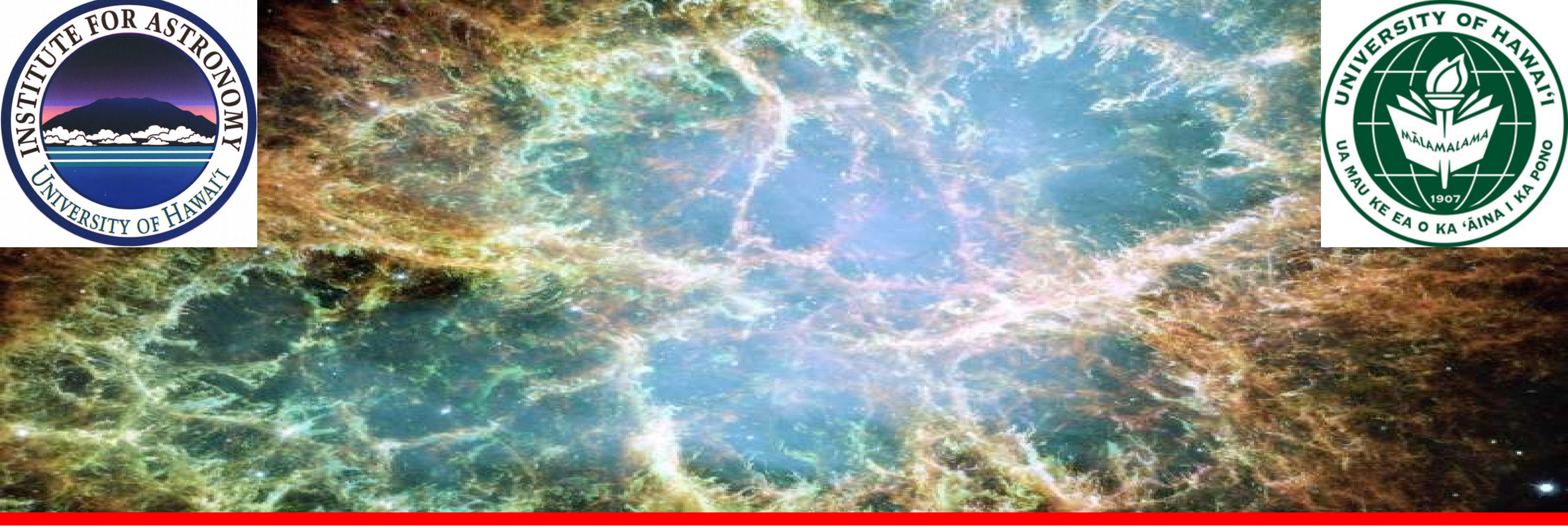

Thomas de Jaeger **(University of Hawai'i, Institute for Astronomy)**
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Type II Supernova Cosmology: Past and Future

Mānoa, March 31st, 2021

Outline

- Introduction
- Expansion rate of the Universe (H_0)
- Density fluctuations (σ_8)
- Conclusions
- What is next ?

Cosmology

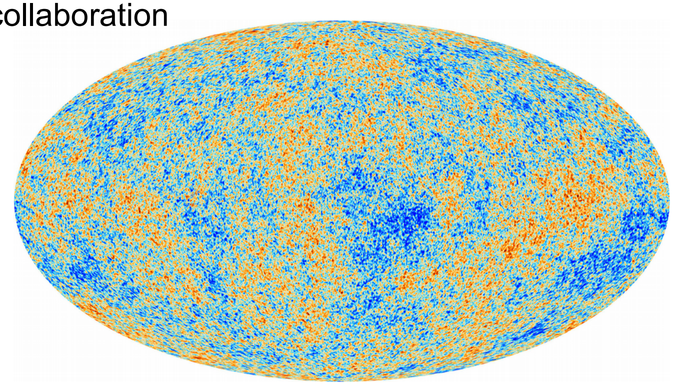
Cosmology : from the Greek κόσμος, kosmos "world" and -λογία, -logia "study of"

→ study of the origin, evolution, composition and dynamics of the Universe

How did the structures form?

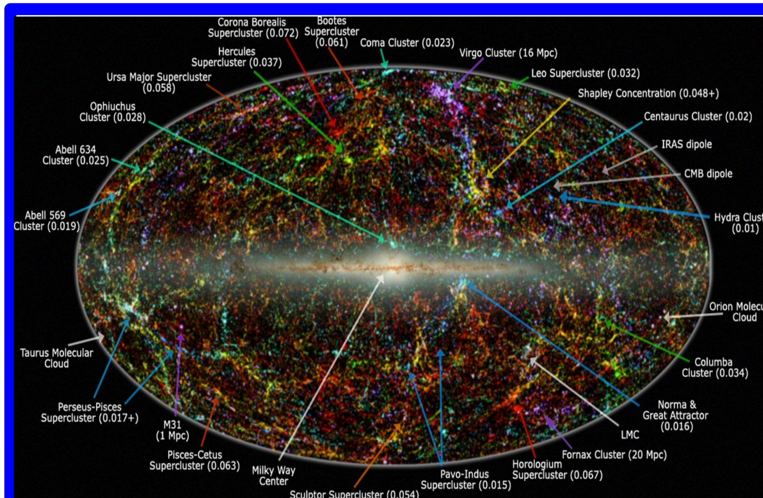
Homogeneous Universe

Planck collaboration



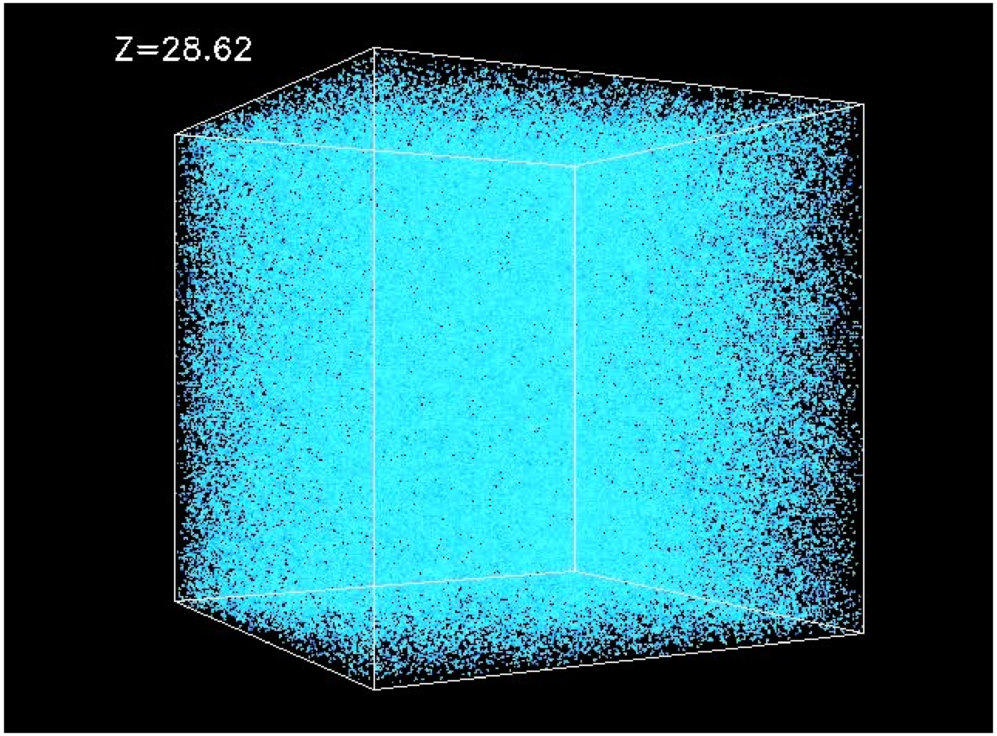
?

Large scale structures



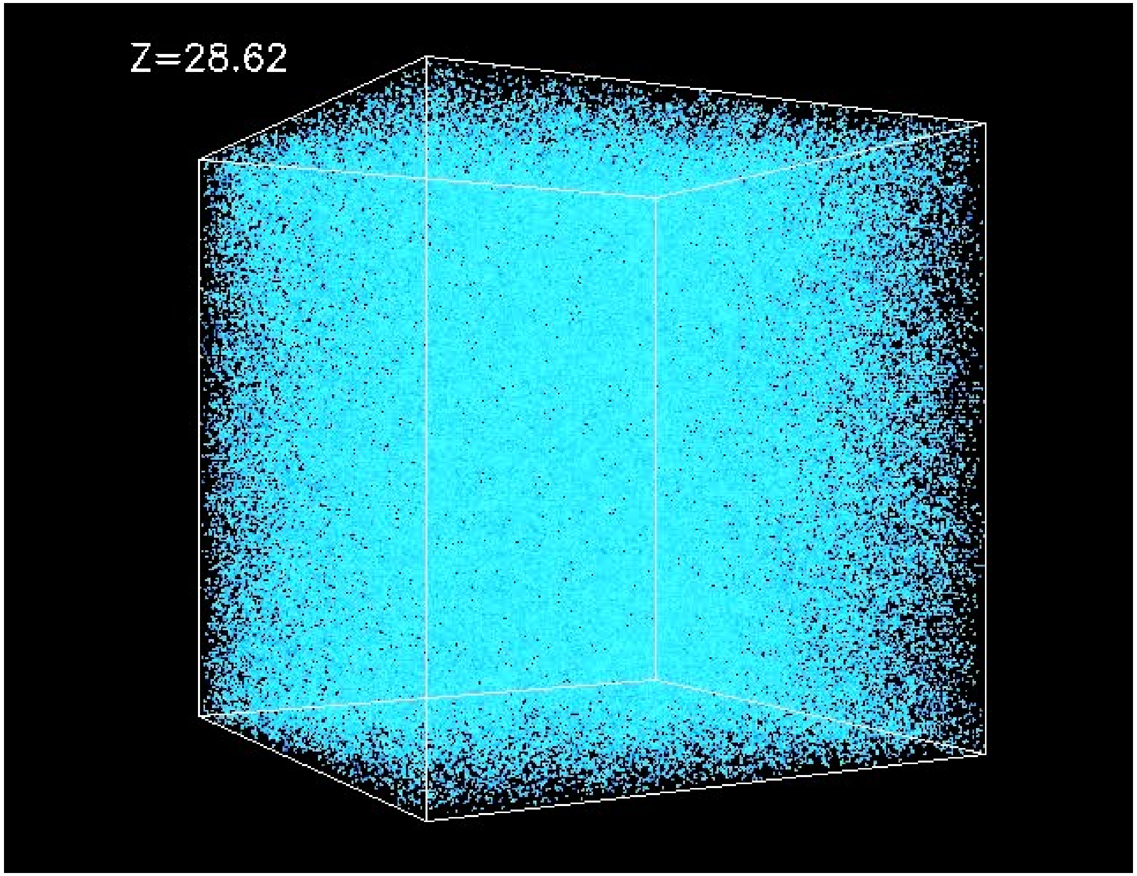
2MASS redshift survey

How did the structures form?



National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.

How did the structures form?



National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.

Cosmology

4 parameters to understand our Universe

→ $\mathbf{\Omega_m}$: Matter density

→ $\mathbf{\Omega_\Lambda}$: Dark energy density

→ $\mathbf{H_0}$: current expansion rate of the Universe

→ $\boldsymbol{\sigma_8}$: root mean square density fluctuation within spheres of 8Mpc/h

Cosmology

4 parameters to understand our Universe

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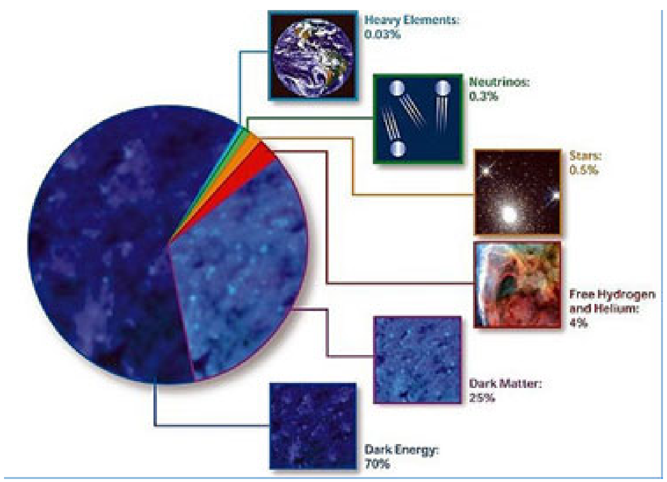
→ $\boldsymbol{\sigma_8}$: root mean square density fluctuation within spheres of 8Mpc/h

Composition of the Universe



Cosmology

Age of the Universe

4 parameters to understand our Universe

→ $\mathbf{\Omega_m}$: Matter density

→ $\mathbf{\Omega_\Lambda}$: Dark energy density

→ $\mathbf{H_0}$: current expansion rate of the Universe

→ $\mathbf{\sigma_8}$: root mean square density fluctuation within spheres of 8Mpc/h

$$t_H = \frac{1}{H_0}$$

Cosmology

Matter distribution

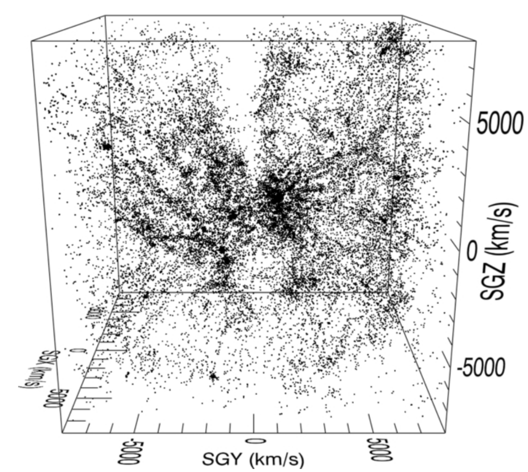
4 parameters to understand our Universe

→ Ω_m: Matter density

→ Ω_Λ: Dark energy density

→ H_0: current expansion rate of the Universe

→ σ_8: root mean square density fluctuation within spheres of 8Mpc/h



Courtois et al. 13

Cosmology

4 parameters to understand our Universe

→ Ω_m: Matter density

→ Ω_Λ: Dark energy density

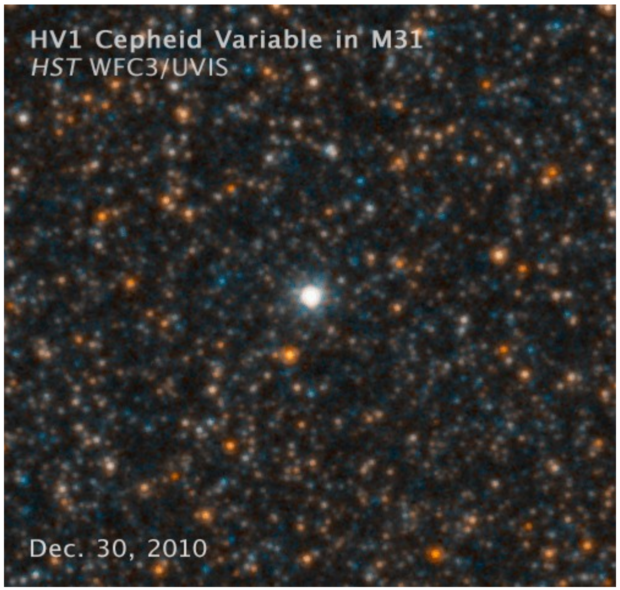
→ H_0: current expansion rate of the Universe

→ σ_8: root mean square density fluctuation within spheres of 8Mpc/h

Distances

Cepheids : period-luminosity relation

Henrietta Leavitt



Leavitt et al. 1908

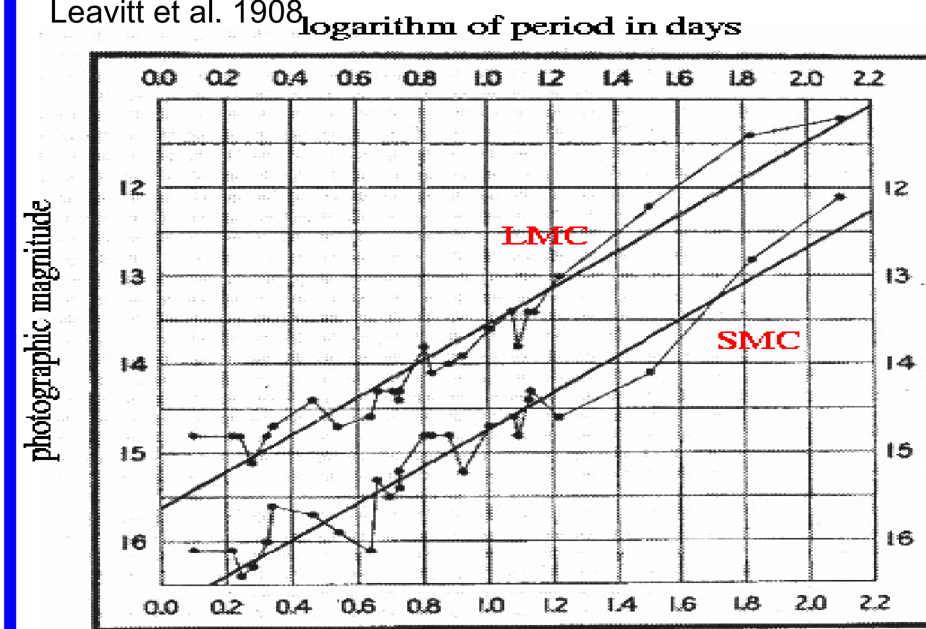


FIG. 2.

Expansion of the Universe (H_0)

Edwin
Hubble

1929 : **UNIVERSE IS EXPANDING!!!**

→ **More distant galaxies are moving faster away from us!!!**

Velocities measured by Slipher

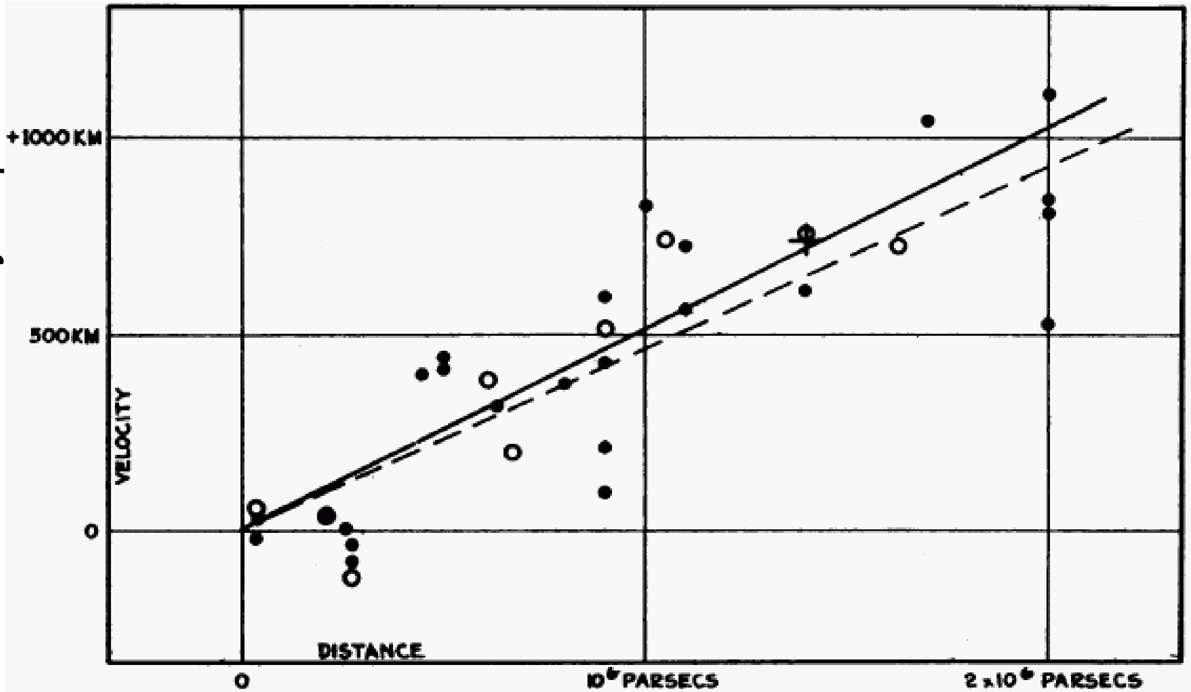


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Distance measured with Cepheids by Hubble

Oops… sorry Hubble

Georges Lemaître

In **1927** : Annales de la Société Scientifique de Bruxelles, A47, p. 49-59

6. CONCLUSION.

Nous avons obtenu une solution qui vérifie les conditions suivantes :

1. La masse de l'univers est constante et est liée à la constante cosmologique par la relation d'Einstein

$$\sqrt{\lambda} = \frac{2\pi^2}{\kappa M} = \frac{1}{R_0}$$

2. Le rayon de l'univers croît sans cesse depuis une valeur asymptotique R_0 pour $t = -\infty$.

3. L'éloignement des nébuleuses extra-galactiques est un effet cosmique dû à l'expansion de l'espace et permettant de calculer le rayon R_0 par les

σ_8

What? RMS density fluctuation within spheres of 8Mpc/h

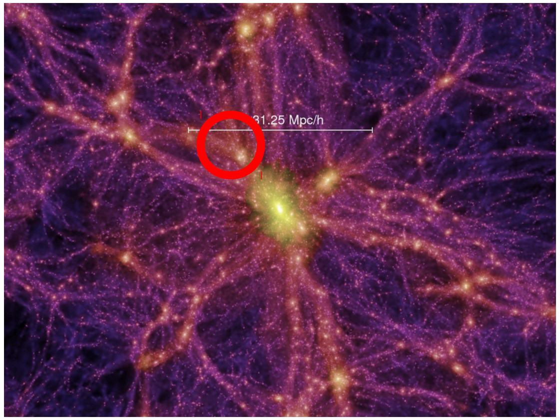
σ_8

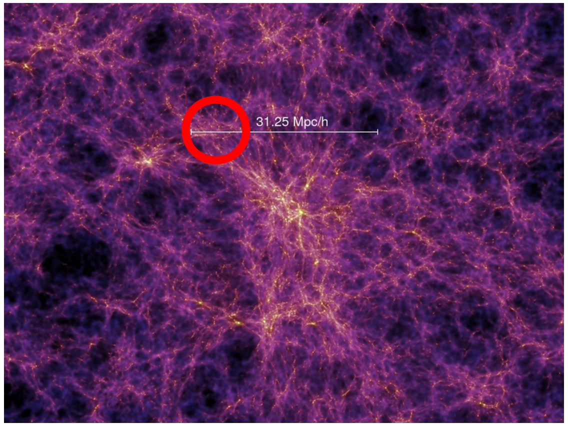
What? RMS density fluctuation within spheres of 8Mpc/h

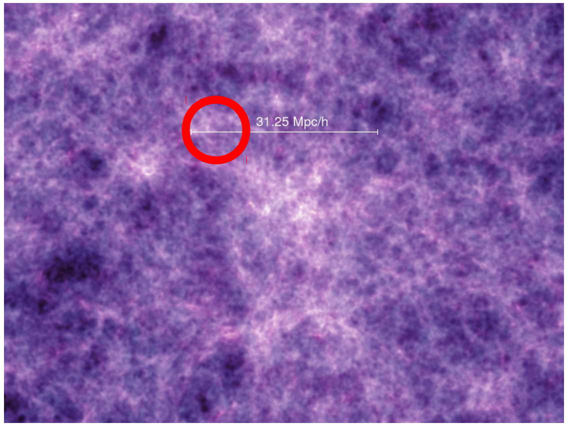
Why? Specifies how that matter is distributed

Increasing z (0,5.7,18.3)

Millennium simulation







Decreasing σ_8

$f\sigma_8$

In practice we measure $\mathbf{f\sigma_8}$: where:

→ **f** is the growth rate of the structure

$$f = \frac{d\ln(D)}{d\ln(a)}$$

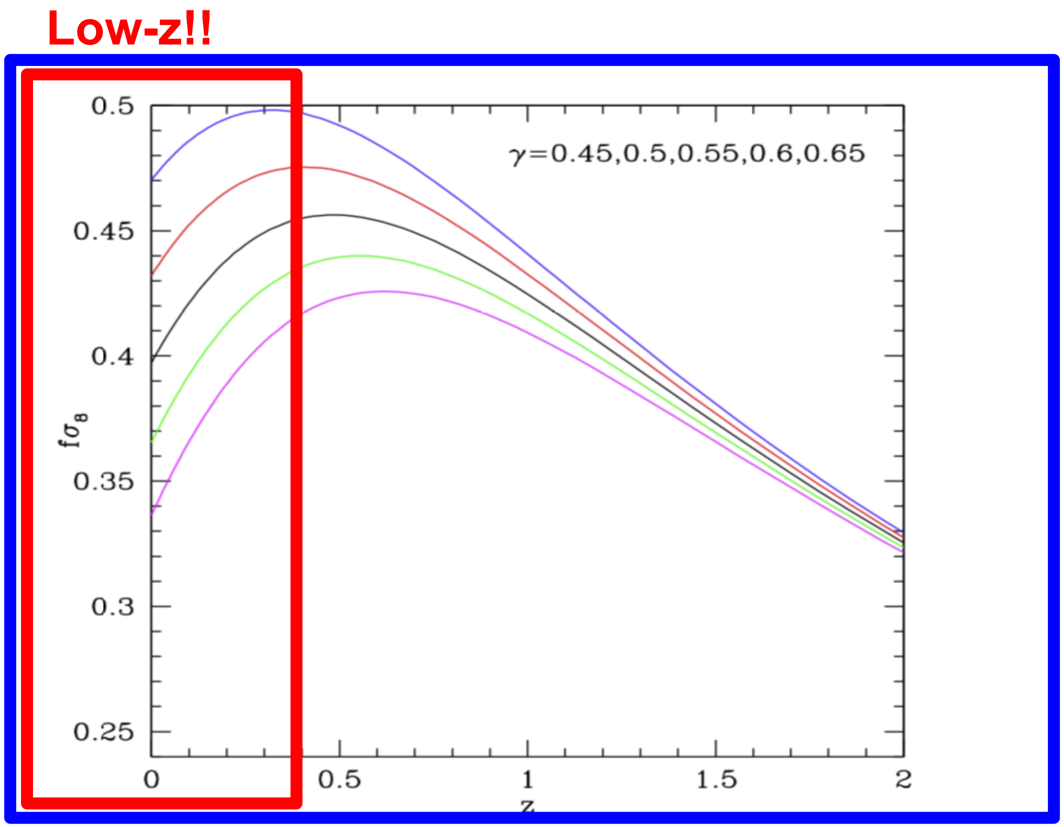
Linear growth factor

$f\sigma_8$

Test gravity!!!

$$f \approx \Omega_m^\gamma$$

$$\gamma_{\rm GR} = 0.55$$



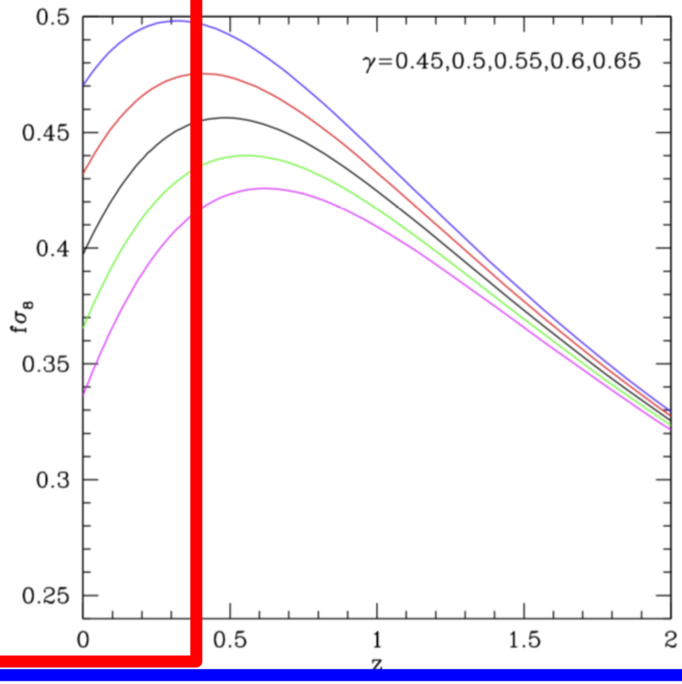
Linder 13

$f\sigma_8$

Test gravity!!!

$$f \approx \Omega_m^\gamma$$
$$\gamma_{\rm GR} = 0.55$$

Low-z!!



Linder 13

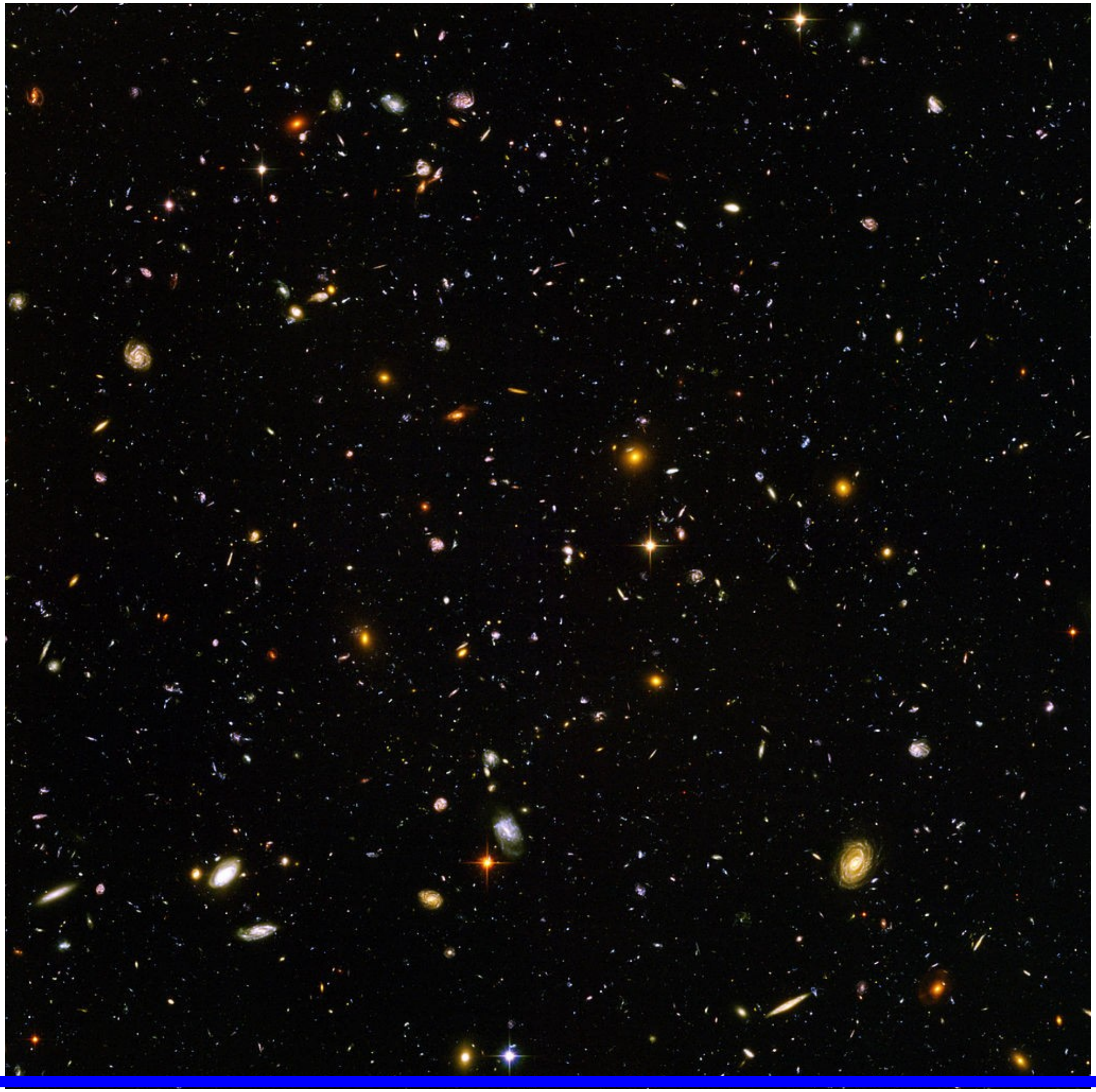
≠ ways to measure $f\sigma_8$ at z<CMB:

→ **Peculiar velocities**
  →**Supernovae**
  →Redshift space distortion

→ Weak gravitational lensing

→ Cluster abundance

Measuring great distances



Credit : HST

Supernovae

- **A supernova (Zwicky 1931) is a stellar explosion that briefly outshines an entire galaxy (10^9–10^{10} L⊙).**

They play an important role in:

→ **Cosmology**

→ **Distances**

→ $\Omega_m, \Omega_\Lambda, H_0, \sigma_8$

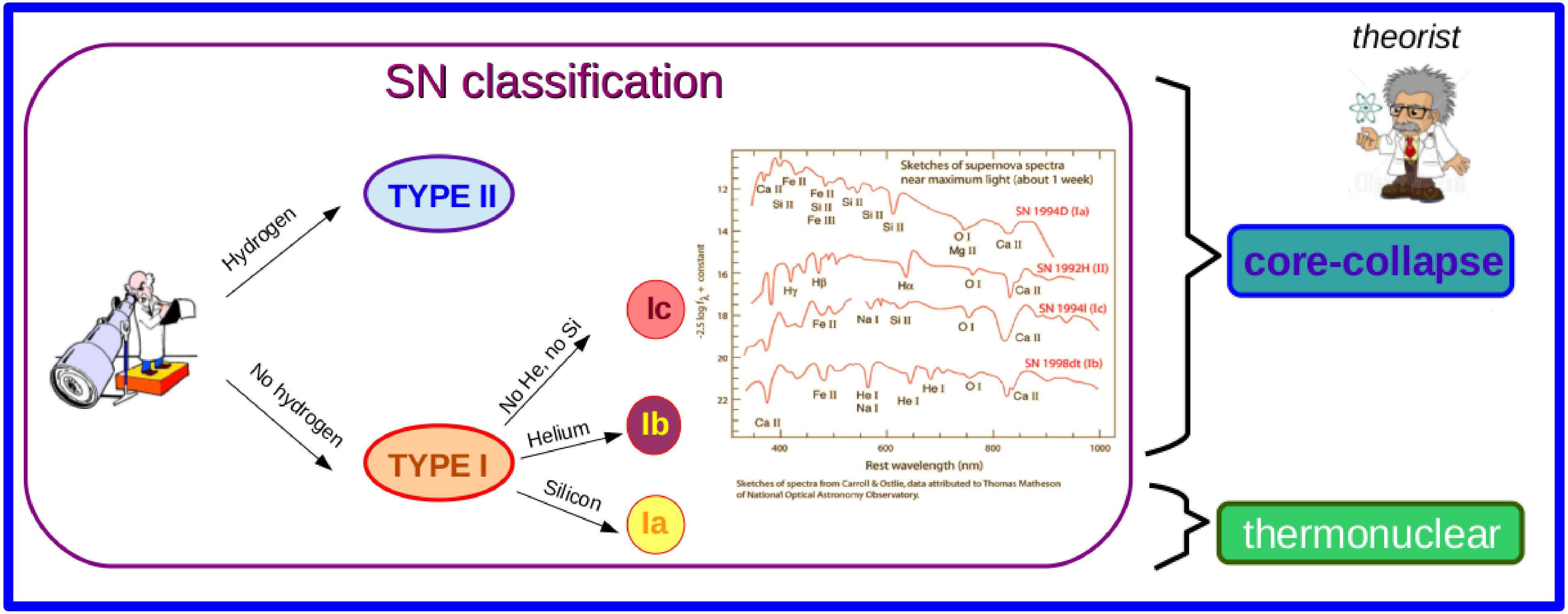
They are:

→ **Much brighter than Cepheids!!**

SN 1987A in LMC

Supernovae

- Classification based on the Hydrogen lines:
  - Presence of Hydrogen lines: **II**
  - Absence of Hydrogen lines: **Ia, Ib, Ic**



SNe cosmology

$$\mu =$$

Distance modulus

OBSERVED

SNe cosmology

Apparent magnitude

from measurements

$$\mu = m -$$

Distance modulus

OBSERVED

SNe cosmology

Apparent magnitude

from measurements

$$\mu = m - M =$$

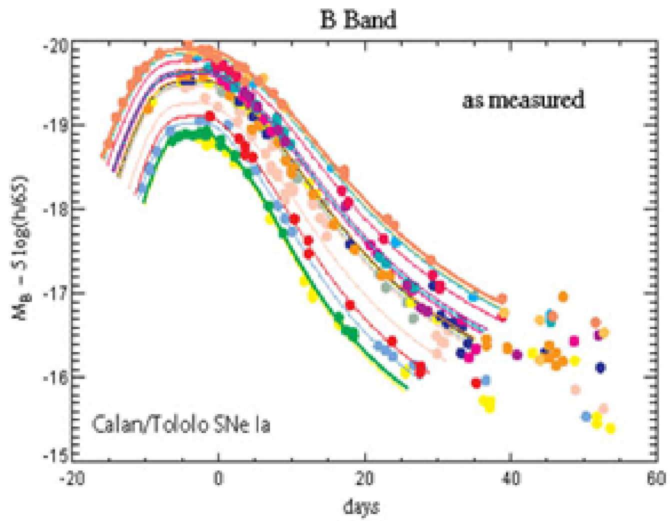
Distance modulus

Absolute magnitude

constant for standard candles.

SNe are **not perfect standard candles**

OBSERVED



SNe cosmology

Apparent magnitude

from measurements

$$\mu = m - M =$$

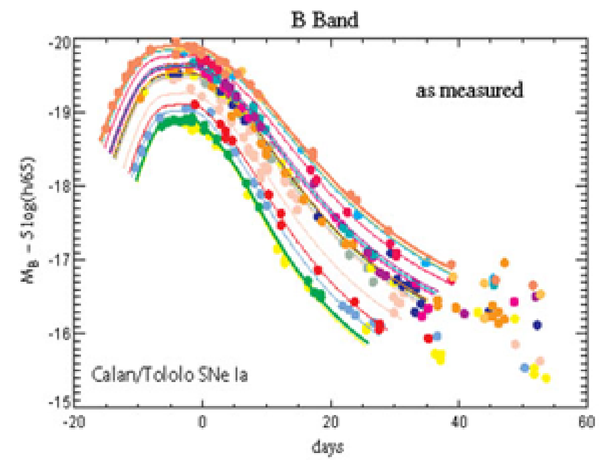
Distance modulus

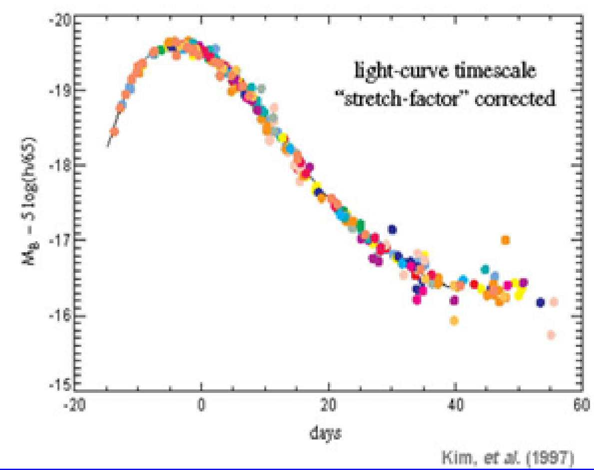
Absolute magnitude

constant for standard candles.

SNe are **not perfect standard candles**

But they **are standardisable**





SNe cosmology

Apparent magnitude

from measurements

Redshift
Measured via
SN/host galaxy
spectrum

Cosmological parameters
Quantities of interest
Ω_m, Ω_Λ, w, H_0

$$\mu = m - M = 5\log_{10}\left(\frac{D_L(z, C)}{1\,Mpc}\right) + 25$$

Distance modulus

Absolute magnitude

constant for standard candles.

SNe are **not perfect standard candles**

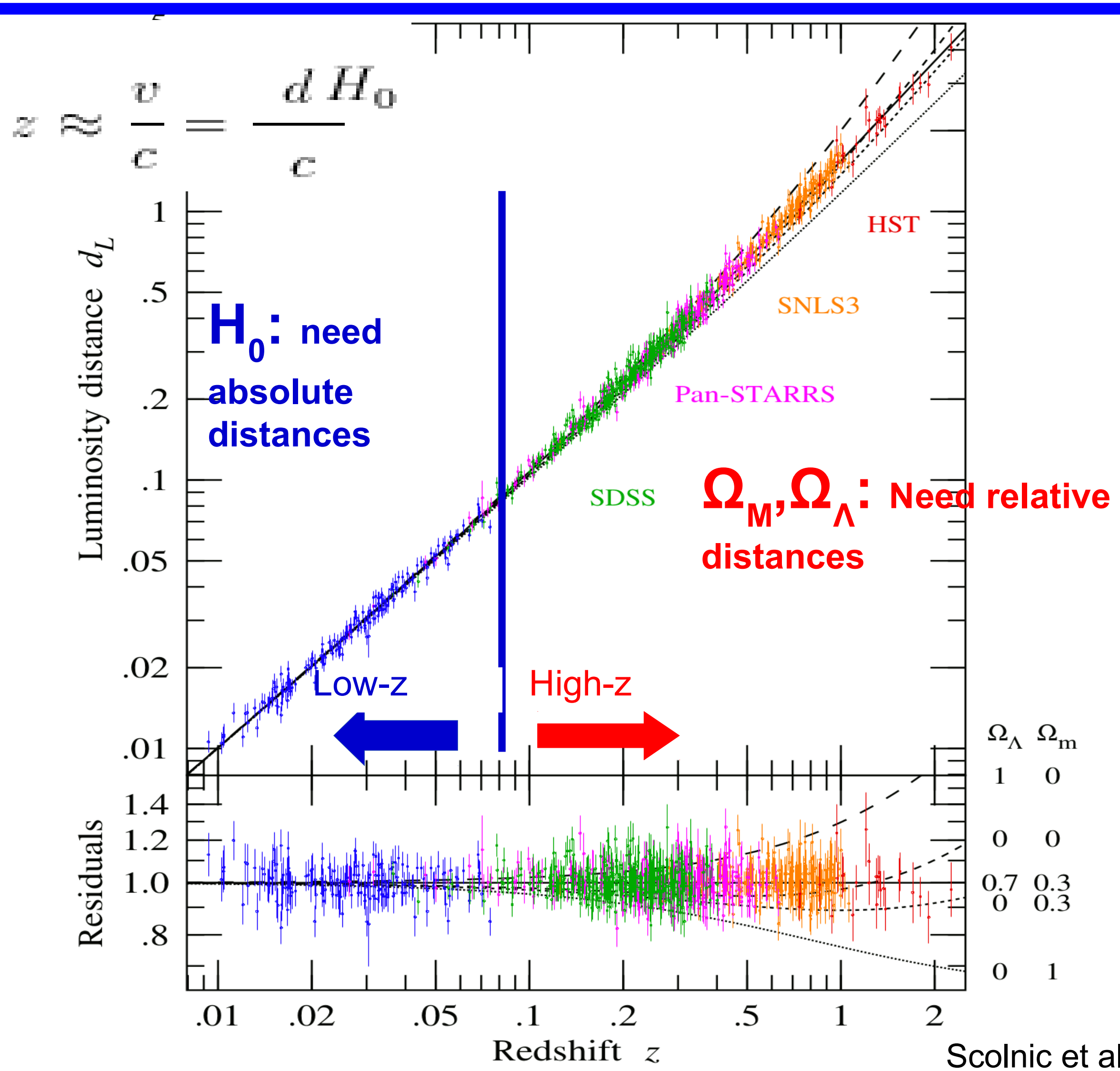
But they **are standardisable**

Luminosity distance

THEORITICAL MODELS

$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3 + \Omega_k(1+z')^2 + \Omega_\Lambda(1+z')^{3(1+\omega)}}}$$

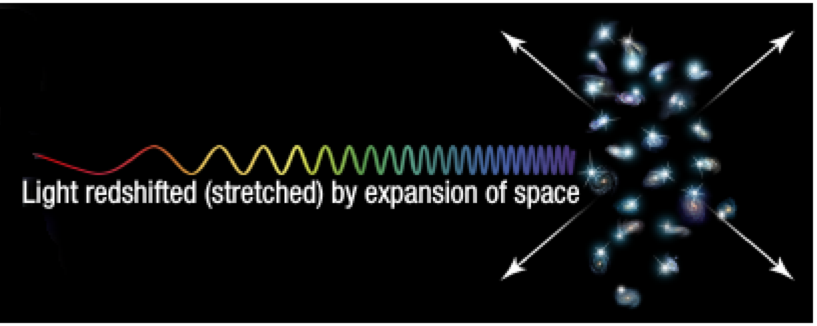
Hubble diagram



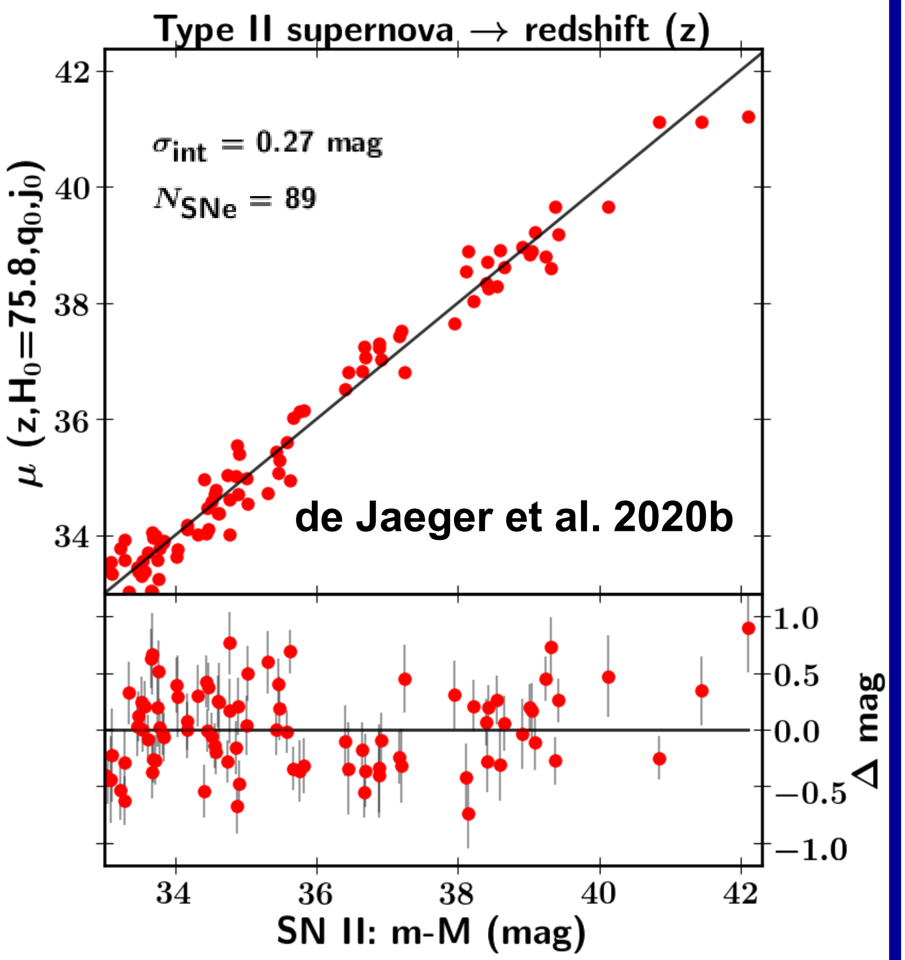
Scolnic et al. 2017

H0: Distance ladder 3

Distances to galaxies in the Hubble flow measured using **Type II supernovae**



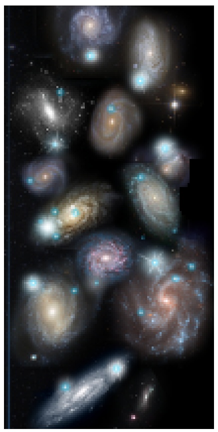
Credit NASA, ESA and A. Riess (STScI)

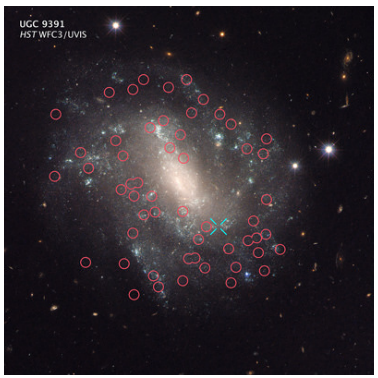


Desmond et al. 2020

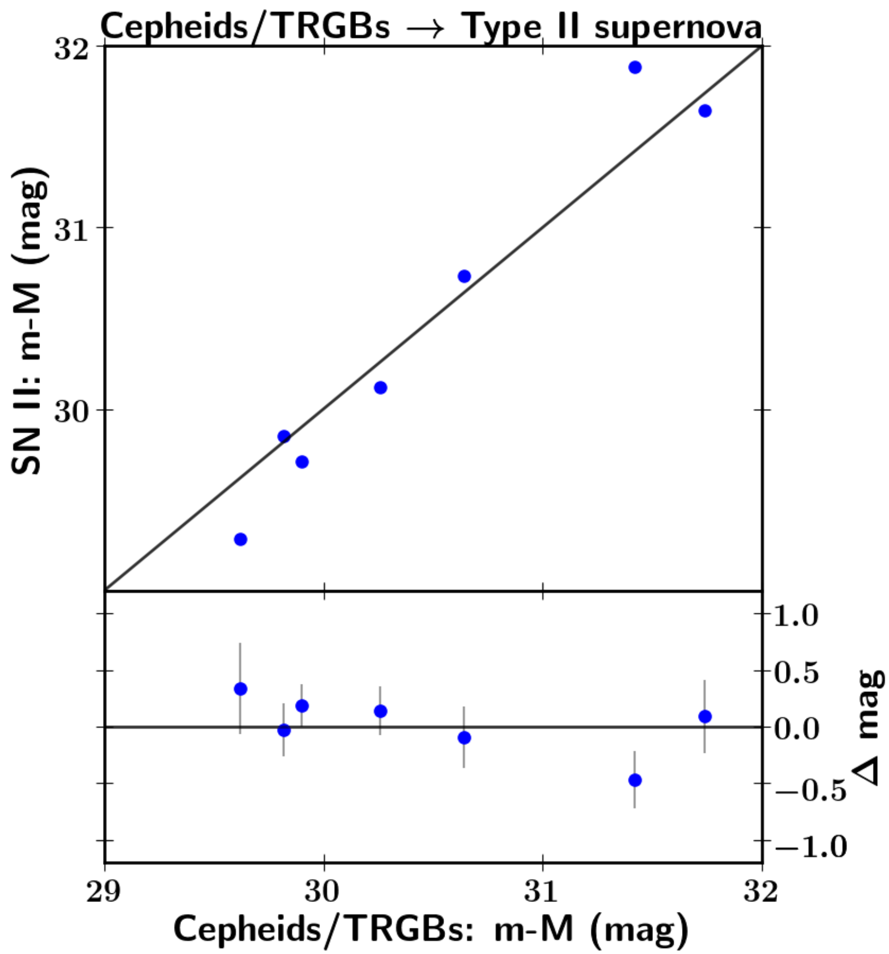
H0: Distance ladder 2

Nearby galaxies hosting Type II supernovae and Cepheids/TRGBs



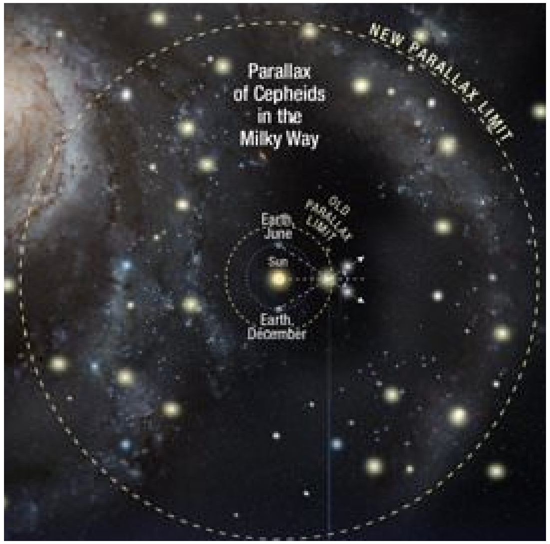


Credit NASA, ESA and A. Riess (STScI)

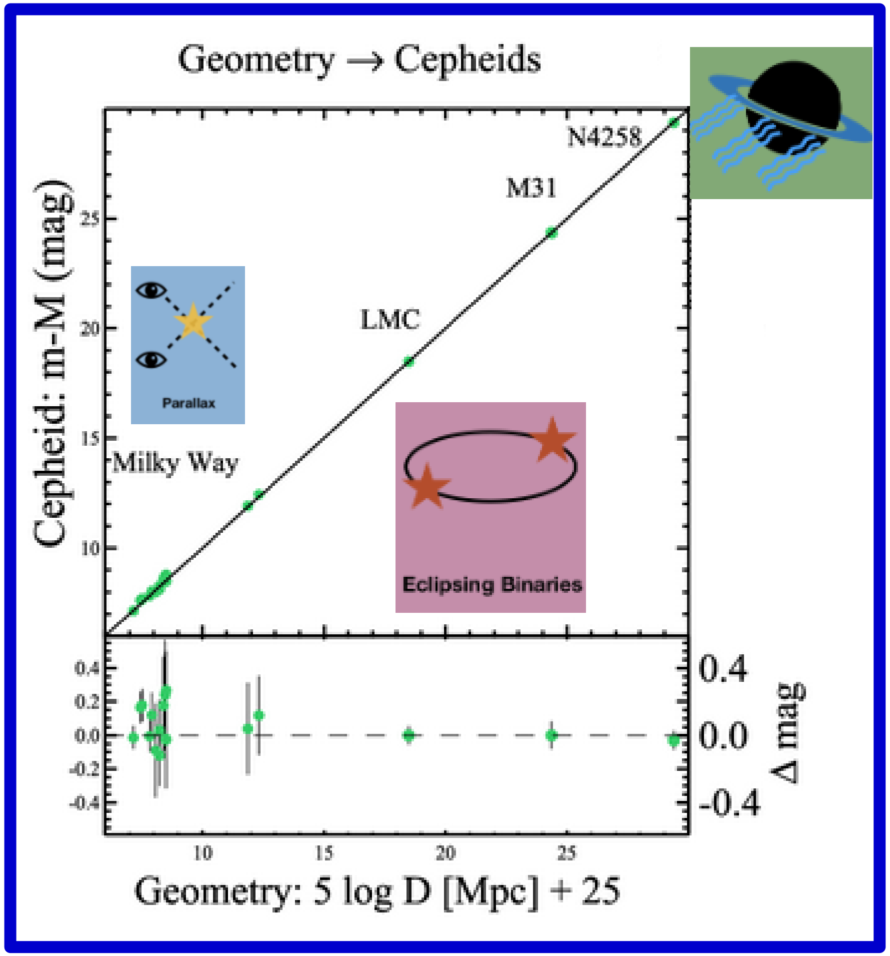


H0: Distance ladder 1

Cepheid and TRGB calibration
→ Milky Way Cepheid parallaxes
→ Masers
→ Detached eclipsing binary stars

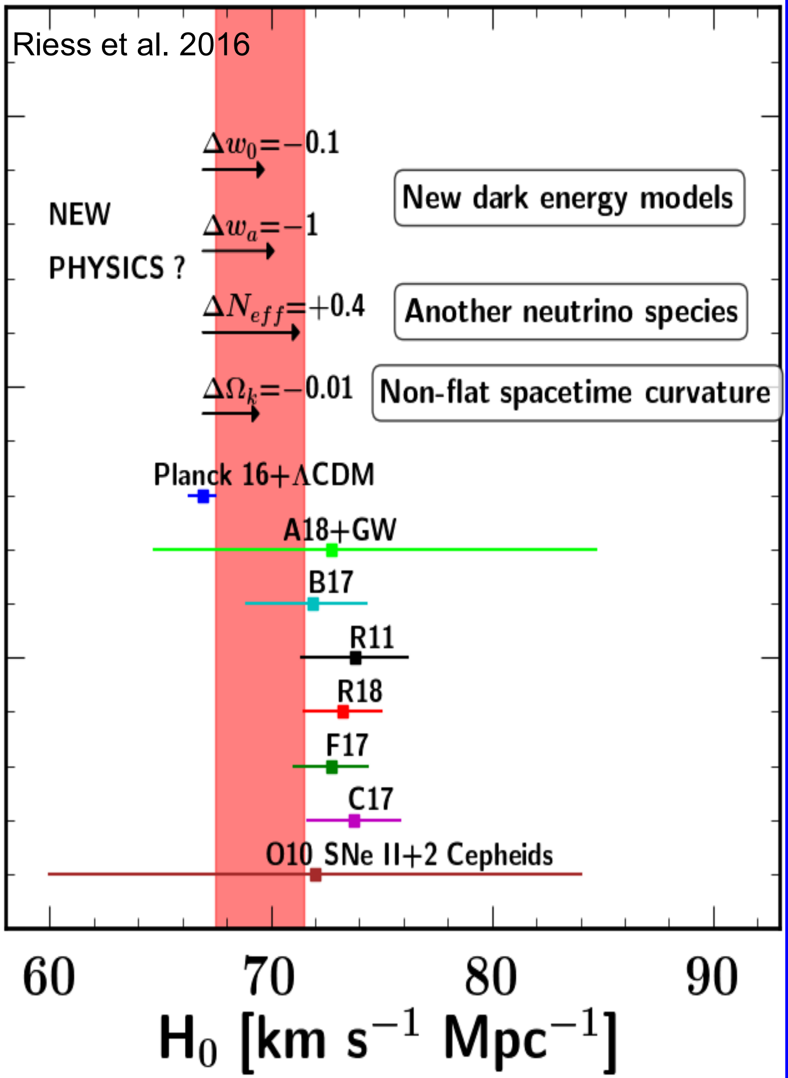


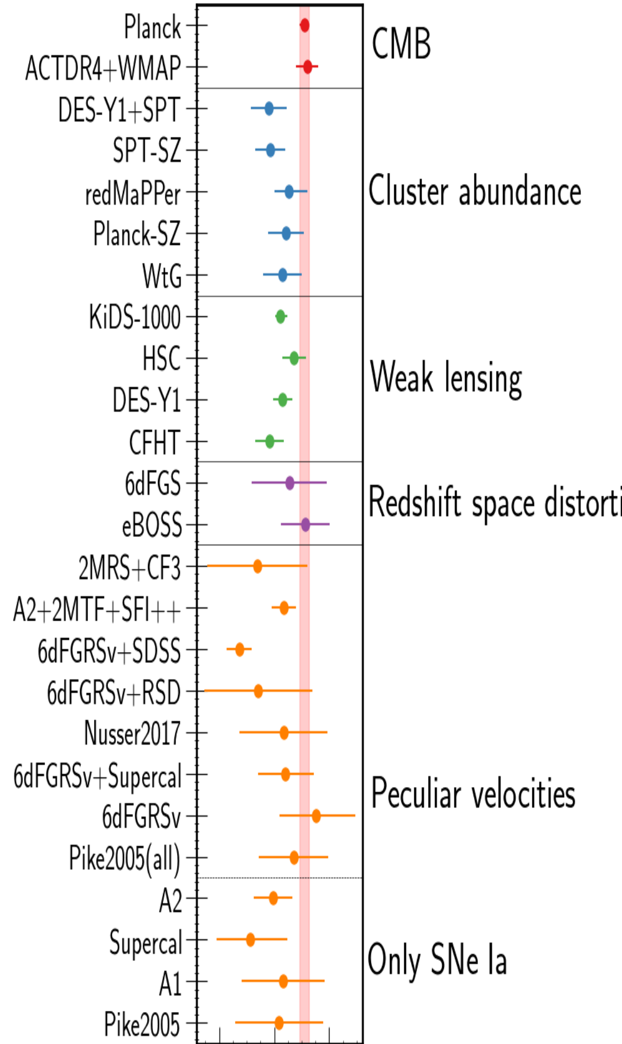
Credit NASA, ESA and A. Riess (STScI)



Riess et al. 2016

SNe cosmology

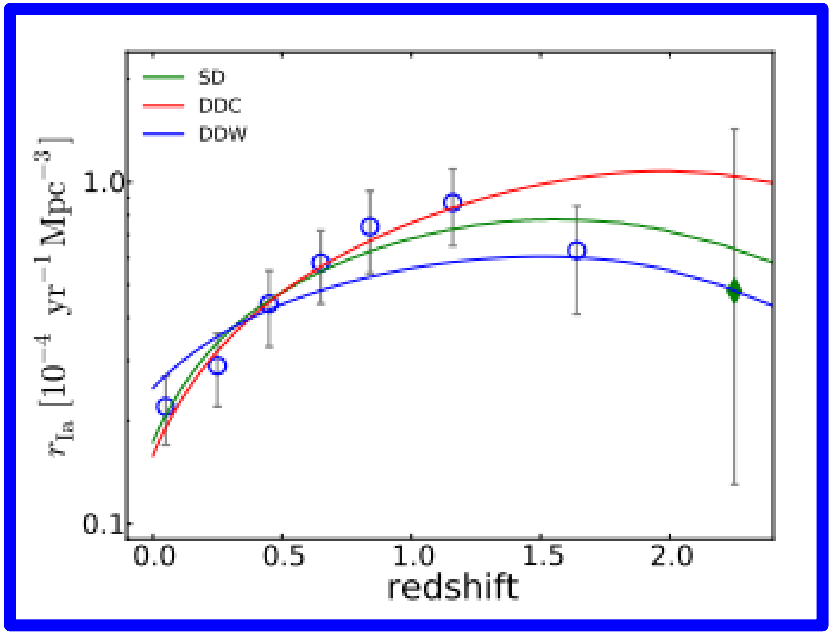


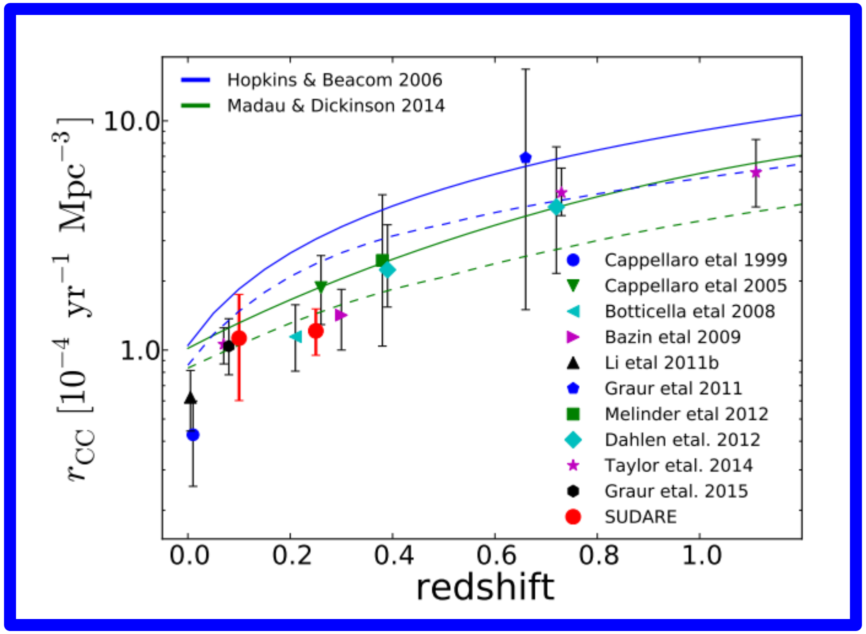


Stahl, **de Jaeger** et al.
submitted 2020

Why SNe II?

- **Their rate is expected to peak at higher redshifts than SNe Ia** (Cappellaro et al. 15)

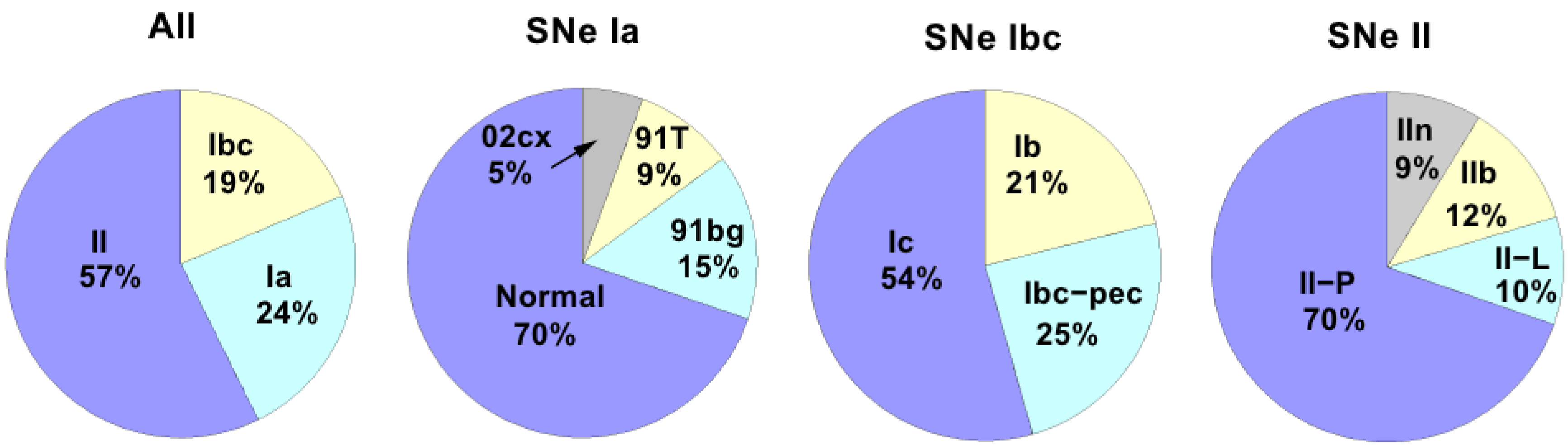




Why SNe II?

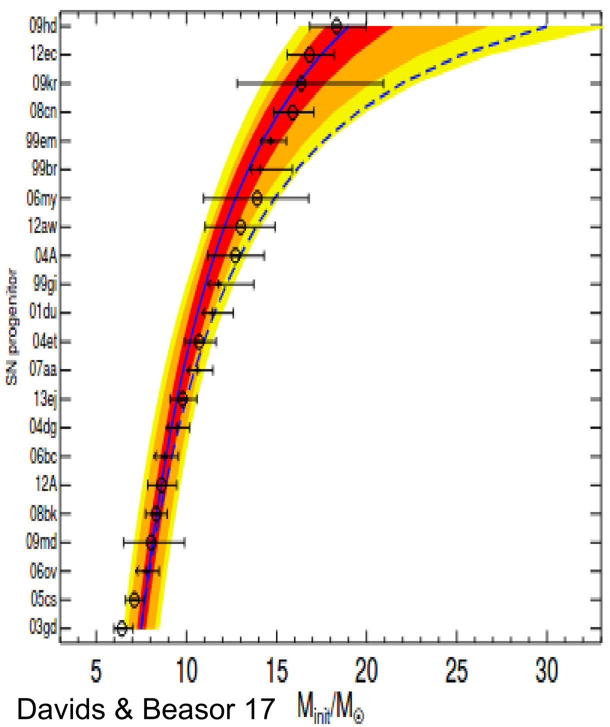
•Their rate is expected to peak at higher redshifts than SNe Ia (Cappellaro et al. 15)

•They are more abundant than the SNe Ia in a limited volume (Li et al. 11)

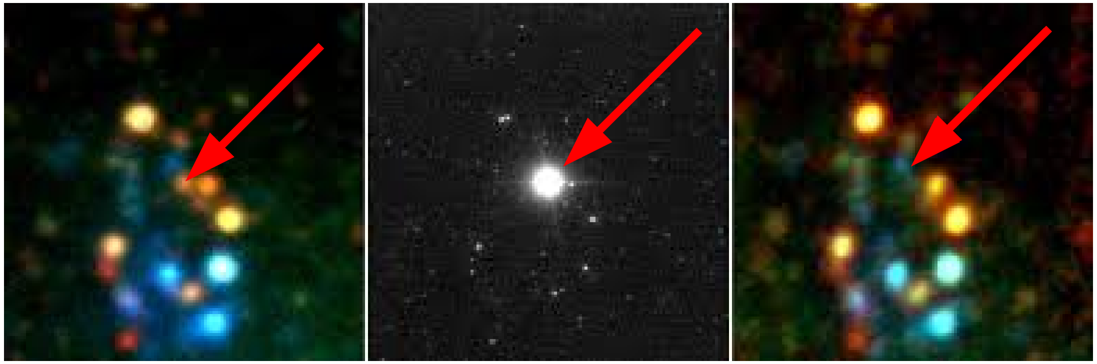


Why SNe II?

- Their rate is expected to peak at higher redshifts than SNe Ia (Cappellaro et al.15)
- They are more abundant than the SNe Ia in a limited volume (Li et al. 11)
- **Their progenitors and environments (only late-type galaxies) are better understood than those of SNe Ia**



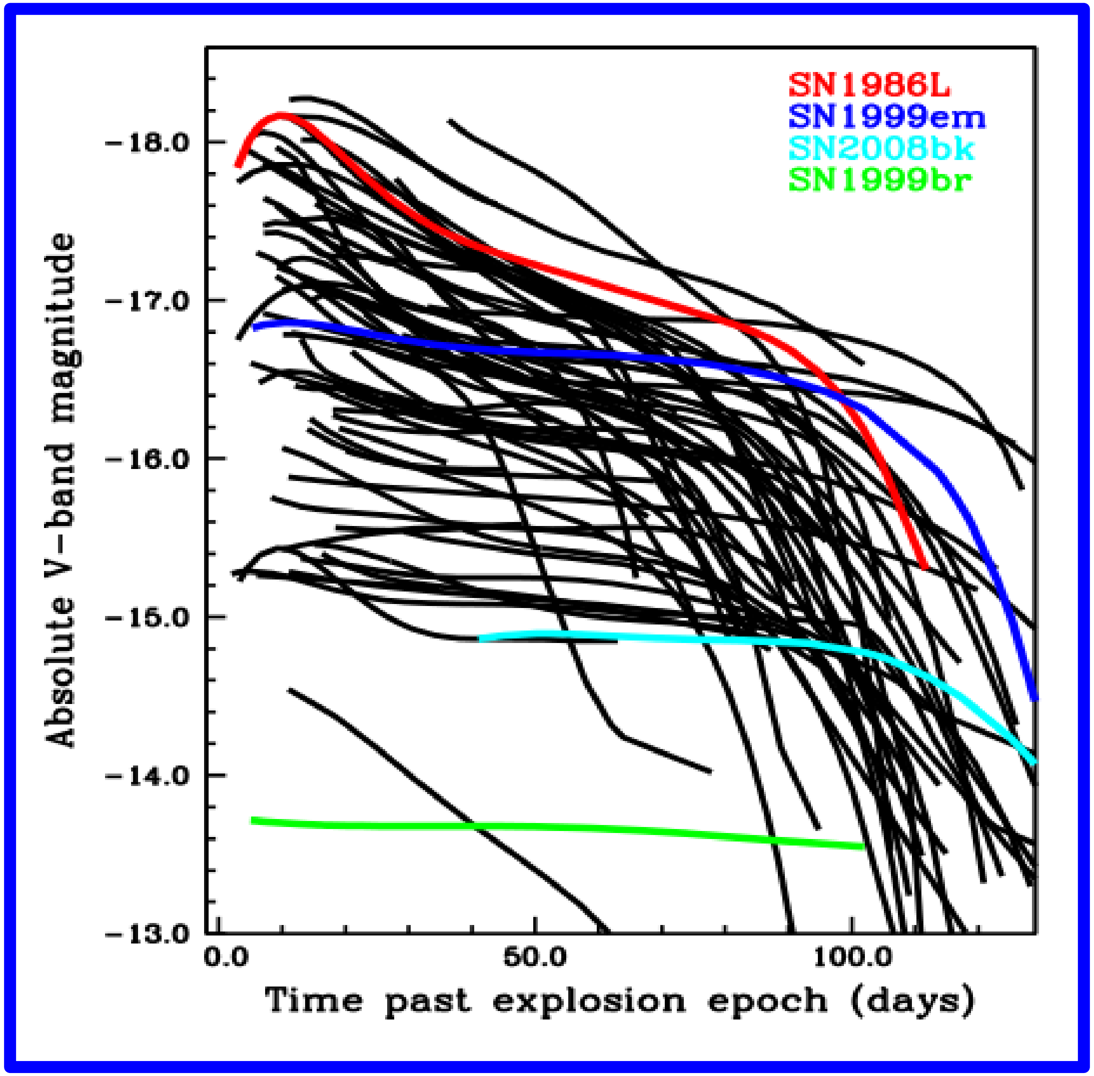
Davids & Beasor 17



Pre-explosion   SN 2008bk   ~1000d after

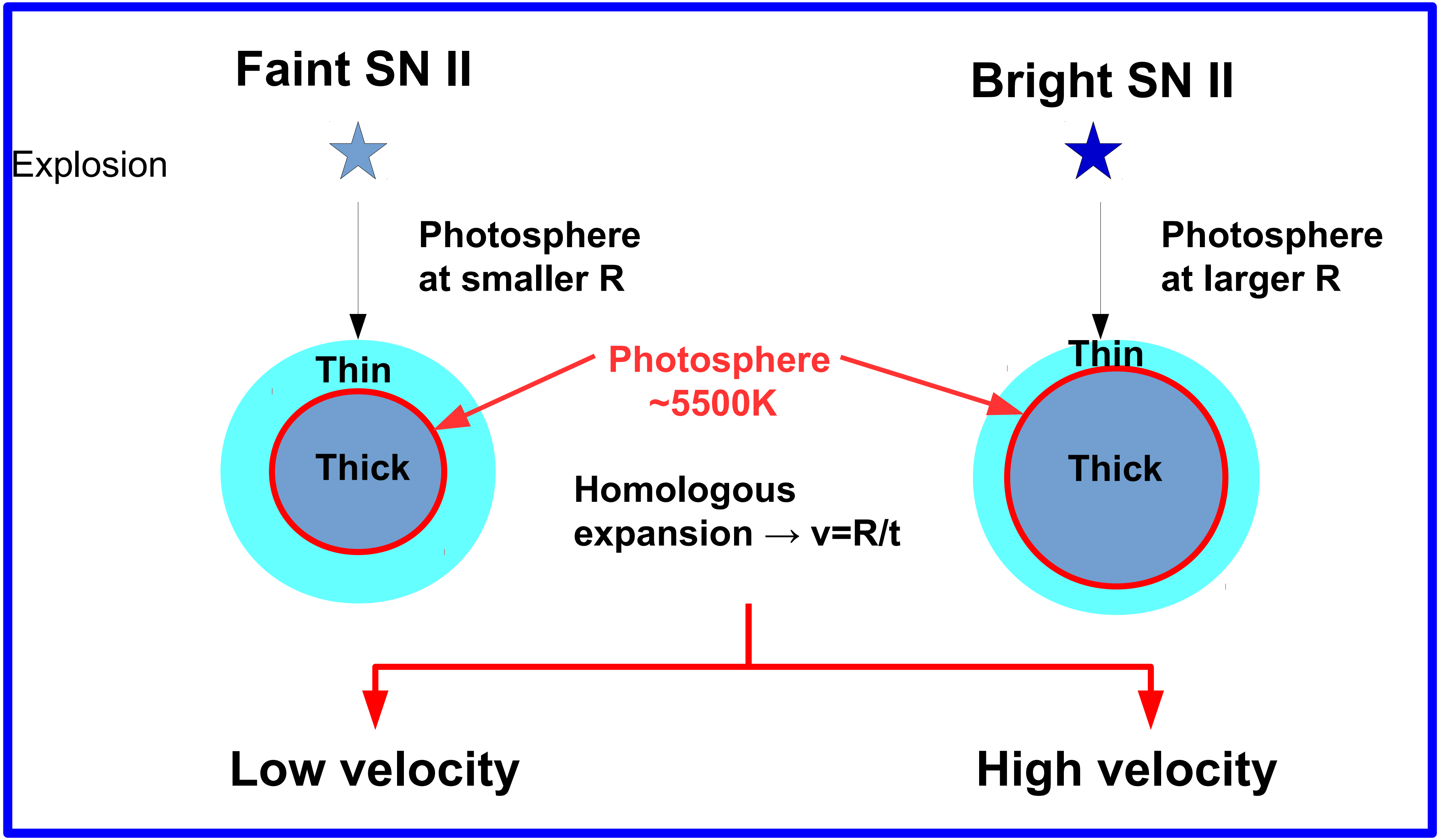
Matilla et al. 2010

Are SNe II standard candles?

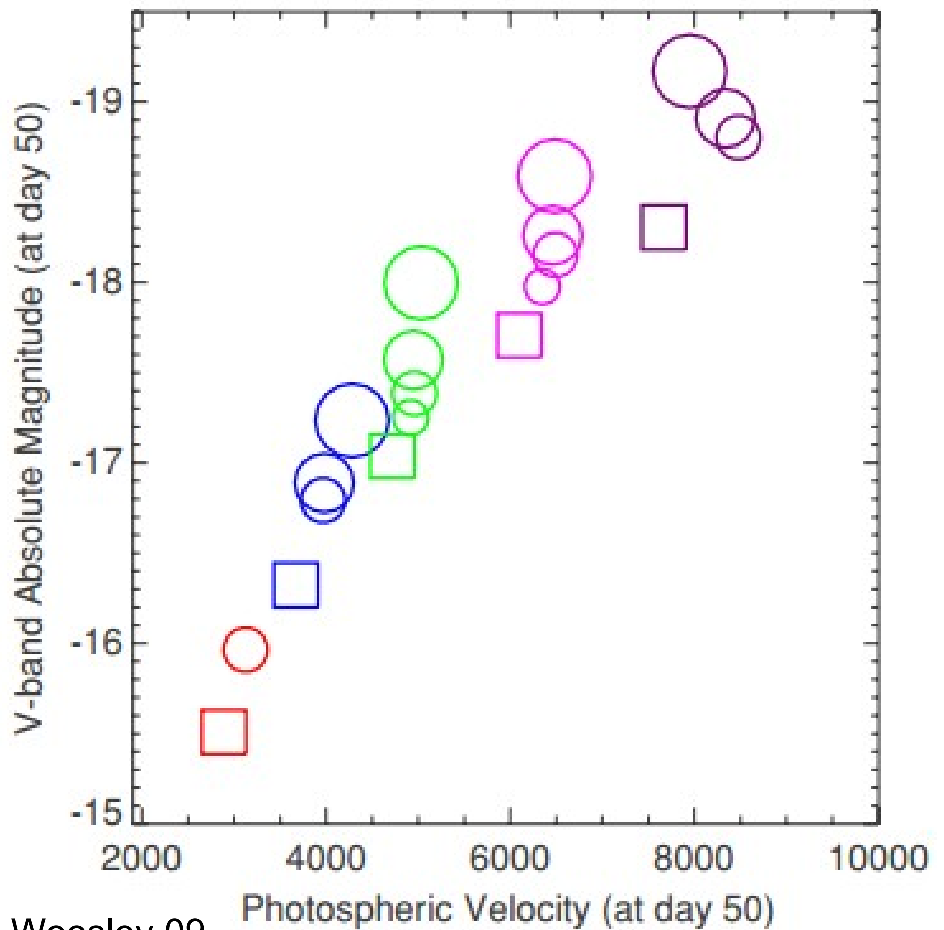


Anderson et al. 2014

Expansion velocity



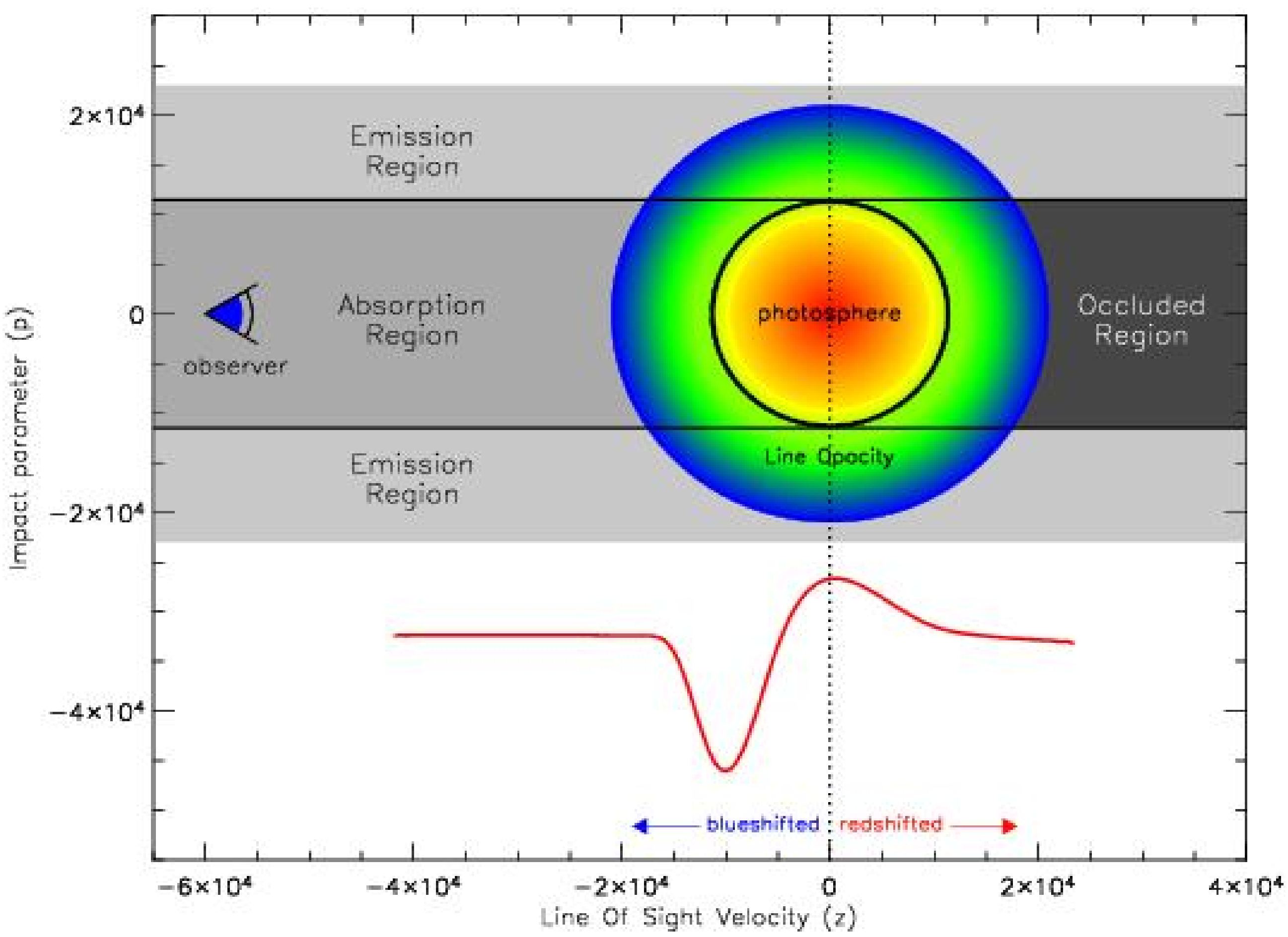
Luminosity-velocity relation observations match theory !!



Kasen & Woosley 09

→ **RMS~ 0.27 mag (13 % in distances)**

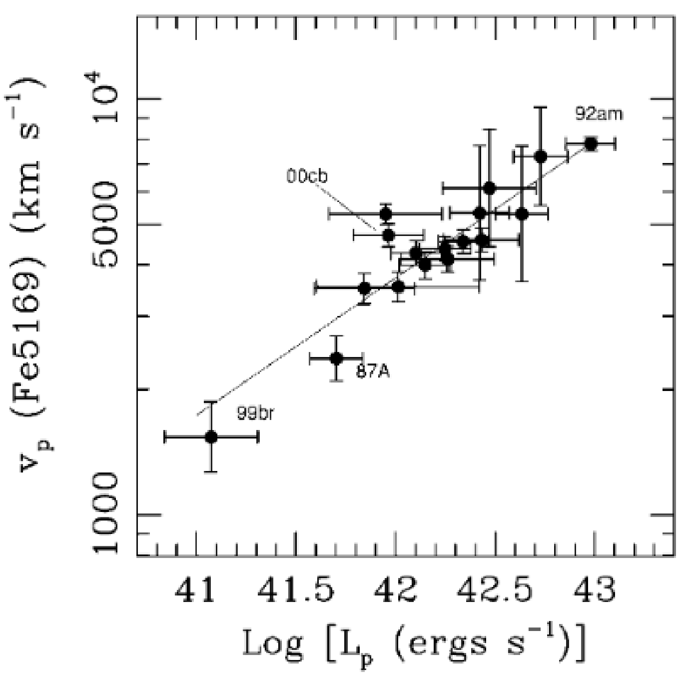
P-Cygni Profile



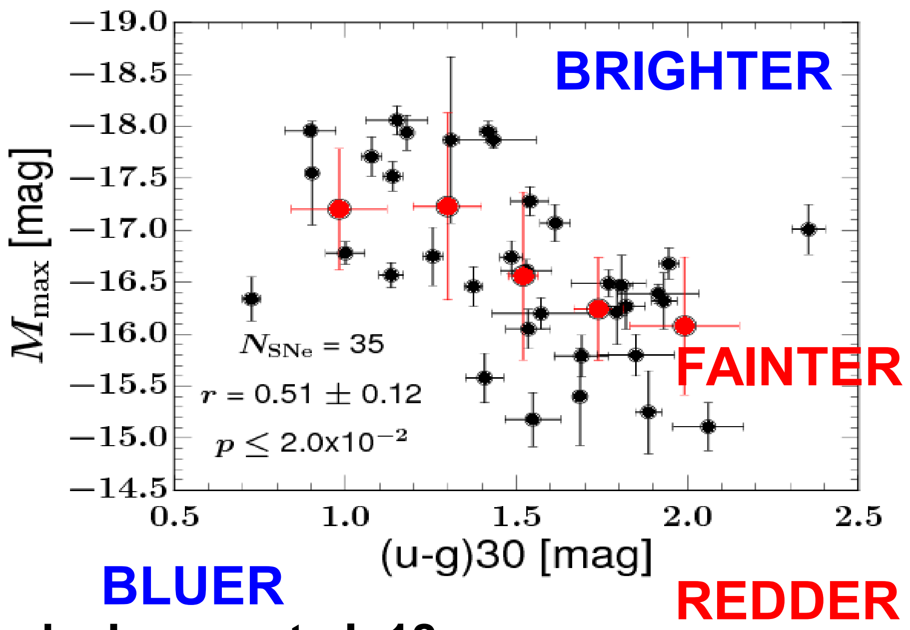
SNe II are standardisable!!! (Standard Candle Method:)

Expansion velocities of the ejecta:
More luminous SN have faster ejecta

Colour: Brighter SN are bluer
(~ to SNe Ia) → Nugent et al. 06

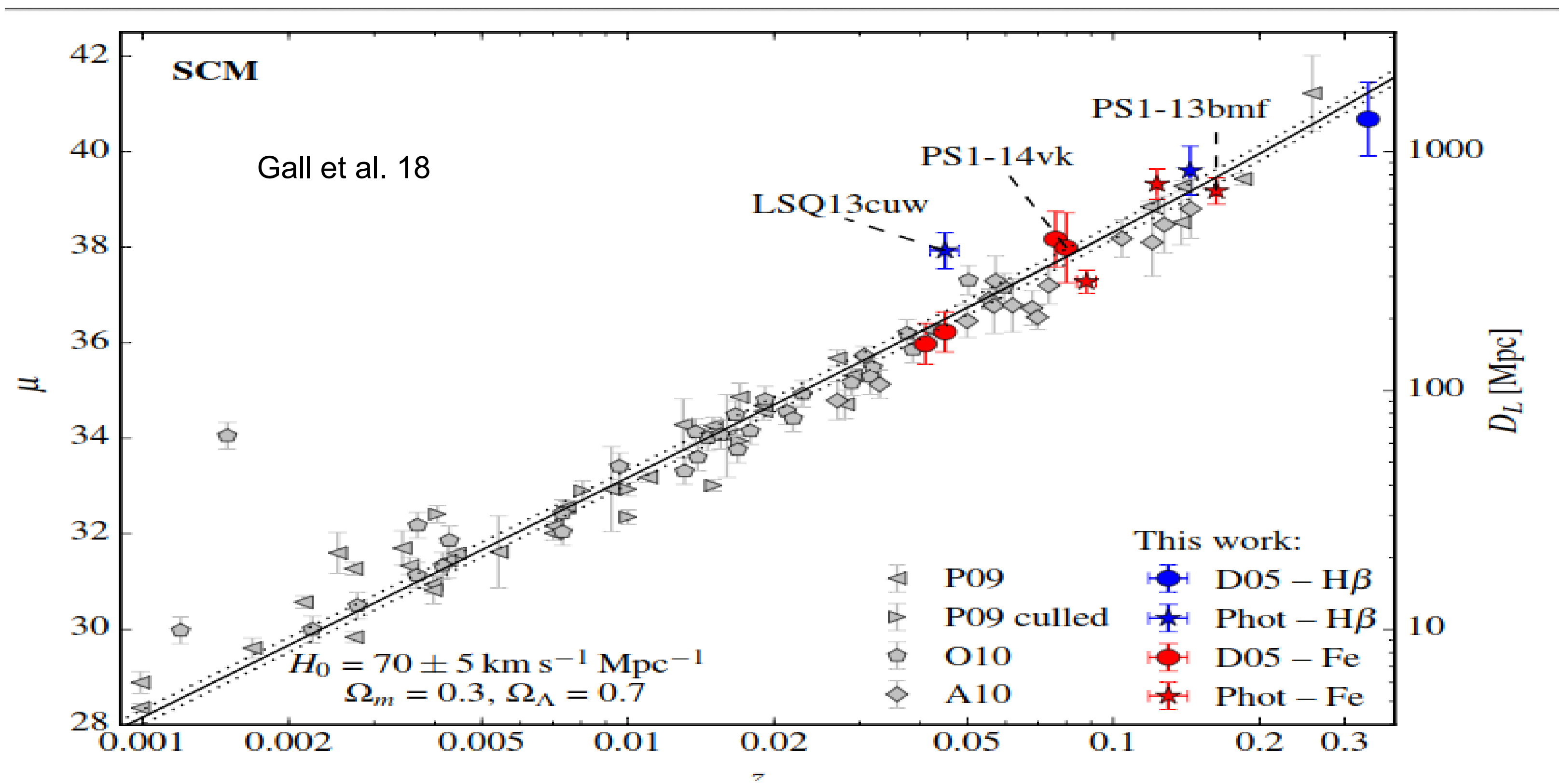


Hamuy & Pinto 2002



de Jaeger et al. 18a

Standard Candle Method (SCM)



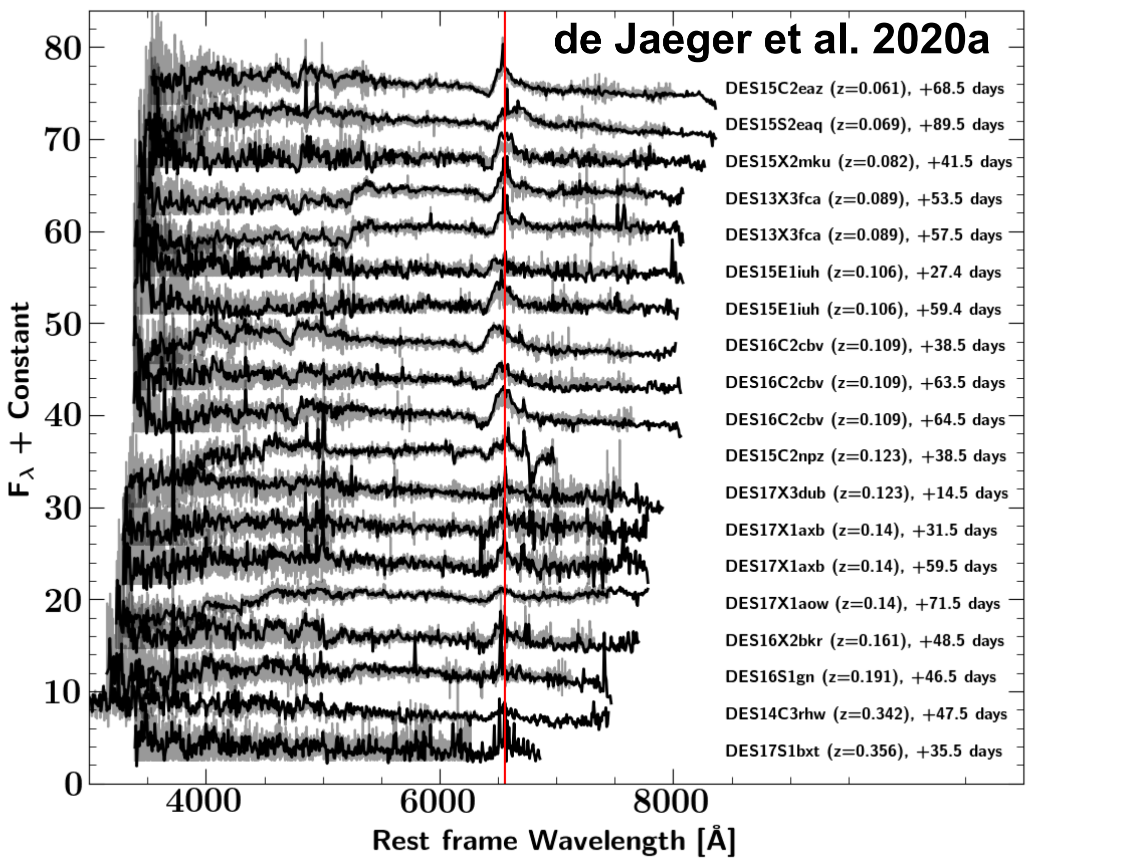
Dispersion~ 0.25-0.3 mag (10-14 % in distances)

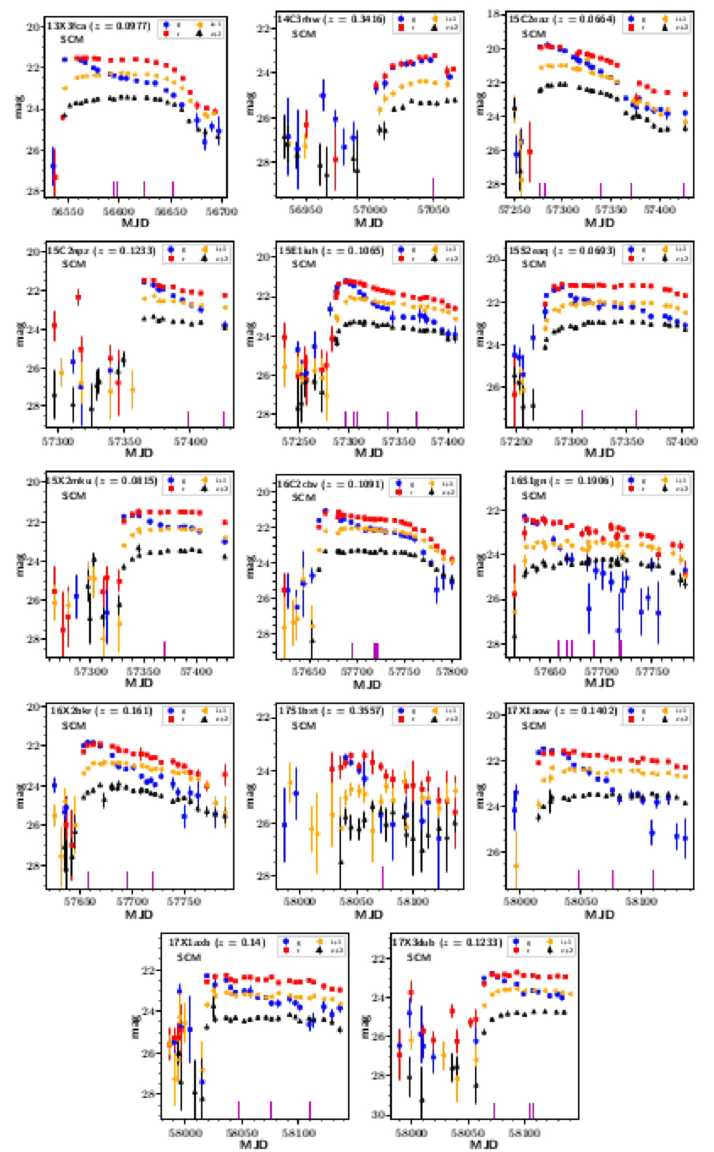
Hamuy & Pinto 02
Poznanski et al. 09/10
Olivares et al. 10
Emilio Enriquez et al. 14
de Jaeger et al. 15a,b,17a,20a,b
Nugent et al. 06
D'Andrea et al. 10
Maguire et al. 10
Rodríguez et al. 14,19
Gall et al. 17,18

Data (DES)

- **56** SNe II (spectroscopic confirmation):

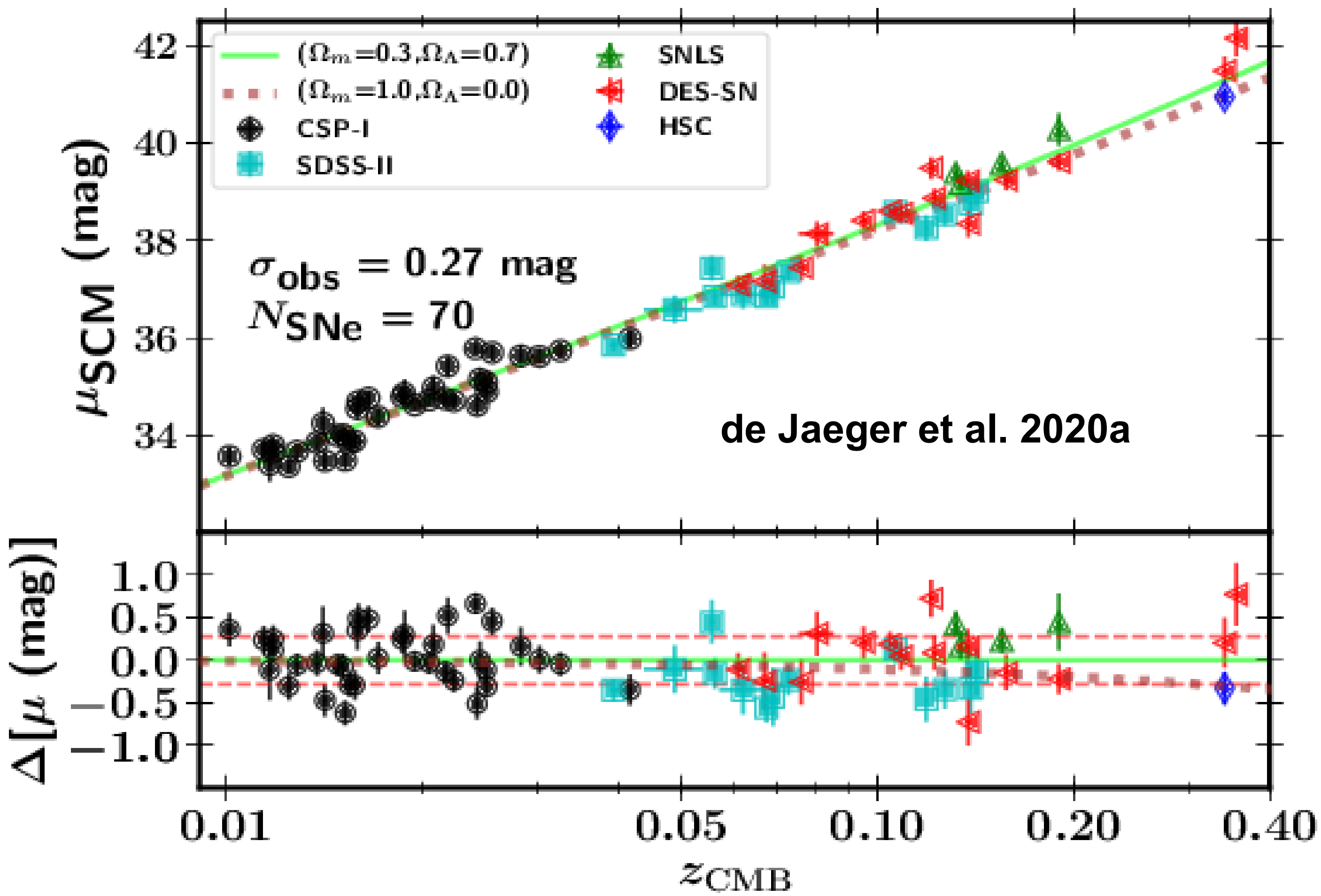
→ **14** SNe II useful SCM



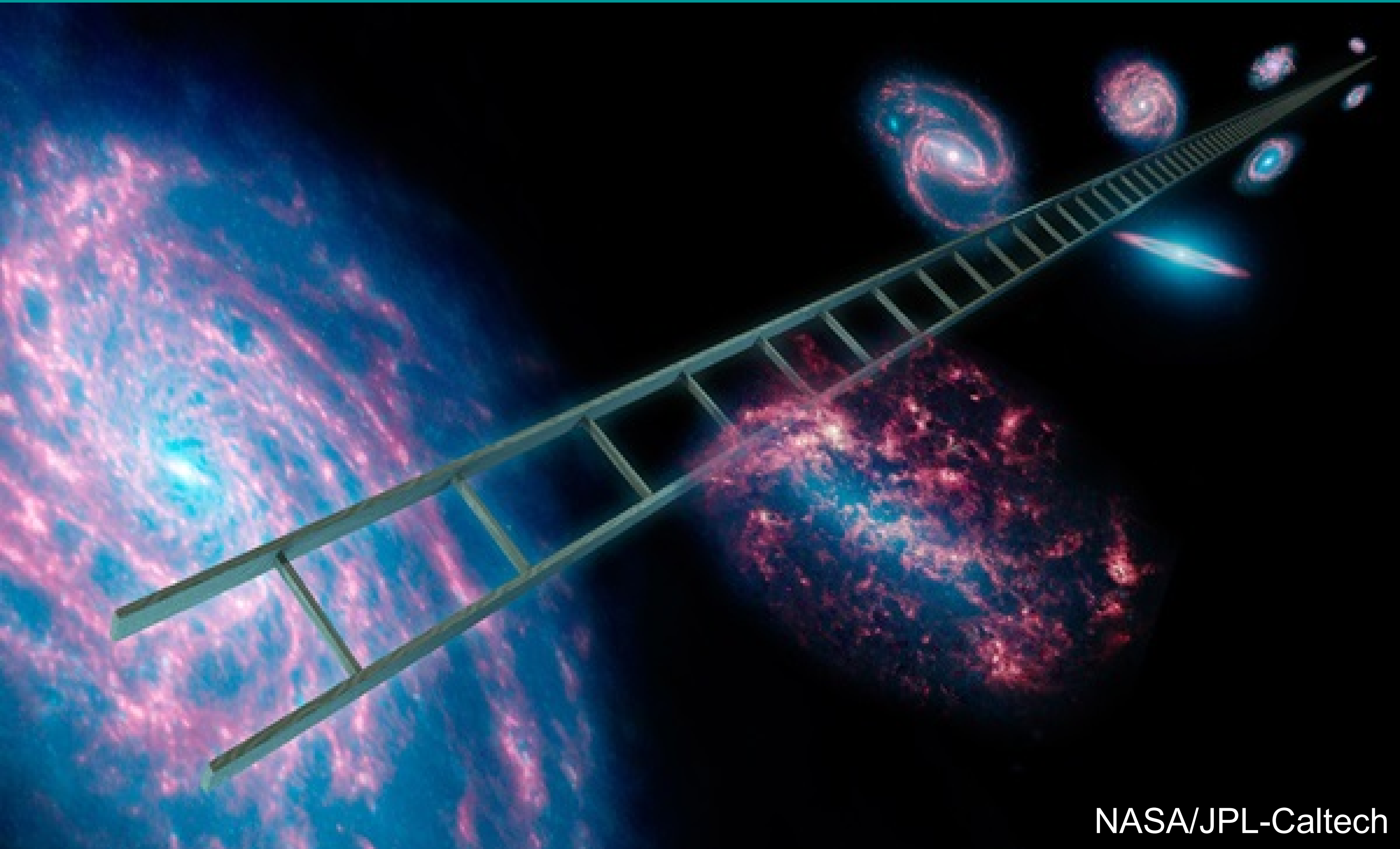


SCM

$$m_i^{\rm model} = \mathcal{M}_i - \alpha \log_{10}\left(\frac{v_{\rm H\beta}}{< v_{\rm H\beta} > \ \ {\rm km\ s^{-1}}}\right) + \beta(r-i) + 5\log_{10}(\mathcal{D}_L(z_{\rm CMB}|\Omega_{\rm m},\Omega_\Lambda))$$

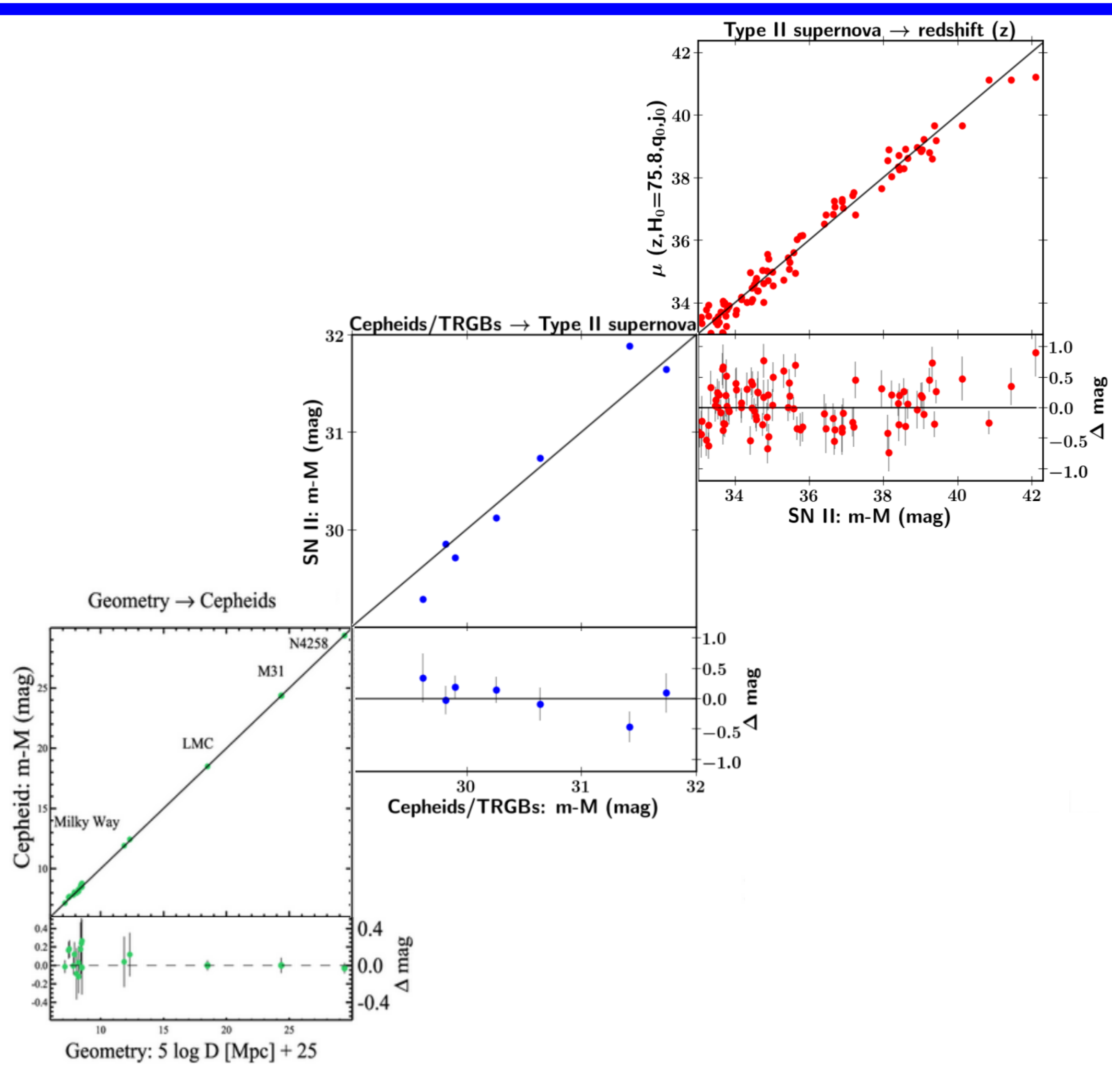


H0: Hubble-Lemaître constant



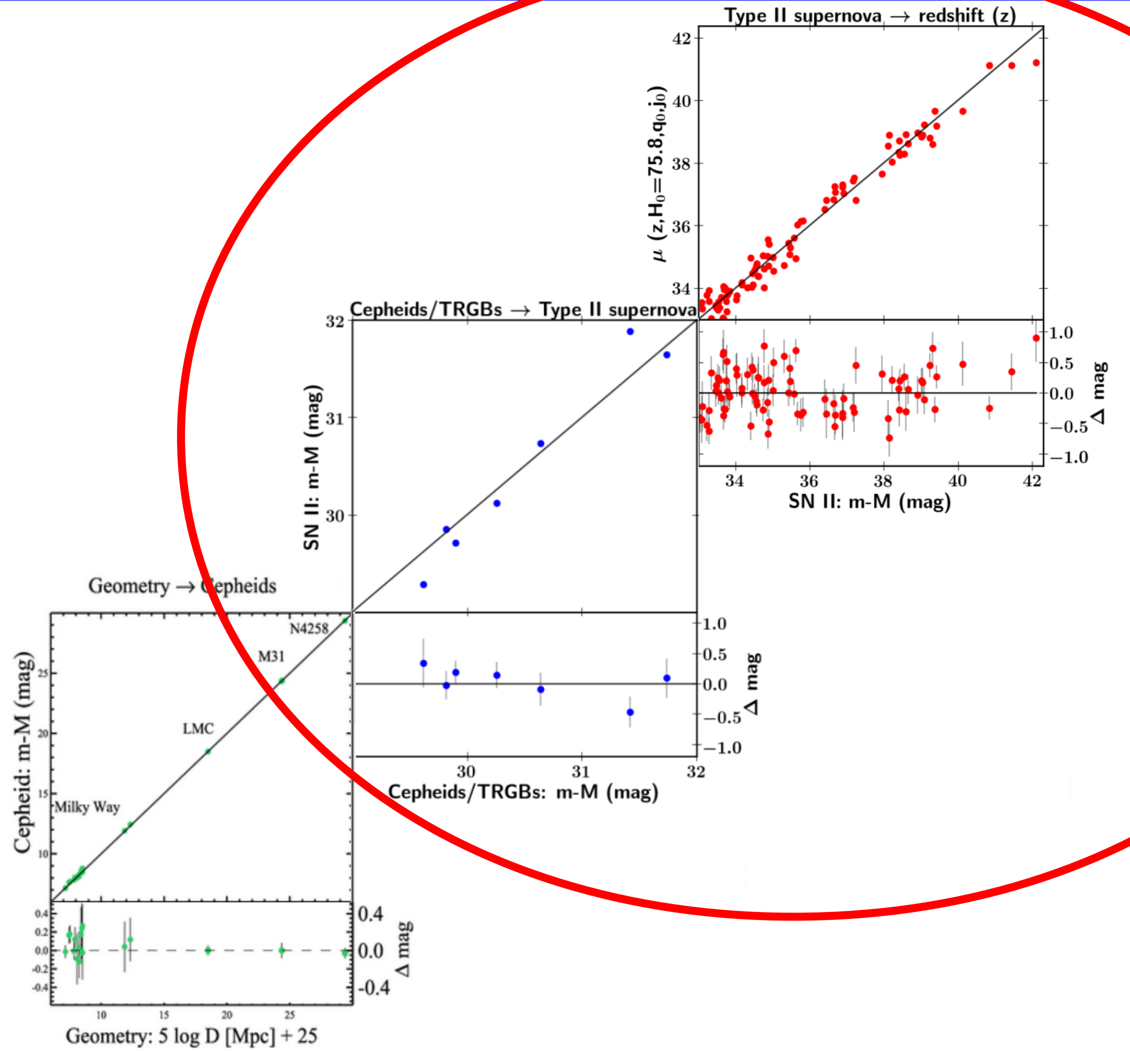
NASA/JPL-Caltech

H0: Distance ladder final



Adapted from Riess et al. 2016

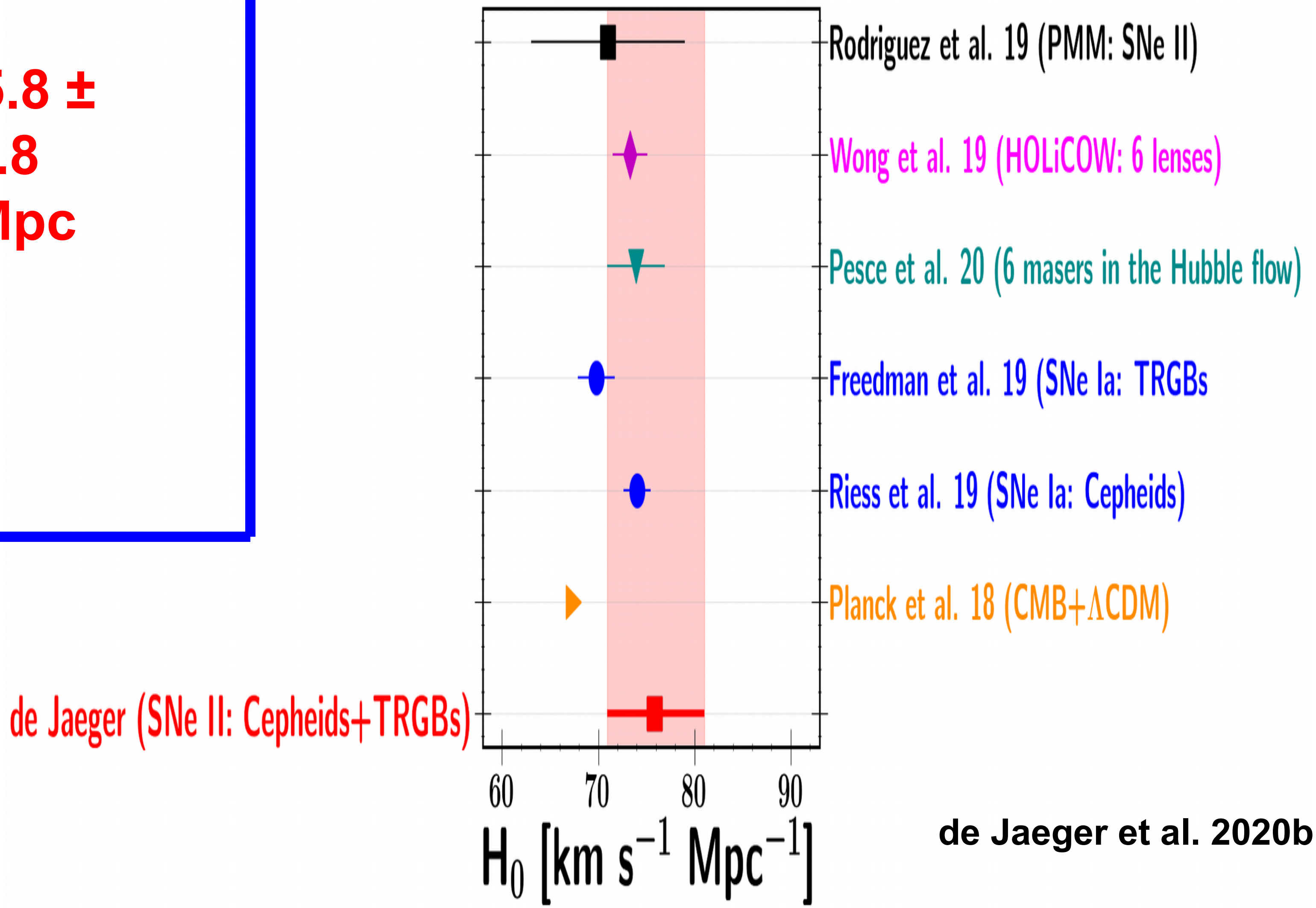
H0: Distance ladder final



Adapted from Riess et al. 2016

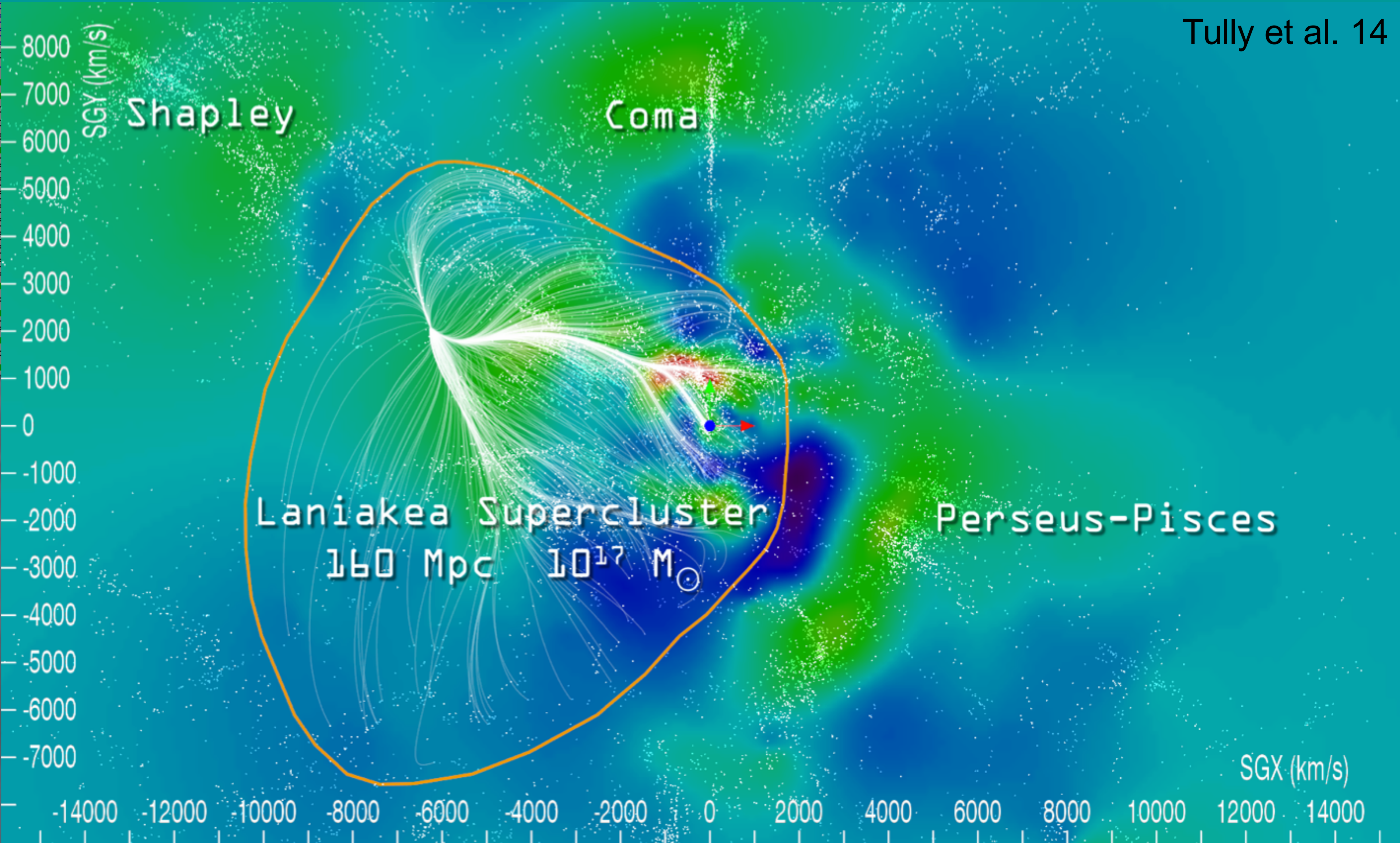
H0 (results)

H0= 75.8 ± 5.0 ± 2.8 km/s/Mpc

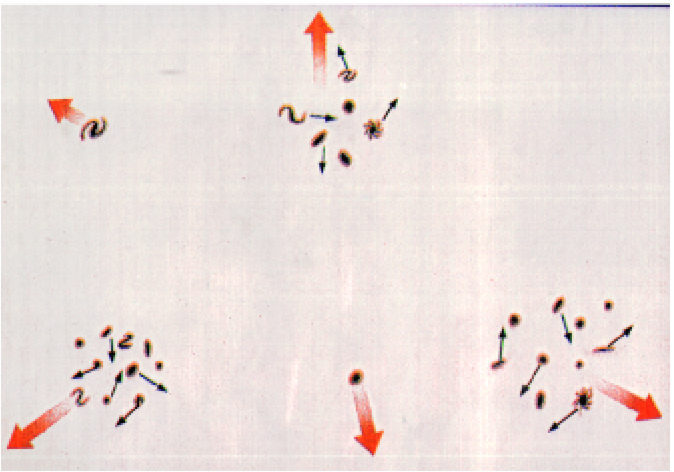


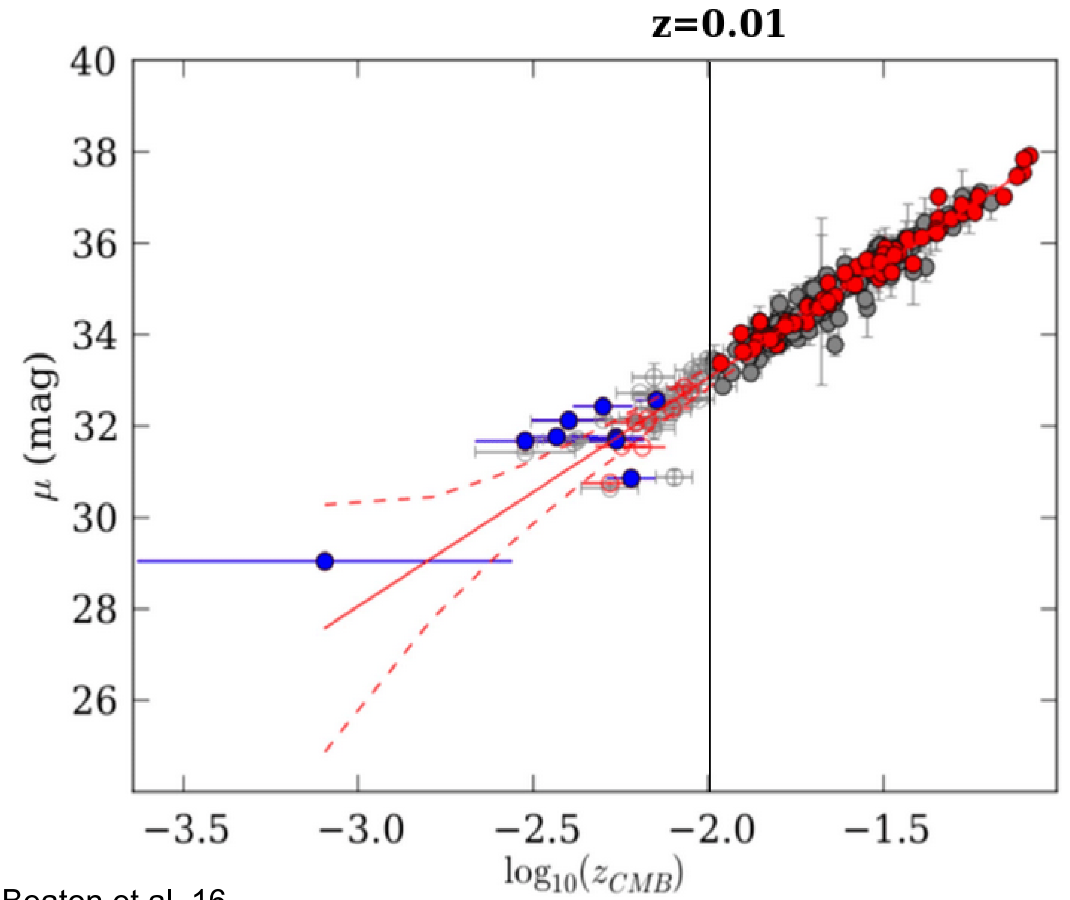
de Jaeger et al. 2020b

Peculiar velocities



Peculiar velocities

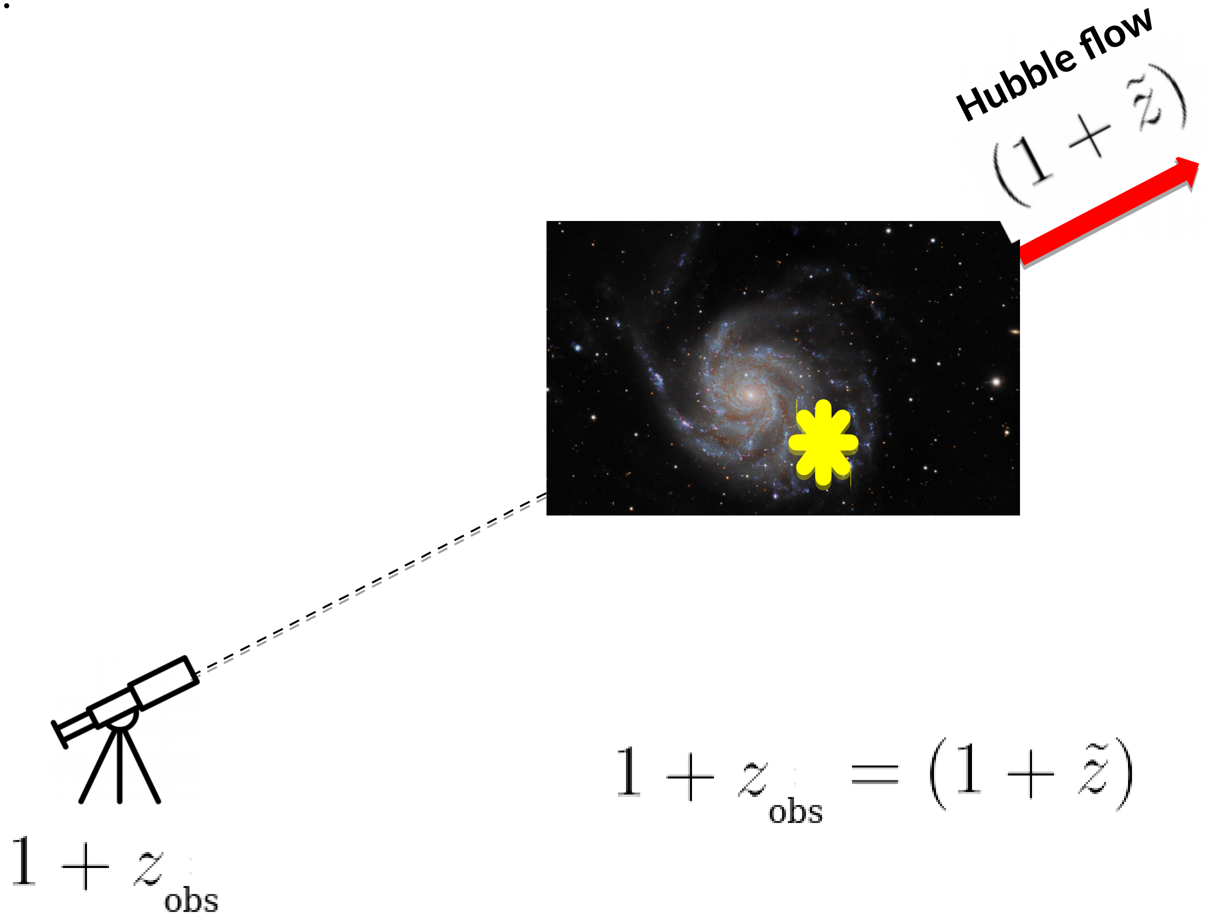




Beaton et al. 16

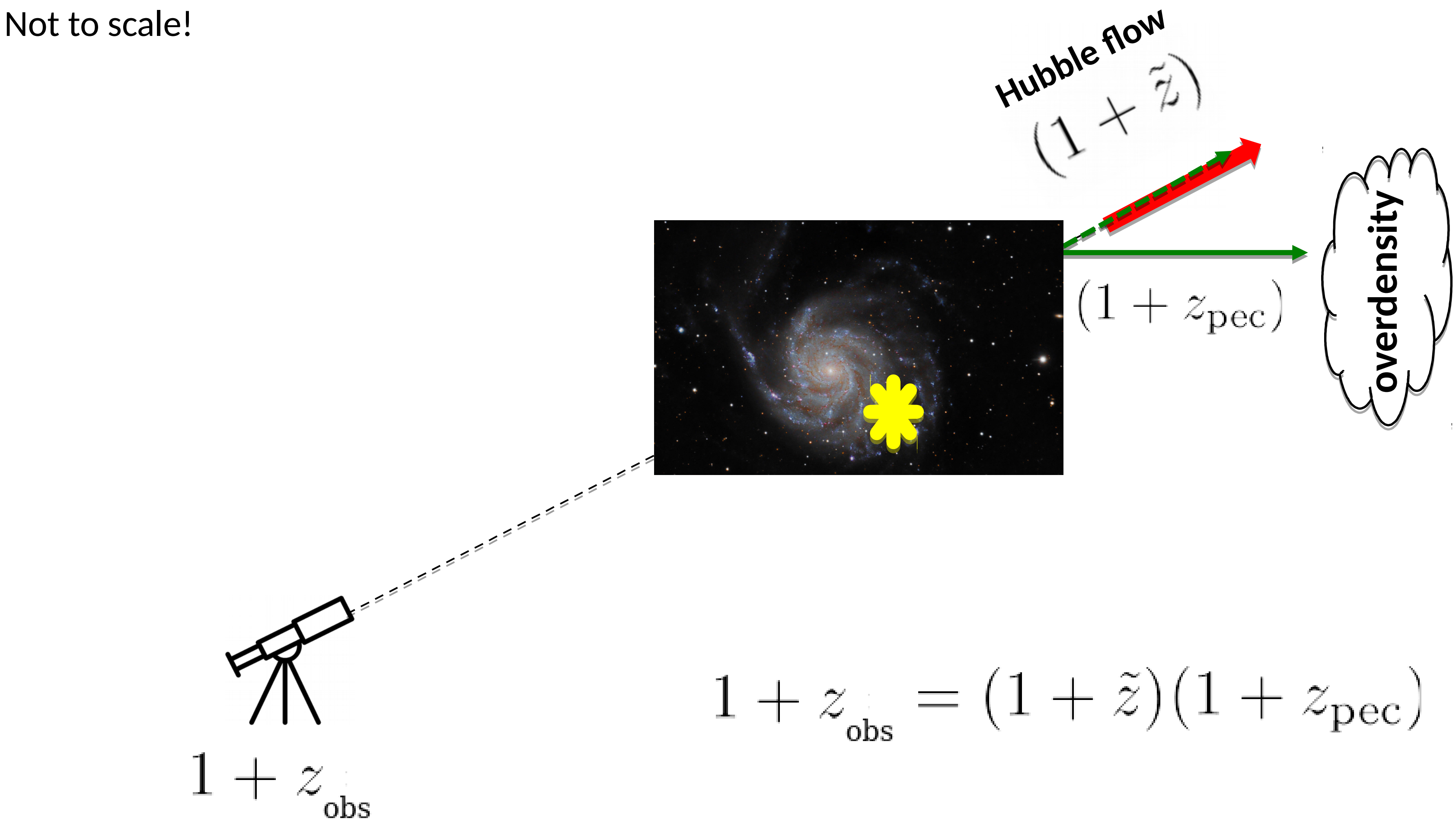
Peculiar velocities

Not to scale!



$$1+z_{\text{obs}} = (1+\tilde{z})$$

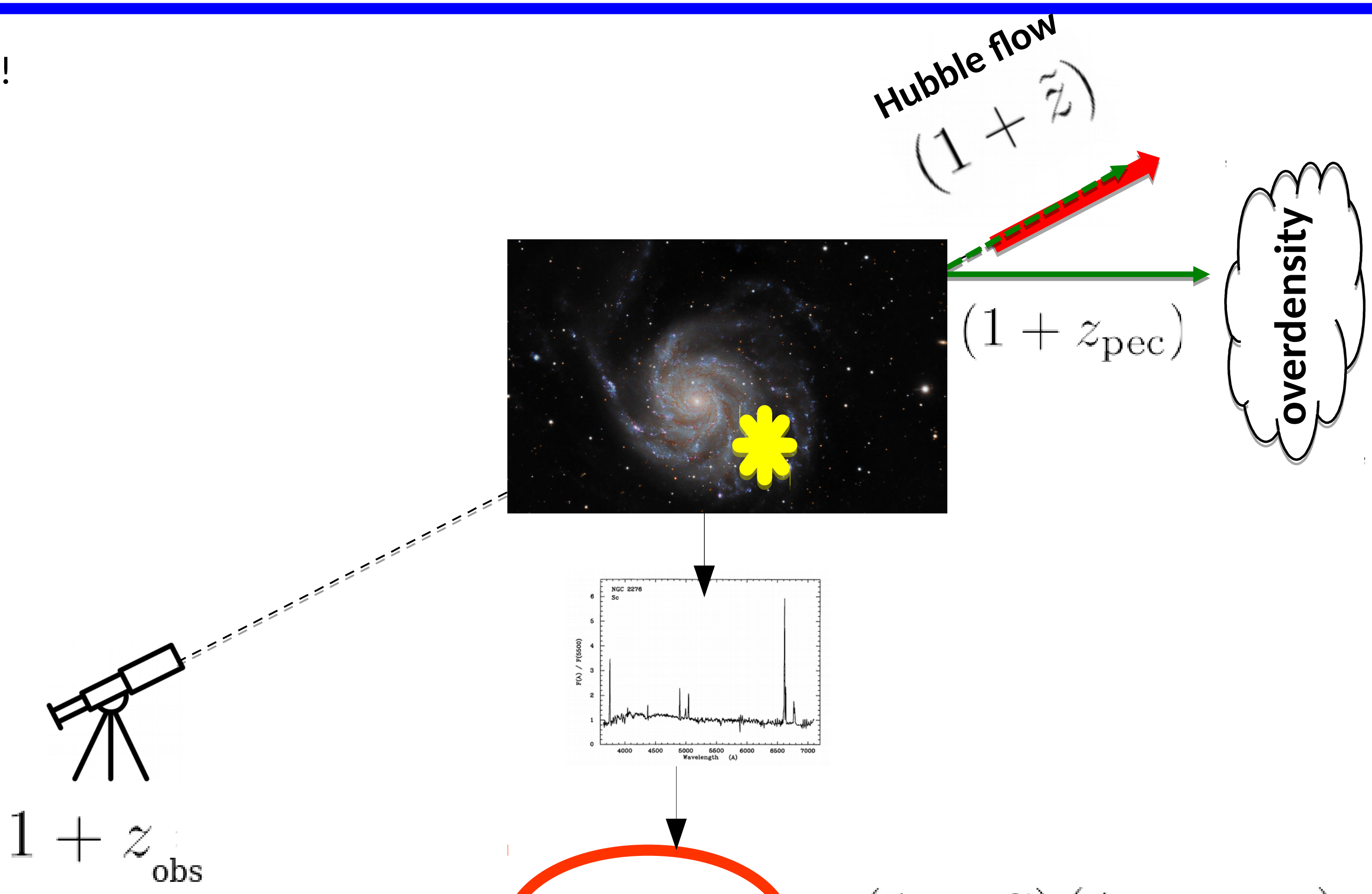
Peculiar velocities



$$1+z_{\rm obs} = (1+\bar{z})(1+z_{\rm pec})$$

Peculiar velocities

Not to scale!



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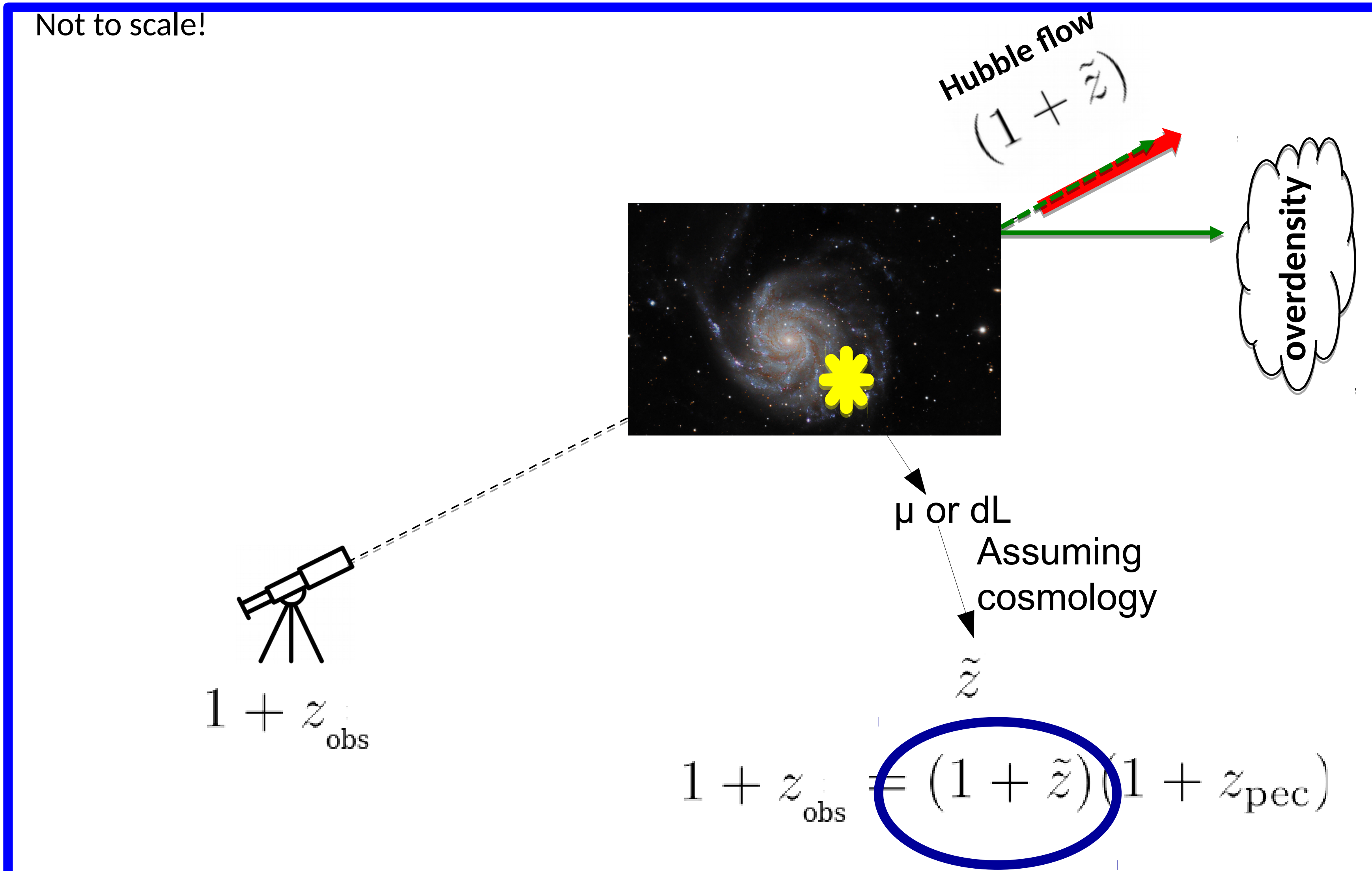
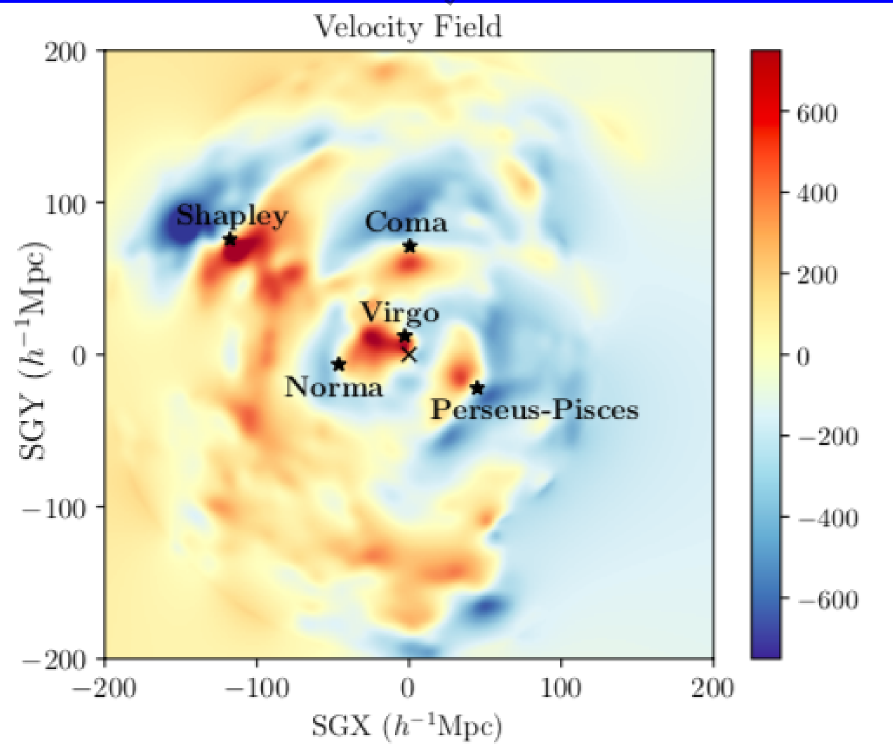
Peculiar velocities



Peculiar velocities: Why?

Linear perturbation theory: (Peebles 93)

$$\mathbf{v}(\mathbf{r}) = \frac{H_0 f}{4\pi} \int d^3\mathbf{r}'\delta(\mathbf{r}') \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3}$$



Boruah+ 2020, reconstruction field from 2M++ (Carrick et al. 15)

Peculiar velocities: Why?

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(Peebles 93)

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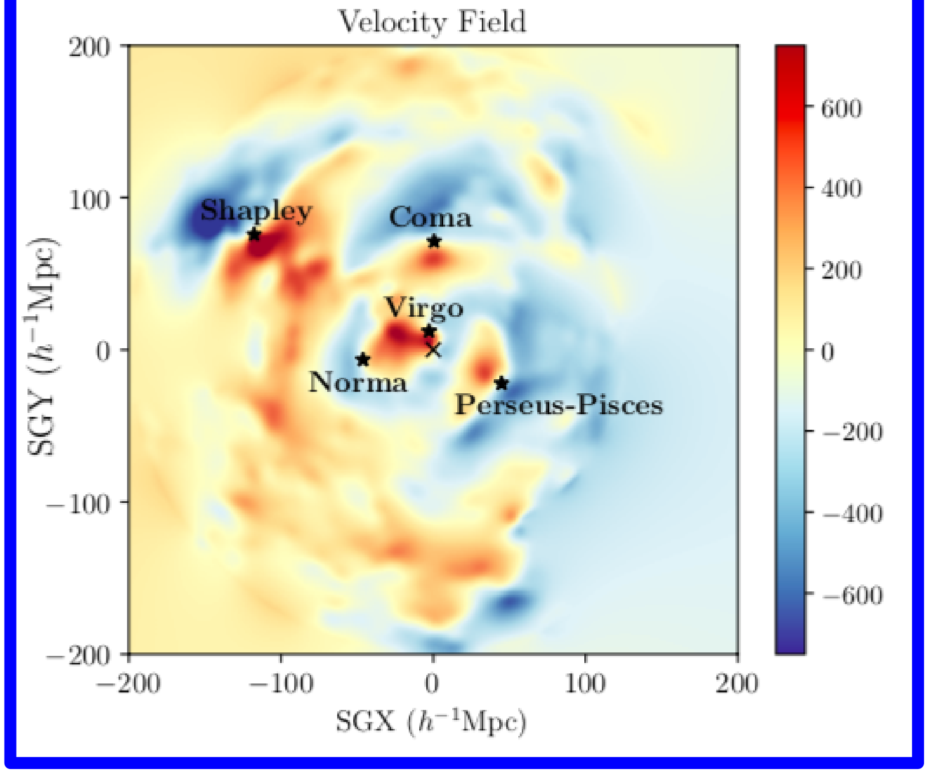

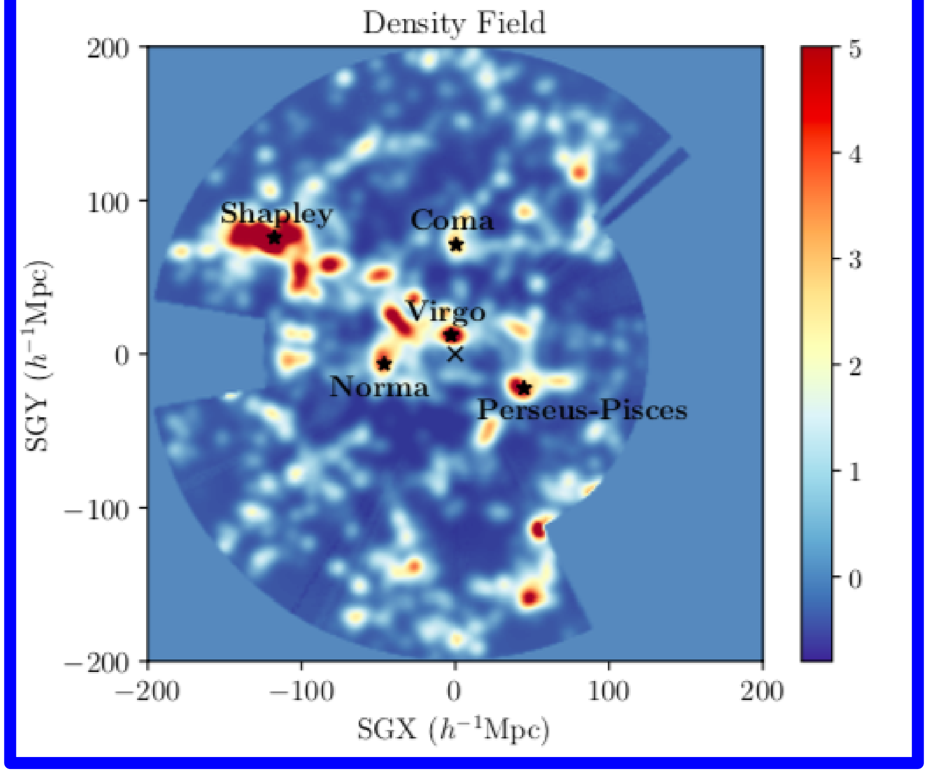

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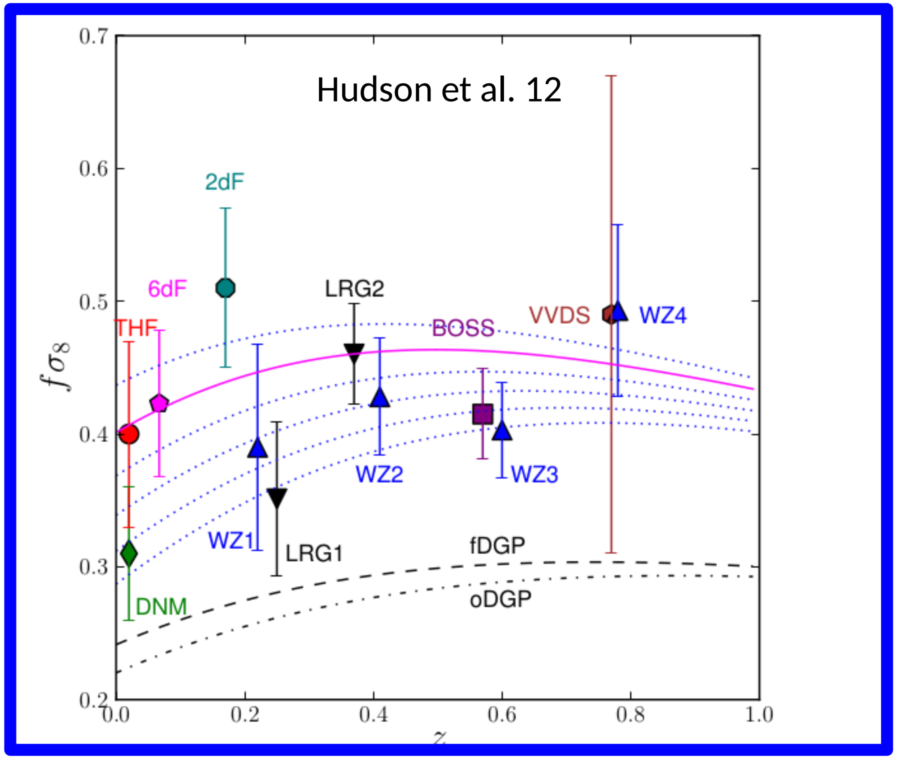
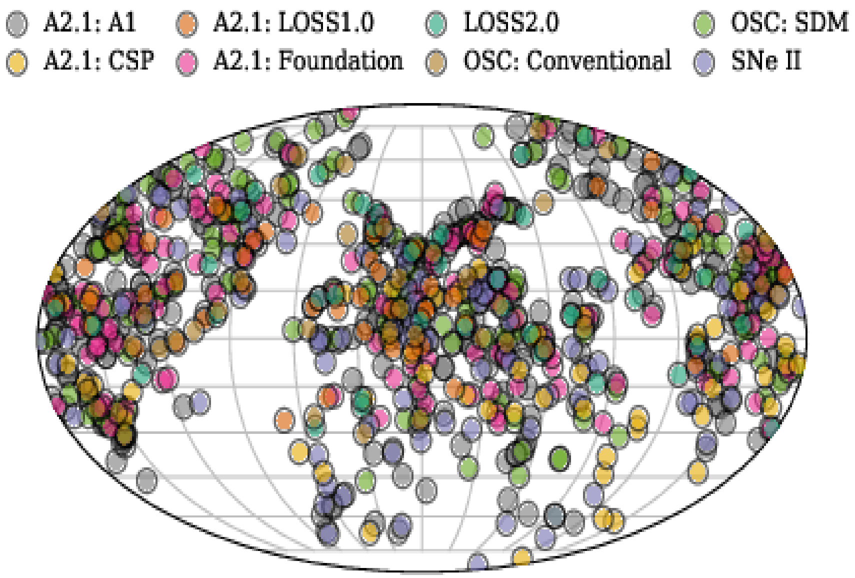
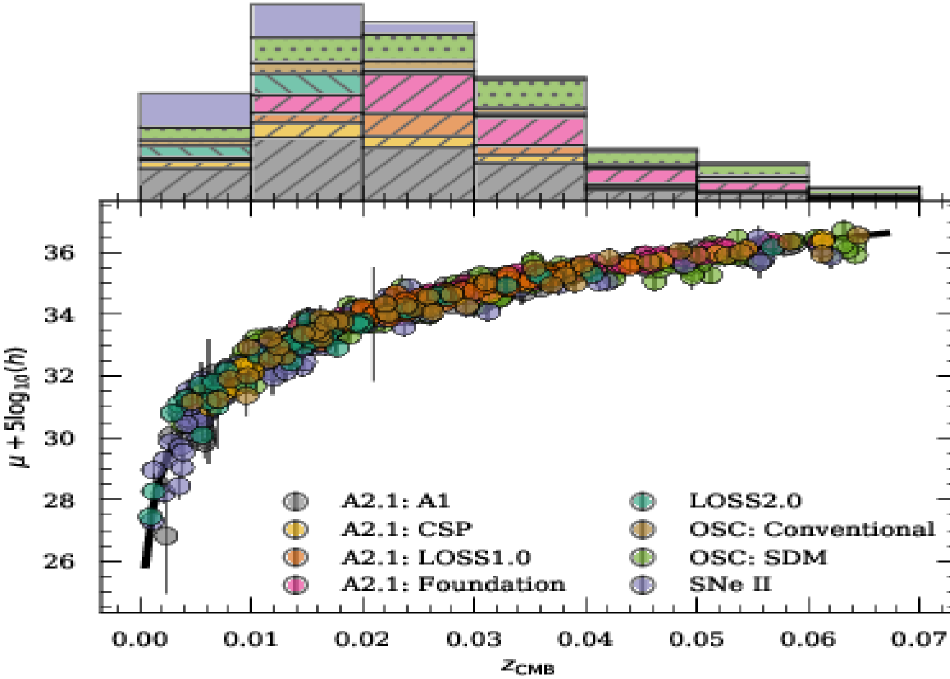


Peculiar velocities: Results

Stahl, **de Jaeger** et al. submitted 2021

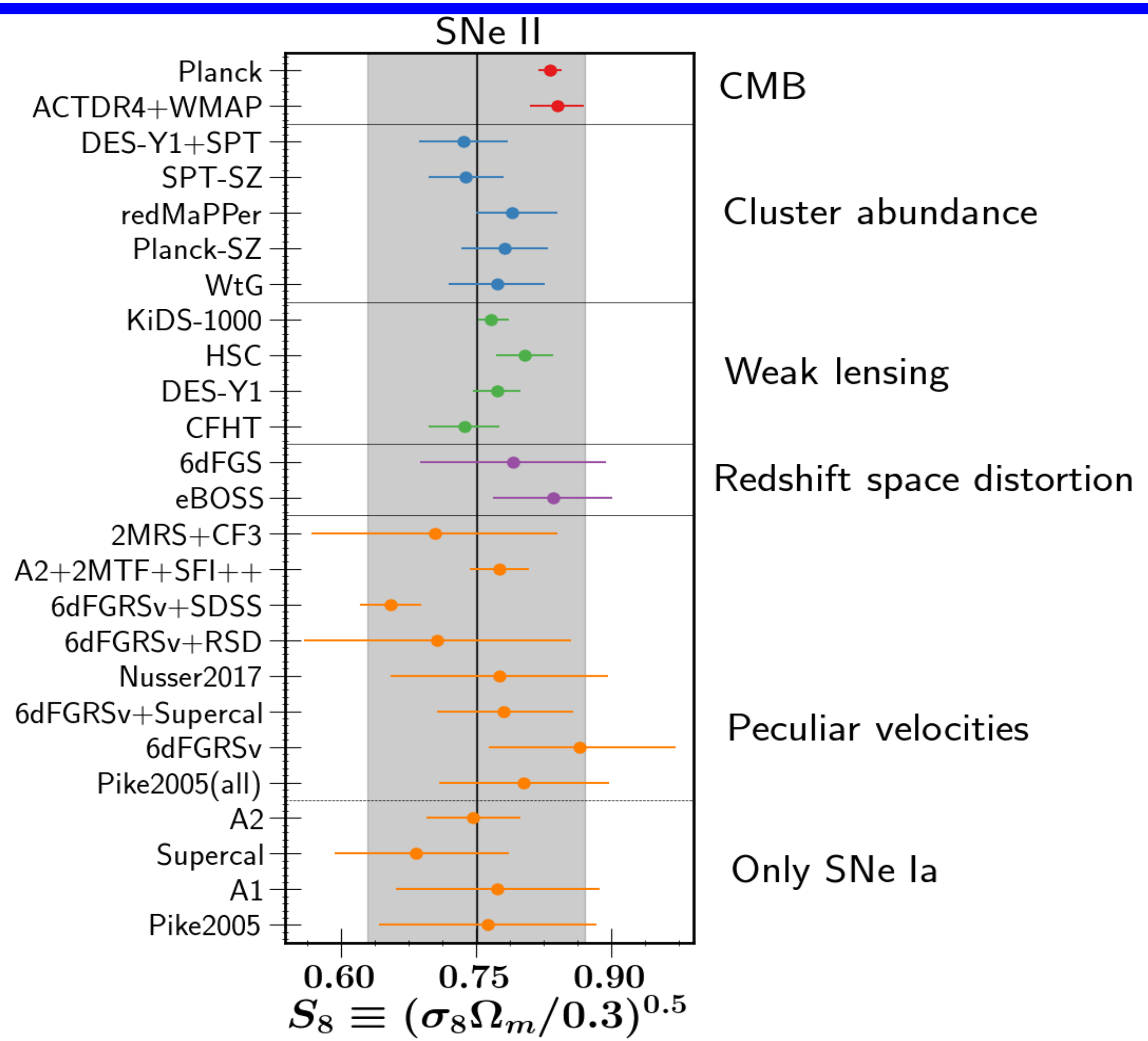
Benjamin
Stahl





Peculiar velocities: Results

Stahl, **de Jaeger** et al. submitted 2021



Conclusions

- Precision of SNe Ia : 0.15 mag (7% in distance)
- Precision of SNe II : 0.30 mag (14% in distance)
  → Affected by different systematics
  → « free » data
- Precision of galaxies : ~0.5mag (25% in distance)
- Most precise H_0 from type II
- Peculiar velocities

Type II future

- Measuring H0 :
  → Increase the calibrator sample : Cepheids + TRGBs

- Expand the sample to high-z supernovae :
  → LSST
  → Gemini + Magellan + Keck spectroscopic followup

- New SNe II template :
  → Type II light-curve fitter?
  → Improve K-corrections

- SNe II environnments
  → Metallicity
  → IFU/MUSE

- Peculiar velocities

My future

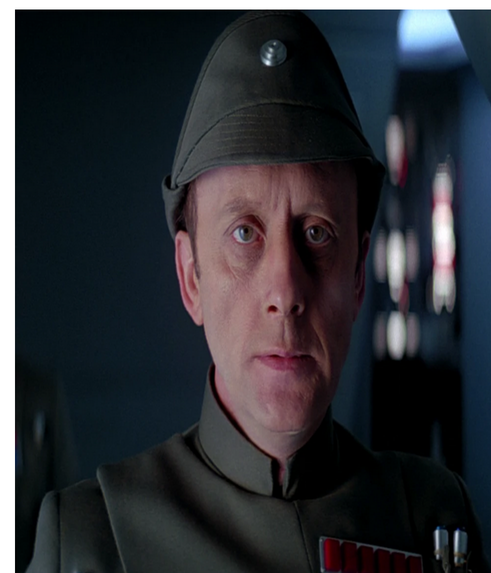
Type II Supernovae

Type Ia Supernovae

Hawai'i SN Flows





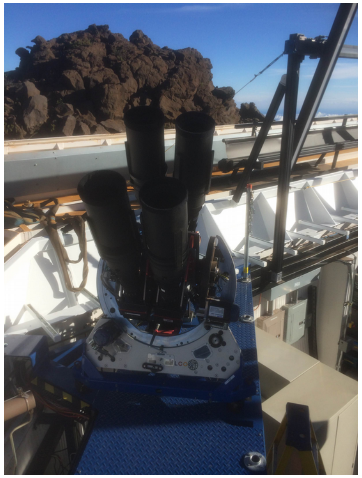
Hawai'i SN Flows





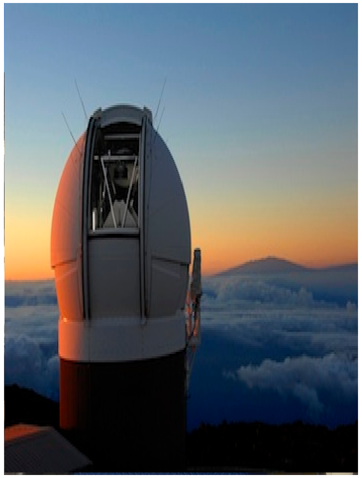

Hawai'i the best place!!!

ATLAS



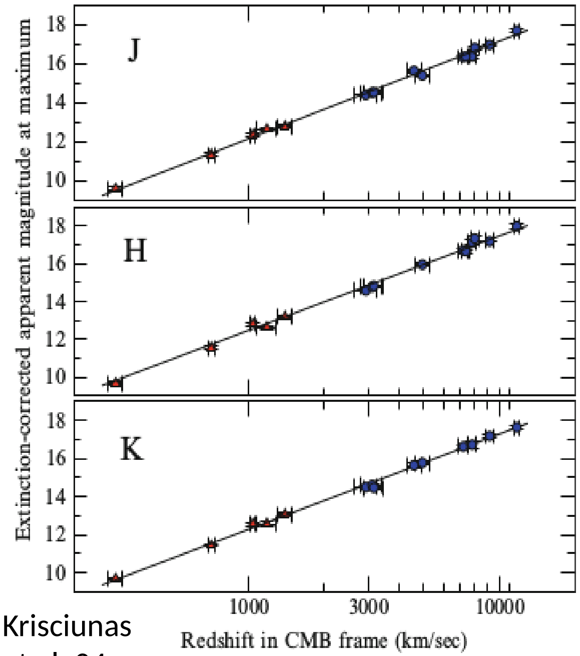
ASAS-SN

UH-2.2



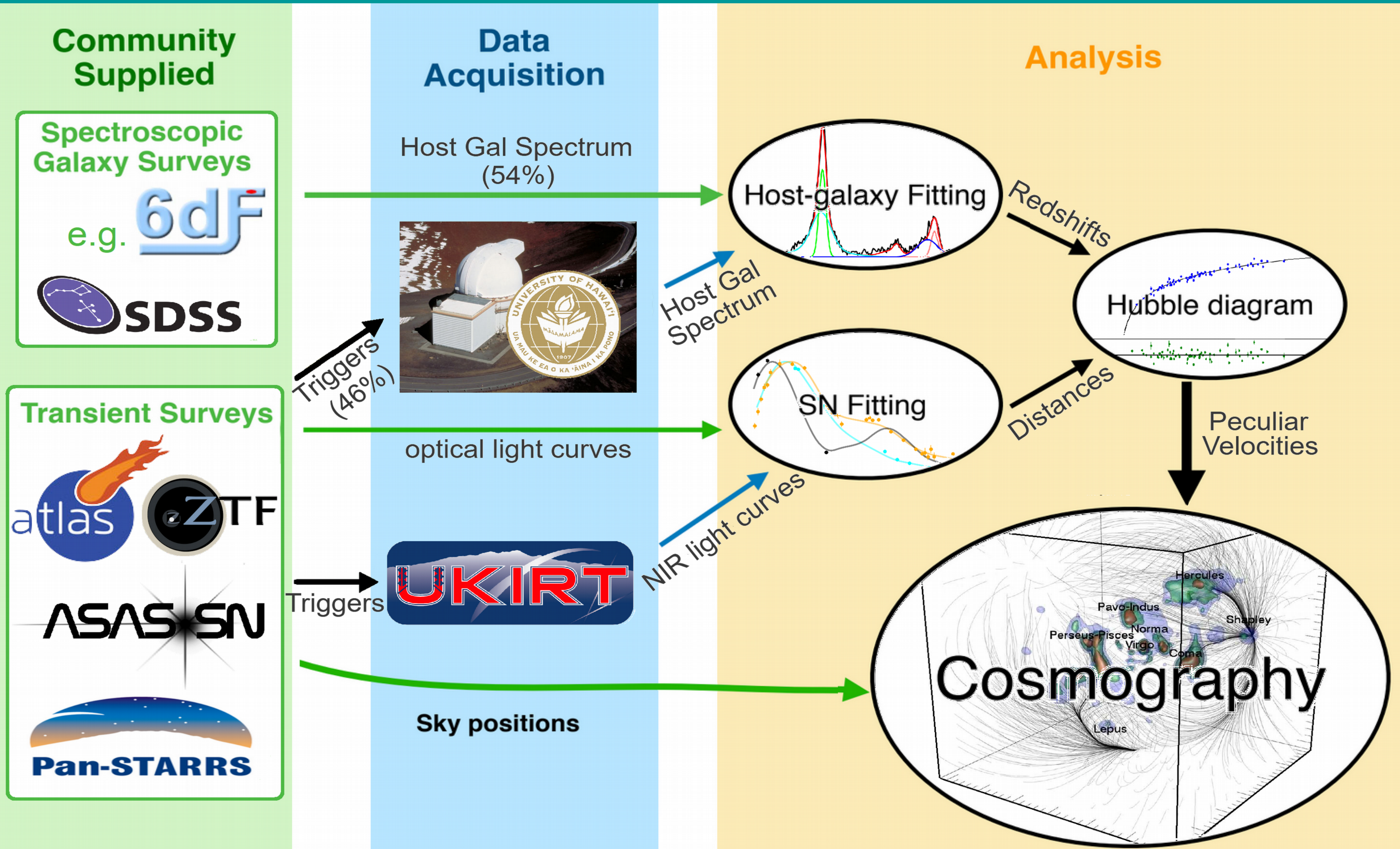
Pan-STARRS

UKIRT

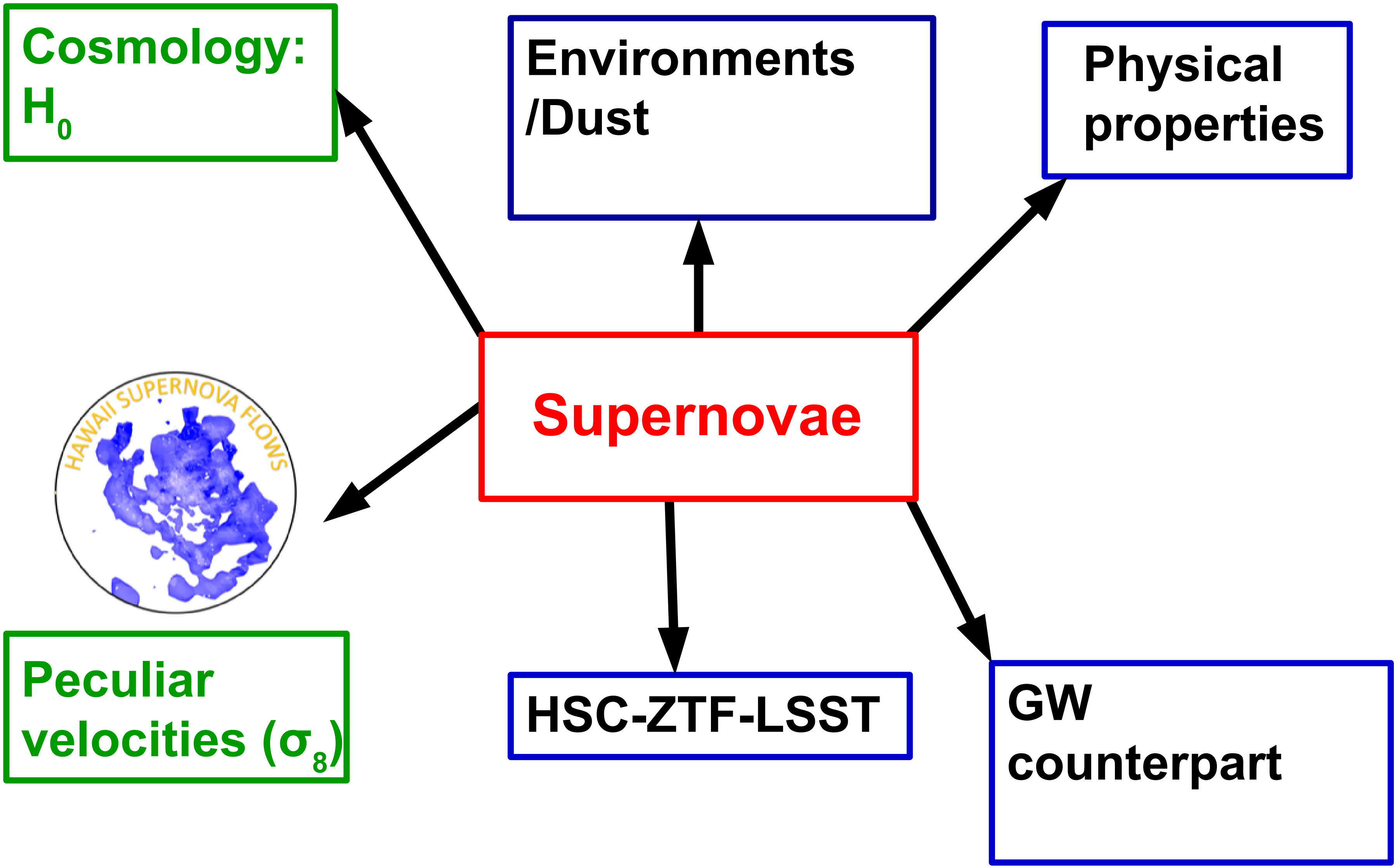


Krisciunas et al .04

Hawai'i SN Flows



Research interests



Mahalo!!!

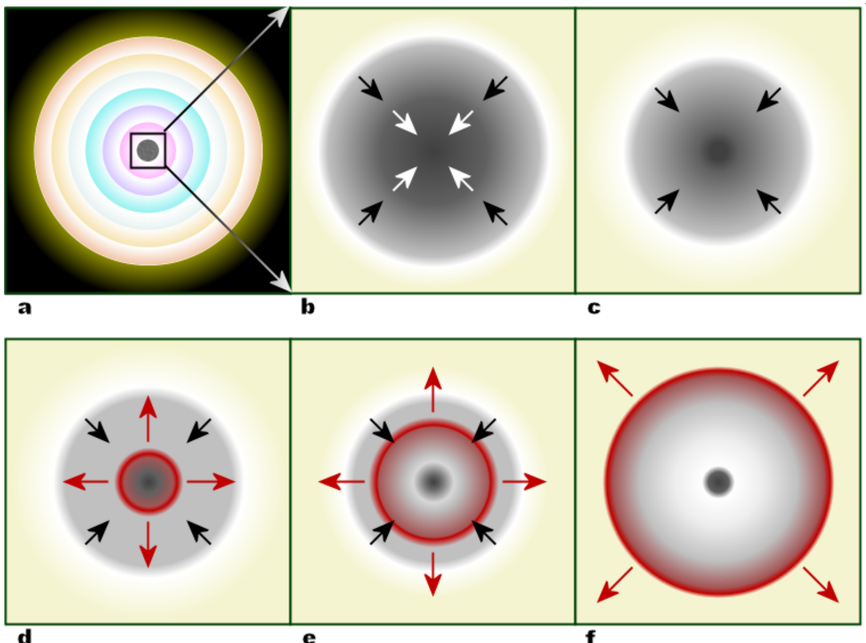
Backup

Expanding Universe

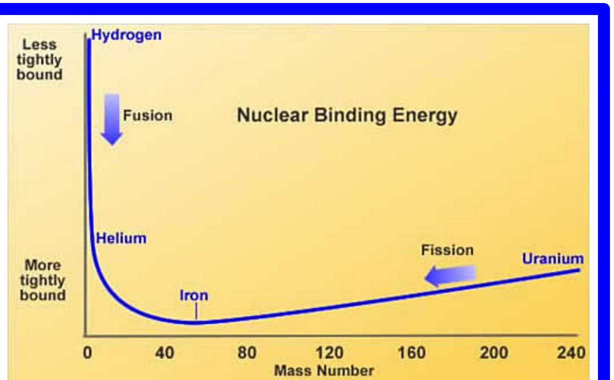
Expanding Universe

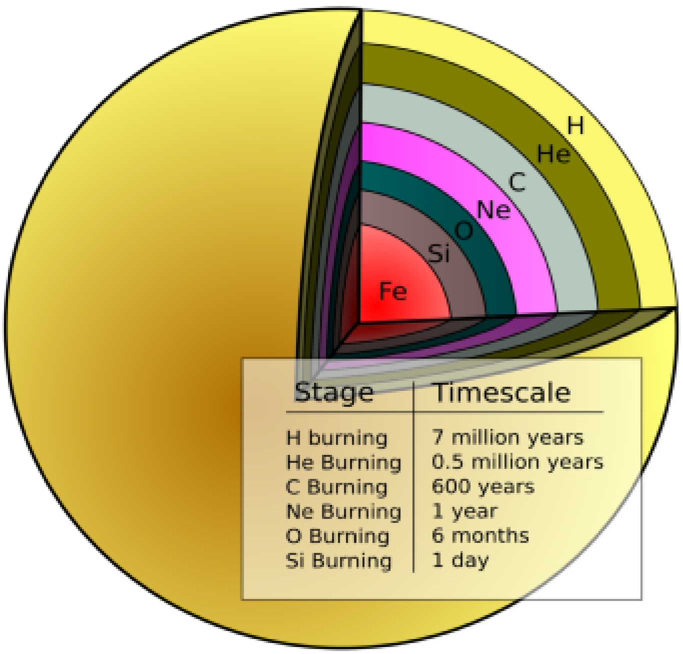
CCSNe

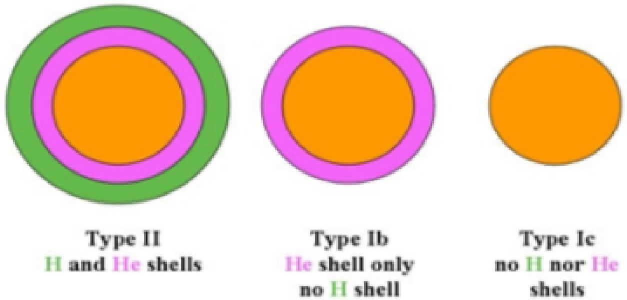
core collapse of massive stars M>8Msol:



R.J. Hall

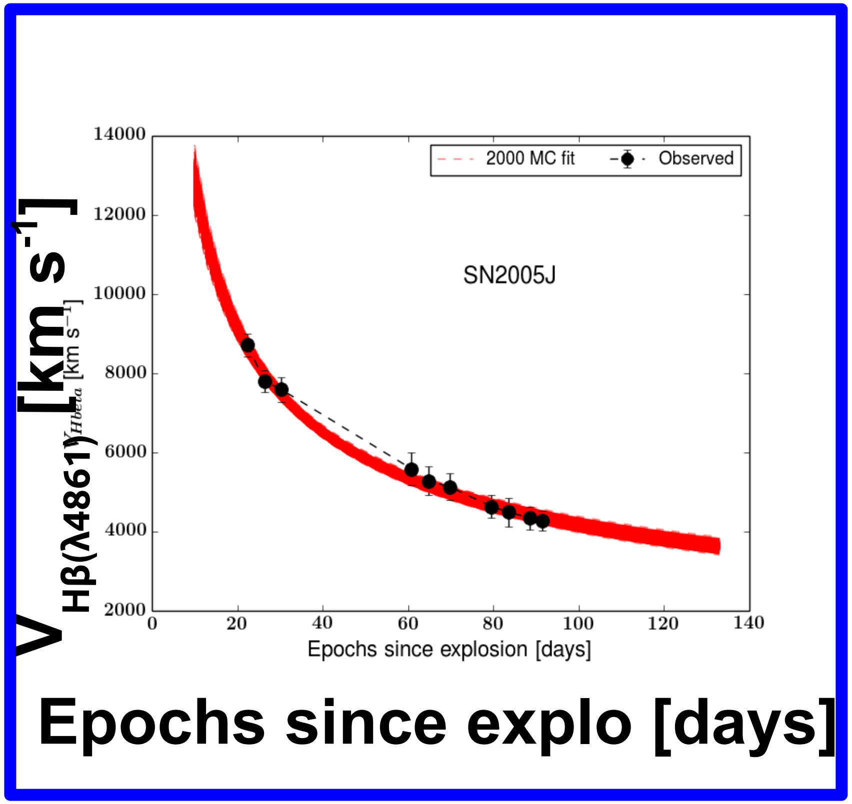




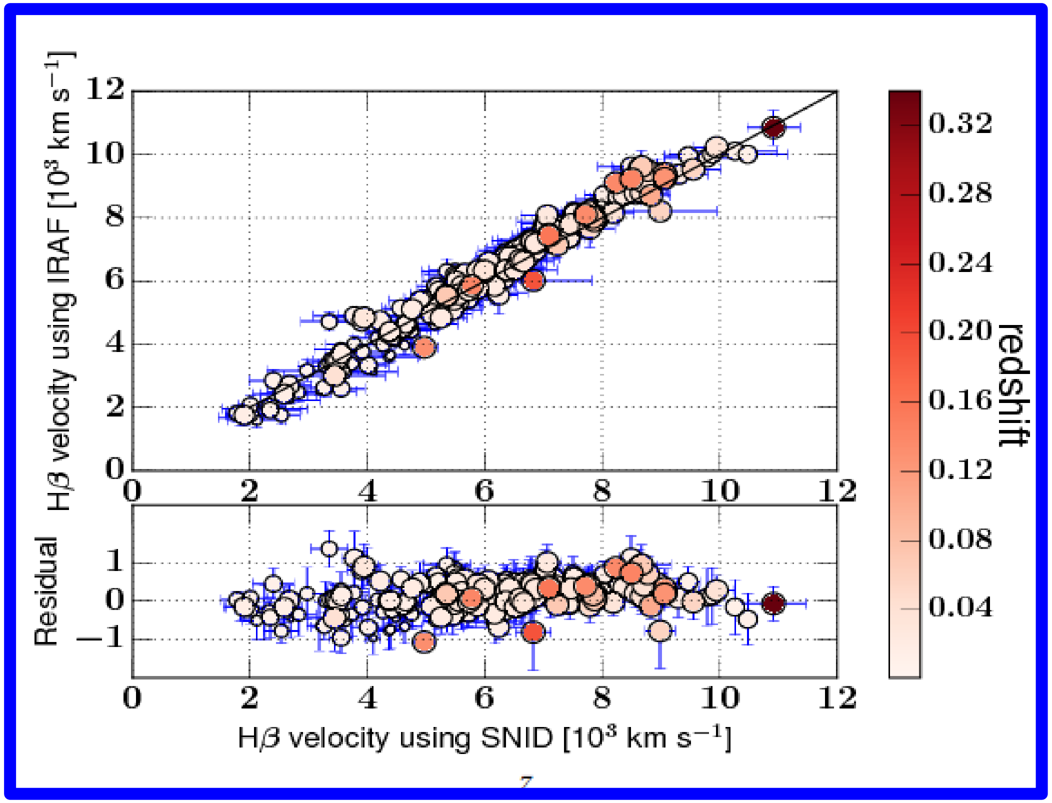


Velocity

Power law fit



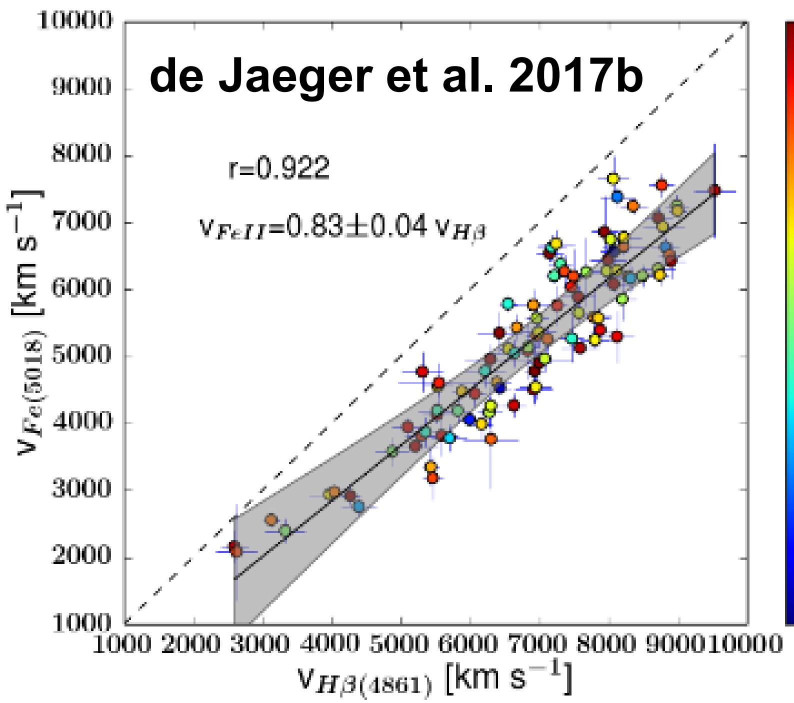
Cross correlation vs minimum absorption



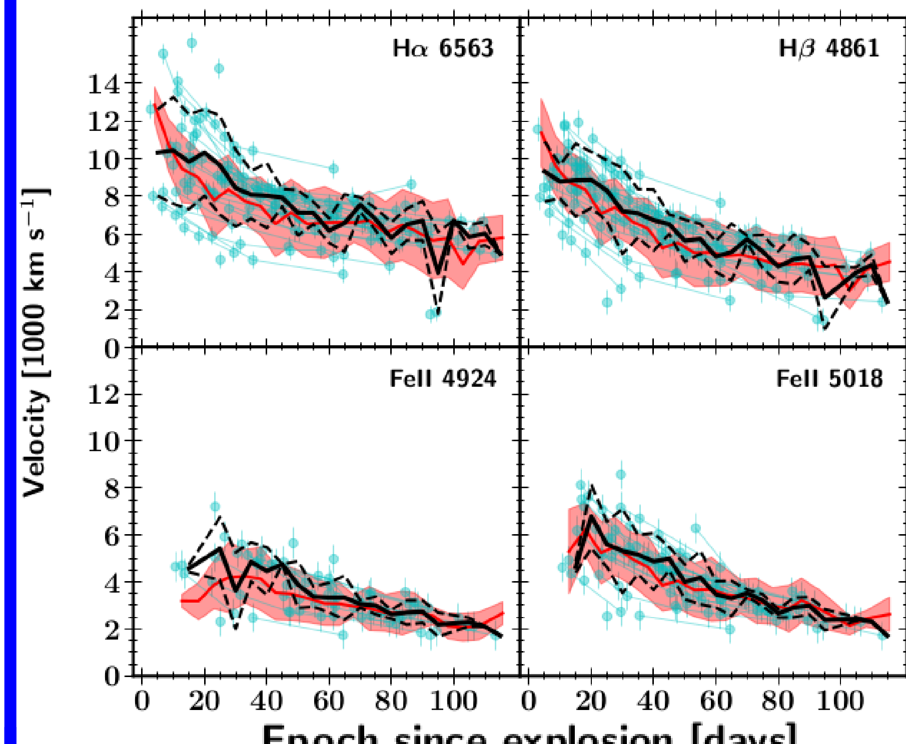
de Jaeger et al. 2017b

Velocity

Fe vs H_β

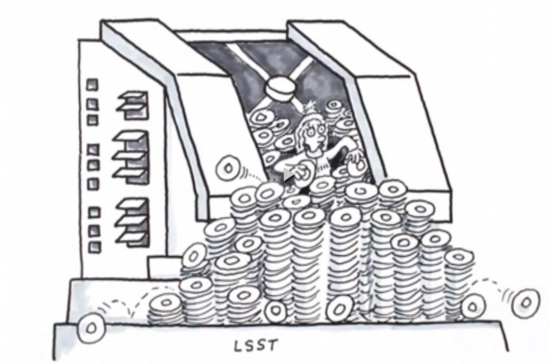


Line velocity evolution

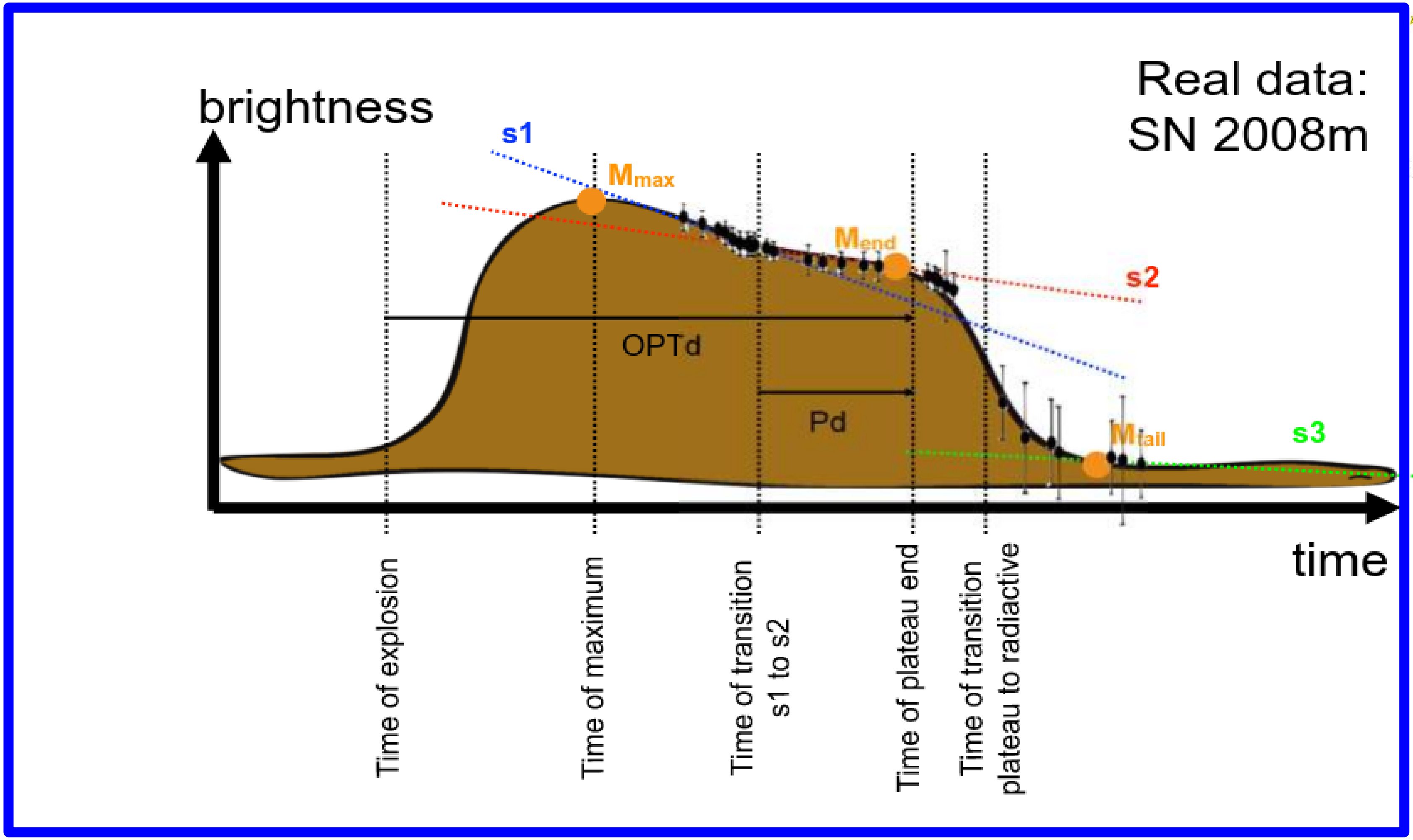


BUT If we did not have spectroscopic information?

Can we come up with a method solely based on photometry?



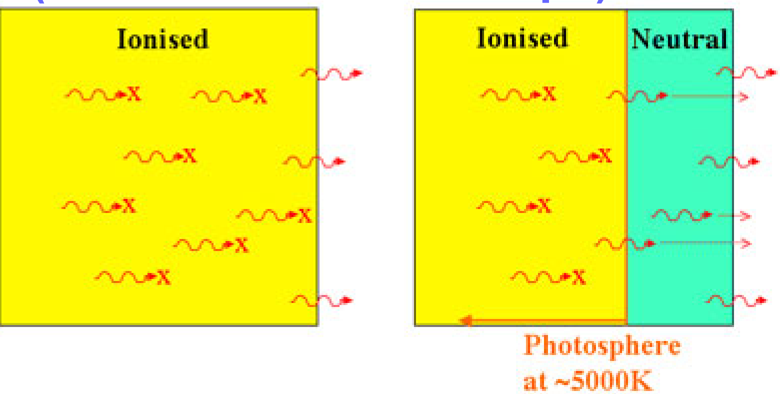
PCM

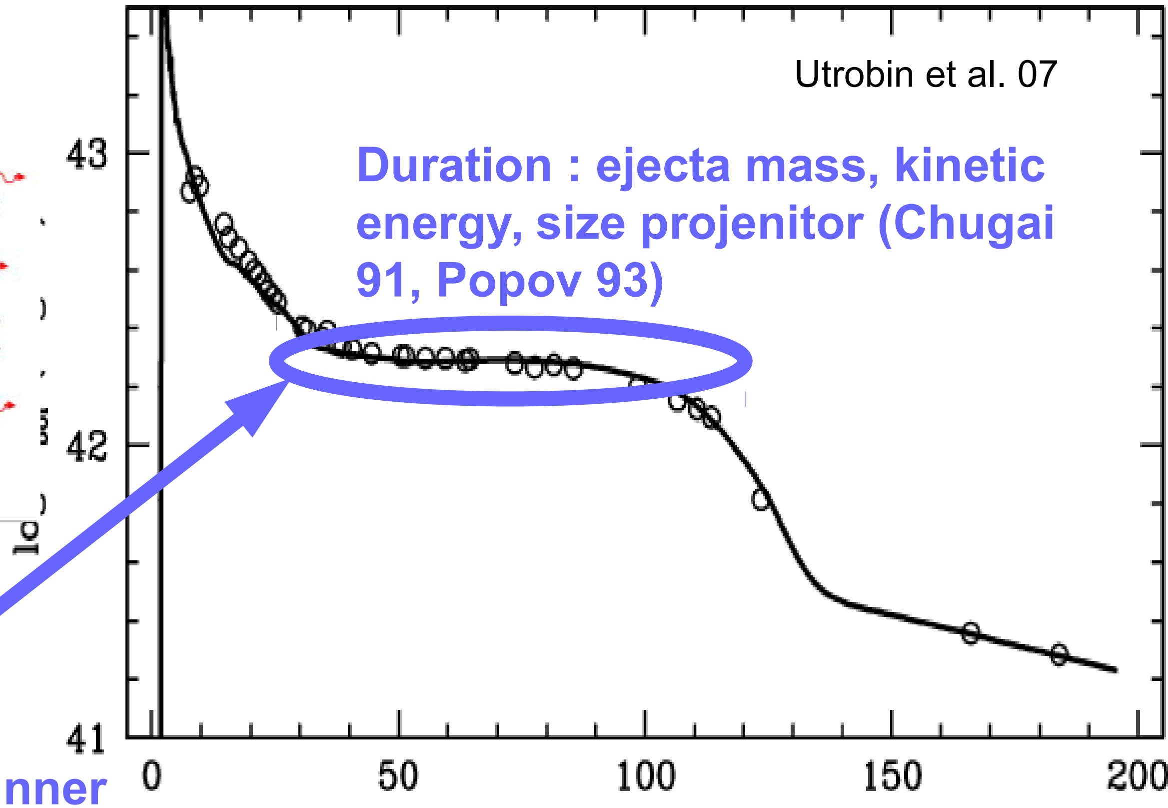


Courtesy Lluis Galbany

Plateau

After SBO, all H is ionised (radiation cannot escape)



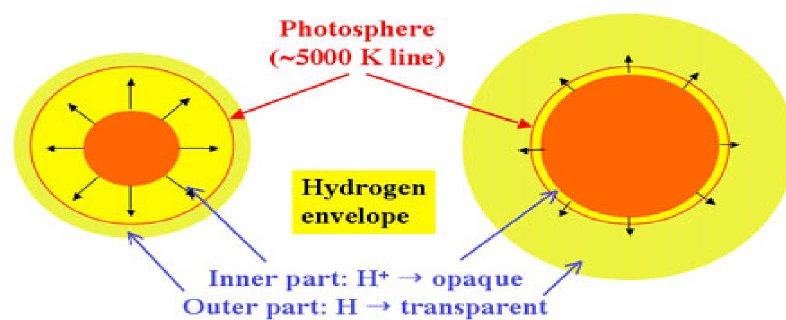


Duration : ejecta mass, kinetic energy, size projenitor (Chugai 91, Popov 93)

The outer parts of the star have cooled sufficiently that the ionised hydrogen is able to RECOMBINE (~5000K)

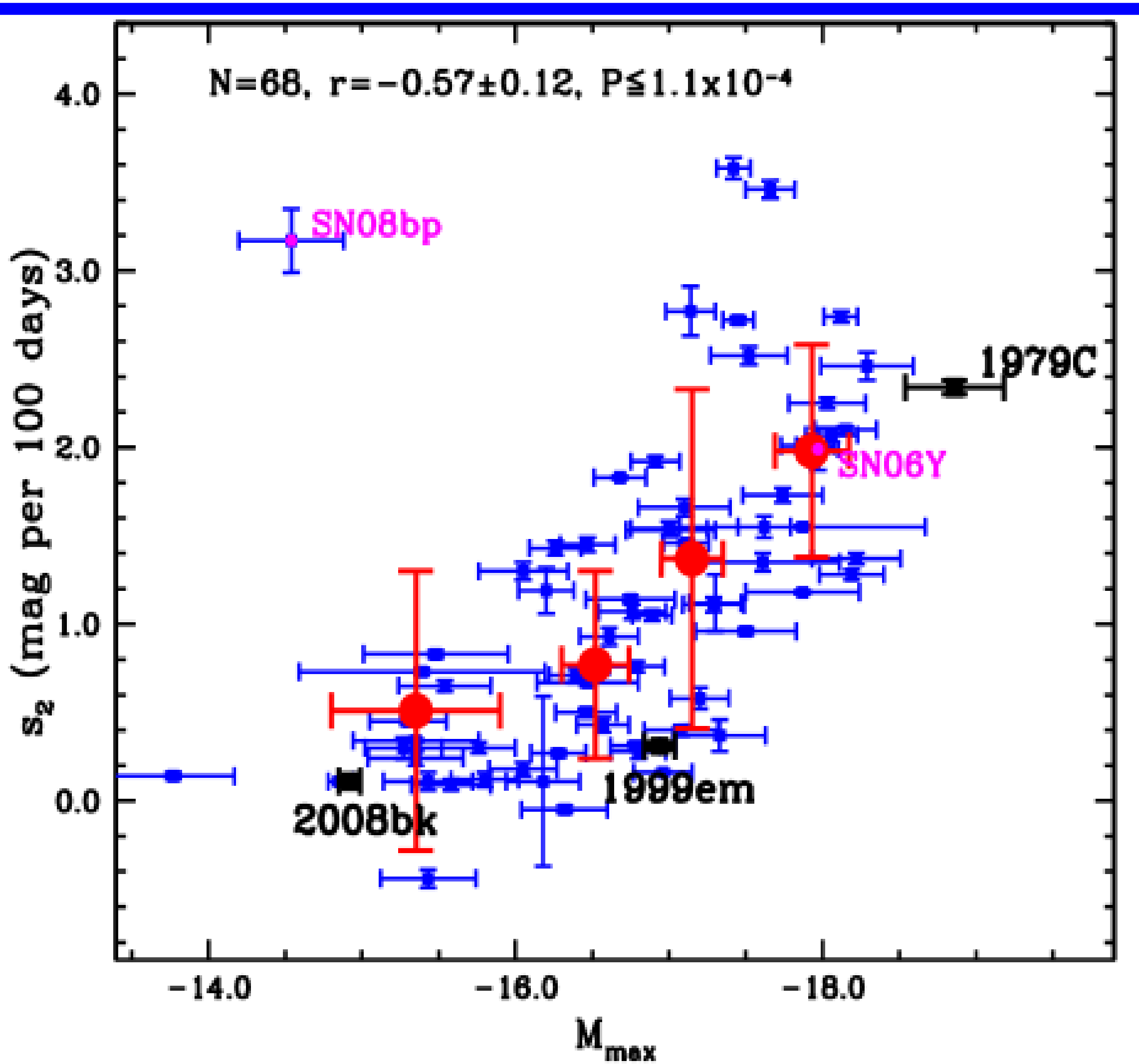
Photons from the hotter, inner regions are able to escape. We see deeper into the ejecta

T is constant as the photosphere receeds through the hydrogen envelope, a plateau is created in the light curve.



PCM

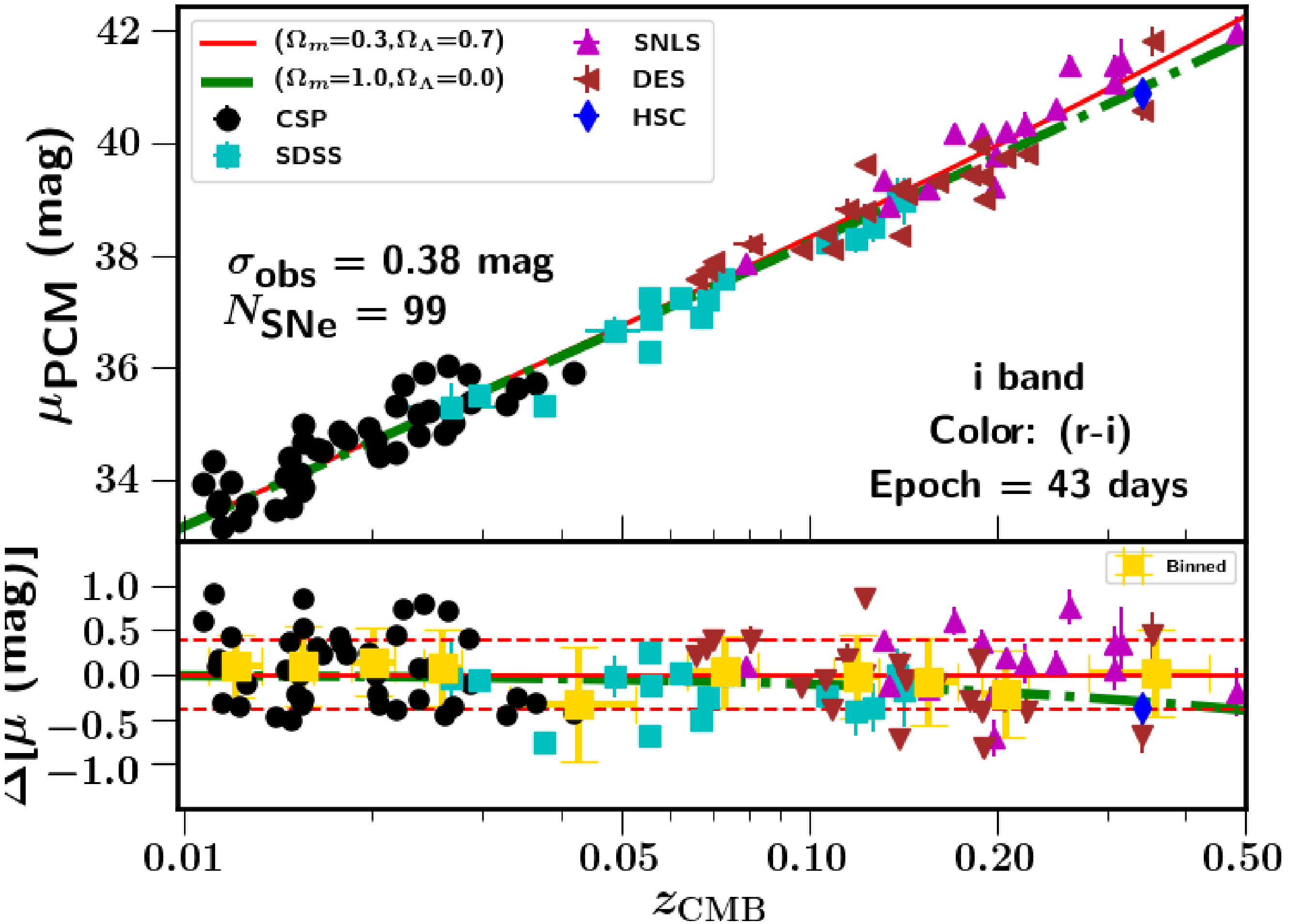
Plateau slope (s_2): **Brighter** SNe have **steeper** plateau



Anderson et al. 2014

PCM

$$m_i^{\rm model} = \mathcal{M}_i - \alpha s_2 + \beta(r-i) + 5\log_{10}(\mathcal{D}_L(z_{\rm CMB}|\Omega_{\rm m}, \Omega_\Lambda))$$



Others methods

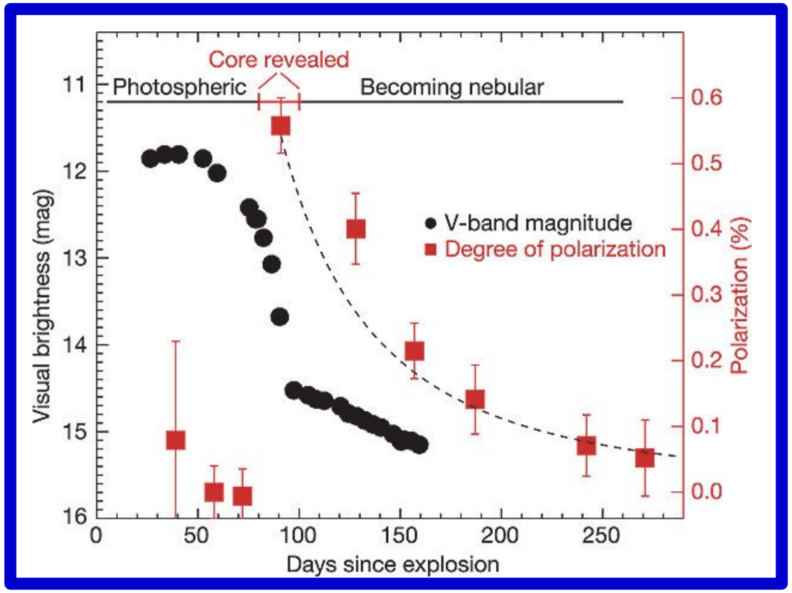
Expanding Photosphere Method: relation physical and angular radius → Θ=R/D

Assuming:

- **Homologus expansion**: R(t)= Ro + v (t-to)
- **Spherical symmetry** (Leonard et al. 02)
- **SN ~ Black body**

$$\Theta = \sqrt{\frac{f_\lambda}{\zeta_\lambda^2 \pi B_\lambda(T) 10^{-0.4 A(\lambda)}}}$$

t= to + D (Θ/v)



Leonard et al. 06

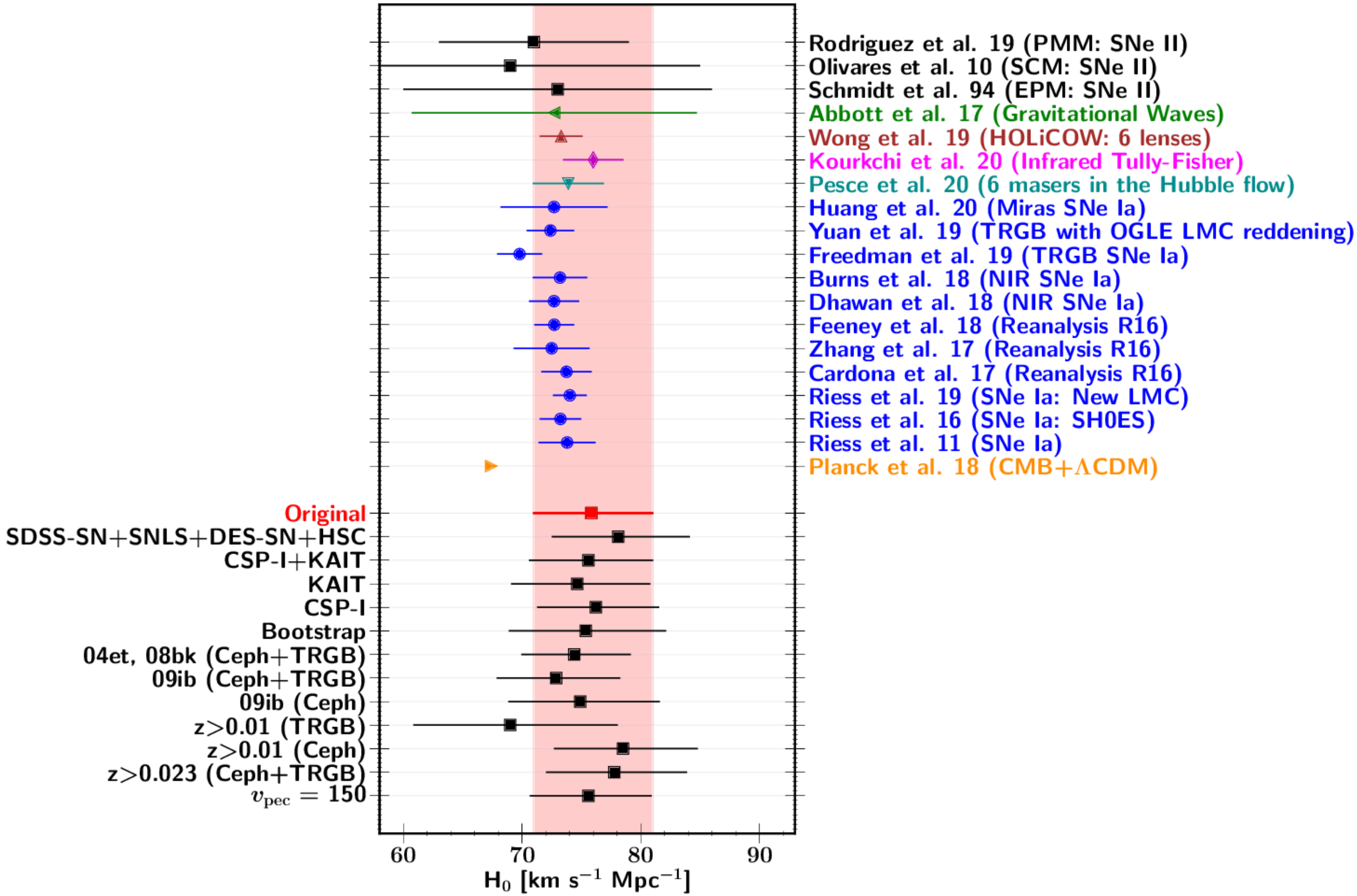
Pros:

- **Independant from calibration (Cepheids)**
  → H0

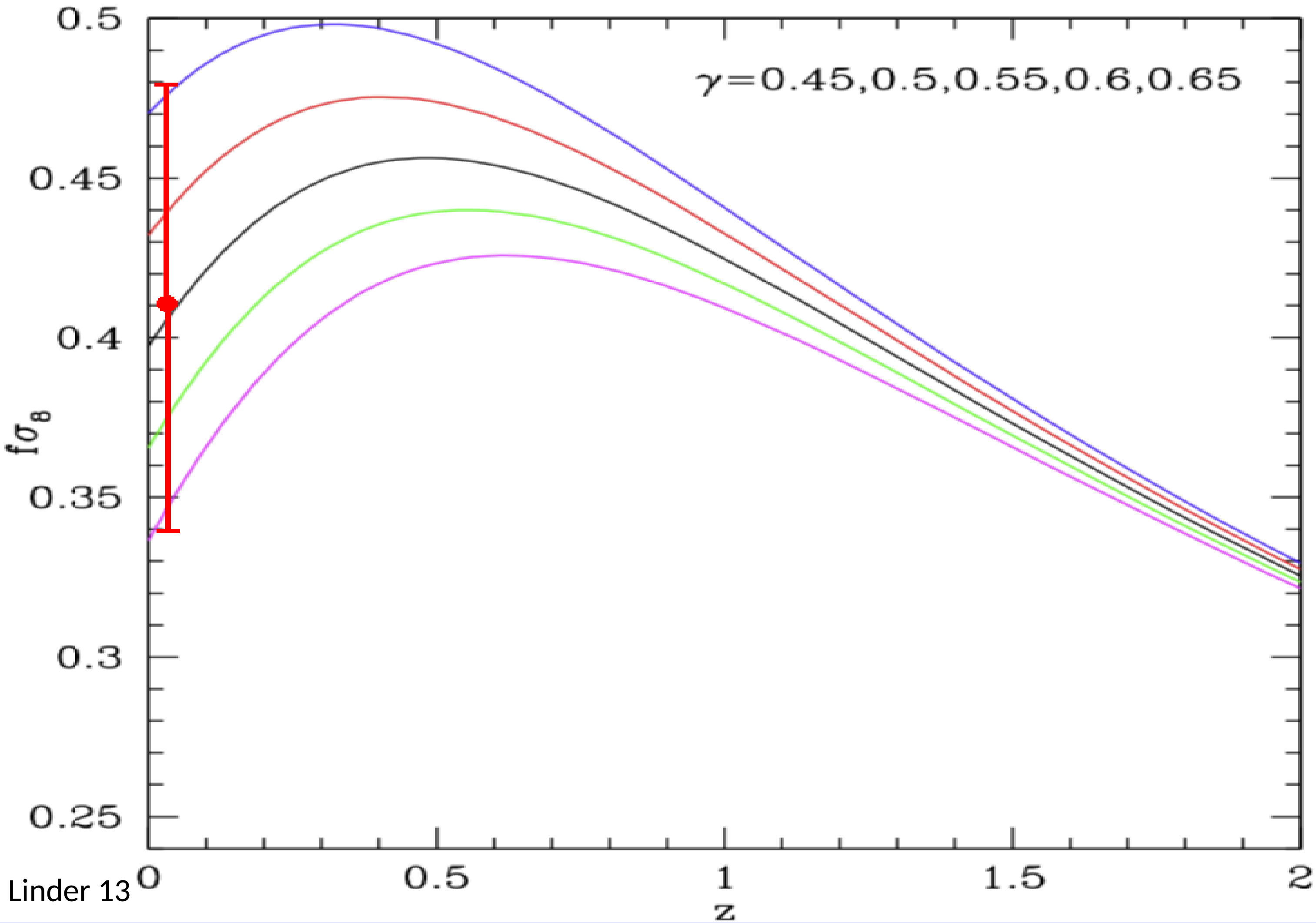
Cons:

- **Needs at least 2 spectra**
- **Needs models for dilution factors**
- **Not easy at high z**

Backup slides



Peculiar velocities: Why?



Linder 13

Peculiar velocities: Why?

Linear perturbation theory: $\mathbf{v}(\mathbf{r}) = \frac{H_0 f}{4\pi} \int d^3\mathbf{r}' \delta(\mathbf{r}') \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3}$

Idea: comparing the observed peculiar velocity field to a reconstructed prediction of the velocity field and contrain $f\sigma_8$.

$$\mathbf{v}(\mathbf{r}) = \frac{H_0}{4\pi} \frac{f}{b} \int_0^\infty d^3\mathbf{r}\, \delta_g(\mathbf{r}') \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3} \,.$$

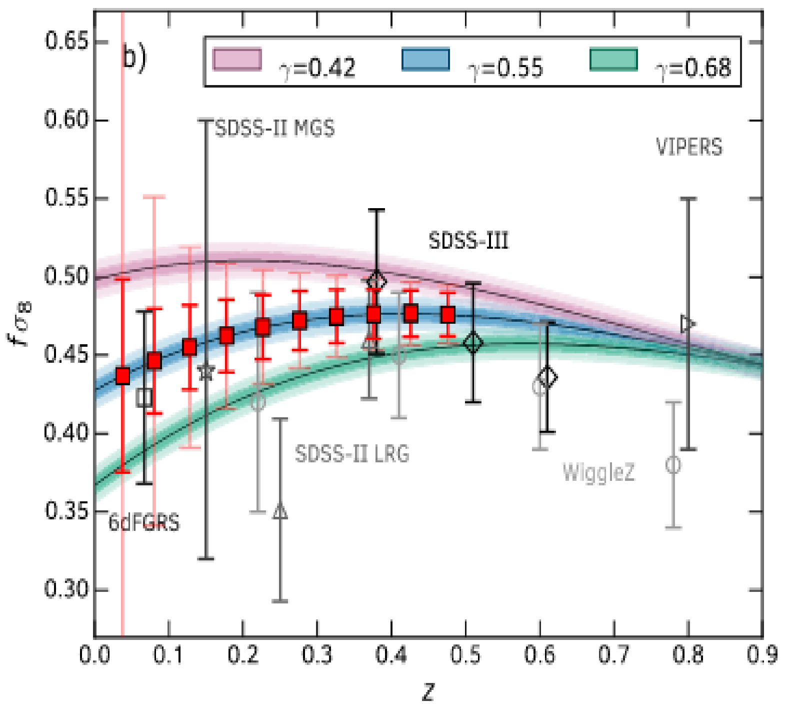
$b\delta=\delta_g$

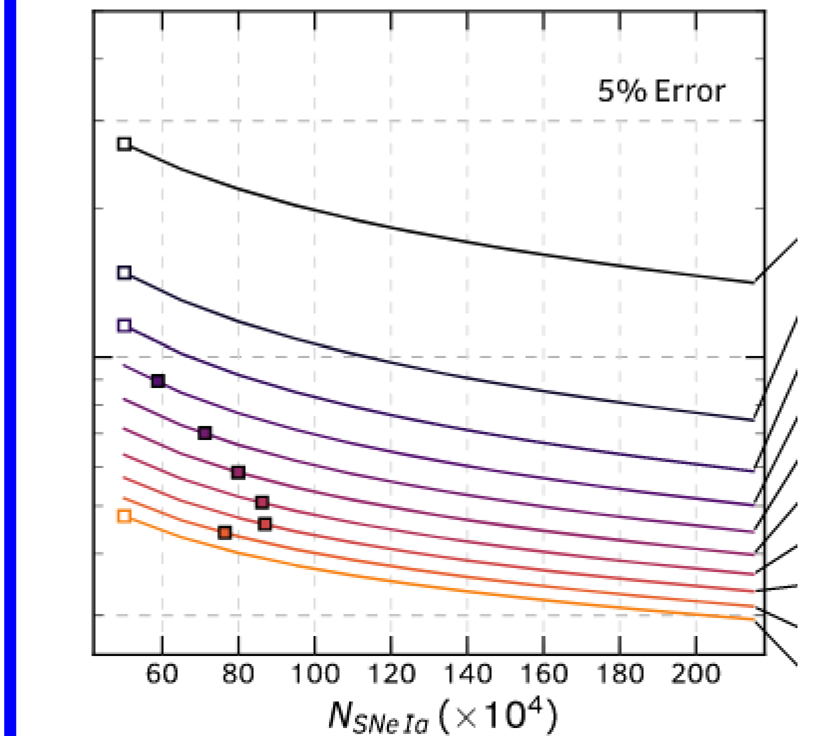
$\beta=f/b$

$f\sigma_8=\beta b\sigma_8$

$f\sigma_8=\beta\sigma_{8,g}$

Why so many SNe Ia





Howlett et al. 17

Peculiar velocities: Why?

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$b\delta = \delta_g$

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$f\sigma_8 = \beta \sigma_{8,g}$