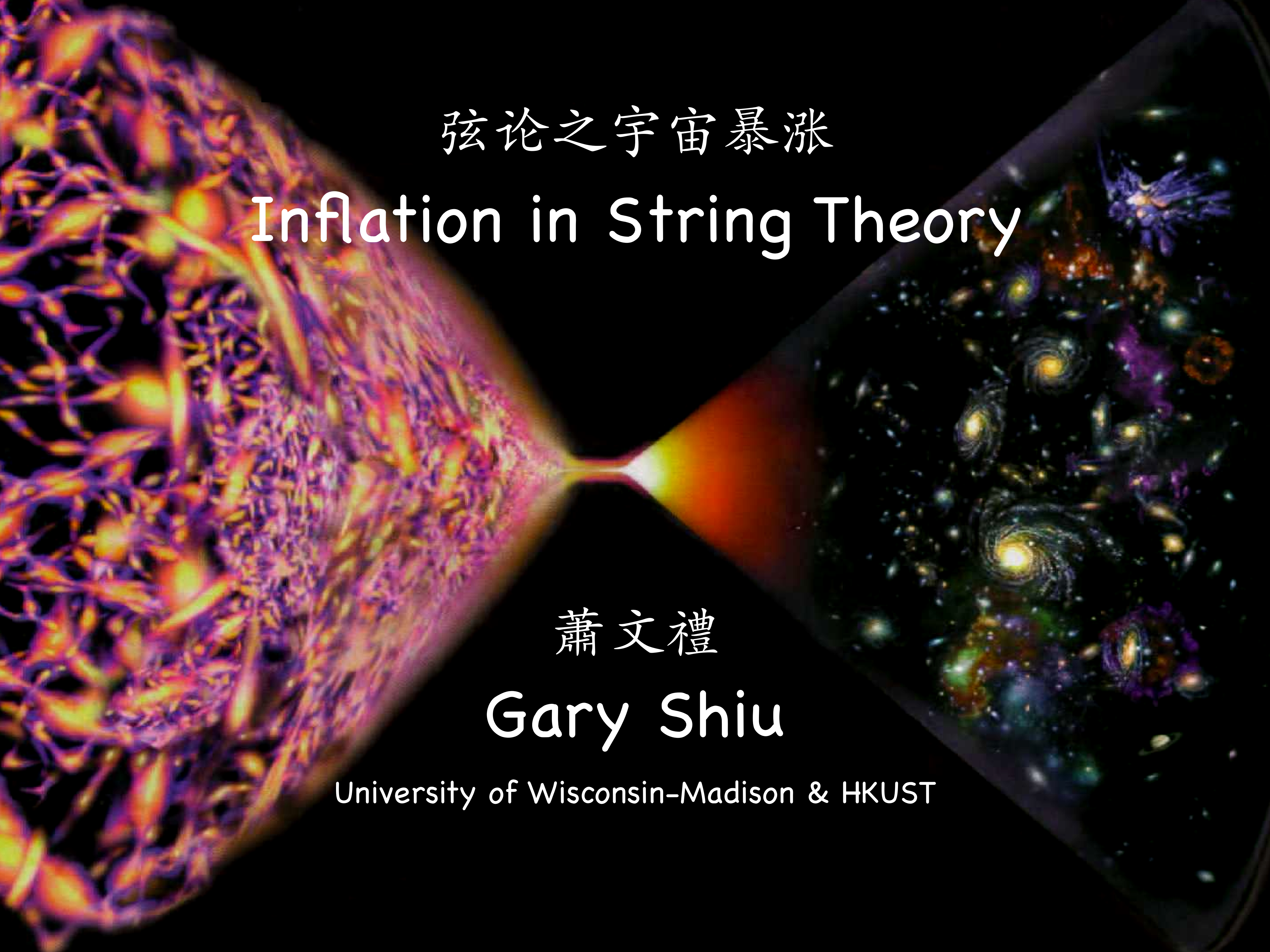


弦论之宇宙暴涨

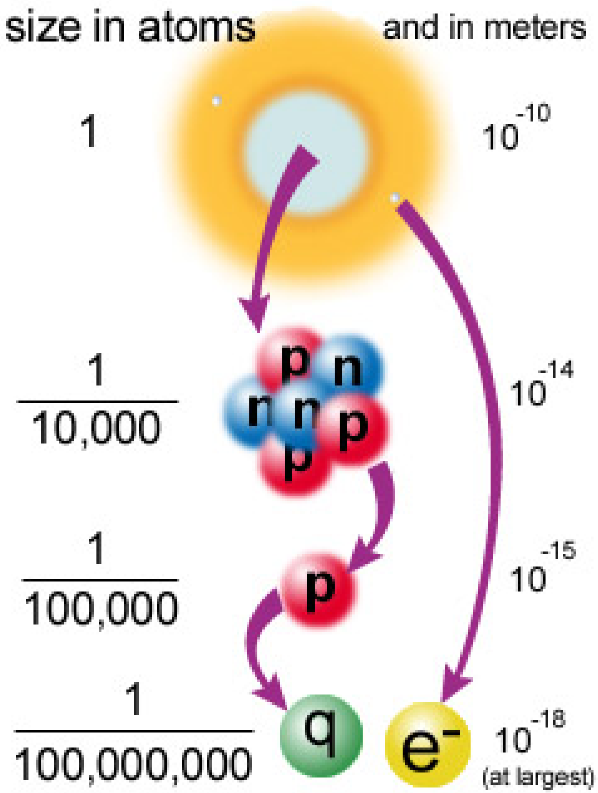
Inflation in String Theory

萧文禮

Gary Shiu

University of Wisconsin-Madison & HKUST

String Theorists Think Small



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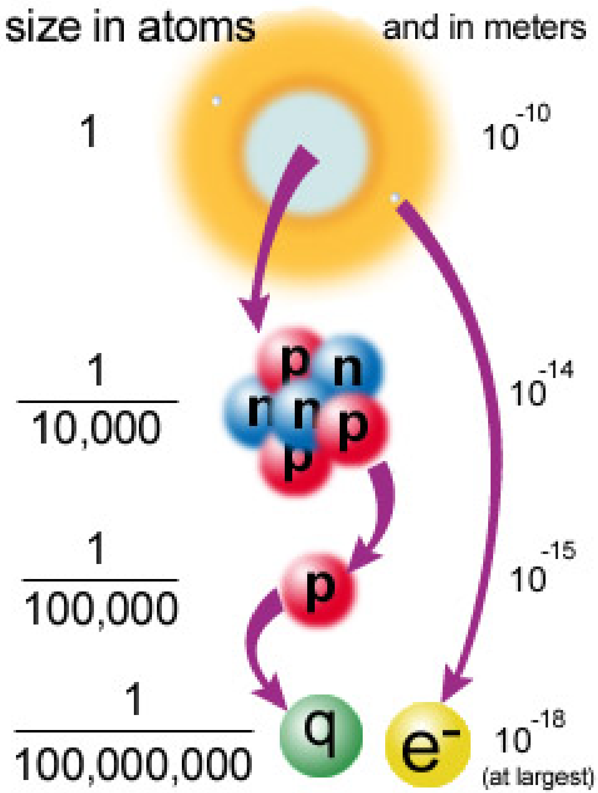

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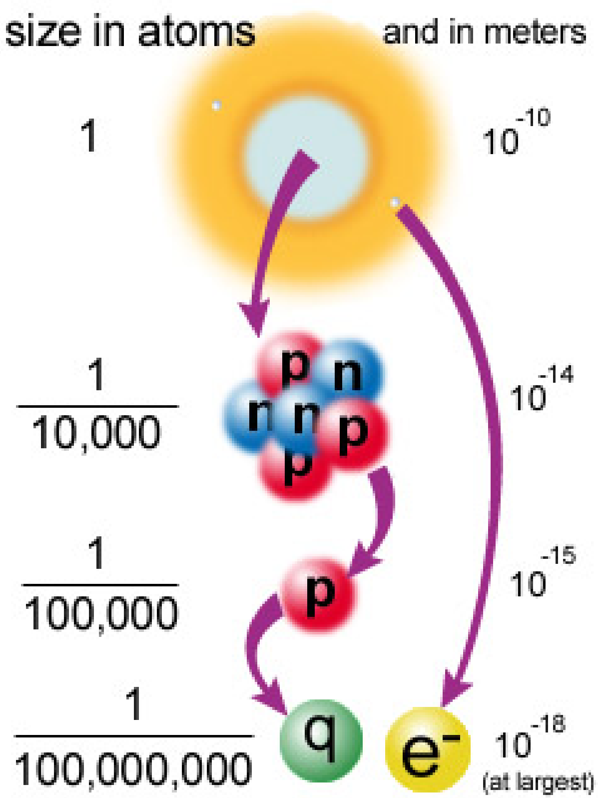
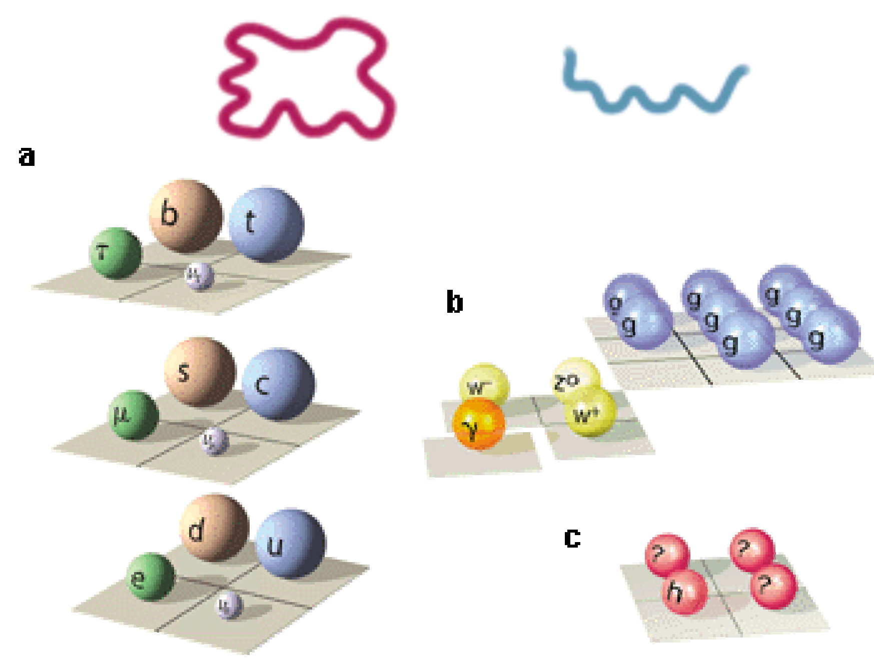




Unification of elementary particles and forces!

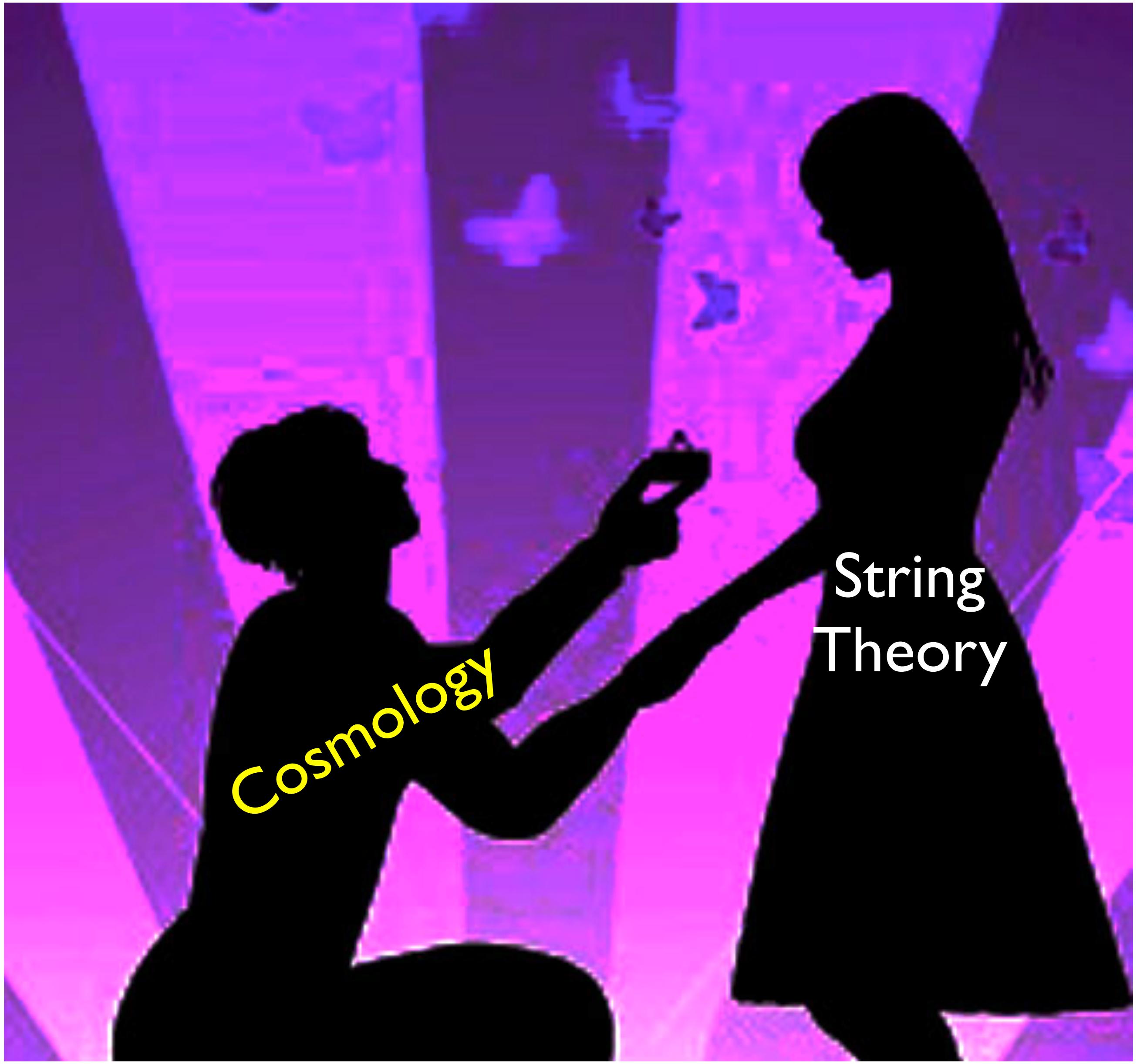
Cosmologists Think Big

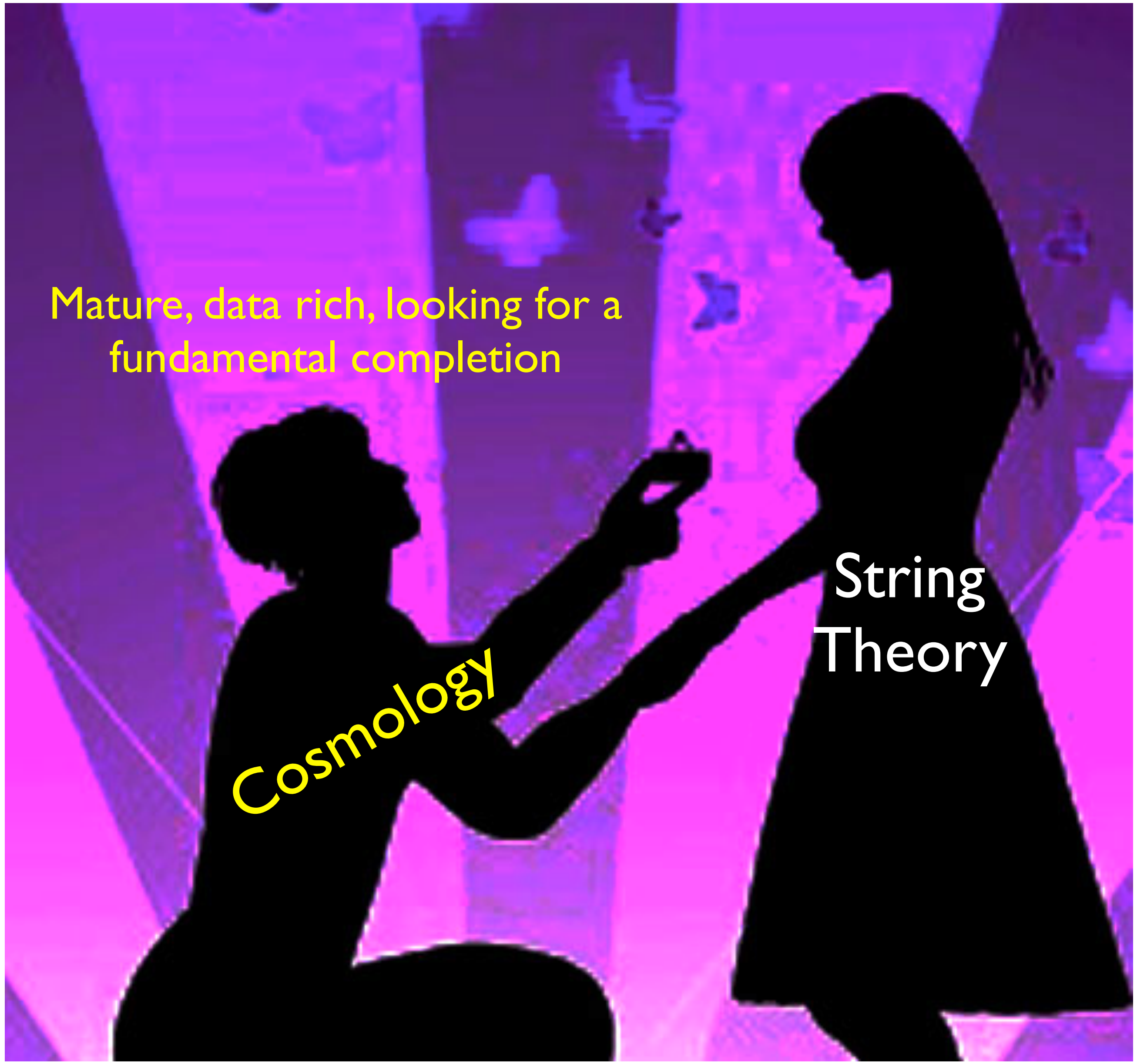
400 billion stars in our galaxy

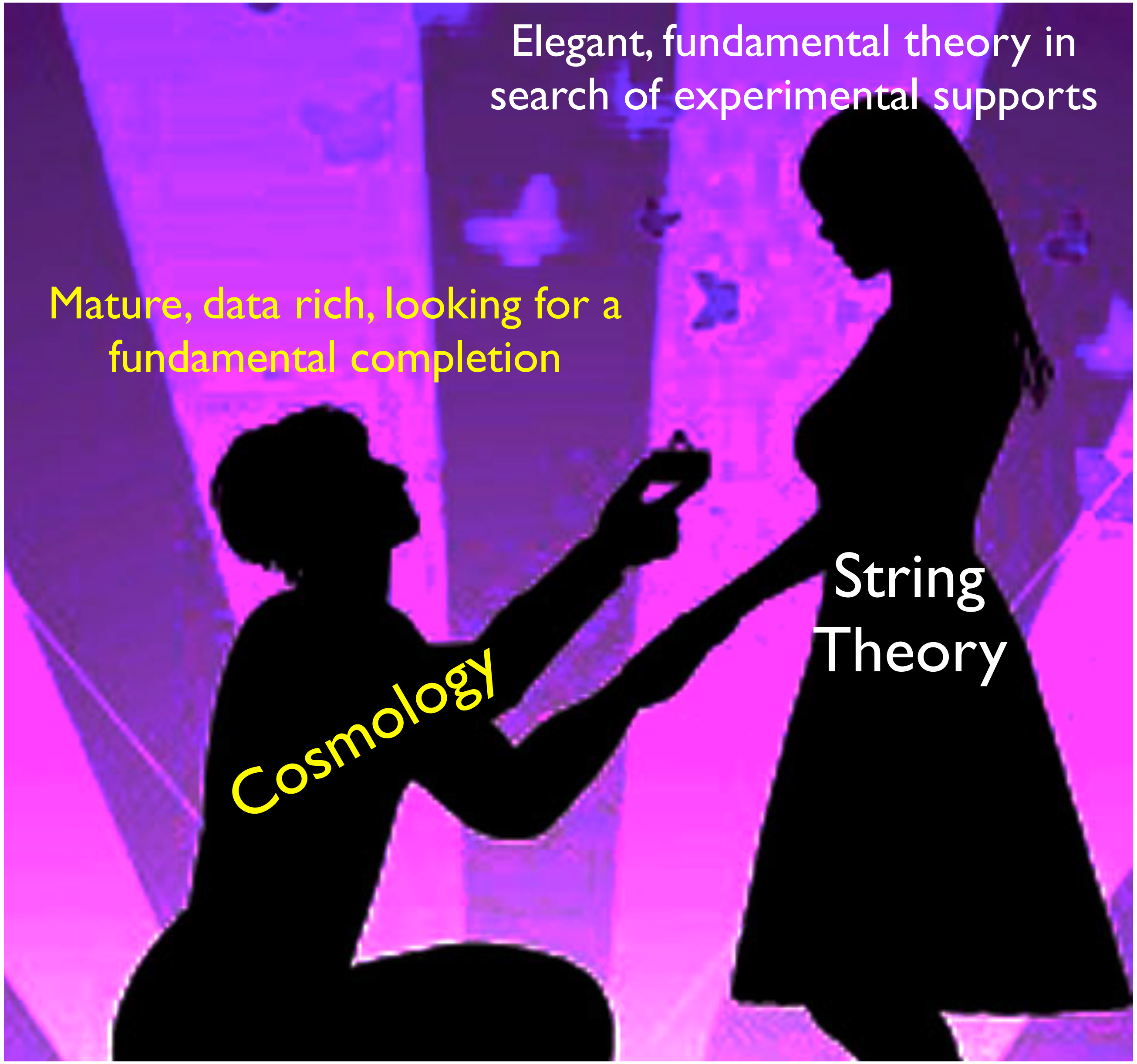
Hubble Space Telescope

And ... there are many billions of galaxies in our universe.

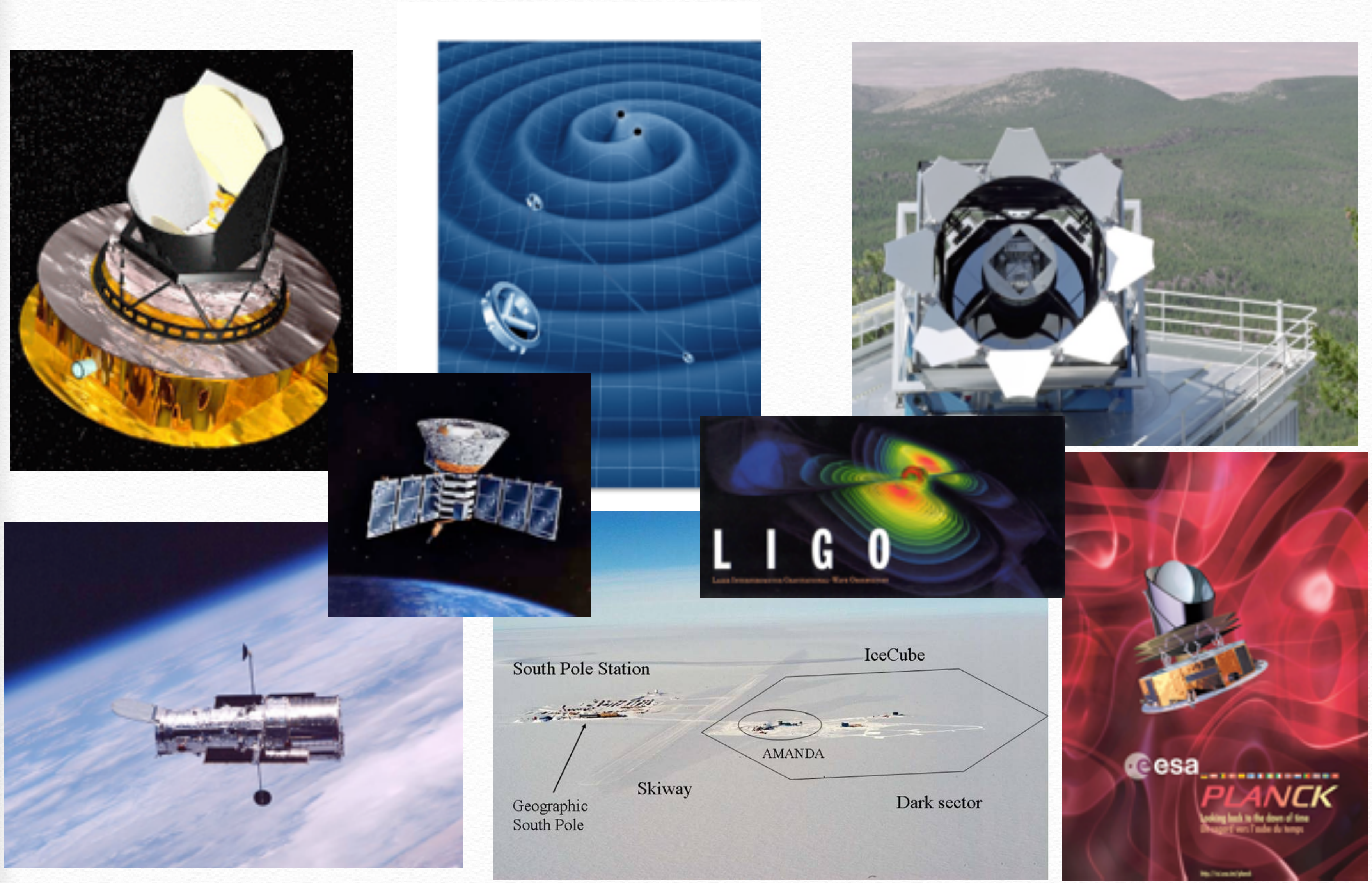
What is String Cosmology?


String
Theory
Cosmology


Mature, data rich, looking for a fundamental completion
Cosmology
String Theory

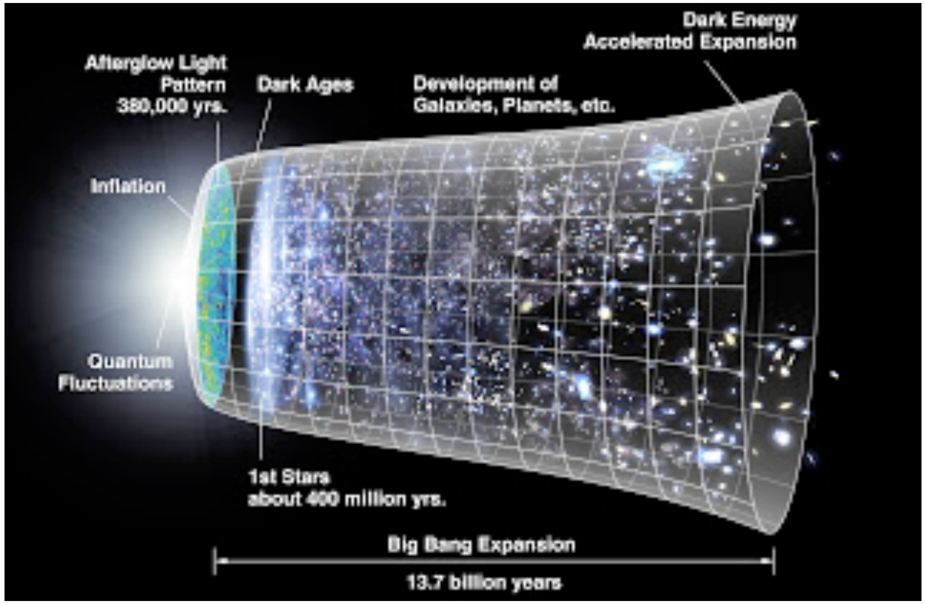

Elegant, fundamental theory in search of experimental supports
Mature, data rich, looking for a fundamental completion
String Theory
Cosmology

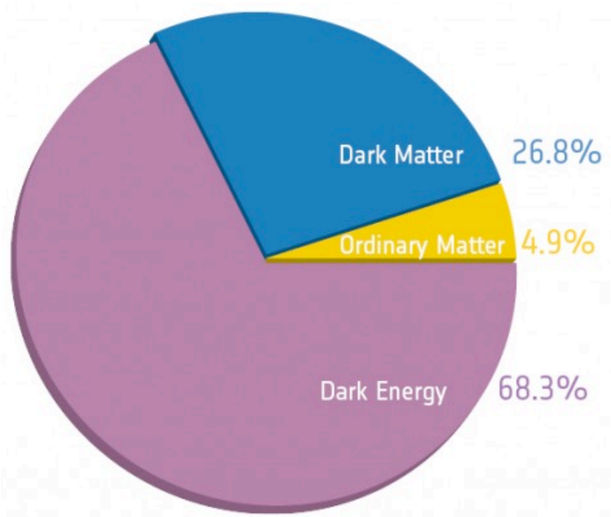
Multiple Cosmological Probes



Precision Cosmology

- Observational cosmology has given us a new window into our universe, complementary to particle physics experiments.

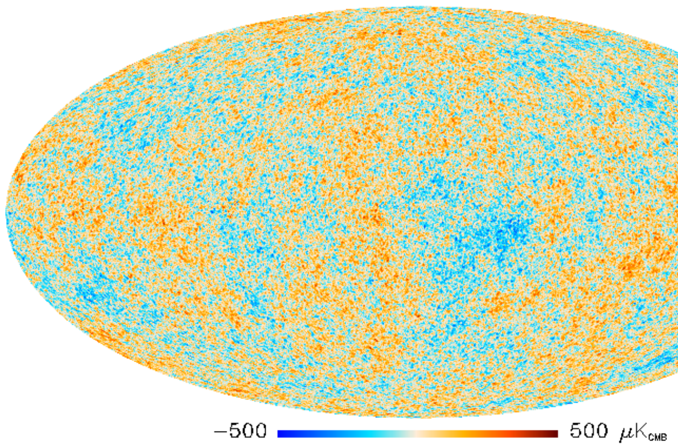


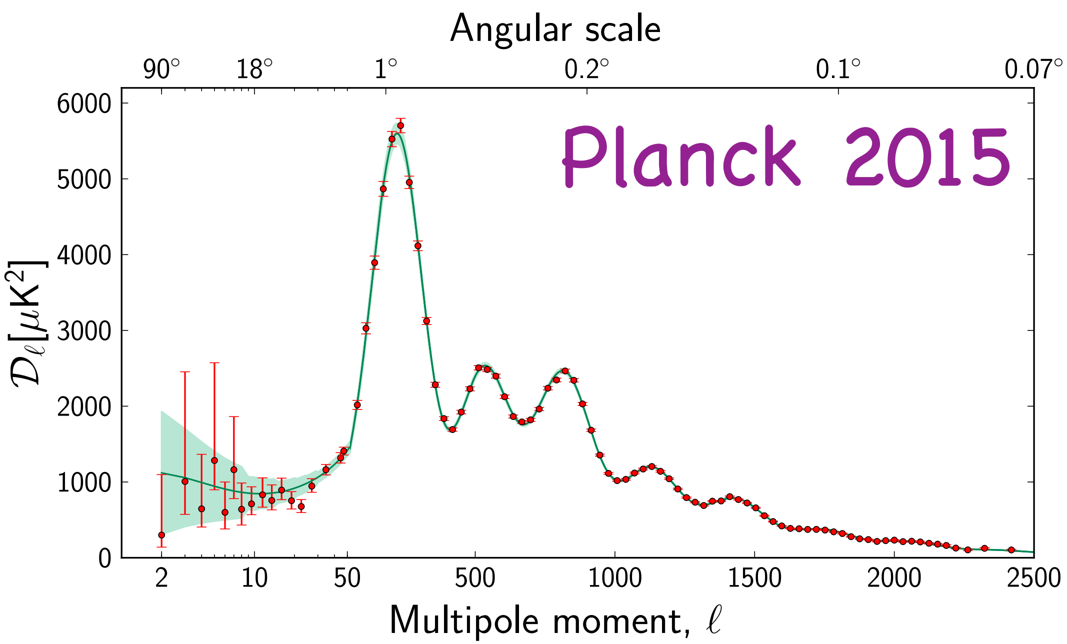


- ***Quantitative*** info about our universe, both at its earliest moment and at the present time, *but* many puzzles remain…. e.g., the physics of **inflation**, **dark matter** & **dark energy**.

Inflation

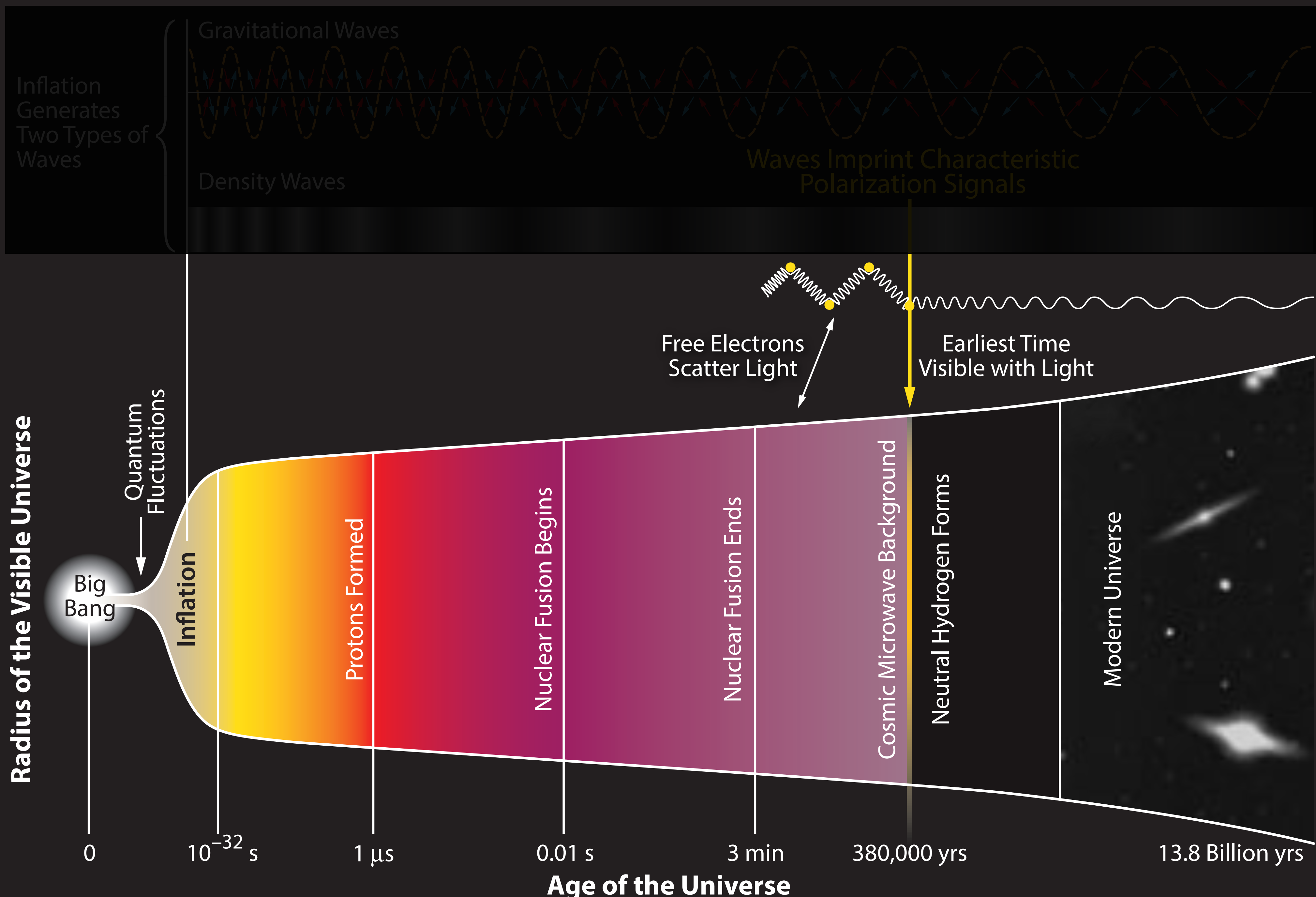
- *Generic predictions* of inflation are in excellent agreement with data, e.g., Cosmic Microwave Background:





- ***What is the origin of cosmic inflation? Are there smoking gun signatures of inflation? What further observables are expected for theoretically motivated models of inflation?***

History of the Universe



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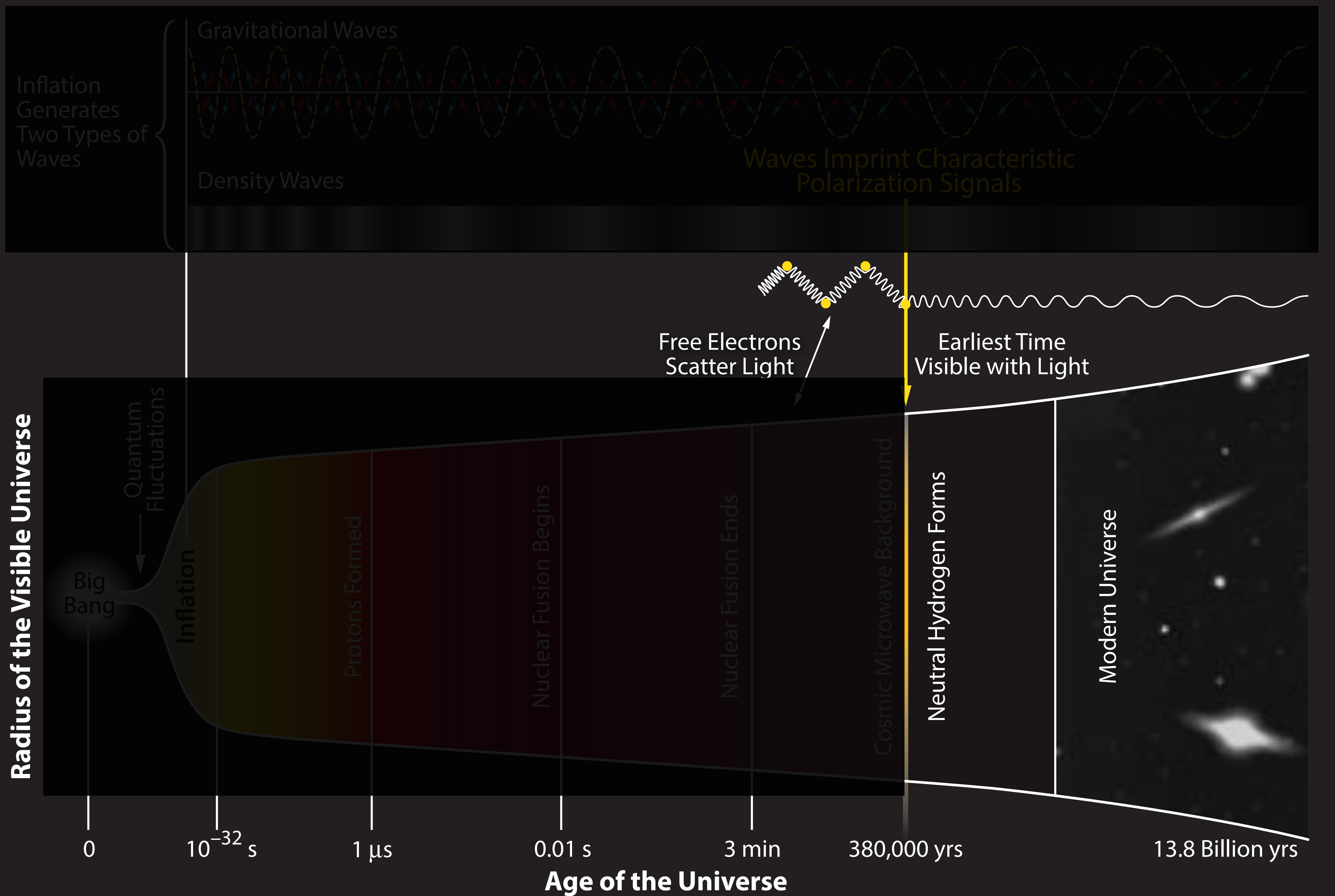
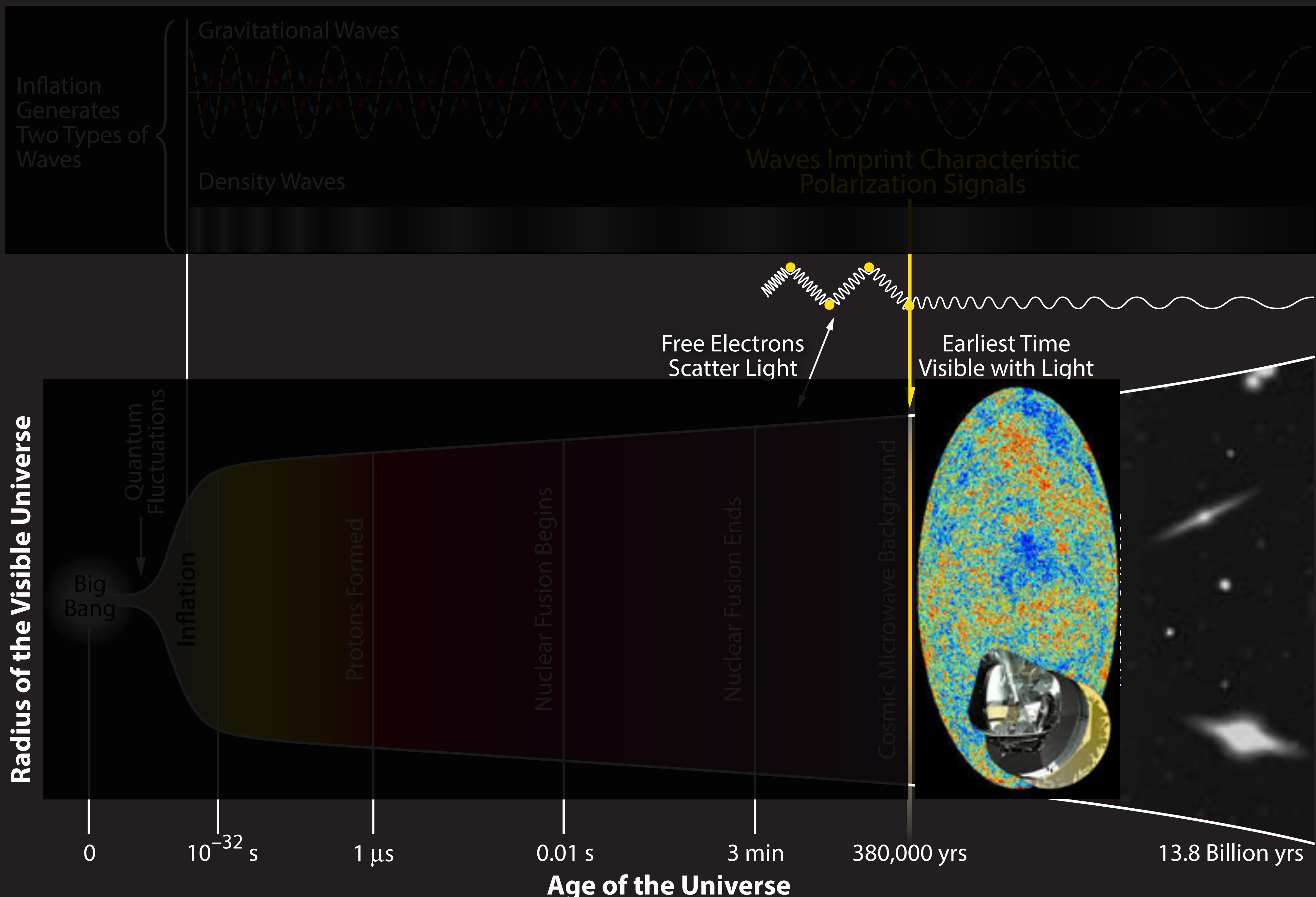
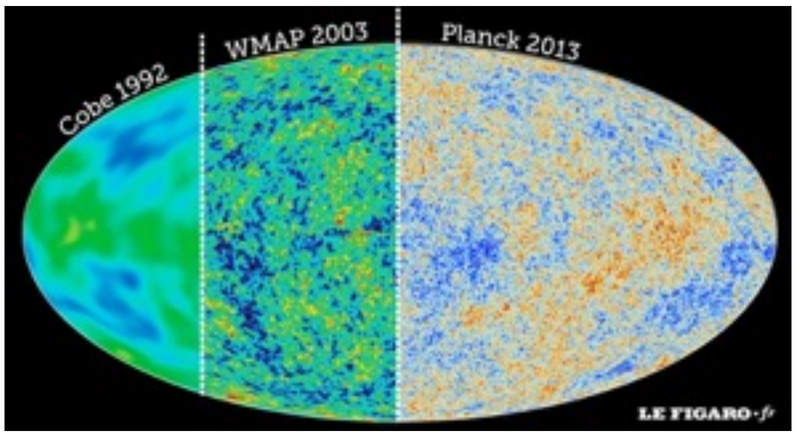
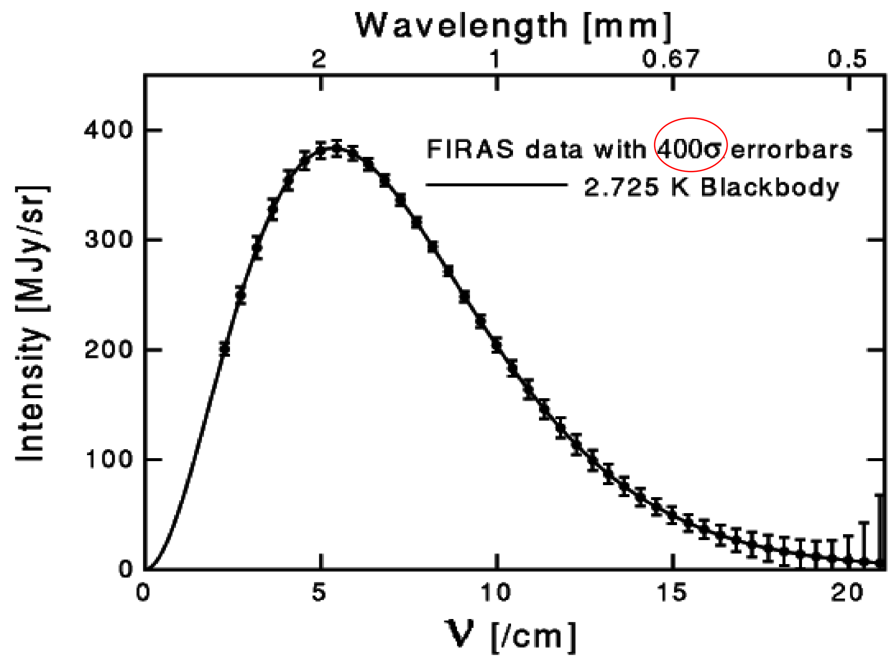


History of the Universe



Cosmic Microwave Background

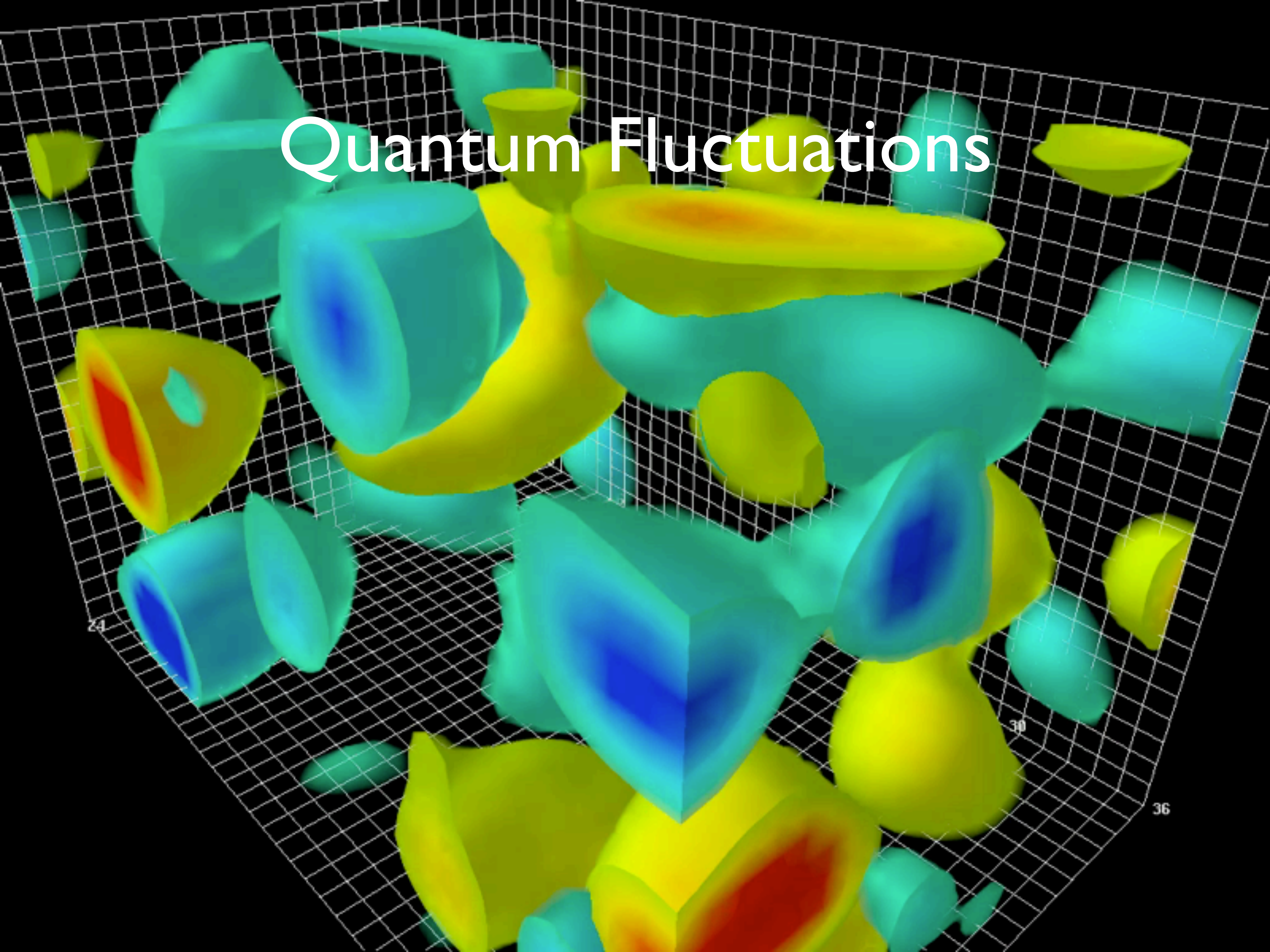




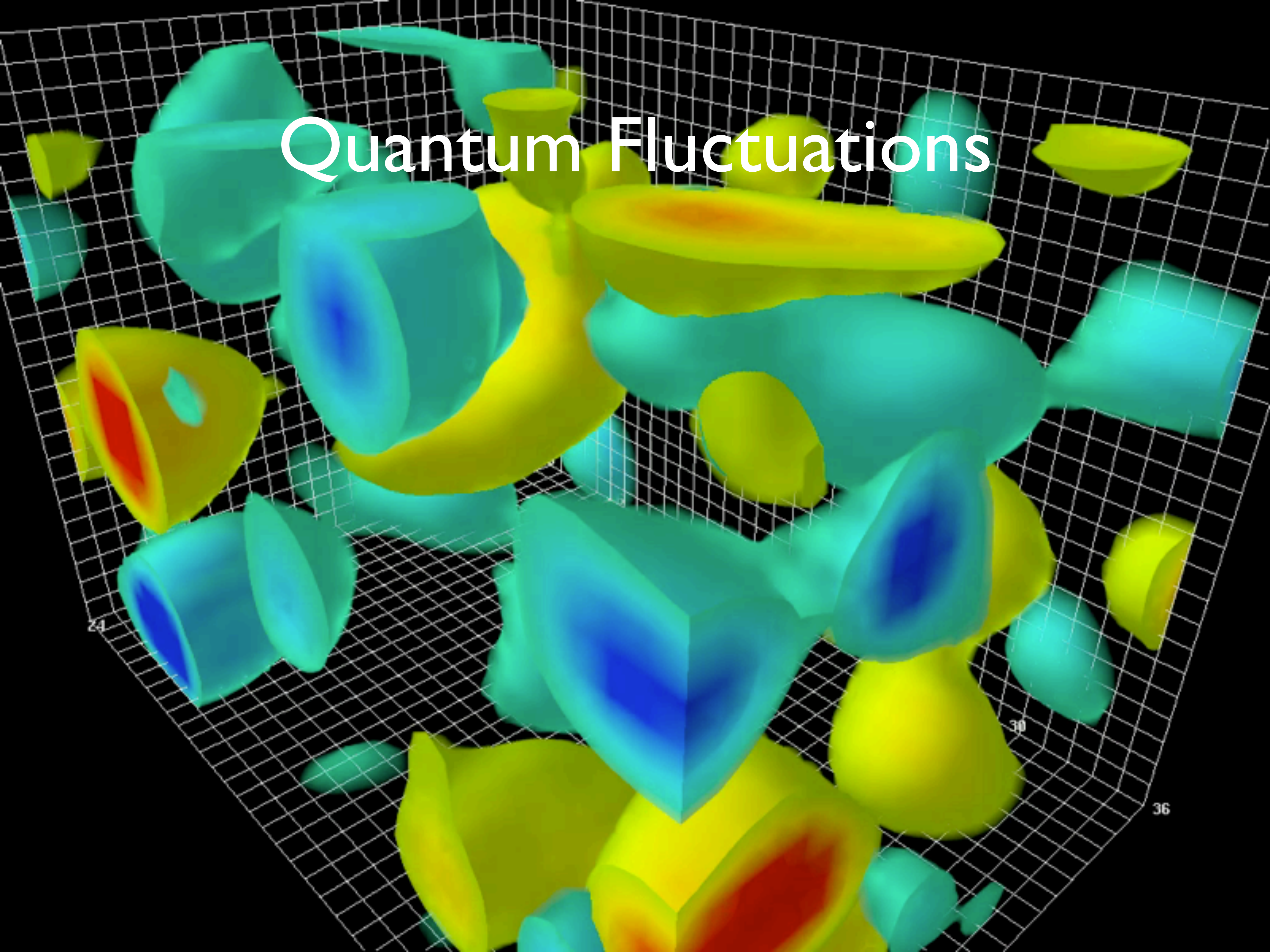
The CMB is **homogeneous and isotropic** to 1 part in 100,000.

Originally proposed as a solution to the flatness and horizon problems in standard big bang cosmology, **inflation** has emerged to be the leading paradigm for explaining the observed **CMB anisotropies**.

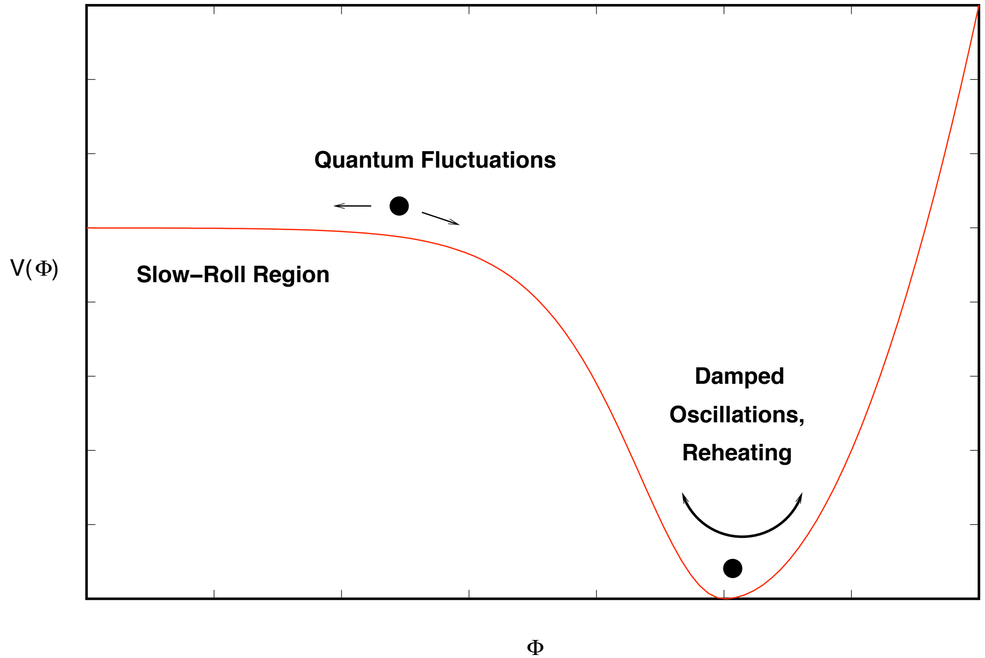
Quantum Fluctuations

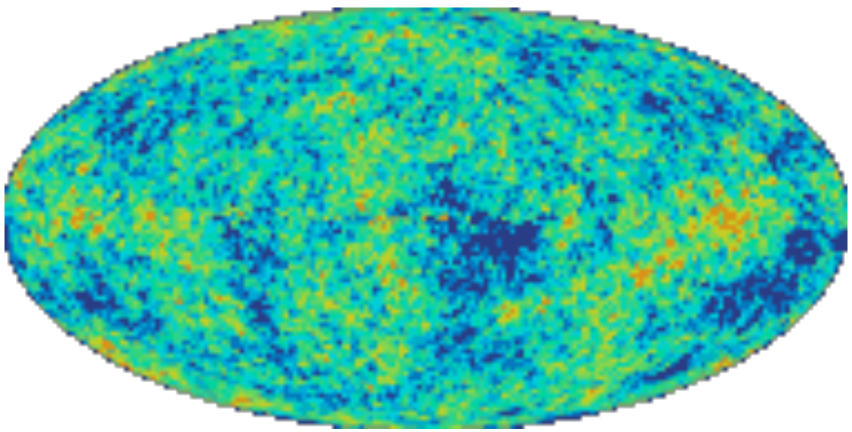


Quantum Fluctuations



Quantum Fluctuations

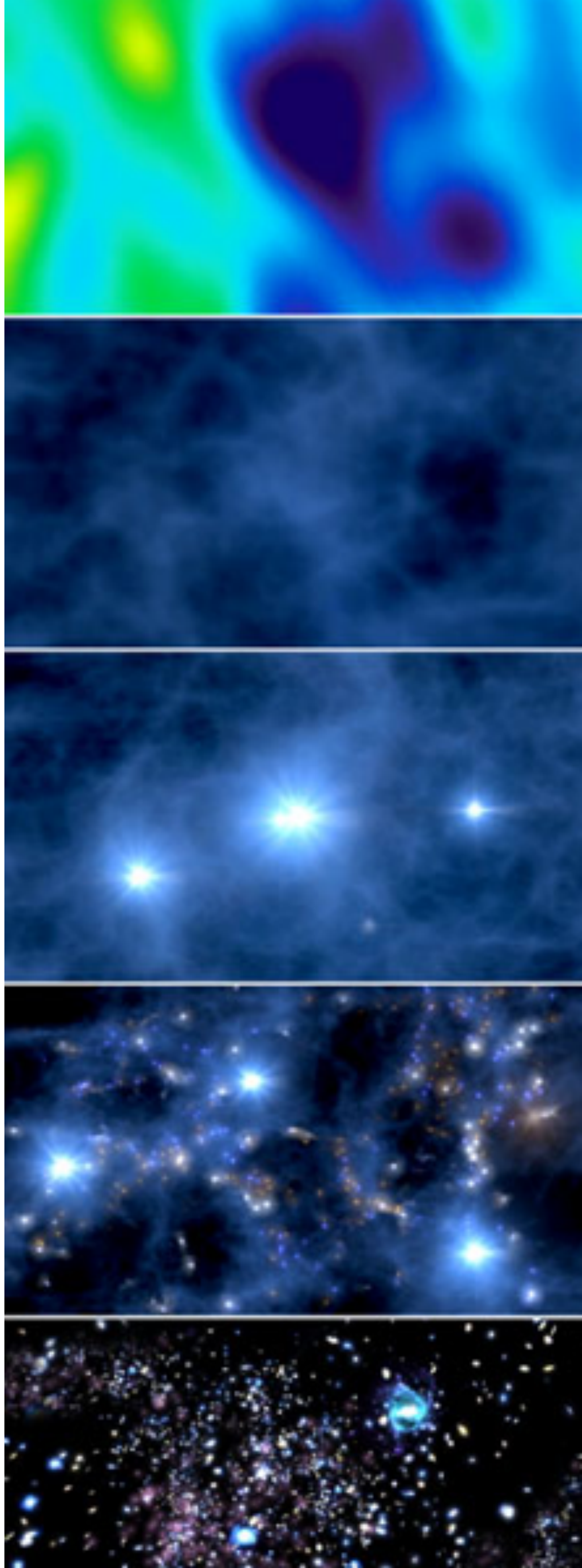




WMAP

Quantum fluctuations translate to perturbations in local energy density, & explains the measured temperature anisotropy: $\delta T/T$

Quantum fluctuations
(when the universe is 10^{-35} second old)
provide the seed of density perturbations



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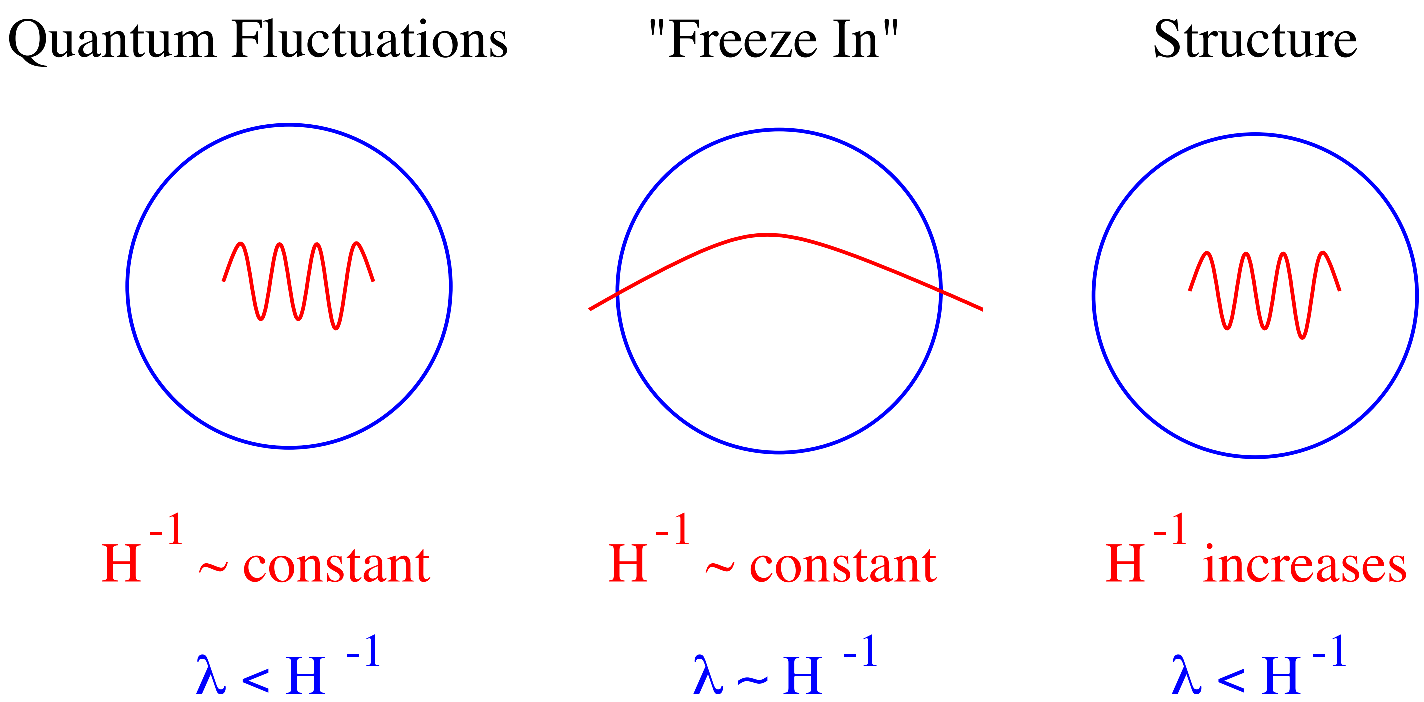

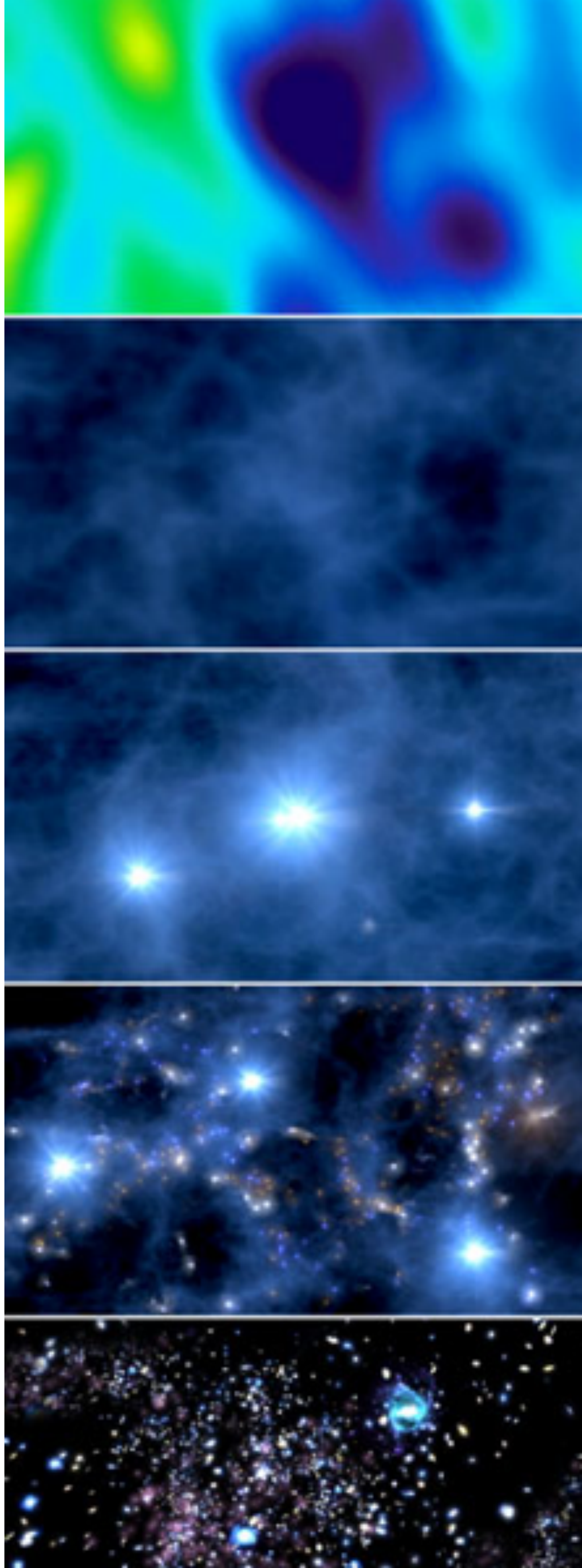

Quantum fluctuations
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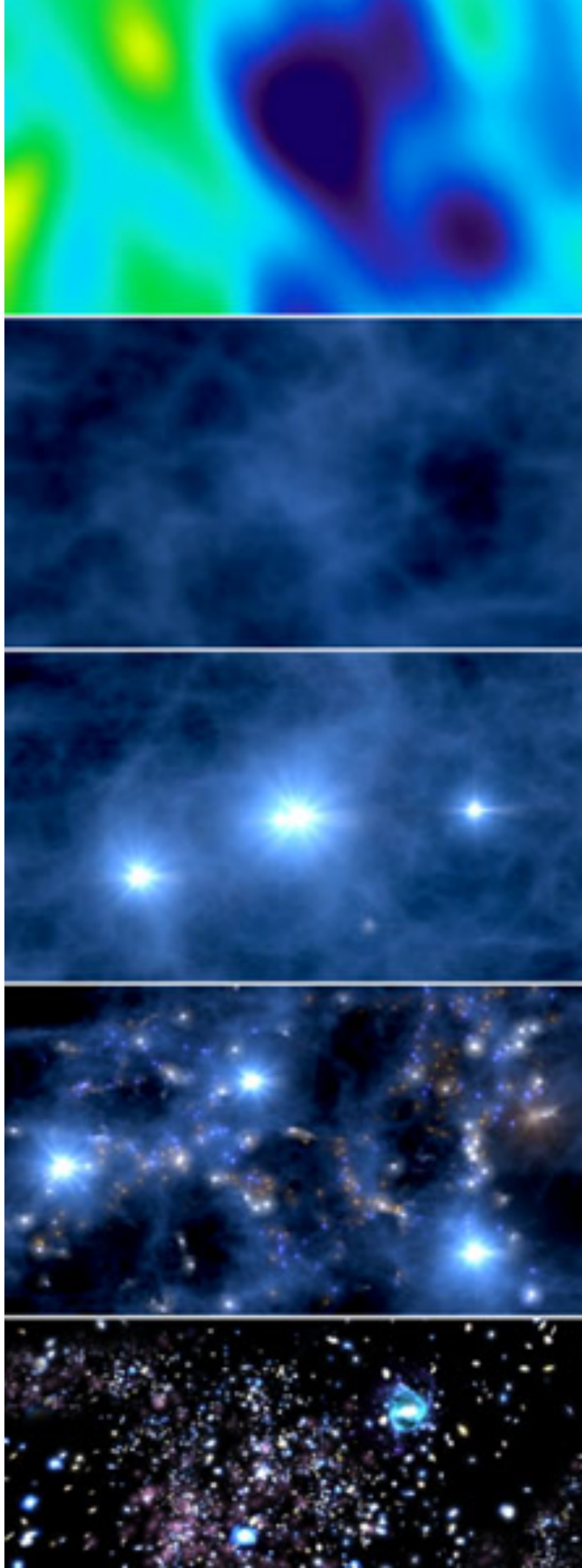
provide the seed of density perturbations

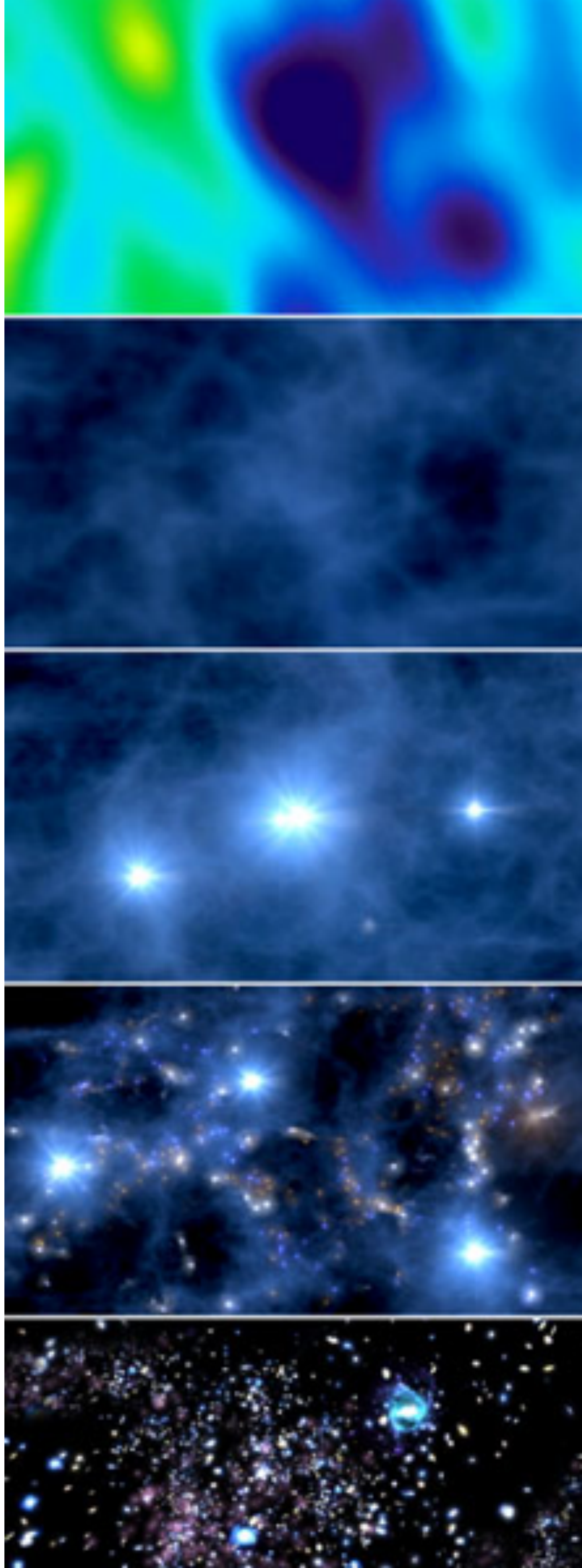
Tiny density perturbations grew
under the influence of gravity



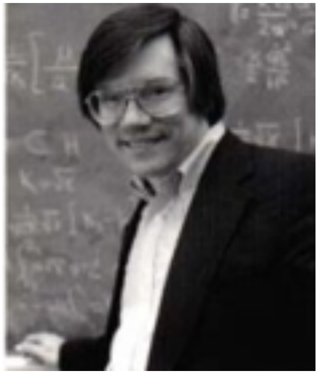
Quantum fluctuations
(when the universe is 10^{-35} second old)
provide the seed of density perturbations

Tiny density perturbations grew
under the influence of gravity

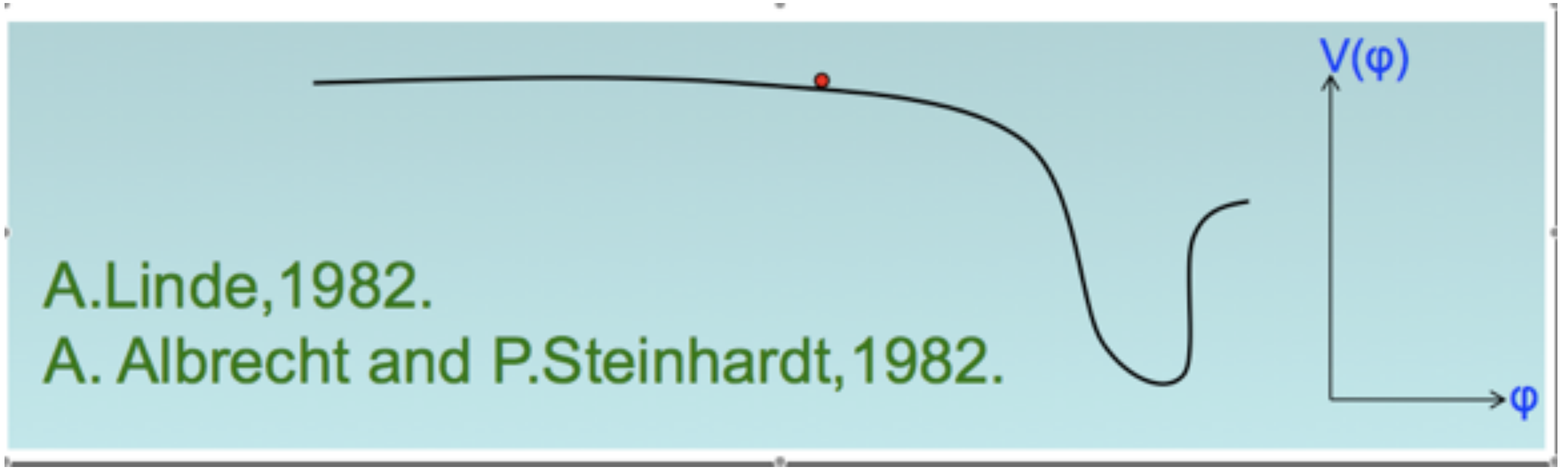
Galaxies and structures are
quantum effects writ large!



Inflation is an *effective theory* in search of a fundamental description!



Alan Guth



To solve the flatness & horizon problems, need to satisfy

"Slow-roll": $\epsilon = \frac{1}{2} M_P^2 \left(\frac{V'}{V}\right)^2 << 1$; $\eta = M_P^2 \frac{V''}{V} << 1$

These conditions are sensitive to Planck scale physics:

$$\delta V \sim \frac{V}{M_P^2}\phi^2 \quad \Longrightarrow \quad \eta \sim \mathcal{O}(1)$$

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Effective Field Theory:

- Physics can be understood *scale by scale*.
- Short distance physics: "irrelevant operators".

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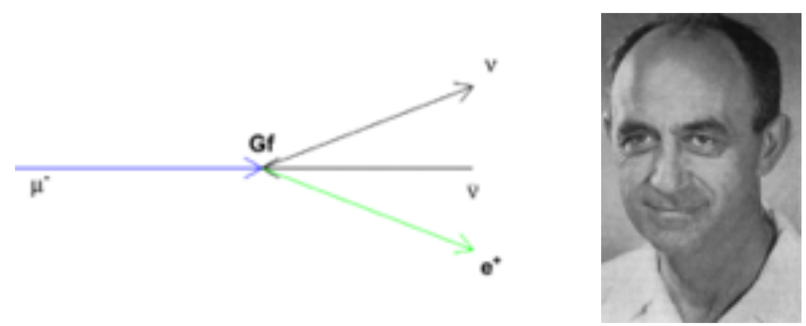
Effective Field Theory:

- Physics can be understood *scale by scale*.
- Short distance physics: "irrelevant operators".

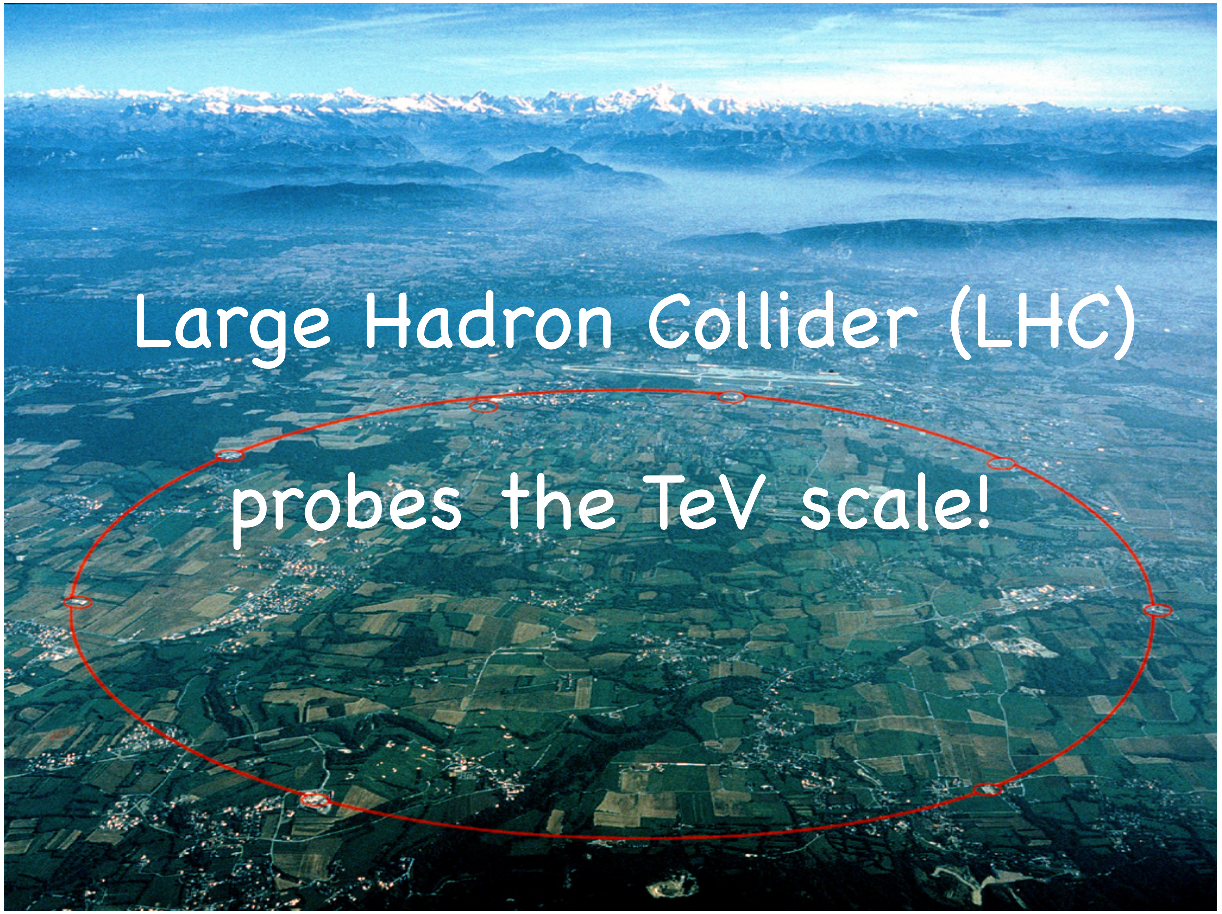
Examples:

BCS Theory of Superconductivity



Fermi theory of weak interaction

Particle Physics



Precision tests, such as those that constrain the proton lifetime, are sensitive to GUT scale physics

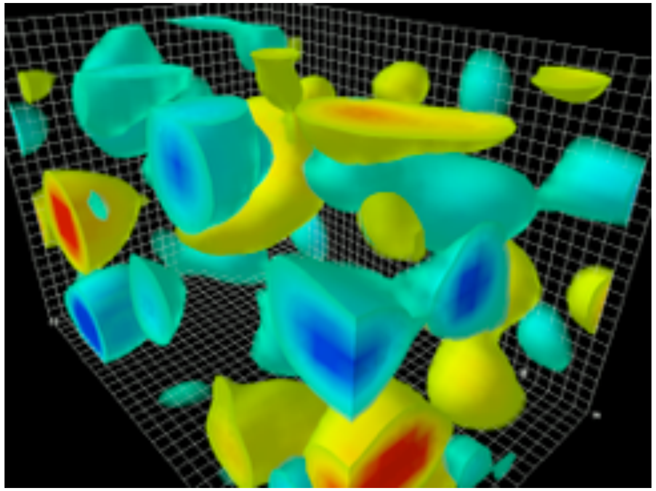
Inflation & UV Physics

A sufficient degree of UV completeness is needed to calculate such corrections.

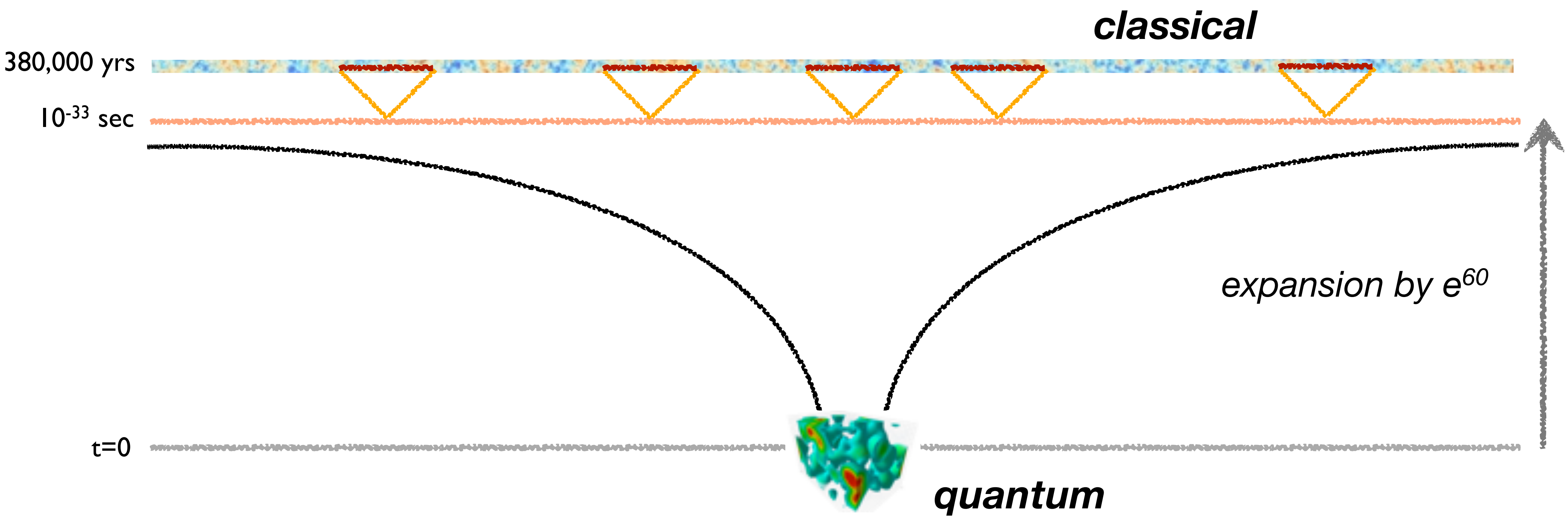
This applies to any model of inflation.

Models with detectable non-Gaussianities and gravity waves are even more UV sensitive!

Any massless field experiences quantum fluctuations during inflation:



Inflation stretches these to macroscopic scales:



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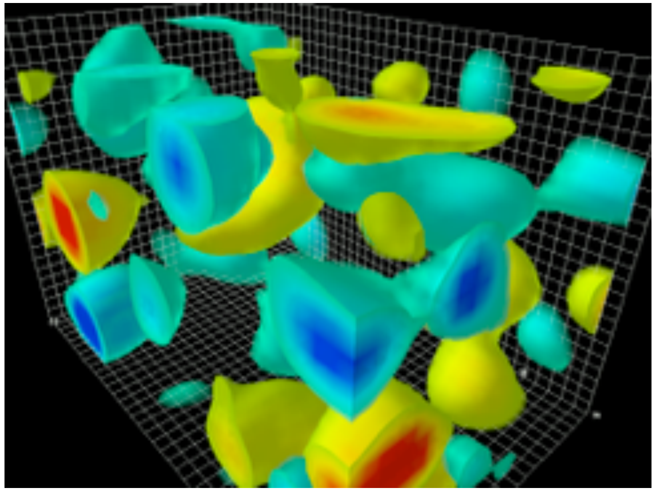

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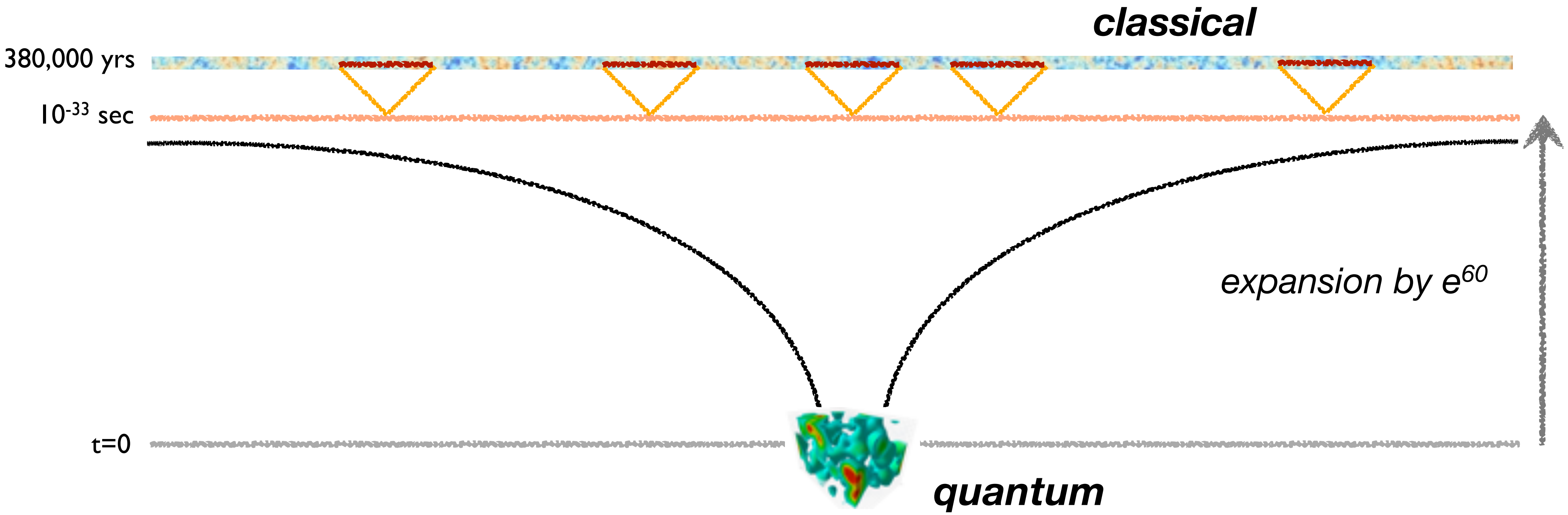

Two massless fields that are guaranteed to exist are:

ζ **Goldstone boson**

of broken time translations

h_{ij} **graviton**

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of broken time translations

$$\Delta_s^2 = \frac{1}{4\pi^2}\frac{H^4}{f_\pi^4}$$

symmetry breaking

($= \dot{\phi}^2$ for slow-roll inflation)

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expansion

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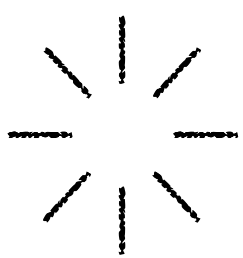
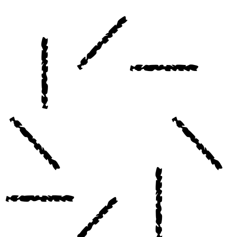
E-modes:



B-modes:



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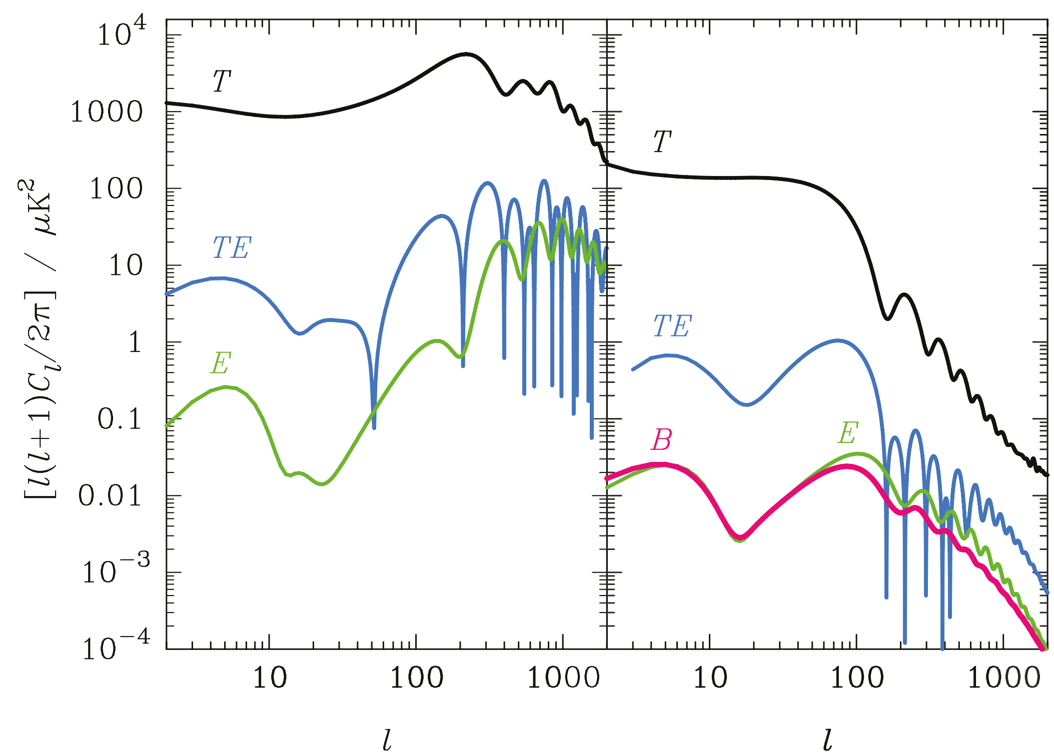
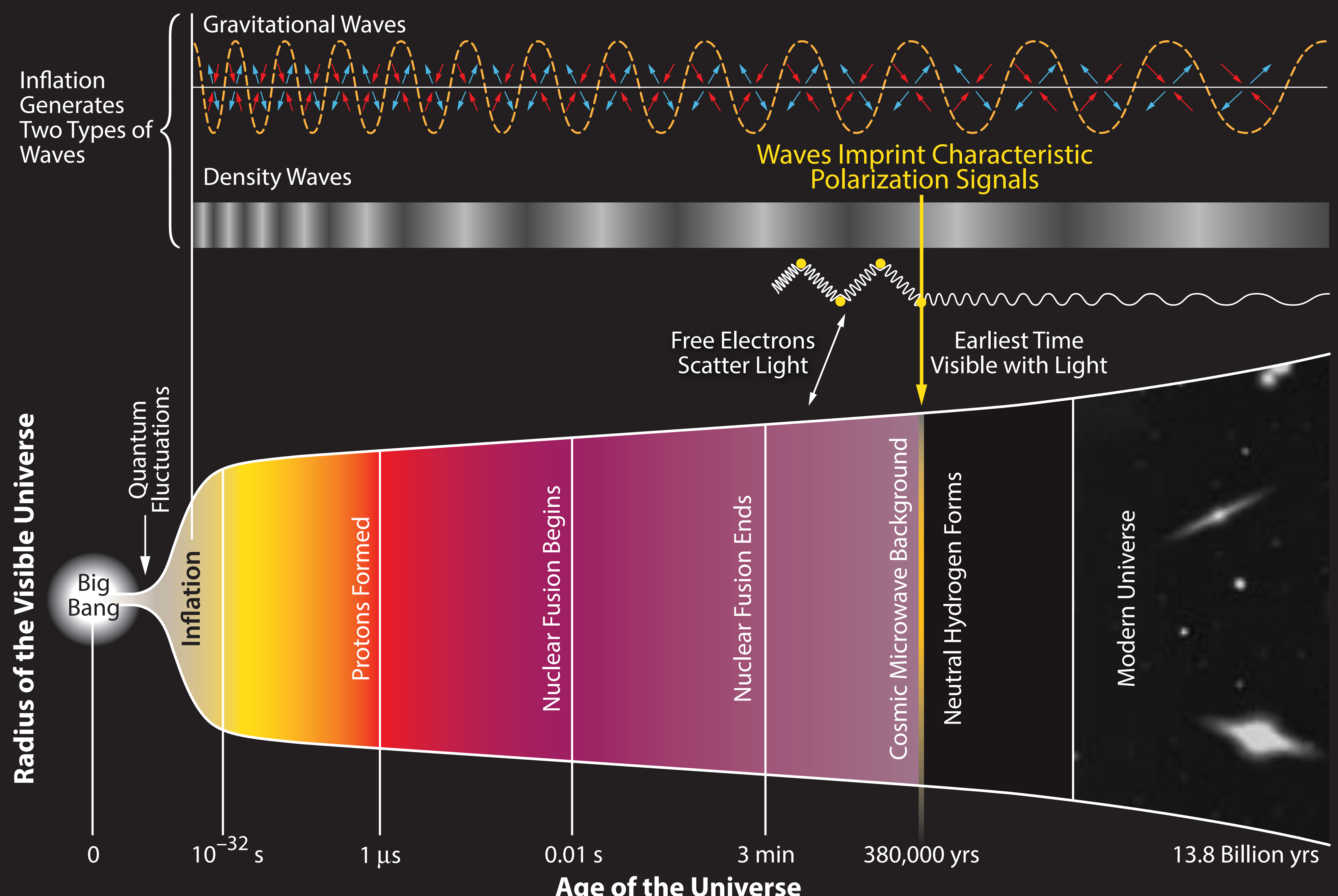


History of the Universe



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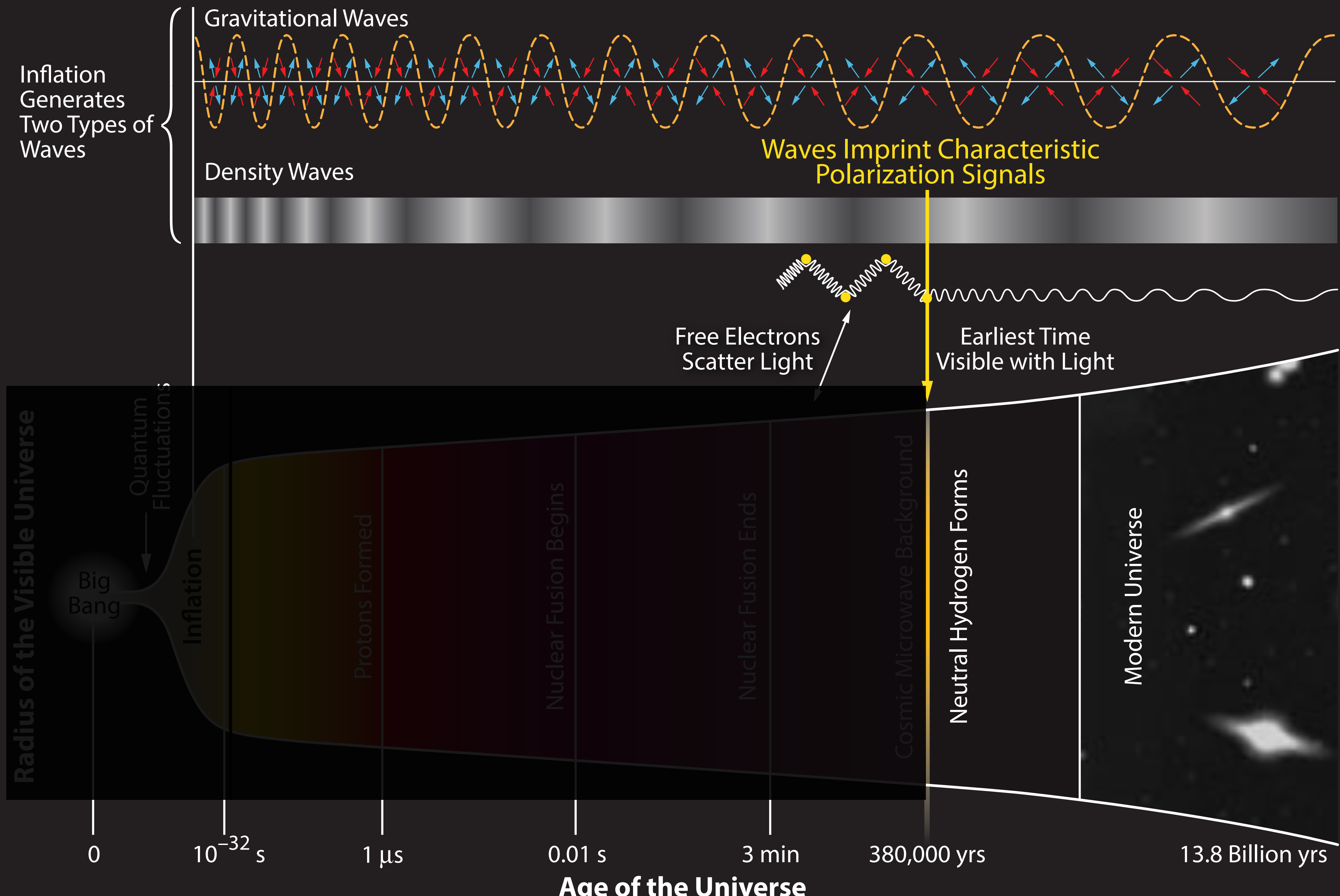

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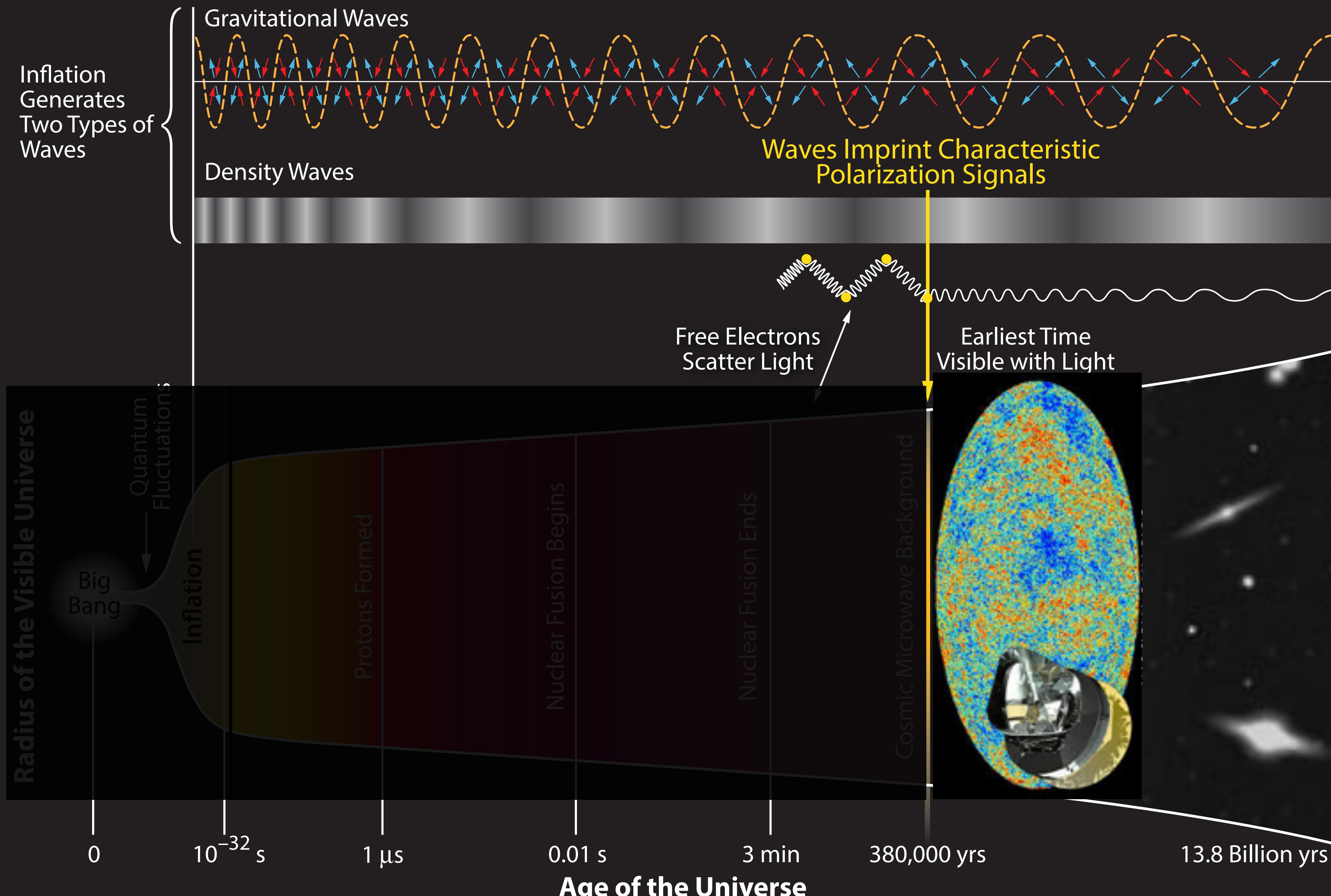

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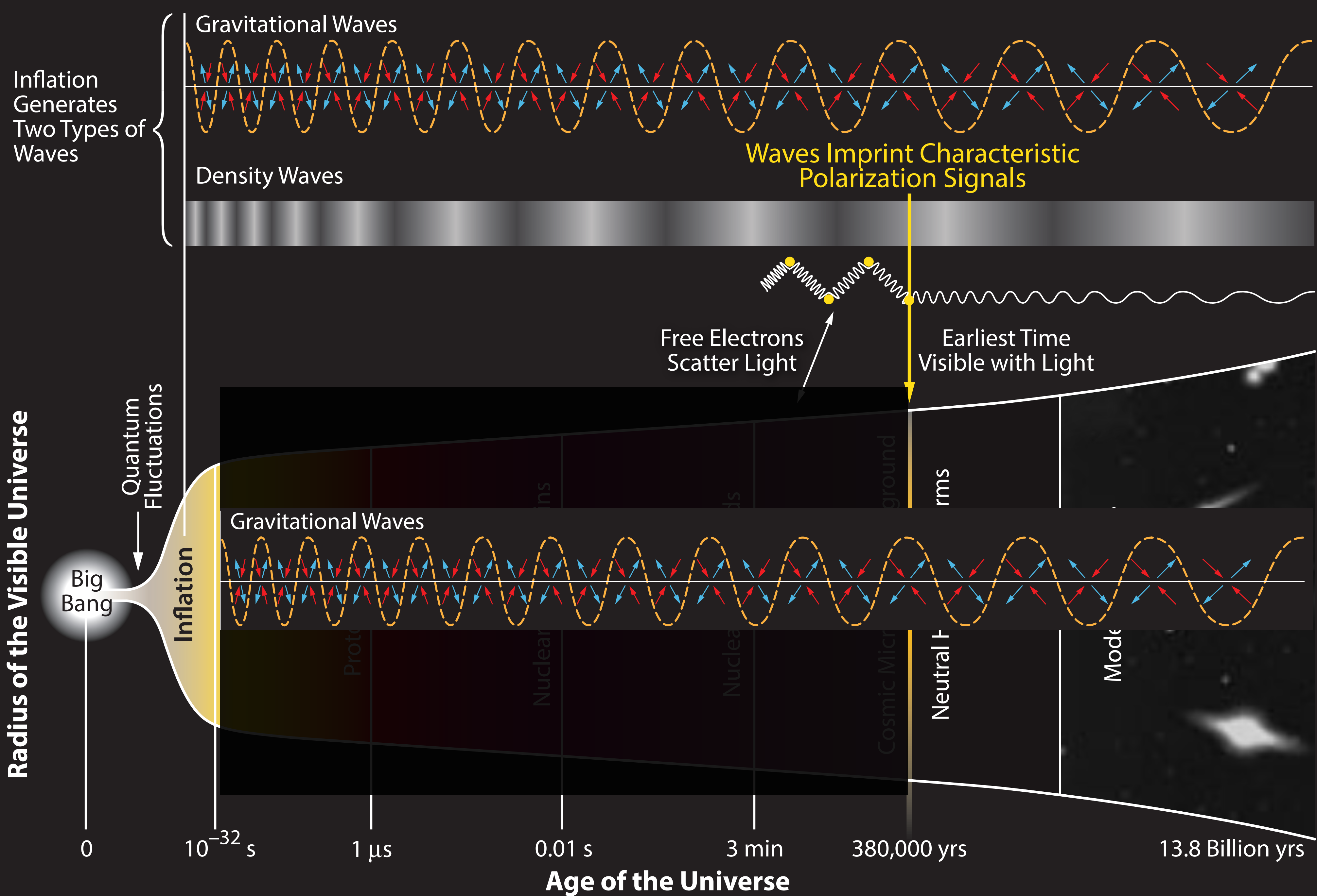
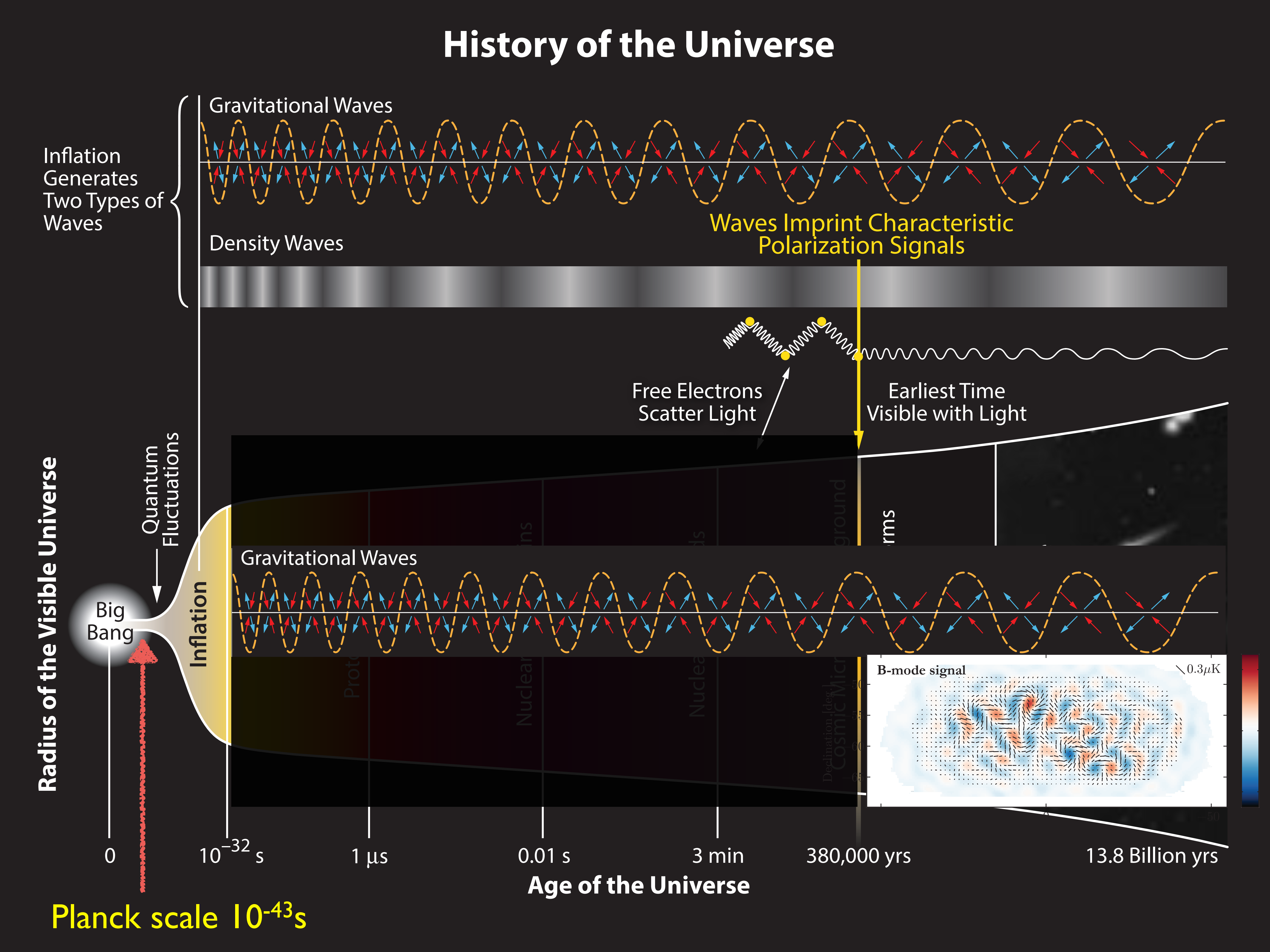
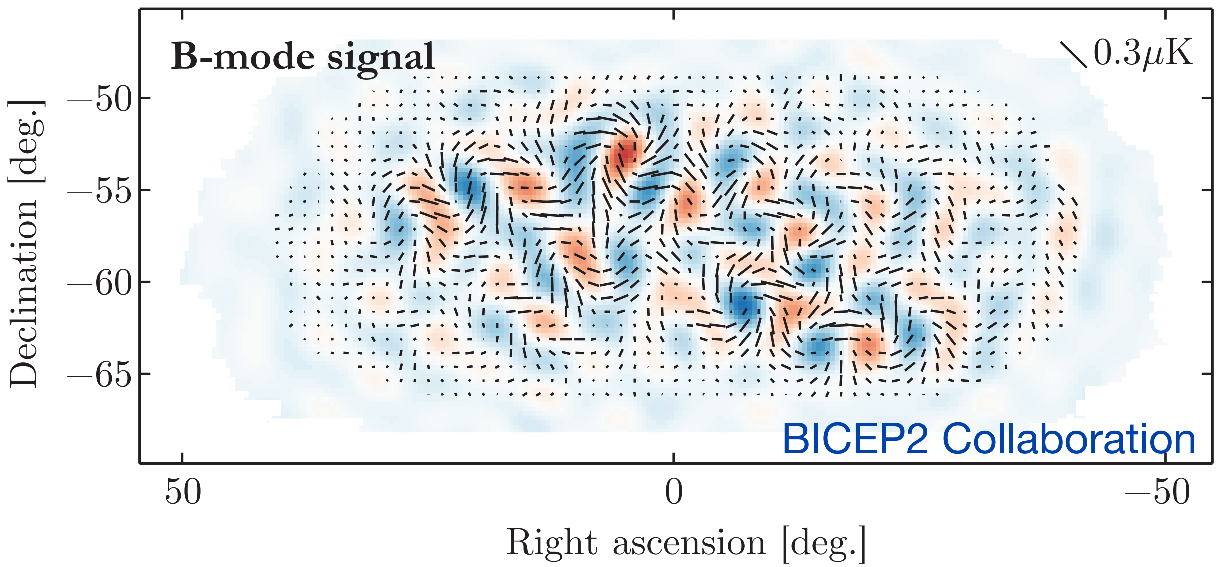
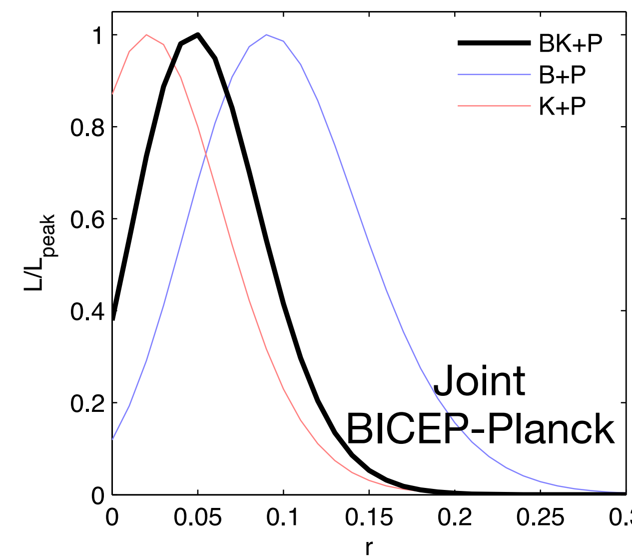



History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Quantum Fluctuations
Radius of the Visible Universe
Big Bang
Inflation
Gravitational Waves
B-mode signal
0.3μK
0
10^−32 s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe
Planck scale 10^-43s

A distinguishing parameter is the tensor-to-scalar ratio r.





Many experiments including BICEP/KECK, PLANCK, ACT, PolarBeaR, SPT, SPIDER, QUEIT, Clover, EBEX, QUaD… can potentially detect such primordial B-mode if $r \lesssim 10^{-2}$.

LiteBIRD may even have the sensitivity to detect $r \sim 10^{-3}$.

B-mode and Inflation

<u>If</u> primordial B-mode is detected, natural interpretations:

- Inflation took place
- The energy scale of inflation is the GUT scale

$$E_{\rm inf} \simeq 0.75 \times \left(\frac{r}{0.1}\right)^{1/4} \times 10^{-2} M_{\rm Pl}$$

- The inflaton field excursion was super-Planckian

$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

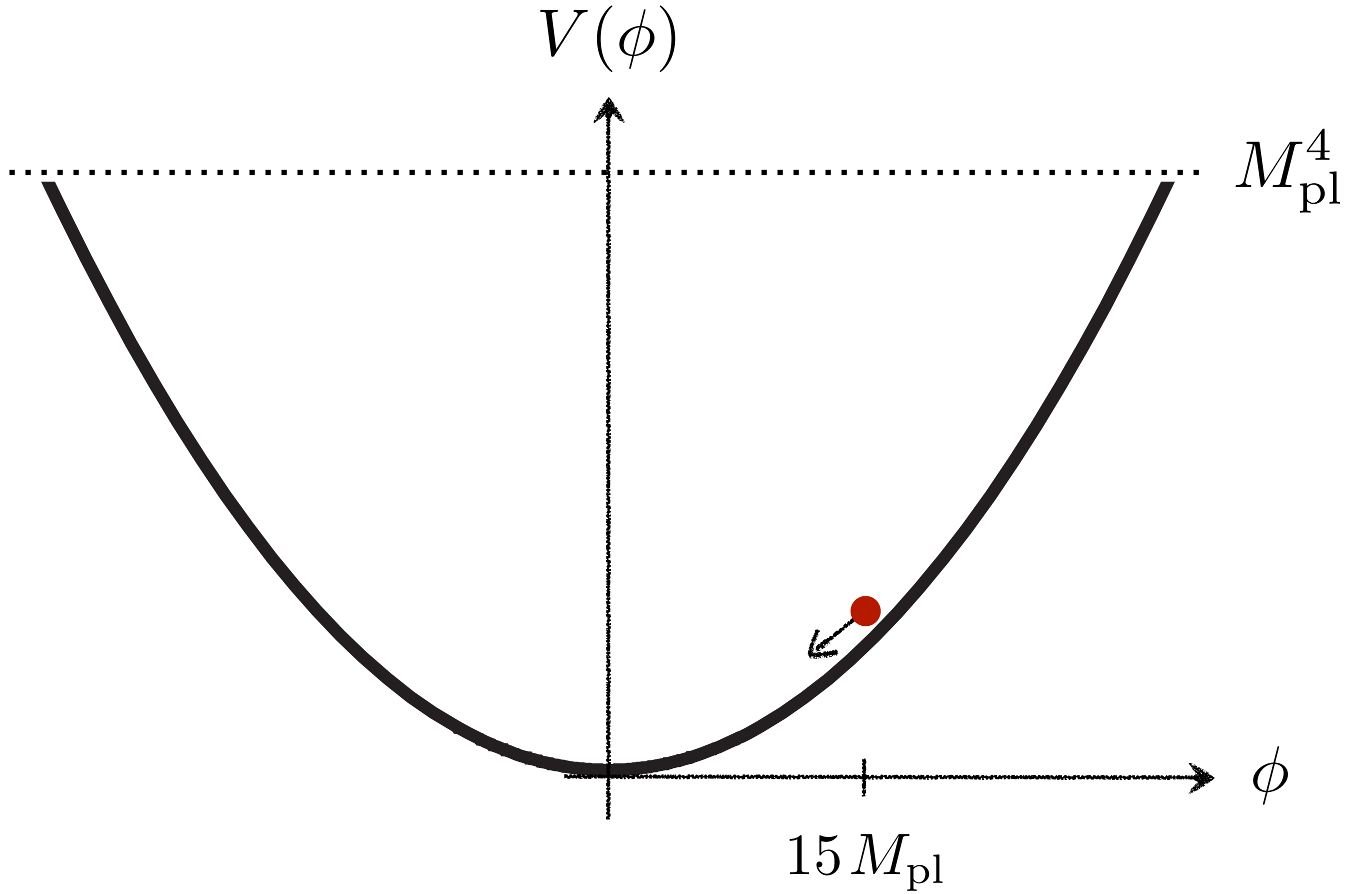
Lyth '96

- Great news for string theory due to strong UV sensitivity!

Super-Planckian Fields

Chaotic Inflation

Linde '86



Chaotic Inflation

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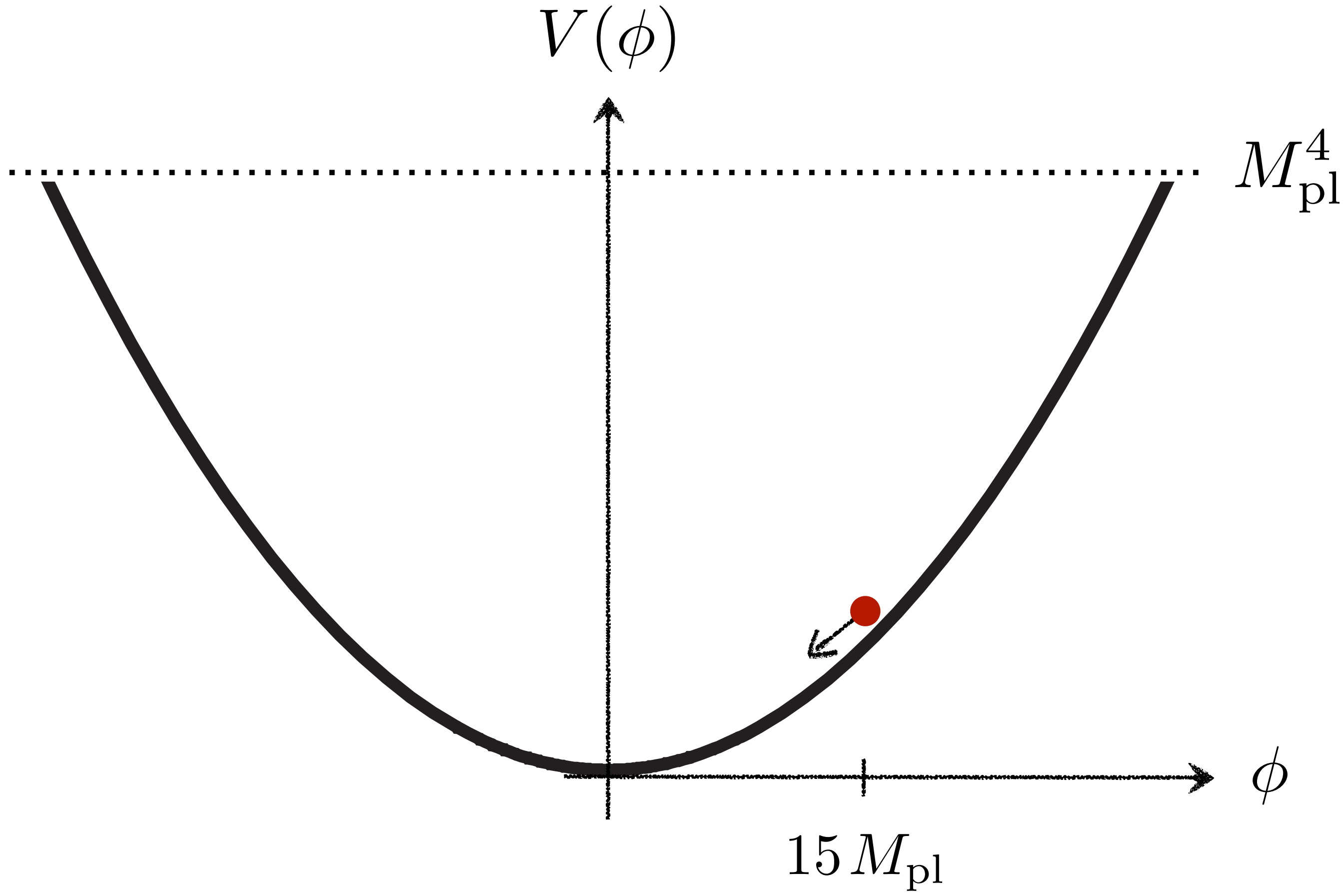
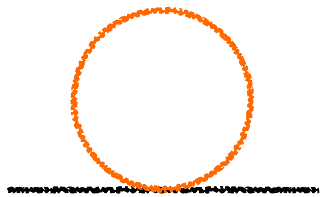
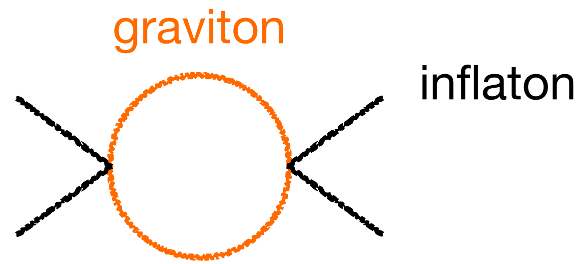


Classical backreaction is under control.

Chaotic Inflation

Linde '86





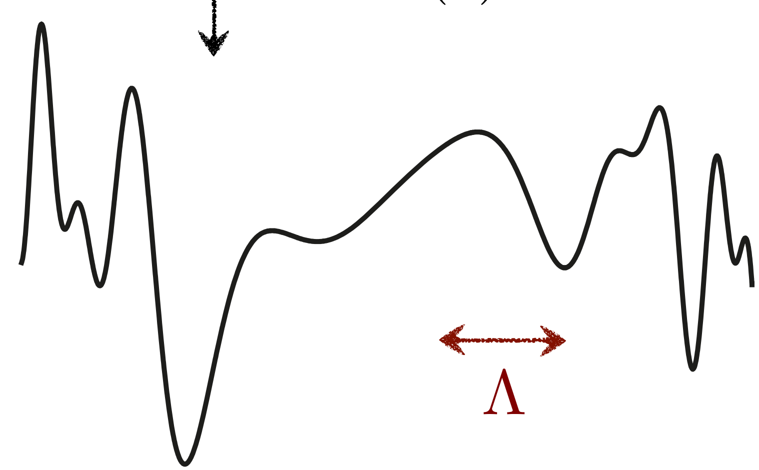
$$\frac{\Delta m^2}{m^2} = c_1 \frac{m^2}{M_{\mathrm{pl}}^2} + c_2 \frac{m^2 \phi^2}{M_{\mathrm{pl}}^4} \ll 1$$

Quantum corrections are small.

Concerns arise if we consider coupling the theory to the UV degrees of freedom of a putative theory of quantum gravity.

$$\mathcal{L}_{\rm eff}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2\left(1 + \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}} + \cdots\right)$$

$c_i \sim \mathcal{O}(1)$



Light fields can become heavy;

Heavy fields can become light

Large Field Inflation in String Theory

Large corrections, unless the inflaton couples weaker than gravitationally to everything else.

This even stronger UV sensitivity intrinsic to *large field inflation* should be explained in the UV-completion.

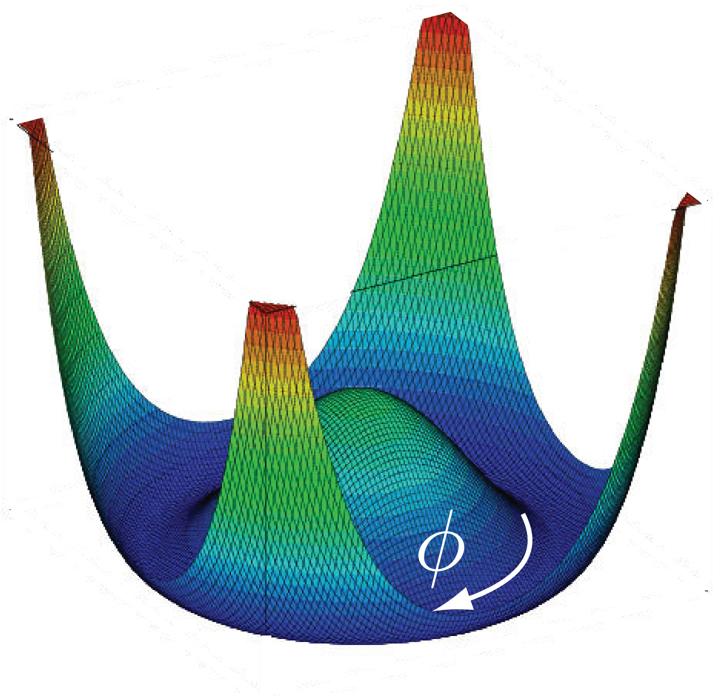
Controlling an *infinite number of corrections* seems hopeless.

Natural inflaton candidates are fields with symmetries.

“Symmetries dictate interactions”

Axions & Large Field Inflation

Pseudo-Nambu-Goldstone bosons
are natural inflaton candidates:



Natural Inflation: [Freese, Frieman, Olinto];
Axion Monodromy: [McAllister Silverstein, Westphal]; [Marchesano, GS, Uranga]

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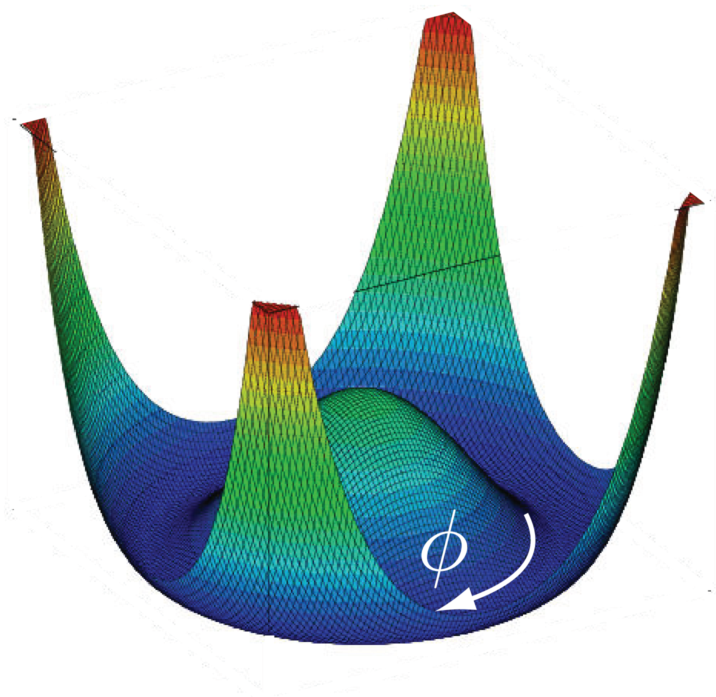
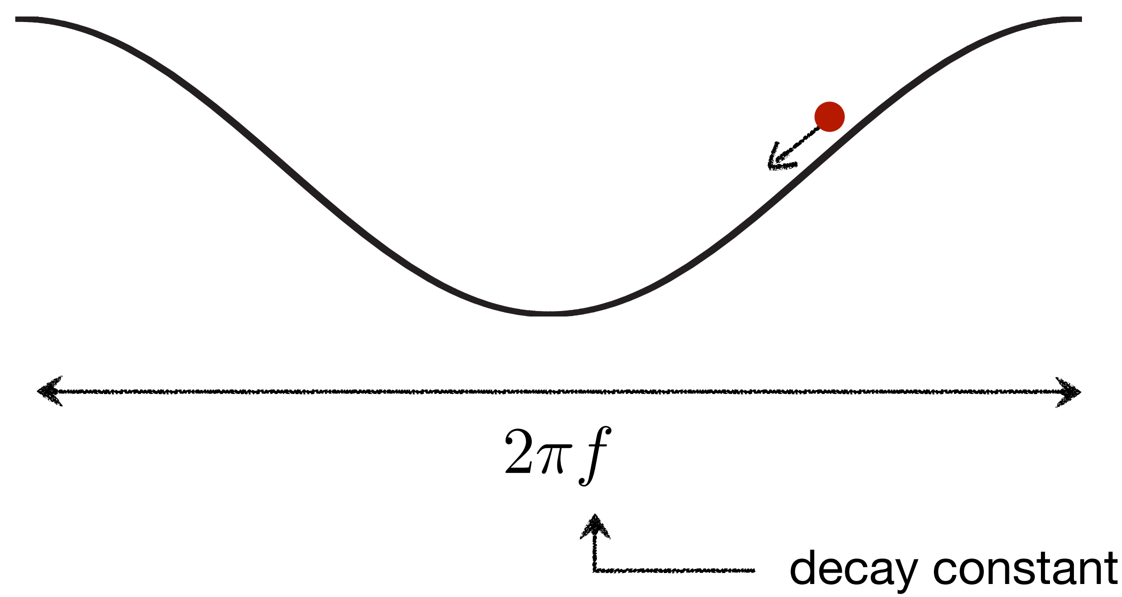


They satisfy a shift symmetry that is only
broken by non-perturbative effects:



Natural Inflation: [Freese, Frieman, Olinto];
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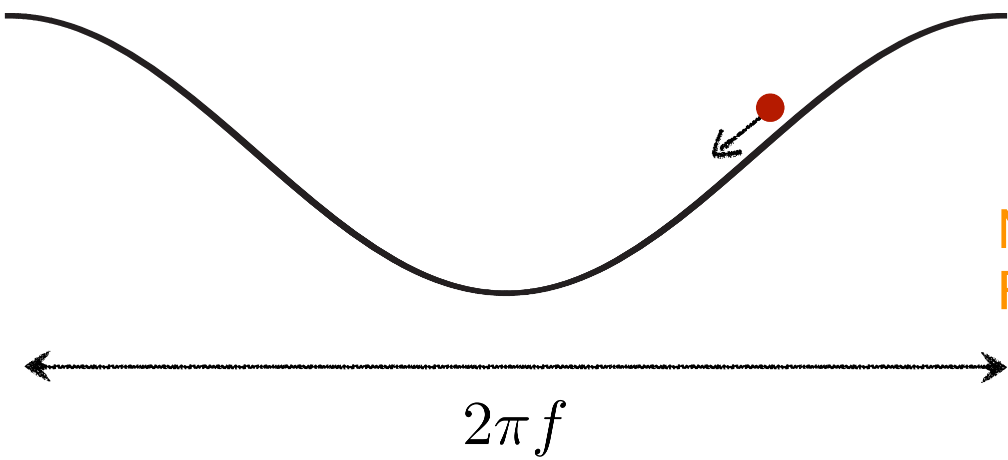
Axions & Large field inflation

- Inflation with axion: $\Lambda^{(k)} \sim e^{-km}\,, \qquad m \sim \frac{1}{g^2}$

$$V(\phi) = 1 - \Lambda^{(1)} \cos\left(\frac{\phi}{f}\right) + \sum_{k>1} \Lambda^{(k)} \left[1 - \cos\left(\frac{k\phi}{f}\right)\right]$$



Natural Inflation:
Freese, Frieman, Olinto

- Slow roll conditions imply

$$f > M_P \qquad \frac{\Lambda^{(n+1)}}{\Lambda^{(n)}} \sim e^{-m} \ll 1 \Longrightarrow m \gtrsim 1$$

Axions in String Theory

String theory has many **higher-dimensional form-fields**:

e.g. $$F = \mathrm{d}A$$

3-form flux → F

2-form gauge potential: → A

gauge symmetry: $A \to A + \mathrm{d}\Lambda$

Integrating the 2-form over a 2-cycle gives an **axion**:

$$a(x) \equiv \int_{\Sigma_2} A$$

The gauge symmetry becomes a **shift symmetry.**

Axions with super-Planckian decay constants don't seem to exist in controlled limits of string theory.

Svrcek and Witten

Banks et al.

Multiple Axions

- N-flation [Dimopoulos, Kachru,McGreevy,Wacker '05]
- Alignment [Kim, Nilles, Peloso '04];[Bachlechner, Long, McAllister, '14]
- Kinetic and Stuckelberg Mixings [GS, Staessens, Ye, '15]

seem to give $f_{eff} > M_{p}$. ***Can these models trick fool quantum gravity or they lie in the swampland?***

The
Weak Gravity Conjecture

The Weak Gravity Conjecture

Arkani-Hamed et al. '06

- The conjecture:

"Gravity is the Weakest Force"

- For every long range gauge field there exists a particle of charge q and mass m, s.t.

$$\frac{q}{m} M_P \geq \text{``1''}$$

$M_P \equiv 1$

The Weak Gravity Conjecture

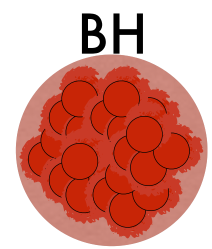
- Take a U(1) and a single family with q < m (~~WGC~~)

$M_P \equiv 1$

The Weak Gravity Conjecture

- Take a U(1) and a single family with q < m (~~WGC~~)

- Form bound states



$2m > M_2 > 2q$ $\quad$ $3m > M_3 > 3q$ $\quad \cdots \quad$ $Nm > M_N > Nq$ $\quad \cdots \quad$ $M_\infty \to Q_\infty$

- Trouble with remnants

Susskind '95

$M_P \equiv 1$

The Weak Gravity Conjecture

- Take a U(1) and a single family with $q < m$ (~~WGC~~)

  - Form bound states

$2m > M_2 > 2q$ $\quad$ $3m > M_3 > 3q$ $\quad \cdots \quad$ $Nm > M_N > Nq$ $\quad \cdots \quad$ $M_\infty \to Q_\infty$

  - Trouble with remnants

Susskind '95

- Need a light state into which they can decay

$$\frac{q}{m} \geq \text{“}1\text{”} \equiv \frac{Q_{Ext}}{M_{Ext}}$$

The Weak Gravity Conjecture

Arkani-Hamed et al. '06

- The conjecture:

"Gravity is the Weakest Force"

- For a U (1) symmetry there must exist a particle with charge q and mass m such that

$$\frac{q}{m} \geq \text{``}1\text{''} \equiv \frac{Q_{Ext}}{M_{Ext}}$$

Strong-WGC: satisfied by *lightest* charged particle

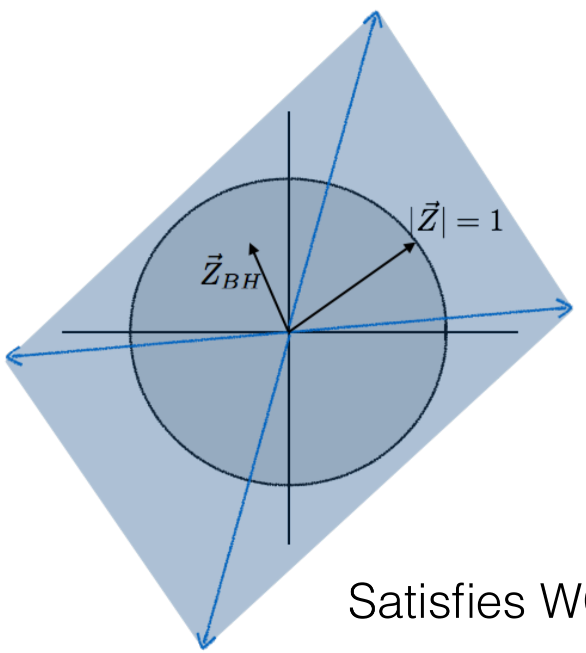
Weak-WGC: satisfied by *any* charged particle

Convex Hull Condition

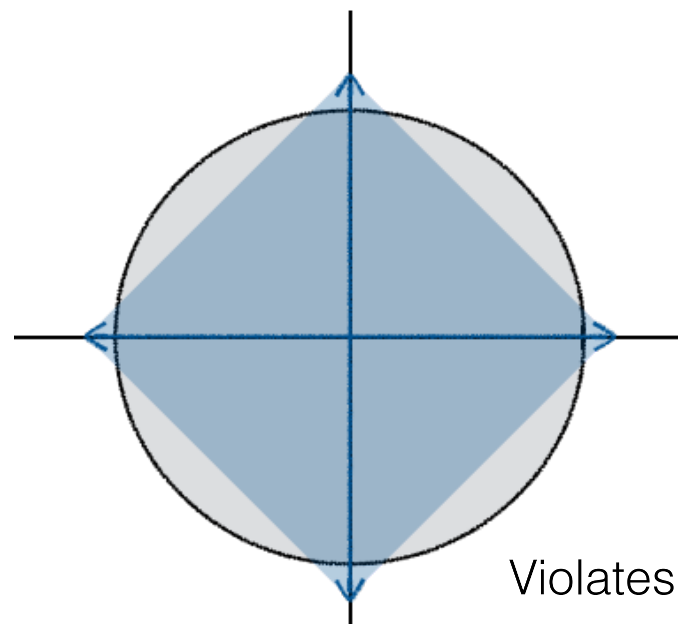
- For multiple U(1)'s and multiple charged particles, construct the vectors in charge space

$$\vec{z}_k = \frac{\vec{q}_k M_P}{m_k}$$

- Convex hull generated by the vectors $\pm\vec{z}_k$ must contain the ball of radius $|\vec{Z}|_{EBH}$ [Cheung et al, '14]



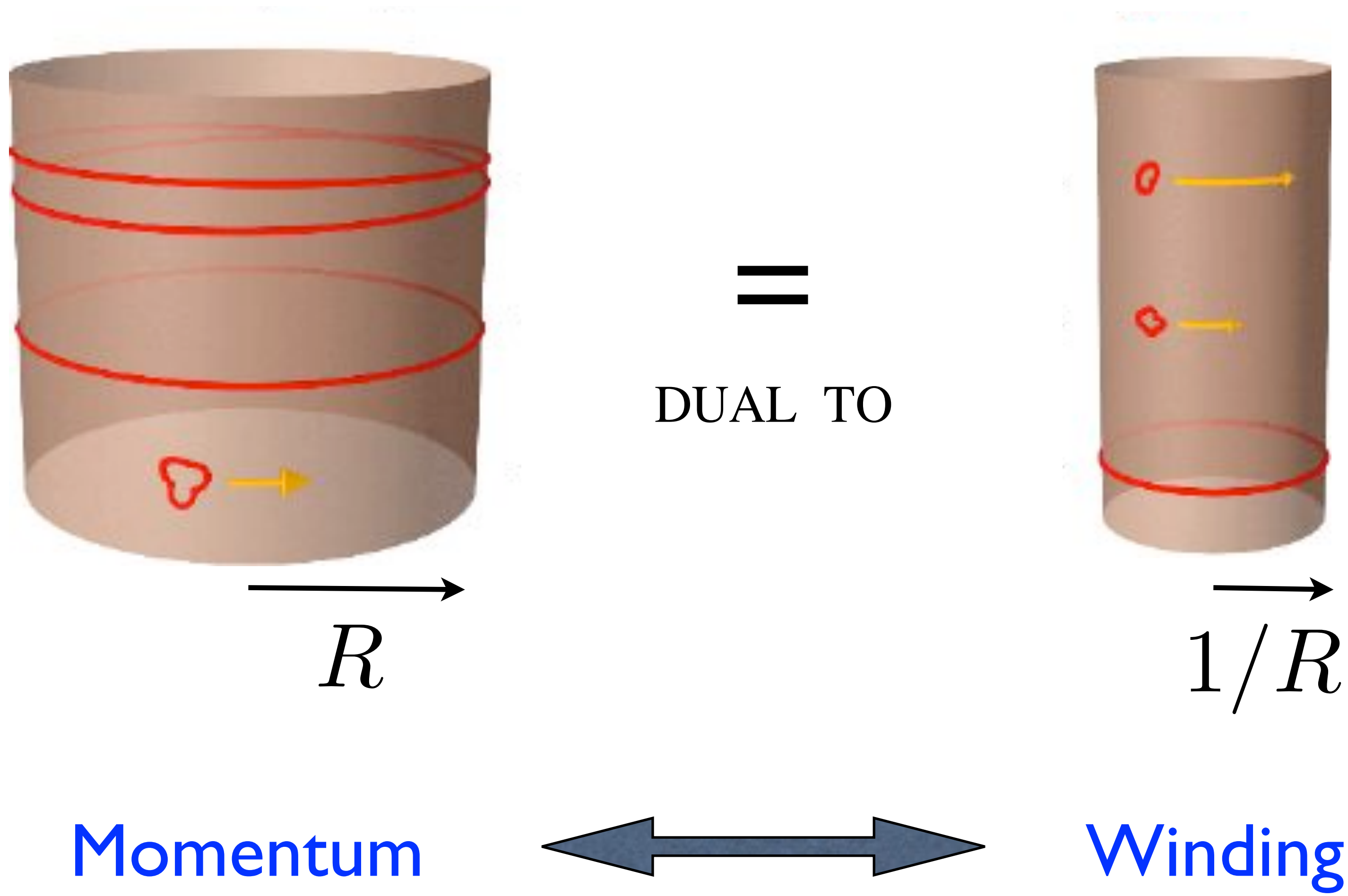
Satisfies WGC



Violates WGC

T-duality

An equivalence between different universes:

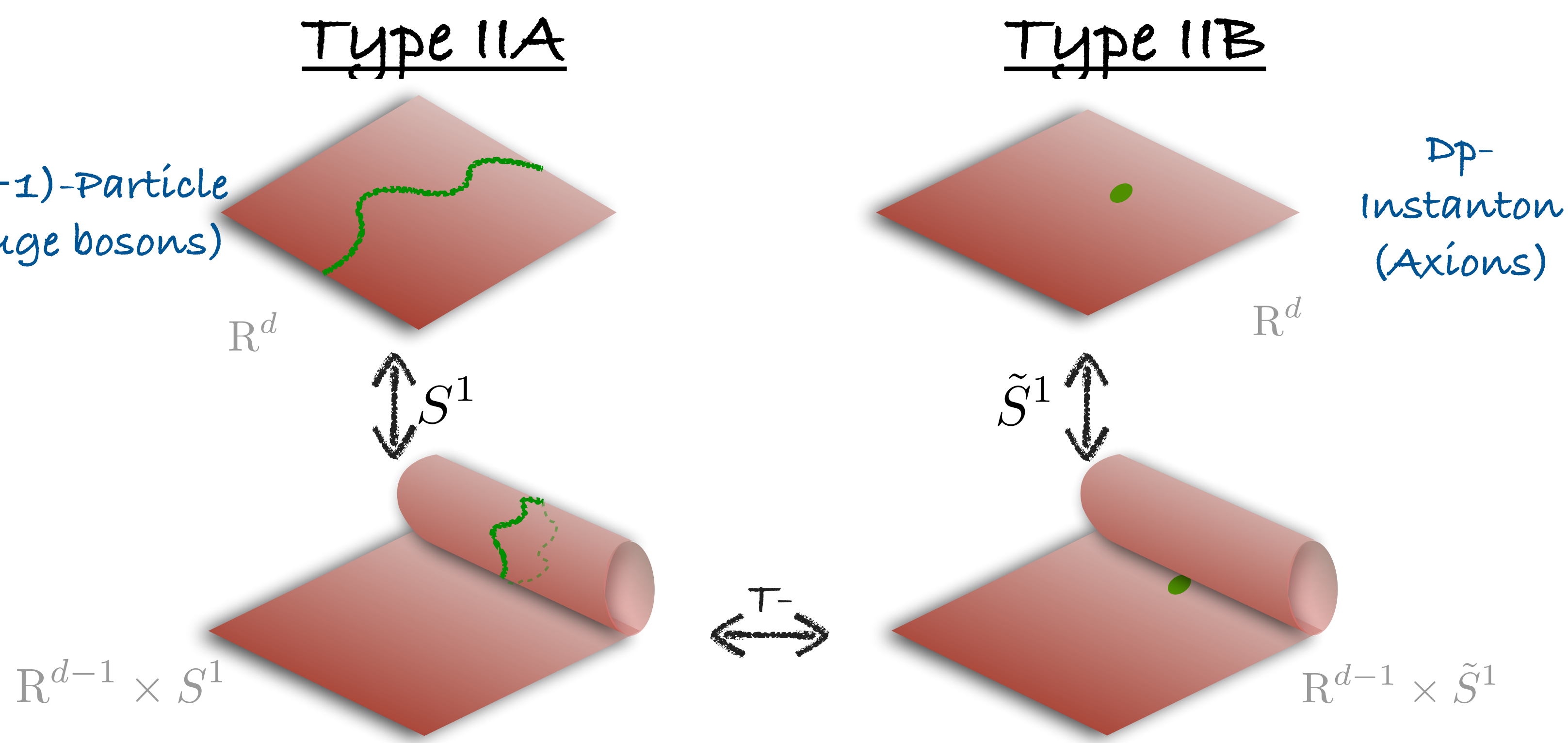


T-duality: WGC for Axions

- Consider C_2 axions, canonically normalized as c^i

$$V \supset \sum_k \Lambda^4 e^{-m_k} \left(1 - \cos\left(\mathcal{Q}^i_k \frac{c^i}{M_p}\right)\right)$$

- Compactify and T-dualize (c-map)



T-duality: WGC for Axions

[Brown,Cottrell, GS, Soler]

- Through this T-duality:
  - Axions → U(1) gauge fields
  - Instantons → particles

- These particles are charged under U(1) symmetries

$$\vec{z}_k = \frac{\vec{\mathcal{Q}}_k}{m_k}$$

- Considering EBH in the T-dual theory, the WGC states

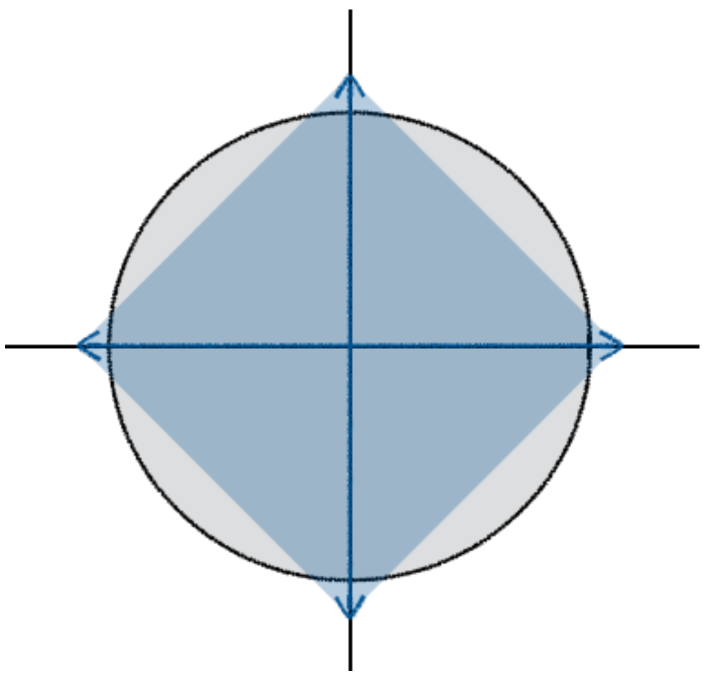
The convex hull generated by $\vec{z}_k$ *must contain the ball of radius* $2/\sqrt{3}$.

Apply WGC to Axion Inflation

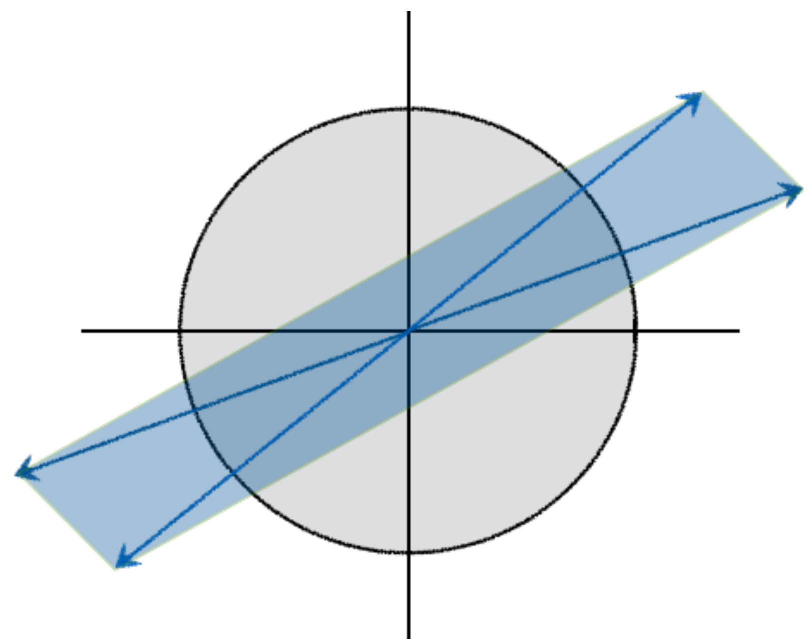
- For a single axion and an instanton **Q**=M_p/f:

$$f \cdot m \leq \frac{\sqrt{3}}{2} M_p$$

- For multiple axions

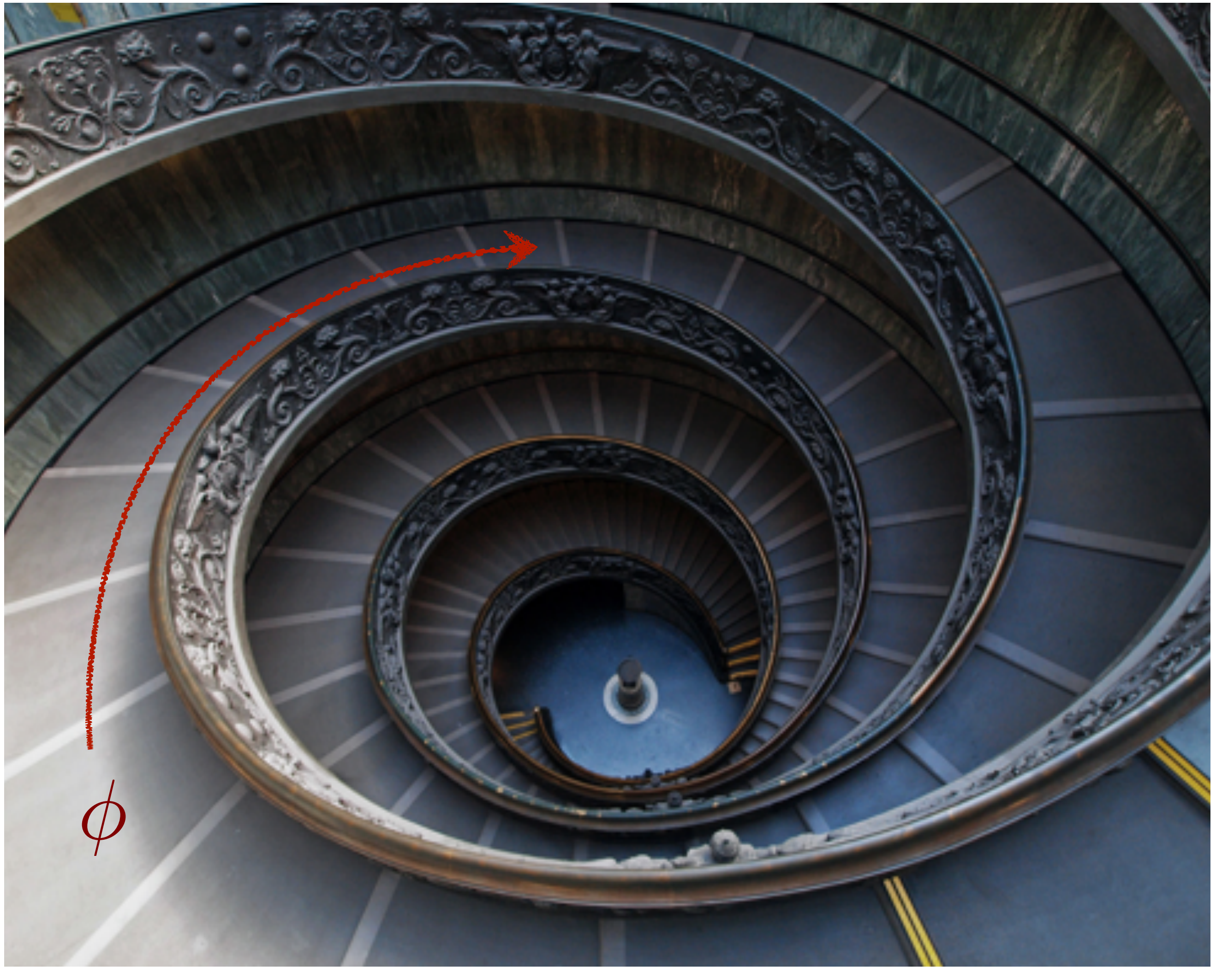


N-flation



Aligned Inflation

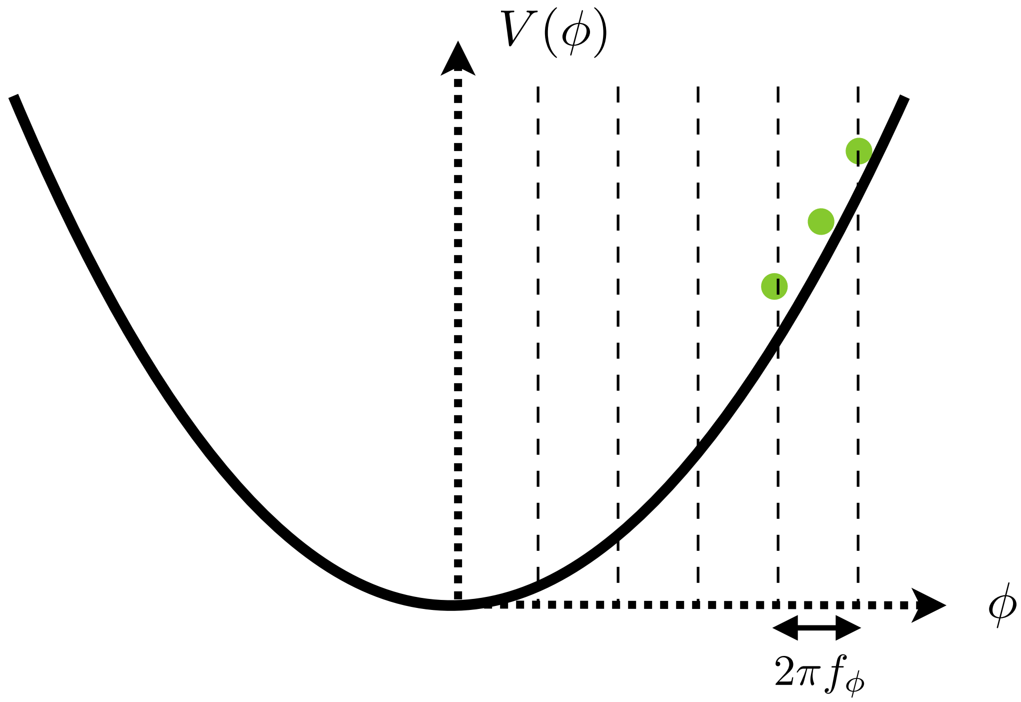
Axion Monodromy



[McAllister, Silverstein and Westphal];[**Marchesano, GS, Uranga**]

Axion Monodromy Inflation

Idea: Combine chaotic inflation and natural inflation



The axion periodicity is lifted, allowing for super-Planckian displacements. The UV corrections to the potential should still be constrained by the underlying symmetry.

Axion Monodromy Inflation

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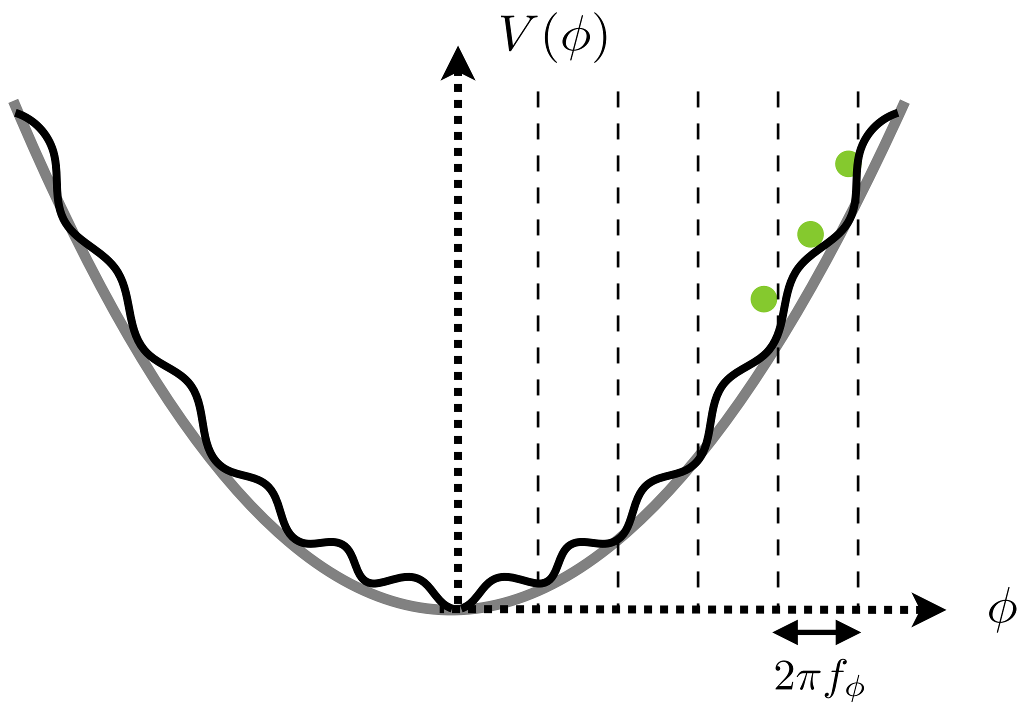

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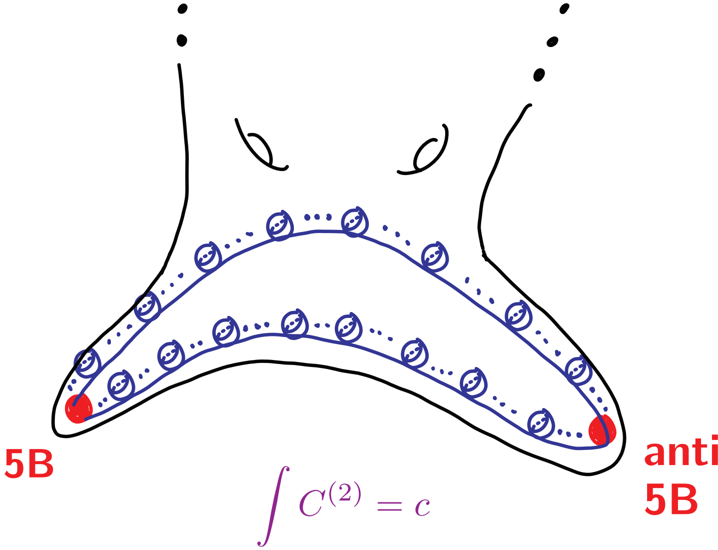
Axion Monodromy Inflation

- In string theory one may elegantly implement large field inflation by identifying the inflaton with an axion and applying the axion-monodromy proposal

Silverstein & Westphal '08

- String theory constructions using boundaries:

McAllister, Silverstein, Westphal '08
Berg, Pajer, Sjörs '09
Palti & Weigand '14



taken from McAllister, Silverstein, Westphal '08

F-term Axion Monodromy

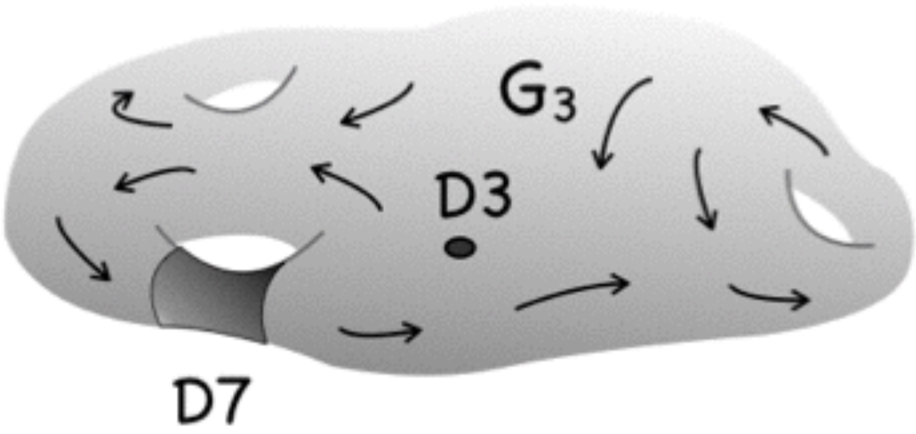
Obs:

Marchesano, GS, Uranga '14

Axion Monodromy ~ Giving a mass to an axion

- Done in string theory within the moduli stabilisation program: adding ingredients like background fluxes generate superpotentials in the effective 4d theory

Idea: Use same techniques to generate an inflation potential



taken from Ibañez & Uranga '12

F-term Axion Monodromy Inflation

Advantages:

- Simpler models, all sectors understood at weak coupling
- Spontaneous SUSY breaking, no need for brane-anti-brane
- Supergravity description at small field, allows to connect with large field inflation models in SUGRA
- Realizes Kaloper-Sorbo 4d formalism in string theory

$$\int d^4x\, |dC_3|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2 \longrightarrow \int d^4x\, |F_4|^2 + |d\phi|^2 + \phi F_4$$

$$F_4 = dC_3$$
$$d\phi = *_4 db_2$$

Kaloper & Sorbo '08
Kaloper, Lawrence, Sorbo '11

Example: (Massive) Wilson line

- Simple example of axion: (4+d)-dimensional gauge field integrated over a circle in a compact space Π_d

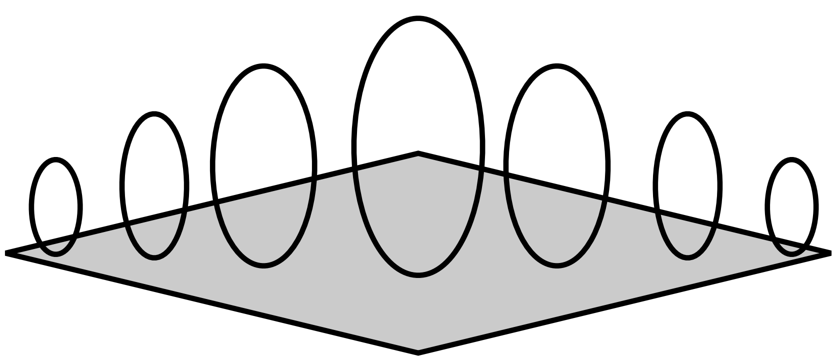
$$\phi = \int_{S^1} A_1 \qquad \text{or} \qquad A_1 = \phi(x)\,\eta_1(y)$$

  - ϕ massless if $\Delta\eta_1 = 0 \Rightarrow S^1$ is a non-trivial circle in Π_d

    exact periodicity and (pert.) shift symmetry

  - ϕ massive if $\Delta\eta_1 = -\mu^2\,\eta_1 \Rightarrow kS^1$ homologically trivial in Π_d

    (non-trivial fibration)



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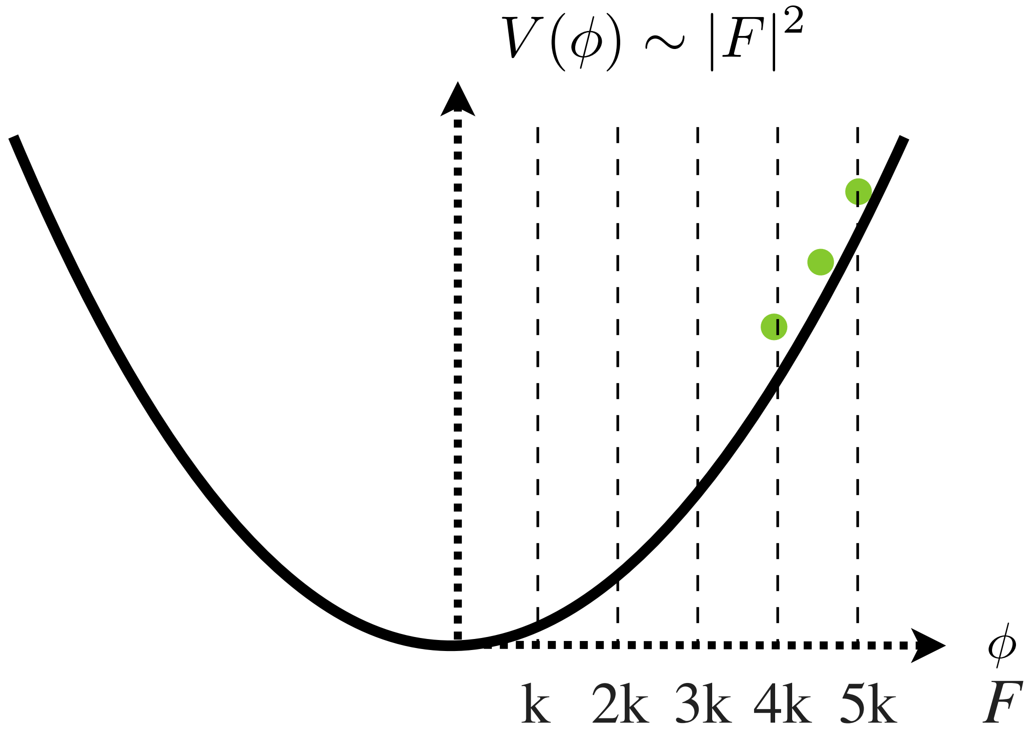
$$F_2 = dA_1 = \phi\, d\eta_1 \sim \mu\phi\,\omega_2 \quad \Rightarrow$$

shifts in ϕ increase energy via the induced flux F_2

⇒ periodicity is broken and shift symmetry approximate

MWL and monodromy



Question: How does monodromy and approximate shift symmetry help prevent wild UV corrections?

Torsion and gauge invariance

- Let us again consider a 7d gauge theory on $M^{1,3}$ x $\tilde{\mathbb{T}}^3$
  - Instead of A_1 we consider its magnetic dual V_4

$$d\eta_1 = k\,\sigma_2$$

$$V_4 = C_3 \wedge \eta_1 + b_2 \wedge \sigma_2 \longrightarrow dV_4 = dC_3 \wedge \eta_1 + (db_2 - kC_3) \wedge \sigma_2$$

  - From dimensional reduction of the kinetic term:

$$\int d^7x\, |dV_4|^2 \longrightarrow \int d^4x\, |dC_3|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2$$

    - Gauge invariance $\quad C_3 \to C_3 + d\Lambda_2 \qquad b_2 \to b_2 + k\Lambda_2$

- Shift symmetry is broken spontaneously

$$\int d^4x\, |F_4|^2 + |d\phi|^2 + \phi F_4$$

$$F_4 = dC_3$$

$$d\phi = *_4 db_2$$

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- Shift symmetry is broken spontaneously

$$\int d^4x\, |F_4|^2 + |d\phi|^2 + \phi F_4 \qquad F_4 = dC_3 \quad d\phi = *_4 db_2$$

an F-term when realized in SUGRA: "F-term axion monodromy"

[Marchesano, GS, Uranga]

Effective 4d theory

- Effective 4d Lagrangian

$$\int d^4x\, |dC_3|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2$$

$$F_4 = dC_3$$
$$d\phi = *_4 db_2$$

- Gauge symmetry ⇒ UV corrections only depend on F_4

$$\mathcal{L}_{\rm eff}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}\mu^2\phi^2 + \Lambda^4 \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}}$$

$$\sum_n c_n \frac{F^{2n}}{\Lambda^{4n}} \longrightarrow \mu^2\phi^2 \sum_n c_n \left(\frac{\mu^2\phi^2}{\Lambda^4}\right)^n$$

⇒ suppressed corrections up to the scale where $V(\phi) \sim \Lambda^4$

⇒ effective scale for corrections $\Lambda \to \Lambda_{\rm eff} = \Lambda^2/\mu$

Effective 4d theory

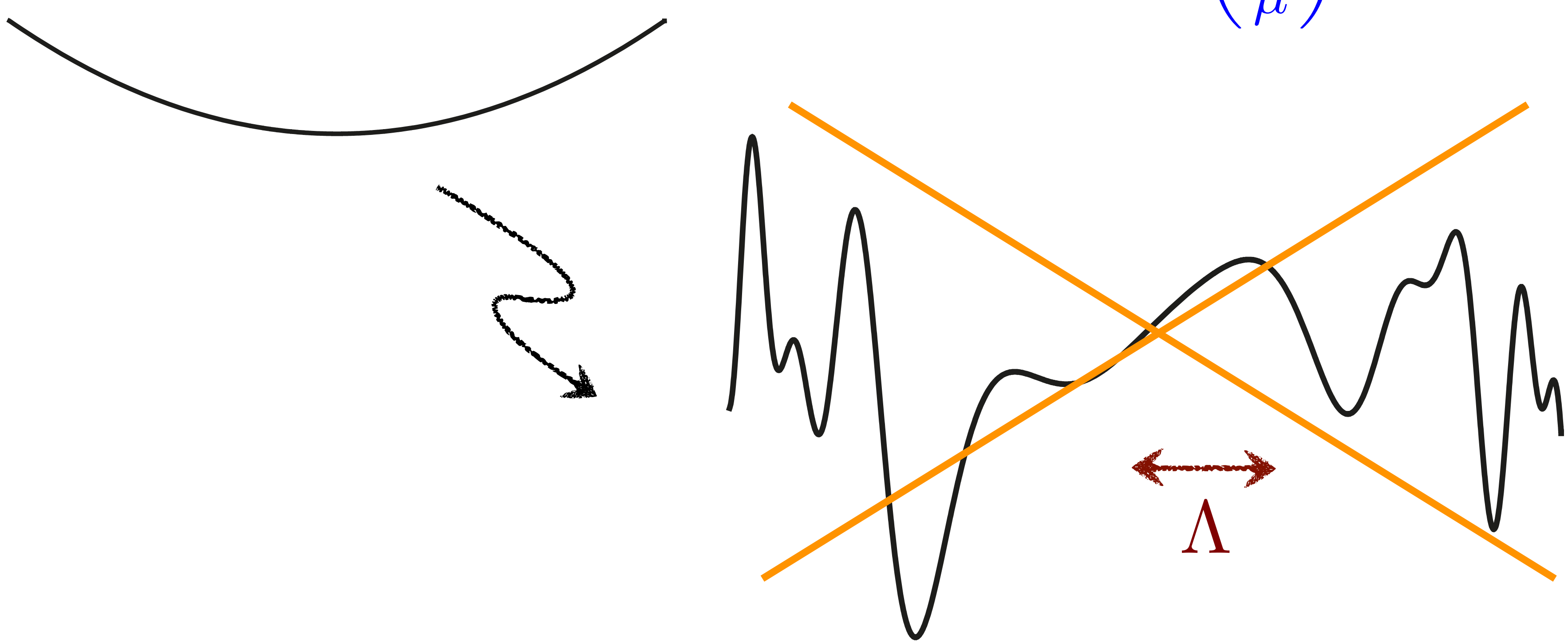
- Effective 4d Lagrangian

$$\int d^4x\, |dC_3|^2 + \frac{\mu^2}{k^2} |db_2 - kC_3|^2$$

$$F_4 = dC_3$$
$$d\phi = *_4 db_2$$

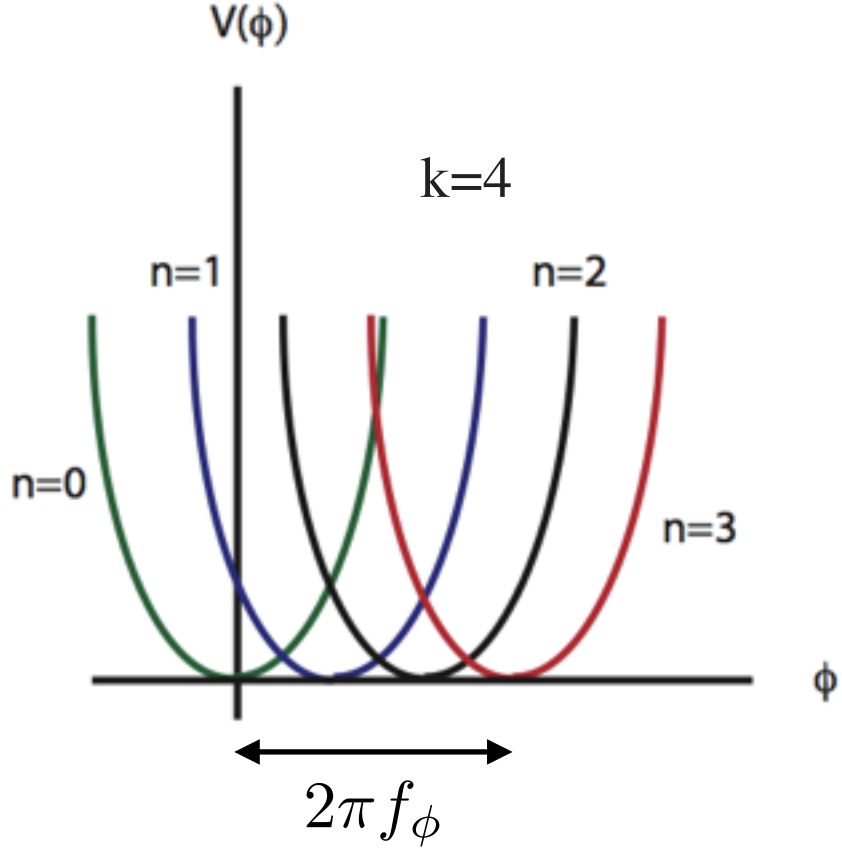
- Gauge symmetry ⇒ UV corrections only depend on F_4

$$\Lambda \to \Lambda_{\text{eff}} = \Lambda \left(\frac{\Lambda}{\mu} \right)$$



Multi-branched Potential

- Related to the torsional homologies of compactifications or K-theory charges of fluxes.



- Branch jumps are made via nucleation of domain walls that couple to C_3, and this puts a maximum to the inflaton range.

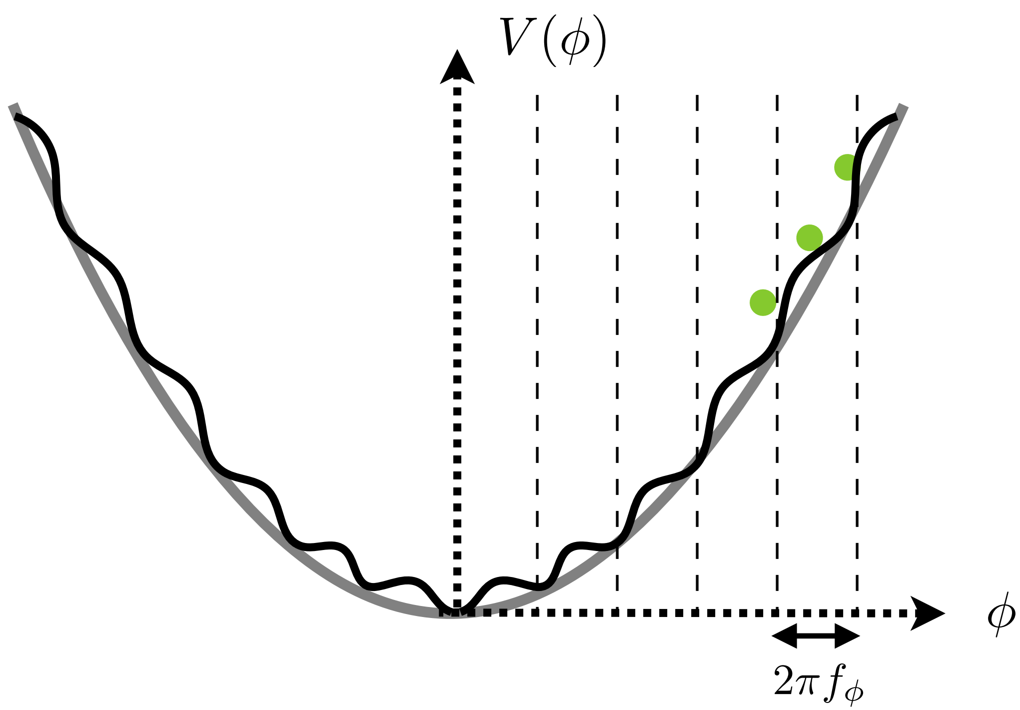
F-term Axion Monodromy Inflation

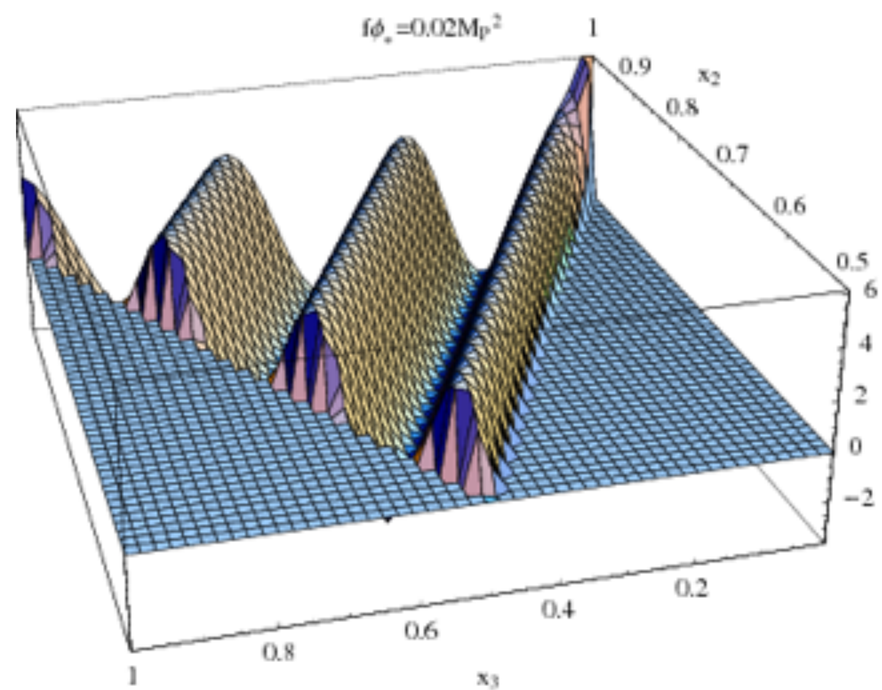
- A wide variety of potentials (**topology in the sky!**):

$$V(\phi) \propto \phi, \phi^{2/3}, \phi^2, \ldots, \text{ or even } V(\phi) = \sum_n c_n \phi^n \text{ with } n > 2$$

- UV effects ***flatten*** the inflaton potential.

- Resonant non-Gaussianity:





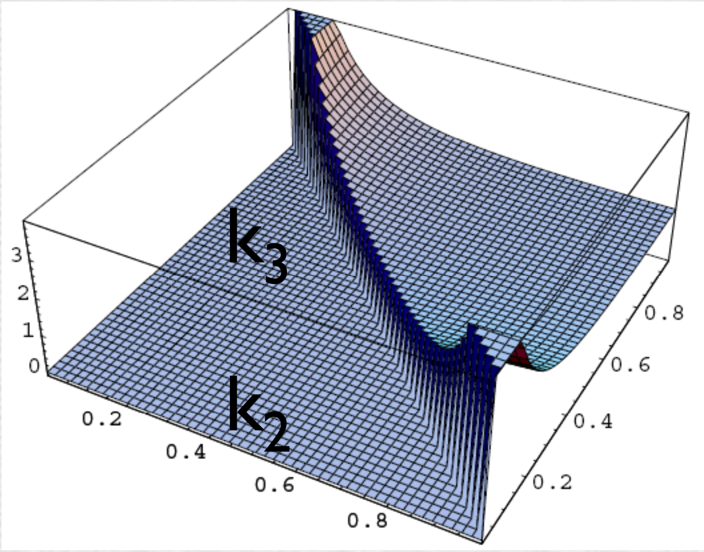
Non-Gaussianity

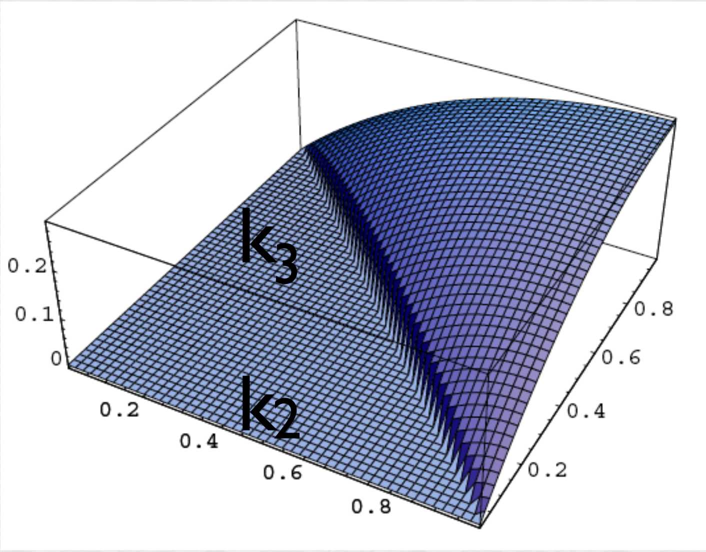
If Gaussian: completely specified $< \zeta(\mathbf{k})\zeta(\mathbf{k}') >= (2\pi)^3\delta^3(\mathbf{k}+\mathbf{k}')P_s(k)$

The leading non-Gaussianity $< \zeta(\mathbf{k_1})\zeta(\mathbf{k_2})\zeta(\mathbf{k_3}) >$

characterized by its size $\mathbf{f_{NL}}$ and **shape** (functional form)

Complete single field result: [Chen, Huang, Kachru, GS]





Current bound [Planck]:

$$f_{NL}^{local} = 2.7 \pm 5.8$$

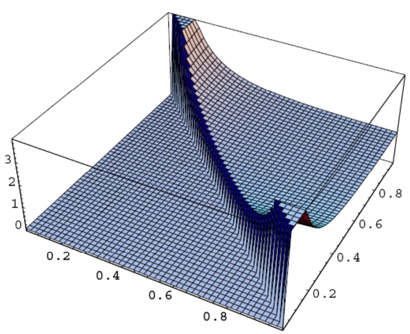
$$f_{NL}^{equil} = -42 \pm 75$$

Large non-Gaussianity probes UV physics!

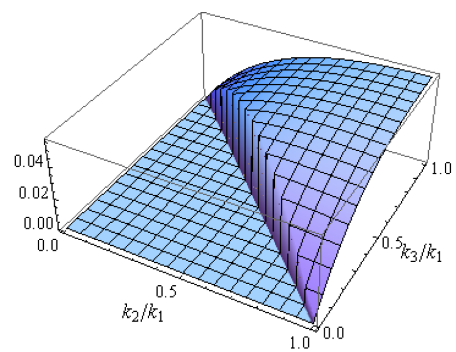
Local shape: $f_{NL}^{local} \sim \mathcal{O}(\epsilon)$ Equilateral shape: $f_{NL}^{equil} \sim \mathcal{O}(\gamma^2)$

Holographic Non-Gaussianity

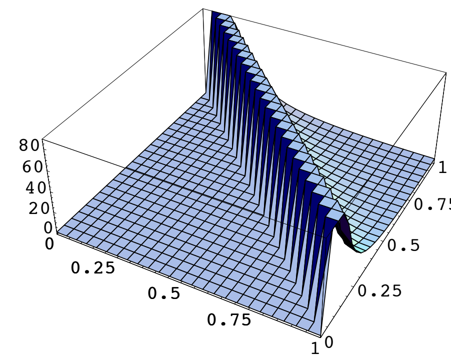
- Motivated partly by CHKS, various shape templates have been proposed:



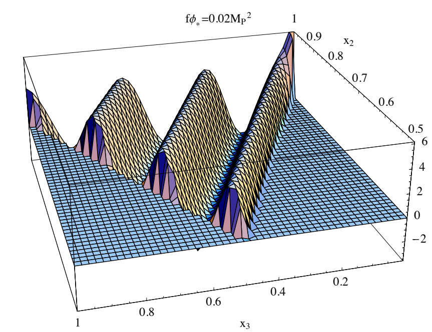
Local (slow-roll)



Equilateral (DBI)

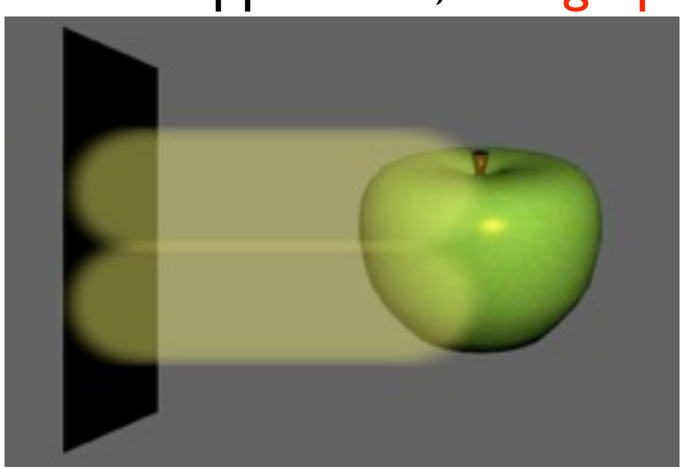


Folded (non BD vacuum)



Resonant (axion-monodromy)

- Inflation is approx. dS, holography may offer an organizing principle for NG:



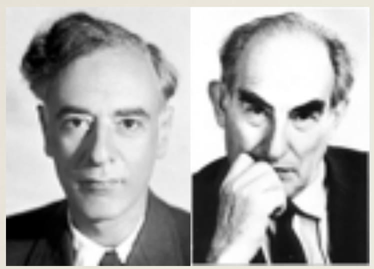
$$\langle \zeta_{\mathbf{k}} \zeta_{-\mathbf{k}} \rangle' = -\frac{1}{2\mathrm{Re}\langle \Theta_{\mathbf{k}} \Theta_{-\mathbf{k}} \rangle'}$$

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle' = \frac{2\mathrm{Re}\langle \Theta_{\mathbf{k}_1} \Theta_{\mathbf{k}_2} \Theta_{\mathbf{k}_3} \rangle'}{\prod_{j=1}^{3} \left(-2\mathrm{Re}\langle \Theta_{\mathbf{k}_j} \Theta_{-\mathbf{k}_j} \rangle' \right)}$$

[Maldacena];[Schalm, GS, van der Aalst]

Inflation is a successful effective theory in search of a microscopic description.

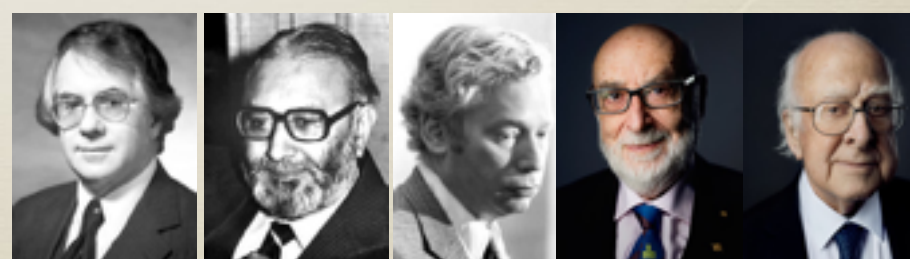
* Superconductivity



Effective theory

Microscopic theory

* Weak Interaction

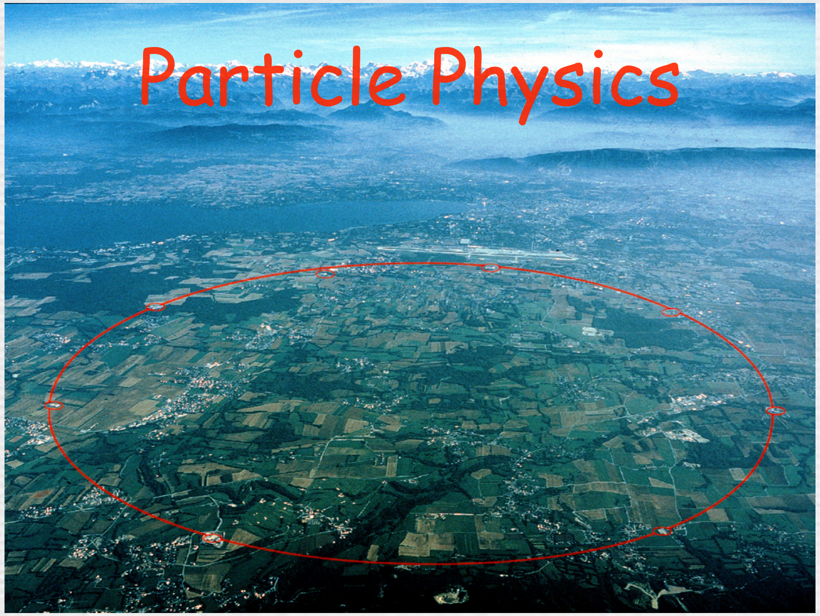


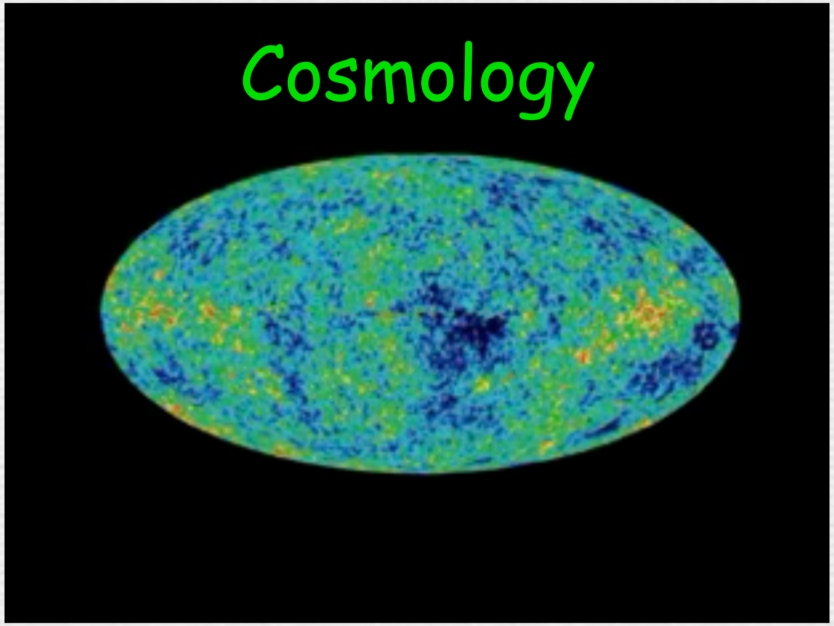
Effective theory

Microscopic theory

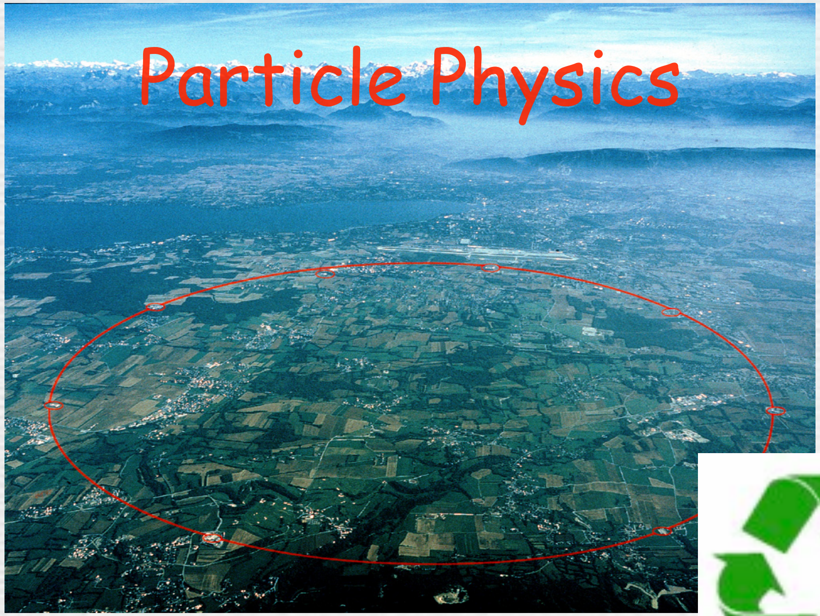
Many Candidates

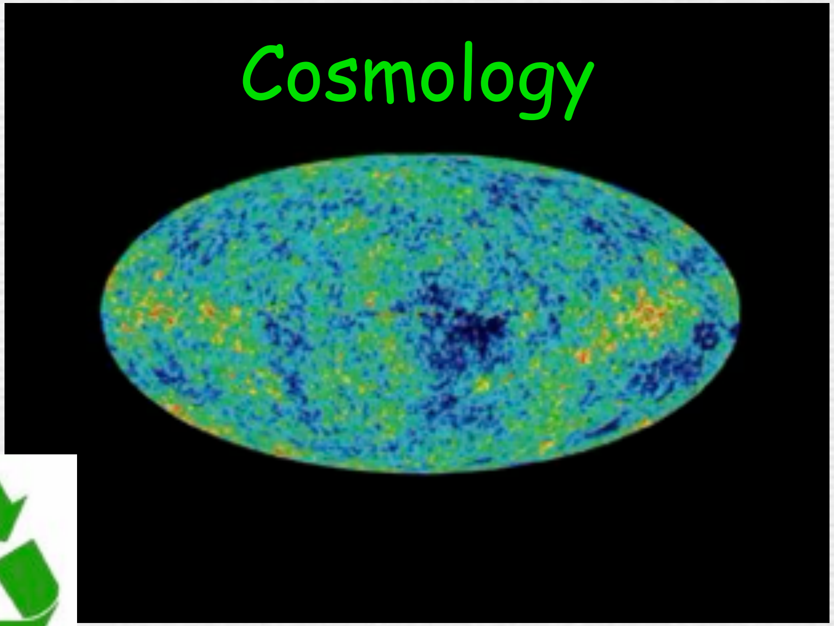
A New Synergy





A New Synergy





Gordon Research Conferences

String Theory & Cosmology

New Ideas Meet New Experimental Data

May 31 - June 5, 2015
The Hong Kong University of Science and Technology
Hong Kong, China

Chair:
Gary Shiu

Vice Chair:
Ulf Danielsson

Application Deadline

Applications for this meeting must be submitted by **May 3, 2015**. Please apply early, as some meetings become oversubscribed (full) before this deadline. If the meeting is oversubscribed, it will be stated here. *Note*: Applications for oversubscribed meetings will only be considered by the Conference Chair if more seats become available due to cancellations.

Gordon Research Conferences

Gordon Research Conferences

String Theory & Cosmology

Gordon Research Conference

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Location

Renaissance Tuscany Il Ciocco
Lucca (Barga), Italy

Organizers

Chair:
Ulf Danielsson

Vice Chairs:
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Check out the website: https://www.grc.org/programs.aspx?id=16939

谢谢！

THANKS