Progress in String Cosmology

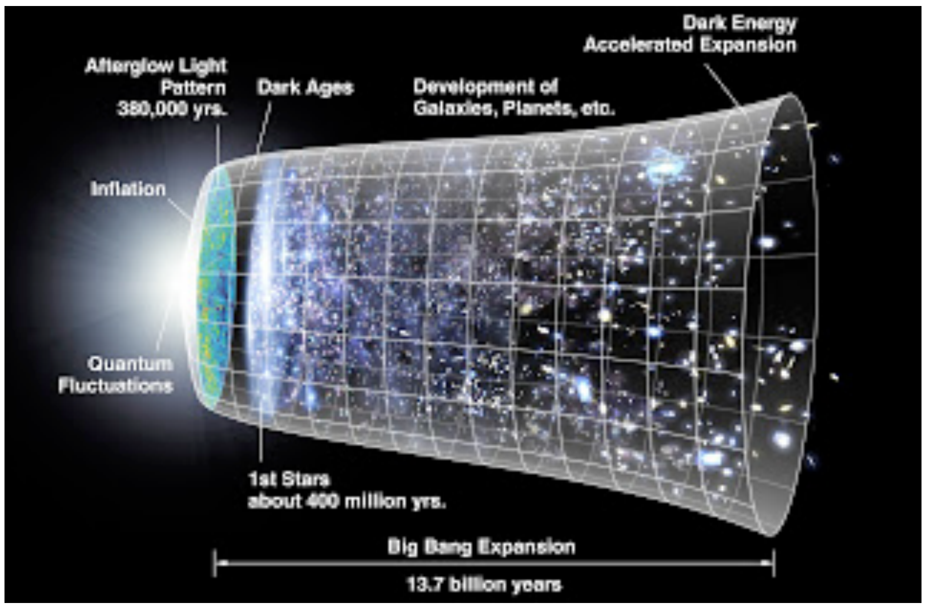
Gary Shiu

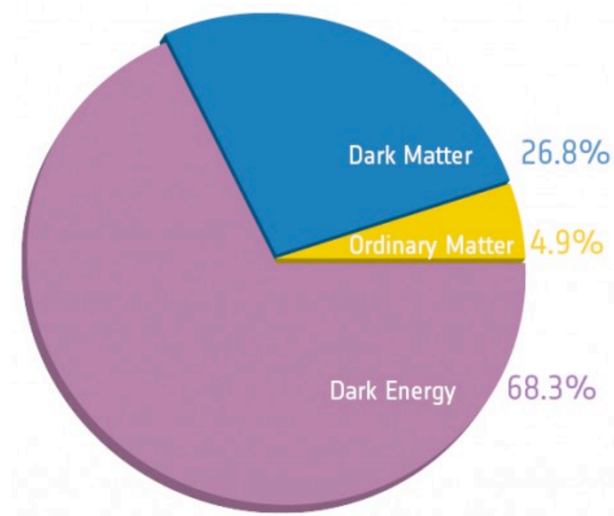
University of Wisconsin & HKUST

Kyoto, July 2014

String Cosmology

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

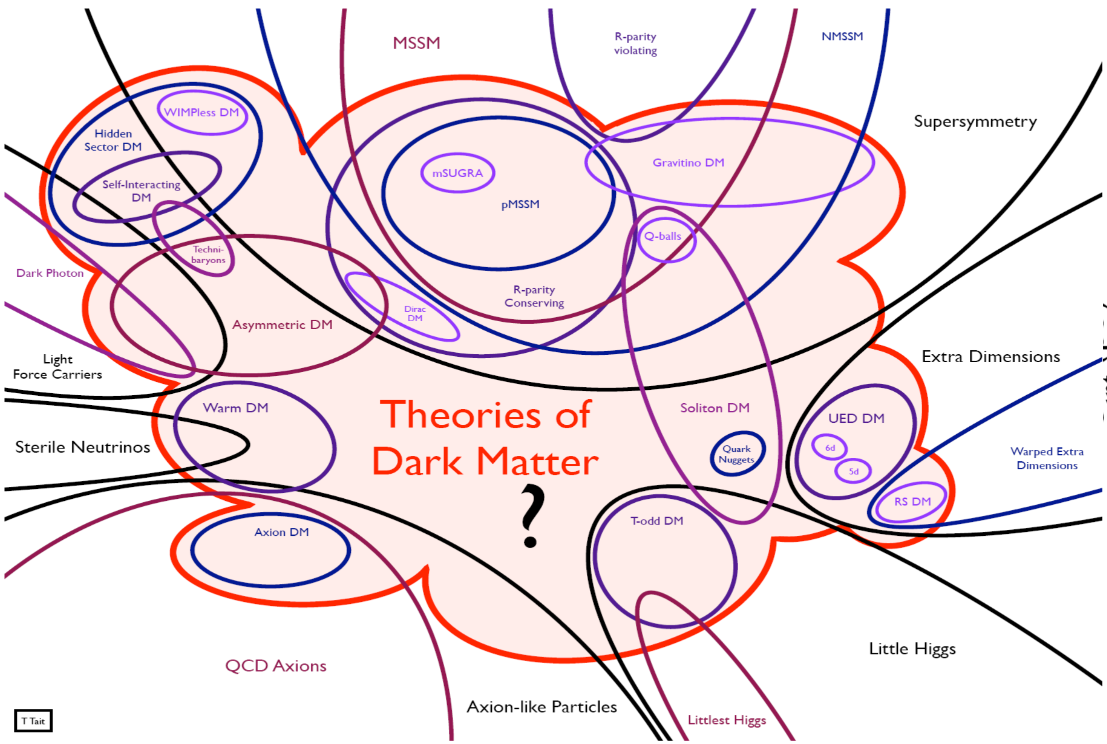


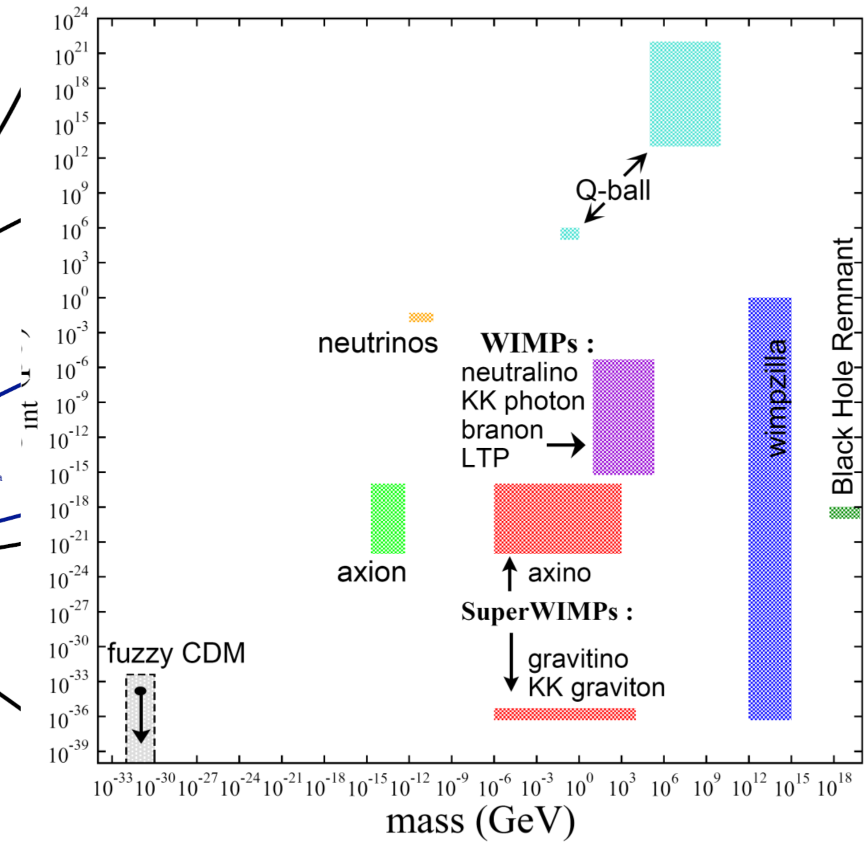


- Quantitative info about our universe, both at its earliest moment and at the present time, *but* many puzzles remain….

Dark Matter

- Many candidates with widely different signatures:





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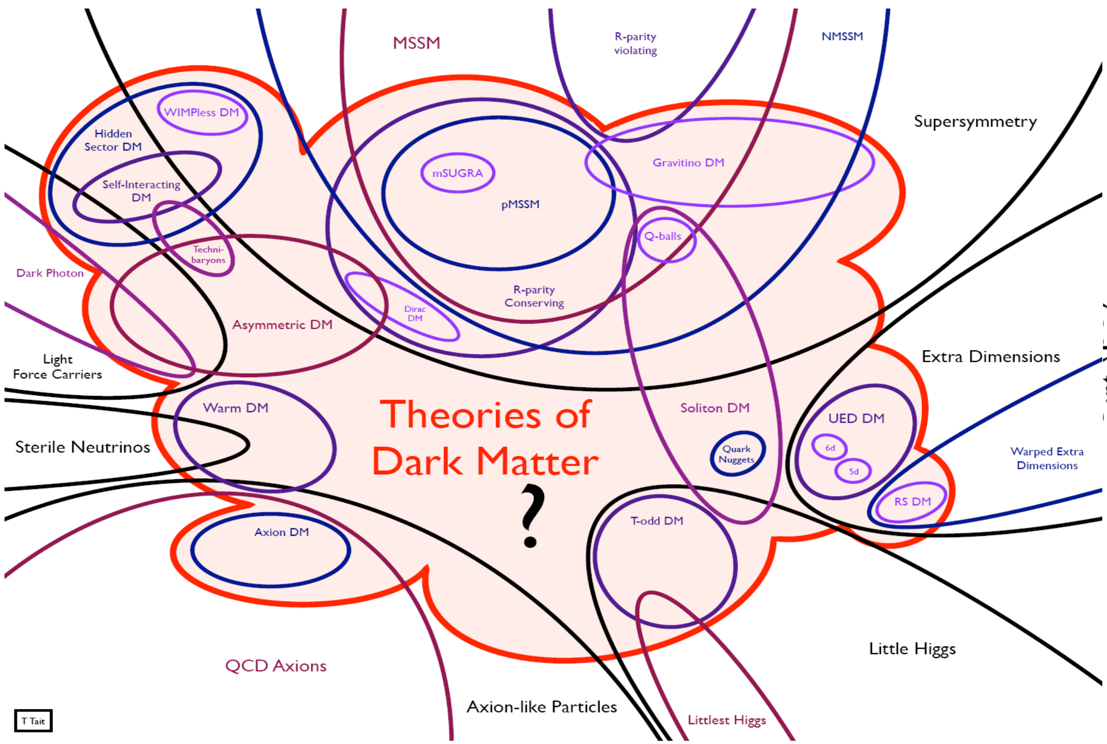
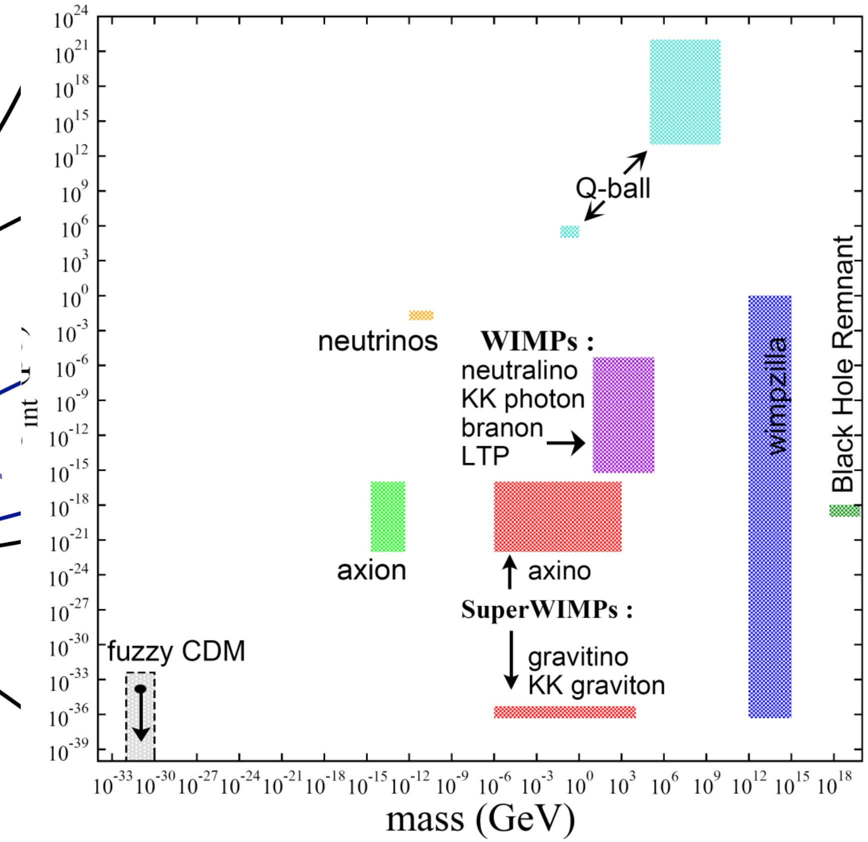


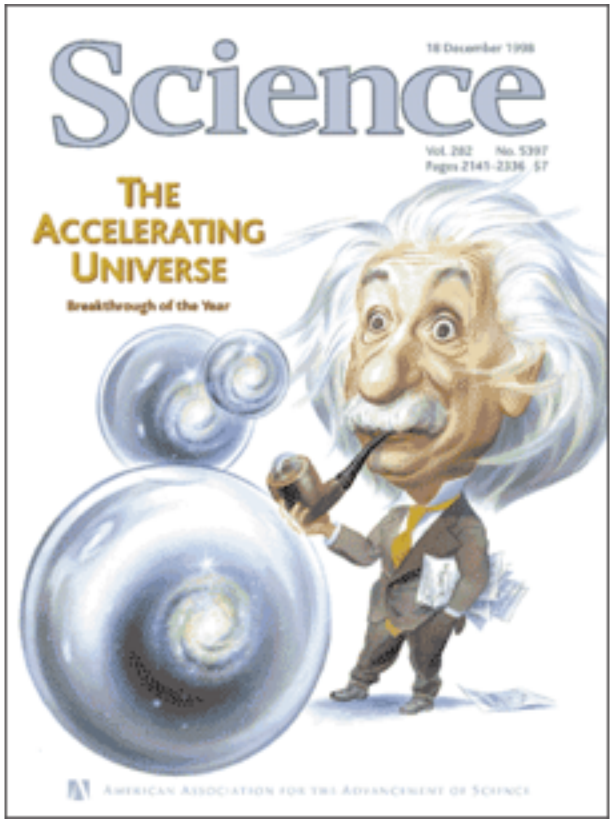


- String theory not only provide new candidates (& mediation mechanisms) but serves as arbitrator of models. *[Soler's talk]*

GS, Soler, Ye, Phys. Rev. Lett. ***110****, 241304 (2013); Feng, GS, Soler, Ye, arXiv: 1401.5880, to appear in PRL; JHEP 1405, 065 (2014) [arXiv:1401.5890 [hep-ph]].*

Dark Energy

- A question for **quantum gravity**:



"The problem of the vacuum energy density or cosmological constant – why it is zero or extremely small by particle physics standards – really only arises in the presence of gravity, since without gravity, we don't care about the energy of the vacuum. Moreover, it is mainly a question about quantum gravity, since classically it would be more or less natural to just decide – as Einstein did – that we do not like the cosmological constant, and set it to zero." (E. Witten, hep-ph/0002297)

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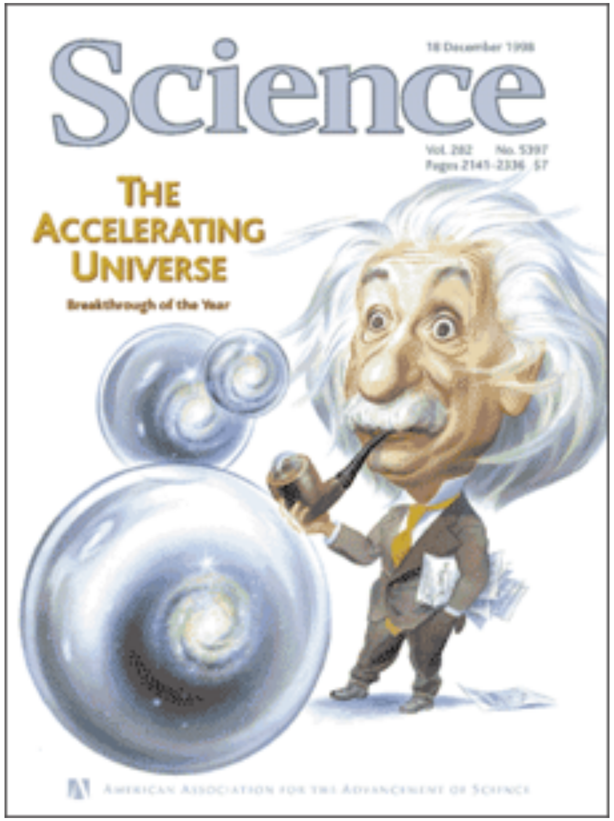

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Can metastable $\Lambda > 0$ vacua be realized in string theory?

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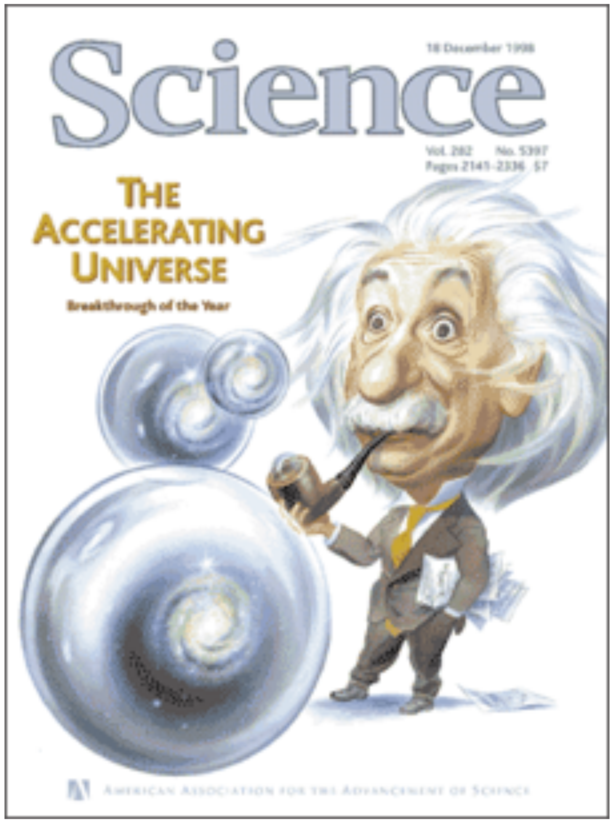

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Can metastable $\Lambda>0$ vacua be realized in string theory?

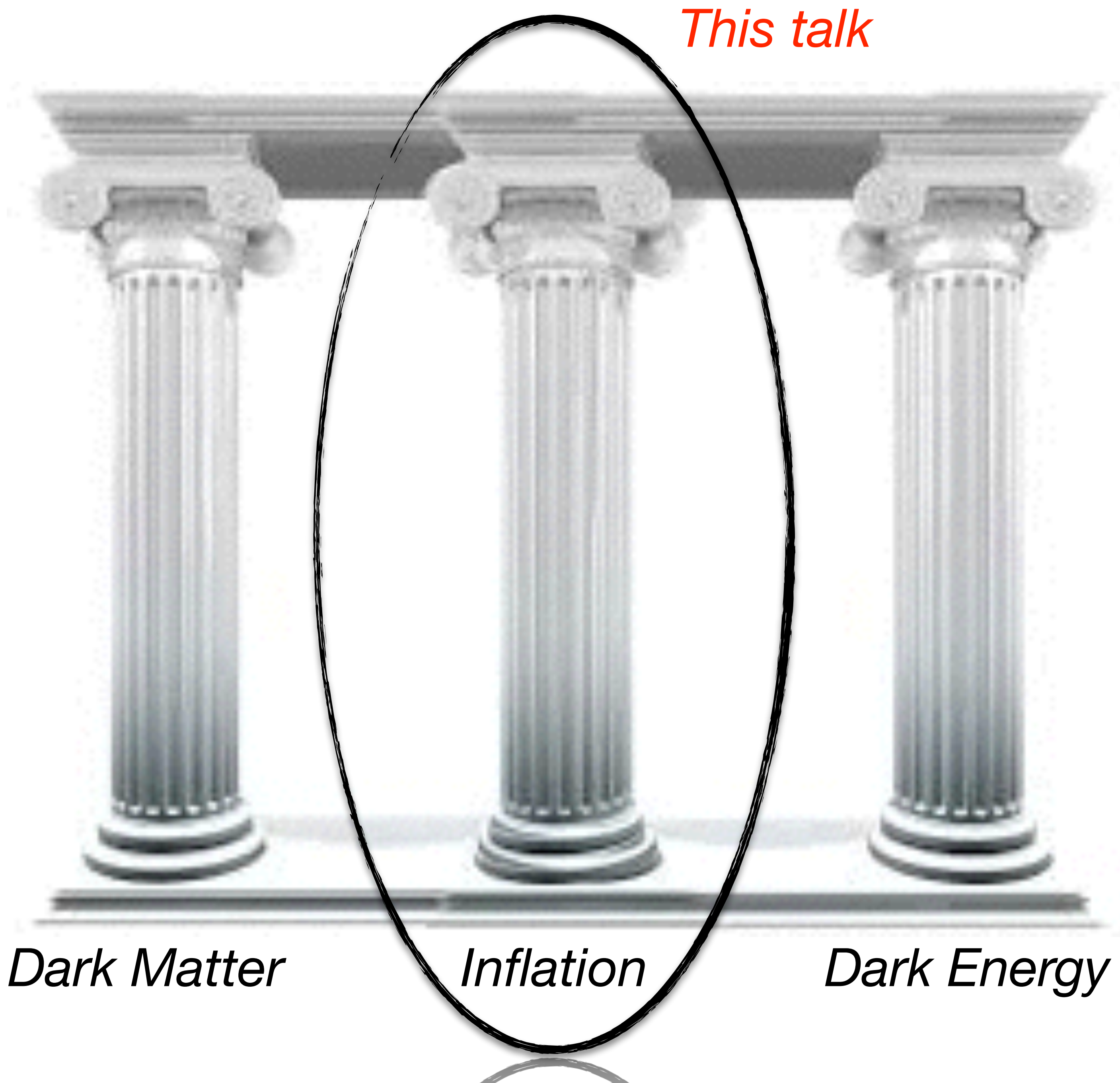
- de Sitter model building deeply related to moduli stabilization.

Work w/ Haque, Underwood, Van Riet, Danielsson, Koerber, Wrase, Sumitomo, McGuirk,Chen,Tye,Junghans; 0810.5328, 0907.2041, 0910.4581, 1103.4858, 1107.2925, 1112.3338, 1212.5178, 1407.0019 *[See Junghans's talk]*

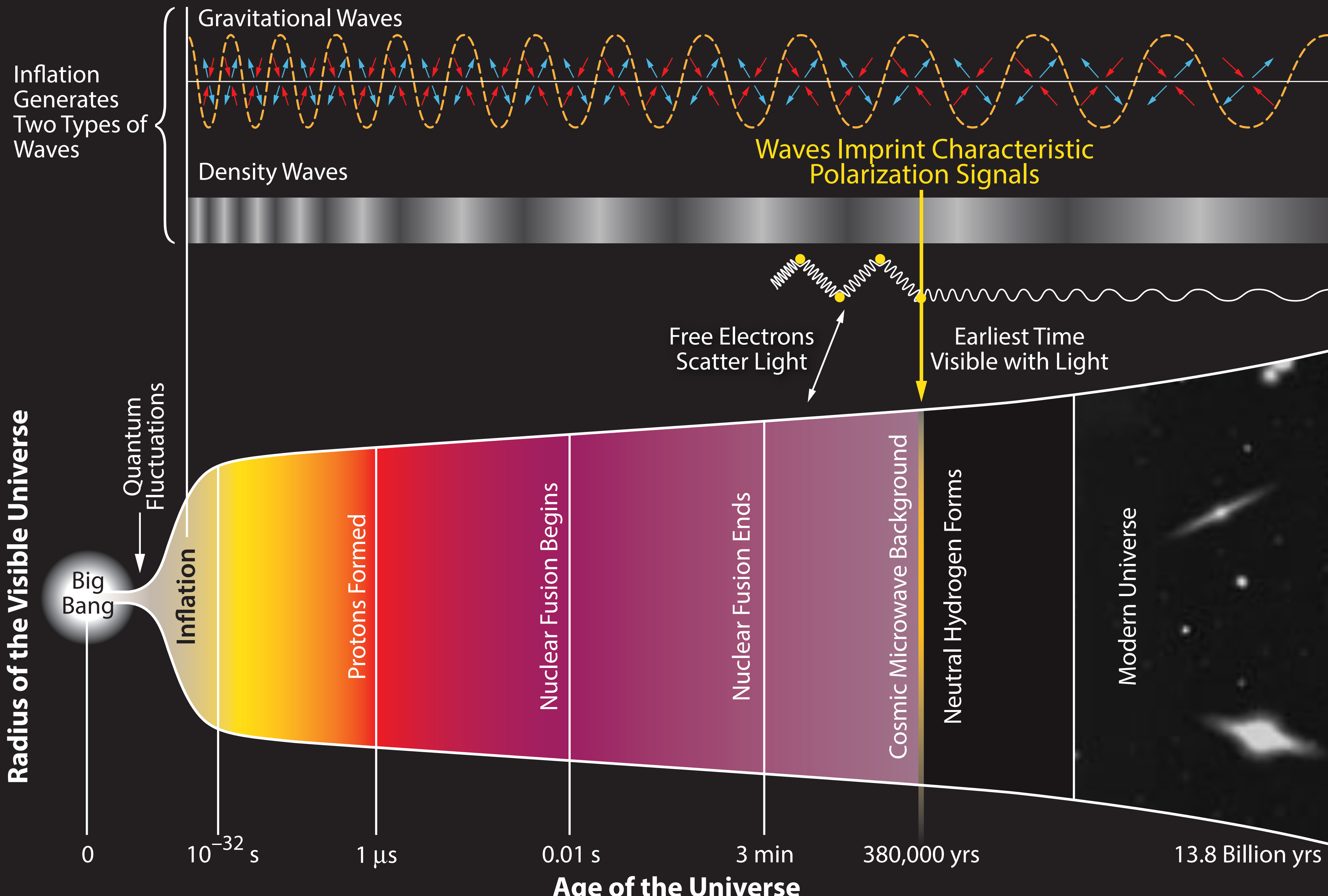
Three Pillars of Modern Cosmology

Dark Matter *Inflation* *Dark Energy*

Three Pillars of Modern Cosmology



History of the Universe



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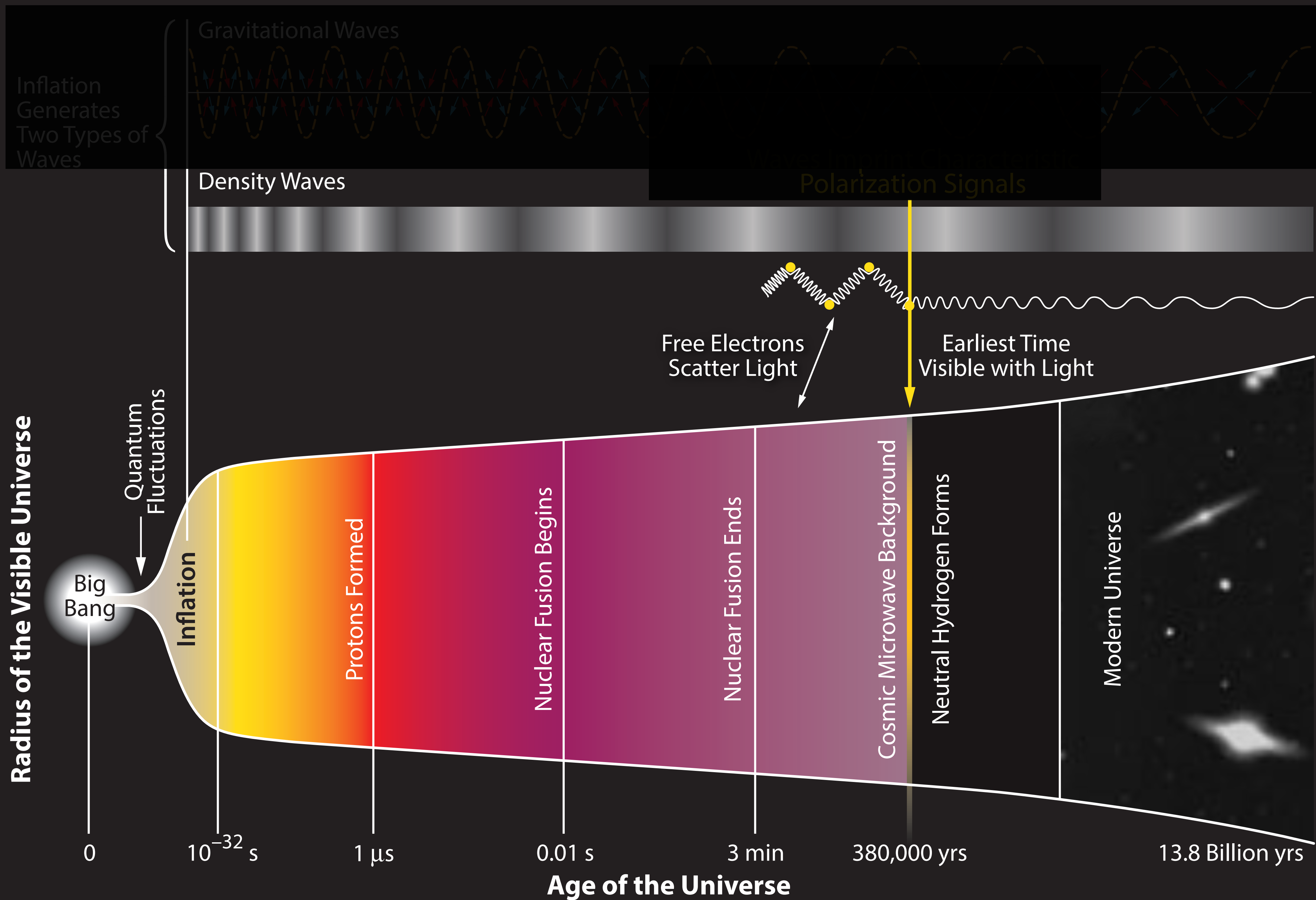

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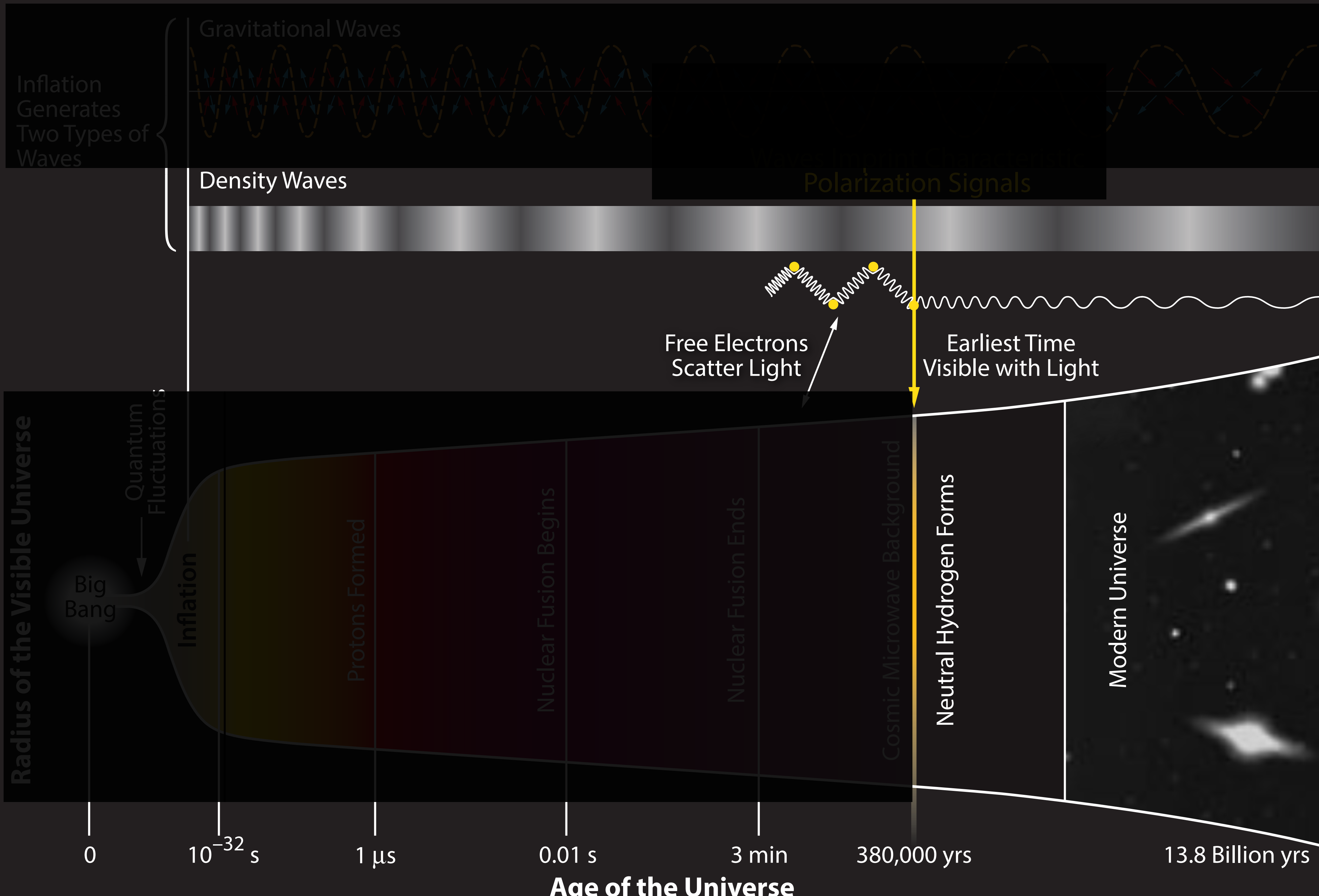

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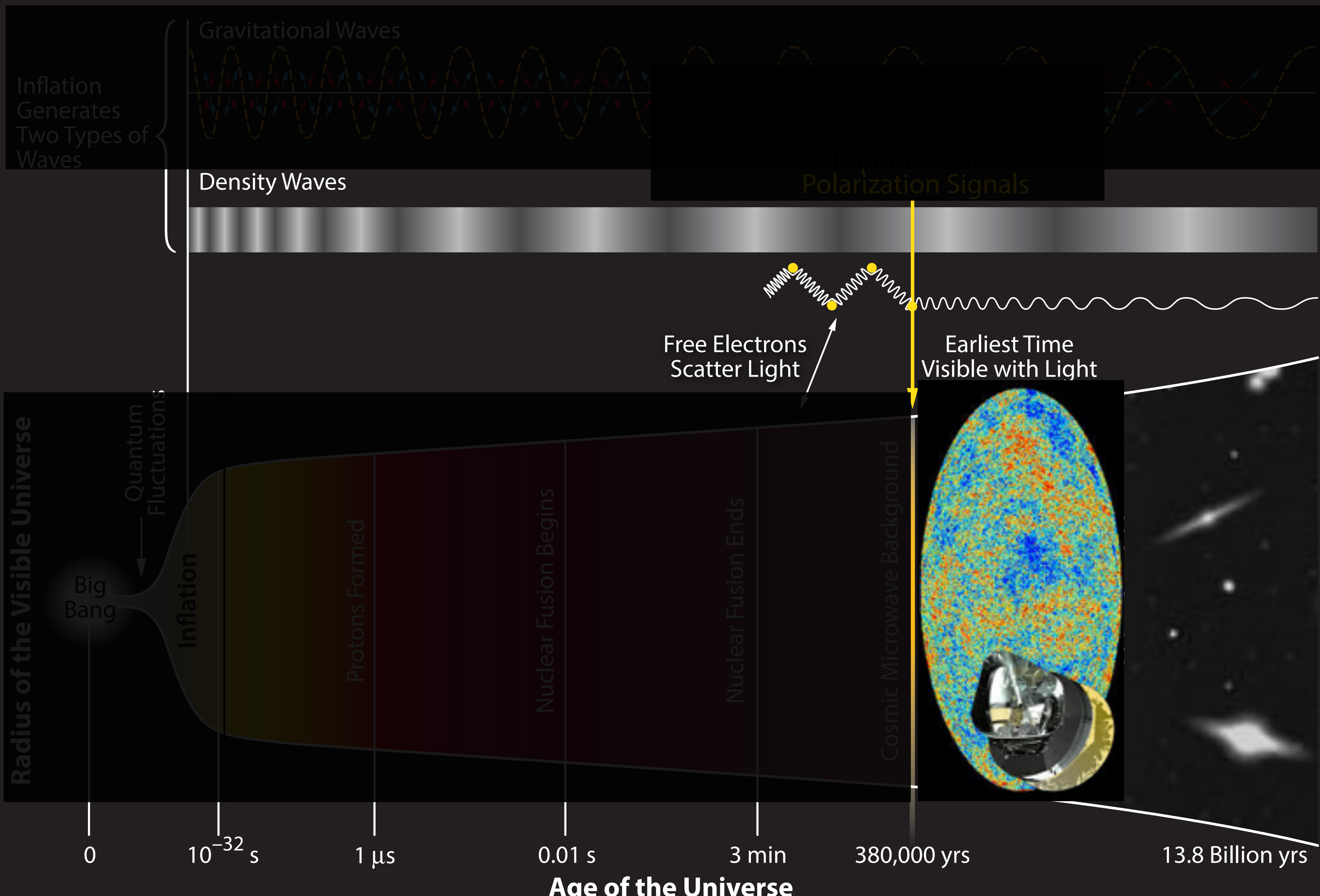

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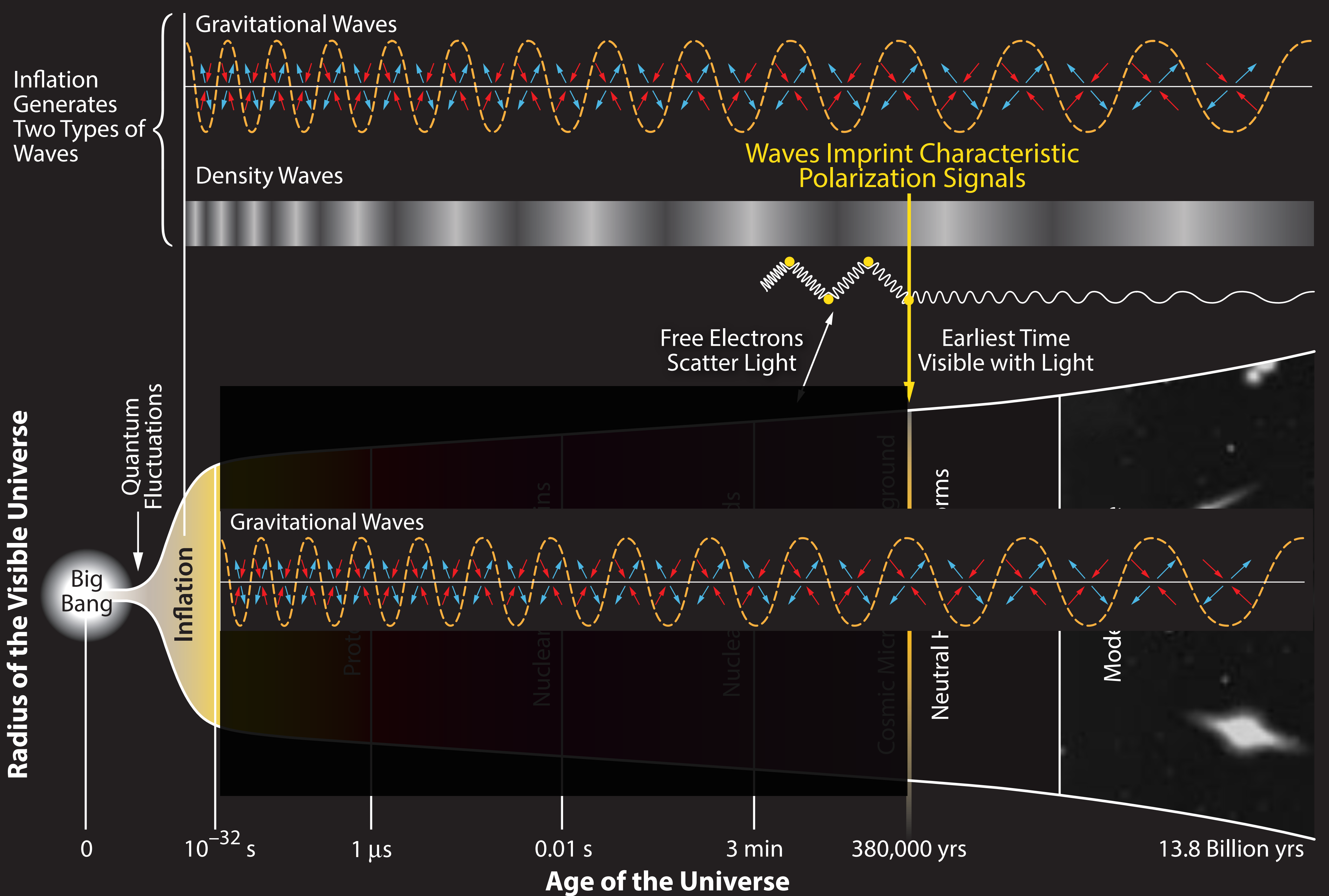

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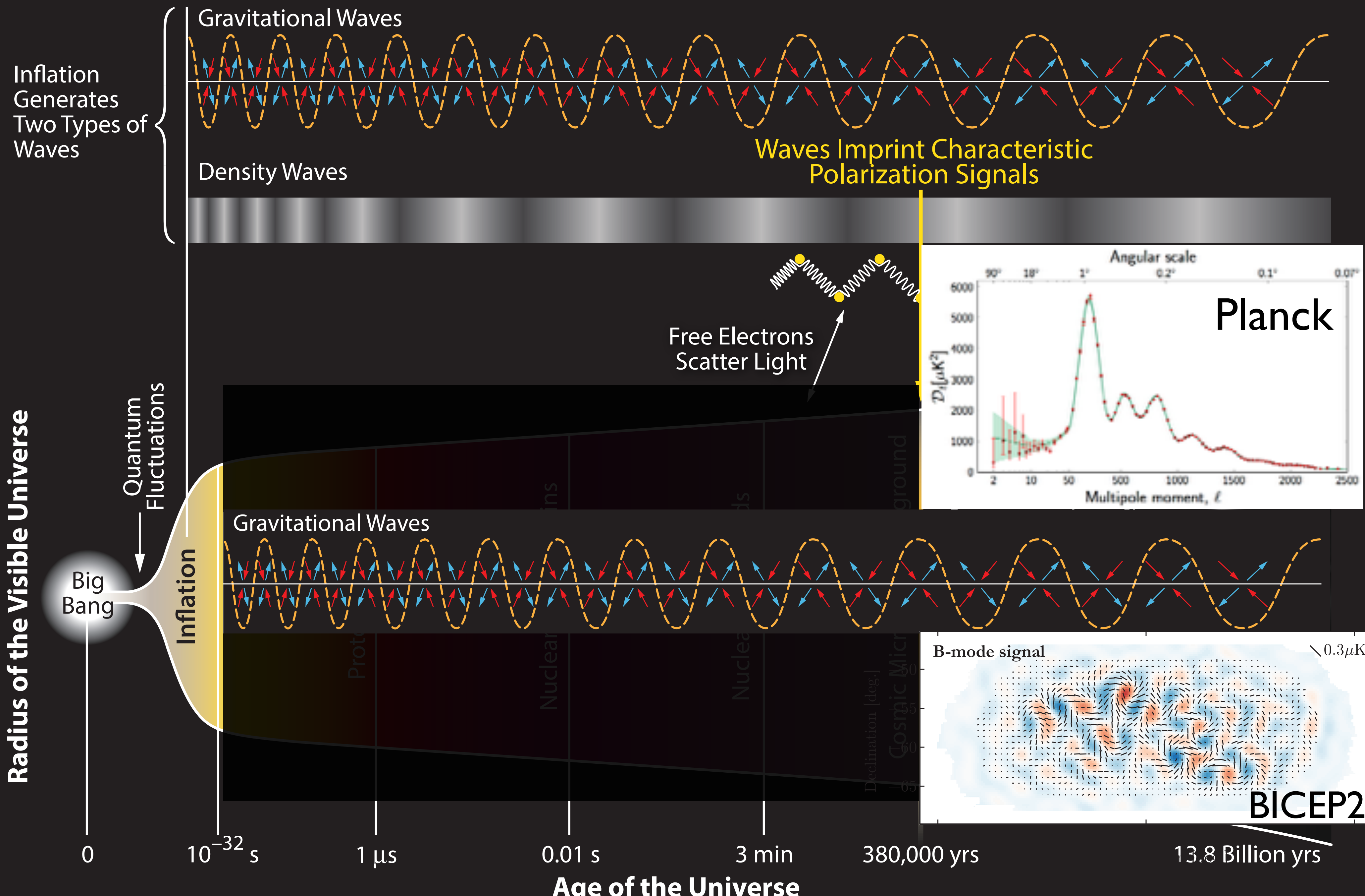

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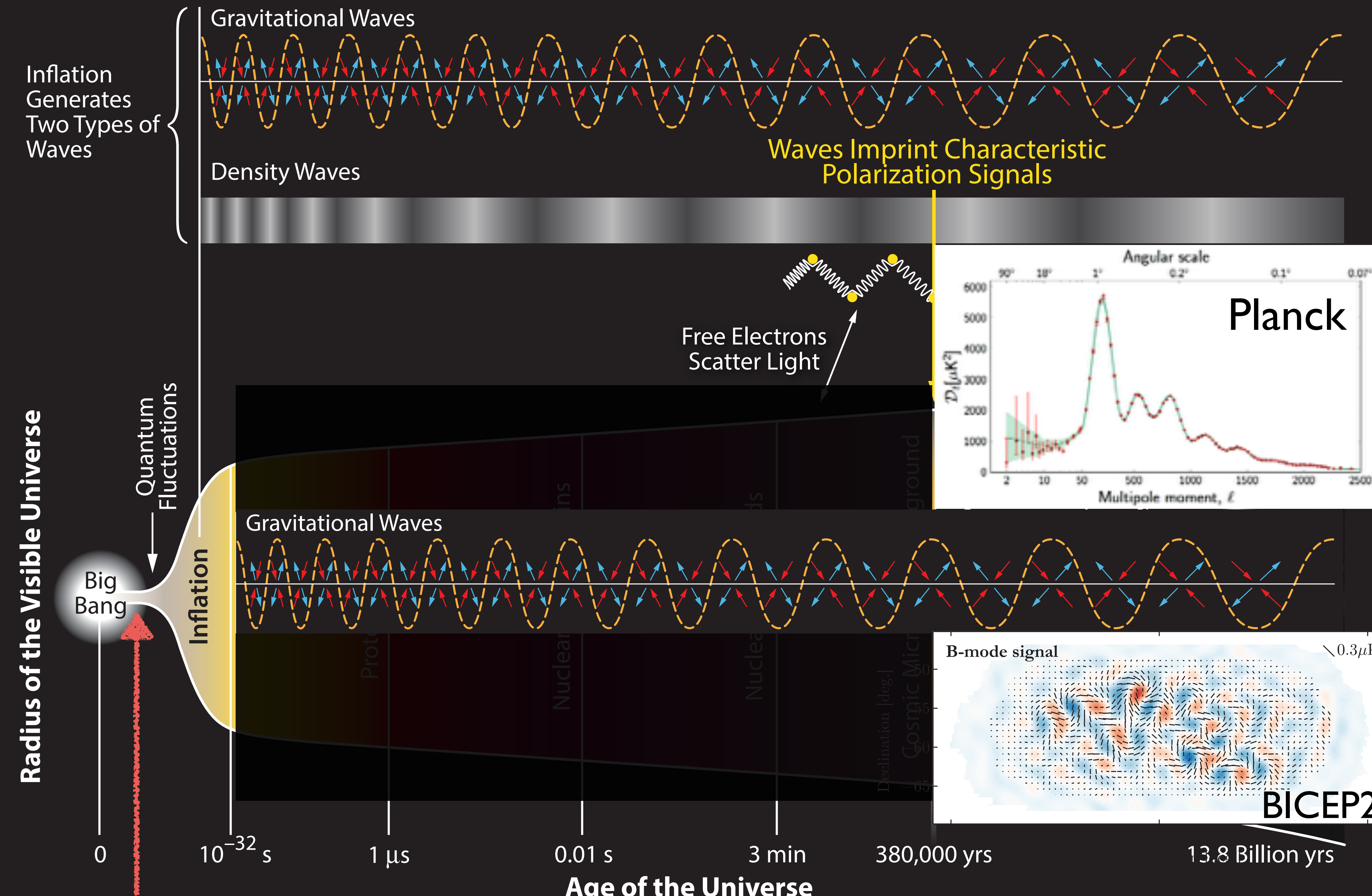
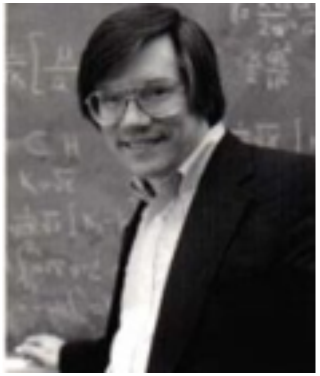


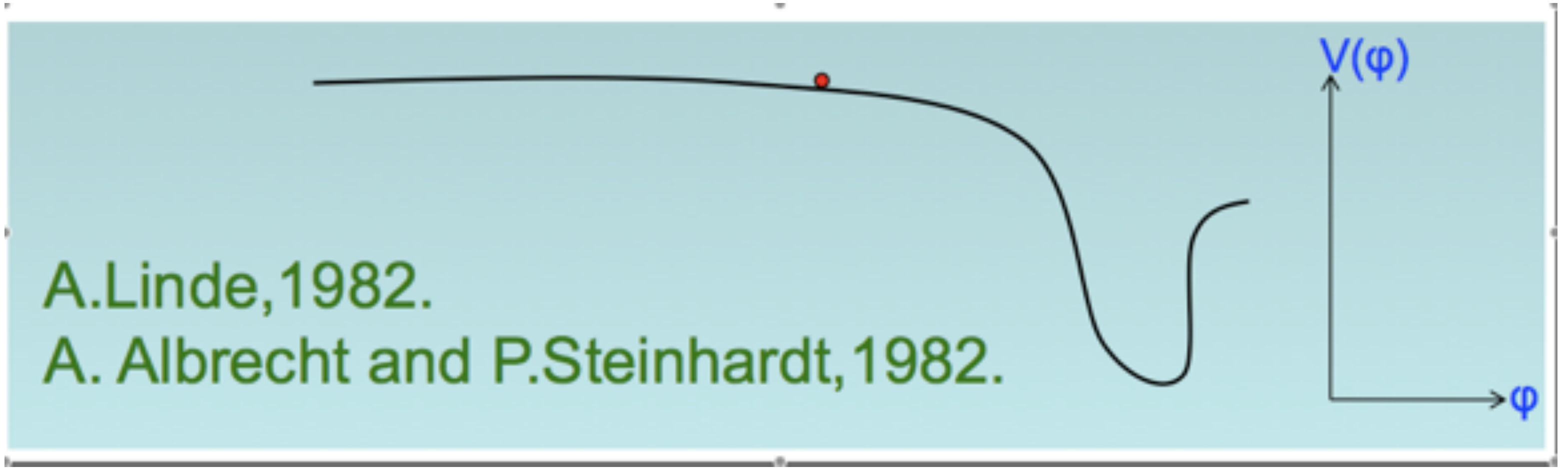
Planck scale 10^{-43}s

Inflation is in good agreement with data

but …it is an *effective theory* in search of a fundamental description!



Alan Guth



To solve the flatness & horizon problems, need to satisfy

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

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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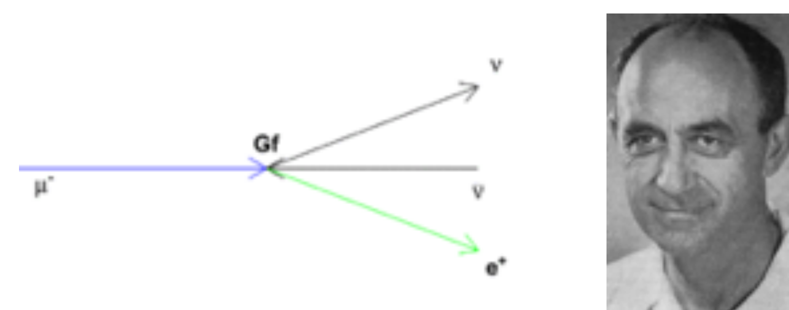
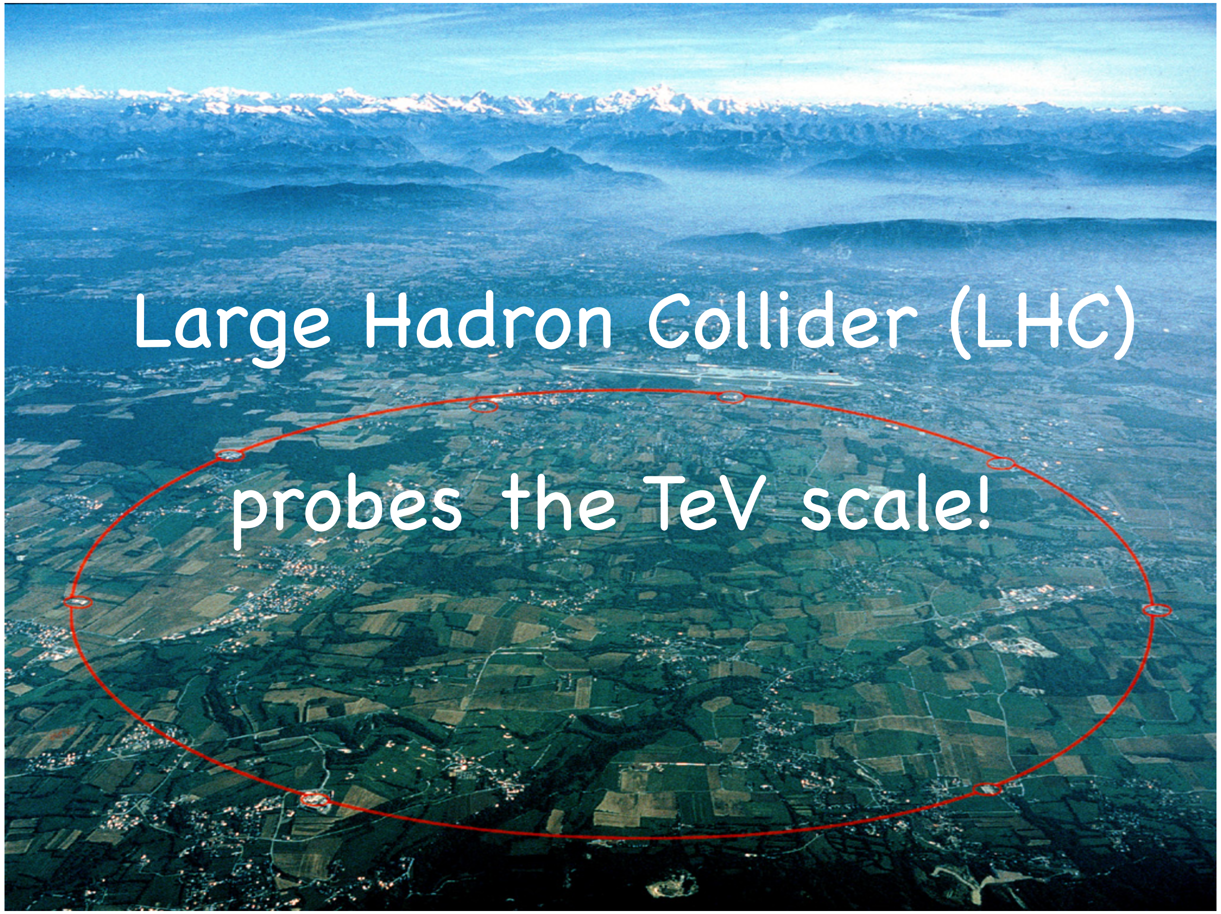
Examples:

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

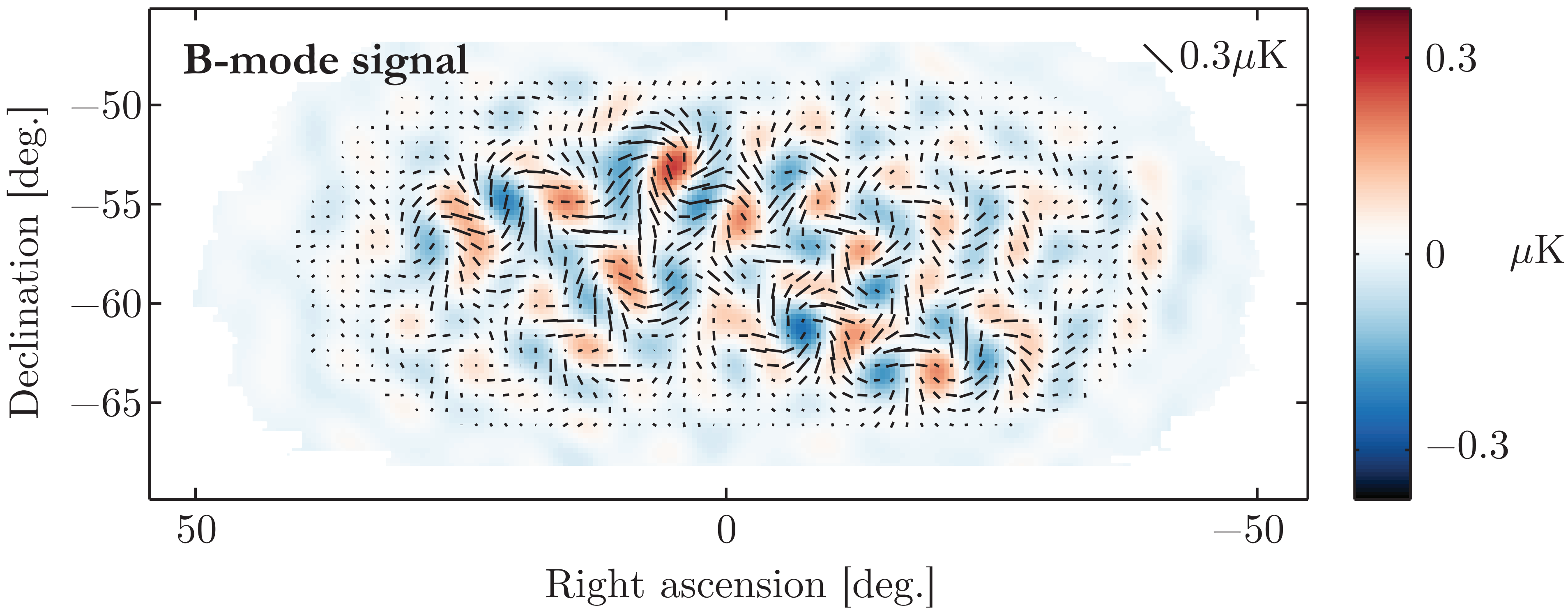
Inflation & UV Physics

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

This applies to <u>any</u> model of inflation.

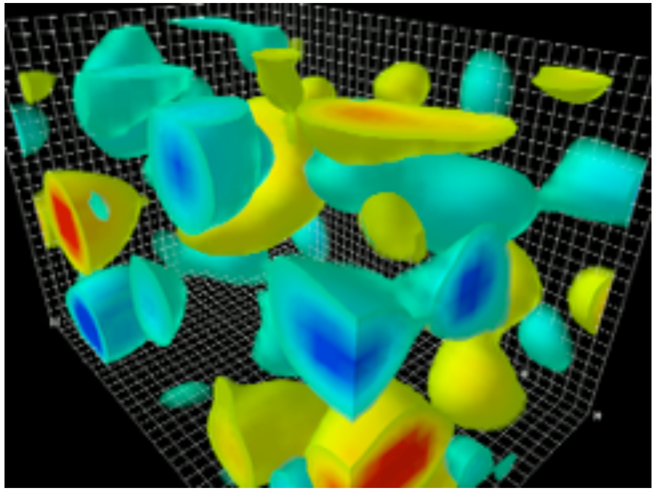
Models with detectable non-Gaussianities and gravity waves are even more UV sensitive!

Primordial B-mode?

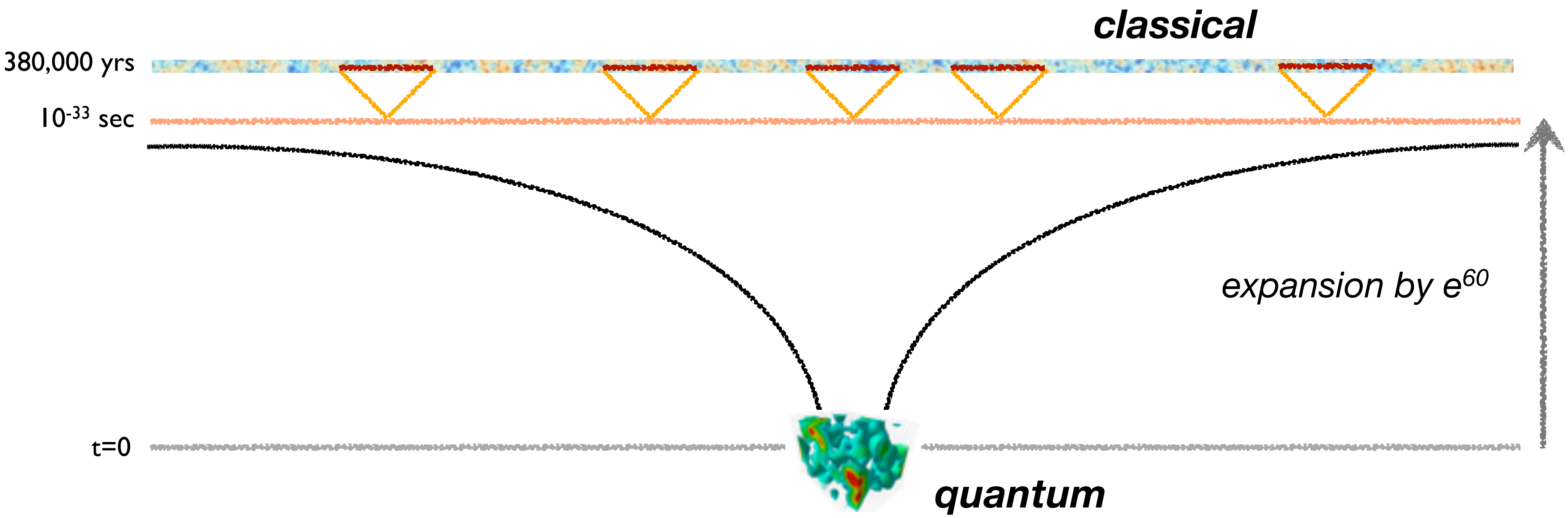


BICEP2 Collaboration

Any massless field experiences quantum fluctuations during inflation:



Inflation stretches these to macroscopic scales:



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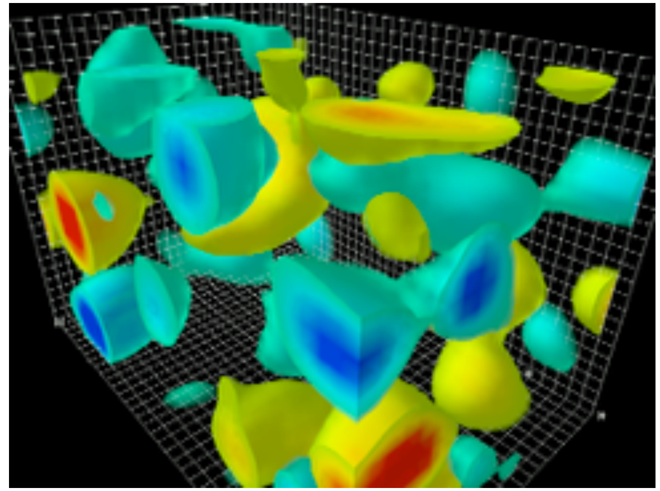

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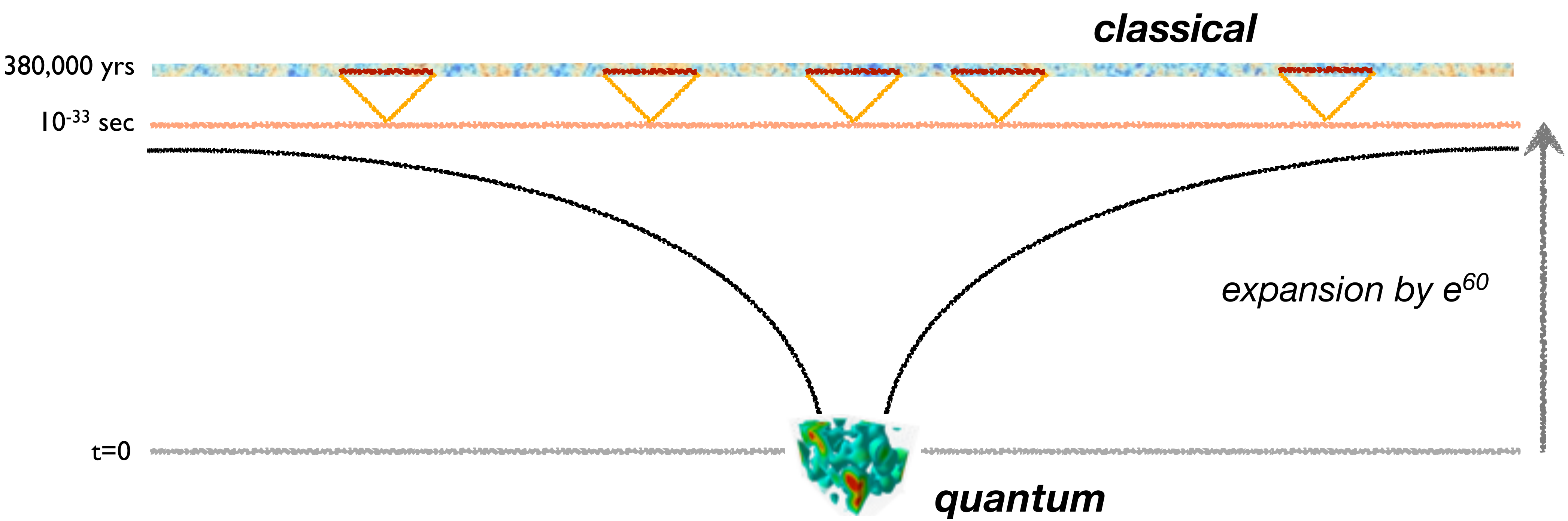

Two massless fields that are guaranteed to exist are:

ζ **Goldstone boson**

of broken time translations

h_{ij} **graviton**

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

symmetry breaking

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

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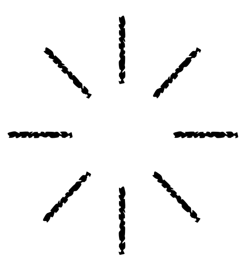
E-modes:



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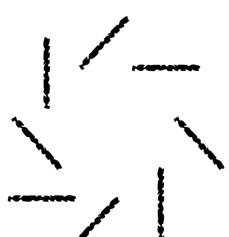
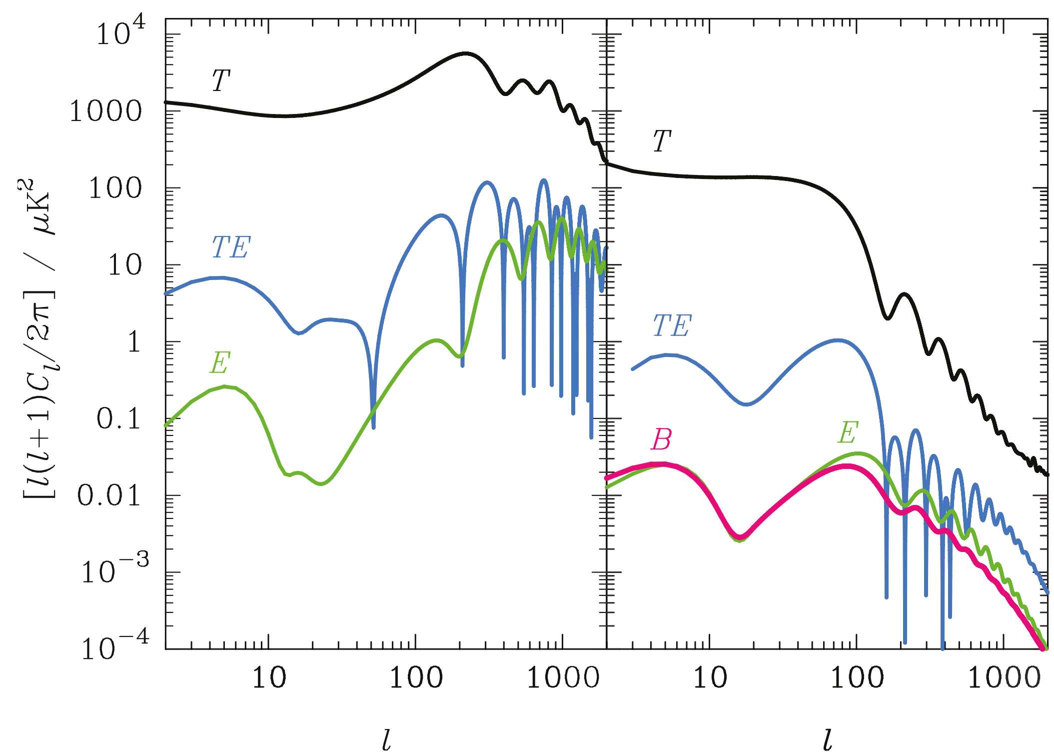
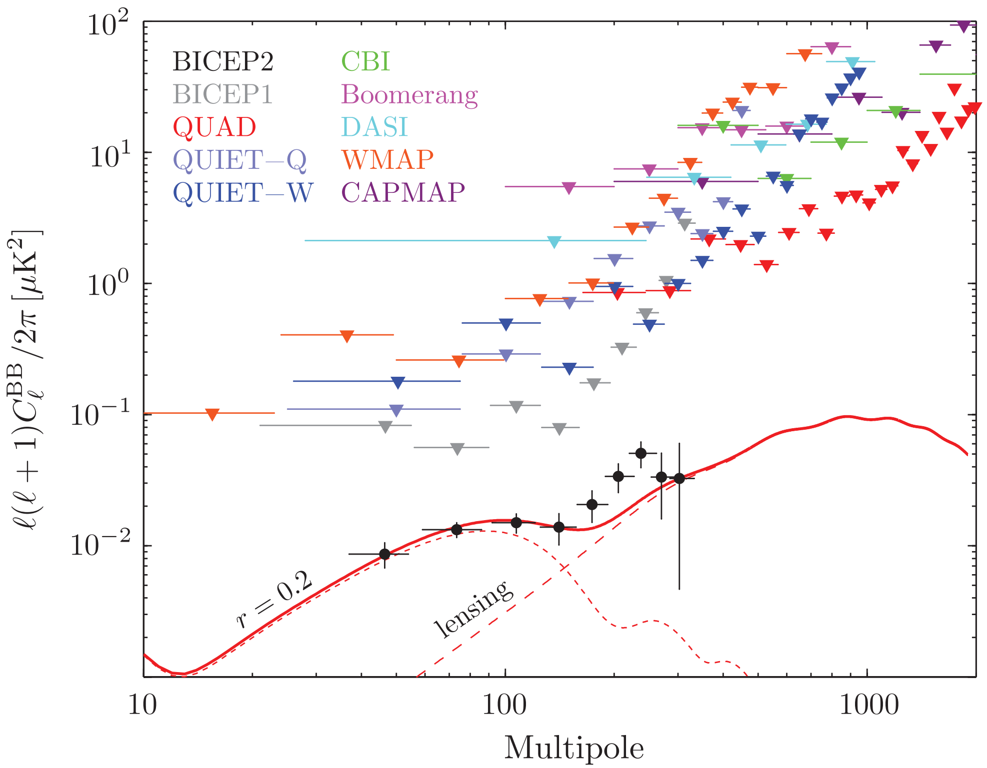
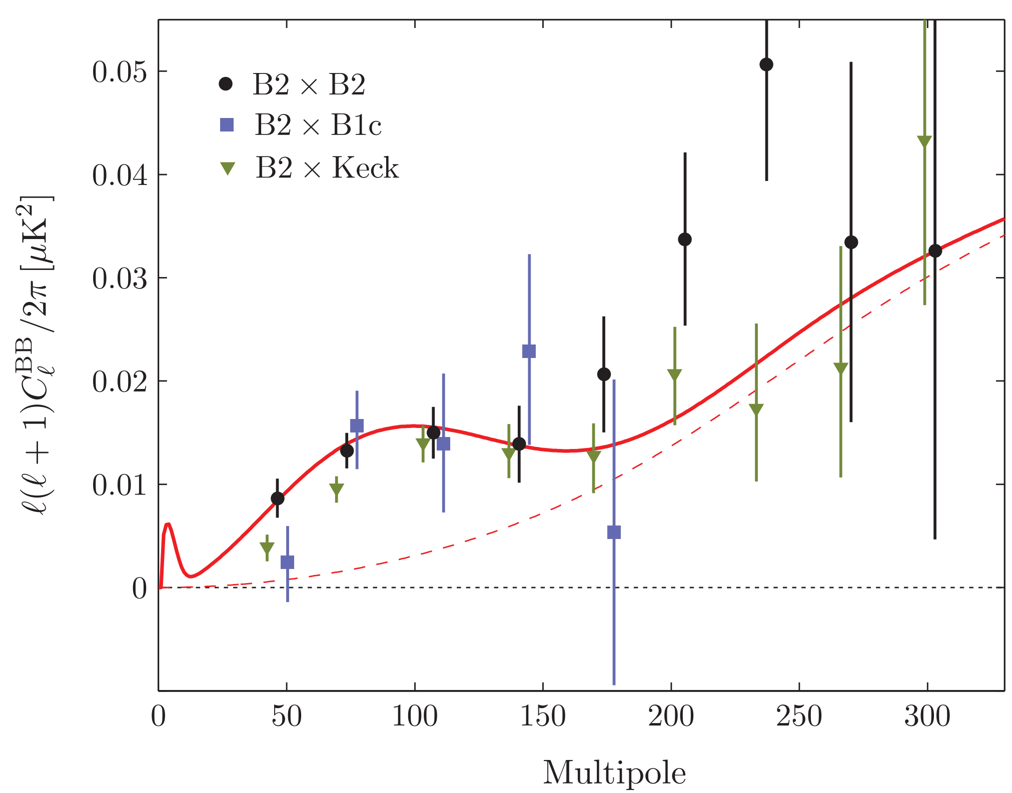




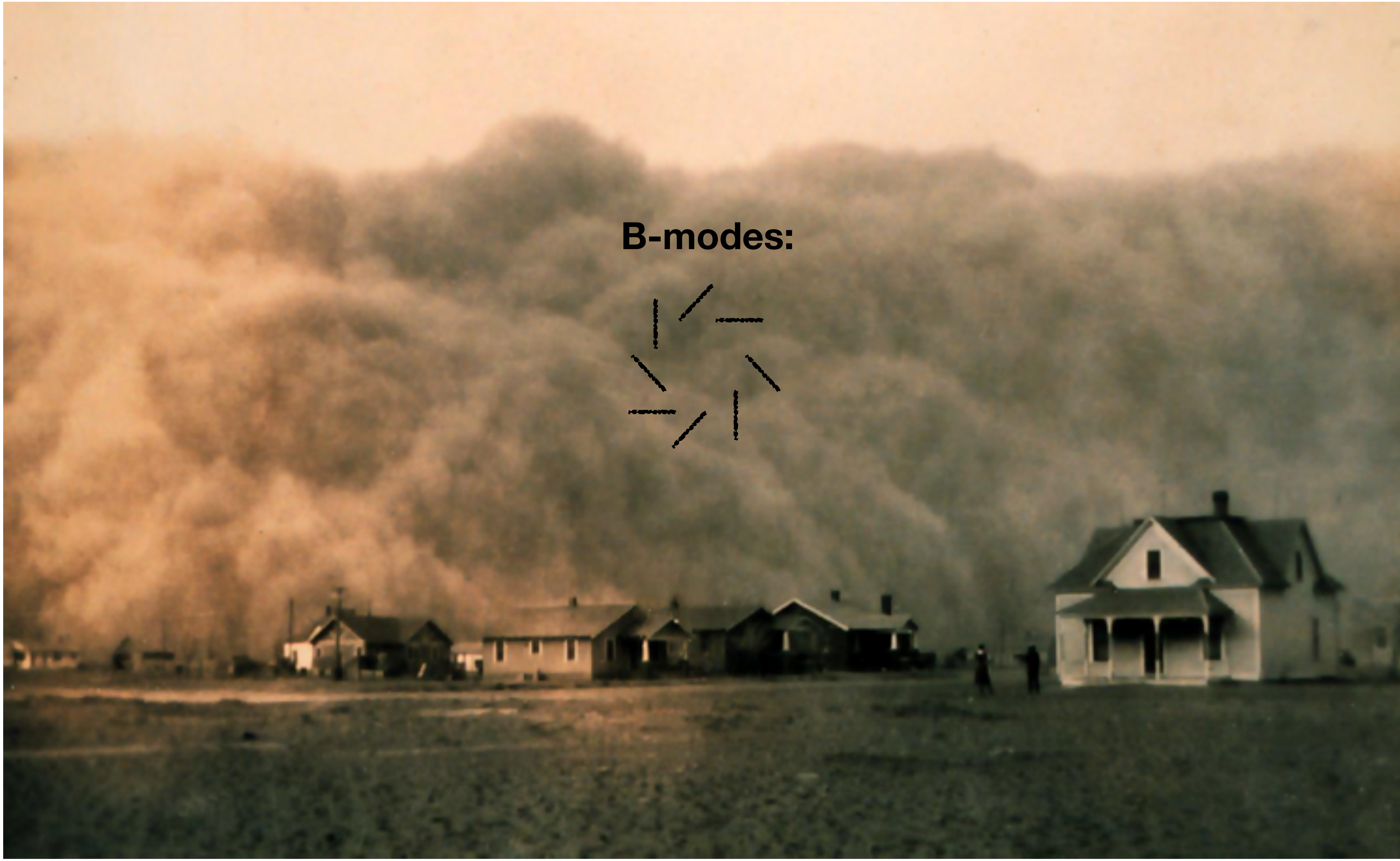
What the doctor ordered?





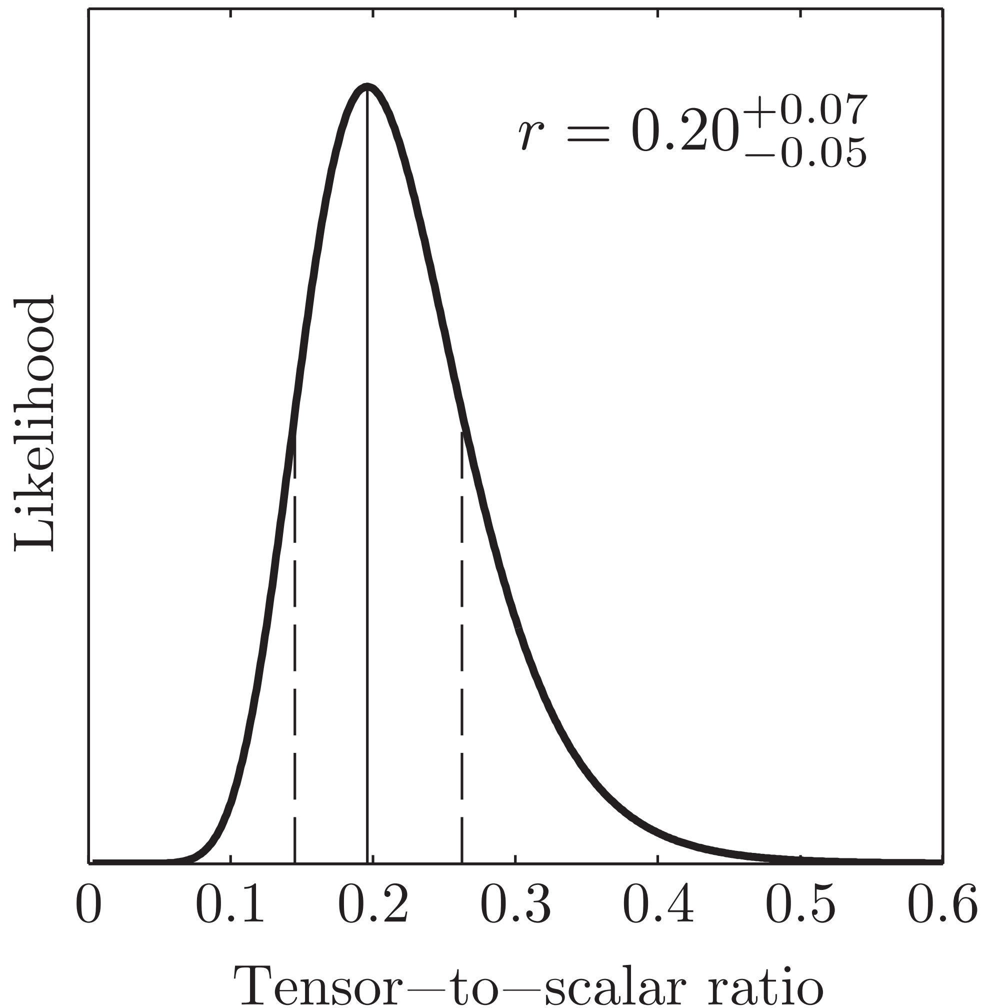
BICEP2 Collaboration

Dust is not entirely settled ...



[Mortonson & Seljak]
[Flauger, Hill & Spergel]

More data is needed ...



BICEP2 Collaboration

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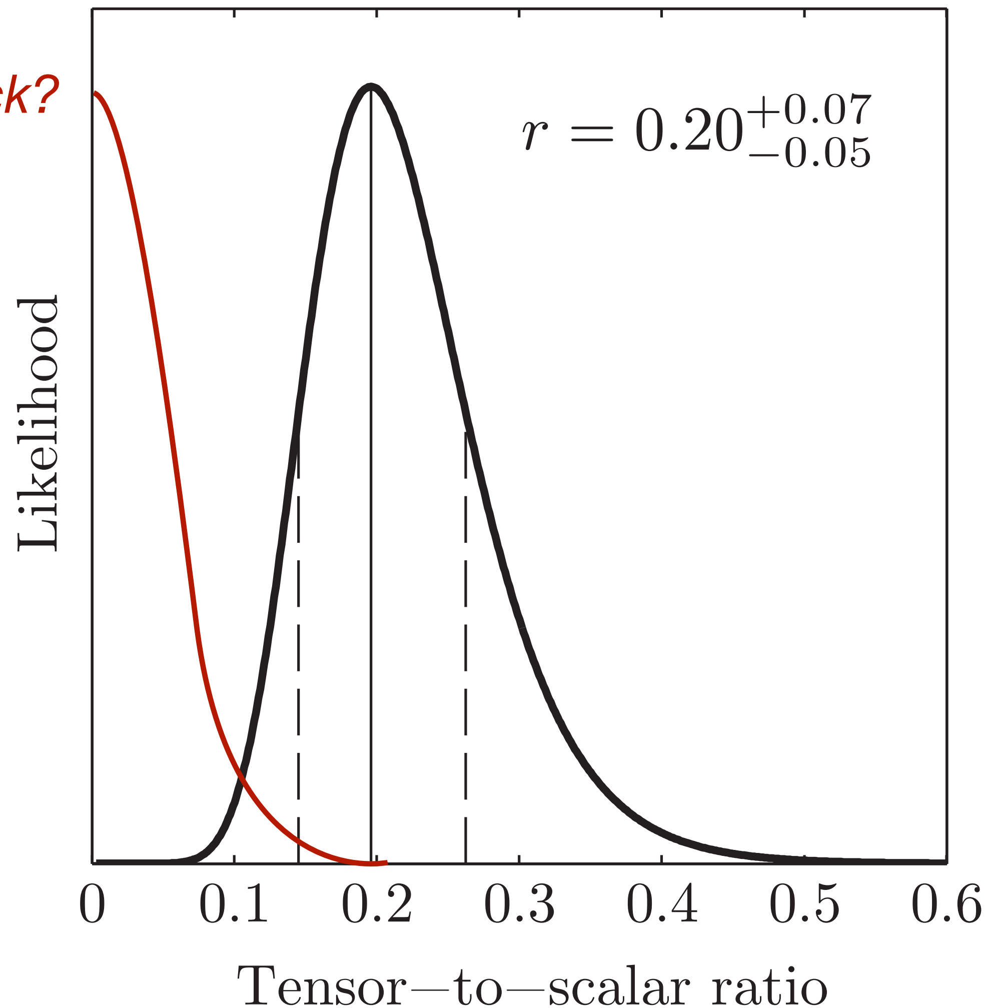
Tension with Planck?

$r < 0.11$



BICEP2 Collaboration

BICEP2 and Inflation

If the BICEP2 results are confirmed to be primordial, 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!

Assumptions in the Lyth Bound

- single field
- slow-roll
- Bunch-Davies initial conditions
- vacuum fluctuations

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Particle production during inflation can be a source of GWs

Cook and Sorbo

Senatore, Silverstein, Zaldarriaga

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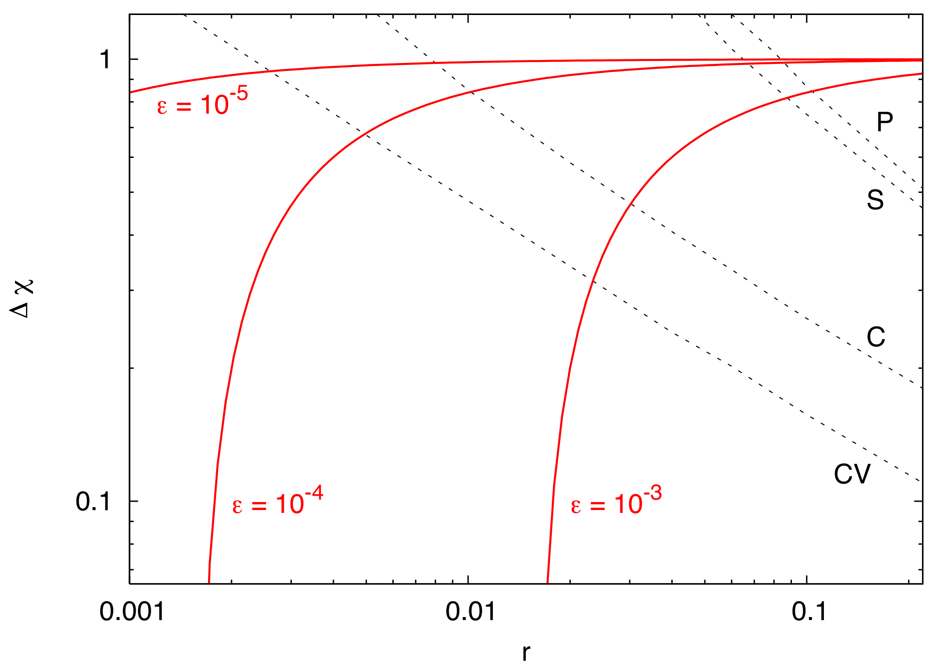


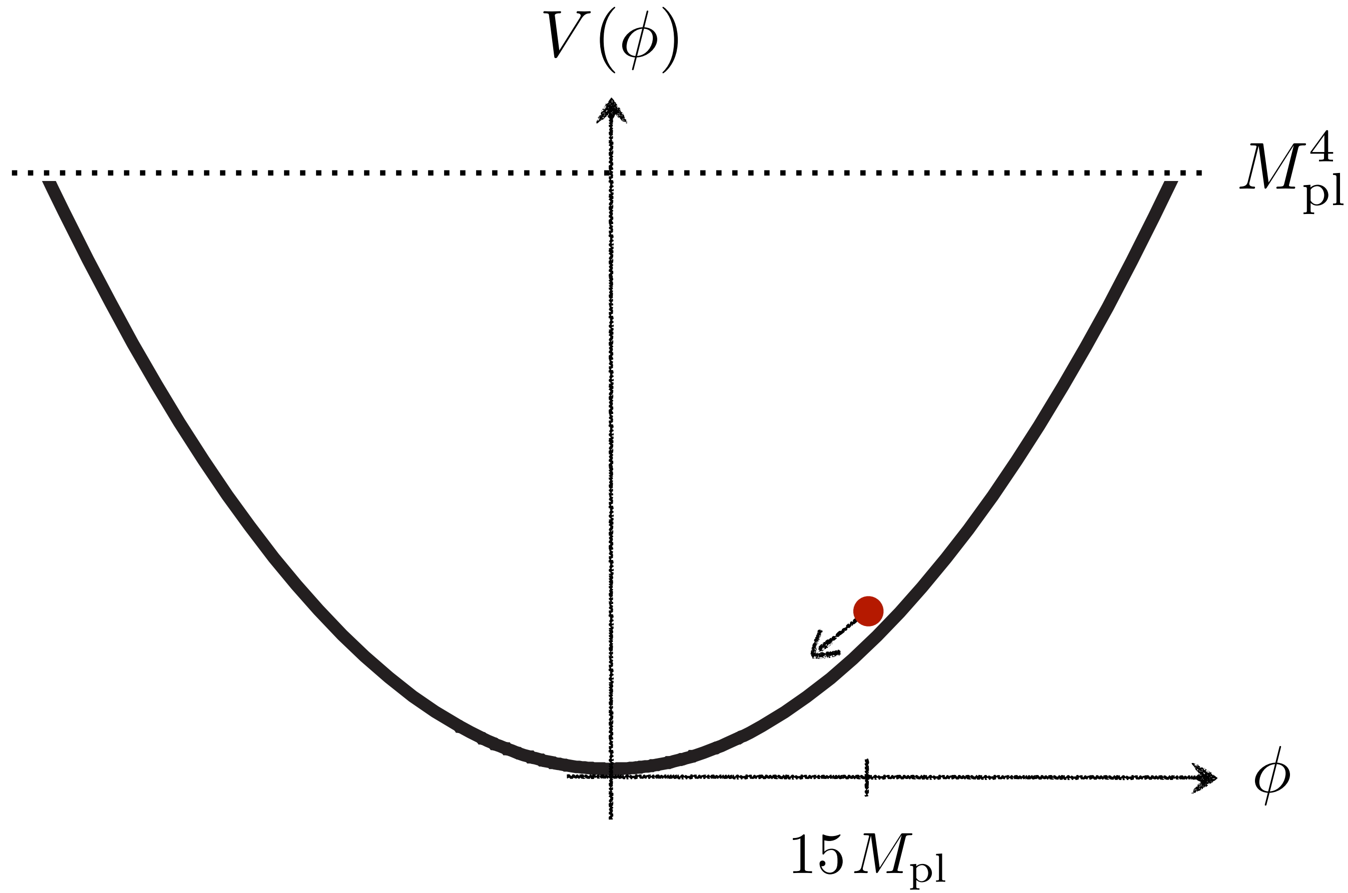
Only known model of particle production that:

- Detectable tensors w/o too large non-Gaussianity
- ***Chiral***, ***non-Gaussian*** tensor spectrum
- Can accommodate a blue tensor tilt

due to an ***axionic*** a $F \wedge F$ coupling

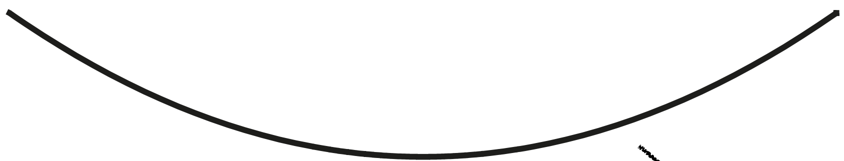
Super-Planckian Fields in Effective Field Theory

Large Field Inflation



Concerns arise if we consider coupling the theory to the UV degrees of freedom (KK states, string states, etc) of a putative theory of quantum gravity.

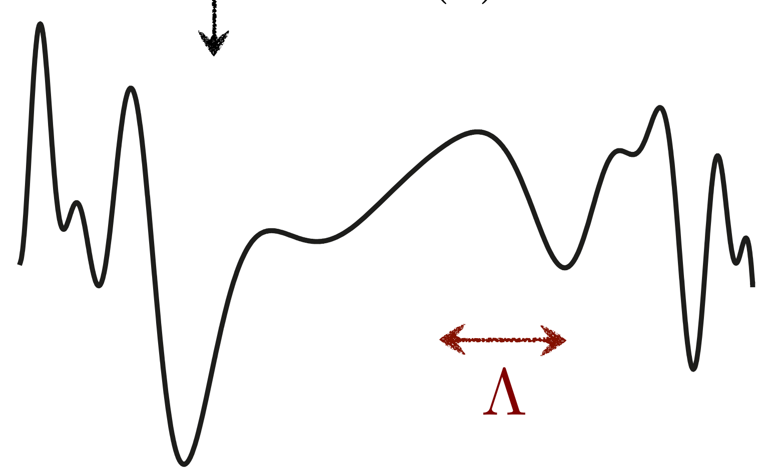
Challenges of Large Field Inflation



$V = m^2\phi^2$

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

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



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.

Attempts to construct large field inflation models in string theory:

Marchesano, GS, Uranga, arXiv:1404.3040 [hep-th]

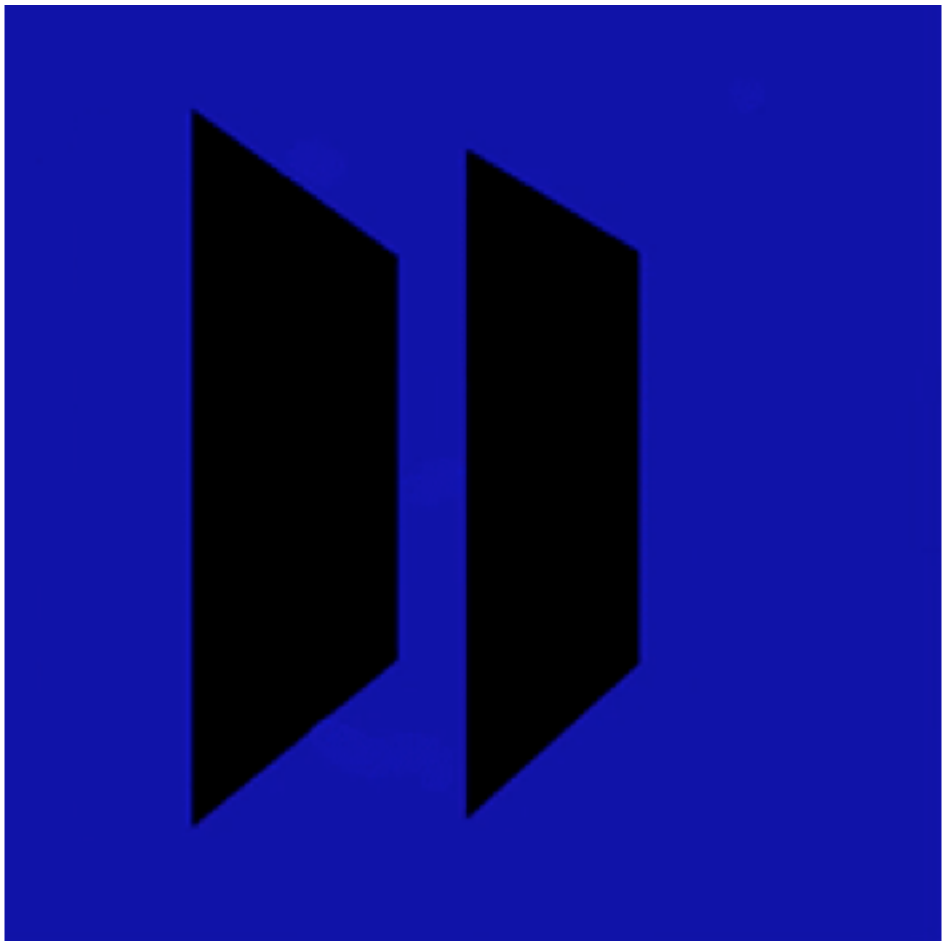
Super-Planckian Fields in String Theory

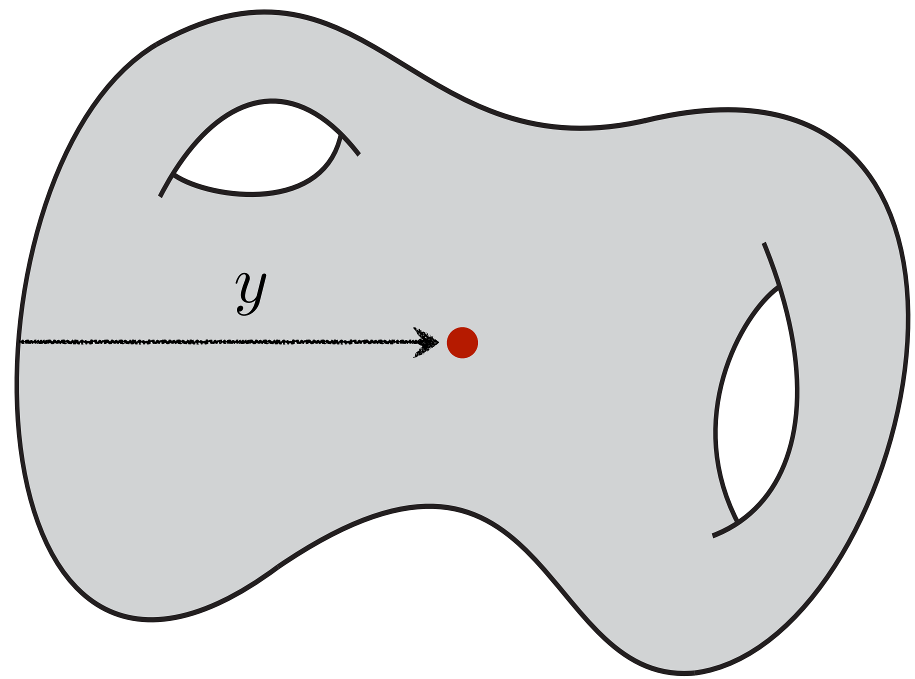
The two key requirements for large-field inflation are:

- The field space has to allow super-Planckian displacements. **Kinematic constraint**

- The potential has to be controlled over a super-Planckian range. **Dynamical constraint**

D3-brane Inflation





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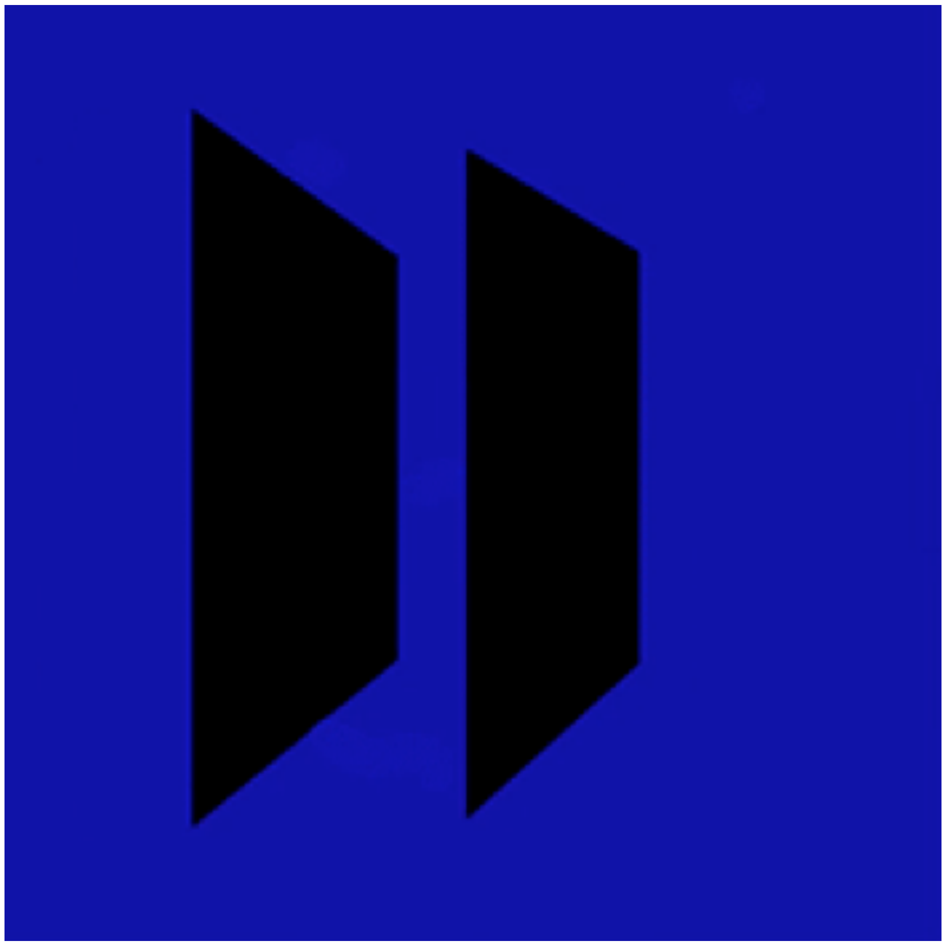

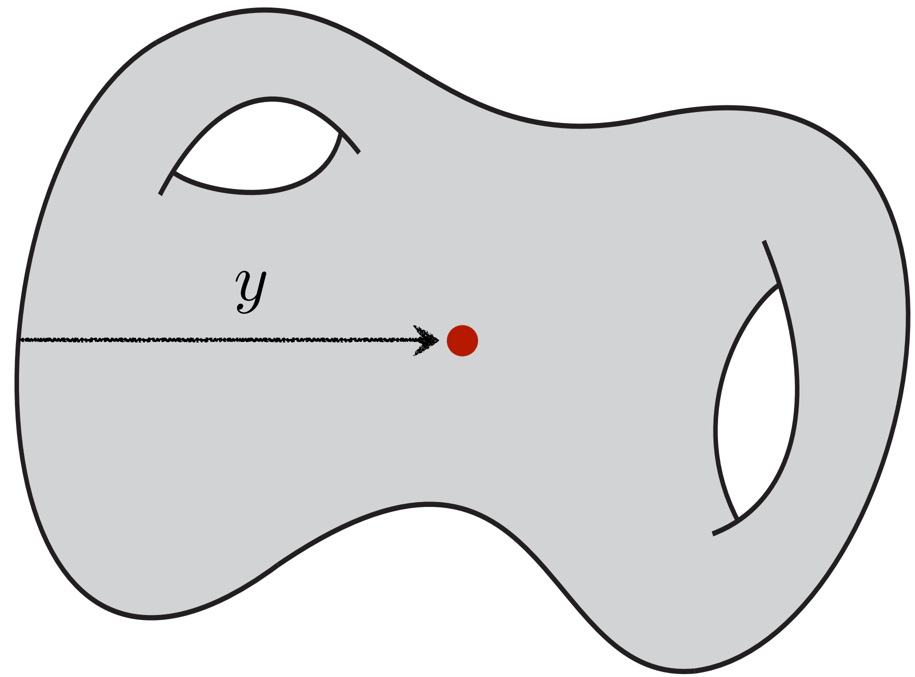

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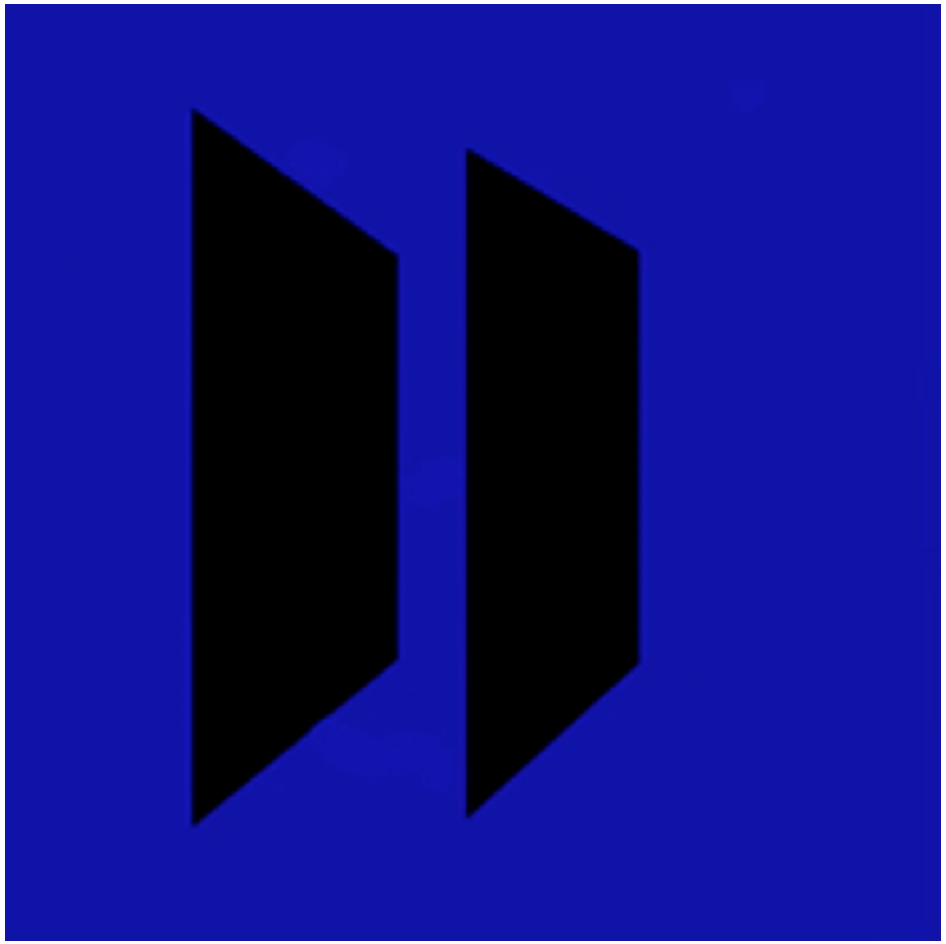
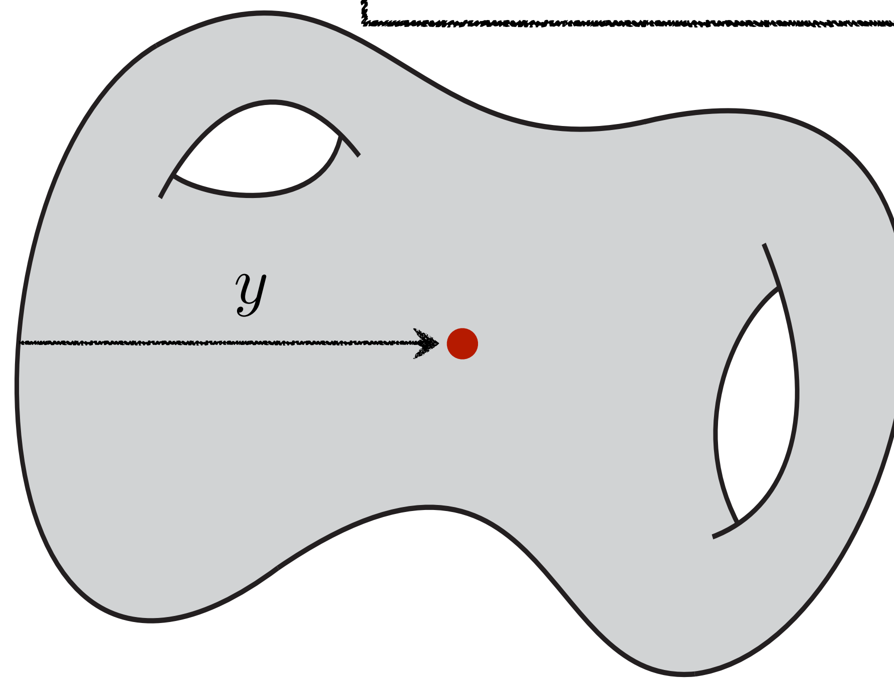


$$\frac{\Delta\phi^2}{M_{\rm pl}^2} \lesssim g_s \left(\frac{\ell_s}{L}\right)^4 \ll 1$$



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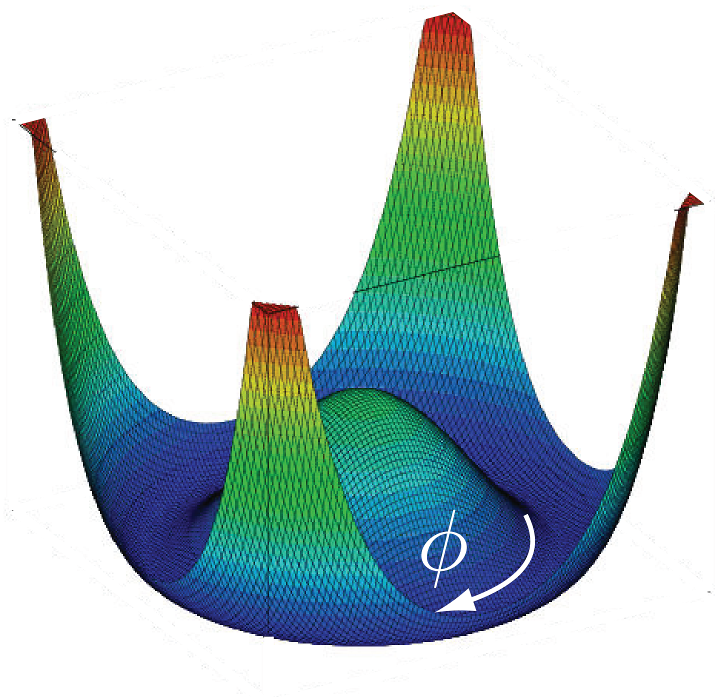
More natural candidates are fields with symmetries.

“Symmetries dictate interactions”

Natural Inflation

Freese, Frieman, Olinto

Pseudo-Nambu-Goldstone bosons
are natural inflaton candidates:



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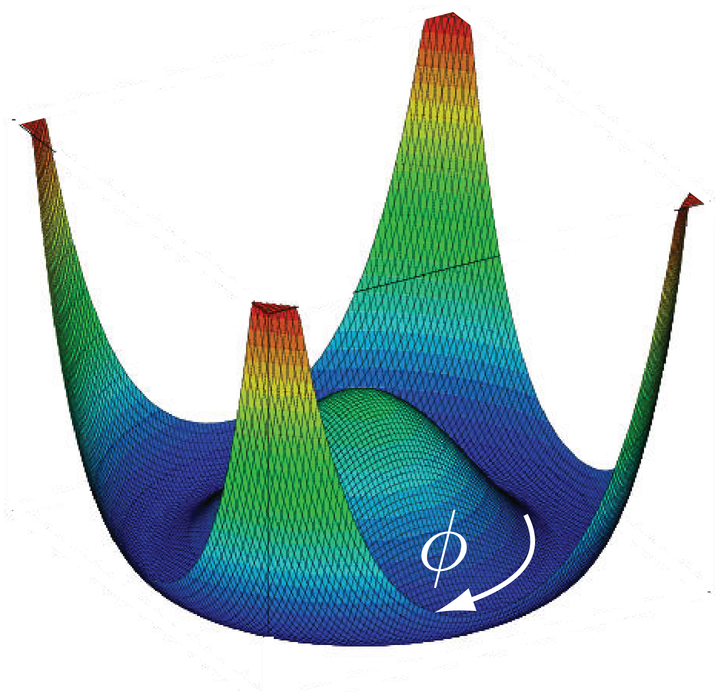
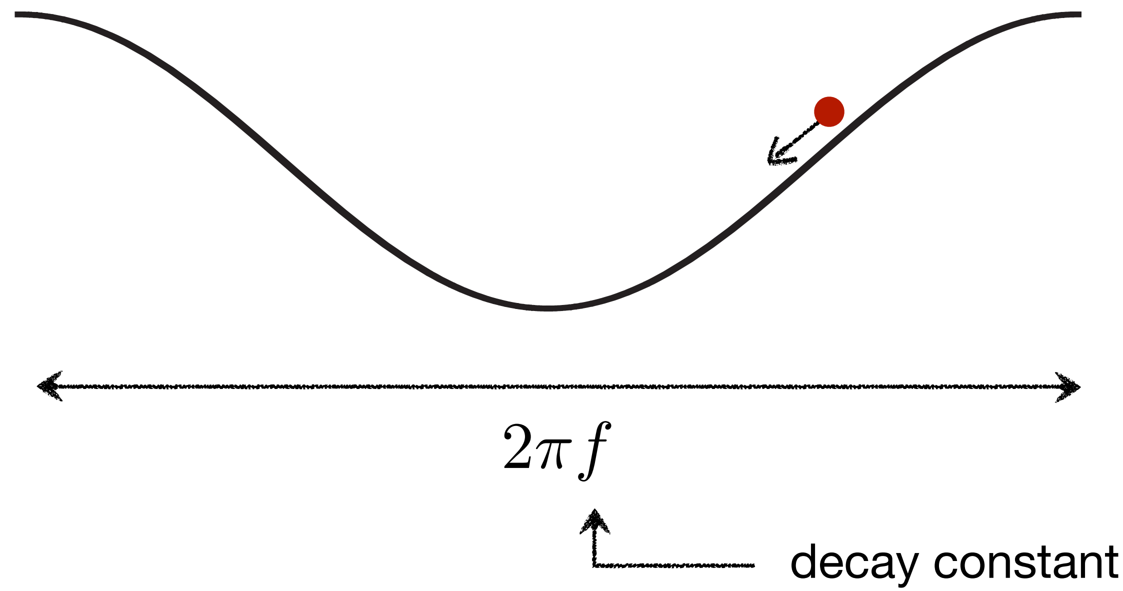


They satisfy a shift symmetry that is only
broken by non-perturbative effects:



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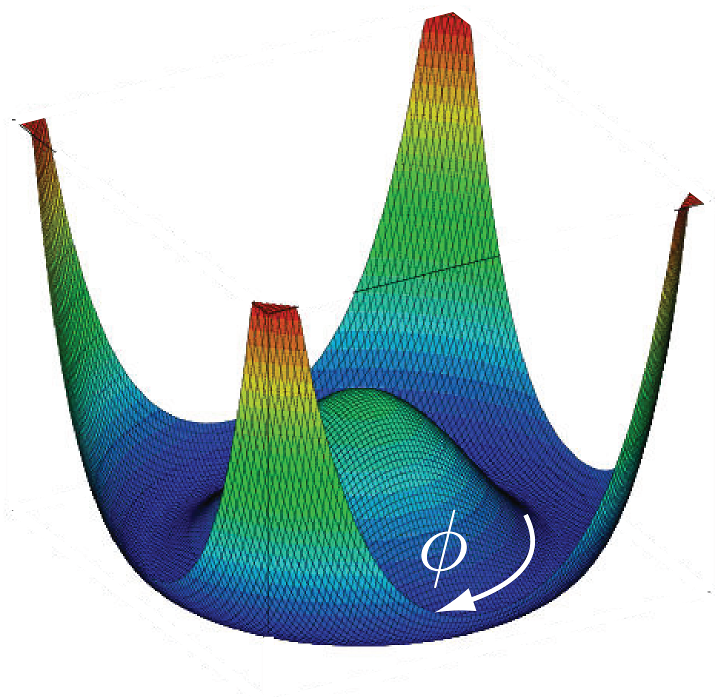

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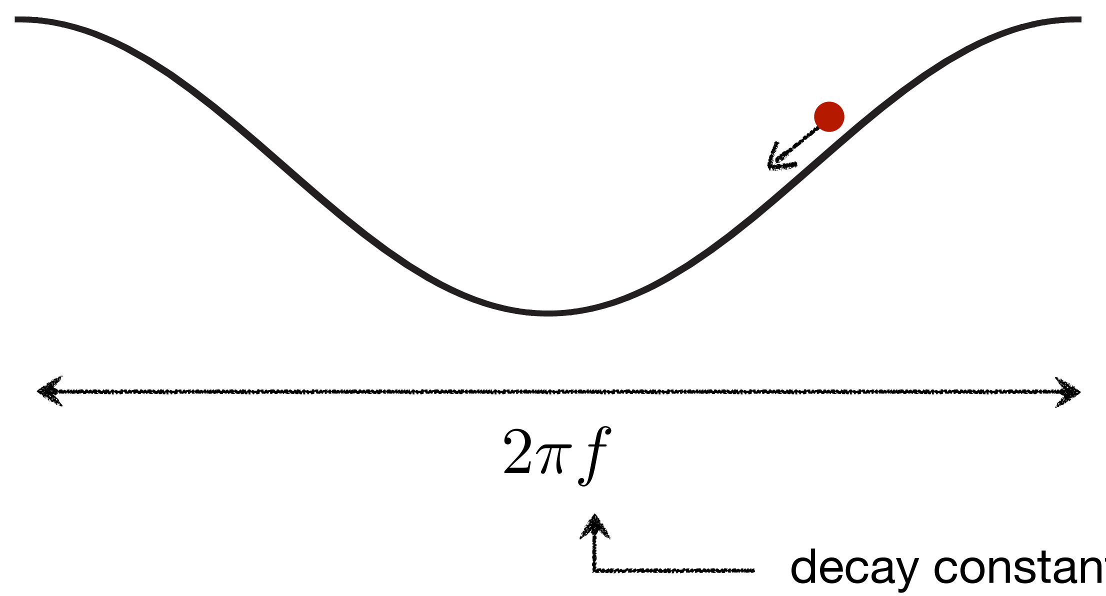


Successful inflation requires a super-Planckian decay constant:

$$f > M_{\rm pl}$$

Axions in String Theory

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

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

3-form flux → F ; A ← 2-form gauge potential:

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.**

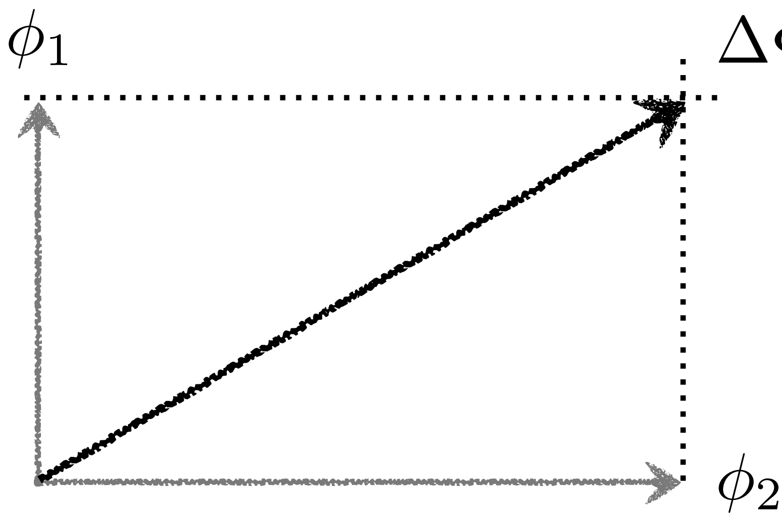
Axions with super-Planckian decay constants don't seem to exist in controlled limits of string theory.

Svrcek and Witten

Banks et al.

N-flation

Dimopoulos et al.



$$\Delta\Phi = \sqrt{N}\Delta\phi$$

can be large for $N \gtrsim 10^3$

Quantum corrections to the Planck mass also scale with the number of axions:

$$\delta M_{\mathrm{pl}}^2 \sim N\Lambda_{\mathrm{UV}}^2$$

So, we don’t win parametrically!

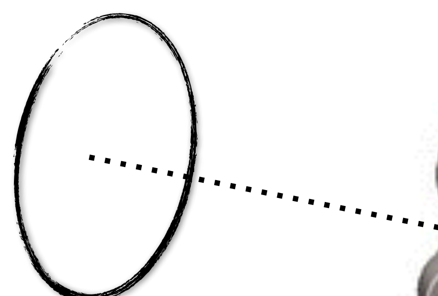
Other scenarios with multiple axions: [Kim, Nilles, Peloso];[Berg, Pajer, Sjors]

Axion Monodromy

= a combination of chaotic inflation and natural inflation

McAllister, Silverstein and Westphal (see also: Kaloper, Lawrence and Sorbo)

A new and better version: Marchesano, GS, Uranga



An ***"apparent" periodicity*** in field space which nonetheless is broken.

Axion Monodromy

= a combination of chaotic inflation and natural inflation

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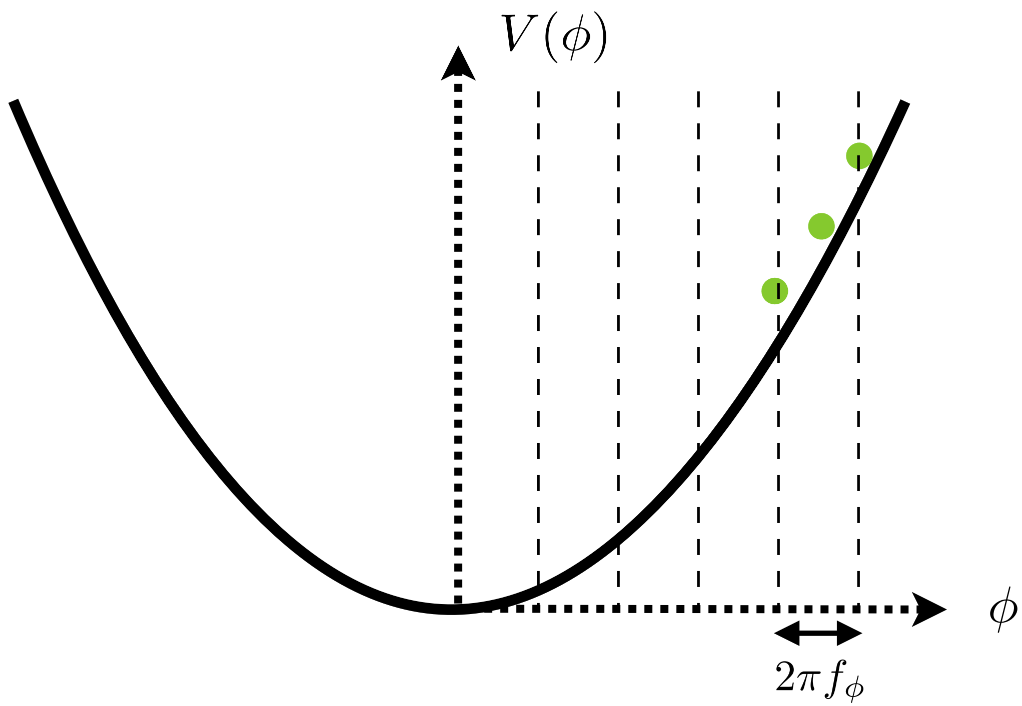
The axion periodicity is lifted, but the symmetry still constrains corrections to the potential:

Axion Monodromy Inflation

Siverstein & Westphal '08

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.

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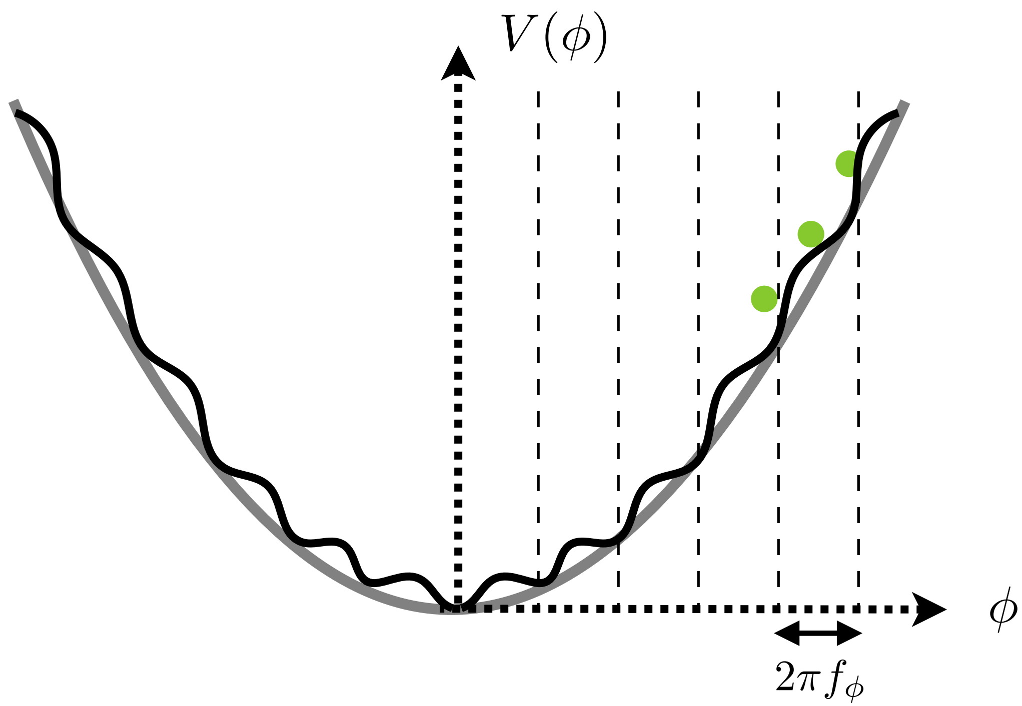

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Axion Monodromy

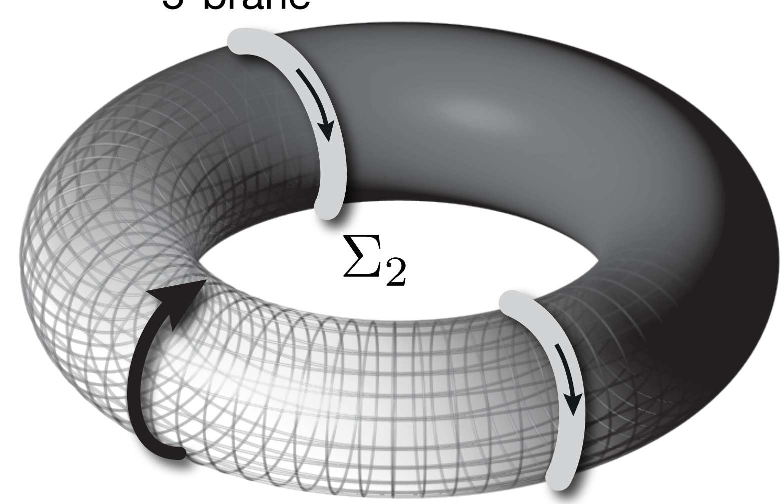
The axion shift symmetry in string theory is broken only by non-perturbative effects (instantons) or boundaries [Wen, Witten];[Dine, Seiberg]

Non-perturbative effects → discrete symmetry (no monodromy)

A 5-brane wrapping the 2-cycle breaks the axion shift symmetry:

$$V = 2T_5 \int_{\Sigma_2} \mathrm{d}^2\sigma \sqrt{-\det(G+A)}$$

$$= 2T_5 \sqrt{\ell_{\Sigma_2}^2 + a^2}$$

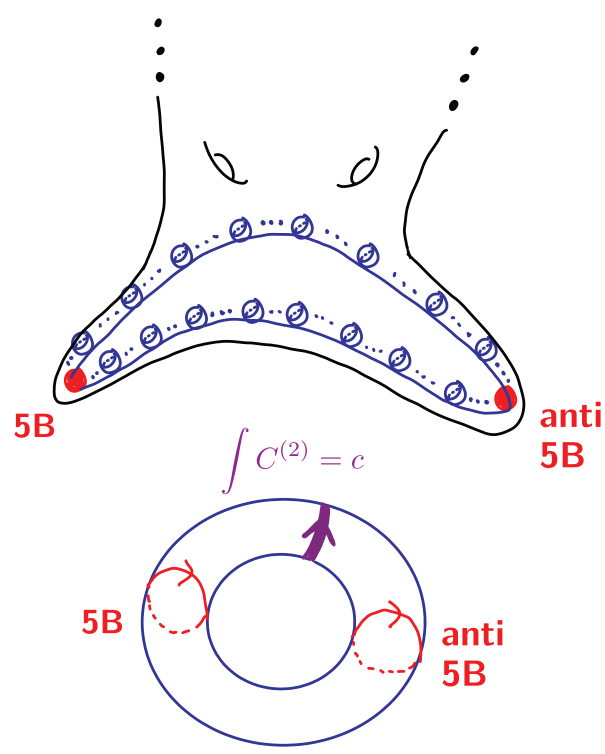


McAllister, Silverstein and Westphal

Axion Monodromy

Road blocks found in earlier attempts (and some quick fixes):

- η problem ⇒ NS5-branes (not D5-branes)
- Gauss's law ⇒ anti 5-brane wrapping "homologous" cycles.
- Brane annihilation ⇒ far from each other, at different warped throats



McAllister, Silverstein and Westphal

- Backreaction ⇒ whole system embedded into another throat.

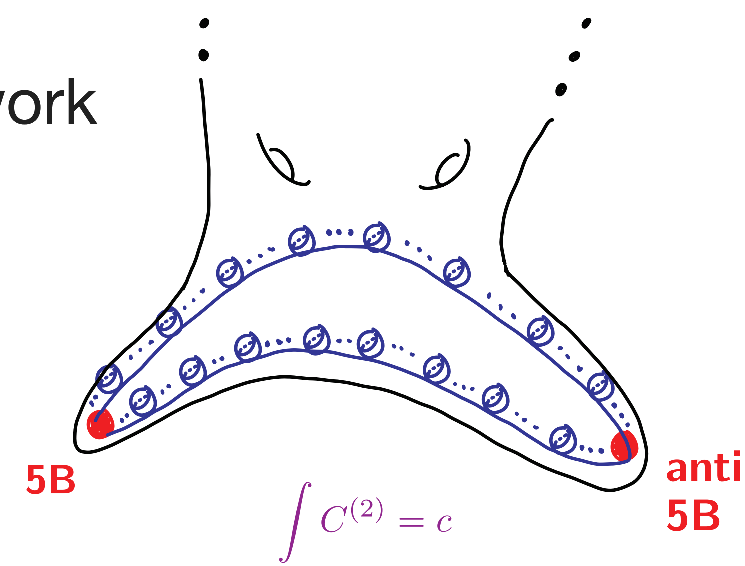
Axion Monodromy Inflation

Siverstein & Westphal '08

Idea: Combine chaotic inflation and natural inflation

Early developments:

- ✦ McAllister, Silverstein, Westphal → String scenarios
- ✦ Kaloper, Lawrence, Sorbo → 4d framework



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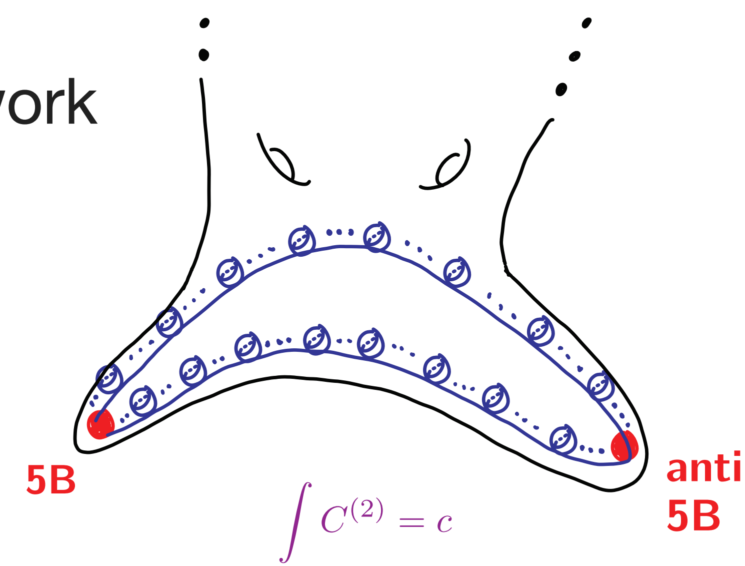

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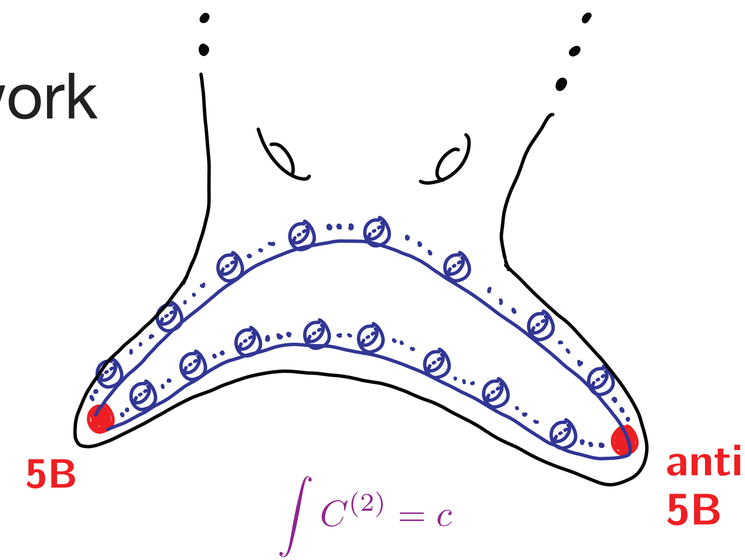
  UV completion?



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F-term Axion Monodromy Inflation

Obs: Axion Monodromy ~ Giving a mass to an axion

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

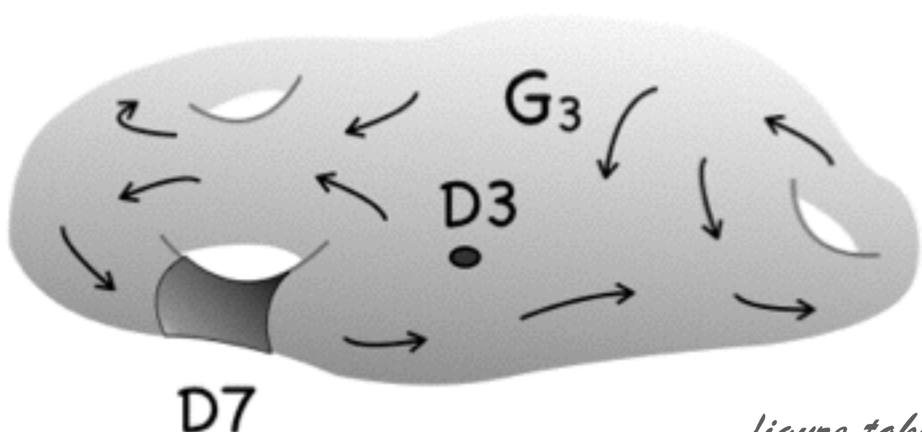

figure taken from Ibañez & Uranga '12

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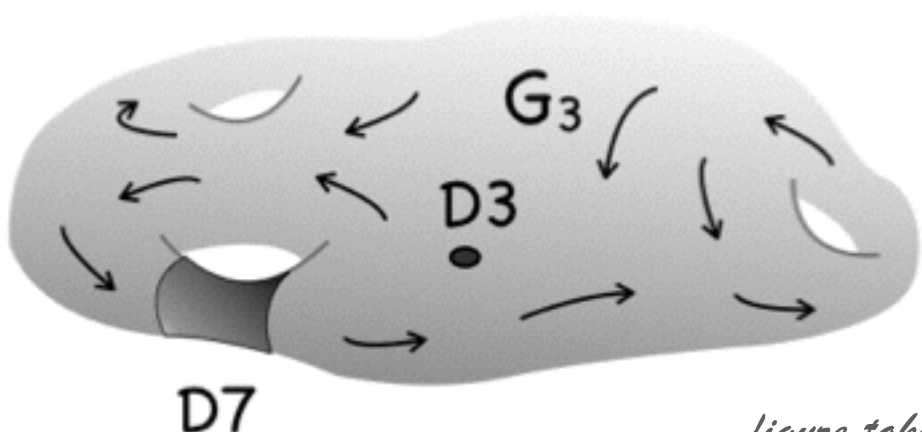

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Idea: Use same techniques to generate an inflation potential

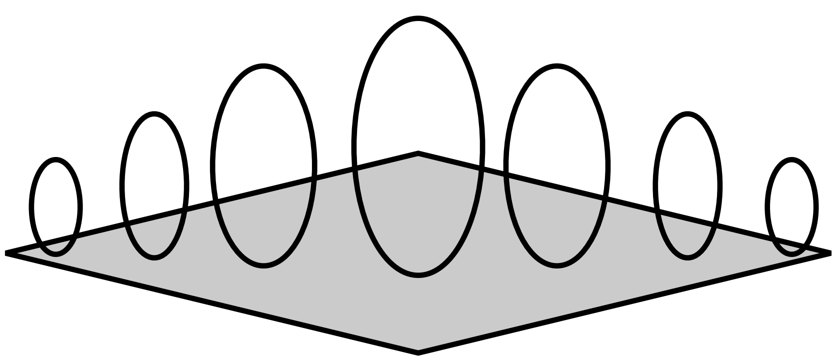
- Simpler models, all sectors understood at weak coupling
- Spontaneous SUSY breaking, no need for brane-anti-brane
- Clear endpoint of inflation, allows to address reheating

Toy 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

$\Rightarrow$ periodicity is broken and shift symmetry approximate

MWL and twisted tori

- Simple way to construct massive Wilson lines: consider compact extra dimensions Π_d with circles fibered over a base, like the twisted tori that appear in flux compactifications

- There are circles that are not contractible but do not correspond to any harmonic 1-form. Instead, they correspond to torsional elements in homology and cohomology groups

$$\mathrm{Tor}\, H_1(\Pi_d, \mathbb{Z}) = \mathrm{Tor}\, H^2(\Pi_d, \mathbb{Z}) = \mathbb{Z}_k$$

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- Simplest example: twisted 3-torus $\tilde{\mathbb{T}}^3$

$$H_1(\tilde{\mathbb{T}}^3, \mathbb{Z}) = \mathbb{Z} \times \mathbb{Z} \times \mathbb{Z}_k$$

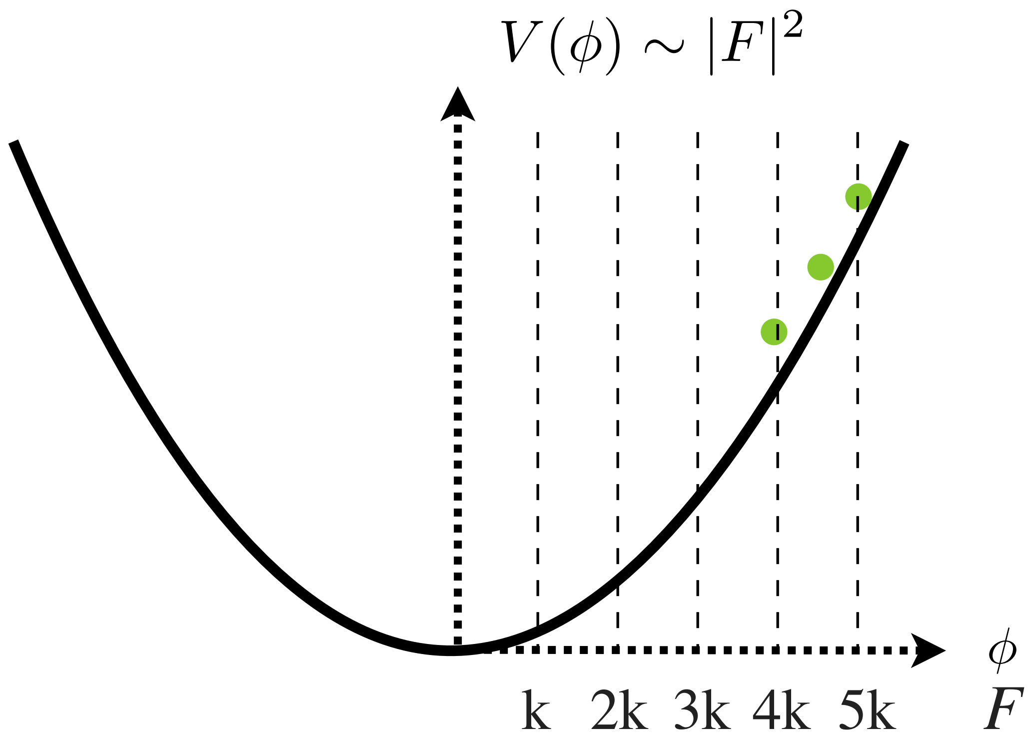
two normal 1-cycles ($\mathbb{Z} \times \mathbb{Z}$); one torsional 1-cycle ($\mathbb{Z}_k$)

$$d\eta_1 = k dx^2 \wedge dx^3 \rightarrow F = \phi\, k\, dx^2 \wedge dx^3$$

$$\mu = \frac{kR_1}{R_2 R_3}$$

under a shift $\phi \to \phi + 1$
F_2 increases by k units

MWL and monodromy



Question:

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

Torsion and gauge invariance

- Twisted tori torsional invariants are not just a fancy way of detecting non-harmonic forms, but are related to a hidden gauge invariance of these axion-monodromy models
- 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

$$V_4 = C_3 \wedge \eta_1 + b_2 \wedge \sigma_2 \xrightarrow{d\eta_1 = k\,\sigma_2} dV_4 = dC_3 \wedge \eta_1 + (db_2 - kC_3) \wedge \sigma_2$$

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  - 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 $C_3 \to C_3 + d\Lambda_2 \qquad b_2 \to b_2 + k\Lambda_2$
    - Generalization of the Stückelberg Lagrangian

Quevedo & Trugenberger '96

Effective 4d theory

- The effective 4d Lagrangian

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

describes a massive axion, has been applied to QCD axion ⇒ generalized to arbitrary V(ϕ)

Kallosh et al. '95
Dvali, Jackiw, Pi '05
Dvali, Folkerts, Franca '13

- Reproduces the axion-four-form Lagrangian proposed by Kaloper and Sorbo as 4d model of axion-monodromy inflation with mild UV corrections

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

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

Kaloper & Sorbo '08

- It is related to an F-term generated mass term

Groh, Louis, Sommerfeld '12

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

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

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

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

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

Effective 4d theory

- Effective 4d Lagrangian

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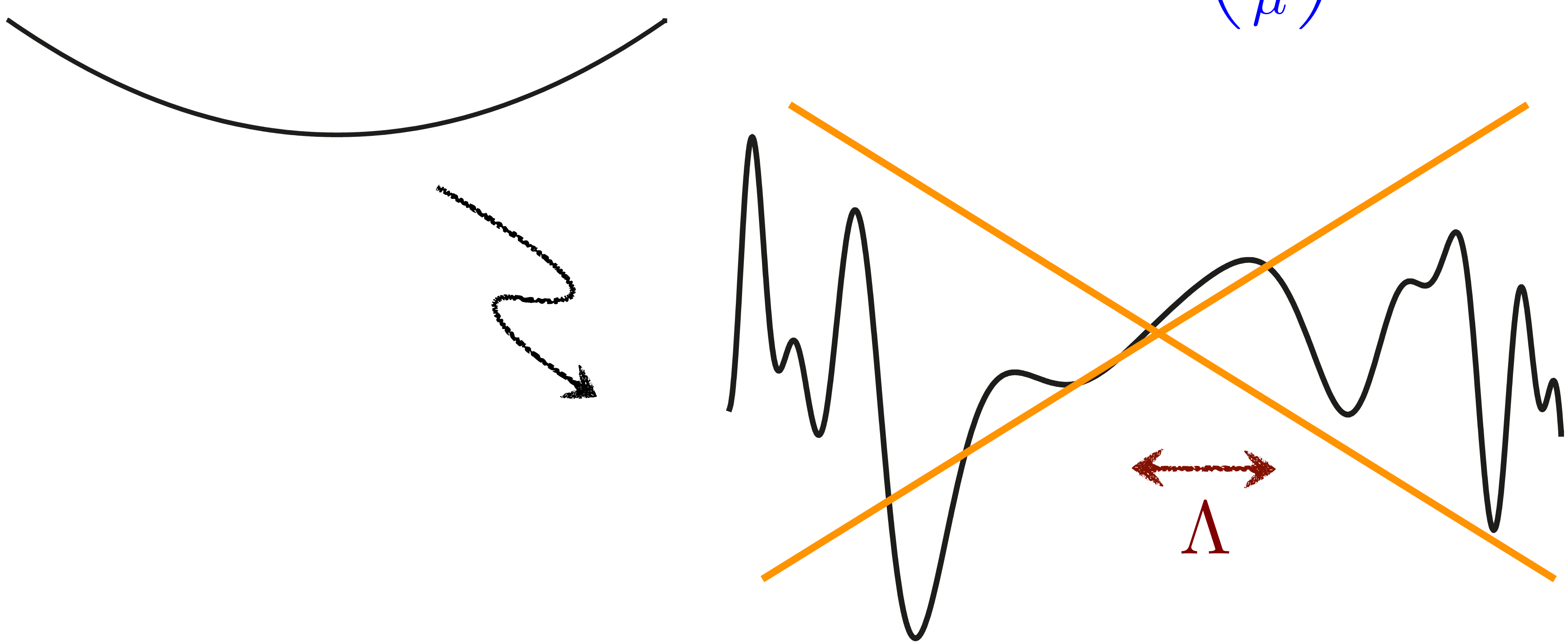
$$\Lambda \to \Lambda_{\text{eff}} = \Lambda \left(\frac{\Lambda}{\mu} \right)$$



Discrete symmetries and domain walls

- The integer k in the Lagrangian

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

corresponds to a discrete symmetry of the theory broken spontaneously once a choice of four-form flux is made. This amounts to choose a branch of the scalar potential

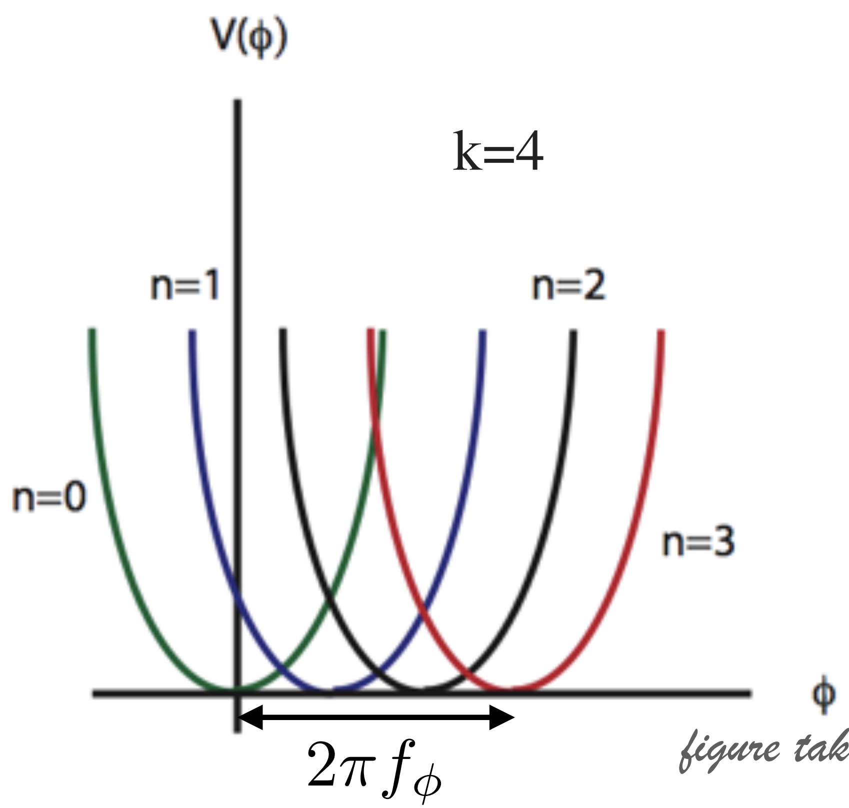


figure taken from Kaloper & Lawrence '14

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

- Domain walls analysed in string constructions:

Berasaluce-Gonzalez, Camara, Marchesano, Uranga '12

  - They correspond to discrete symmetries of the superpotential/ landscape of vacua, and appear whenever axions are stabilised

  - k domain walls decay in a cosmic string implementing $\phi \to \phi+1$

Massive Wilson lines in string theory

- Simple example of MWL in string theory: D6-brane on $M^{1,3} \times \tilde{\mathbb{T}}^3$
- An inflaton vev induces a non-trivial flux F_2 proportional to ϕ but now this flux enters the DBI action

$$\sqrt{\det\left(G + 2\pi\alpha' F_2\right)} \;=\; d\mathrm{vol}_{M^{1,3}} \;\left(|F_2|^2 + \mathrm{corrections}\right)$$

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- For small values of ϕ we recover chaotic inflation, but for large values the corrections are important and we have a potential of the form

$$V = \sqrt{L^4 + \langle\phi\rangle^2} - L^2$$

Similar to the D4-brane model of Silverstein and Westphal except for the inflation endpoint

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Massive Wilson lines and flattening

- The DBI modification

$$\langle\phi\rangle^2 \rightarrow \sqrt{L^4 + \langle\phi\rangle^2} - L^2$$

can be interpreted as corrections due to UV completion

- E.g., integrating out moduli such that $H < m_{mod} < M_{GUT}$ will correct the potential, although not destabilise it

Kaloper, Lawrence, Sorbo '11

- In the DBI case the potential is flattened: argued general effect due to couplings to heavy fields

Dong, Horn, Silverstein, Westphal '10

- Large vev flattening also observed in examples of confining gauge theories whose gravity dual is known [Witten'98]

Dubovsky, Lawrence, Roberts '11

- α' corrections to EFT [See Junghans's talk] are important for inflation and moduli stabilization.

Other string examples

- We can integrate a bulk p-form potential C_p over a p-cycle to get an axion

$$F_{p+1} = dC_p, \quad C_p \to C_p + d\Lambda_{p-1} \qquad\qquad c = \int_{\pi_p} C_p$$

- If the p-cycle is torsional we will get the same effective action

$$\int d^{10}x |F_{9-p}|^2 \longrightarrow \int d^4x \, |dC_3|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2$$

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- The topological groups that detect this possibility are

$$\mathrm{Tor}\, H_p(\mathbf{X}_6, \mathbb{Z}) = \mathrm{Tor}\, H^{p+1}(\mathbf{X}_6, \mathbb{Z}) = \mathrm{Tor}\, H^{6-p}(\mathbf{X}_6, \mathbb{Z}) = \mathrm{Tor}\, H_{5-p}(\mathbf{X}_6, \mathbb{Z})$$

one should make sure that the corresponding axion mass is well below the compactification scale (e.g., using warping)

Franco, Galloni, Retolaza, Uranga '14

Other string examples

- Axions also obtain a mass with background fluxes
- Simplest example: $\phi = C_0$ in the presence of NSNS flux H_3

$$W = \int_{\mathbf{X}_6} (F_3 - \tau H_3) \wedge \Omega \qquad \tau = C_0 + i/g_s$$

- We also recover the axion-four-form potential

$$\int_{M^{1,3}\times\mathbf{X}_6} C_0 H_3 \wedge F_7 = \int_{M^{1,3}} C_0 F_4 \qquad F_4 = \int_{\mathrm{PD}[H_3]} F_7$$

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- M-theory version: *Beasley, Witten '02*
- A rich set of superpotentials obtained with type IIA fluxes

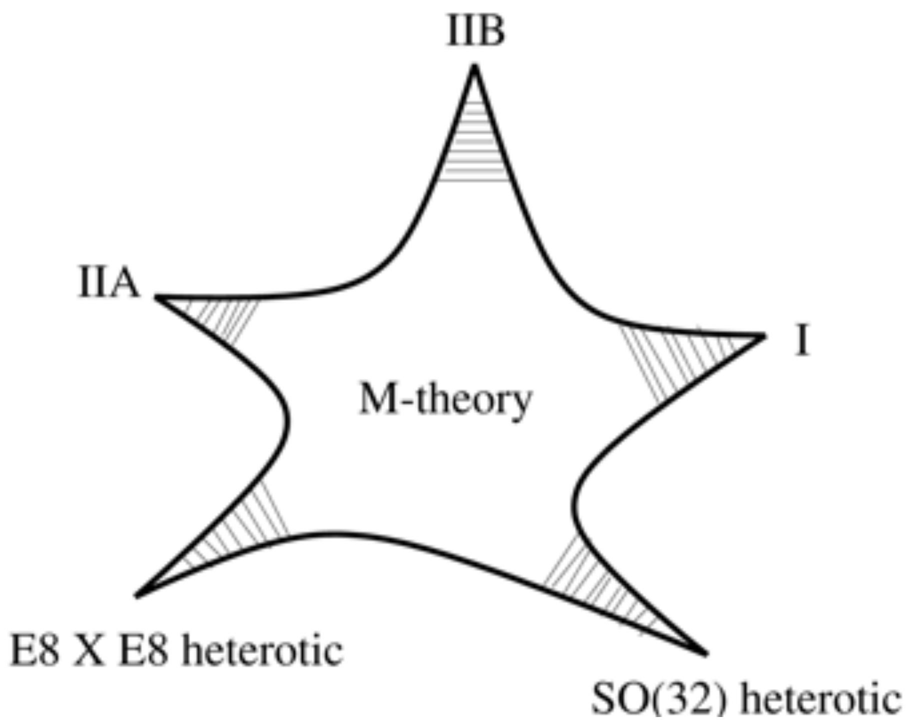
$$\int_{\mathbf{X}_6} e^{J_c} \wedge (F_0 + F_2 + F_4) \qquad J_c = J + iB$$

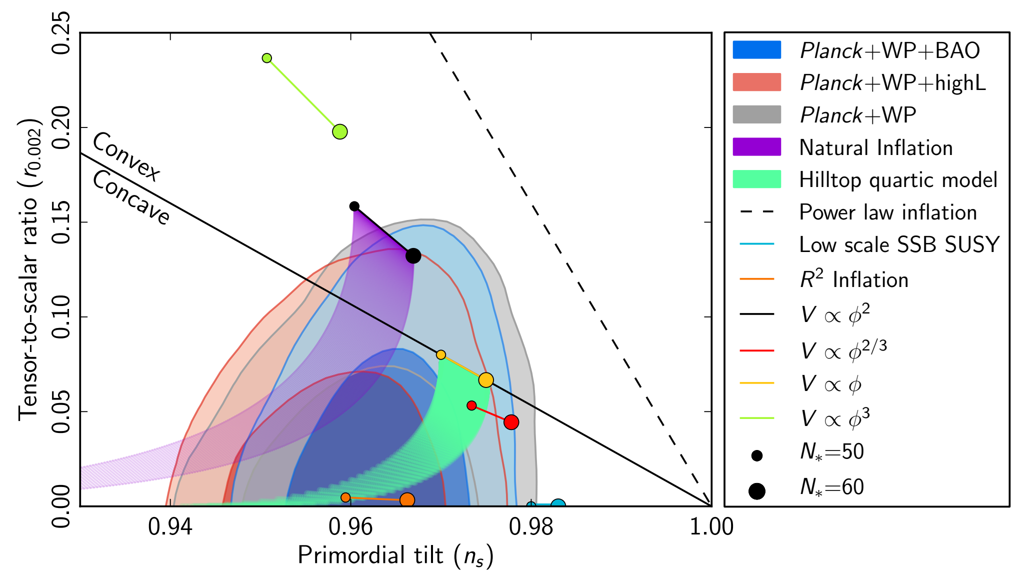
→ **potentials higher than quadratic**

- Massive axions detected by torsion groups in K-theory

F-term Axion Monodromy Inflation

- A broad class of large field inflationary scenarios that can be implemented in any limit of string theory w/ rich pheno:





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

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

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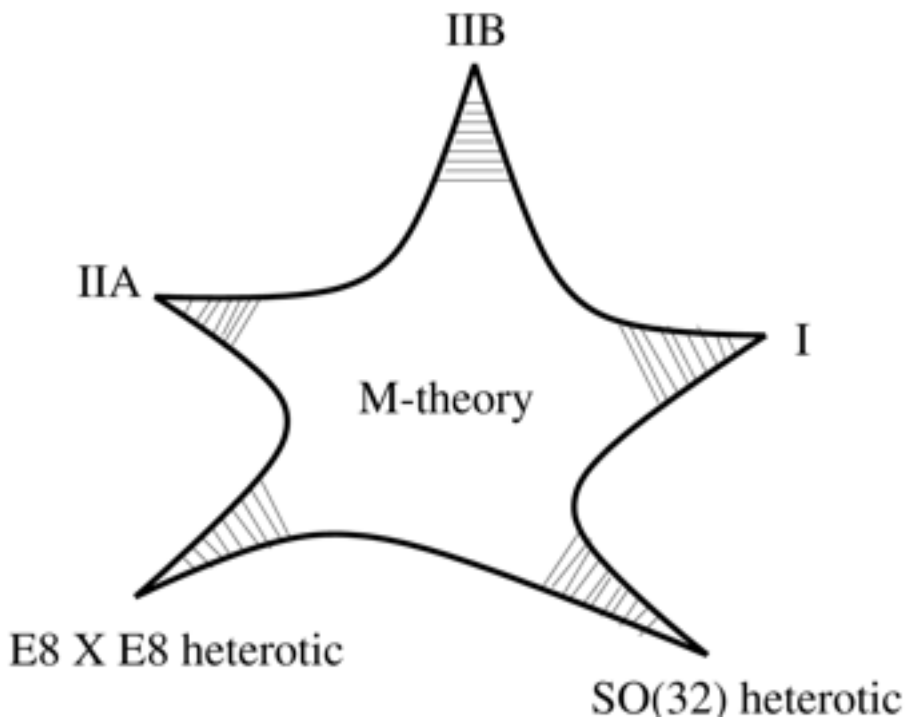

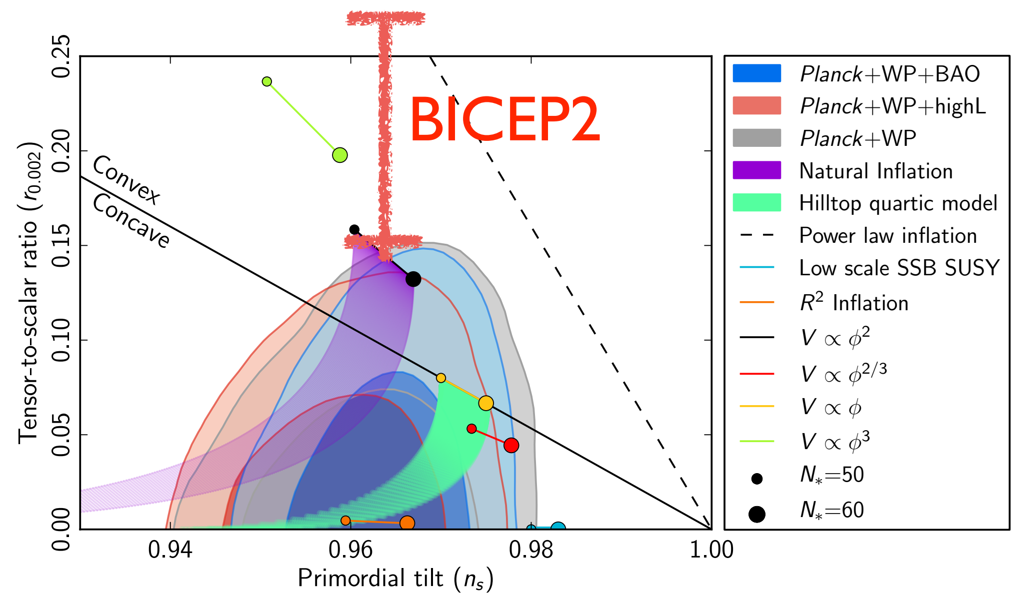

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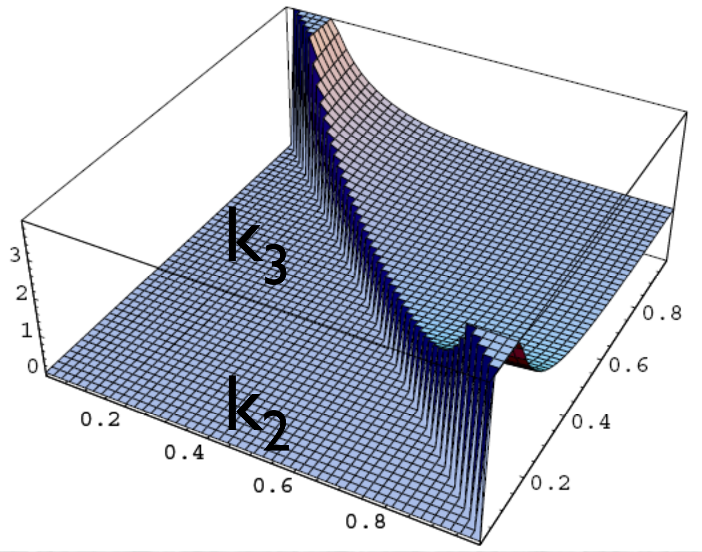
Non-Gaussianity

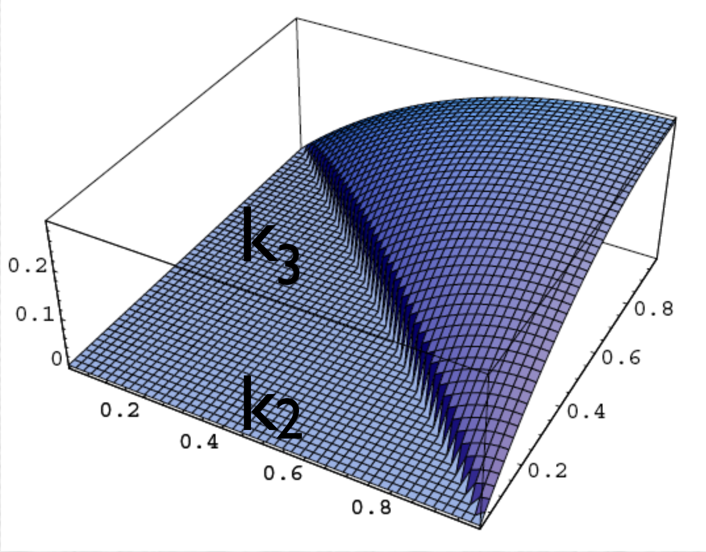
If Gaussian: completely specified $< \zeta(\mathbf{k})\zeta(\mathbf{k}') >= (2\pi)^3\delta^3(\mathbf{k}+\mathbf{k}')P_s(k)$

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

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

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





Current bound [Planck]:

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

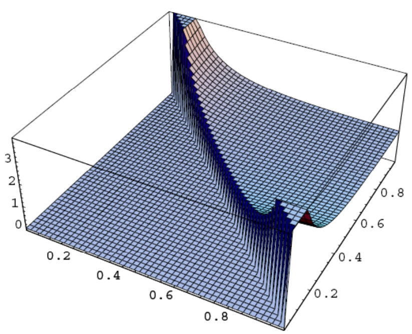
$$f_{NL}^{equil} = -42 \pm 75$$

Large non-Gaussianity probes UV physics!

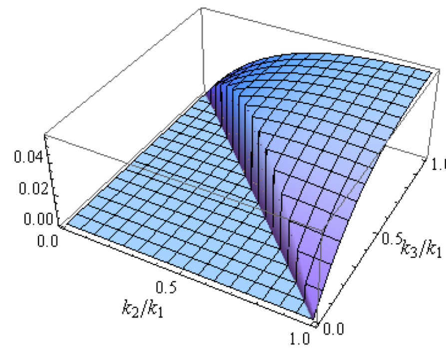
Local shape: $f_{NL}^{local} \sim \mathcal{O}(\epsilon)$ Equilateral shape: $f_{NL}^{equil} \sim \mathcal{O}(\gamma^2)$

Holographic Non-Gaussianity

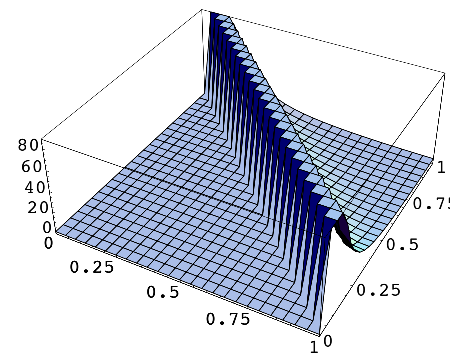
- Motivated partly by CHKS, various shape templates have been proposed:



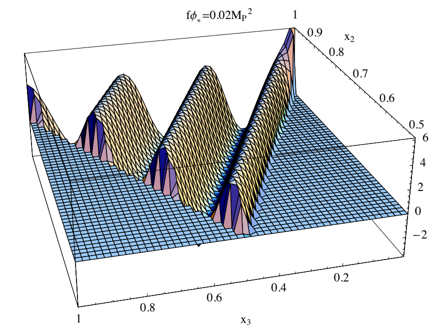
Local (slow-roll)



Equilateral (DBI)

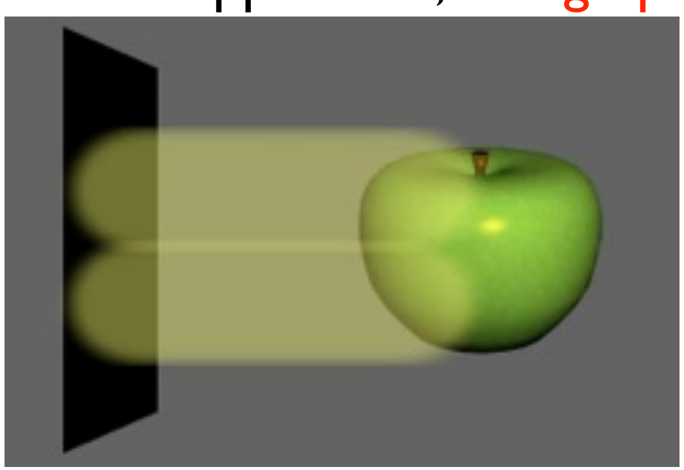


Folded (non BD vacuum)



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

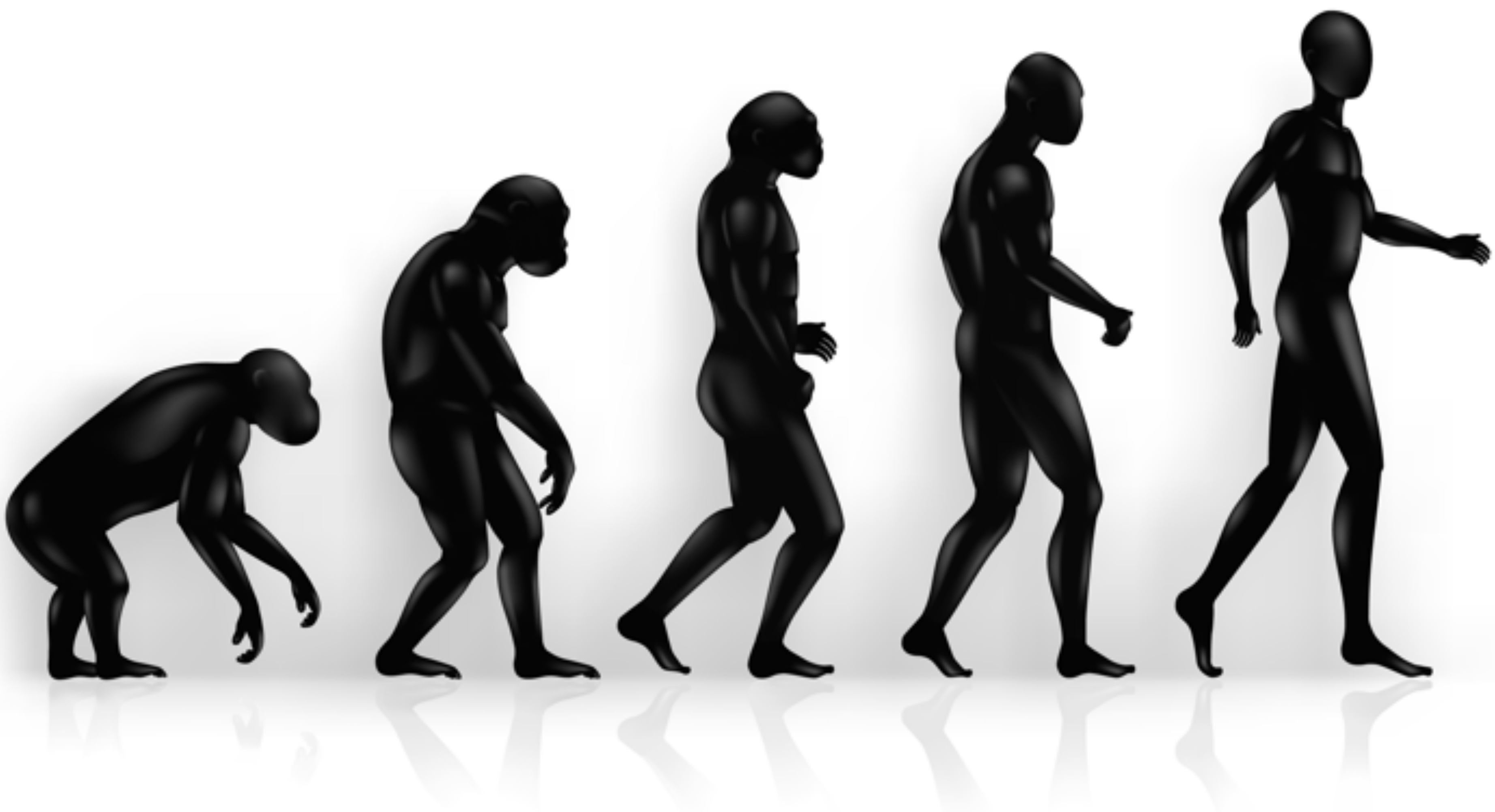
Microscopic theory

* Weak Interaction

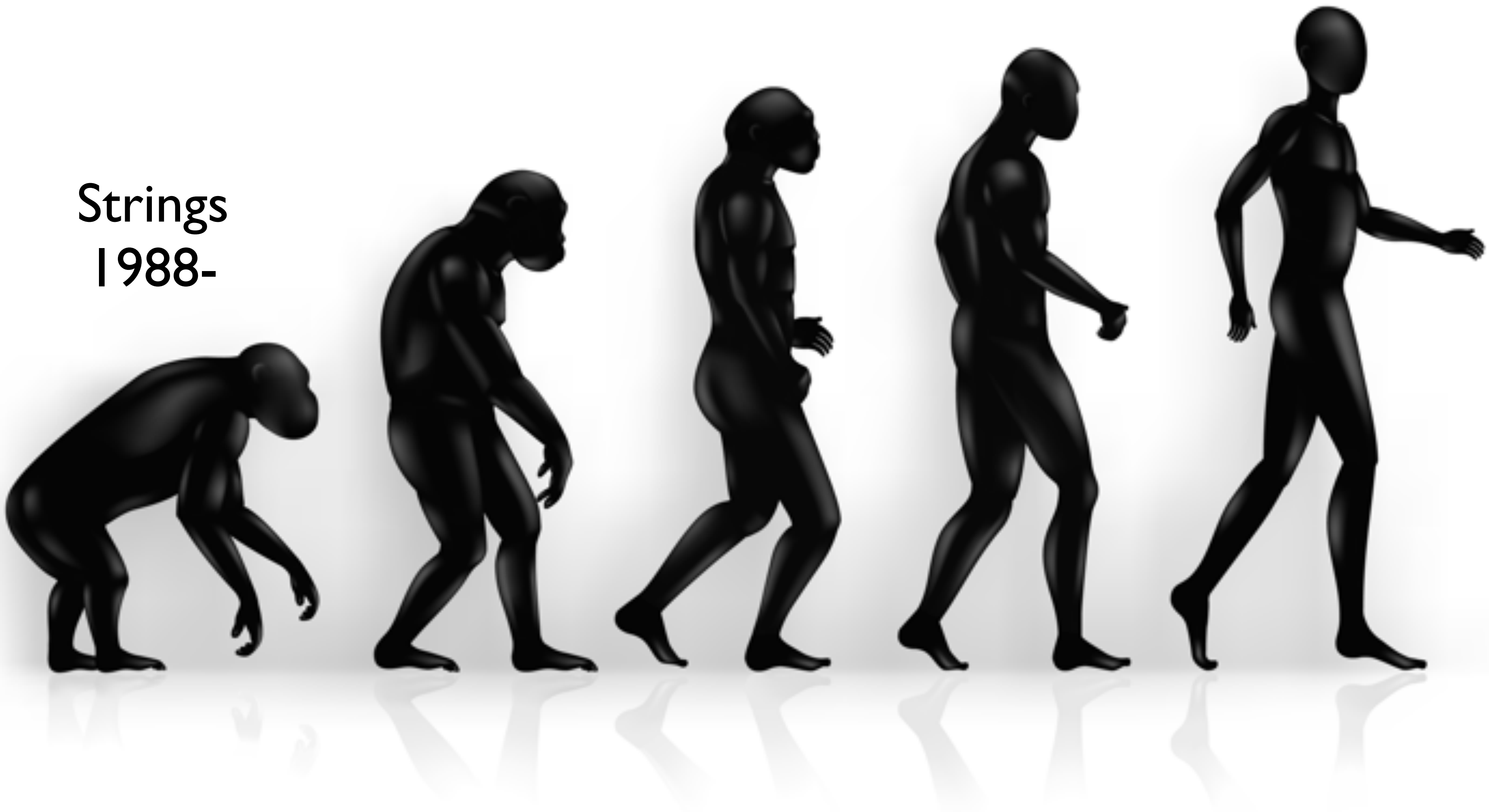
Effective theory

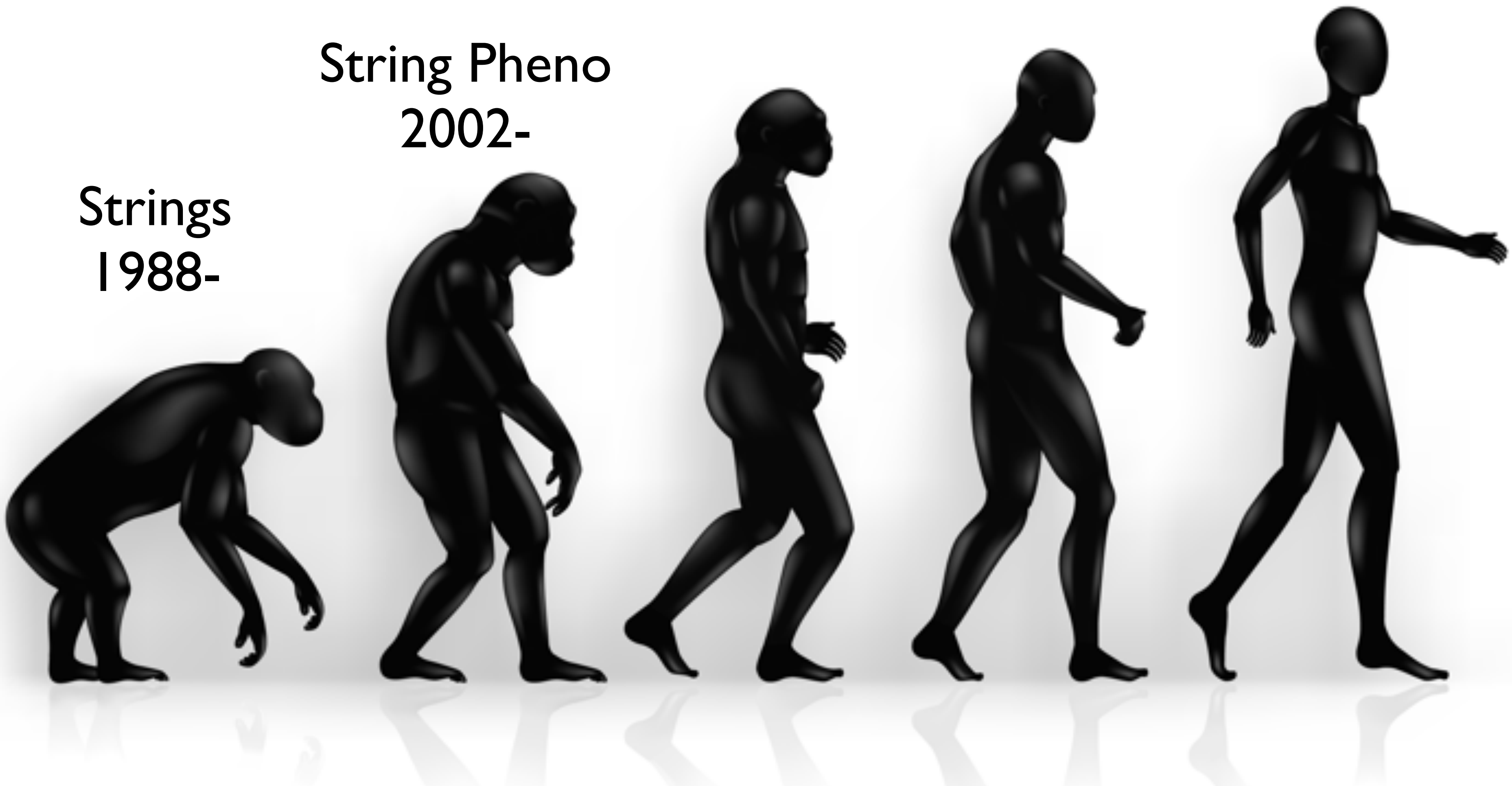
Microscopic theory

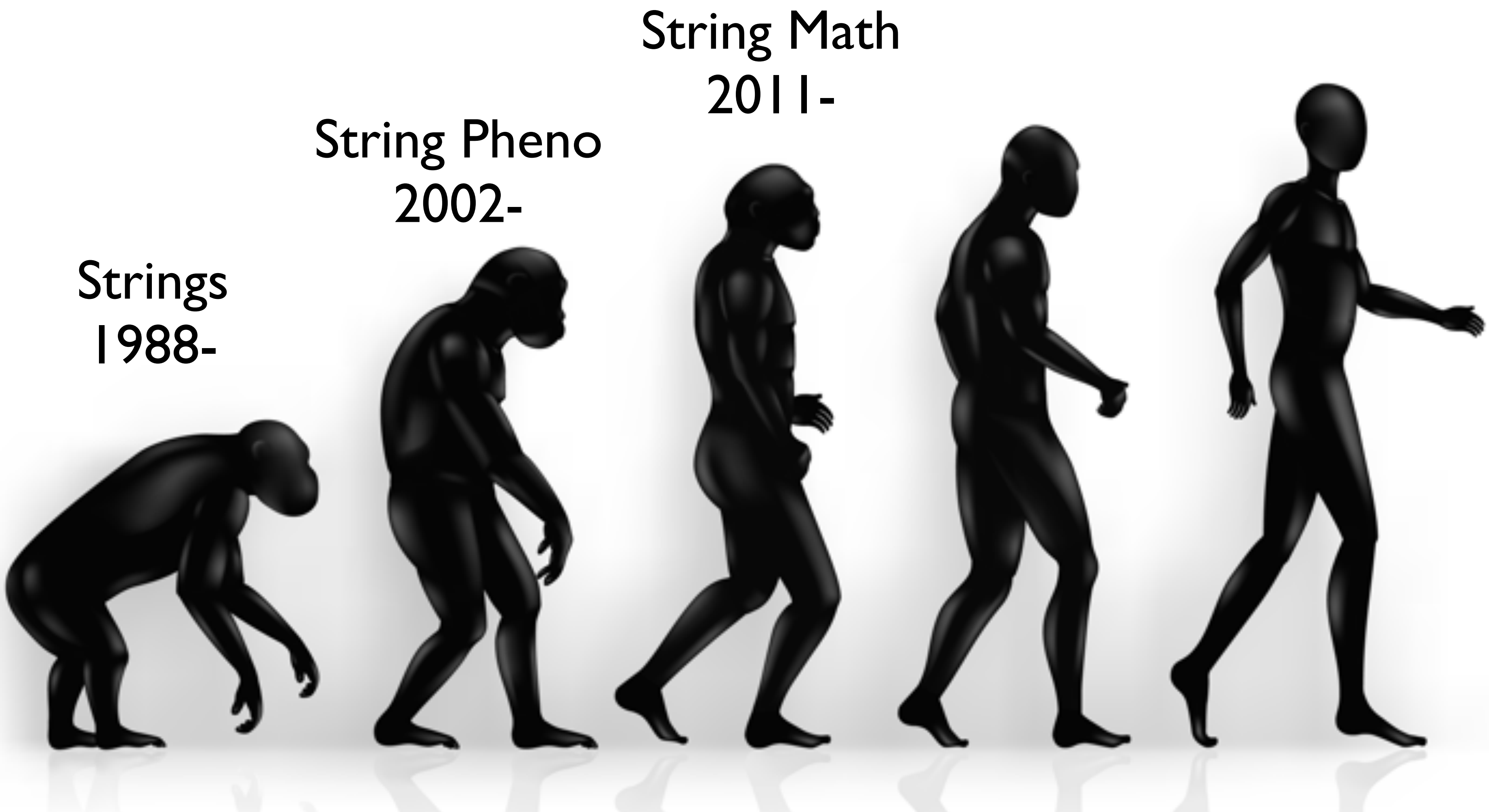

String Theory?
GRAVITY
DARK ENERGY
UNIFICATION
BIG BANG
DARK MATTER
The Smithsonian Associates
Office of Science
U.S. Department of Energy

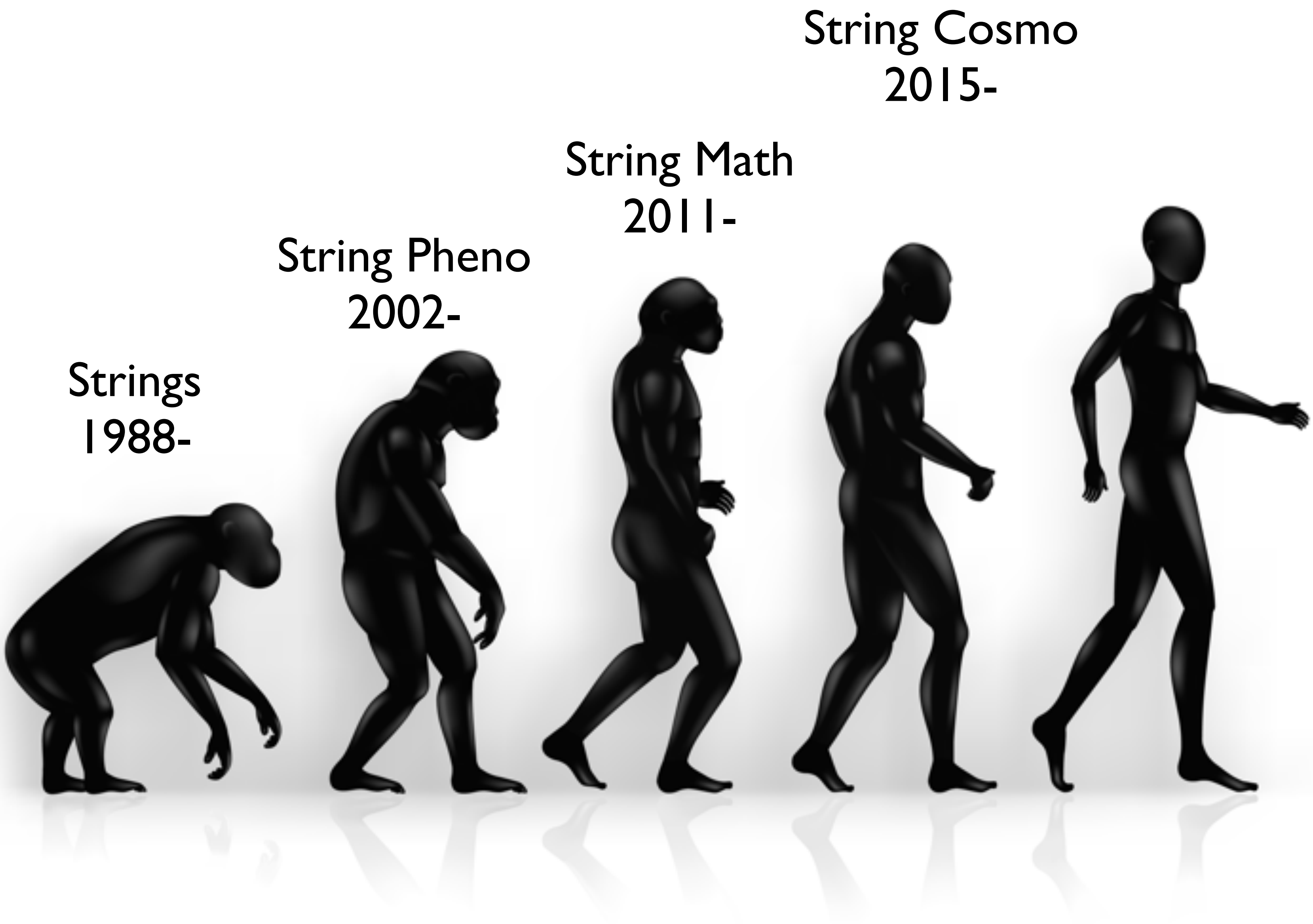


Strings
1988-




Strings
1988-
String Pheno
2002-


Strings
1988-
String Pheno
2002-
String Math
2011-


Strings
1988-
String Pheno
2002-
String Math
2011-
String Cosmo
2015-

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.

Check out the website: http://www.grc.org/programs.aspx?id=16938

Hong Kong Institute for Advanced Study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THANKS