Title: Acceleration, Then and Now

Date: Dec 03, 2013 11:00 AM

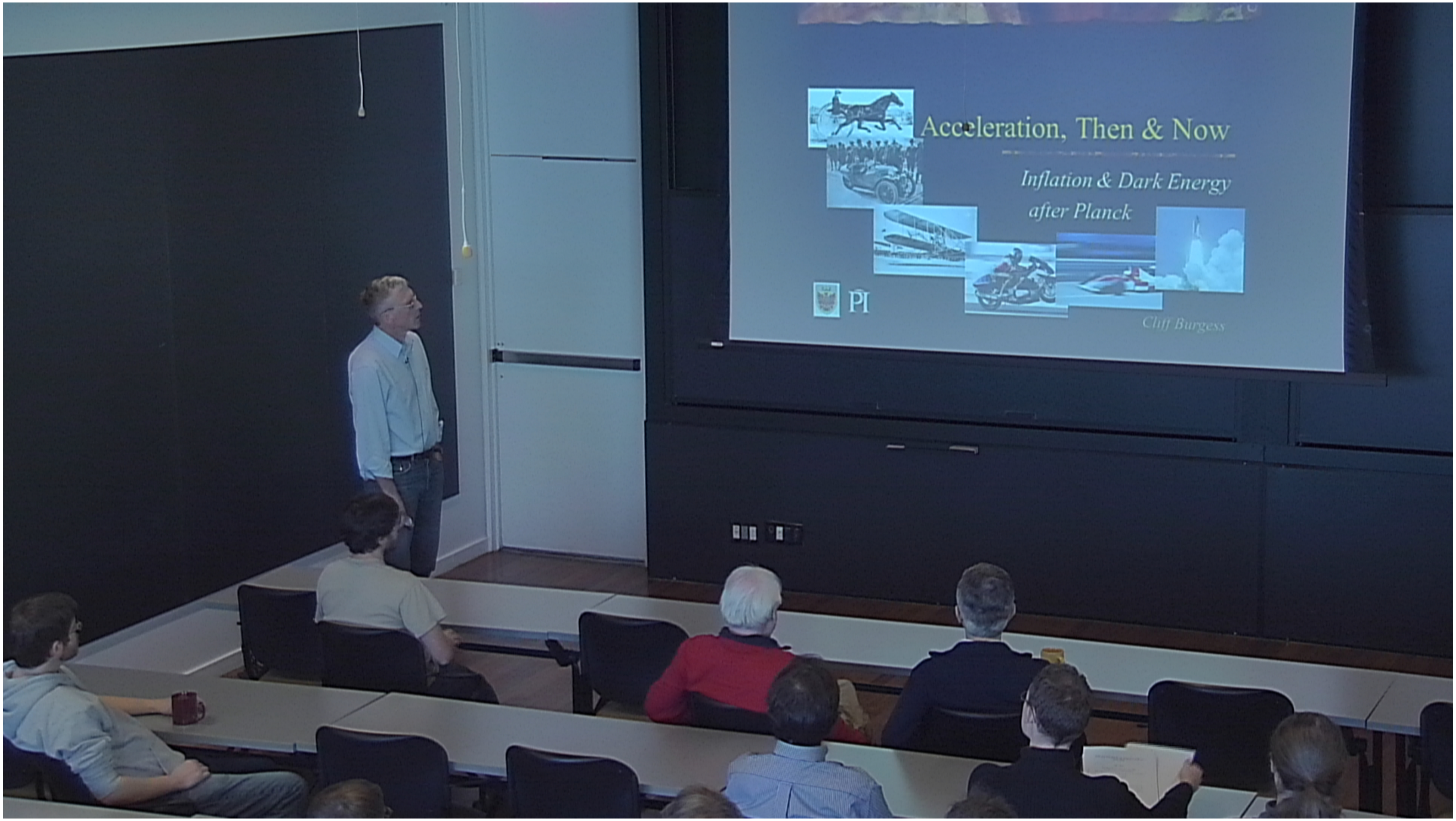
URL: http://pirsa.org/13120059

Abstract: <span>There is good evidence that the universe underwent an epoch of accelerated expansion sometime in its very early history, and that it is entering a similar phase now. This talk is in two parts. The first part describes what I believe to be the take-home message about inflationary models, coming both from the recent Planck results and from attempts to embed inflation within a UV completion (string theory). I will argue that both point to a particularly interesting class of inflationary models that also evade many of the tuning problems of inflation. These models also turn out to make the tantalizing prediction that the scalar-to-tensor ratio, r, could be just out of reach, being predicted to be proportional to (n_s - 1)^2, where n_s ~ 0.96 is the spectral tilt of the scalar spectrum. The second part provides an update on an approach to solving the "cosmological constant problem", which asks why the vacuum energy seems to gravitate so little. This is the main theoretical obstruction that makes it so difficult to understand the origins of the present epoch of acceleration. In the approach described - Supersymmetric Large Extra Dimensions - observations can be reconciled with a large vacuum energy because the vacuum energy curves the extra dimensions and not the ones measured in cosmology. It leads to a picture of very supersymmetric gravity sector coupled to a completely non-supersymmetric particle-physics sector (which predicts in particular no superpartners to be found at the LHC). The update presented here summarizes the underlying mechanism whereby supersymmetry in the extra dimensions acts to suppress the gravitational effects of quantum fluctuations. Because the large quantum contributions are under control it becomes possible to estimate the size of to be expected of the observed dark energy. For the simplest configuratin the result is of order C (m Mg/4 pi Mp)^4, where m is the heaviest particle on the branes (and so no smaller than the top quark mass), Mg is the extra-dimensional gravity scale (no smaller than 10 TeV due to astrophysical constraints, implying two extra dimensions that are of order a micron in size) and Mp is the 4D Planck mass. C is a constant unsuppressed by symmetry-breaking effects, and C = 6 x 10^6 gives the observed dark energy density, using the smallest values given above for m and Mg. If there is time I will sketch arguments as to why there must be other light degrees of freedom in the theory as well, whose implications might ultimately be used to test the picture.

Acceleration, Then & Now

Inflation & Dark Energy after Planck

Cliff Burgess


Acceleration, Then & Now
Inflation & Dark Energy
after Planck
PI
Cliff Burgess

Context: naturalness principles

- Light scalars are unnatural
  - The LHC will see lots of new SUSY particles
  - Inflation will be complex

Patron Saint of All Things Natural

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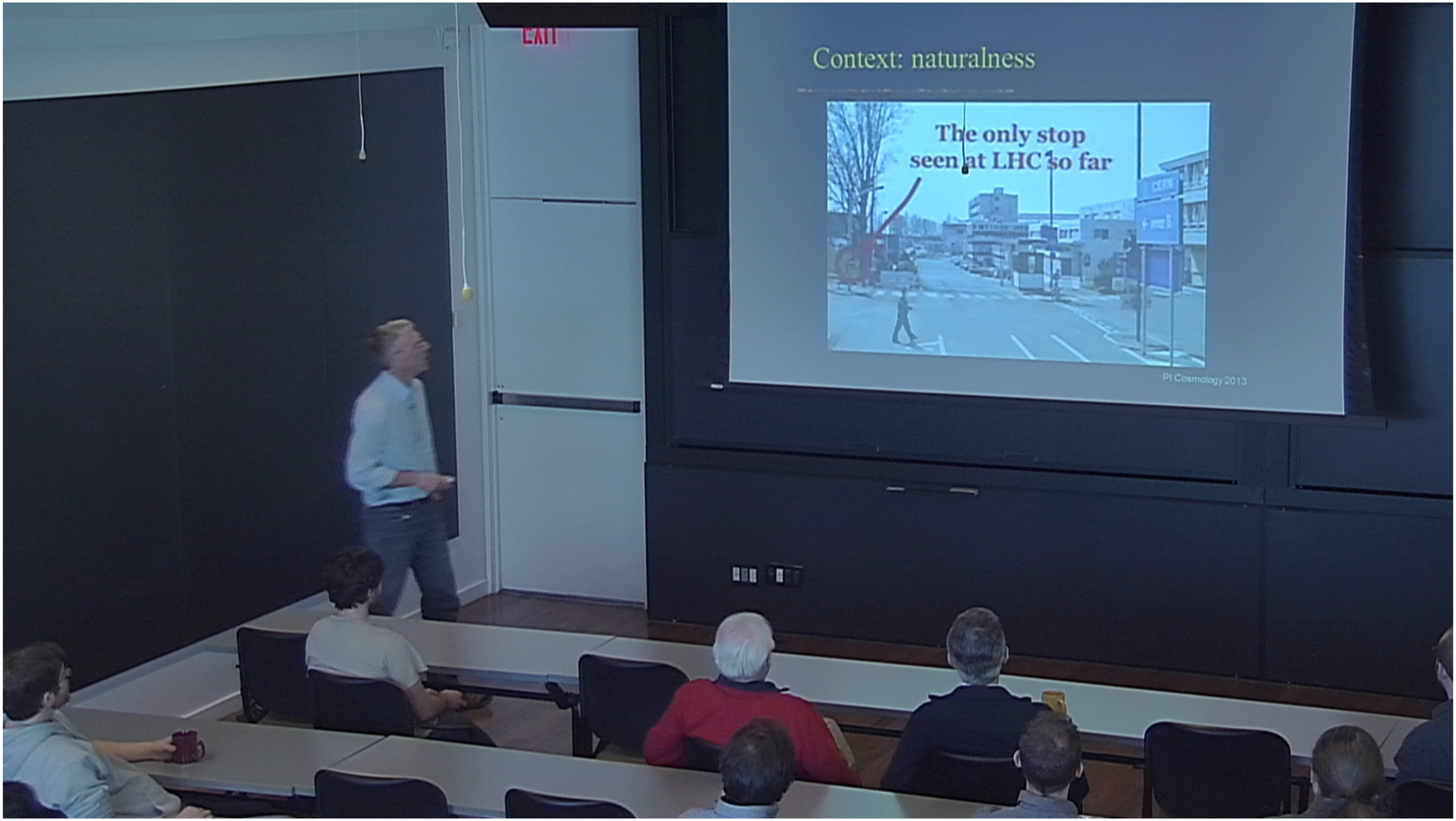
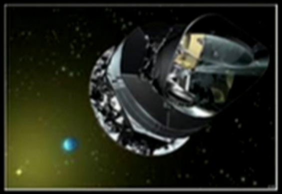
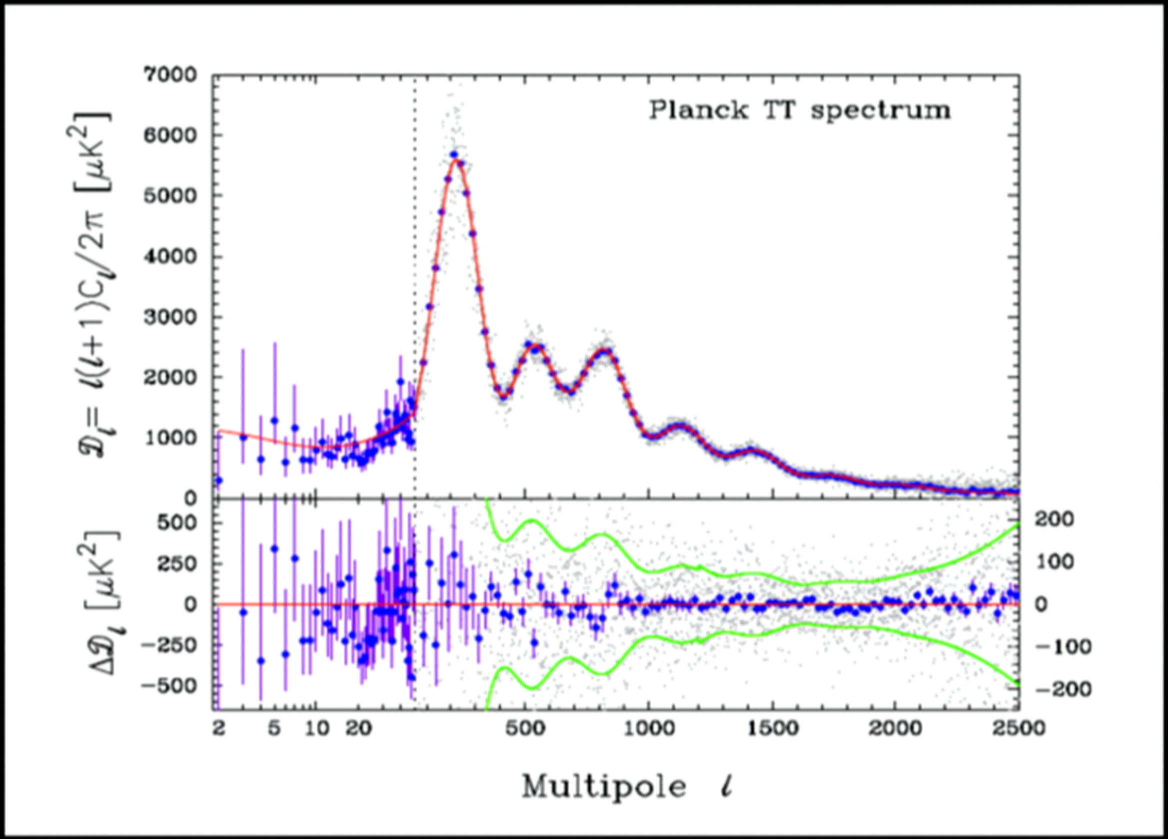

EXIT
Context: naturalness
The only stop
seen at LHC so far
CERN
PI Cosmology 2013

Context: naturalness





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Context: naturalness!

- Is Naturalness Dead?

- Long Live Naturalness!

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Outline

- Acceleration Then (inflation) *(1306.3512)*
  - Things on which (almost) everyone agrees
  - What the data likes
  - Information from the UV?
- Acceleration Now (dark energy) *(1309.4133)*
  - Novel form of SUSY breaking

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Acceleration Then

- W
- W
- U

Common points of departure:

1. *The data is beautiful!*
2. *Seems the universal expansion accelerated*
3. *Simplicity is good, but….*
4. *Some things need UV completion to address*

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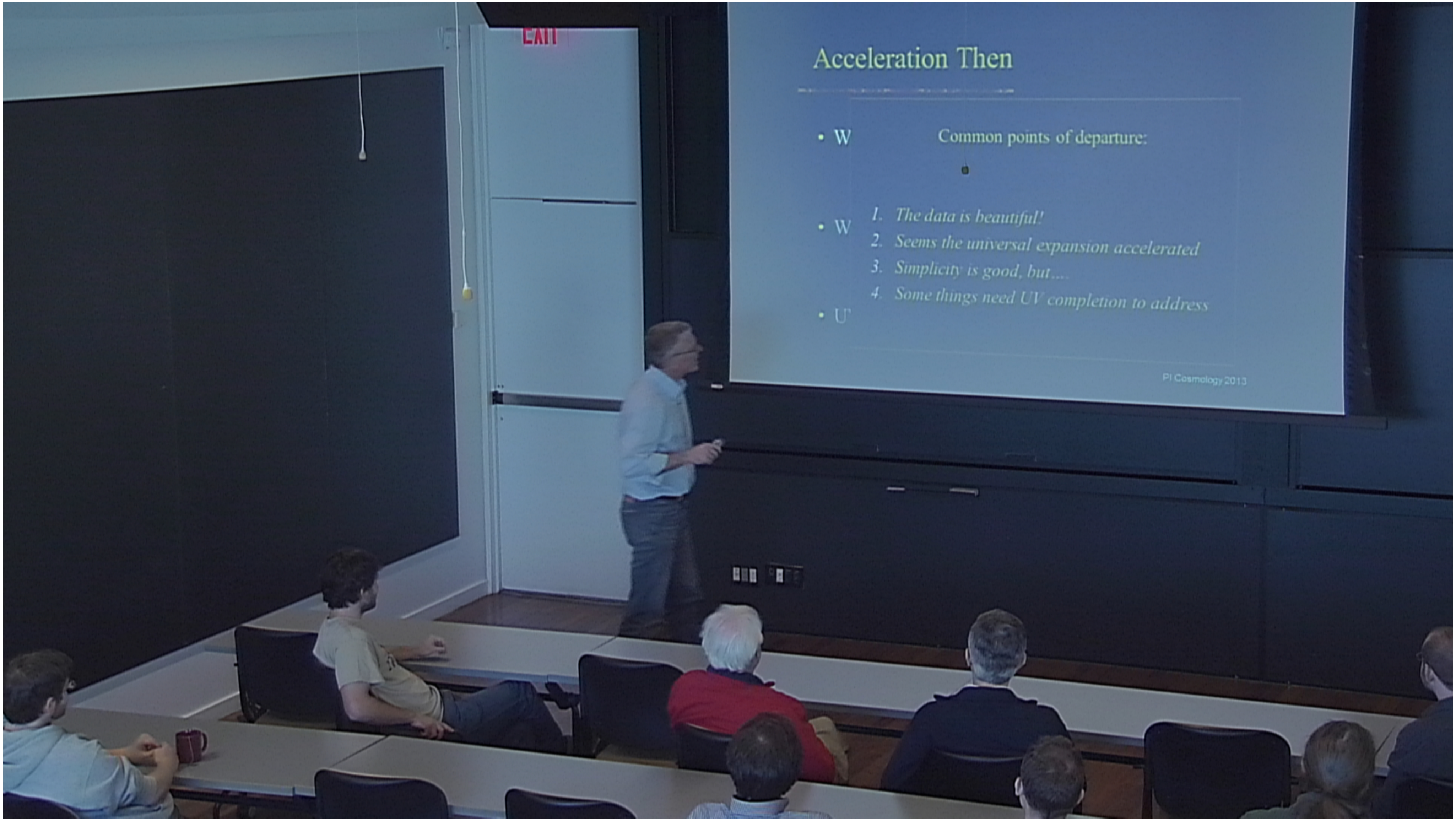
EXIT
Acceleration Then
• W
Common points of departure:
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Acceleration Then

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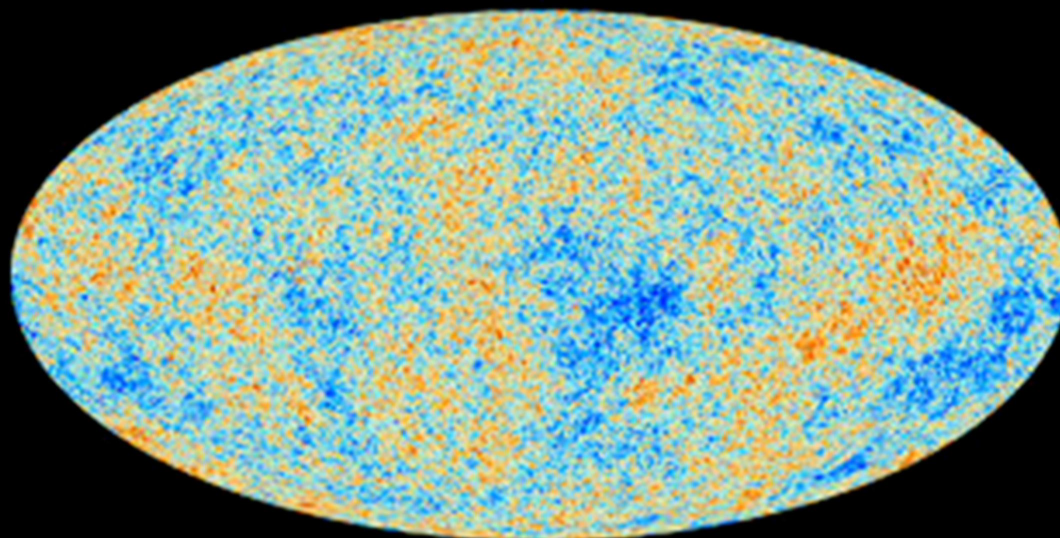

1. Planck's map

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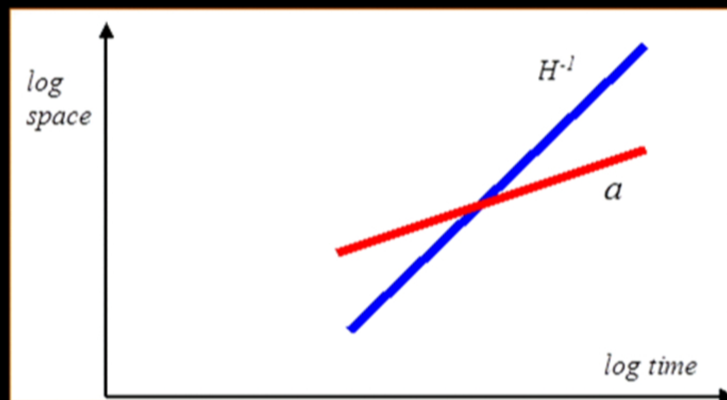
Acceleration Then

- W
- W
- U



2. The problem: *how to generate correlations over scales that were super-Hubble in size?*

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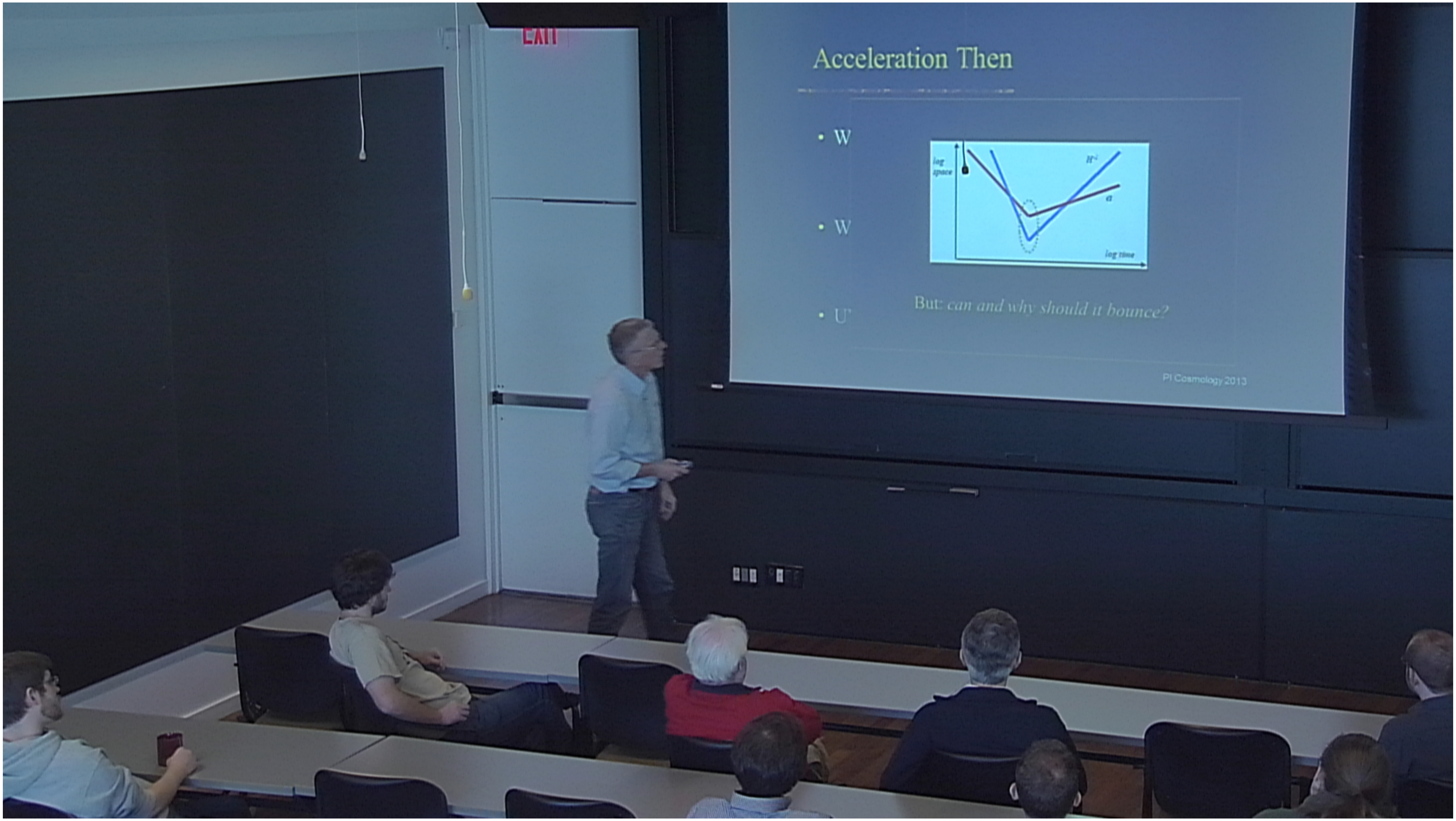
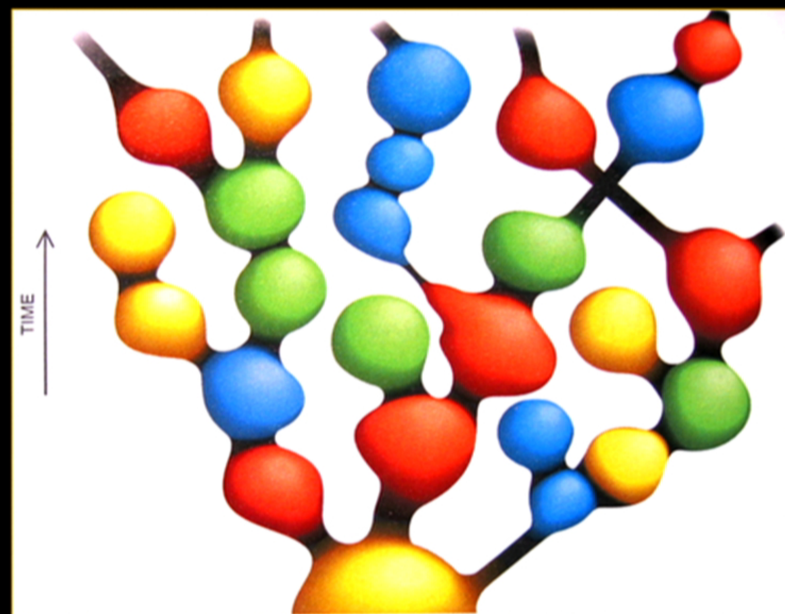

Acceleration Then
• W
• W
• U
log space
H^{-1}
a
log time
But: can and why should it bounce?
PI Cosmology 2013
EXIT

Acceleration Then

fig: Andrei Linde

- W
- W
- U



And: *need it do so everywhere?*

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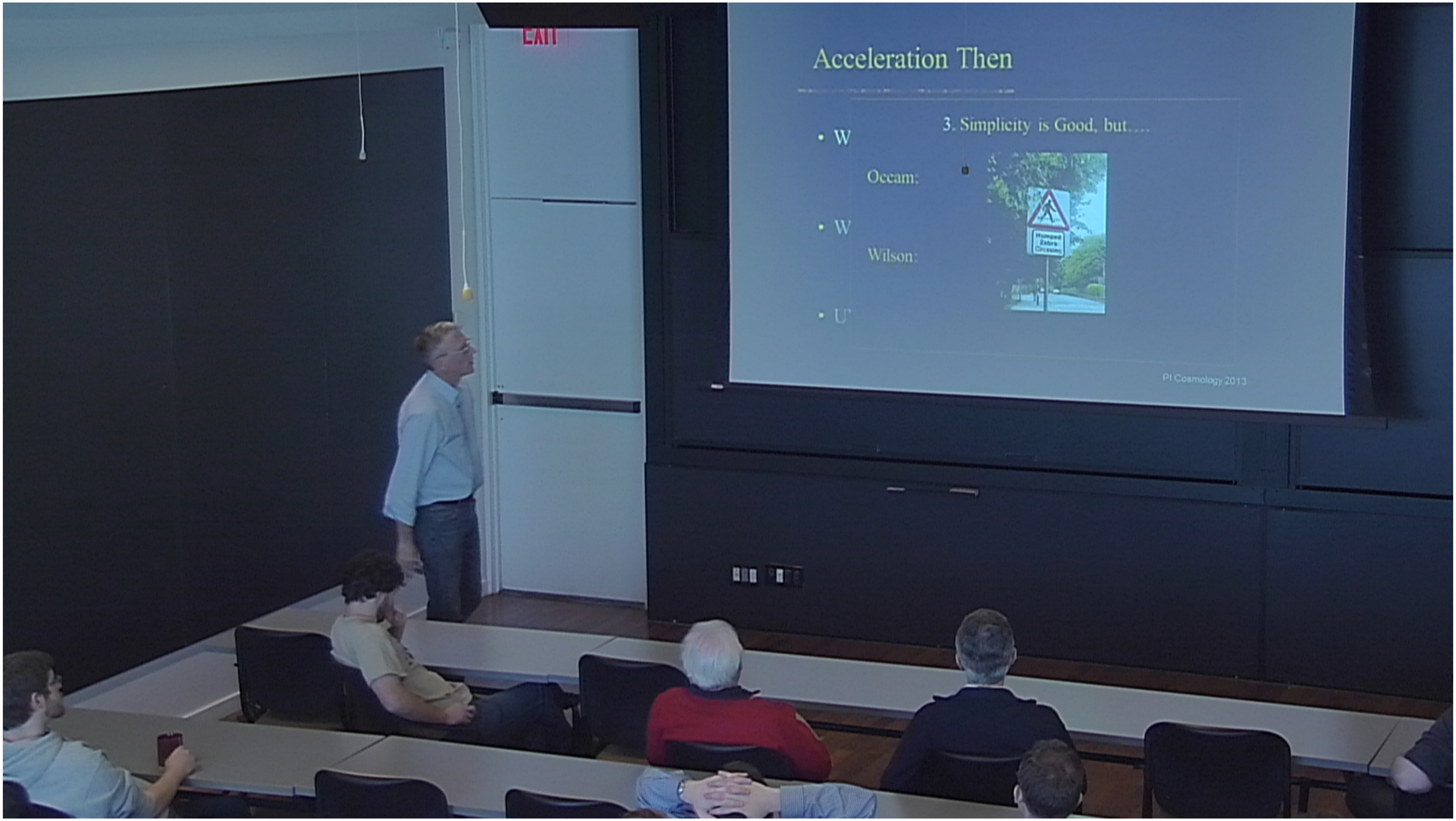
EXIT
Acceleration Then
• W
Occam:
• W
Wilson:
• U
3. Simplicity is Good, but….
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Acceleration Then

- W
- W
- U

3. Simplicity is Good, but….

Occam: *What's the simplest model the data needs?*

Wilson: *Low energy limit is often messy;*
What is generic and stable?

eg Dark Matter or Beyond the Standard Model

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Acceleration Then

- W
- W
- U

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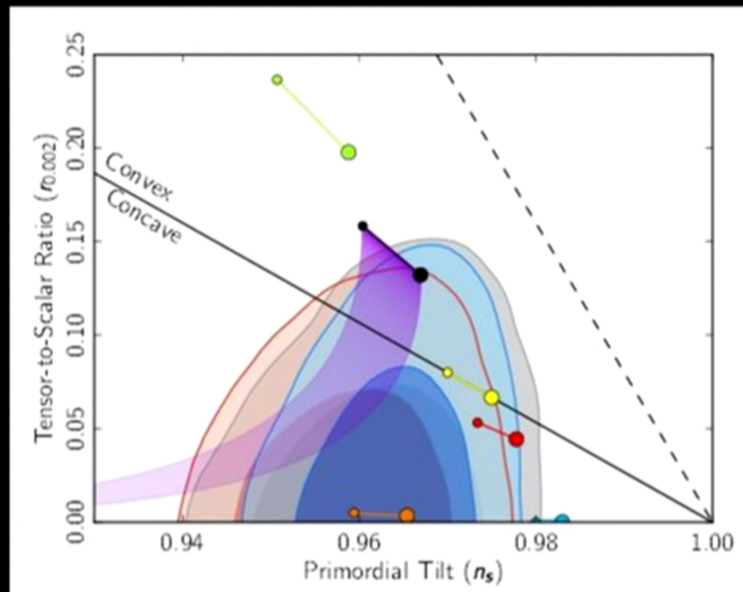
Acceleration Then

Planck 2013

- W
- W
- U



$$P_s(k) = A_s k^{n_s - 1} \qquad r = \frac{A_T}{A_S}$$

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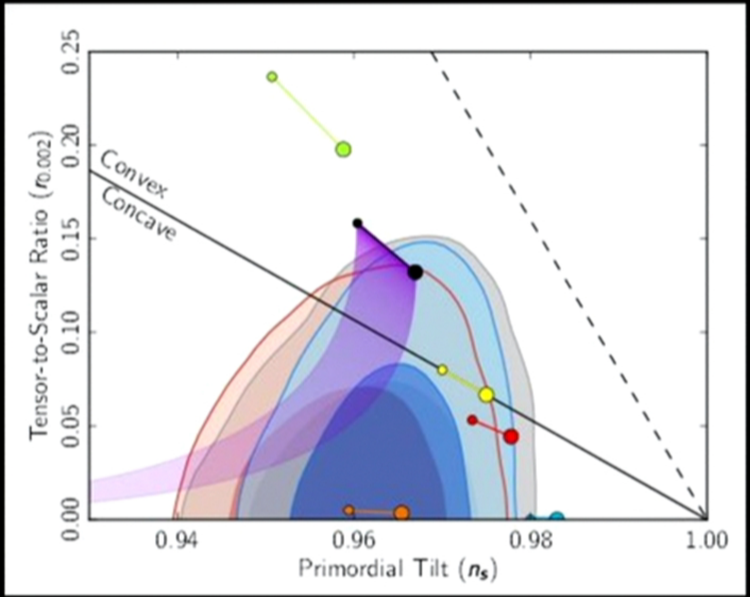
Acceleration Then

Planck 2013

- W
- W
- U



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PI Cosmology 2013

Acceleration Then

Martin, Ringeval & Vennin 2013

- W
- W
- U

Name	Parameters	Sub-models	$V(\phi)$
HI	0	1	$M^4\left(1-e^{-\sqrt{2/3}\phi/M_{\rm Pl}}\right)$
RCHI	1	1	$M^4\left(1-2e^{-\sqrt{2/3}\phi/M_{\rm Pl}}+\frac{A_1}{16\pi^2}\frac{\phi}{\sqrt{6}M_{\rm Pl}}\right)$
LFI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^p$
MLFI	1	1	$M^4\frac{\phi^2}{M_{\rm Pl}^2}\left[1+\alpha\frac{\phi^2}{M_{\rm Pl}^2}\right]$
RCMI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^2\left[1-2\alpha\frac{\phi^2}{M_{\rm Pl}^2}\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
RCQI	1	1	$M^4\left(\frac{\phi}{M_{\rm Pl}}\right)^4\left[1-\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
NI	1	1	$M^4\left[1+\cos\left(\frac{\phi}{f}\right)\right]$
ESI	1	1	$M^4\left(1-e^{-q\phi/M_{\rm Pl}}\right)$
PLI	1	1	$M^4e^{-\alpha\phi/M_{\rm Pl}}$
KMII	1	2	$M^4\left(1-\alpha\frac{\phi}{M_{\rm Pl}}e^{-\phi/M_{\rm Pl}}\right)$
HF1I	1	1	$M^4\left(1+A_1\frac{\phi}{M_{\rm Pl}}\right)^2\left[1-\frac{2}{3}\left(\frac{A_1}{1+A_1\phi/M_{\rm Pl}}\right)^2\right]$
CWI	1	1	$M^4\left[1+\alpha\left(\frac{\phi}{Q}\right)^4\ln\left(\frac{\phi}{Q}\right)\right]$
LI	1	2	$M^4\left[1+\alpha\ln\left(\frac{\phi}{M_{\rm Pl}}\right)\right]$
RpI	1	3	$M^4e^{-2\sqrt{2/3}\phi/M_{\rm Pl}}\left\|e^{\sqrt{2/3}\phi/M_{\rm Pl}}-1\right\|^{2p/(2p-1)}$
DWI	1	1	$M^4\left[\left(\frac{\phi}{\phi_0}\right)^2-1\right]^2$
MHI	1	1	$M^4\left[1-\mathrm{sech}\left(\frac{\phi}{\mu}\right)\right]$
RGI	1	1	$M^4\frac{(\phi/M_{\rm Pl})^2}{\alpha+(\phi/M_{\rm Pl})^2}$

Models: above and many, many more.....

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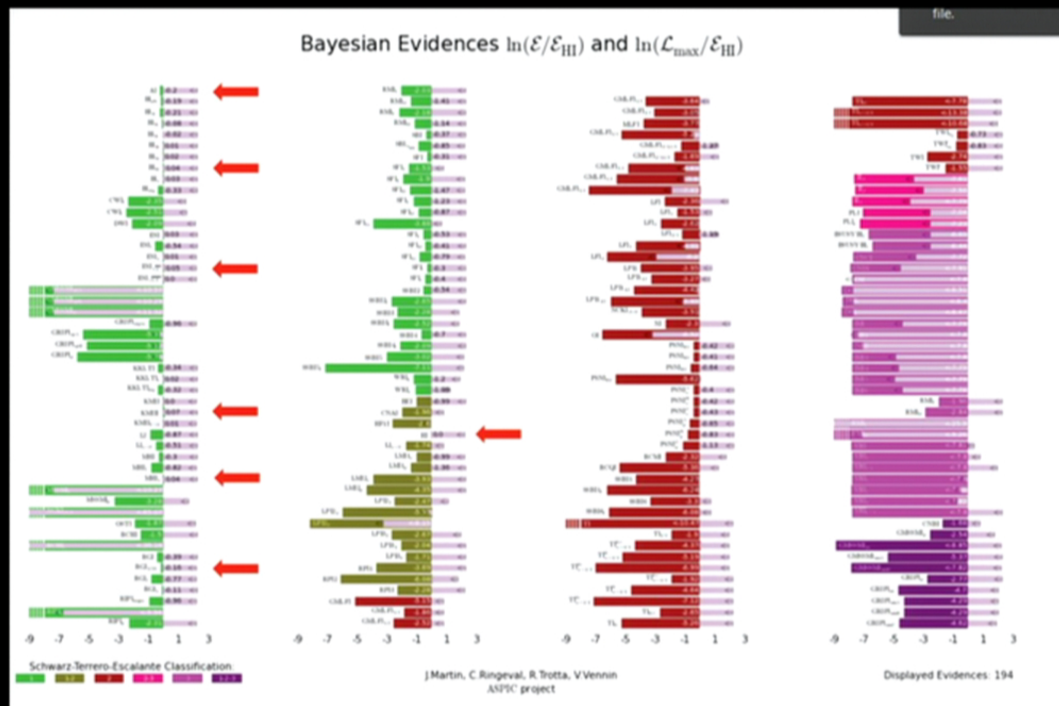
Acceleration Then

Martin, Ringeval & Vennin 2013

- W
- W
- U



A Bayesian comparison of models

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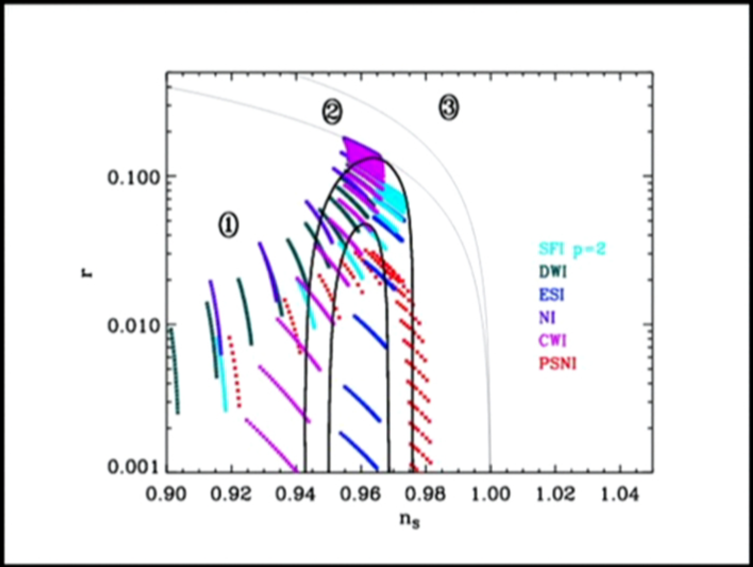
Acceleration Then

Martin, Ringeval & Vennin 2013

- W
- W
- U



Why some do better than others

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Acceleration Then

BMQRZ th/0111025

- W
- W
- U

Exponential potentials: progress on the η problem

$$V(\varphi) = V_0\left(1 - e^{-k\,\varphi} + \cdots\right)$$

so

$$\epsilon = e^{-2k\,\varphi} \quad \textit{and} \quad \eta = e^{-k\,\varphi}$$

so slow roll is same as large field

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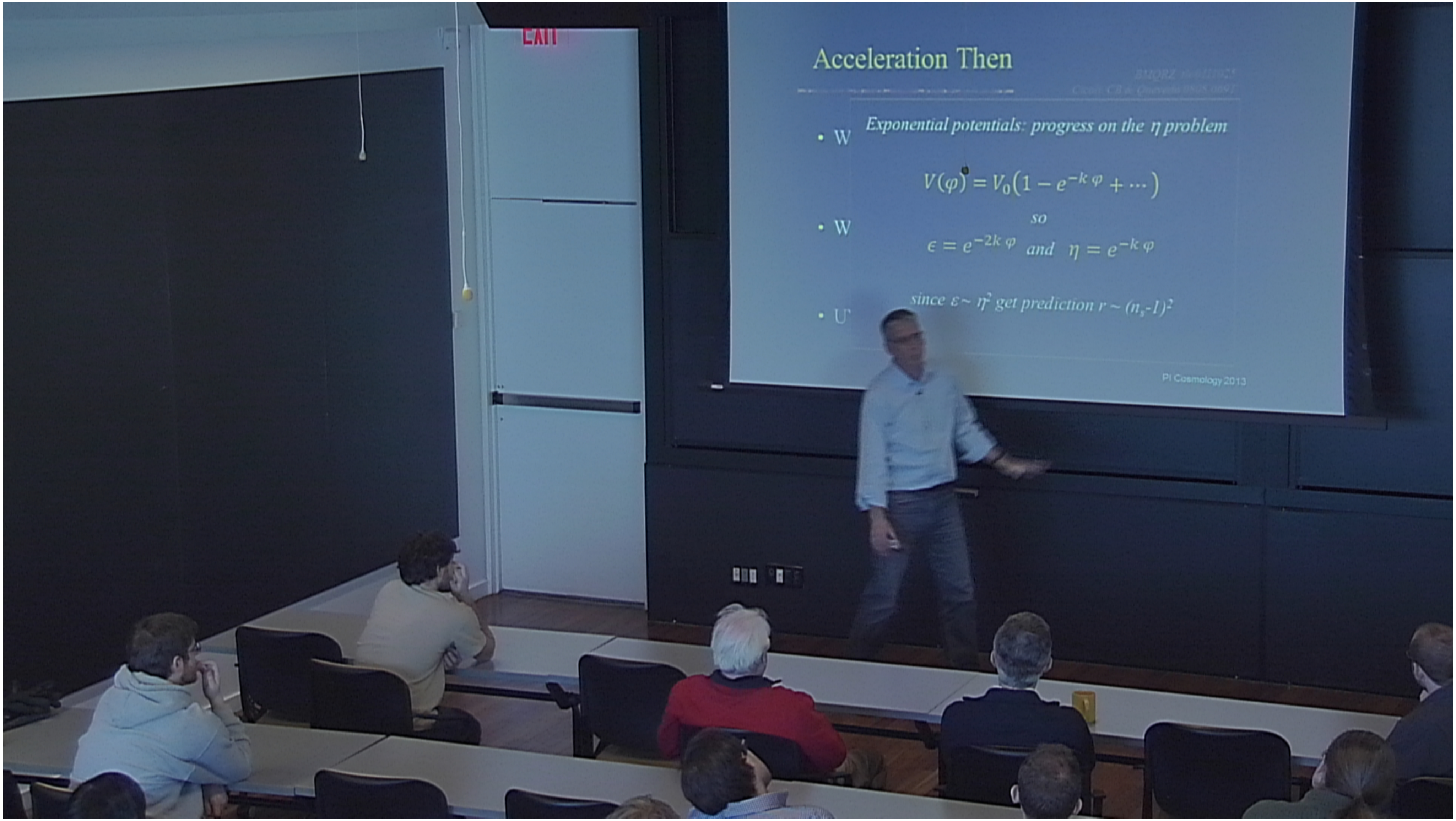
Acceleration Then
Exponential potentials: progress on the η problem
$V(\varphi) = V_0(1 - e^{-k\varphi} + \cdots)$
so
$\epsilon = e^{-2k\varphi}$ and $\eta = e^{-k\varphi}$
since $\varepsilon \sim \eta^2$ get prediction $r \sim (n_s-1)^2$
PI Cosmology 2013

Acceleration Then

- Where most agree
- What the data likes
- UV information?

PI Cosmology 2013

Acceleration Then

Giddings, Kachru & Polchinski 2001
KKLMMT th/0308055

- W
- W
- U

- *Most extensive exploration of UV embeddings of cosmology has been inflation into string theory, where modulus stabilization allows the issues to be crisply framed*
- *That's all very nice, but not predictive: you can get *anything* from string theory.*

PI Cosmology 2013

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Seems to favour small r and exponential potentials are generic for a broad class of inflatons

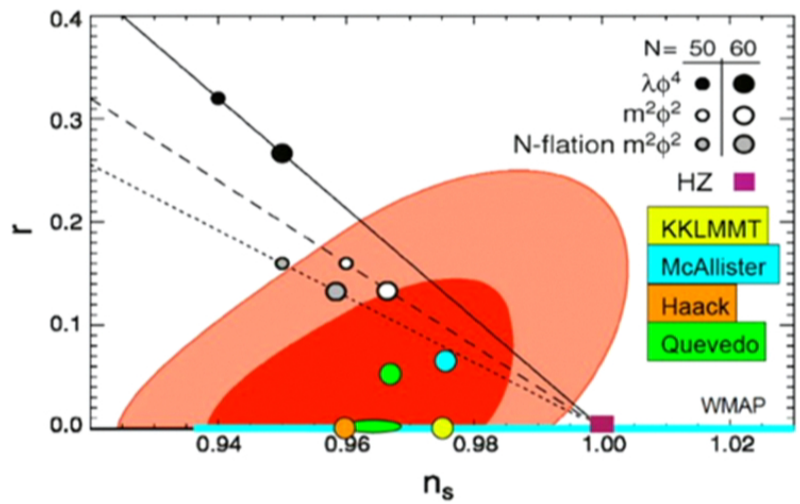
PI Cosmology 2013

Acceleration Then

- W
- W
- U

J. Polchinski ICHEP 08 summary talk

34th International Conference on High Energy Physics, Philadelphia, 2008



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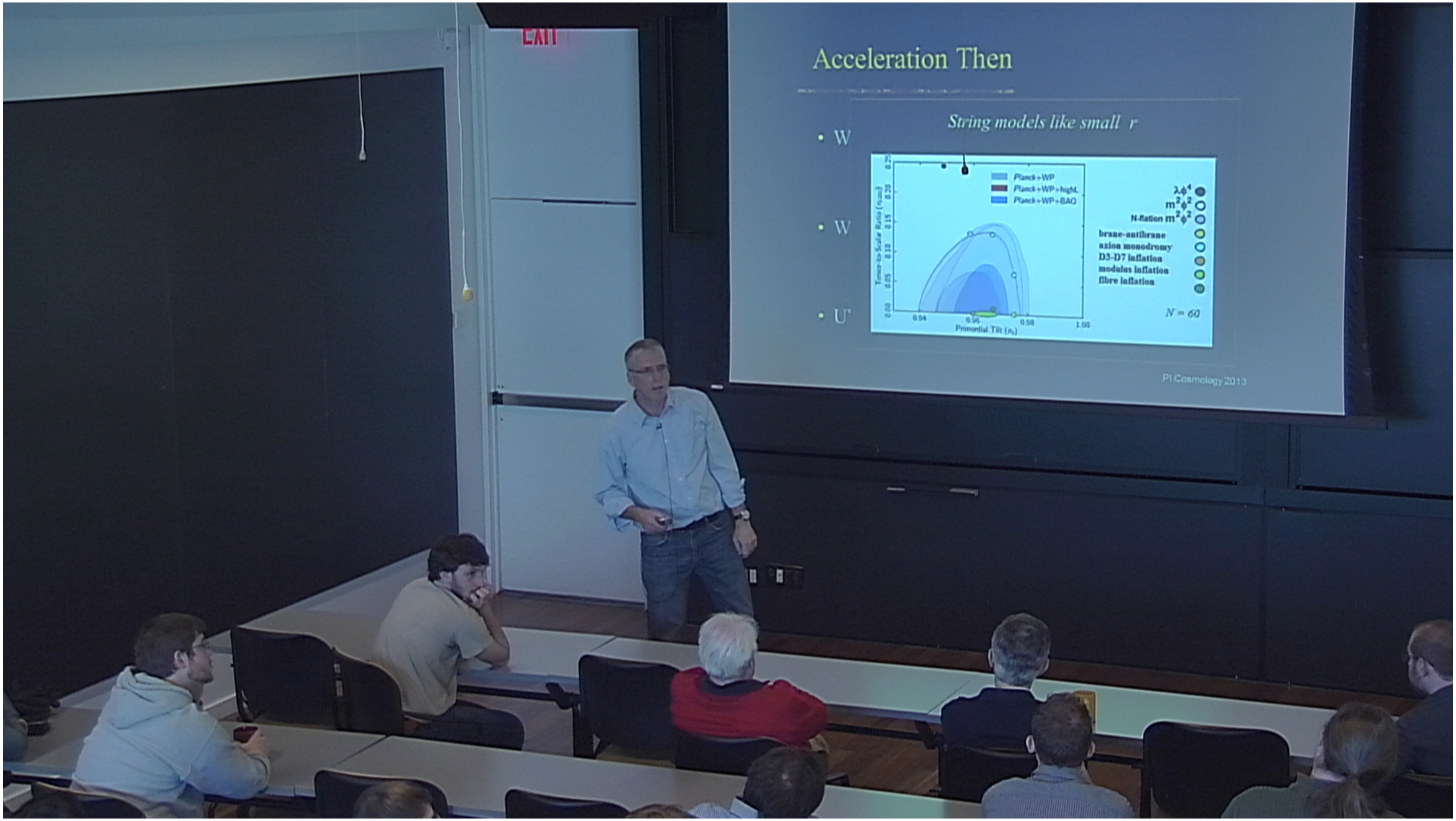
EXIT
Acceleration Then
• W
• W
String models like small r
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
0.94
0.96
0.98
1.00
0.10
0.15
0.20
0.25
$\lambda\phi^4$
$m^2\phi^2$
N-flation $m^2\phi^2$
brane-antibrane
axion monodromy
D3-D7 inflation
modulus inflation
fibre inflation
$N = 60$
PI Cosmology 2013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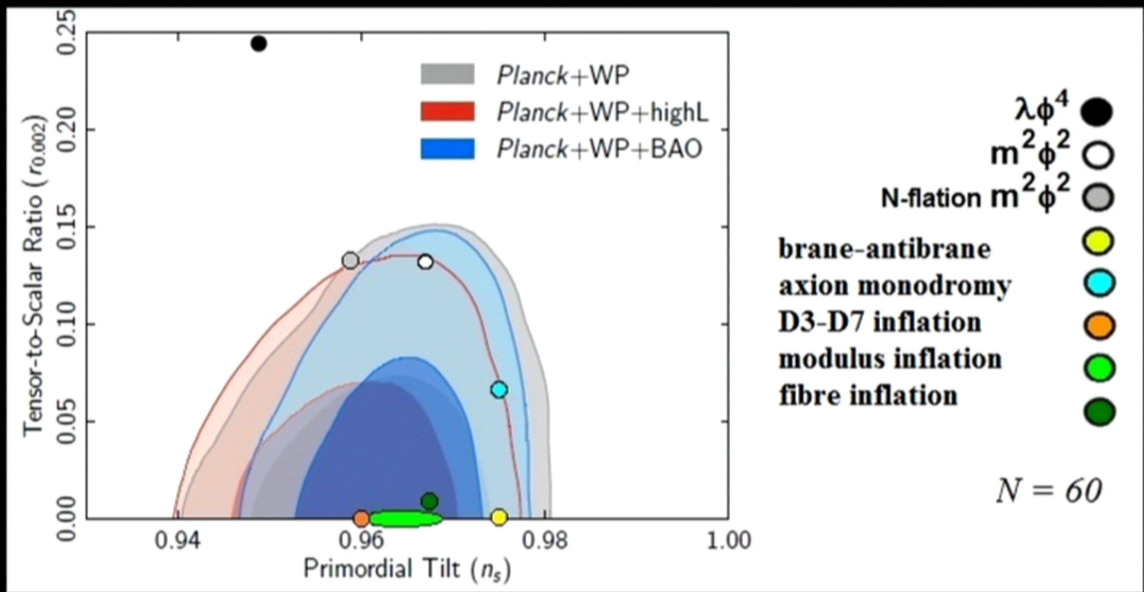
PI Cosmology 2013

Acceleration Then

- W
- W
- U

String models like small r



PI Cosmology 2013

Acceleration Then

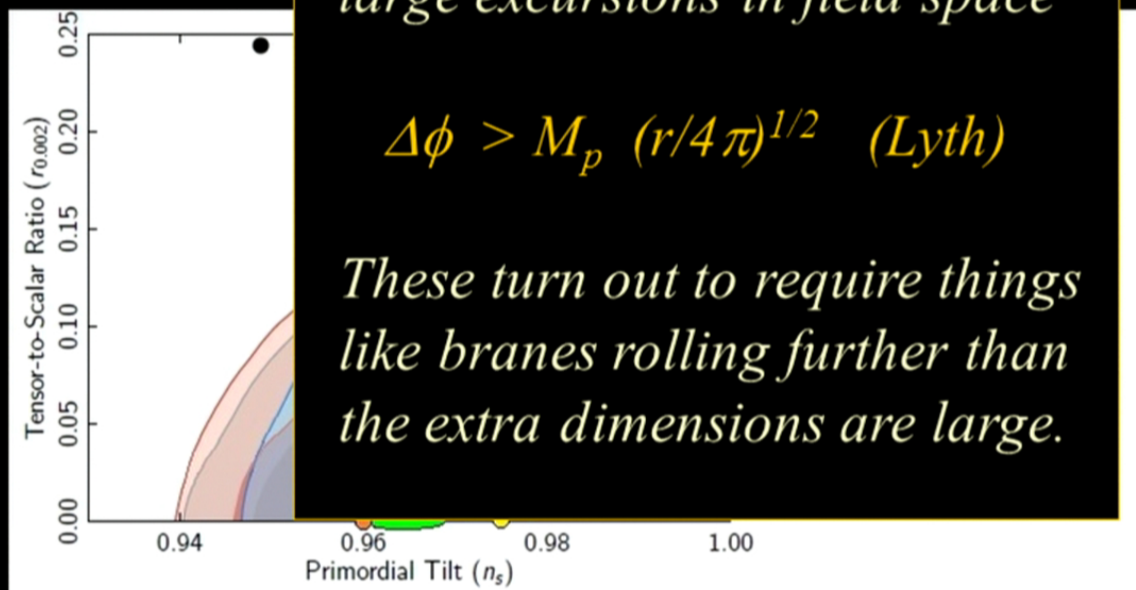
- W
- W
- U

S

Usually large r corresponds to large excursions in field space

$$\Delta\phi > M_p \ (r/4\pi)^{1/2} \quad (Lyth)$$

These turn out to require things like branes rolling further than the extra dimensions are large.



PI Cosmology 2013

Acceleration Then

BMQRZ th/0111025
Conlon & Quevedo th/0509012
Cicoli, CB & Quevedo 0808.0691

- W
- W
- U

Exponential potentials generically arise when extra-dimensional size, r, is the inflaton

$$V(\varphi) = V_0\left(1 - \frac{1}{r^p} + \cdots\right)$$
$$= V_0\left(1 - e^{-k\,\varphi} + \cdots\right)$$

$$since\ L = M^2\frac{(\partial r)^2}{r^2}\ implies\ \frac{r}{\ell} = e^{\varphi/M}$$

PI Cosmology 2013

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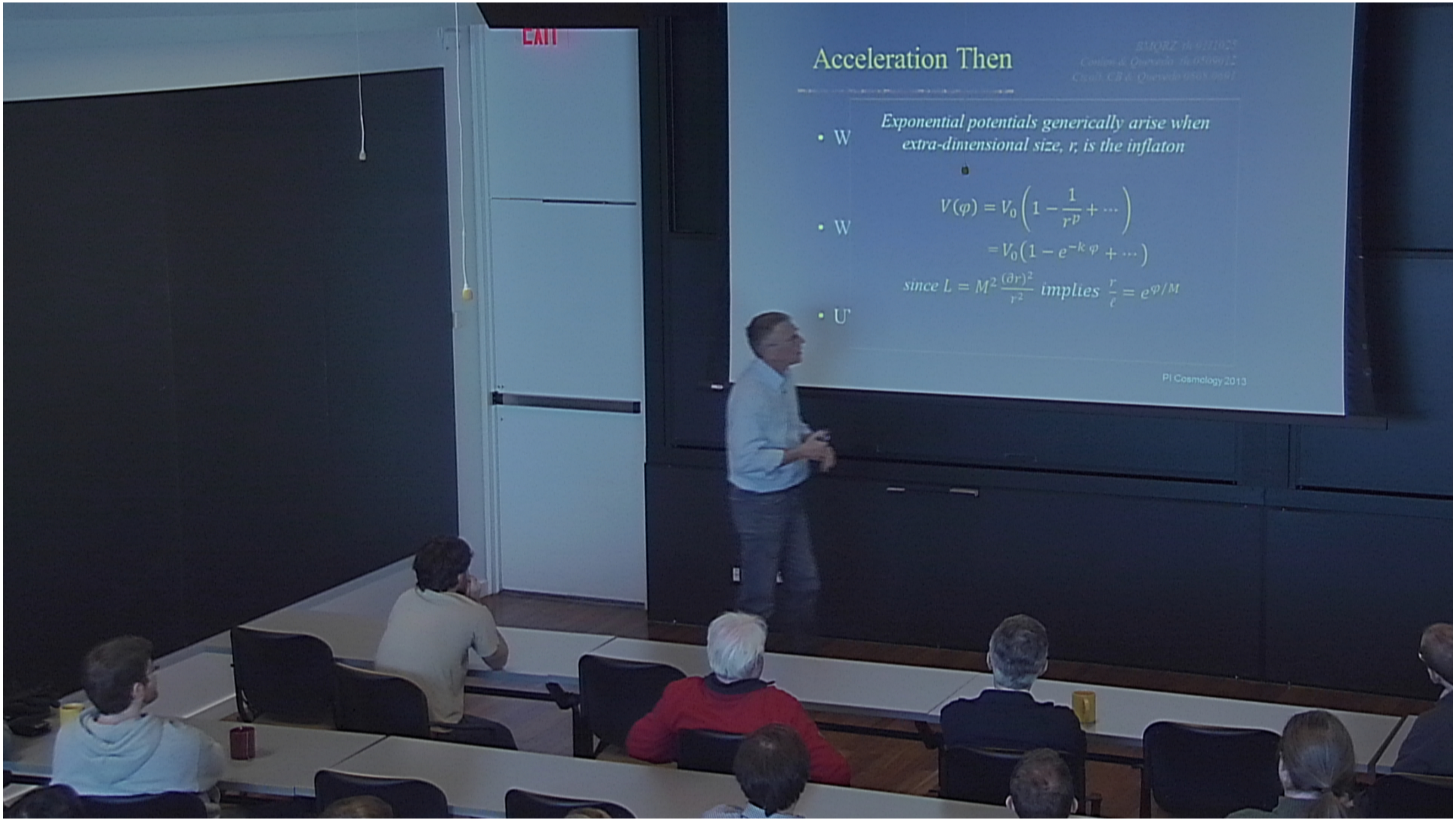
PI Cosmology 2013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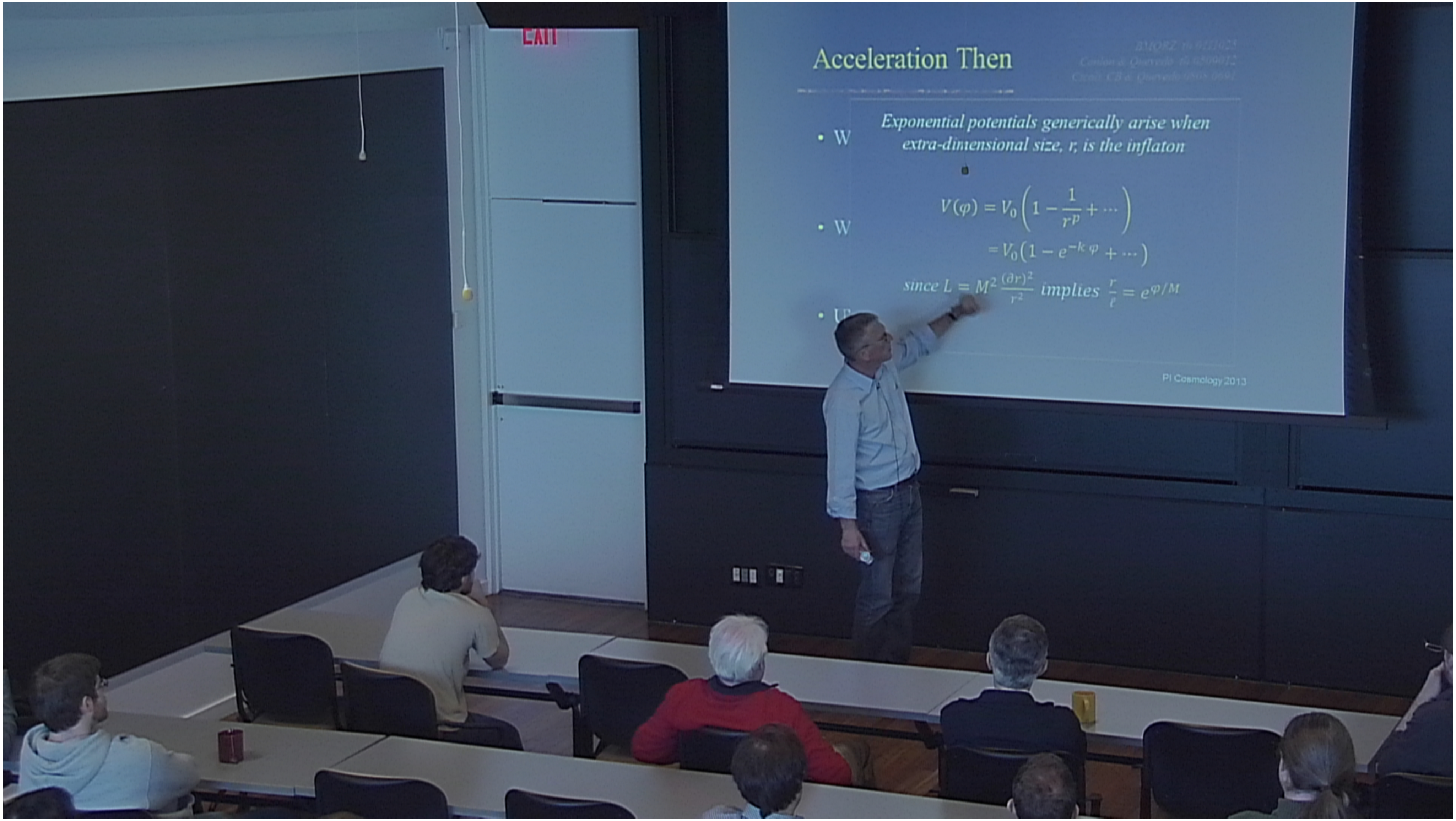
PI Cosmology 2013



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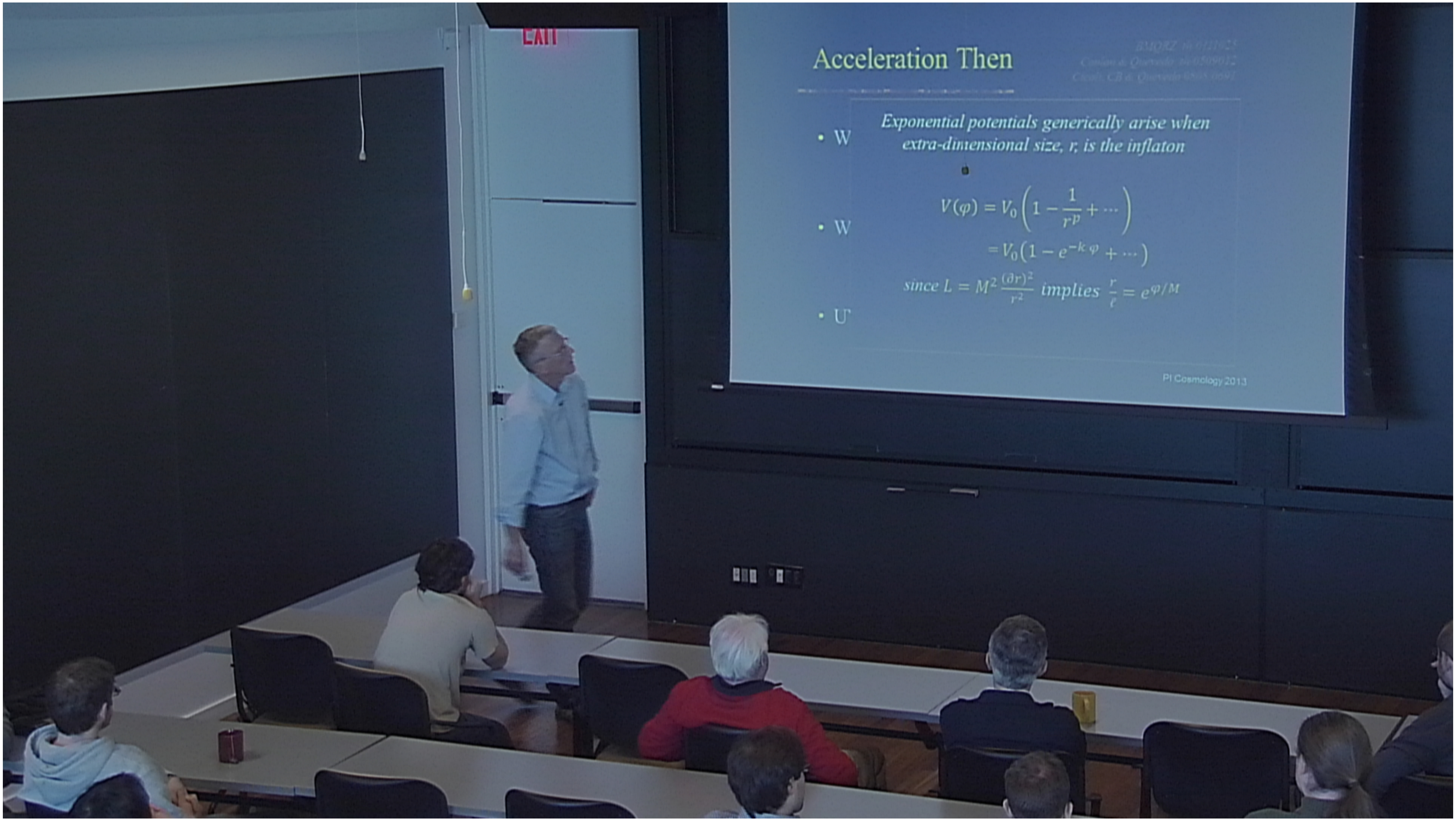
EXIT
Acceleration Then
• W
• W
• U
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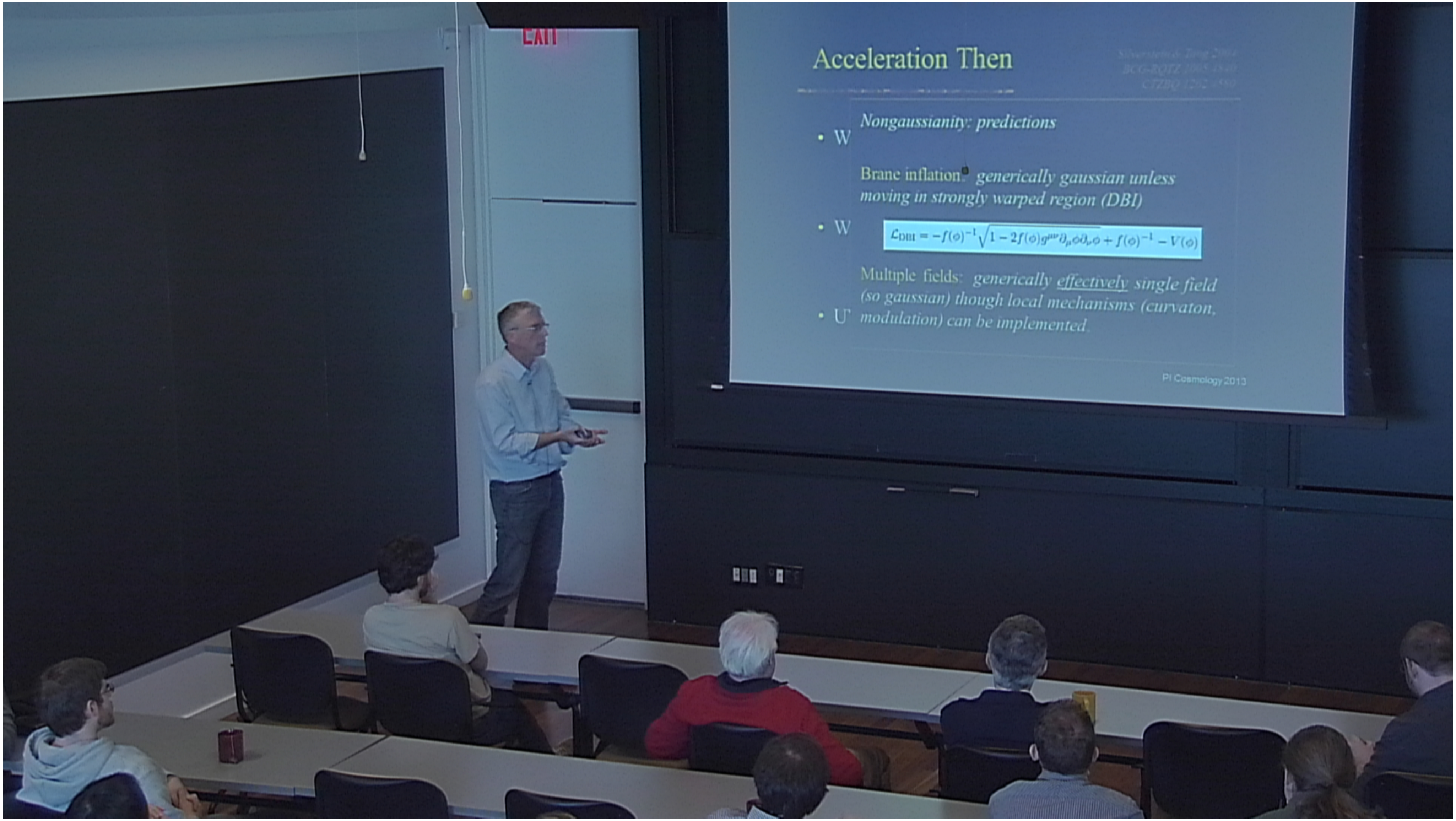
Acceleration Then
Nongaussianity: predictions
Brane inflation: generically gaussian unless moving in strongly warped region (DBI)
$\mathcal{L}_{\rm DBI} = -f(\phi)^{-1}\sqrt{1-2f(\phi)g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi} + f(\phi)^{-1} - V(\phi)$
Multiple fields: generically effectively single field (so gaussian) though local mechanisms (curvaton, modulation) can be implemented.
PI Cosmology 2013

Acceleration Then

Silverstein & Tong 2004
BCG-RQTZ 1005.4840
CTZBQ 1202.4580

- W
- W
- U

Nongaussianity: predictions

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PI Cosmology 2013

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Acceleration Then

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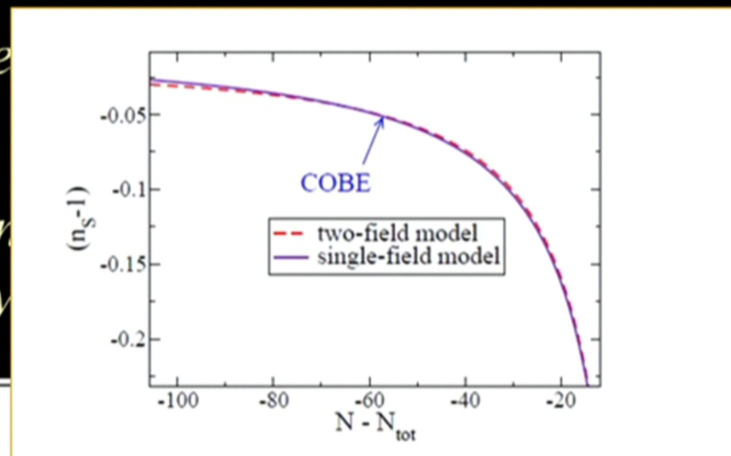
CTZBQ 1202.4580

- W
- W
- U

Nongaussianity: pre

Brane inflation: *ge*
moving in strongly v

$\mathcal{L}_{\mathrm{DBI}} = -f(\phi)^{-1}\sqrt{1}$

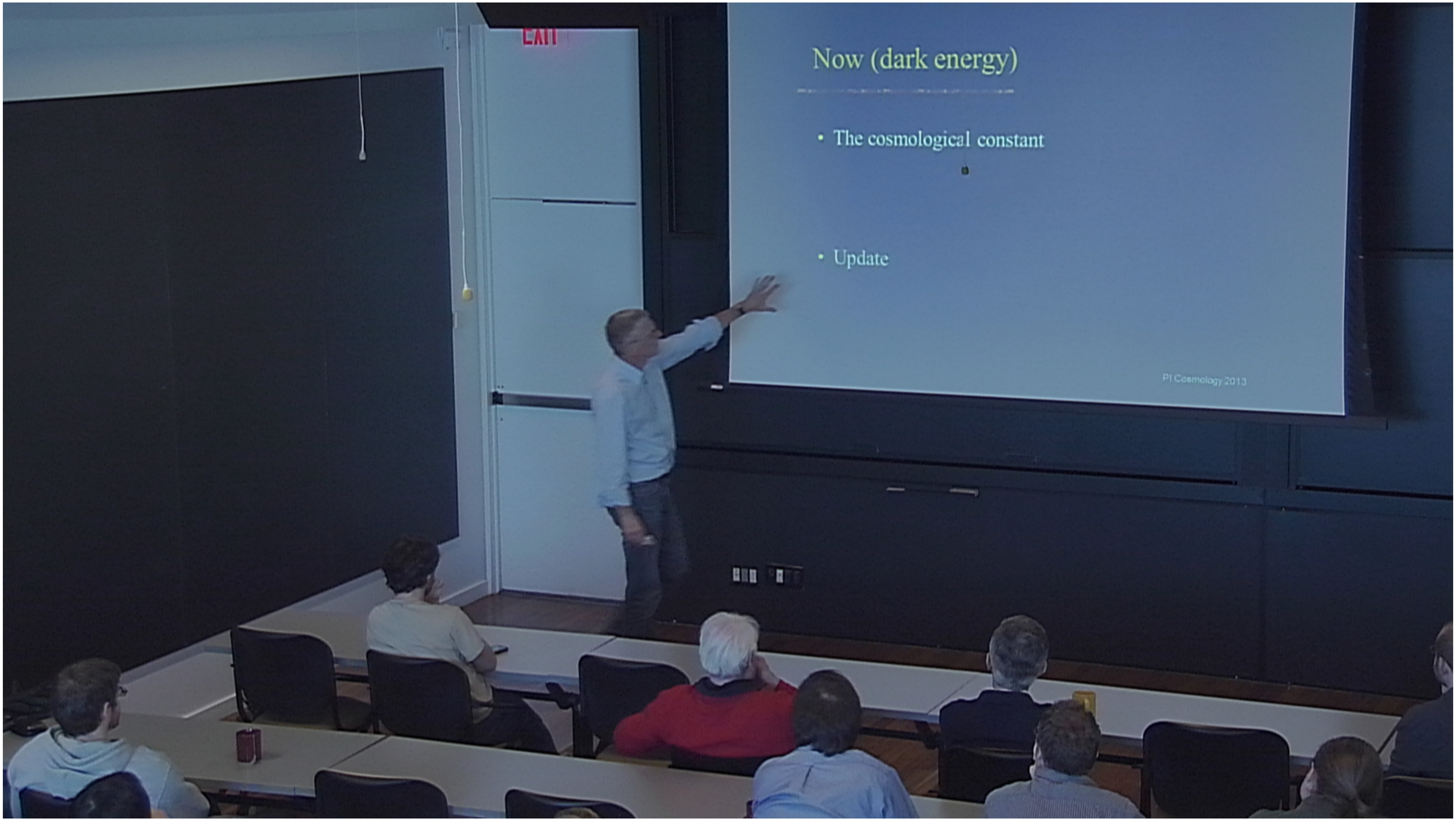


Multiple fields: *generically __effectively__ single field (so gaussian) though local mechanisms (curvaton, modulation) can be implemented.*

Now

with L. van Nierop & M. Williams

and S. Parameswaran & A. Salvio,


EXIT
Now (dark energy)
• The cosmological constant
• Update
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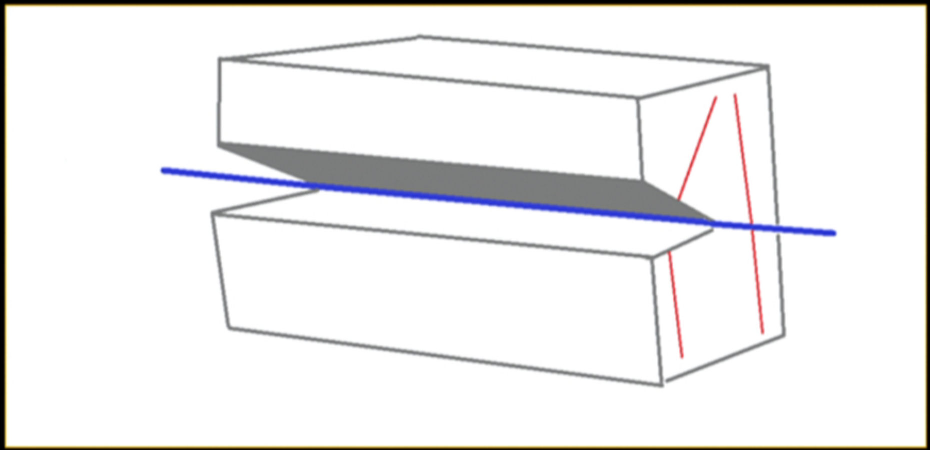
Now (dark energy)

Vilenkin

- Th

- Towards a solution: *higher dimensions can break this link between vacuum energy and curvature (eg cosmic string)*



- Th

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Now (dark energy)

Chen, Luty & Ponton
Carroll & Guica
Aghababaie et al

- Th

- A higher-dimensional analog:
  - Similar *(classical)* examples also with a 4D brane in two extra dimensions: *e.g. the rugby ball*

$$R = -2\kappa^2 \sum T_i \;\; \delta^2(x_i) + R_{smooth}$$

- Th

$$\begin{aligned} \text{4D cc} &= \sum T_i + \frac{1}{2\kappa^2}\int d^2x\, R + \cdots \\ &= \sum T_i + \frac{1}{2\kappa^2}\int d^2x\, \nabla^2\phi \\ &= 0 \;\; \text{for all } T_i \end{aligned}$$

$$\textit{if } \; n\cdot\nabla\phi = 0 \textit{ at branes}$$

$\boxed{\textit{Back-reaction is crucial}}$

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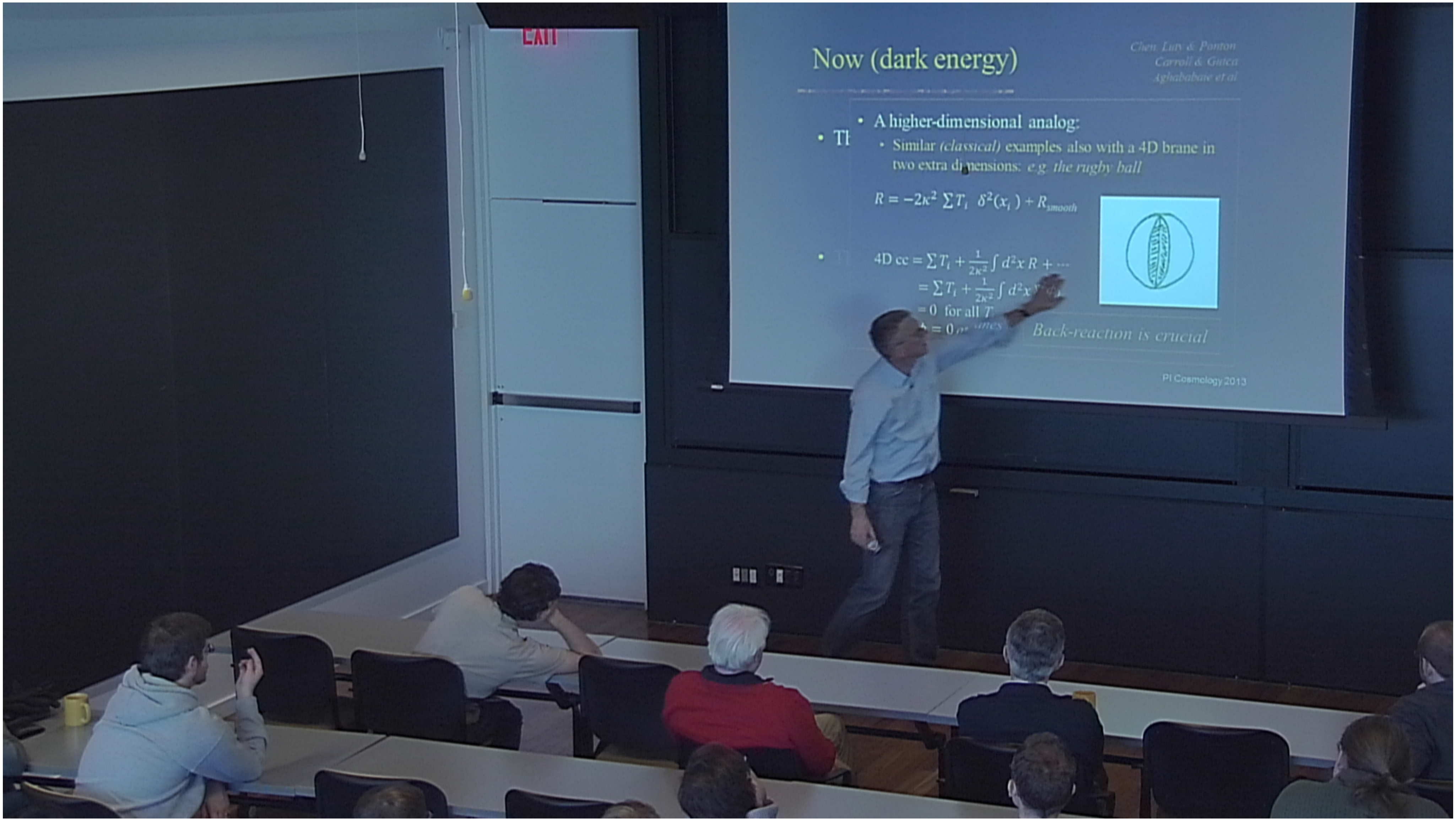
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PI Cosmology 2013

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- Th
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Back-reaction is crucial

PI Cosmology 2013

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- Th

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  - Similar *(classical)* examples also with a 4D brane in two extra dimensions: *e.g. the rugby ball*

$$R = -2\kappa^2 \sum T_i \;\; \delta^2(x_i) + R_{smooth}$$

$$\begin{aligned} \text{4D cc} &= \sum T_i + \frac{1}{2\kappa^2}\int d^2x\, R + \cdots \\ &= \sum T_i + \frac{1}{2\kappa^2}\int d^2x\, \nabla^2\phi \\ &= 0 \quad \text{for all } T_i \end{aligned}$$

$$\textit{if } \; n\cdot\nabla\phi = 0 \textit{ at branes}$$

Back-reaction is crucial

- Th

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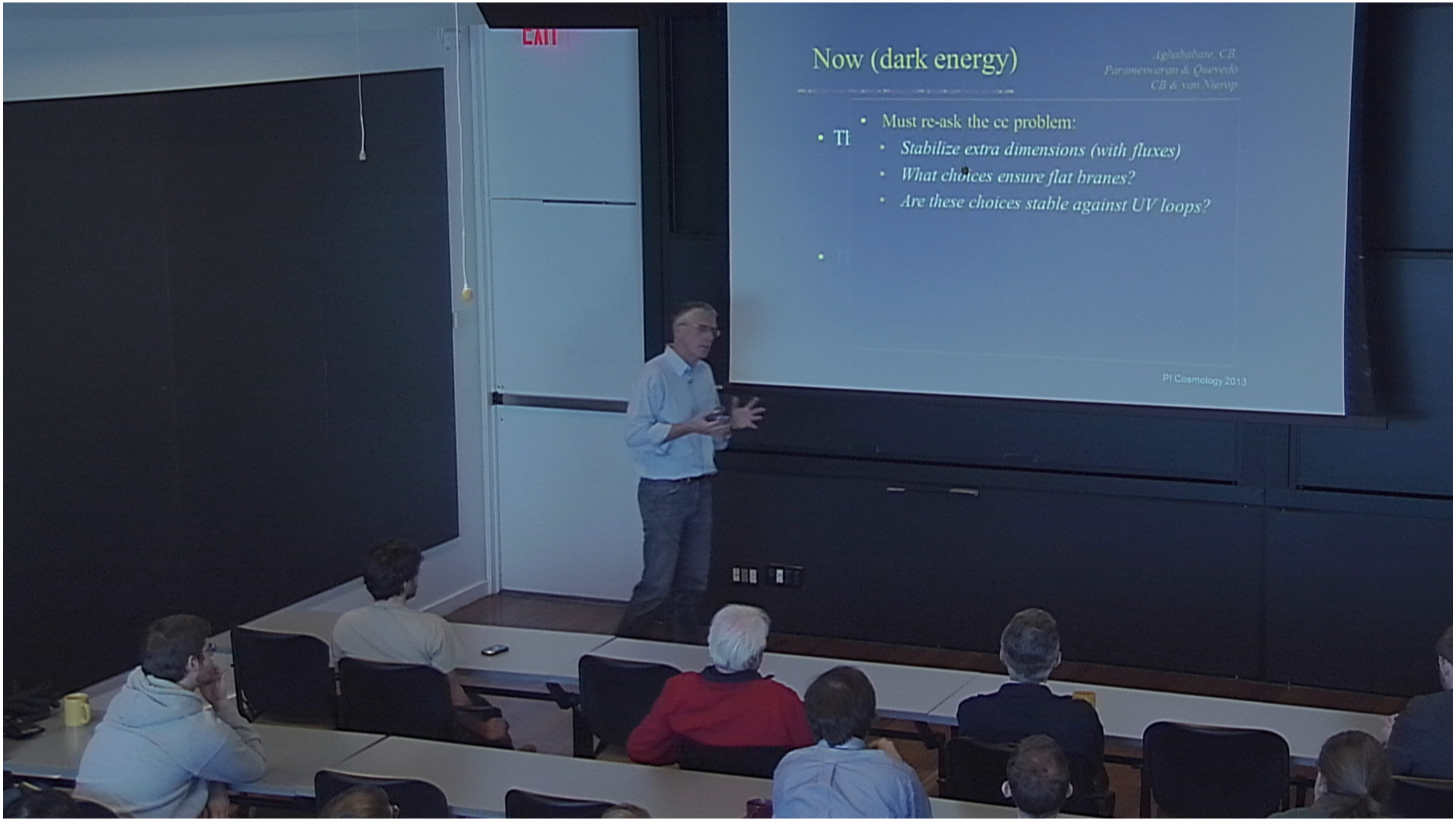

Now (dark energy)
Aghababaie, CB
Parameswaran & Quevedo
CB & van Nierop
Must re-ask the cc problem:
Stabilize extra dimensions (with fluxes)
What choices ensure flat branes?
Are these choices stable against UV loops?
PI Cosmology 2013

Now (dark energy)

Aghababaie, CB,
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CB & van Nierop

- Th

- Must re-ask the cc problem:
  - *Stabilize extra dimensions (with fluxes)*
  - *What choices ensure flat branes?*
  - *Are these choices stable against UV loops?*
- *Upshot:*
  - *Generically: NO…BUT*
  - *BUT, with supersymmetric bulk can have cc ~ KK scale << scale m on branes*

- Th

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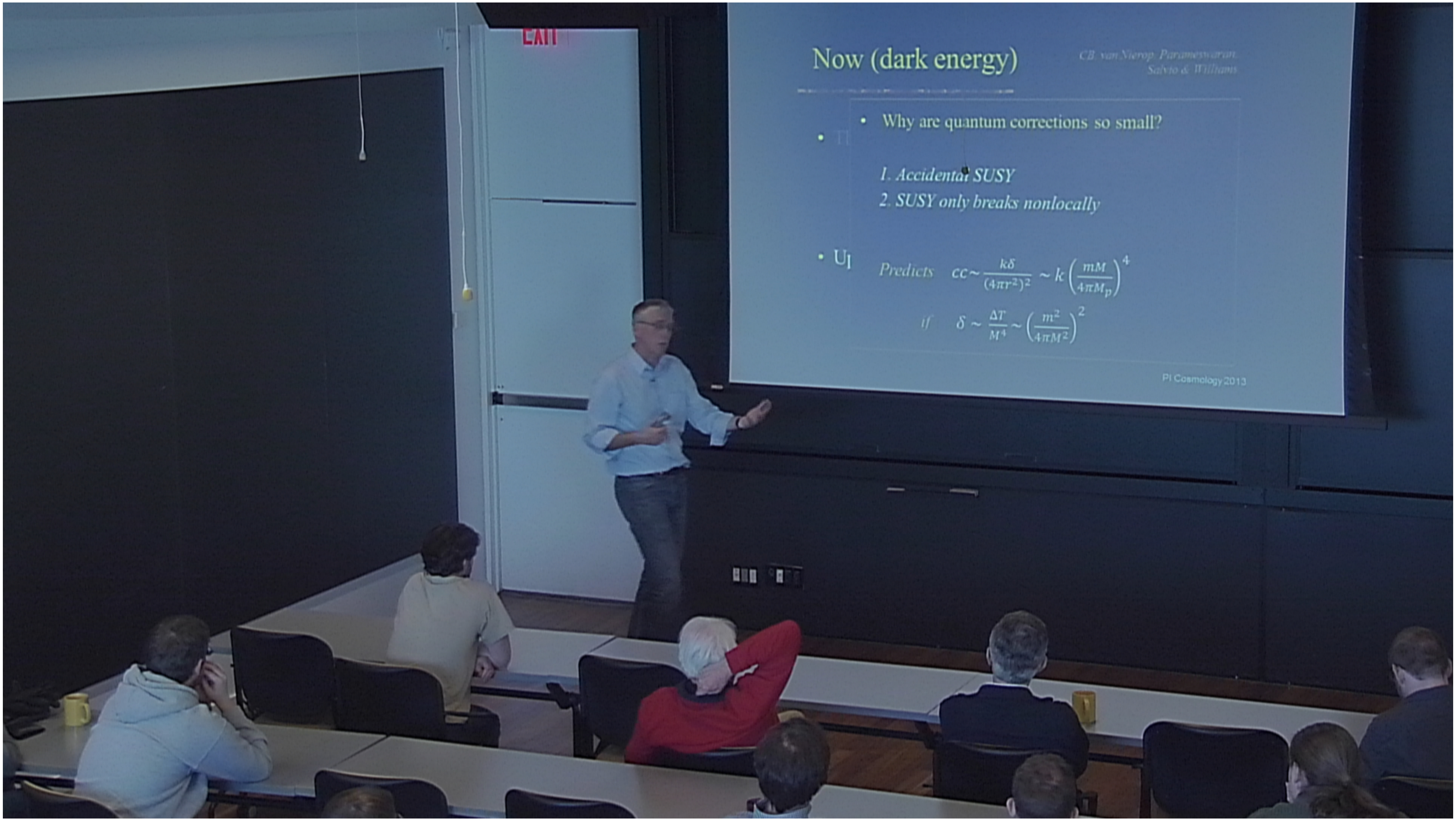
Now (dark energy)
CB, van Nierop, Parameswaran, Salvio & Williams
Why are quantum corrections so small?
1. Accidental SUSY
2. SUSY only breaks nonlocally
Predicts $cc \sim \frac{k\delta}{(4\pi r^2)^2} \sim k\left(\frac{mM}{4\pi M_p}\right)^4$
if $\delta \sim \frac{\Delta T}{M^4} \sim \left(\frac{m^2}{4\pi M^2}\right)^2$
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Now (dark energy)

CB, van Nierop, Parameswaran, Salvio & Williams

- Th

- Why are quantum corrections so small?

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- U

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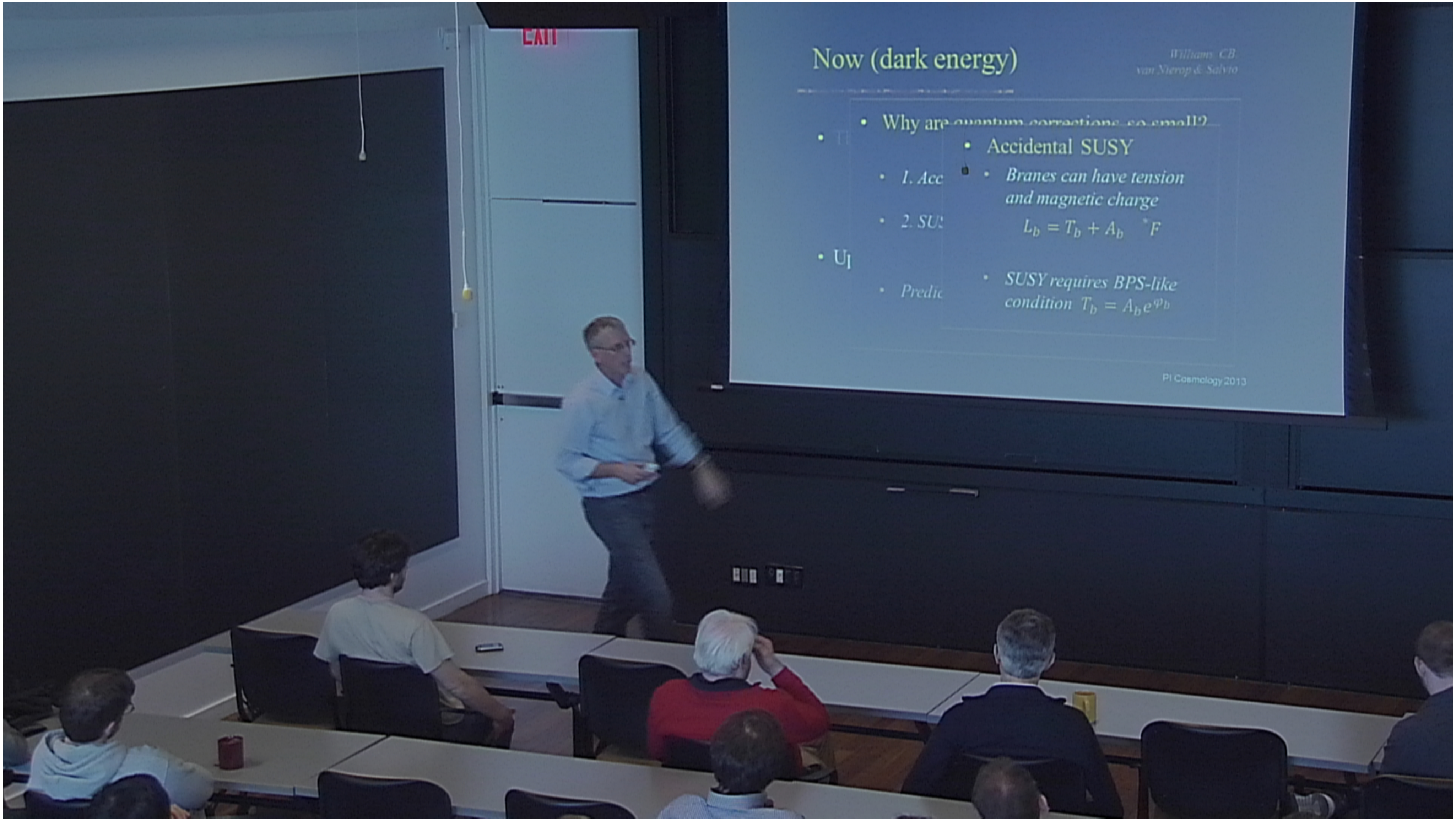
PI Cosmology 2013


EXIT
Now (dark energy)
Williams, CB
van Nierop & Salvio
Why are quantum corrections so small?
Accidental SUSY
Branes can have tension
and magnetic charge
$L_b = T_b + A_b \ {}^*F$
SUSY requires BPS-like
condition $T_b = A_b e^{\varphi_b}$
1. Acc
2. SU
U
Predic
PI Cosmology 2013

Now (dark energy)

Williams, CB,
van Nierop & Salvio

- Th
- Up

- Why are quantum corrections so small?
  - *1. Acc*
  - *2. SUS*
  - *Predic*

- Accidental SUSY
  - *Branes can have tension and magnetic charge*

$$L_b = T_b + A_b \;\; {}^*F$$

  - *SUSY requires BPS-like condition* $T_b = A_b e^{\varphi_b}$

PI Cosmology 2013

Now (dark energy)

Williams, CB,
van Nierop & Salvio

- Th
- Why are quantum corrections so small?
  - *1. Acc*
- Accidental SUSY
  - *Branes can have tension and magnetic charge*

$$L_b = T_b + A_b \; {}^*F$$

Flat direction of bulk, evaluated at b

SUSY requires BPS-like condition $T_b = A_b e^{\varphi_b}$

- U
  - *Predic*

PI Cosmology 2013

"...when you have eliminated the impossible, whatever remains, however improbable, must be the truth."

A. Conan Doyle