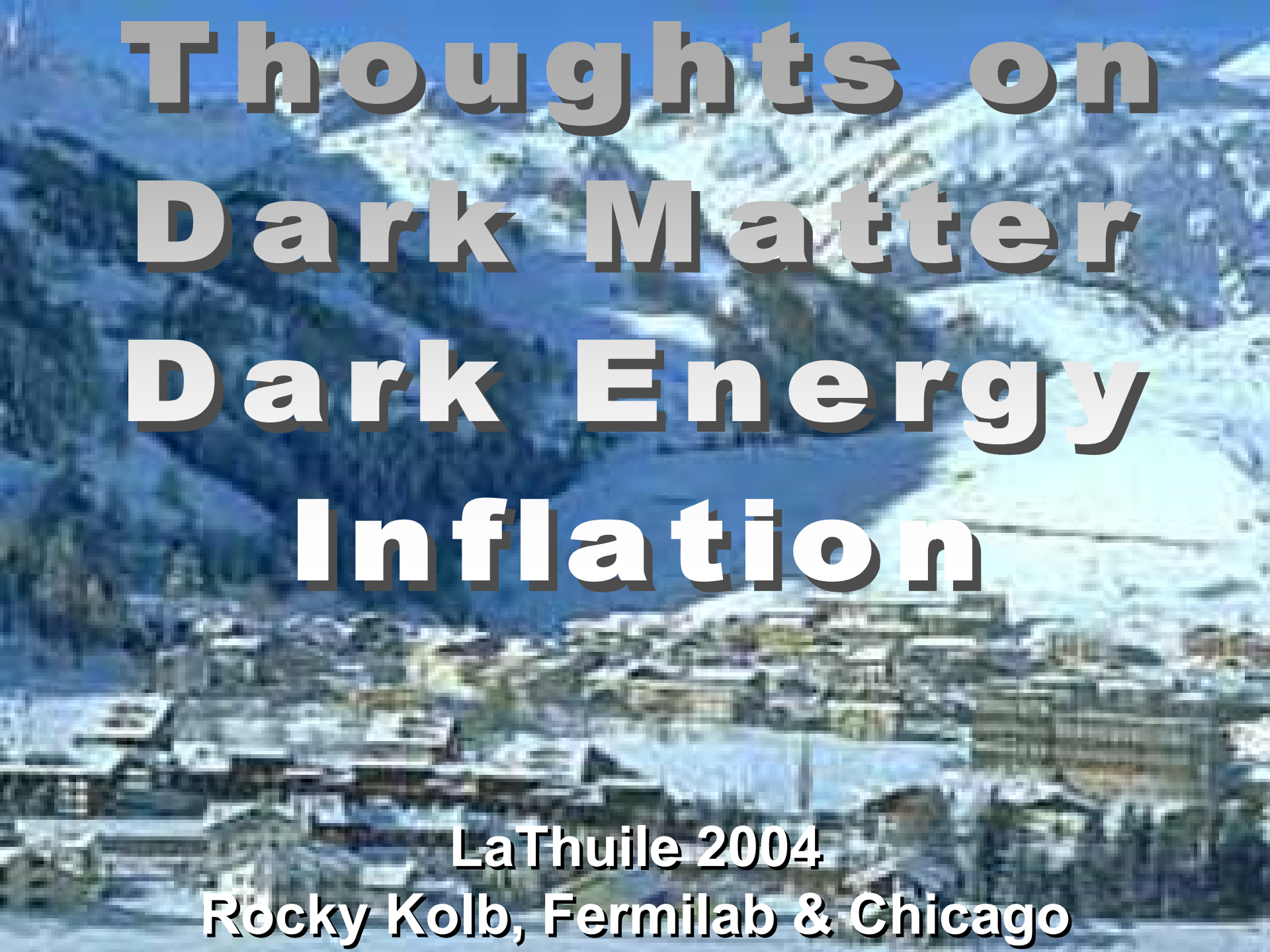


Thoughts on Dark Matter Dark Energy Inflation

LaThuile 2004

Rocky Kolb, Fermilab & Chicago

ΛCDM

Mission accomplished …

… or premature jubilation?

What We "Know" *

1) The matter density is dominated by cold dark matter …
which we know nothing about!

2) The perturbations arise from inflationary dynamics, which depends on particle physics at high energies …
which we know nothing about!

3) The universe is dominated by a cosmological term (dark energy, funny energy, quintessence, polenta, cosmological constant, cosmo-illogical constant, ….) …
which we know less than nothing about!

4) The baryon asymmetry arises in the GUT or EWK era through B, CP, and equilibrium violation
EWK doesn't seem to work….GUT scenarios are complex!

* It ain't what you don't know, it's what you know that ain't so!

Dark matter

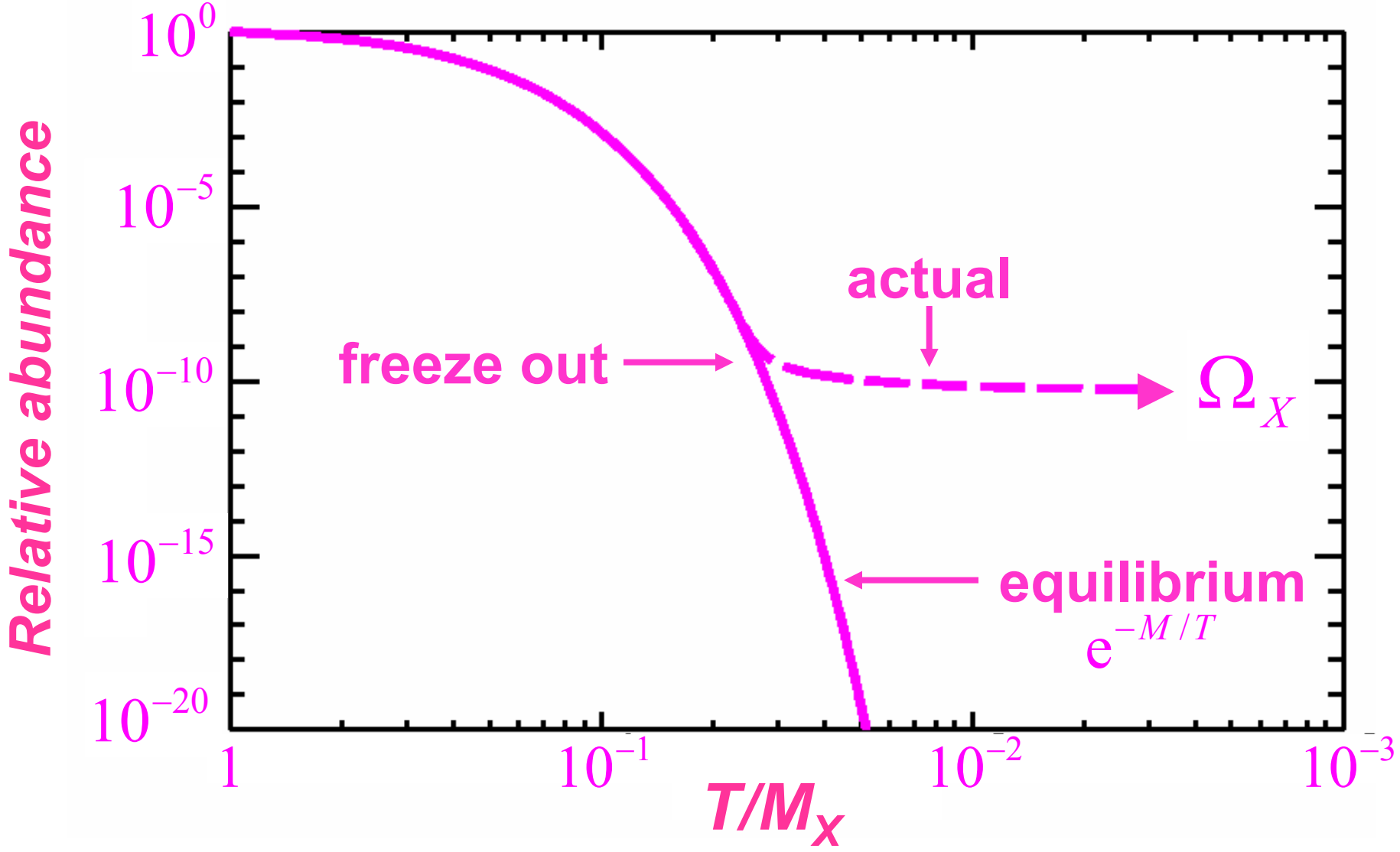
What is dark matter?

“In questions like this, truth is only to be had by laying together many variations of error.”

-- Virginia Wolf

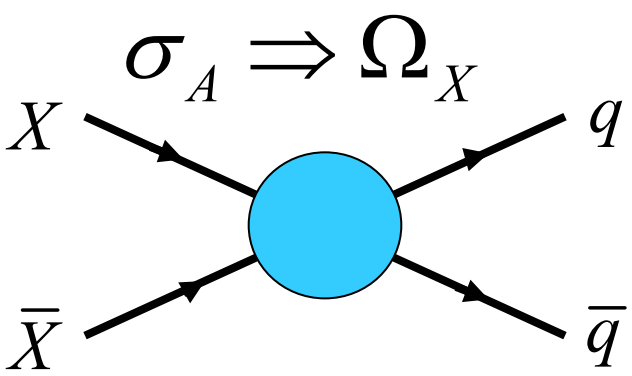
A Room of Ones Own

Cold thermal relics

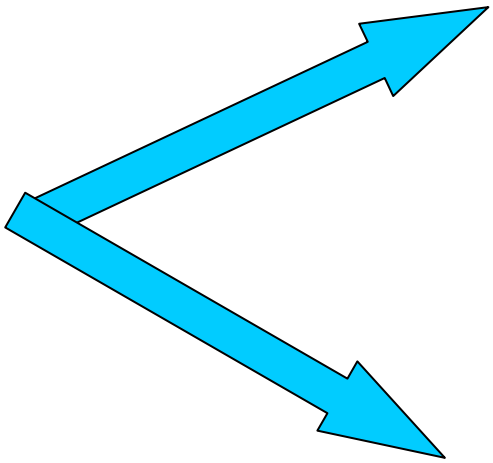


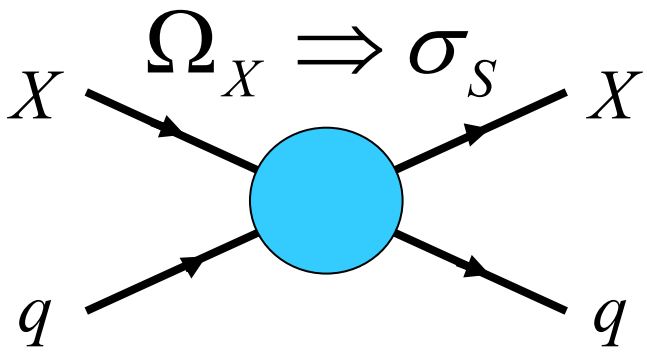
$\Omega_X \propto \sigma_A^{-1}$ *(independent of mass)*

Cold thermal relics $\Omega_X \propto \langle \sigma_A v \rangle^{-1}$

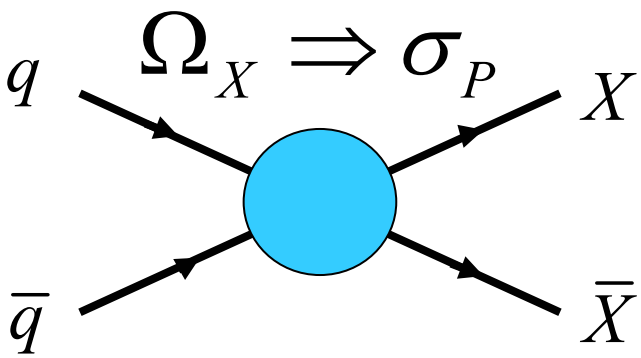


$X + \bar{X} \rightarrow q + \bar{q}$





$X + q \rightarrow X + q$



$q + \bar{q} \rightarrow X + \bar{X}$

Cold thermal relics

- **SUSY LSP (neutralino)**
- **Direct detection**

  More than a dozen experiments
- **Indirect detection**

  Annihilation in sun, Earth, galactic center, subclumps, . . .

  Neutrinos, positrons, antiprotons, γ rays, . . .

  (Role of halo substructure?)
- **Production at accelerators**

The nature of dark matter is a complex natural phenomenon.

The neutralino is a simple, elegant, compelling explanation.

“For every complex natural phenomenon there is a simple, elegant, compelling, but wrong explanation.”

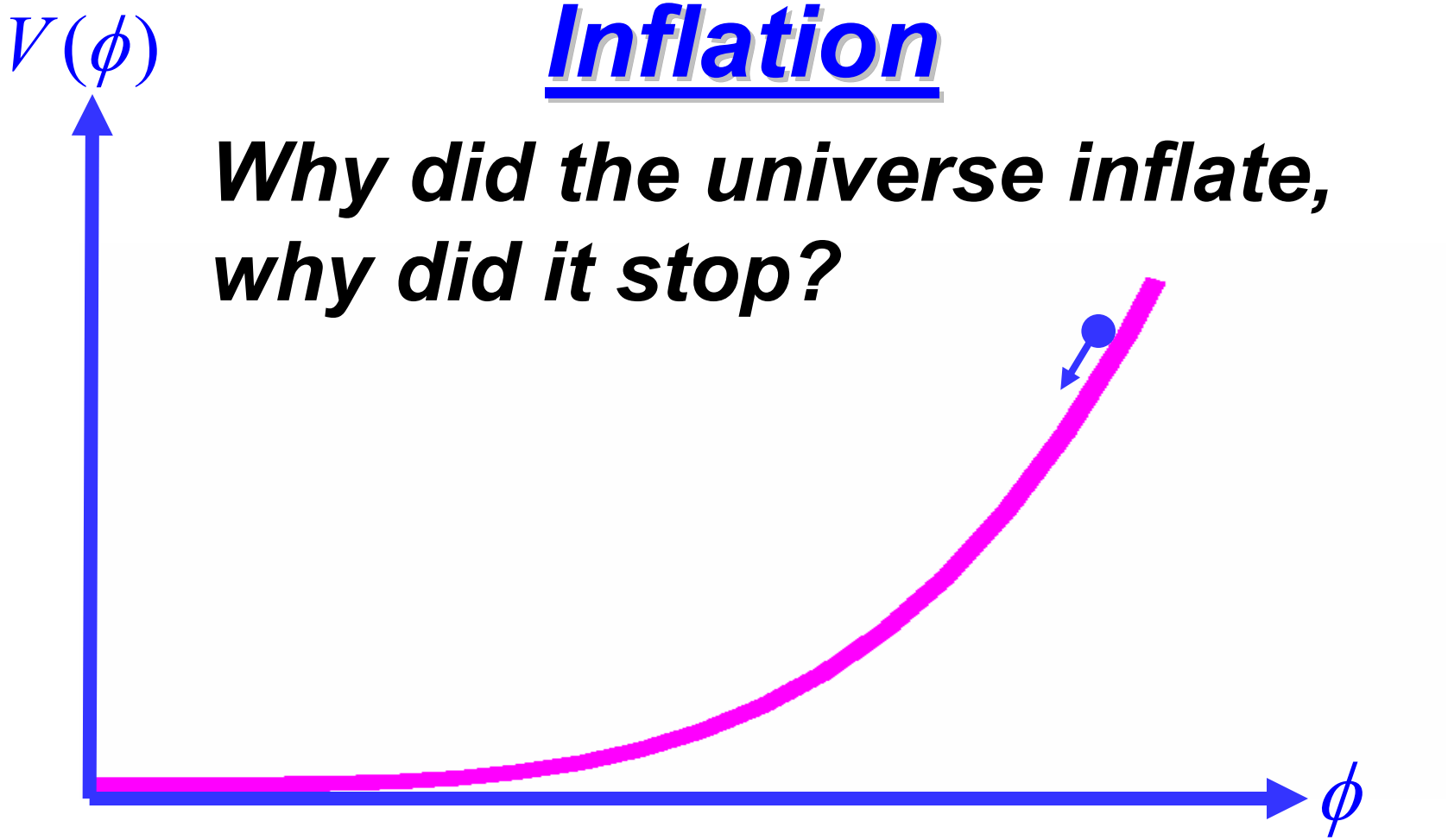
- Tommy Gold

Nonbaryonic dark matter

- **neutrinos** **(hot dark matter)**
- **sterile neutrinos, gravitinos** **(warm dark matter)**
- **LSP (neutralino, axino, …)** **(cold dark matter)**
- **LKP (lightest Kaluza-Klein particle)**
- **axions, axion clusters**
- **solitons (Q-balls; B-balls; Odd-balls, Screw-balls….)**
- **supermassive wimpzillas**

Mass range	Interaction strength range
10^{-6} eV $(10^{-40}$ g) axions	Noninteracting: wimpzillas
$10^{-8} M_{\odot}$ $(10^{25}$ g) axion clusters	Strongly interacting: B balls

Inflation



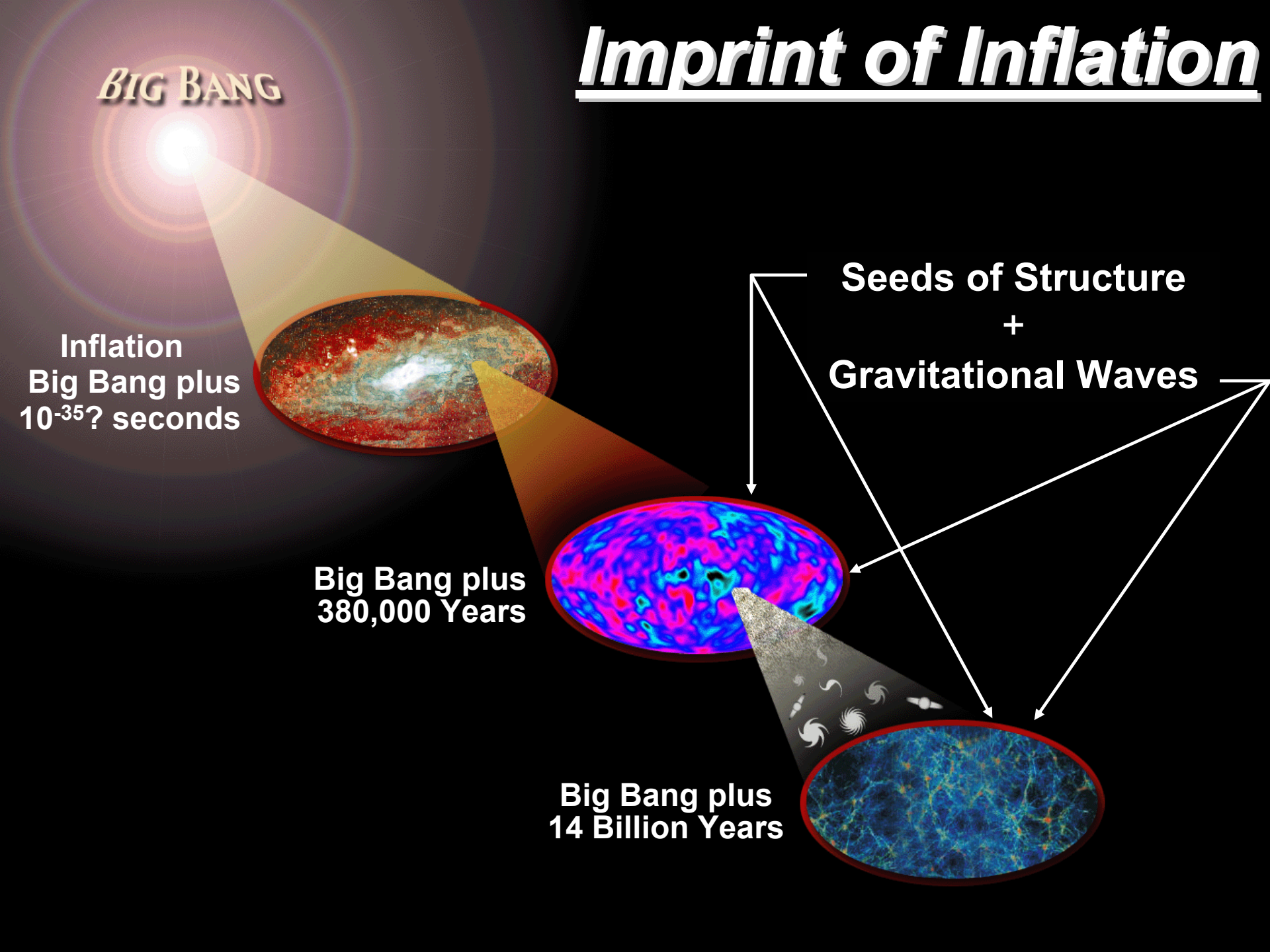
Why did the universe inflate, why did it stop?

"In questions like this, truth is only to be had by laying together many variations of error."

-- Virginia Wolf

A Room of Ones Own

Imprint of Inflation



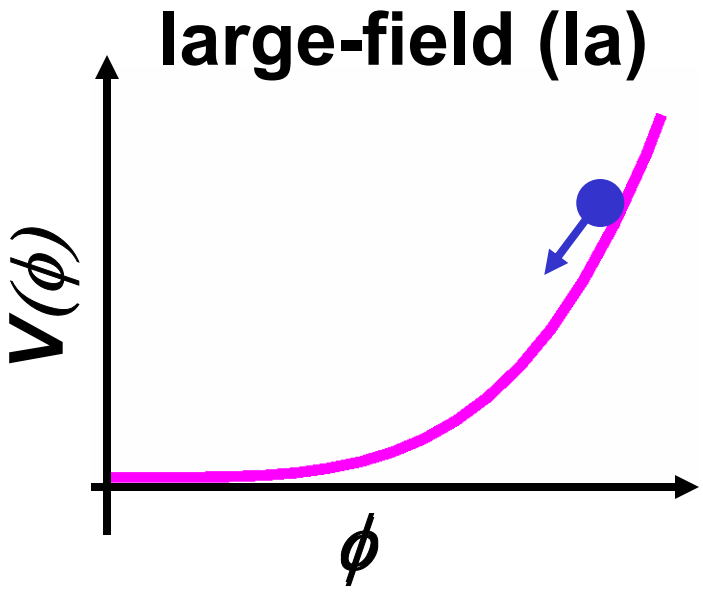
Model Classification*

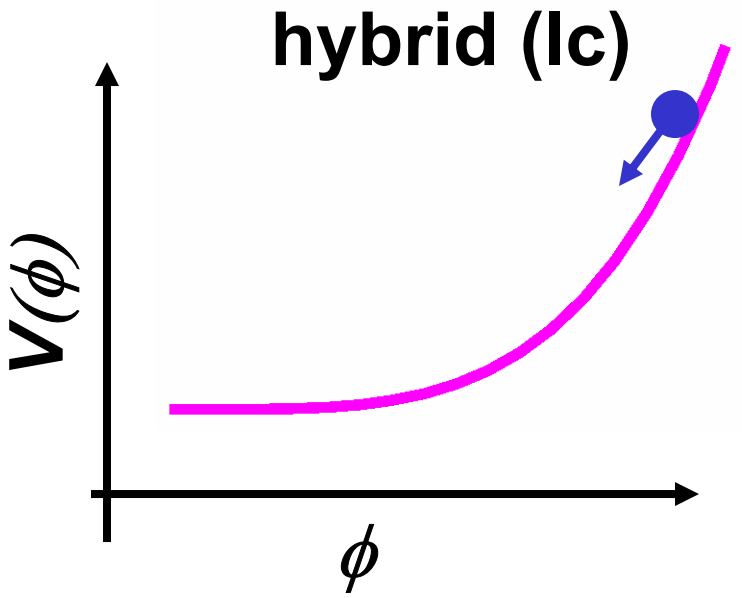
Type I: single-field, slow-roll models
(or models that can be expressed as such)

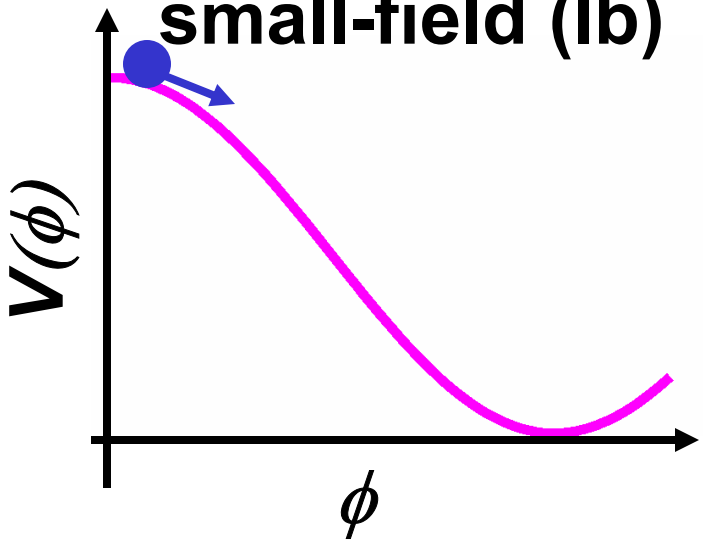
- **Type Ia:** large-field models
- **Type Ib:** small-field models
- **Type Ic:** hybrid models

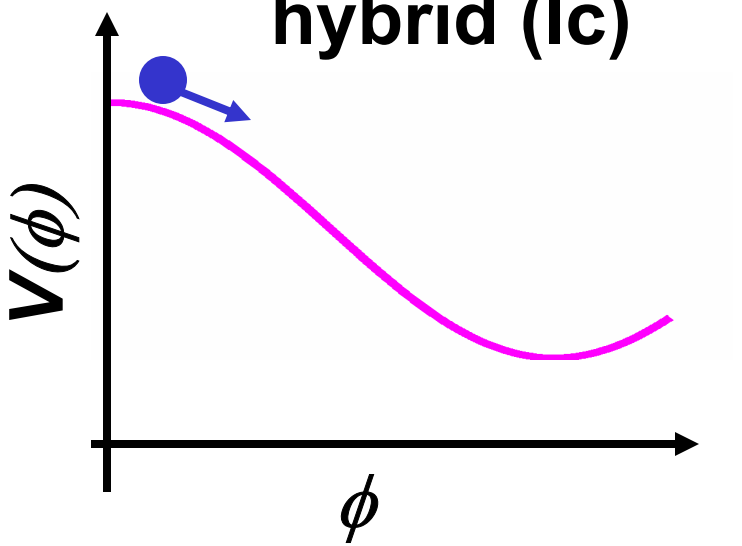
Type II: anything else
(pre-big bang, ekpyrotic, autoerotic, warm, branes, brane gas, bran gas, etc.)

**Used for superstrings, supernovae, superconductors, …*

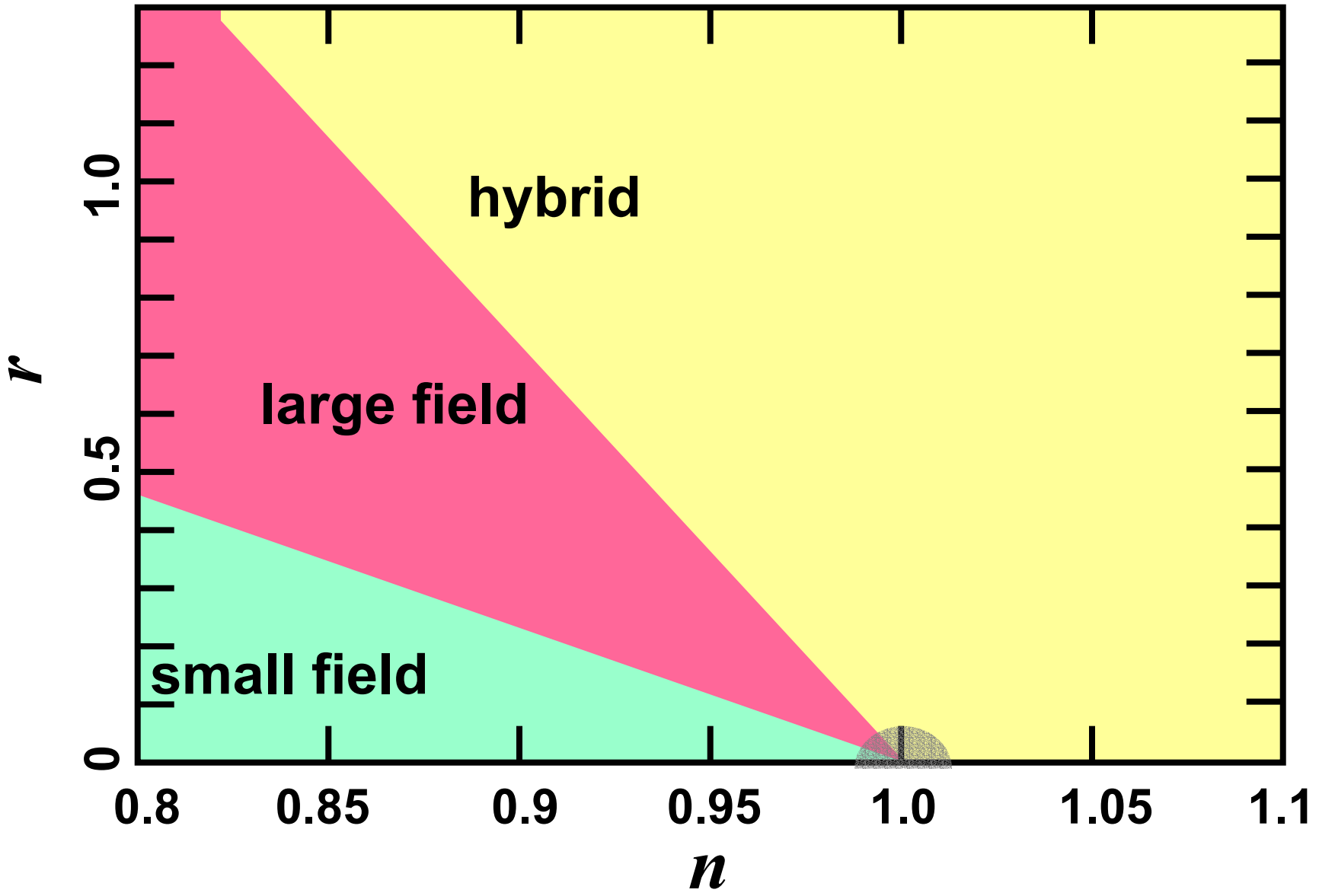

large-field (Ia)
V(ϕ)
ϕ


hybrid (Ic)
V(ϕ)
ϕ


small-field (Ib)
V(ϕ)
ϕ


hybrid (Ic)
V(ϕ)
ϕ

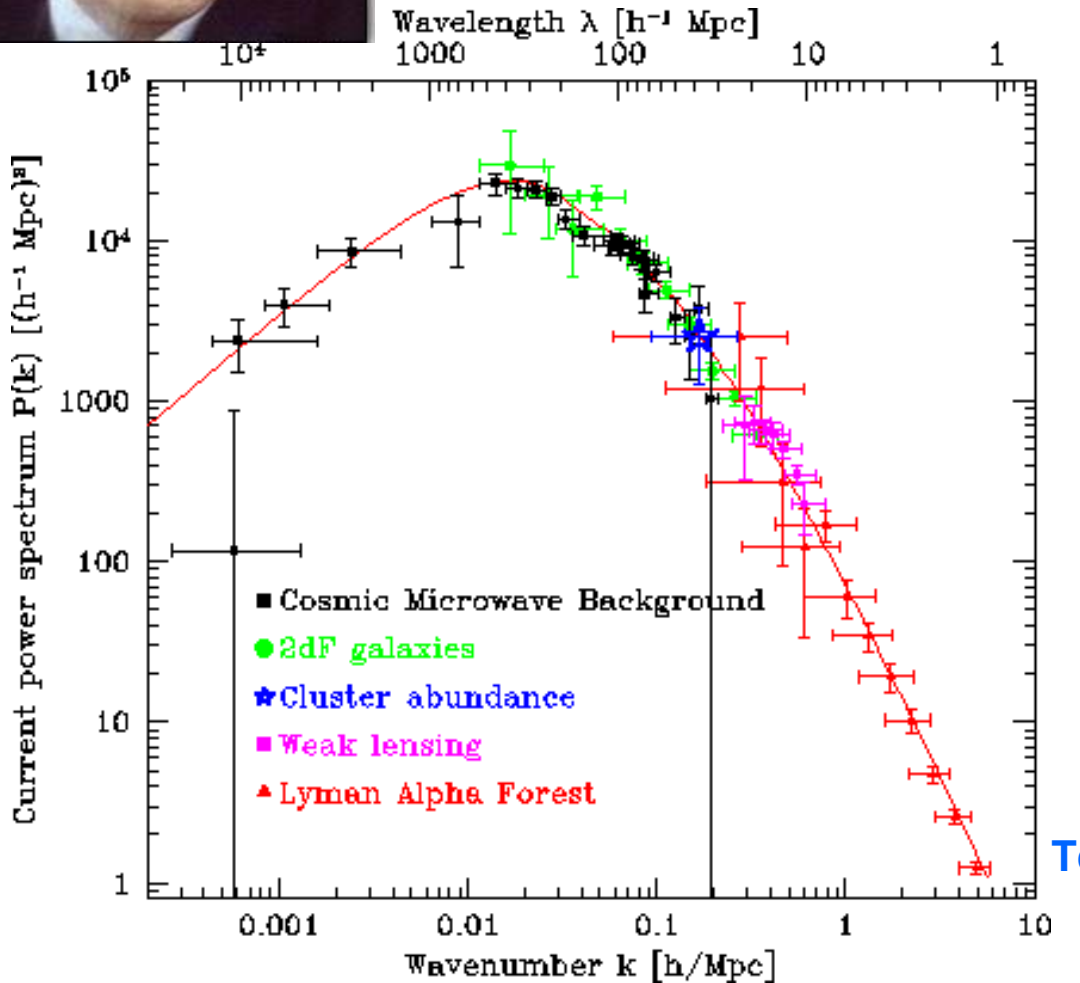
Dodelson, Kinney, Kolb astro-ph/9702156



$r = \left(\text{tensor}/\text{scalar}\right)_{l=2}$ $n = \text{scalar spectral index}$

Harrison-Zel'dovich Spectrum ?

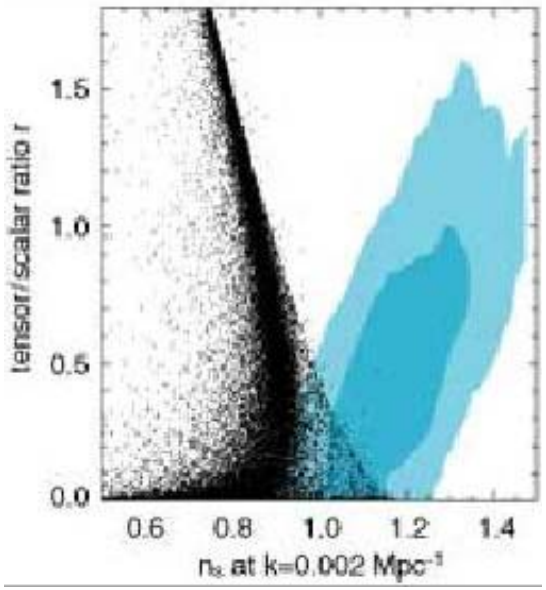
$$n=1?,\ n'=0?,\ r=0?$$



Combine CMB & LSS?

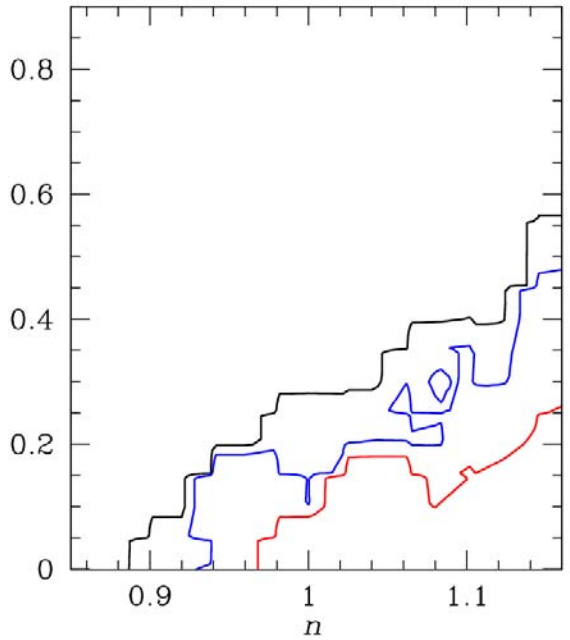
Tegmark

Harrison-Zel'dovich Spectrum ?

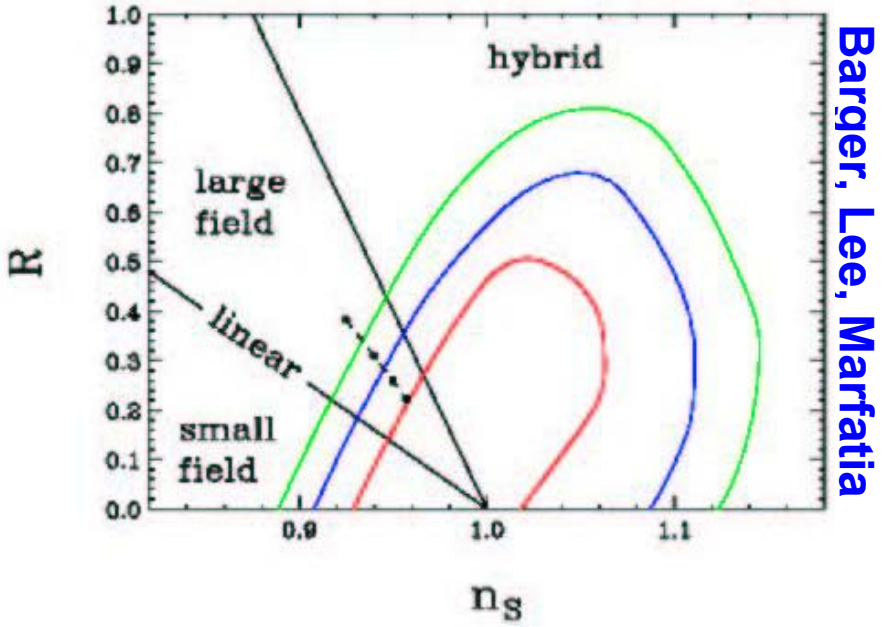


WMAP team - Peiris et al.

1. priors?
2. chain vs. grid?
3. marginalize?
4. data sets used?
5. definition of *r*?
6. …

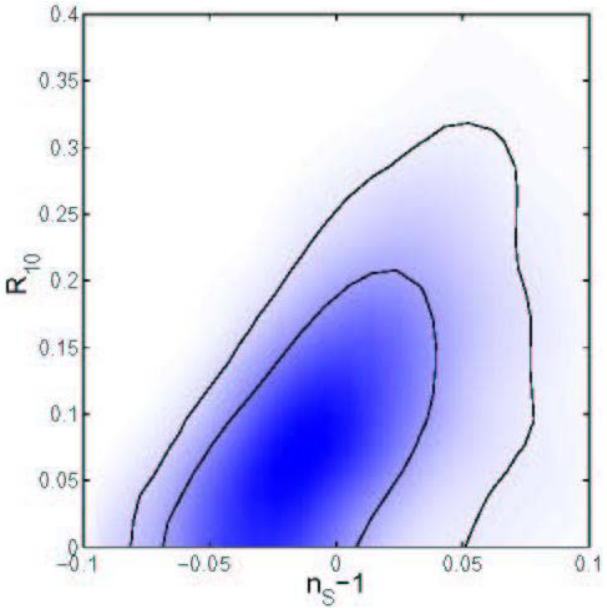


Kinney, Kolb, Melchiorri, Riotto



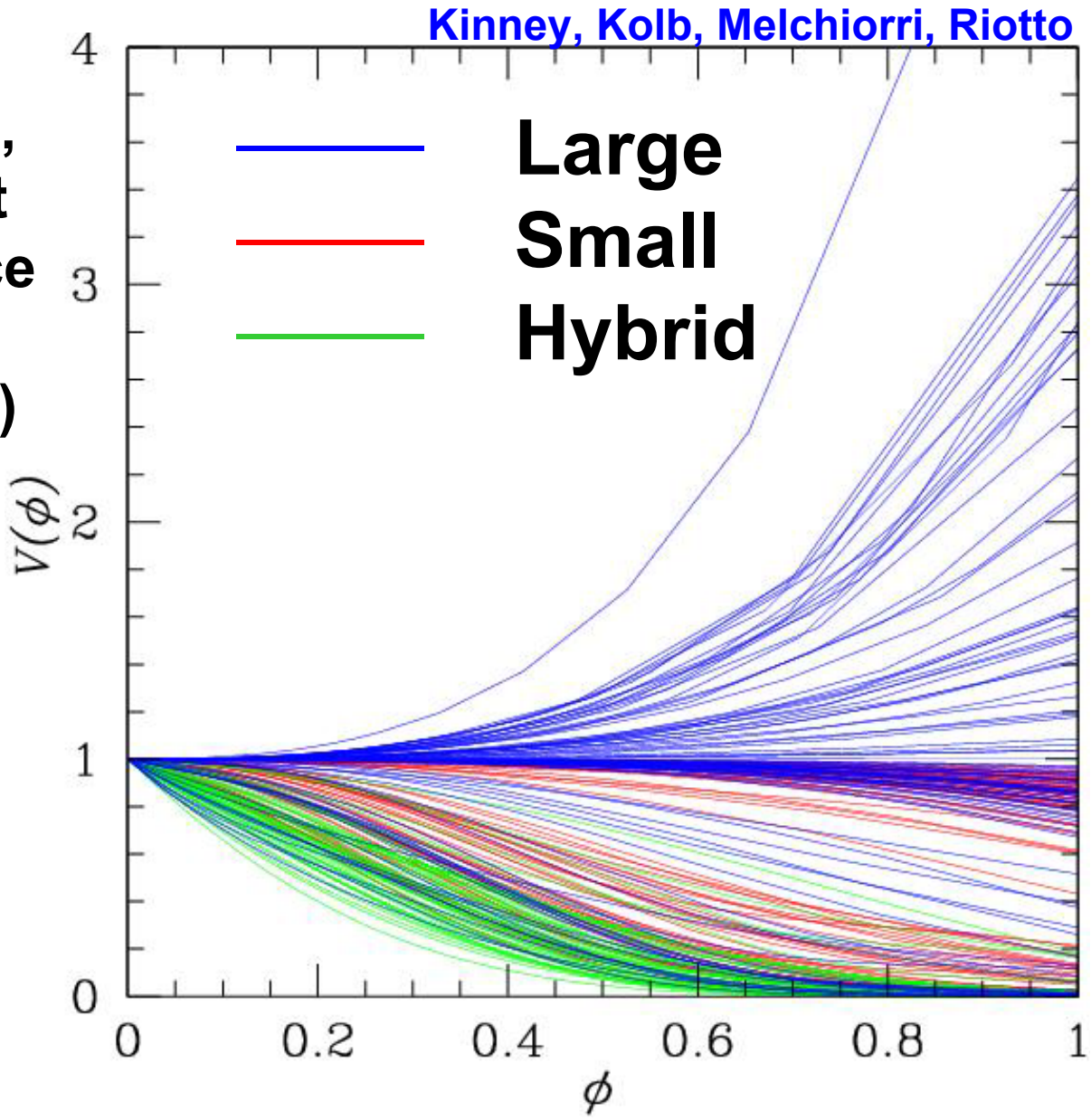
Barger, Lee, Marfatia

Leach & Liddle



Inflation models that fit CMB

1. H-Z consistent, i.e.,
2. $r=0$ still consistent
3. (no strong evidence for running)
4. ($n=1$ still consistent)
5. ϕ^4 still OK?



Issues

1. Who is the inflaton?
   - models of inflation, reconstruction?
2. Transplanckian physics?
   - probe of short-distance physics?
3. Defrosting?
   - preheating, reheating, ….?
4. Extra dimensions, brane, bulk, etc.?
   - new dynamics?
5. Other particle production?
   - WIMPZILLAS, gravitons, ….?
6. Are perturbations from the inflaton fluctuations?
   - curvaton, modulon, …

The nature of inflation is a complex natural phenomenon.

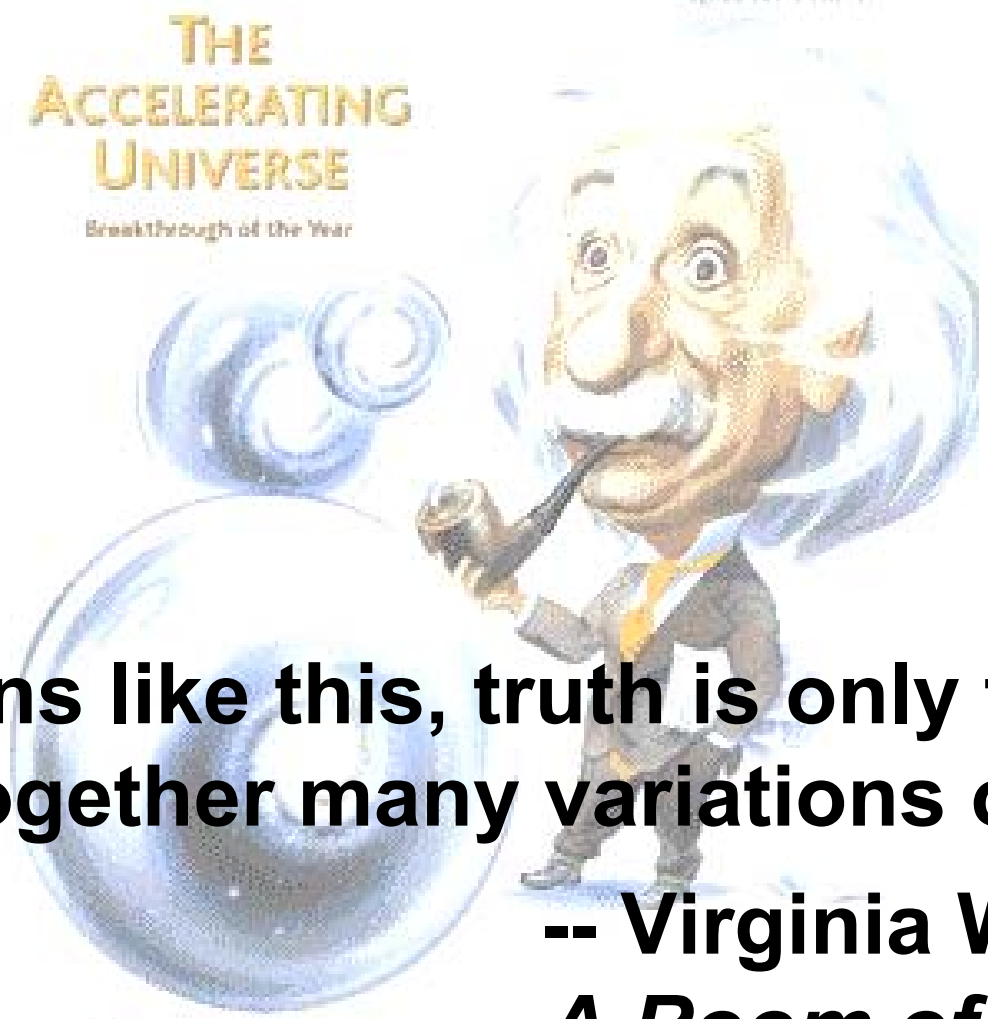
Single-field, slow-roll inflation is a simple, elegant, compelling explanation.

“For every complex natural phenomenon there is a simple, elegant, compelling, but wrong explanation.”

- Tommy Gold

Dark Energy

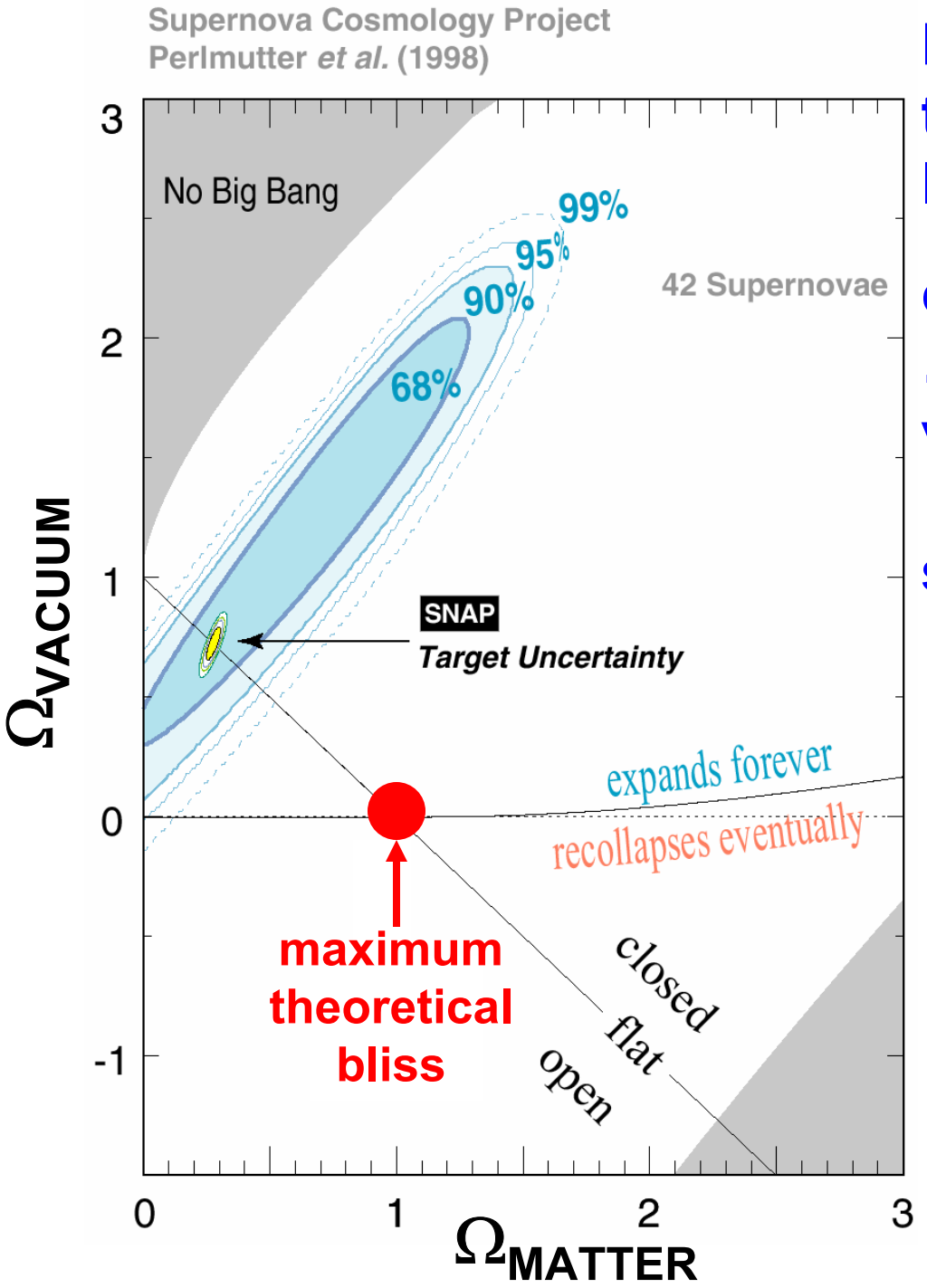
What is the nature of dark energy



“In questions like this, truth is only to be had by laying together many variations of error.”

-- Virginia Wolf

A Room of Ones Own



High-z SNeIa are fainter than expected in an Einstein-deSitter model

cosmological constant, or
…some changing non-zero vacuum energy, or
… or some unknown systematic effect(s)

The case for Λ:

1) Hubble diagram

2) subtraction

$\Omega_{TOTAL} = 1$
$\Omega_M = 0.3$
$1 - 0.3 = 0.7$

3) age of the universe

4) structure formation

Cosmological constant

Mass density of space:

$$\rho_\Lambda \simeq 10^{-30}\,\mathrm{g\,cm^{-3}} \simeq \left(10^{-4}\ \mathrm{eV}\right)^4 = \left(10^{-3}\ \mathrm{cm}\right)^{-4}$$

$$\Lambda = 8\pi G\rho_\Lambda = \left(10^{29}\,\mathrm{cm}\right)^{-2} = \left(10^{-33}\,\mathrm{eV}\right)^2$$

The unbearable lightness of nothing!

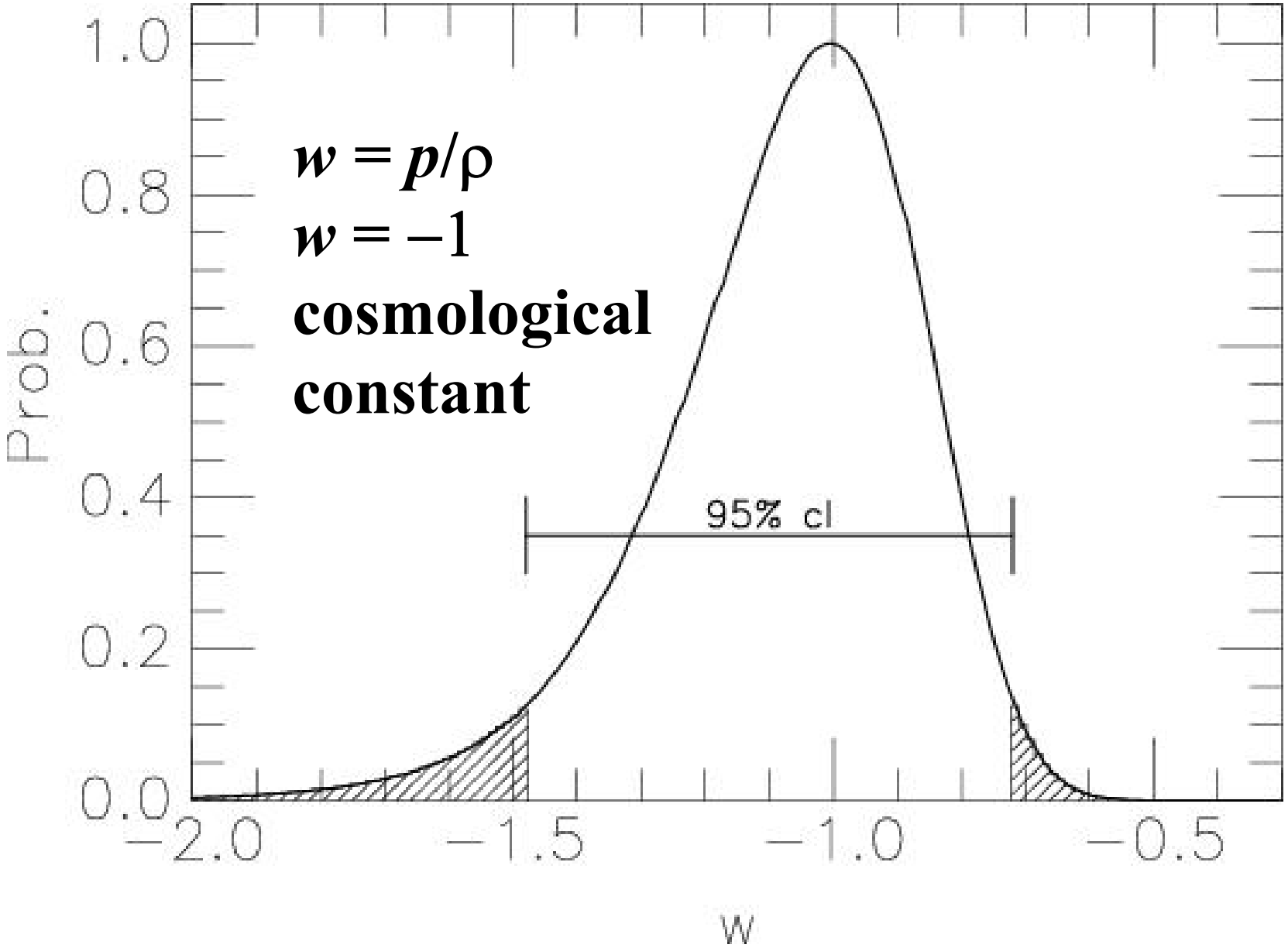
Cosmo-illogical constant?

Numerology:

$$\rho_V = M_Z^4 \exp\left(-2/\alpha\right) \qquad \rho_V = M_{\mathrm{SUSY}}^8 \big/ M_{Pl}^4$$

$$m_\nu = 10^{-3}\ \mathrm{eV} \qquad R_5 = 10^{-4}\ \mathrm{cm}$$

For now…parameterize



High-z supernova team

Aether of the 21st century?

- Astrophysical/astronomical issue
  - — Evolution
  - — Dust
- Particle physics issue
  - — It's an infrared issue & it's an ultraviolet issue!
  - — Scalars (quintessence, trackers, stalkers, ….)
  - — Tensors (all evidence for dark energy is indirect!)
    - gravity at large distances
    - back reactions
    - inhomogeneities

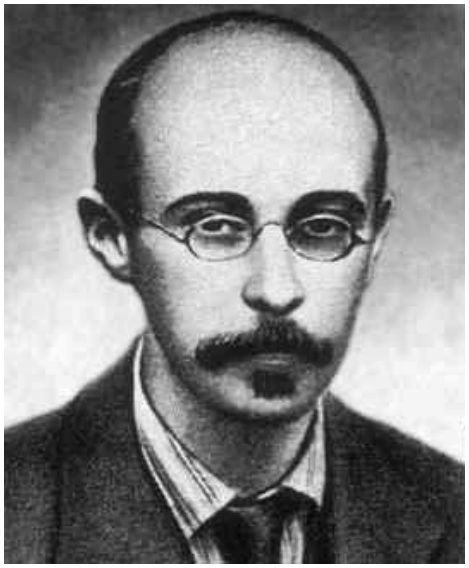
Braneless cosmology

Old Friedmann law:

$$G_{00} = M_{Pl}^{-2}\, T_{00}$$

$$3H^2 = M_{Pl}^{-2}\rho$$

Friedmann (1921)



SNIa evidence for dark energy:

$$\int \frac{dz}{H(z)}$$

Braneful cosmology

New Friedmann law:

Israel jump conditions

Binetruy, Deffayet, Langlois (2000)

$$H^2 = \frac{\Lambda}{6} + \frac{M_*^{-6}}{36}\rho^2 + \frac{c}{a^4(t, y=0)}$$

Brane cosmology

- **Friedmann equation modified today**

$$H^2 = A\rho\left[1+\left(\rho/\rho_{\text{cutoff}}\right)^{n-1}\right]$$

Freese & Lewis

- **Gravitational force law modified at large distance**

  Five-dimensional at cosmic distances

Deffayet, Dvali & Gabadadze

- **Tired gravitons**

  Gravitons metastable - leak into bulk

Gregory, Rubakov & Sibiryakov
Dvali, Gabadadze & Porrati

- **Gravity repulsive at cosmological distance**

$$R \sim \text{Gpc}$$

Csaki, Erlich, Hollowood & Terning

- ***n=1* KK graviton mode very light**

$$m \sim \left(\text{Gpc}\right)^{-1}$$

Kogan, Mouslopoulos, Papazoglou, Ross & Santiago

- **3+1 Lorentz invariance broken**

  In the IR!

Chung, Kolb & Riotto

Inhomogeneities

Work with Notari (SNS), Matarrese & Riotto (Padova)

- **Homogeneous/Isotropic metric**

$$G_{00} = T_{00} \Rightarrow H^2_{FRW} = \rho$$

- **Inhomogeneous/anisotropic metric**

$$G_{00} = G^{FRW}_{00} - \text{inhomogeneities}$$

$$\Rightarrow H^2 = H^2_{FRW} - \text{inhomogeneities}$$

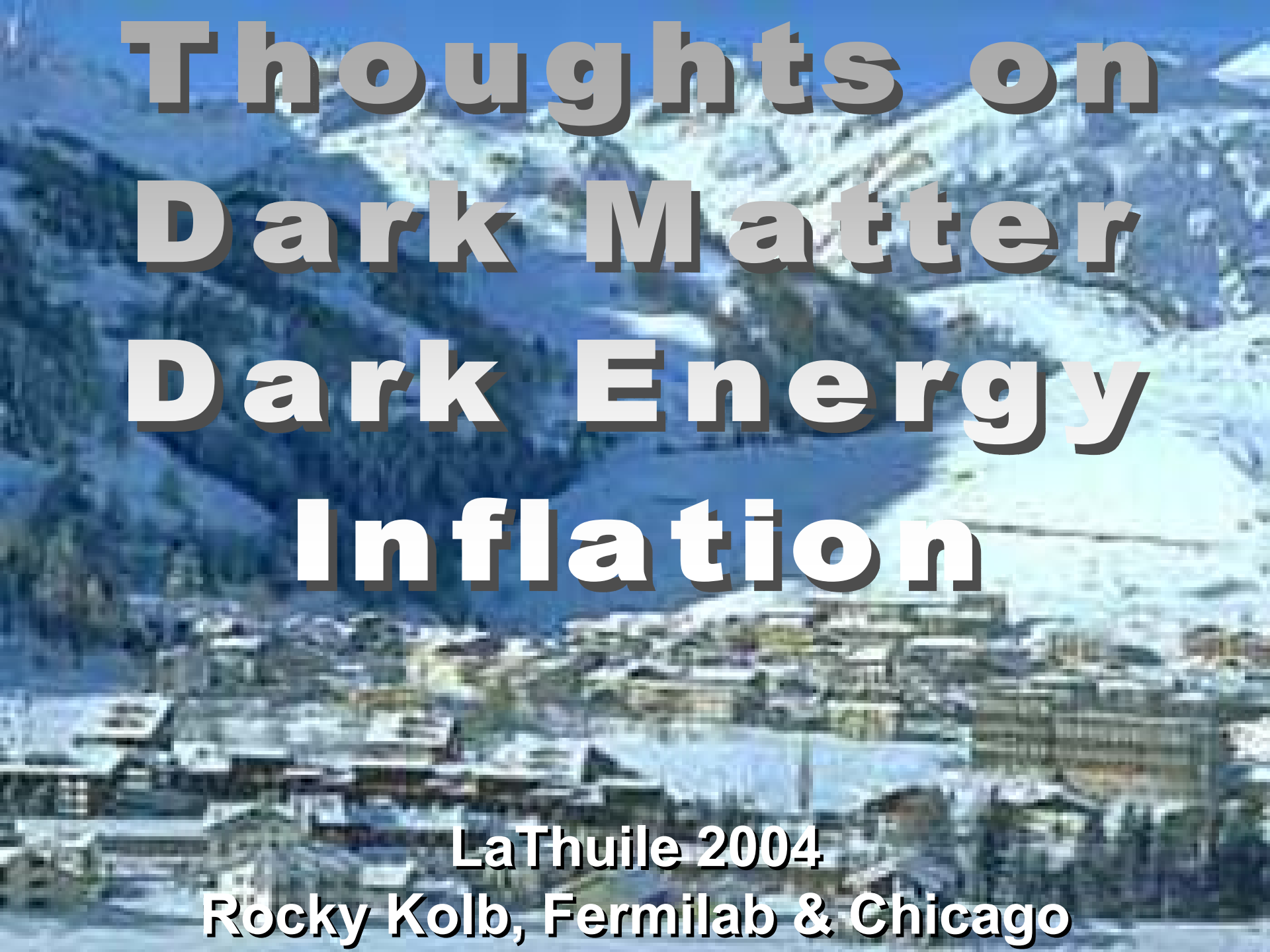
$$\Rightarrow \; H^2 = \langle \rho \rangle + \text{inhomogeneities}$$

The nature of dark energy is a complex natural phenomenon.

There are no simple, elegant, compelling explanations.

How do we sort it out?

Nature's nice	Nature's a bitch
• **Neutralino dark matter:** *Direct detection* *Indirect detection* *Accelerator production*	• **Wimpzilla dark matter:** *Only gravitational interactions* *No direct or indirect detection* *No production*
• **Inflation dynamics:** *Departure from H-Z* *Gravitational waves*	• **Inflation dynamics:** *H-Z – no dynamics?* *Mass scale too small for tensors*
• **Dark energy:** w *differs from -1*	• **Dark energy:** w *= -1 – it's just a number!*



Thoughts on Dark Matter Dark Energy Inflation

LaThuile 2004

Rocky Kolb, Fermilab & Chicago