Asoke Nath Mitra Memorial Lecture-2026

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Intertwining of Particle Physics and Cosmology: A view from the bridge

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Asoke Nath Mitra

- AN Mitra is remembered as a highly respected researcher with wide ranging interests from particle physics to physics of life, and for a life long commitment to science.

- I last met Asoke around mid seventies when I gave a talk at the Delhi University related to supergravity theory I was working on at that time. I was impressed by the keen interest shown by Asoka in my work.

- Above all I was impressed by his humility, a rare attribute for a physicist of his stature and magnitude.

Intertwining of particle physics and cosmology has a history of over 100 years.

Contents of talk:

1. A brief history of intertwining of particle physics and cosmology
2. Manifest unification of particle physics and gravity in SUGRA models: SUGRA, cosmology, strings.
3. Cosmological anomaly: Hubble tension and particle physics: $\boldsymbol{\Lambda}$CDM$\rightarrow$ $\boldsymbol{\mathcal{Q}}$CDM.
4. Is the cosmological constant $\boldsymbol{\Lambda}$ really a constant?
5. Gravitational waves: General discussion of GW within first order phase transition (FOTP).
6. Pulsar Timing Array signal (NANOGrav, EPTA, PPTA) and supercooled phase transitions.
7. Brief summary.

1. A brief history of intertwining of particle physics and cosmology

Saha ionization equation (1920-21)

- Megnad Saha (1893-1956) was a particle physicist but he applied his knowledge of particle theory to work on ionization in 1920-21 on solar chromosphere and on stellar spectra. He developed what is called the Saha ionization equation[1,2]

- Saha equation plays a role in describing the process of recombination, decoupling of photons from matter and the release of the cosmic microwave background (CMB).

- Years later (in 1966) Phillip James Edwin Peebles employed the Saha equation to predict the primordial abundance of helium-4 [3] which earned him the Nobel Prize in 2019.

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[1] M. Saha, "Ionization in the solar chromosphere," Philosophical Magazine, vol. 40, 1920, pp. 472–488.

[2] M. Saha, "On a Physical Theory of Stellar Spectra," Proceedings of the Royal Society A, vol. 99, 1921, pp. 135–153.

[3] P. J. E. Peebles, "Primordial Helium Abundance and the Primordial Fireball. II," Astrophys. J. 146, 542 (1966).

Chandrasekhar Limit on the mass of white dwarfs in 1931

- Subrahmanyan Chandrasekhar[4] used the degeneracy of electron gas to calculate the maximum mass of stable white dwarfs.

  $$M_{\mathrm{Ch}} \sim \frac{1}{m_e^2}\left(\frac{\hbar c}{G}\right)^{3/2}\frac{1}{m_N^2},$$

  It is a remarkable formula in that $\hbar$ enters in the determination of the maximum white dwarf mass!

- This was a pioneering moment in merging microphysics with macro-physics.
- Chandra's work was initially disputed by A. Eddington which is chronicled in an article by K C Wali[5]

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[4] S. Chandrasekhar, "The Maximum Mass of Ideal White Dwarfs," *Astrophysical Journal*, 74, 81 (1931).

[5] K C Wali,"Chandrasekhar vs Eddington", An Unanticipated Confrontation. "Physics Today, vol. 35, no.10. (October 1982), pp.33-40).

Work on Big Bang Nucleosynthesis (BBN) in 1940's

In the late 1940s, Ralph Alpher, Hans Bethe, George Gamow, and Robert Herman applied nuclear physics to explain the formation of light elements in the early universe.

1. **Ralph Alpher, Hans Bethe, and George Gamow**, 'The Origin of Chemical Elements," Physical Review, 73, 803 (1948). This paper is often referred to as the **'alpha-beta-gamma"** paper and is a milestone in nucleosynthesis theory.

2. Ralph A. Alpher, Robert C. Herman, and George Gamow, "Thermonuclear Reactions in the Expanding Universe," Physical Review, 74, 1198 (1948).

Further work continued

In the 1950's on synthesis of elements in stars

- The work on nucleosynthesis was followed by the synthesis of elements by $\mathbf{B^2FH}$

  M. E. Burbidge, G. R. Burbidge, W. A. Fowler and F. Hoyle, "Synthesis of the elements in stars," Rev. Mod. Phys. 29, 547-650 (1957).

And in the sixties on baryogenesis

- A. D. Sakharov, "Violation of CP invariance, C asymmetry, and baryon asymmetry of the Universe," Pisma Zh. Eksp. Teor. Fiz. 1967,5, 32–35[6].

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[6] Three Sakharov conditions for baryon asymmetry in the universe: (i) Baryon number violation, (ii) C and CP violation, (iii) Departure from thermal equilibrium.

Are Particle physics and cosmology really intertwined at the fundamental level?

- Despite many great successes there was a significant part of the particle physics community in the early days which was skeptical of any fundamental intertwining.
- The main reasoning here was the notion that cosmology is largely driven by gravity while gravity is negligible in analyses of particle physics phenomena. Briefly put the argument was, that cosmology deals with large scales and particle physics with small scales and so these are basically different disciplines.

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- By early nineteen seventies attitude of particle physicists had began to shift after the book **" Gravitation and cosmology" by Steven Weinberg** came out. It was a book written by a particle physicist for particle physicists.
- In the 1975 the work of Richard Arnowitt and myself on extending Einstein gravity to superspace[1] and subsequent works [2],[3] connected gravity more closely to particles physics as providing a framework for unification.

[1] S. Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*, John Wiley & Sons, 1972.

[2]: P.N. and R. L. Arnowitt, "Generalized Supergauge Symmetry as a New Framework for Unified Gauge Theories," Phys. Lett. B **56**, 177-180 (1975).

R. L. Arnowitt, PN and B. Zumino, "Superfield Densities and Action Principle in Curved Superspace," Phys. Lett. B **56**, 81-84 (1975).

[3]: D. Z. Freedman, P. van Nieuwenhuizen and S. Ferrara,"Progress Toward a Theory of Supergravity,"Phys. Rev. D **13**, 3214-3218 (1976).
[4]: S. Deser and B. Zumino, "Consistent Supergravity," Phys. Lett. B **62**, 335 (1976).

Connection of Gauge Supersymmetry to standard Supergravity

- Gauge Supersymmetry has the tangent space group $\boldsymbol{OSp(3,1|4N)}$ and contains a parameter $\boldsymbol{k}$ which acts a metric in the fermionic space, while standard supergravity has the tangent space group $\boldsymbol{O(3,1)\times O(N)}$.

- The gauge supergroup $\boldsymbol{OSp(3,1|4N)}$ is the largest supergroup one has in four-dimensional space-time and it contains $\boldsymbol{O(3,1)\times O(N)}$ as a subgroup. Thus one may go from $\boldsymbol{OSp(3,1|4N)}$ to $\boldsymbol{O(3,1)\times O(N)}$ via a Inonu-Wigner group contraction [7].

- We carried out a geometric contraction of contracting the group and also deduced the dynamical equations of motion of standard supergravity from gauge supersymmetry in the limit $\boldsymbol{k\to 0}$ assuming the particle content to be spin 2 and spin $\boldsymbol{3/2}$ [8]

- Supergravity as a geometry was also later deduced by several others [9].

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[7] E. Inonu and E. P. Wigner. "On the Contraction of groups and their represenations", Proc. Nat. Acad. Sci., 39:510–524, 1953.

[8] PN and Richard L. Arnowitt. "Supergravity and Gauge Supersymmetry", Phys. Lett. B,65:73–77, 1976.

[9] e.g., L. Brink, M. Gell-Mann, P. Ramond and J. H. Schwarz, "Supergravity as Geometry of Superspace," Phys. Lett. B **74**, 336 (1978).

2. Manifest unification of particle physics and gravity in SUGRA models: SUGRA, cosmology, strings.

Gravity and particle physics

- The connection of particle physics to gravity got deeper after it was discovered that in gravity mediated breaking of supersymmetry, the sparticle masses are of gravitational origin. Here one finds that[10]

  $$\tilde{m}_{\text{sparticles}} \sim \kappa m^2$$

  where $\kappa \sim M_{Planck}^{-1}$, and m is an intermediate mass. So here $m \sim 10^{10-11}$ GeV leads to sparticle masses lying in several hundred GeV to several TeV. This means a new spectroscopy exists in the TeV scale consisting of

  Squarks, sleptons, charginos, neutralinos, gluinos

  In mSUGRA model the masses of these particles are determined in terms of just four parameters of the model. So mSUGRA and other SUSY breaking models can be experimentally tested at colliders.

- Furthermore, after mSUGRA with R parity produced a candidate for dark matter in the form of a neutralino $\tilde{\chi}^0$, particle physicists took note, and mSUGRA and its various variants have become candidates for discovery at colliders and in astrophysical and cosmological data.

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[10] A. H. Chamseddine, R. L. Arnowitt and PN, Phys. Rev. Lett. **49**, 970 (1982). R. Barbieri, S. Ferrara and C. A. Savoy, Phys. Lett. B **119**, 343 (1982).

Comparison of SUGRA model with the Standard Model

- **Gauge and Yukawa coupling unification:** In the standard model, extrapolation does bring the gauge coupling constants close to each other at scales of $\mathbf{10^{14} - 10^{15}}$ GeV. However, the meeting of all three at one scale is missed by a wide margin. Within MSSM/mSUGRA the gauge coupling unification does provide greater promise and the couplings do unify within a few percent. The third generation of Yukawa coupling also unify better.

- **Upper limit on the Higgs boson mass in SUGRA:** In the standard model the Higgs boson mass could be as large as $\boldsymbol{O(1)}$ TeV, limited only by unitarity. SUGRA models put an upper bound of about 130 GeV. It is remarkable that the Higgs boson mass was discovered at 125 GeV consistent with SUGRA prediction.

- **Vacuum stability in SUGRA vs in standard model:** With a Higgs boson mass of 125 GeV, in the standard model, vacuum stability is guaranteed only up to RG scale of $\mathbf{10^{10-11}}$ **GeV** with the current measurement of the top quark mass. In supersymmetric models, the quartic couplings of the Higgs are determined by the electroweak gauge couplings, which remain positive up to the Planck scale, and thus guarantee stability of the vacuum up to very high scales.

Further tests of SUGRA

- It is very likely that the **sparticle spectrum is split** so that it includes light as well as heavy particles. Light particles: chargino $\tilde{\chi}^{\pm}$, neutralino χ^0, sleptons $\tilde{\tau}$. Heavy particles: squarks $\tilde{q}$, gluino $\tilde{g}$ and Higgses $H^{\pm}$, A^0. The light particles should be accessible at the high luminosity HL-LHC.

- **Compressed spectrum:** Here the mass difference between the next to lightest sparticle (NLSP) and the lightest (LSP) is small, i.e., $\Delta m = m_{\text{sparticle}} - m_{\chi_1^0}$ is relatively small. If Δm is small enough it could produce a long lived NLSP which could decay inside the detector and be observed.

- Electric dipole moment EDM: **In SM:** $d_e < 10^{-39} e$cm.
  Exp: $d_e < 1.1 \times 10^{-29} e$cm. SUGRA produces an EDM in the observable range.

- **Proton decay:** The mode $p \to \bar{\nu} K^+$ will provide a direct support for SUSY/SUGRA GUTs. **The decay** $p \to e_L^+ + \pi^0$ **while** $p \to e_R^+ + \pi^0$ **is suppressed will provide support for strings** (Friedmann & Witten).

SUGRA and Cosmology

SUGRA dark matter candidates: gravitino, neutralino, axion

- **Gravitino:** Assuming that gravitino has a thermal production and under the constraint that the gravitino relic density does not overclose the universe, Primack and Pagels deduced a bound on its mass so that $\boldsymbol{m_{3/2} \leq O(1\text{keV})}$. More recent analyses put a limit of $\boldsymbol{m_{3/2} \leq O(4.7\text{eV})}$**.**

- **Neutralino:** At colliders, the neutralino can be observed as missing energy, and it can be observed in direct dark matter experiments.There are several experiments investigating neutralino dark matter: LUX-ZEPLIN (LZ), XENONnT, PandaX-4T. The mass limits are model dependent. The neutralino mass could be as low as $\boldsymbol{O(1)}$ GeV or as high as $\boldsymbol{O(1)}$ TeV mass.

- **Ultralight axion:** String theory predicts that axions could be as light as $\boldsymbol{10^{-22}}$ eV [11]. This is sometimes referred to as fuzzy dark matter. Explicit Sugra and string models exhibit this possibility[12].

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[11] Lam Hui, Jeremiah P. Ostriker, Scott Tremaine, and Edward Witten. Ultralight scalars as cosmological dark matter. Phys. Rev. D, 95(4):043541, 2017.

[12] James Halverson, Cody Long, and PN. Ultralight axion in supersymmetry and strings, and cosmology at small scales. Phys. Rev. D, 96(5):056025, 2017.

SUGRA and strings

- The connection between superstring and SUGRA was noticed in the work of Candelas et al. early on [13]. The analysis was for the $\boldsymbol{E_8 \times E_8}$ heterotic string, and they indicated that one of the $\boldsymbol{E_8}$ could be the hidden sector where supersymmetry is broken as is done in sugra models.

- The connection of supergravity with strings goes much deeper. Thus for each of the string theories, Type IIA, Type IIB, Type I and heterotic, we have associated supergravities.

- Now string theory in the low energy limit gives 10 dimensional supergravity coupled to supersymmetric Yang-Mills which contains both a Yang-Mills Chern-Simon's form as well as a Lorentz-group Chern-Simons form so that the derivative of the massless anti-symmetric field $\boldsymbol{B_{IJ}}$ in 10 dimensional supergravity takes the form[14]

$$\boldsymbol{\partial_{[K} B_{IJ]} \to \partial_{[K} B_{IJ]} + \omega^{(Y)}_{KIJ} - \omega^{(L)}_{KIJ}}$$

- Couplings of the above type contain a Stueckelberg mechanism for mass growth for the gauge bosons without the Higgs mechanism.

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[13] P. Candelas, G. T. Horowitz, A. Strominger and E. Witten, Nucl. Phys. B **258**, 46-74 (1985).

[14] Michael B. Green and John H. Schwarz, Anomaly cancellations in supersymmetric d= 10 gauge theory and superstring theory. Physics Letters B, 149:117–122, 1984.

Stueckelberg extension of the standard model[15]

- The Stueckelberg mechanism is a phenomenon in which an Abelian gauge boson can become massive by absorbing an axionic field without spontaneous symmetry breaking: $\boldsymbol{A_\mu + \frac{1}{m}\partial_\mu \sigma}$.

- The 10-d kinetic term for the tensor $\boldsymbol{B_{IJ}}$ along with the Yang-Mills Chern-Simons term can be expanded in the form

$$\boldsymbol{\partial_{[I} B_{JK]} + A_{[I} F_{JK]} + \cdots}\,.$$

- In dimensional reduction from $\mathbf{10} \rightarrow \mathbf{4}$ dimensions, the use of the expectation value of the internal gauge field strengths $\boldsymbol{< F_{ij} > \neq 0}$ leads to the form

$$\boldsymbol{\partial_\mu B_{ij} + A_\mu F_{ij}}.$$

  If we identify $\boldsymbol{B_{ij}}$ as the axionic scalar and $\boldsymbol{< F_{ij} >}$ as the mass parameter $\boldsymbol{m}$, we arrive at the combination $\boldsymbol{\partial_\mu \sigma + m A_\mu}$, which is the Stueckelberg combination.

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[15] B. Kors and P. Nath, Phys. Lett. B **586**, 366-372 (2004).

Stueckelberg extension and milli-charges

- **Milli charges** do not exist in the standard model or in grand unified theories.
- **Witten effect**[16]: Witten showed that in a non-abelian gauge theory with a $\boldsymbol{\theta}$ term: $\frac{\theta}{32\pi^2} F_\mu \tilde{F}^{\mu\nu}$, a magnetic monopole acquires an electric charge and becomes a dyon:

$$q = ne + \frac{e\theta}{2\pi}.$$

However, experimentally $|\theta_{\mathrm{QCD}}| \lesssim 10^{-10}$ which leads to $\Delta q \leq 10^{-11} e,$ which is too small to be observed.

- **Stueckelberg extension of the hidden sector** naturally leads to milli-charges for fields in the hidden sector[17]. They arise from the Stueckelberg mass mixing of B_μ (hypercharge field) and A_μ (stueckelberg field) and the charges can be much larger.
- An application of milli charges arises in explaining the **EDGES anomaly** where the 3% of milli-charged dark matter can produce enough baryon cooling to explain the EDGES effect at redshift of $z \sim 17$. [18]

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[16] E. Witten, Nuclear Physics B 149 (1979)285.

[17] Boris Kors, PN Phys. Lett. B, 586:366–372, 2004.

[18] A. Aboubrahim, PN, and Zhu-Yao Wang. A cosmologically consistent millicharged dark matter solution to the EDGES anomaly of possible string theory origin. JHEP, 12:148, 2021.

EDGES: Experiment to Detect the Global Epoch of Reionization Signature[19]

- EDGES is a radio astronomy experiment designed to measure signals from the early universe, specifically the so-called *21-cm line* of neutral hydrogen.

- This signal allows us to probe the time when the first stars formed, roughly a few hundred million years after the Big Bang.

- EDGES found that the hydrogen gas in the early universe appeared to be cooler than predicted by **Λ**CDM.

  The discrepancy between the observed and the expected cooling of baryons is known as the EDGES anomaly.

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[19] Located at the Murchison Radio-astronomy Observatory (MRO) in the desert of Western Australia.

Leading Experiments Searching for Millicharged Particles

- A dedicated detector near CMS searching for millicharged particles produced in proton–proton collisions.
  Reference:
  S. Alcott et al., "Search for millicharged particles in proton-proton collisions at $\boldsymbol{\sqrt{s} = 13.6}$ TeV,"
  Phys. Rev. Lett. 135, 121802 (2025).

- L. Barak et al. (SENSEI Collaboration),
  "Search for Millicharged Particles Produced in the NuMI Beam,"
  Phys. Rev. Lett. 133, 071801 (2024).

- R. Acciarri et al. (ArgoNeuT Collaboration),
  "Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab,"
  arXiv:1911.07996.

- A forward detector concept designed to search for millicharged particles produced in the far-forward region at the LHC.
  M. Citron et al., "FORMOSA: A Forward Search Experiment for Millicharged Particles."

Cosmological phenomena where particle physics and cosmology are fully merged

- Hubble tension.
- DESI data on equation of state of dark energy which indicates possible deviation from the standard model of cosmology, i.e., $\mathbf{\Lambda}$CDM model.
- Gravitational waves.

3. Cosmological anomaly: Hubble tension and particle physics: ΛCDM $\rightarrow$ $\mathcal{Q}$CDM.

Cosmological data related to measurements of H_0 and Λ

- **Planck + Lensing:** Results from Planck satellite, combined with gravitational lensing measurements of the cosmic microwave background (CMB).
- **BAO**(Baryon Acoustic Oscillations).
- **PantheonPlus:** Compilation of Type Ia supernova data.
- **Union3:** Another large compilation of Type Ia supernova data.
- **DESY5**: (Dark Energy Survey Year 5). It uses multiple probes including weak gravitational lensing, galaxy clustering, and supernovae to constrain cosmological parameters, specifically those related to dark energy.
- **DESI** (Dark Energy Spectroscopic Instrument): Measures redshifts of millions of galaxies and quasars.
- **SHOES** (Supernovae and H_0 for the Equation of State): SHOES is a program that measures the Hubble constant using a distance ladder approach.
- **WiggleZ:** WiggleZ is a galaxy redshift survey that mapped large-scale structure and measured BAO at intermediate redshifts. It provided important constraints on dark energy and the growth of cosmic structure.
- **Cepheids** are highly luminous, pulsating stars that brighten and dim in regular cycles, serving as vital ”standard candles” for provide cosmic distance ladder.

The Standard Cosmological Model

- The current cosmological model is $\mathbf{\Lambda}$CDM

$$S_{\Lambda\mathrm{CDM}} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{16\pi G}(R-2\Lambda)+\mathcal{L}_{\mathrm{CDM}}\right].$$

$\mathbf{\Lambda}$CDM is successful but there are issues to resolve.

  - H_0 anomaly:
    Measurements at high redshift[20], $z > 1000$ (CMB, BAO) give

$$H_0 = (68.53 \pm 0.80) km/s/Mpc$$

  - Measurements at low redshift $z < 1-2$. Thus SH0ES collaboration using Cepheids and supernovae gives

$$H_0 = (73.04 \pm 1.04) km/s/Mpc$$

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[20] Redshift z is related to the scale factor a of the universe as $z = 1/a - 1$.

Possible solutions to resolving H_0 anomaly

There are several suggested approaches.

- A simple possibility is having extra relativistic degrees of freedom present during recombination, which would cause an increase in $\boldsymbol{H_0}$ and bring it closer to its measured local value but at the same time not impact BBN.
- One finds that the discrepancy between high redshift and low redshift measurements can be aleviated if

  $$\mathbf{0.2} \leq \boldsymbol{\Delta N_{eff}} \leq \mathbf{0.5}$$

  using CMB, BAO data.
- Thus, for example, a hidden sector with feeble coupling to the visible sector can provide the desired degrees of freedom where a massive scalar particle decays after BBN time to light pseudo-scalar fields[21].

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[21] A. Aboubrahim, M. Klasen and PN, JCAP **04**, no.04, 042 (2022).

Replace ΛCDM with a dynamical field-quintessence

- Quintessence is generally treated as a scalar field couples with dark matter.
- The first work to my knowledge on dark energy interacting with dark matter in a Lagrangian approach was given by Farrar and Peeble in 2004[22]. However, this paper did not provide a general formalism for analysis of DE-DM interaction.
- In the absence of a general formalism based on an action principle, a common approach often taken is to use fluid equations which involve energy densities along with sources. Thus for dark energy field ϕ and dark matter field χ one writes

$$\begin{aligned} \rho'_\phi + 3\mathcal{H}(1+w_\phi)\rho_\phi &= Q \\ \rho'_\chi + 3\mathcal{H}(1+w_\chi)\rho_\chi &= -Q, \end{aligned}$$

where $w = p/\rho$ is the equation of state (EoS). The choice $\pm Q$ on the right hand is done to ensure that energy is conserved. This set up has been used for **the past quarter century**. However, this set up is **inconsistent with diffeomorphism**[23].

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[22] G. R. Farrar and P. J. E. Peebles, Astrophys. J. **604**, 1-11 (2004).

[23] Aboubrahim and PN, JCAP **09**, 076 (2024).

ΛCDM $\to$ $\mathcal{Q}$CDM[24]

A theory of quintessence interacting with dark matter

$$\rho'_\phi + 3\mathcal{H}(1+w_\phi)\rho_\phi = Q_\phi$$

$$\rho'_\chi + 3\mathcal{H}(1+w_\chi)\rho_\chi = Q_\chi\,,$$

$$Q_\phi + Q_\chi = V'_{int},$$

$$\rho = \rho_\phi + \rho_\chi - V_{int}$$

$$\rho' + 3\mathcal{H}(1+w)\rho = 0.$$

$$\Omega_{0i} = \frac{\rho_i}{\rho_{0,\mathrm{crit}}}(1-\delta_i), \qquad \sum_i \Omega_{0i} = 1, \qquad \delta_i = \frac{\sum_{j\neq i} V_{ij}}{\sum_j \rho_j}.$$

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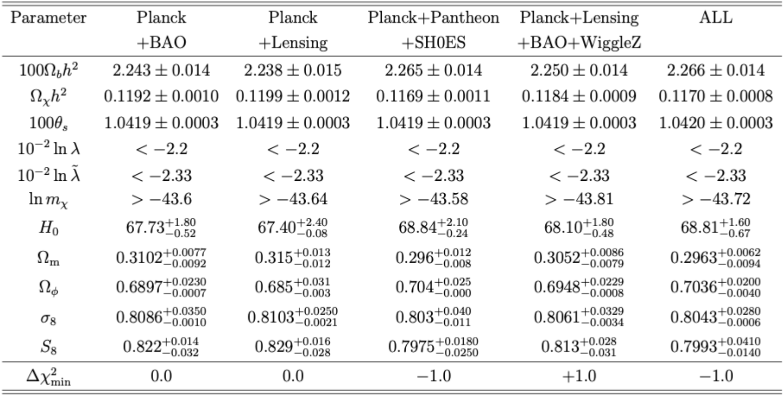
[24] Aboubrahim and PN, JCAP **09**, 076 (2024).

An illustrative model with dark energy-dark matter interaction

$$\begin{aligned} V(\phi,\chi) &= V_1(\chi)+V_2(\phi)+V_3(\phi,\chi), \\ V_1(\chi) &= \frac{1}{2}m_\chi^2\chi^2+\frac{\lambda}{4}\chi^4 && \text{(DM)} \\ V_2(\phi) &= \mu^4\left[1+\cos\left(\frac{\phi}{F}\right)\right] && \text{(DE)}, \\ V_3(\phi,\chi) &= \frac{\tilde{\lambda}}{2}\chi^2\phi^2, && \text{(DM/DE interaction)} \end{aligned}$$



Parameter	Planck +BAO	Planck +Lensing	Planck+Pantheon +SH0ES	Planck+Lensing +BAO+WiggleZ	ALL
$100\Omega_b h^2$	2.243 ± 0.014	2.238 ± 0.015	2.265 ± 0.014	2.250 ± 0.014	2.266 ± 0.014
$\Omega_\chi h^2$	0.1192 ± 0.0010	0.1199 ± 0.0012	0.1169 ± 0.0011	0.1184 ± 0.0009	0.1170 ± 0.0008
$100\theta_s$	1.0419 ± 0.0003	1.0419 ± 0.0003	1.0419 ± 0.0003	1.0419 ± 0.0003	1.0420 ± 0.0003
$10^{-2}\ln\lambda$	< -2.2	< -2.2	< -2.2	< -2.2	< -2.2
$10^{-2}\ln\tilde{\lambda}$	< -2.33	< -2.33	< -2.33	< -2.33	< -2.33
$\ln m_\chi$	> -43.6	> -43.64	> -43.58	> -43.81	> -43.72
H_0	$67.73^{+1.80}_{-0.52}$	$67.40^{+2.40}_{-0.08}$	$68.84^{+2.10}_{-0.24}$	$68.10^{+1.80}_{-0.48}$	$68.81^{+1.60}_{-0.67}$
$\Omega_{\rm m}$	$0.3102^{+0.0077}_{-0.0092}$	$0.315^{+0.013}_{-0.012}$	$0.296^{+0.012}_{-0.008}$	$0.3052^{+0.0086}_{-0.0079}$	$0.2963^{+0.0062}_{-0.0094}$
Ω_ϕ	$0.6897^{+0.0230}_{-0.0007}$	$0.685^{+0.031}_{-0.003}$	$0.704^{+0.025}_{-0.000}$	$0.6948^{+0.0229}_{-0.0008}$	$0.7036^{+0.0200}_{-0.0040}$
σ_8	$0.8086^{+0.0350}_{-0.0010}$	$0.8103^{+0.0250}_{-0.0021}$	$0.803^{+0.040}_{-0.011}$	$0.8061^{+0.0329}_{-0.0034}$	$0.8043^{+0.0280}_{-0.0006}$
S_8	$0.822^{+0.014}_{-0.032}$	$0.829^{+0.016}_{-0.028}$	$0.7975^{+0.0180}_{-0.0250}$	$0.813^{+0.028}_{-0.031}$	$0.7993^{+0.0410}_{-0.0140}$
$\Delta\chi^2_{\rm min}$	0.0	0.0	-1.0	$+1.0$	-1.0

Table: Fits to cosmological data with **Q**CDM and comparison with **Λ**CDM[25]. The lowermost row shows $\boldsymbol{\Delta\chi^2_{\rm min} = \chi^2_{{\rm min},\mathcal{Q}{\rm CDM}} - \chi^2_{{\rm min},\Lambda{\rm CDM}}}$.

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[25] Aboubrahim and PN, JCAP **09**, 076 (2024).

4. Is the cosmological constant Λ really a constant?

DESI DR2 $w_0 - w_a$ plot [26]

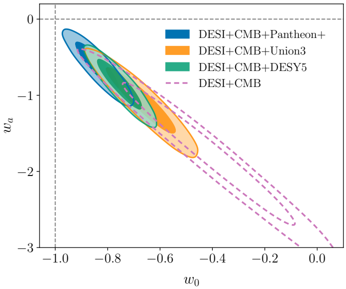

Fig.3: Distributions of $\boldsymbol{w_0}$ and $\boldsymbol{w_a}$, from fits of the CPL model to DESI in combination with CMB and three SNe datasets. The contours enclose 68% and 95% of the posterior probability. Intersection of dashed lines is $\boldsymbol{\Lambda}$CDM.

In the analysis DESI uses Chevallier-Polarski-Linder (CPL) equation of state (EoS) parameterization

$$\boldsymbol{w(a) = w_0 + (1 - a)w_a.}$$

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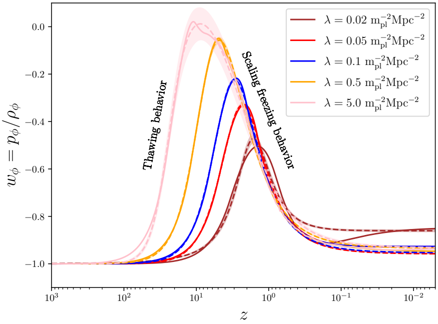
[26] M. Abdul Karim et al. [DESI], [arXiv:2503.14738 [astro-ph.CO]].

We have done an independent analysis using an equation of state given by[27]

$$\boldsymbol{w(a) = -1 + \frac{\alpha\, a^p e^{-p\, a}}{1 + (\beta a)^q}}, \tag{1}$$

where $\boldsymbol{a}$ is the scale parameter, and $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{p}$ and $\boldsymbol{q}$ are the fit parameters. This parametrization exhibits the phenomenon of quintessence transmutation, where quintessence transmutes from thawing at early times to scaling freezing at late times.



The solid lines are $\boldsymbol{w_\phi}$ predicted by QCDM and the dashed lines are fits based on Eq. (1) including a $\boldsymbol{1\sigma}$ error band around each curve. In each case, quintessence transmutes from thawing (left shoulder) to scaling freezing (right shoulder) induced by $\boldsymbol{\lambda}$.

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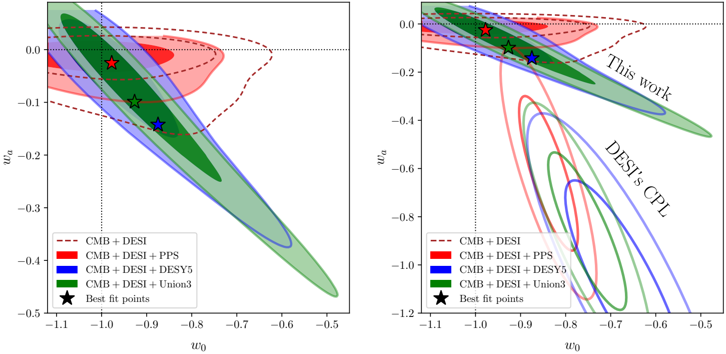
[27] A. Aboubrahim and PN, JCAP **10**, 081 (2025).

Full $\mathcal{Q}$CDM analysis for three sets of data [28]



Caption: Left panel: Results for the distributions of $\boldsymbol{w_0}$ and $\boldsymbol{w_a}$ for the three data set combinations: CMB+DESI+PPS (red contours), CMB+DESI+DESY5 (blue contours) and CMB+DESI+Union3 (green contours). The intersection of the dashed vertical and horizontal lines corresponds to $\boldsymbol{\Lambda}$CDM ($\boldsymbol{w_0 = -1}$ and $\boldsymbol{w_a = 0}$). Right panel: same as left panel with the addition of DESI's (unfilled) contours.

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[28] A. Aboubrahim and PN, JCAP **10**, 081 (2025); A. Aboubrahim, A. H. Giman and P. Nath, [arXiv:2511.22559 [astro-ph.CO]].

5. Gravitational waves: General discussion of GW within first order phase transition (FOTP).

Gravitational waves and fundamental physics

The observation of gravitational waves in black hole mergers in 2016 [29] opened up a new avenue to explore fundamental physics.

- There are various possible sources of gravitational waves
  - Compact binary inspiral gravitational waves (LIGO).
  - Continuous GW (from spinning neutron stars).
  - GWs from Gamma Ray Bursts (GRB's) and possibly from other sources of unknown origin.
  - Stochastic GW.
- Stochastic GW could reveal fundamental new physics
  - Inflation
  - Cosmic strings, primordial black hole evaporation.
  - **Cosmic phase transitions, specifically First Order Phase Transition (FOPT).**

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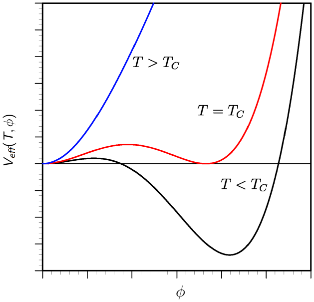
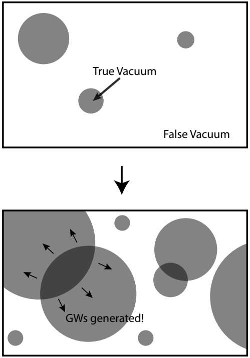
[29] B. P. Abbott *et al.* [LIGO Scientific and Virgo], Phys. Rev. Lett. **116**, no.6, 061102 (2016).

The First-order Phase Transition





Gravitational Wave Detectors

1. **LIGO (Laser Interferometer Gravitational-Wave Observatory, USA)**
   First detector to directly observe gravitational waves in 2015.
2. **Virgo, Italy:**
   Operational (Advanced Virgo with ongoing upgrades).
3. **KAGRA (Kamioka Gravitational Wave Detector, Japan)**
   Operational / commissioning.
4. **LISA (Laser Interferometer Space Antenna, ESA/NASA)**
   Planned mission (ESA/NASA, expected 2030s launch).
5. **GEO600, Germany:**
   Operational (R&D-focused, lower sensitivity than LIGO/Virgo).
6. **LIGO-India:**
   A third LIGO detector to improve global network sensitivity and localization.
   Approved / under construction.
7. **Einstein Telescope (ET), Europe**
   Proposal / planning stage.
8. **Cosmic Explorer, USA**
   Proposal / conceptual design stage.
9. **DECIGO (DECi-hertz Interferometer Gravitational Wave Observatory, Japan)**
   Proposal / long-term planning stage.
10. **BBO (Big Bang Observer, NASA)**
    Conceptual / proposal stage (NASA study).
11. **μAres (Micro-Ares, Space based)**
    Early concept / proposal stage.
12. **Taiji, China**
    Planned / technology development phase.

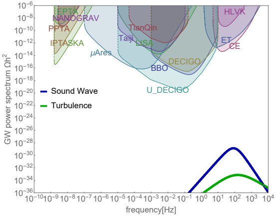
Nano-Hertz Gravitational Wave Experiments

- **NANOGrav** (North American Nanohertz Observatory for Gravitational Waves). Data is collected at the Arecibo Observatory Green Bank Telescope in USA.

- **EPTA** (European Pulsar Timing Array). Data collected at Effelsberg Radio Telescope and the Lovell Telescope at Jodrell Bank.

- **PPTA** (Parkes Pulsar Timing Array). Data collected at Parkes Observatory (Murriyang-Australia).

Stochastic gravitational waves from the standard model



- The standard model of particle physics does not produce a strong enough gravitational wave measurable by current/proposed detectors.

$$\boldsymbol{\Omega_{GW} h^2 \leq 10^{-28}} \qquad \text{(reach of standard model)}.$$

$$\boldsymbol{\Omega_{GW} h^2 \geq 10^{-20}} \qquad \text{(reach of proposed detectors)}.$$

- **BSM physics and extended SM with hidden sectors can generate GW in the observable range. We will focus on GW arising from first order phase transitions (FOTP).**

FOTP analysis involves temperature dependent potentials

- The potential governing the FOPT involves, tree, the zero-temperature 1-loop Coleman-Weinberg potential, and the one loop thermal potential, and daisy diagrams[30]

$$V^{\mathrm{h}}_{\mathrm{eff}}(\Phi, \mathrm{T_h}) = V_{0h} + V^{(0)}_{1h} + \Delta V^{(T_h)}_{1h} + V^{\mathrm{daisy}}_{h}(T_h)\,,$$

$$\Delta V^{(T_h)}_{1h}(\chi_c, T_h) = \sum_i g_i \int_0^\infty \mathrm{d}q\, q^2 \ln\left[1 \mp \exp\left(-\sqrt{q^2 + m_i^2/T_h^2}\right)\right], \quad i = (B, F)\,.$$

- The daisy loop contributions are only for the scalars and for the longitudinal mode of vectors. The temperature dependent potential is given by

$$V^{\mathrm{daisy}}(i, T_h) = -\frac{T_h}{12\pi}\left\{\left[m_i^2 + \Pi_i(T_h)\right]^{3/2} - m_i^3\right\}.$$

Here $\Pi_i(T_h)$ is the thermal contribution to the zero temperature mass m_i^2 arising from "daisy" diagrams and known as the "Debye mass". It can be computed using Matsubara and Kubo-Martin-Schwinger imaginary time formalism[31]

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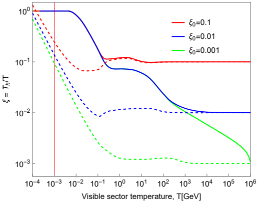
[30] W. Feng, J. Li and PN, Phys. Rev. D **110**, no.1, 015020 (2024).

[31] T. Matsubara, Prog. Theor. Phys. **14**, 351-378 (1955); R. Kubo, J. Phys. Soc. Japan 12 (1957) 570; P.C. Martin and J. Schwinger, Phys. Rev. 115 (1959) 1342.

Thermal evolution of hidden and visible sectors

- In most previous analyzes, thermal evolution of visible and of hidden sector has been evolved independently assuming entropy conservation of each sector.
- However, it is reasonable to assume that there is feeble couplings (via kinetic mixing or Stueckelberg mass mixing). In this case the effects at low temperatures can be very significant.
- The parameter that determines the synchronous evolution by $\boldsymbol{\xi}$ defined by[32]

$$\boldsymbol{\xi = T_h/T.}$$



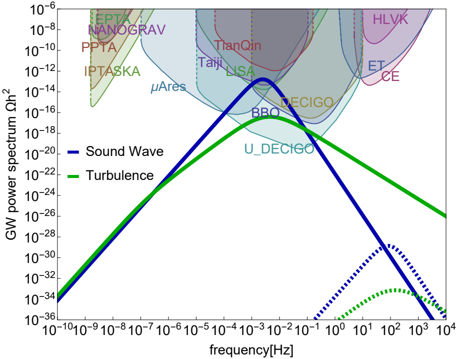
- The relativistic degrees of freedom generated by the hidden sector dark photon is given by

$$\boldsymbol{\Delta N_{eff} \simeq \frac{12}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \xi^4.}$$

---

[32] A. Aboubrahim, W. Z. Feng, PN, Z. Y. Wang, Phys. Rev. D **103**, no.7, 075014 (2021).

Contributions of sound waves and turbulence to the power spectrum [33]



Solid lines: Hidden sector. Dashed lines: Visible sector. $\boldsymbol{\epsilon_{\text{turb}} = 0.1}$.

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[33] W. Feng, J. Li and PN, Phys. Rev. D **110**, no.1, 015020 (2024).

6. Pulsar Timing Array signal (NANOGrav, EPTA, PPTA) and supercooled phase transitions.

The first gavitational wave signal since the Ligo observation in 2016 is in the nano-Hertz region

- Recently a signal in the Pulsar Timing Array in the nano-Hertz range ($\mathbf{10^{-10} - 10^{-8}}$)Hz has been observed by NANOGrav[34], EPTA[35], and PPTA[36].
- Within the first order phase transition, generating a gravitational signal with sufficient power spectrum to be in NANOGrav et.al. region, requires a supercooled phase transition.

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[34] G. Agazie *et al.* [NANOGrav], Astrophys. J. Lett. **951**, no.1, L8 (2023)

[35] J. Antoniadis *et al.* [EPTA and InPTA:], Astron. Astrophys. **678**, A50 (2023).

[36] D. J. Reardon, A. Zic, R. M. Shannon, G. B. Hobbs, M. Bailes, V. Di Marco, A. Kapur, A. F. Rogers, E. Thrane and J. Askew, *et al.* Astrophys. J. Lett. **951**, no.1, L6 (2023).

Supercooled Phase Transition

A supercooled phase transition occurs when the transition happens at temperature $\boldsymbol{T_*}$ much lower than the critical temperature $\boldsymbol{T_c}$, i.e., $\boldsymbol{T_*/T_c \ll 1}$. This idea was first proposed by A. H. Guth in early 1980s [37] in the context of cosmology and followed by others including Stephen Hawking [38].

A supercooled phase transition is determined by the following set of parameters

- $\boldsymbol{T_n}$: Nucleation temperature.
- $\boldsymbol{T_p}$: percolation temperature.
- $\boldsymbol{\alpha}$: Defined by $\boldsymbol{\alpha = \Delta\rho/\rho_{rad}(T_*)}$, $\boldsymbol{\Delta\rho \equiv \rho_{\text{false}} - \rho_{\text{true}}}$ where $\underline{\boldsymbol{T_*}}$ is the temperature of phase transition which is taken to be the percolation temperature.
- $\boldsymbol{\beta}$: The inverse time scale of the phase transition which determines how fast the phase transition occurs.
- $\boldsymbol{v_w}$: The bubble wall velocity which determines the bubble expansion.
- $\boldsymbol{\kappa}$: Efficiency coefficient which determines the fraction of the vacuum energy transferred into the fluid bulk kinetic energy.

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[37] A.H. Guth (1981), Physical Review D, 23(2), 347–356.

[38] S. W. Hawking and I. G. Moss, Phys. Lett. B **110**, 35-38 (1982).

- In order to explain NANOGrav data via FOTP we need the phase transition to be supercooled FOTP. Typically GW frequency in FOTP is

$$f \sim 10^{-4}\frac{\beta/H}{100}\left(\frac{T}{100\text{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}\text{Hz}.$$

  The above indicates that for $f \sim 10^{-10} - 10^{-8}$ one needs $T \sim O(1)$ MeV, i.e., the FOTP needs to be supercooled.

- Subsequent to the nano-Hz data several works appeared to explain the observed effect in BSM in supercooled phase transitions.
- A more recent work[39] pointed to challenges typically ignored in supercooled phase transitions:
  - Such a late transition risks interfering with Big Bang Nucleosynthesis (BBN)
  - The energy release and entropy injection from the transition must not spoil the light element abundances.
  - Transition may be too slow and never complete.
- All the above challenges have been overcome in more recent work by inclusion of hidden sectors and taking synchronous thermal evolution into account[40].

---

[39] P. Athron, A. Fowlie, C. T. Lu, L. Morris, L. Wu, Y. Wu and Z. Xu, “Can Supercooled Phase Transitions Explain the Gravitational Wave Background Observed by Pulsar Timing Arrays?,” Phys. Rev. Lett. **132**, no.22, 221001 (2024).

[40] J. Li and P.N., Phys. Rev. D **111**, no.12, 123007 (2025).

Strength of gravitational wave production

$$\boldsymbol{\alpha = \frac{\Delta\rho_{\rm vac}}{\rho_{\rm rad}}, \quad \Delta\rho = \rho_{\rm false} - \rho_{\rm true}} \qquad \text{(latent heat)}$$

The critical strength $\boldsymbol{\alpha_\infty}$ is defined so that

$$\boldsymbol{\alpha_\infty \equiv \frac{\Delta V - \sum_i \frac{c_i}{24} m_i^2(\phi) T^2}{\rho_{\rm rad}},}$$

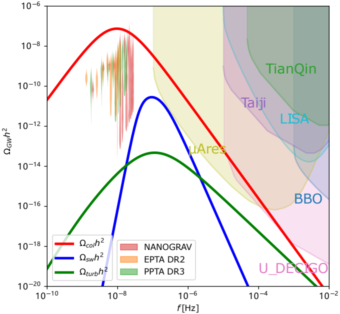
where $\boldsymbol{\Delta V}$ is the vacuum energy difference across the wall, and $\boldsymbol{m_i(\phi)}$ are the field-dependent particle masses.

1. $\boldsymbol{\alpha < \alpha_\infty}$: Bubble walls reach a terminal velocity (non-runaway). Here most of the released energy goes into bulk fluid motion, i.e., sound waves and turbulence, which contribute to gravitational waves.

2. $\boldsymbol{\alpha > \alpha_\infty}$: Bubble walls run away, i.e., accelerating indefinitely, and the excess energy is deposited in the scalar field gradients at the wall (runaway). In this case bubble collisions dominate the dominate gravitational waves.

3. Thus, $\boldsymbol{\alpha_\infty}$ marks the transition between the fluid-dominated and vacuum-dominated regimes of gravitational wave production.

Contributions to the GW Signal



The three primary contributions to the GW signal for BP3:

Red: bubble collisions
Blue: sound waves
Green: turbulence

Bubble collisions make the dominant contribution in the nano-Hertz region[41]. .

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[41] J. Li and P.N., Phys. Rev. D **111**, no.12, 123007 (2025).

7. Brief summary

In all of the discussions in this talk particle physics enters in a central way in the analysis of cosmological anomalies and phenomena:

- Hubble tension
- DESI results indicating EoS of dark energy may be time dependent.
- Stochastic gravitational waves.
- In the above we see the intertwining of particle physics and cosmology at the very fundamental level and the trend points towards a likely unification of all natural laws.

Mitra's last paper on the arXiv.
"Symmetry-cum-Unification in physical theories"
A.N. Mitra (2014)
Published in: Nucl.Phys.B Proc.Suppl. 251-252 (2014) 22-26

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