Did the universe bang or bounce?

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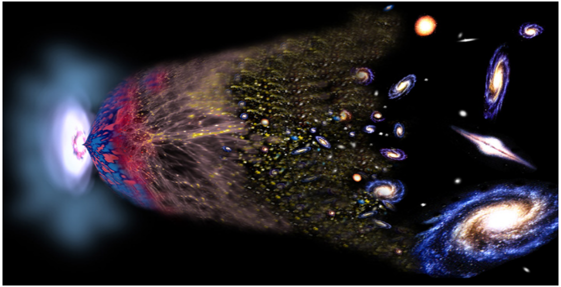

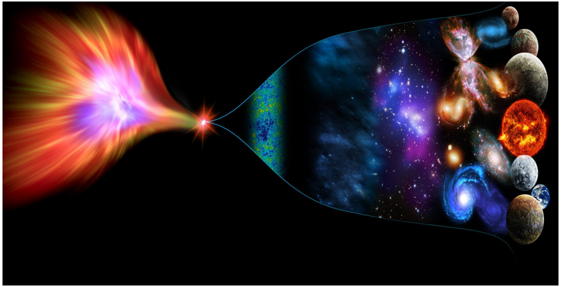

Seminar, Bharathidasan University, Tiruchirappalli

March 13, 2020

Plan of the talk

1. The hot big bang model

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2. The inflationary paradigm

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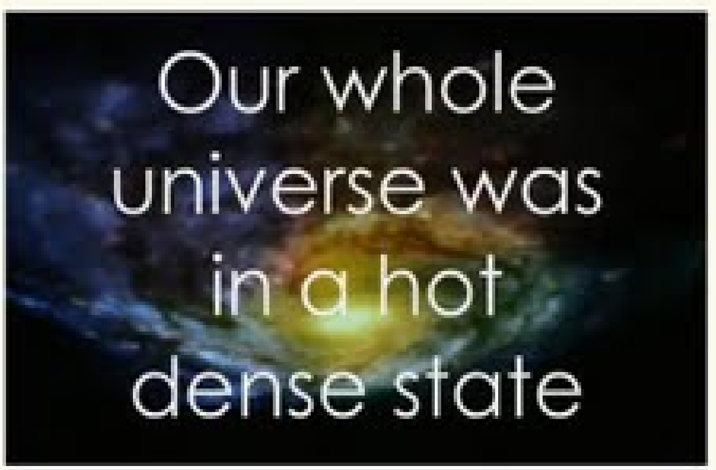
3. The bouncing scenario

Plan of the talk

1. The hot big bang model
2. The inflationary paradigm
3. The bouncing scenario
4. Outlook

Plan of the talk

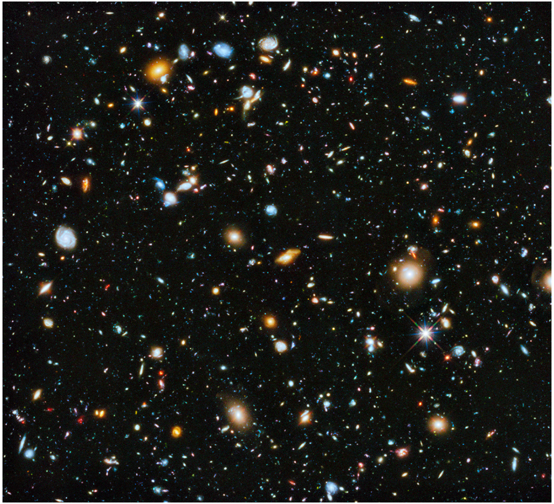
The big bang model seems popular!



The current view of the universe, encapsulated in the hot big bang model, seems popular. The above image is a screen grab from the theme song of the recent American sitcom 'The Big Bang Theory'[1]!

[1] See http://www.cbs.com/shows/big_bang_theory/.

Deepest views in space



An ultra deep field image from the Hubble Space Telescope. The image contains a bewildering variety of galaxy shapes and colors[2].

[2]Image from http://hubblesite.org/newscenter/archive/releases/2014/27.

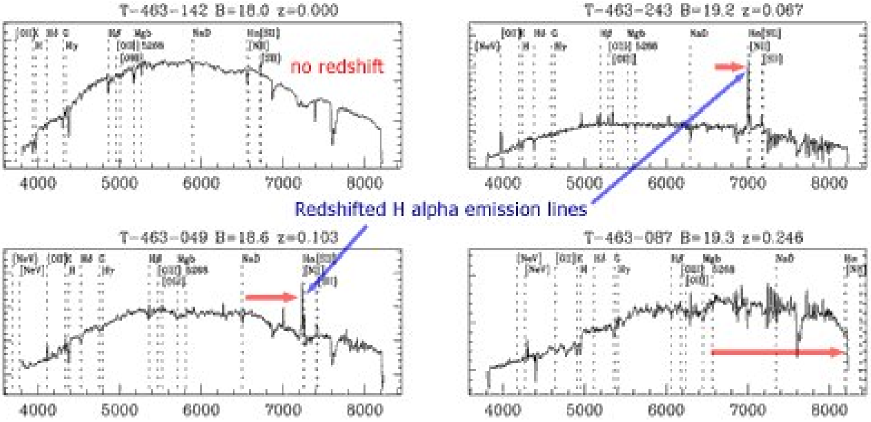
Distribution of galaxies in the universe

The Sloan Digital Sky Survey is one of the most ambitious and influential surveys in the history of astronomy[3]. Over eight years of operations, it has obtained deep, multi-color images covering more than a quarter of the sky and created three-dimensional maps containing more than $930,000$ galaxies and more than $120,000$ quasars.

▸ Play SDSS movie

[3]See, http://www.sdss.org/.

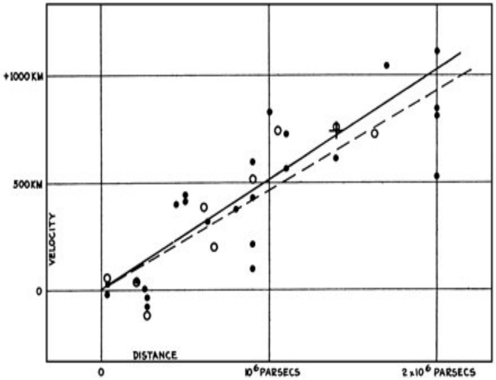
Runaway galaxies

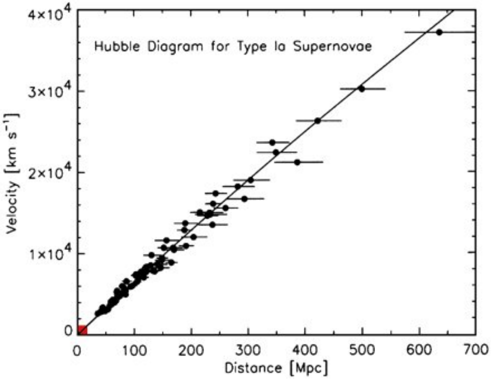


Spectra of four different galaxies from the 2dF redshift survey[4]. On top left is the spectrum of a star from our galaxy, while on the bottom right we have the spectrum of a galaxy that has a redshift of $z = 0.246$. The other two galaxies show prominent Hα emission lines, which have been redshifted from the rest frame value of 6563 Å.

[4] Image from http://outreach.atnf.csiro.au/education/senior/astrophysics/spectra_astro_types.html.

The Hubble's law





Left: The original Hubble data. The slope of the two fitted lines are about $500\ \mathrm{km/sec/Mpc}$ and $530\ \mathrm{km/sec/Mpc}$.

Right: A more recent Hubble diagram. The slope of the straight line is found to be about $72\ \mathrm{km/sec/Mpc}$. The small red region in the lower left marks the span of Hubble's original diagram[5].

[5] R. Kirshner, Proc. Natl. Acad. Sci. USA **101**, 8 (2004).

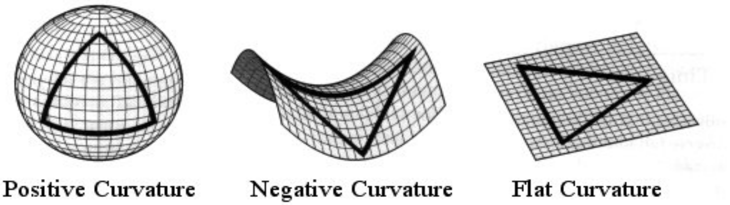
The Friedmann-Lemaître-Robertson-Walker metric

The homogeneous, isotropic and expanding universe can be described by the following Friedmann-Lemaître-Robertson-Walker (FLRW) line element:

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-\kappa\, r^2} + r^2\ \left(d\theta^2 + \sin^2\theta\ d\phi^2\right)\right],$$

where t is the cosmic time and $a(t)$ denotes the scale factor, while $\kappa = 0, \pm 1$.

The quantity κ denotes the spatial geometry of the universe. It can be flat ($\kappa = 0$), closed ($\kappa = 1$) or open ($\kappa = -1$) depending on the total energy density of matter present in the universe[6].



[6] Image from http://abyss.uoregon.edu/~js/lectures/cosmo_101.html.

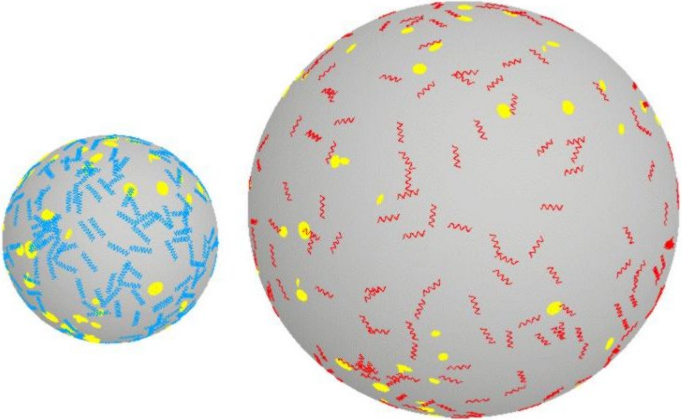
The Friedmann equations

If ρ and p denote the energy density and pressure of the smooth component of the matter field that is driving the expansion, then the Einstein's equations for the FLRW metric lead to the following equations for the scale factor $a(t)$:

$$H^2 + \frac{\kappa}{a^2} = \frac{8\pi\, G}{3}\,\rho \quad \text{and} \quad \frac{\ddot{a}}{a} = -\frac{4\pi\, G}{3}\,(\rho + 3\,p)\,,$$

where $H = \dot{a}/a$ is the Hubble parameter.

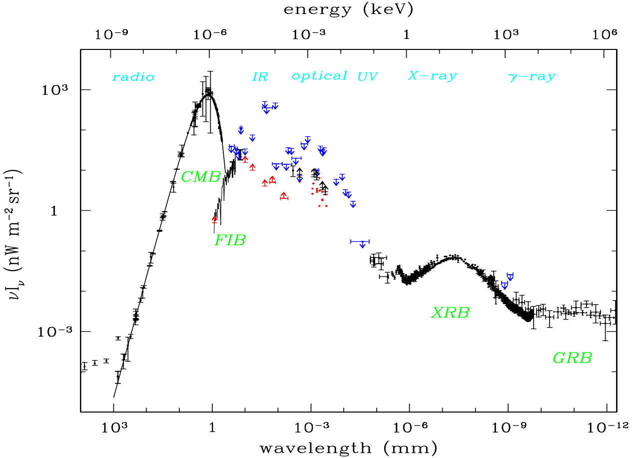
Visualizing the expanding universe



A two-dimensional analogy for the expanding universe[7]. The yellow blobs on the expanding balloon denote the galaxies. Note that the galaxies themselves do not grow, but the distance between the galaxies grows and the wavelengths of the photons shift from blue to red as the universe expands.

[7] Image from http://www.astro.ucla.edu/~wright/balloon0.html.

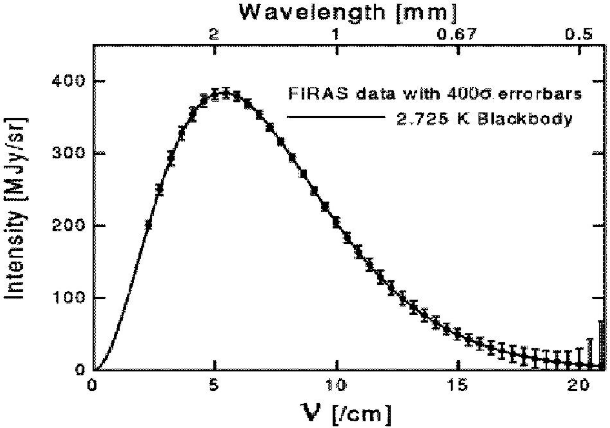
The spectrum of radiation in the universe



The energy density spectrum of the cosmological background radiation has been plotted as a function of wavelength[8]. Note that the Cosmic Microwave Background (CMB) contributes the most to the overall background radiation.

[8] Figure from, D. Scott, arXiv:astro-ph/9912038.

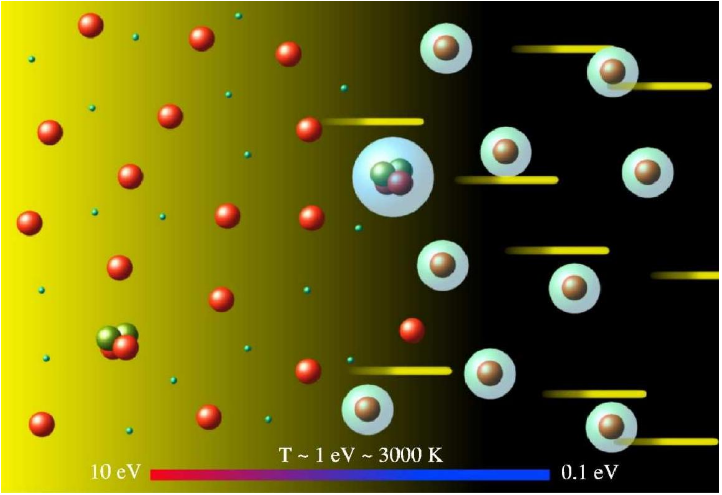
The spectrum of the CMB



The spectrum of the CMB as measured by COBE[9]. It is such a perfect Planck spectrum (corresponding to a temperature of 2.725° K) that it is unlikely to be bettered in the laboratory. The error bars in the graph above have been amplified 400 times so that they can be seen!

[9] Image from http://www.astro.ucla.edu/˜wright/cosmo_01.htm.

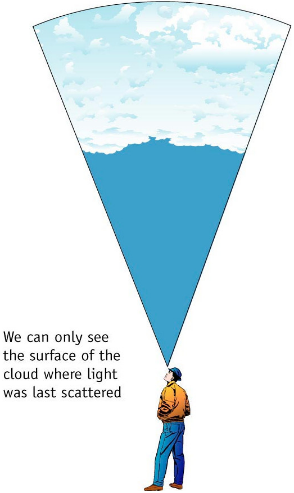
Decoupling of matter and radiation[10]

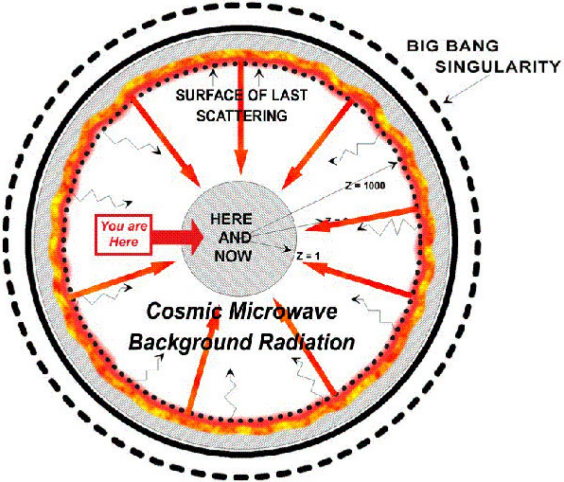


Matter and radiation cease to interact at a temperature of about $T \simeq 3000^\circ$ K, which corresponds to a redshift of about $z \simeq 1000$.

[10] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

The last scattering surface and the freestreaming CMB photons

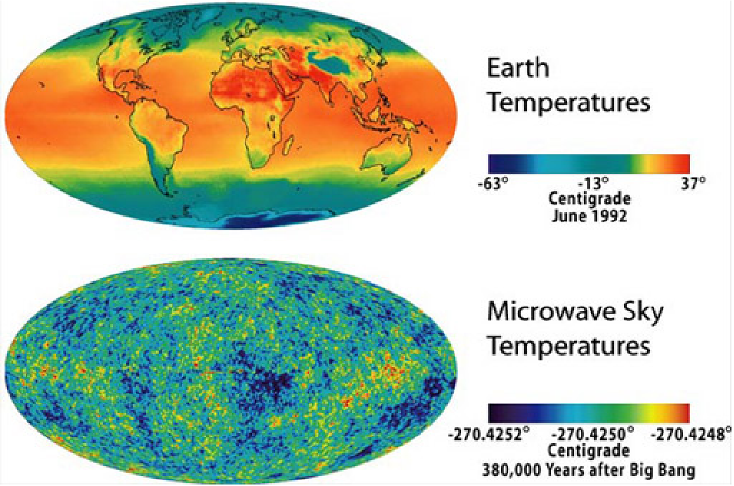




The CMB photons streams to us freely from the last scattering surface when radiation decoupled from matter[11].

[11] Image from http://planck.caltech.edu/epo/epo-cmbDiscovery4.html.

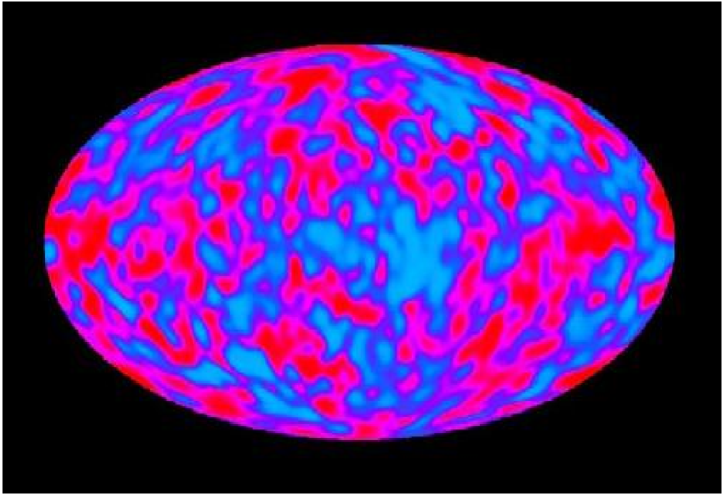
Projecting the last scattering surface



The temperature of the CMB on the last scattering surface can be projected on to a plane as the surface of the Earth is often projected[12].

[12] Image from http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/planckcmb.html.

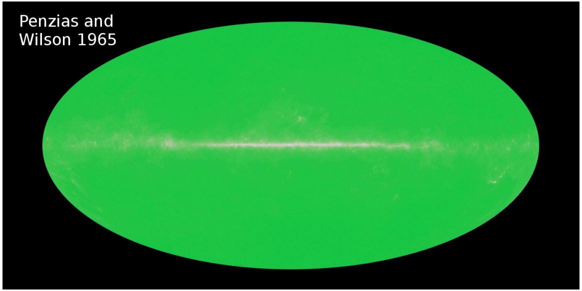
The extent of isotropy of the CMB

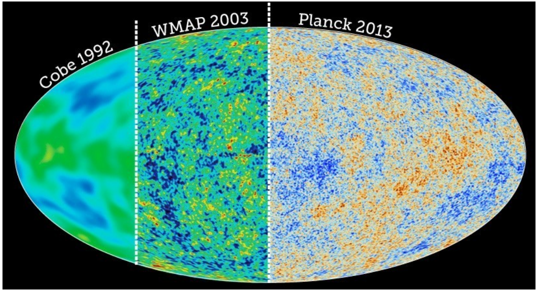


The fluctuations in the temperature of the CMB as seen by COBE[13]. The CMB turns out to be isotropic to one part in 10^5.

[13]Image from http://aether.lbl.gov/www/projects/cobe/COBE_Home/DMR_Images.html.

Measuring the CMB anisotropies with increasing precision





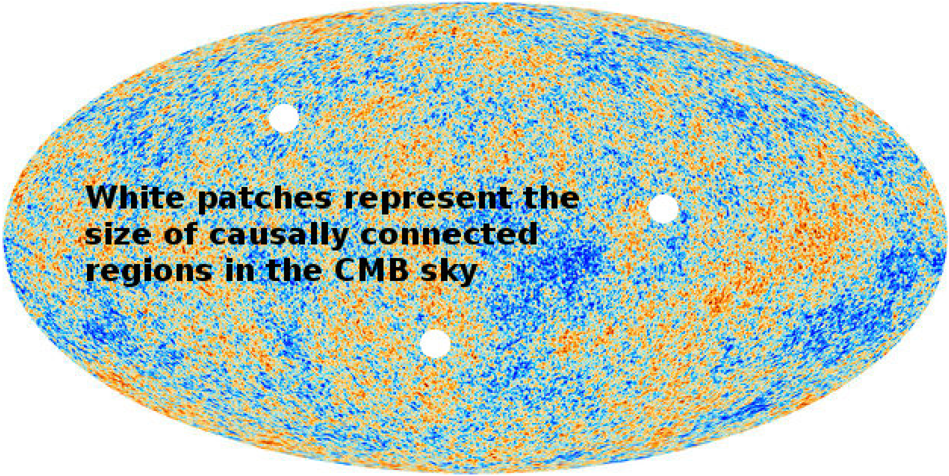
Left: A map of the CMB sky when it was originally discovered about half-a-century ago[14].
Right: The increasingly precise observations of the anisotropies in the CMB as measured by the space based missions, *viz.* COBE, WMAP and Planck, over the last couple of decades[15].

[14] Image from http://planck.cf.ac.uk/science/cmb.

[15] Image from https://briankoberlein.com/2015/06/15/science-in-the-raw/.

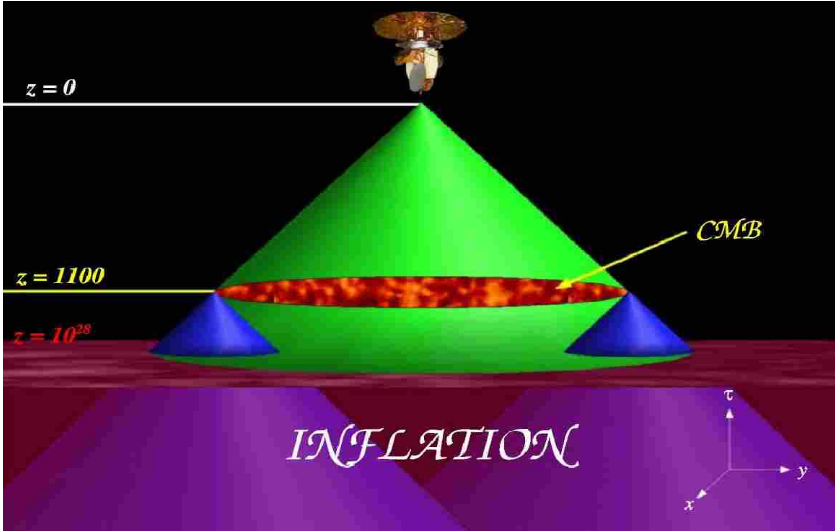
Plan of the talk

The horizon problem



The radiation from the CMB arriving at us from regions separated by more than the Hubble radius at the last scattering surface, which subtends an angle of about 1° today, could not have interacted before decoupling.

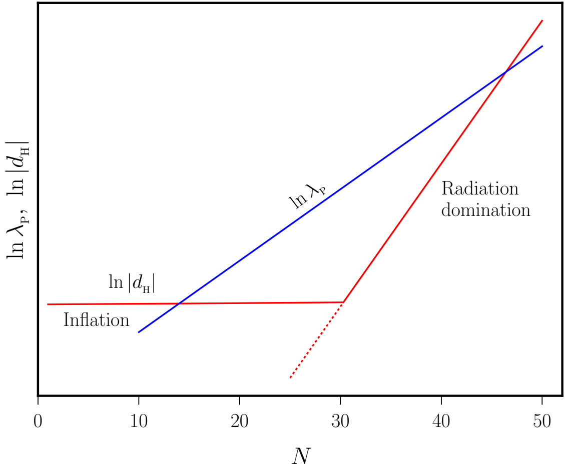
Inflation resolves the horizon problem



An early and sufficiently long epoch of inflation resolves the horizon problem[16].

[16] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

Bringing the modes inside the Hubble radius

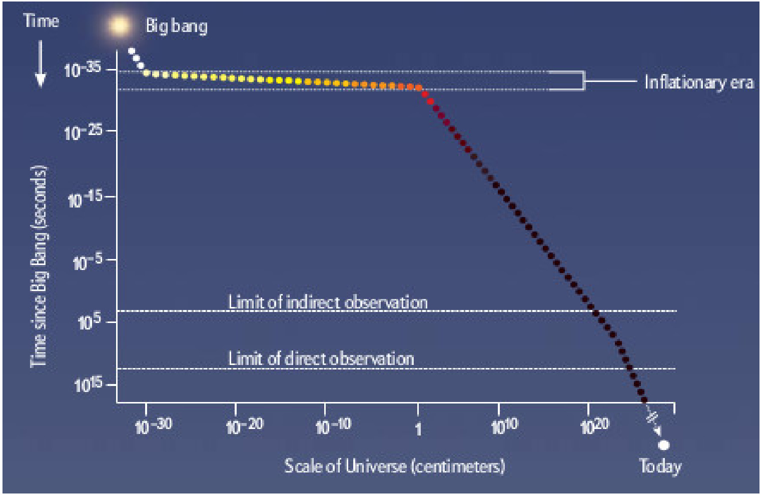


Back to bounces

Behavior of the physical wavelength $\lambda_{\rm P} \propto a$ (in blue) and the Hubble radius $d_{\rm H} = H^{-1}$ (in red) in the inflationary scenario[17]. Recall the scale factor is expressed in terms of e-folds N as $a(N) \propto {\rm e}^{N}$.

[17] See, for example, E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley Publishing Company, New York, 1990), Fig. 8.4.

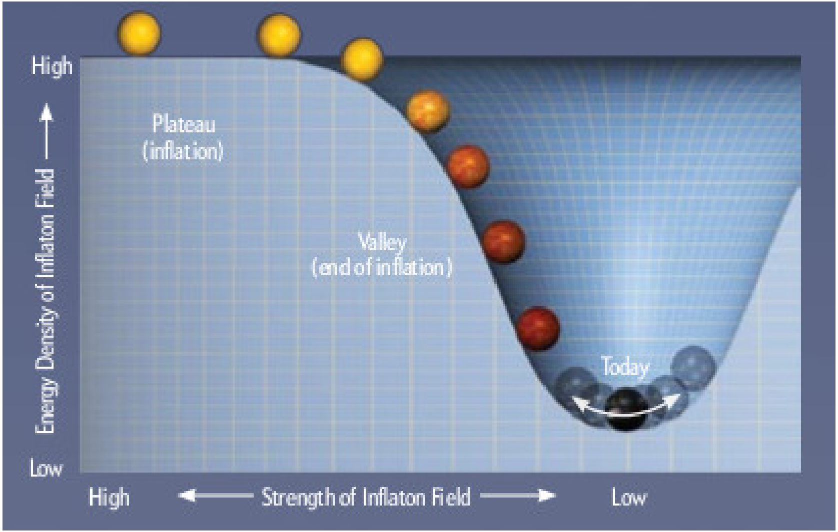
The time and duration of inflation



Inflation – a brief period of accelerated expansion – is expected to have taken place during the very stages of the universe[18].

[18] Image from P. J. Steinhardt, Sci. Am. **304**, 18 (2011).

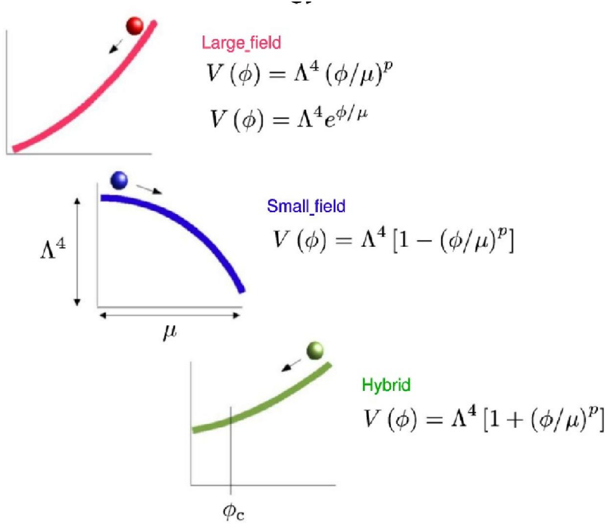
Driving inflation with scalar fields



Inflation can be achieved with scalar fields encountered in high energy physics[19].

[19] Image from P. J. Steinhardt, Sci. Am. **304**, 34 (2011).

A variety of potentials to choose from



A variety of scalar field potentials have been considered to drive inflation[20].

[20] Image from W. Kinney, astro-ph/0301448.

The origin and the evolution of the perturbations

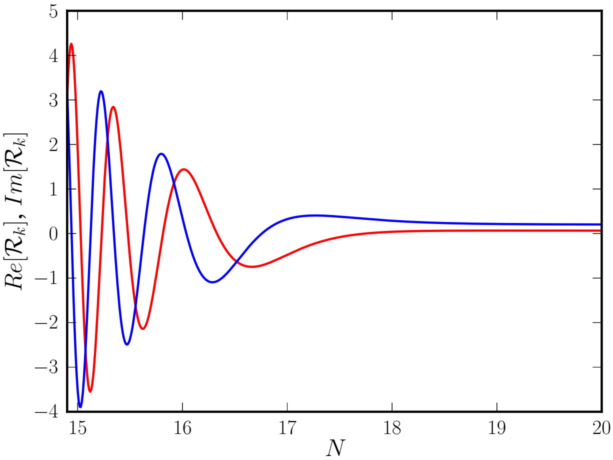
- Inflation is typically driven with the aid of scalar fields. It is the quantum fluctuations associated with these scalar fields which are responsible for the origin of the perturbations.
- These perturbations are amplified during the inflationary epoch, which leave their imprints as anisotropies in the CMB.

Play movie

- The fluctuations in the CMB in turn grow in magnitude due to gravitational instability and develop into the structures that we see around us today.

Play movie

Typical evolution of perturbations during inflation



Back to bounces

Typical evolution of the perturbations during slow roll inflation. The mode considered leaves the Hubble radius at about 18 e-folds[21].

[21] Figure from V. Sreenath, *Computation and characteristics of inflationary three-point functions*, Ph.D. Thesis, Indian Institute of Technology Madras, Chennai, India (2015).

Spectral indices and the tensor-to-scalar ratio

While comparing with the observations, for convenience, one often uses the following power law, template scalar and the tensor spectra:

$$\mathcal{P}_{\mathrm{S}}(k) = \mathcal{A}_{\mathrm{S}} \left(\frac{k}{k_*}\right)^{n_{\mathrm{S}}-1}, \qquad \mathcal{P}_{\mathrm{T}}(k) = \mathcal{A}_{\mathrm{T}} \left(\frac{k}{k_*}\right)^{n_{\mathrm{T}}},$$

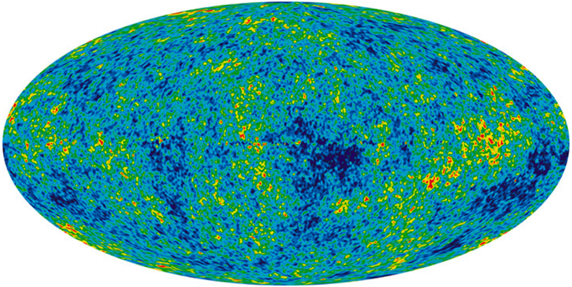
with the spectral indices n_{S} and n_{T} assumed to be constant.

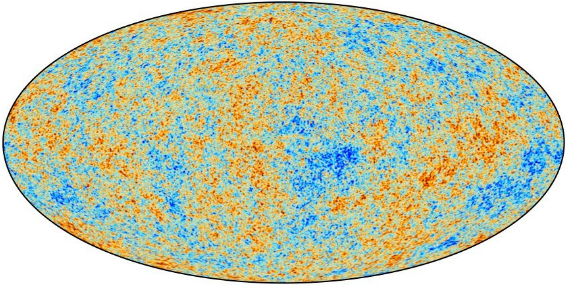
The tensor-to-scalar ratio r is defined as

$$r(k) = \frac{\mathcal{P}_{\mathrm{T}}(k)}{\mathcal{P}_{\mathrm{S}}(k)}$$

and it is usual to further set $r = -8\, n_{\mathrm{T}}$, *viz.* the so-called consistency relation, which is valid during slow roll inflation.

CMB anisotropies as seen by WMAP and Planck





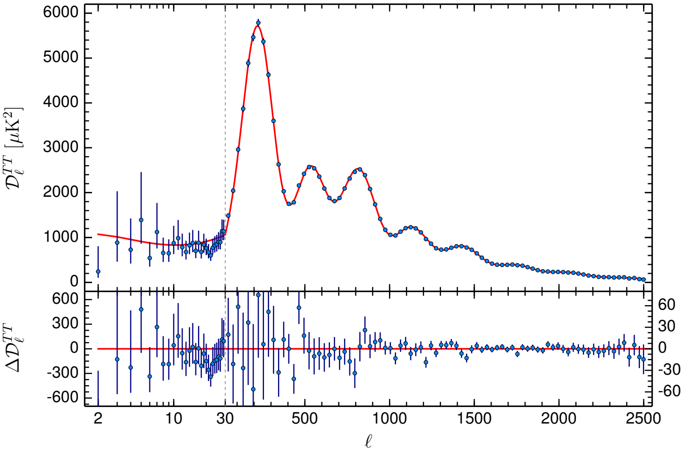
Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data[22].

Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\,\mathrm{MHz}$ observations[23]. The above images show temperature variations (as color differences) of the order of $200^\circ\,\mu\mathrm{K}$. These temperature fluctuations represent the seeds of all the structure around us today.

[22] Image from http://wmap.gsfc.nasa.gov/media/121238/index.html.

[23] Planck Collaboration (R. Adam *et al.*), Astron. Astrophys. **594**, A1 (2016).

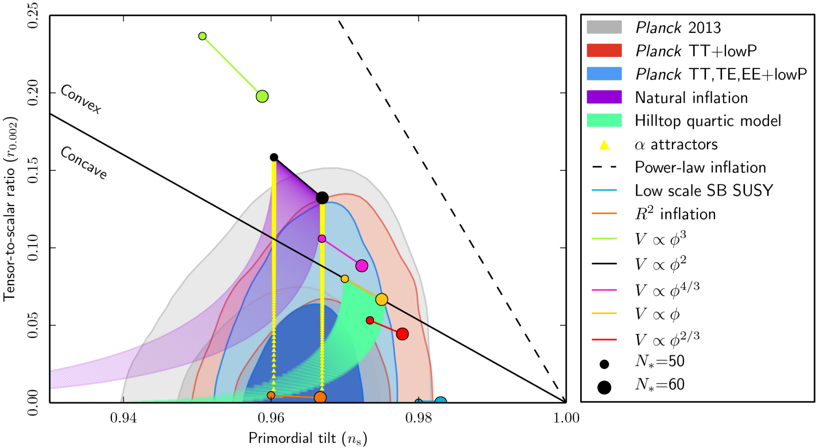
CMB TT angular power spectrum from Planck



The CMB TT angular power spectrum from the Planck 2015 data (the blue dots with error bars) and the theoretical, best fit ΛCDM model with a power law primordial spectrum (the solid red curve)[24].

[24] Planck Collaboration (P. A. R. Ade *et al.*), Astron. Astrophys. **594**, A20 (2016).

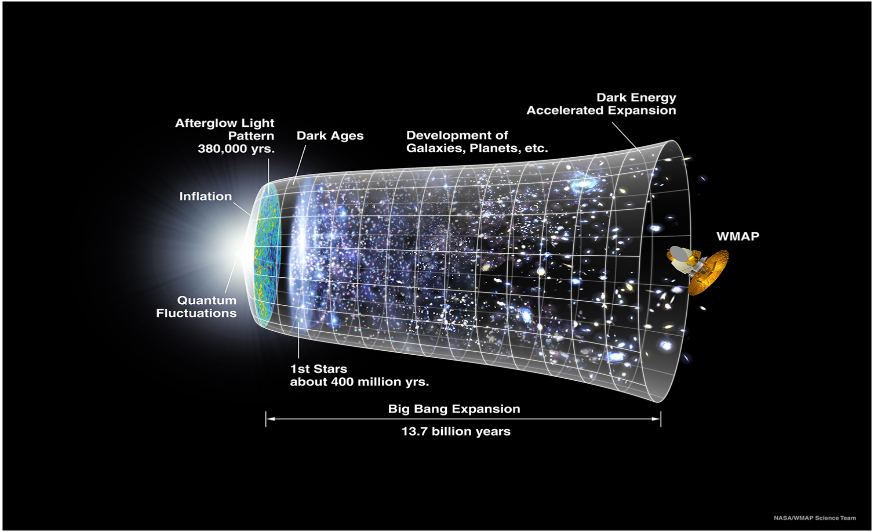
Performance of models in the $n_{\rm s}$-r plane



Marginalized joint $68\,\%$ and $95\,\%$ CL regions for $n_{\rm s}$ and $r_{0.002}$ from Planck in combination with other data sets, compared to the theoretical predictions of selected inflationary models[25].

[25] Planck Collaboration (P. A. R. Ade *et al.*), Astron. Astrophys. **594**, A20 (2016).

The timeline of the universe



A pictorial timeline of the universe[26].

[26] See http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.

Proliferation of inflationary models

5-dimensional assisted inflation
anisotropic brane inflation
anomaly-induced inflation
assisted inflation
assisted chaotic inflation
boundary inflation
brane inflation
brane-assisted inflation
brane gas inflation
brane-antibrane inflation
braneworld inflation
Brans-Dicke chaotic inflation
Brans-Dicke inflation
bulky brane inflation
chaotic hybrid inflation
chaotic inflation
chaotic new inflation
D-brane inflation
D-term inflation
dilaton-driven inflation
dilaton-driven brane inflation
double inflation
double D-term inflation
dual inflation
dynamical inflation
dynamical SUSY inflation
eternal inflation
extended inflation
extended open inflation
extended warm inflation
extra dimensional inflation
F-term inflation
F-term hybrid inflation
false vacuum inflation
false vacuum chaotic inflation
fast-roll inflation
first order inflation
gauged inflation
generalised inflation
generalized assisted inflation
generalized slow-roll inflation
gravity driven inflation
Hagedorn inflation
higher-curvature inflation
hybrid inflation
hyperextended inflation
induced gravity inflation
induced gravity open inflation
intermediate inflation
inverted hybrid inflation
isocurvature inflation
K inflation
kinetic inflation
lambda inflation
large field inflation
late D-term inflation
late-time mild inflation
low-scale inflation
low-scale supergravity inflation
M-theory inflation
mass inflation
massive chaotic inflation
moduli inflation
multi-scalar inflation
multiple inflation
multiple-field slow-roll inflation
multiple-stage inflation
natural inflation
natural Chaotic inflation
natural double inflation
natural supergravity inflation
new inflation
next-to-minimal supersymmetric hybrid inflation
non-commutative inflation
non-slow-roll inflation
nonminimal chaotic inflation
old inflation
open hybrid inflation
open inflation
oscillating inflation
polynomial chaotic inflation
polynomial hybrid inflation
power-law inflation
pre-Big-Bang inflation
primary inflation
primordial inflation
quasi-open inflation
quintessential inflation
R-invariant topological inflation
rapid asymmetric inflation
running inflation
scalar-tensor gravity inflation
scalar-tensor stochastic inflation
Seiberg-Witten inflation
single-bubble open inflation
spinodal inflation
stable starobinsky-type inflation
steady-state eternal inflation
steep inflation
stochastic inflation
string-forming open inflation
successful D-term inflation
supergravity inflation
supernatural inflation
superstring inflation
supersymmetric hybrid inflation
supersymmetric inflation
supersymmetric topological inflation
supersymmetric new inflation
synergistic warm inflation
TeV-scale hybrid inflation

A (partial?) list of ever-increasing number of inflationary models[27]. Actually, it may not even be possible to rule out some of these models!

[27] From E. P. S. Shellard, *The future of cosmology: Observational and computational prospects*, in *The Future of Theoretical Physics and Cosmology*, Eds. G. W. Gibbons, E. P. S. Shellard and S. J. Rankin (Cambridge University Press, Cambridge, England, 2003).

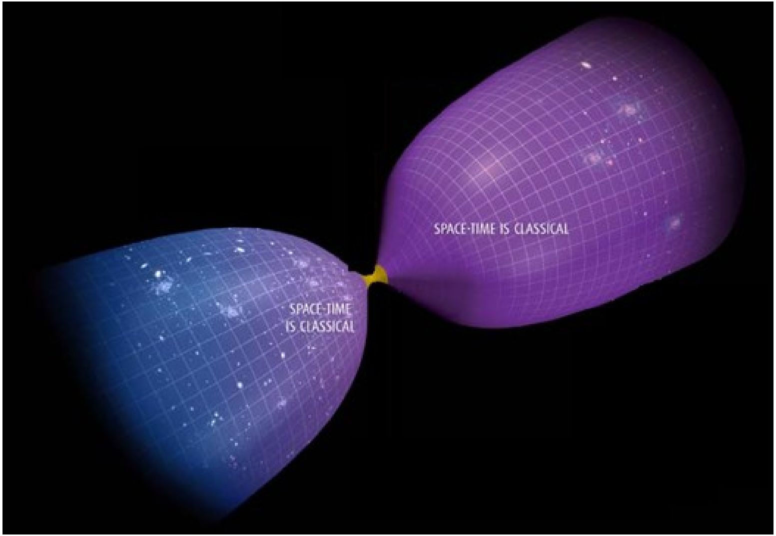
Plan of the talk

Bouncing scenarios as an alternative to inflation[28]

- Bouncing models correspond to situations wherein the universe initially goes through a period of contraction until the scale factor reaches a certain minimum value before transiting to the expanding phase.
- They offer an alternative to inflation to overcome the horizon problem, as they permit well motivated, Minkowski-like initial conditions to be imposed on the perturbations at early times during the contracting phase.
- However, matter fields may have to violate the null energy condition near the bounce in order to give rise to such a scale factor.

[28] See, for instance, M. Novello and S. P. Bergliaffa, Phys. Rep. **463**, 127 (2008); D. Battefeld and P. Peter, Phys. Rep. **571**, 1 (2015).

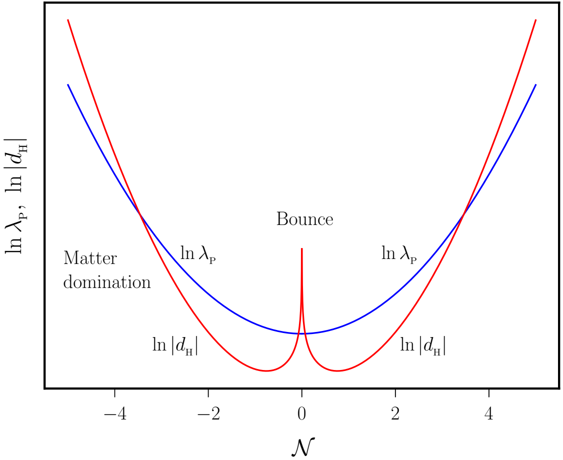
Visualizing bounces



Visualizing the bouncing scenario[29].

[29] Image from, http://www.physics.princeton.edu//˜cosmo/bouncingcosmology/index.html.

Overcoming the horizon problem in the bouncing scenario



Behavior of the physical wavelength $\lambda_P \propto a$ and the Hubble radius $d_H = H^{-1}$ in a bouncing scenario[30]. Note that the scale factor is expressed as $a(\mathcal{N}) \propto e^{\mathcal{N}^2/2}$.

Behavior in inflation

[30] Figure from, D. Chowdhury, *Inflation, bounces and primordial correlations*, Ph.D. Thesis, Indian Institute of Technology Madras, Chennai, 2018.

Classical bounces and sources

Consider, for instance, bouncing models of the form

$$a(\eta) = a_0 \left(1 + \frac{\eta^2}{\eta_0^2}\right)^{1+\varepsilon} = a_0 \left(1 + k_0^2\, \eta^2\right)^{1+\varepsilon},$$

where a_0 is the value of the scale factor at the bounce (*i.e.* when $\eta = 0$), $\eta_0 = 1/k_0$ denotes the time scale of the duration of the bounce, and $\varepsilon > 0$.

The above scale factor can be achieved with the help of two fluids (with constant equation of state parameters) whose energy densities behave as

$$\rho_1 = \frac{\rho_0}{(a/a_0)^{(3+2\,\varepsilon)/(1+\varepsilon)}}, \quad \rho_2 = -\frac{\rho_0}{(a/a_0)^{2\,(2+\varepsilon)/(1+\varepsilon)}}.$$

where $\rho_0 = 12\, M_{_{\rm Pl}}^2\, (k_0/a_0)^2\, (1+\varepsilon)^2$.

Note that the model depends only on the parameters k_0/a_0 and λ. While $\varepsilon = 0$ corresponds to the matter bounce scenario, $\varepsilon \ll 1$ corresponds to near-matter bounces.

Driving near-matter bounces with scalar fields

Near-matter bounces with scale factor of the above form can also be achieved with the aid of two scalar fields, say, ϕ and χ, that are governed by the action[31]

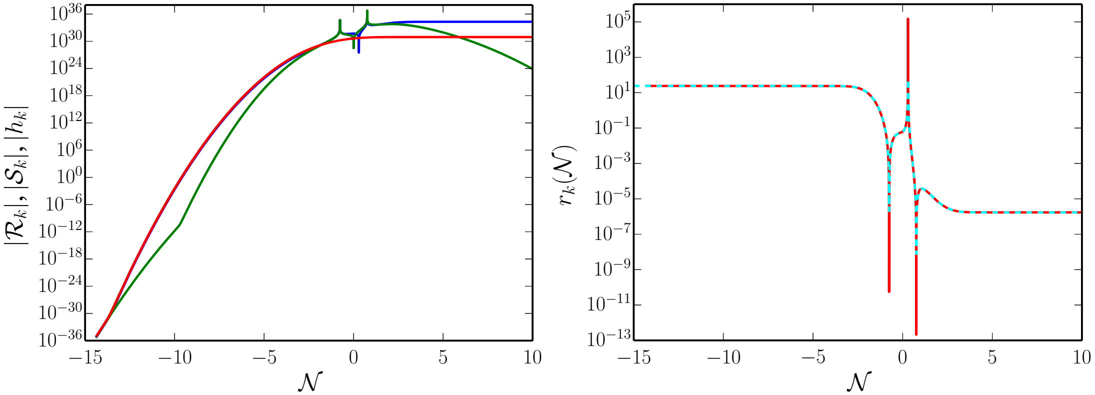
$$S[\phi, \chi] = -\int \mathrm{d}^4x \sqrt{-g}\, \left[\frac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi + V(\phi) + U_0\, \left(-\frac{1}{2}\,\partial_\mu\chi\,\partial^\mu\chi\right)^{(2+\varepsilon)/(1+\varepsilon)}\right],$$

where U_0 is a constant of suitable dimensions, and the potential $V(\phi)$ is given by

$$V(\phi) = \frac{(3+4\,\varepsilon)}{(1+\varepsilon)}\,\frac{\rho_0}{12}\,\cosh^{-2\,(3+2\,\varepsilon)}\left[\frac{(\phi-\phi_0)/M_{\rm Pl}}{2\,\sqrt{(1+\varepsilon)\,(3+2\,\varepsilon)}}\right].$$

[31] R. N. Raveendran and L. Sriramkumar, arXiv:1812.06803 [astro-ph.CO].

Viable power spectra in a near-matter bounce



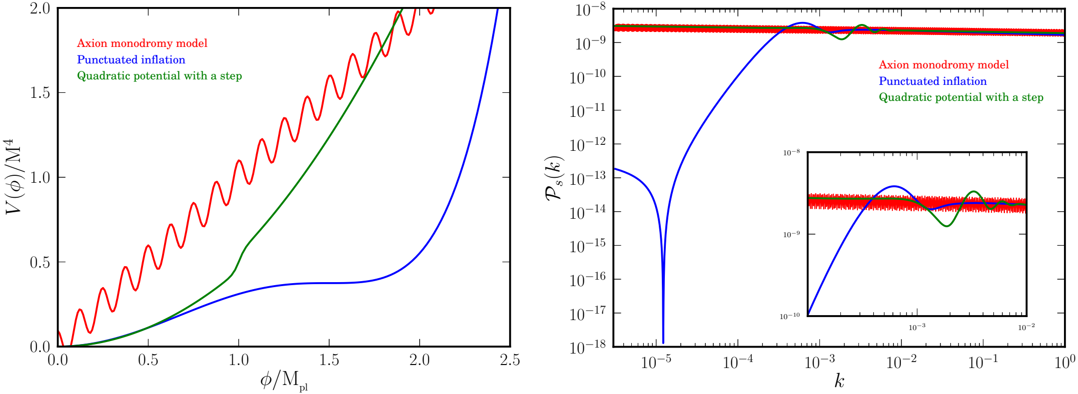
The evolution of the curvature (in blue), isocurvature (in green) and the tensor (in red) perturbations in a near-matter bounce that leads to a nearly scale invariant COBE normalized power spectrum of curvature perturbations with a spectral index of $n_{\mathrm{s}} \simeq 0.96$[32] (on the left), and the evolution of the tensor-to-scalar ratio in the matter bounce[33] (on the right).

Behavior in inflation

[32] R. N. Raveendran and L. Sriramkumar, arXiv:1812.06803 [astro-ph.CO].

[33] R. N. Raveendran and L. Sriramkumar, JCAP **1801**, 030 (2018).

Generating features in the inflationary scenario



Inflationary potentials that admit departures from slow roll (on the left) and the corresponding scalar power spectra (on the right). These spectra lead to a better fit to the CMB data than the more conventional, nearly scale invariant spectra[34].

[34] R. K. Jain, P. Chingangbam, J.-O. Gong, L. Sriramkumar and T. Souradeep, JCAP **0901**, 009 (2009);
D. K. Hazra, M. Aich, R. K. Jain, L. Sriramkumar and T. Souradeep, JCAP **1010**, 008 (2010);
M. Aich, D. K. Hazra, L. Sriramkumar and T. Souradeep, Phys. Rev. D **87**, 083526 (2013).

Achieving stable contraction

The power law scale factor

$$a(\eta) = a_1 \left(\frac{\eta}{\eta_1}\right)^{2/(\lambda^2-2)}$$

corresponding to the constant equation of state $w = (\lambda^2 - 3)/3$, can be driven with the aid of a canonical scalar field described by the exponential potential

$$V(\phi) = V_0\, \exp - \left(\frac{\lambda\,\phi}{M_{\rm Pl}}\right) = -\frac{2}{(a_1\,\eta_1)^2}\, \frac{\lambda^2-6}{(\lambda^2-2)^2}\, \exp - \left(\frac{\lambda\,\phi}{M_{\rm Pl}}\right).$$

It can be easily shown that, in an expanding universe, the solutions are stable when $\lambda^2 < 6$. Whereas, in a contracting universe, the solutions are found to be stable (*i.e.* they are attractors) when $\lambda^2 > 6$.

Note that, when $\lambda^2 > 6$, the potential $V(\phi)$ is *negative definite* resulting in $w > 1$. Such a *stiff* equation of state leads to a period of slow contraction (*i.e.* an ekpyrotic phase), which generates a *strongly blue* curvature perturbation spectrum[35].

[35] See, for instance, A. M. Levy, A. Ijjas and P. J. Steinhardt, Phys. Rev. D **92**, 063524 (2015).

Extending the single field model

The model we shall consider involves two scalar fields ϕ and χ, which are governed by the following action consisting of the potential $V(\phi, \chi)$ and a function $b(\phi)$[36]:

$$S[\phi, \chi] = \int \mathrm{d}^4x\, \sqrt{-g}\, \left[-\frac{1}{2}\, \partial_\mu\phi\, \partial^\mu\phi - \frac{\mathrm{e}^{2\, b(\phi)}}{2}\, \partial_\mu\chi\, \partial^\mu\chi - V(\phi, \chi)\right].$$

We shall work with the potential $V(\phi, \chi) = V_{\mathrm{ek}}(\phi) = V_0\, \mathrm{e}^{-\lambda\, \phi/M_{\mathrm{Pl}}}$ and choose $b(\phi) = \mu\, \phi/(2\, M_{\mathrm{Pl}})$, where λ and μ are positive constants.

To convert the isocurvature perturbations into curvature perturbations, since the field ϕ dominates during the ekpyrotic phase, we shall require a turn along the χ direction. We achieve such a turn by multiplying the original potential $V_{\mathrm{ek}}(\phi)$ by the term[37]

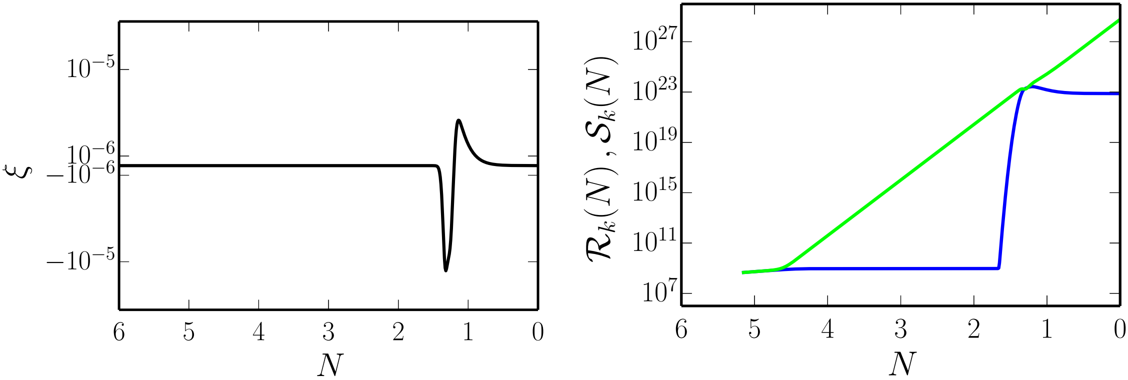
$$V_{\mathrm{c}}(\phi, \chi) = 1 + \beta\, \chi\, \exp - \left(\frac{\phi - \phi_{\mathrm{c}}}{\Delta\phi_{\mathrm{c}}}\right)^2,$$

where β, ϕ_{c} and $\Delta\phi_{\mathrm{c}}$ are constants.

[36] See, for example, A. Ijjas, J.-L. Lehners and P. J. Steinhardt, Phys. Rev. D **89**, 123520 (2014).

[37] R. N. Raveendran and L. Sriramkumar, arXiv:1809.03229 [astro-ph.CO], to appear in Phys. Rev. D.

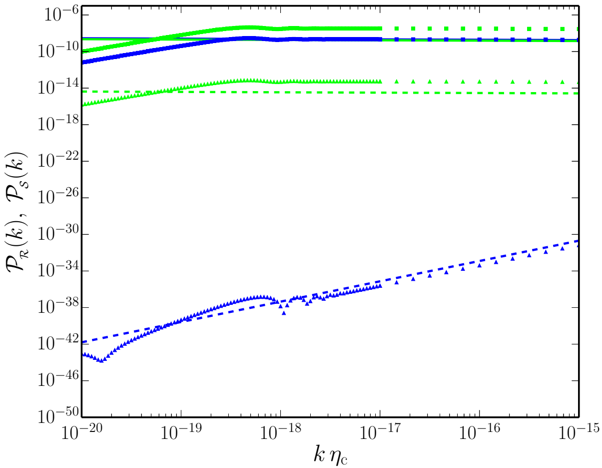
Converting isocurvature perturbations into curvature perturbations



The behavior of the coupling function ξ (on the left) and the corresponding effects on the curvature (in blue) and the isocurvature (in green) perturbations (on the right) have been plotted as a function of e-folds N, defined as usual as $a(N) \propto e^{N}$. However, note that time runs forward from left to right and the choice of $N = 0$ is arbitrary[38].

[38] R. N. Raveendran and L. Sriramkumar, arXiv:1809.03229 [astro-ph.CO], to appear in Phys. Rev. D.

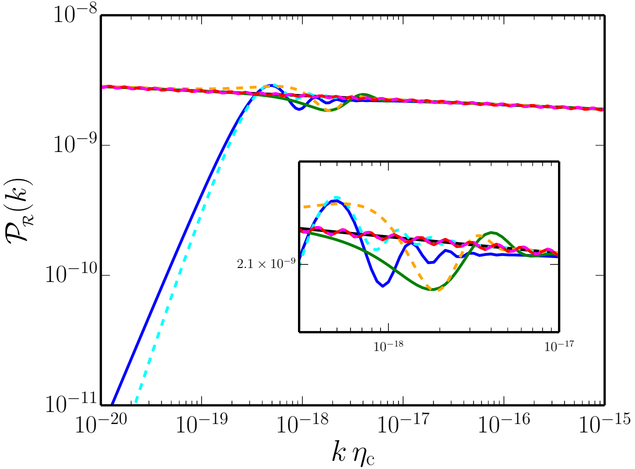
The effects of conversion on the power spectra



The spectra of the curvature and the isocurvature perturbations (in blue and green, respectively), have been plotted prior to (as dashed lines and triangles) as well as during the turn (as solid lines and squares) in field space[39].

[39] R. N. Raveendran and L. Sriramkumar, arXiv:1809.03229 [astro-ph.CO], to appear in Phys. Rev. D.

Features from ekpyrosis



The power spectra of the curvature perturbation with the three types of features generated in the ekpyrotic (solid lines) and the inflationary (dashed lines) scenarios have been plotted over scales of cosmological interest[40].

[40] R. N. Raveendran and L. Sriramkumar, arXiv:1809.03229 [astro-ph.CO], to appear in Phys. Rev. D.

Plan of the talk

Outlook

- Inflation is a simple, effective and compelling paradigm. However, its efficiency has led to a profusion of inflationary models even leading to the concern whether, as a paradigm, inflation can be falsified at all.
- In complete contrast, it is often challenging to construct a viable bouncing scenario that is free of pathologies. Also, many theoretical issues, such as, for instance, the possible quantum gravitational effects near the bounce, remain to be addressed satisfactorily.

Thank you for your attention