Navigating Quantum Systems to Detect Ultra-Cold Neutrinos from the Big Bang

Chris Tully
Princeton University

PERPECTIVES ON QUANTUM SENSING AND COMPUTATION FOR PARTICLE PHYSICS
8 JULY 2021
Cosmic Neutrino Background

Number density: $n_\nu = 112/cm^3$

Temperature: $T_\nu \sim 1.95K$

Time of decoupling: $t_\nu \sim 1$ second

~50% of the Total Energy Density of the Universe

neutron/proton ratio

@start of nucleosynthesis

Velocity distribution: $\langle v_\nu \rangle \sim T_\nu / m_\nu$

Dicke, Peebles*, Roll, Wilkinson (1965)

Cosmology's Century (2020)

CNB Anisotropies

PTOLEMY Publications:  https://ptolemy.lngs.infn.it/publications/
“Multi-Messenger Astrophysics with the Cosmic Neutrino Background”, JCAP 06 (2021) 053

CNB dipole/quad anisotropies grow like $1/n^2$ following non-rel. transition over ~100-200 Mpc distance scales and ~0.02 Mpc$^{-1}$ k-modes
Relic Neutrino Sky Map

Sky map of $m_\nu = 0.05$ eV

Fractional variations in neutrino capture rates


Tully, Zhang, https://iopscience.iop.org/article/10.1088/1475-7516/2021/06/053
“Multi-Messenger Astrophysics with the Cosmic Neutrino Background”, JCAP 06 (2021) 053
Neutrinos can see behind the Milky Way!
If relic neutrinos exist in the Universe today, then we can validate the over- and underdensities in the nearest 100-200 Mpc.
• Early universe quantum theory
  – Sensitivity to inflationary power spectrum at k-modes of $\sim 0.02 \text{ Mpc}^{-1}$
  – Complementary constraints on scalar spectral index (from high k-modes)
  – Fixes precision cosmology data with lab-measured mass, number density and anisotropies to further improve sensitivity on time-varying dark energy

• Nature of neutrinos directly affecting CNB measurement
  – Over 100 theory citations on PTOLEMY observables
  – Dirac or Majorana
  – Finite neutrino lifetime
  – Decay chains of new particles into light neutrino species (Majoron, sterile, etc.)
  – New light neutrino production mechanisms (dark energy radiation, RH production)
  – Self-interactions
  – Interactions with DM

• Rich physics program beyond CNB
  – Neutrino mass (next gen KATRIN, Project 8 programs)
  – Sterile neutrino detection (next gen TRISTAN program)
  – Directional Dark matter detection with oriented CNT
  – Development R&D for low energy electron detection/measurement experiments
Tritium $\beta$-decay (12.3 yr half-life)

Neutrino momentum $\sim 0.17$ meV

For $m_\nu = 50$ meV,
$KE = \frac{p^2}{2m}$
$= 0.17 \text{ meV} \times (0.17 \text{ meV}/100 \text{ meV})$
$= 0.3 \mu\text{eV}$

Ultra-Cold!
Detection Concept: Neutrino Capture

- Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in 1962 [Phys. Rev. 128:3, 1457] applied for the first time to massive neutrinos in 2007 by Cocco, Mangano, Messina [DOI: 10.1088/1475-7516/2007/06/015] (no molecular smearing included)

![Diagram of neutrino capture](image)

What do we know?

- Electron flavor expected with \( m > \sim 50 \text{meV} \) from neutrino oscillations
- Gap (2m) constrained to \( m < \sim 200 \text{meV} \) from Cosmology
Quantum Systems Impacting CNB Detection

• Kinetic Energy calculation (micro eV)
  – Detection sensitivity set by mass
• Quantum Excitations in Target Substrate
  – Minimizing Zero-Point Energy (graphene, Au(111), superfluid \(^4\)He)
  – Polarized targets for mapping the sky
• 0.1fW RF detection
  – Phased arrays with Low(est) Noise Amplification methods
  – Ultimate limit set by limit on microwave photon detection
  – \(B^2\) improvement 27 GHz @1T \(\rightarrow\) 80-90 GHz @3T
  – Fast 5G/Xilinx ZNYQ RFSoC Trigger – similar to QuBit gate processing
• Superconducting dipoles with custom fringe fields
  – Novel EMF design with working iron-return-yoke mockups (1T \(\rightarrow\) 3T w/SC)
  – Fast HV ramping for filter, precision HV references for target-microcalorimeter
  – Einzel Lens low energy electron transport
• TES Microcalorimetry
  – Evaluated with Fast, IR Photon Counting
  – New Thin Film prototypes for eV electron energy measurement
  – Microwave multiplexing for electron calorimeter
PTOLEMY Conceptual Block Diagram

\[ E_{Total} = q(V_{TES} - V_{Target}) + E_{RFcorr} + E_{cal} \]

Graphene
monoatomic T storage

RF antenna
measure of K and K' 

Dynamic EM Filter
particle selector 

Calorimeters
TES provide a differential E measurement

\[ K_L \]

is reduced around few eV

https://ptolemy.lngs.infn.it
Filter R&D Development Setup

Example small-scale end-to-end configuration

Target
RF
EM Filter
Microcalorimeter

Andy Tan (Princeton)
Neutrino capture on tritium is a “sudden” process replacing a ground state tritium atom with a recoiling \(^3\)He nucleus

How do we “hold” target nuclei in space?

(diatomic \(T^2\) ro-vibrational, Graphene-\(T\) 3D SHO, Au(111)-\(T\) 2D diffusive, superfluid \(^4\)He-Impurities 1D \(~5\) Å spatial spread, …)

Are the outgoing \(^3\)He atoms populating a broad range of atomic excited states of the target substrate/molecule?

Can we measure these experimentally through \(^3\)He Energy-Loss Spectroscopy? Expect quantum band structure measurements to be the new standard for QS experiments.

What materials/targets minimize spread on outgoing electron kinetic energy to preserve the basic separation power of the neutrino mass observables? (Small number of well separated \(~0.3\)eV quantum levels with high population in lowest excitation state)

More theory input vital to achieving detection of CNB: (Existing literature: \(T^2\) studies in full-quantum calculation, semi-classical estimates on graphene in review/arXiv, full-quantum graphene in preparation, new papers on alternative targets in preparation)
Angular-resolved photoemission spectroscopy (ARPES)

\[ k_x = \frac{p_x}{\hbar} = \sqrt{2mE_{\text{kin}}} \sin \theta \cos \phi \]

\[ k_y = \frac{p_y}{\hbar} = \sqrt{2mE_{\text{kin}}} \sin \theta \sin \phi \]

\[ E_B = h\gamma - E_{\text{kin}} - \phi_A \]

E vs k dispersion can be obtained
Absorb tritium on a carbon nanostructure (as planar or nanoporous graphene, or carbon nanotubes).

- Reached ~30-40% H and D uploading with 6 eV Kaufmann source.
- Very stable in temperature (up to 900 K)
- Working on an optimised up-loading technique (in collaboration with CIEMAT - nuclear fusion)
- Study graphene transparency on electron

Working on the tritium uploading on carbon nanostructure (KIT)
Demonstrate tritium loaded graphene is a “solid” radioactive source

Collaboration with condensed matter experts (Sapienza - RomaTre - Radboud)

See PBC talk of G. Cavoto (https://indico.cern.ch/event/1045067/)
The proposal to measure electron energies at the endpoint of the tritium spectrum with RF cyclotron radiation was proposed by the Project 8 Collaboration – using the relativistic frequency shift measured to very high precision.

For the purpose of the PTOLEMY experiment, the RF signal is being used for an RF tracking system – measuring the total energy and parallel/transverse momentum components with sufficient accuracy to trigger on the small percentage of electrons near the endpoint (10 eV is $10^{-10}$ of the total activity).

A huge advantage of measurements in the frequency domain is that only endpoint electrons will produce a significant signal in the corresponding RF frequency band.

In free space, the total radiated power $P$ is given by the Larmor formula [18],

$$P(\gamma, \theta) = \frac{1}{4\pi\varepsilon_0} \frac{2}{3} \frac{e^4}{m_e^2} B^2 (\gamma^2 - 1) \sin^2 \theta,$$

where $\varepsilon_0$ is the permittivity of free space and $\theta$ is the pitch angle of the electron, defined as the angle between the momentum vector of the electron and the direction of the magnetic field. For an electron with an energy near the 18.6-keV end point of $^3\text{H}$, approximately 1.2 fW is radiated in a 1-T magnetic field at a pitch angle of 90°.
RF Tracking

Time Series (~26 GHz)

Power (~0.1 fW)
RF Microwave Photon Detection

Single electron RF microwave photon detection will ultimately drive the scalability of the PTOLEMY experiment.

**How much signal-to-noise gain will come from coherent source analysis?**
Big gains for LIGO/VIRGO-like Chirps

**Will phased arrays increase the volume coverage and target (surfaces) per filter element?**
Current Low Noise Factory HEMT LNAs work well for horns, more novel quantum-noise limited amplification may greatly improve performance for low microwave photon fluxes per patch antenna

**What RF processing technologies will be able to extract electron momentum parameters with high accuracy and low latency?**
Currently exploring Xilinx ZYNQ RFSoC evaluation boards

Strong overlap with RFSoC fast turn around RF processing and QuBit controls.
PTOLEMY Filter Concept

Auke Pieter Colijn (PATRAS 2019)

I: $\vec{E} \times \vec{B}$ drift

1. net drift, $v_{\text{drift}} = \frac{E}{B}$
2. no work, drift along equipotential planes

PTOLEMY: two types of drift

1. net drift, $v_{\text{drift}} = \frac{E}{B}$
2. no work, drift along equipotential planes

II: $\frac{\mu}{B^2} \nabla \times \vec{B}$ drift, with magnetic moment $\mu = \frac{m_e v_1^2}{2B}$

1. net drift, $v_{\text{drift}} = \mu \frac{\nabla B}{B}$
2. Allows $E$ field to work (!): $\frac{dT_1}{dt} = e \vec{E} \cdot \vec{v}_{\text{drift}}$

$V_{\nabla B}(z)|_{y=0} = -\frac{\mu}{qB_x} \frac{d B_x}{dz} \hat{y}.$

$V_{E \times B}^y(z)|_{y=0} = E_z \times B_x = \frac{E_z}{B_x} \hat{y}$

yields $E_z(z)|_{y=0} = -\frac{\mu}{q} \frac{dB_x(z)}{dz}$
Shaping Magnetic Fields

Done here with iron return-yoke and field shaping “horns”.

An equivalent design could be made based on superconducting dipole coils.
Electron Transport through RF antennas

RF Antenna Region

Target

Dynamic EM Filter Region

Einzel lens to Calorimeter

Wonyong Chung
The “Filter Element” is the primary repeated component in a large-scale CNB experiment – expect to scale from 10 to 10,000 or more to cover 100g of tritium target

**How compact and power efficient can the magnet geometry be?**
Superconducting dipole windings not so dissimilar to LHC dipole coils would greatly decrease wall power budget (trade for cryogenic) and gain in filter performance as $B^2$.

**Are there accelerator/kicker technologies that can be applied to the fast ramping of filter electrode HV needed for high electron transport efficiency?**
Electron energy is referenced to precision static voltage difference between target and microcalorimeter, but the filter fast HV ramp (~1msec for 10 kV is important for reducing flux on microcalorimeter).

**Is the Einzel lens the best method for eV electron transport?**
Limited focusing sets the area coverage required by microcalorimeter.

Strong overlap with collider technologies and LHC production scales.
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 \((\tau)\) also small \(<\mu\text{sec}\).

\[ \tau = \frac{C}{G} \]

\(~100\ \text{mK} \) cold bath (refrigerator)
$E_e = e(V_{cal} - V_{target}) + E_{cal} + RF_{corr}$

Now: 0.11 eV @ 0.8 eV and 106 mK and 10x10 µm$^2$

TiAuTi 90nm [ Ti(45nm) Au(45nm) ] ($\tau \sim 137$ ns)

Design Goal (PTOLEMY): $\Delta E_{FWHM} = 0.05$ eV @ 10 eV

translates to $\Delta E \propto E^\alpha$ ($\alpha \leq 1/3$)

$\Delta E_{FWHM} = 0.022$ eV @ 0.8eV

$\Delta E \propto T^{3/2}$ $\Rightarrow$ $T_c = 36$ mK @10x10 µm$^2$ (t=90 nm)
New PCB design

2 channels dc-SQUID chip
Ultimate energy resolution measured with microcalorimeter achieving absolute energy measurement uncertainties with a resolution of 50 meV

**What is the ultimate limit on electron energy resolution?**
Transition-Edge Sensor technology can be optimized for thin films and low critical temperatures. Other differential energy measurement devices in the eV range may be possible.

**How many calorimeter channels are needed per filter element?**
Transport from end-of-filter to zero B field region of microcalorimeter is currently modeled with an Einzel lens and electrostatic transport to avoid dead regions

**Will microwave multiplexing be important for scalability?**
Smaller pixels have lower heat capacitance and higher resolution.

Strong overlap of eV scale electron calorimetry methods and other areas of quantum measurement.
PTOLEMY R&D at LNGS
PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield

R&D effort hosted at the Gran Sasso National Laboratory

Exploring possible future sites that can host telescope operation with a 10mg tritium target (expertise from TLK group)
What will the full-scale (100 g T) experiment look like?

No Longer a Table-Top Experiment at Full Scale

- Estimated target activity on linear scale ~ 1mg T per filter element (~0.1mg/m²)
- Stacking of filter elements depends on optimization of B field flux, cryogenics, vacuum system, microcalorimeter coverage – expect at least ~10,000

**Key property for target/filter:**
- Start in locally high B field at target substrate and transitions into low B field vacuum region – increases electron deflection ~1/B from target to RF region

**Dipole magnet flux return:**
- RF regions have uniform high B field ~3T, this flux can thread several dipole coils in sequence (toroidal flux return)

**Size of RF region:**
- Depends on antenna design and S/N from coherent source

**Target to microcalorimeter distance:**
- Current designs use distances of ~1m, this distance may be able to be reduced

**Low local target activity:**
- No significant advantage to increasing local activity of target, reduces pile-up, improves voltage reference, and increases ease of target handling/safety controls
Circular Geometry
w/ microcalorimeter at center
Hydrogen doping on graphene reveals magnetism.


Polarized Tritium Target

Point at the Sky with Tritium Nuclear Spin

Detection (capture) of cold neutrinos: $d\sigma/d\cos\theta (v/c) \sim (1+\cos\theta)$

Hydrogen doping on graphene reveals magnetism


Akhmedov, 2019. 10.1088/1475-7516/2019/09/031

CGT, G. Zhang, 2021. 10.1088/1475-7516/2021/06/053
Summary

CNB direct detection is at a much more advanced phase than it was 6 years ago
- Basic principles have evolved into concrete designs
- Prototype construction has yielded good results with several publications
- Theoretical interest continues to grow with more and more PTOLEMY citations
- The particle physics community has grown more familiar with quantum material properties and techniques with new and productive collaborations

We hope to enter an exciting new phase with PTOLEMY this year with a rich experimental program focused on achieving CNB detection

PTOLEMY: MPS 2015 Targeted Grant Award from the SIMONS FOUNDATION
Recent Publications and Funding

The Simons Foundation:
https://www.simonsfoundation.org/grant/targeted-grants-in-mps/?tab=awardees

European Funding (NWO – The Netherlands):

Neutrino Physics Program (CNB, Mass, Sterile,...):
Neutrino physics with the PTOLEMY project, M.G. Betti et al.,
JCAP 07 (2019) 047,
DOI: 10.1088/1475-7516/2019/07/047,
e-Print: arXiv:1902.05508

INFN Detector R&D at LNGS:
https://ptolemy.lngs.infn.it

The John Templeton Foundation:
(prior) https://www.templeton.org/grant/the-universe-at-one-second-after-the-big-bang

Transverse Filter Design:
A design for an electromagnetic filter for precision energy measurements at the tritium endpoint,
M.G. Betti et al.,
Prog.Part.Nucl.Phys. 106 (2019) 120-131,
DOI: 10.1016/j/ppnp.2019.02.004,
e-Print: arXiv:1810.06703

Papers in Progress (and many others in R&D):
• Experimental Design of the PTOLEMY Concept
• Low Field Optimization of PTOLEMY Electromagnetic Filter (in progress)
• Multi-Messenger Astrophysics with the Cosmic Neutrino Background (published in JCAP)
PTOLEMY World-Wide Collaboration

Telescopio di neutrini cosmologici
Kosmische neutrino telescoop
Telescopio de neutrinos cósmicos
Kosmisk neutrinoteleskop
Cosmic neutrino telescope

2015 Targeted Grant Award from the Simons Foundation
ADDITIONAL SLIDES
RF Power Distribution


Andy Tan (Princeton)
• Linearity of the solution to Maxwell Eq in CST checked.
• Assign all electrodes (bounce, wire, vacuum chamber, iron and all top ones) to 0 V except the $n^{th}$ one at 100 V (100 is an arbitrary number);
• Generate $E_z^n(z)|_{y=0}$
First 5 Templates

• Except outmost 2 templates on each side, others are:
  – the same under translation, i.e., \( E_{z}^{n+1}(z) = E_{z}^{n}(z + d) \), where \( d \) is the step size (1.25 cm for 80 electrodes);
  – antisymmetric, i.e., \( E_{z}^{n}(z) = -E_{z}^{n}(2z_{n} - z) \), where \( z_{n} \) is the \( z \) of the center of the \( n^{th} \) electrode;

• Therefore, an overall constant shift on the voltage \( \Phi^{n} \) won’t change \( \sum_{n=1}^{80} E_{z}^{n}(z) \) significantly (\( E_{y} \) and \( \Phi \) at \( y = 0 \) will change).
Olber's paradox (1758–1840)

Why is the night sky not bright?

A static copy of the Milky Way Galaxy distributed uniformly over an infinite expanse of space predicts that every direction on the sky ends on the surface of a star.

Light Intensity $\sim 1/r^2$

Number of Stars in Concentric Shells $\sim r^2$

$\text{Light/Star} \times \text{# Stars} \sim \text{Constant}$

---

Celestial Globes

Johann Schöner, c.1534

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

Figure 1: Fluctuations in the Cosmic Microwave Background (CMB). What produced them?

1 The Microscopic Origin of Structure

1.1 TASI 2009: The Physics of the Large and the Small

The fluctuations in the temperature of the cosmic microwave background (CMB) (see Fig. 1) tell an amazing story. Measured now almost routinely by experiments like the Wilkinson Microwave Anisotropy Probe (WMAP), the temperature variations of the microwave sky bear testimony of minute fluctuations in the density of the primordial universe. These fluctuations grew via gravitational instability into the large-scale structures (LSS) that we observe in the universe today. The success in relating observations of the thermal afterglow of the Big Bang to the formation of structures billions of years later motivates us to ask an even bolder question: what is the fundamental microphysical origin of the CMB fluctuations? An answer to this question would provide us with nothing less than a fundamental understanding of the physical origin of all structure in the universe.

In these lectures, I will describe the currently leading working hypothesis that a period of cosmic inflation was integral part of this picture for the formation and evolution of structure. Inflation [1–3],
Past Light-Cone
Recombination
Particle Horizon
Conformal Time
Last-Scattering Surface
Big Bang Singularity

During matter or radiation domination the scale factor evolves as
\[ a(\tau) / (\tau - \tau_{\text{RD}}) \propto (\tau - \tau_{\text{MD}}). \]

If and only if the universe had always been dominated by matter or radiation, this would imply the existence of the Big Bang singularity at \( \tau_i = 0 \).

The conformal diagram corresponding to standard Big Bang cosmology is given in Figure 8. The horizon problem is apparent. Each spacetime point in the conformal diagram has an associated past light cone which defines its causal past. Two points on a given \( \tau = \) constant surface are in causal contact if their past light cones intersect at the Big Bang, \( \tau_i = 0 \). This means that the surface of last-scattering, \( \tau_{\text{CMB}} \), consisted of many causally disconnected regions that won’t be in thermal equilibrium. The uniformity of the CMB on large scales hence becomes a serious puzzle.

During inflation, \( H \propto \text{const.} \), the scale factor is
\[ a(\tau) = H \tau, \]
and the singularity, \( a = 0 \), is pushed to the infinite past, \( \tau_i \to 1 \). The scale factor (60) becomes infinite at \( \tau = 0 \). This is because we have assumed de Sitter space with \( H = \text{const.} \), which means that inflation will continue forever with \( \tau = 0 \) corresponding to the infinite future.

Incredibly Uniform \( \delta \sim 10^{-5} \) at \( z \sim 1100 \)

Common Past?
What Experimental Measurements Support the Big Bang Theory?

1. Hubble Expansion
   Galaxies recede from us (no matter which direction we look) as a linear function of their distance from us:
   \[ \text{Recession Velocity} \sim H_0 \times d \]

Hubble constant (today’s value):
\[ H_0 \sim 70 \text{ km/s per Mpc} \]
(1 Mpc ~ 3.3 million light years)
(67-73 depending on how you measure it)
Looking Back in Time

Le Sphere du Monde (1549)

https://iiif.lib.harvard.edu/manifests/view/drs:18260773$26i
https://gravity.princeton.edu/events/gravity-initiative-opening-celebration-november-7-8-2019

Robbert Dijkgraaf | Public Lecture - November 7, 2019
What Experimental Measurements Support the Big Bang Theory?

2. Big Bang Nucleosynthesis

The ratio of light elements in the Universe are consistent with intense nuclear fusion reactions that ran for a few minutes everywhere in space.

- Helium (A=4) is ~25% by mass while Hydrogen (A=1) is ~74%.
- Lithium (A=7) is ~0.1 ppb by number (off by a factor of 3-4 from Big Bang theory).
What Experimental Measurements Support the Big Bang Theory?

3. Cosmic Microwave Background
The light emitted ~380,000 years after the Big Bang, when the Universe became optically transparent, is a Blackbody spectrum at Microwave Frequencies (~150 GHz) with intensity fluctuations that come from relativistic baryon/photon plasma sound waves!

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

(*frequents Small World Coffee)

New book:

Cosmology’s Century (2020)
Future Measurements!!!

Future #4. Cosmic Neutrino Background

At One Second after the Big Bang, the Universe became transparent to neutrinos and released so many neutrinos that today, there are predicted to be $\sim 330$ neutrinos/cm$^3$.

(whether these “relic” neutrinos are with us in the present and in the correct numbers has never been validated by an experiment)
View of the Sun

~8 min. away
Neutrino view of the Sun
Overall Modeling of Cosmology

Pretty Good on the one hand. 6 Parameters from a fit describe nearly all the general features of the Big Bang.

Not So Good on the other hand. Two physical "entities" were invented to make this work and the origin of the values of the other parameters is not known. A pre-Big Bang existence is required to make it work – and even there, theory disagrees on how to stop it.
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 $0.14 \pm 0.02$. 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 $t \approx 0.14$ 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 24, and an initial value of $t \approx 0.14 \pm 0.03$, 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
Head-On Collision with Andromeda Galaxy

- Head-on collision estimated to start in 4 billion years
- Andromeda Luminal Spiral: ~6 times diameter of Full Moon
- Andromeda Dark Matter Halo: ~100 times diameter of Full Moon

(Image credit: ICRAR)
Expansion rate of the Universe: \( \dot{a} \)

\( \rightarrow \) Kinetic Energy \( \propto \dot{a}^2 \)

Energy density of the Universe:

\( \rightarrow \) Potential Energy \( \propto \rho \)

\[ \rho_{\text{matter}} \propto 1/\alpha^3 \]

sum from all matter, radiation and vacuum energy

\[ \rho_{\text{radiation}} \propto 1/\alpha^4 \]

\[ \rho_\Lambda \propto \text{constant} \]
Neutrinos 48.8%

Electrons/Positrons 32.6%

Neutrinos 41%

Photon Decoupling (t=1 second)

Nuclear (keV)

Big Bang Nucleosynthesis (1 minute)

Baryons 8%

Dark Matter 42%

Atomic (eV)

Matter-Radiation Equality (75,000 years)
Balance of Kinetic and Potential Energy

(ratio) $\Omega = 1.000(3)$ (known to better than 0.3%)

Expansion in a dark energy (cosmological constant) dominated Universe
Cosmic Elements

3 element theory

\[ \gamma \text{ (photons)} \]
\[ \nu \text{ (neutrinos)} \]
\[ p,n \text{ (baryons)} \]

4 element theory

\[ \chi \text{ (cold dark matter)} \]

5 element theory (+Aether/ Void)

\[ \Lambda \text{ (dark energy)} \]
Individual neutrino contributions assuming Normal Hierarchy and 
$
m_3 = 0.05 \text{ eV},$
$
m_2 = 0.009 \text{ eV},$
$
m_1 = 0$
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.

A clumpy universe slowly contracts under pressure, gradually smoothing out.

The smooth, flat contracting universe is saved from fully collapsing and begins to expand instead.

The smooth, flat universe expands — becoming clumpier and more warped over time, until it contracts and starts the cycle over again.
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.

In the early universe, gravity clumps matter together, immediately warping space-time. The curvy, clumpy universe continues to expand forever.

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

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.

A clumpy universe slowly contracts under pressure, gradually smoothing out. The smooth, flat universe expands... becoming clumpier and more warped over time, until it contracts and starts the cycle over again.
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.

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

Big Bang: The universe begins as a tiny uniform patch of space-time that rapidly inflated.

The inflation results in a uniform universe.

Over billions of years, subtle density fluctuations become magnified by gravity.

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

A clumpy universe slowly contracts under pressure, gradually smoothing out. The smooth, flat universe is saved from fully collapsing and begins to expand instead. The smooth, flat universe expands... becoming clumpier and more warped over time, until it contracts and starts the cycle over again.
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

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

A clumpy universe slowly contracts under pressure, gradually smoothing out. The smooth, flat universe is saved from fully collapsing and begins to expand instead. The smooth, flat universe expands... ...becoming clumpier and more warped over time, until it contracts and starts the cycle over again.
In tempi anteriori, la materia era in uno stato noto come “plasma”, elettroni e protoni non erano legati a formare atomi neutri e interagivano mutuamente emettendo e riassorbendo fotoni. In queste condizioni la radiazione elettromagnetica, una volta prodotta, non era libera di viaggiare indisturbata per raggiungere oggi i nostri rivelatori, perché era assorbita e riemessa inesistentemente.

Vi sono due possibilità per studiare l’evoluzione dell’universo in tempi più remoti: usare altre particelle, la cui presenza lasci una traccia, anche se indiretta, su quantità che possiamo osservare direttamente, oppure adoperare il fatto che ogni particella interagisce gravitazionalmente in modo, per così dire, “democratico”, indipendentemente cioè dalla sua particolare natura. L’esempio principe della seconda possibilità è la materia oscura (vd. p. 31, ndr), della cui esistenza abbiamo numerose indicazioni indirette legate al campo gravitazionale che essa produce, senza il quale l’universo ci apparirebbe molto differente da quello che osserviamo.

L’esempio canonico del primo tipo, che è quello che qui ci interessa, è rappresentato invece dai neutrini. Queste particelle, “inventate” dalla fantasia visionaria di Wolfgang Pauli nel 1930 per “salvare” il principio di conservazione dell’energia nel decadimento beta dei nuclei, non finiscono mai di sorprendere i fisici per le loro straordinarie proprietà. Come i fotoni, anche i neutrini popolano l’universo sin dalle origini. A differenza dei primi, interagiscono con le altre particelle soltanto attraverso le interazioni deboli che, come dice il nome, sono molto più flabili di quelle elettromagnetiche. Questo fa sì che il loro ultimo scattering abbia avuto luogo in tempi molto più remoti, addirittura circa un secondo dopo il Big Bang! In quest’epoca, l’universo era in piena attività e i neutrini erano fra gli attori principali: le loro interazioni con protoni, neutroni ed elettroni sono il primo passo che porta alla formazione dei nuclei leggeri (deuterio ed elio). Misurando oggi le abbondanze di questi elementi, tenendo anche conto di quanto è stato prodotto in tempi più recenti dalle stelle, abbiamo un modo per studiare com’era fatto l’universo nei primi secondi della sua vita e per capire meglio le proprietà dei neutrini, in modo complementare agli esperimenti di laboratorio: ad esempio, se il numero di specie di neutrini corrisponde a quanto misurato negli acceleratori (cioè tre) o se ve ne siano più di tre. I neutrini, inoltre, sono dotati di energia e come tali producono un loro campo gravitazionale. Questo influenza, secondo la teoria della relatività generale, la velocità di espansione dell’universo, che pertanto possiamo verificare in tempi così remoti!
Challenges: Resolution and Backgrounds

- Figure 2: Same as Fig. 1 for inverted ordering of neutrino masses.

- Inverted Ordering
Molecular Broadening

\[ T-T \rightarrow (T-\text{He}^3)^* \]

\[ \text{4.7eV} \]

\[ \approx 3\text{eV He}^3 \text{ recoil at endpoint} \]

\[ <3\text{eV binding energy} \]

Graphene
Molecular Broadening

First Tritiated-Graphene Samples Produced by SRNL
Cold Plasma Loading

Figure 3: Probabilities of reflection, transmission, and adsorption as a function of incident kinetic energy.

Figure 4: Positions of reflection, transmission, and adsorption events for the quantum-classical calculations. In a representative graphene hexagon, using SCC-DFTB. Adsorption (left) shows clustering of hydrogen atoms around the lattice carbons. Reflection (center) is most probable at the perimeter of the hexagon where interactions are strongest. Transmission (right) can occur at most points in the lattice for high energies but tends to occur at the hexagon center due to the low barrier.


http://www.nanoscalereslett.com/content/7/1/198

XPS Hydrogenation Results from Princeton

40% H Coverage ➔ World Record

Y. Raitses et al.
RF Sensing

Time Series (~26 GHz)

Power (~0.1 fW)

Luca Ficcadenti
Gran Sasso
National Laboratory, Italy

PTOLEMY kick-off meeting
11-12 December 2017
http://ptolemy.lngs.infn.it
High Radio-Purity Carbon

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

Graphene fabrication from CO$_2$ → CH$_3$OH

Kinder Morgan Doe Canyon CO$_2$ facility in southwestern Colorado
Refractor $\rightarrow$ Reflector Telescopes
Galilean $\rightarrow$ Newtonian

Yerkes (1895)

Atacoma (2010)
MAC-E “Telescope”

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.

\[ \mu = \frac{E}{B} = \text{const.} \]
During inflation, the scale factor (60) becomes $a = 0$ corresponding to the infinite future $\tau = 0$. This means that the surface of last-scattering (recombination) at $\tau_{\text{rec}}$ (Fig. 8) consisted of many causally disconnected regions that won't be in thermal equilibrium billions of years later motivates us to ask an even bolder question: what is the fundamental microphysical origin of the CMB fluctuations? An answer to this question would provide us with nothing less than a fundamental understanding of the physical origin of all structure in the universe.

Anisotropy Probe (WMAP), the temperature variations of the microwave sky bear testimony of fluctuations in the temperature of the cosmic microwave background (CMB) (see Fig. 1) tell us that the fundamental origin of all structure in the universe was integral part of this picture for the formation and evolution of structure. Inflation [1–3], which means $\ddot{a} = 0$, is pushed to the infinite past, $\tau = -\infty$, the scale factor (60) becomes $a = 0$, is always at 45 degrees when it's hard enough to find your way around Chinatown. If and only if the universe had always been dominated by matter or radiation, this would imply the Big Bang singularity. The conformal diagram corresponding to standard Big Bang cosmology is given in Figure 8.

The uniformity of the CMB on large scales hence becomes a serious puzzle. The existence of the study horizons in inflationary cosmology is apparent. Each spacetime point in the conformal diagram has an associated past light cone which defines its causal past. Two points on a given horizon problem is apparent. During inflation ($\tau_i < 0$), the scale factor is $a(\tau) \sim e^{H\tau}$ of a “de Sitter”-like spacetime.
5.1.2 Flatness Problem Revisited
Recall the Friedmann Equation (41) for a non-flat universe

$$1 = \left(\frac{a}{a_H}\right)^2.$$  

If the comoving Hubble radius decreases this drives the universe toward flatness (rather than away from it). This solves the flatness problem! The solution $\ddot{a}/a = 1$ is an attractor during inflation.

5.1.3 Horizon Problem Revisited
A decreasing comoving horizon means that large scales entering the present universe were inside the horizon before inflation (see Figure 2). Causal physics before inflation therefore established spatial homogeneity. With a period of inflation, the uniformity of the CMB is not a mystery.

Figure 7: Left: Evolution of the comoving Hubble radius, $(a_H)^2$, in the inflationary universe. The comoving Hubble sphere shrinks during inflation and expands after inflation. Inflation is therefore a mechanism to 'zoom-in' on a smooth sub-horizon patch. Right: Solution of the horizon problem. All scales that are relevant to cosmological observations today were larger than the Hubble radius until $a \ll 10^{-5}$. However, at sufficiently early times, these scales were smaller than the Hubble radius and therefore causally connected. Similarly, the scales of cosmological interest came back within the Hubble radius at relatively recent times.

5.2 Conditions for Inflation
Via the Friedmann Equations a shrinking comoving Hubble radius can be related to the acceleration and the pressure of the universe

$$\frac{d}{dt} \left(\frac{a}{a_H}\right) < 0 \quad \text{and} \quad \frac{d^2 a}{dt^2} > 0.$$  

The three equivalent conditions for inflation therefore are:

- Nonthermal cosmic neutrino background
- Standard C$
u$B
- $T'_{\text{th}} \approx 412 \text{ cm}^{-3} \cdot 10^{-4} \text{ eV}
- T'_{\text{BBN}} \approx 1.95 \text{ K}
- n'_{\text{th}} \approx 336 \text{ cm}^{-3} \cdot N_e = 3.2 \pm 0.5$

Ade et al. (2016)
5.1.2 Flatness Problem Revisited
Recall the Friedmann Equation (41) for a non-flat universe
\[ \ddot{a} + \frac{1}{a} \dot{a} = \frac{8\pi G}{3} \rho \]
If the comoving Hubble radius decreases this drives the universe toward flatness (rather than away from it). This solves the flatness problem! The solution \( \ddot{a} = 0 \) is an attractor during inflation.

5.1.3 Horizon Problem Revisited
A decreasing comoving horizon means that large scales entering the present universe were inside the horizon before inflation (see Figure 2). Causal physics before inflation therefore established spatial homogeneity. With a period of inflation, the uniformity of the CMB is not a mystery.

Figure 7: Left: Evolution of the comoving Hubble radius, \( (aH)_{1} \), in the inflationary universe. The comoving Hubble sphere shrinks during inflation and expands after inflation. Inflation is therefore a mechanism to 'zoom-in' on a smooth sub-horizon patch.

Right: Solution of the horizon problem. All scales that are relevant to cosmological observations today were larger than the Hubble radius until \( a \sim 10^{-5} \). However, at sufficiently early times, these scales were smaller than the Hubble radius and therefore causally connected. Similarly, the scales of cosmological interest came back within the Hubble radius at relatively recent times.

5.2 Conditions for Inflation
Via the Friedmann Equations a shrinking comoving Hubble radius can be related to the acceleration and the pressure of the universe
\[ \frac{d}{dt} \dot{a} = \frac{8\pi G}{3} \rho - \frac{4\pi G}{3} p \]
The three equivalent conditions for inflation therefore are:
\[ \frac{d^2 a}{dt^2} > 0 \]
\[ \frac{d^2 a}{dt^2} > 0 \]
\[ \frac{d^2 a}{dt^2} > 0 \]
Fastest Growing Black Hole

Recent Discovery!
(Gaia, SkyMapper & WISE)

https://arxiv.org/abs/1805.04317

Primordial Black Hole?


Figure 2:

There is undeniable evidence for the expansion of the universe: the light from distant galaxies is systematically shifted towards the red end of the spectrum, and the observed abundances of the light elements (H, He, and Li) matches the predictions of Big Bang Nucleosynthesis (BBN).

1.2 Structure and Evolution of the Universe

We will calculate explicitly the statistical properties and the scale dependence of the spectrum of density fluctuations produced by inflation. This result provides the input for all studies of cosmological probes that provide us with information about the structure and evolution of the universe. In this sense inflation provides the most dramatic example by which inflation transformed microscopic quantum fluctuations into macroscopic fluctuations in the energy density of the universe. In this sense inflation was integral part of this picture for the formation and evolution of structure. Inflation [1–3], structure formation and is one of the great triumphs of modern theoretical cosmology.

Simons Observatory

The central focus of this lecture series will be to explain in full detail the physical mechanism for the theme of the origin of large scale structure billions of years later motivates us to ask an even bolder question: what is the fundamental microphysical origin of the CMB fluctuations? An answer to this question would provide us with nothing less than a fundamental understanding of the physical origin of all structure in the universe.

The Physics of the Large and the Small
The Cosmic Neutrino Background Anisotropy - Linear Theory

Figure 2. Sky maps of the primary neutrino power spectra, $C_{\Theta l}$, with the dipole included, for $m_\nu = 10^{-5}$ eV (top-left), $10^{-3}$ eV (top-right), $10^{-2}$ eV (bottom-left) and $10^{-1}$ eV (bottom-right). The maps have been generated using random numbers with the HEALPIX package [35].

The massless case (i.e. $10^{-5}$ eV) is consistent with the result of [30]. At high $l$ the spectra are almost identical, and do not depend on the neutrino mass. The reason for this can be understood from the following argument: Above a certain $k$-value, $k_{FS}$, neutrinos are completely dominated by free-streaming and this $k$-value is proportional to $m_\nu$. In order to convert this to an $l$-value one then uses the relation $l_{FS} \sim k_{FS} \chi^*$ (where $\chi^*$ is the comoving coordinate from which the neutrinos originate) and since $\chi^* \propto m_\nu^{-1}$ for non-relativistic particles [36], $l_{FS}$ does not depend on $m_\nu$. Inserting numbers one finds $l_{FS} \sim 100$ which is in good agreement with Fig. 1. At smaller angular scales, $l > l_{FS}$, the anisotropy comes from the Sachs-Wolfe effect during radiation domination.

For smaller $l$-values the anisotropy increases dramatically as the mass increases. This can be understood as follows. As soon as neutrinos go non-relativistic the $\epsilon_k 3_q \psi d \ln f_0$ term in $\dot{\Psi}_1$ begins to dominate the Boltzmann hierarchy evolution. This quickly makes the higher $l$-modes increase as well, and the final amplitude simply depends on the time elapsed after neutrinos go non-relativistic. The effect can be seen in Fig. 3 which shows the evolution of $\Psi_1$, $\Psi_2$ and $\Psi_{10}$ for three different neutrino masses and two different $k$-values. As soon as neutrinos go non-relativistic $\Psi_1$ immediately begins to grow, and the higher $\Psi_l$'s follow with a slight delay for $k = 0$.1 $h$ Mpc$^{-1}$. This exactly matches the low $l$ behaviour seen in Fig. 1.

$m_\nu < 0.00001$ eV

$m_\nu \sim 0.001$ eV

$m_\nu \sim 0.01$ eV

$m_\nu \sim 0.1$ eV
Distance to Last Scattering Surface for Massive Neutrinos

Distance to Last Scattering Surface

Distance to LSS (Mpc/h)

Redshift

Distance (billions light-years)

Cosmic Neutrino Flux (normalized)

Distance to Last Scattering Surface (billions light-years)

http://doi.org/10.1103/PhysRevLett.103.171301
The expansion rate of the Universe appears to be different depending on what is being tracked. The expansion rate is universal.

\[ H_0 = 73.2 \pm 1.3 \text{ km/s/Mpc (late Universe)} \]
\[ H_0 = 67.4 \pm 0.5 \text{ km/s/Mpc (CMB)} \]
Line-of-Sight Calculations

Primordial power spectrum coverage: \( \sim A_s (k/k_{\text{pivot}})^{ns-1} \)

- **CMB:** LSS \( \sim 10^4 \text{ Mpc/h, } k \sim 5 \times 10^{-3} \)
- **CNB:** LSS \( \sim 10^3 \text{ Mpc/h, } k \sim 5 \times 10^{-2} \)

(linear) \( k \)-mode in gravity potential

Detection (capture) of cold neutrinos:
\[ \sigma(v/c) \sim \text{constant} \sim 10^{-44} \text{ cm}^2 \]

Neutrino pile-up from non-rel. velocities

Neutrino velocity \( \sim 2\% \) c at peak

**CNB** angular power spectrum:
\( k \)-modes get highly amplified from \( 1/v^2 \) term, roughly \( [(1/0.02)^2]^2 \sim x10^7 \)

We can see these regions in the optical galactic surveys
Neutrino Flux on the Sky

Cosmic Microwave Background (CMB)

\[ T \sim 2.725 \, \text{K} \]
\[ \sigma_T \sim \sqrt{8000(\mu\text{K})^2} \sim 100 \, \mu\text{K} \]
fluctuations < 0.01%

Cosmic Neutrino Background (CNB)

\[ T \sim 1.95 \, \text{K} \]
\[ \sigma_T \sim \sqrt{10^{10}(\mu\text{K})^2} \sim 10^5 \, \mu\text{K} \]
fluctuations > 1-10%
Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in 1962 [Phys. Rev. 128:3, 1457].

What do we know?
- Gap (2m) constrained to $m < \sim 0.2\text{eV}$ from Cosmology.
- Electron flavor expected with $m > \sim 0.05\text{eV}$ from neutrino oscillations.

Tritium and other isotopes studied for relic neutrino capture in this paper:
Experimental Perspective

Too much rate (need to filter)

Need very high energy resolution ($\sigma \sim m_\nu$)

Small fraction (dynamical selection)

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