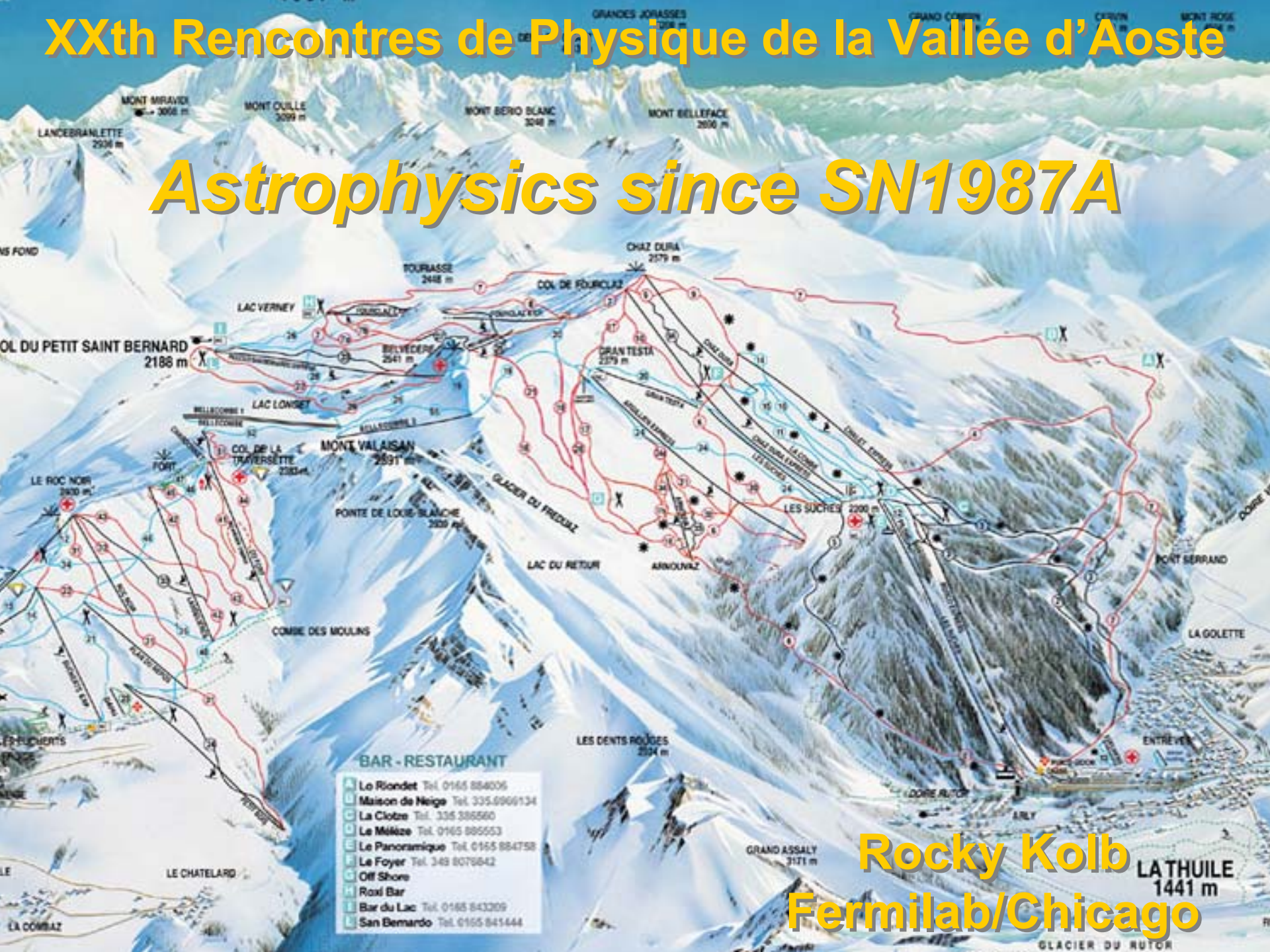


XXth Rencontres de Physique de la Vallée d'Aoste

Astrophysics since SN1987A



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Rocky Kolb
Fermilab/Chicago

LATHUILE
1441 m

© Anglo-Australian Observatory
Supernova 1987A in the Large Magellanic Cloud
(Type II SN)



Astrophysics since SN1987A

30 minutes to cover 19 years ~ 1.5 minutes year⁻¹

Neutrinos from
SN 1987A
Solar
Atmospheric

CMB temperature fluctuations

Hubble deep field, Hubble ultra-deep field

Gamma-ray bursts

Chandra discovery of ubiquity of black holes

GZK suppression (or not) in UHE cosmic rays

Dark energy

Historical supernovae

Monastic Chronicles re: Supernova 1006:

“In 1006 there was a very great famine and a comet appeared for a long time.”

“At the same time a comet, which always announces human shame, appeared in the southern regions, which was followed by a great pestilence.”

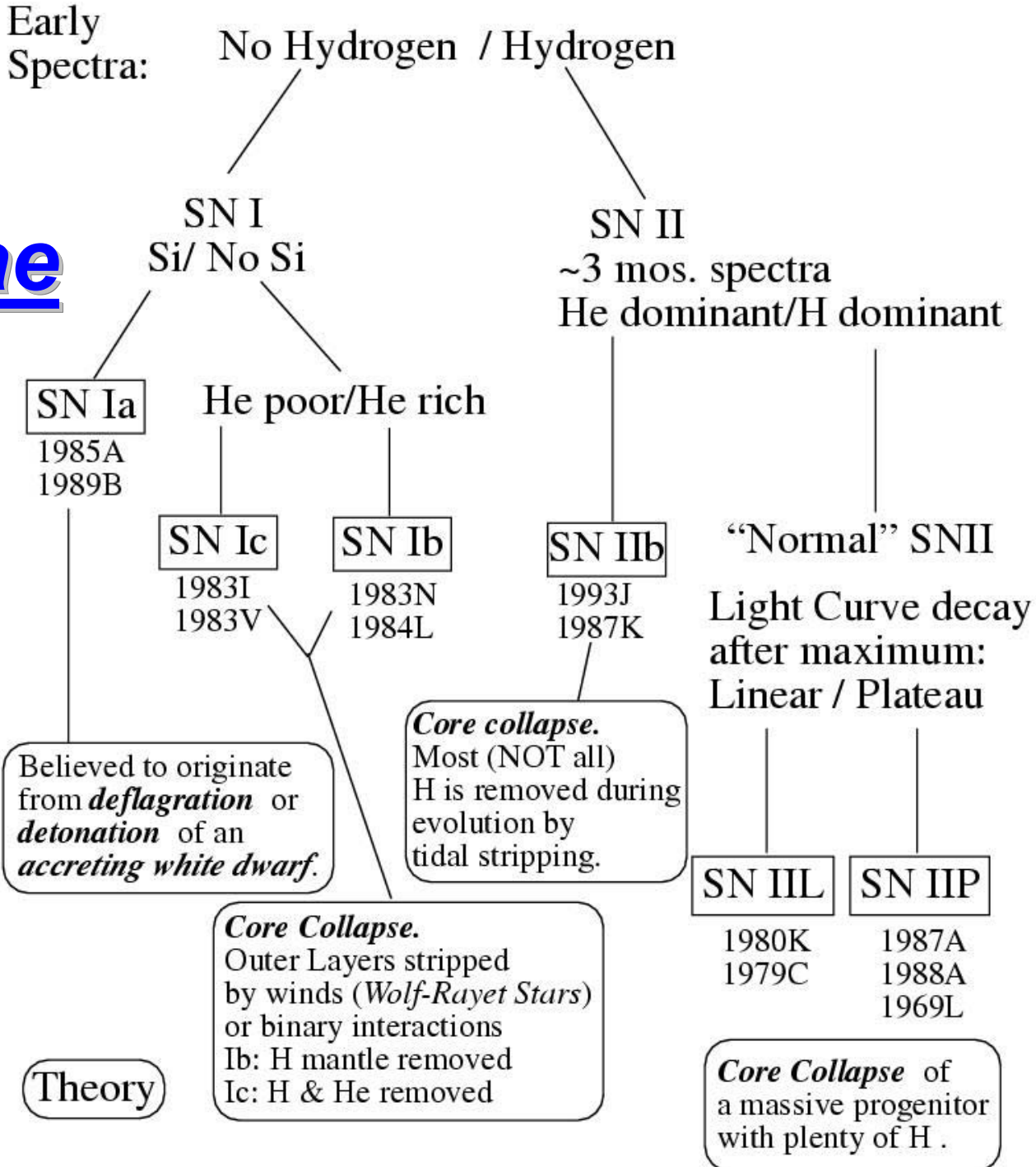
“Three years after the king was raised to the throne, a comet with a horrible appearance was seen in the southern part of the sky, emitting flames this way and that.”

George Busch (German painter) in 1572:

“It is a sign that we will be visited by all sorts of calamities such as inclement weather, pestilence, and Frenchmen.”

Scientific supernovae

Supernova Taxonomy



The intersection of astronomy & physics



viale

dell'Astronomia

via

della Fisica

Type-II supernovae

Astronomy → Physics

Neutral currents:

First detection	1006
Confirmed in	1054
	1572
	⋮

Physics → Astronomy

**Neutron star binding energy released in neutrinos
(Colgate and White 1964)**

Astronomy → Physics

Neutrinos detected from 1987A

Limits on neutrino masses, lifetimes, interactions, ...

Physics → Astronomy

Neutrino oscillation important for explosion dynamics



rkm.com.au

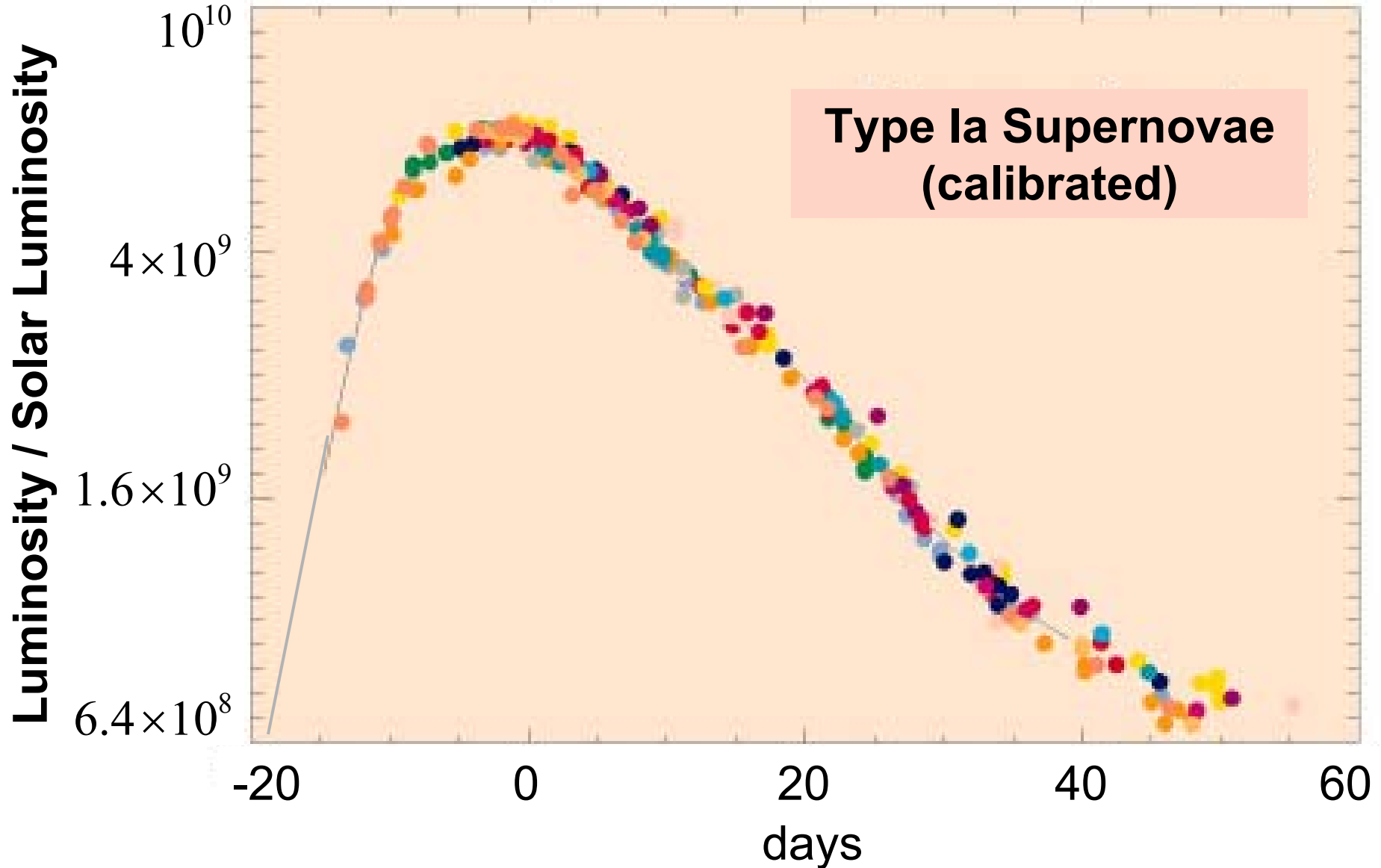


SN Ia



Type Ia supernova

Supernova Cosmology Project

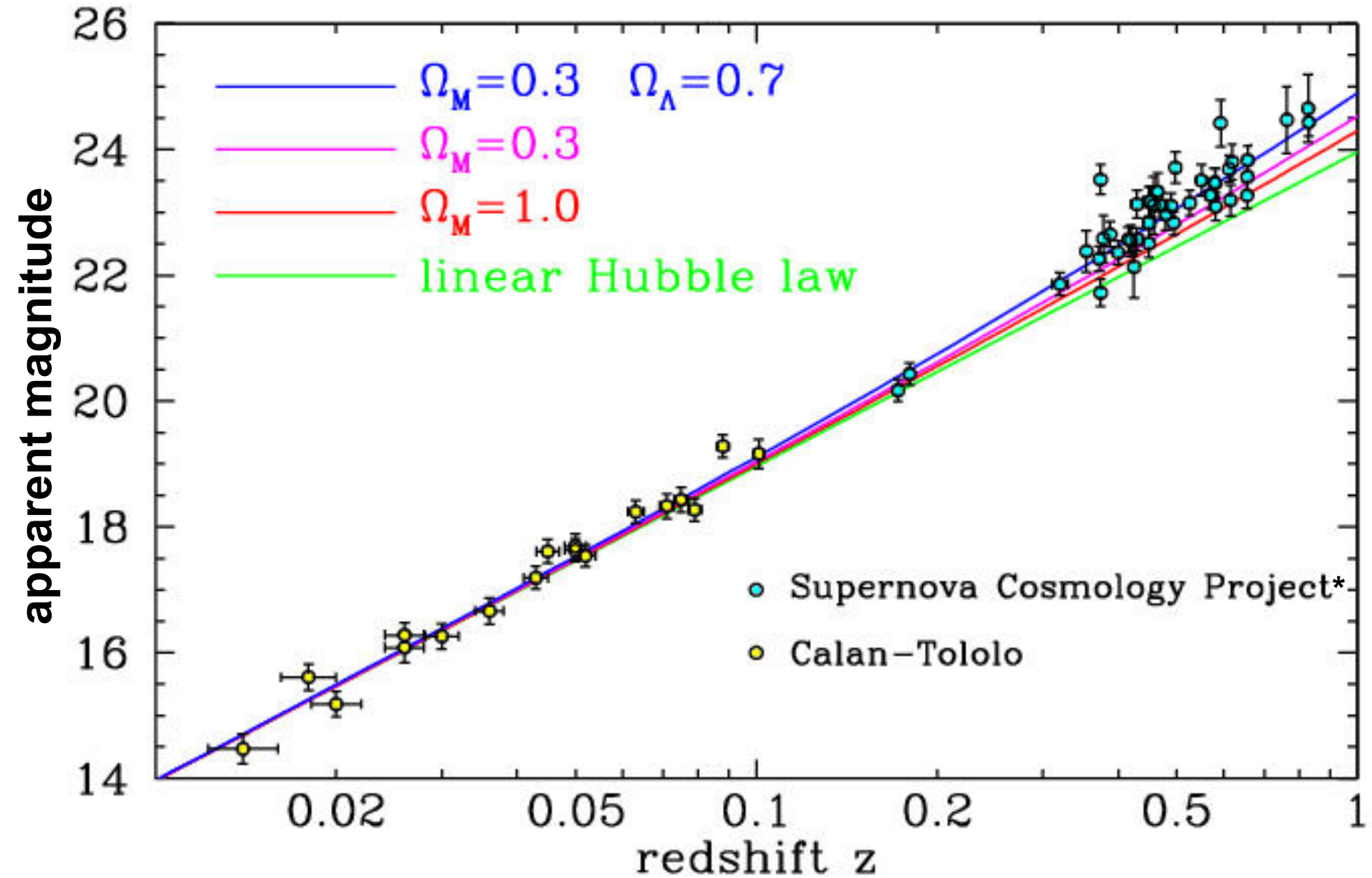


Edwin
Hubble

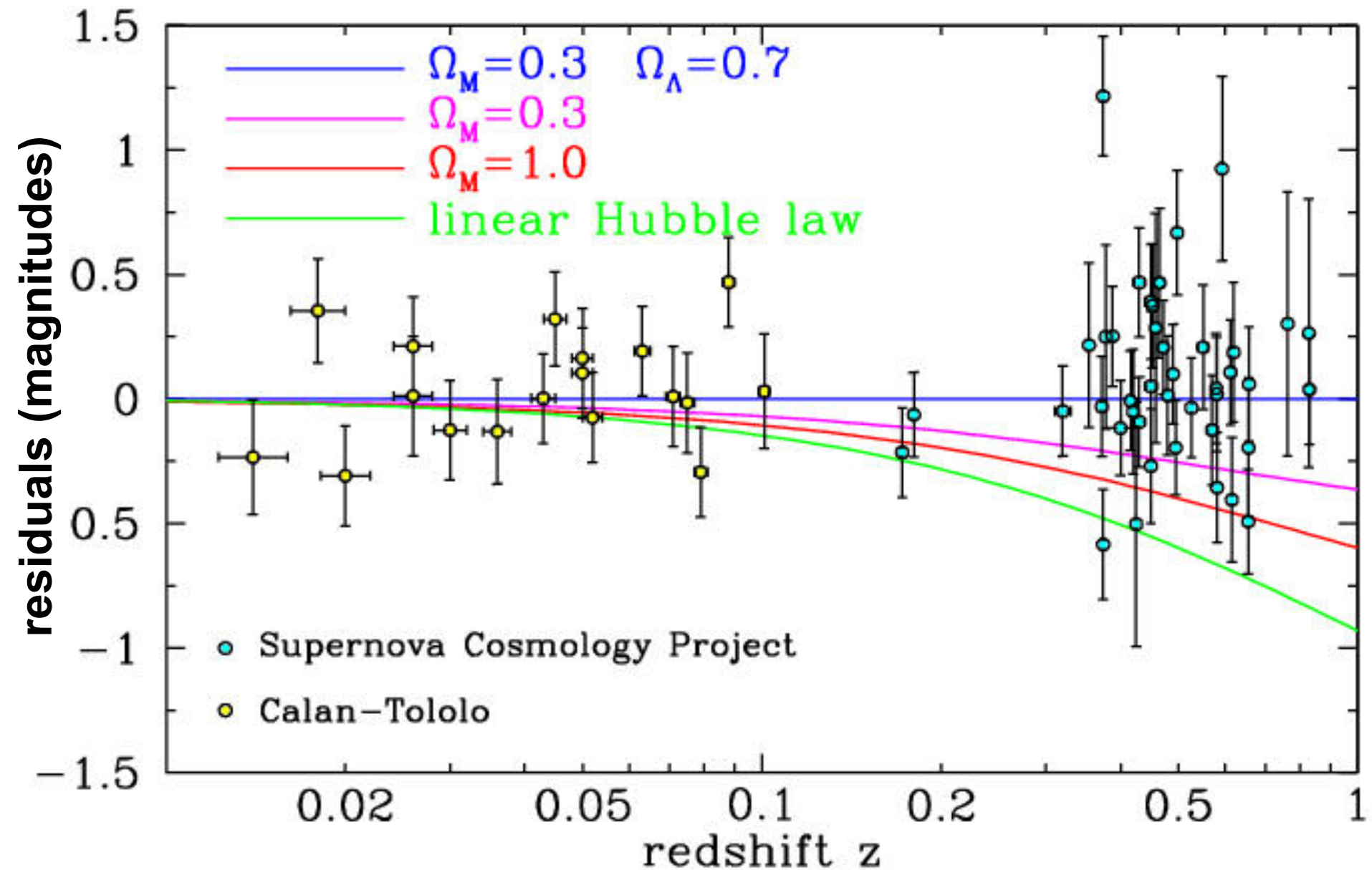


University of Chicago 1909 National Champions

Type Ia supernova

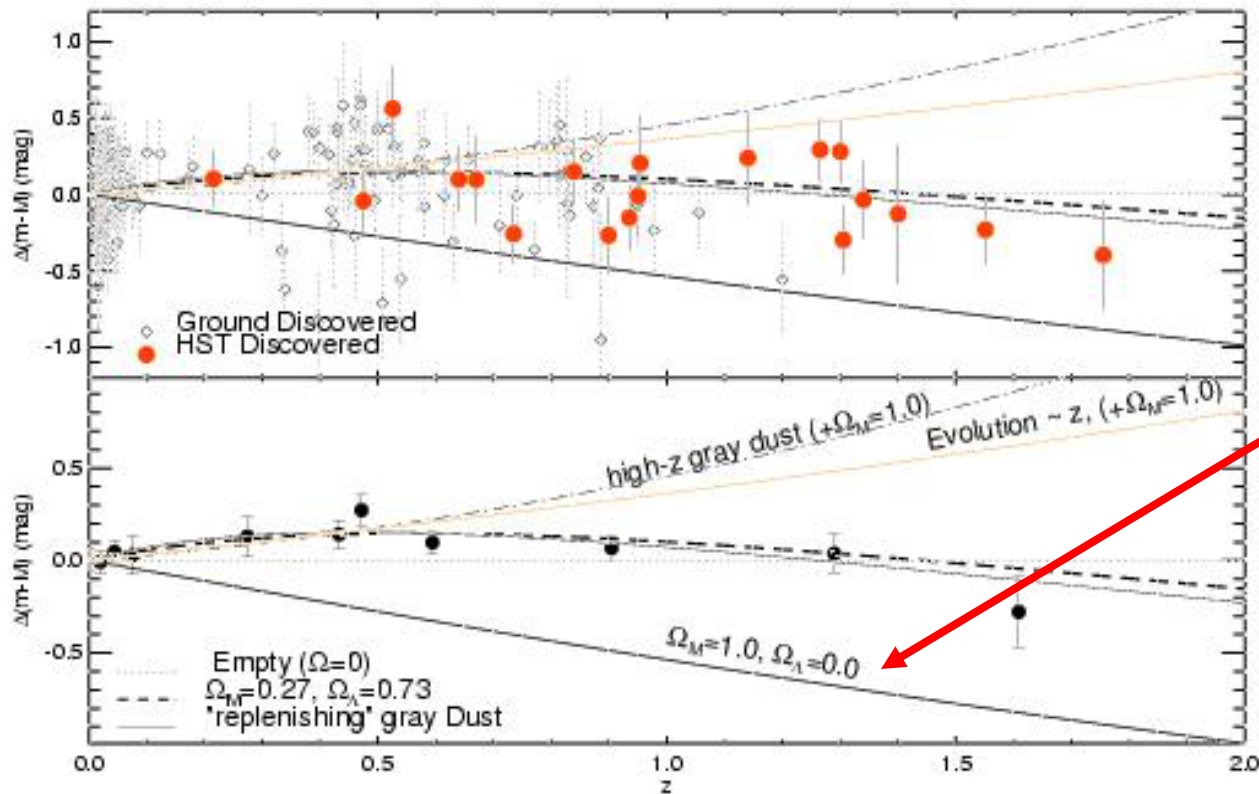


Type Ia supernova



High-z Ia SNe are fainter than in the Einstein-deSitter model

Riess et al. (2004)



Einstein-de Sitter: flat,
matter-dominated model
(maximum theoretical bliss)

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

The case for Λ :

- 1) Hubble diagram $d_L(z)$
- 2) subtraction

Subtraction

$$\Omega_i \equiv \rho_i / \rho_C$$

$$\rho_C \equiv 3H_0^2 / 8\pi G$$

dynamics

lensing

x-ray gas

cmb

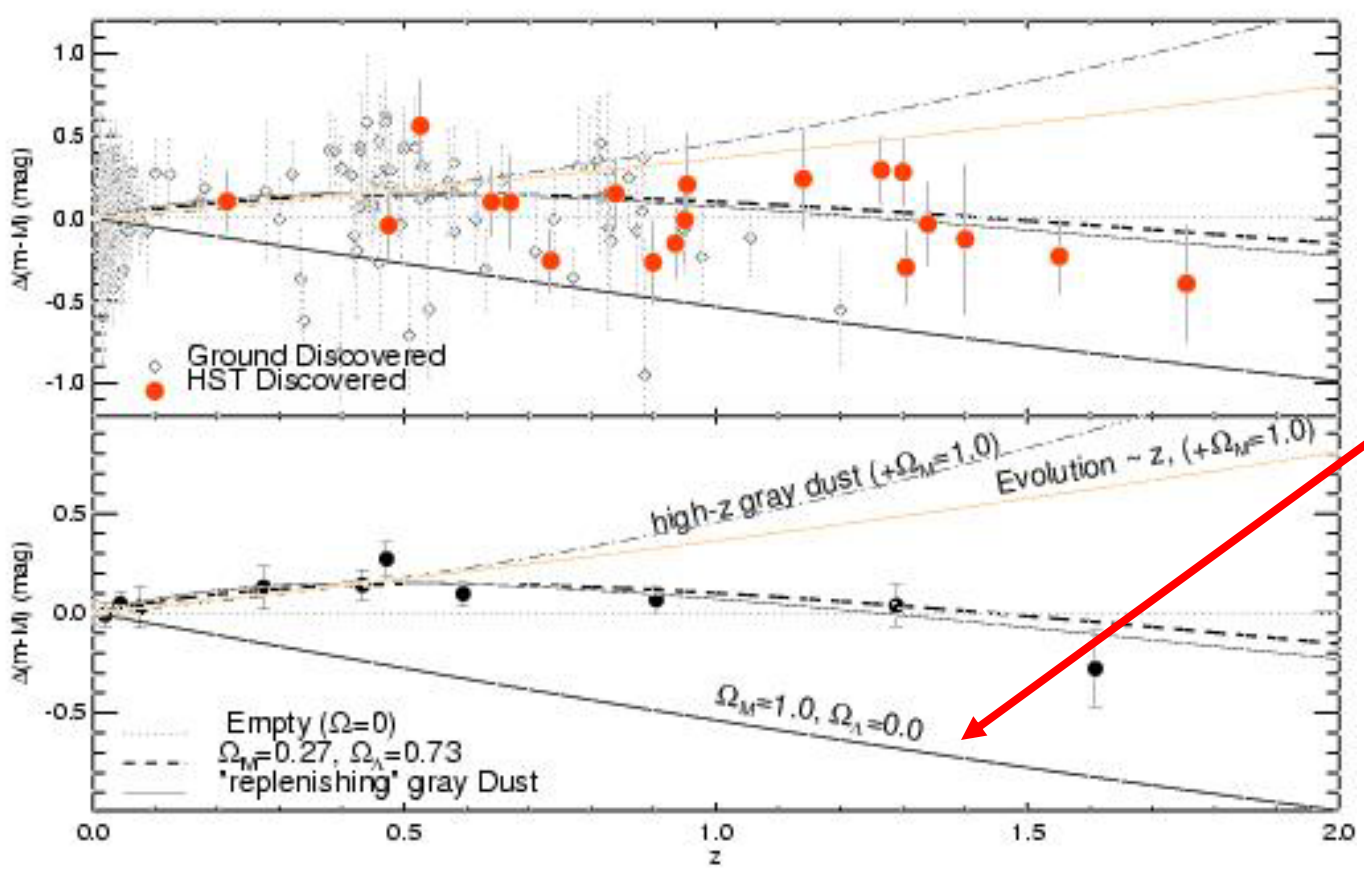
simulations

power
spectrum

$$\Omega_{\text{TOTAL}} = 1 \text{ (CMB)}, \quad \Omega_M = 0.3, \quad 1 - 0.3 = 0.7$$

High-z SNe are fainter than expected in the Einstein-deSitter model

Riess et al. (2004)



Einstein-de Sitter: flat, matter-dominated model (maximum theoretical bliss)

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

The case for Λ :

- 1) Hubble diagram $d_L(z)$
- 2) subtraction
- 3) age of the universe
- 4) structure formation

Λ CDM

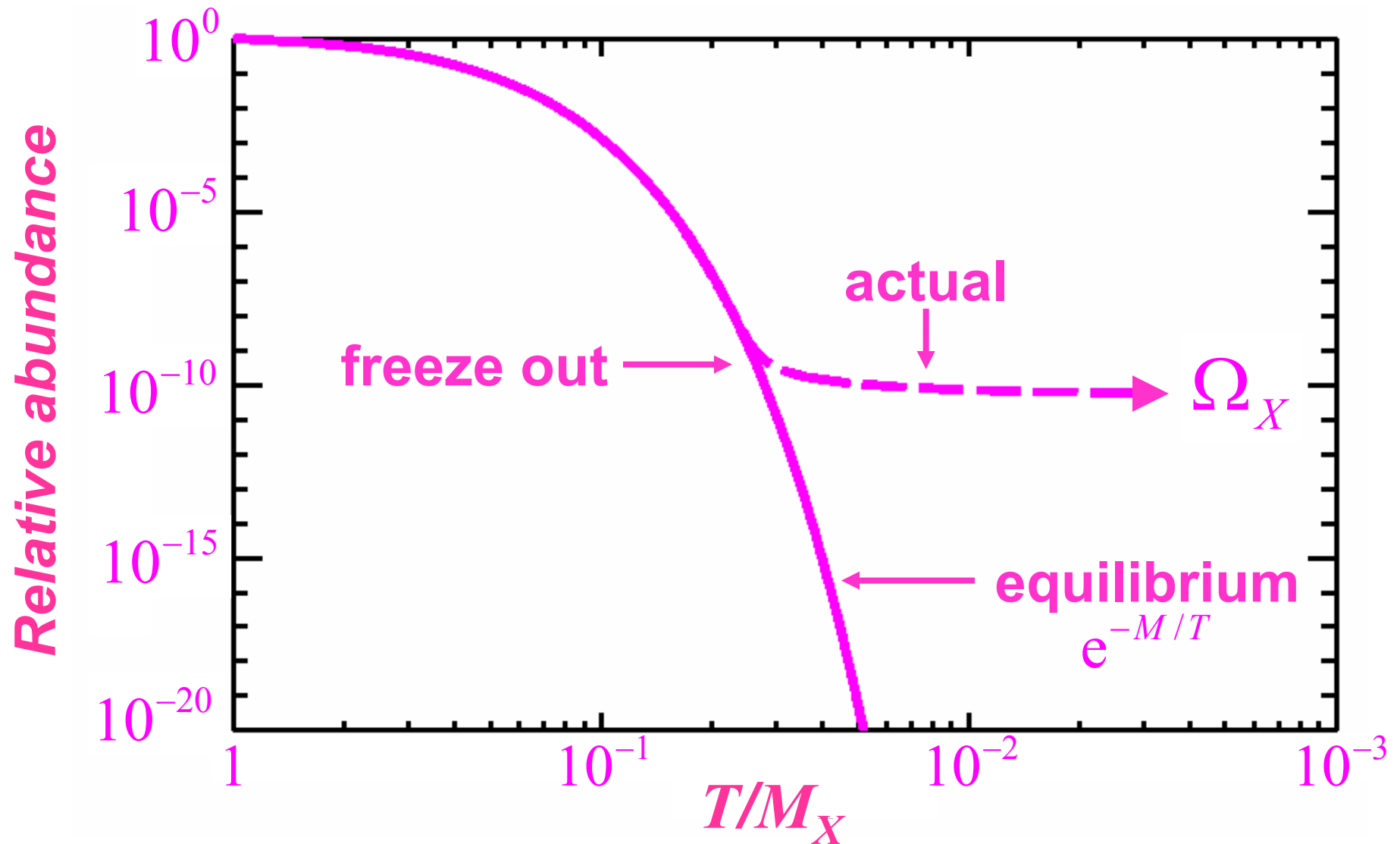


- Inflation-produced perturbations
- Baryo/leptogenesis

Dark Matter?



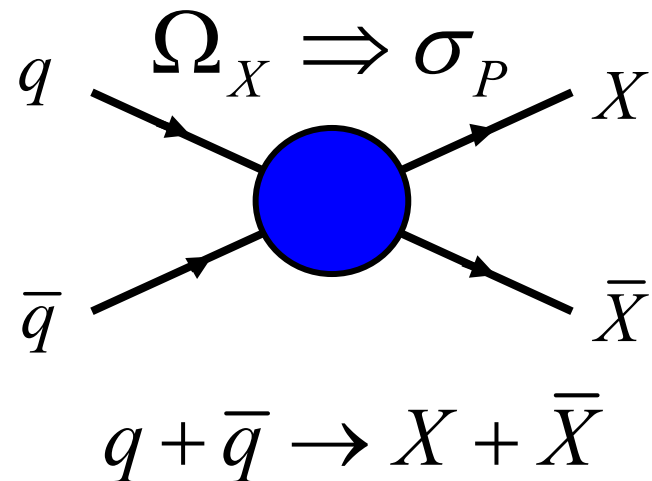
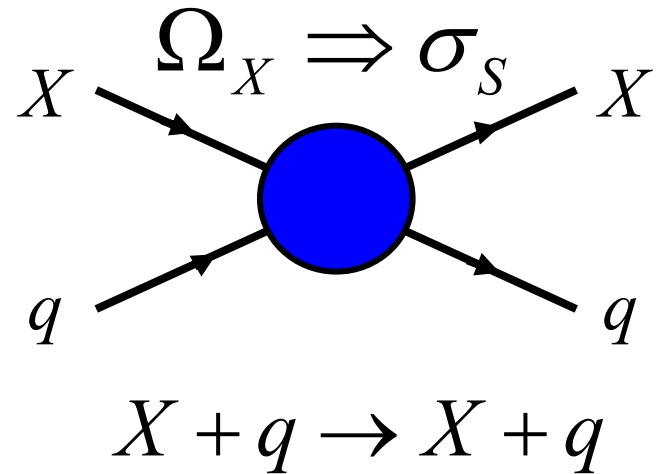
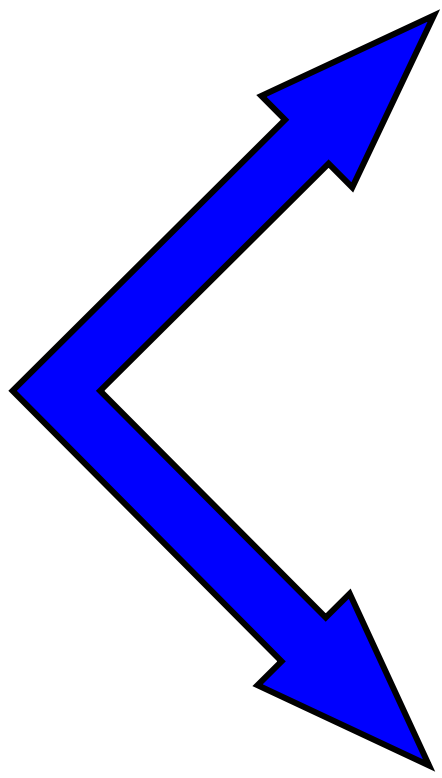
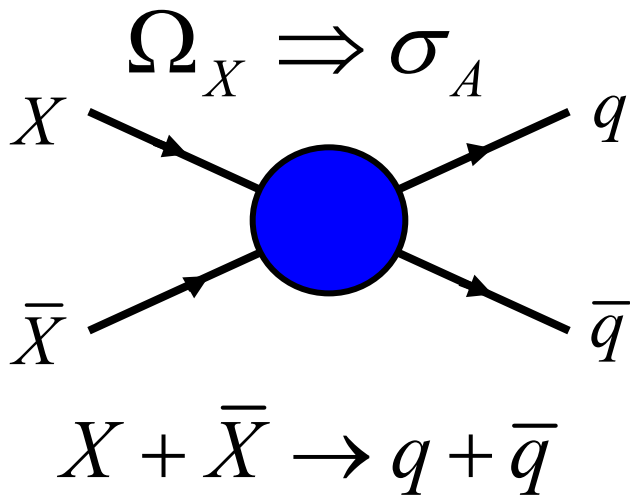
Cold thermal relics



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

Cold thermal relics

$$\Omega_X \propto \sigma_A^{-1}$$

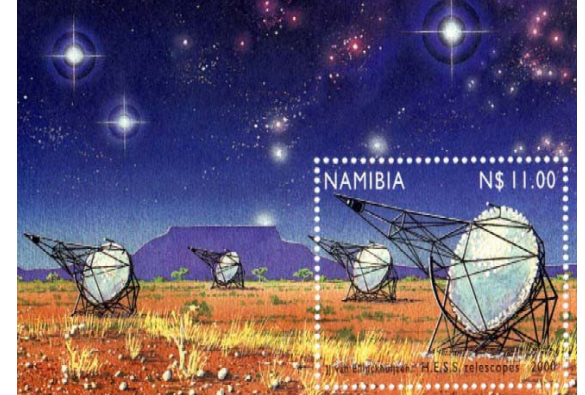


Cold thermal relics (neutralino)

- **Direct detection (σ_S)**
More than a dozen experiments
- **Indirect detection (σ_A)**
Annihilation in sun, Earth, galaxy. . .
neutrinos, positrons,
antiprotons, γ rays, . . .
- **Accelerator production (σ_P)**
Tevatron, LHC, ILC



HIGH ENERGY STEREOSCOPIC SYSTEM TELESCOPES IN NAMIBIA



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, wrong explanation.”

- Tommy Gold

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

10^{-6} eV (10^{-40} g) axions

$10^{-8} M_{\odot}$ (10^{25} g) axion clusters

Interaction strength range

Noninteracting: wimpzillas

Strongly interacting: B balls

The gravity of dark energy



Merriam-Webster OnLine

Merriam-Webster FOR KIDS

Encyclopædia BRITANNICA

Merriam-Webster ONLINE

Merriam-Webster COLLEGIATE®

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Main Entry: **grav·i·ty**

Function: *noun*

Etymology: Middle French or Latin; Middle French *gravité*, from Latin *gravitat-*, *gravitas*, from *gravis*

1 a : dignity or sobriety of bearing b : IMPORTANCE, SIGNIFICANCE; especially : SERIOUSNESS c : a serious situation or problem

2 : WEIGHT

3 a (1) : the gravitational attraction of the mass of the earth, the moon, or a planet for bodies at or near its surface (2) : a fundamental physical force that is responsible for interactions which occur because of

Take sides!

- Can't hide from the data – Λ CDM too good to ignore
 - SNIa
 - Subtraction: $1.0 - 0.3 = 0.7$
 - Age
 - Large-scale structure
 - ...

$H(z)$ not given by
Einstein–de Sitter

$$3H^2 \neq 8\pi G \rho_{\text{MATTER}} \rightarrow G_{00} \neq 8\pi G T_{00}(\text{matter})$$

- Dark energy (modify right-hand side of Einstein equations)
 - “Just” Λ , a cosmological constant
 - If not constant, what drives dynamics (scalar field)
- Gravity (modify left-hand side of Einstein equations)
 - Beyond Einstein (non-GR: branes, *etc.*)
 - (Just) Einstein (GR: back reaction of inhomogeneities)

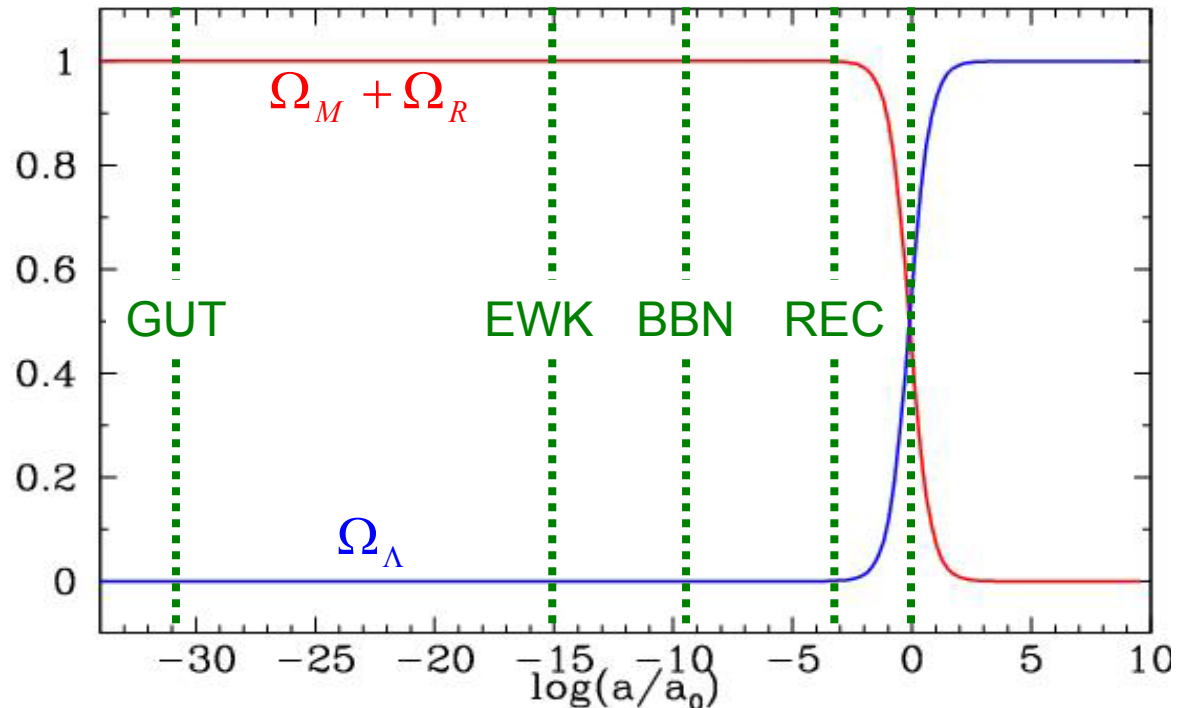
Cosmo-illogical constant?

Illogical magnitude (what's it related to?):

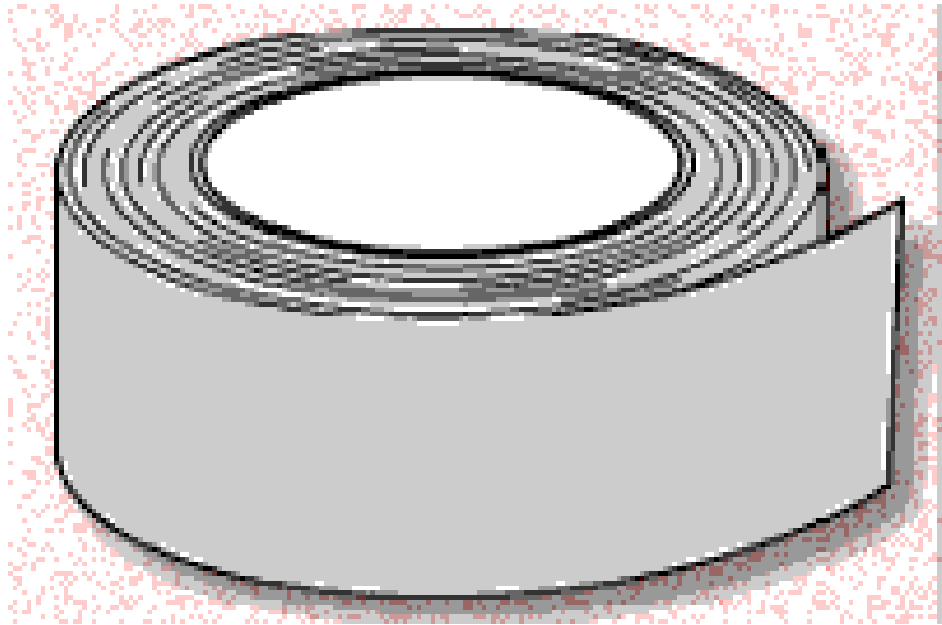
$$\rho_\Lambda \simeq 10^{-30} \text{ g cm}^{-3} \simeq (10^{-4} \text{ eV})^4 \simeq (10^{-3} \text{ cm})^{-4}$$

$$\Lambda = 8\pi G \rho_\Lambda \simeq (10^{29} \text{ cm})^{-2} \simeq (10^{-33} \text{ eV})^2$$

Illogical timing (why now?):



Practical tools for dark energy



**anthropic principle
(the landscape)**

scalar fields



Entertaining conjecture

Now entertain conjecture of a time
When creeping murmur and the poring dark
Fills the wide vessel of the universe.

— *Shakespeare, King Henry Vth*

All evidence for creeping murmur (dark energy) is indirect!

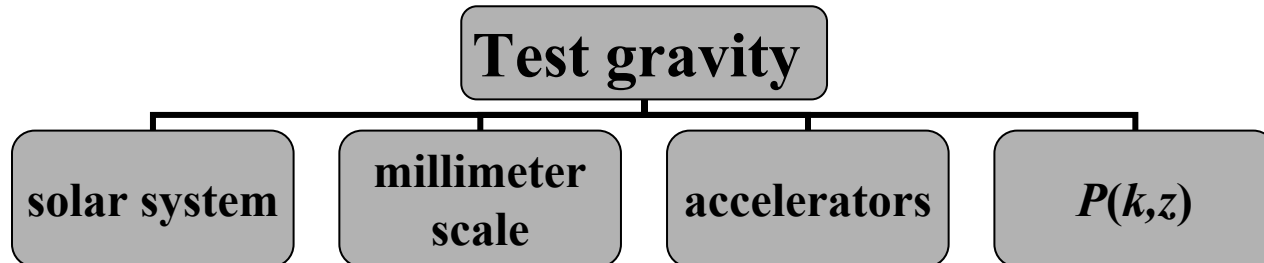
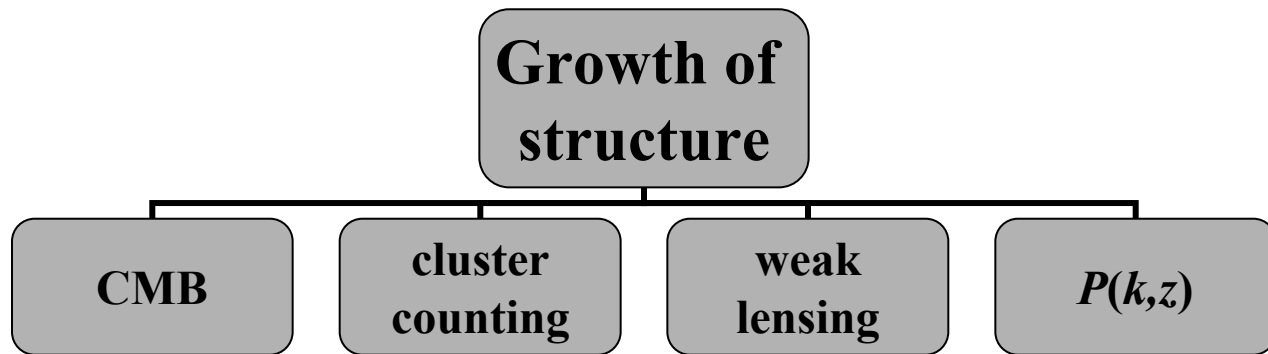
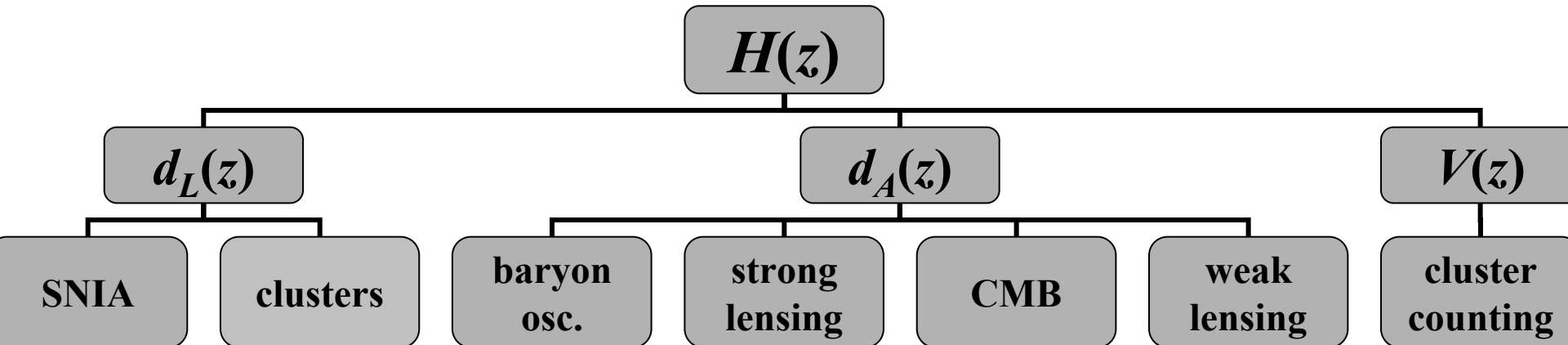
- Observed evolution of $H(z)$ does not fit Einstein–de Sitter.
- We infer the existence of dark energy on right-hand side!
- Could left-hand side of Friedmann equation be modified, and no dark energy?

Modifying the left-hand side

- Braneworld modifies Friedmann equation Binetruy, Deffayet, Langlois
- Phenomenological approach Freese & Lewis
$$H^2 = A\rho \left[1 + \left(\rho / \rho_{\text{cutoff}} \right)^{n-1} \right]$$
- Gravitational force law modified at large distance Deffayet, Dvali & Gabadadze
Five-dimensional at cosmic distances
- Tired gravitons Gregory, Rubakov & Sibiryakov;
Dvali, Gabadadze & Porrati
Gravitons metastable - leak into bulk
- Gravity repulsive at distance $R \approx \text{Gpc}$ Csaki, Erlich, Hollowood & Terning
- $n = 1$ KK graviton mode very light, $m \approx (\text{Gpc})^{-1}$ Kogan, Mouslopoulos,
Papazoglou, Ross & Santiago
- Einstein & Hilbert got it wrong Carroll, Duvvuri, Turner, Trodden
$$S = (16\pi G)^{-1} \int d^4x \sqrt{-g} \left(R - \mu^4 / R \right)$$
- Backreaction of inhomogeneities Räsänen; Kolb, Matarrese, Notari & Riotto;
Notari; Kolb, Matarrese & Riotto

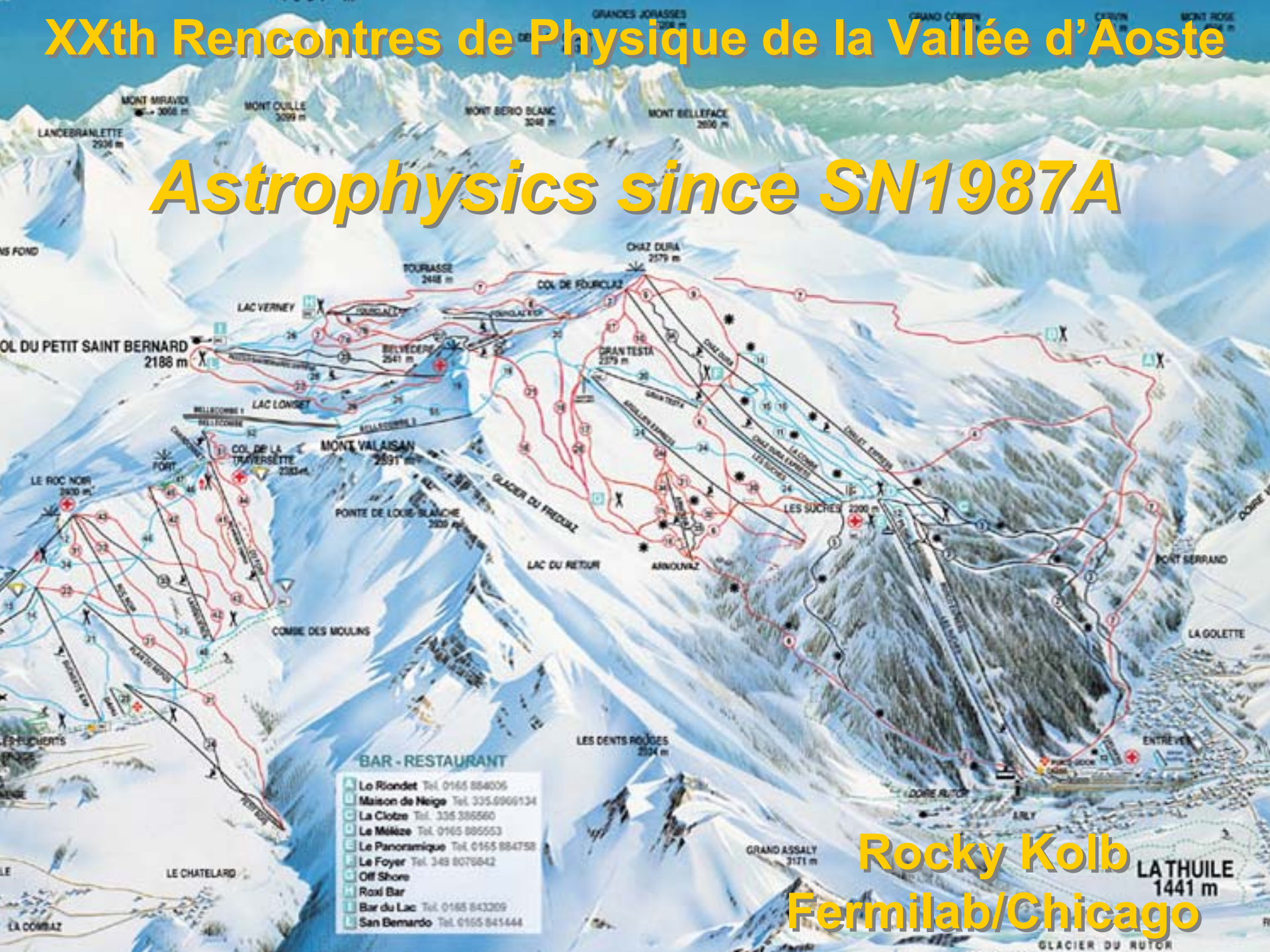
How Do We Sort It Out?

Precision measurements of $\rho_{\text{VAC}}(t)$



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