The Astrophysics of Cosmology

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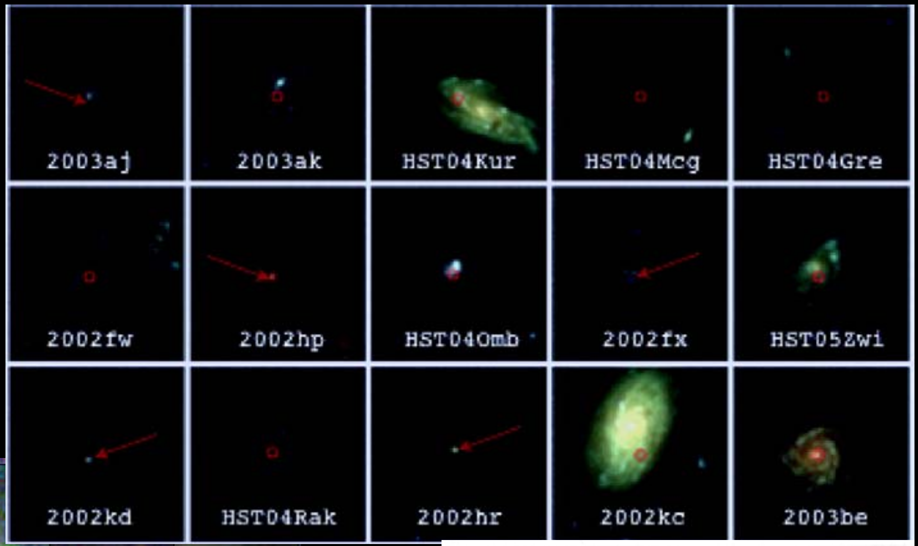
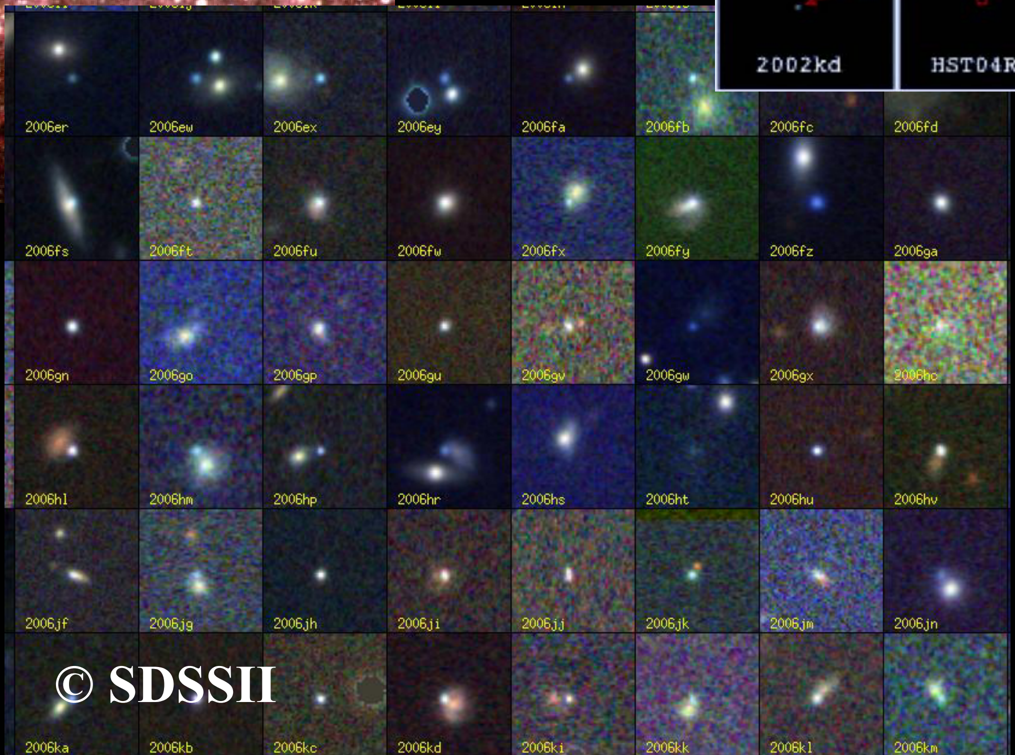
The expanding universe





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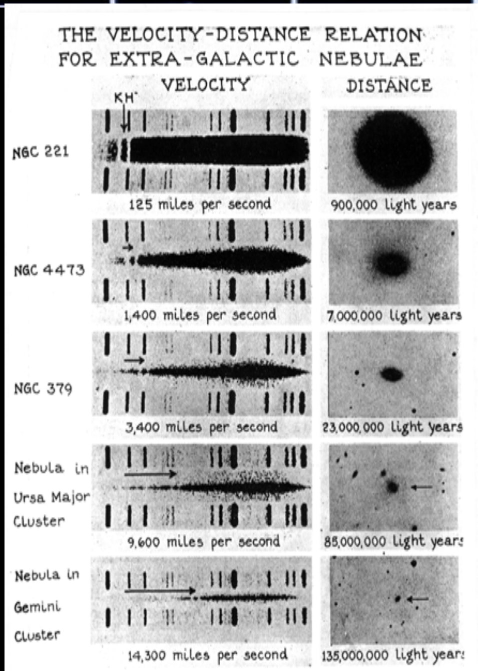


The original Hubble Diagram

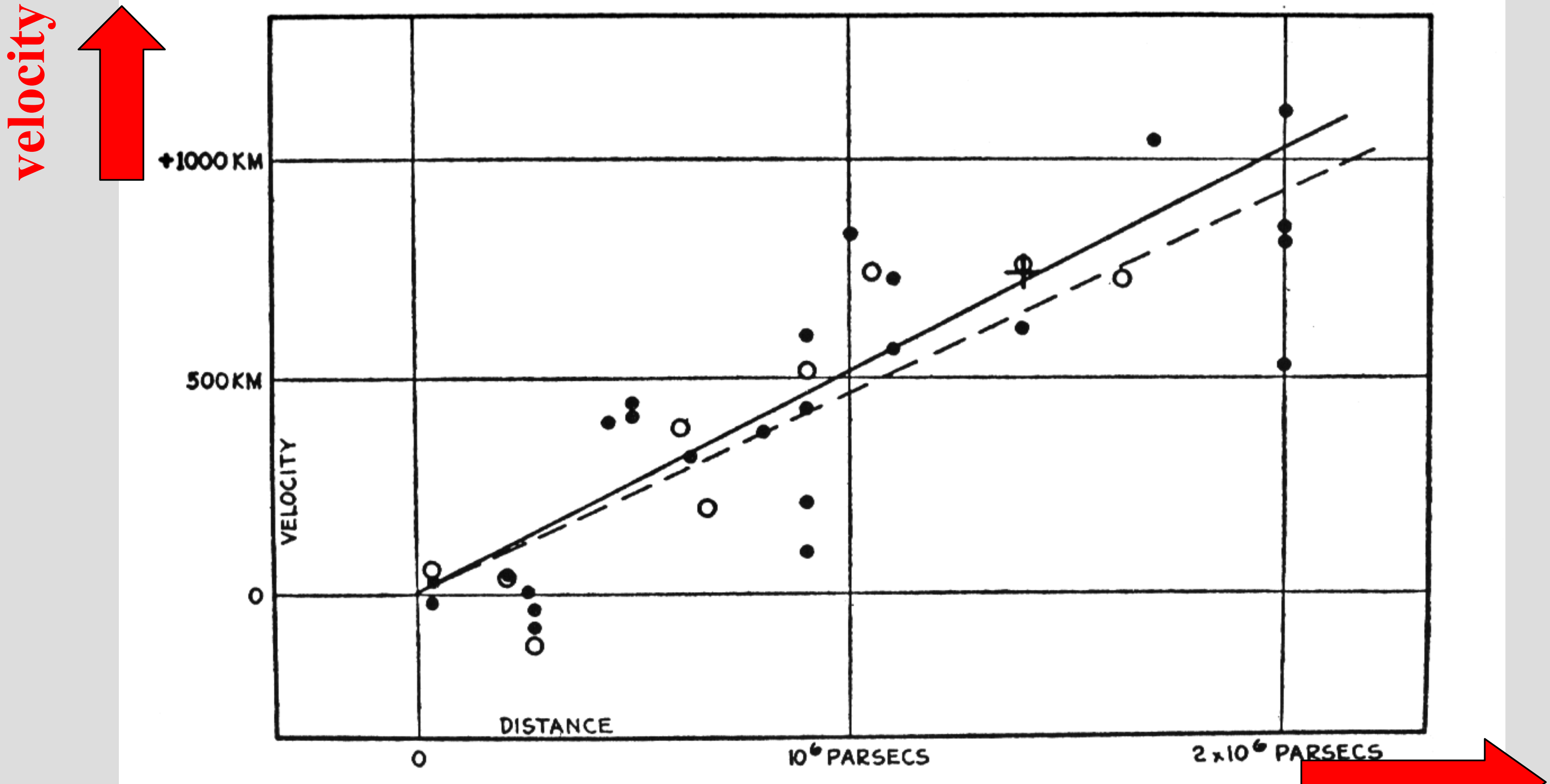
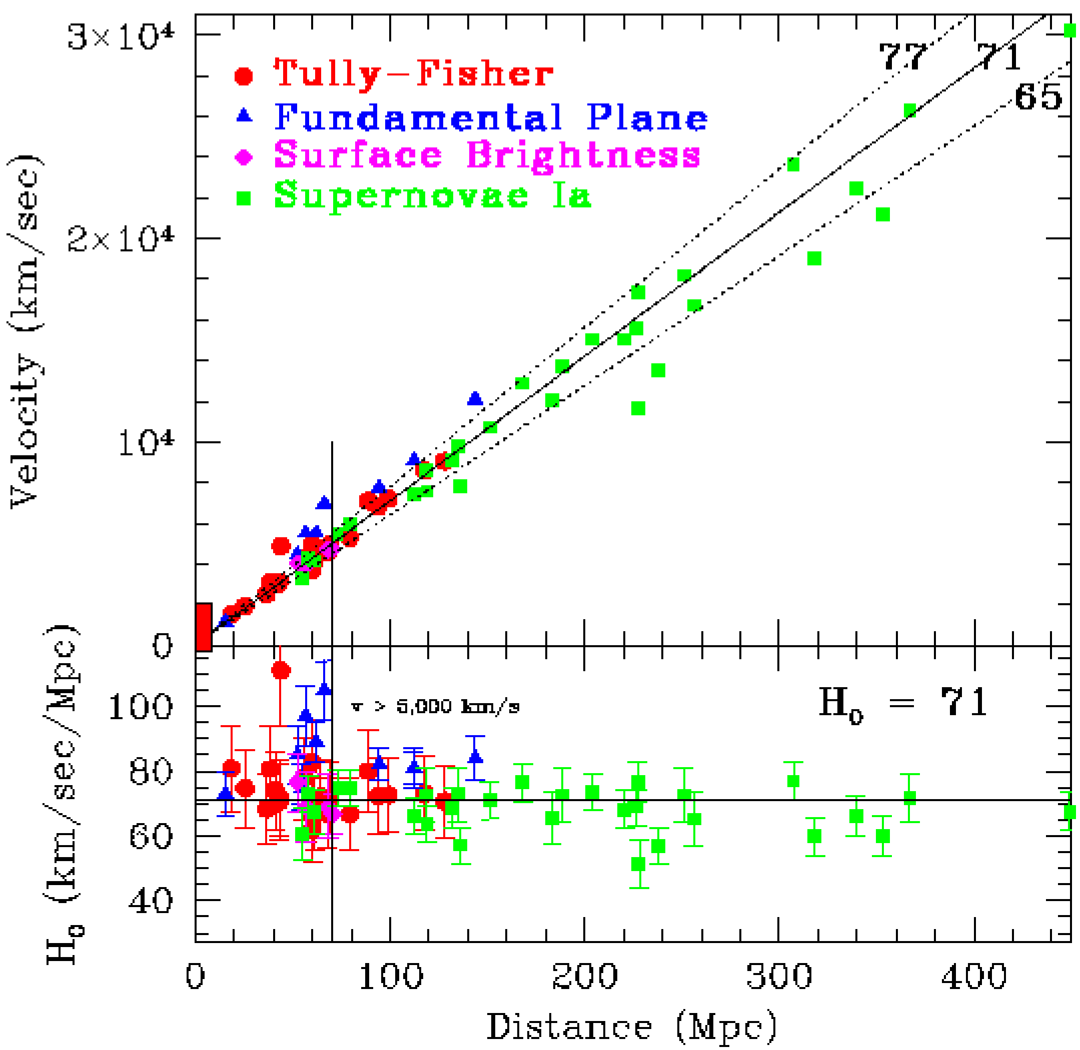


FIG. 9. *The Formulation of the Velocity-Distance Relation.*

A modern Hubble Diagram



The expansion of the universe

Luminosity distance in an isotropic, homogeneous universe as a Taylor expansion

$$D_L = \frac{cz}{H_0}\left\{1 + \frac{1}{2}(1-q_0)z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 \pm \frac{c^2}{H_0^2 R^2}\right]z^2 + O(z^3)\right\}$$

Hubble's Law **acceleration** **jerk/equation of state**

$$H_0 = \frac{\dot{a}}{a} \qquad q_0 = -\frac{\ddot{a}}{a}H_0^{-2} \qquad j_0 = \frac{\dddot{a}}{a}H_0^{-3}$$

Astrophysics

To measure cosmological parameters (distances) you need to

- understand your source
- understand what can affect the light on its path to the observer ('foregrounds')
- know your local environment

The principle

Establish a cosmological distance indicator in the local universe (z<0.05)

---

evolution (primary and secondary)
interstellar and intergalactic dust
gravitational lensing

Measure objects at cosmological distances

- **establish identity of distance indicator**
- **control measurement errors**

The experiment

Establish a cosmological distance indicator in the local universe (z<0.05)

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evolution ➔ light curve shapes, colours, spectroscopy

dust ➔ colours, spectroscopy

gravitational lensing ➔ difficult, need mapping of light beam

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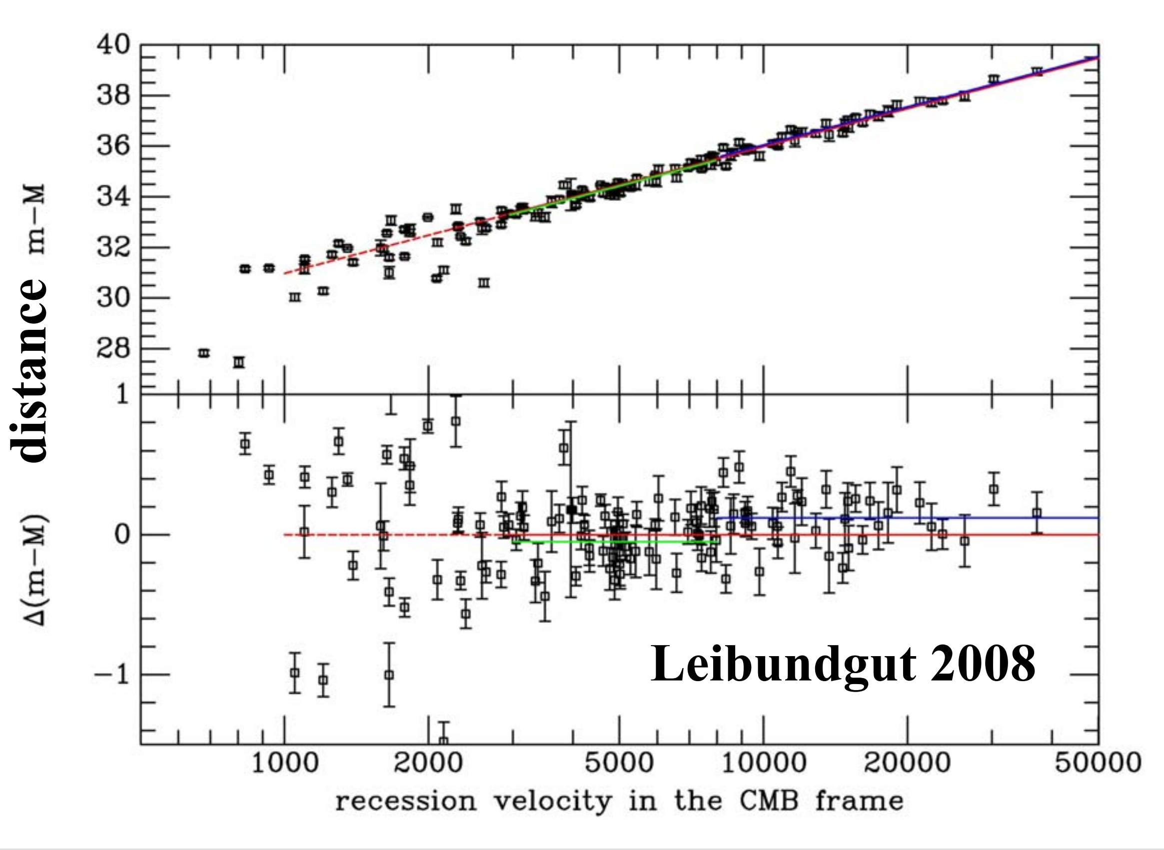
Measure objects at cosmological distances

- High-z SN Search Team, Supernova Cosmology Project, SNLS, ESSENCE, HST searches

Supernovae as distance indicators

Type Ia Supernovae are extremely accurate distance indicators



Systematics

Contamination
Photometry
K-corrections
Malmquist bias
Normalisation
Evolution
Absorption
Local expansion field

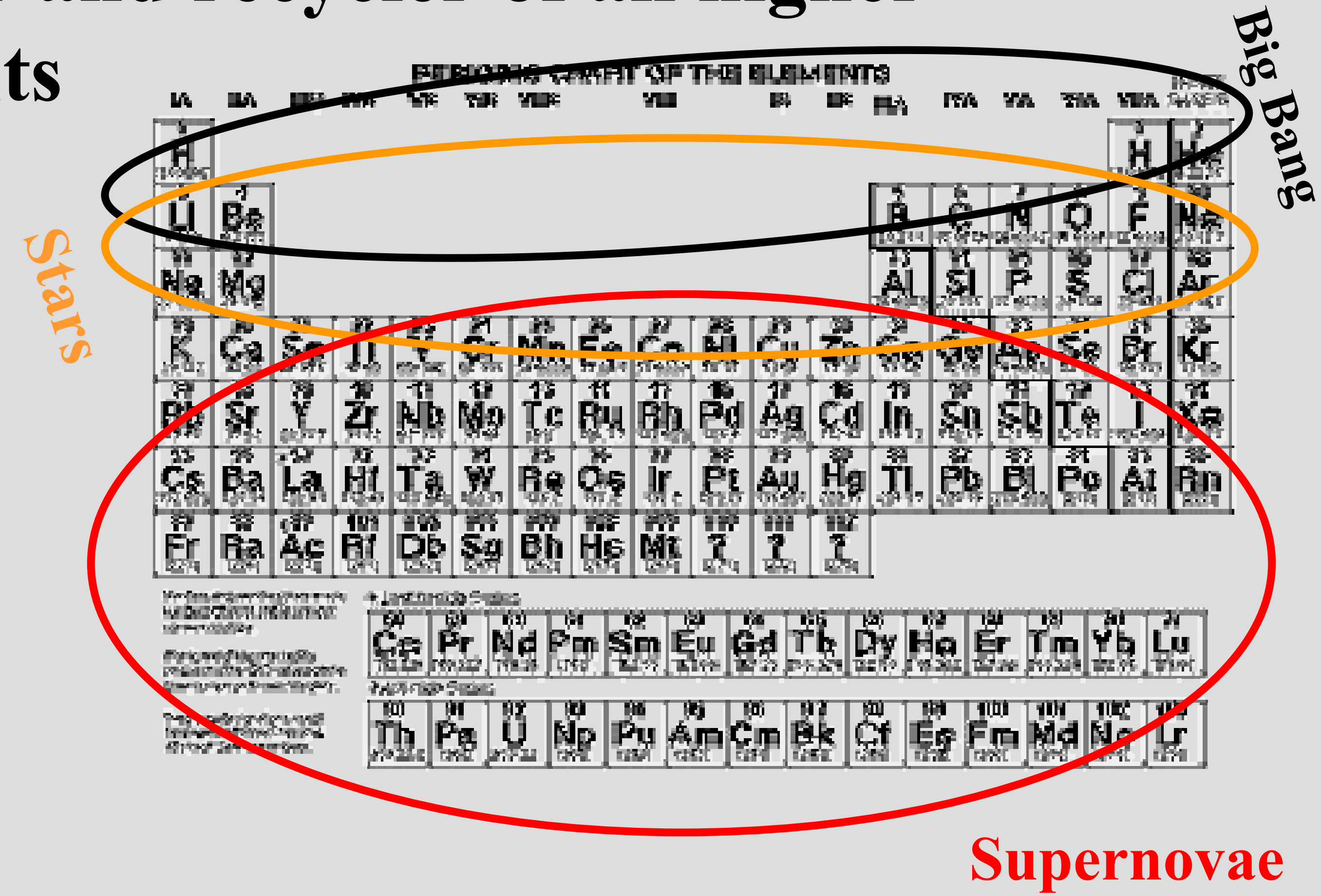
Systematics

Contamination	
Photometry	measurement
K-corrections	
Malmquist bias	
Normalisation	source
Evolution	
Absorption	path
Local expansion field	local environment

What are supernovae?

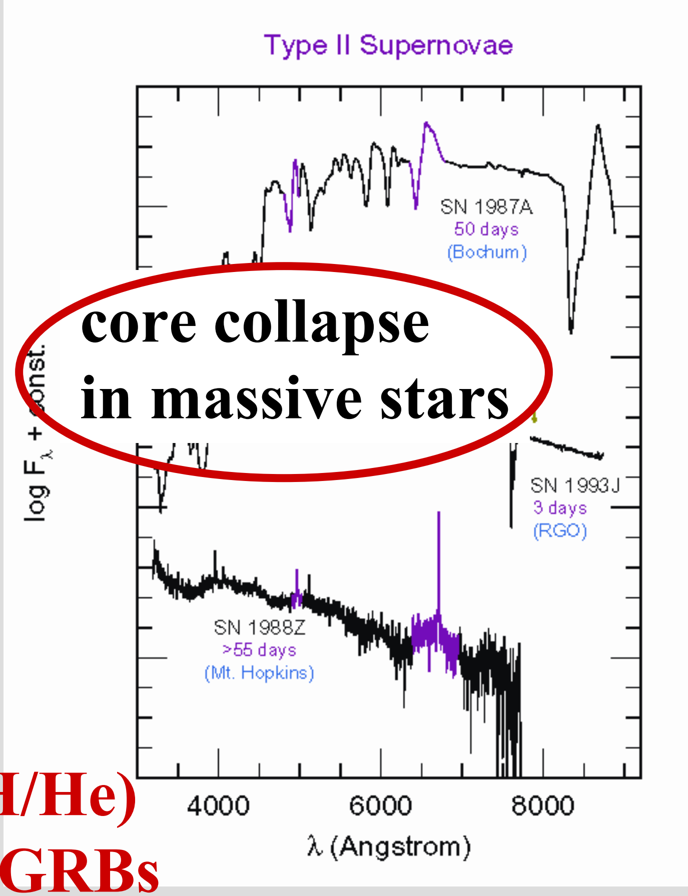
Stellar explosions

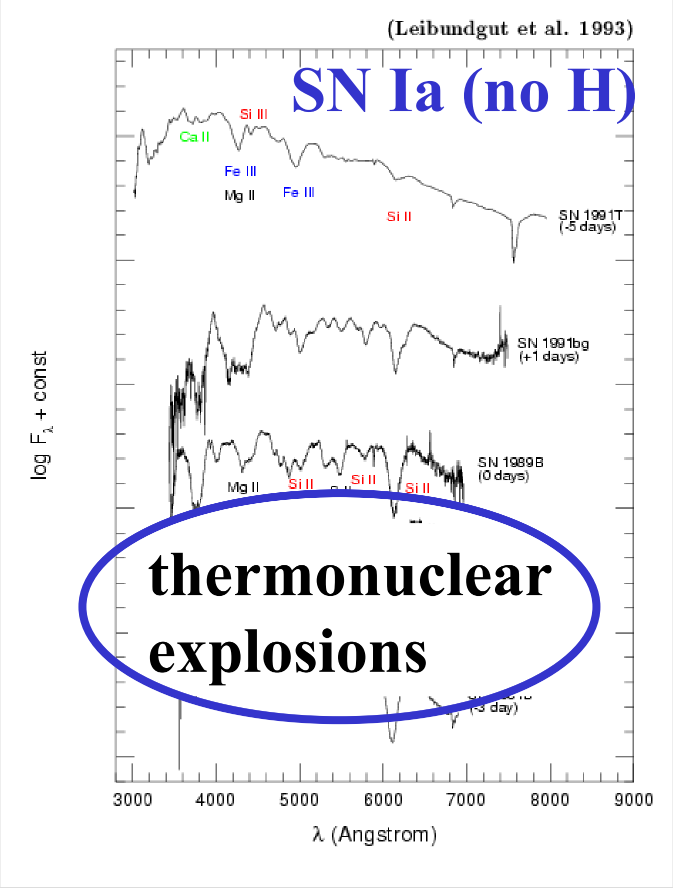
Producer and recycler of all higher elements



Supernova classification

Based on spectroscopy





SN II (H)
SN Ib/c (no H/He)
Hypernovae/GRBs

Know your source

Type Ia Supernovae

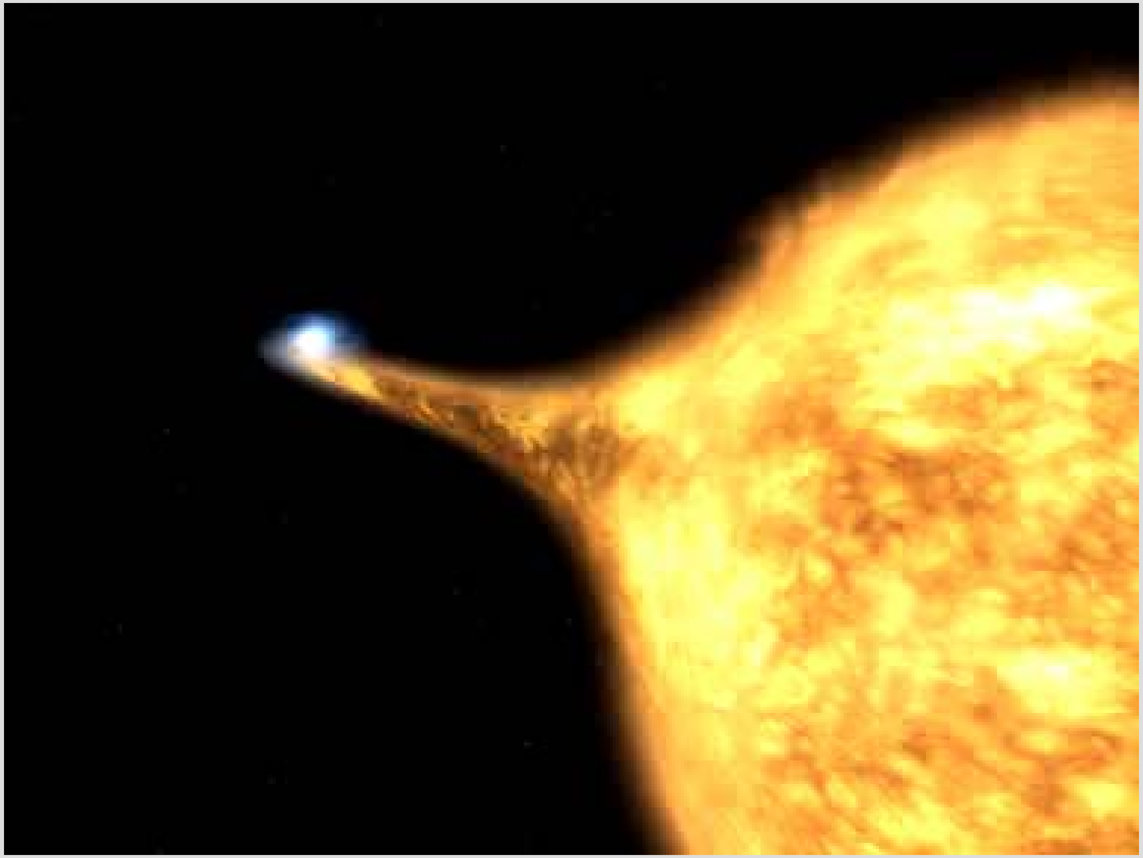
- **complicated source**
- **interesting physics**
- **progenitor systems**

→ **determine the global parameters of the explosions**

  – fuel → nickel mass → distribution in the ejecta
  – total mass
  – explosion energy

Thermonuclear Supernovae

The "standard model"



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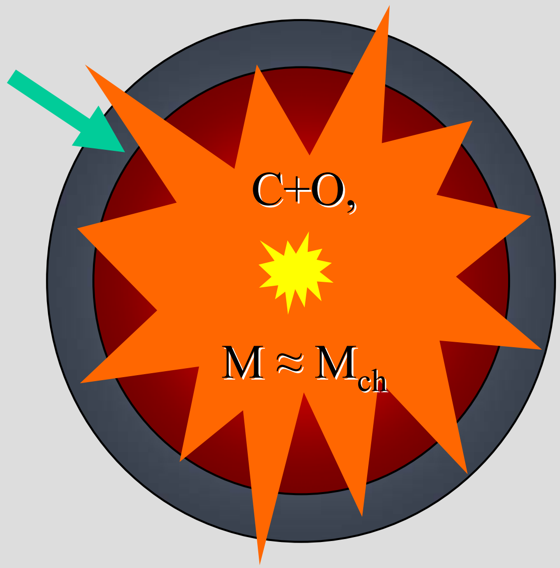
White dwarf in a binary system

Growing to the Chandrasekhar mass (M_{Chand}=1.4 $M_{\odot}$) by mass transfer from a nearby star

The "standard model"

He (+H) from binary companion



Density ~ 10^9 - 10^{10} g/cm

Temperature: a few 10^9 K

Radii: a few 1000 km

Explosion energy:

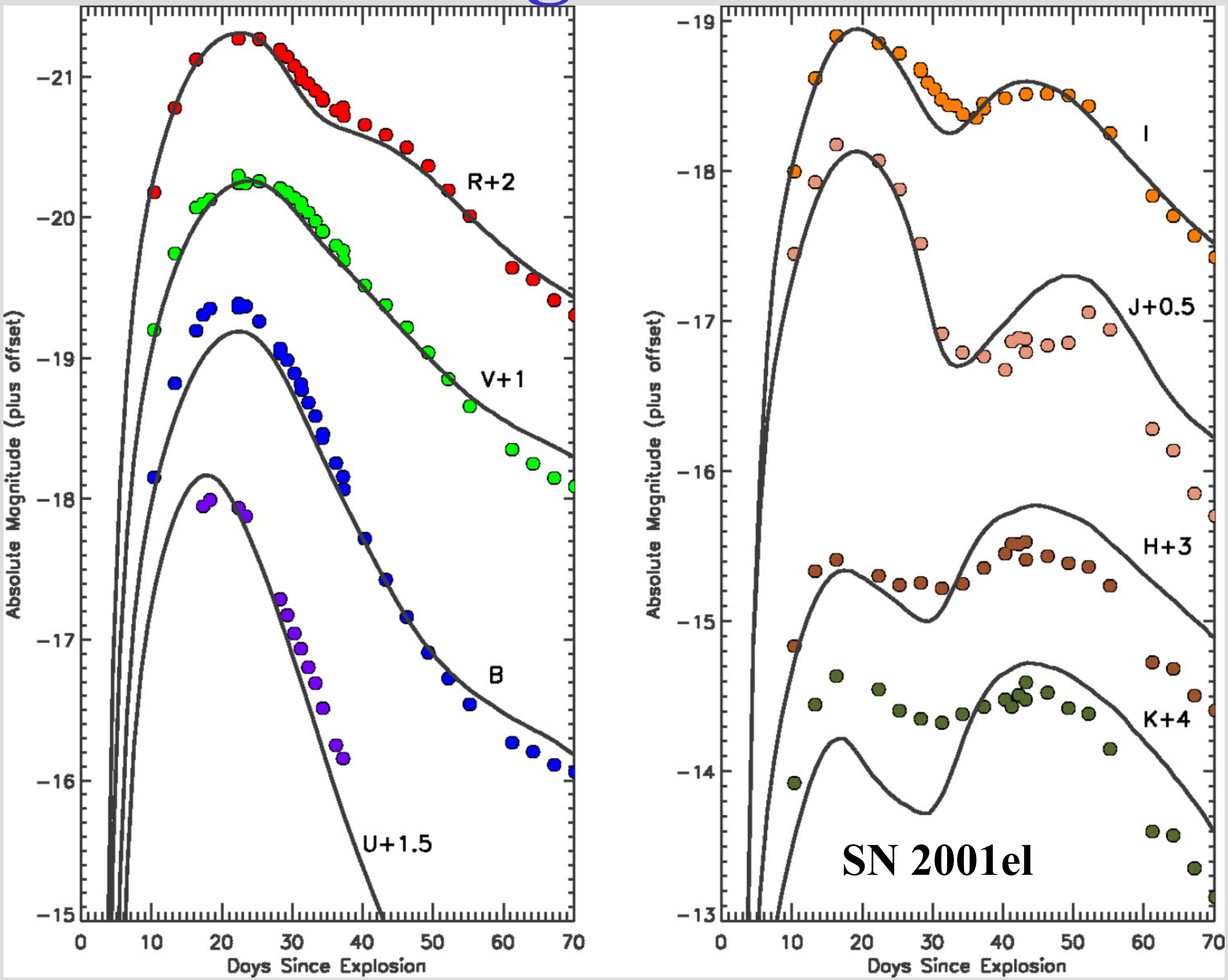
Fusion of

C+C, C+O, O+O

⇒ "Fe"

There is a lot more to this – you need to contact your explosive theory friends

SN light curve calculations



Kasen 2006

Are SNe Ia standard candles?

No!

- **large variations in**
  - light curve shapes
  - colours
  - spectral evolution
  - polarimetry
- **some clear outliers**
  - what is a type Ia supernova?
- **differences in physical parameters**
  - Ni mass
  - ejecta mass

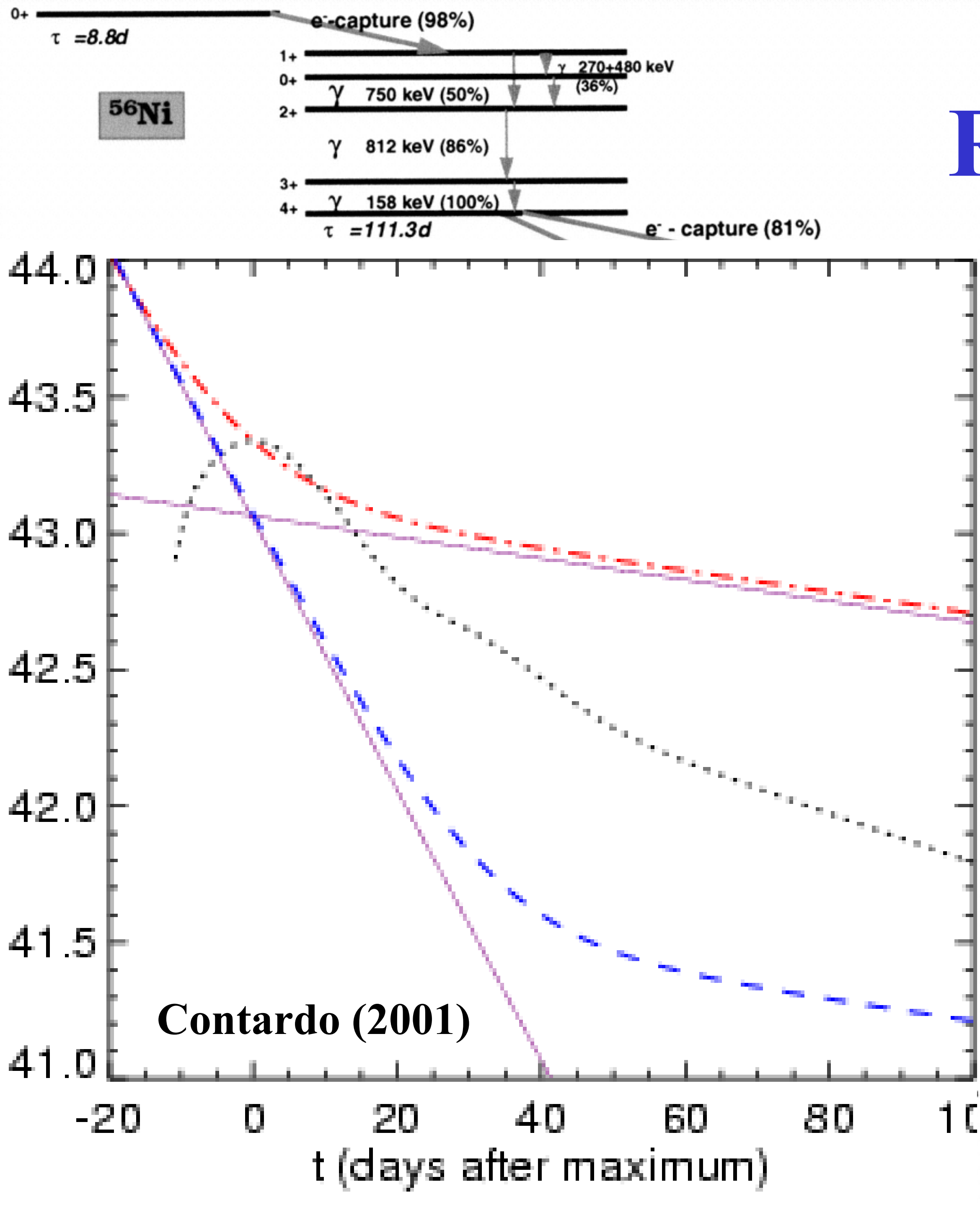
Global explosion parameters

Determine the nickel mass in the explosion from the peak luminosity

- **large variations (up to a factor of 10)**

Possibly determine

- **total mass of the explosion or**
- **differences distribution of the nickel, i.e. the ashes of the explosion or**
- **differences in the explosion energies**

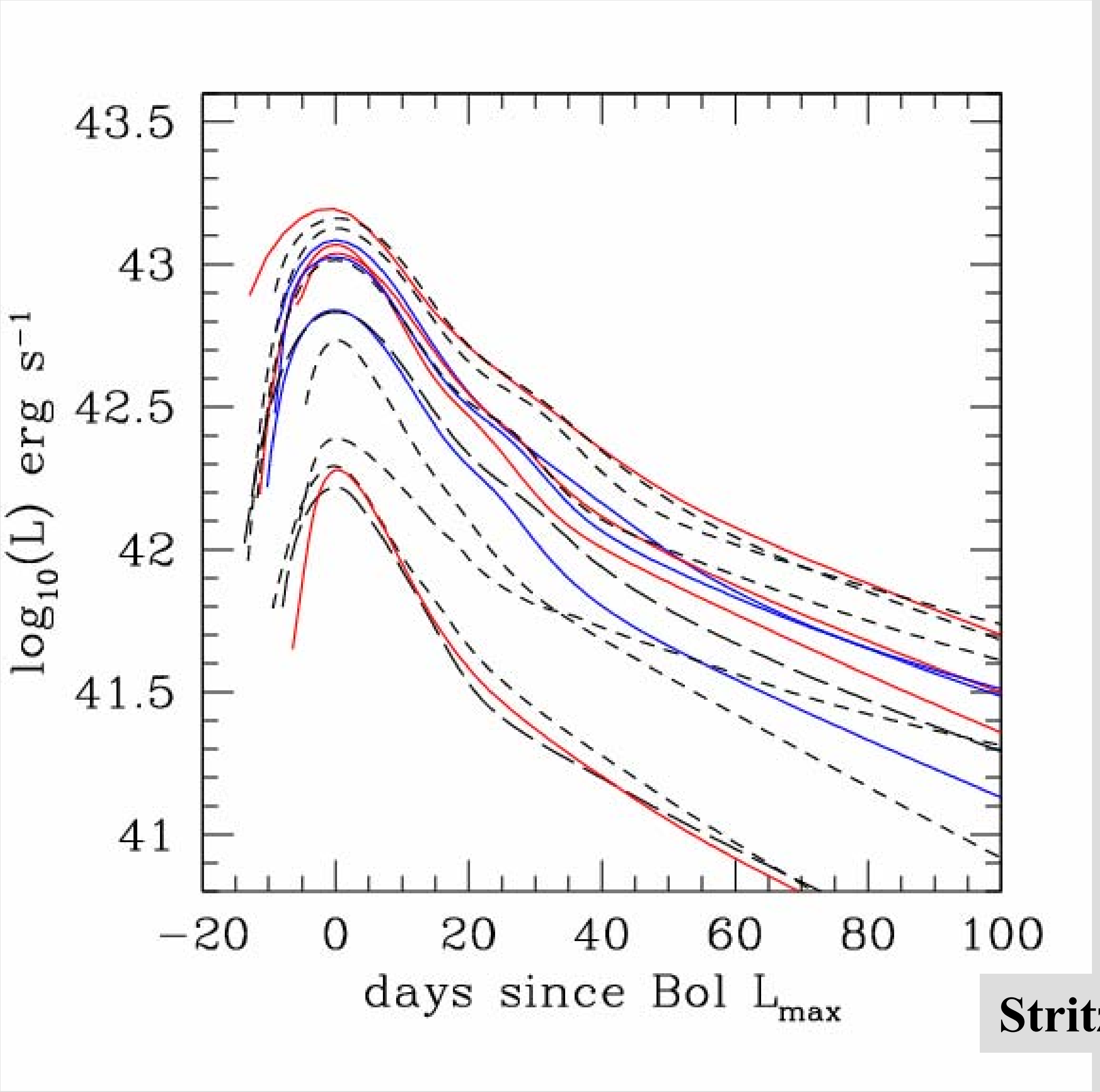


Radioactivity

Isotopes of Ni and other elements

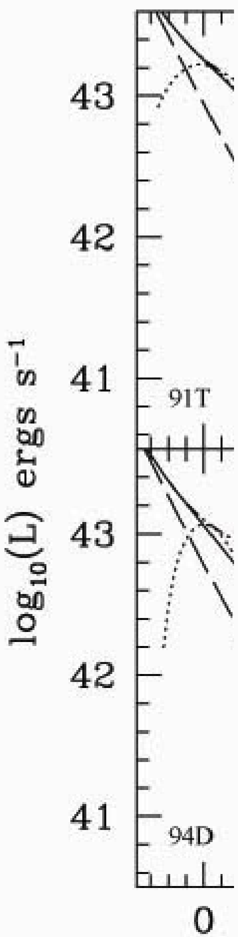
- conversion of γ-rays and positrons into heat and optical photons

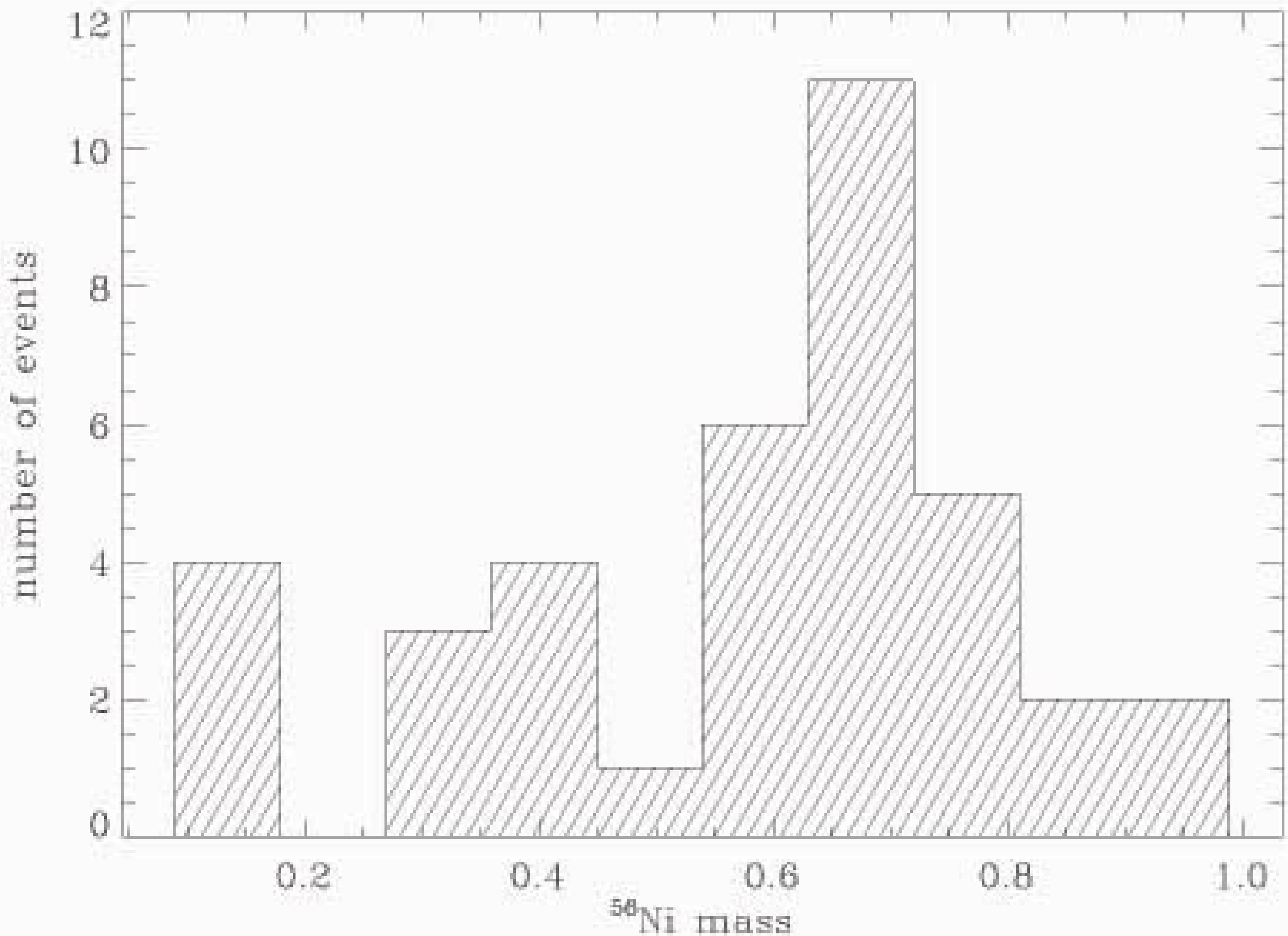
Bolometric light curves



Stritzinger

Ni masses from light curves

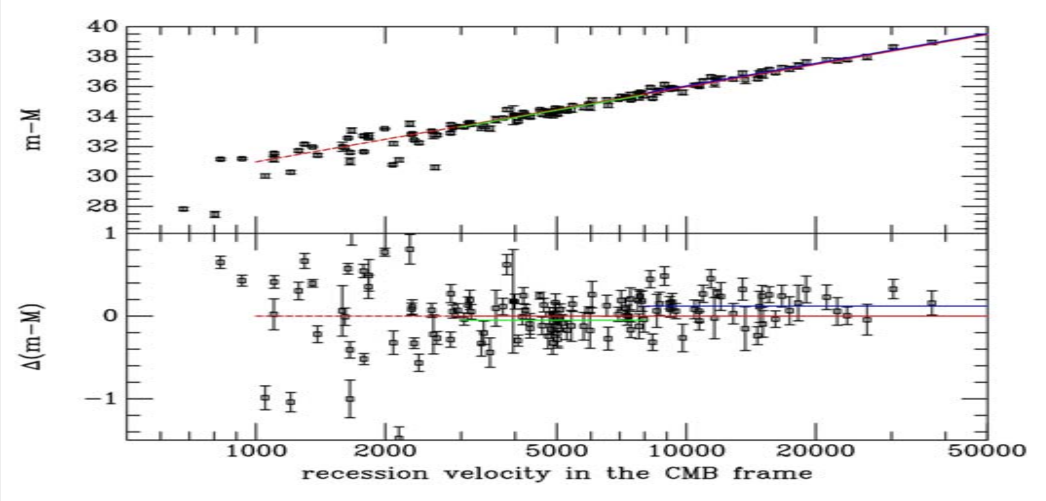




Are SNe Ia good distance indicators?

Yes!

- **normalisation through the light curve shape**
  - still problems with methods!
- **Hubble diagram of nearby SNe Ia**
- **peak luminosities of nearby supernovae**



Determining H_0 from models

Hubble's law

$$D = \frac{v}{H_0} = \frac{cz}{H_0}$$

Luminosity distance

$$D_L = \sqrt{\frac{L}{4\pi F}}$$

Ni-Co decay

$$E_{Ni} = \frac{\lambda_{Ni}\lambda_{Co}}{\lambda_{Ni} - \lambda_{Co}} \left\{ \left[Q_{Ni}\left(\frac{\lambda_{Ni}}{\lambda_{Co}} - 1 \right) - Q_{Co} \right] e^{-\lambda_{Ni}t} + Q_{Co} e^{-\lambda_{Co}t} \right\} N_{Ni,0}$$

H_0 from the nickel mass

$$H_0 = \frac{cz}{D} = cz\sqrt{\frac{4\pi F}{L}} = cz\sqrt{\frac{4\pi F}{\alpha E_{Ni}}} = cz\sqrt{\frac{4\pi F}{\alpha \varepsilon(t) M_{Ni}}}$$

Hubble Law
Luminosity distance
Arnett's rule
Ni-Co decay and rise time

α: conversion of nickel energy into radiation ($L=\alpha E_{Ni}$)
$\varepsilon(t)$: energy deposited in the supernova ejecta

Need bolometric flux at maximum F and the redshift *z* as observables

Stritzinger & Leibundgut (2005)

Assumptions

Rise time (15-25 days) → about 10% uncertainty

Arnett's rule

energy input at maximum equals radiated energy (i.e. $\alpha \approx 1$, $\varepsilon(t_{max}) \approx 1$)

Nickel mass from models

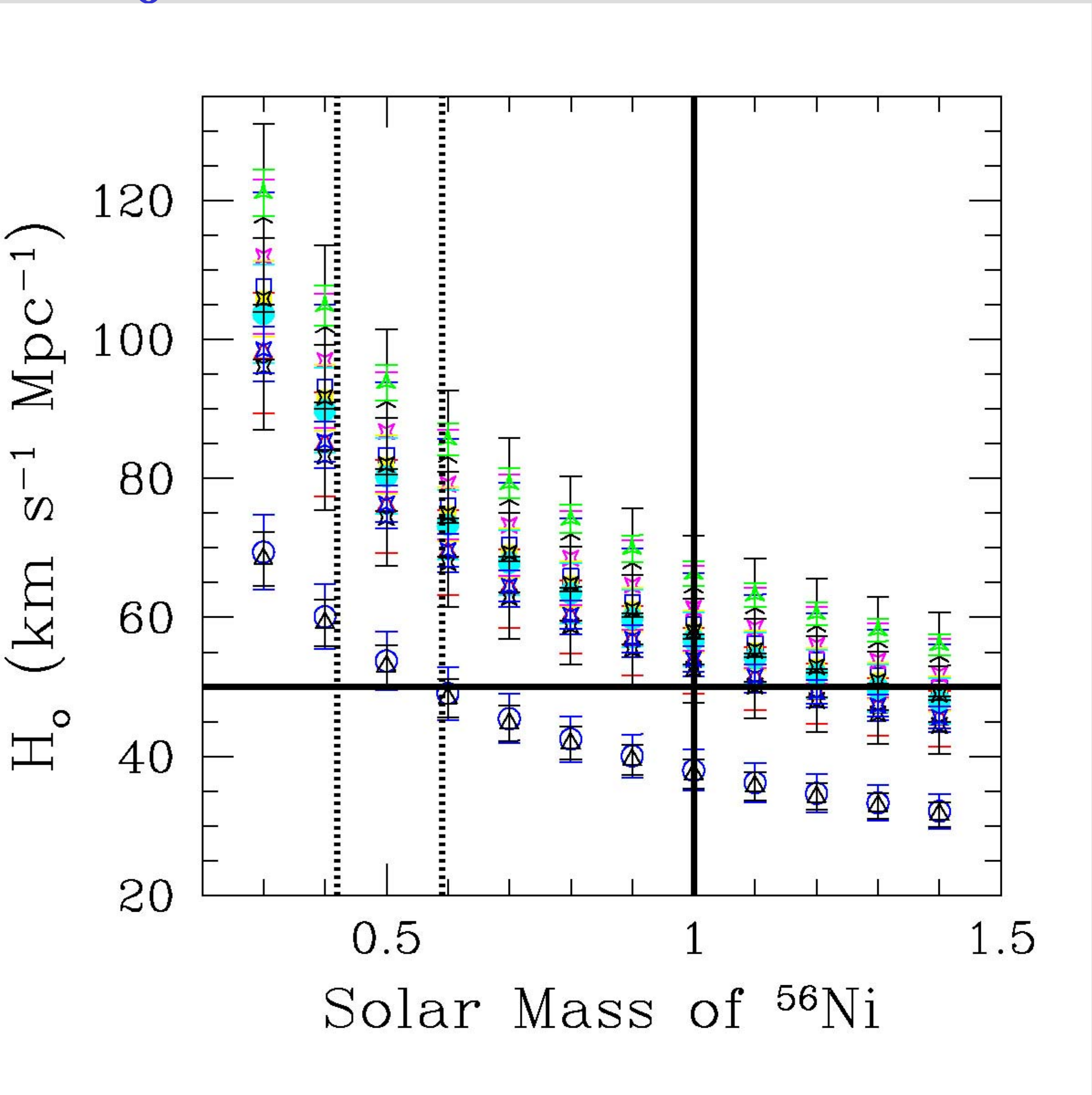
→ uniquely defines the bolometric peak luminosity

H_0 and the Ni mass

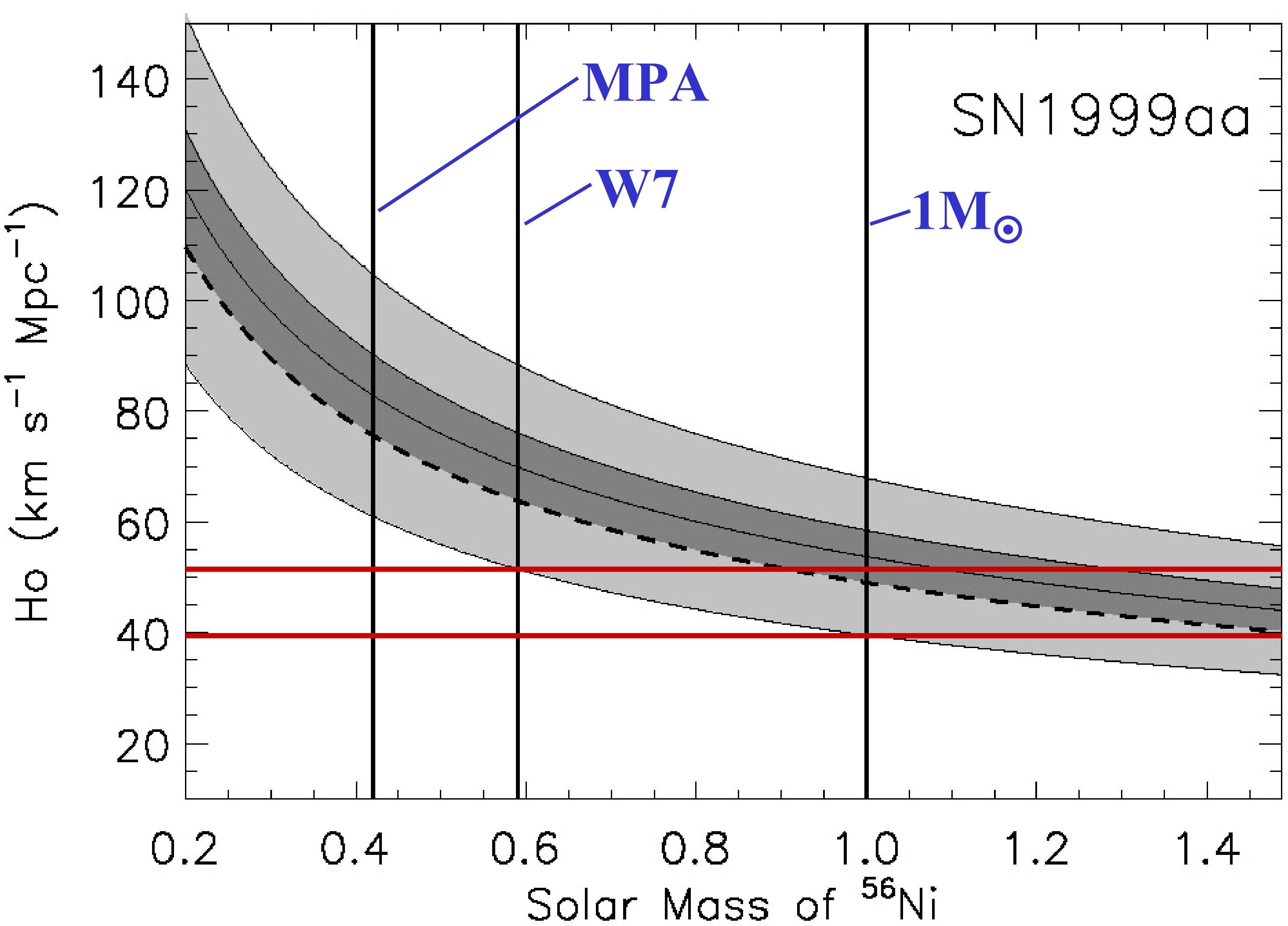
Individual SNe follow the 1/M dependency.

Problem:

Since they have individual Ni masses it is not clear which one to apply!



Determine a lower limit for H_0



Acceleration

Originally thought of as deceleration due to the action of gravity in a matter dominated universe

$$D = \frac{cz}{H_0}\left[1 + \frac{1}{2}(1 - q_0)z\right]$$

$$q_0 = -\frac{\ddot{a}}{a} H_0^{-2}$$


$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^4} T_{\mu\nu}$
A. EINSTEIN
FOR WORLD
CUP

Friedmann cosmology

Assumption:
homogeneous and isotropic universe

Null geodesic in a Friedmann-Robertson-Walker metric:

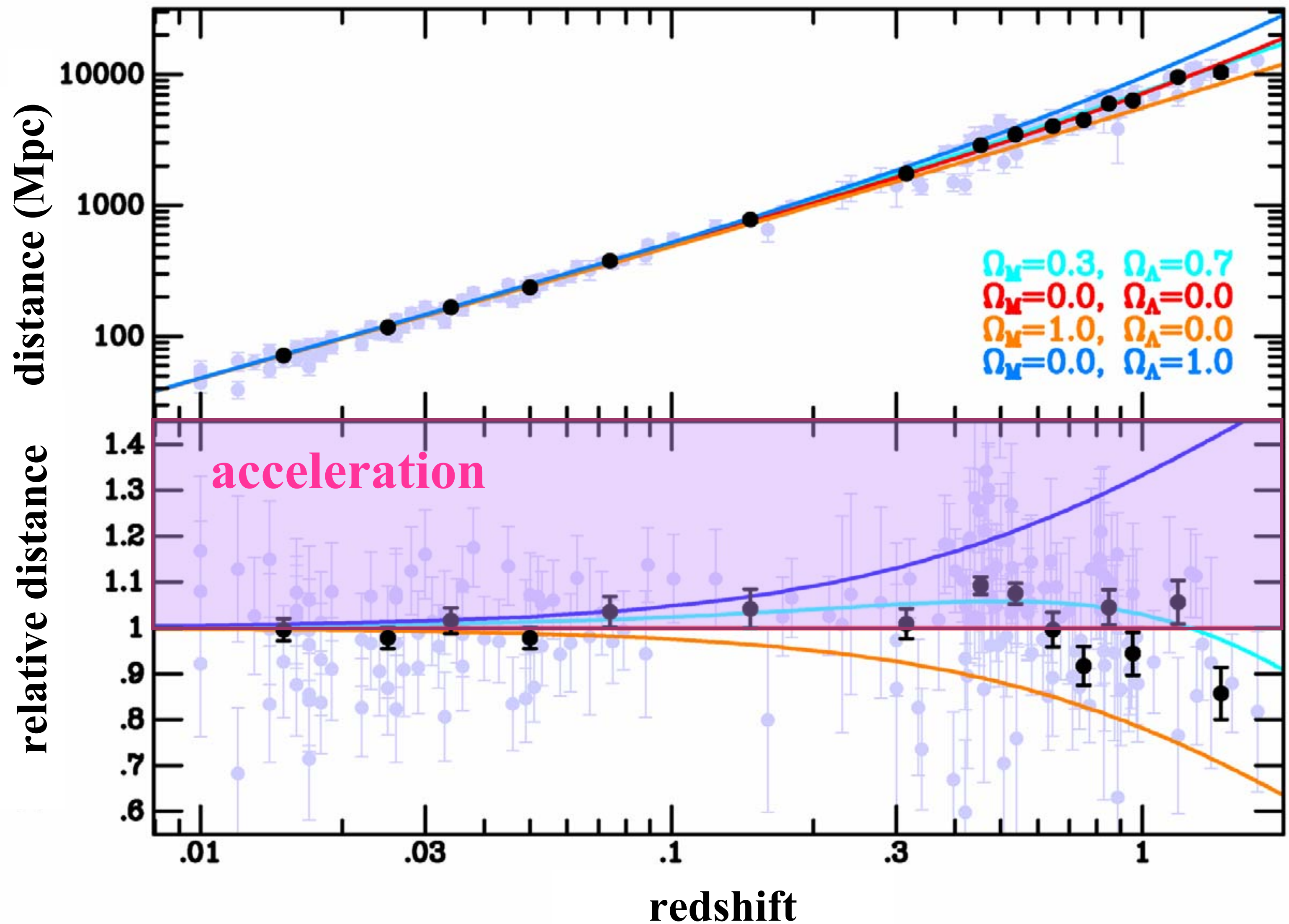
$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}} S\left\{ \sqrt{|\Omega_\kappa|} \int_0^z \left[\Omega_\kappa (1+z')^2 + \Omega_M (1+z')^3 + \Omega_\Lambda \right]^{-1/2} dz' \right\}$$

$$\Omega_M = \frac{8\pi G}{3H_0^2}\rho_M$$

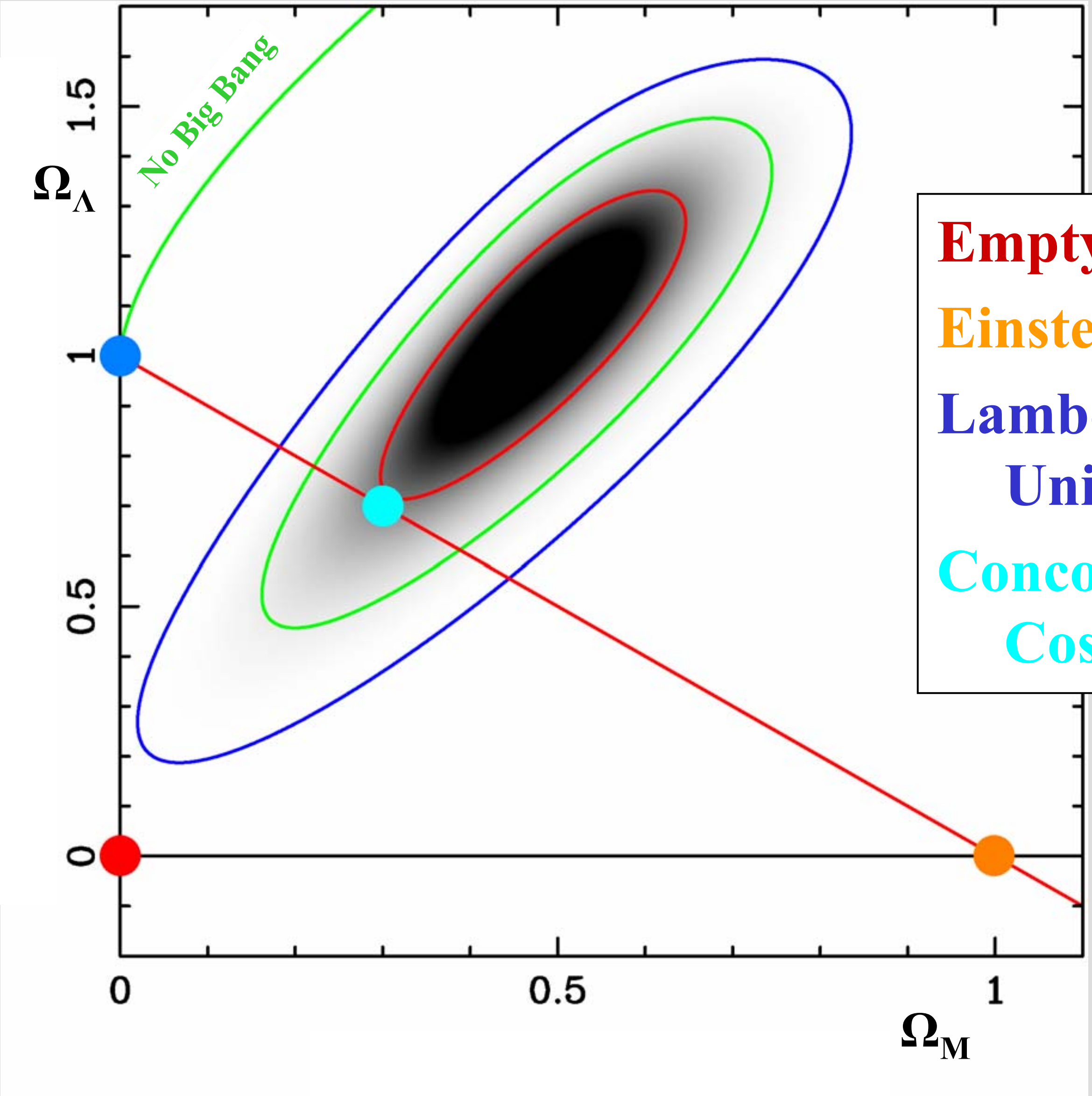
$$\Omega_k = -\frac{kc^2}{R^2 H_0^2}$$

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$$

Measure acceleration



Cosmological implication



Empty Universum

Einstein – de Sitter

Lambda-dominated Universe

Concordance Cosmology

ESSENCE

World-wide collaboration to find and characterise SNe Ia with 0.2 < z < 0.8

Search with CTIO 4m Blanco telescope

Spectroscopy with VLT, Gemini, Keck, Magellan

Goal: Measure distances to 200 SNe Ia with an overall accuracy of 5%
→ determine ω to 10% overall

SNLS – The SuperNova Legacy Survey



World-wide collaboration to find and characterise SNe Ia with $0.2 < z < 0.8$

Search with CFHT 4m telescope

Spectroscopy with VLT, Gemini, Keck, Magellan

Goal: Measure distances to 700 SNe Ia with an overall accuracy of 5% → determine ω to 7% overall

The equation of state parameter ω

General luminosity distance

$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}} S\left\{\sqrt{|\Omega_\kappa|}\int_0^z \left[\Omega_\kappa(1+z')^2 + \sum_i \Omega_i (1+z')^{3(1+\omega_i)}\right]^{-1/2} dz'\right\}$$

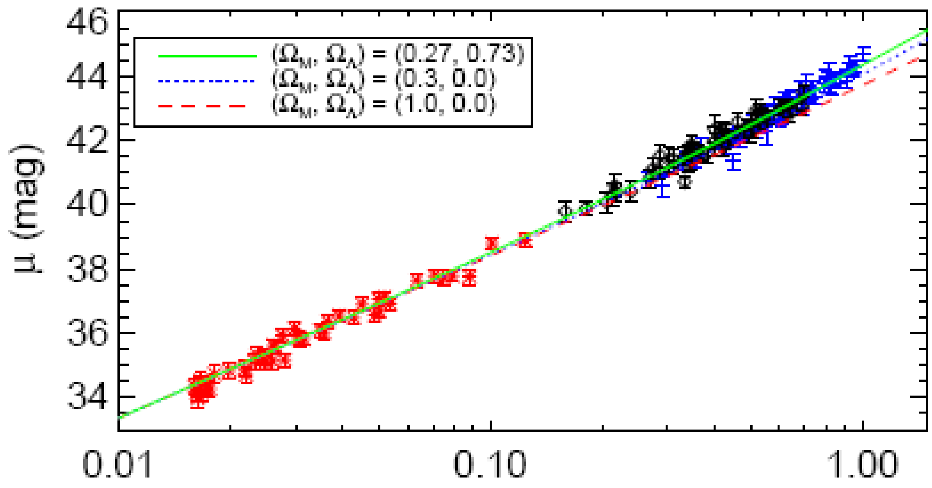
- **with** $\Omega_\kappa = 1 - \sum_i \Omega_i$ **and** $\omega_i = \dfrac{p_i}{\rho_i c^2}$

ω_M= 0 (matter)

ω_R= ⅓ (radiation)

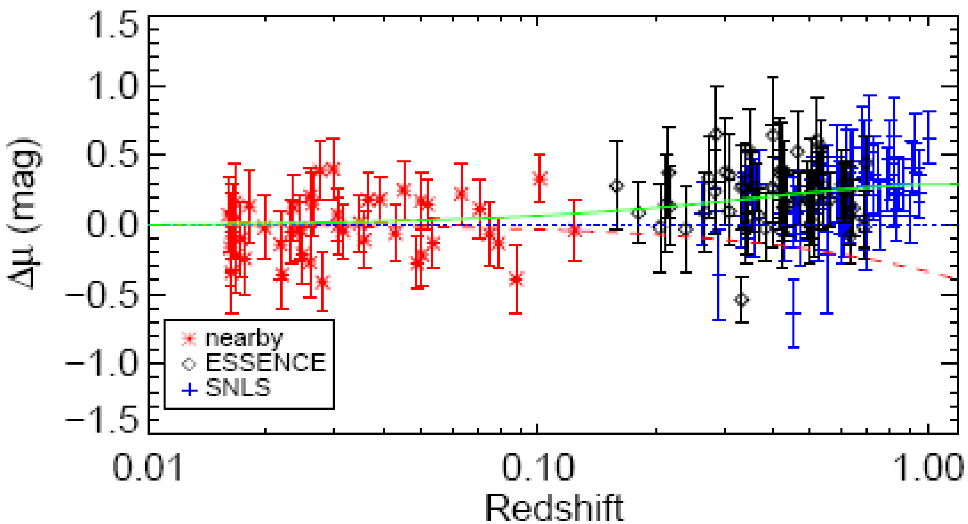
ω_Λ= -1 (cosmological constant)

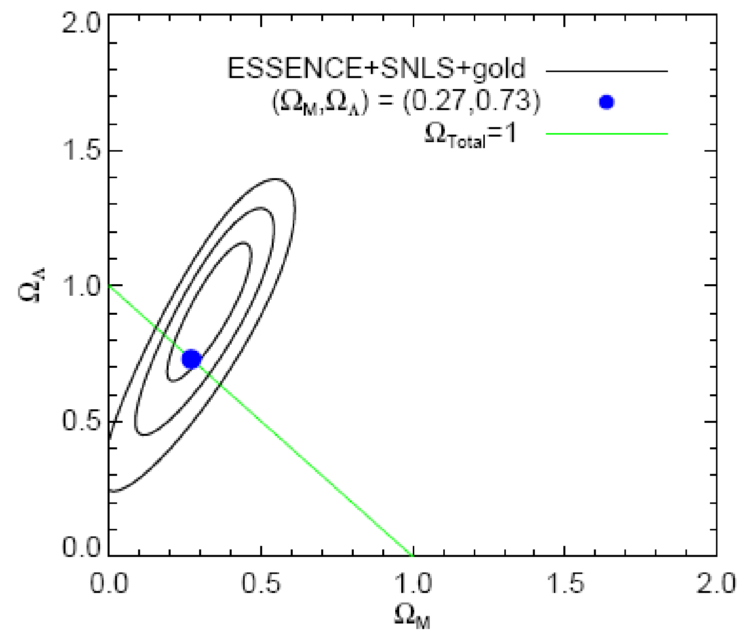
The SN Ia Hubble Diagram



Combination of ESSENCE, SNLS and nearby SNe Ia

Wood-Vasey et al. 2007





Cosmology results

SNLS 1st year (Astier et al. 2006)

- **71 distant SNe Ia**
  - flat geometry and combined with BAO results

  $\Omega_M = 0.271 \pm 0.021$ *(stat)* ± 0.007 *(sys)*

  $w = -1.02 \pm 0.09$ *(stat)* ± 0.054 *(sys)*

ESSENCE 3 years (Wood-Vasey et al. 2007)

- **60 distant SNe Ia**
  - plus 45 nearby SNe Ia, plus 57 SNe Ia from SNLS 1st year
  - flat geometry and combined with BAO

  $w = -1.07 \pm 0.09$ (*stat*) ± 0.13 (*sys*)

  $\Omega_M = 0.27 \pm 0.03$

The so far most complete SN Ia sample

(Riess et al. 2007)

Collected all available distant SNe Ia

- Riess et al. (2004)
- Astier et al. (2006)
- Wood-Vasey et al. (2007)

→ 23 SNe Ia with z>1

→ total of 182 SNe Ia with z>0.0233 (v=7000 km/s)

lower redshift limit to avoid any local effects

The currently most complete sample

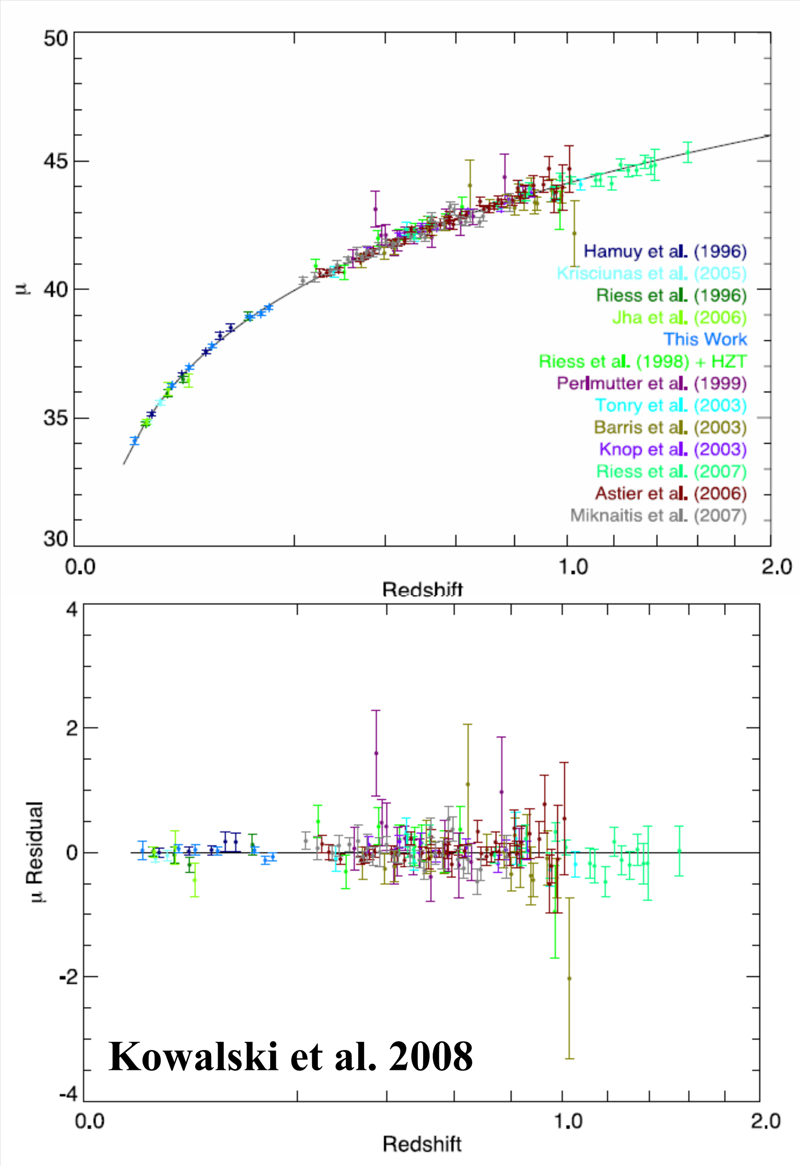
(Kowalski et al. 2008)

Federate all available SNe Ia

- ► 58 low redshift SNe Ia ($0.015<z<0.15$)
- ► 41 SNe Ia from the Supernova Cosmology Project (Perlmutter et al. 1999 and Knop et al. 2003) and 42 SNe Ia from the High-z Supernova Search Team (Schmidt et al. 1998, Riess et al. 1998, Tonry et al. 2003, Barris et al. 2004)
- ► 72 SNe Ia from SNLS (Astier et al. 2006) and 75 SNe Ia from ESSENCE (Wood-Vasey et al. 2007)
- ► 29 SNe Ia from HST (Riess et al. 2007)
- ► (22 at $z>1$)

→ A total of 307 SNe Ia

The most complete SN Hubble Diagram



Binned distribution shown

- **13 different data sources**
- **uniform light curve fitting**
- **uniform cosmological analysis**

Cosmological result

SNe Ia combined with BAO and CMB results assuming flat geometry

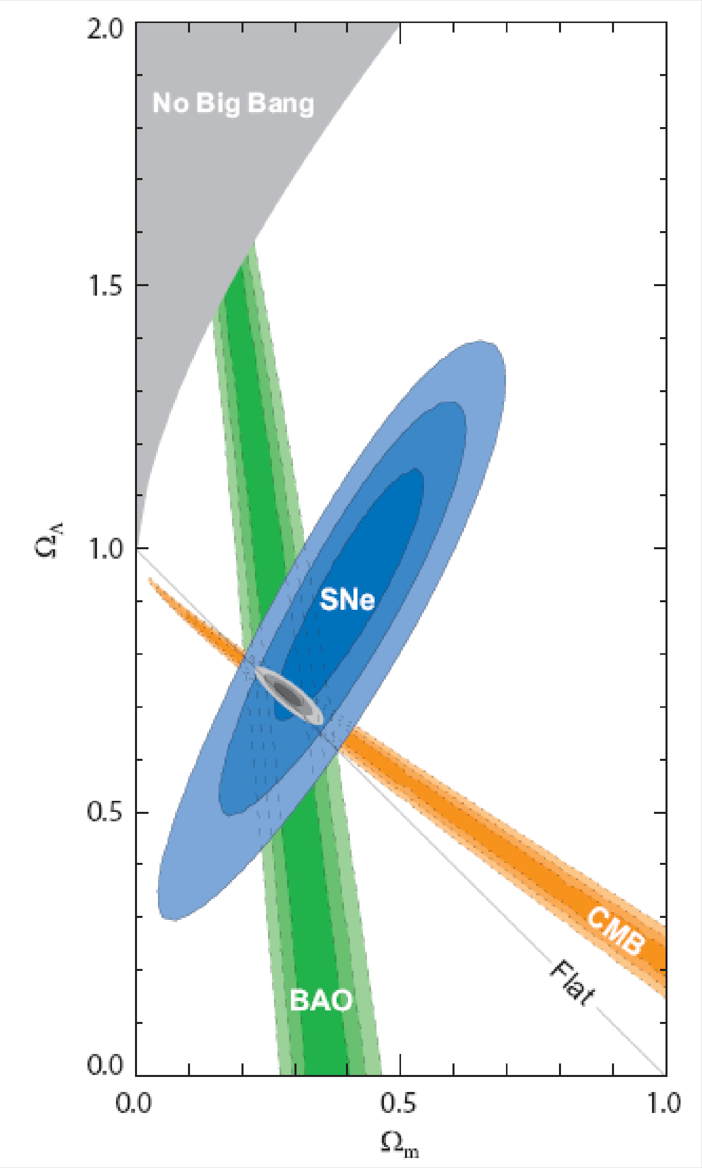
- $\Omega_M = 0.274 \pm 0.016$ *(stat)* ± 0.012 *(sys)*
- $w = -0.969 \pm 0.06$ *(stat)* ± 0.07 *(sys)*

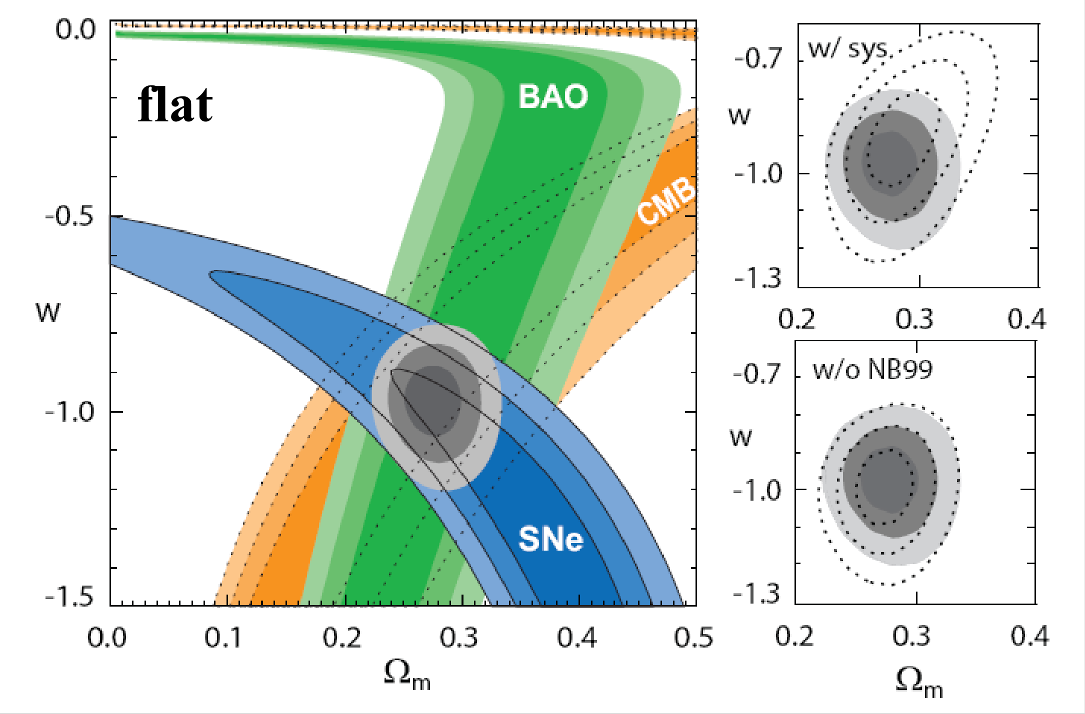
SNe Ia combined with BAO and CMB results

- $\Omega_M = 0.285 \pm 0.020$ *(stat)* ± 0.010 *(sys)*
- $\Omega_K = -0.010 \pm 0.010$ *(stat)* ± 0.005 *(sys)*
- $w = -1.001 \pm 0.07$ *(stat)* ± 0.08 *(sys)*

Cosmological results

No changes compared to previous data sets





Kowalski et al. 2008

Systematics table

Wood-Vasey et al. 2007

Table 5. Potential Sources of Systematic Error on the Measurement of w

Source	dw/dx	Δx	Δ_w	Notes
Phot. errors from astrometric uncertainties of faint objects	1/mag	0.005 mag	0.(	
Bias in differential image photor				
CCD linearity				
Photometric zeropoint difference				
Zeropoint offset between low and				
K-corrections				
Filter passband structure				
Galactic extinction				
Host-galaxy R_V				
Host-galaxy extinction treatmen				
Intrinsic color of SNe Ia				
Malmquist bias/selection effects				
SN Ia evolution				
Hubble bubble				
Gravitational lensing	$1/\sqrt{N}$ / mag	0.01 mag	< 0.001	Holz & Linder (2005)
Grey dust	1 / mag	0.01 mag	0.01	
Subtotal w/o extinction+color	···	···	0.082	
Total	···	···	0.13	
Joint ESSENCE+SNLS comparison	···	···	0.02	photometric system
Joint ESSENCE + SNLS total	···	···	0.13	

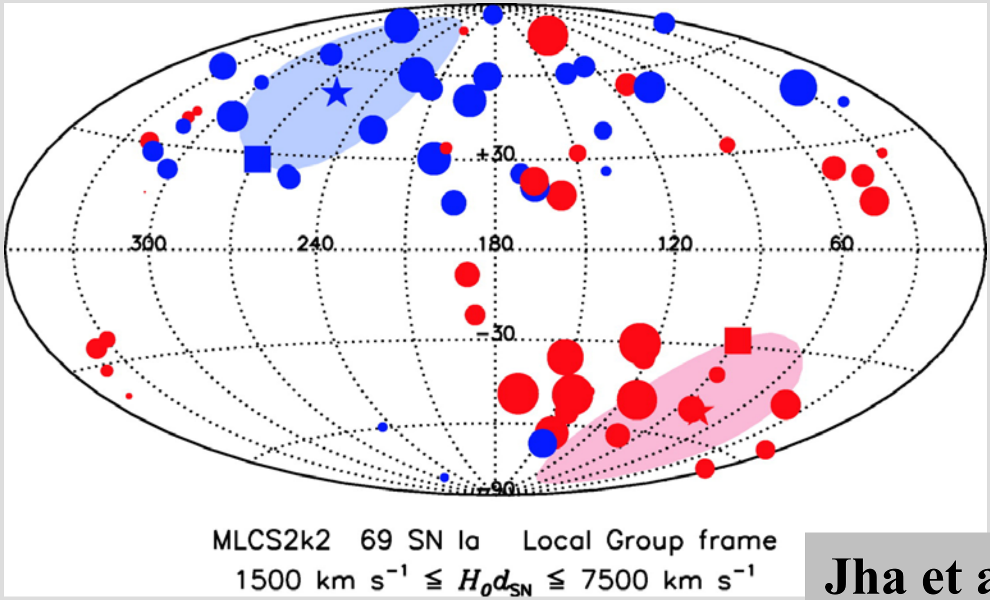
Kowalski et al. 2008

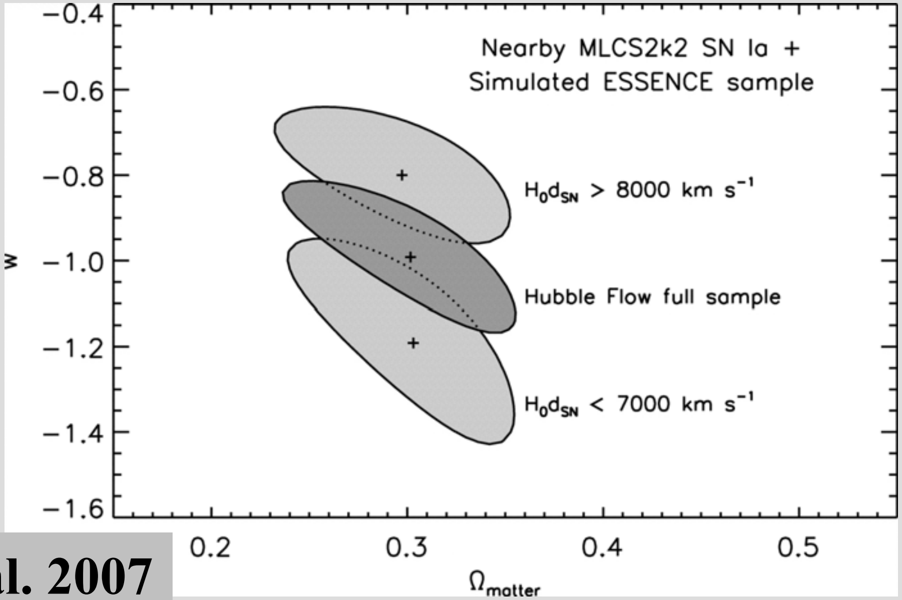
Source	common (mag)	sample-dependent (mag)
$\alpha\&\beta$ correction	0.015	-
Contamination	-	0.015
Lightcurve model	0.028	-
Zero point	0.021	0.021
Malmquist bias	-	0.020
Gravitational lensing	-	0.009*
Galactic extinction	0.013	-
Total in mag	$\Delta M = 0.040$	$\Delta M_i = 0.033$

Caveat

All cosmological interpretations make use of the same local sample!

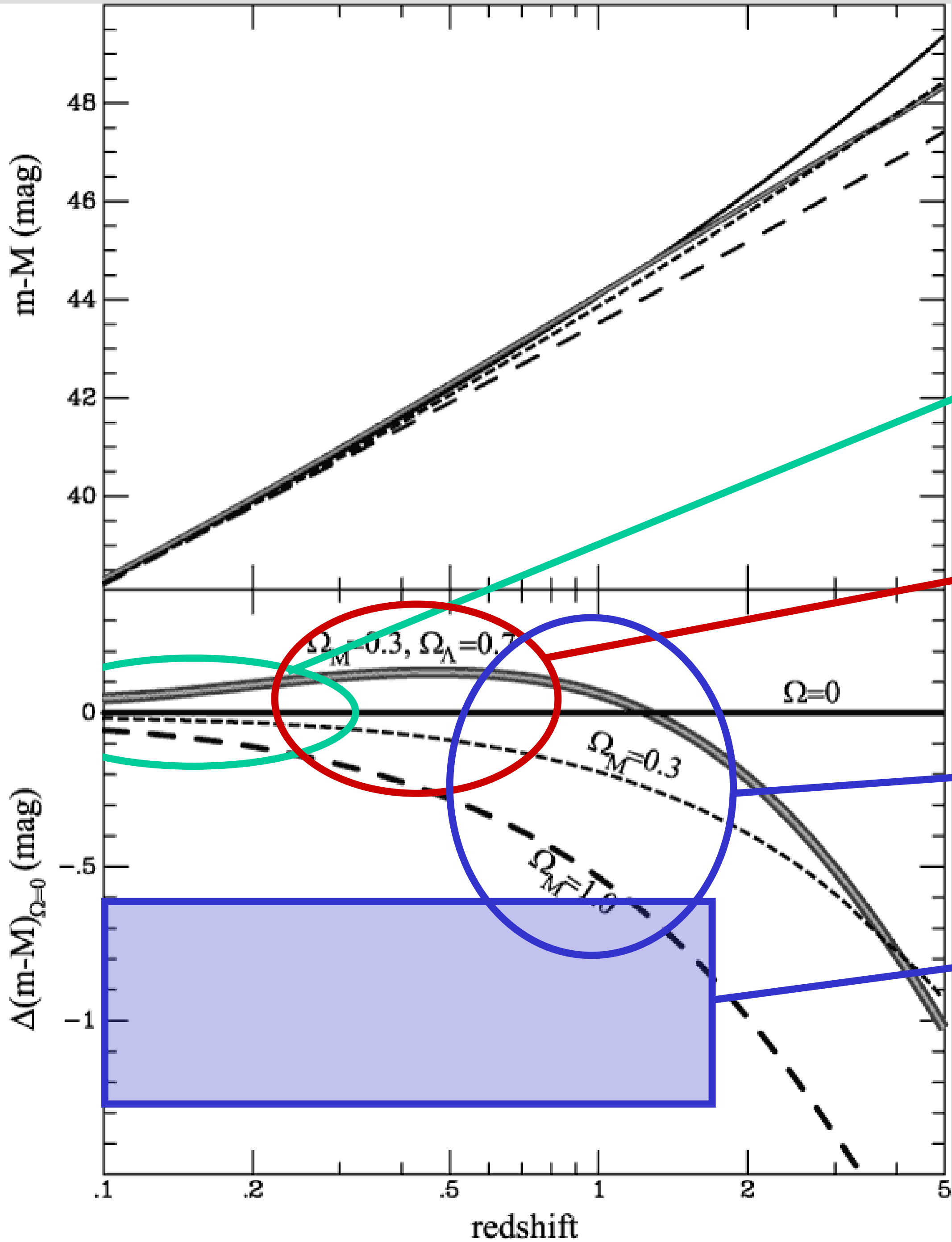
Systematics of the local sample could be a problem (local impurities in the expansion field, e.g. 'Hubble bubble')





Jha et al. 2007

SN Projects



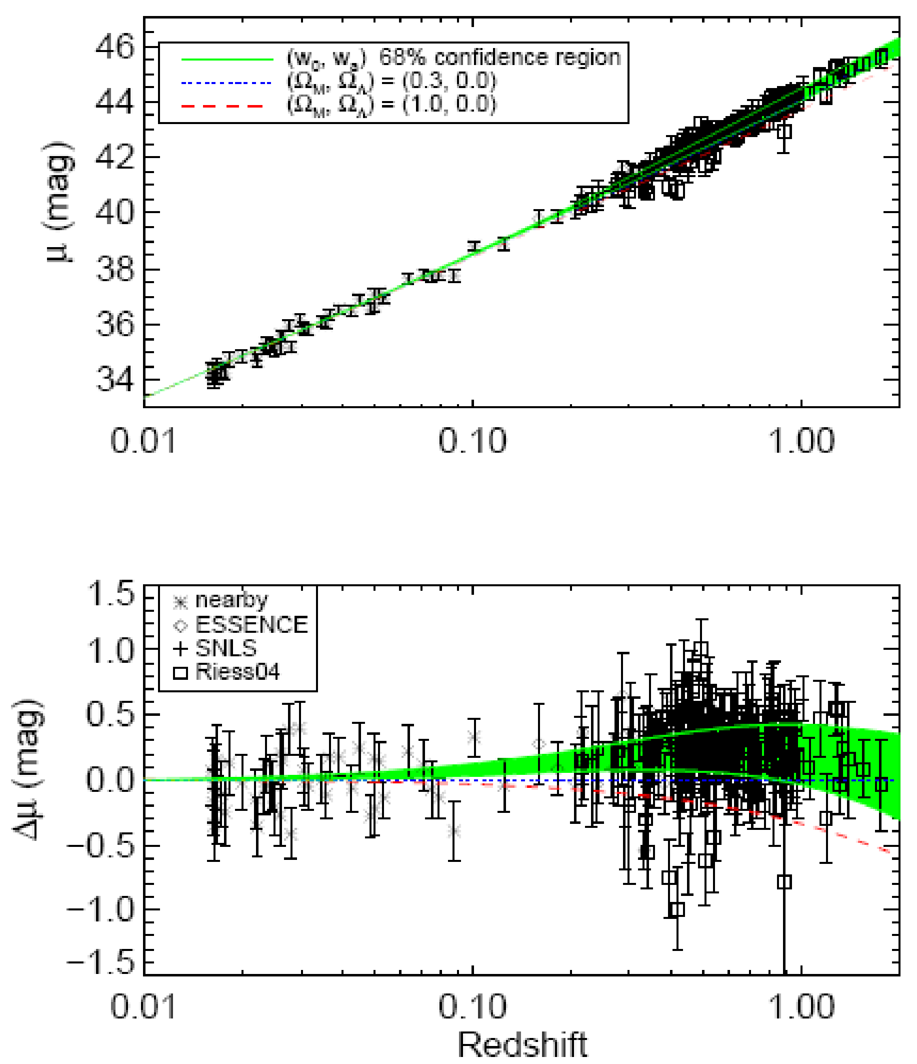
SN Factory
Carnegie SN Project
SDSSII

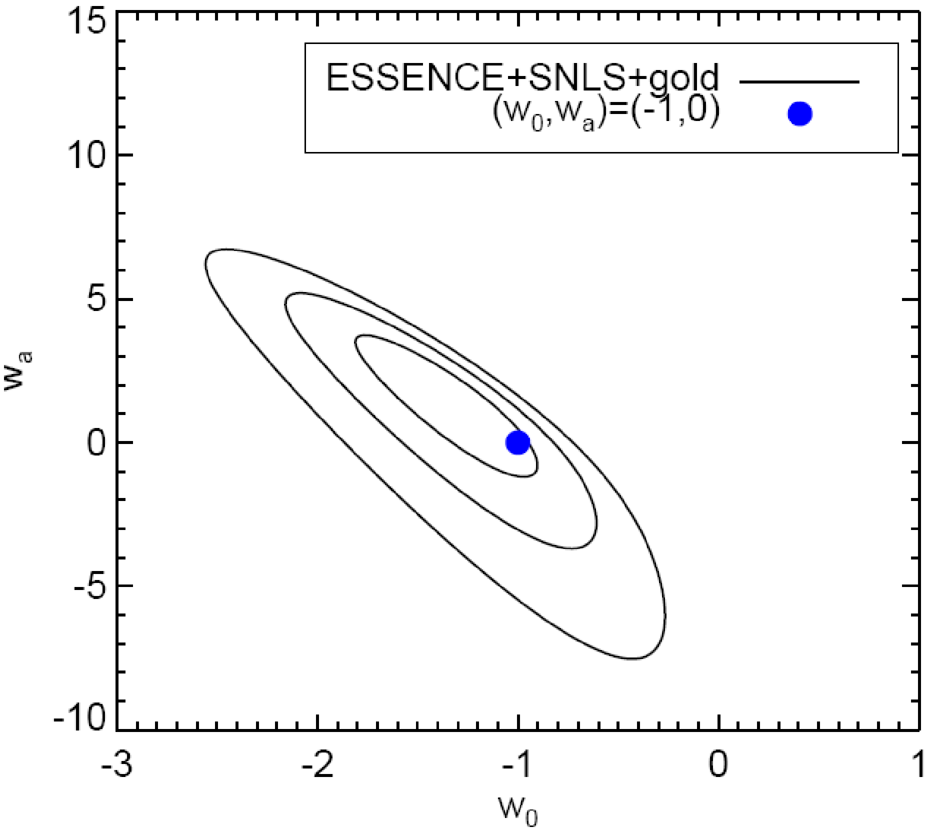
ESSENCE
CFHT Legacy Survey

Higher-z SN Search (GOODS)

SNAP/LSST/EUCLID

Time variable ω?

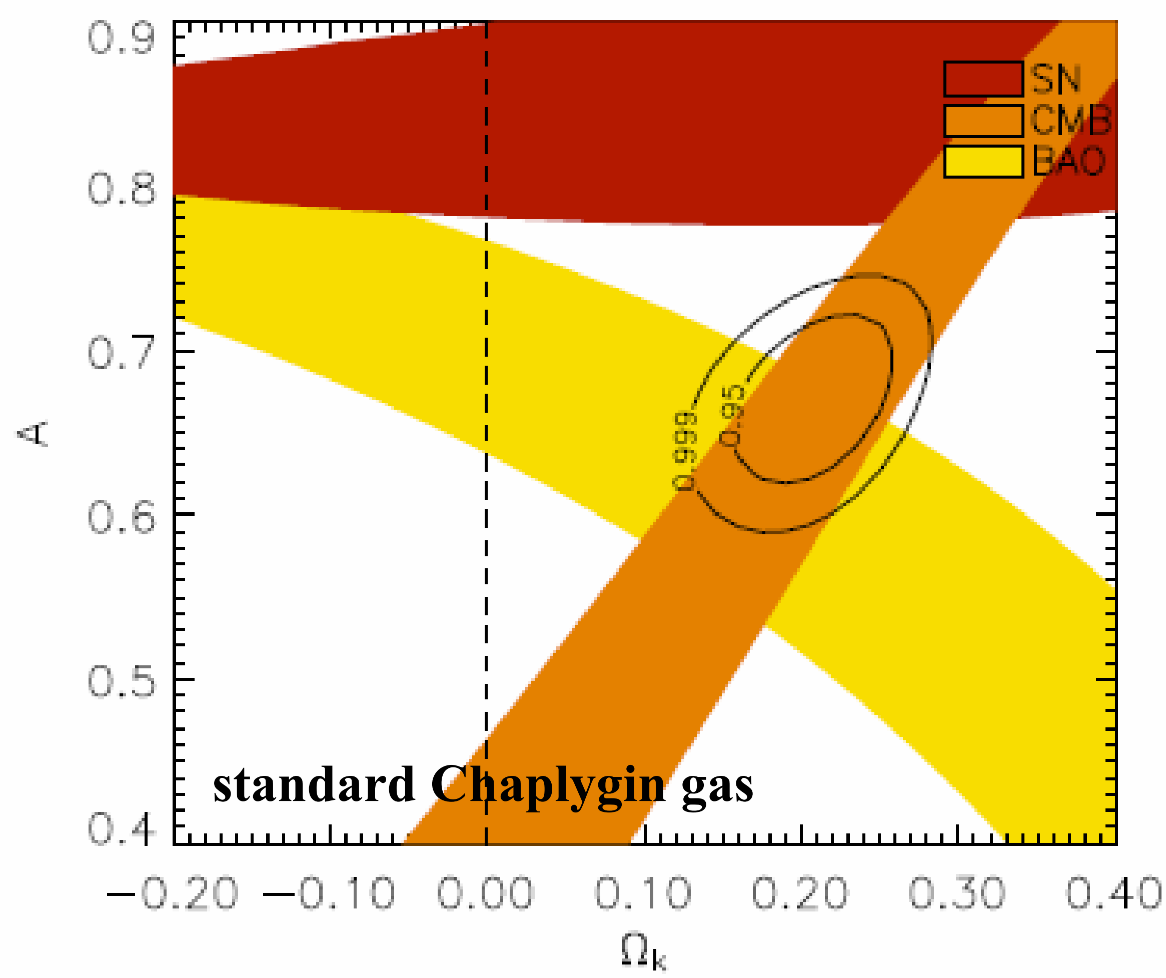




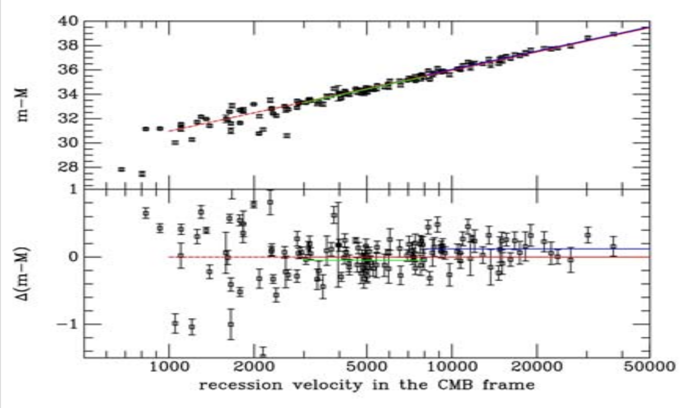
Wood-Vasey et al. 2007

Comparison to other models

Davis et al. 2007



The SN Ia Hubble diagram



Powerful tool to

- **establish SNe Ia as good distance indicators**
- **measure the absolute scale of the universe (H_0)**
- **determine the amount of dark energy**
- **measure the equation of state parameter of dark energy**
  – current best results are consistent with w=-1

Dark Energy

- **Accelerating expansion of the universe appears very safe by now**
- **Time-variable ω will be difficult to determine, unless another breakthrough in distance determinations can be achieved**
- **Current SN experiments find a ω consistent with a cosmological constant**