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

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for the PTOLEMY Collaboration

LNGS SCIENTIFIC COMMITTEE OPEN SESSION

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

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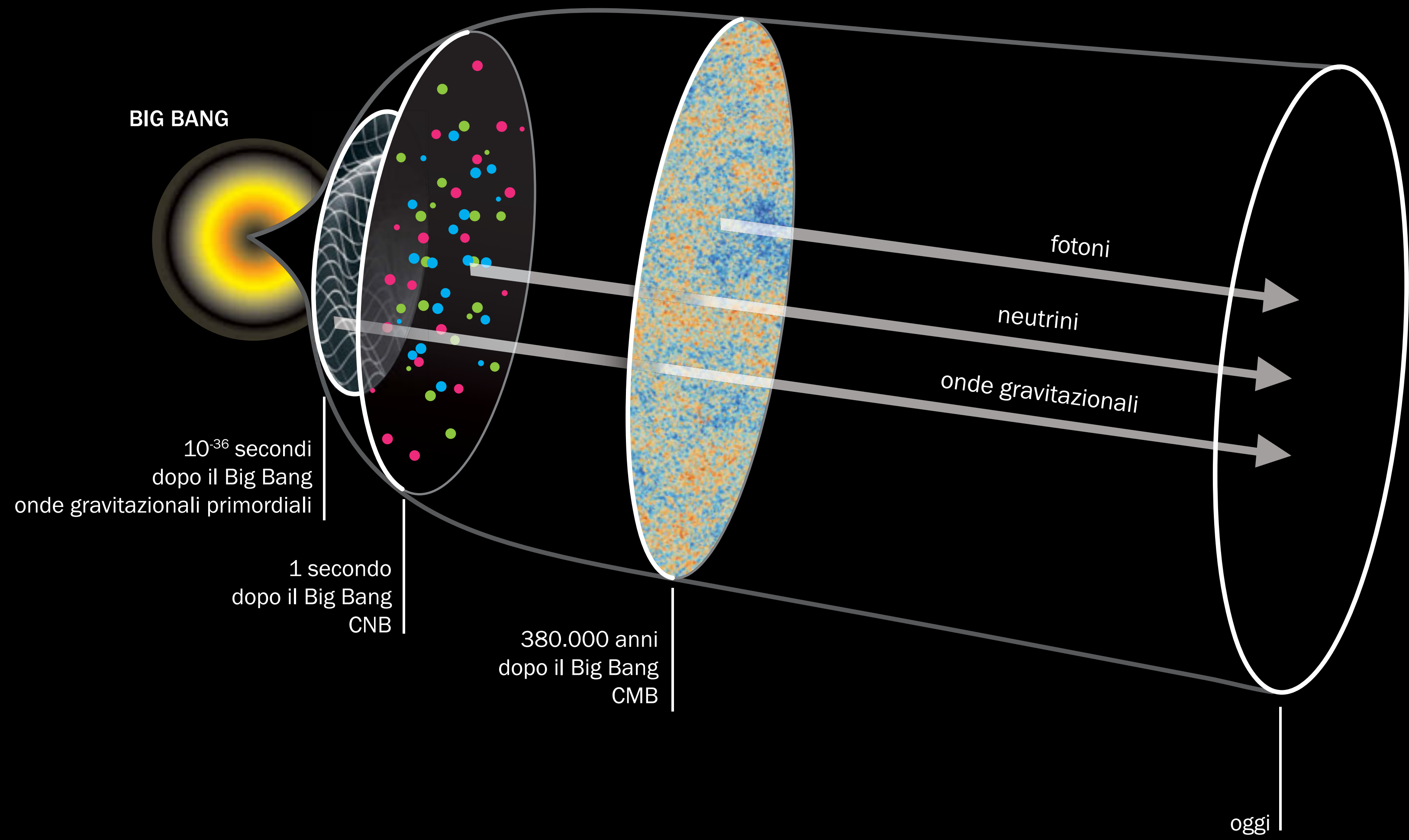
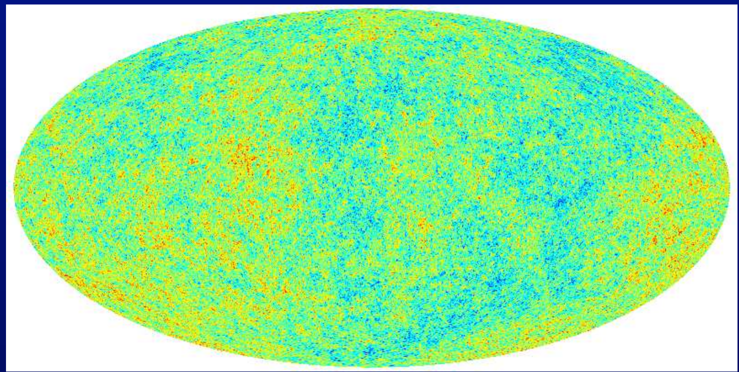
Looking Back in Time

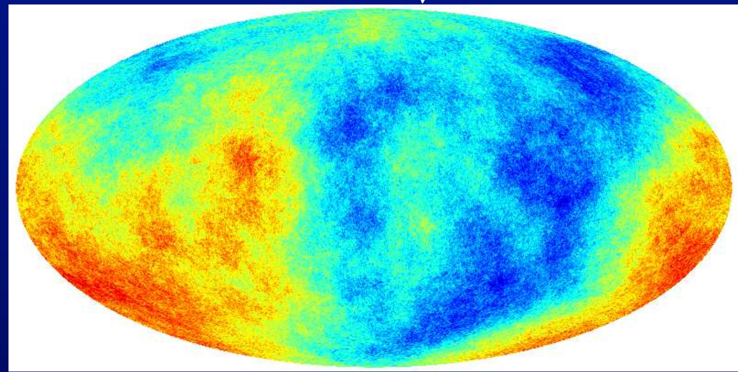


The Neutrino Sky

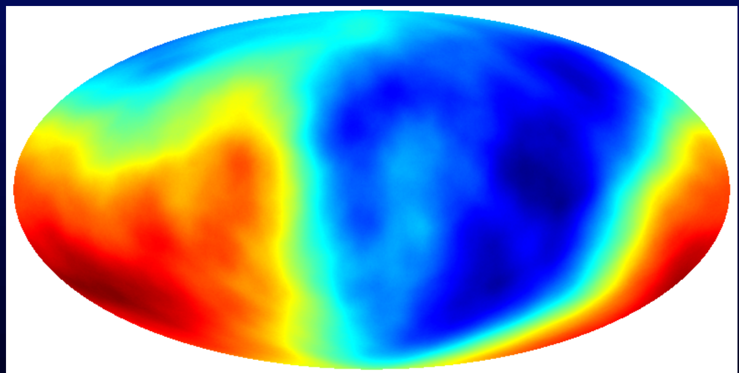
$m_\nu < 0.00001$ eV



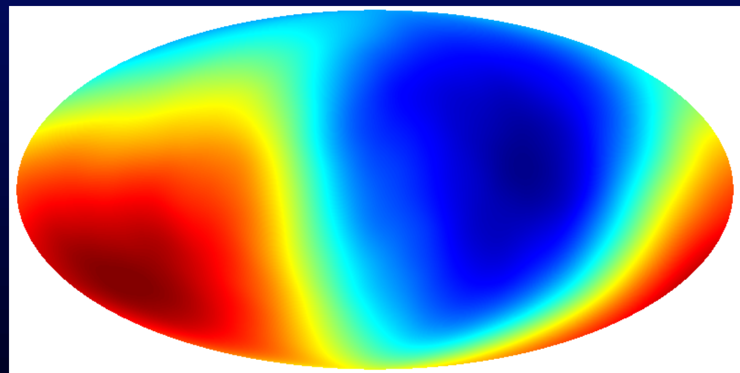
$m_\nu \sim 0.001$ eV



Hannestad, Brandbyge (2009)

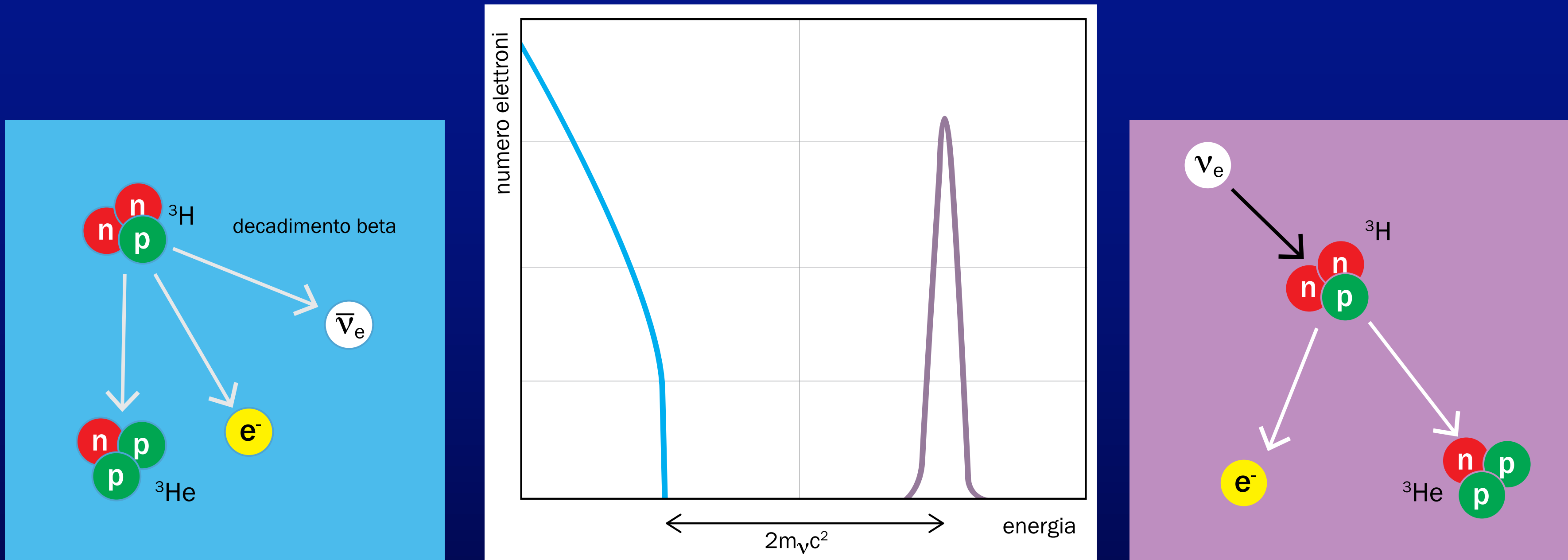


$m_\nu \sim 0.01$ eV

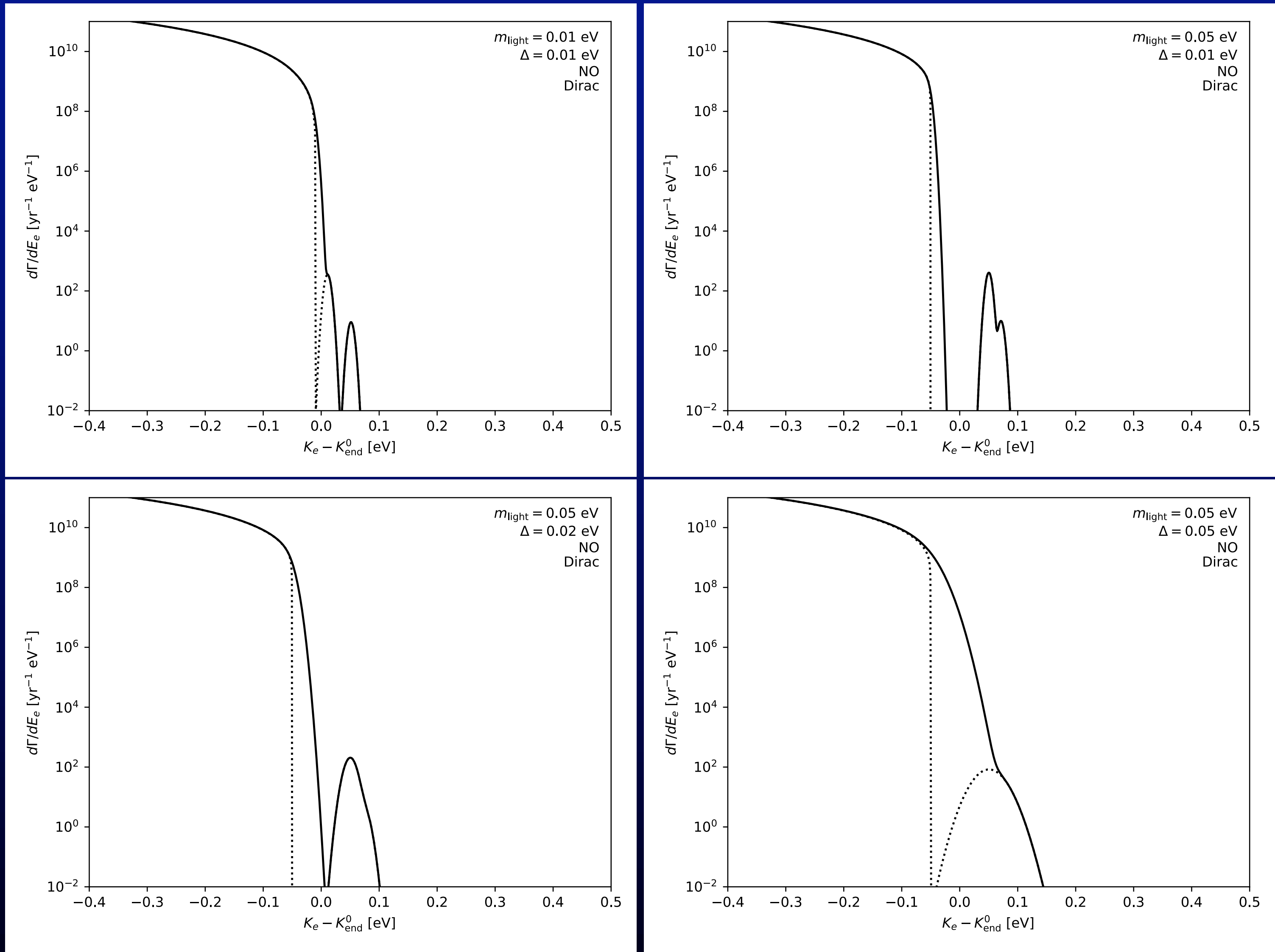


$m_\nu \sim 0.1$ eV

Detection Concept: Neutrino Capture



Challenges: Resolution and Backgrounds

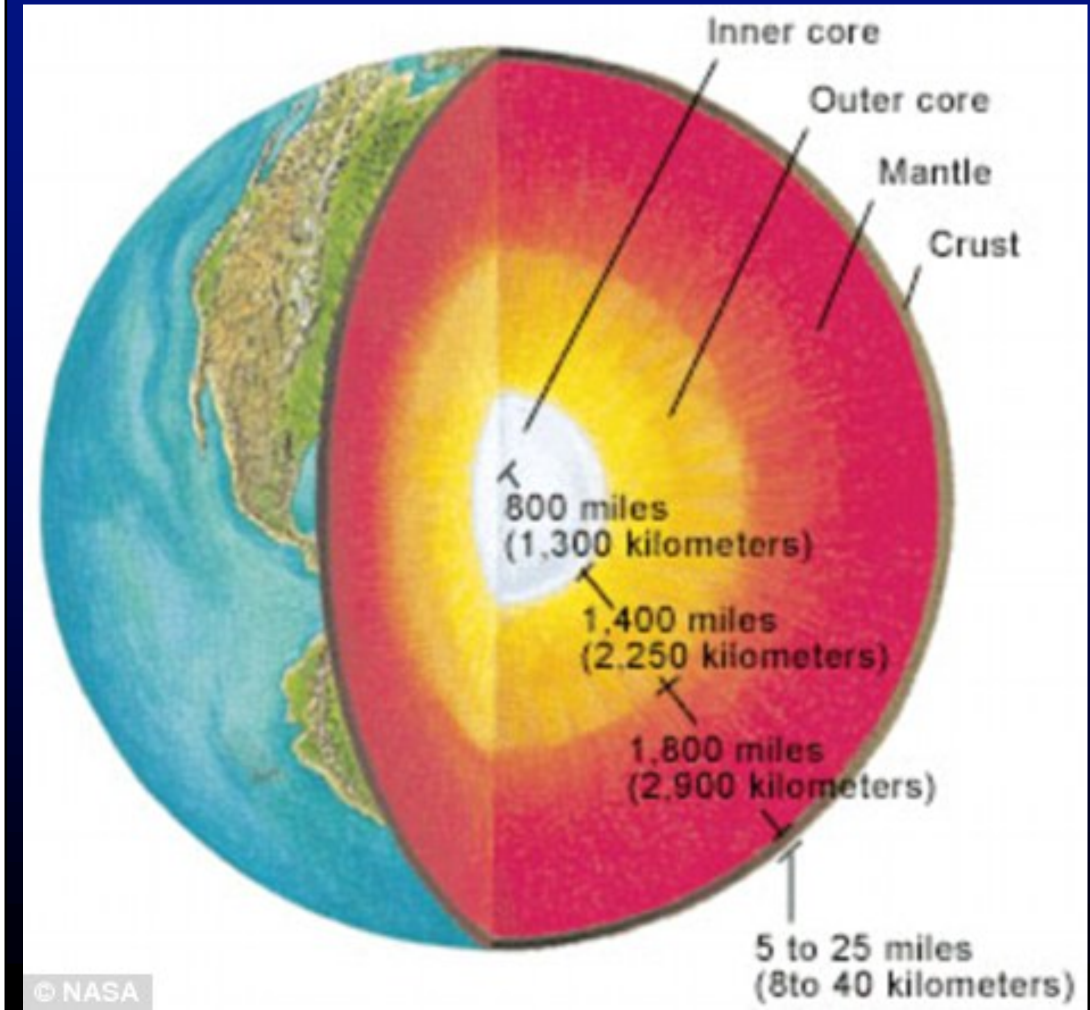


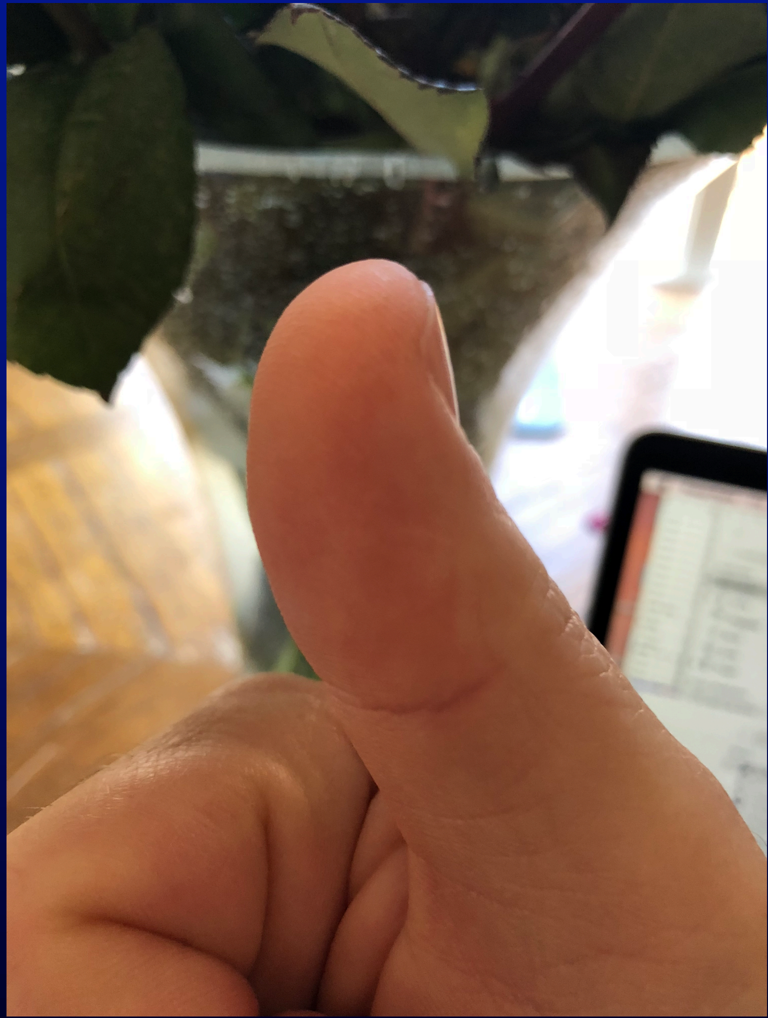
Normal Ordering

High Radio-Purity Carbon

Thumb radioactivity (1 per second → 1 per 100 years)

Graphene fabrication from CO_2 → CH_3OH → CH_4



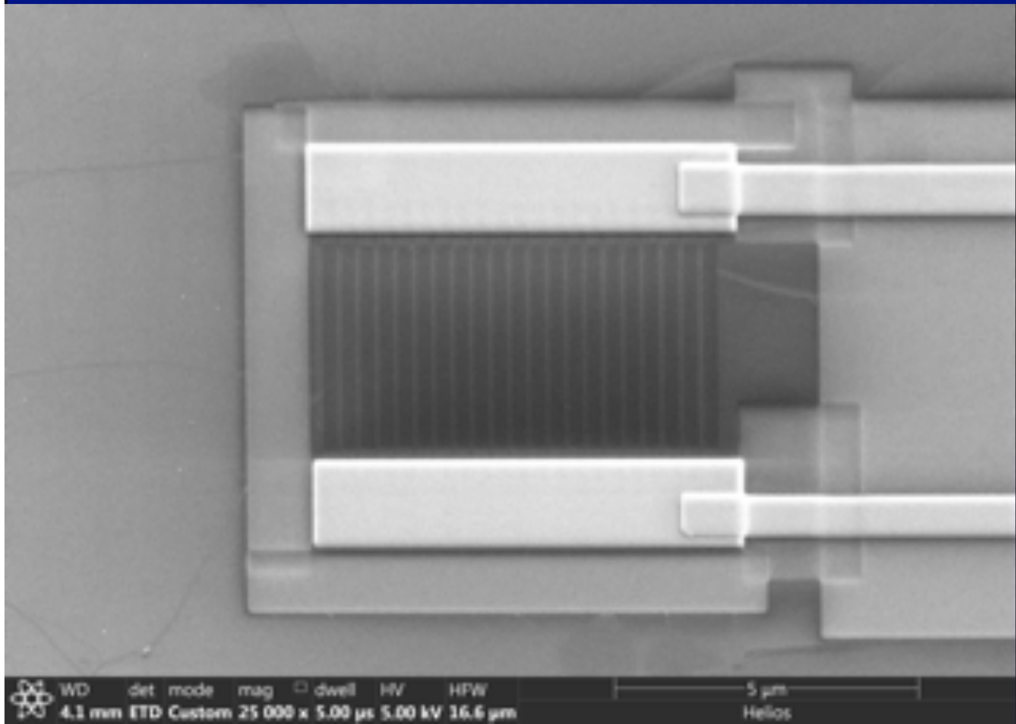


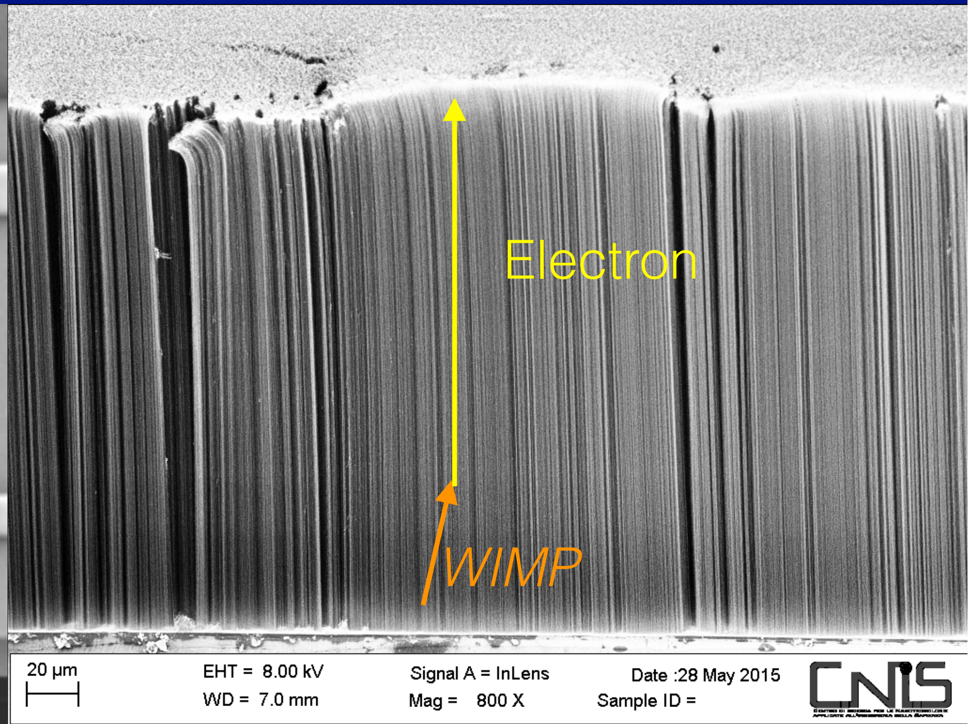
Kinder Morgan Doe Canyon CO_2 facility in southwestern Colorado

Graphene Targets: Two Concepts

PTOLEMY-G^3

PTOLEMY-CNT

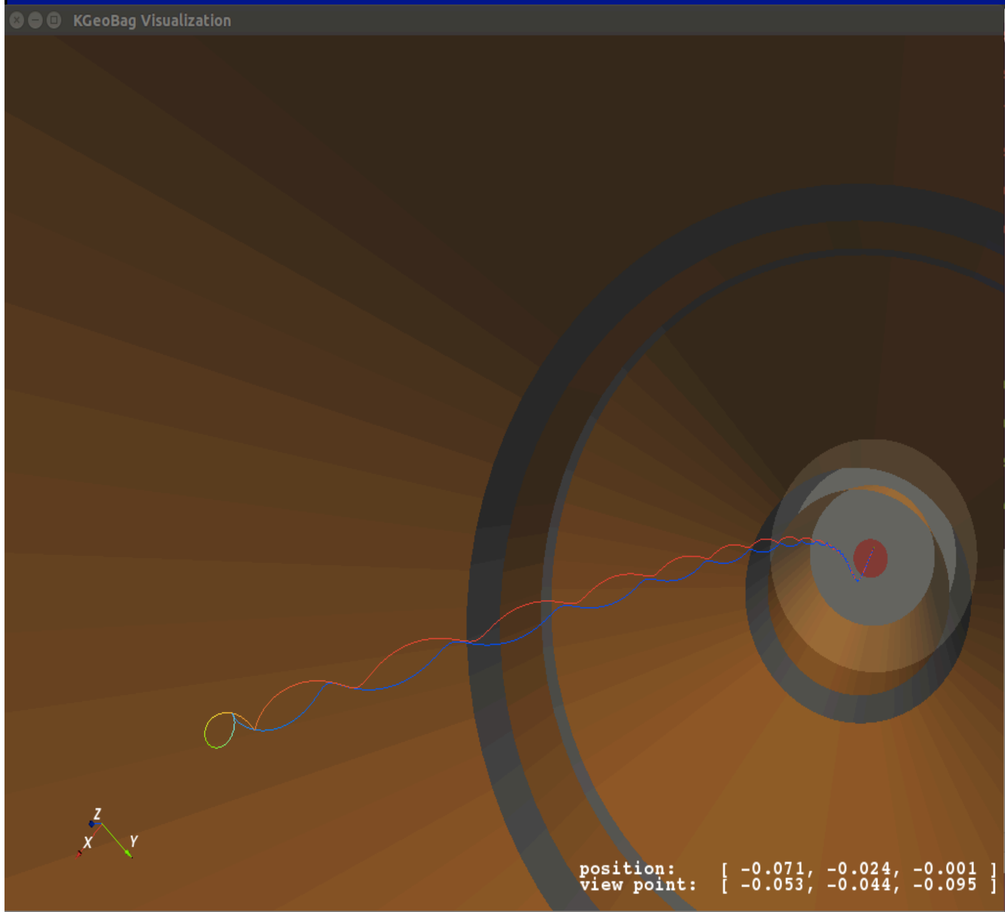


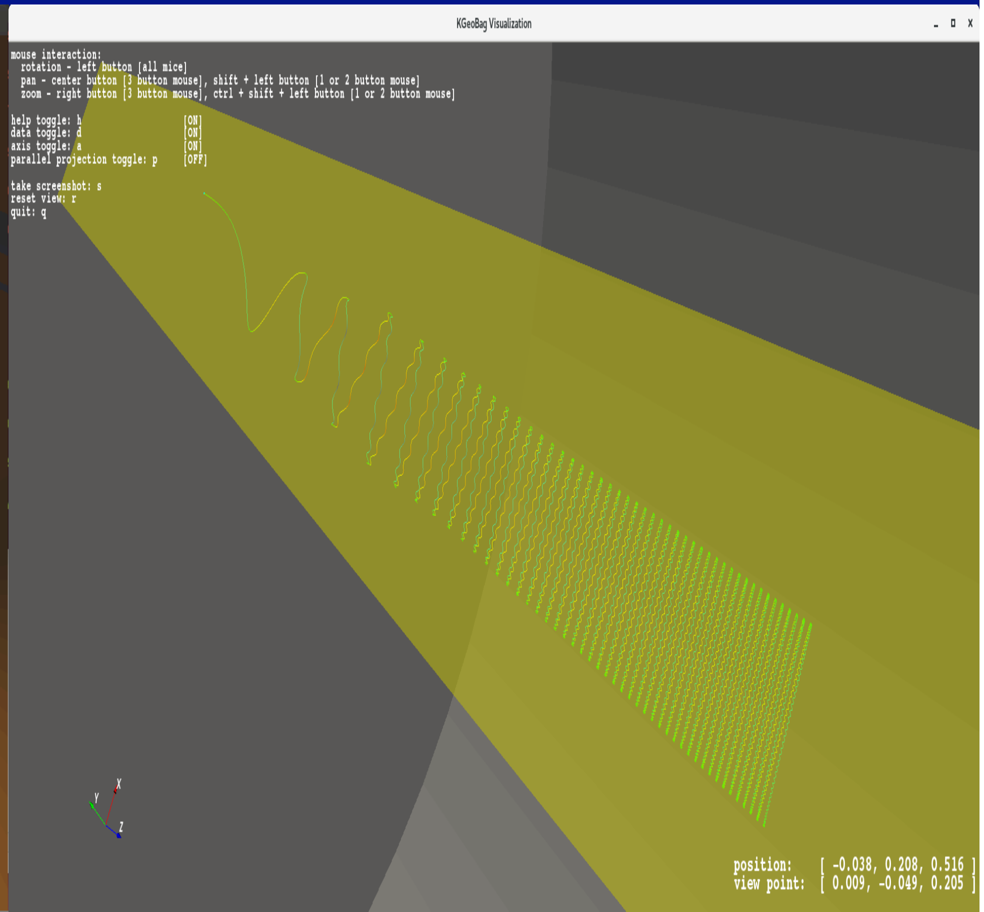


Self-instrumented with G-FETs

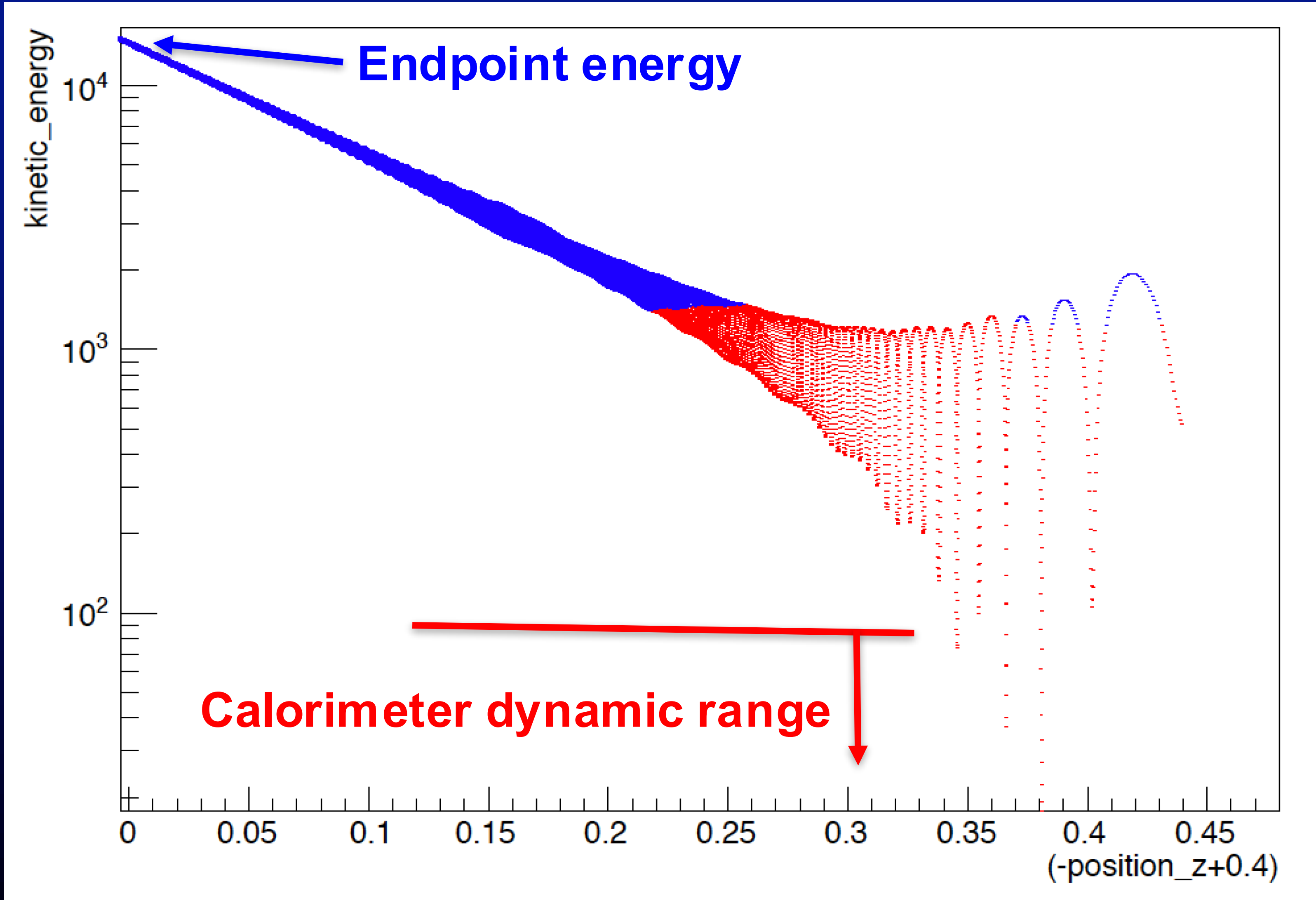
Anisotropy of aligned CNTs

Electromagnetic Telescope Optics



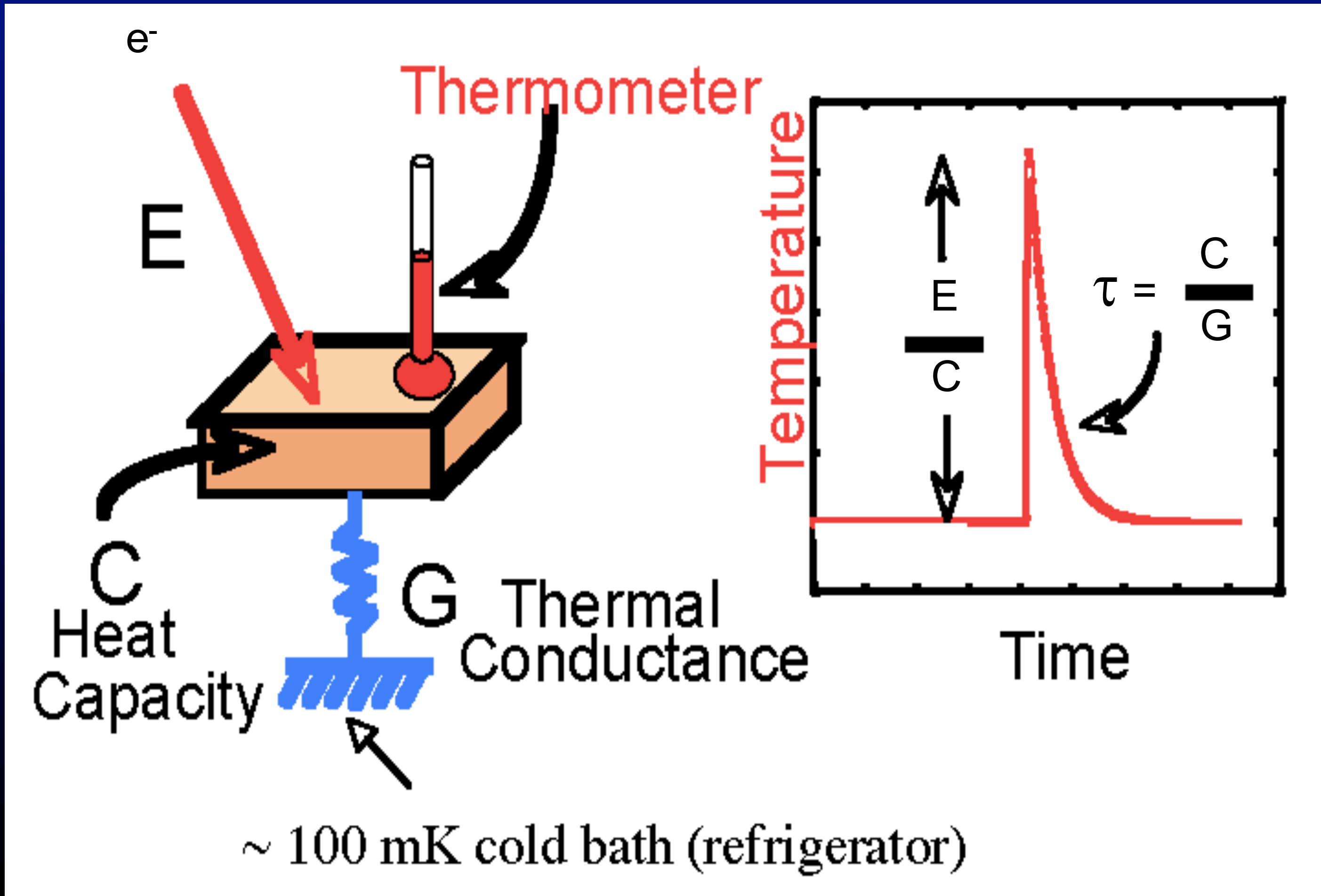


Measurement of Endpoint Energies



Microcalorimetry

- Optimize Transition-Edge Sensors for low energy electron calorimetry with an energy resolution sufficient to resolve the neutrino mass

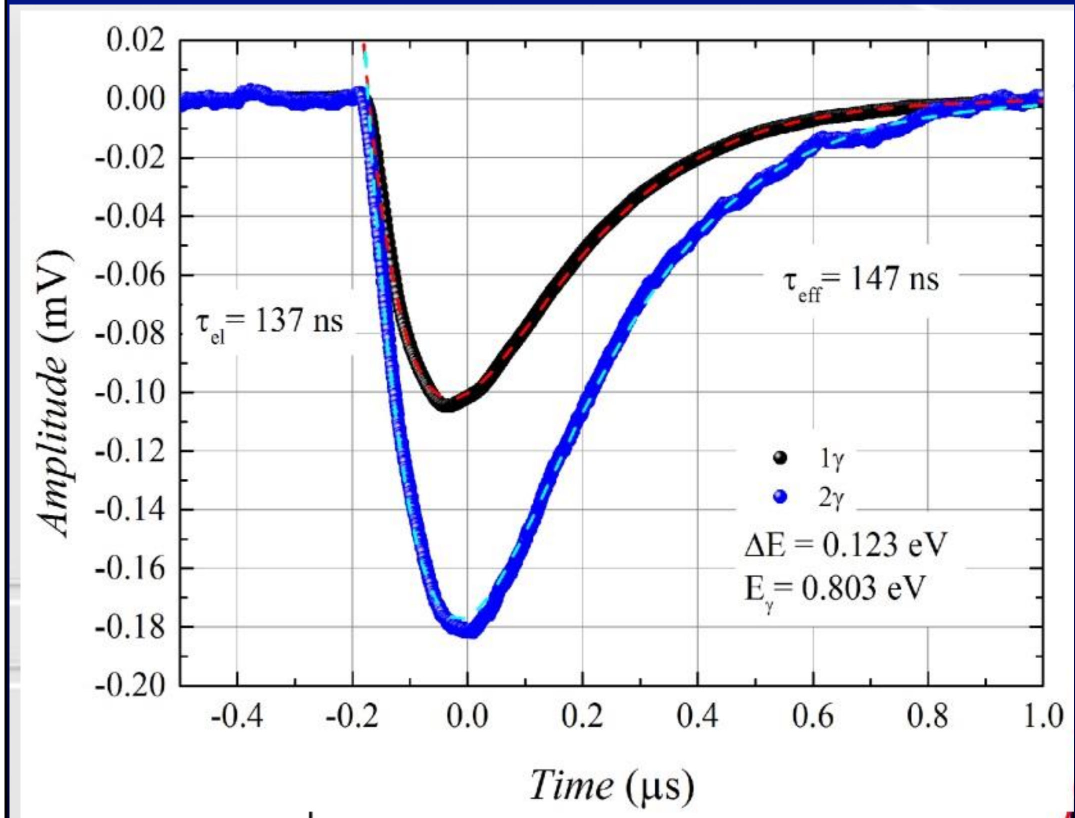


Thin sensors:
~1 eV electron can be stopped with very small C

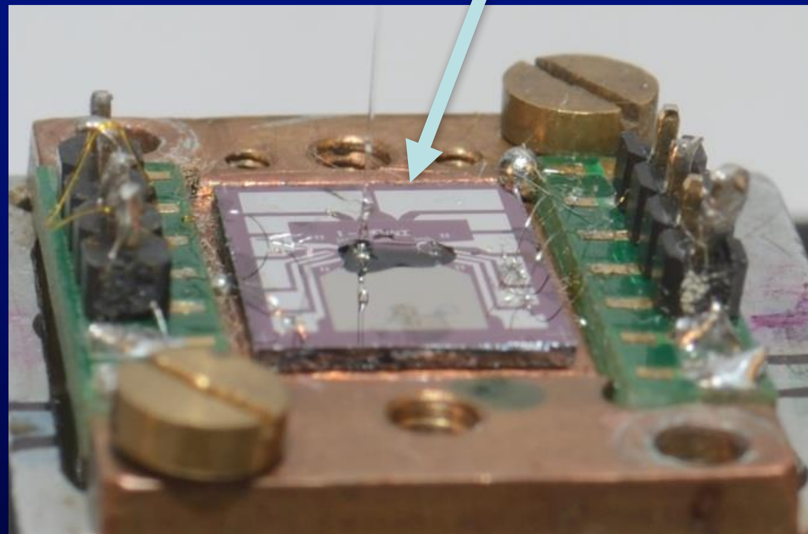
Fast time response:
Time response (τ) also small (<μsec)

Single Infrared Photon Detectors

Results from INRIM (Torino) - Istituto Nazionale di Ricerca Metrologica



Transition-Edge Sensor

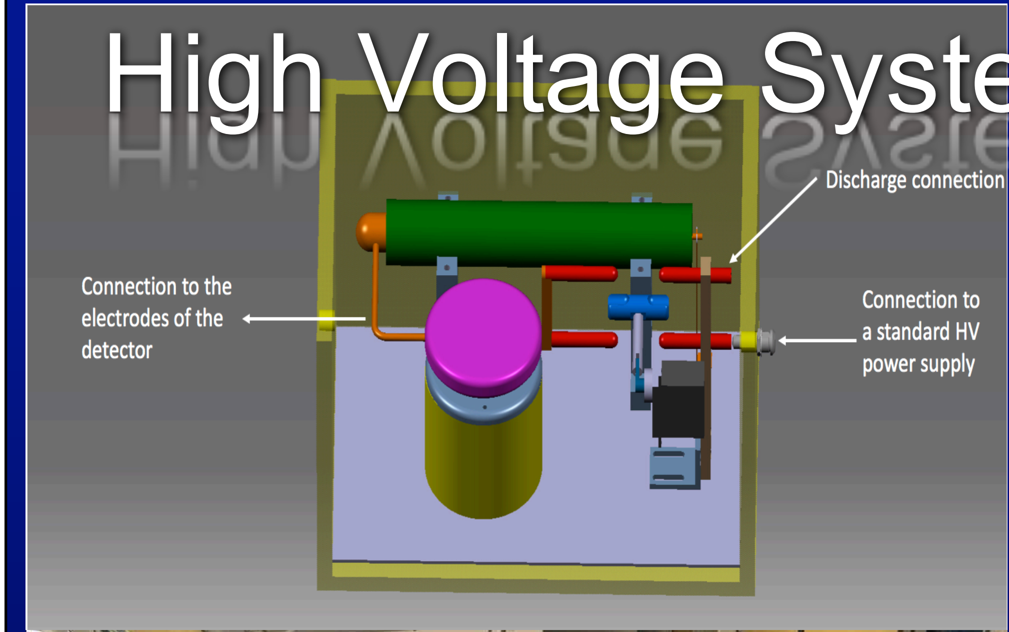


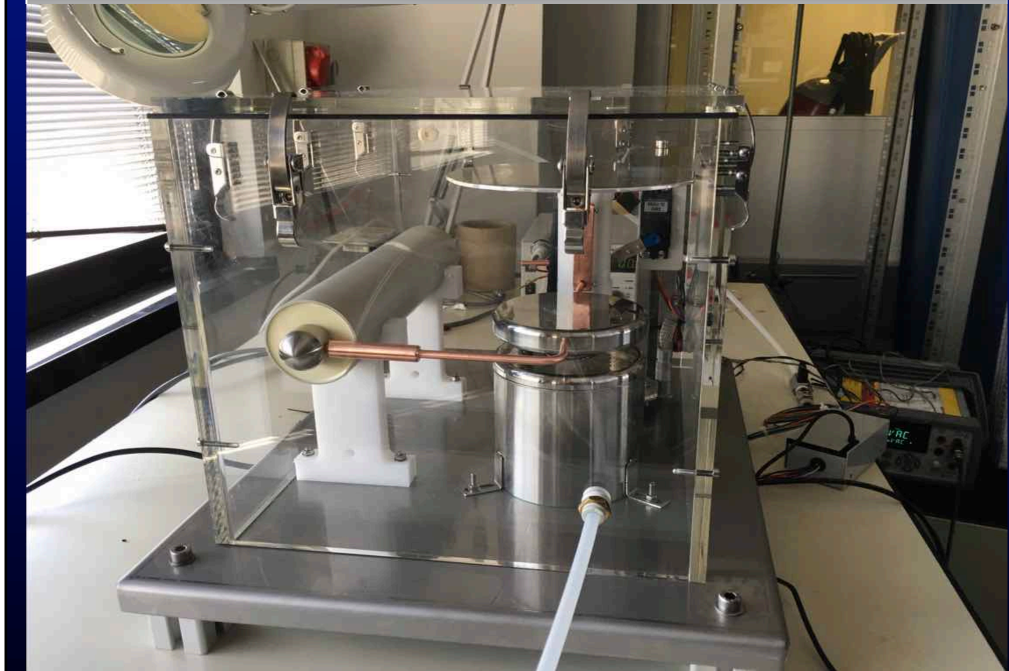
Infrared Photons E=0.8eV

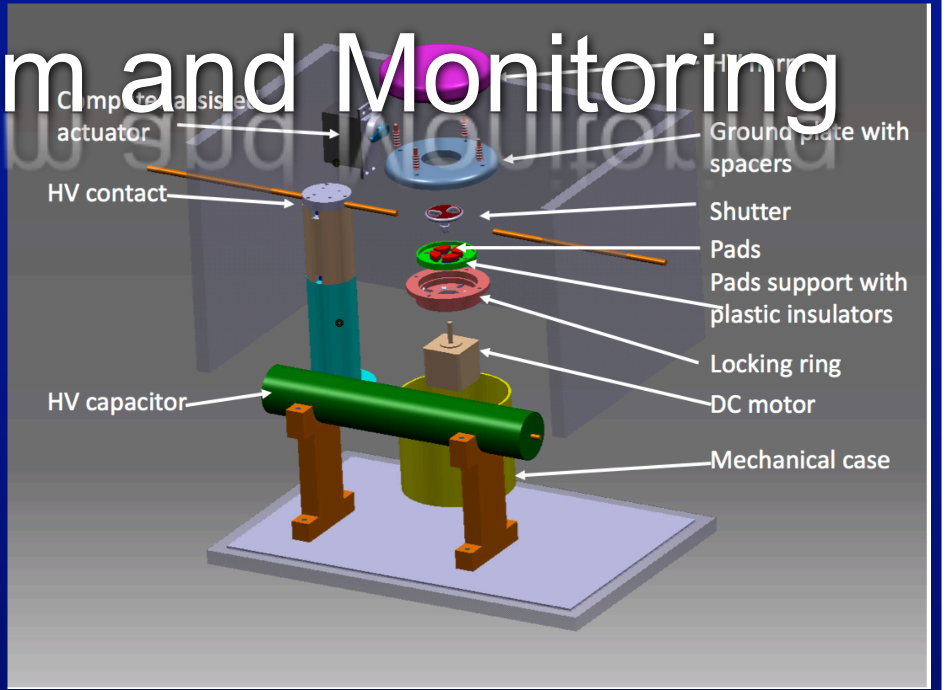
σ_E = 0.05 eV @ 300mK

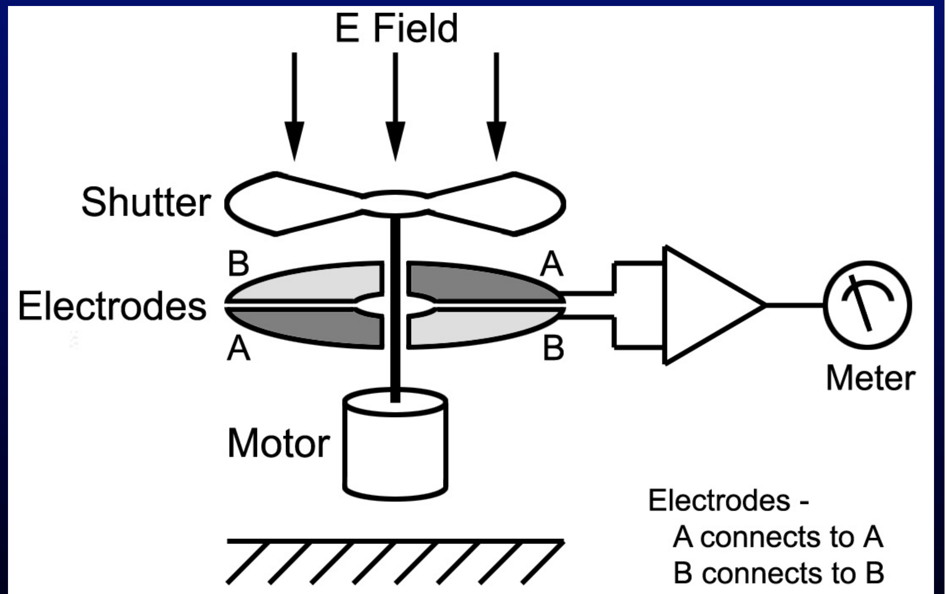
→ Exceeding goals for energy resolution

High Voltage System and Monitoring







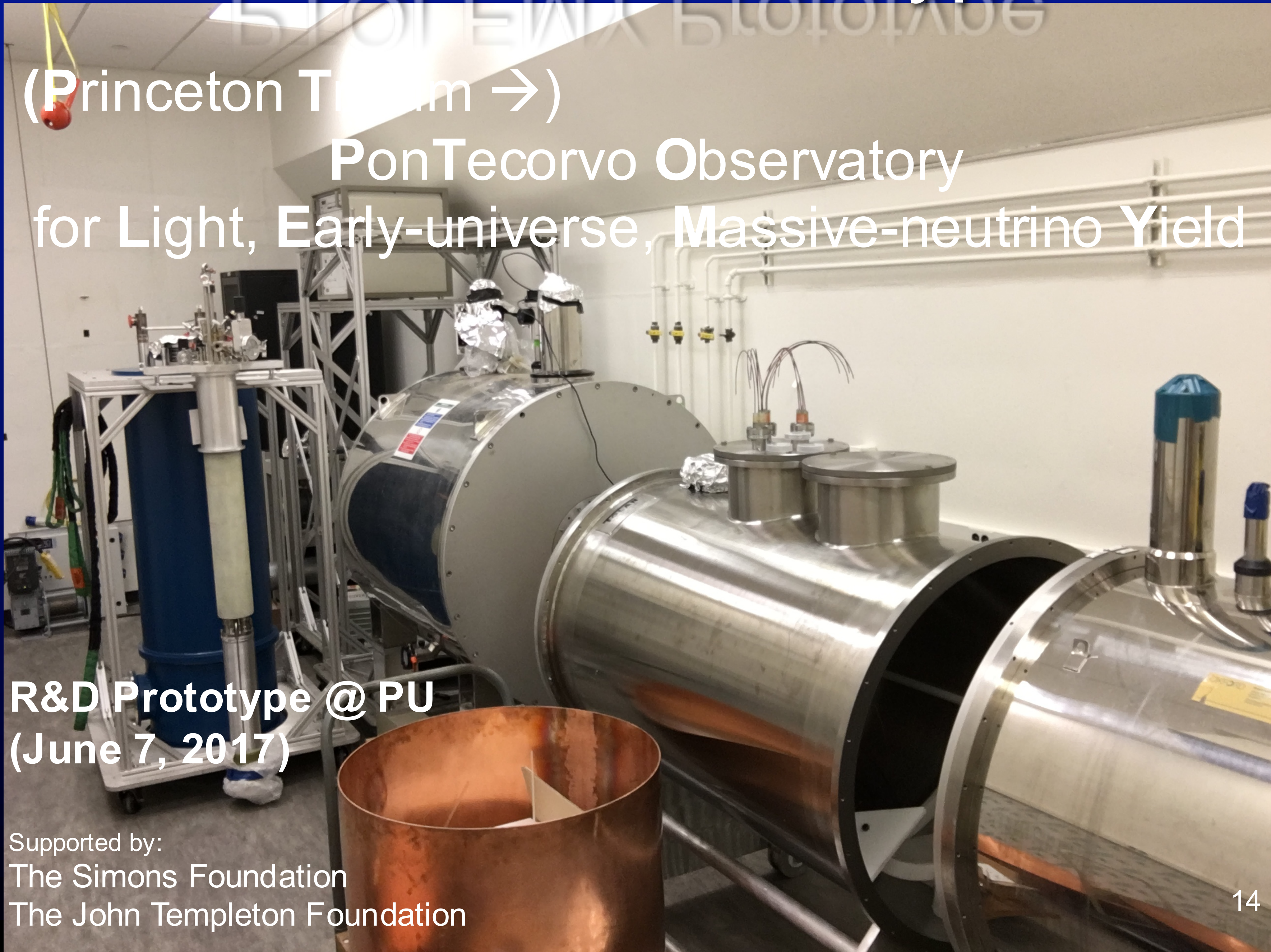


PTOLEMY Prototype

(**P**rinceton **T**ritium →)

Pon**T**ecorvo **O**bservatory

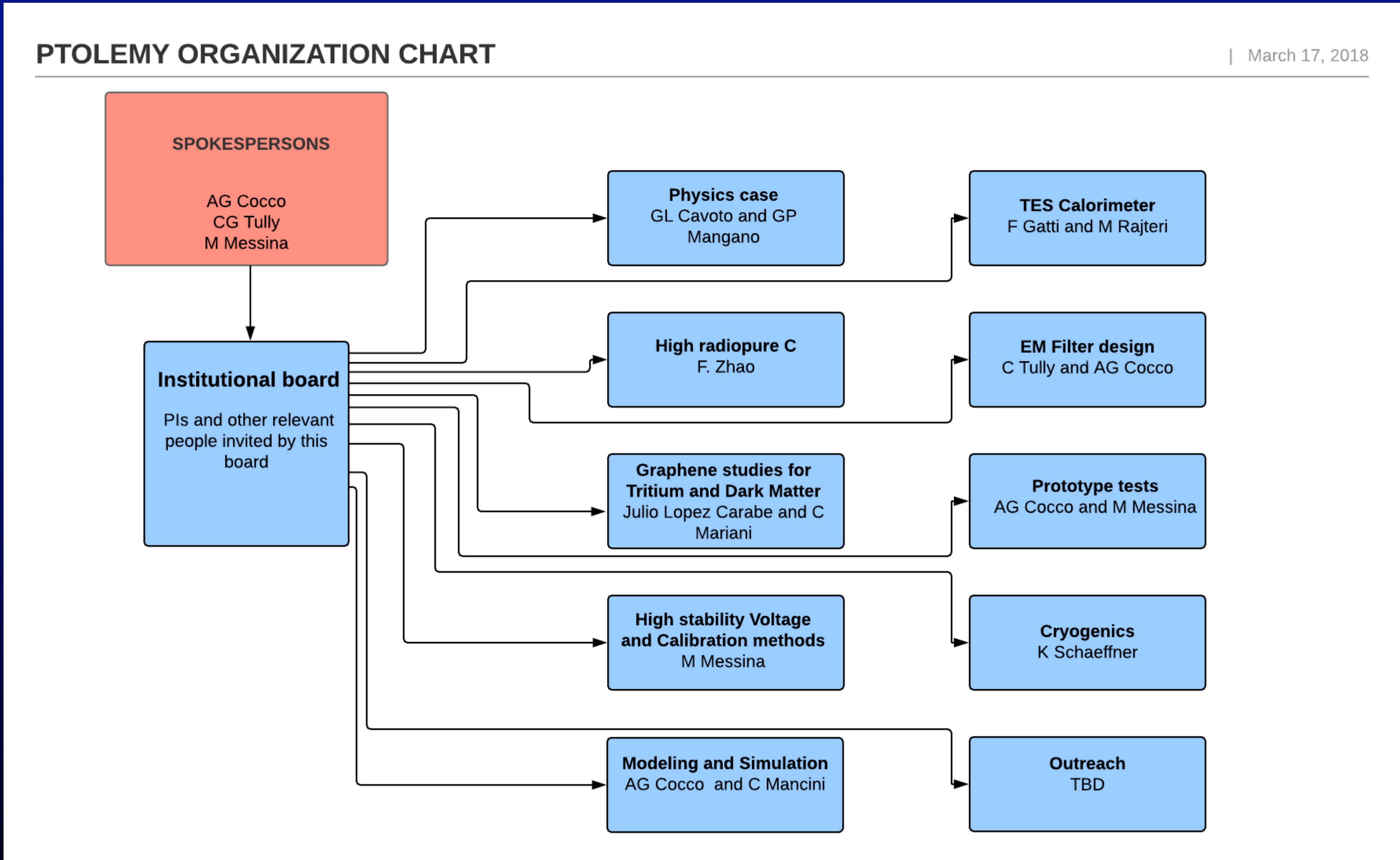
for **L**ight, **E**arly-universe, **M**assive-neutrino **Y**ield



R&D Prototype @ PU
(June 7, 2017)

Supported by:
The Simons Foundation
The John Templeton Foundation

PTOLEMY Working Groups



PTOLEMY Collaboration

PPPL Princeton Plasma Physics Laboratory
Princeton University
KICP Kavli Institute for Cosmological Physics at The University of Chicago
Argonne National Laboratory
Berkeley University of California
Berkeley Lab Lawrence Berkeley National Laboratory
Politécnica
IFIC Institut de Física Corpuscular
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
Stockholm University
Uppsala Universitet
Nikhef
Università degli Studi di Genova
INRiM Istituto Nazionale di Ricerca Metrologica
Sapienza Università di Roma
Università degli Studi di Milano Bicocca
Università di Pisa
INFN
GSSI Gran Sasso Science Institute
Università degli Studi di Napoli Federico II
האוניברסיטה העברית בירושלים The Hebrew University of Jerusalem
جامعة نيويورك أبوظبي NYU Abu Dhabi

טלסקופ ניטרינים קוסמיים

Telescopio di neutrini cosmologici

Kosmische neutrinotelescoop

Telescopio de neutrinos cósmicos

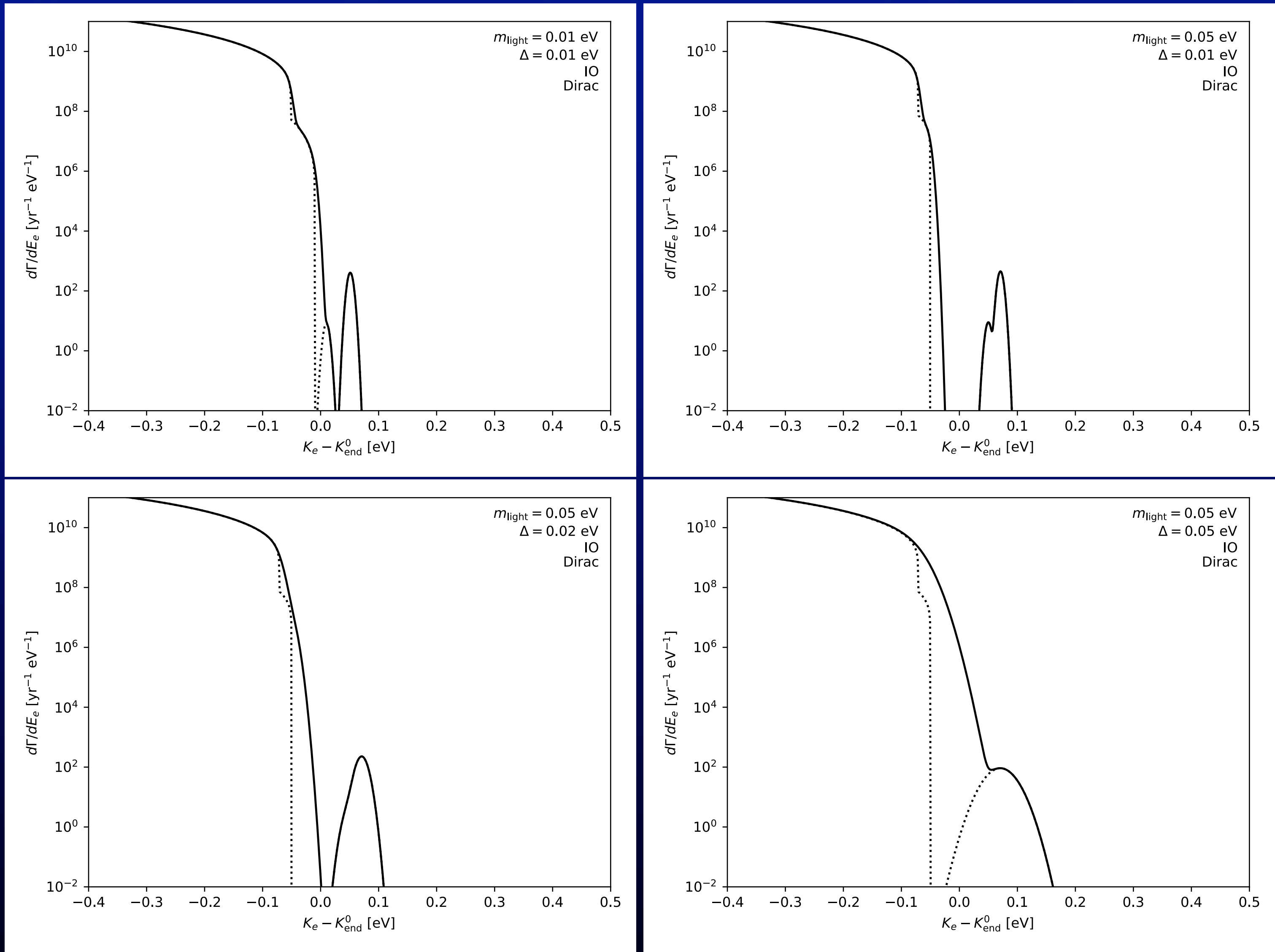
Kosmisk neutrinoteleskop

تلسكوب الأشعة الكونية (نيوترينو)

Cosmic neutrino telescope

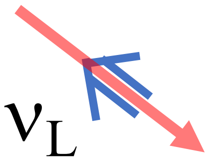
Commentary

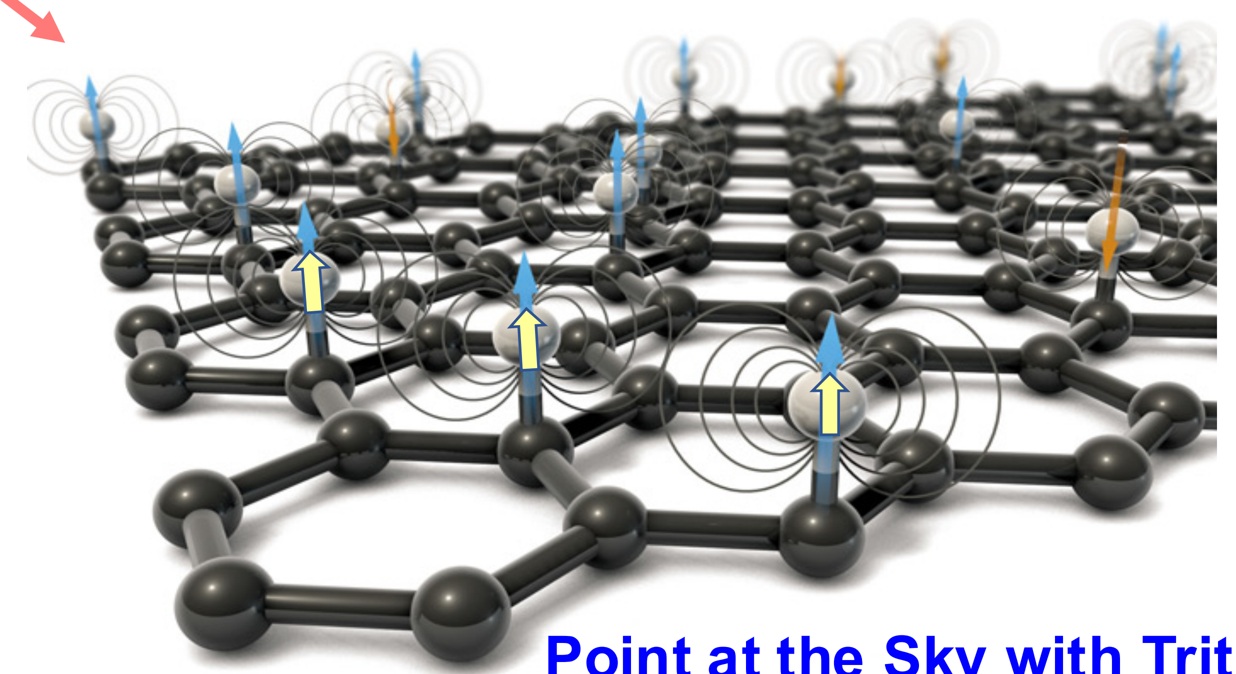
Challenges: Resolution and Backgrounds



Inverted Ordering

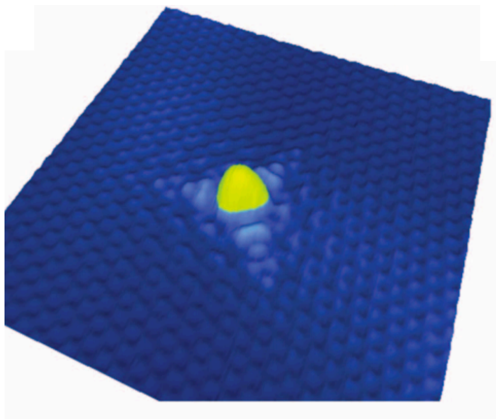
Polarized Tritium Target

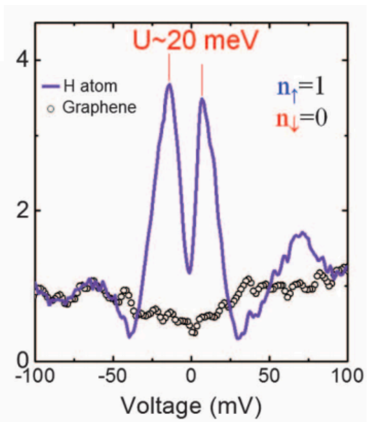




Lisanti, Safdi, CGT, 2014.

Point at the Sky with Tritium Nuclear Spin





Hydrogen doping on graphene reveals magnetism

Gonzalez-Herrero, H. *et al.* Atomic-scale control of graphene magnetism by using hydrogen atoms. *Science (80).* **352,** 437–441 (2016).

Polarized ^{3}H Decay

$$\frac{d^5\omega}{dE_e d\Omega_e d\Omega_\nu} = \frac{G_F^2}{(2\pi)^5} p_e E_e (\Delta m - E_e)^2 \xi [1 + a\boldsymbol{\beta}\cdot\hat{\boldsymbol{\nu}} + \hat{\mathbf{P}}\cdot(A\boldsymbol{\beta} + B\hat{\boldsymbol{\nu}})] \ , \tag{1}$$

where G_F is the Fermi constant, Δm is the difference between the ^{3}H and ^{3}He mass, p_e (E_e) is the electron impulse (energy), $\boldsymbol{\beta}$ ($\boldsymbol{\nu}$) is the electron (neutrino) three-velocity, and $\hat{\mathbf{P}}$ is the ^{3}H polarization versor. The quantities ξ, a, A and B contain the nuclear matrix elements, and and can be written in terms of the "standard" Fermi (F) and Gamow-Teller (GT) matrix elements as

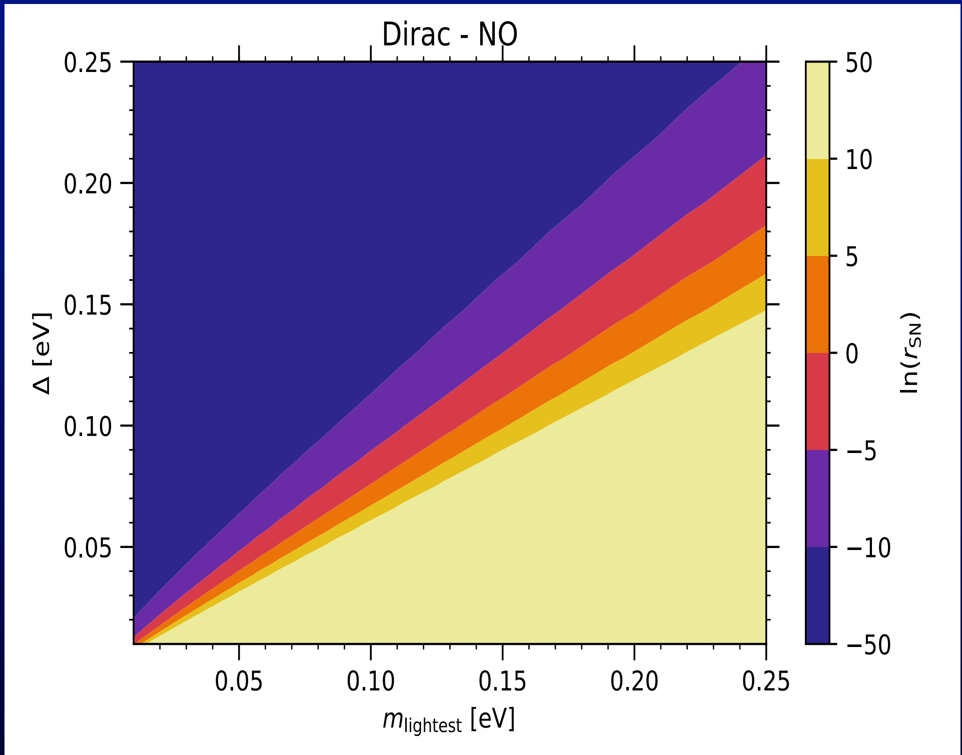
$$\xi = |F|^2 + g_A^2|GT|^2 \ , \tag{2}$$

$$a\xi = |F|^2 - \frac{g_A^2}{3}|GT|^2 \ , \tag{3}$$

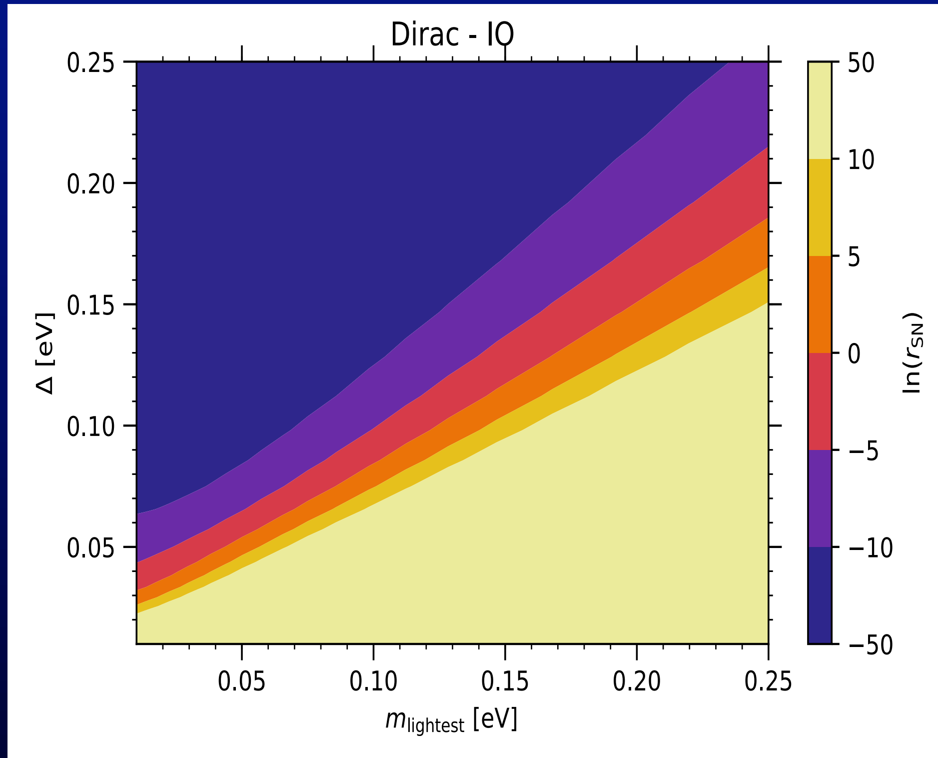
$$A\xi = -\frac{2}{3}g_A^2|GT|^2 + \frac{2}{\sqrt{3}}|GT||F| \ , \tag{4}$$

$$B\xi = +\frac{2}{3}g_A^2|GT|^2 + \frac{2}{\sqrt{3}}|GT||F| \ . \tag{5}$$

CNB Signal-to-Noise

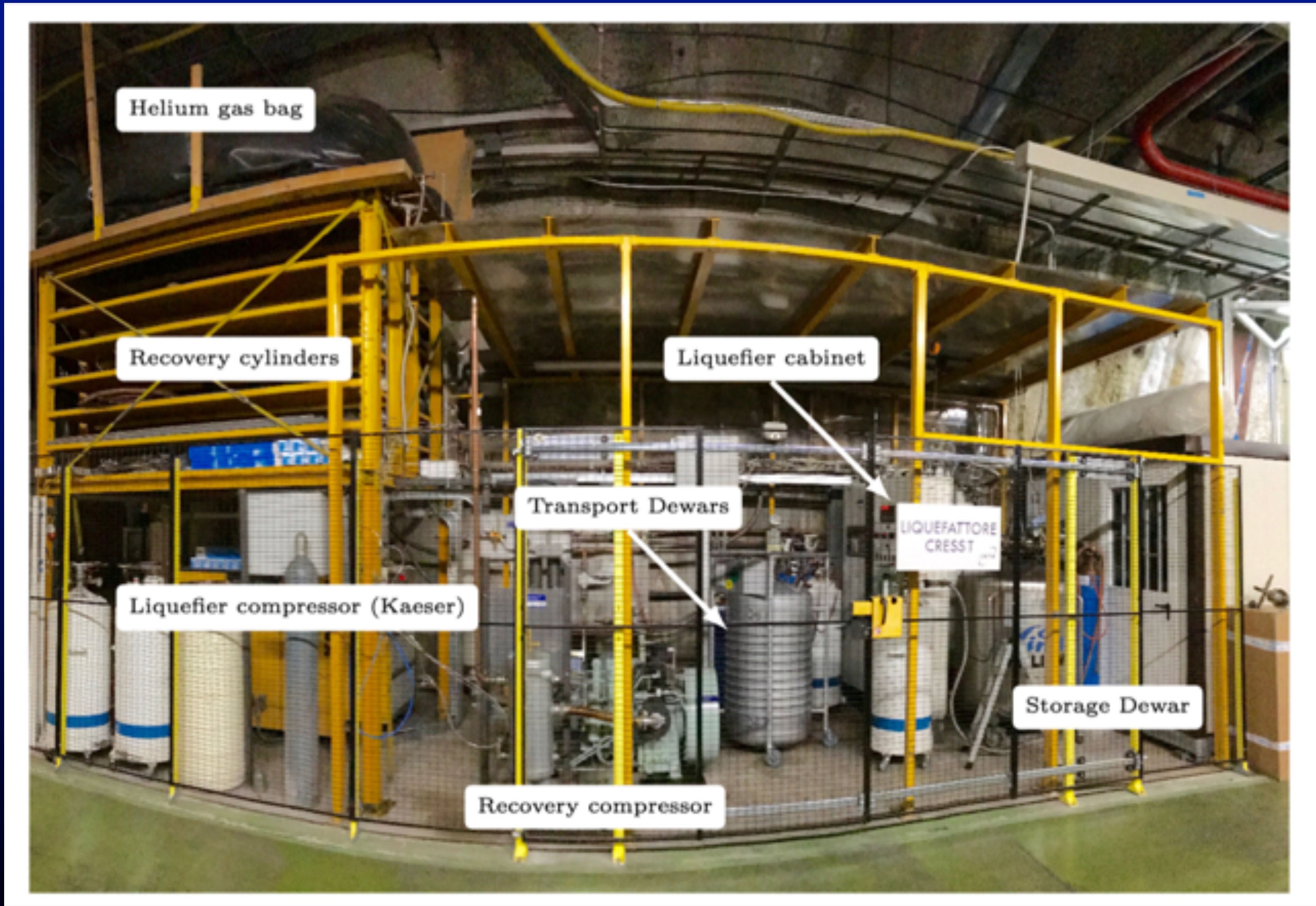


Normal Ordering

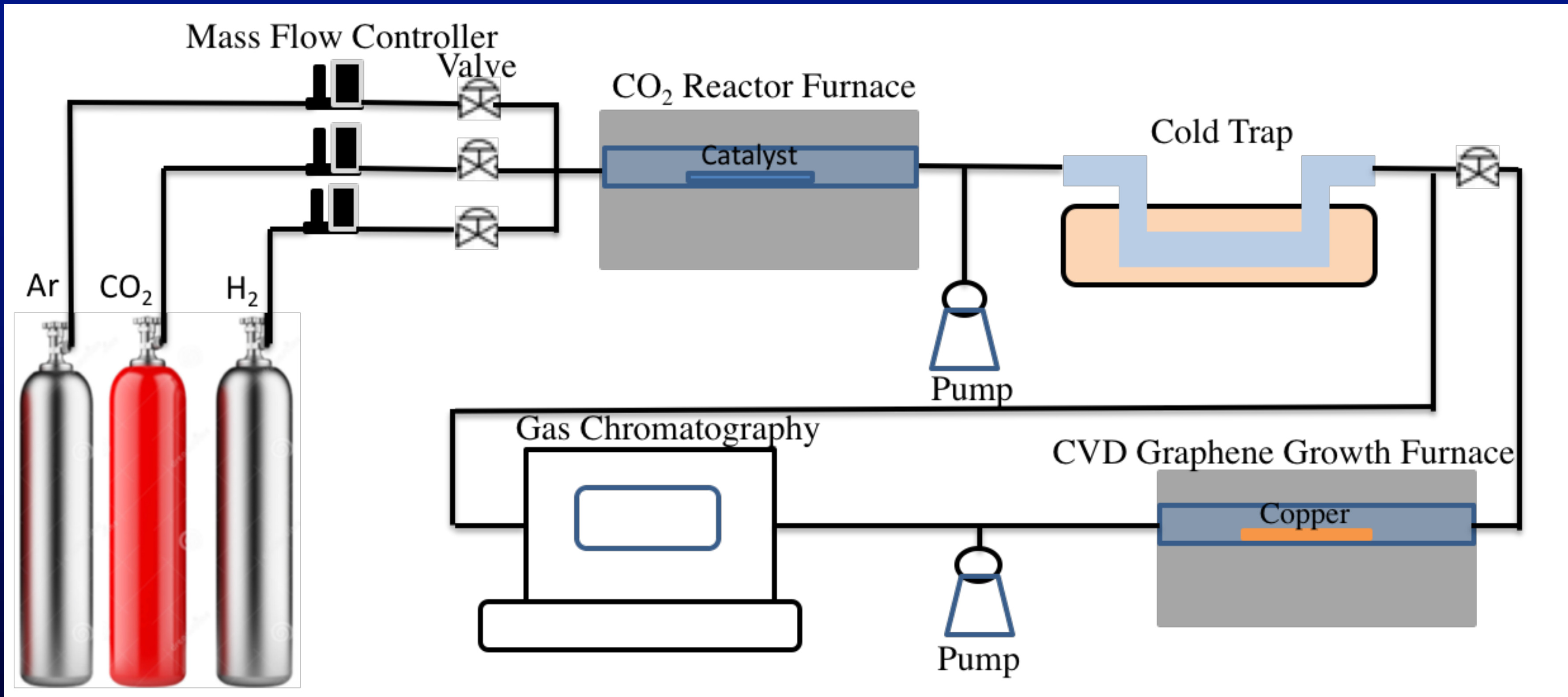


Inverted Ordering

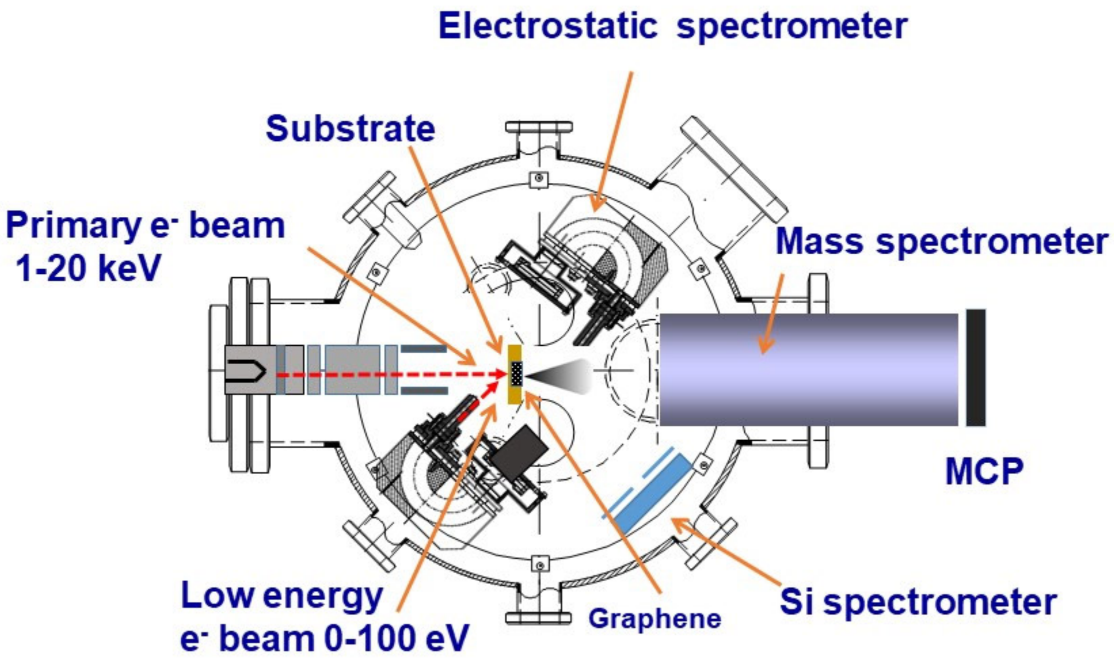
Cryogenic System of CRESST



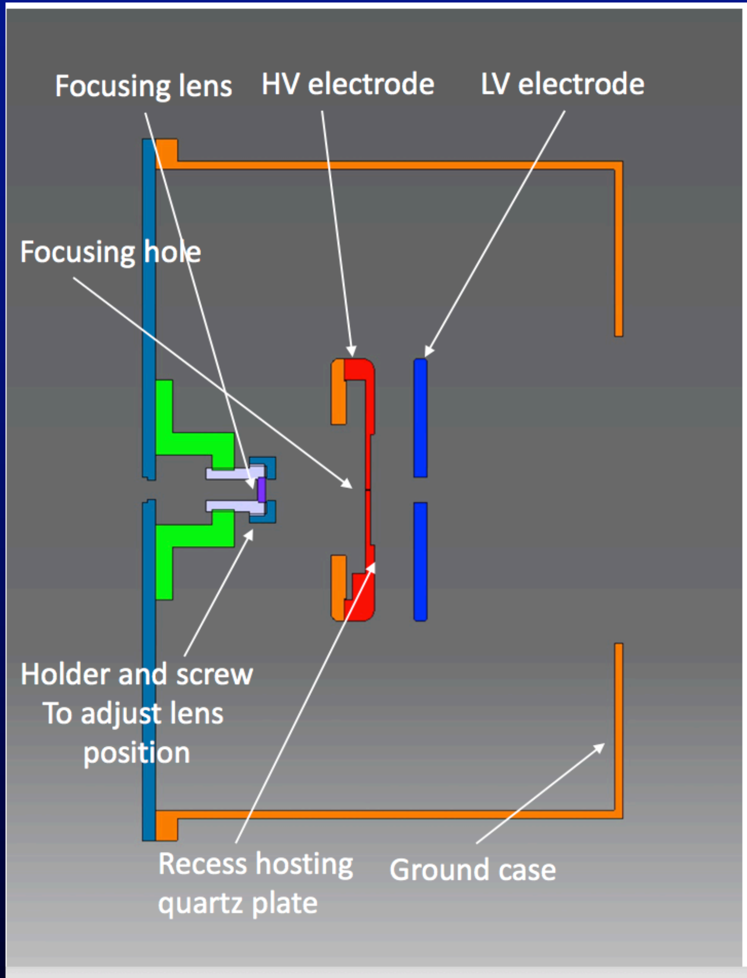
High Radio-Pure ^{12}C ($CO_2 \rightarrow CH_4$)

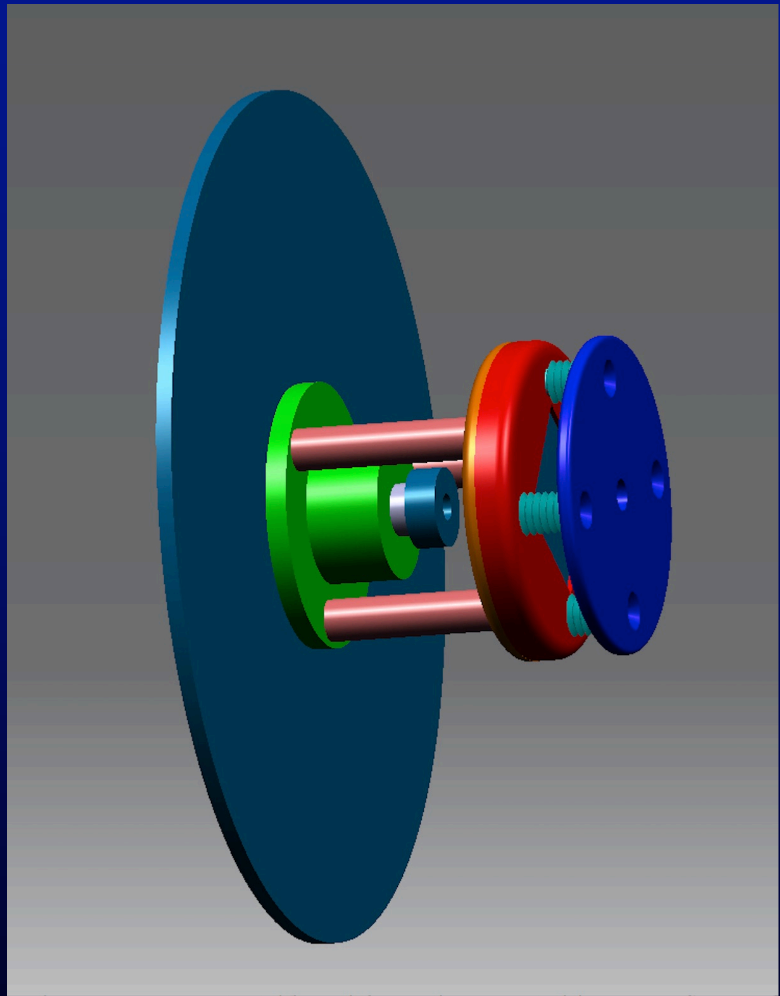


Electron-Graphene Interaction Chamber



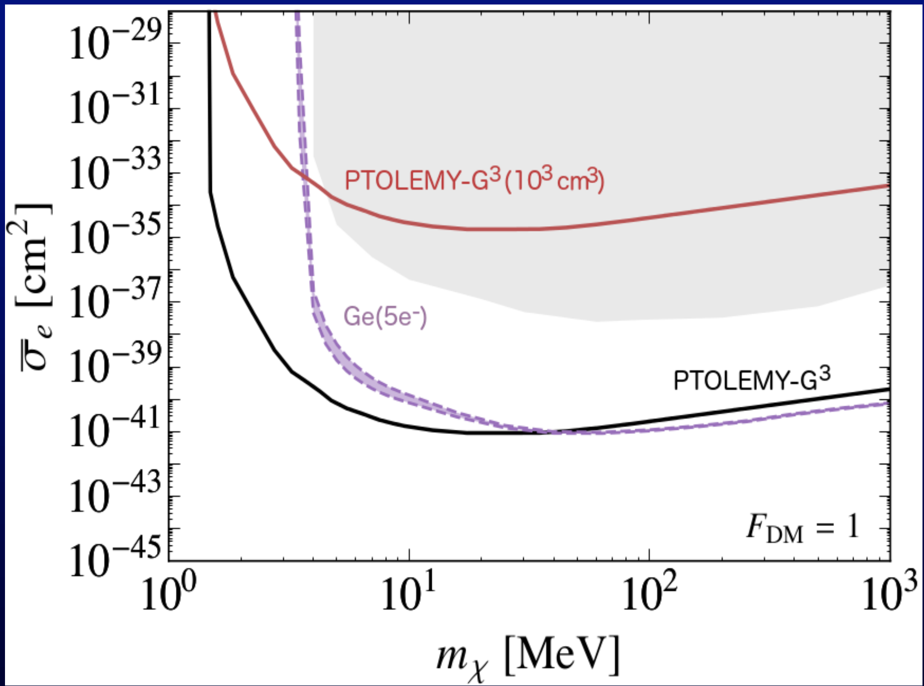
Electron Gun





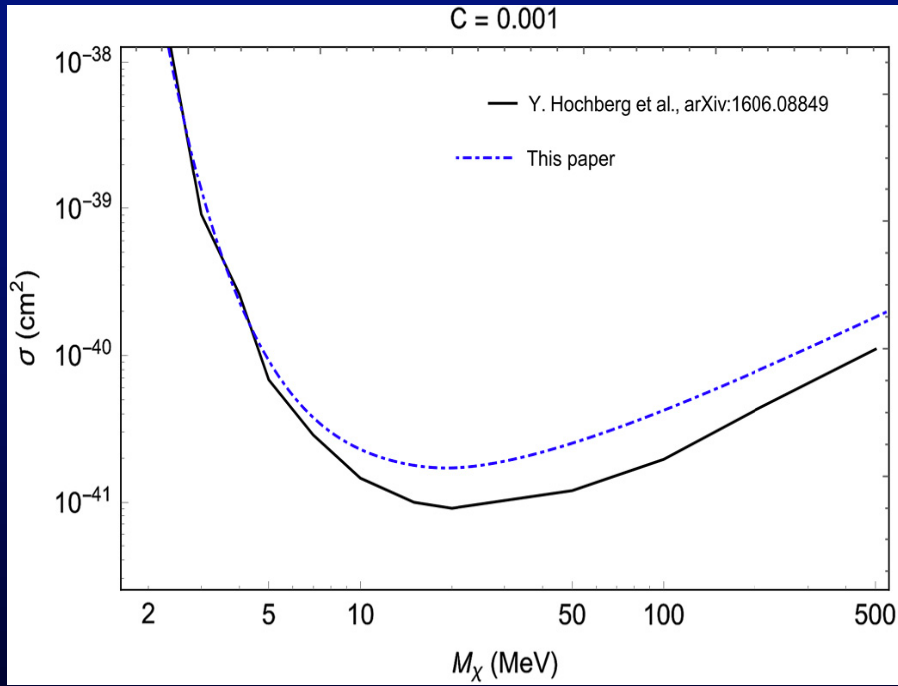
Direction Detection MeV Dark Matter Searches

PTOLEMY-G^3



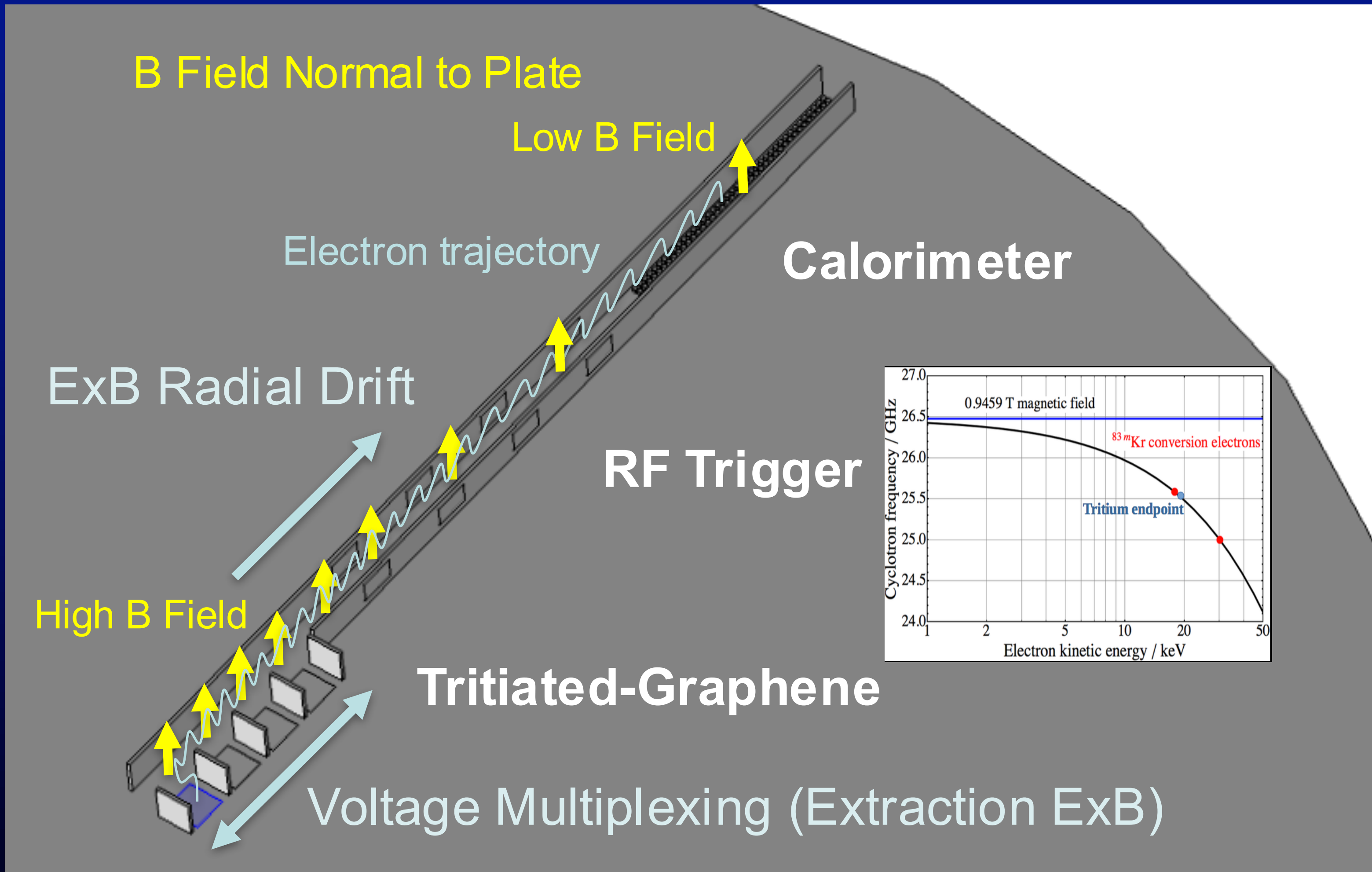
Self-instrumented with G-FETs

PTOLEMY-CNT

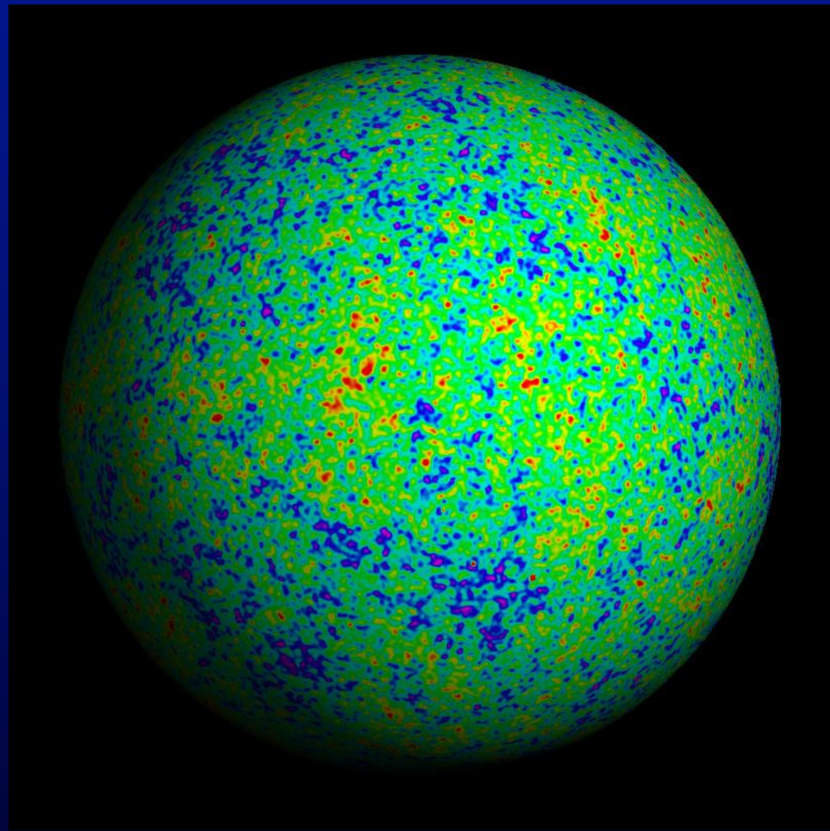


Anisotropy of aligned CNTs

Scalable Underground Design



Celestial Globes

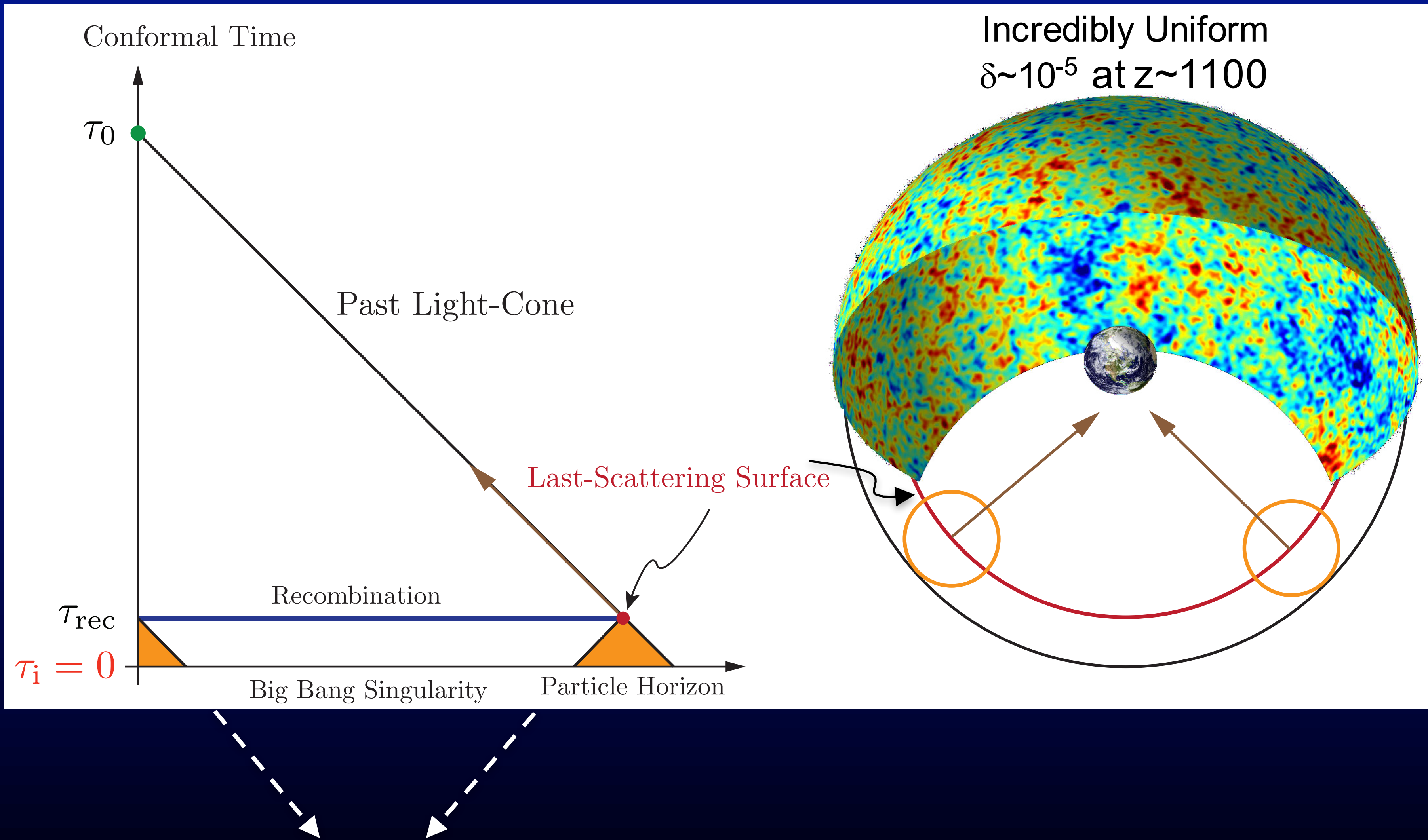


Adiabatic Density Anisotropies $\delta \sim 10^{-5}$
at z~1100

Johann Schöner, c.1534

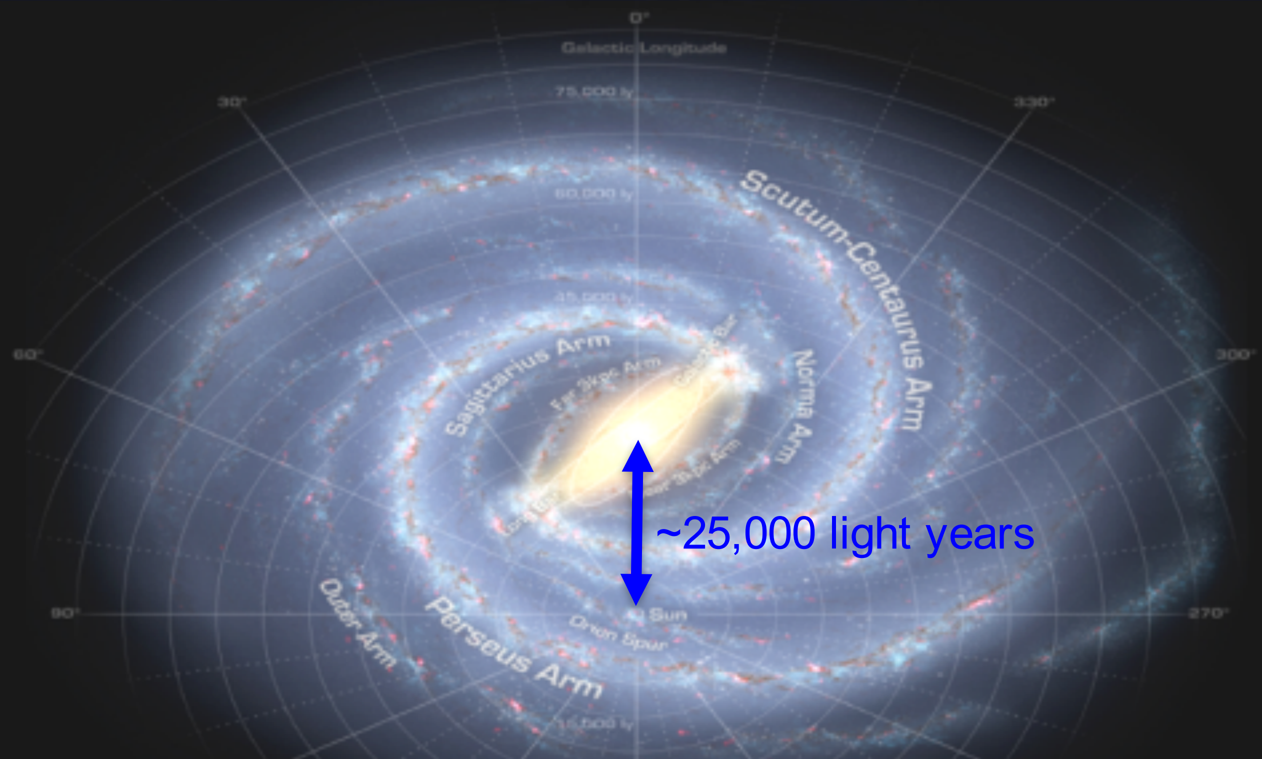
WMAP, c.2009

Big Bang Cosmology



Common Past?

Our Home in the Universe



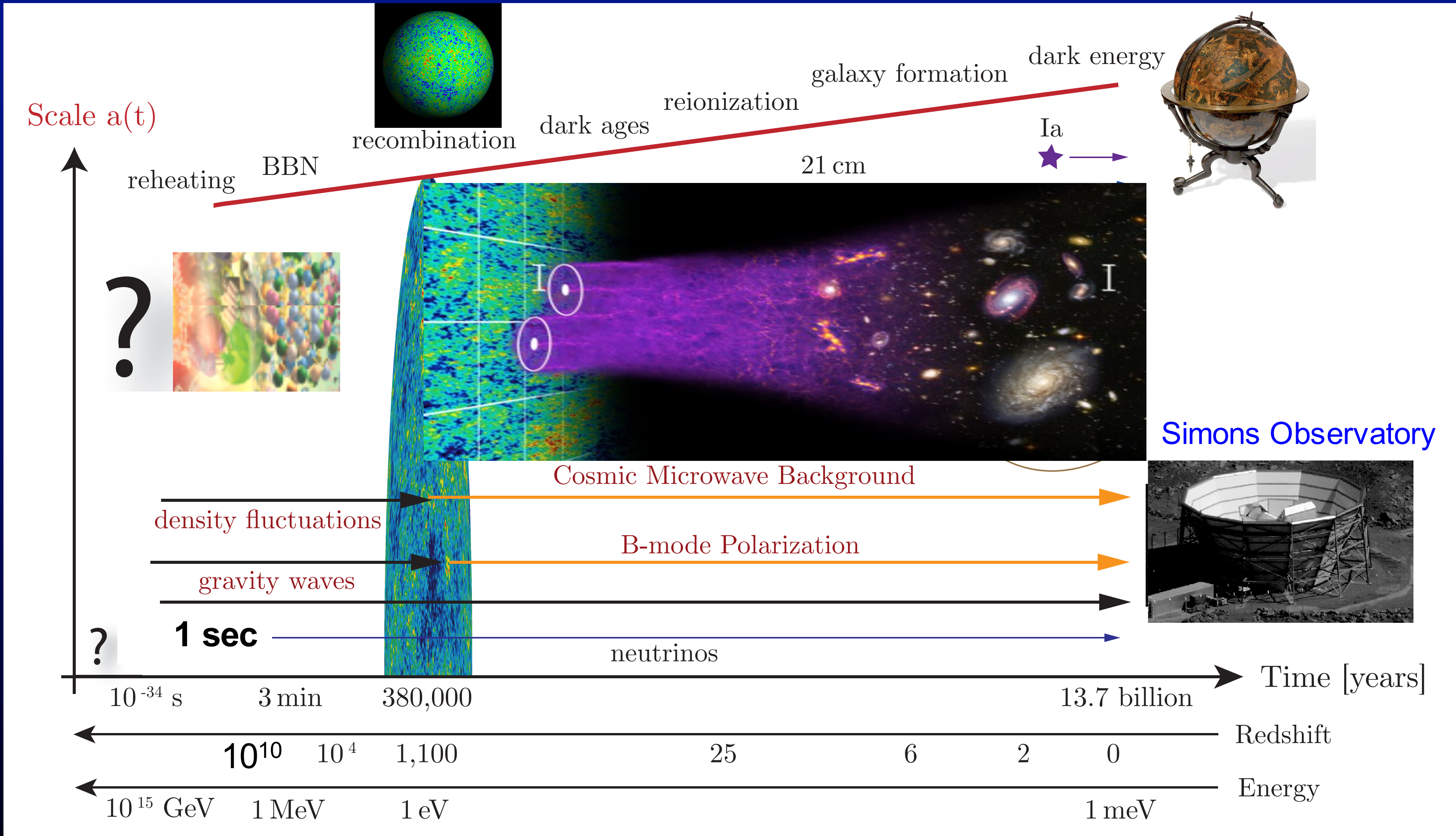
Ostriker, J.P. & Peebles, P.J.E. **1973**, *Ap. J.* 186, 467.

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical *N*-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \simeq 0.14$ has been found by a variety of methods.

Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

Subject headings: galactic structure — stellar dynamics

Origin of Large Scale Structure



Baumann
(TASI 2012)

Expanding Universe

Expansion rate of the Universe: $\dot{a}$

→ Kinetic Energy $\propto \dot{a}^2$

Energy density of the Universe:

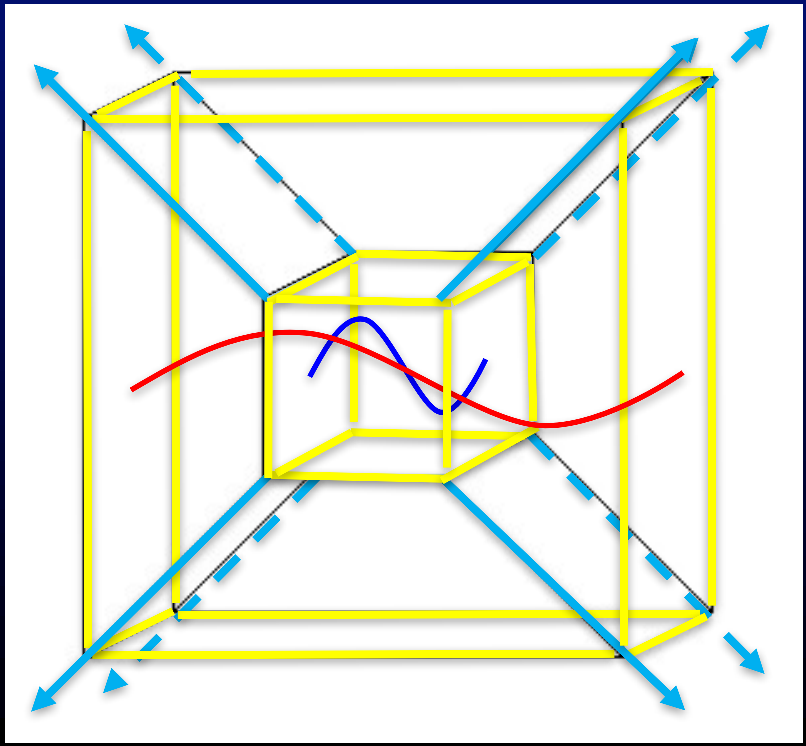
→ Potential Energy $\propto \rho$

$\rho_{matter} \propto 1/a^3$

sum from all matter, radiation and vacuum energy

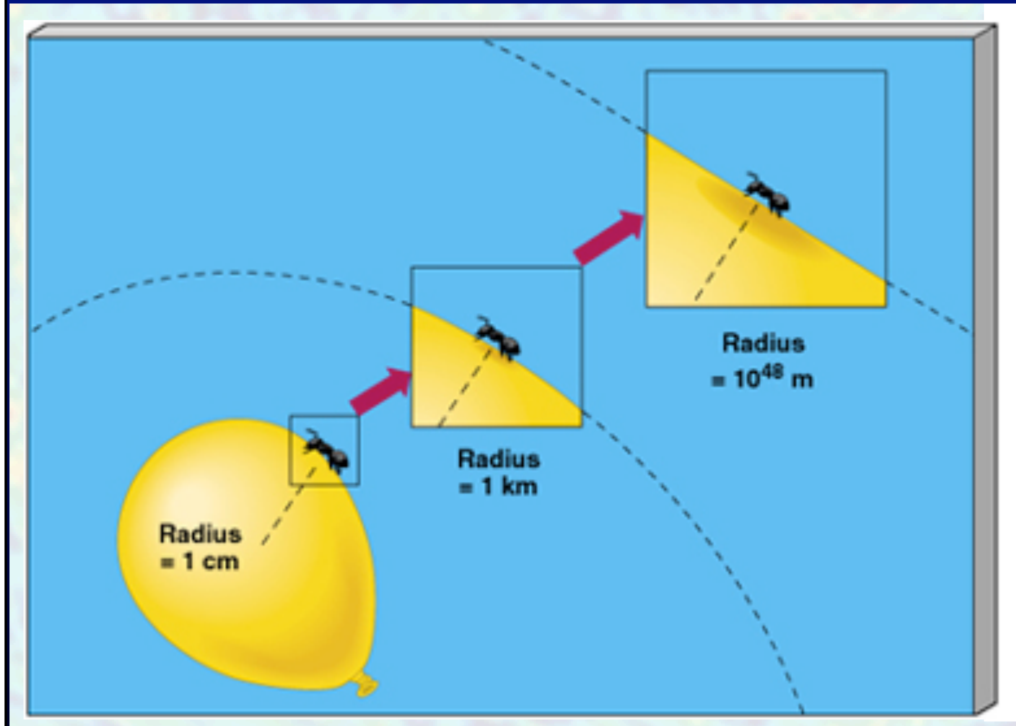
$\rho_{radiation} \propto 1/a^4$

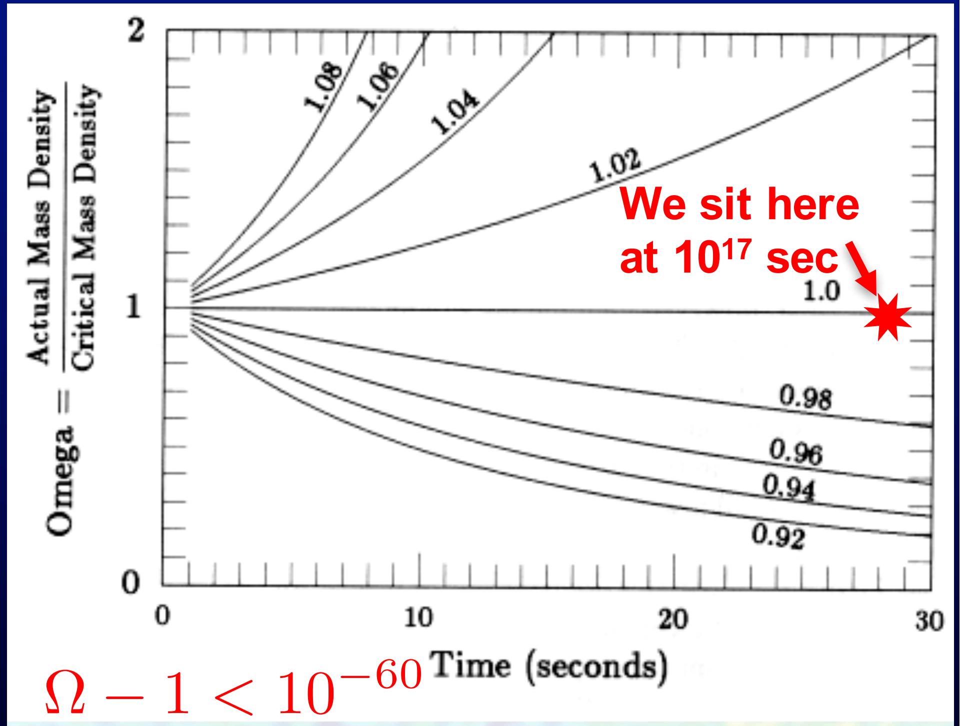
$\rho_{\Lambda} \propto$ constant



Balance of Kinetic and Potential Energy

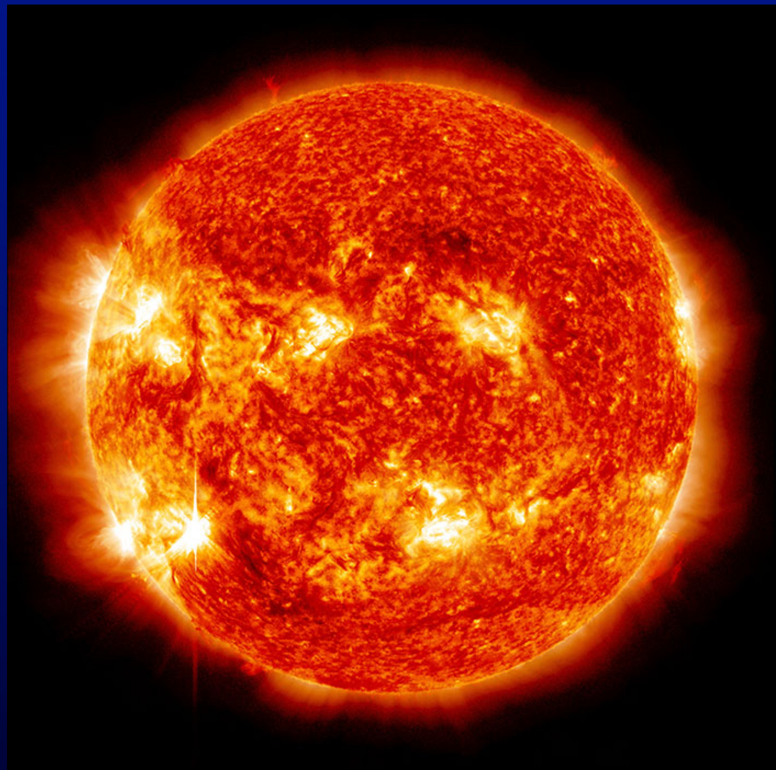
(ratio) Ω = 1.000(3) (known to better than 0.3%)





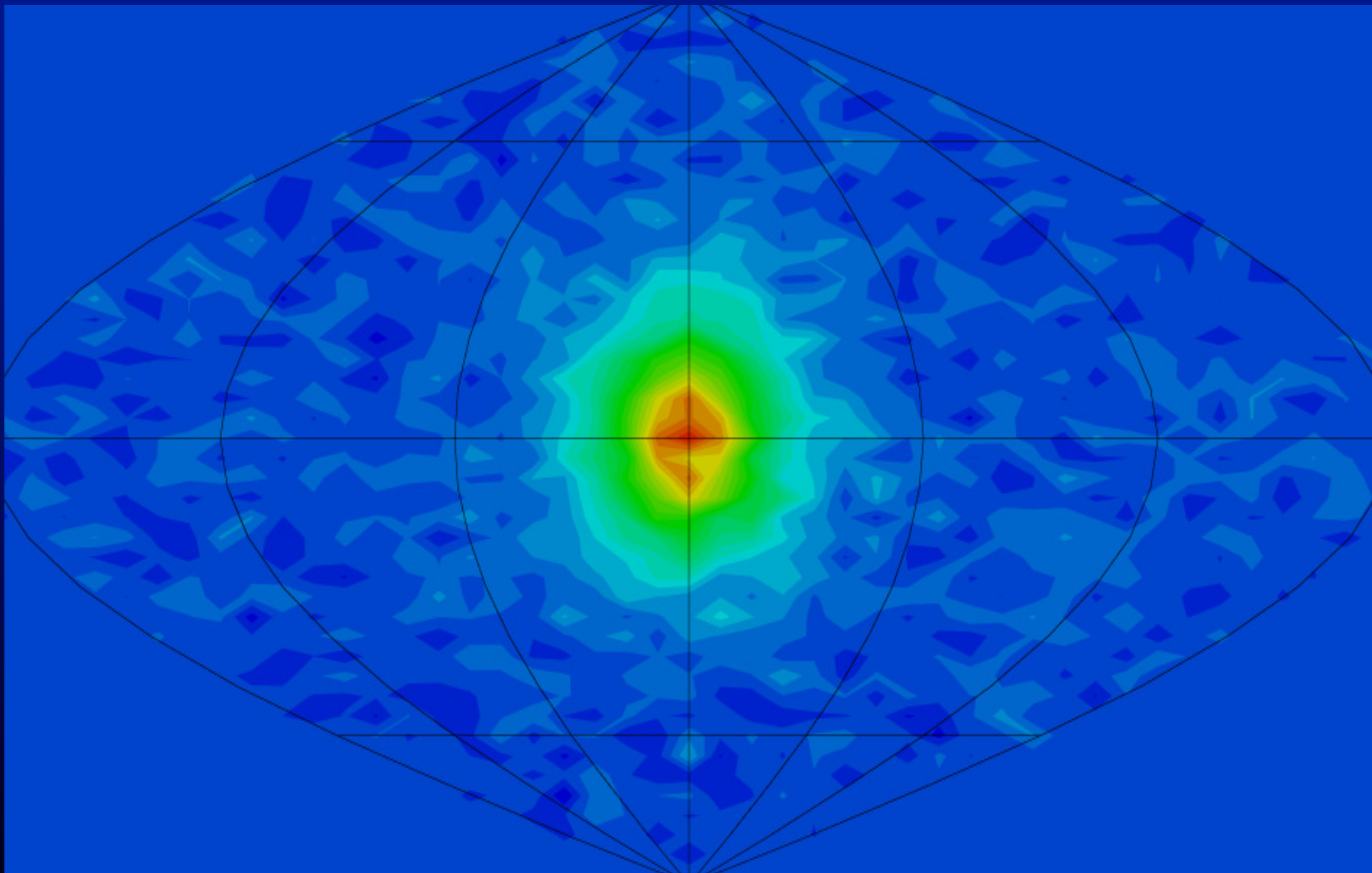
Expansion in a dark energy (cosmological constant) dominated Universe

View of the Sun

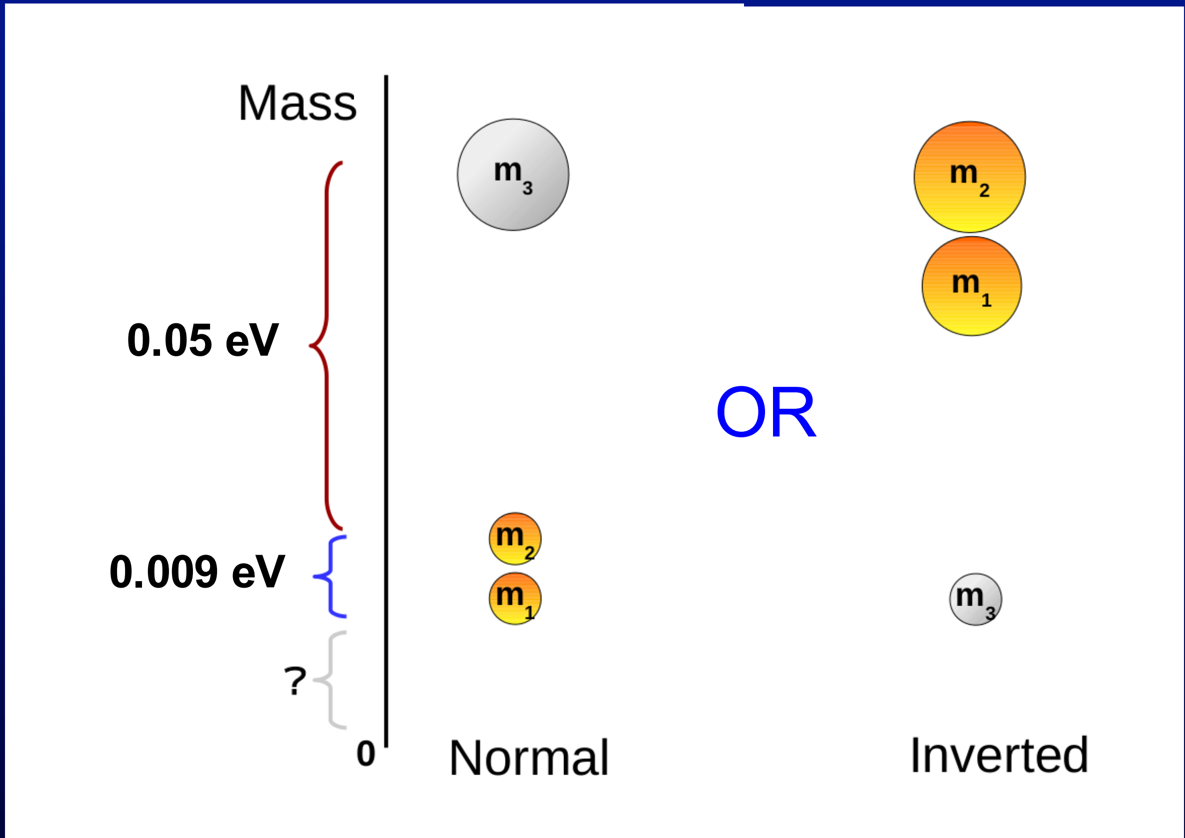


~8 min. away

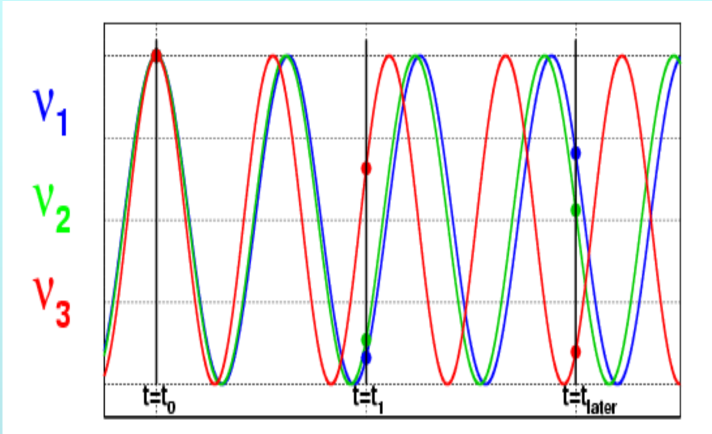
Neutrino view of the Sun



Neutrino Masses from Oscillations



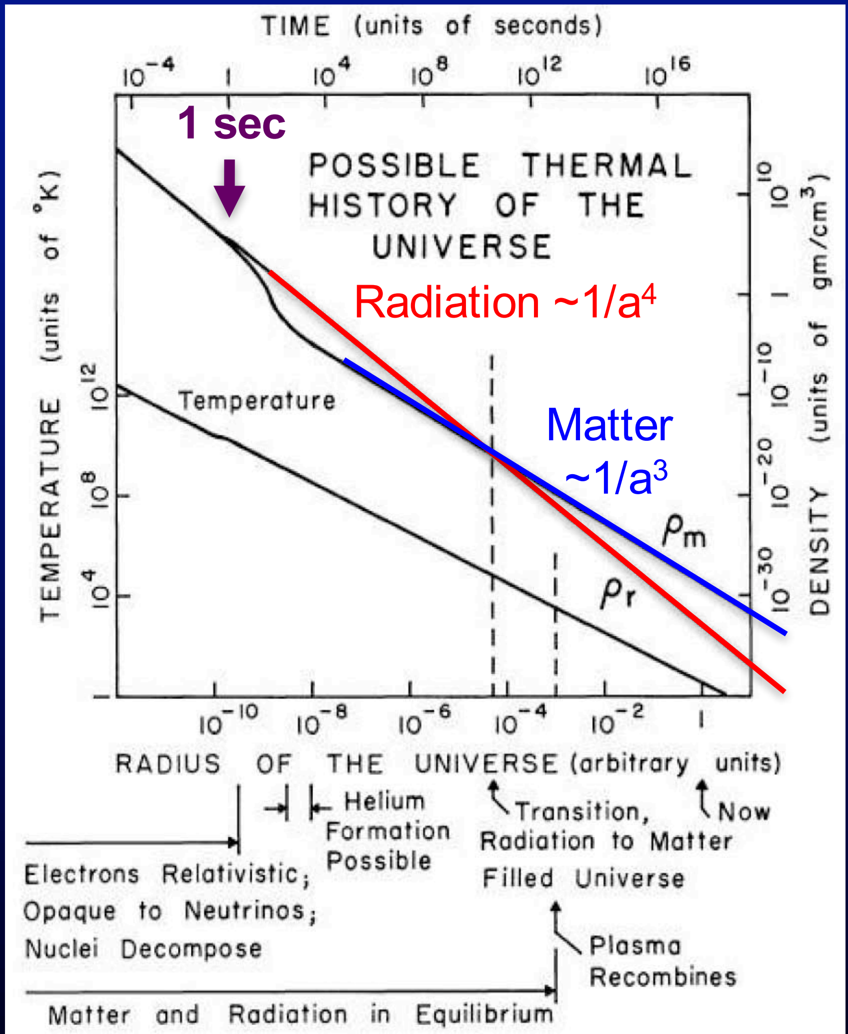
3 masses
X
3 flavors
(electron, muon, tau)



The absolute neutrino masses are not known.

It's not known at this time whether neutrinos masses are "Normal" or "Inverted".

Cosmic Neutrino Background



Dicke, Peebles, Roll, Wilkinson (**1965**)

Number density:

$n_\nu = 112/cm^3$

Temperature:

$T_\nu \sim 1.95K$

Time of decoupling:

$t_\nu \sim 1$ second

neutron/proton ratio @start of nucleosynthesis

Velocity distribution:

$<v_\nu> \sim T_\nu / m_\nu$

Non-linear distortions Villaescusa-Navarro et al (2013)

Cosmic Elements

3 element theory

γ **(photons)**

ν **(neutrinos)**

p,n (baryons)

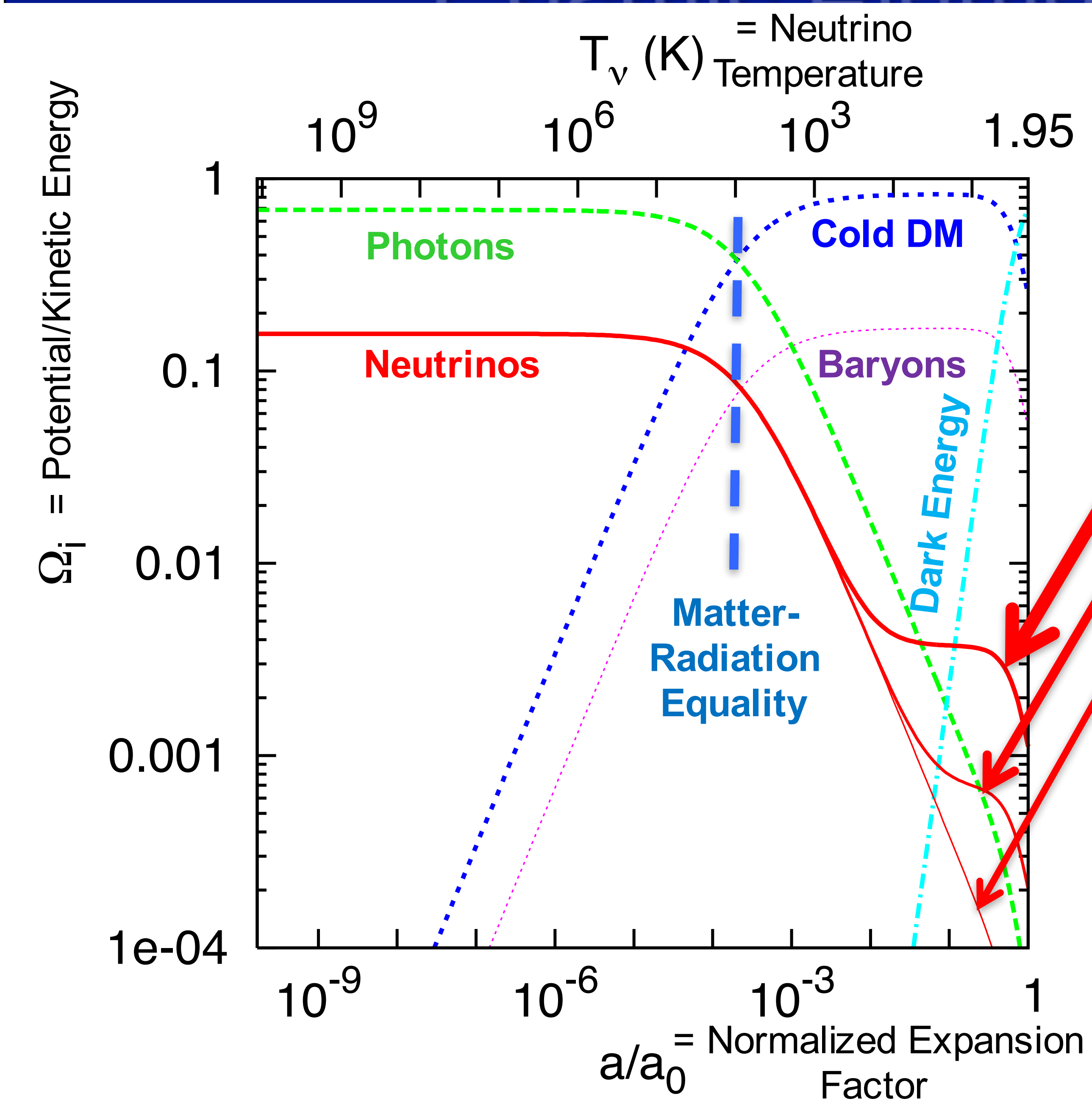
4 element theory

χ **(cold dark matter)**

5 element theory (+Aether/Void)

Λ **(dark energy)**

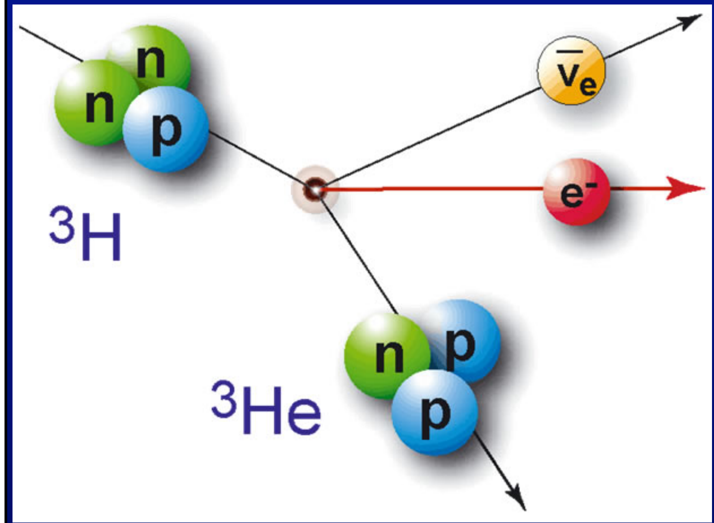
Cosmic Elements



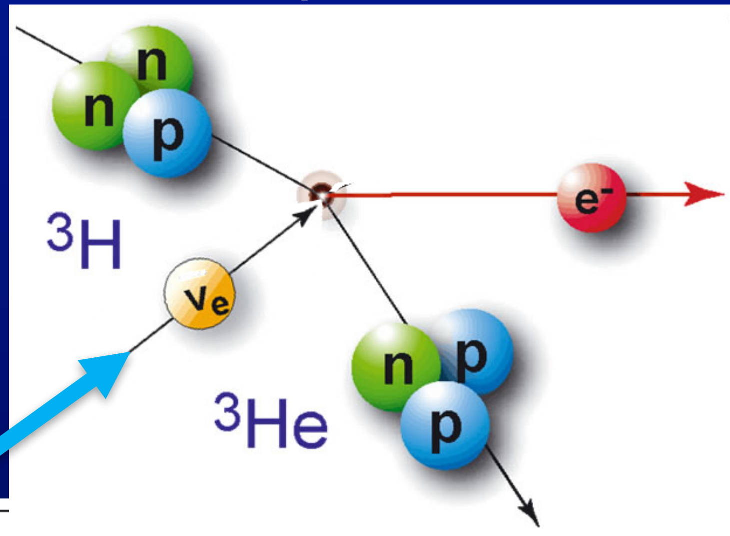
J. Lesgourgues

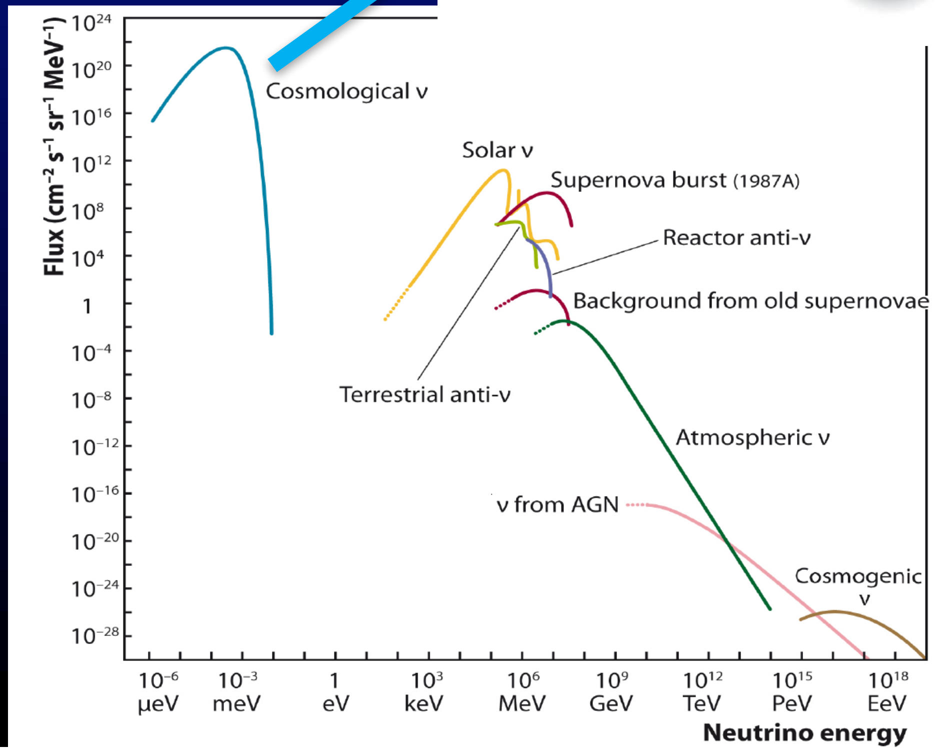
Individual neutrino contributions assuming Normal Hierarchy and
m_3 = 0.05 eV,
m_2 = 0.009 eV,
m_1 = 0

Neutrino capture on Tritium



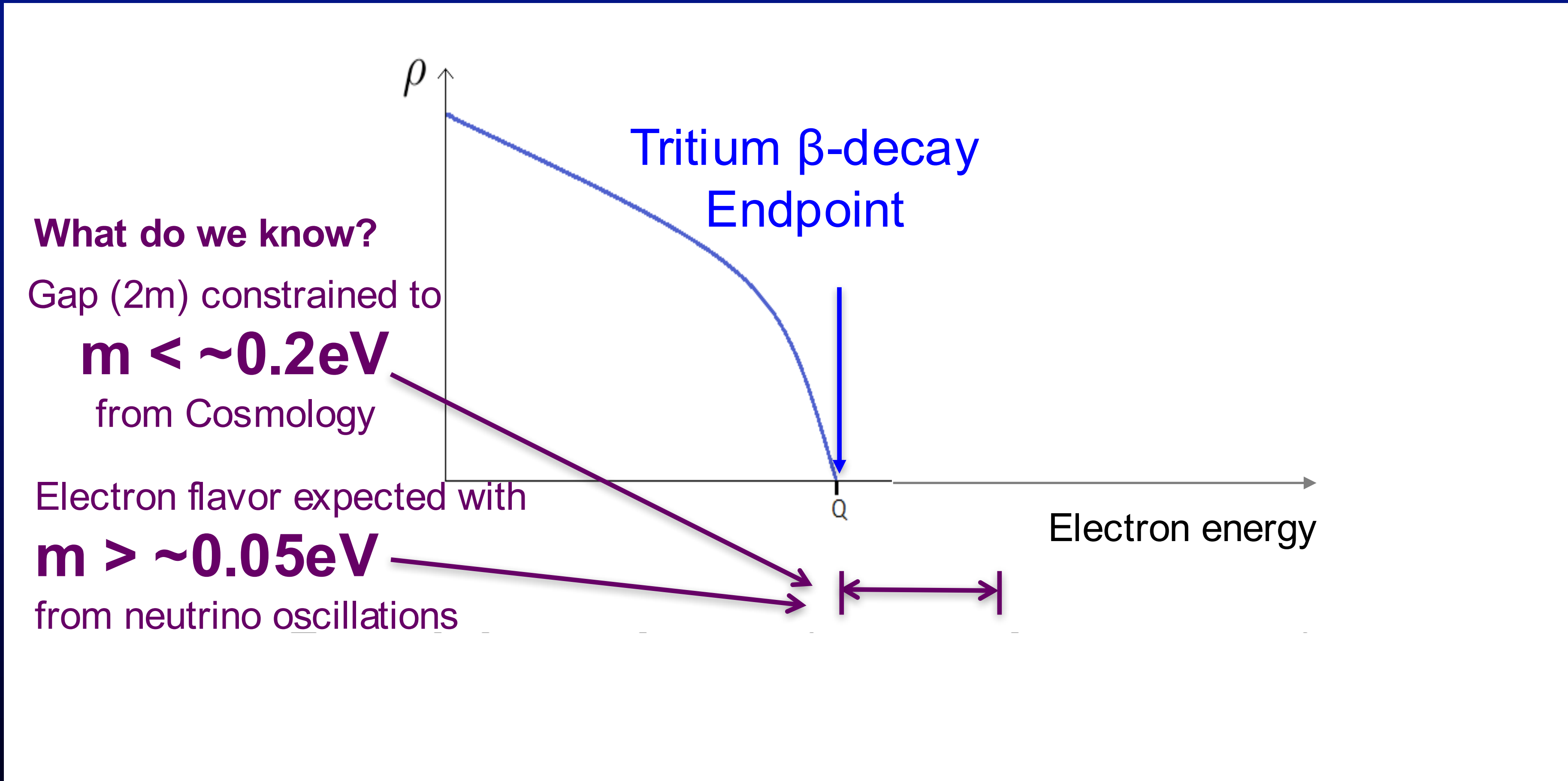
Tritium β-decay
(12.3 yr half-life)





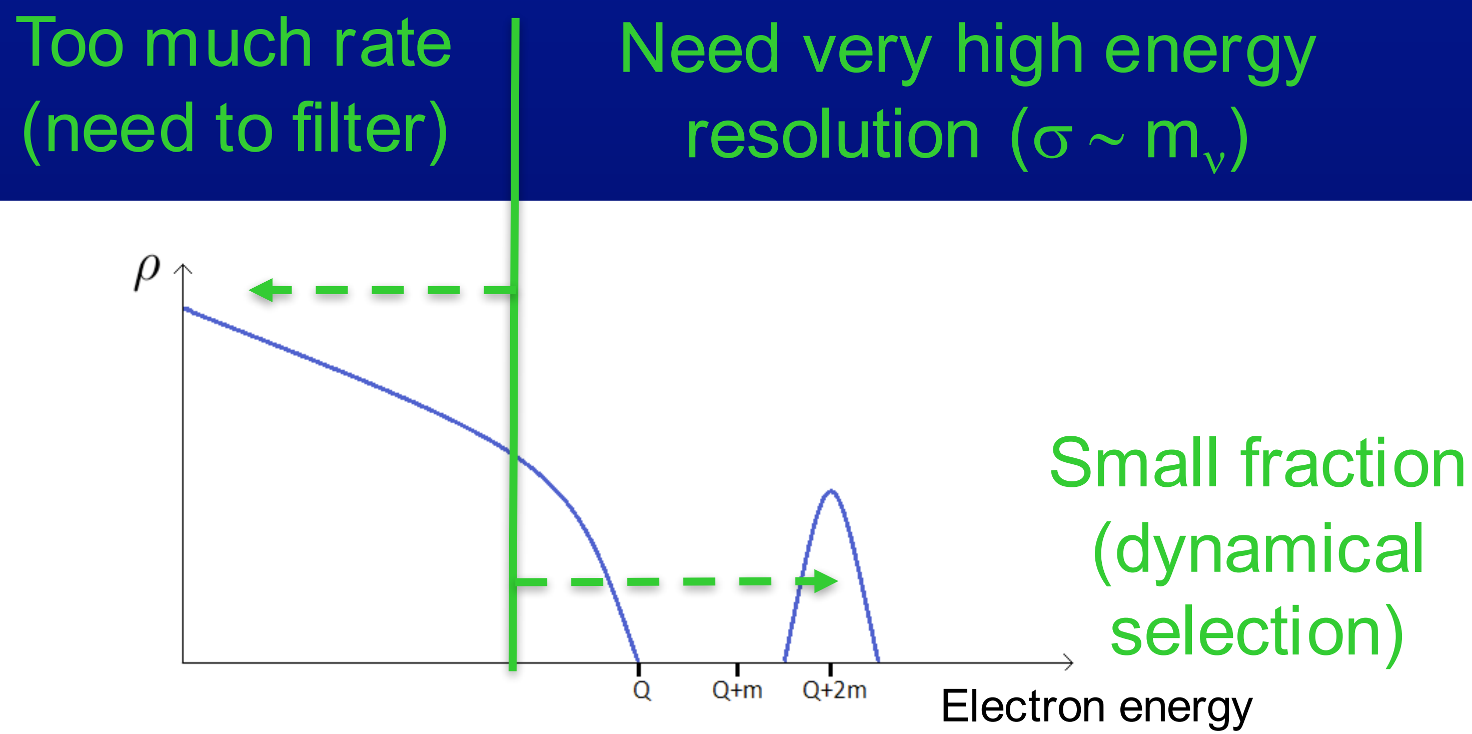
Relic Neutrino Detection

- Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in **1962** [*Phys. Rev*. 128:3, 1457]



Tritium and other isotopes studied for relic neutrino capture in this paper:
JCAP 0706 (2007)015, hep-ph/0703075 by Cocco, Mangano, Messina

Experimental Perspective

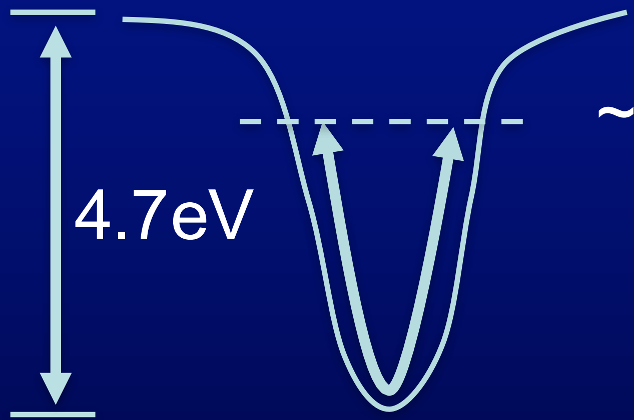


Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

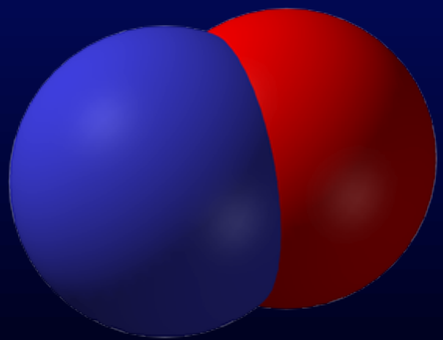
Graphene (2-D Material)

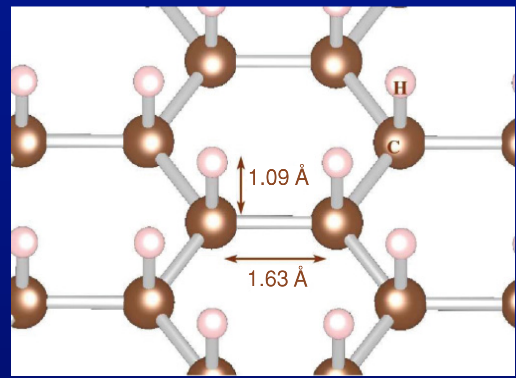
Molecular Broadening

T-T → $(T\text{-}He^3)^*$



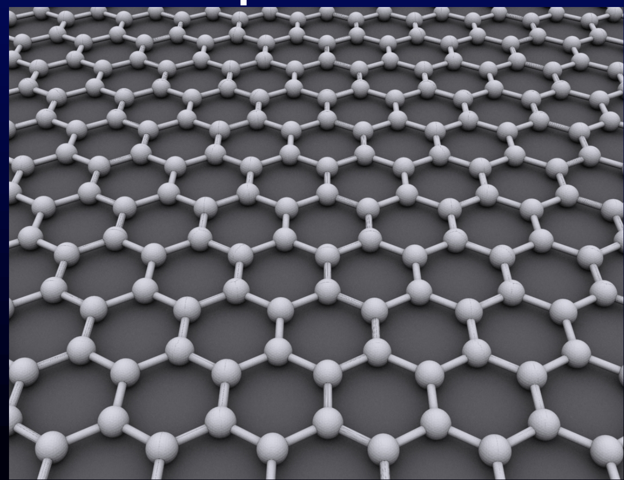
~3eV He^3 recoil at endpoint



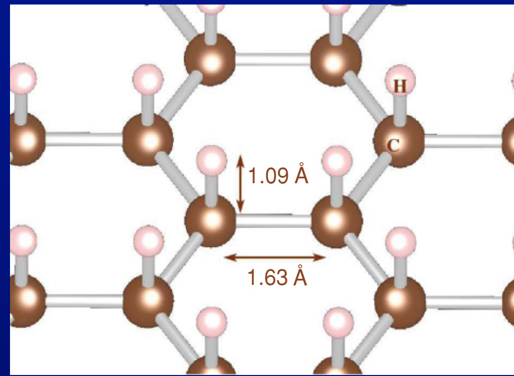


<3eV binding energy

Graphene

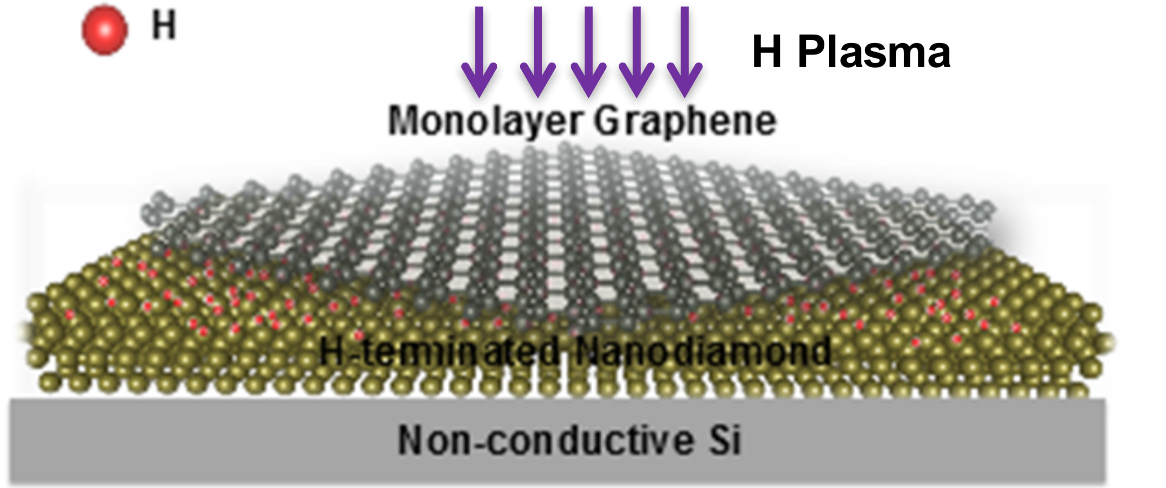


Molecular Broadening

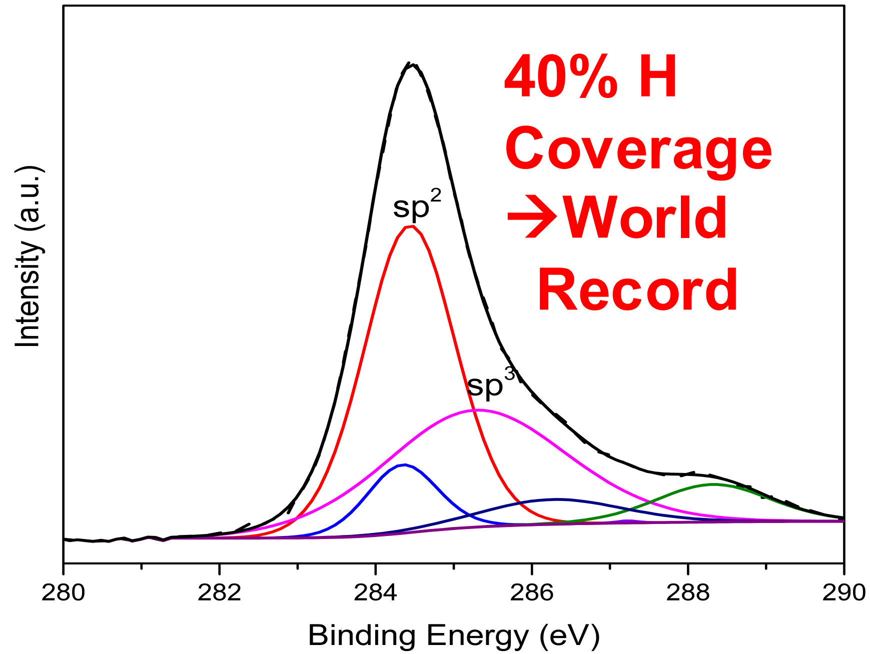


First Tritiated-Graphene Samples Produced by SRNL

Cold Plasma Loading

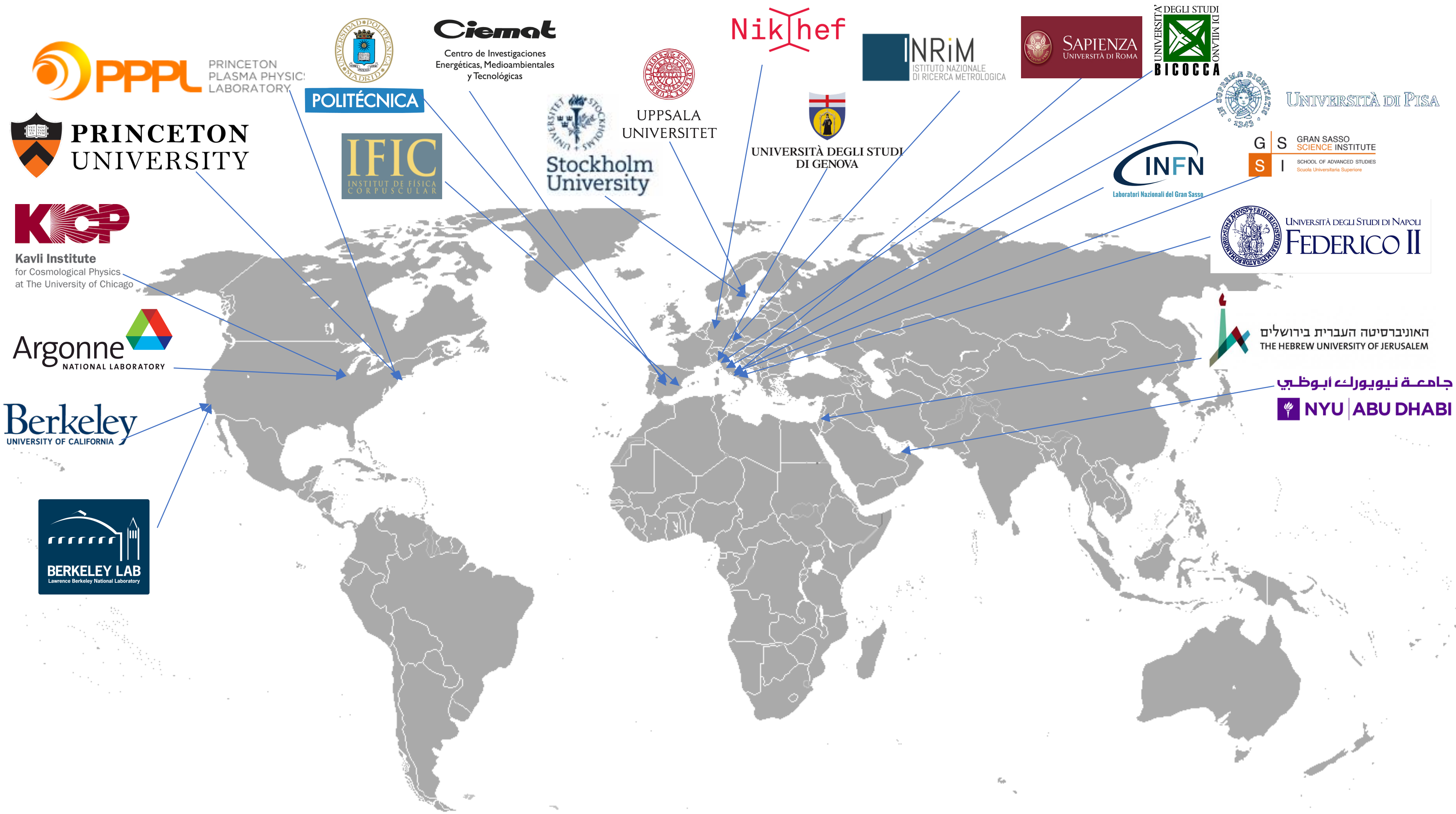


XPS Hydrogenation Results from Princeton



PTOLEMY World-Wide Collaboration

2015 Targeted Grant Award from the SIMONS FOUNDATION



Underground Environment

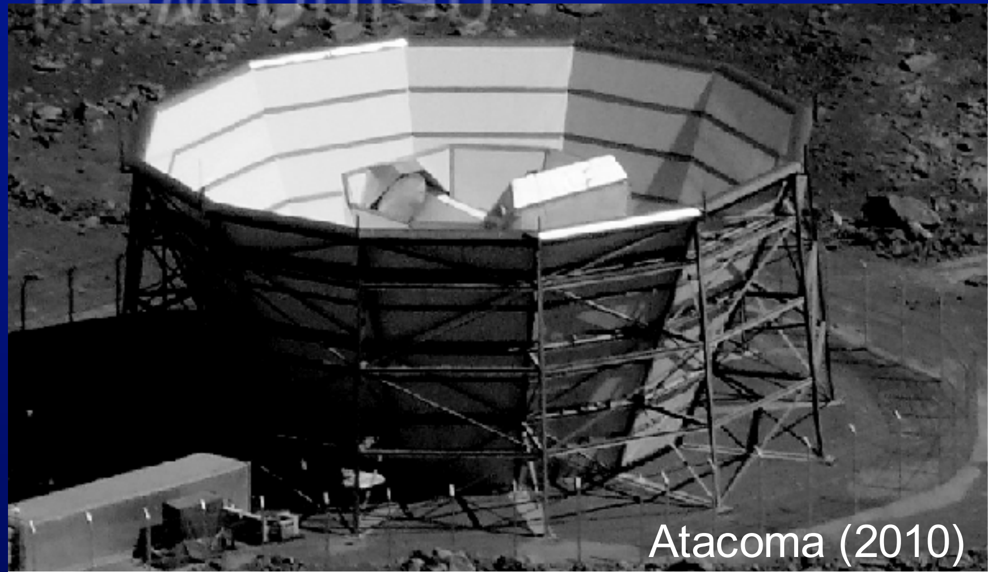
Gran Sasso
National Laboratory, Italy

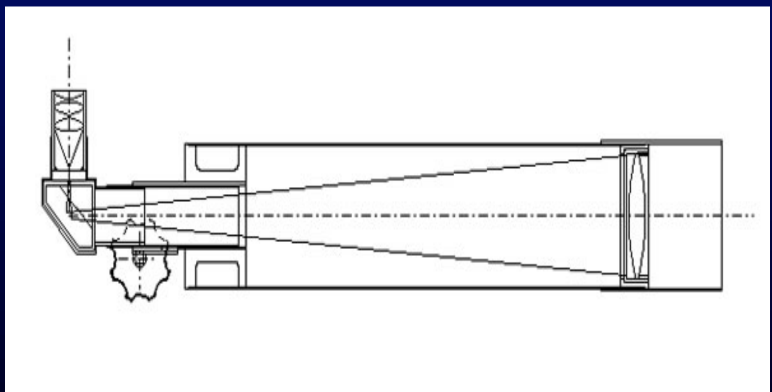
PTOLEMY kick-off meeting
11-12 December 2017

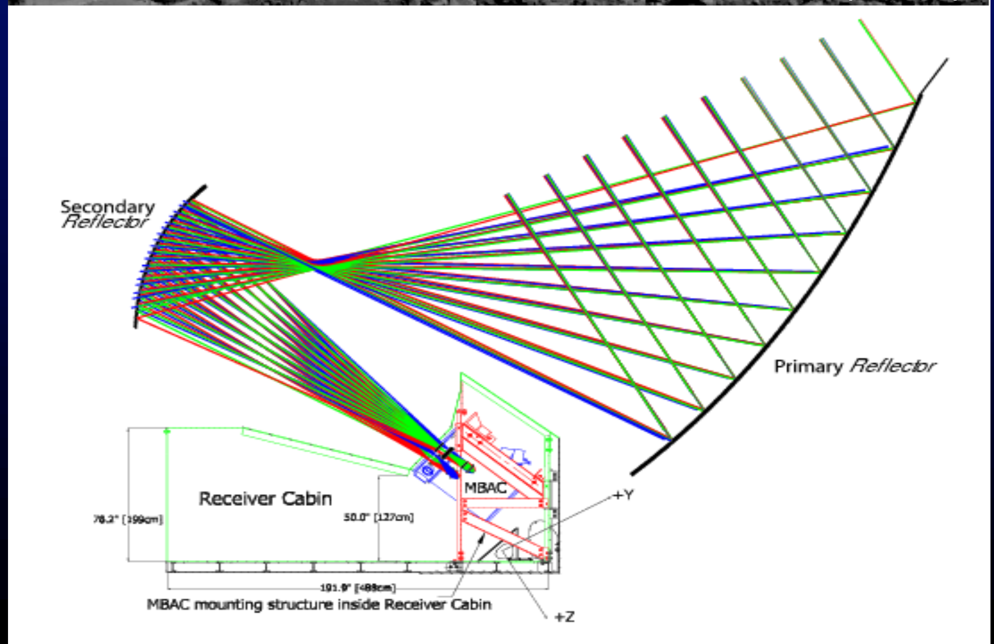
http://ptolemy.lngs.infn.it

Refractor → Reflector Telescopes
Galilean → Newtonian


Yerkes (1895)


Atacoma (2010)

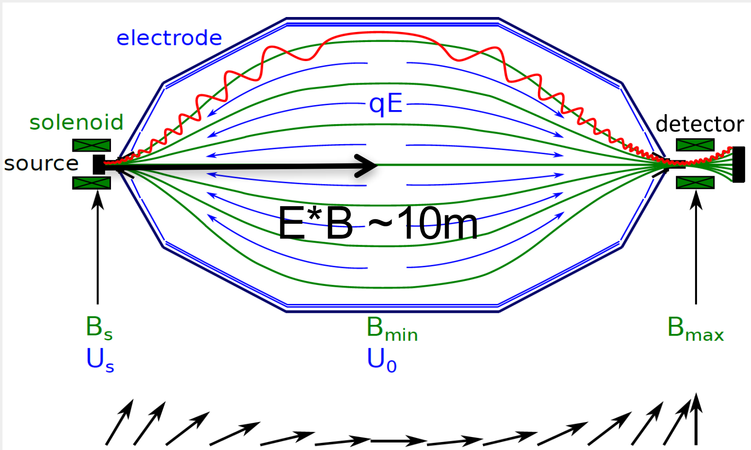




MAC-E "Telescope"

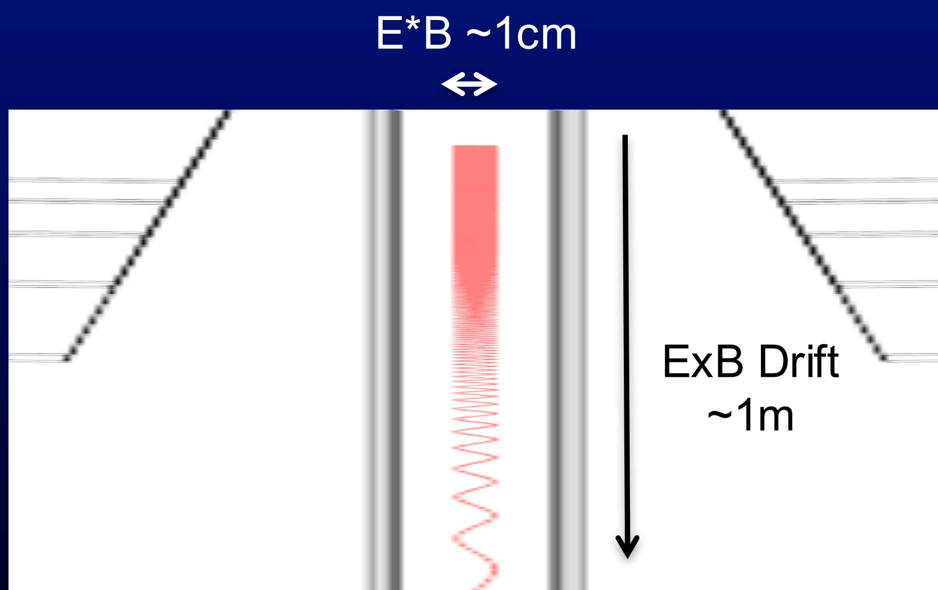
MAC-E filter technique

Magnetic Adiabatic Collimation with Electrostatic filter
Picard et al., NIM B63 (1992) 345



$$\mu = \frac{E_\perp}{B} = \text{const.}$$

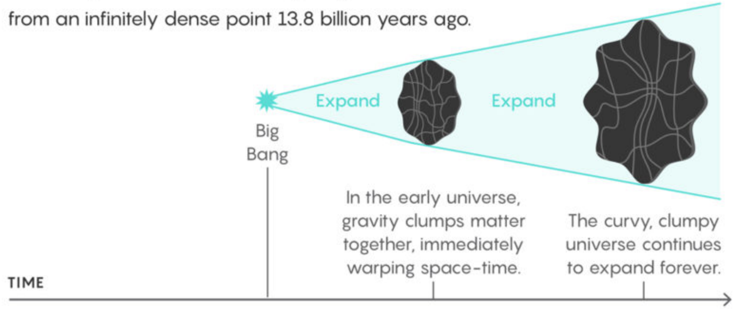
PTOLEMY implements a "reflector" method that is four orders of magnitude more compact along the direction of the B field



Filtering of the energy is in the vertical direction

The Big Bang

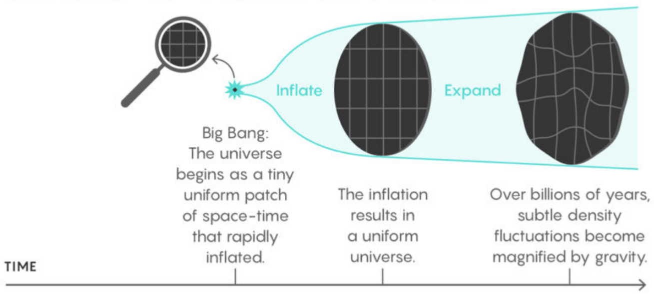
To explain why the universe was expanding, cosmologists began theorizing in the 1920s that a Big Bang event birthed the universe from an infinitely dense point 13.8 billion years ago.



But cosmologists observe a uniform early universe, not a clumpy crumpled one. Something was missing.

Cosmic Inflation

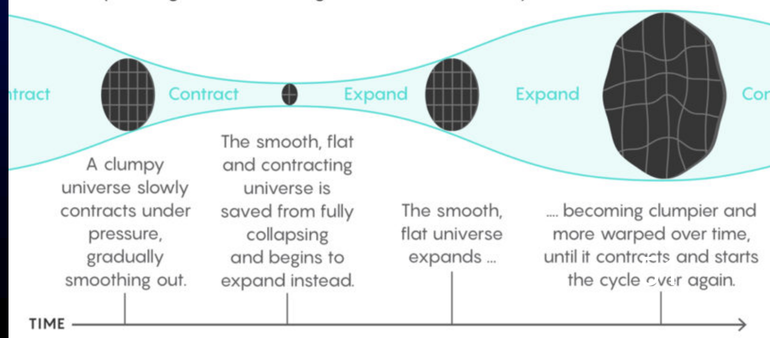
About 30 years ago, cosmologists proposed an updated Big Bang theory called "cosmic inflation" to explain our smooth, flat universe.



But what happened before the Big Bang and where did the original patch of space-time come from?

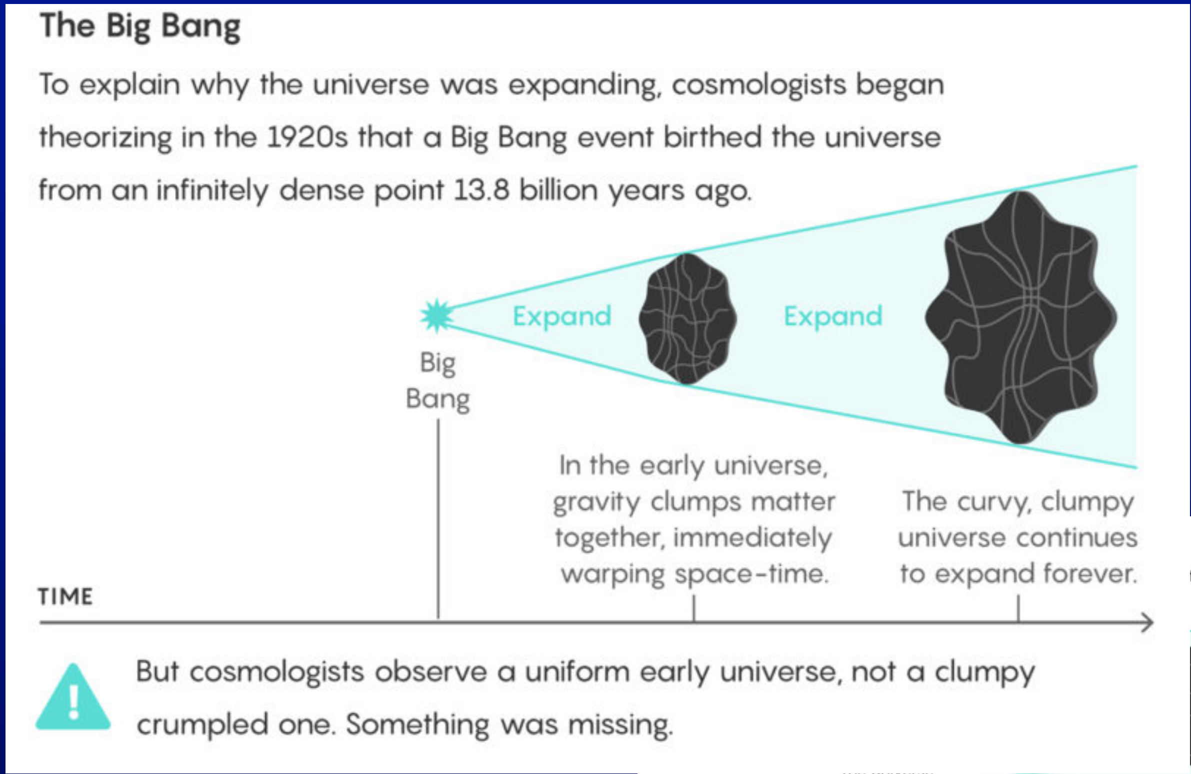
The Big Bounce

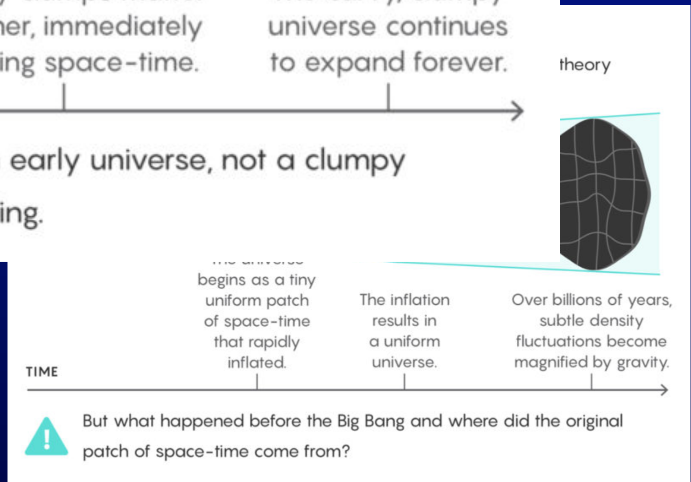
Recently, researchers have been taking a new look at the possibility of an expanding and contracting universe that could cycle forever.

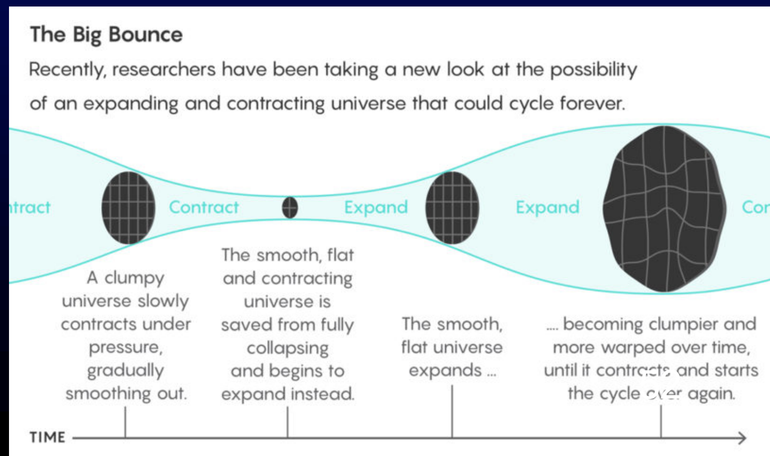


Quanta magazine

https://www.quantamagazine.org/big-bounce-models-reignite-big-bang-debate-20180131







Quanta magazine

https://www.quantamagazine.org/big-bounce-models-reignite-big-bang-debate-20180131

The Big Bang

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TIME

But cosmol
crumpled c

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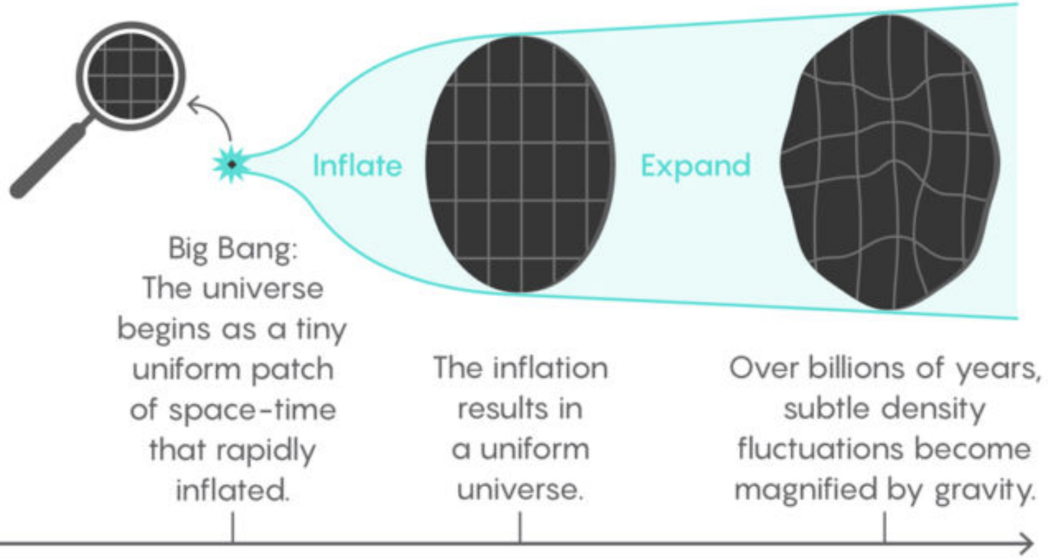

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https://www.quantamagazine.org/big-bounce-models-reignite-big-bang-debate-20180131

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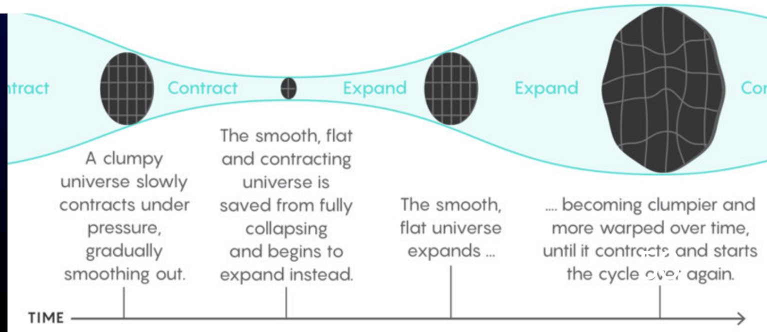

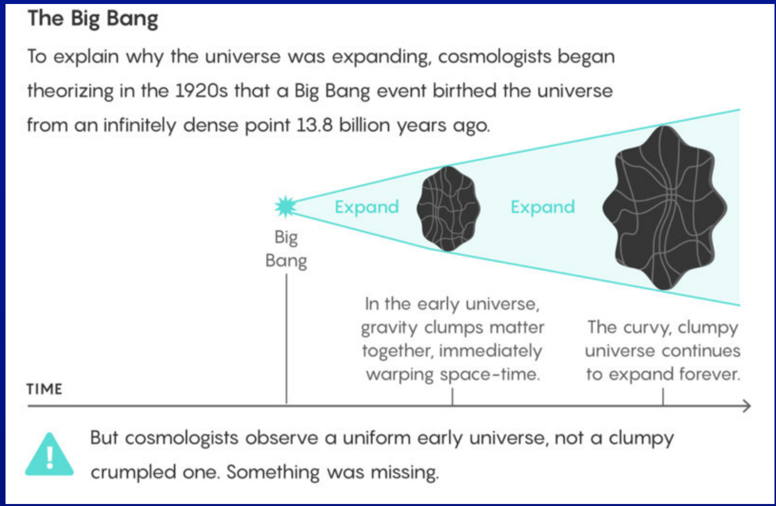

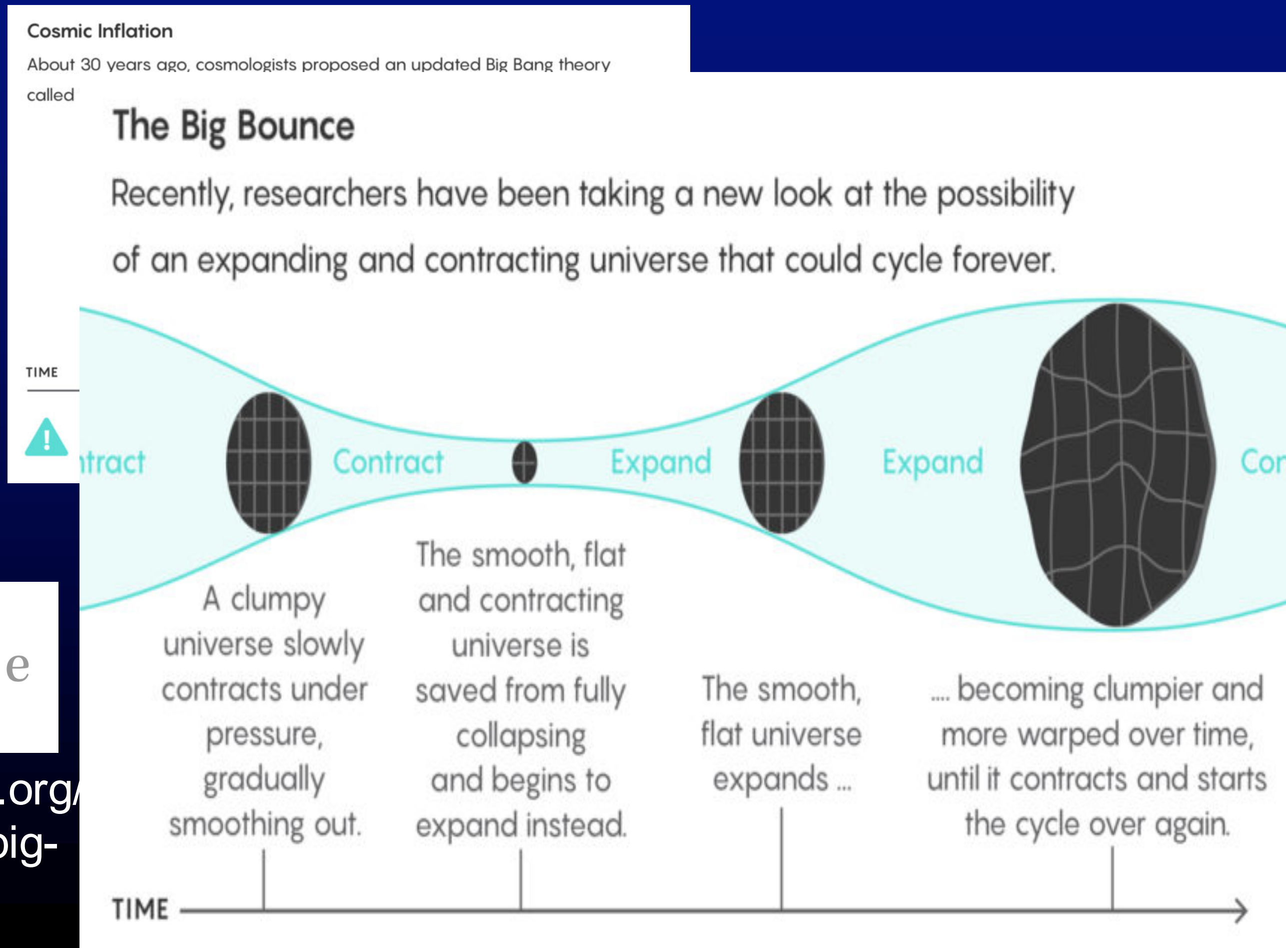

Quanta magazine

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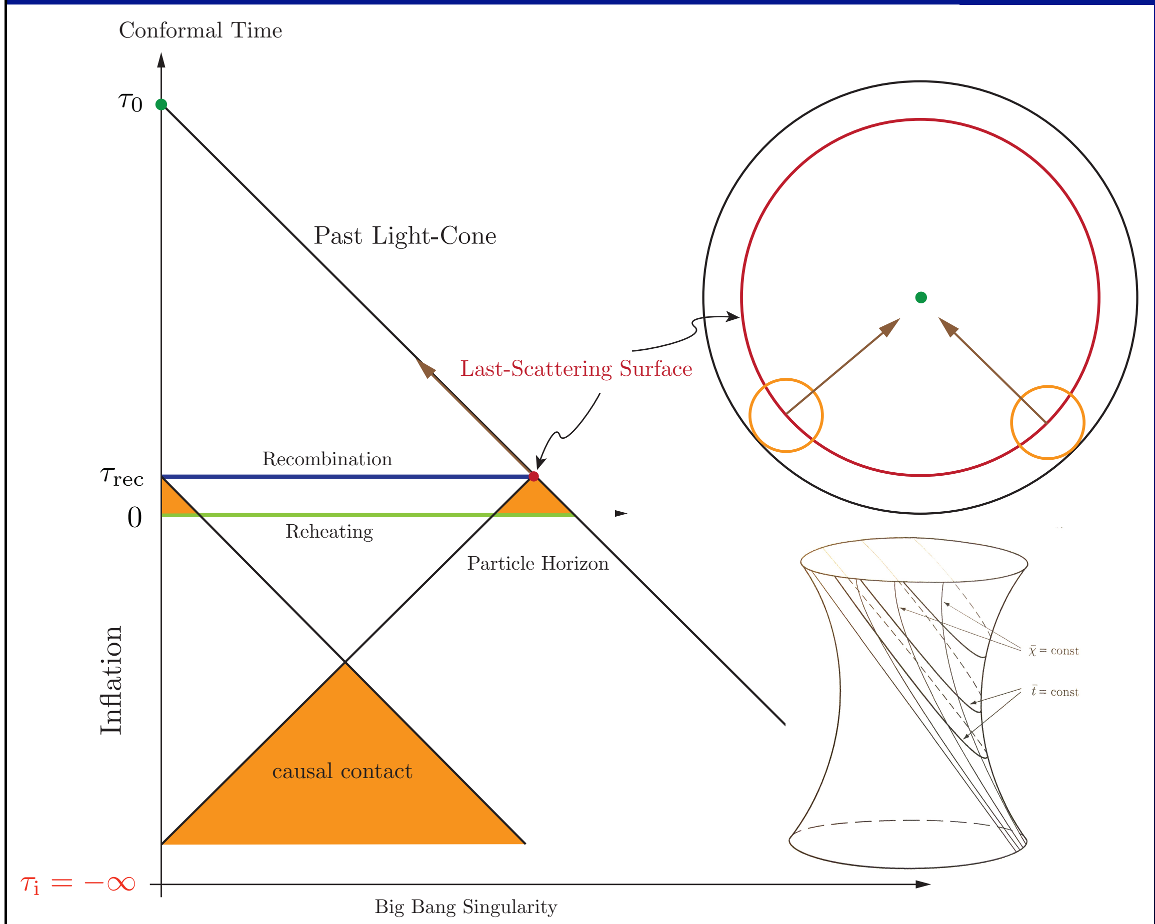
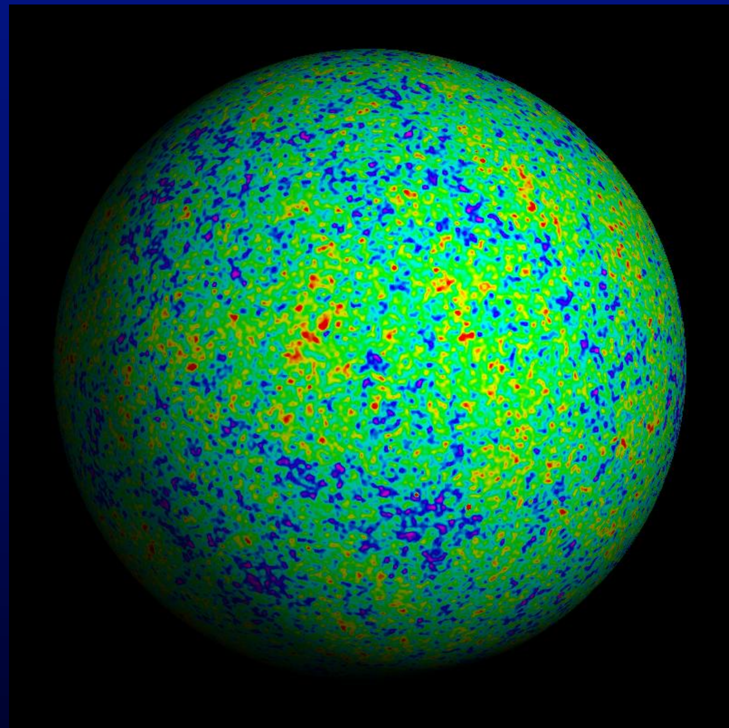
Big Bang Cosmology

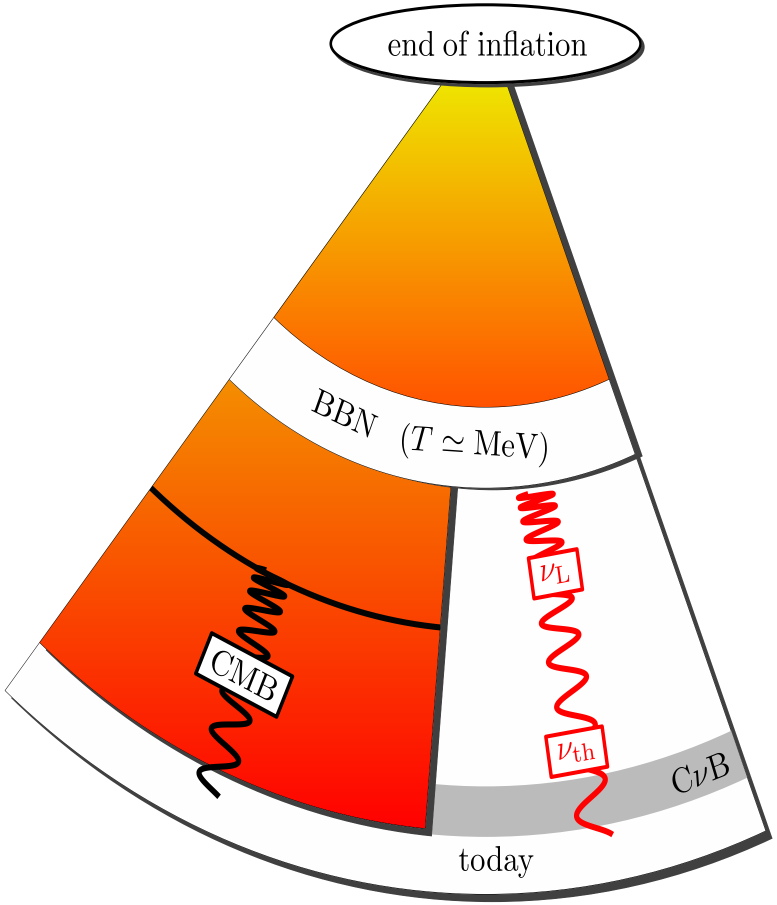


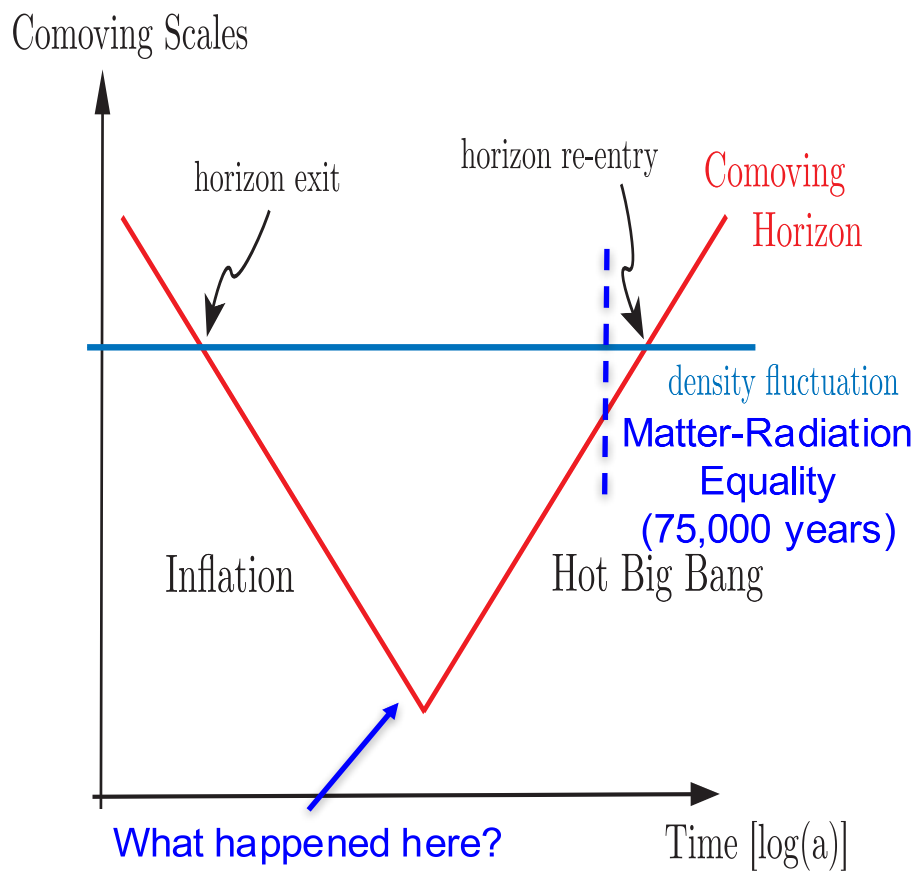
Adiabatic Density Anisotropies
$\delta \sim 10^{-5}$ at $z \sim 1100$



Where we think there is an initial $\tau_i = 0$ Big Bang Singularity is believed to be the "end" of an inflation period that slowly pulled out (>60 e-folds $a(\tau) \sim e^{H\tau}$) of a "de Sitter"-like spacetime

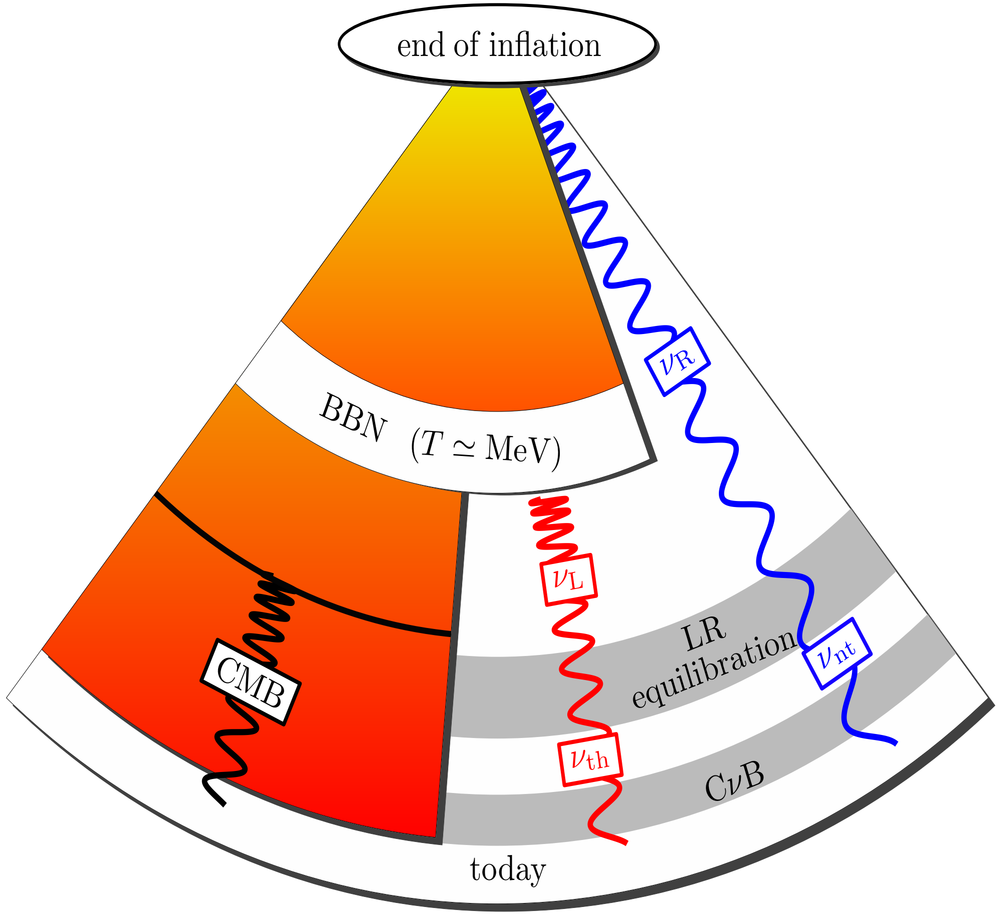
Inflation → Hot Big Bang

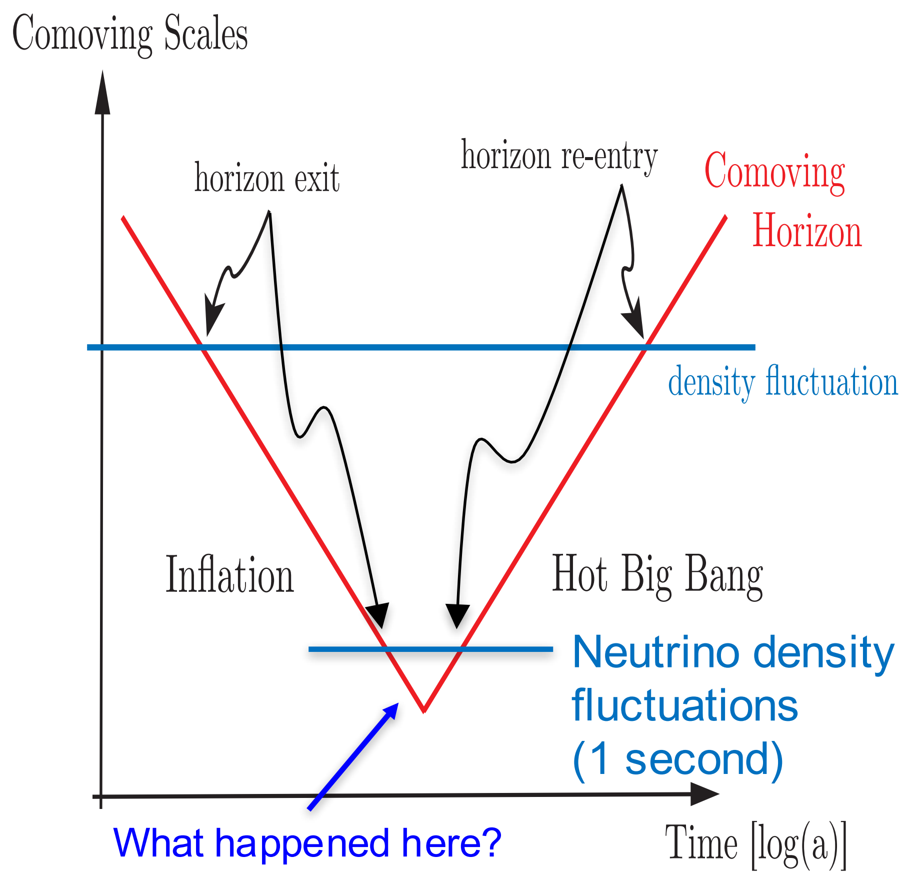




Baumann
(TASI 2012)

Inflation → Hot Big Bang



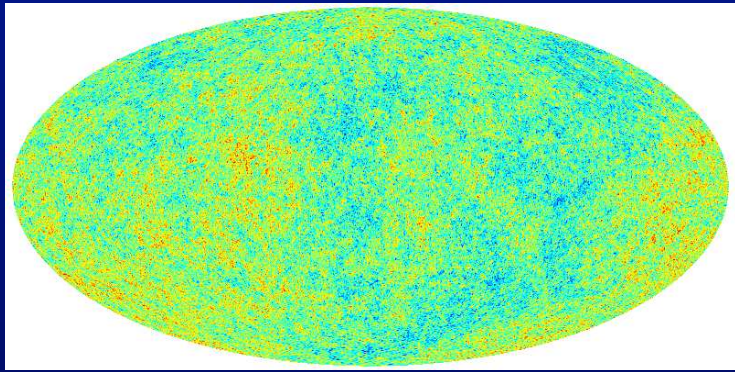


Ratz
(Erice 2017)

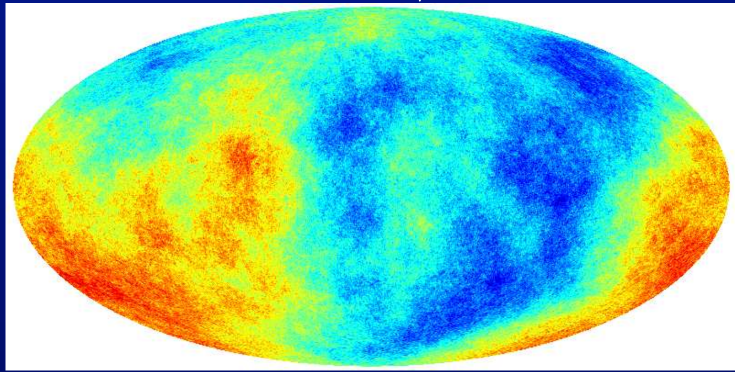
The Future: Celestial Globes from Neutrinos

Martin Rees@CMB50

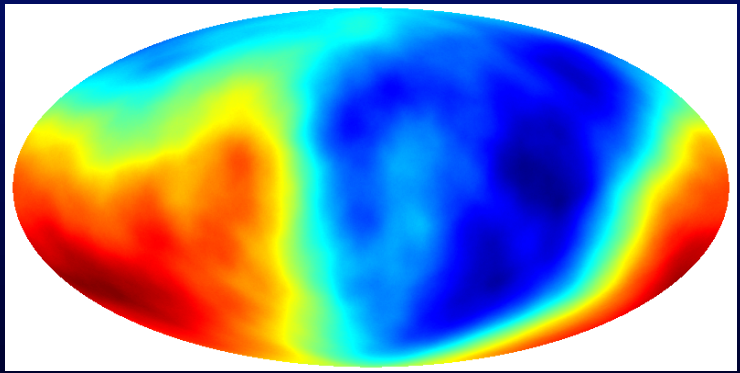
$m_\nu < 0.00001$ eV



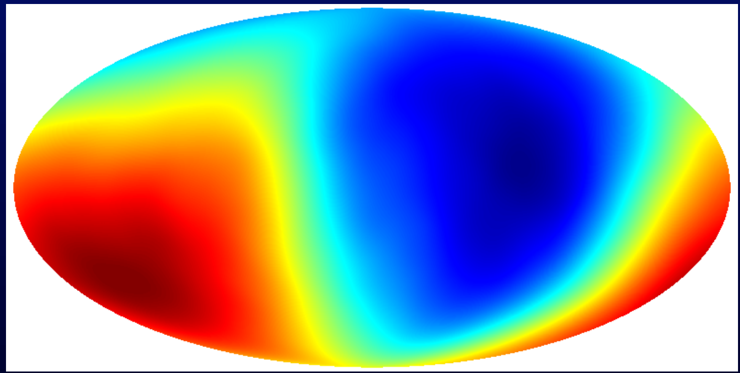
$m_\nu \sim 0.001$ eV



Hannestad, Brandbyge (2009)



$m_\nu \sim 0.01$ eV



$m_\nu \sim 0.1$ eV

2015 Targeted Grant Award from the SIMONS FOUNDATION

and additional support from the John Templeton Foundation