SNOLAB: An international hub for fundamental physics exploration

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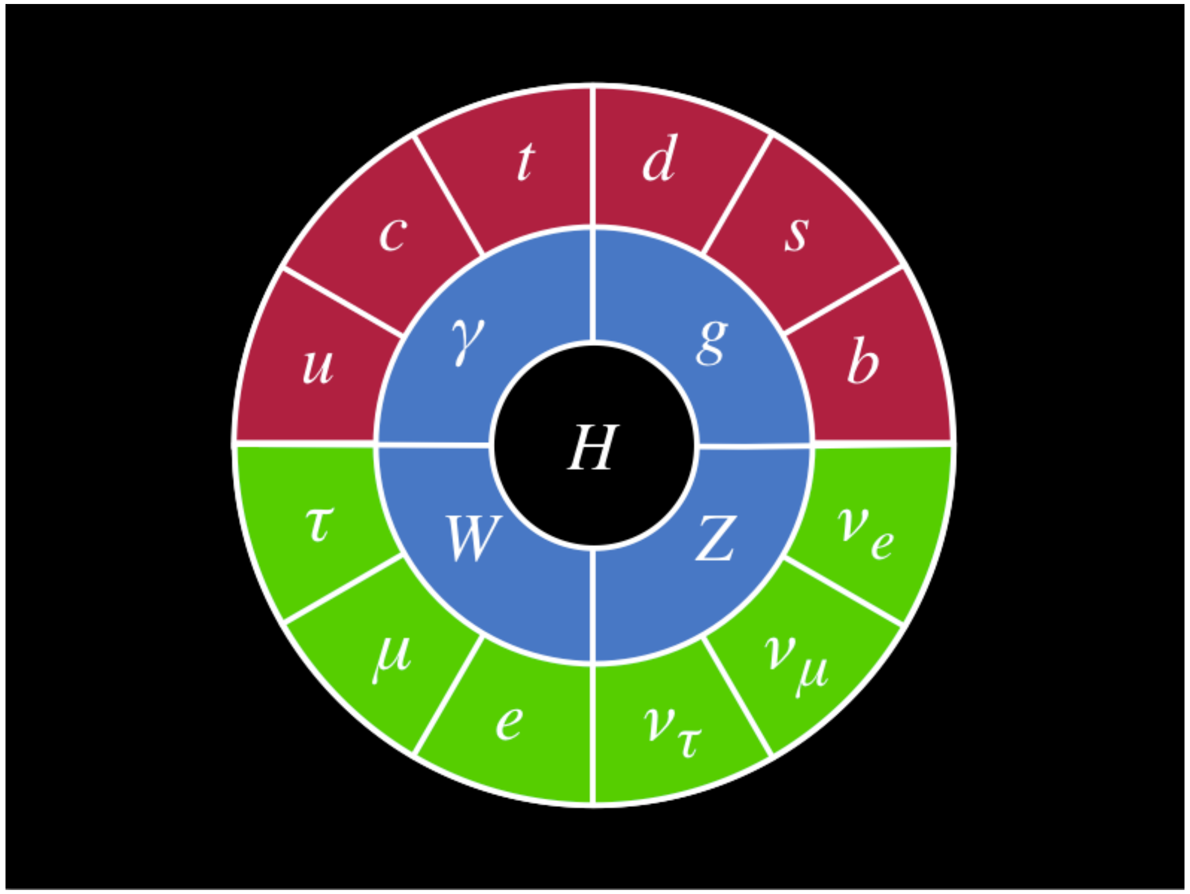
The Standard Model

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



Contains ~20 particles and ~20 parameters

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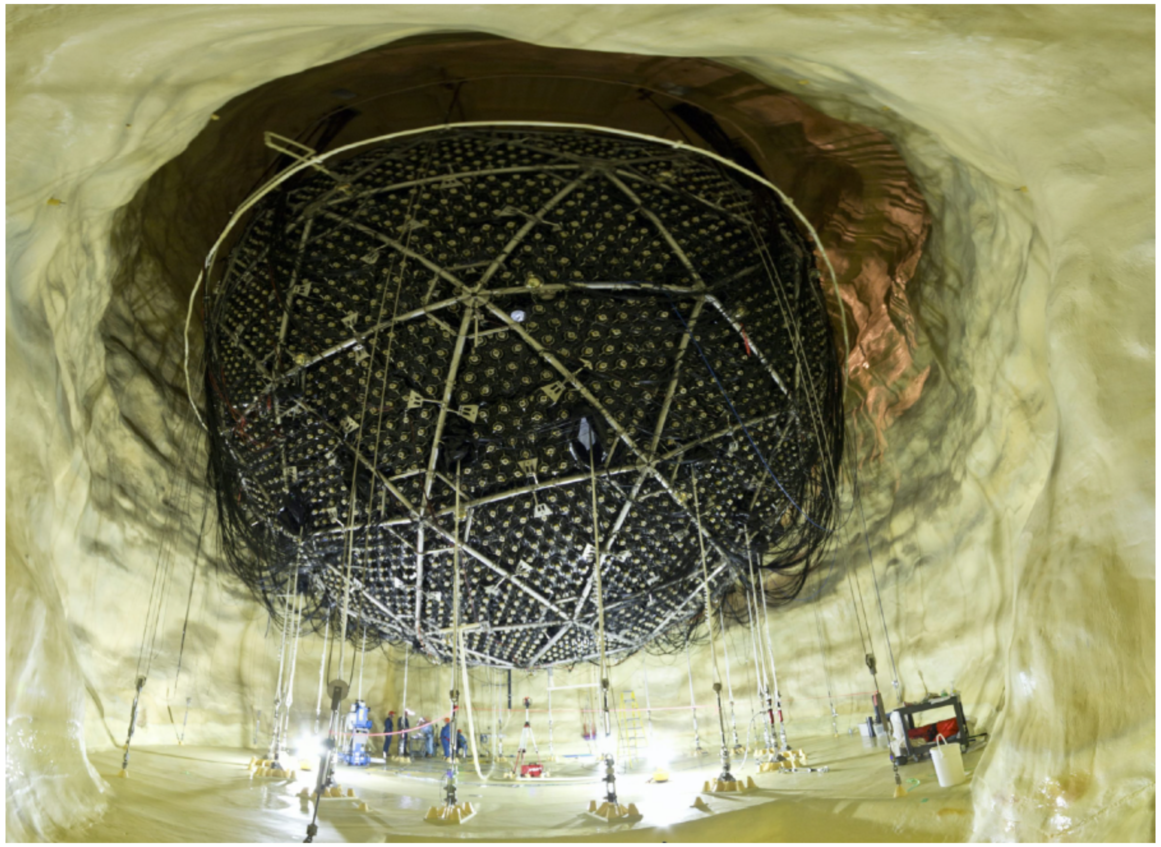
- A lot to learn about the neutrino sector
  - Neutrino parameters of the PMNS matrix
  - Are neutrinos their own antiparticle? (Dirac vs Majorana)
  - The Cosmic Neutrino Background



SNO+

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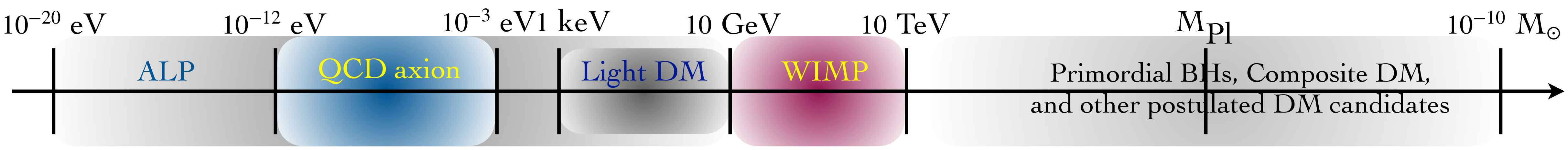
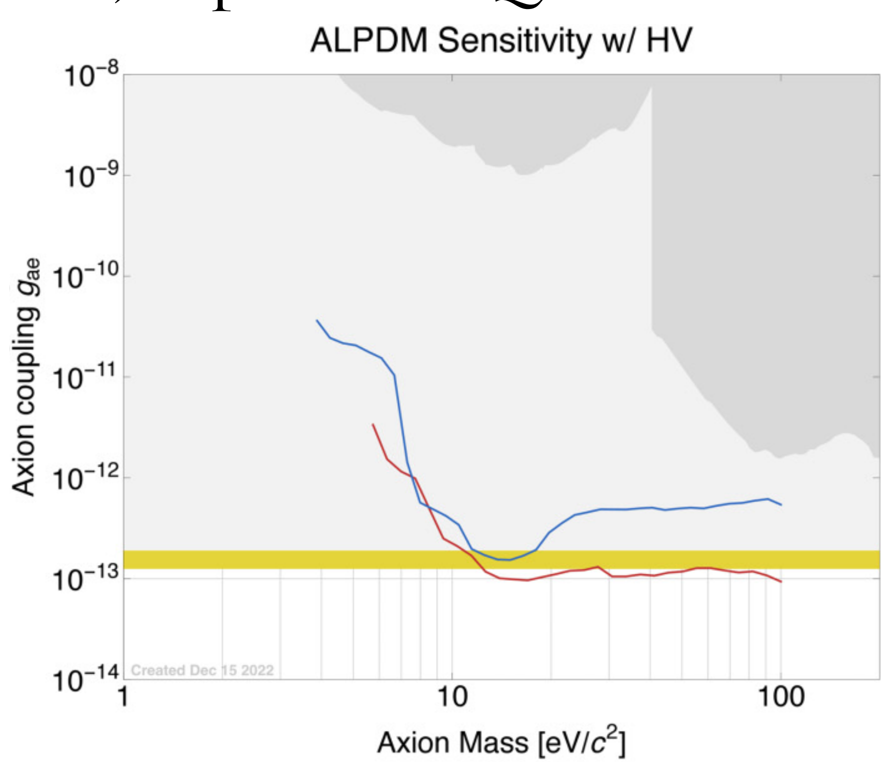
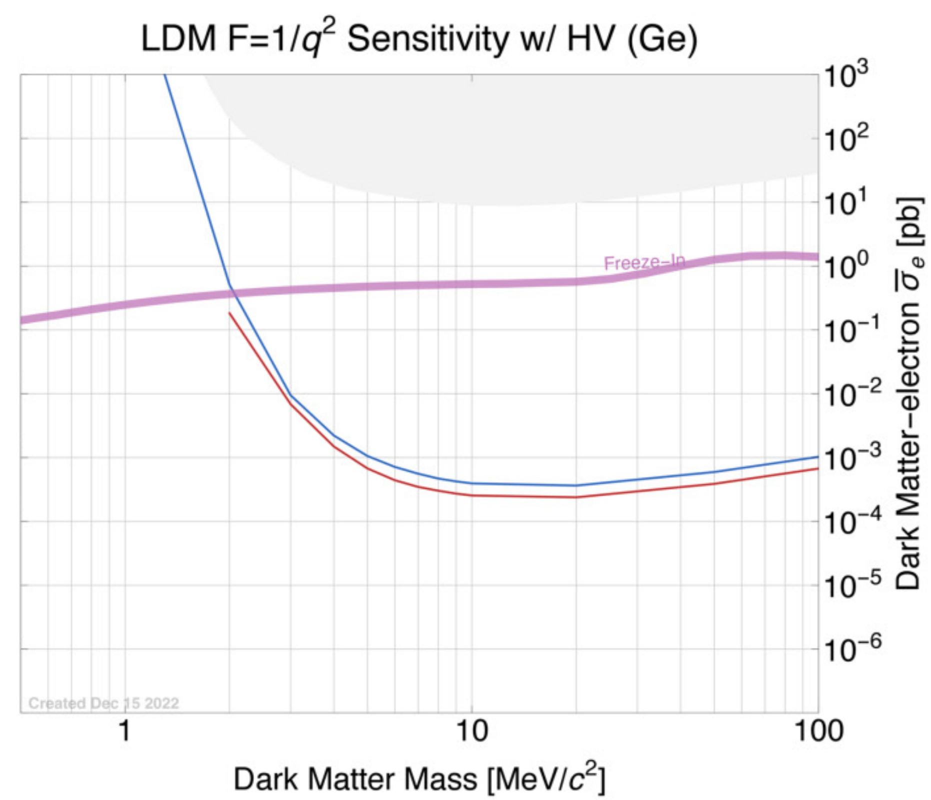
The nature of Dark Matter



Candidates with consistent cosmology: Axion particles and WIMP, Light DM

Candidates that have a reason other than DM to be there:
Axions, in particular QCD axion and the WIMP





SuperCDMS(see talk by Miriam Diamond)

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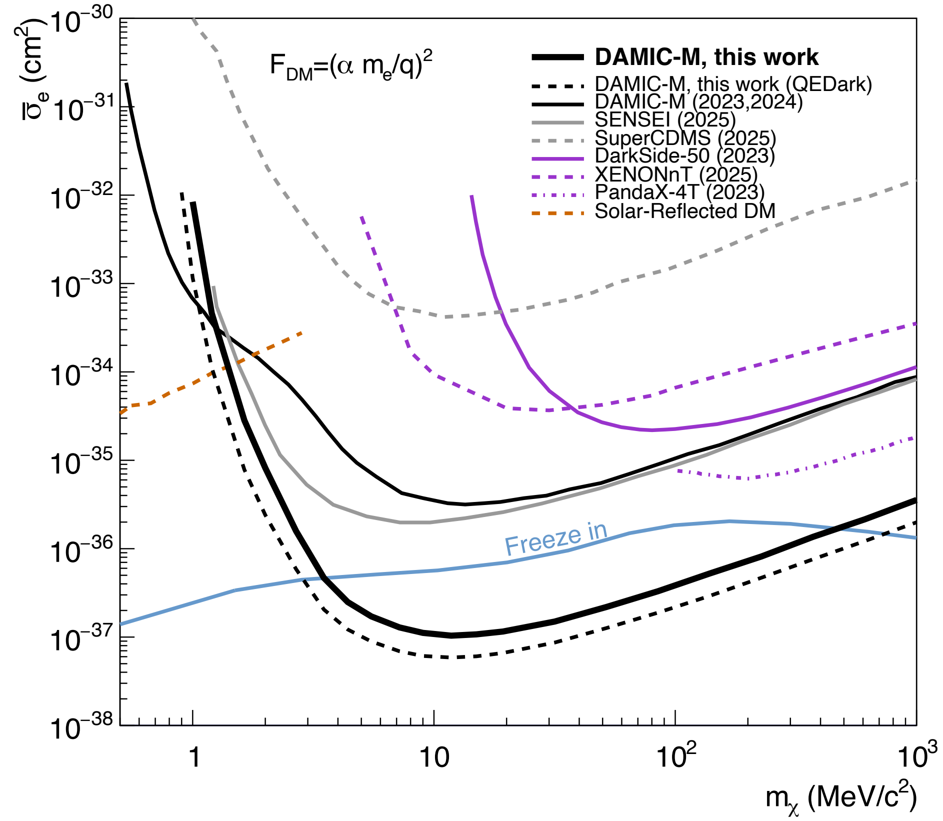
March 2025 results from DAMIC-M
based on the DAMIC experiment started at SNOLAB
(see Yoni Kahn's talk)

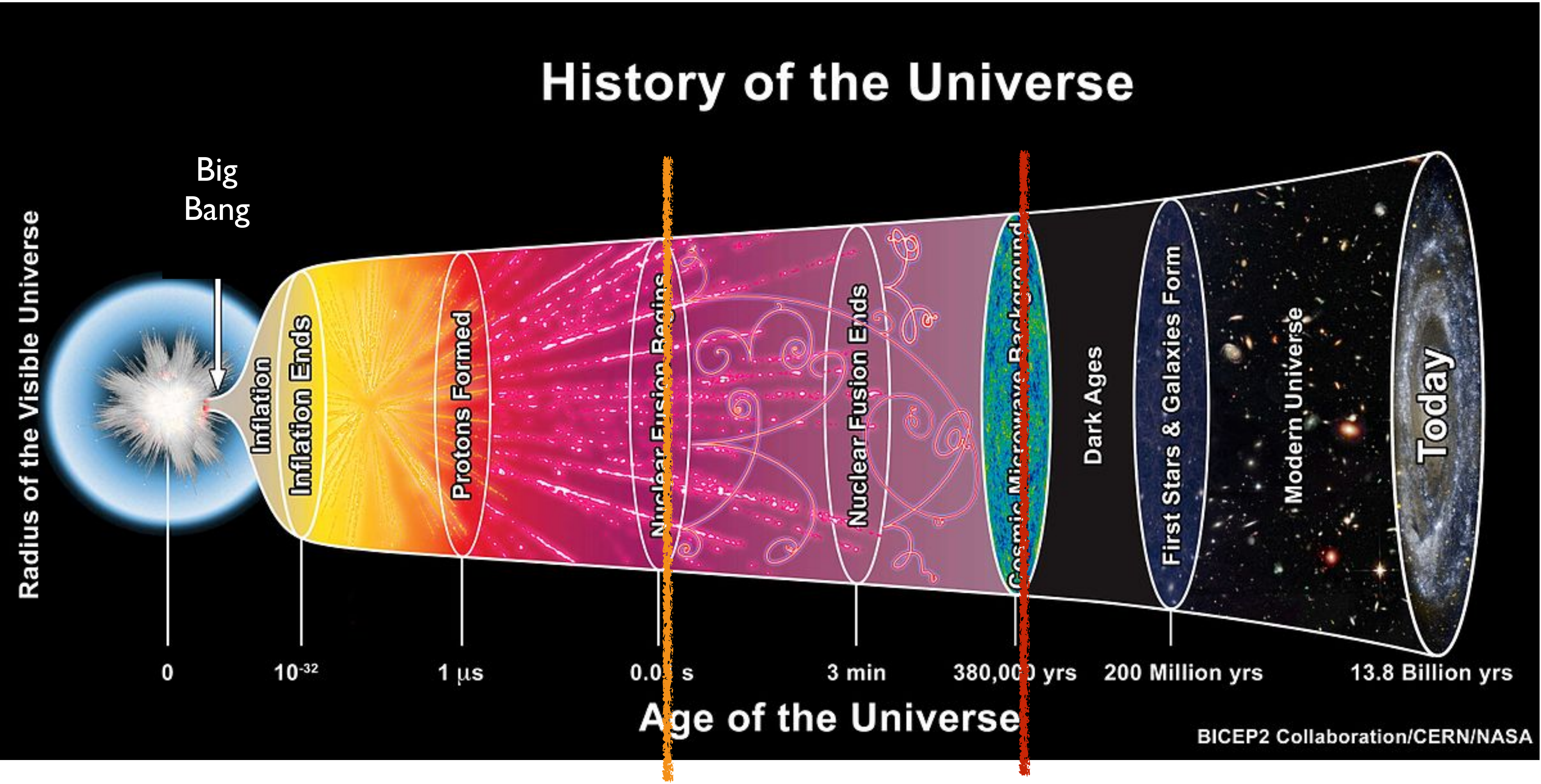


SNOLAB in the next 15+ years:
Nursery of fundamental physics experiments

Superradiant aka coherent inelastic interactions of cosmic noise

in collaboration with S. Dimopoulos, M. Galanis

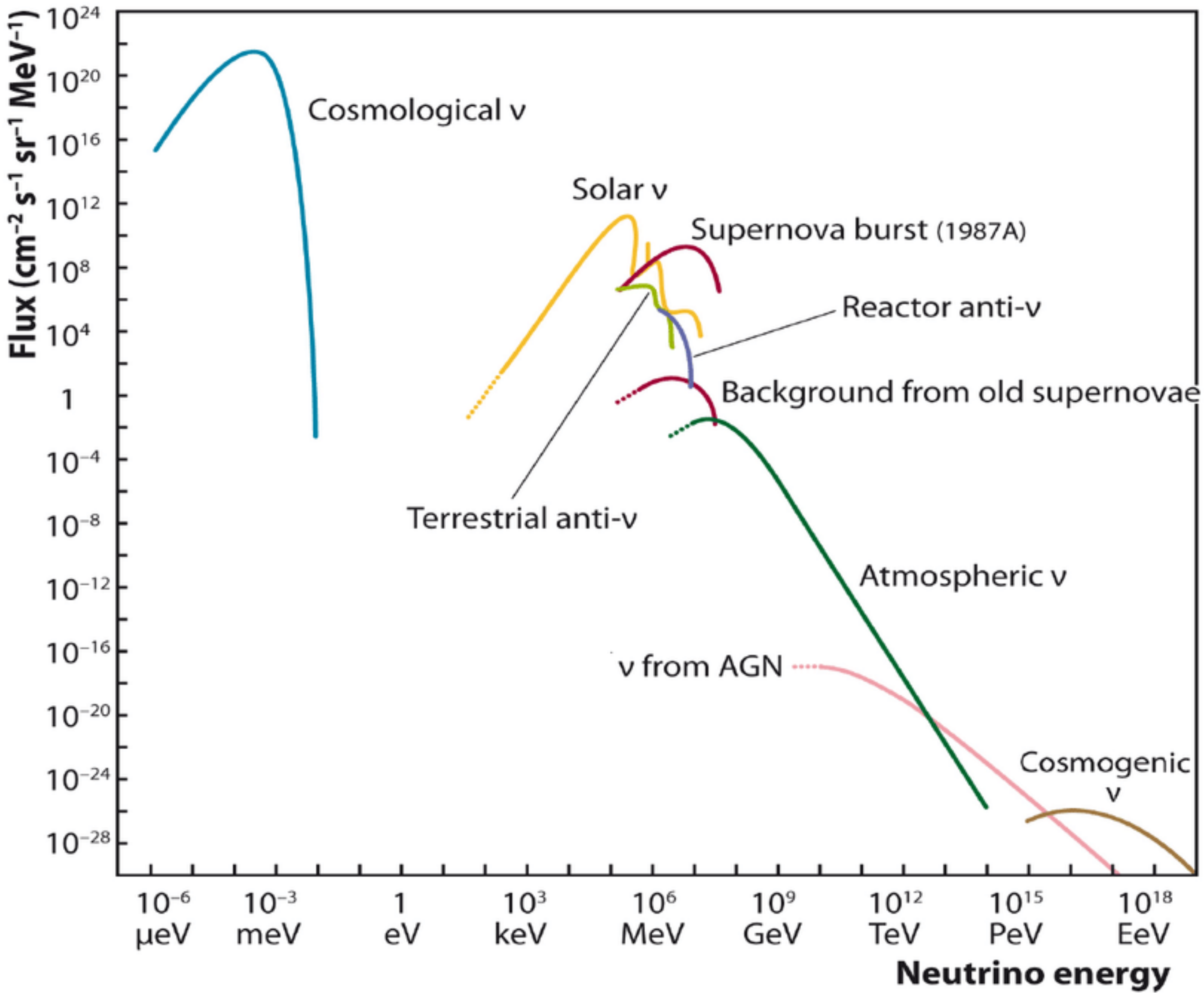
A Brief History of the Universe



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
    - $\langle E_\nu \rangle = 1.6 \times 10^{-6}\ \text{eV} \left(\dfrac{0.1\ \text{eV}}{m_\nu} \right)$
    - $\langle \lambda_\nu \rangle = 2.1$ mm
    - $n_\nu = 56\ \text{cm}^{-3}$ per flavor, per helicity model

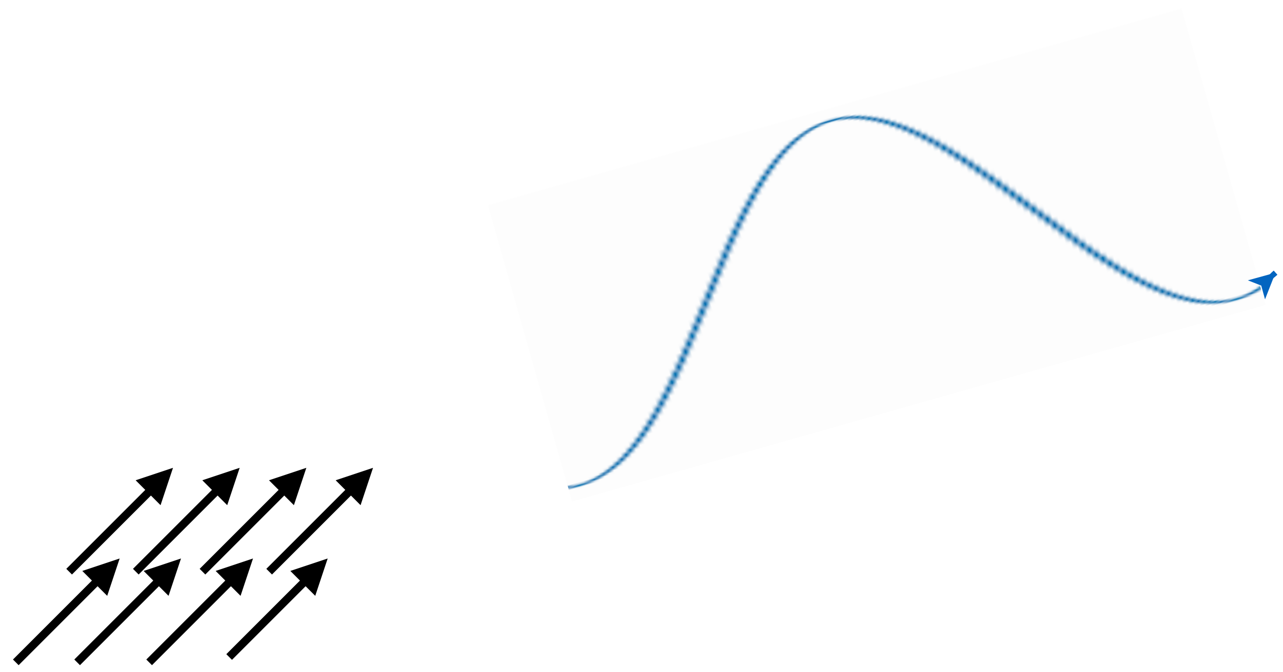
Why is the CνB important?

- 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: Need a $(100\ \mathrm{km})^3$ volume to have one interaction over a 3 year period!
- Can we enhance the interaction through coherence so that the rate scales like N^2?
- Besides coherent elastic scattering, are there inelastic processes that are enhanced by N^2 ?

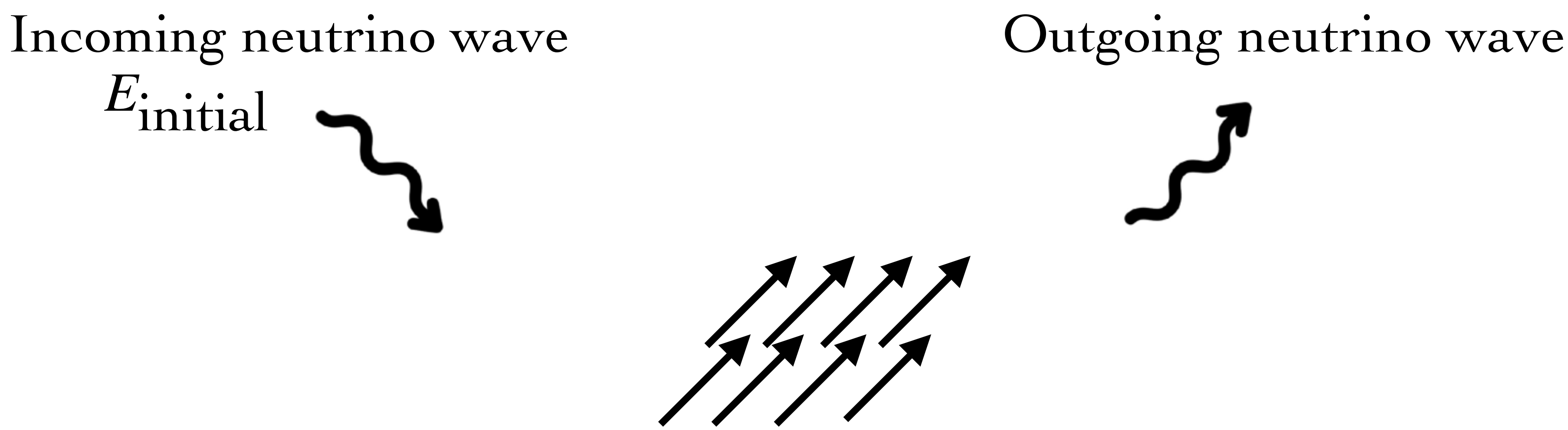
Coherence in emission and absorption of light



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

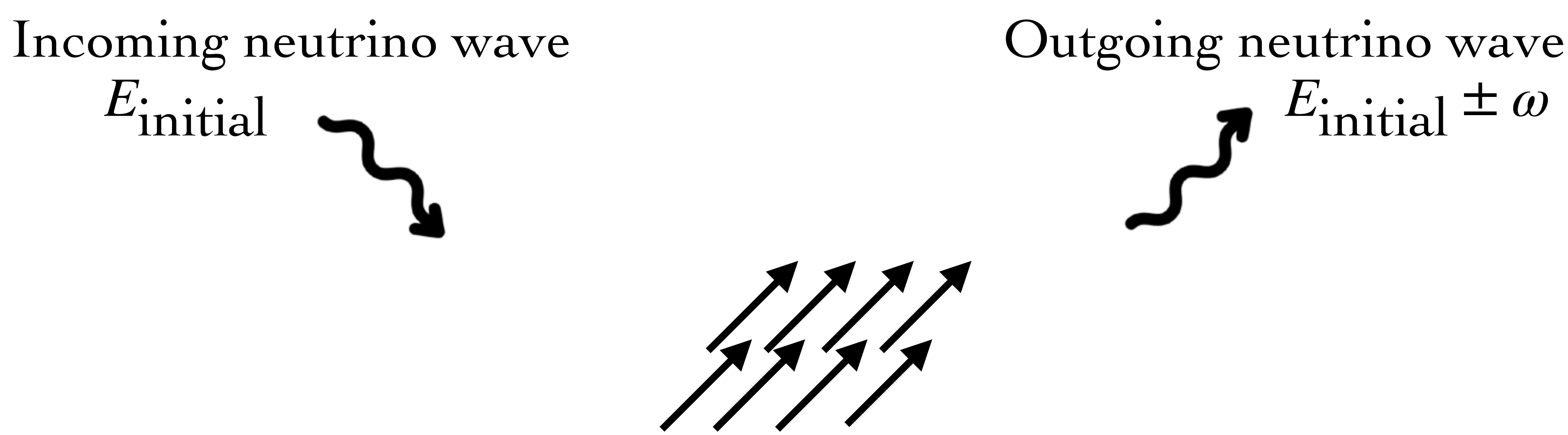
Known as Dicke Superradiance (1954)

Coherence in inelastic scattering processes



- Spin dependent interaction between neutrinos and spins results in a time-dependent potential $H \sim \frac{G_F}{\sqrt{2}} \delta^{(3)}(\vec{x}_\nu - \vec{x}_S) N \ \vec{\sigma}_\nu \cdot \vec{\sigma}_S \cos(\omega t)$
- Scattered outgoing neutrino energies $E_{\text{initial}} \pm \omega$
- Scattering rate scales like N^2
- Energy conservation and coherence dictates that $\omega \leq \frac{v_\nu}{R}$
- Effect measured because of energy conservation; scattering changes the state of spins

Coherence in inelastic scattering processes



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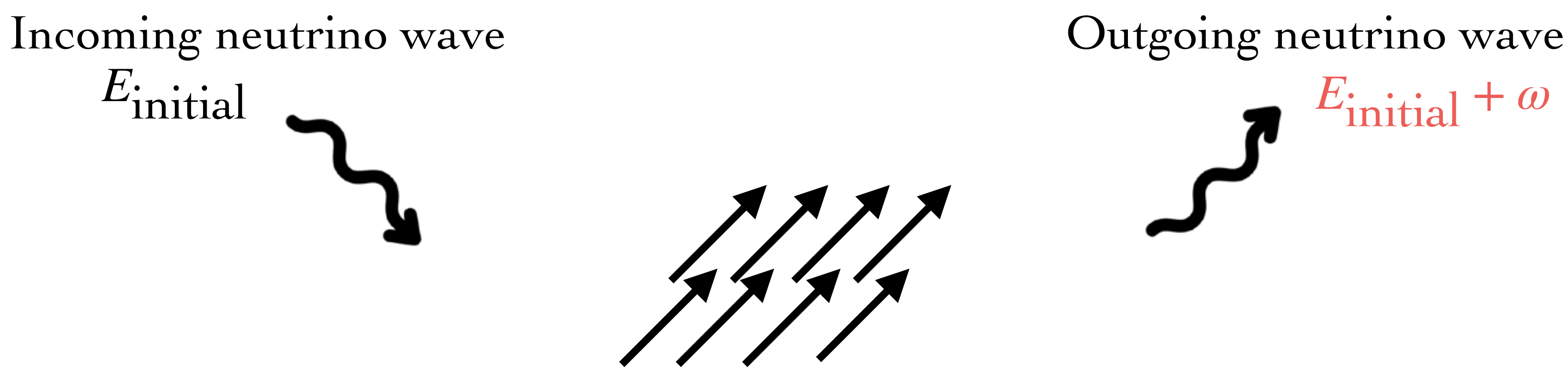
- Energy conservation and coherence dictates that $\omega \leq \frac{v_\nu}{R}$

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

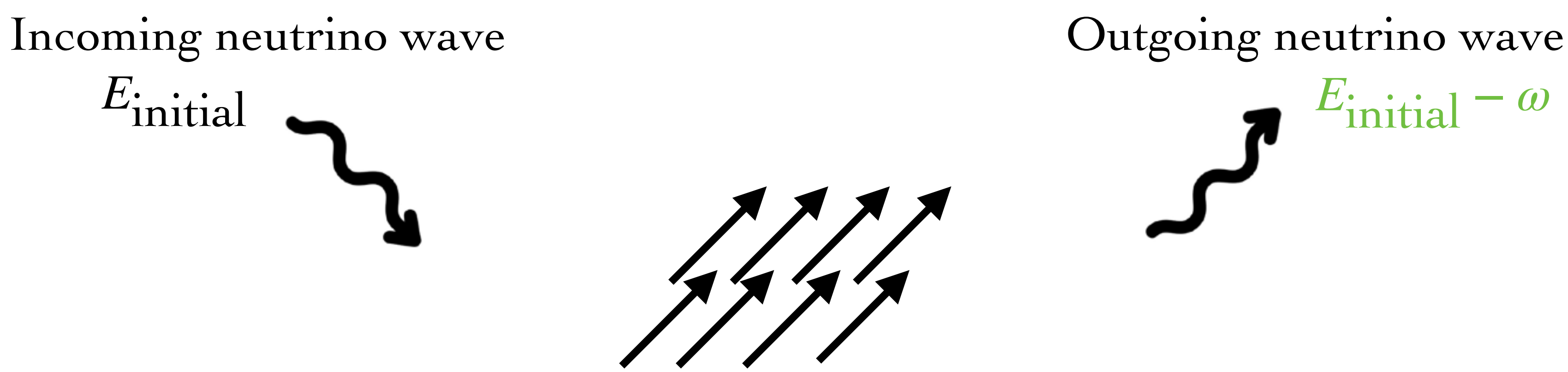
- Ideal system: nuclear spins in a magnetic field

Coherent inelastic scattering of the CNB

For $m_\nu = 0.1$ eV



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

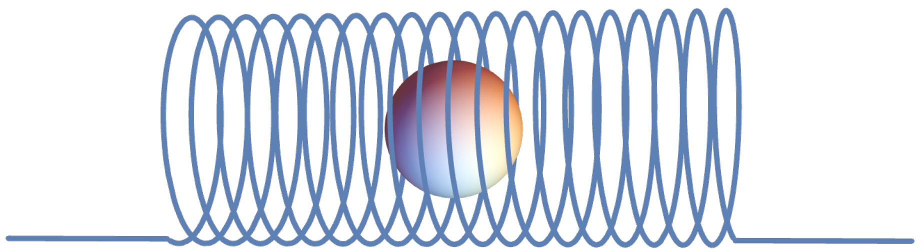


- Neutrino - spin excitation scattering rate $\sim \left(0.2 \text{ Hz} - 0.001 \text{ Hz} \frac{10 \text{ cm}}{R}\right) \frac{n^2}{(3 \times 10^{22}\ cm^{-3})^2} \frac{R^4}{(10 \text{ cm})^4}$

Incoherent part: 10^{-22} **Hz** $\frac{n}{3 \times 10^{22}\ \mathbf{cm}^{-3}} \frac{R^3}{(10\ \mathbf{cm})^3}$

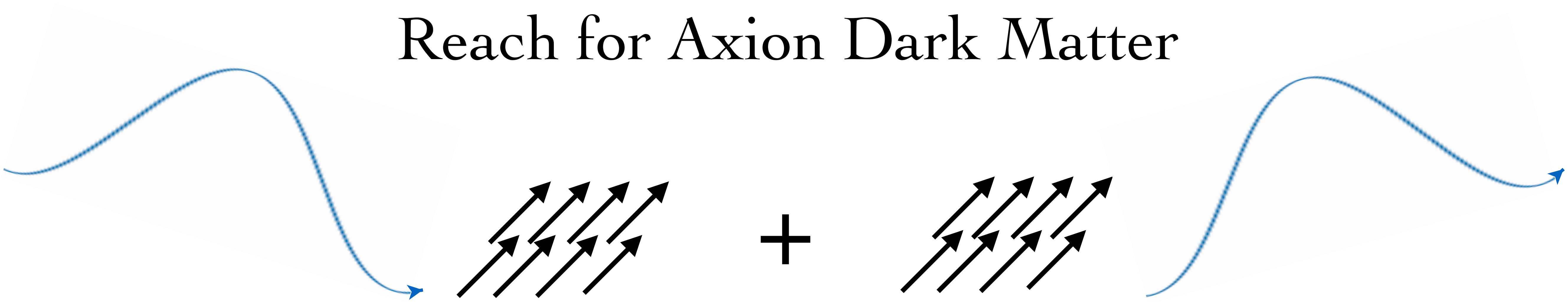
Towards measuring coherent inelastic interactions

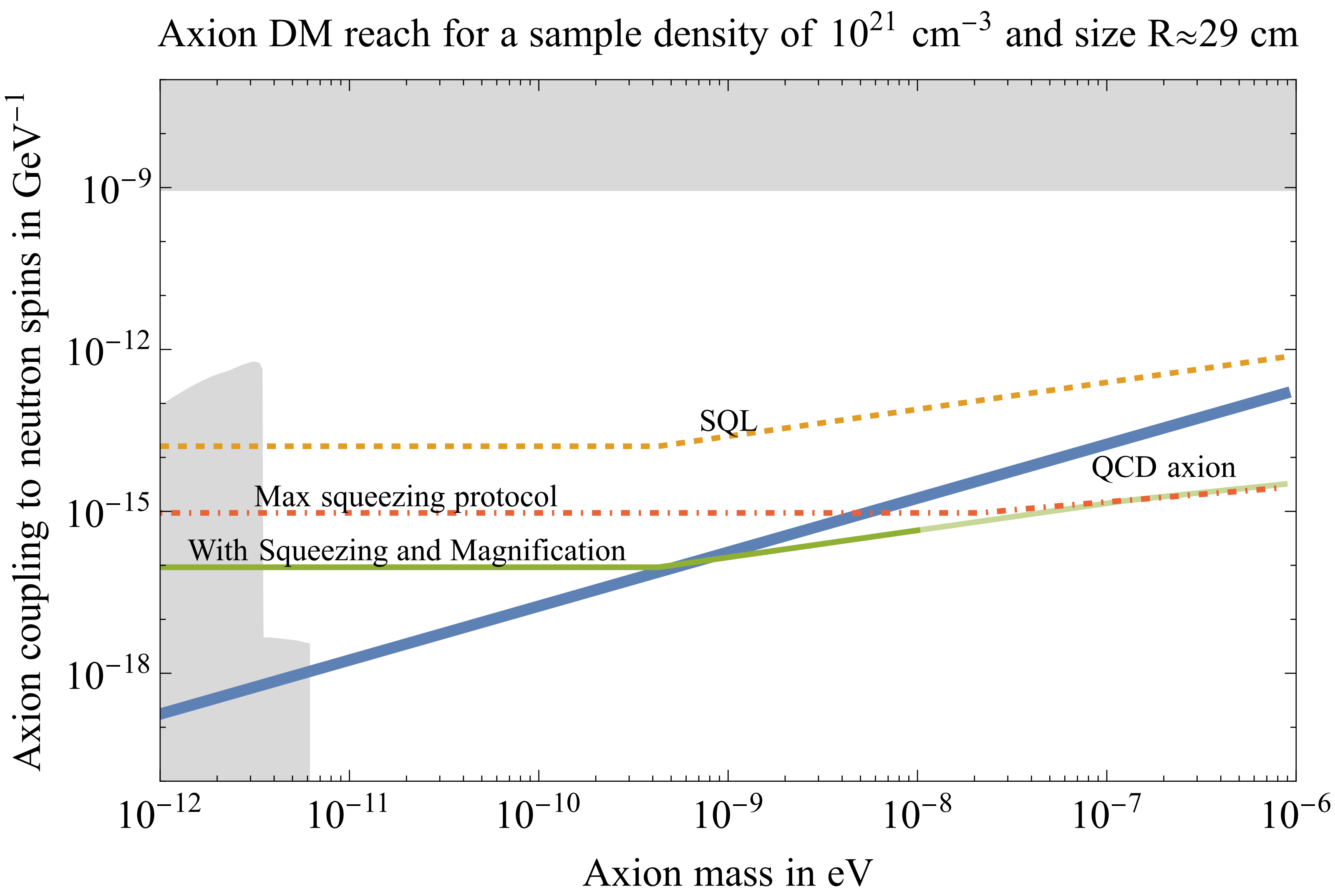
Nuclear spin polarized sphere coupled to an LC circuit



- 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
- For the CNB, can improve by a factor of 100 compared to KATRIN
- QCD axion DM is now easy

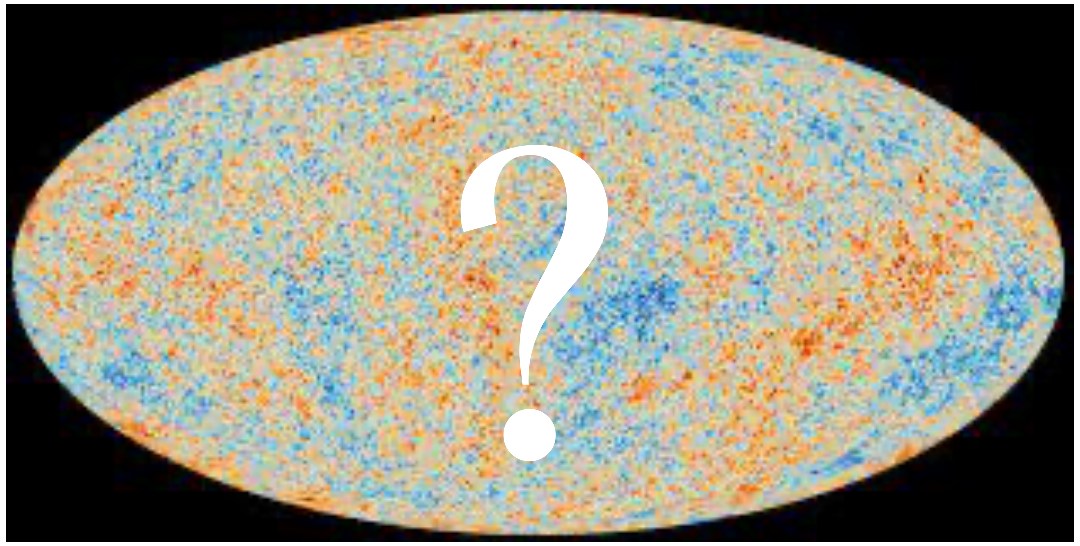
Reach for Axion Dark Matter





*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

- Fundamental Physics means Neutrinos and DM but can include New Forces, New Particles, New Dimensions…

- HEP Model of a Users Facility plus Local Personnel

- Can be a natural expansion of CUTE