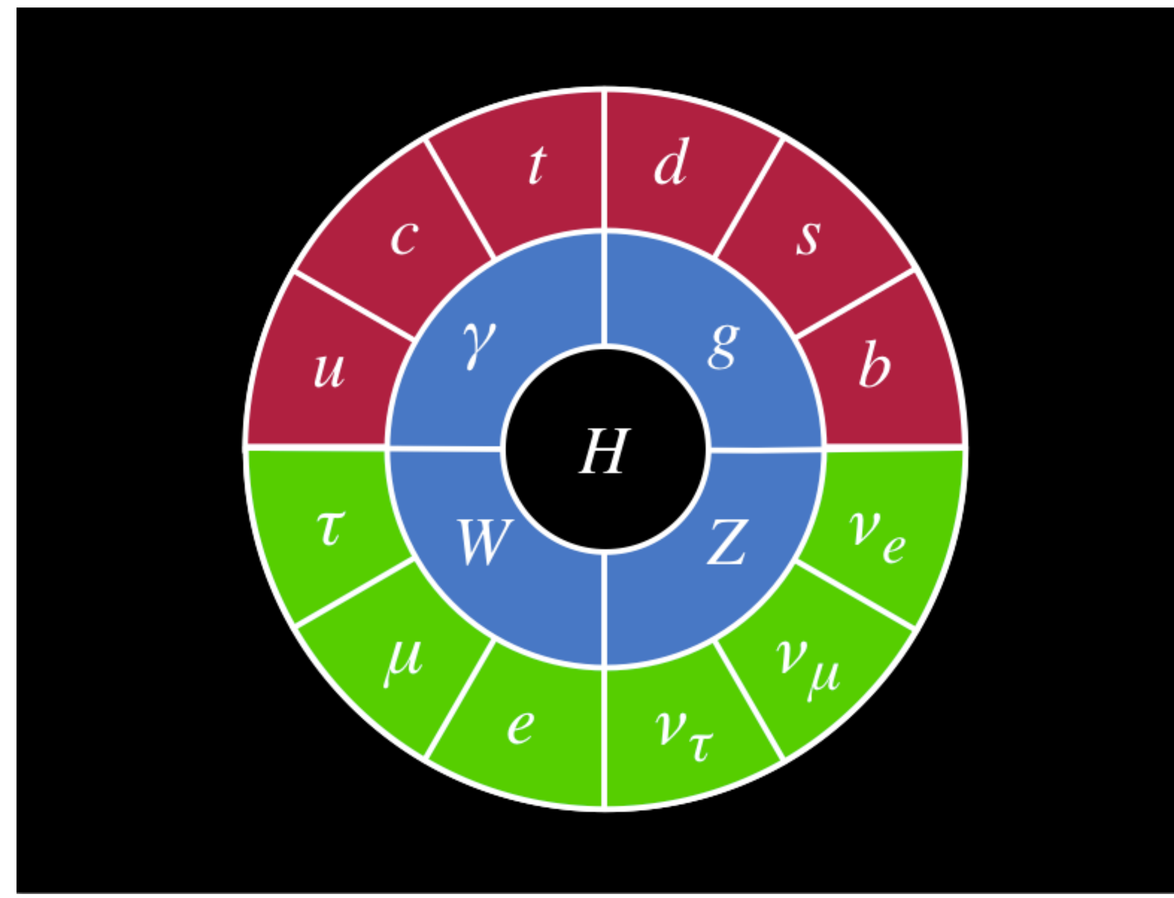
SNOLAB: An international hub for fundamental physics exploration

Asimina Arvanitaki
Perimeter Institute for Theoretical Physics

The Standard Model

$$
\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi \\
& + \bar{\psi}_i y_{ij} \psi_j \phi \\
& + |D_\mu \phi|^2 - V(\phi) \\
& + M_{pl}^2 R \; - \rho_{vacuum}
\end{aligned}
$$



Contains ~20 particles and ~20 parameters

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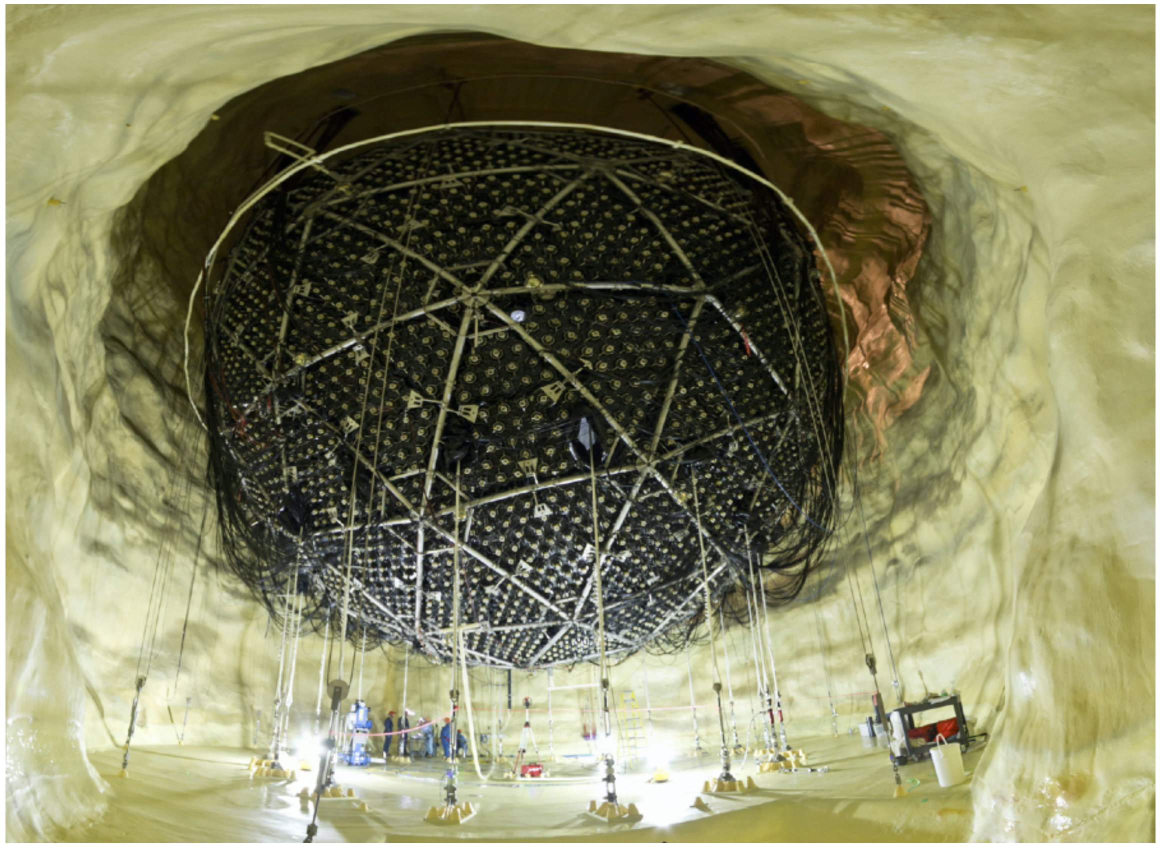
- A lot to learn about the neutrino sector
    - Neutrino parameters of the PMNS matrix
    - Are neutrinos their own antiparticle? (Dirac vs Majorana)
    - The Cosmic Neutrino Background



SNO+

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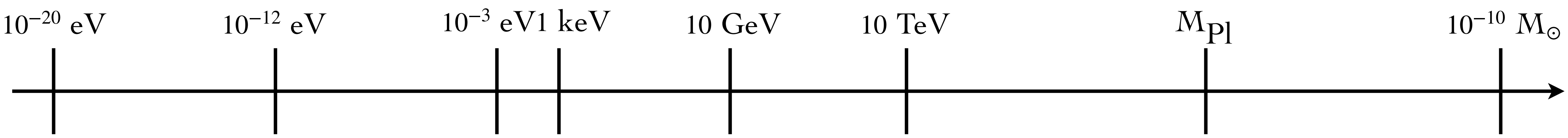
The nature of Dark Matter



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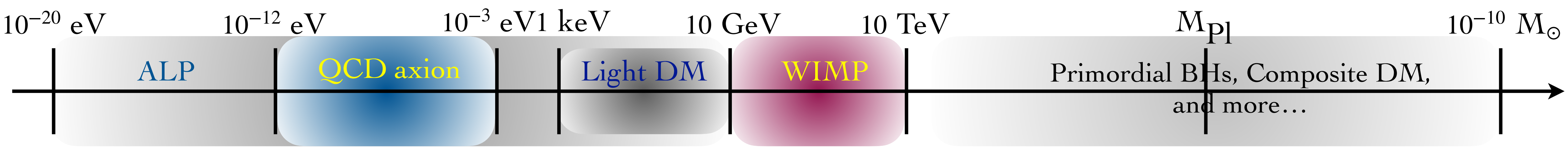

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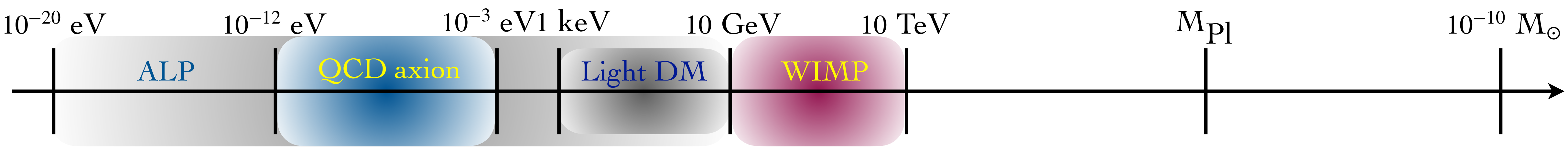
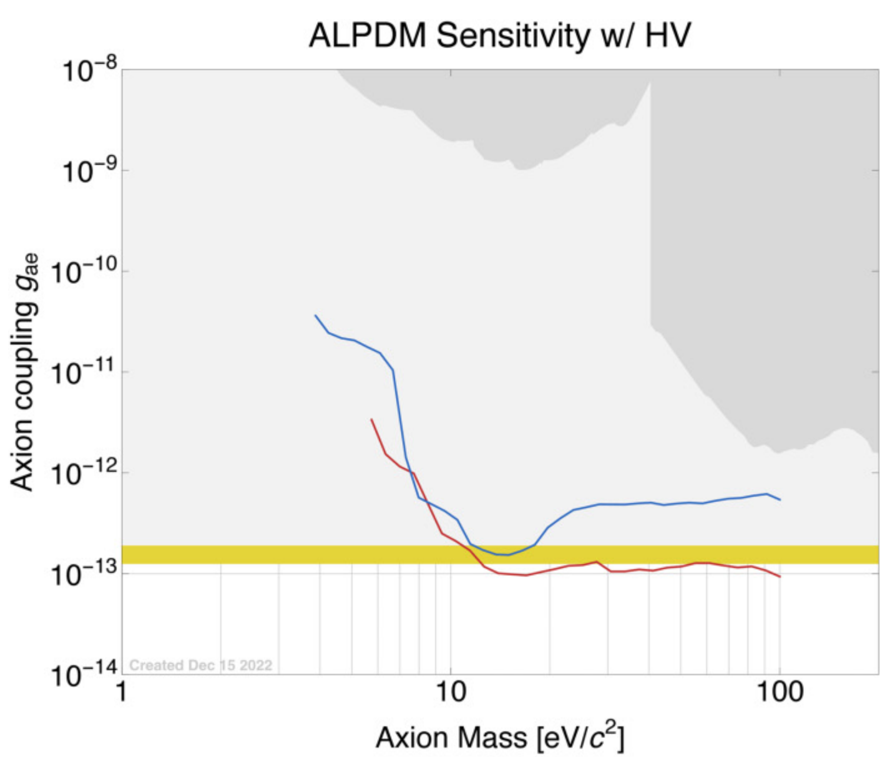
The nature of Dark Matter



Candidates with a good production mechanism Axion particles and WIMP, Light DM



SuperCDMS(see talk by Miriam Diamond)

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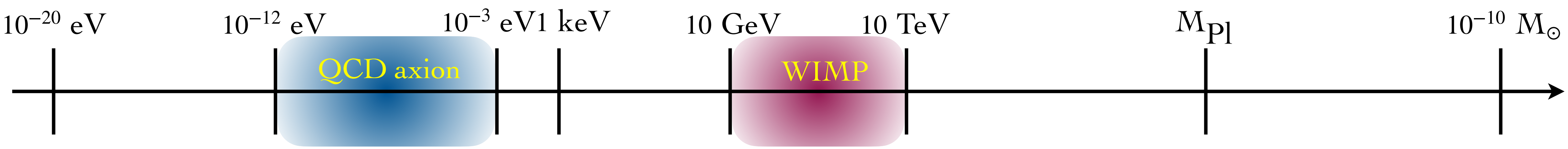
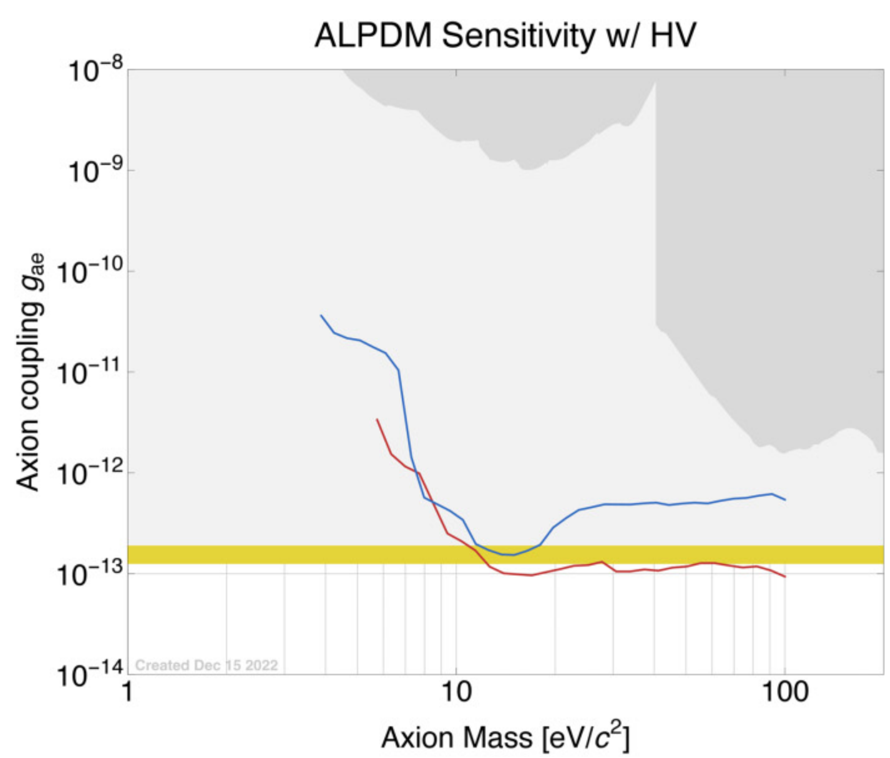
The nature of Dark Matter



Candidates with a good production mechanism

Candidates that have a reason other than DM to be there: The QCD axion and the WIMP



SuperCDMS(see talk by Miriam Diamond)

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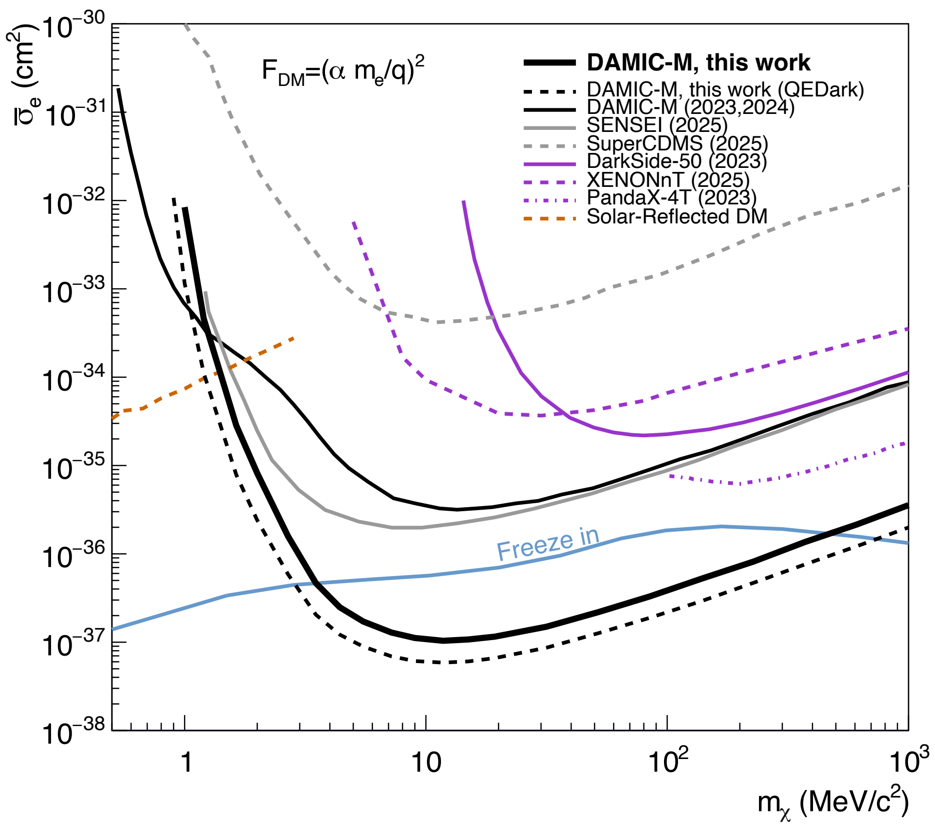
March 2025 results from DAMIC-M
based on the DAMIC experiment started at SNOLAB
(see Yoni Kahn's talk)



CUTE facility

SNOLAB: An international hub for fundamental physics exploration

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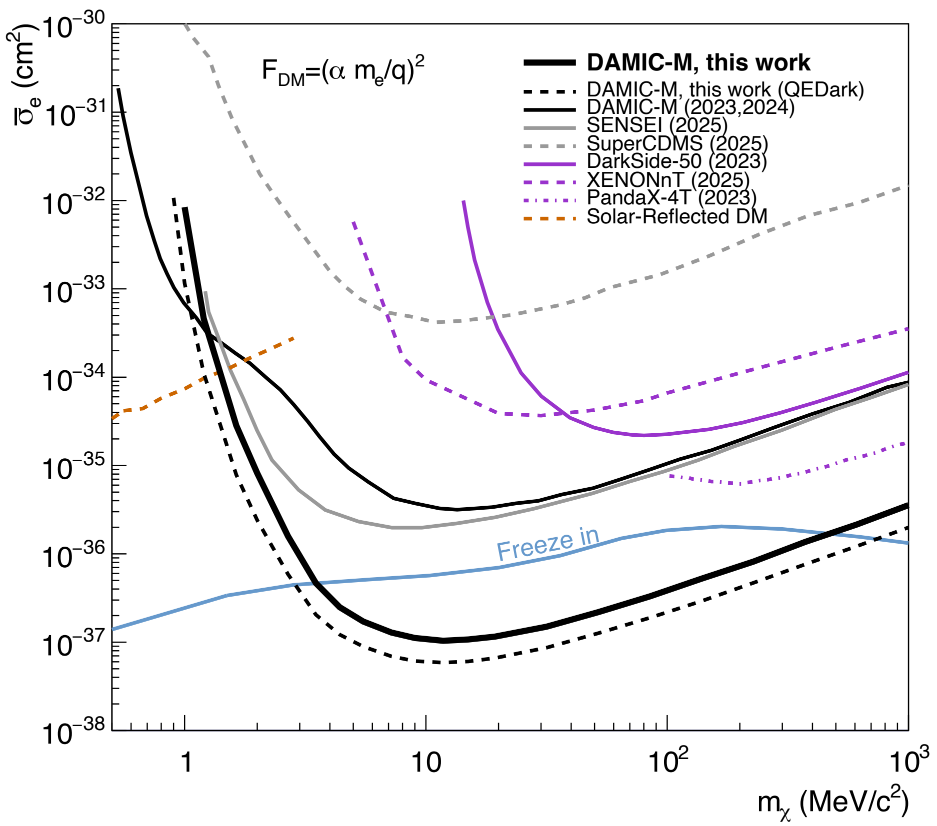


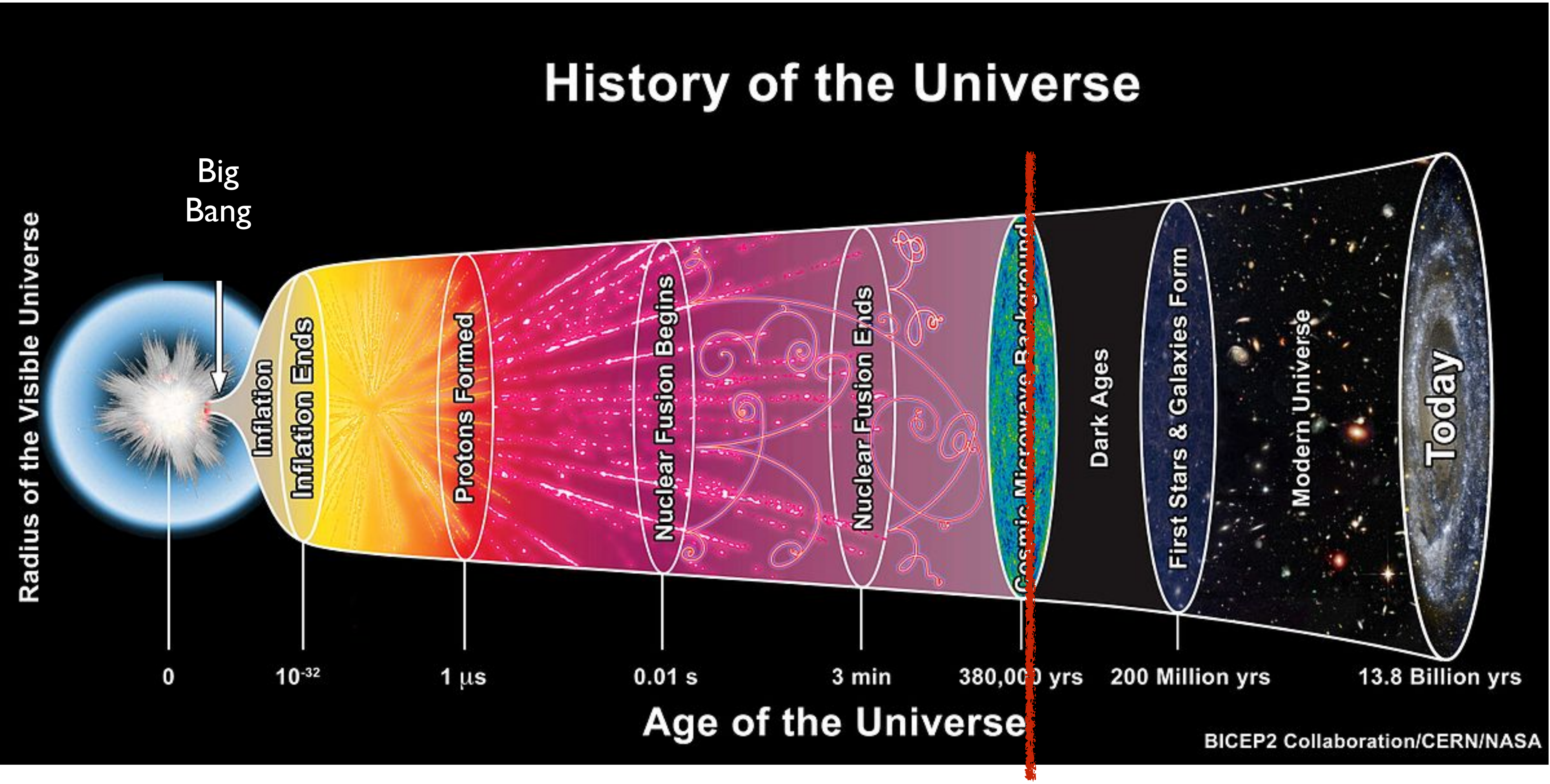
CUTE facility

SNOLAB:
Nursery of fundamental physics experiments

Superradiant aka coherent inelastic interactions of cosmic relics

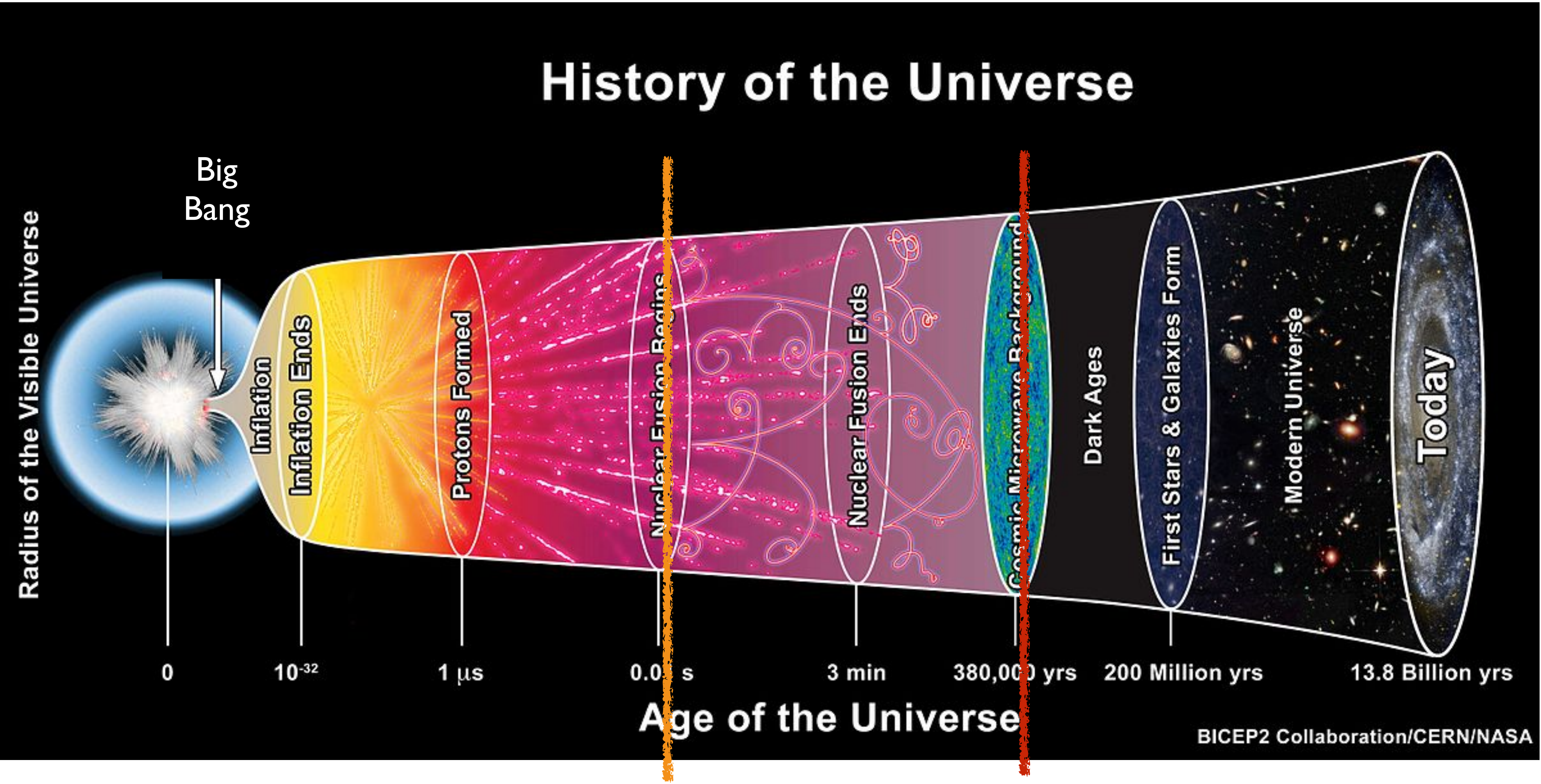
in collaboration with S. Dimopoulos, M. Galanis

A Brief History of the Universe



The CMB

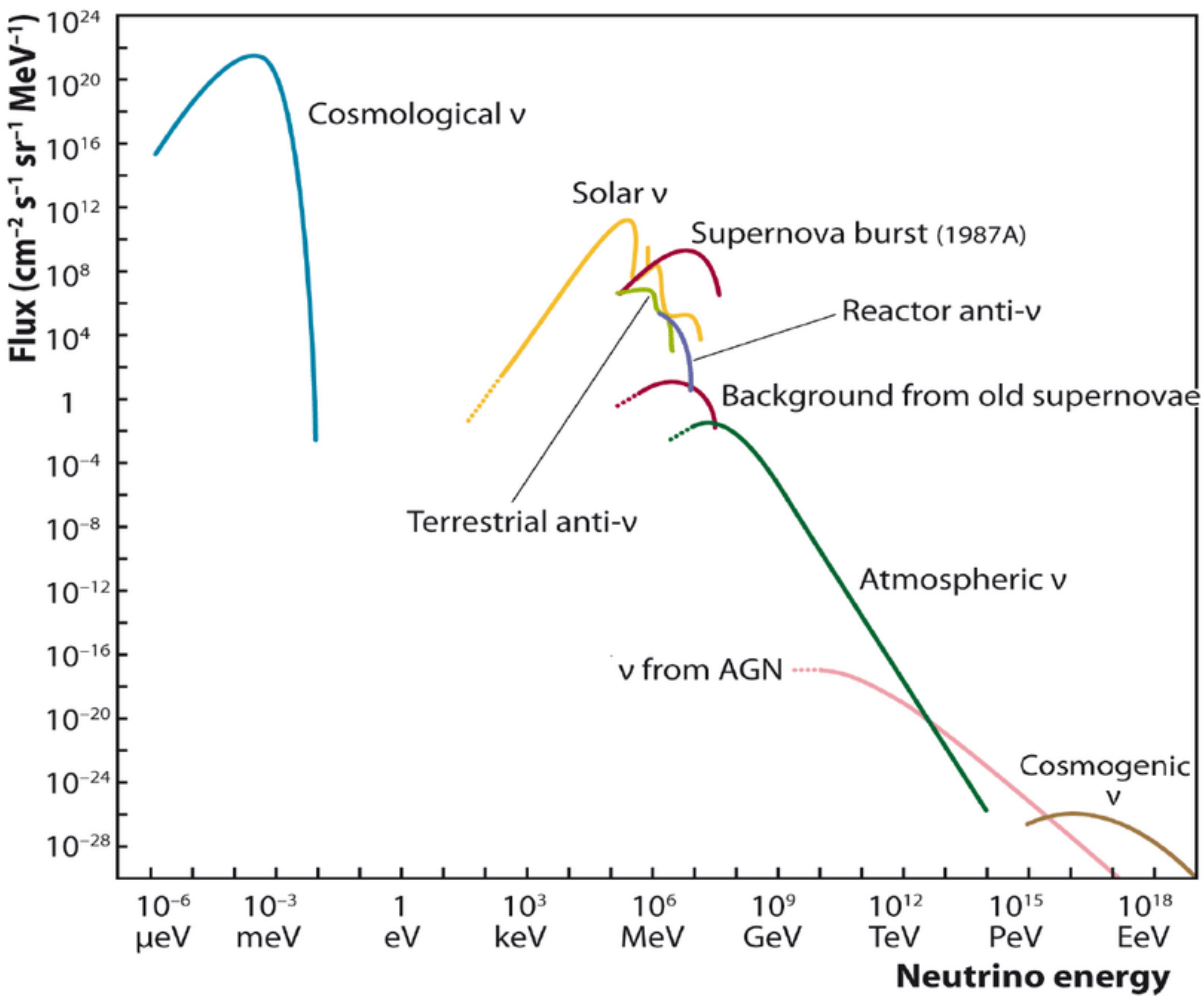
A Brief History of the Universe



The Cosmic Neutrino Background (CνB)

The CMB

Other neutrino sources vs the CNB



The Cosmic Neutrino Background (CνB)

- Relic neutrinos from the pre-BBN era $\tau_{\text{universe}} \sim 0.1$ sec

- They follow a Fermi-Dirac distribution with:
  - $\langle p_\nu \rangle = 6 \times 10^{-4}$ eV
  - $\langle E_\nu \rangle = 1.6 \times 10^{-6}\ \text{eV} \left(\frac{0.1\ \text{eV}}{m_\nu} \right)$
  - $\langle \lambda_\nu \rangle = 2.1$ mm
  - $n_\nu = 56\ \text{cm}^{-3}$ per flavor, per helicity model

Why is the CνB important?

- Probes physics at a time much earlier than the CMB
- An entire sector of the Standard Model: 3 flavors and 7+ parameters
- Using non-relativistic particles for 3D tomography of the Universe

Why is the CNB hard to detect?

- Weak interactions are very weak for low energy particles: $\mathcal{O}(10^{-64}\ \mathrm{cm}^2)$ elastic interaction cross-section per nucleon

- Besides coherent elastic scattering, are there inelastic processes that are enhanced by N^2 ?

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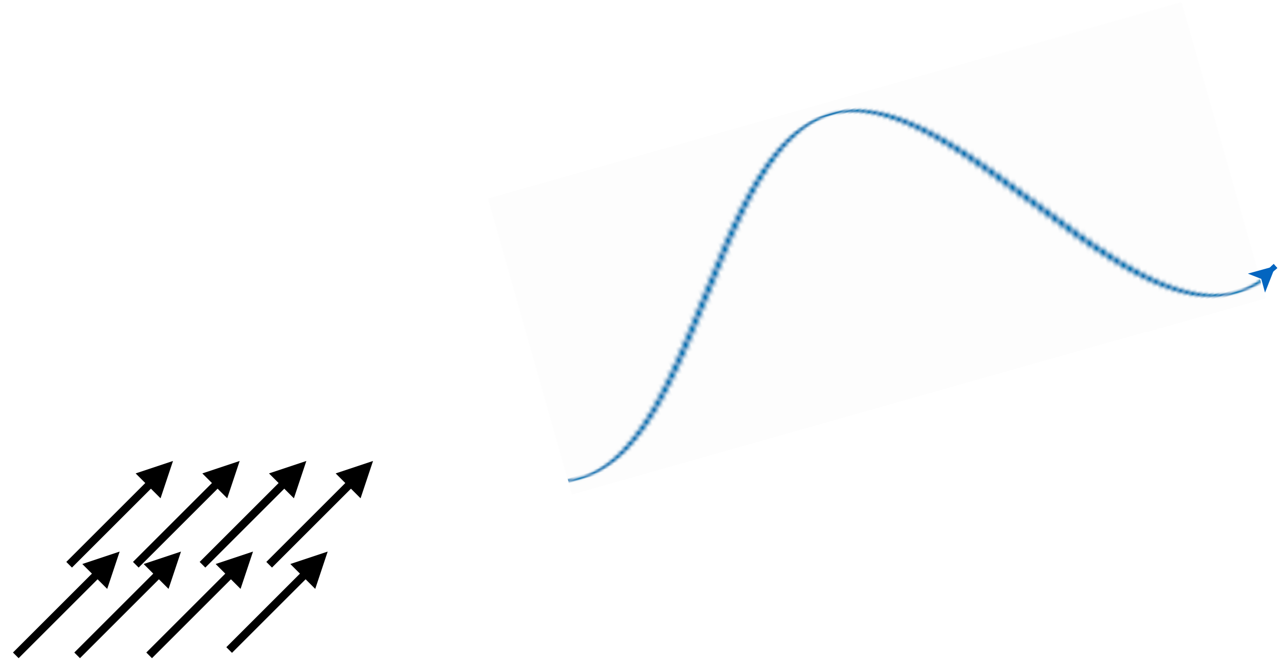
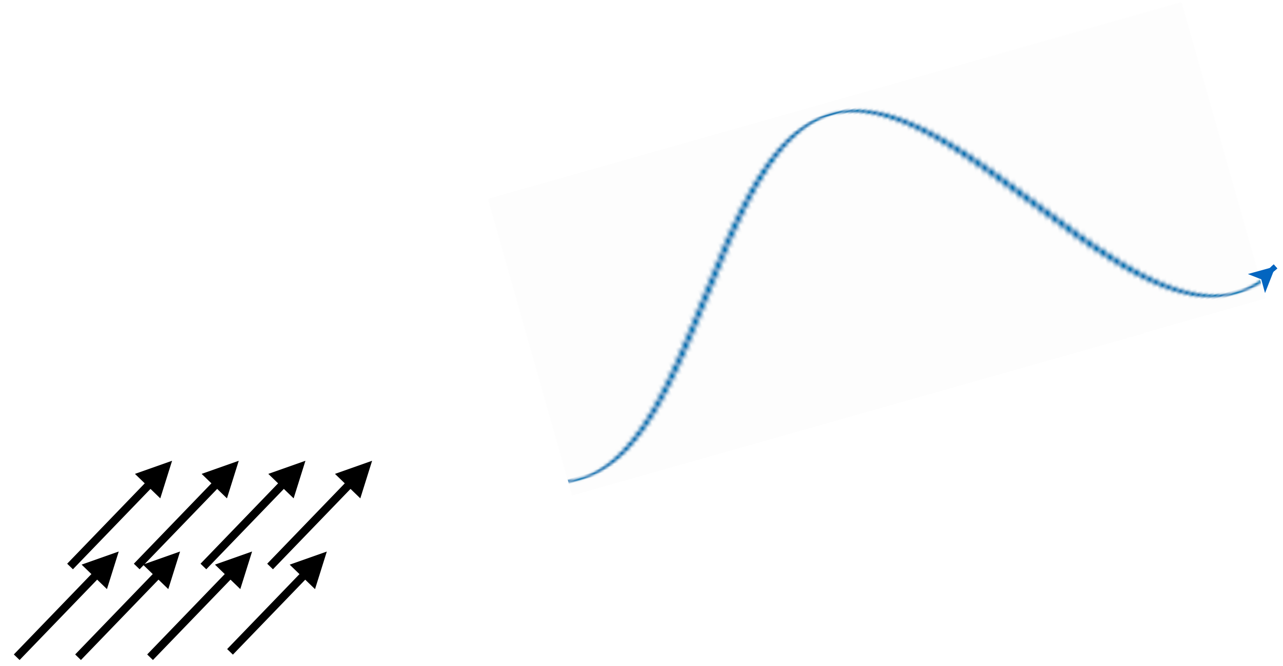
Coherence in emission and absorption of light



Coherence in emission and absorption of light



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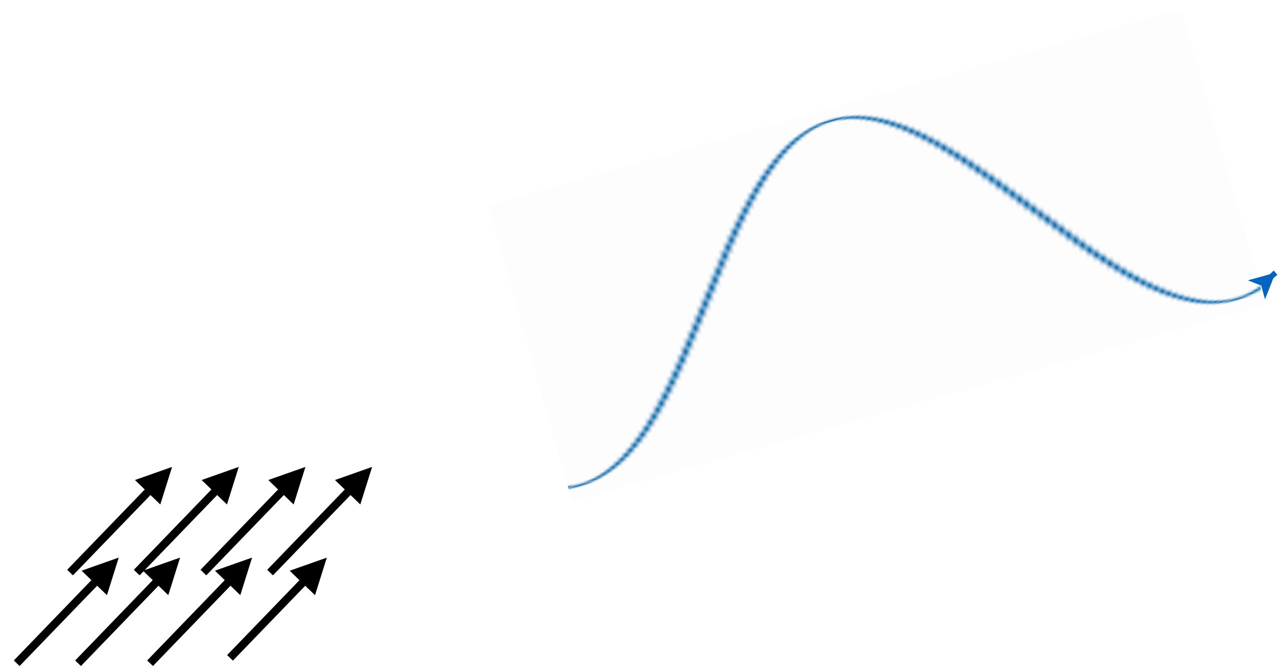
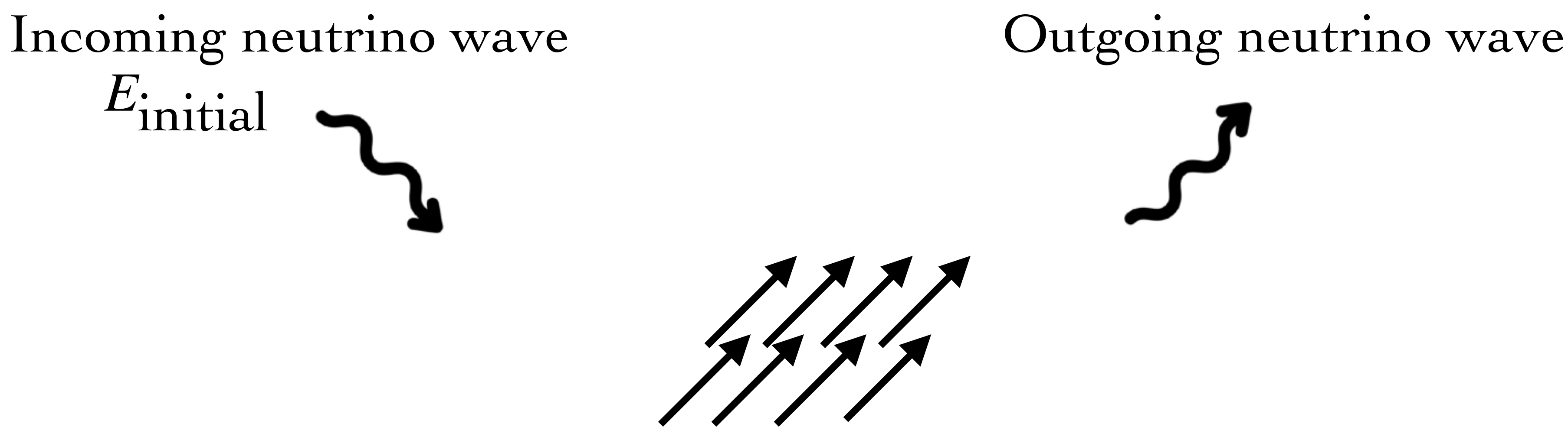


Power of light emitted by dipoles grows like the N^2 as long
as all precessing dipoles are within the wavelength

Known as Dicke Superradiance (1954)

Coherence in inelastic scattering processes

AA, S. Dimopoulos, M. Galanis (2024)



- Spin dependent interaction between neutrinos and spins results in a time-dependent potential $H \sim \frac{G_F}{\sqrt{2}} \delta^{(3)}(\vec{x}_\nu - \vec{x}_S) N \, \vec{\sigma}_\nu \cdot \vec{\sigma}_S \cos(\omega t)$

Coherence in inelastic scattering processes

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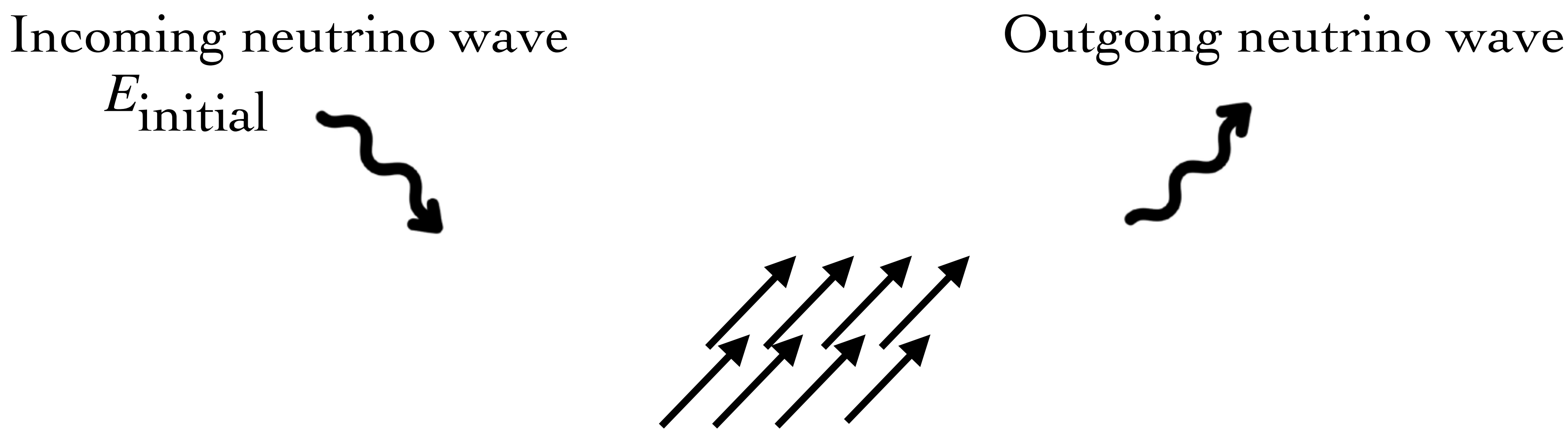

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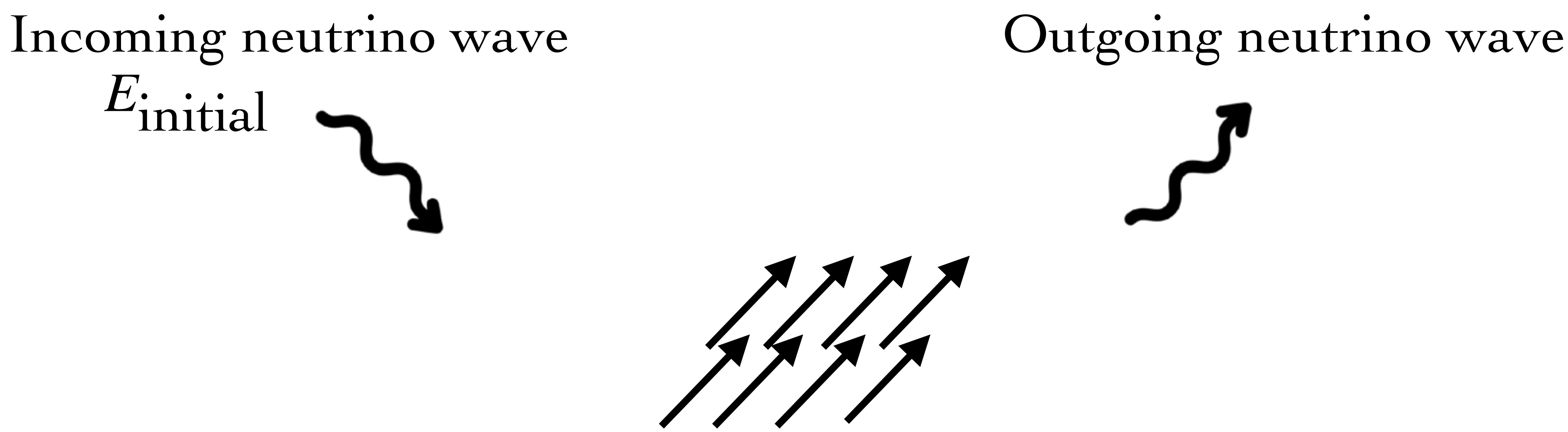

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- Scattered outgoing neutrino energies $E_{\text{initial}} \pm \omega$ and scattering rate scales like N^2

Coherence in inelastic scattering processes

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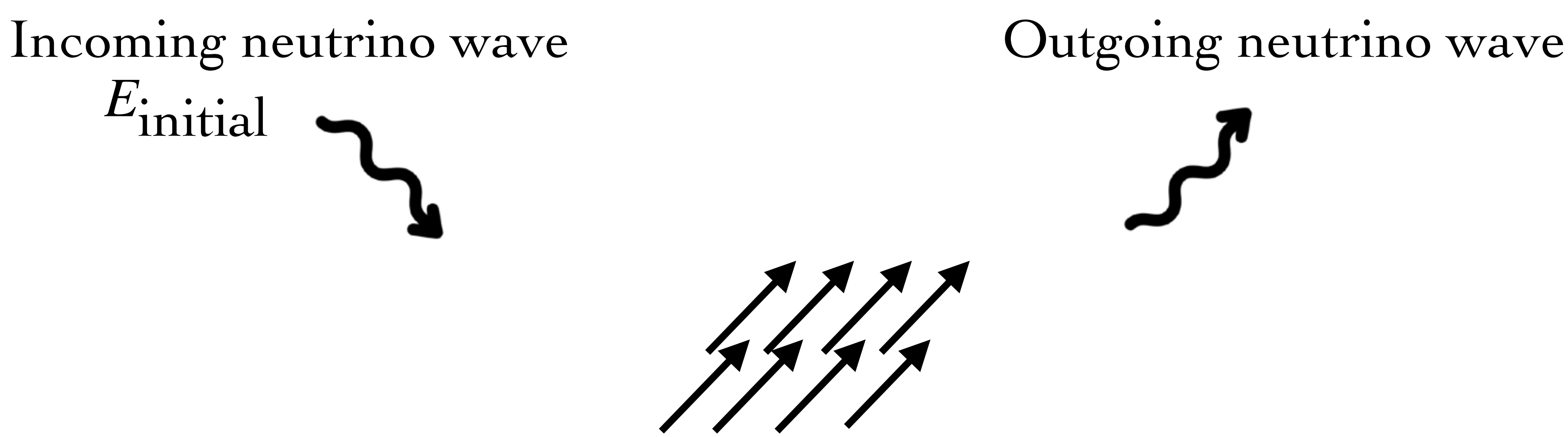

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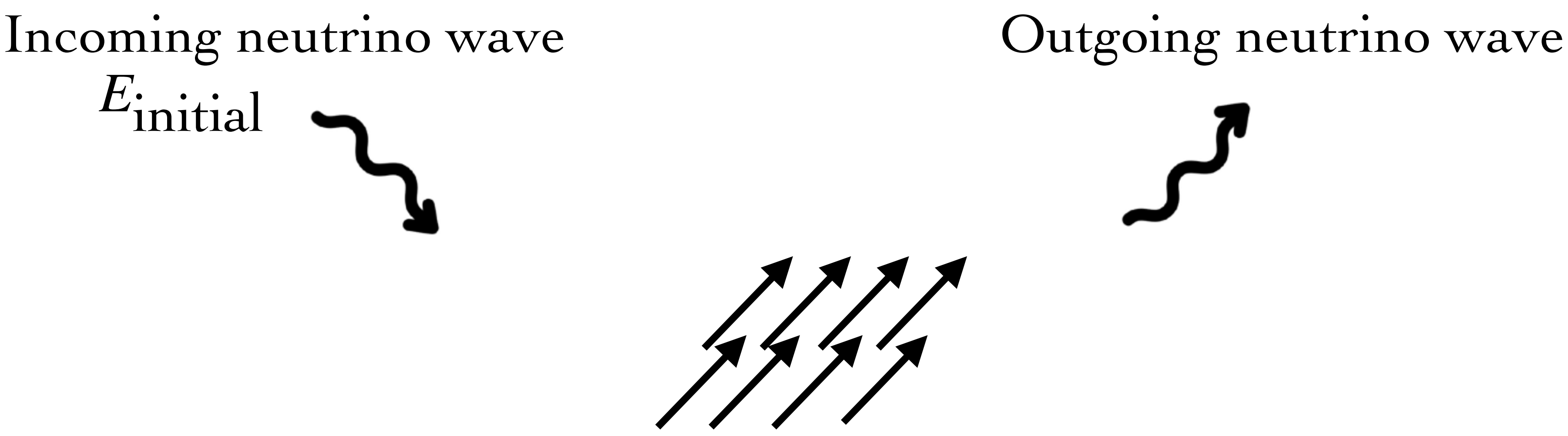
- Energy conservation and coherence dictates that $\omega \leq \frac{v_\nu}{R}$

Coherence in inelastic scattering processes

AA, S. Dimopoulos, M. Galanis (2024)



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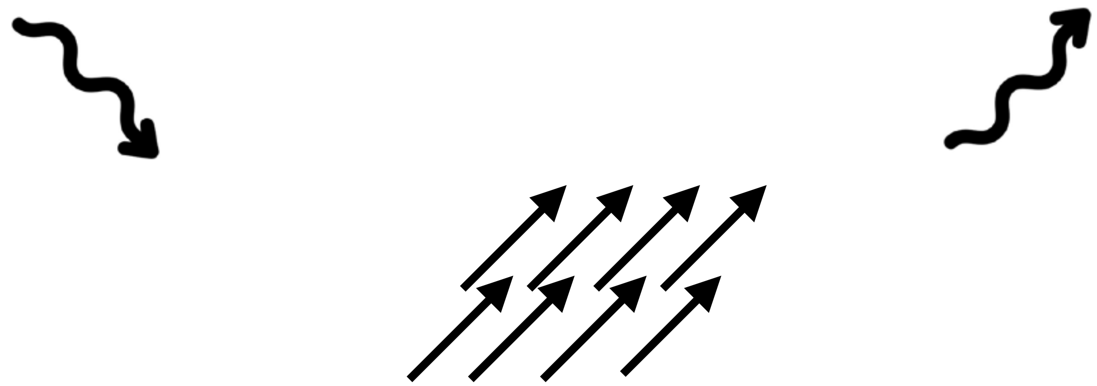
- Effect measured because of energy conservation; scattering changes the state of spins

Coherence in inelastic scattering processes

AA, S. Dimopoulos, M. Galanis (2024)

Incoming neutrino wave E_{initial}

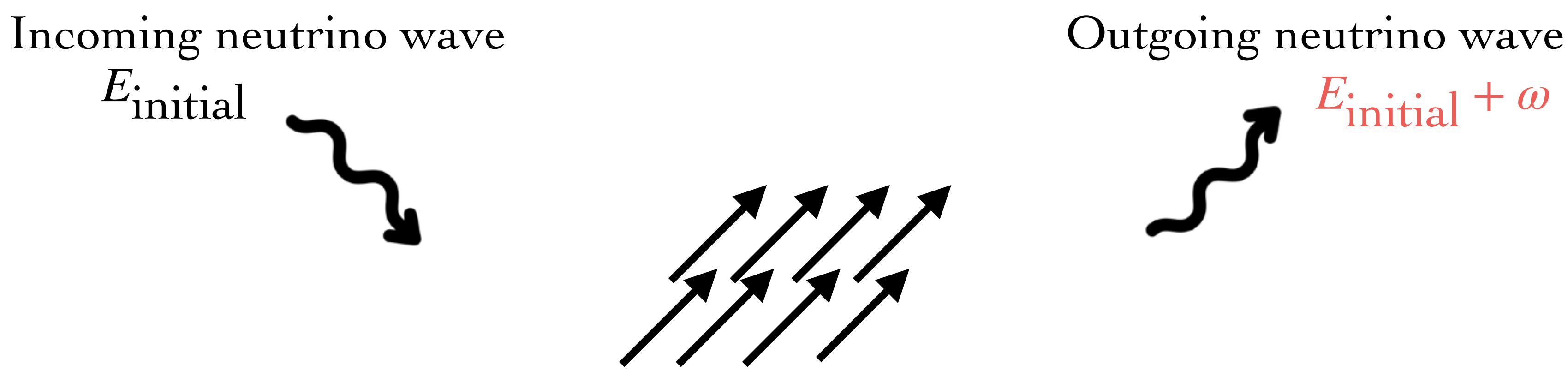
Outgoing neutrino wave $E_{\text{initial}} \pm \omega$



- Spin dependent interaction between neutrinos and spins results in a time-dependent potential $H \sim \frac{G_F}{\sqrt{2}} \delta^{(3)}(\vec{x}_\nu - \vec{x}_{\text{spin}}) N \; \vec{\sigma}_\nu \cdot \vec{\sigma}_{\text{spin}} \cos(\omega t)$
- Energy conservation and coherence dictates that $\omega \leq \frac{v_\nu}{R}$
- Effect measured because of energy conservation; scattering changes the state of spins
- Ideal system: nuclear spins in a magnetic field

Coherent inelastic scattering of the CNB

For $m_\nu = 0.1$ eV



- Neutrino - spin de-excitation scattering rate $\sim 0.2\ \text{Hz}\dfrac{n^2}{(3\times 10^{22}\ cm^{-3})^2}\dfrac{R^4}{(10\ \text{cm})^4}$

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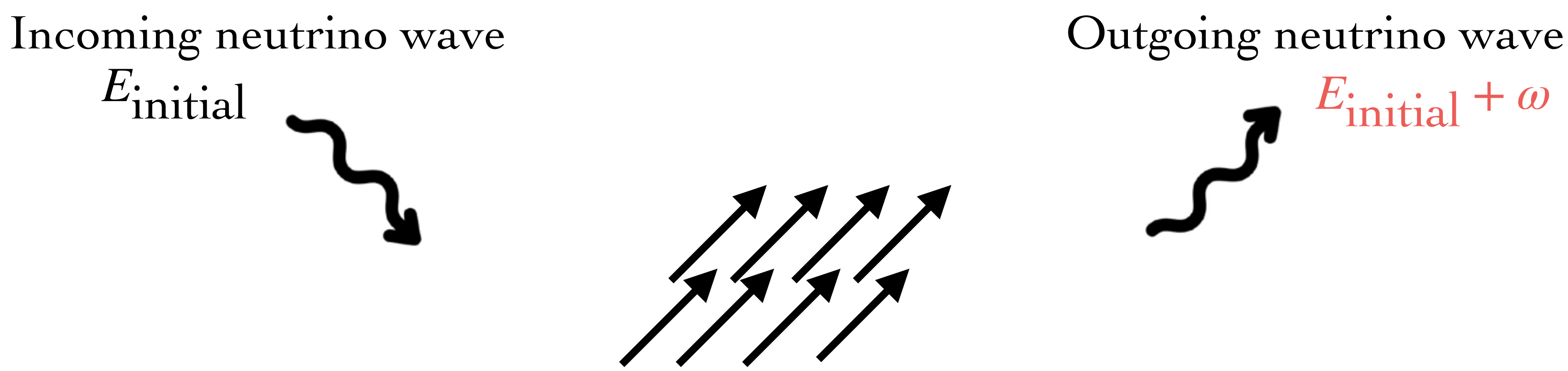

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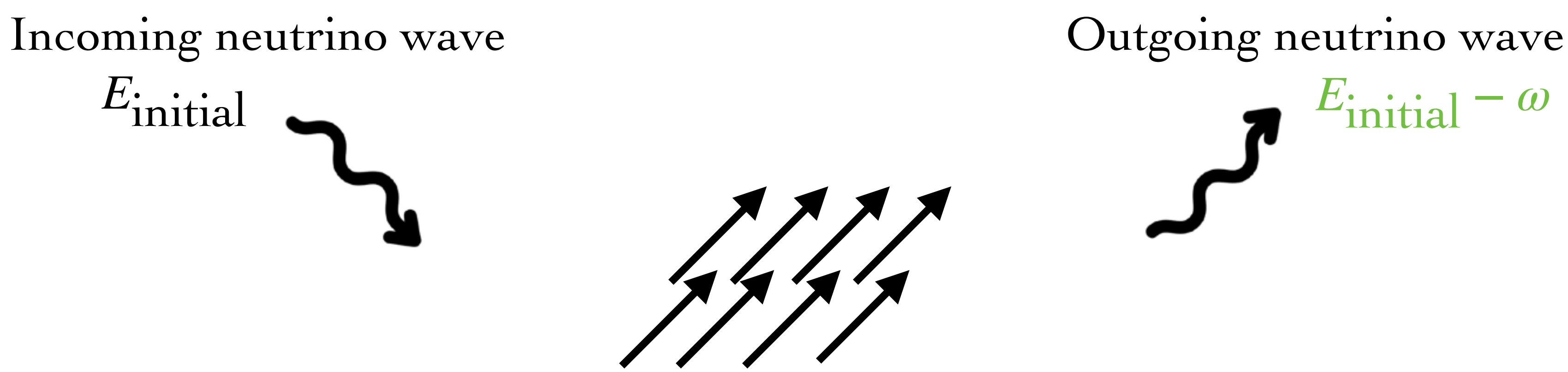


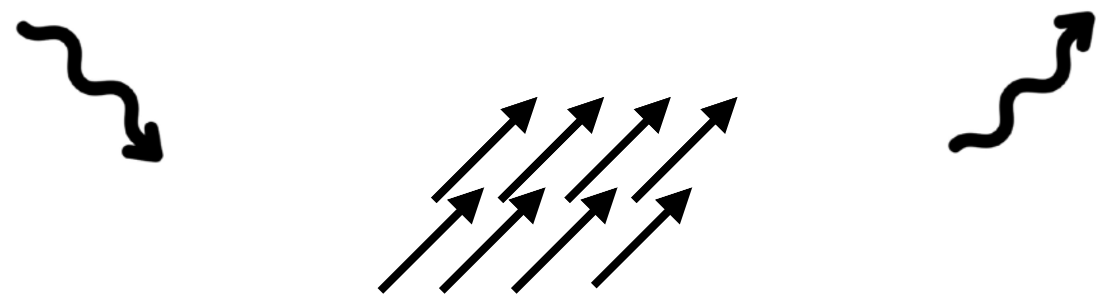
- Neutrino - spin excitation scattering rate $\sim \left(0.2\ \text{Hz} - 0.001\ \text{Hz} \dfrac{10\ \text{cm}}{R}\right) \dfrac{n^2}{(3 \times 10^{22}\ cm^{-3})^2} \dfrac{R^4}{(10\ \text{cm})^4}$

Coherent inelastic scattering of the CNB

For $m_\nu = 0.1$ eV

Incoming neutrino wave E_{initial}

Outgoing neutrino wave $E_{\text{initial}} + \omega$



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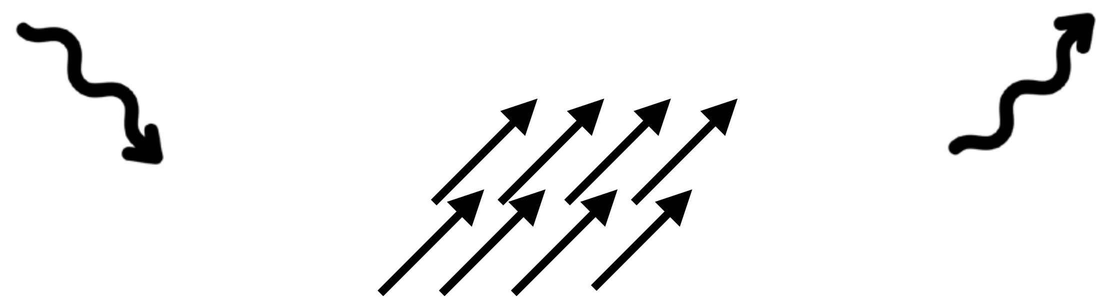
Incoming neutrino wave E_{initial}

Outgoing neutrino wave $E_{\text{initial}} - \omega$



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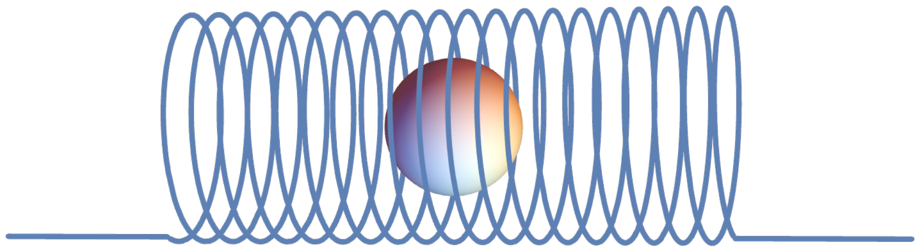
Incoherent part: $10^{-22}\ \textbf{Hz} \dfrac{n}{3 \times 10^{22}\ \textbf{cm}^{-3}} \dfrac{R^3}{(10\ \textbf{cm})^3}$

Towards measuring coherent inelastic interactions

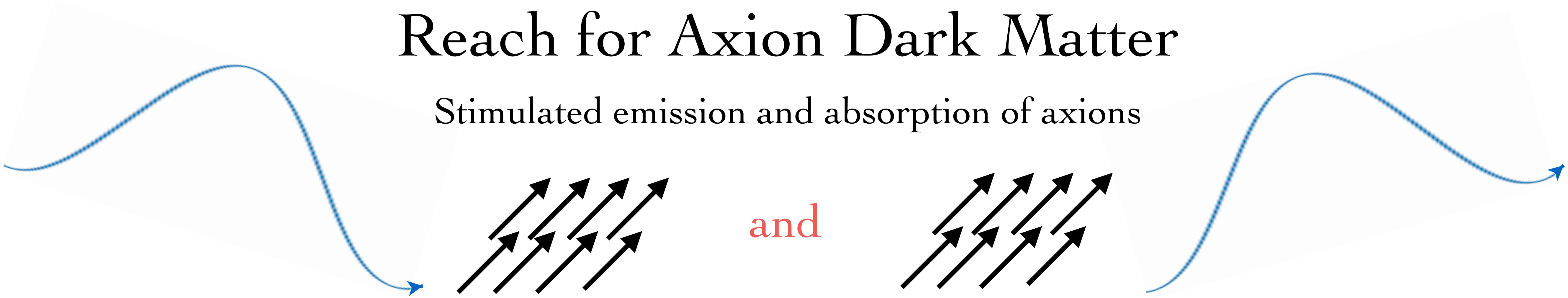
Nuclear spin polarized He-3 coupled to an LC circuit 10s of kHz to ~1 GHz

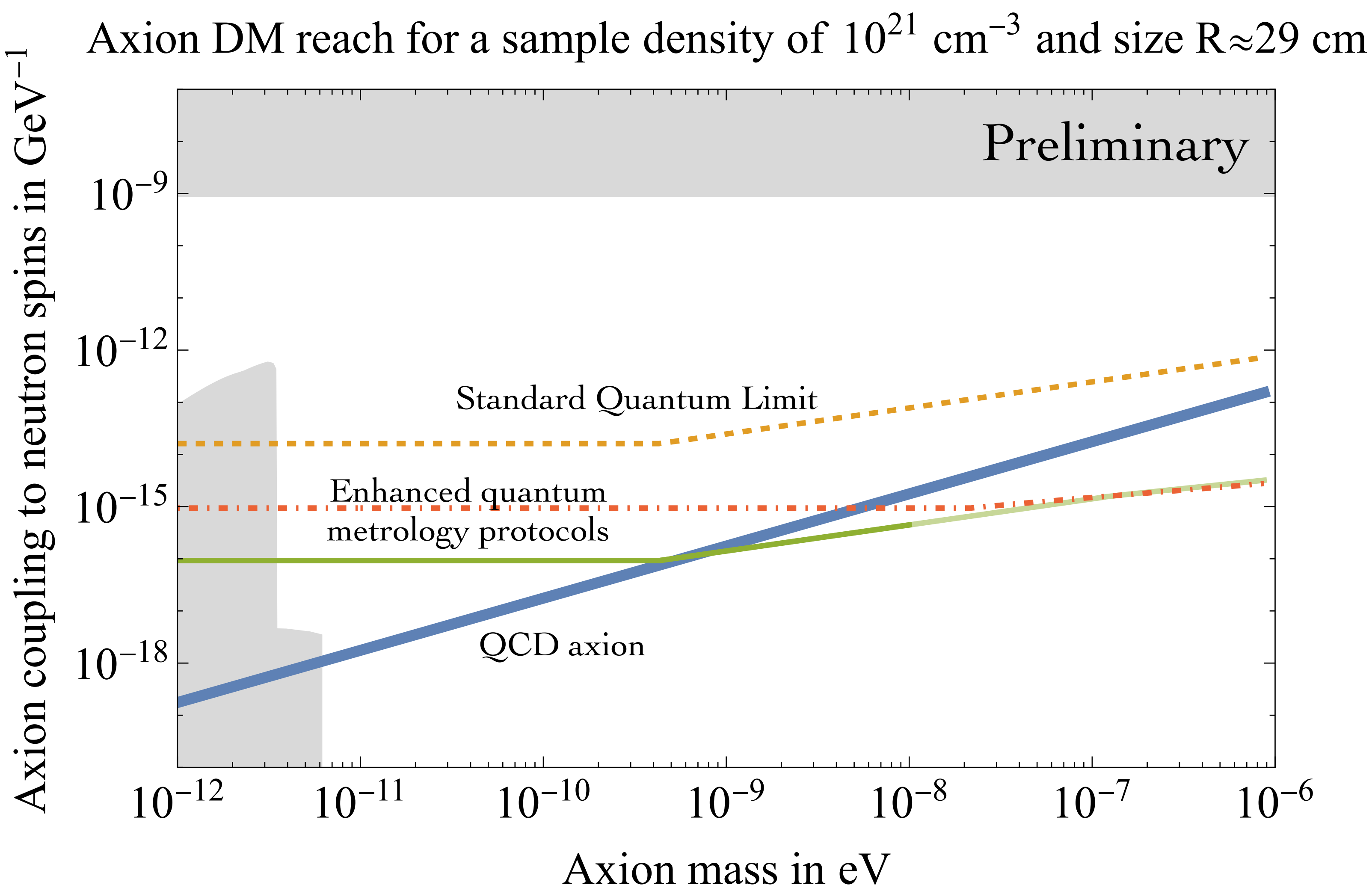


- Measure the change in the energy of the spins (excitation-deexcitation)
- Measure the uncertainty of spins (excitation+deexcitation)
- Quantum optics techniques to reduce the spins quantum uncertainty
- QCD axion DM is now "easy" (Rate of a Hz corresponds to 10^{16} atoms instead of 10^{26} atoms for the CNB)

Reach for Axion Dark Matter

Stimulated emission and absorption of axions





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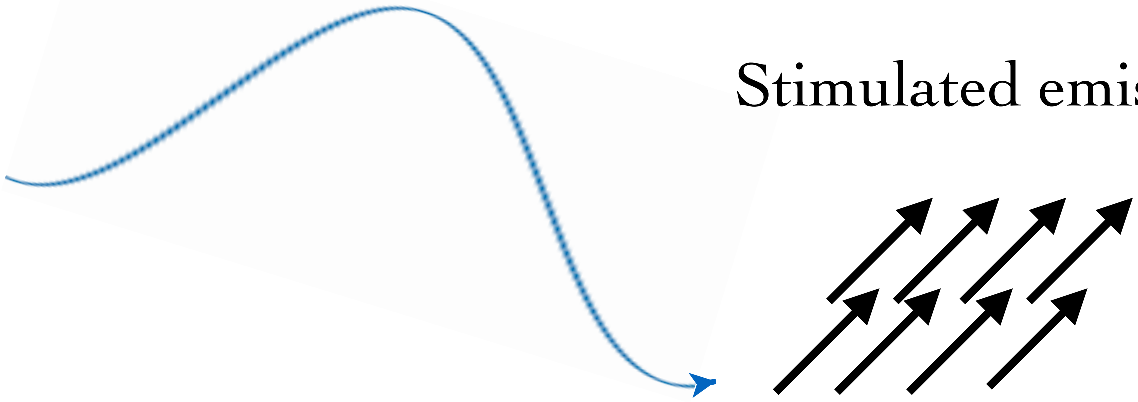
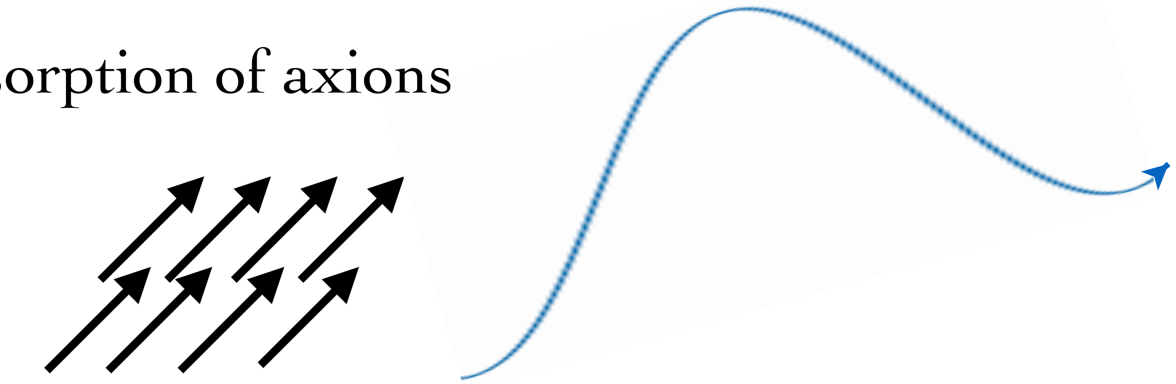
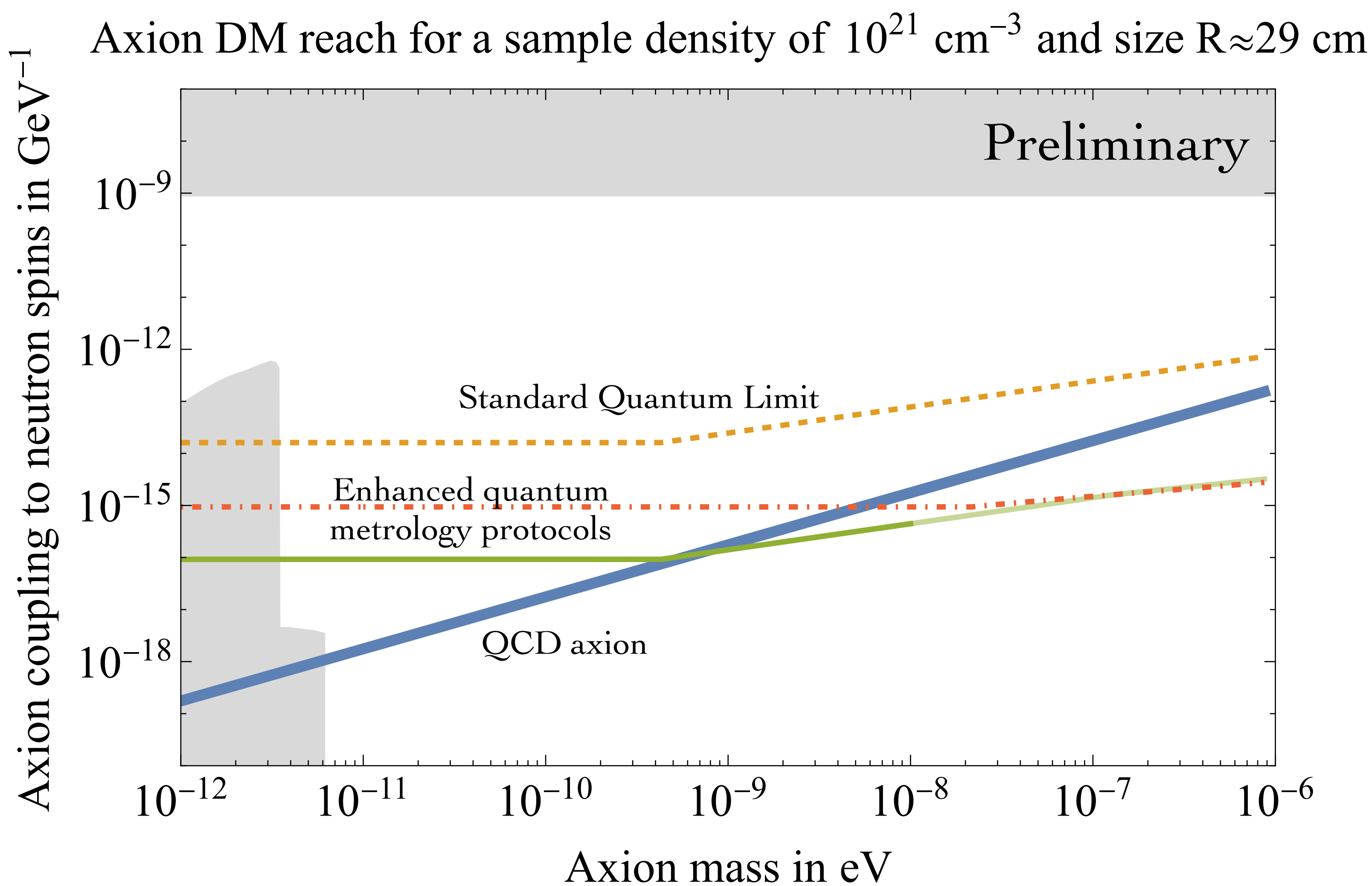


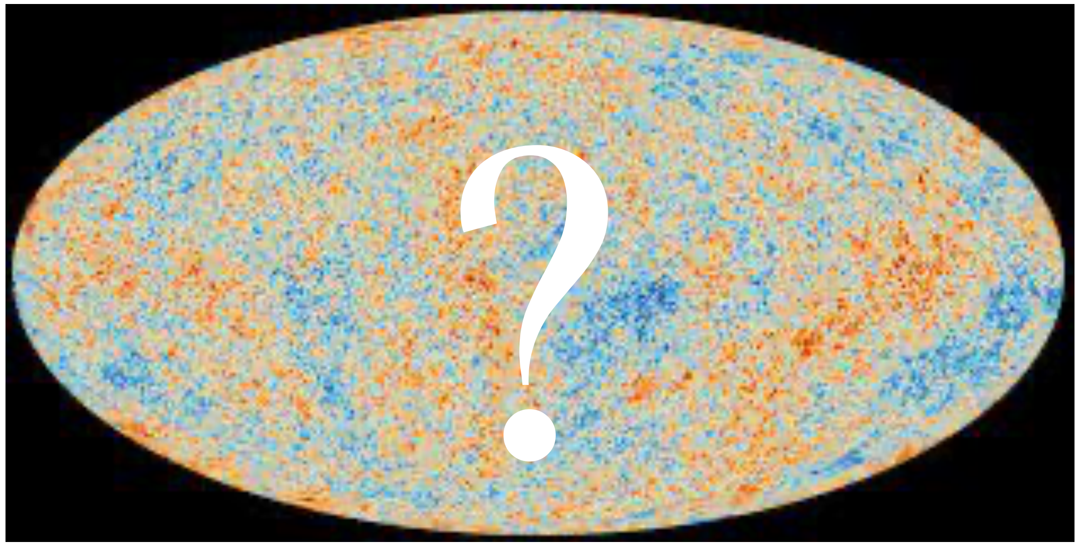
and





*For the CνB this matches the KATRIN

A Cosmic Neutrino Background Telescope?



How did the Universe looked like when it was less than 1 second old?…

SNOLAB: Super-Lab for Fundamental Physics?

- A Laboratory housing small scale experiments on fundamental physics at different levels of development

- Possibility of user facility operations where experimental R&D is performed?

- R&D Axion DM experiments can be a nursery for Cosmic Neutrino Background telescopes