String Theory and Cosmology in the 21st Century

Ivonne Zavala

CTN, Groningen

The String Theory Universe, Mainz, September 2014

String Cosmology Overview

Ivonne Zavala

CTN, Groningen

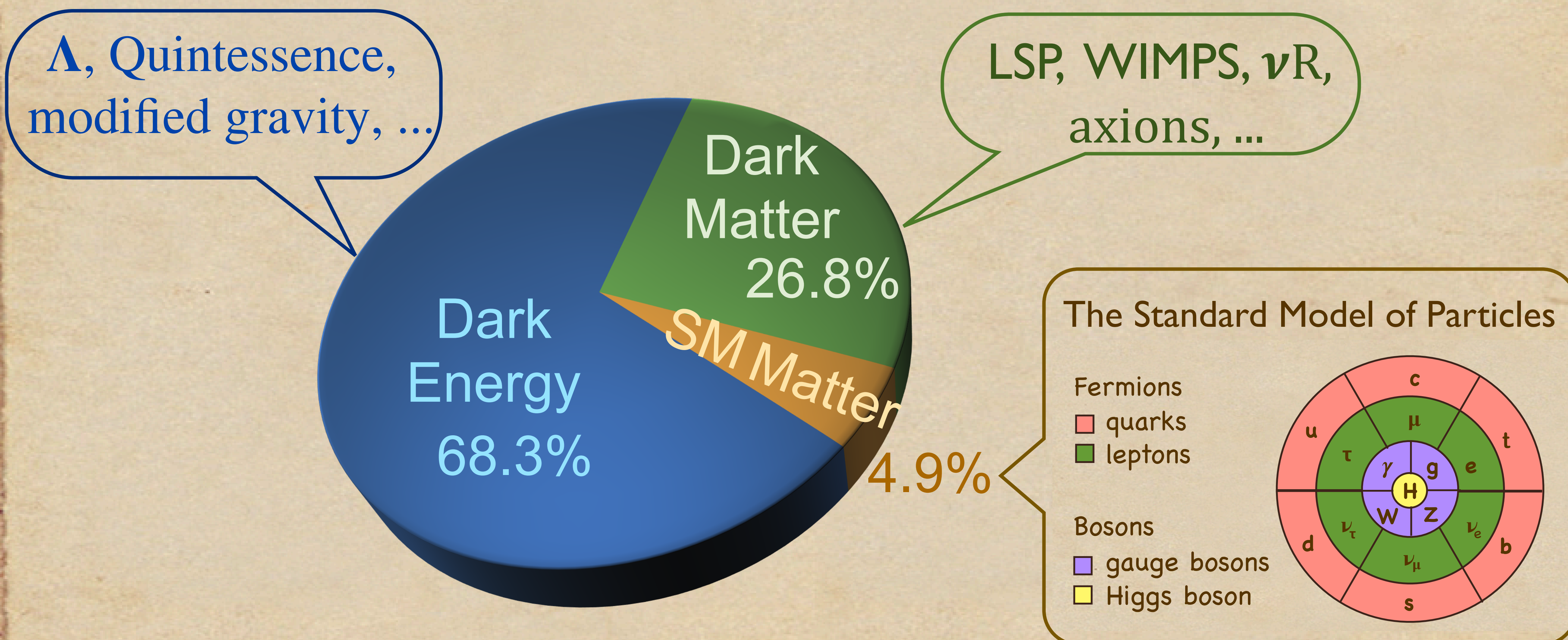
The String Theory Universe, Mainz, September 2014

A view of our Universe today

A view of our Universe today

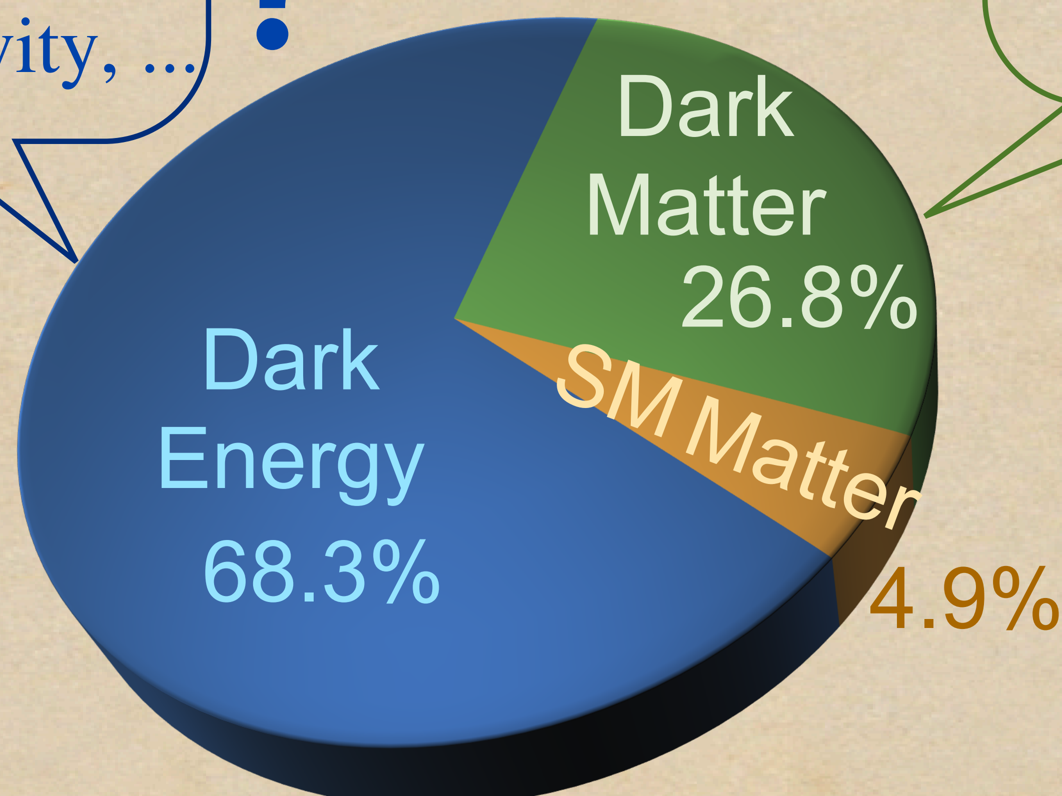
?

A view of our Universe today: ΛCDM +

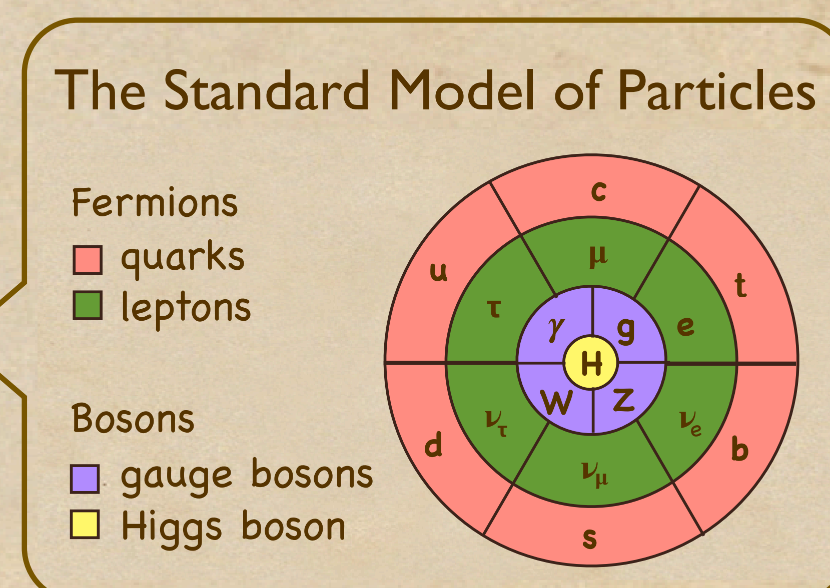


A view of our Universe today: ΛCDM +

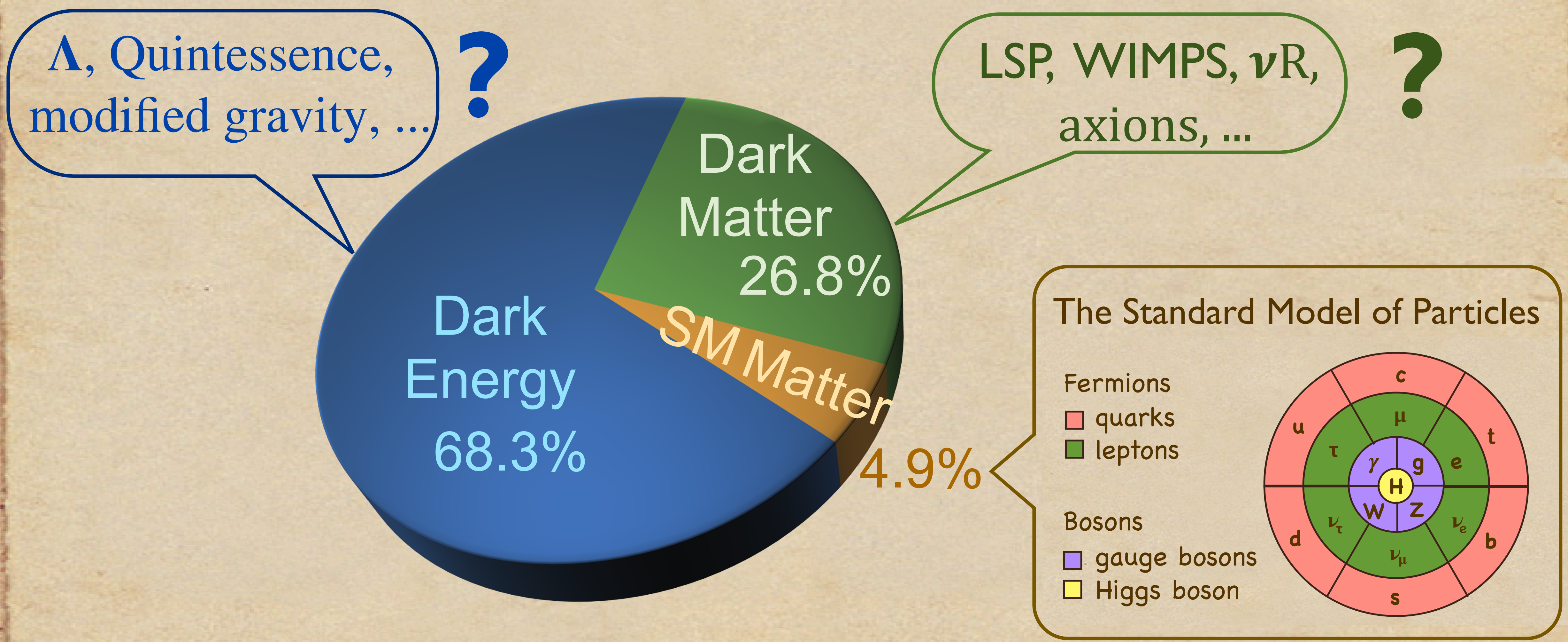
Λ, Quintessence, modified gravity, ... ?



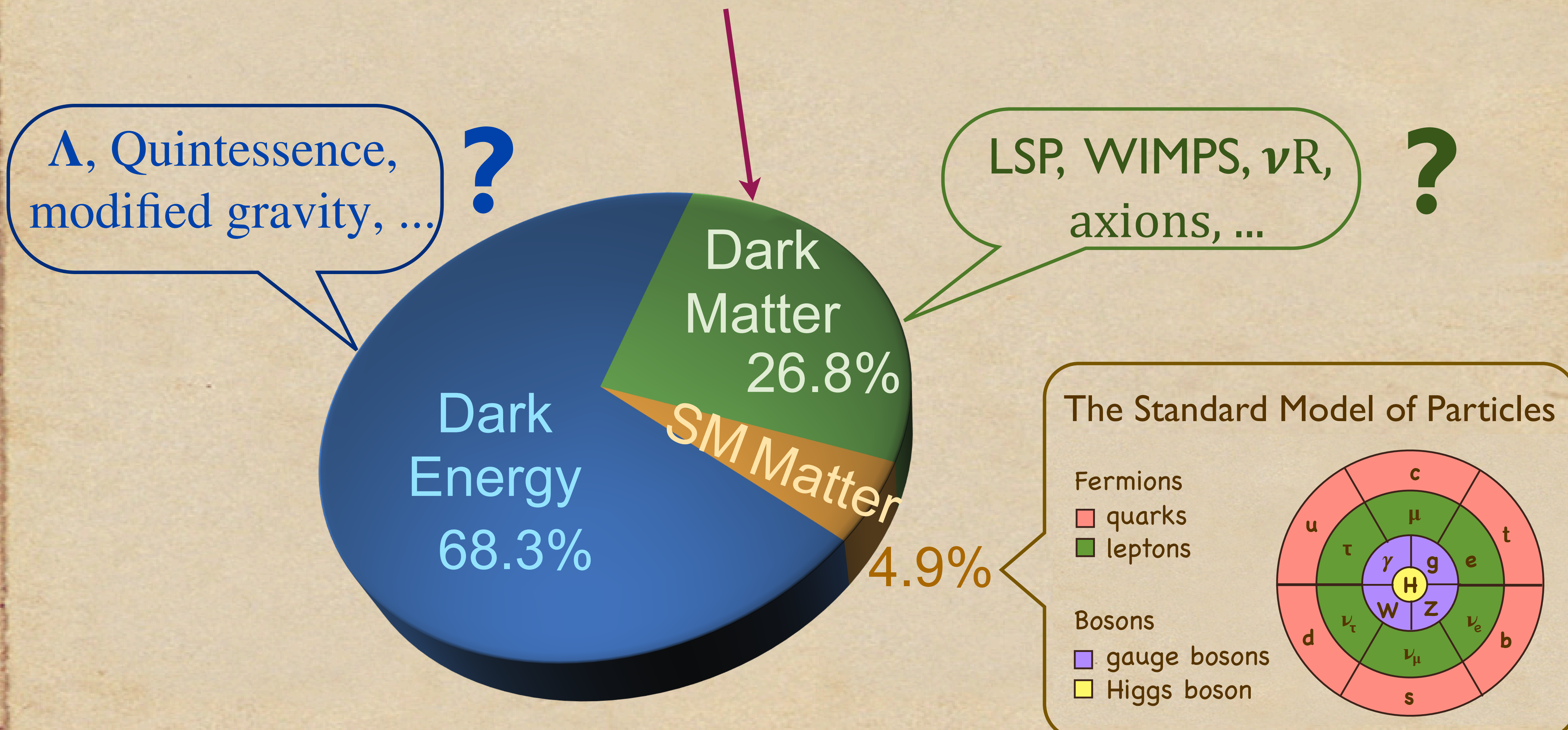
LSP, WIMPS, νR, axions, ...



A view of our Universe today: ΛCDM +

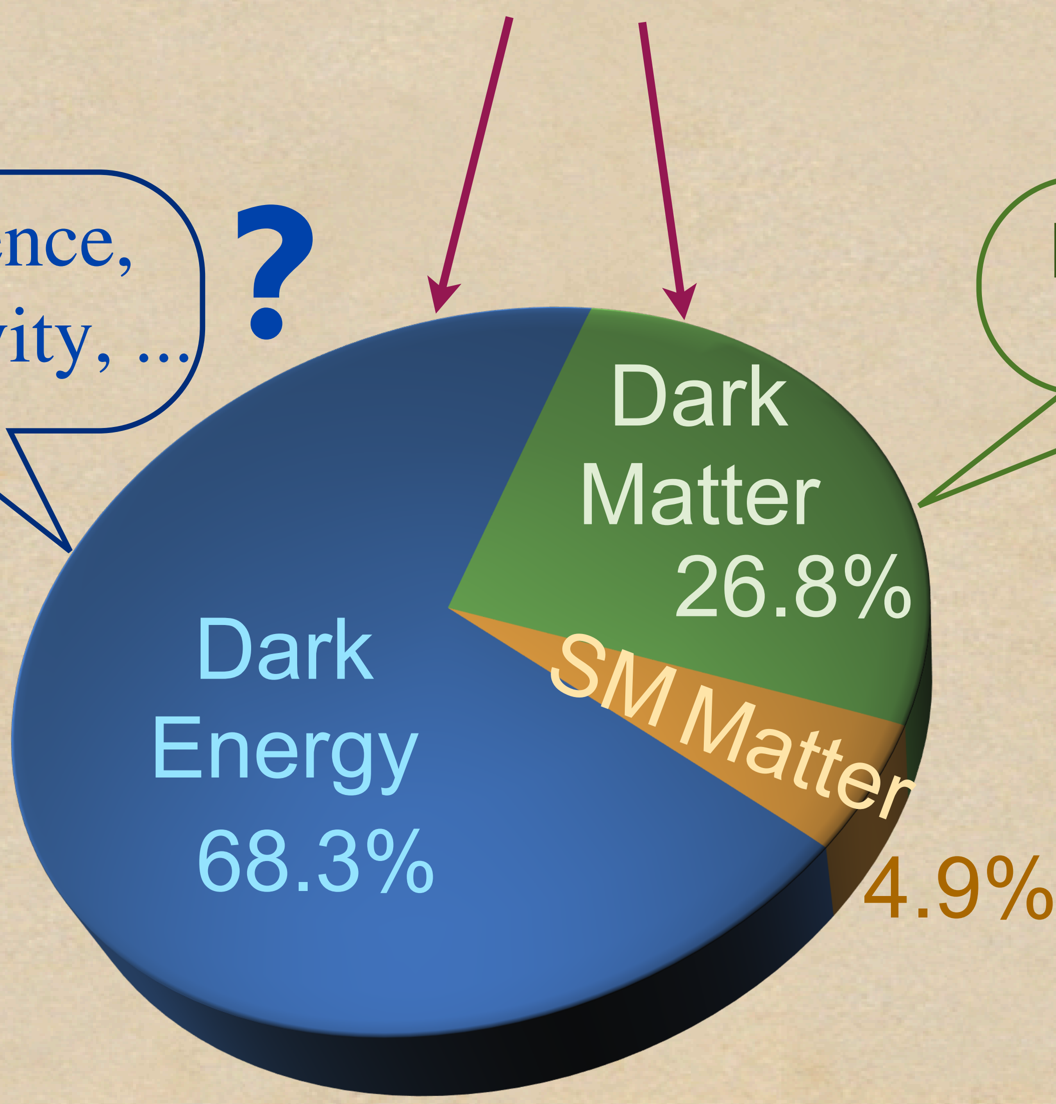


A view of our Universe today: ΛCDM +



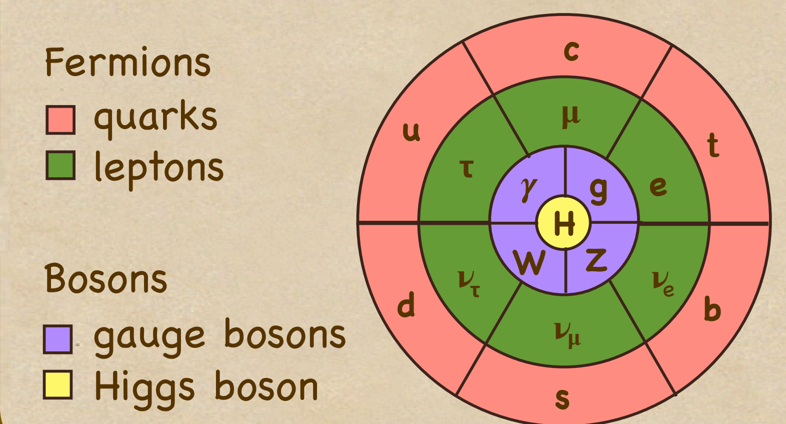
A view of our Universe today: ΛCDM +

Λ, Quintessence, modified gravity, ... ?

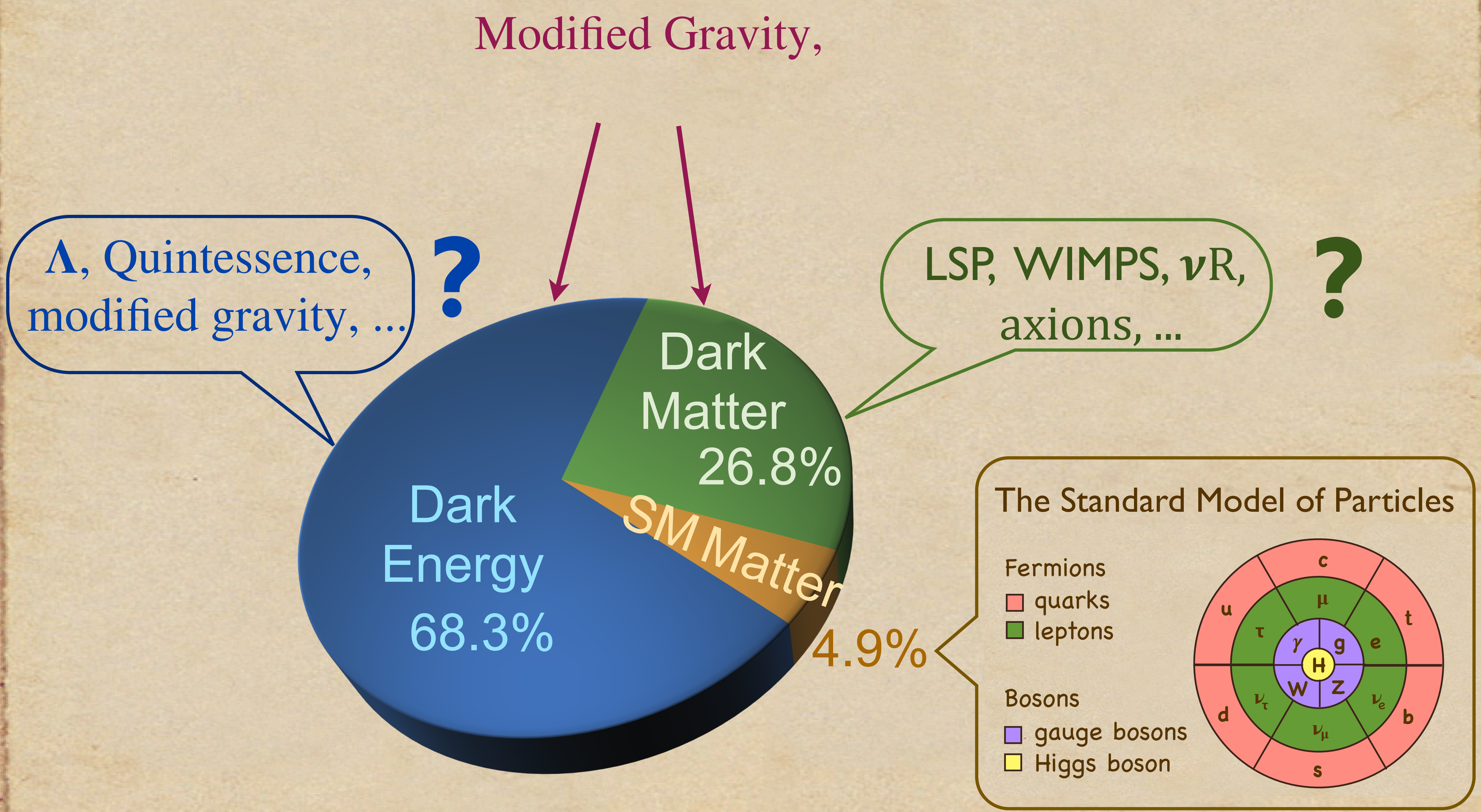


LSP, WIMPS, νR, axions, ... ?

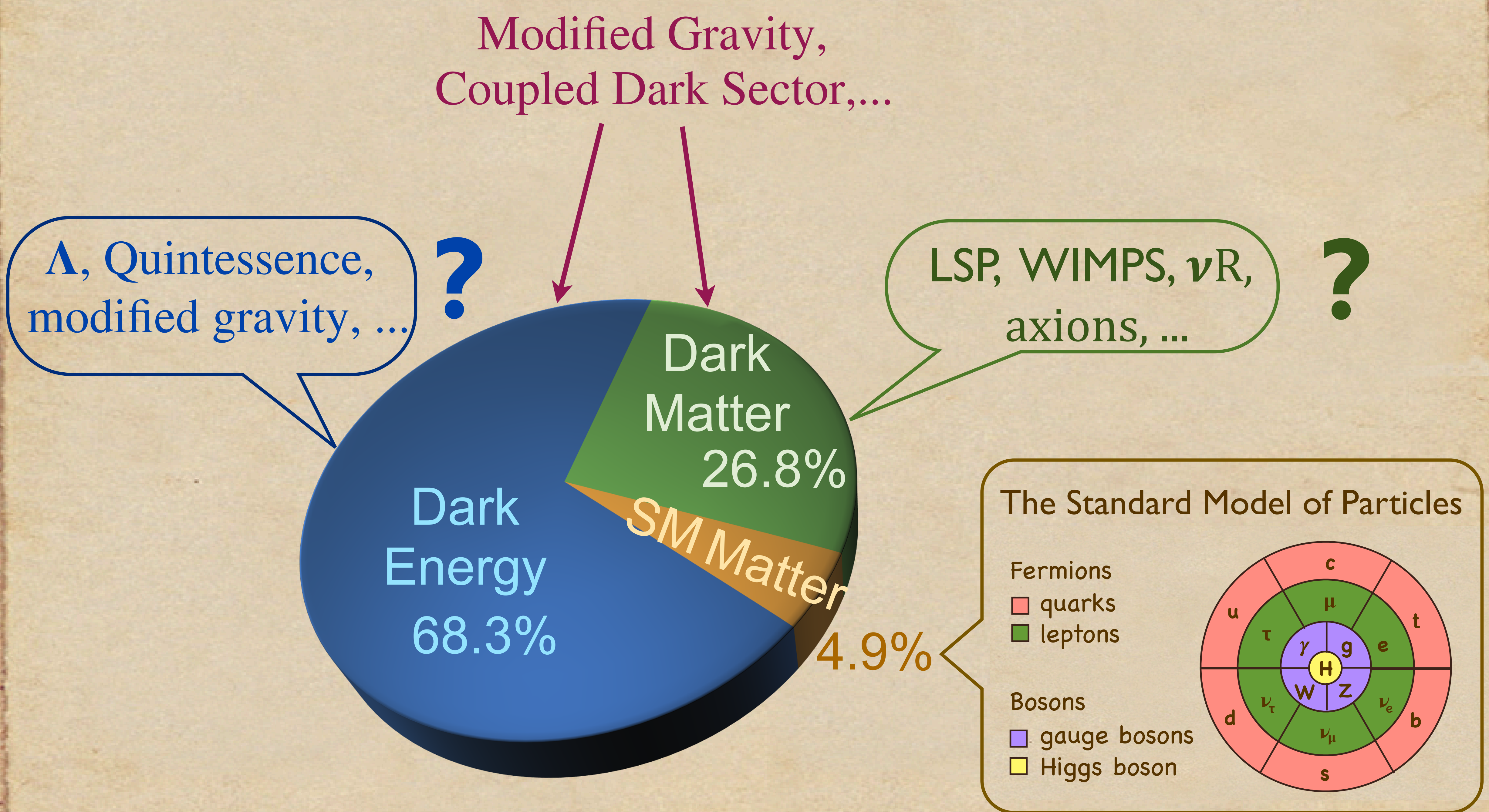
The Standard Model of Particles



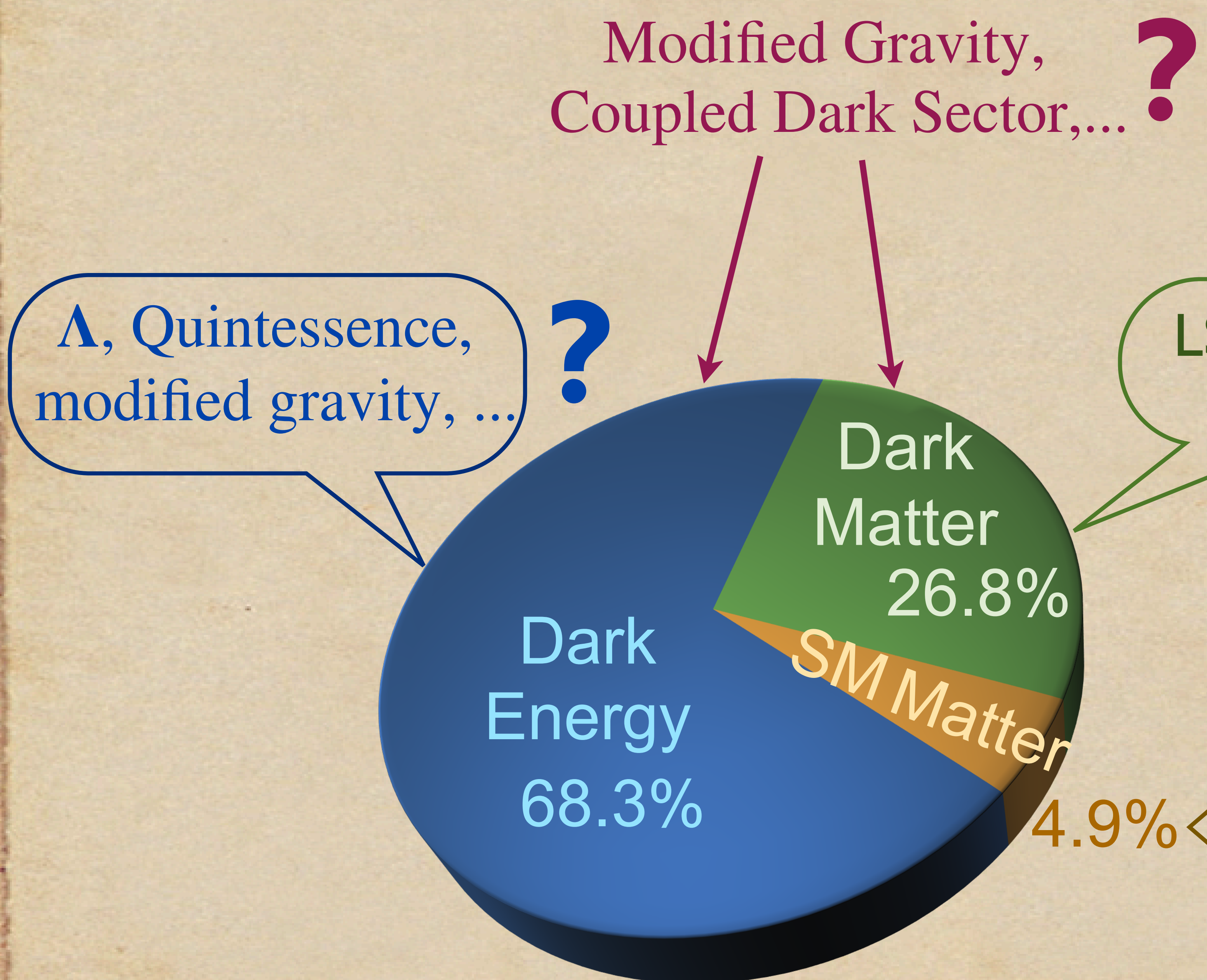
A view of our Universe today: ΛCDM +

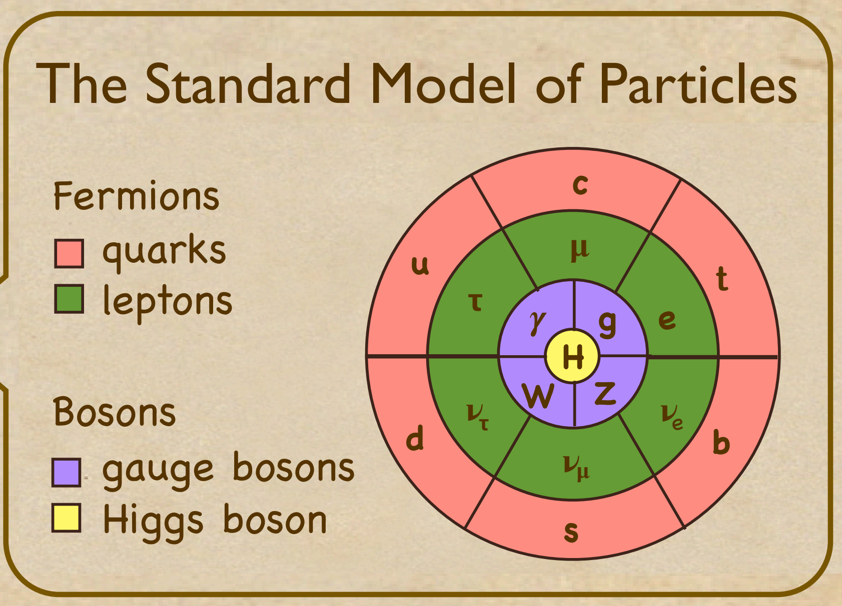


A view of our Universe today: ΛCDM +



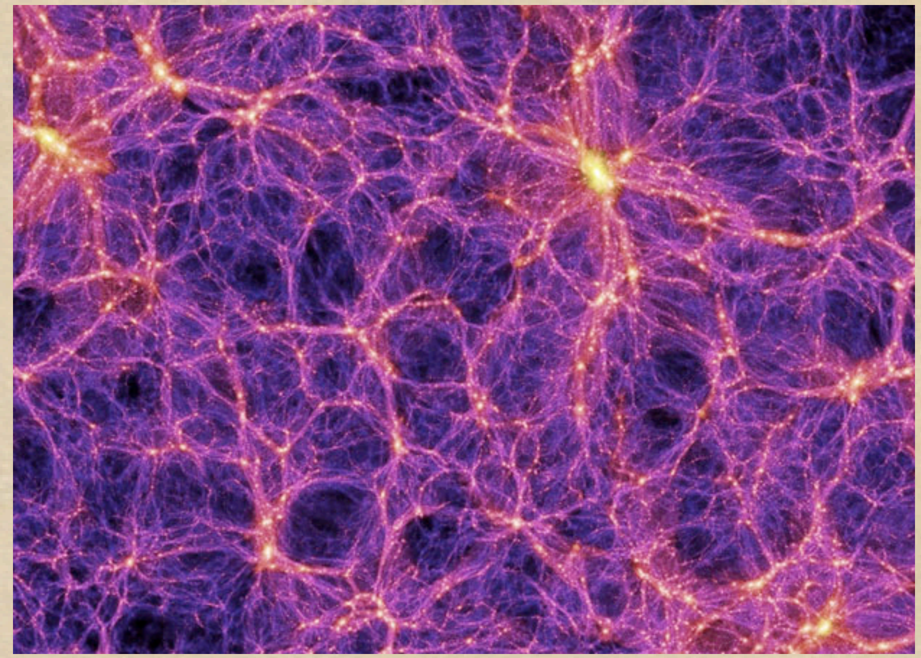
A view of our Universe today: ΛCDM +



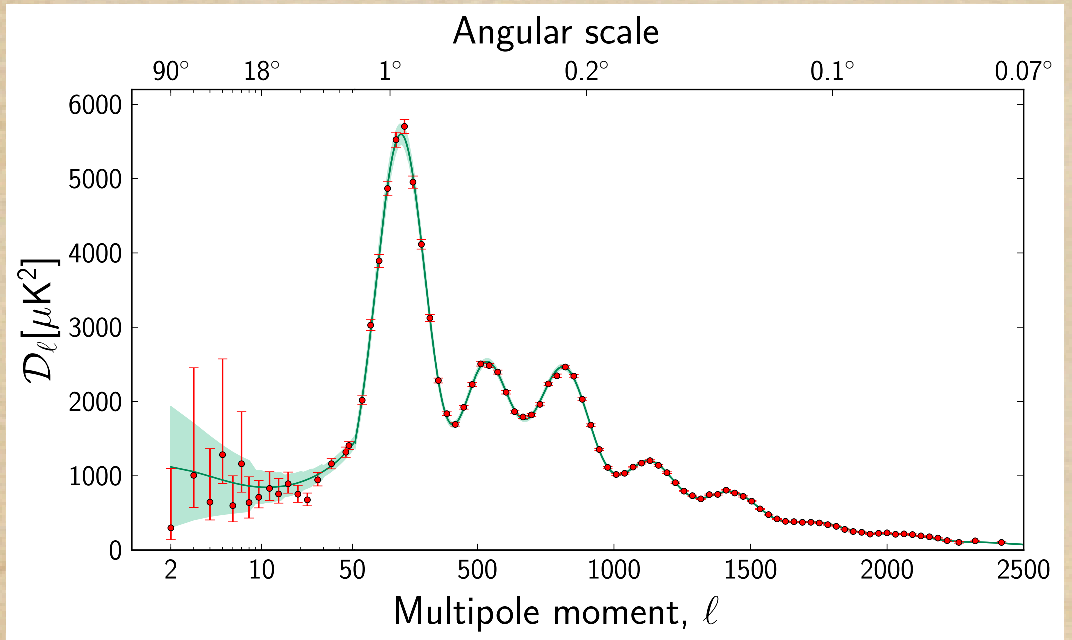


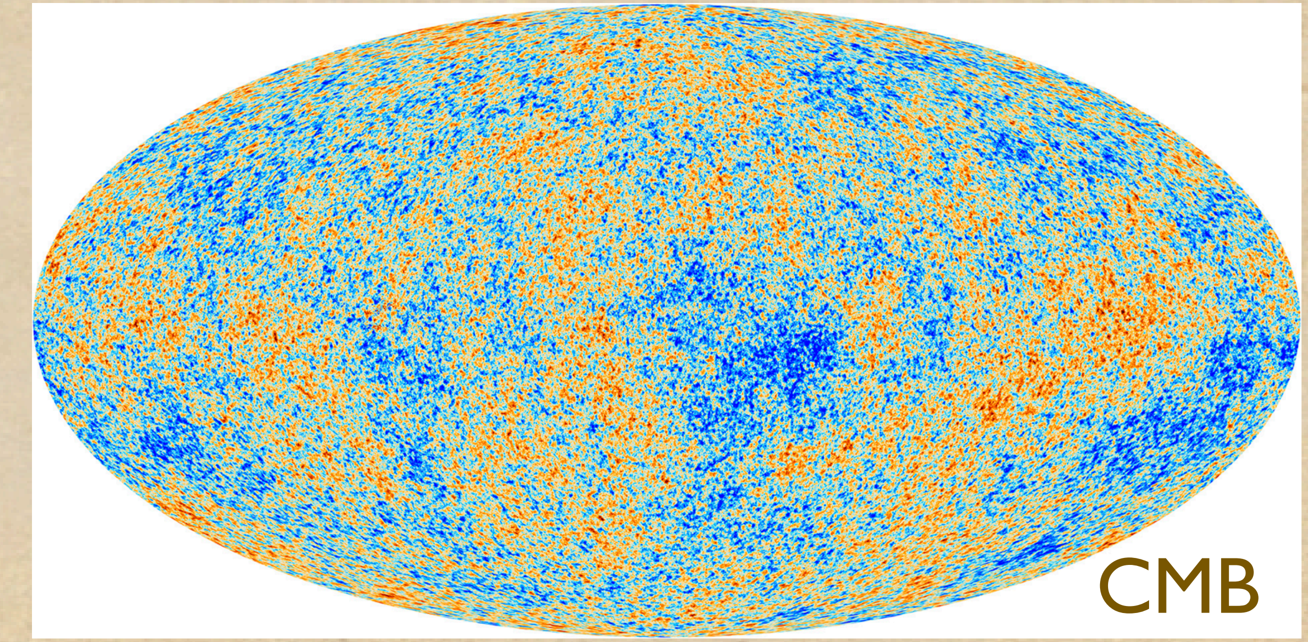
A view of our Universe “yesterday”

Cosmological Inflation



as the mechanism to produce the density fluctuations that seeded structure formation in the universe





String Cosmology 2014

- Early Universe Acceleration:
  - Inflation and observations (the Planck & BICEP2 delusion?)
  - String Inflation
- Dark String Cosmology:
  - Matter content: DM/DR/DE
  - Late Universe Acceleration: Λ, DE

[See talks by: Achúcarro, Blumenhagen, Ibáñez, Kallosh, Nilles, Shiu]

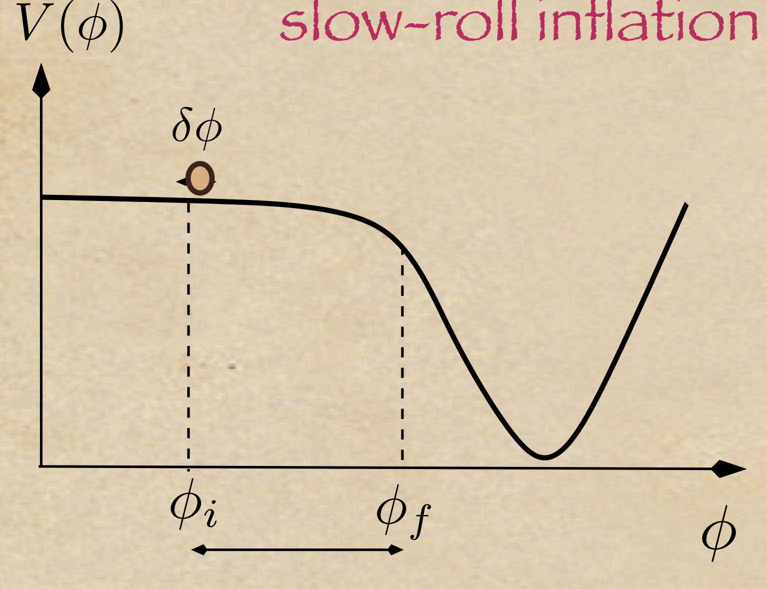
Early Universe Acceleration: Inflation

Inflation and cosmological perturbations

- Inflation in its simplest form: single scalar field with very flat potential which drives prolonged acceleration

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

slow-roll inflation



$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1, \quad \eta = M_P^2 \frac{V'}{V} \ll 1$$

$$ds^2 = -dt^2 + a(t)^2 dx_i dx^i$$

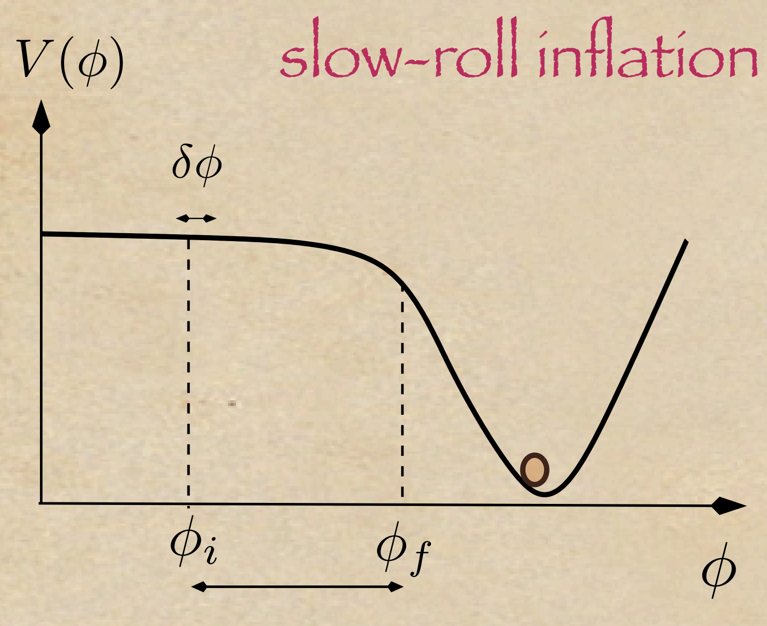
$$a(t) = a(0)e^{Ht}, \quad H \sim const.$$

- Explains why the universe is approximately homogeneous and spatially flat

Inflation and cosmological perturbations

- Inflation in its simplest form: single scalar field with very flat potential which drives prolonged acceleration

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$$



$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1, \quad \eta = M_P^2 \frac{V'}{V} \ll 1$$

$$ds^2 = -dt^2 + a(t)^2 dx_i dx^i$$

$$a(t) = a(0)e^{Ht}, \quad H \sim const.$$

- Explains why the universe is approximately homogeneous and spatially flat

Inflation and cosmological perturbations

- Generic predictions on the properties of the density perturbations: $\langle \zeta\zeta \rangle \sim \mathcal{P}_\zeta,$
  - They are approximately scale invariant $n_s \neq 1$

    $$\mathcal{P}_\zeta \sim A_s\, k^{n_s - 1 + \ldots}\,, \qquad A_s = \frac{V}{24\pi^2 M_{Pl}^4}\frac{1}{\epsilon}$$

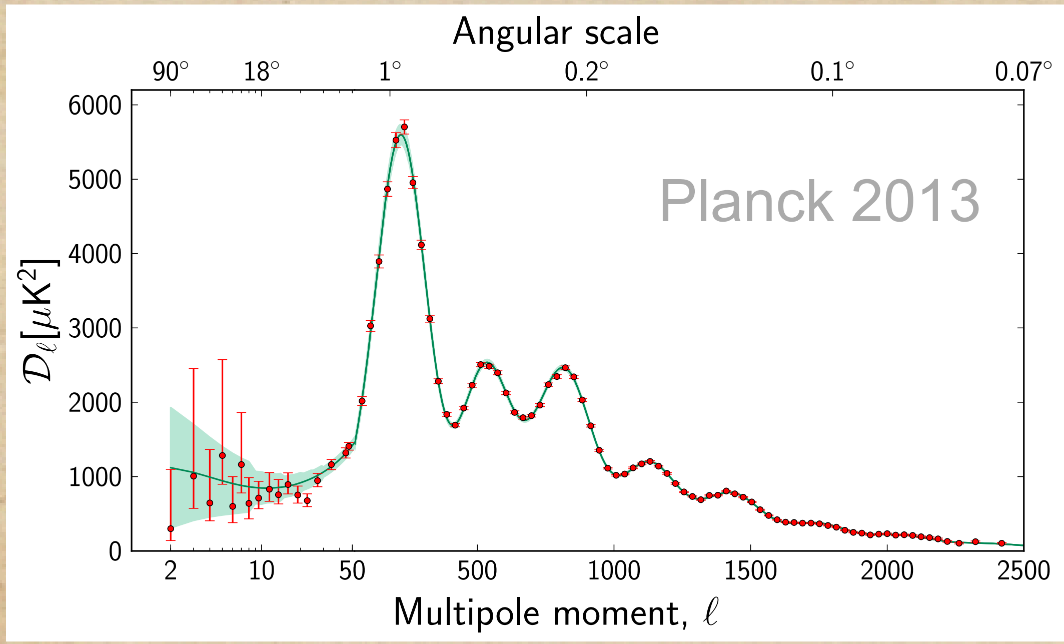
  - They are approximately Gaussian $f_{nl} \sim 0$
  - Statistically isotropic and homogeneous to high degree $g \sim 0$

    $$\mathcal{P}_\zeta(k) = \mathcal{P}_0(k)\big[1 + g\,(d\cdot k)^2 + \cdots\big]$$

    [Ackerman, Carroll, Wise,'07]

- Primordial gravitational waves $r = \dfrac{\mathcal{P}_t}{\mathcal{P}_\zeta} \simeq 16\epsilon$

Planck results confirm



- nearly scale invariant spectrum

$$n_s = 0.9603 \pm 0.0073$$

- nearly gaussian

$$f_{NL} = 2.7 \pm 5.8 \quad \textit{local}$$
$$f_{NL} = -42 \pm 75 \quad \textit{equilateral}$$
$$f_{NL} = -25 \pm 39 \quad \textit{orthogonal}$$

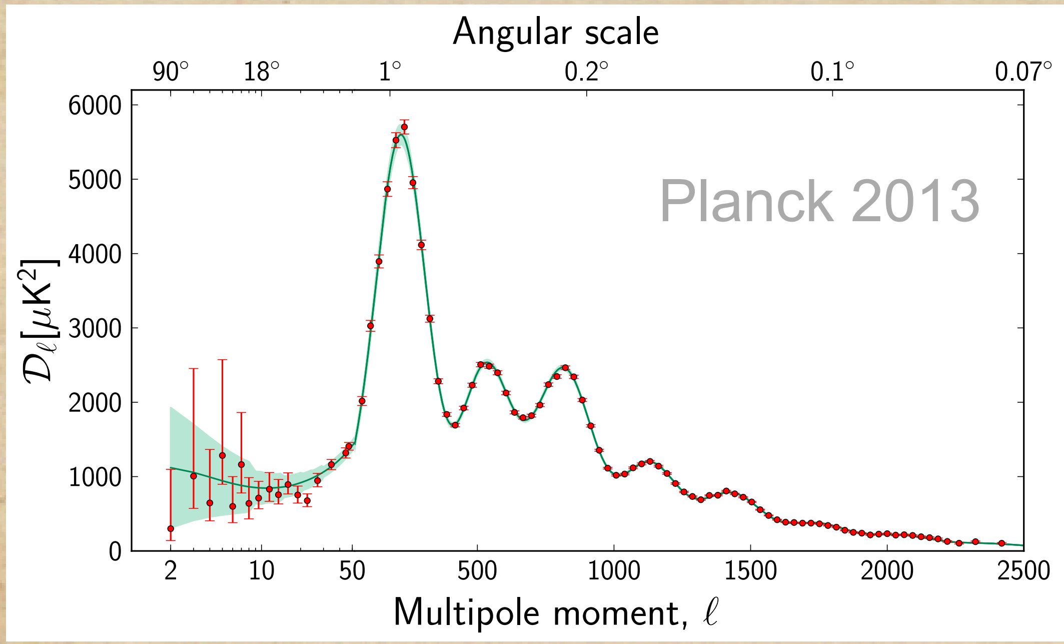
- nearly isotropic [Kim-Komatsu '13]

$$g = 0.002 \pm 0.016 \ (68\% CL)$$

- upper bound on r $r < 0.11$

$$V = \frac{3\pi^2 A_s M_{Pl}^4}{2} \, r$$

Planck results confirm



- nearly scale invariant spectrum

$$n_s = 0.9603 \pm 0.0073$$

- nearly gaussian

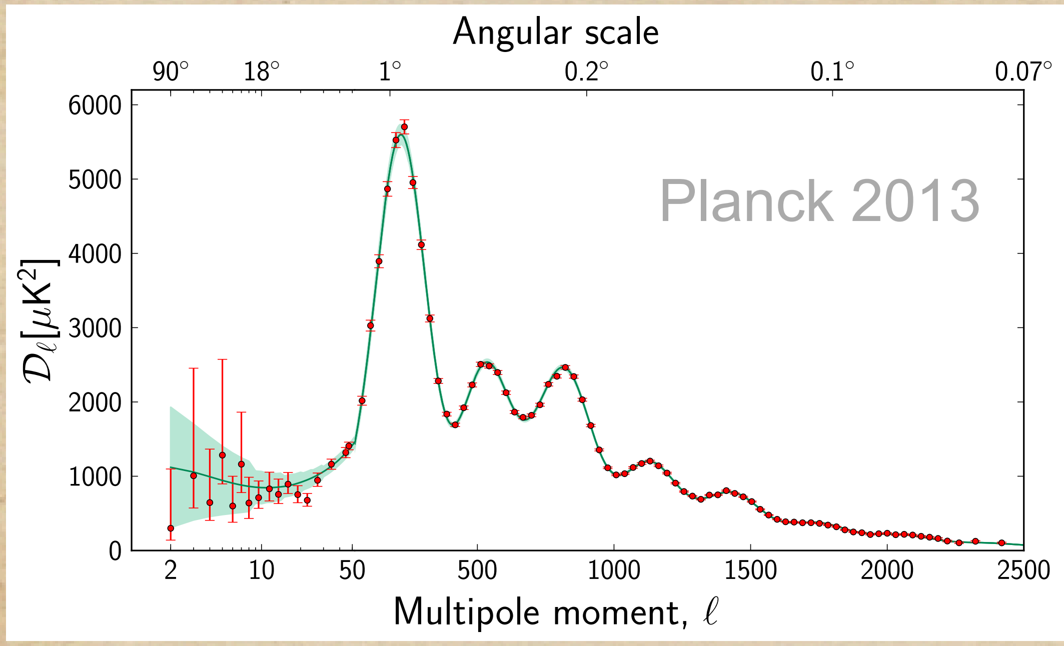
$$f_{NL} = 2.7 \pm 5.8 \quad \textit{local}$$
$$f_{NL} = -42 \pm 75 \quad \textit{equilateral}$$
$$f_{NL} = -25 \pm 39 \quad \textit{orthogonal}$$

- nearly isotropic [Kim-Komatsu '13]

$$g = 0.002 \pm 0.016 \ (68\% CL)$$

- upper bound on r $r < 0.11$

Planck results confirm



- nearly scale invariant spectrum

$$n_s = 0.9603 \pm 0.0073$$

- nearly gaussian

$$f_{NL} = 2.7 \pm 5.8 \quad \textit{local}$$
$$f_{NL} = -42 \pm 75 \quad \textit{equilateral}$$
$$f_{NL} = -25 \pm 39 \quad \textit{orthogonal}$$

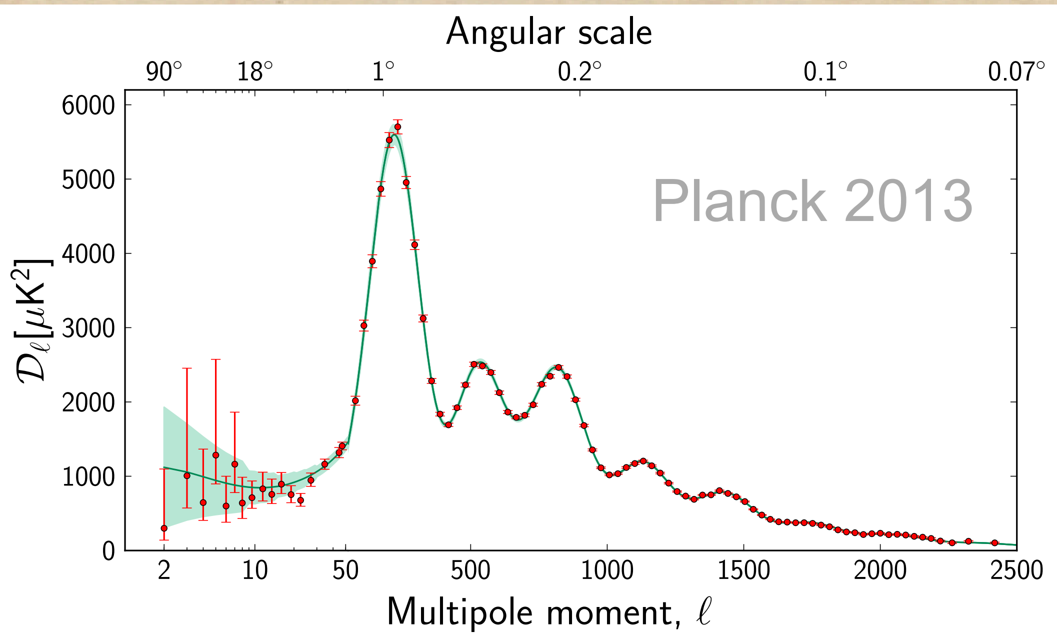
- nearly isotropic [Kim-Komatsu '13]

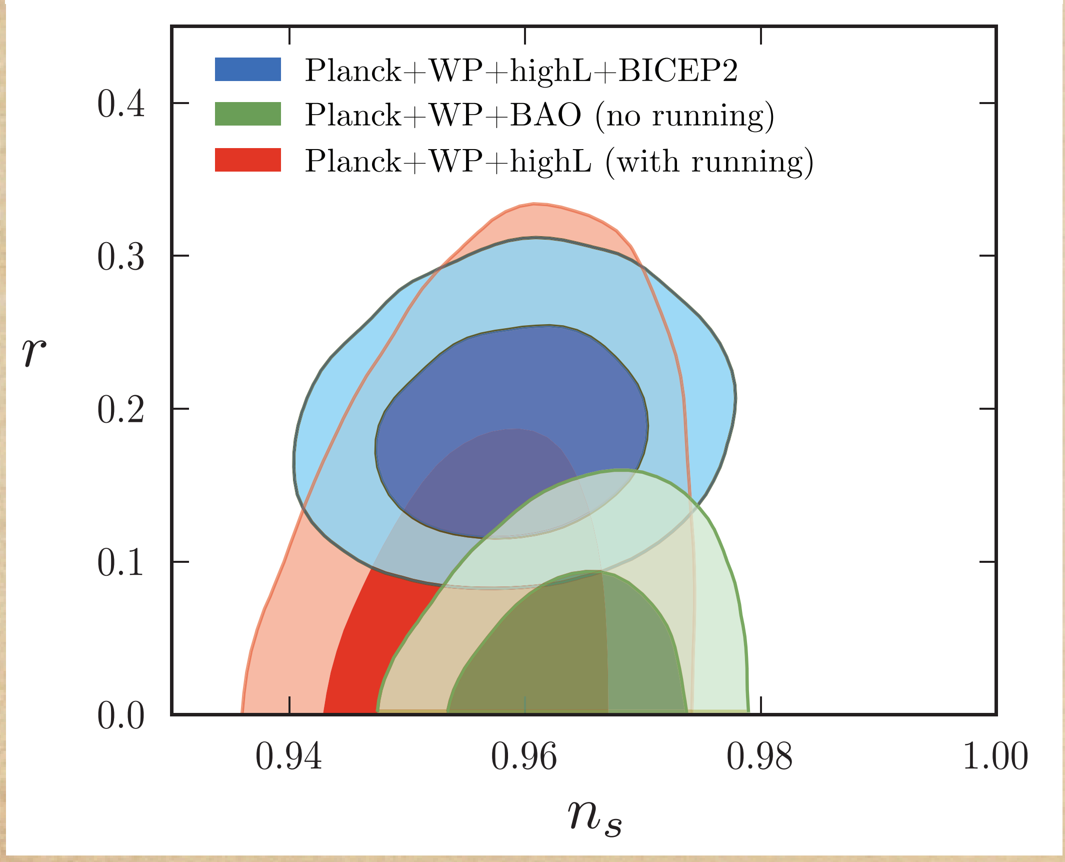
$$g = 0.002 \pm 0.016 \ (68\% CL)$$

- upper bound on r $r < 0.11$

$$V^{1/4} = 1.94 \times 10^{16} \mathrm{GeV} \left(\frac{r}{0.12}\right)^{1/4}$$

Planck results confirm





- nearly scale invariant spectrum

$$n_s = 0.9603 \pm 0.0073$$

- nearly gaussian

$$f_{NL} = 2.7 \pm 5.8 \quad \textit{local}$$
$$f_{NL} = -42 \pm 75 \quad \textit{equilateral}$$
$$f_{NL} = -25 \pm 39 \quad \textit{orthogonal}$$

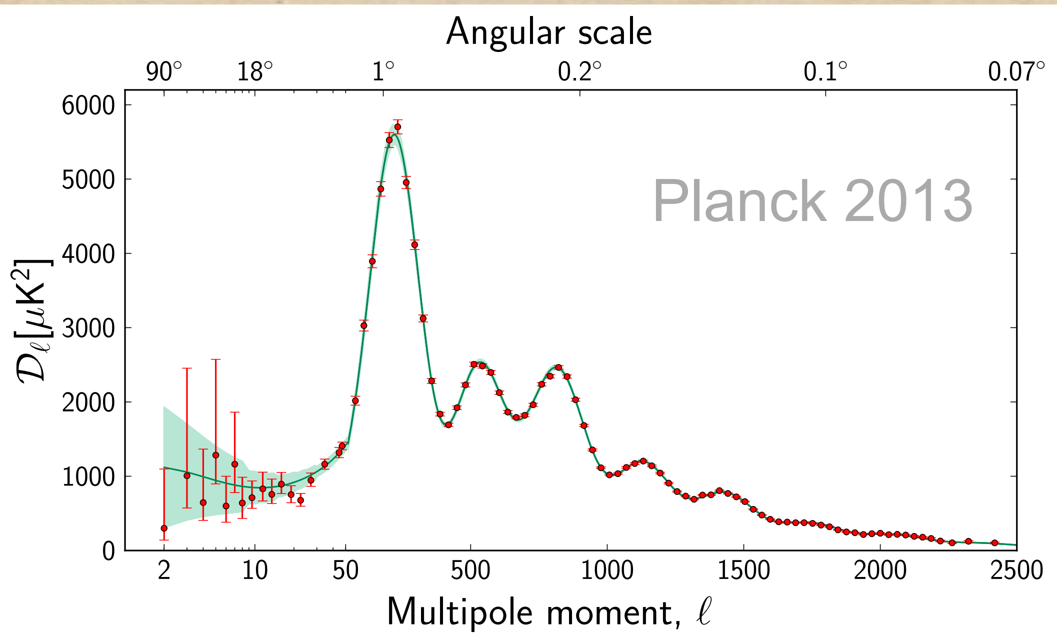
- nearly isotropic [Kim-Komatsu '13]

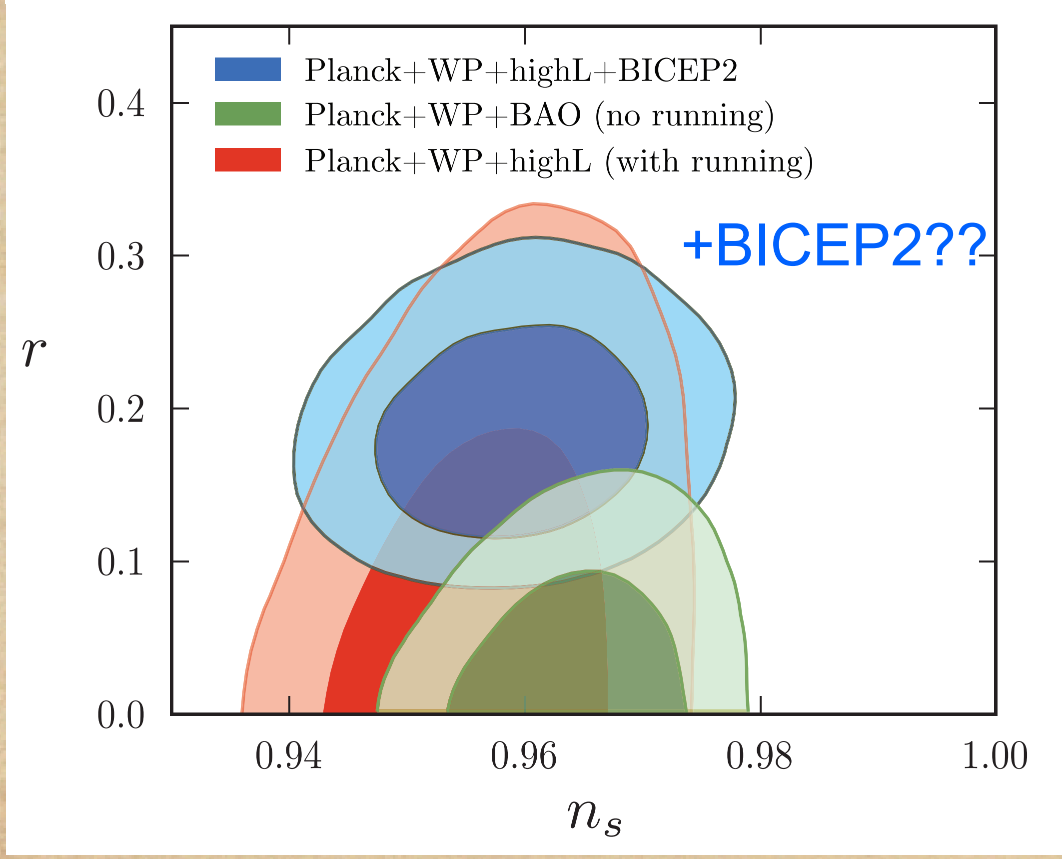
$$g = 0.002 \pm 0.016 \ (68\% CL)$$

- upper bound on r $r < 0.11$

$$V^{1/4} = 1.94 \times 10^{16} \text{GeV} \left(\frac{r}{0.12} \right)^{1/4}$$

Planck results confirm





- nearly scale invariant spectrum

$$n_s = 0.9603 \pm 0.0073$$

- nearly gaussian

$$f_{NL} = 2.7 \pm 5.8 \quad \textit{local}$$
$$f_{NL} = -42 \pm 75 \quad \textit{equilateral}$$
$$f_{NL} = -25 \pm 39 \quad \textit{orthogonal}$$

- nearly isotropic [Kim-Komatsu '13]

$$g = 0.002 \pm 0.016 \ (68\% CL)$$

- upper bound on r $r < 0.11$

$$V^{1/4} = 1.94 \times 10^{16} \mathrm{GeV} \left(\frac{r}{0.12}\right)^{1/4}$$

Windows on the mechanism of inflation

- non-Gaussianity probes interactions: more fields, non standard k.t. inflation $\langle\zeta\zeta\zeta\rangle$

[Achúcarro's talk]

- breaking of isotropy: vector fields present during inflation?

- primordial gravitational waves: reveals the energy scale of inflation, inflaton mass and inflaton's field range

$$V^{1/4} = 1.94 \times 10^{16}\mathrm{GeV} \left(\frac{r}{0.12}\right)^{1/4}$$

[Blumenhagen,Ibáñez, Nilles, Shiu talks]

The (Boubekeur-)Lyth bound

[Lyth, '96]

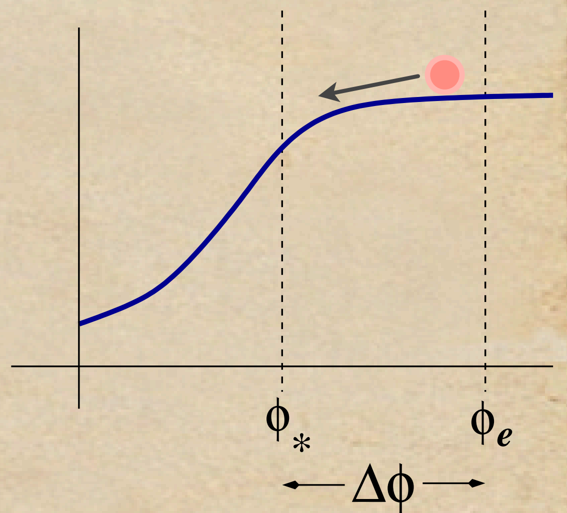
$$r = \frac{8}{M_{Pl}^2}\left(\frac{\dot\phi}{H}\right)^2 = \frac{8}{M_{Pl}^2}\left(\frac{d\phi}{dN}\right)^2 \qquad (dN \equiv H dt = d\ln a)$$

Total field range

$$N_* \approx 60$$

$$\frac{\Delta\phi}{M_{Pl}} = \int_{N_e}^{N_*} dN \sqrt{\frac{r(N)}{8}}\,, \qquad \frac{\Delta\phi}{M_{Pl}} \approx \left(\frac{r}{0.002}\right)^{1/2}\left(\frac{N_*}{60}\right)$$

[Boubekeur-Lyth, '05]



The (Boubekeur-)Lyth bound

[Lyth, '96]

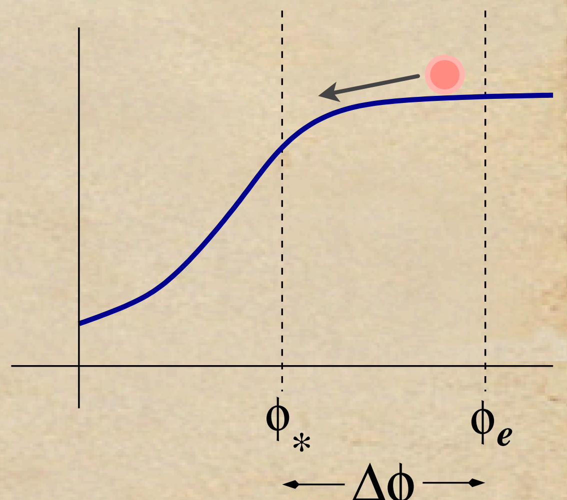
$$r = \frac{8}{M_{Pl}^2}\left(\frac{\dot\phi}{H}\right)^2 = \frac{8}{M_{Pl}^2}\left(\frac{d\phi}{dN}\right)^2 \qquad (dN \equiv H\,dt = d\ln a)$$

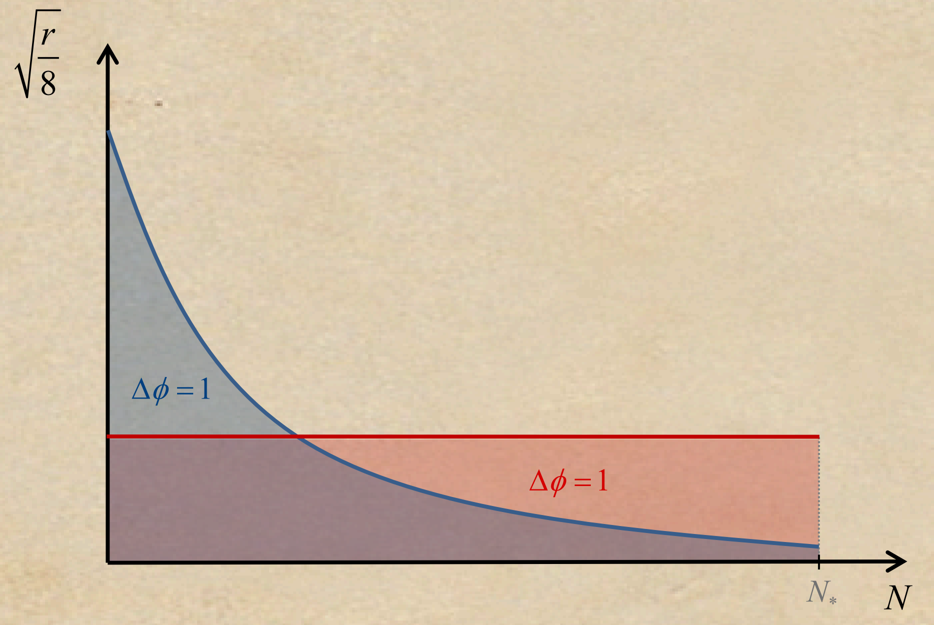
Total field range

$$\frac{\Delta\phi}{M_{Pl}} = \int_{N_e}^{N_*} dN\,\sqrt{\frac{r(N)}{8}}\,, \qquad \frac{\Delta\phi}{M_{Pl}} \approx \left(\frac{r}{0.002}\right)^{1/2}\left(\frac{N_*}{60}\right)$$

[Boubekeur-Lyth, '05]

$N_* \approx 60$





[Garcia-Bellido, Roest, Scalisi, IZ '14]

The (Boubekeur-)Lyth bound

[Lyth, '96]

$$r = \frac{8}{M_{Pl}^2}\left(\frac{\dot\phi}{H}\right)^2 = \frac{8}{M_{Pl}^2}\left(\frac{d\phi}{dN}\right)^2$$

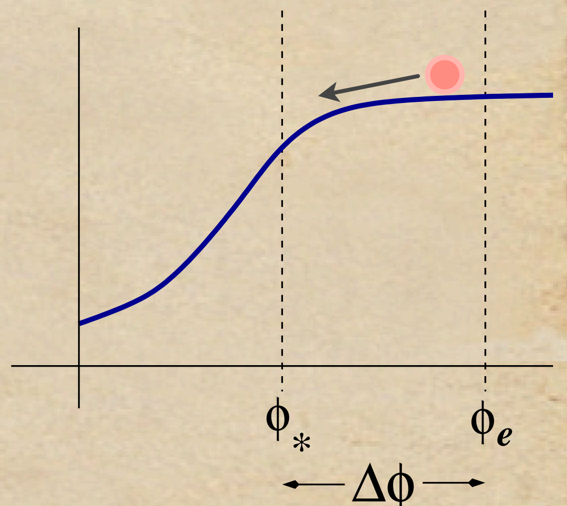
$$(dN \equiv H dt = d\ln a)$$

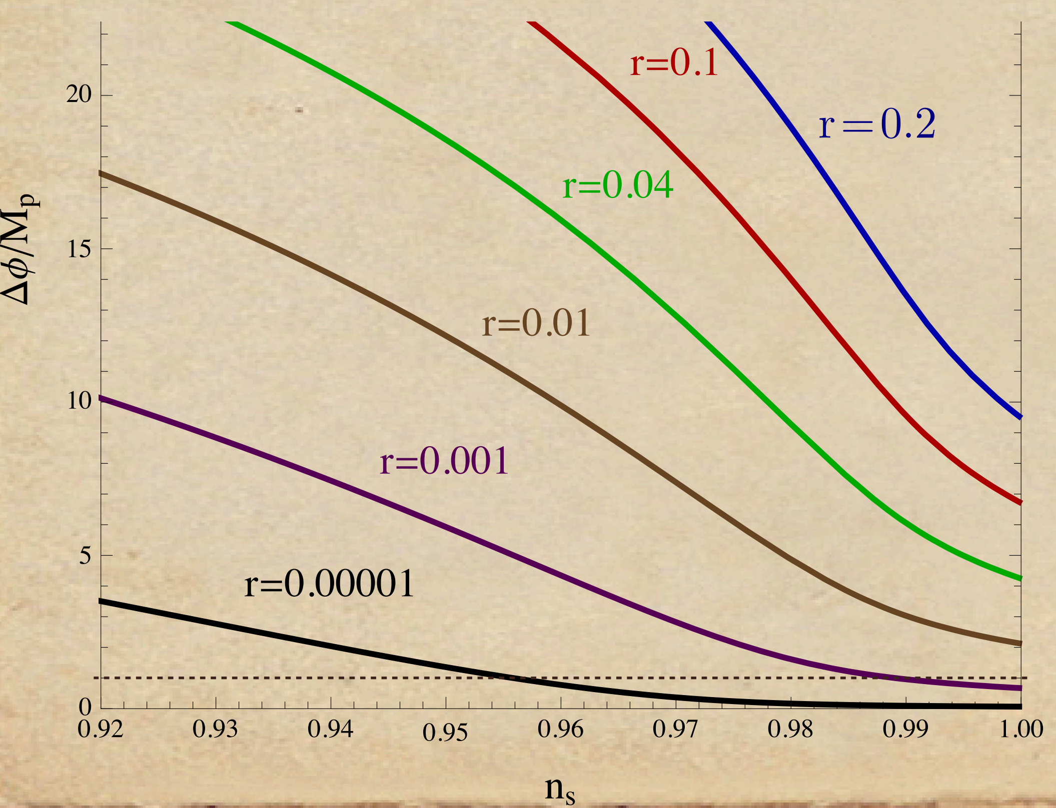
Total field range

$$\frac{\Delta\phi}{M_{Pl}} = \int_{N_e}^{N_*} dN \sqrt{\frac{r(N)}{8}}\,, \qquad \frac{\Delta\phi}{M_{Pl}} \approx \left(\frac{r}{0.002}\right)^{1/2}\left(\frac{N_*}{60}\right)$$

[Boubekeur-Lyth, '05]

$N_* \approx 60$





The (Boubekeur-)Lyth bound

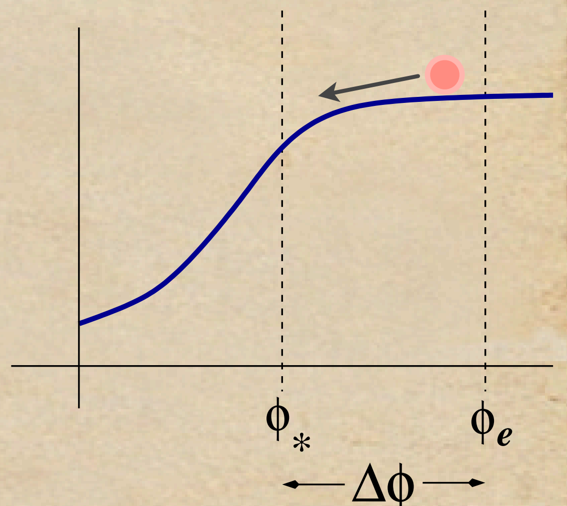
[Lyth, '96]

$$r = \frac{8}{M_{Pl}^2}\left(\frac{\dot{\phi}}{H}\right)^2 = \frac{8}{M_{Pl}^2}\left(\frac{d\phi}{dN}\right)^2 \qquad (dN \equiv H dt = d\ln a)$$

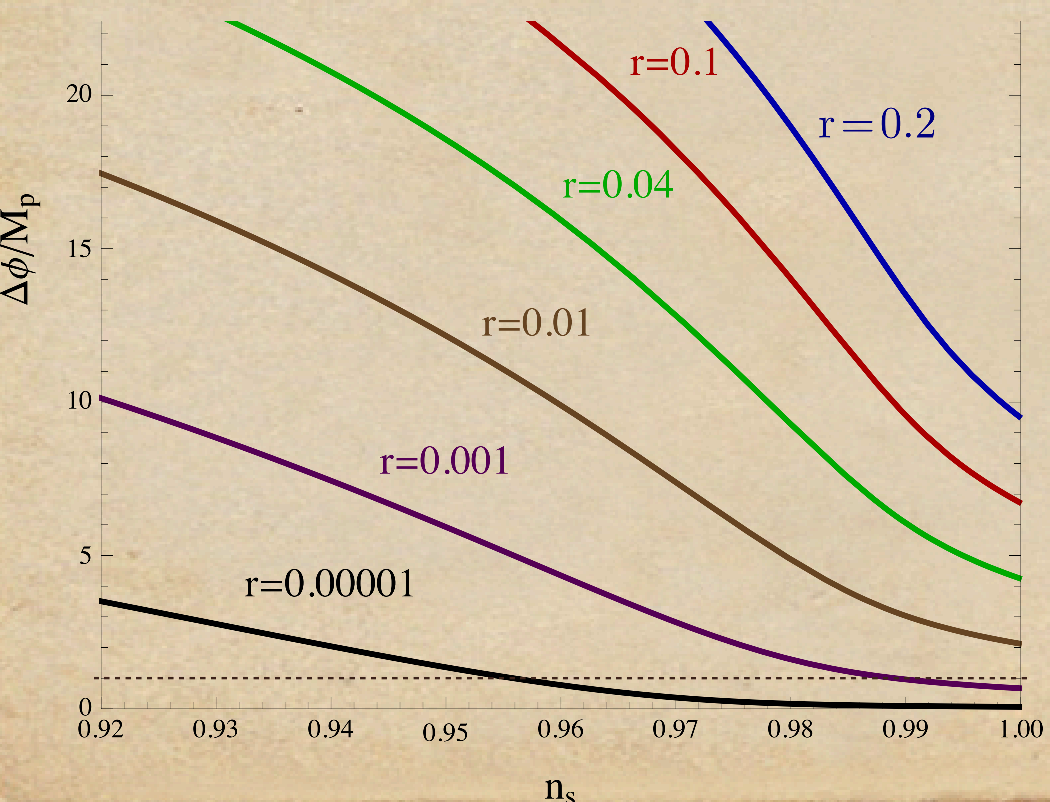
Total field range

$$\frac{\Delta\phi}{M_{Pl}} = \int_{N_e}^{N_*} dN \sqrt{\frac{r(N)}{8}}\,, \qquad \frac{\Delta\phi}{M_{Pl}} \approx \left(\frac{r}{0.002}\right)^{1/2}\left(\frac{N_*}{60}\right)$$

$N_* \approx 60$



[Boubekeur-Lyth, '05]



(super-)Planckian field ranges for

The (Boubekeur-)Lyth bound

$$r = \frac{8}{M_{Pl}^2}\left(\frac{\dot\phi}{H}\right)^2 = \frac{8}{M_{Pl}^2}\left(\frac{d\phi}{dN}\right)^2$$

[Lyth, '96]

$$(dN \equiv H dt = d\ln a)$$

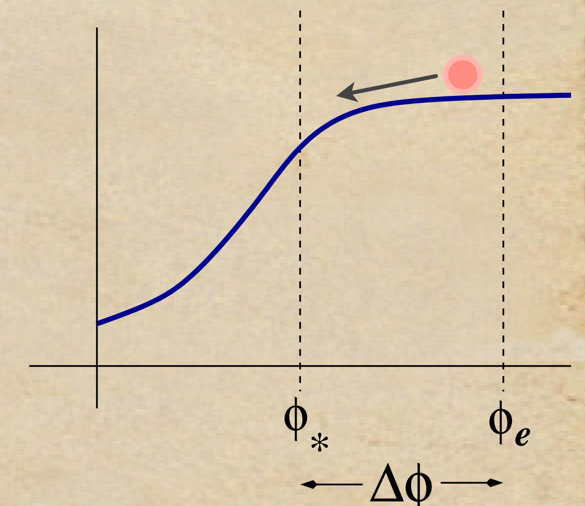
Total field range

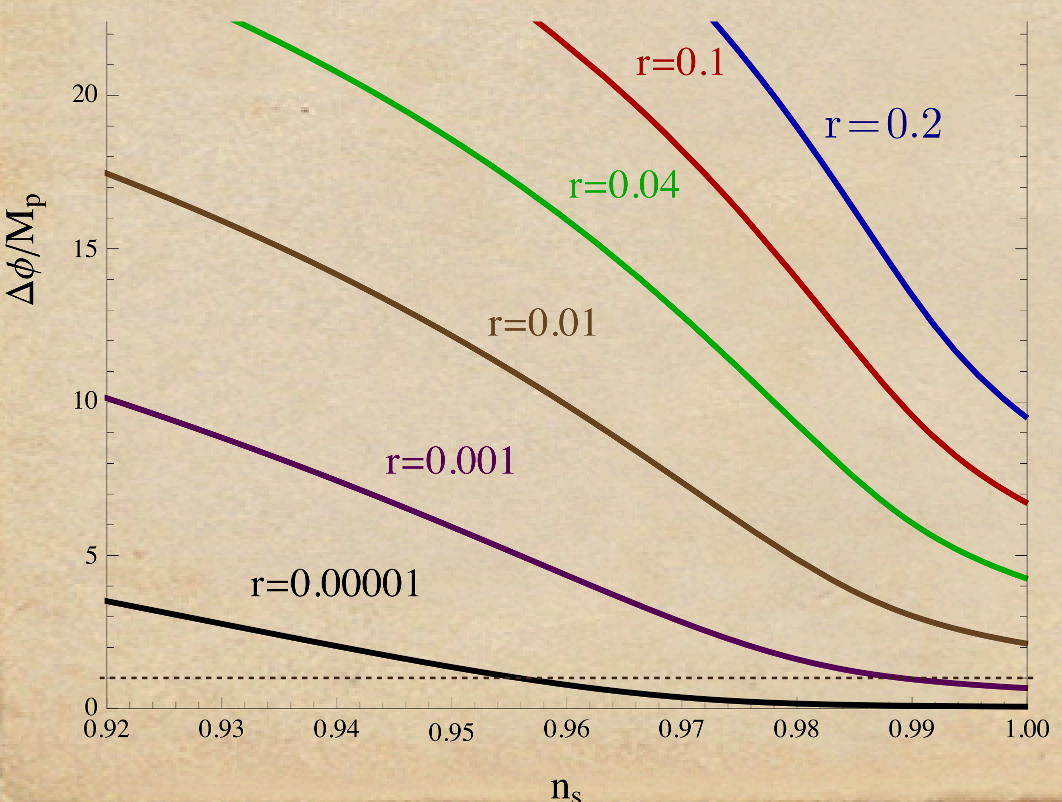
$$\frac{\Delta\phi}{M_{Pl}} = \int_{N_e}^{N_*} dN \sqrt{\frac{r(N)}{8}}\,,$$

$$\frac{\Delta\phi}{M_{Pl}} \approx \left(\frac{r}{0.002}\right)^{1/2}\left(\frac{N_*}{60}\right)$$

[Boubekeur-Lyth, '05]

$N_* \approx 60$





(super-)Planckian field ranges for

$$r \gtrsim 10^{-5}$$

String Theory Inflation?

- Inflation occurs at high energy scales. It is sensitive to Planck scale physics. Needs a UV completion of gravity!

  opportunity for string theory!

- Sensitive to couplings among inflation and other fields; Planck suppressed corrections to the potential. *Large field inflation* makes it more dramatic

$$\mathcal{O}_{p\geq 6} \quad \rightarrow \quad V(\phi)\left(\frac{\phi}{M_P}\right)^{p-4}$$

$$\Delta\eta \quad \rightarrow \quad \left(\frac{\phi}{M_P}\right)^{p-6} \gtrsim 1$$

[Talks by: Blumenhagen, Ibáñez, Nilles, Shiu]

- Not isolated phenomenon. Inflaton's energy is transferred to Standard Model particles at the end of inflation to initiate hot Big-Bang: *reheating*

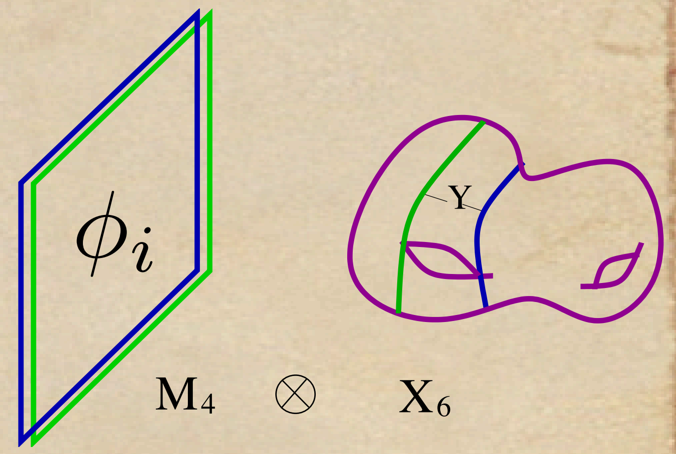
String Phenomenology: reproduce the *SM* from string theory, but how did we get there?

[Talks by: Ibáñez, Marchesano]

- String theory can shed light on *Dark Side of the Universe*: what is the nature of Dark Energy and Dark Matter? (see later)

- It is not hard to build low energy theories, where inflation can be successfully realised, also with super-Planckian field ranges.
- The problem is to understand whether these theories are natural and can be embedded in a UV complete theory
- In a UV completion of gravity, expect more (heavy) massive fields to be present. Need to understand how these affect inflationary dynamics (integrating out)

Moduli stabilization



- Compatifications in string theory come with many *massless scalars:* moduli

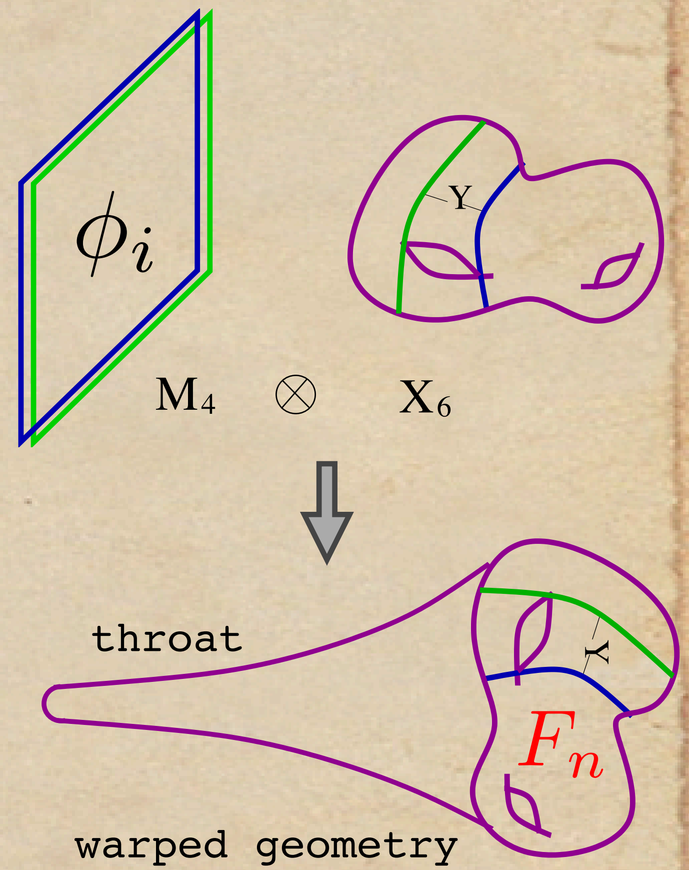
- Understanding the dynamics of moduli is crucial for describing cosmological evolution (overclose the universe 5th forces, decompactification stability, ...).

- *Key development* of the first decade of the XX1 century in *string cosmology* is the emergence of *moduli stabilisation* mechanism

Moduli stabilization

- Compatifications in string theory come with many *massless scalars:* moduli

- Understanding the dynamics of moduli is crucial for describing cosmological evolution (overclose the universe 5th forces, decompactification stability, ...).



- *Key development* of the first decade of the XX1 century in *string cosmology* is the emergence of *moduli stabilisation* mechanism

Flux compactifications (internal fluxes lift moduli)

$$F_n \neq 0 \qquad\qquad \mathcal{M}_4 \otimes X_6^{F_n}$$

[Giddings-Kachru-Polchinski, '01]

- For cosmology, compactification with stabilised moduli should be a dS space-time.

  - KKLT set up in IIB

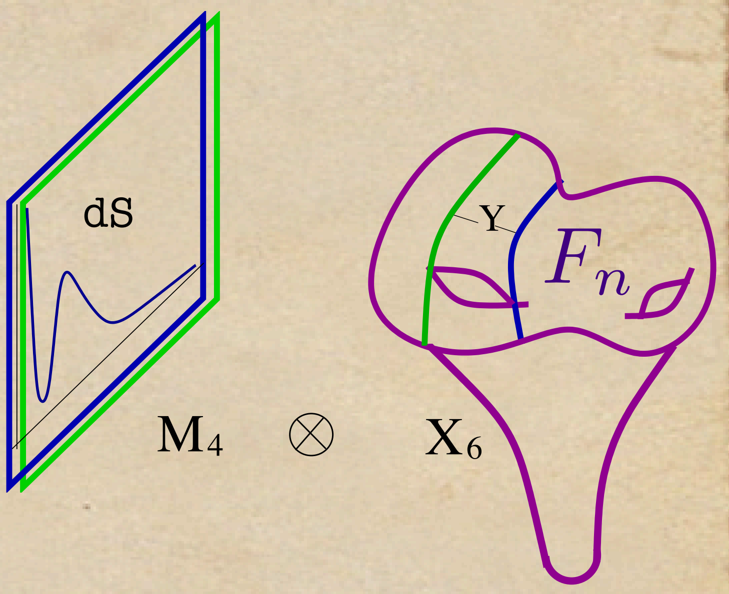
[KKLT, '03]

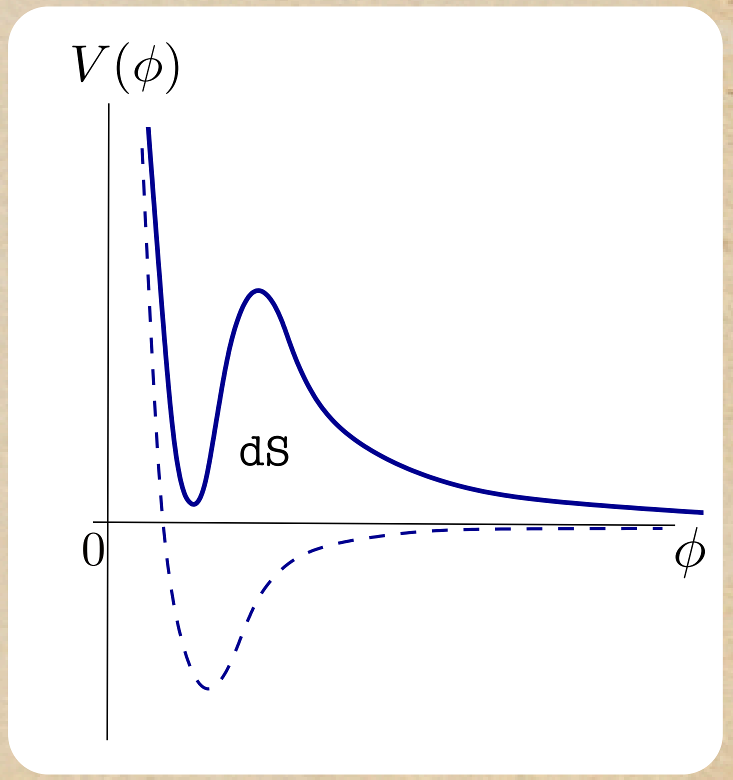
[Damian et al.'13]
[Blåback, Roest, IZ, '13]
[Danielsson, Dibitetto, '13]
[Kallosh et al. '14]

  - Large Volume scheme in IIB
    (theoretical control in 1/volume expansion)

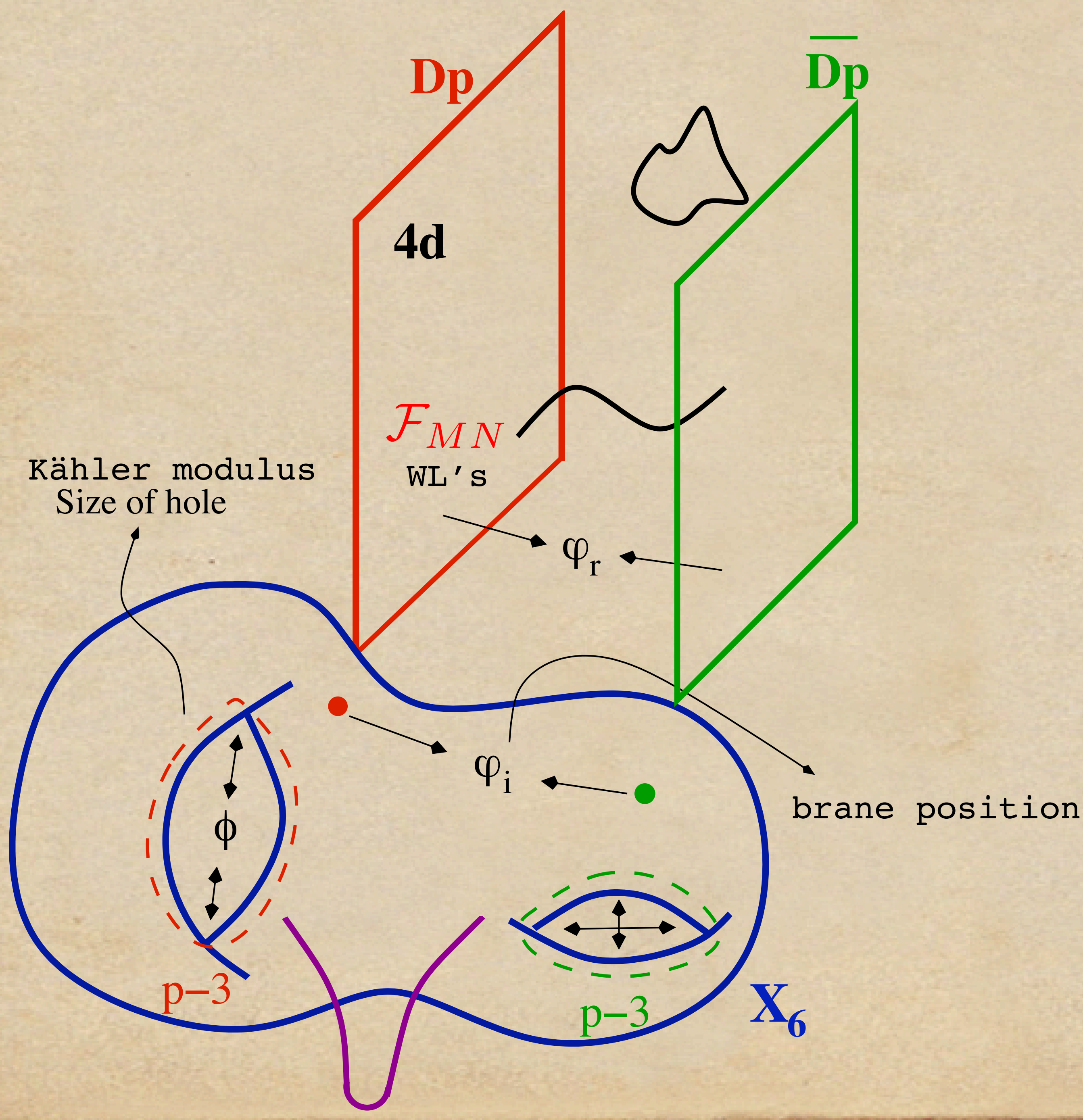
[Balasubramanian, Berglund, Conlon, Quevedo, '05]

[Cicoli et al.'12-'13]
[Quevedo, '14]





String Inflationary zoo

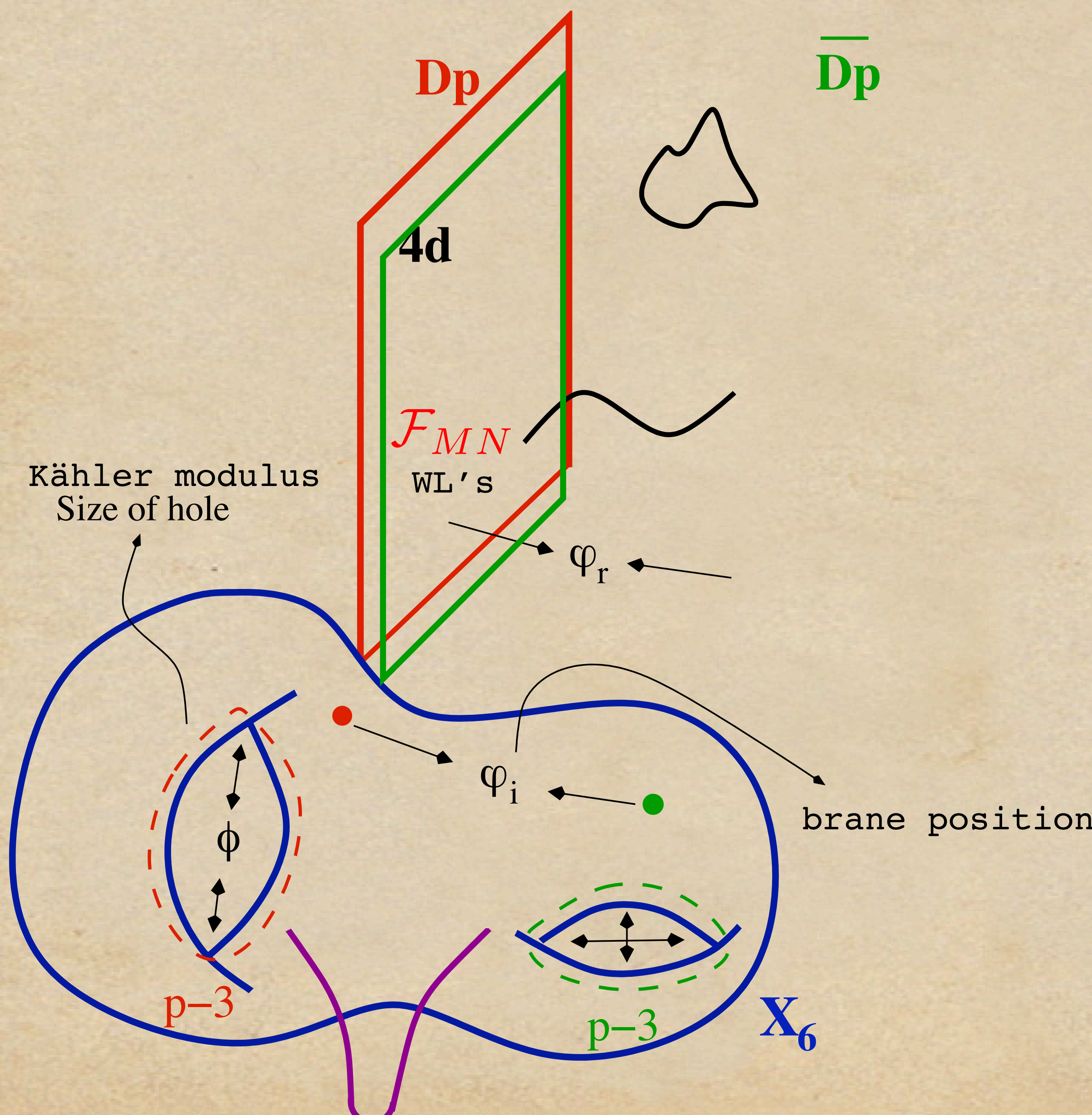


Inflaton candidates:

- D-brane positions
- Wilson Lines
- Kähler moduli
- Axions

[Review: Baumann-McAllister,'14]

String Inflationary zoo



Inflaton candidates:

- D-brane positions
- Wilson Lines
- Kähler moduli
- Axions

[Review: Baumann-McAllister,'14]

String Theory Inflationary models

- Small field: $\Delta\phi \ll M_{Pl}, \quad r \ll \mathcal{O}(1/N^2)$,

  D-brane inflation, unwarped Wilson Lines, (blow up Kähler moduli)

- Planck range: $\Delta\phi \sim M_{Pl}, \quad r \sim \mathcal{O}(1/N^2)$

  warped WL, Kähler fiber and poly-instanton inflation

- Large field: $\Delta\phi \gg M_{Pl}\,, \quad r \sim \mathcal{O}(1/N)$

  Axions, monodromy inflation

[Marchesano, Shiu, Uranga '14; Blumenhagen, Plauschinn, '14' Hebecker, Kraus, Witkowski '14; McAllister, Silverstein, Westphal, Wrase '14; Franco, Galloni, Retolaza, Uranga, '14; Long, McAllister, McGuirk, '14; Ibáñez, Valenzuela, '14]

[See talks by: Blumenhagen, Ibáñez, Nilles, Shiu]

Windows on string inflation

Primordial gravitational waves
(the BICEP2 delusion?)

Audience Poll

1. The BICEP2 observation is (roughly) correct and around 10% of the B-modes is due to primordial GW's $r \sim 0.1$

2. The BICEP2 observation is incorrect, but eventually we will know that 1% of the B-modes is due to primordial GW's $r \sim 0.01$

3. The BICEP2 observation is incorrect, and much less than 1% of the B-modes is due to primordial GW's

$$r \ll 10^{-3}$$

Windows on string inflation

Primordial gravitational waves
(the BICEP2 delusion?)

- Hopefully 1. or 2. will be confirmed
- In both cases, large inflationary scale and field range, UV sensitive

$$V^{1/4} = 1.94 \times 10^{16} \mathrm{GeV} \left(\frac{r}{0.12}\right)^{1/4}$$

- High scale moduli stabilisation. LED gone
- If 2, axions are likely excluded
- ...

Windows on string inflation

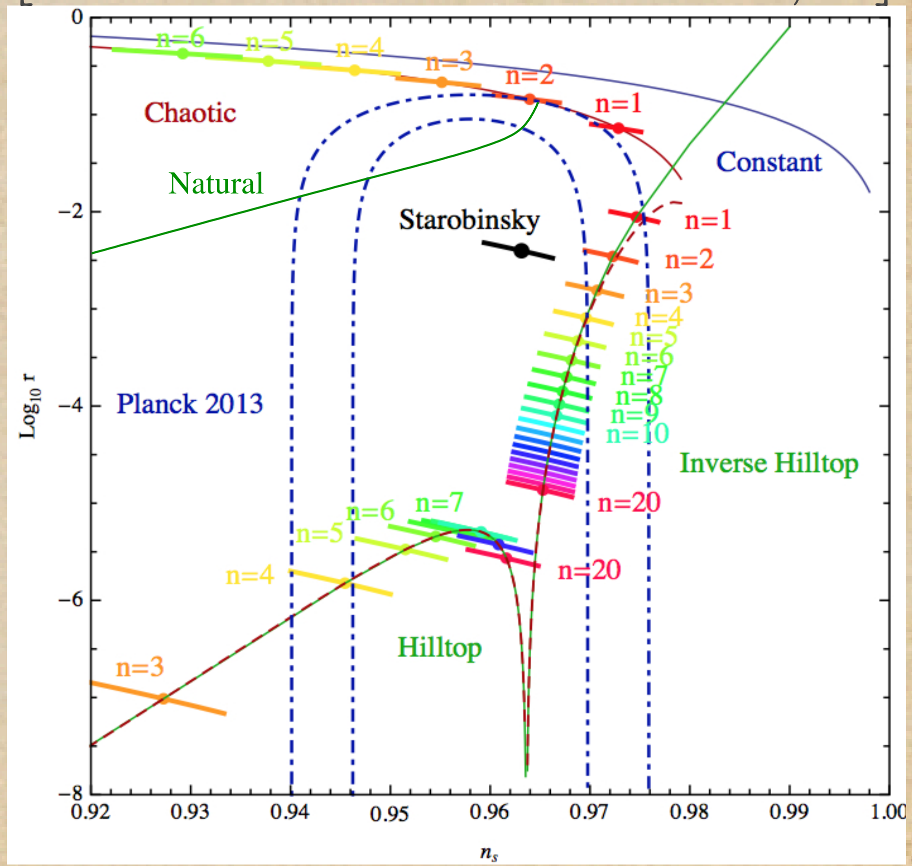
Primordial gravitational waves
(the BICEP2 delusion?)

- Hopefully 1. or 2. will be confirmed
- In both cases, large inflationary scale and field range, UV sensitive

$$V^{1/4} = 1.94 \times 10^{16}\mathrm{GeV} \left(\frac{r}{0.12}\right)^{1/4}$$

- High scale moduli stabilisation. LED gone
- If 2, axions are likely excluded
- ...

[Modified from García-Bellido & Roest, '14]



Windows on string inflation

Non-Gaussianity in string theory $\langle\zeta\zeta\zeta\rangle$
(the Planck delusion?)

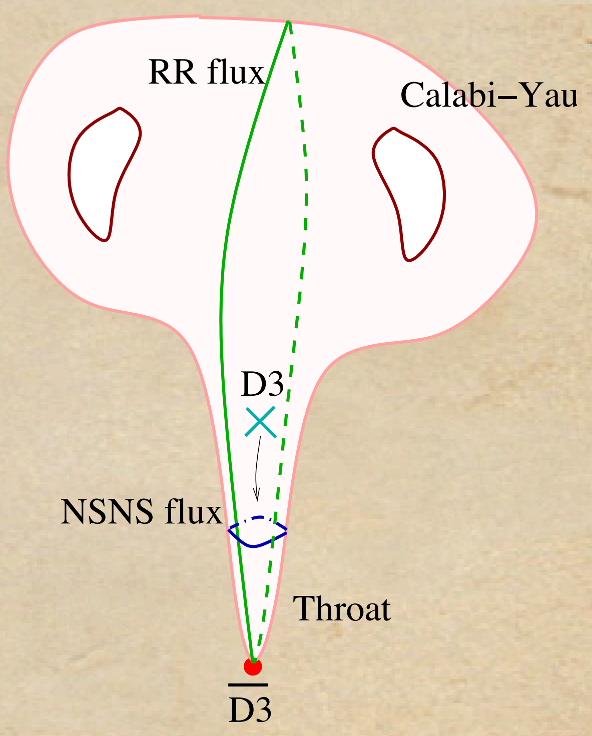
- Inflation in string theory is generically involves other light fields, giving interactions that can generate Non-Gaussianity. Moreover:

  - *Single field DBI* inflation: nG of equilateral shape (constraint by Planck)

  - (DBI) multifield inflation:

$$r = 16\epsilon\, c_s \cos^2\Theta$$

$$f_{nl}^{\rm eq} = -\frac{35}{108}\frac{1}{c_s^2}\cos^2\Theta$$



[Silverstein, Tong, '03; Alishahiha, Silverstein, Tong, '04]
[Chen et al. '06]

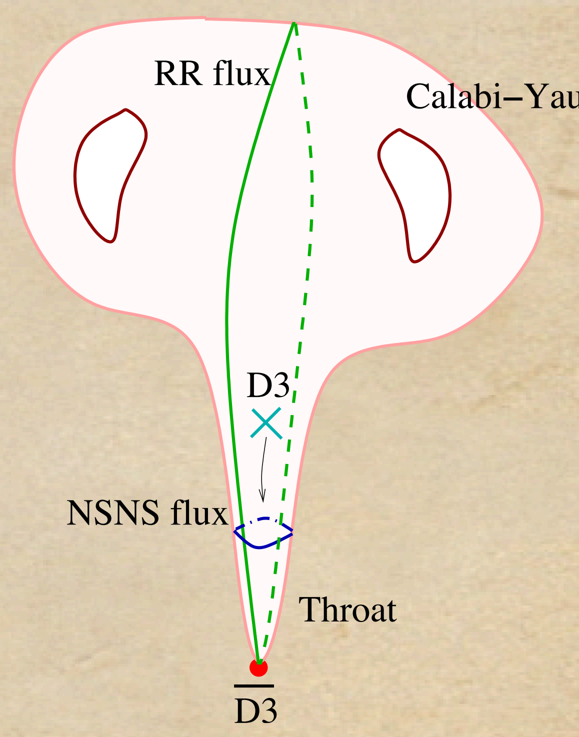
Windows on string inflation

Non-Gaussianity in string theory $\langle\zeta\zeta\zeta\rangle$
(the Planck delusion?)

- Inflation in string theory is generically involves other light fields, giving interactions that can generate Non-Gaussianity:

Slow roll multifield inflation: curvaton and modulated reheating in Large Volume scenario

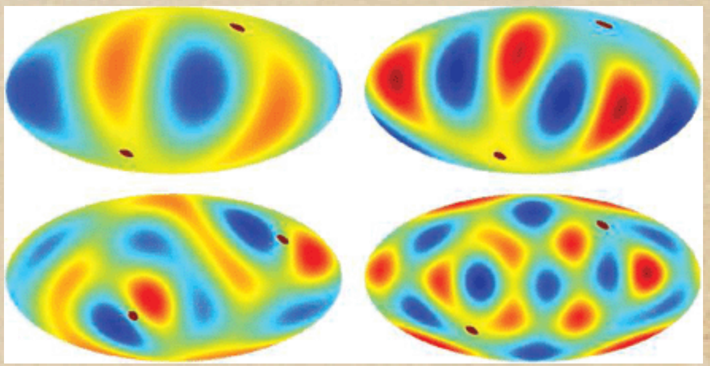
$$f_{nl}^{\rm loc} \sim \mathcal{O}(\text{few})\times 10$$



[Burgess et al.'10, '12]

Windows on string inflation

Anisotropies from string inflation?

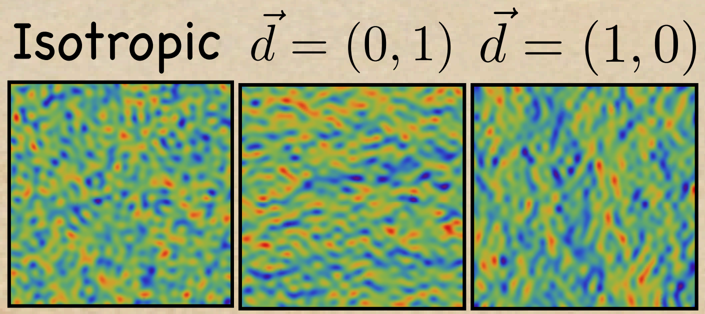


- The simplest way to generate a preferred direction is via vector fields
- If suitable couples to inflaton or light, they may leave anisotropic imprints in the power spectra

$$\mathcal{P}_\zeta(k) = \mathcal{P}_0(k)\left[1 + g\,(d \cdot k)^2 + \cdots\right]$$

[Ackerman, Carroll, Wise,'07]

- Several phenomenological 4D models



(pictures from Karčiauskas)

[Dimopoulos et al '07-'13]
[Wagstaff-Dimopoulos, '10]
[Yokoyama-Soda '08; Watanabe-Kanno-Soda '09-'10; Soda et al. '13; Shiraishi, Komatsu, Peloso,'13]

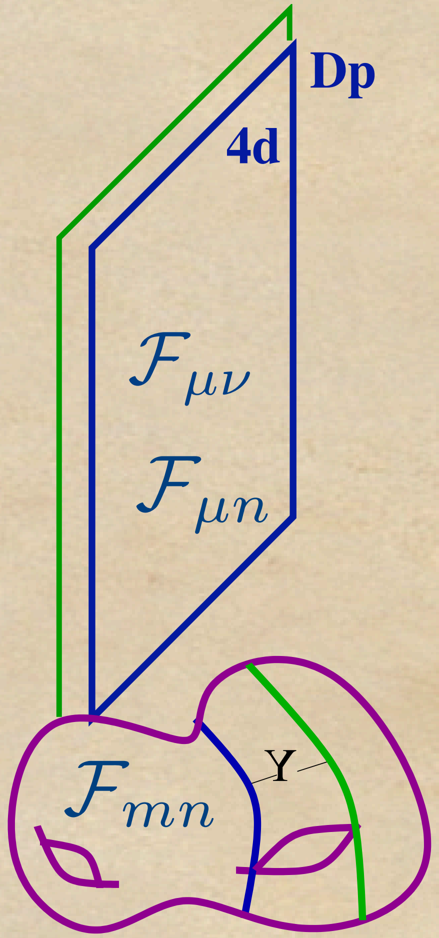
Windows on string inflation

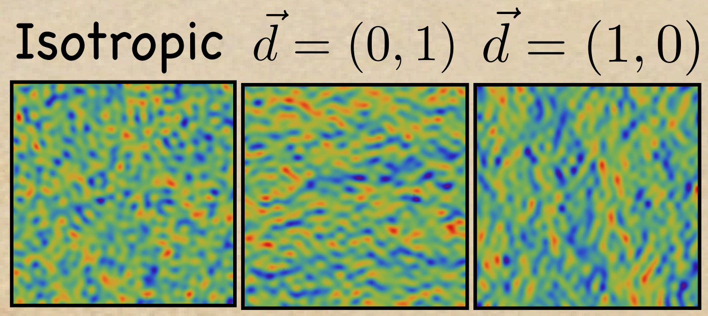
Anisotropies from string inflation?

- D-branes feature gauge fields $\mathcal{F}_{MN}$ on their world volumes

- The mixed components are the WL, that can act as inflatons

- The 4D components can give rise to anisotropies



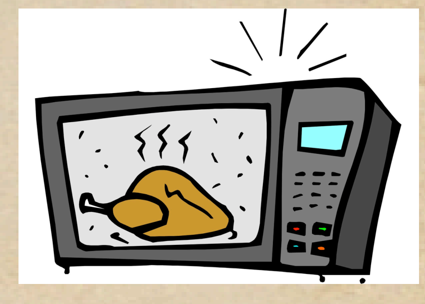


(pictures from Karčiauskas)

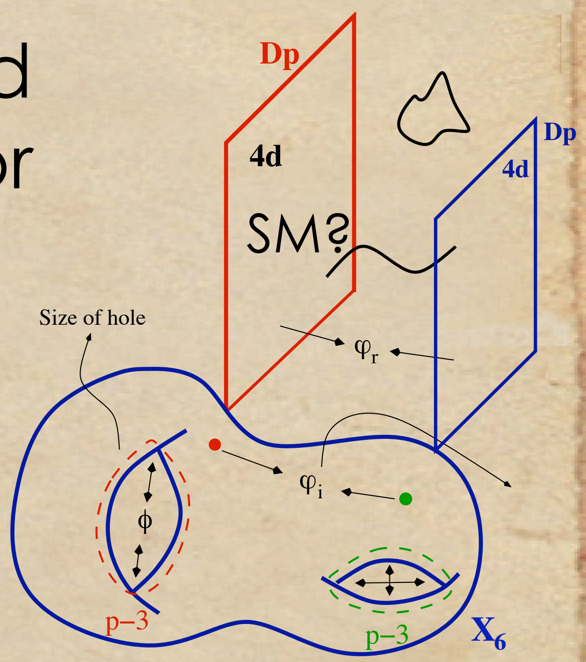
[Dimopoulos, Wills, IZ, '11, '13]

End of Inflation

[Review: Baumann-McAllister,'14]

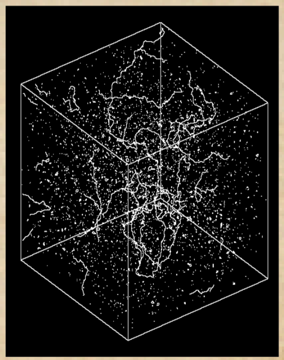


- At end of inflation the inflaton's energy must be (efficiently) transferred to SM particles to initiate the hot Big-Bang: *reheating*



- Reheating crucially involves the Standard Model. Essential to specify how the visible sector is realized.

- Inflation with a shift symmetry makes reheating harder: the symmetry protecting the inflaton limits the couplings of the inflaton to the visible sector.



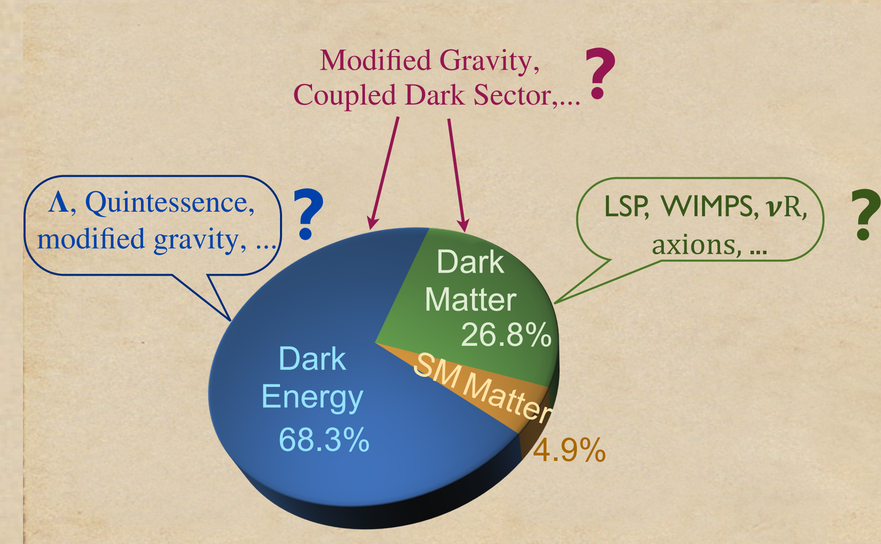
- A happy side effect of D-brane inflation is the production of *cosmic superstrings*, potentially observable via gravitational radiation!

[Sarangi, Tye,'02]
[Copeland, Myers, Polchinski,'03]

Dark String Cosmology

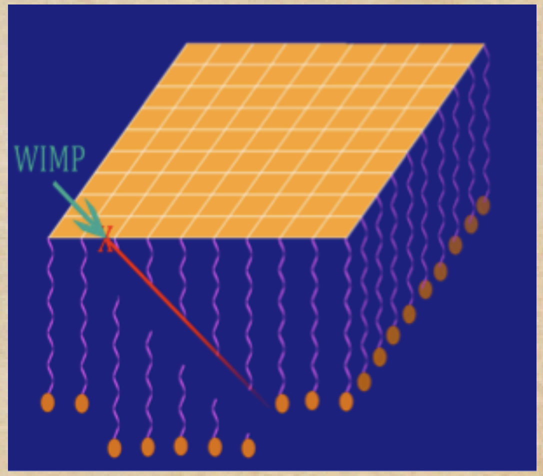
The Dark Matter puzzle

- ~85% of matter in the Universe is not known. CDM from CMB cosmology

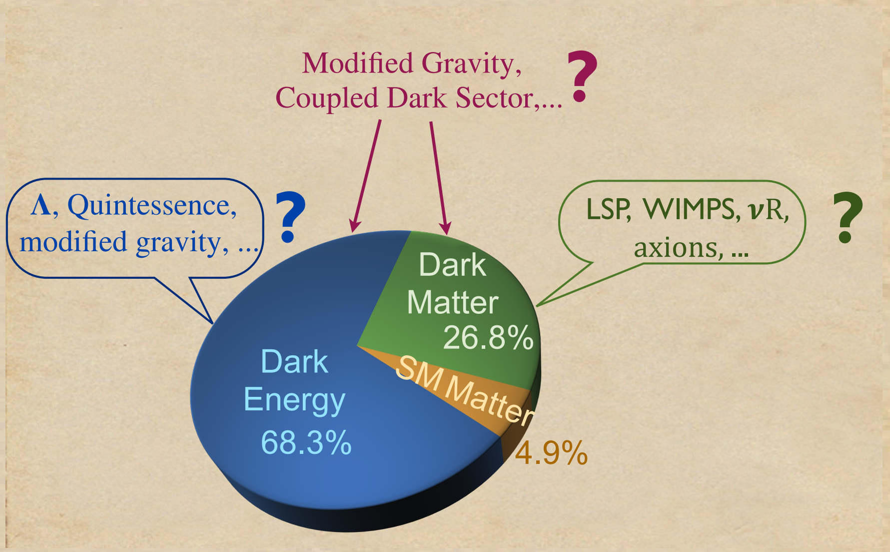


- We have mostly "negative" information about DM nature:
  - No electric charge
  - No color charge
  - No strong self-interactions
  - Not a particle in the Standard Model

- *Several ongoing/planned experiments to detect (direct/indirect) DM*



Dark Matter from strings



- Axionic Dark Matter

[Arvanitaki et al. '09]
[Acharya, Bobkov, Kumar, '10]
[Cicoli, Goodsell, Ringwald, '12]

- Non-thermal Dark Matter and Baryogenesis from moduli decay

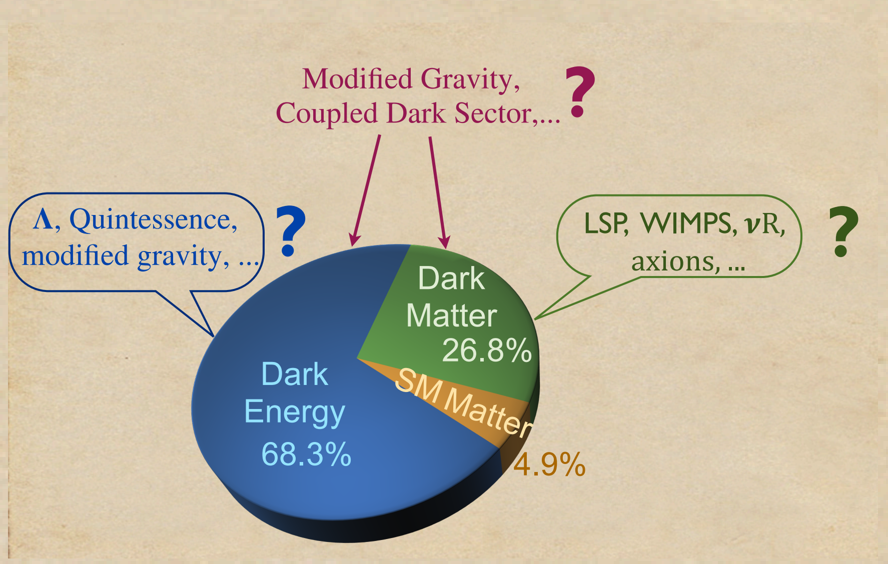
[Acharya et al. '08]
[Allahverdi et al. '13]

- *Dark Radiation*: decay of the overall volume modulus in LVS to its axionic partner

[Cicoli, Conlon, Quevedo, '12; Higaki, Takahashi, 12]
[Conlon, Marsh, '13]
[Angus et al.'13; '14]
[Hebecker et al.'14]

Dark Energy Puzzle

- Most of energy density content is in the form of DE. While a cosmological constant is not excluded, there is no strong reason to exclude a time dependent component



- Several forthcoming experiments expected to provide more accurate limits on equation of state of DE:

$$p = \omega\rho\,, \qquad -1 < \omega < -1/3\,, \qquad \omega = -1$$

acceleration cosmological constant

Dark Energy Survey (DES), Large Synoptic Survey Telescope, LSST, Hobby-Eberly Telescope Dark Energy Experiment (HETDEX), Euclide.

Dark Energy in String Theory

- *Quintessence*: most obvious candidate for dark energy is a scalar field. In the simplest case, as in inflation, it requires a flat enough potential and

$$\rho_{DE} \sim (0.003 \text{ eV})^4 \,, \qquad m_\phi \lesssim 10^{-33}\text{eV}$$

[Caldwell et al, '98]

- *Axions* as Quintessence in string theory

[Kaloper, Sorbo, '08]
[Panda, Sumitomo, Trivedi, '10]
[Gupta, Panda, Sen, '11]

- *Kähler moduli* as Quintessence: coupling to SM suppressed by volume

[Cicoli, Pedro, Tasinato, '12]

Coupled DM/DE

- *Cosmic Coincidence Puzzle*: why is dark energy density of same order as that of matter in the present cosmological epoch, as observed?

- If it is not accidental, an exchange of energy is plausible, and therefore a coupling, between dark energy and dark matter.

- Given that we do not know the nature of either DE or DM, cannot exclude a coupling between them.

- A resolution of the 'cosmic coincidence' problem implies that dark energy and dark matter follow the same *scaling solution* during a significant period of evolution.

energy densities of DM and DE scale with same power

$$a^{-3(1+\omega^{eff})}$$

- Intense investigation of phenomenological models of coupled quintessence in the literature.

[see 1310.0085 for a review]

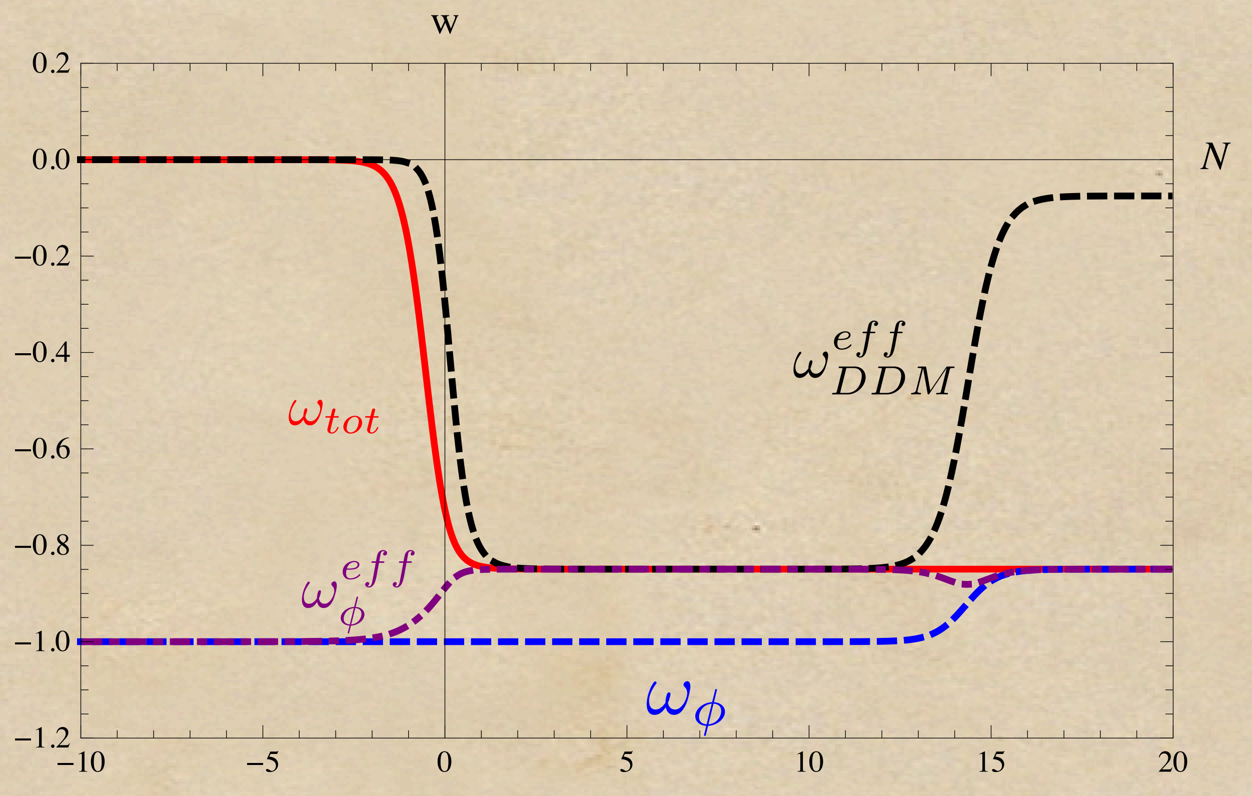
Disformally Coupled Quintessence

[Koivisto, Wills, IZ, '13]

- A naturally coupled DM/DE system arises in string theory in terms of D-branes
- Dark Energy is identified with brane's position as it moves in internal space
- Dark Matter is identified with matter living on the D-brane (has no or little interaction with SM D-branes)
- Disformal coupling among DM and DE dictated by the geometry and theory

$$\tilde{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi) \partial_\mu \phi \partial_\nu \phi$$

Scaling solutions arise from this set up thanks to the coupling



Summary

- String Cosmology has born and its life expectations are promising, but we need to take care of it
- Early Universe: inflation offers a unique opportunity for string theory.
- Observations are motivating further theoretical developments, while string theory inspires novel cosmological scenarios
- It remains important to understand end of inflation and late time cosmology within string theory, also in view of forthcoming observations
- We should not miss the opportunity to make predictions before forthcoming observations reveal new data