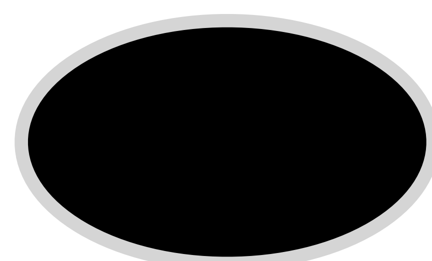
Relic Neutrino Background

Martin Bauer, 1.7.2024

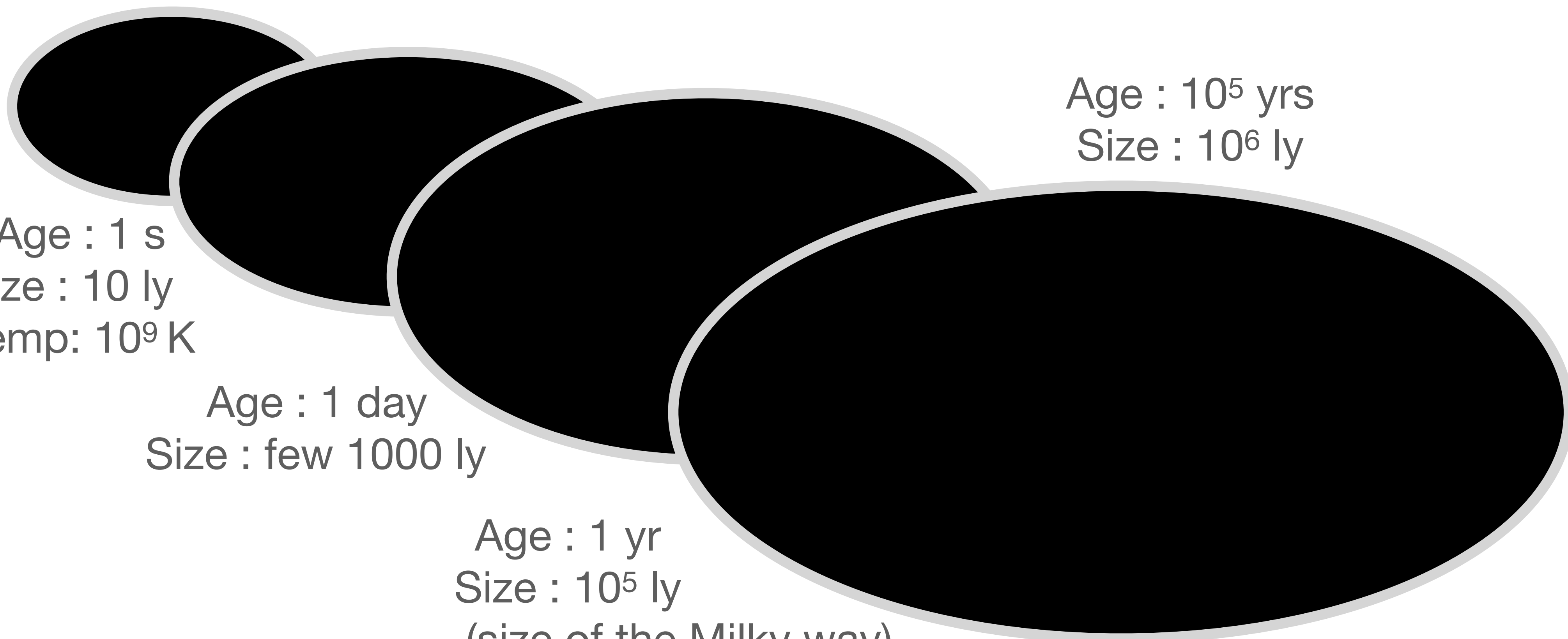
MB, Shergold, *Phys.Rev.D* 104 (2021)
MB, Shergold, *JCAP* 01 (2023) 003

This is a picture of the Universe 1 second after the Big Bang

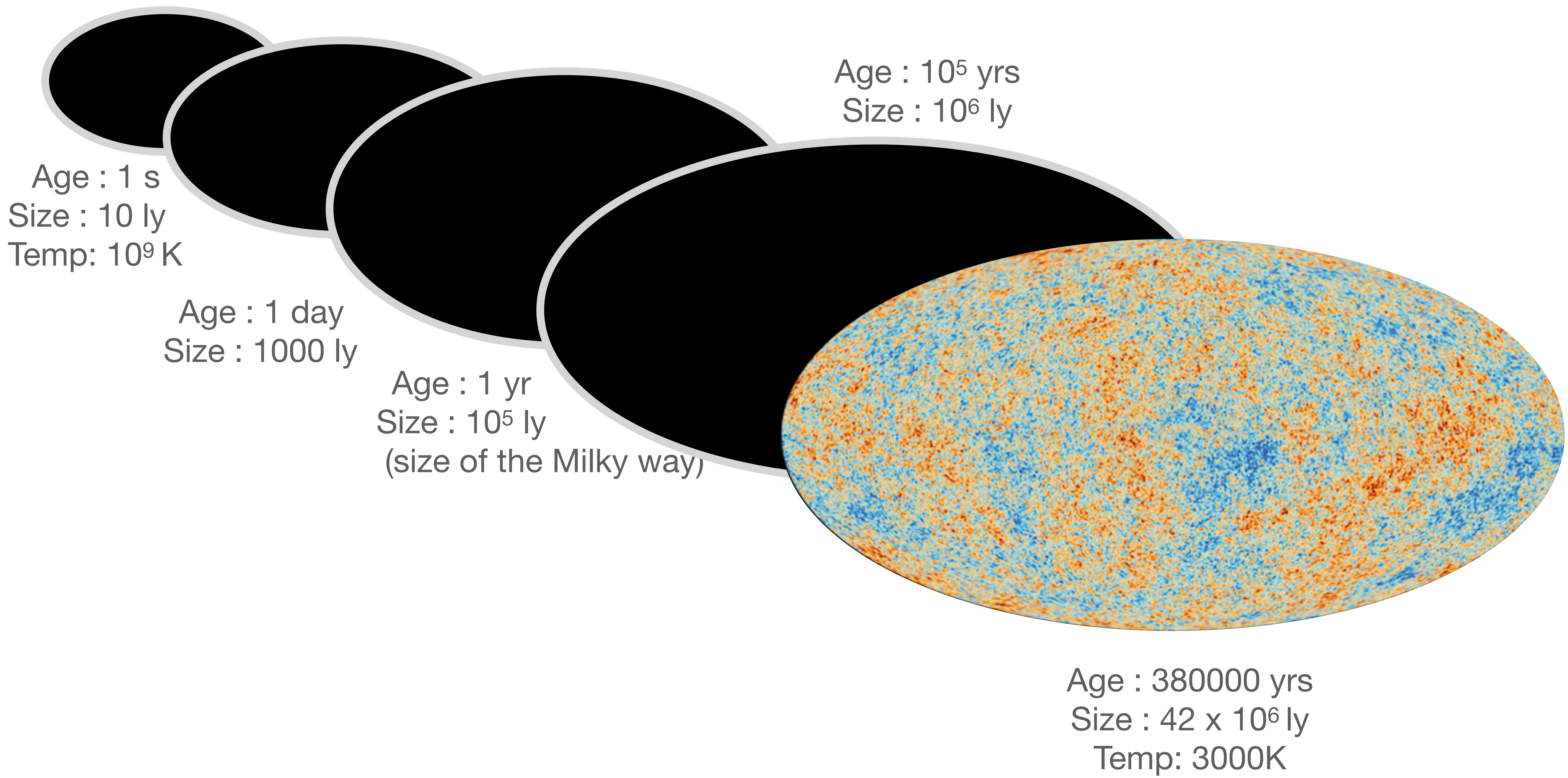


Age : 1 s
Size : 10 ly
Temp: 10^9 K

This is a picture of the Universe 100 000 yrs after the Big Bang



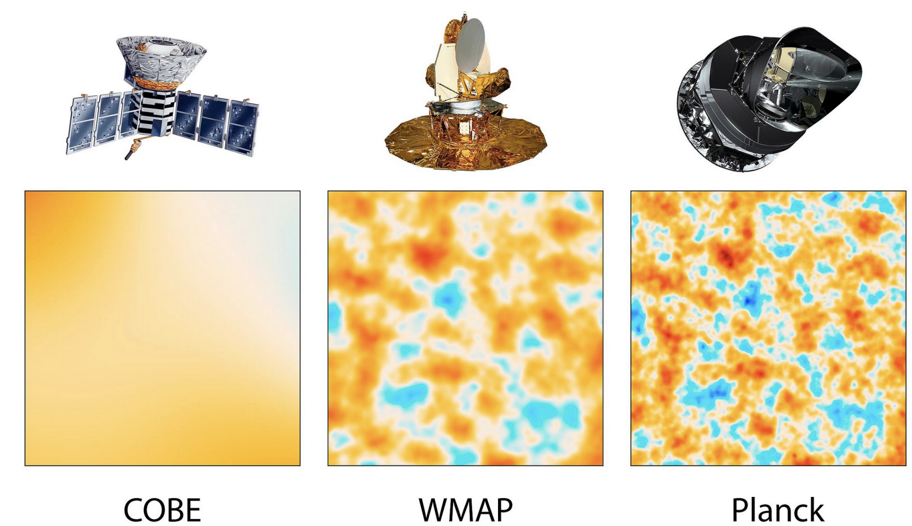
This is a picture of the Universe 380 000 yrs after the Big Bang

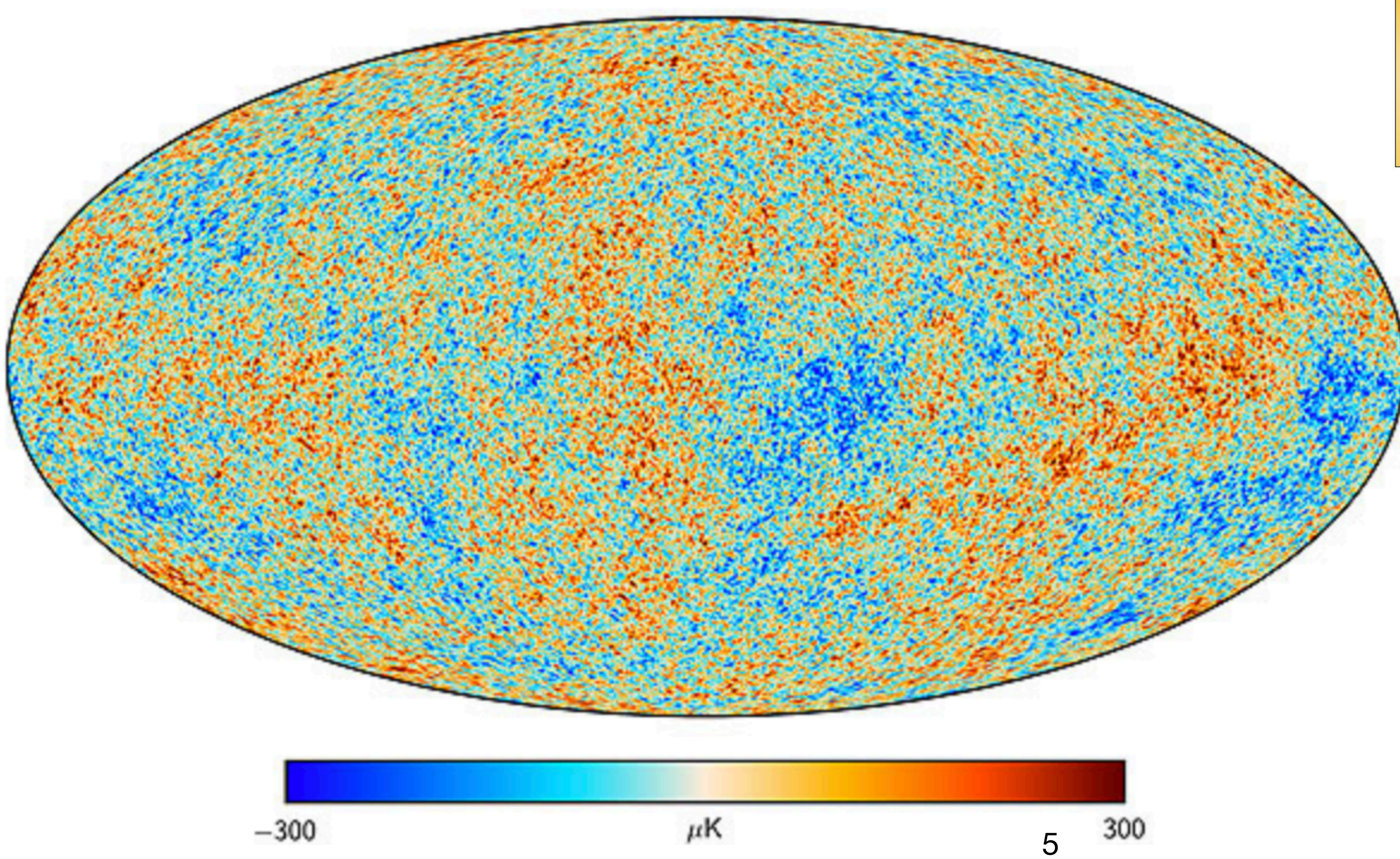


This is a picture of the Universe 380 000 yrs after the Big Bang

The cosmic microwave background is the ‘afterglow’ of the Big Bang. It emerged when photons decoupled from the thermal bath.

Planck provides the most sensitive measurement





$$T_\gamma = 2.4 \cdot 10^{-4}\mathrm{eV}$$

Aghanim et al [Planck],
Astron. Astrophys. **641** (2020), A6
588 (2020) 61

CMB temperature

Why is the very early Universe opaque?

Photons decoupled when atoms formed. We can guess the temperature $T \sim 13.6$ eV.

CMB temperature

Why is the very early Universe opaque?

Photons decoupled when atoms formed. We can guess the temperature T ~ 13.6 eV.

Formally, decoupling happens when the interaction rate $\mathbf{\Gamma}$ equals the expansion parameter **H**. A careful calculation yields T ~ 1 eV

$$\Gamma = \frac{c}{\lambda} = n_e \sigma_e c \quad \approx \quad H$$

mean free path

number of free electrons

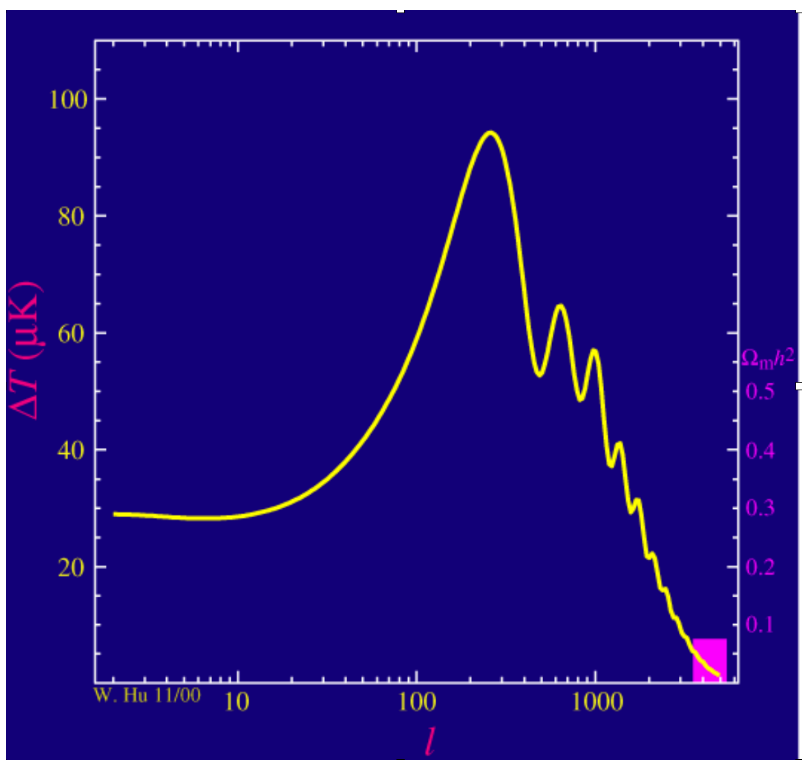
Scattering cross section

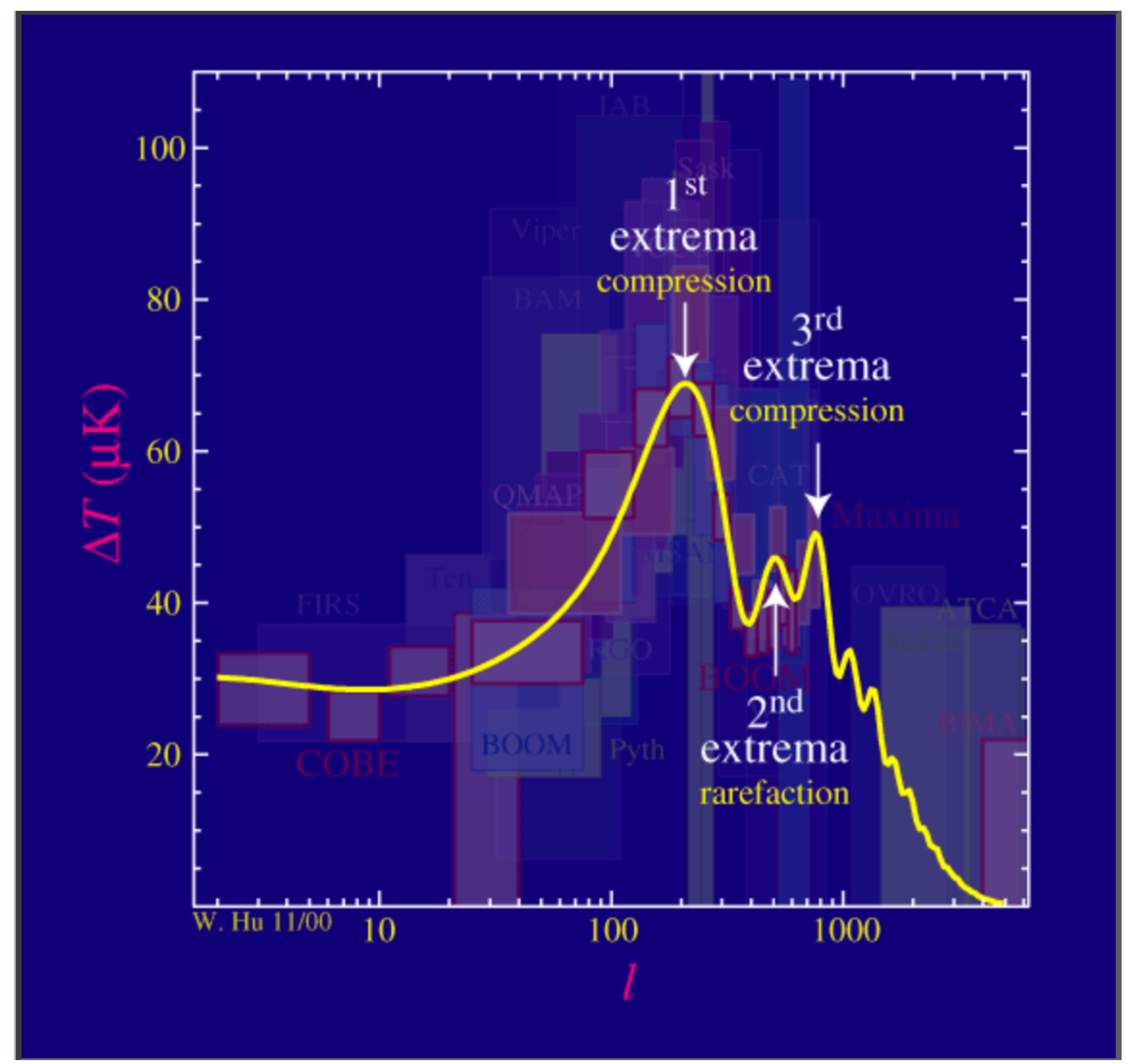
CMB temperature fluctuations

The multipole spectrum is the richest source of information about the early Universe we have.

For example the amount of dark matter in the Universe can be measured in this spectrum

Graphics from Wayne Hu





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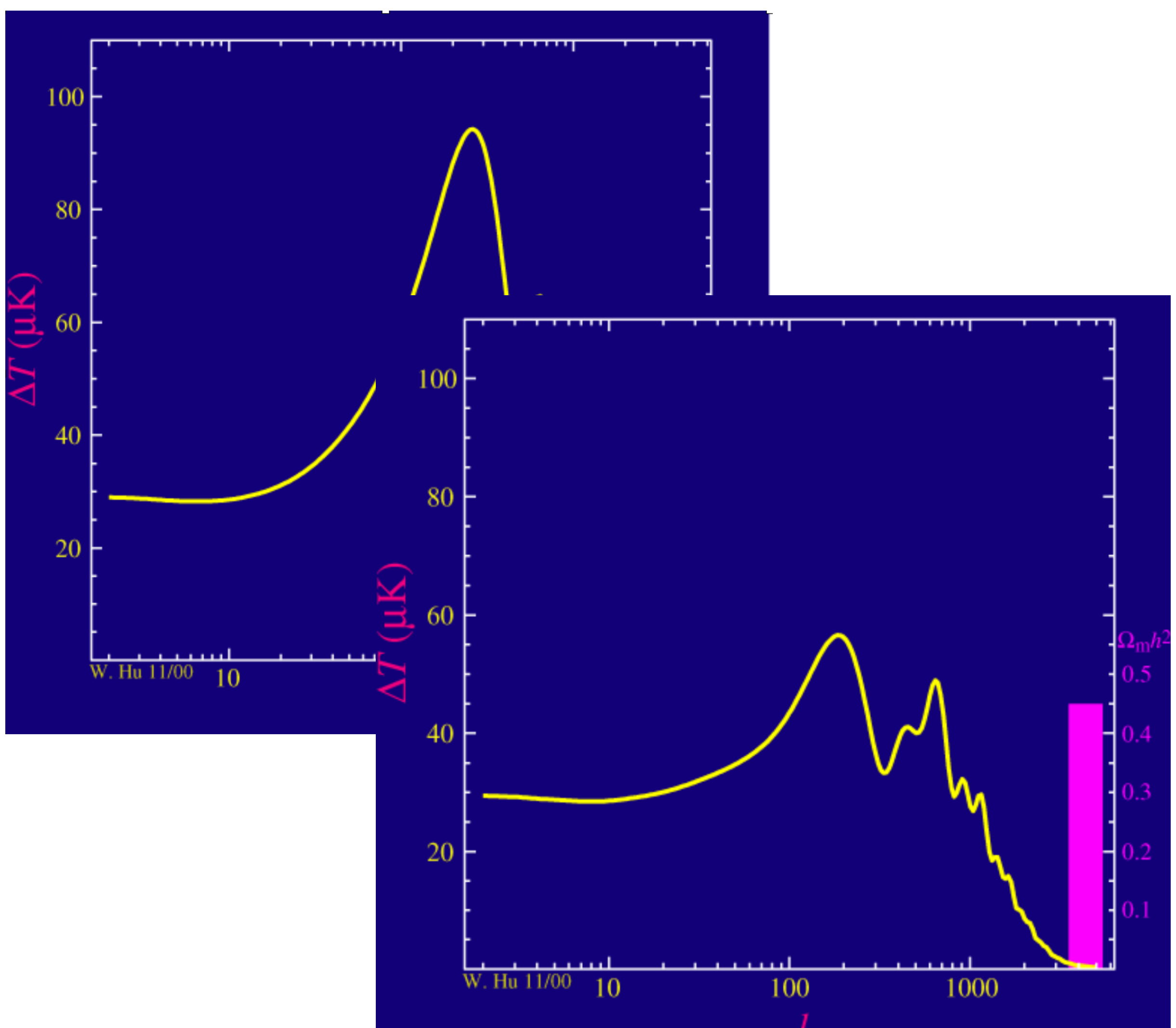
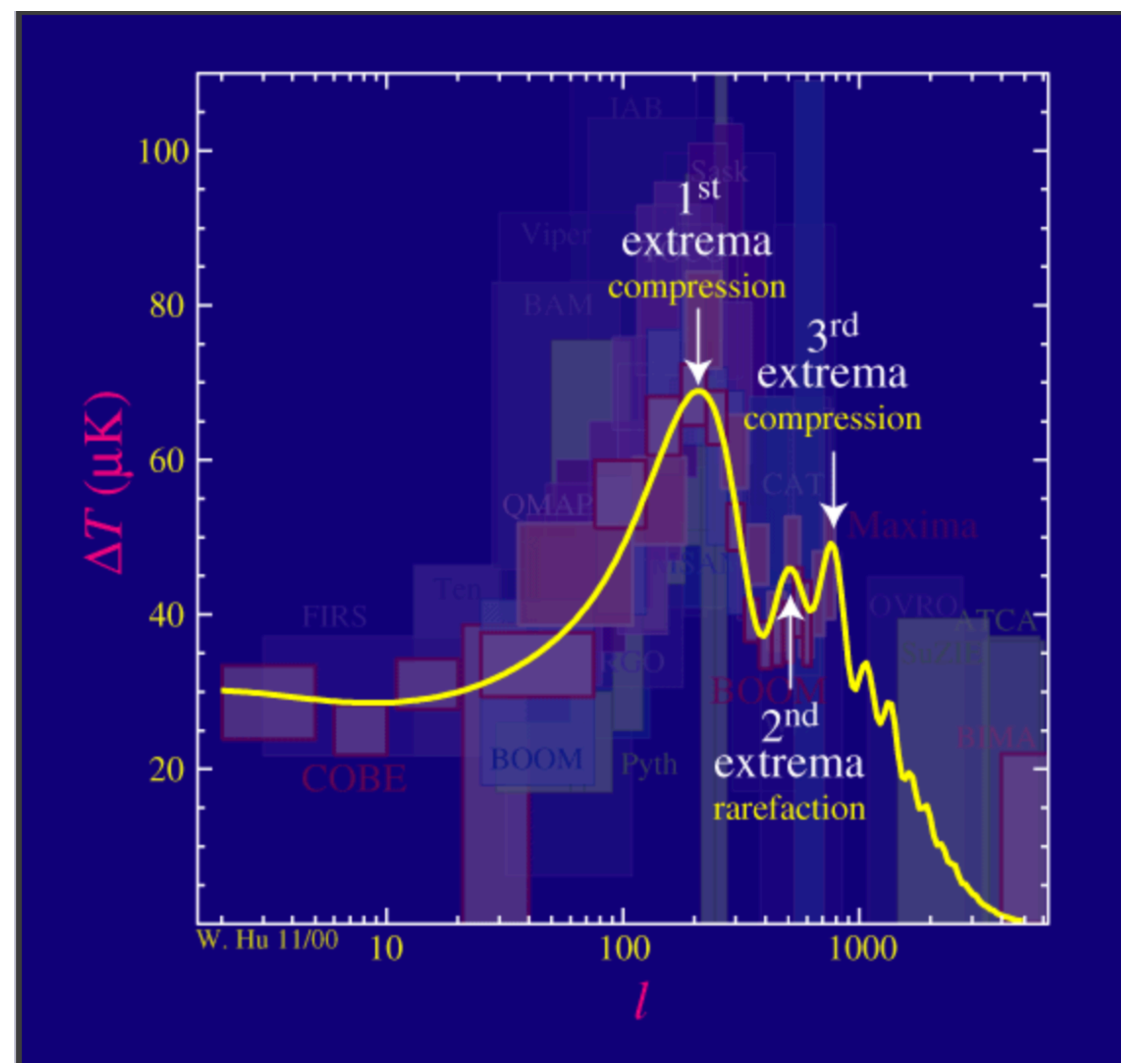




CMB temperature fluctuations

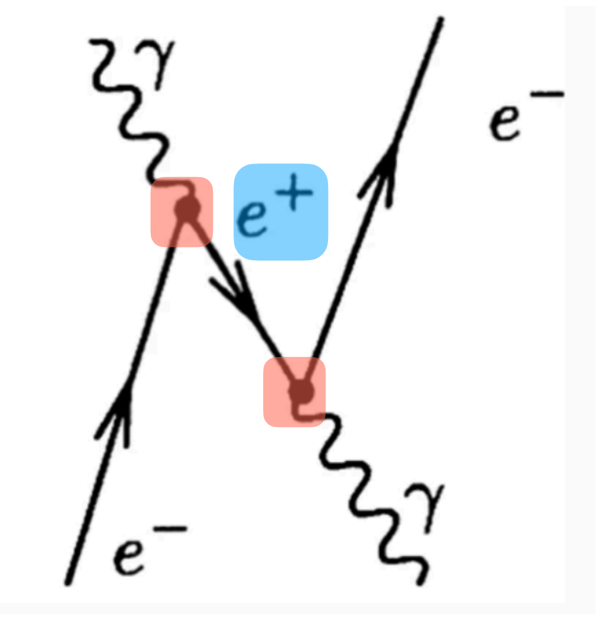
The Universe was relatively old when photons decoupled.

One reason for that is the scattering cross section isn't small

$$\Gamma = \frac{c}{\lambda} = n_e \sigma_e c \quad \approx \quad H$$

Compton Scattering cross section

$$\sigma_e = \frac{\pi \alpha^2}{m_e^2}$$

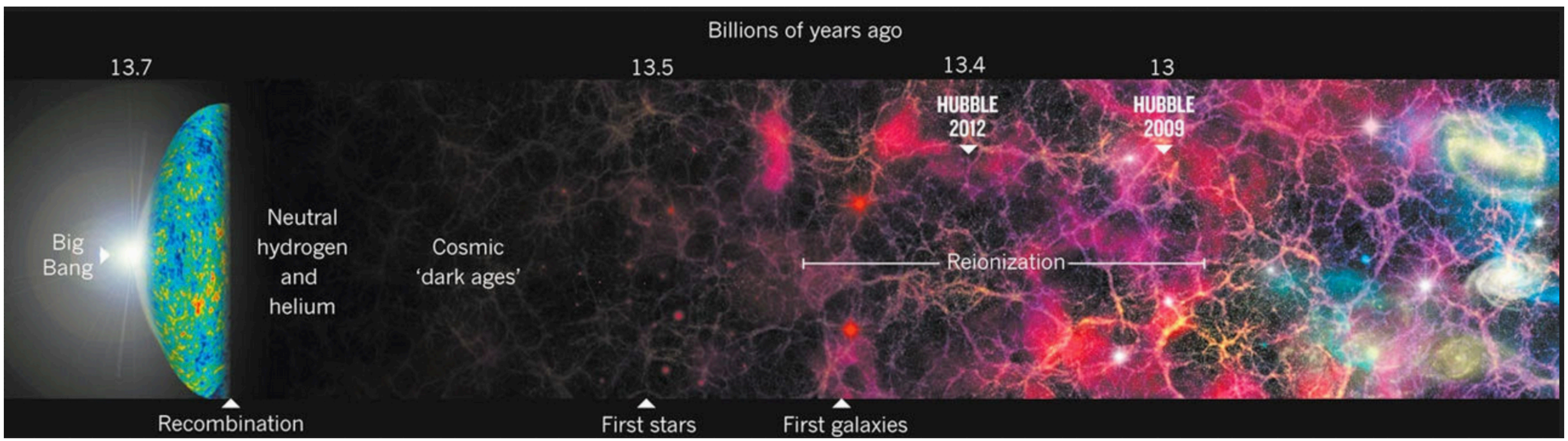


If the interaction strength α were **smaller** or the electron mass m_e were **larger,** decoupling would happen **earlier**.

Neutrino Decoupling

Other fundamental particles decouple earlier than photons.

Unstable particles then decayed and electrons, protons and neutrons organised into larger structures since then (atoms, molecules, galaxies).

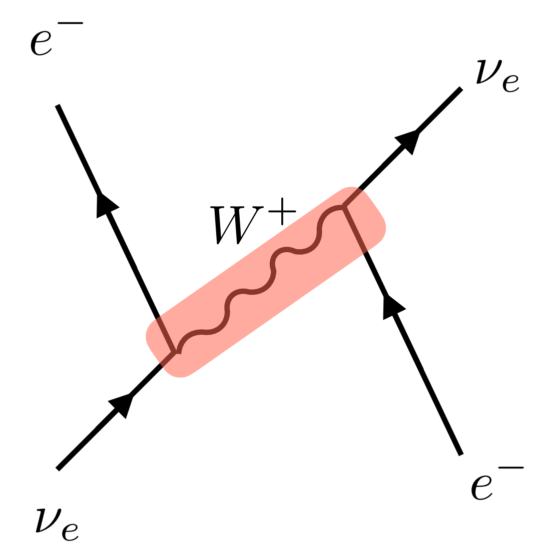


But neutrinos are so light and interact so weakly that they are expected to still be around as 'background radiation': **The cosmic neutrino background** (CvB)

Neutrino Decoupling

We can calculate the time of neutrino decoupling

$$\Gamma = \frac{c}{\lambda} = n_e \sigma_\nu c \quad \approx \quad H$$

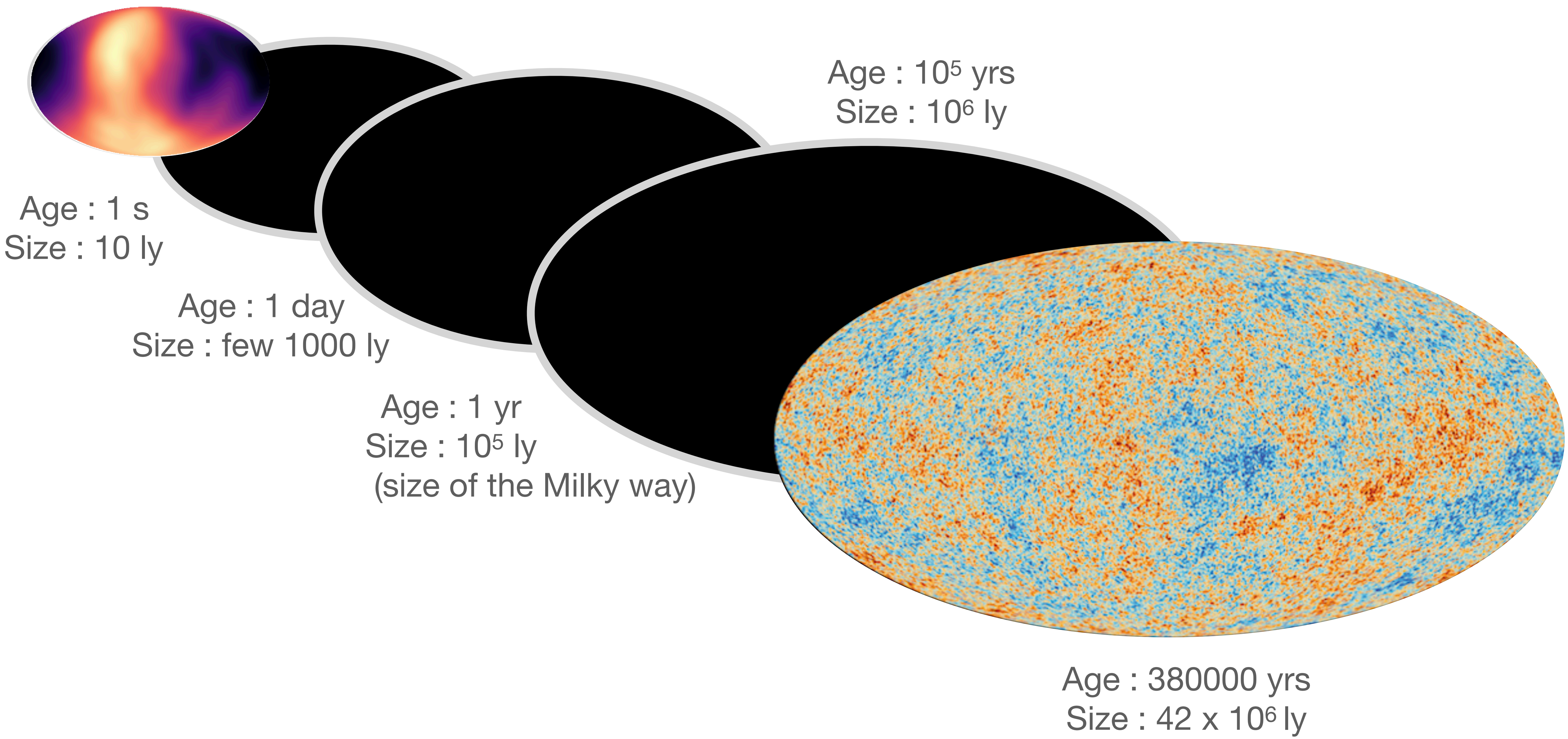


Neutrino Scattering cross section

$$\sigma_\nu = G_F^2 T^2 = \frac{\pi^2 \alpha^2}{2 M_W^4} T^2$$

Photons decoupled after 380000 yrs, neutrinos decoupled after only 1s !

It would give us a picture of the Universe 1s after the Big Bang



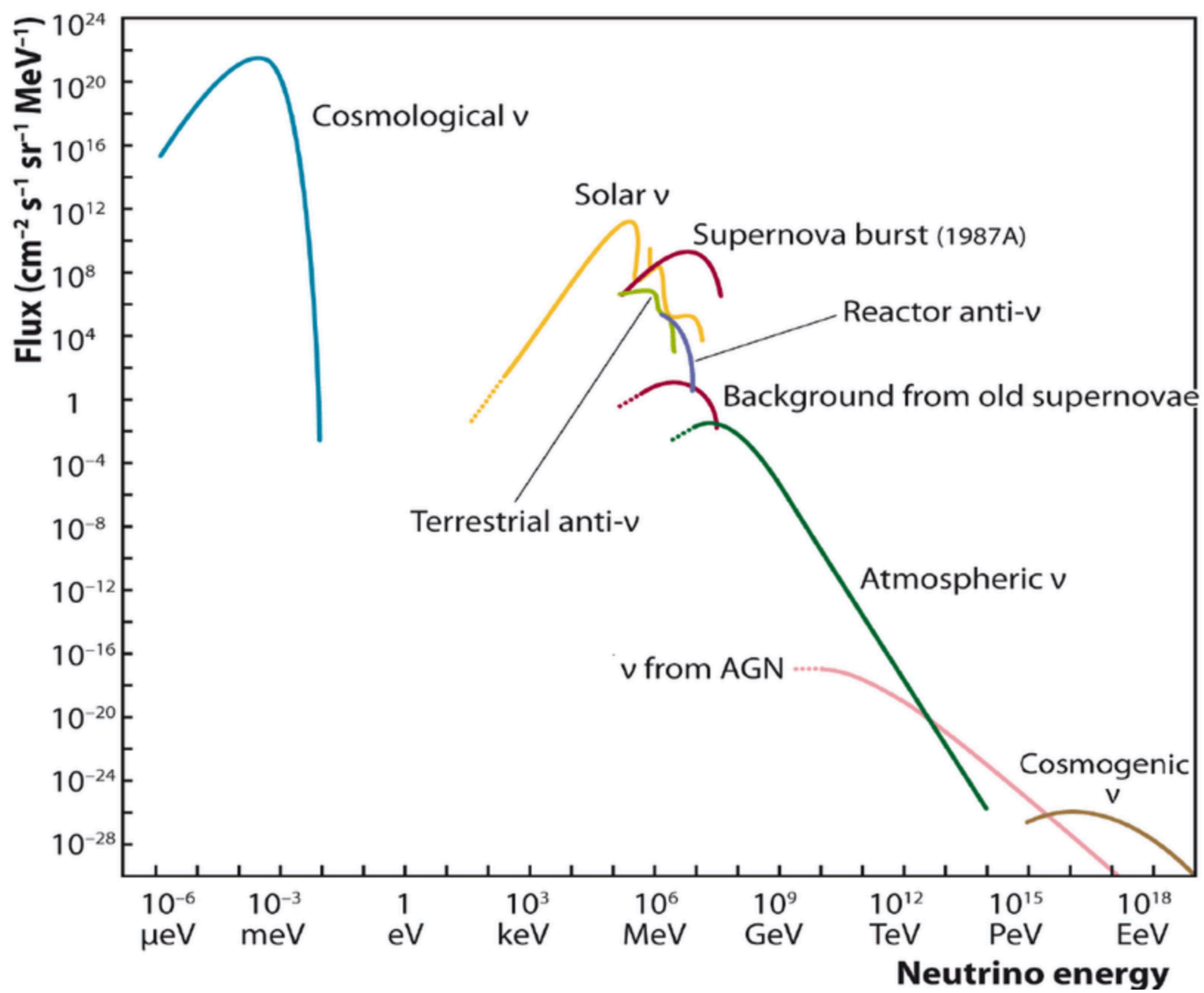
Tully, Zhang. *JCAP* 06 (2021) 053

Properties of the cosmic neutrino background

Temperature: $T_\nu = 1.7 \cdot 10^{-4}\text{eV}$ $(T_\gamma = 2.4 \cdot 10^{-4}\text{eV})$

Number density: $n_\nu = 56 \cdot 6\,\text{cm}^{-3} = 336\,\text{cm}^{-3}$ $(n_\gamma = 420\,\text{cm}^{-3})$

The flux is enormous:

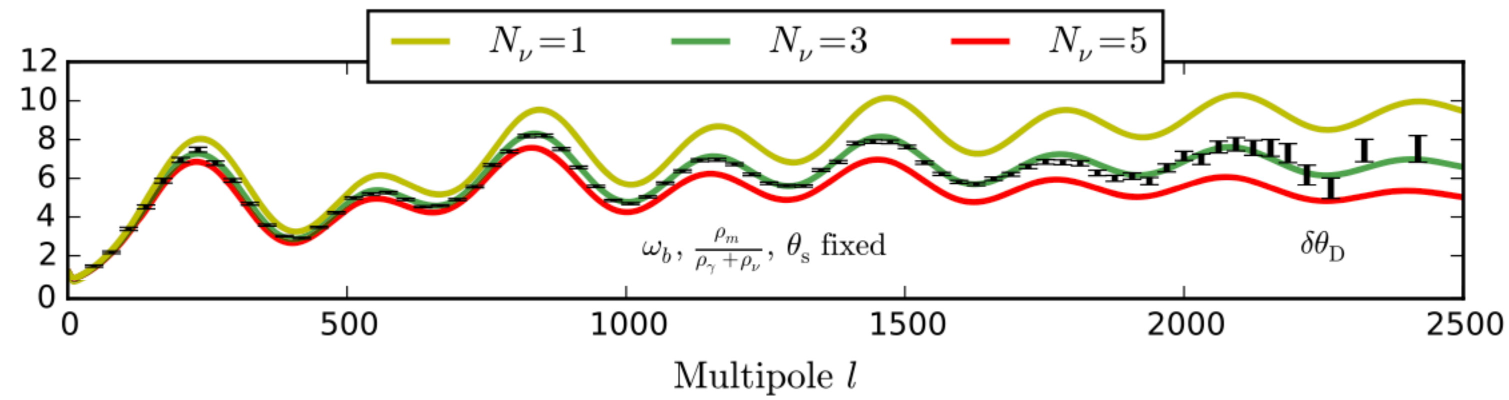


Katz, Spiering. High-Energy Neutrino Astrophysics: Prog. Part. Nucl. Phys., 67:651–704, 2012

Indirect evidence

Follin, Knox, Millea, Pan PRL 115, 091301 (2015)

CMB:

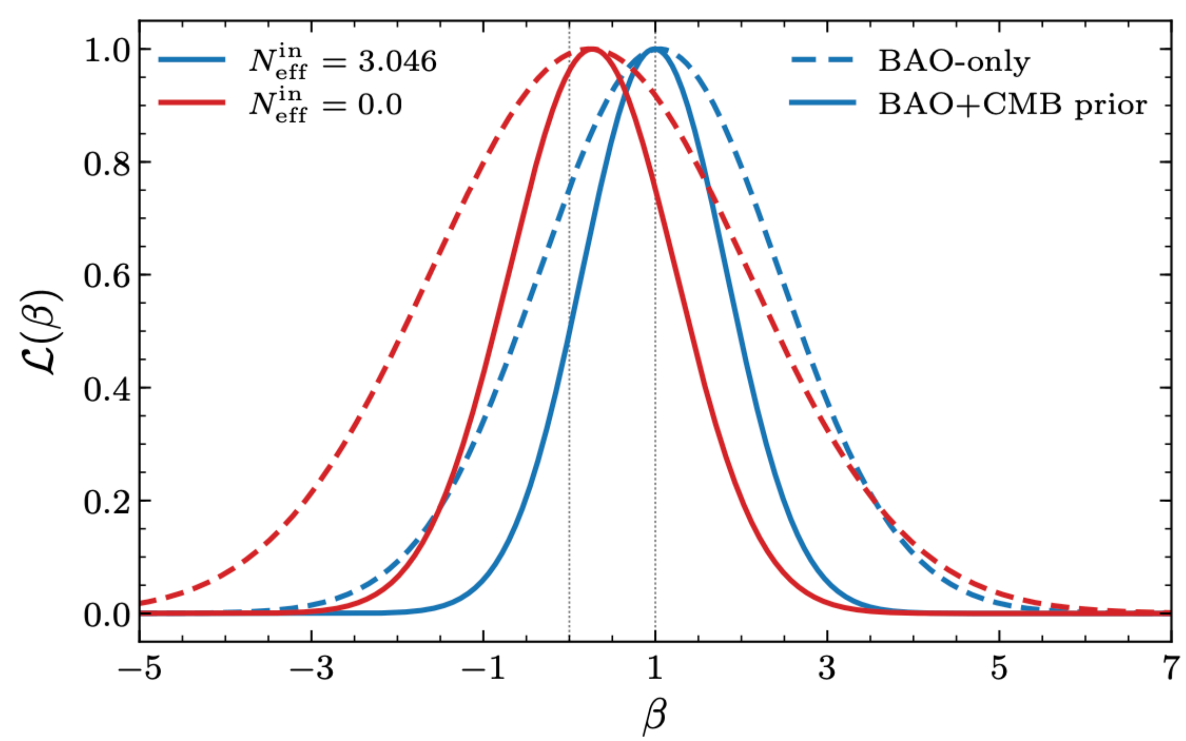


CMB: Photon-neutrino scattering affects B-mode spectrum, in reach of Simons Observatory

Khodagholizadeh, Mohammadi, Xue *Phys.Rev.D* 90 (2014)

BAO: phase shift

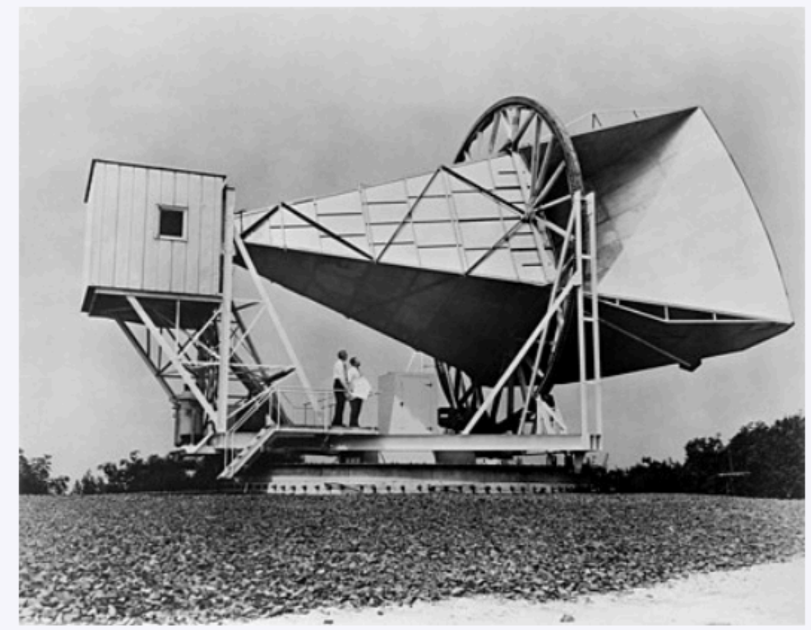
Baumann et al. *Nature Phys.* 15 (2019)



How to detect cosmic neutrinos?

Cosmic microwave photons were discovered per accident

Why is it so hard to see cosmic neutrinos? Compare the scattering cross sections



The Holmdel Horn Antenna in use in 1962

EM cross section:

$$\sigma_{\mathrm{EM}} = \frac{\alpha^2}{E_\gamma^2} \approx 10^{-20} \left(\frac{\mathrm{keV}}{E}\right)^2 \mathrm{cm}^2$$

Neutrino cross section:

$$\sigma_\nu = G_F^2 E_\nu^2 \approx 5 \cdot 10^{-50} \left(\frac{E_\nu}{\mathrm{keV}}\right)^2 \mathrm{cm}^2$$

We have only ever detected energetic neutrinos

How to detect cosmic neutrinos?

Some ideas:

1. **Cosmic rays**

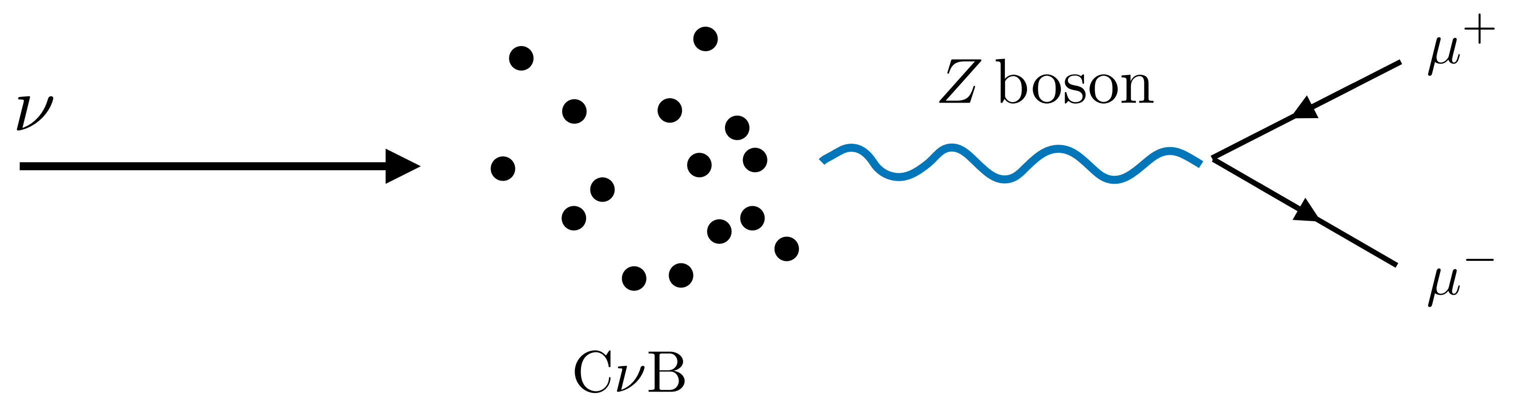
2. Neutrino absorption (PTOLEMY)

3. Accelerators

Cosmic Rays

Eberle, Ringwald, Song,Phys. Rev. D 70 (2004)

Cosmic neutrinos are hit by ultra-high energy cosmic rays



At resonance $\sigma = \frac{1}{M_Z^2} \mathrm{Br}(Z \to \nu\bar{\nu}) \approx 10^{-34}\,\mathrm{cm}^2$

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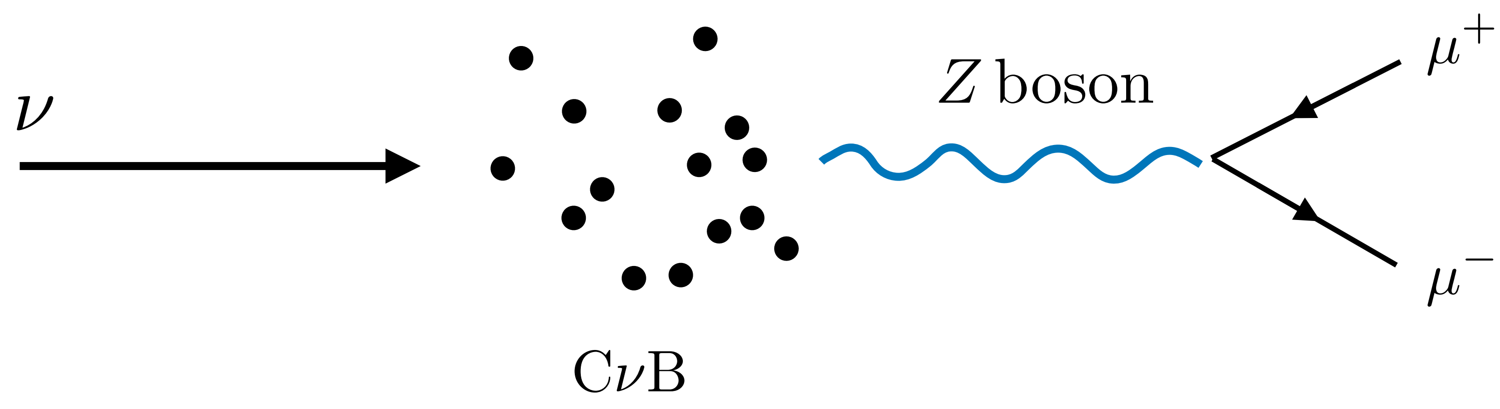

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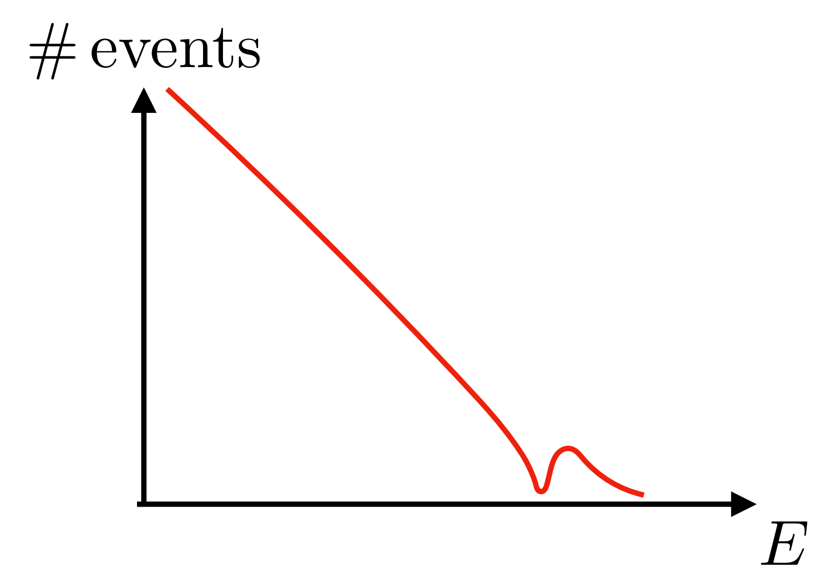


This results in a resonance dip in the cosmic ray spectrum

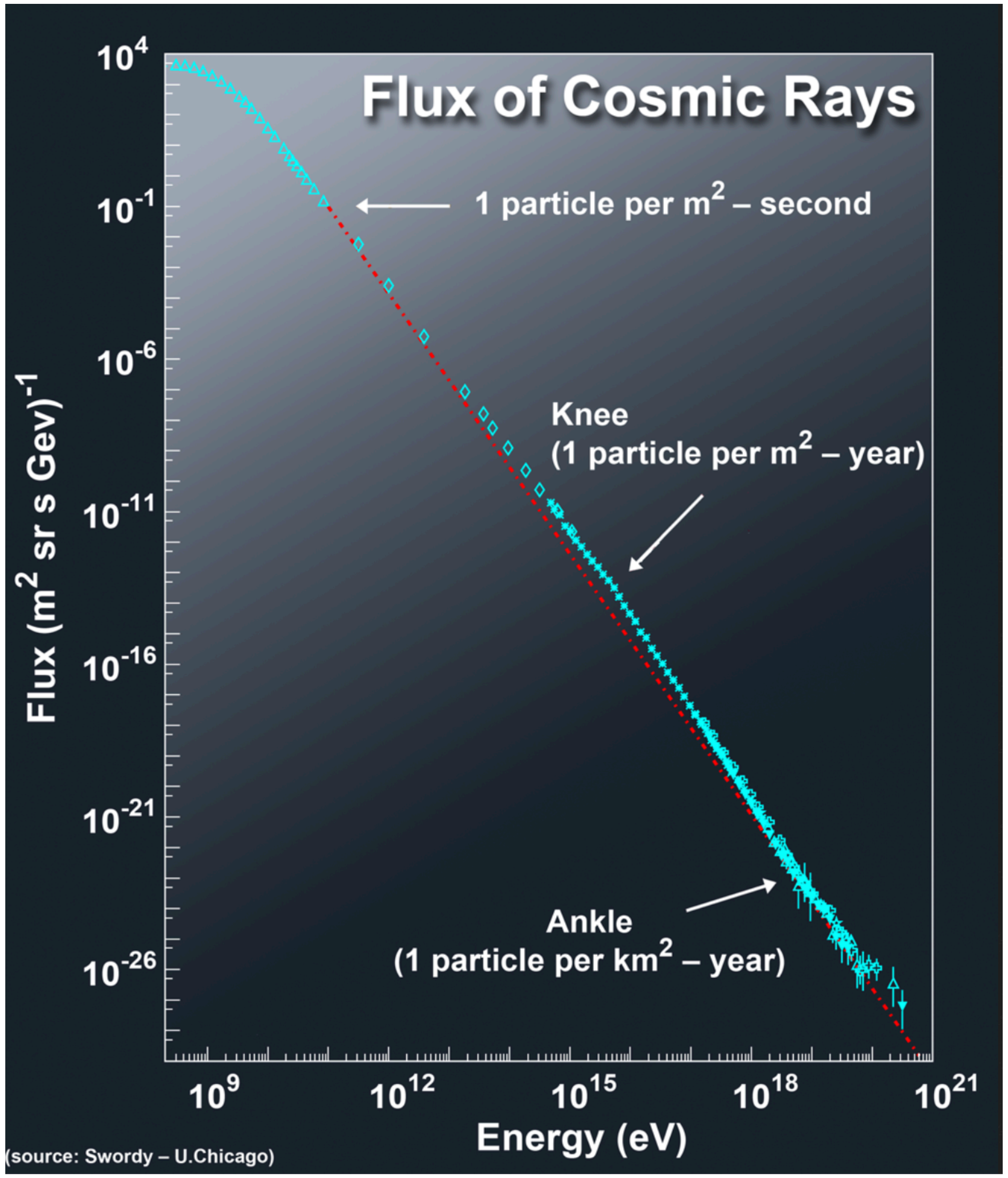
It requires UHE scattering neutrinos with energy

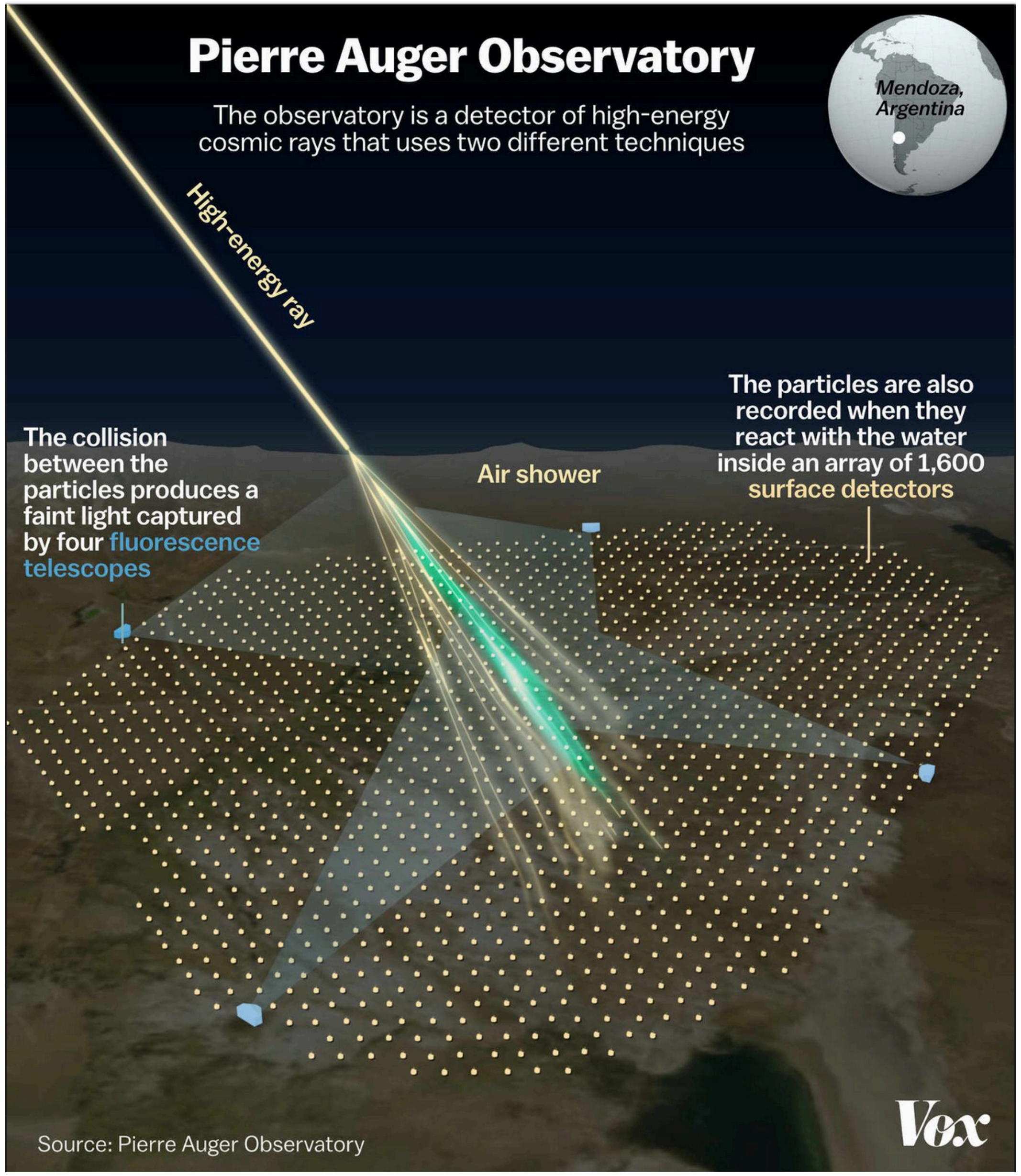
$$E_\nu = \frac{M_Z^2}{2m_\nu} = 10^9\,\mathrm{TeV}$$

Cosmic Rays

Eberle, Ringwald, Song,Phys. Rev. D 70 (2004)

What are the chances to see this “Z burst” at E ~ 10^9 TeV = 10^{21} eV ?





10^{20} eV events have a frequency of 1/km²/100 yrs.

How to detect cosmic neutrinos?

Some ideas:

1. Cosmic rays

2. Neutrino absorption (PTOLEMY)

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PTOLEMY

Weinberg, Phys. Rev. 128 (1962), 1457-1473
Baracchini et al. [PTOLEMY], 1808.01892

Neutrinos are produced in beta decay. Inverse beta decay can absorb neutrinos

$$N \to P^+ + e^- + \bar{\nu}$$

$$P^+ + \bar{\nu} \to N + e^+$$

Looking for positrons produced by neutrino capture would be a clean process to discover the CvB, but the beta gap is 782 keV.

Homestake discovered solar neutrinos

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar}^+ + \mathrm{e}^-$$

But the CvB has an energy of $m_\nu < 1$ eV

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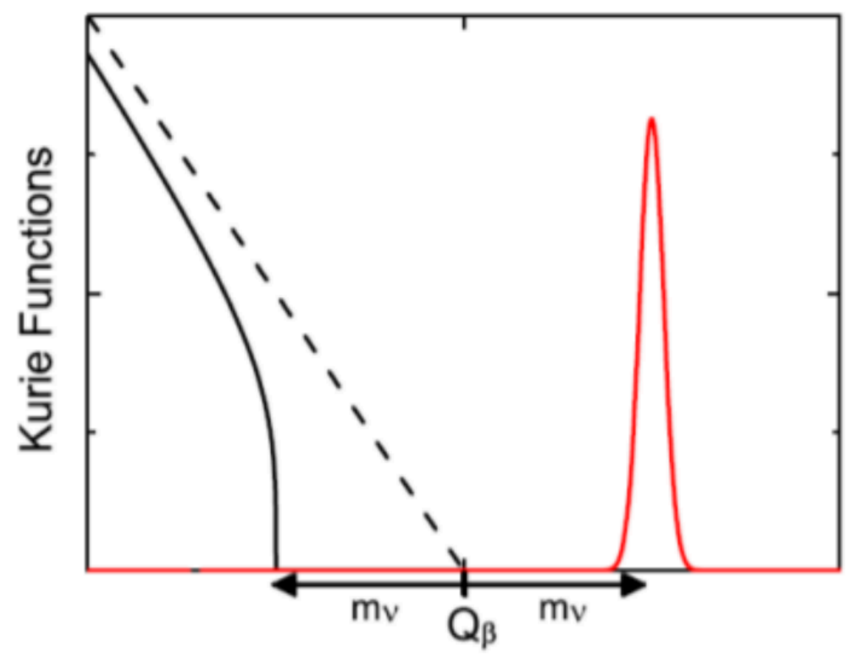
Weinberg had the idea to use tritium, which has no beta gap.

$$\beta \text{ decay}: \quad {}^{3}\text{H} \to {}^{3}\text{He} + e^{-} + \bar{\nu}$$

$$\nu \text{ capture}: \quad \nu + {}^{3}\text{H} \to {}^{3}\text{He} + e^{-}$$



PTOLEMY

Weinberg, Phys. Rev. 128 (1962), 1457-1473
Baracchini et al. [PTOLEMY], 1808.01892

The capture cross section on Tritium is

$$\sigma(E_e) = G_F^2 F(Z, E_E) E_e |\vec{p}_e| \sim 4 \cdot 10^{-45}\,\mathrm{cm}^2$$

This implies an event rate

$$R = n_\nu N_T \sigma(E_e) \sim 4 \left(\frac{N_T}{100\,g}\right) \mathrm{yr}^{-1}$$

Challenges:

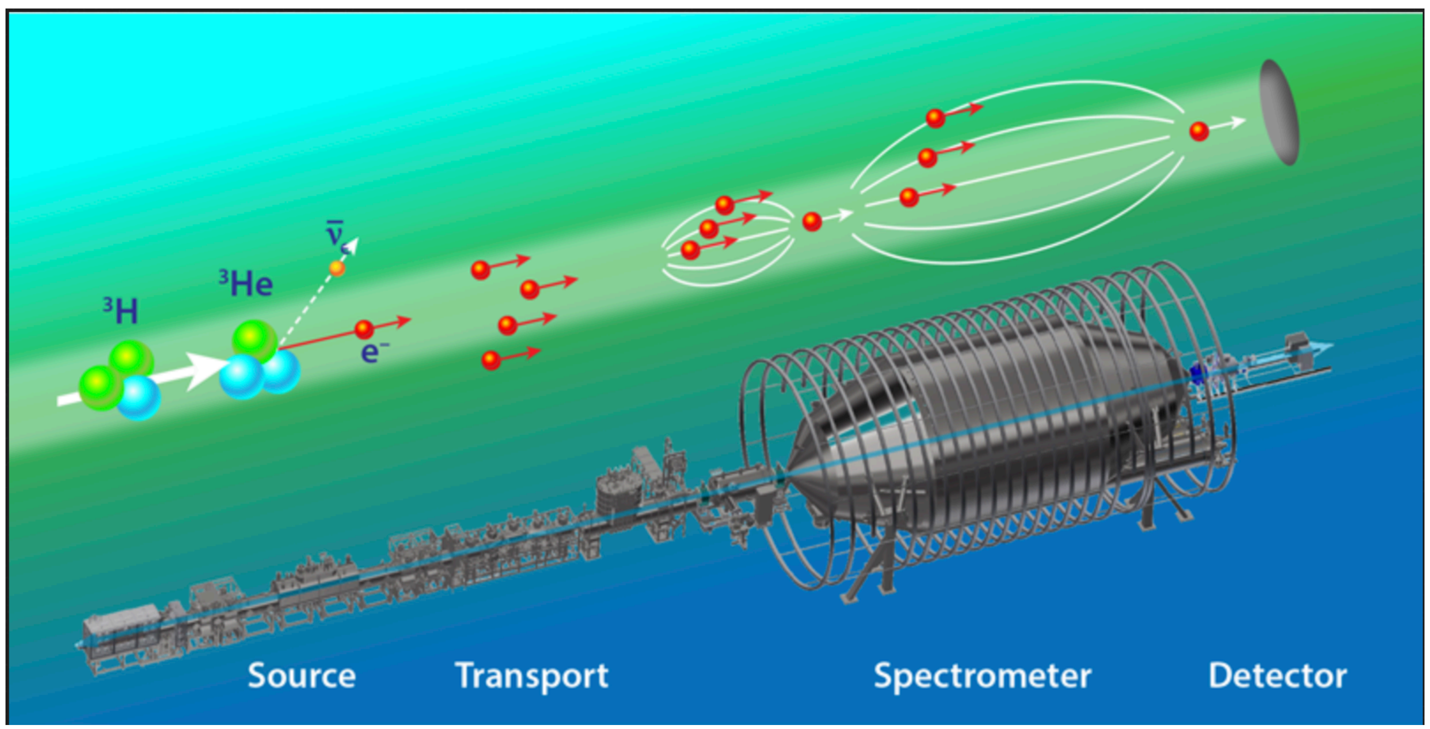
- 100 g active tritium (10^6 m^2 loaded graphene)
- Sensitivity to electron endpoint energy~ neutrino mass
- Backgrounds of 10^{14} Hz/g

PTOLEMY

Weinberg, Phys. Rev. 128 (1962), 1457-1473
Baracchini et al. [PTOLEMY], 1808.01892

Nevertheless the PTOLEMY project is the most advanced experimental programme towards a detection of relic neutrinos

A similar experiment was build to measure the neutrino mass : KATRIN



KATRIN is 70m long and uses 0.0004 g tritium.

PTOLEMY has ~40 members

How to detect cosmic neutrinos?

Some ideas:

1. Coherent scattering

2. Cosmic rays

3. Neutrino absorption (PTOLEMY)

3. Accelerators

Accelerator searches

MB, Shergold, *Phys.Rev.D* 104 (2021)
MB, Shergold, *JCAP* 01 (2023) 003

Back to this argument

$$N \to P^+ + e^- + \bar{\nu}$$

$$P^+ + \bar{\nu} \to N + e^+$$

Looking for positrons produced by neutrino capture would be a clean process to discover the CvB, but the beta gap is **782 keV**. The CvB has an energy of $\mathbf{m_\nu < 1}$ **eV**.

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MB, Shergold, *Phys.Rev.D* 104 (2021)
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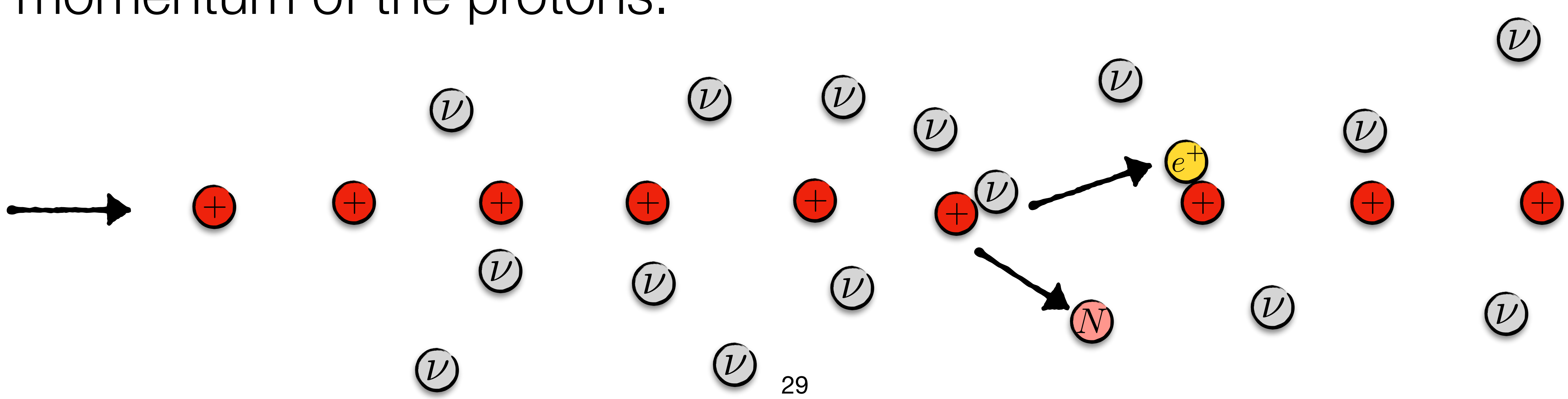
We can't increase the momentum of the neutrinos, but we can increase the momentum of the protons.



Accelerator searches

MB, Shergold, *Phys.Rev.D* 104 (2021)
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The cross section grows with energy

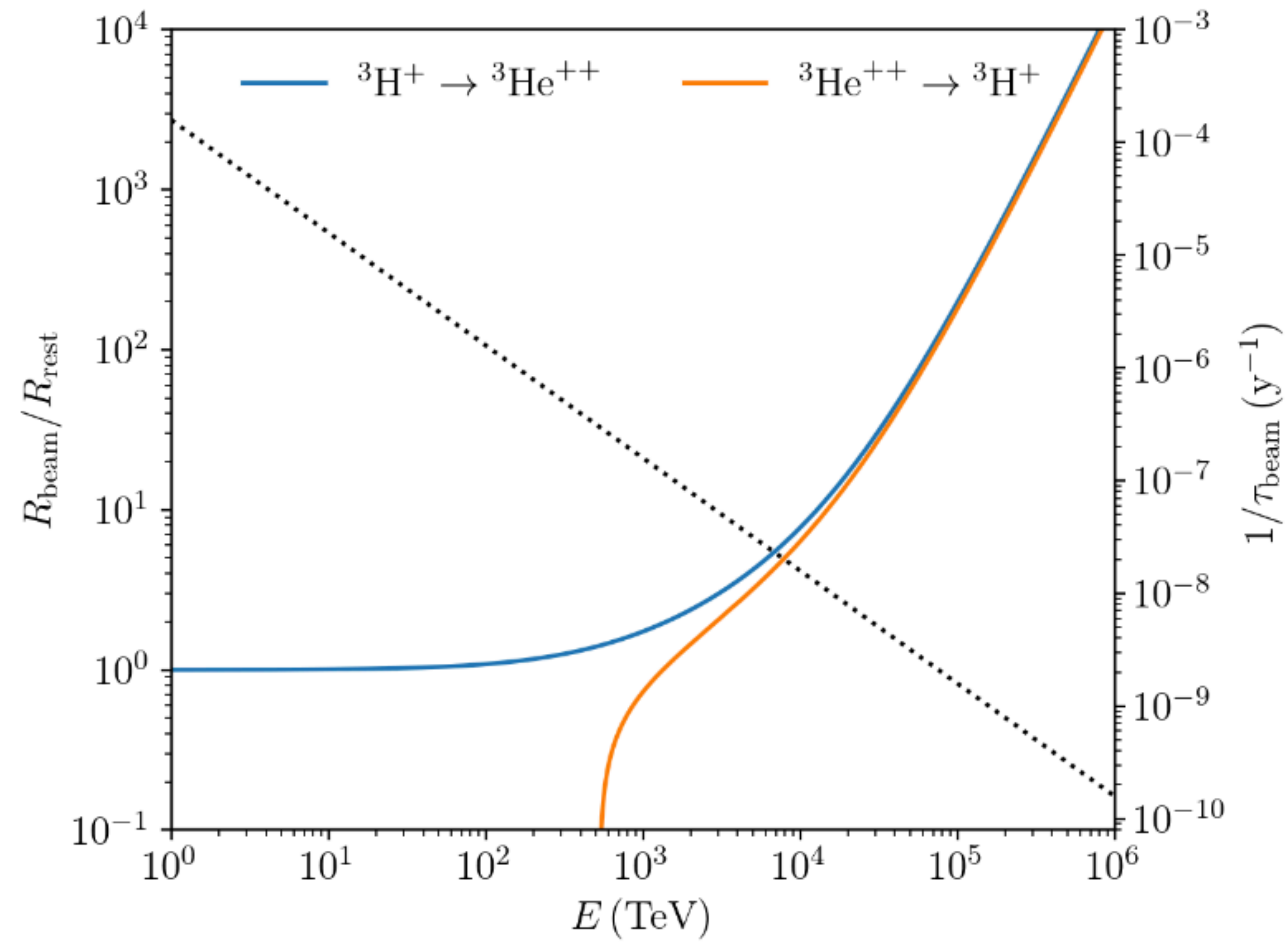
$$\sigma(E_e) \sim G_F^2 E^2$$

Background is suppressed

$$\tau = \gamma t$$

But requires unrealistic energies

$$E > \frac{2 m_e M}{m_\nu} \gtrsim 3\,\mathrm{PeV}$$



And heavier ions need even higher energy.

Accelerator searches : Resonant Processes

The main reason the cross section is so small is the G_F suppression

$$\sigma(E_e) \sim G_F^2 E^2$$

Resonant processes can overcome this suppression. As in the case of cosmic rays, where at the Z-pole

$$\sigma = \frac{1}{M_Z^2} \mathrm{Br}(Z \to \nu\bar{\nu}) \propto G_F$$

Can we use an accelerator to hit a resonance?

Accelerator searches : Resonant Processes

Resonant processes can have very large cross sections. Consider the processes of a parent ion (P) producing a daughter ion (D):

Resonant bound beta decay $$P + \nu \quad \rightarrow \quad D + e^{-}(\mathrm{bound})$$

Electron capture $$P + e^{-}(\mathrm{bound}) + \bar{\nu} \quad \rightarrow \quad D$$

The resonant cross sections are proportional to the decay width

$$\sigma_{\mathrm{Res}} = 2.5 \cdot 10^{-15} \left(\frac{\mathrm{keV}}{Q}\right)^2 \mathrm{Br}(D \rightarrow P)\,\mathrm{cm}^2$$

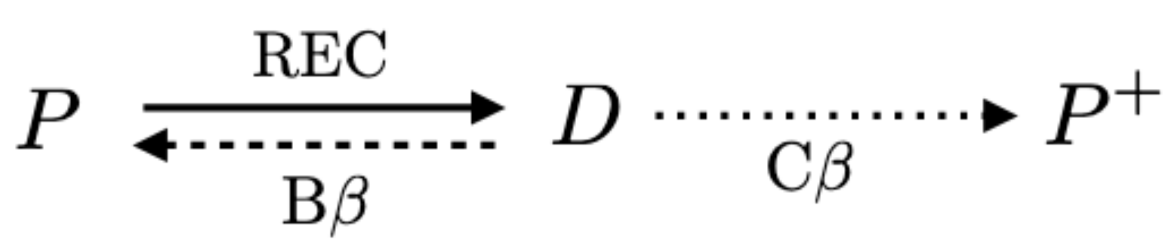
needs a beam energy of $$E = \frac{MQ}{m_\nu}$$

Accelerator searches : Resonant Processes

The problem is a large resonant decay width corresponds to a short lifetime

$$\sigma_{\text{Res}} = 2.5 \cdot 10^{-15} \left(\frac{\text{keV}}{Q}\right)^2 \text{Br}(D \to P)\, \text{cm}^2$$

Once the daughter states are produced they will decay back into the parent by reabsorbing the bound electron or via bound beta decay. In addition they can decay continuously

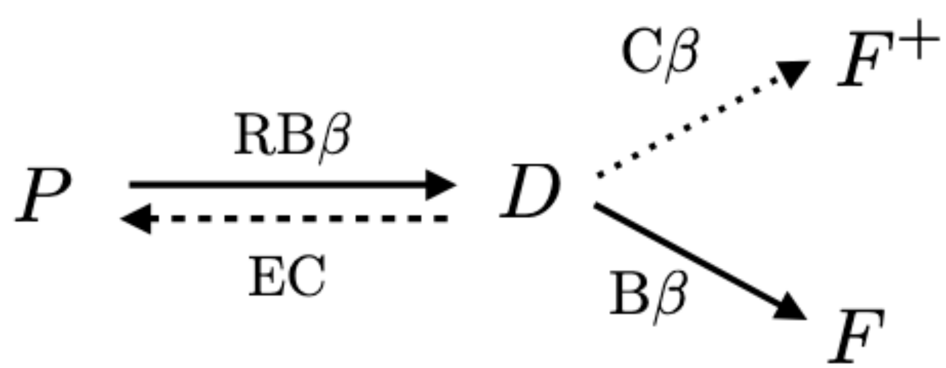


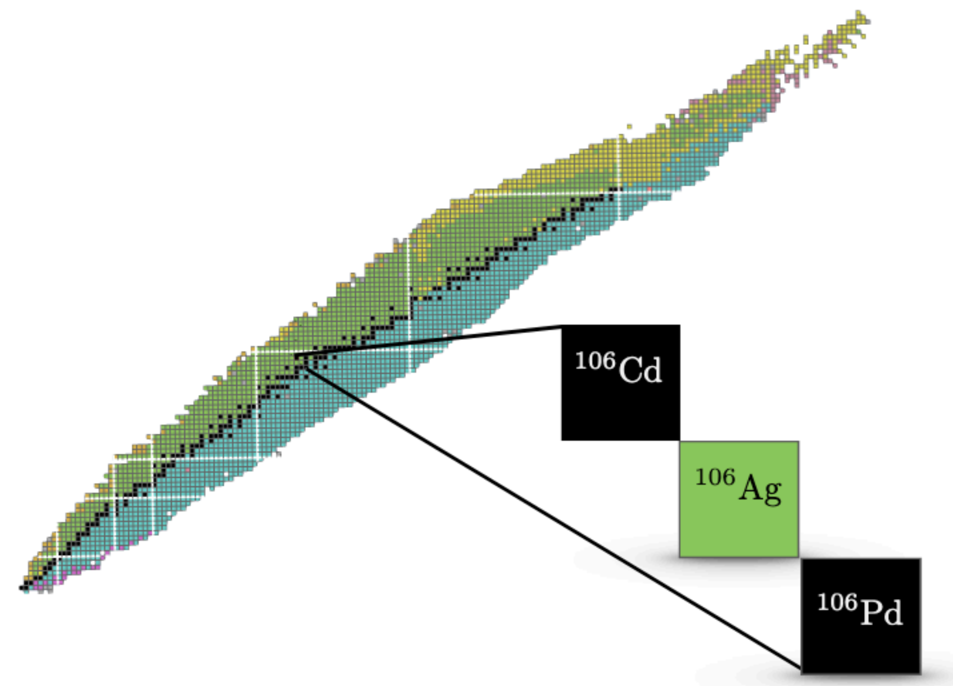
The states D are a clean signal, but if you produce many you'll loose them fast.

Accelerator searches : Resonant Processes

Both beam processes are doomed to fail. Is this a no-win scenario?

There is a loophole: 3-state systems. These are systems in which D likes to decay into another, stable isotope; the final state (F)





The final state (F) will remain on the beam indefinitely.

Accelerator searches : Resonant Processes

Real world examples:

2-state system $^{157}\mathrm{Gd} \quad \rightarrow \quad ^{157}\mathrm{Tb}$

$$Q \approx 150\,\mathrm{keV}, \quad \frac{E}{A} \approx 1\,\mathrm{PeV}, \quad \frac{N_D}{N_0} \approx 10^{-23}$$

3-state system $^{100}\mathrm{Mo} \quad \rightarrow \quad ^{100}\mathrm{Tc} \quad \rightarrow \quad ^{100}\mathrm{Ru}$

$$Q \approx 10\,\mathrm{keV}, \quad \frac{E}{A} \approx 100\,\mathrm{TeV}, \quad \frac{N_D}{N_0} \approx 4 \cdot 10^{-24}$$

10x-100x larger rates than PTOLEMY, but 10^{23} ions on the beam?

Accelerator searches : Resonant Processes

What is the maximal number of ions in an ion storage ring?

$$N_T^{\max} = \; 4 \cdot 10^{17} \left[\frac{50}{Z}\right]^2 \left[\frac{m_\nu}{0.1\mathrm{eV}}\right]^5 \left[\frac{\mathrm{keV}}{Q}\right]^5$$

("Death beam limit")

For accelerator processes the gap Q is the most important variable

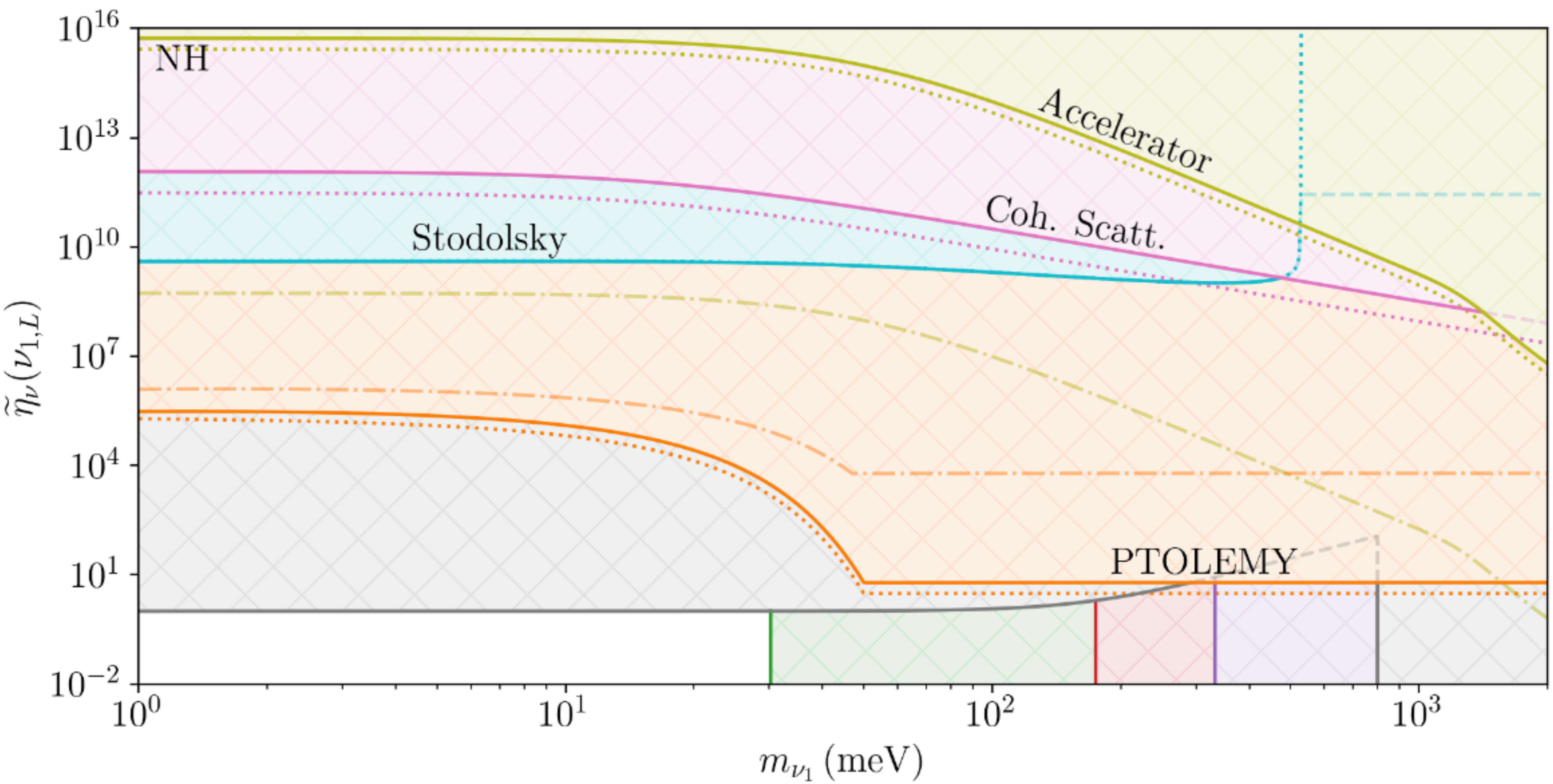
$$E \sim Q, \quad \sigma_{\mathrm{Res}} \sim Q^{-2}\,, \quad N_T \sim Q^{-5}$$

unrealistic example (?) of a 10 eV gap would yield

$$Q \approx 10\,\mathrm{eV}, \quad \frac{E}{A} \approx 50\,\mathrm{GeV}\,, \quad \frac{N_D}{N_0} \approx 10^{-19}\,, \;\; N_T^{\max} = 10^{27}$$

Comparison of CvB search methods

Mass dependence for fixed temperature



Runtime of 1 yr each.

MB, Shergold, *JCAP* 01 (2023) 003

Conclusions

The cosmic neutrino background is one of the most challenging targets for 21st century physics

A successful detection would give us a snapshot of the Universe when it was only 1s old.

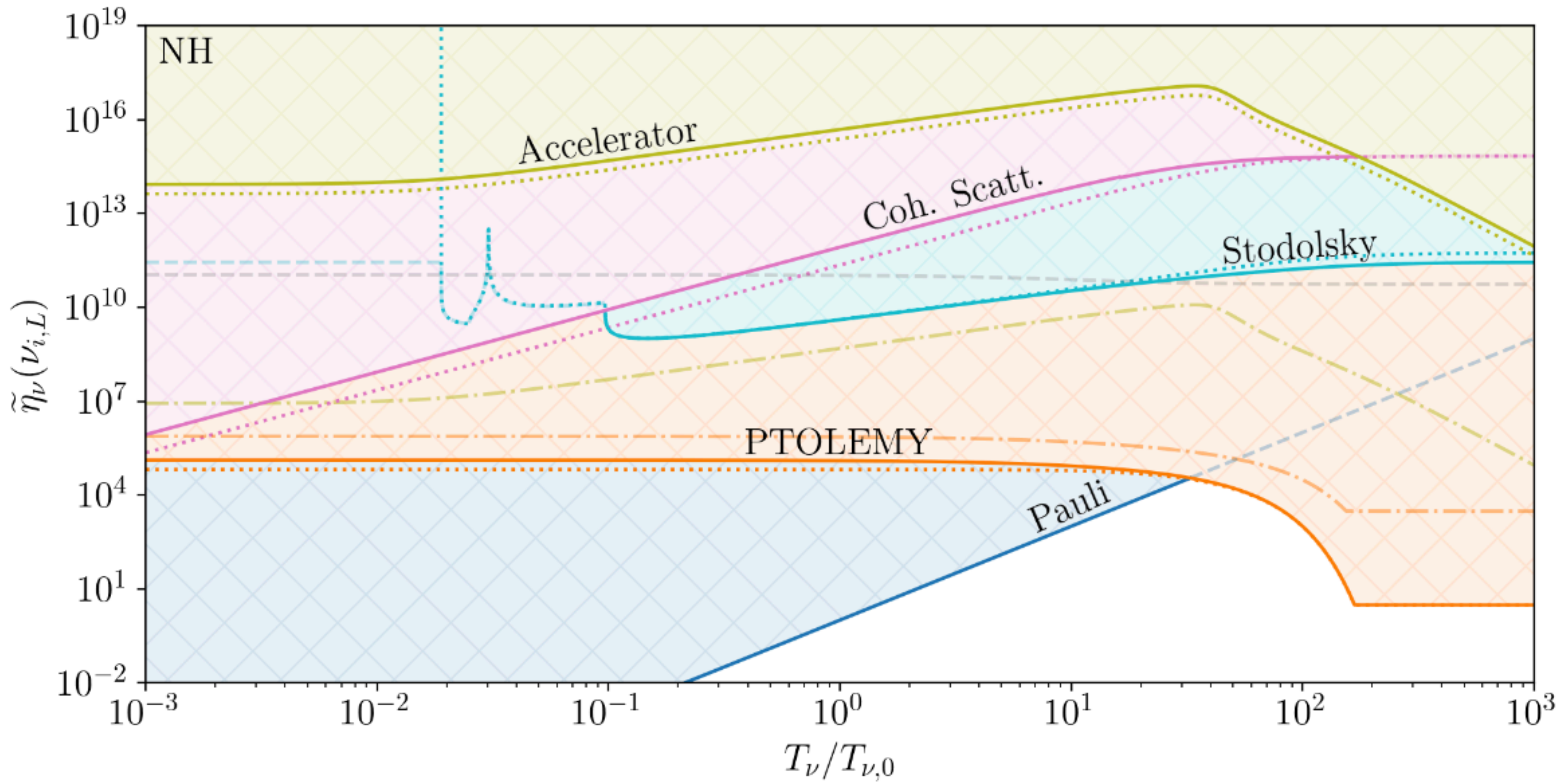
Different techniques have been proposed, no obvious way to success.

For this question new ideas can have enormous impact.

Backup

Comparison of CvB search methods

Temperature dependence for fixed mass $m_{\nu_l} = 10\,\mathrm{meV}$



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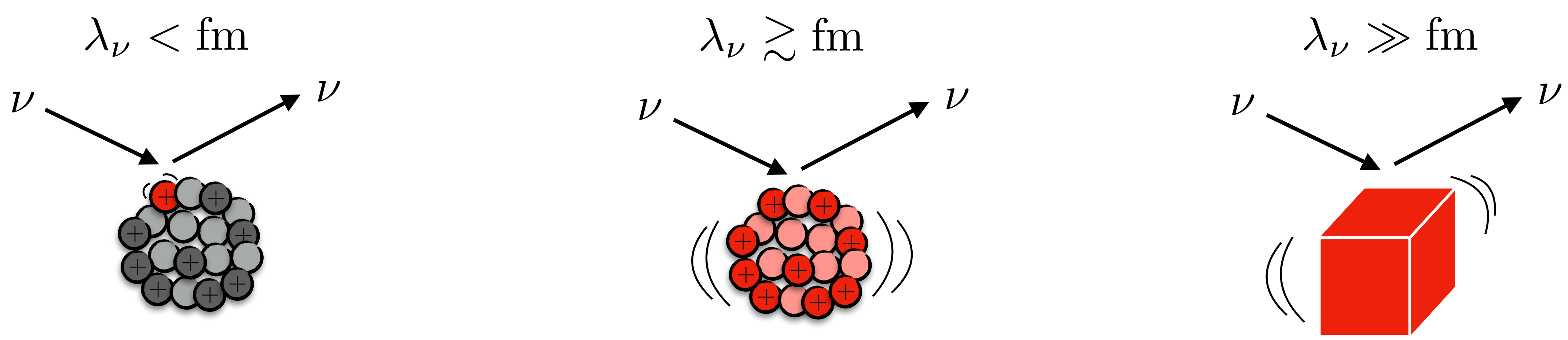
Coherent Scattering

Opher, Astron. Astrophys. 37 (1974)

For large wave lengths neutrinos can scatter coherently



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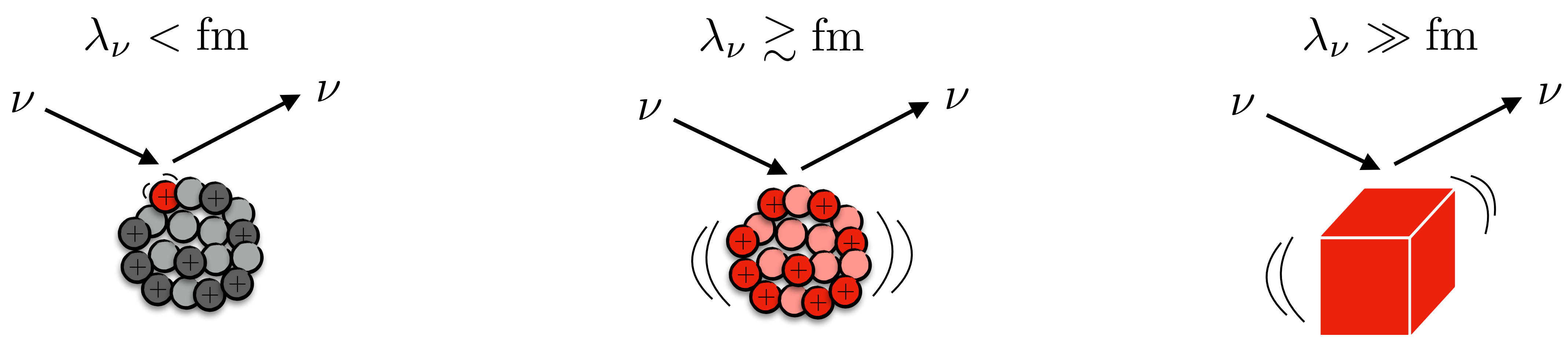

Coherent elastic neutrino nucleus scattering has just been discovered

CEνNs

$$\lambda_\nu = \frac{2\pi}{10\,\mathrm{MeV}} \approx 100\,\mathrm{fm}$$

$$\begin{aligned}\sigma_c &= G_F^2 E_\nu^2 N^2 \\ &= 5 \cdot 10^{-50} \cdot 10^8 \cdot 10^3\,\mathrm{cm}^2 \\ &= 10^{-39}\,\mathrm{cm}^2\end{aligned}$$

COHRENT *Science* 357 (2017) 6356, 1123-1126

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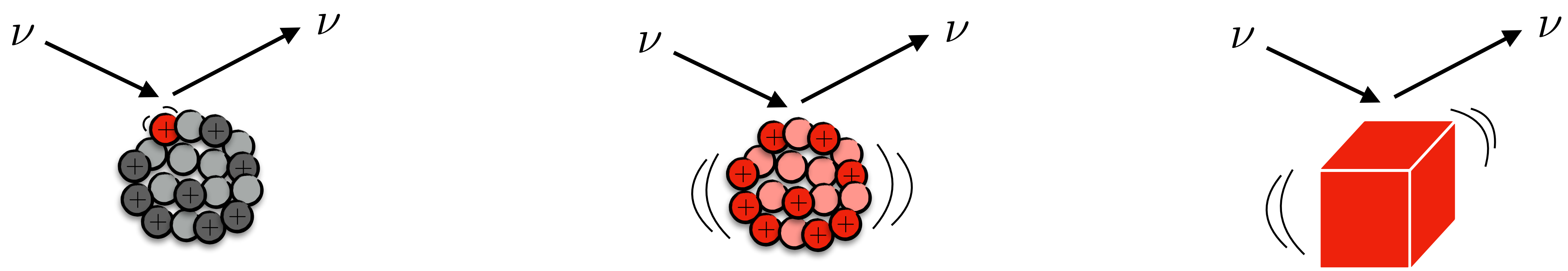
$\lambda_\nu < \mathrm{fm}$ $\qquad$ $\lambda_\nu \gtrsim \mathrm{fm}$ $\qquad$ $\lambda_\nu \gg \mathrm{fm}$



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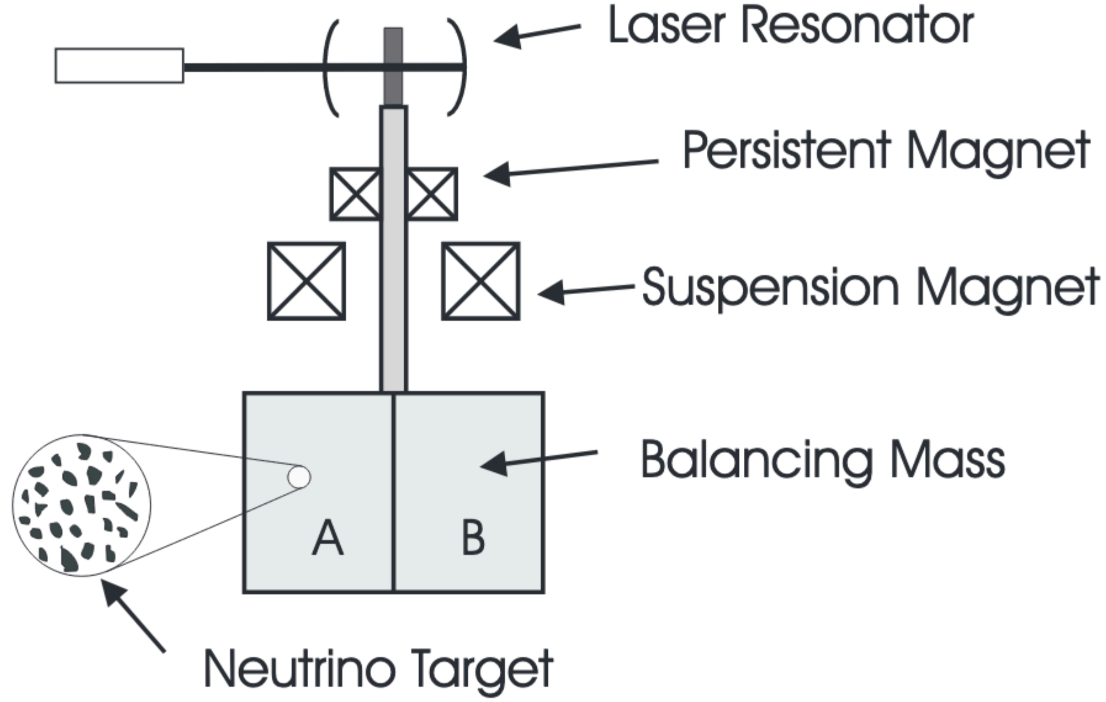
CνB

$$\lambda_\nu^{C\nu B} = \frac{2\pi}{m_\nu v} = \frac{2\pi}{10^{-4} \cdot 10^{-3}\mathrm{eV}} \approx 1 - 10\,\mathrm{mm}$$

$$\begin{aligned}\sigma_c &= G_F^2 E_\nu^2 N^2 \\ &= 5 \cdot 10^{-50} \cdot 10^{-8} \cdot 10^{40}\,\mathrm{cm}^2 \\ &= 10^{-18}\,\mathrm{cm}^2\end{aligned}$$

Coherent Scattering

COHERENT measures nuclear recoil with a 30 kg Argon target.
The CvB requires a mm^3 target. The best option is a torsion pendulum



Haagman (1999)

The acceleration is $$a_{C\nu B} \approx \frac{1}{M}\Gamma\Delta p_\nu = \frac{1}{M}\sigma_\nu\beta_\nu n_\nu \Delta p_\nu \approx 10^{-35}\,\frac{\mathrm{cm}}{\mathrm{s}^2}$$

Best achieved sensitivity $$a \geq 10^{-15}\,\frac{\mathrm{cm}}{\mathrm{s}^2}$$

Best projected sensitivity $$a \geq 10^{-23}\,\frac{\mathrm{cm}}{\mathrm{s}^2}$$

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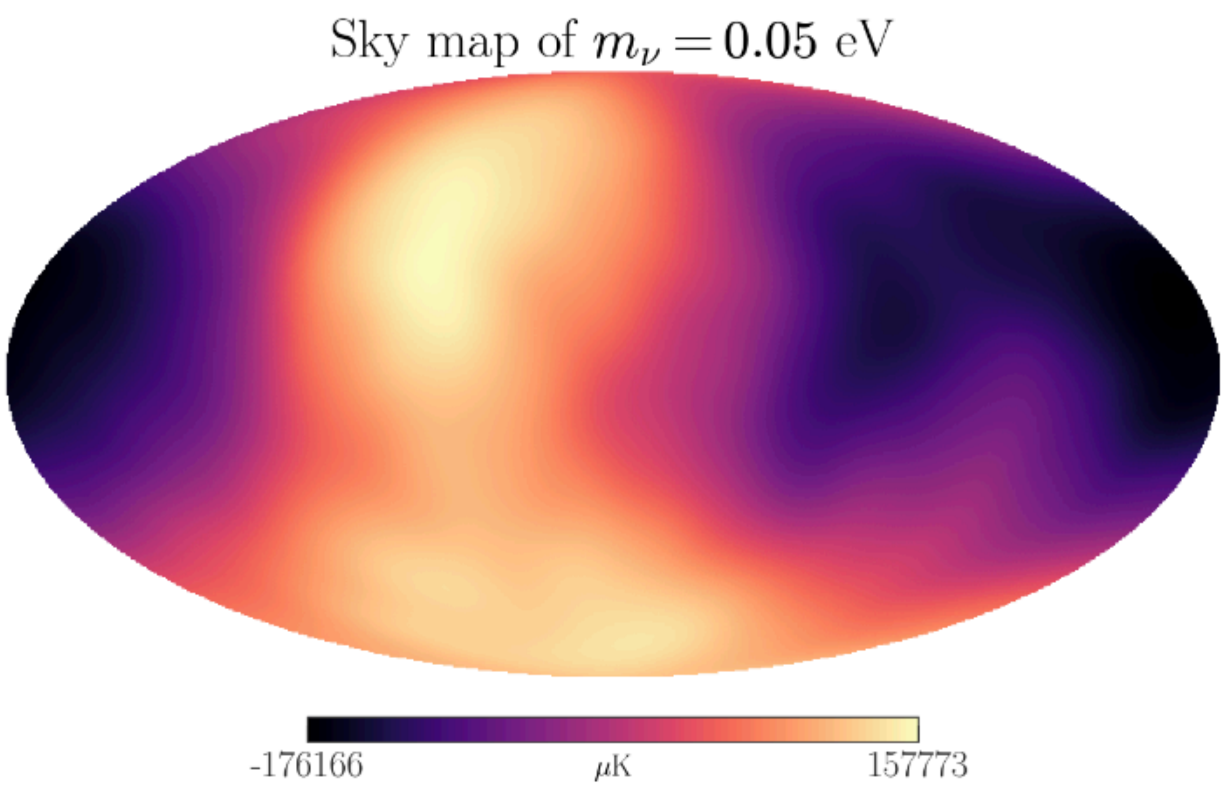
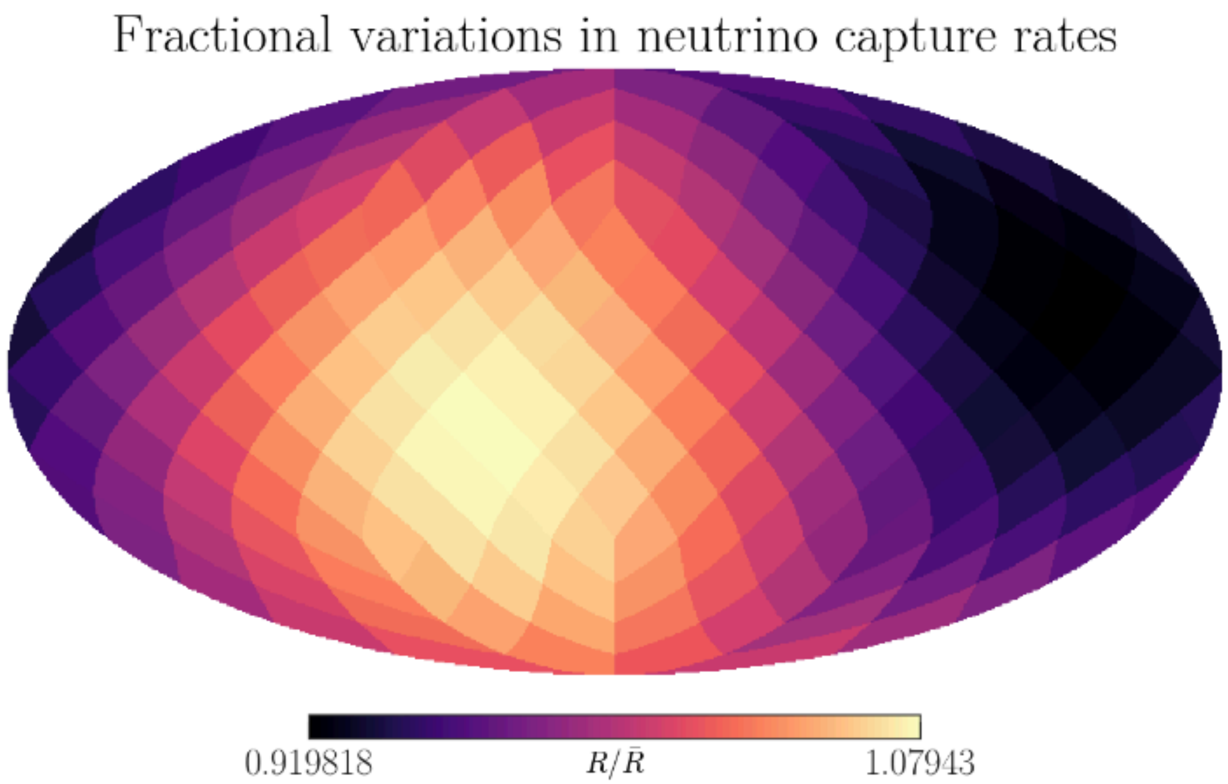
Cosmic Neutrino Map





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