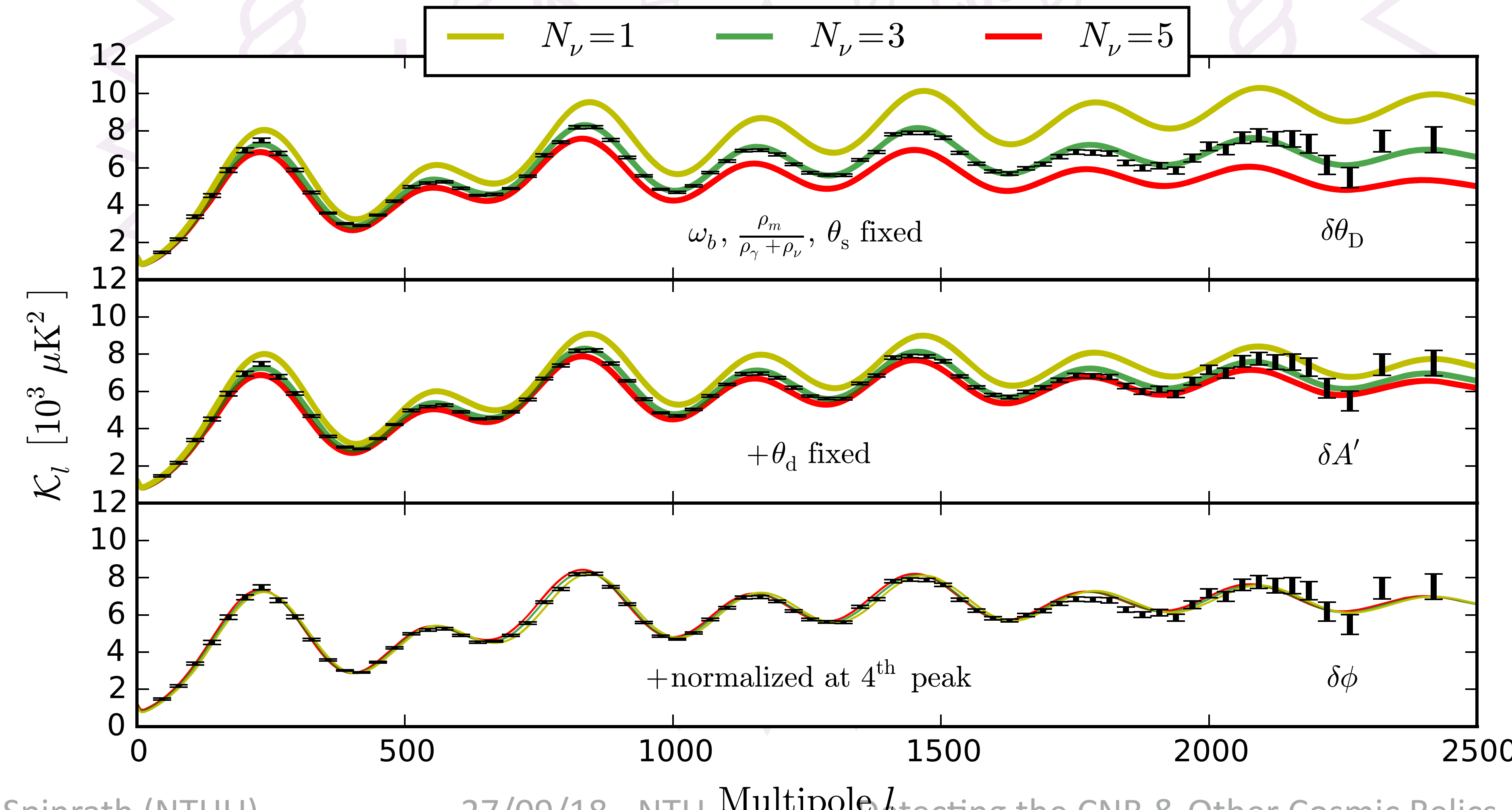
Summary and Conclusions

- 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
- It is fun to think about other ideas as well...

Backup

Indirect Evidence

- Big Bang Nucleosynthesis
- Imprint on Baryon Acoustic Oscillations



[Follin, Knox, Millea, Pan '15]

Theory: Magnetic Torque

[Domcke, MS ’17; see also Duda *et al.* '01, ..., Stodolsky '75]

- Neutrino background splits electron energy levels (spin effect → magnetic effect)

$$a^R_{G_F} = \frac{N_{AV}}{A\, m_{AV}} \frac{2\sqrt{2}}{\pi} G_F\, \beta^{\text{CMB}}_{\oplus} \frac{\gamma}{R} \sum_{\alpha=e,\mu,\tau} (n_{\nu_\alpha} - n_{\bar{\nu}_\alpha})\, g^\alpha_A$$

- For one flavour

$$a^R_{G_F} \approx 4 \cdot 10^{-29}\, \frac{n_{\bar{\nu}_\mu} - n_{\nu_\mu}}{2\,\bar{n}_\nu}\, \text{cm/s}^2$$

- Caveats:
  - Experimentally difficult (magnetic effect)
  - Needs lepton asymmetry

Theory: Scattering I

[Domcke, MS ’17; see also Duda *et al.* '01, ..., 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 1g test material: $N_{AV}/(A m_A V)$
- Neutrino-nucleus cross-section: $\sigma_{\nu-A}$
- Coherence factor: N_c
- Average momentum transfer: $\langle \Delta p \rangle$

Theory: Scattering II

[Domcke, MS ’17; see also Duda *et al.* '01, ..., Opher '74]

- Neutrinos can come in three kinematics
  - relativistic (R)
  - non-relativistic non-clustered (NR-NC)
  - non-relativistic clustered (NR-C)
- Two important numbers
  - The cross-section: $\sigma_{\nu-A} \approx 10^{-27}\ \mathrm{pb} = 10^{-63}\ \mathrm{cm}^2$
  - The coherence factor: $N_c = \frac{N_{AV}}{A\, m_{AV}}\, \rho\, \lambda_\nu^3 \sim 10^{20}$

Wind vs. Nudges I

[Domcke, MS '17]

- The scattering rate

$$R = \frac{a_{G_F^2}}{\langle \Delta p \rangle}$$

- Numbers for the CNB

$$R_{(\mathrm{R})} \approx 1 \cdot 10^{-4} \, \frac{n_\nu}{2\,\bar{n}_\nu} \, \mathrm{g}^{-1}\,\mathrm{s}^{-1}$$

$$R_{(\mathrm{NR\text{-}NC})} \approx 0.02 \, \frac{n_\nu}{2\,\bar{n}_\nu} \, \frac{m_\nu}{0.1 \ \mathrm{eV}/c^2} \, \mathrm{g}^{-1}\,\mathrm{s}^{-1}$$

$$R_{(\mathrm{NR\text{-}C})} \approx 0.4 \, \frac{n_\nu}{2\,\bar{n}_\nu} \, \frac{0.1 \ \mathrm{eV}/c^2}{m_\nu} \left(\frac{10^{-3}}{\beta_{\mathrm{vir}}}\right)^2 \, \mathrm{g}^{-1}\,\mathrm{s}^{-1}$$

Wind vs. Nudges II

[Domcke, MS '17]

- Solar neutrinos

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

- Cold WIMP Dark Matter (m_X > 1 GeV)

$$R_{\text{DM}} \approx 8 \cdot 10^{-3} \left(\frac{100\ \text{GeV}/c^2}{m_X}\right)\left(\frac{\sigma_{X-N}}{10^{-33}\,\text{cm}^2}\right)\left(\frac{\rho_{\text{dark(local)}}}{10^{-24}\,\text{g}/\text{cm}^3}\right)\left(\frac{\beta_X}{10^{-3}}\right)\,\text{g}^{-1}\,\text{s}^{-1}$$

- Light WIMP Dark Matter (m_X = 3.3 keV)

$$R_{\text{light DM}} \approx 4 \cdot 10^{5} \left(\frac{3.3\ \text{keV}/c^2}{m_X}\right)^4\left(\frac{\sigma_{X-N}}{10^{-42}\,\text{cm}^2}\right)\left(\frac{\rho_{\text{dark(local)}}}{10^{-24}\,\text{g}/\text{cm}^3}\right)\left(\frac{\beta_X}{10^{-3}}\right)\,\text{g}^{-1}\,\text{s}^{-1}$$

Helicity Composition

[Long, Lunardini, Sabancilar ’14]

- Dirac neutrinos
  - left-handed active neutrino: $n(\nu_{h_L}) = n_0$
  - right-handed active anti-neutrino: $n(\bar{\nu}_{h_R}) = n_0$
  - right-handed sterile neutrino: $n(\nu_{h_R}) \approx 0$
  - left-handed sterile anti-neutrino: $n(\bar{\nu}_{h_L}) \approx 0$
- $n_0 = 56\ \mathrm{cm}^{-3}$

Helicity Composition

[Long, Lunardini, Sabancilar '14]

- Majorana neutrinos
  - left-handed active neutrino: $n(\nu_{h_L}) = n_0$
  - right-handed active neutrino: $n(\nu_{h_R}) = n_0$
  - right-handed sterile neutrino: $n(N_{h_R}) \approx 0$
  - left-handed sterile neutrino: $n(N_{h_L}) \approx 0$
- $n_0 = 56\ \mathrm{cm}^{-3}$

Capture Cross Section

[Long, Lunardini, Sabancilar '14]

$$\sigma_j(s_\nu) v_{\nu_j} = \frac{G_F^2}{2\pi} |V_{ud}|^2 |U_{ej}|^2 F(Z, E_e) \frac{m_p}{m_n} E_e \, p_e \, A(s_\nu)(f^2 + 3g^2) \; ,$$

$$F(Z, E_e) = \frac{2\pi Z \alpha E_e / p_e}{1 - e^{-2\pi Z \alpha E_e / p_e}} \; ,$$

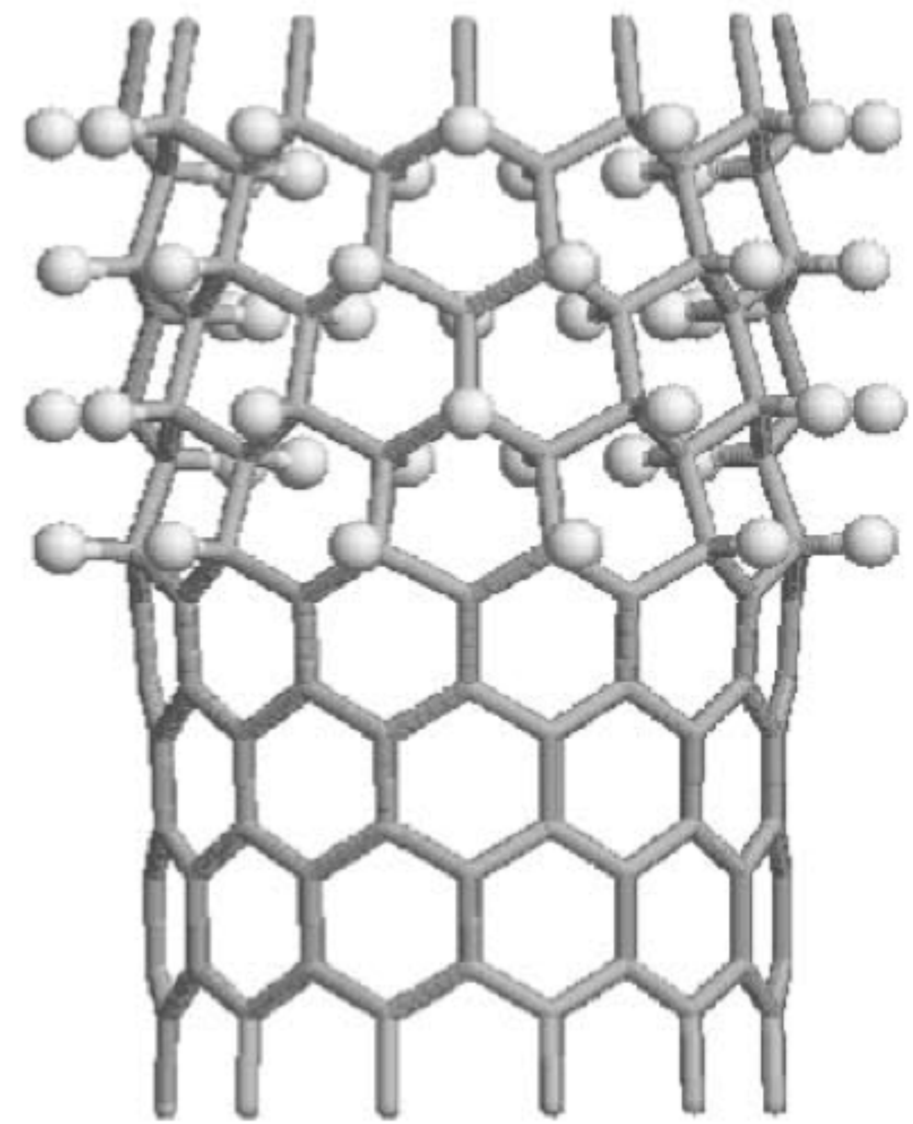
$$A(s_\nu) \equiv 1 - 2 s_\nu v_{\nu_j} = \begin{cases} 1 - v_{\nu_j} & , \quad s_\nu = +1/2 \qquad \text{right helical} \\ 1 + v_{\nu_j} & , \quad s_\nu = -1/2 \qquad \text{left helical} \end{cases}$$

$$\Rightarrow \bar{\sigma} \equiv \frac{\sigma_j(s_\nu) v_{\nu_j}}{A(s_\nu) |U_{ej}|^2 c} \simeq 3.834 \times 10^{-45} \text{ cm}^2 = 3.834 \times 10^{-6} \text{ fb}$$

Tritium Target

[PTOLEMY '13]

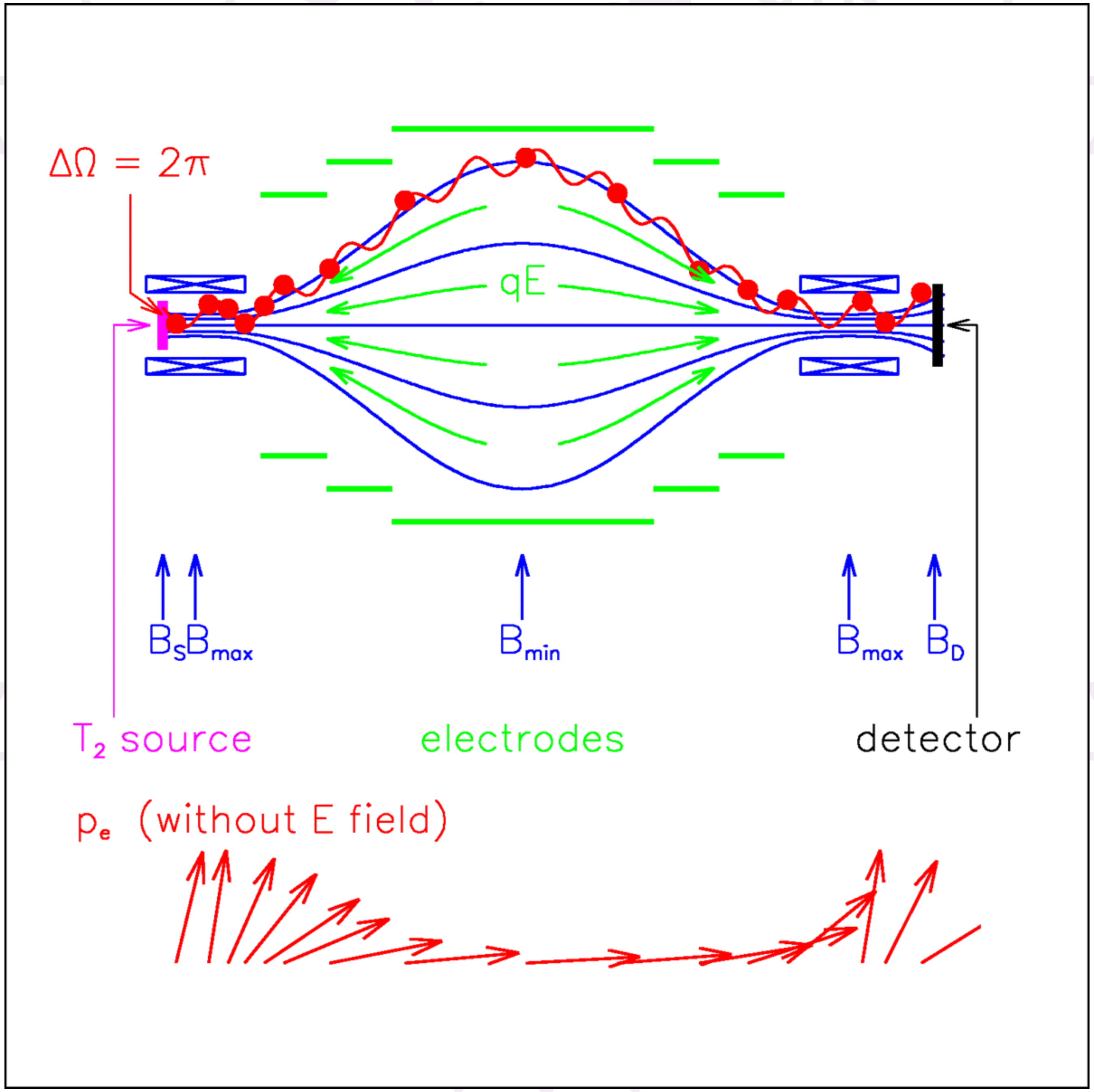
- Tritium half-life 12.32 yr
- Princeton Plasma Physics Lab has high intensity tritium source
- Use graphene as substrate exposed to tritium plasma
- Plan: 100 g tritium target material



MAC-E Filter

- Magnetic Adiabatic Collimation followed by Electrostatic filter
- Proposed in 1980 by Beamson *et al.*, used in Troitsk, Mainz, KATRIN
- Theory of operation:
  - Guide electrons magnetically, adiabatically to a detector
  - Varying magnetic fields rotate the electron momentum along the field lines
  - Superimpose perpendicular electrostatic field which filters low energy electrons

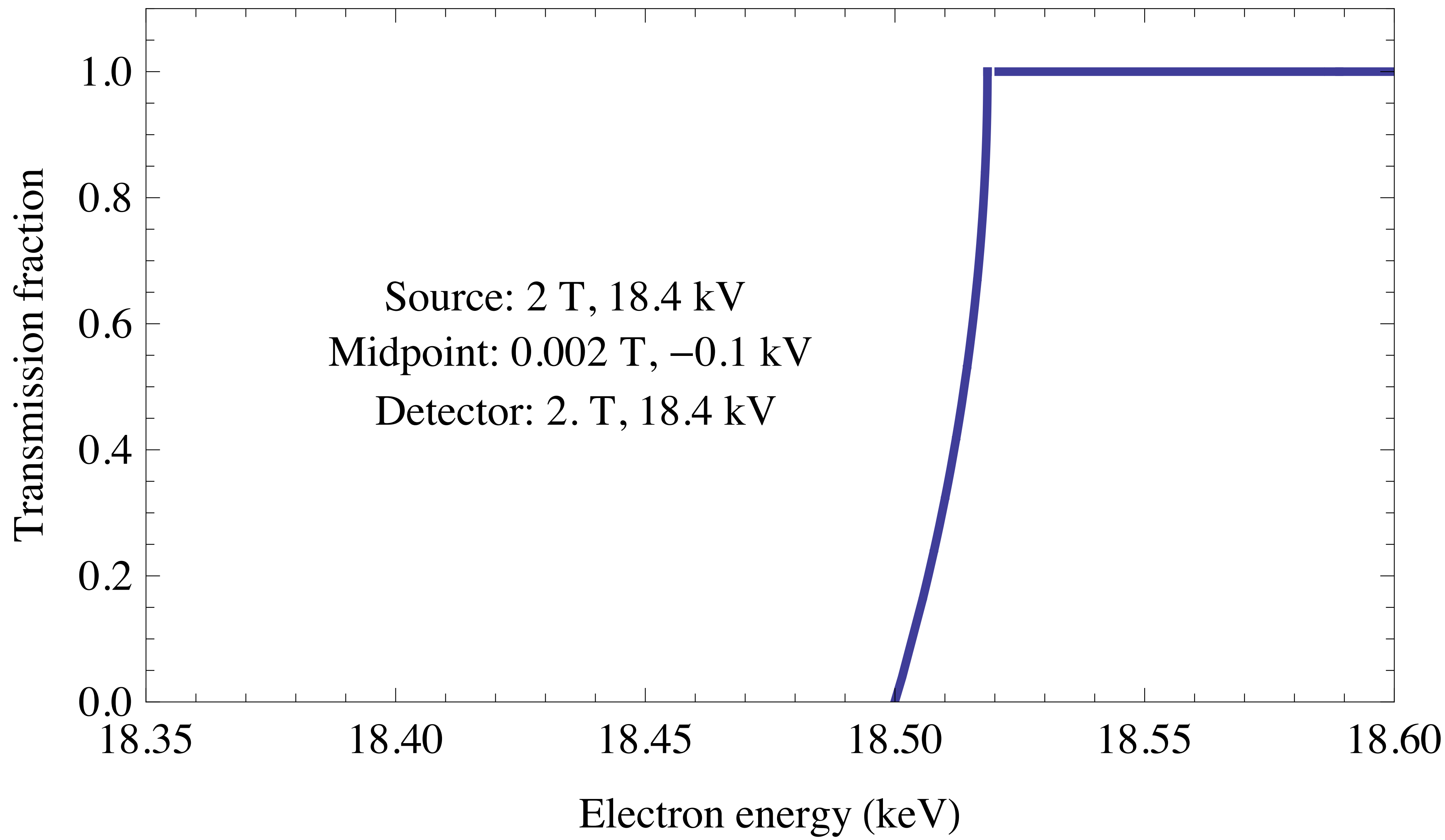
MAC-E Filter



[taken from www.katrin.kit.edu/79.php]

MAC-E Filter

[PTOLEMY ’13]



Cryogenic Calorimeter

[PTOLEMY '13]

- Design goal resolution: 0.15 eV @ 100 eV
- Combination of
  - Superconducting quantum interference devises (SQUIDs)
  - Transition-edge sensors (TES)
- Tests at T = 70 mK