Title: Cosmology 2

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Abstract:

Supernova Legacy Survey (SNLS)

Goal: Characterize the Dark Energy equation of state "w" parameter

A component of the

CFHT Legacy Survey

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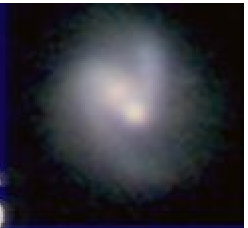
CFHT Legacy Survey

SNLS Collaboration

- Toronto Group: Carlberg*, Mark Sullivan, Andy Howell, Kathy Perrett, Alex Conley
- Victoria Group: Chris Pritchet*, Don Neill, Dave Ballam
- French Group: Reynald Pain, Pierre Astier, Julien Guy, Nicolas Regnault, Jim Rich, Stephane Basa
- Follow-up Collaborators:
  - Oxford: Isobel Hook (Gemini & VLT)
  - LBL: Saul Perlmutter & Peter Nugent (Keck)
  - Caltech: Richard Ellis* (Keck)
  - Carnegie: Wendy Freedman*, Mark Phillips (Magellan)
- PLUS many students and associates
- * CIAR



Complementary Approaches

- CMB: P(k) in linear regime
- Gravitational lensing:
  - P(k,a) nonlinear
- Galaxy (& other baryons) clustering: P(k)
- Galaxy Cluster counts: growth of P(k)
- Supernovae: pure distance

Expansion History of the universe and Mass-Energy content

Size scale factor, a(t)

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

Observable redshift, z. a=1/(1+z)

Define H(z) = da/dt / a(t)

Expansion History of the universe and Mass-Energy content

Size scale factor, a(t)

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

Observable redshift, z. a=1/(1+z)

Define H(z) = da/dt / a(t)

$$H^2(z) = H_o^2[\Omega_M(1+z)^3 + \Omega_R(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w)}],$$

with $1 = \Omega_M + \Omega_R + \Omega_\Lambda$,

where Ω's are ρ's ratioed to critical

Observable Distance (from flux)

$r = \int c\,/H(z)\,dz$

infer w.

Supernova Distances

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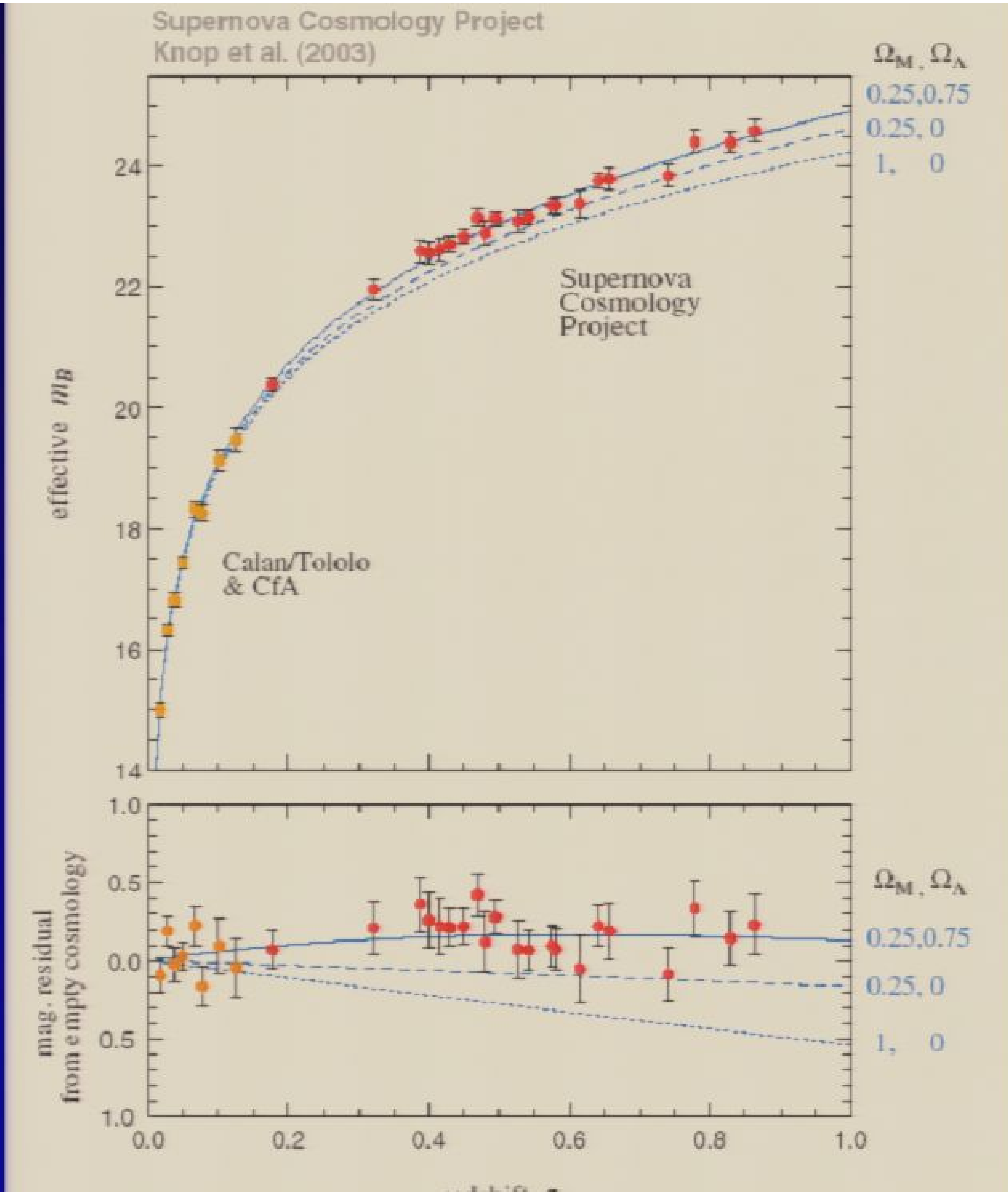
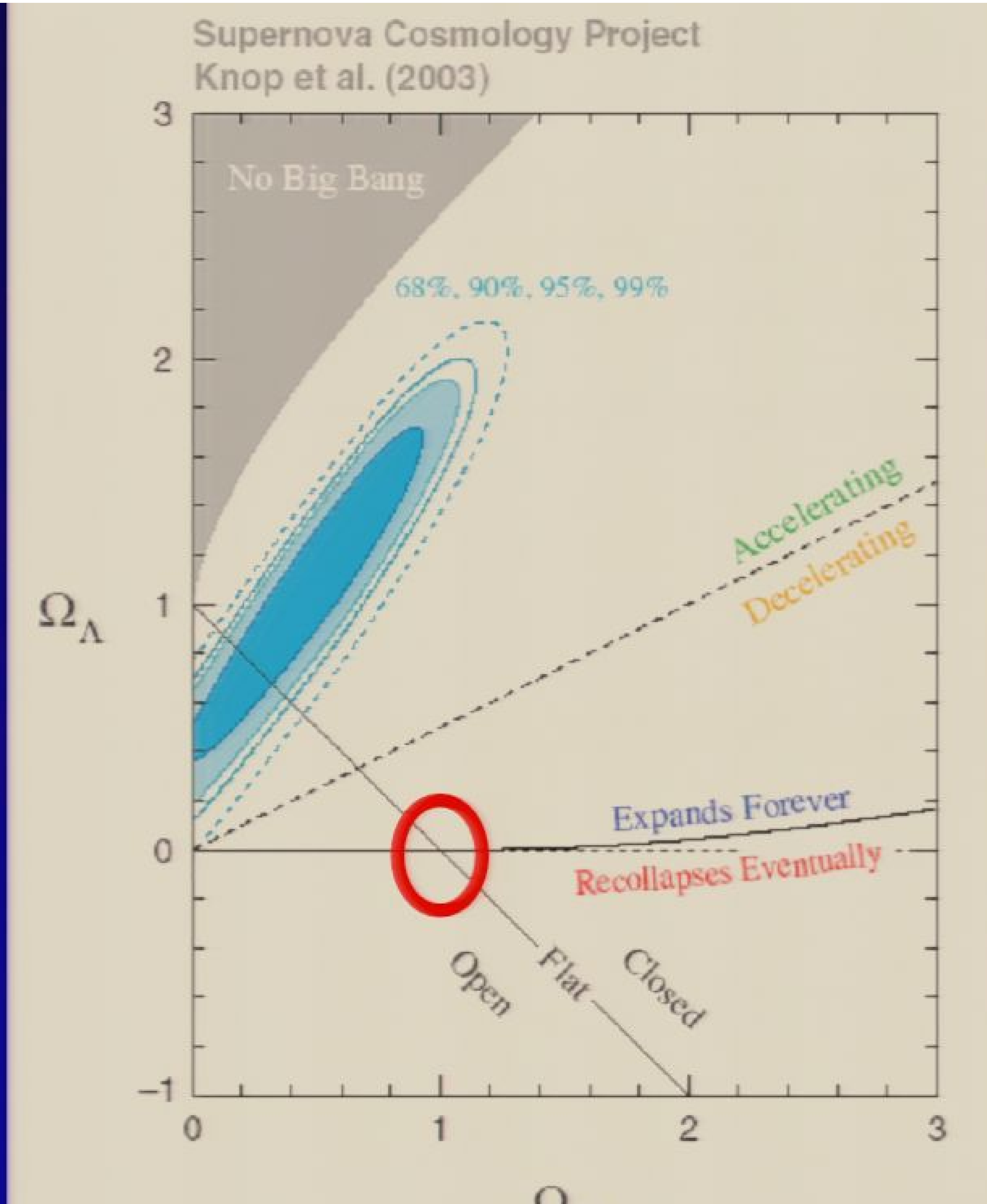
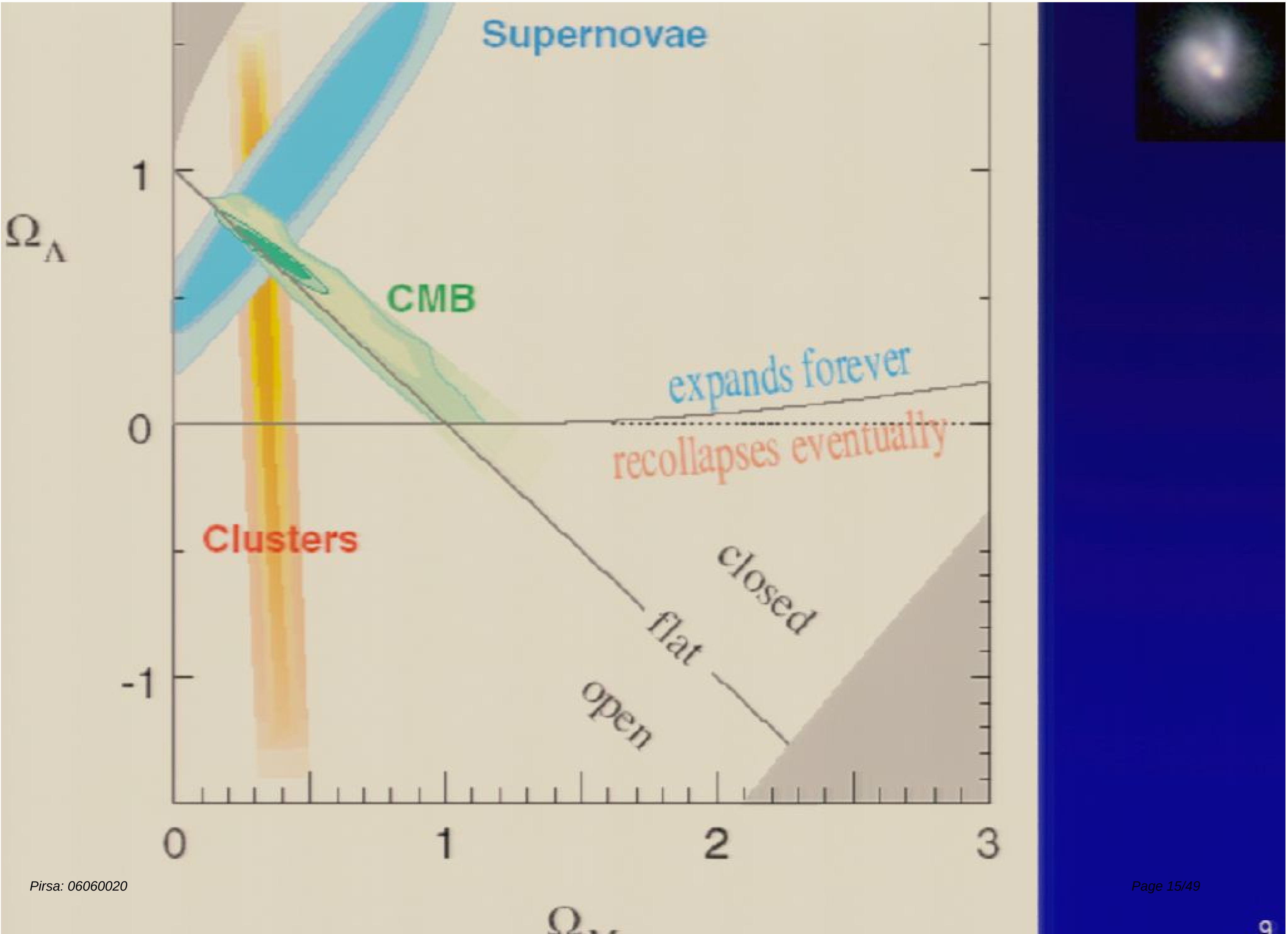
- Quickly burns most of its ~1.4 solar masses to Iron Peak elements
- Neutrino flux propels explosion
- Ni^{56} decay powers light curve
  - About as bright as a typical galaxy for weeks


Supernova Cosmology Project
Knop et al. (2003)
Ω_M, Ω_Λ
0.25,0.75
0.25, 0
1, 0
Supernova Cosmology Project
Calan/Tololo & CfA
effective m_B
24
22
20
18
16
14
1.0
0.5
0.0
0.5
1.0
mag. residual from empty cosmology
0.0
0.2
0.4
0.6
0.8
1.0

Reiss etal obtained an identical result

First reports in 1999.

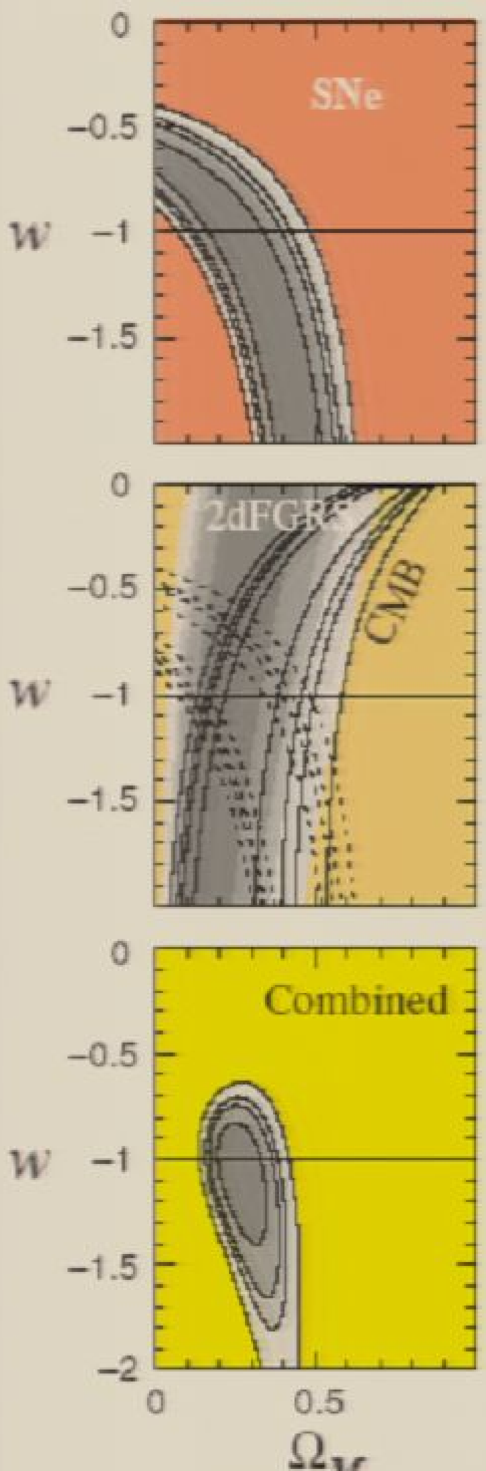



Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
1
0
-1
0
1
2
3
Ω_M
9

w

- Friedmann eqn $P/\rho = w$
- For a cosmological constant $w=-1$.
- Big rip if $w<-1$.
- Various field models have $-1<w<-0.7$
- Original quintessence had $w\sim-0.8$.

Supernova Cosmology Project
Knop *et al.* (2003)



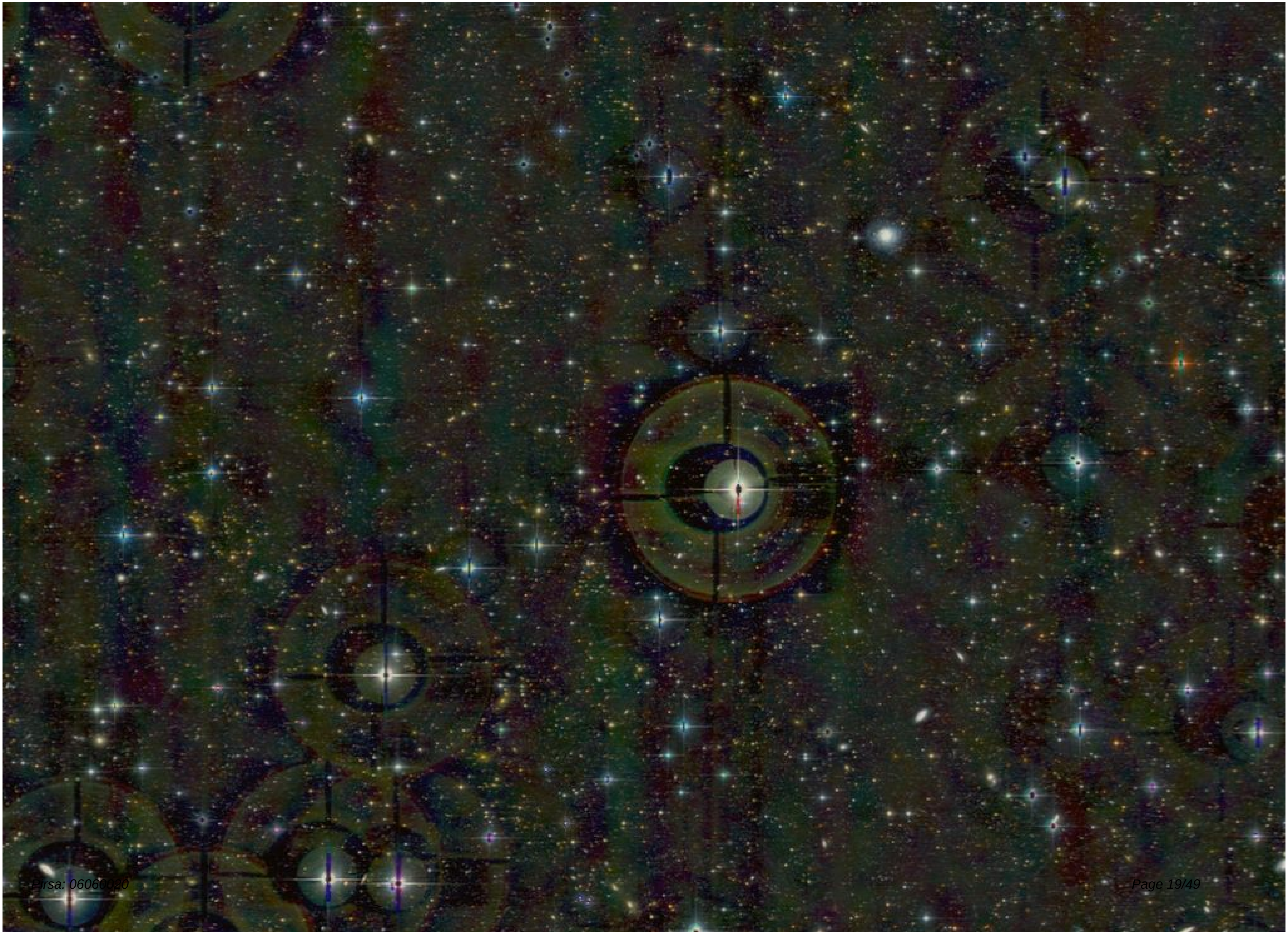
Assuming constant w

With limits from;
2dFGRS (Hawkins et al. 2002)
and CMB (Bennet et al. 2003,
Spergel et al. 2003)

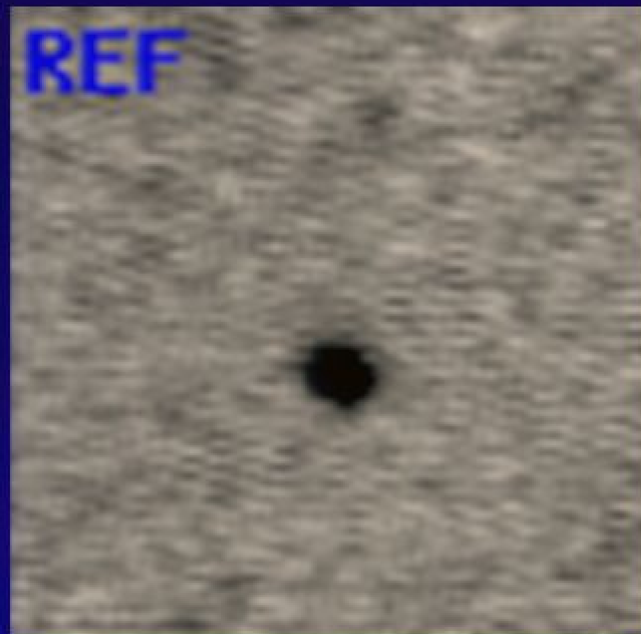
$$w = -1.05 \ ^{+0.15}_{-0.20} \ \text{(statistical)}$$
$$\pm 0.09 \ \text{(systematic)}$$

SNLS goals

- A measurement of w good to 5%
  - Discriminates between current theories
  - Comparable to complementary data ~2008
- Requires:
  - More data (500+ supernova of type Ia)
  - Better data
    - More colours
    - Better sampling of rise and fall of supernova light



Found in about 100,000 galaxies



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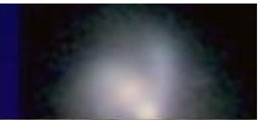

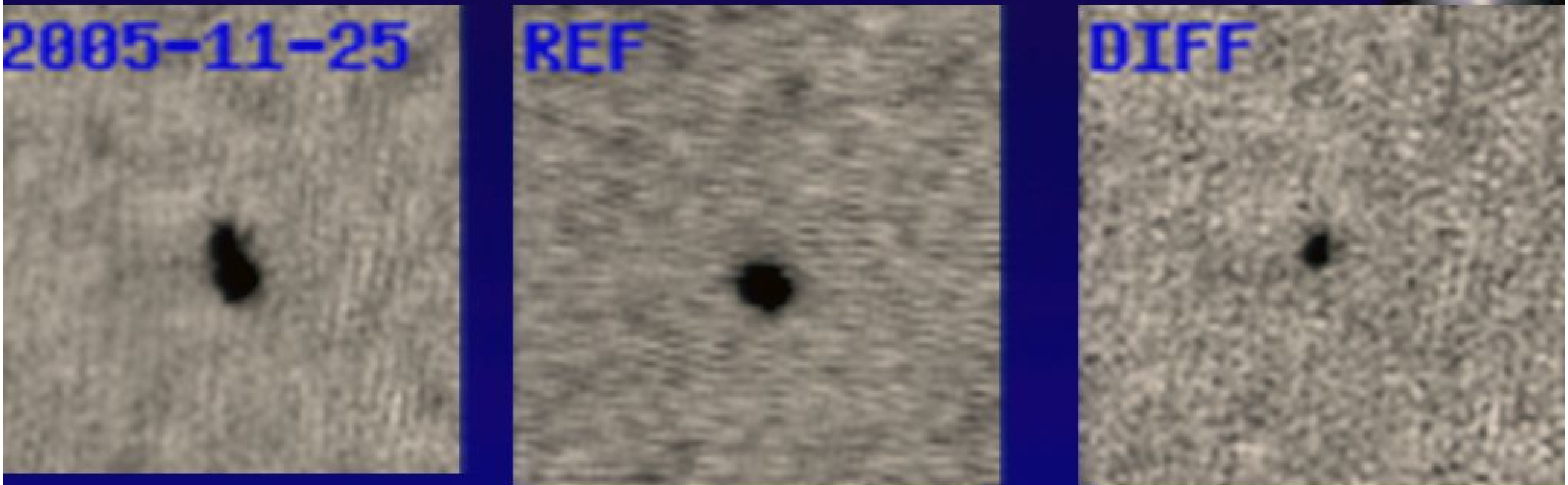

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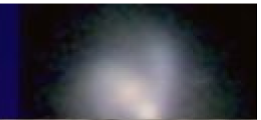
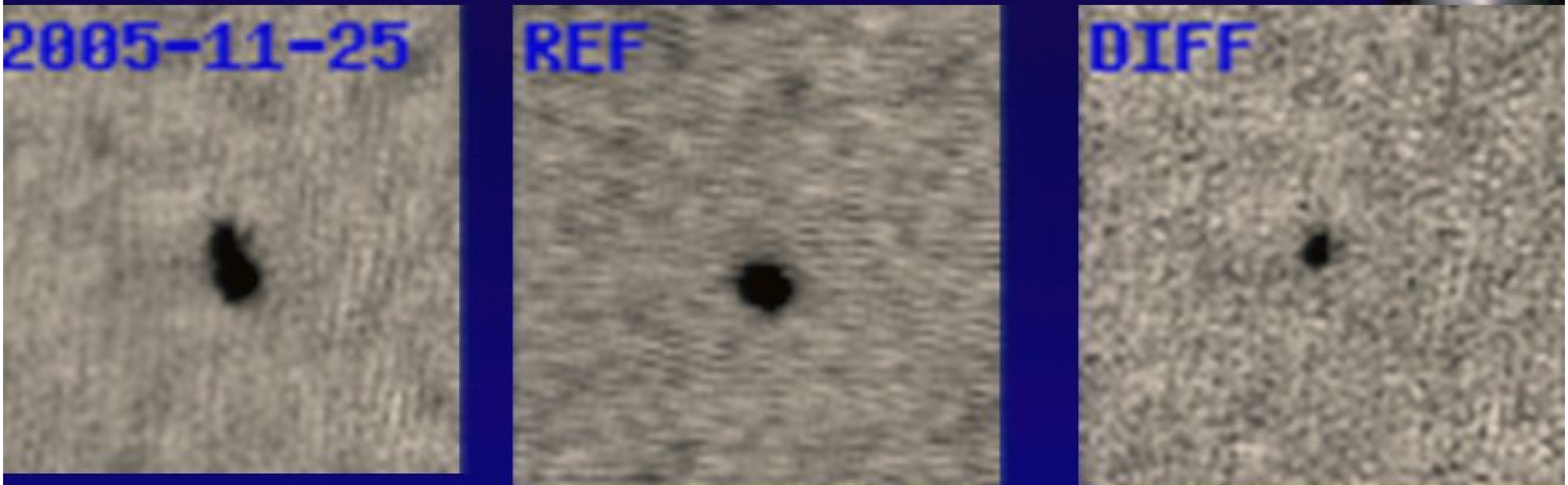

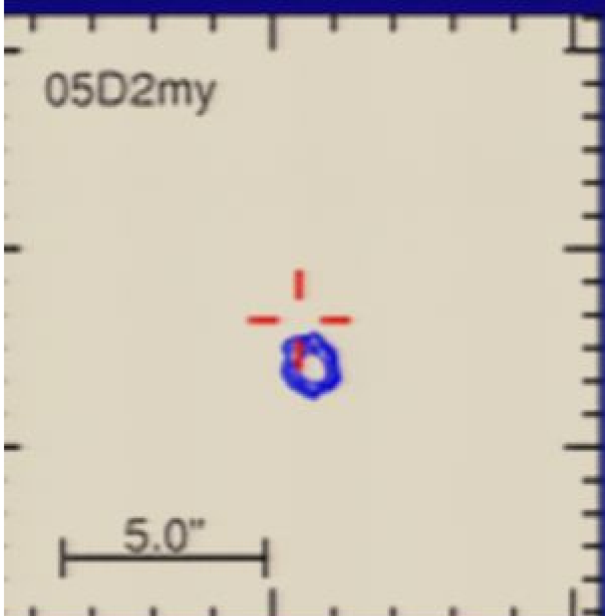

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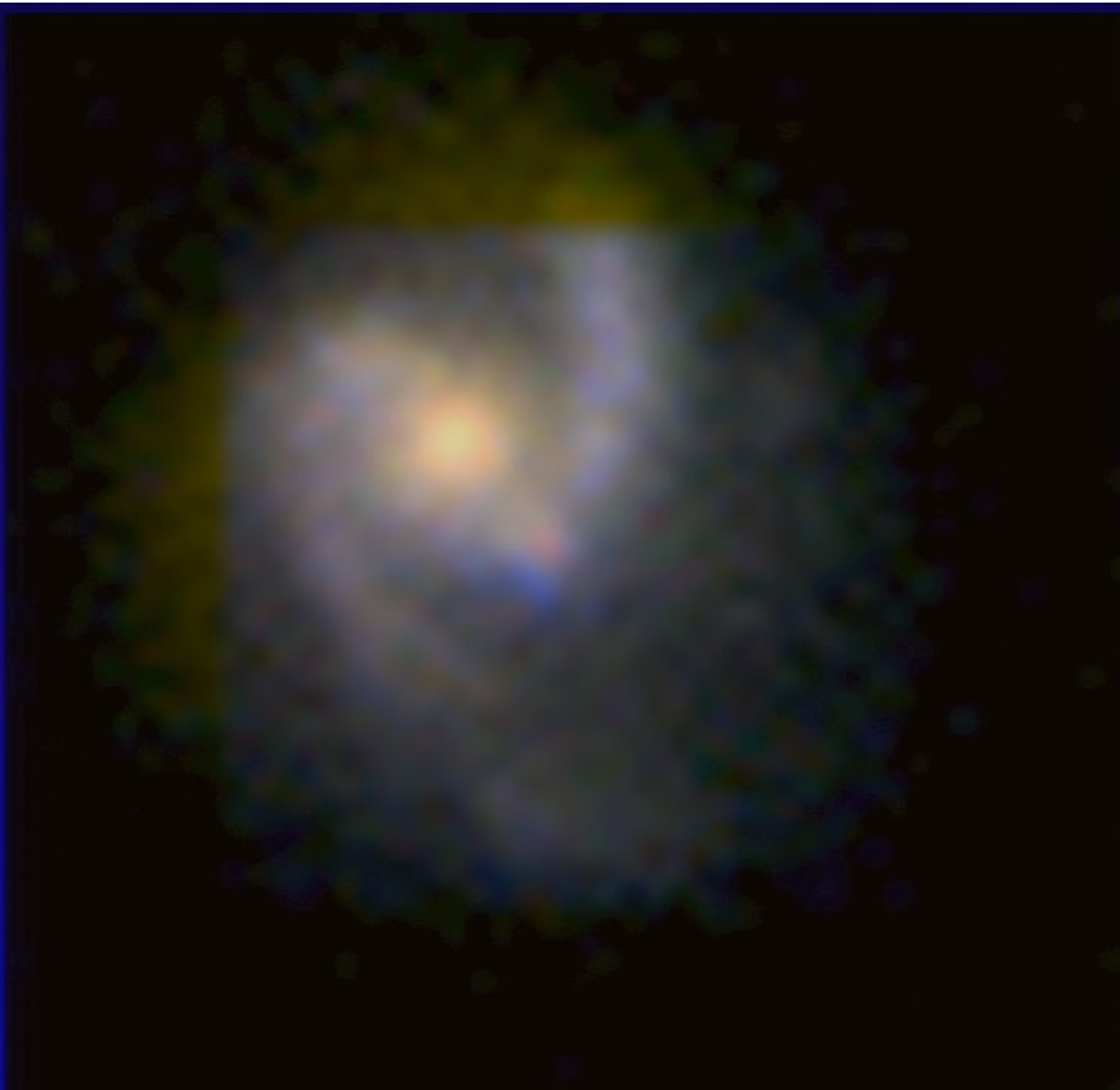
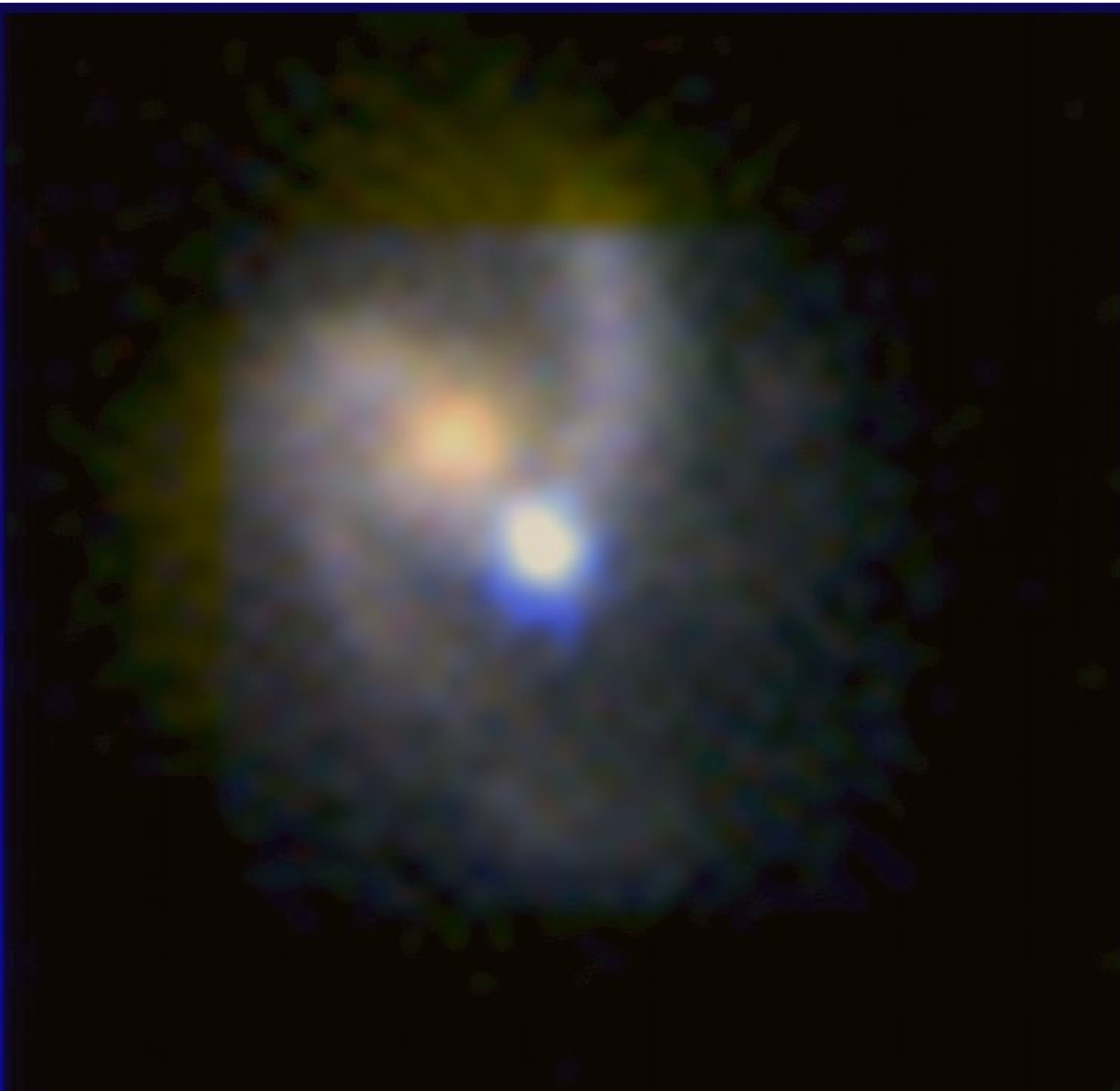
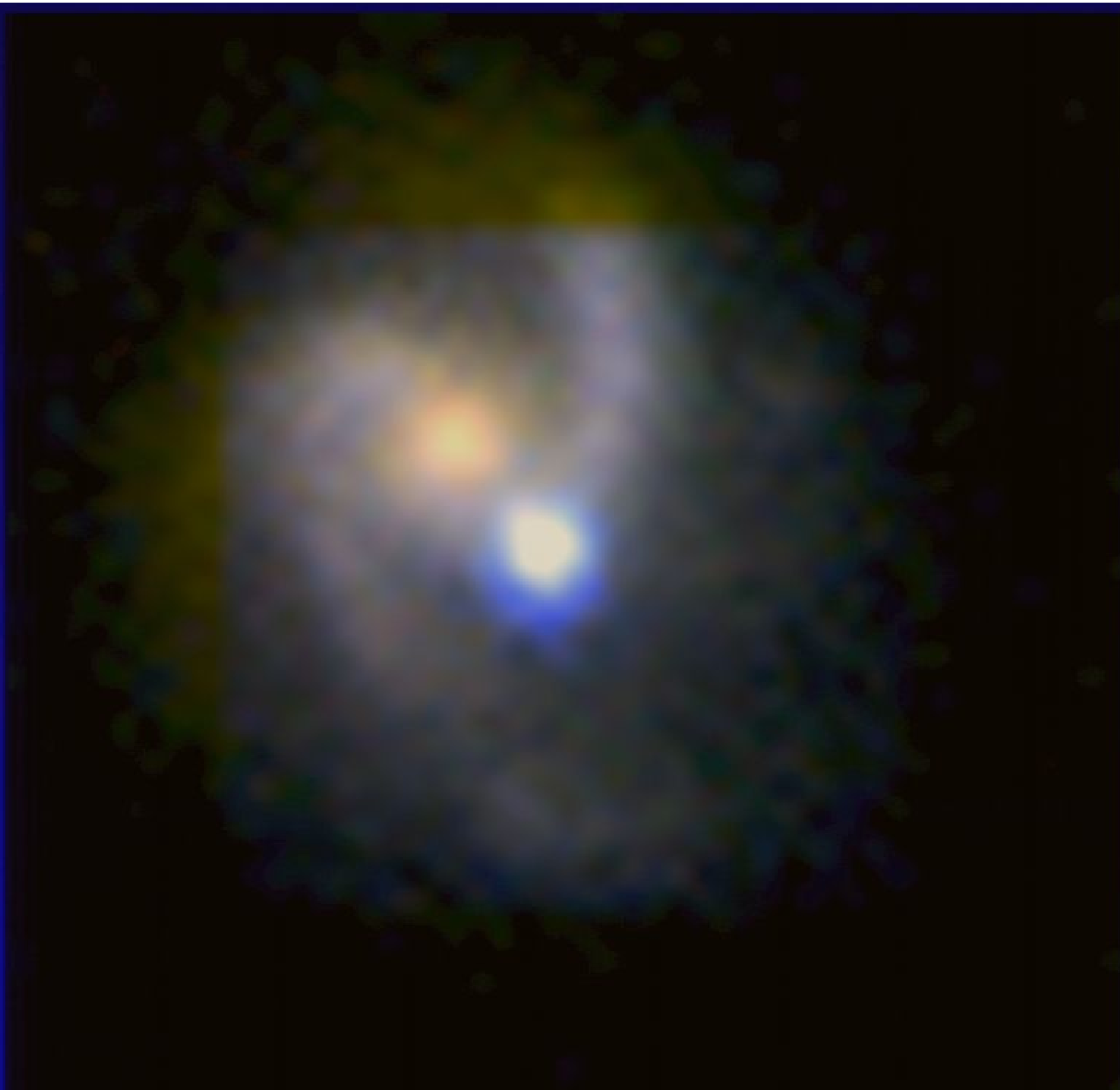
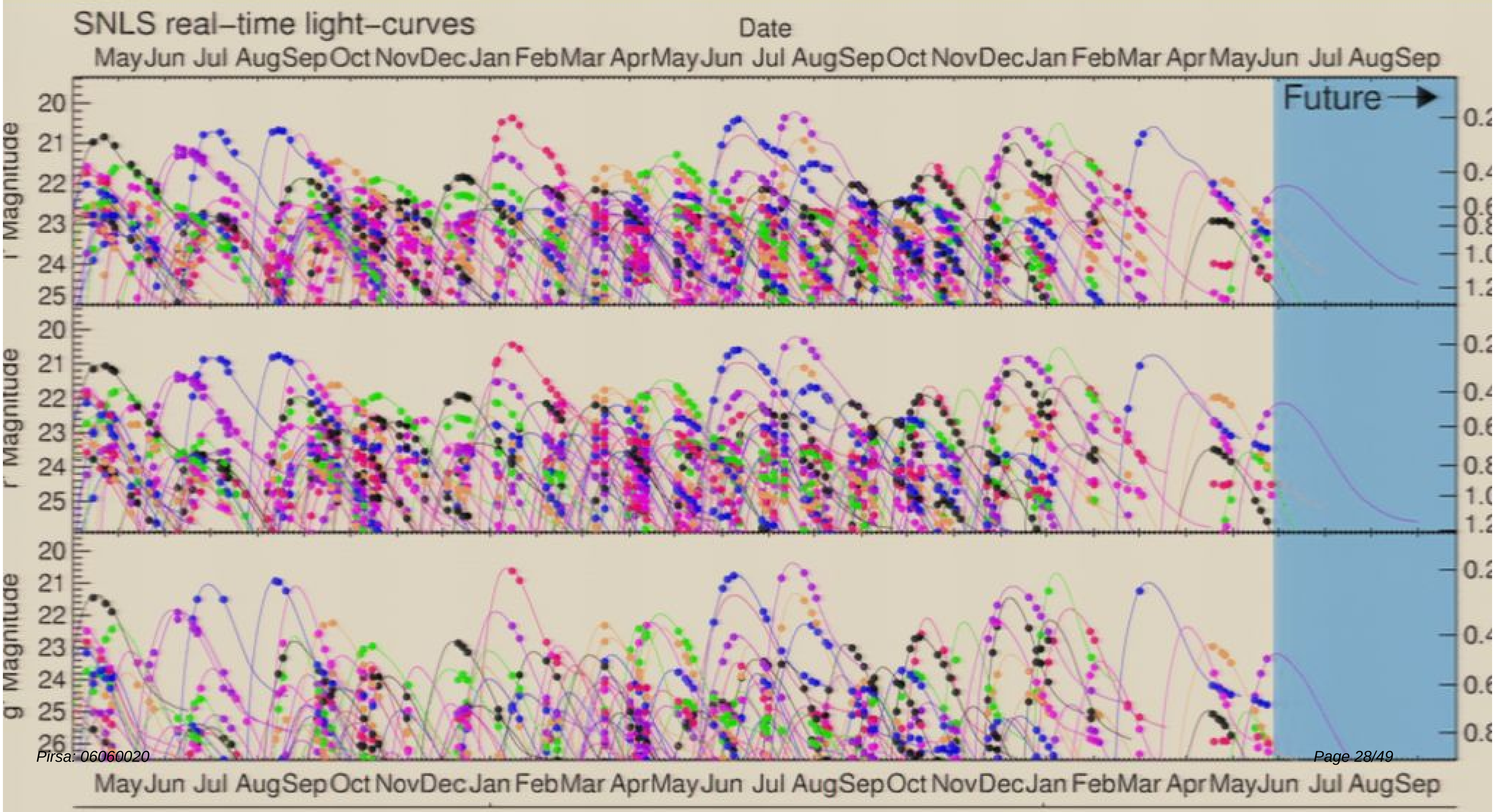
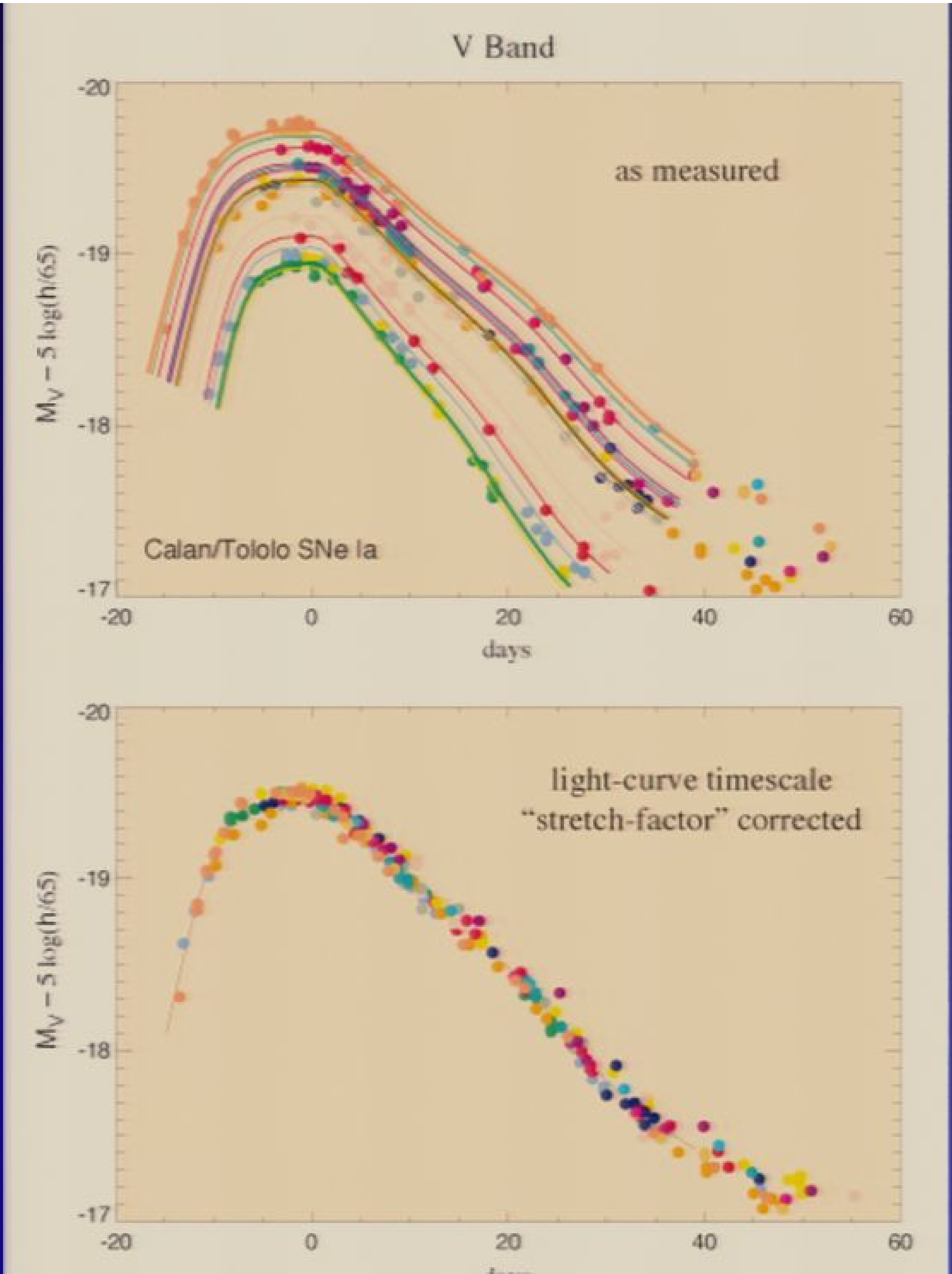


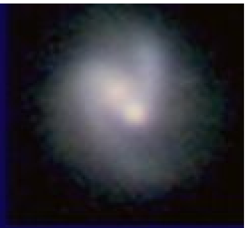


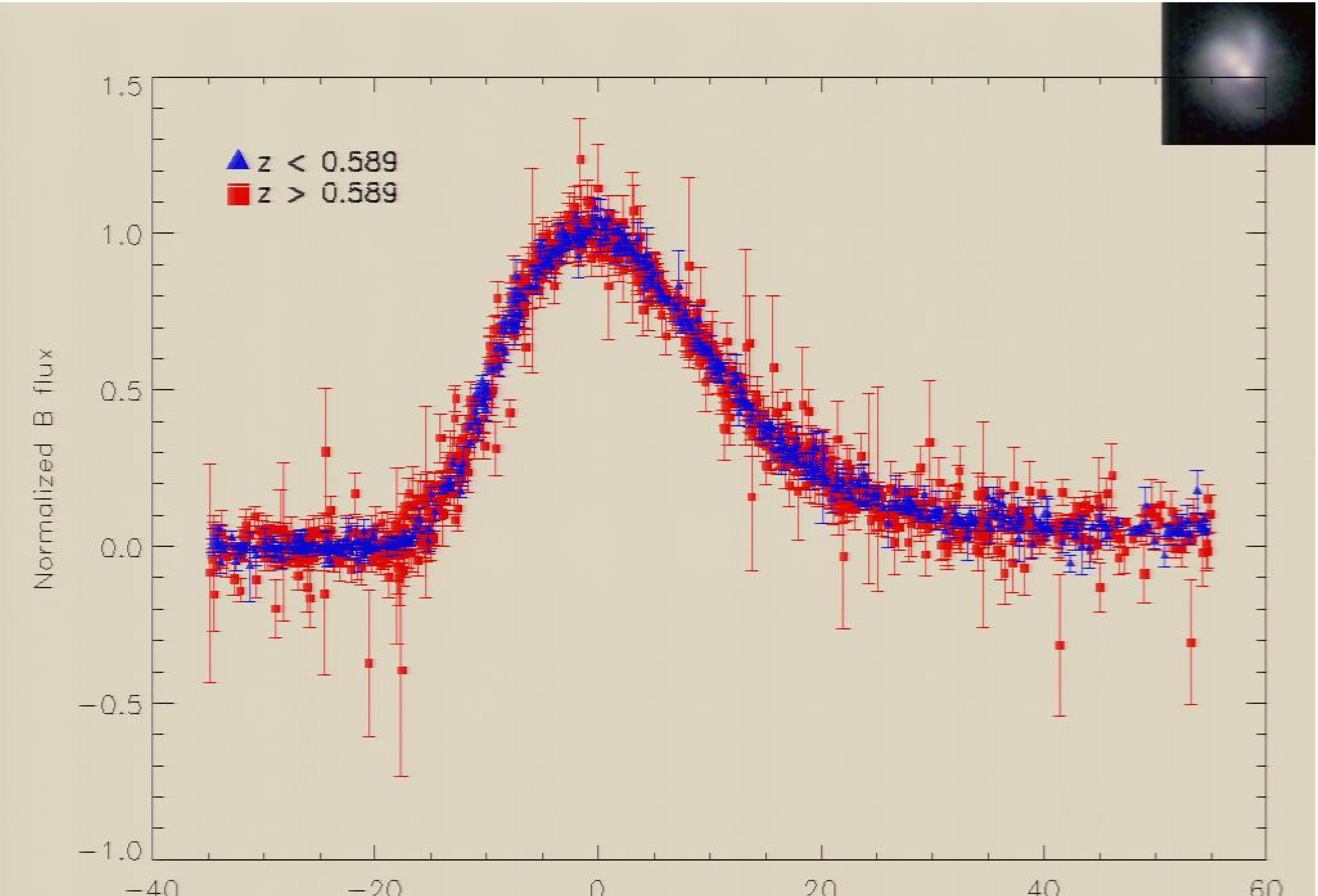


15


SNLS real–time light–curves
Date
May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
Future →
i' Magnitude
r' Magnitude
g' Magnitude


V Band
as measured
Calan/Tololo SNe Ia
$M_V - 5 \log(h/65)$
-20
-19
-18
-17
-20
0
20
40
60
days
light-curve timescale
"stretch-factor" corrected




z < 0.589
z > 0.589
Normalized B flux
Effective Day
1.5
1.0
0.5
0.0
−0.5
−1.0
−40
−20
0
20
40
60

The supernova distance model

Peak B luminosity depends on:

The supernova distance model

Peak B luminosity depends on:

- Colour, c: Bluer-brighter relation

The supernova distance model

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  - Hotter is more luminous at same size

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Peak B luminosity depends on:

- Colour, c: Bluer-brighter relation
  - Hotter is more luminous at same size
- Rate of fading, s: Slower-brighter relation

The supernova distance model

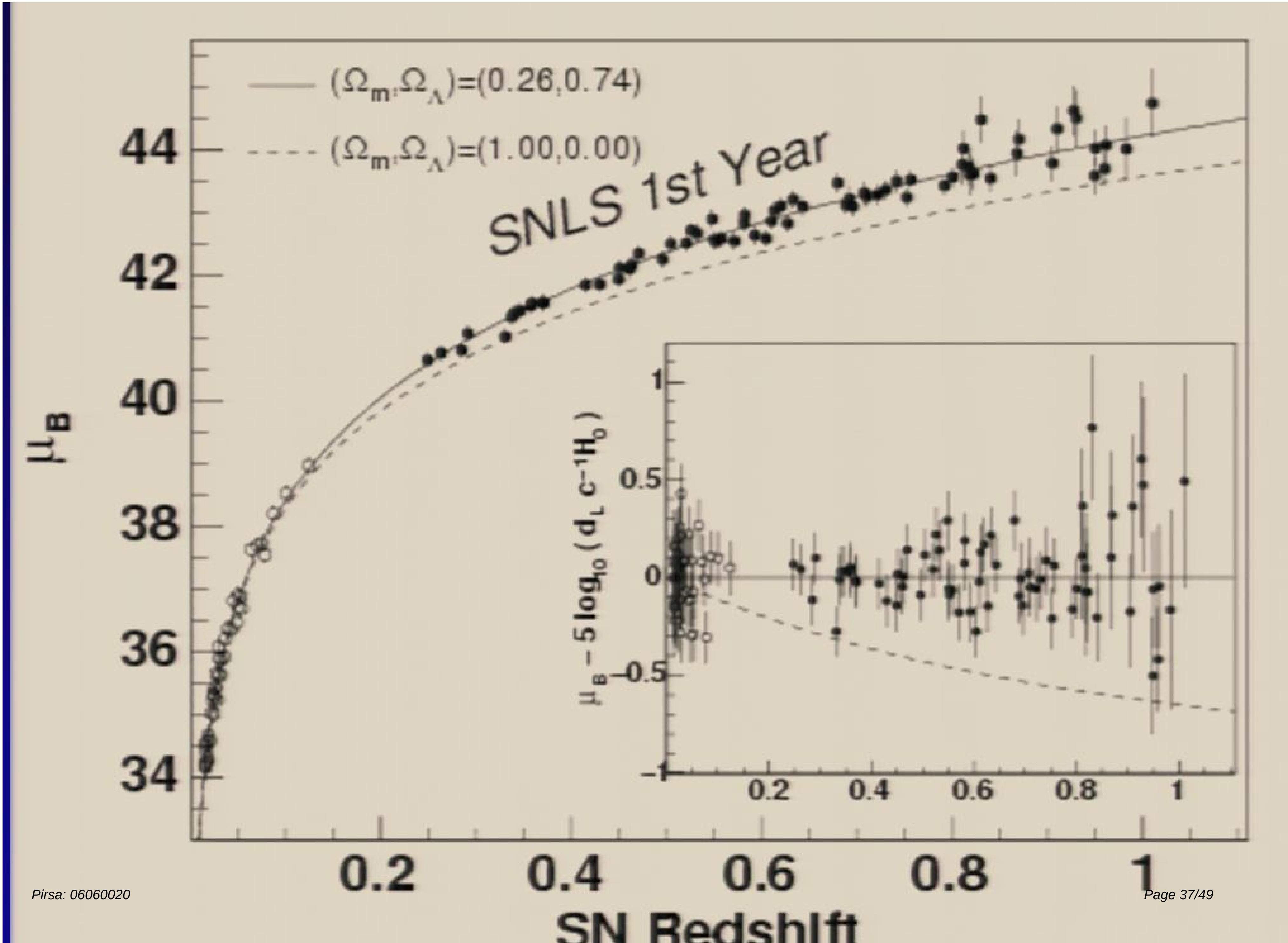
Peak B luminosity depends on:

- Colour, c: Bluer-brighter relation
  - Hotter is more luminous at same size
- Rate of fading, s: Slower-brighter relation
  - More luminous have more highly ionized, more opaque atmospheres
- $M_B = M_s + \alpha(s-1)+\beta c$

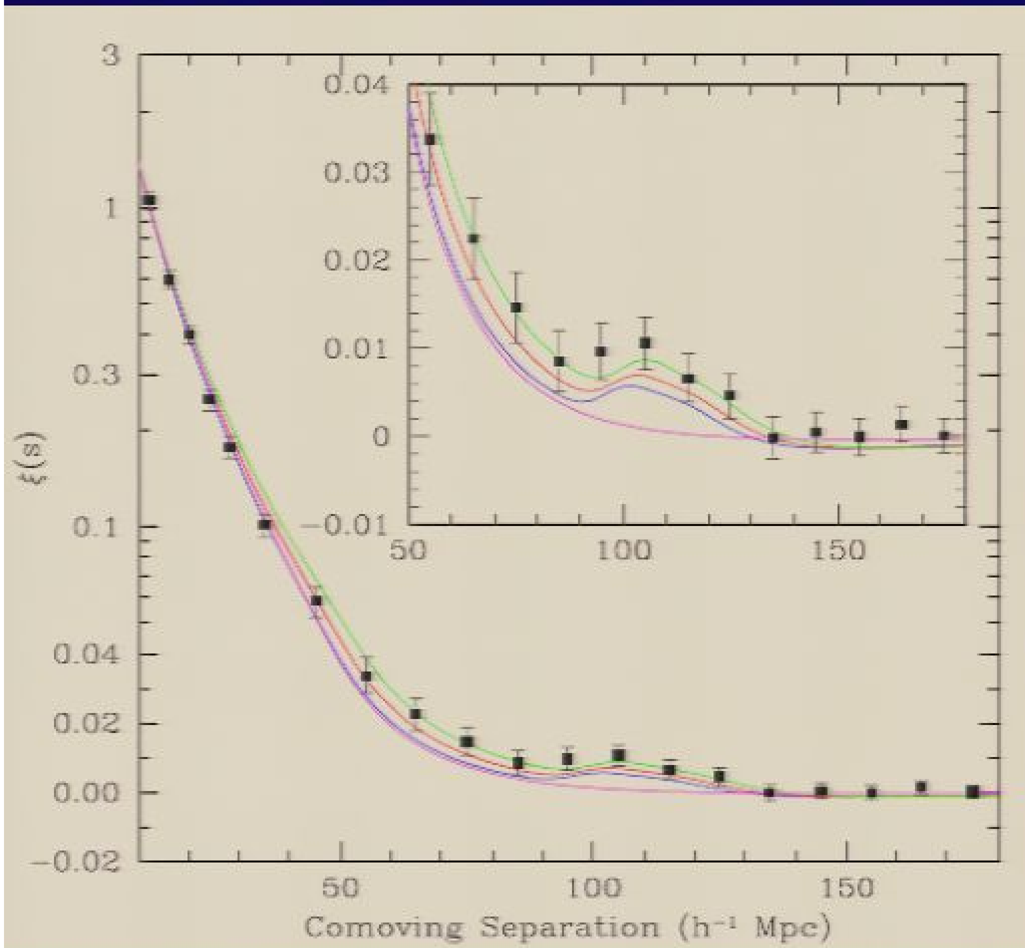
The supernova distance model

Peak B luminosity depends on:

- Colour, c: Bluer-brighter relation
  - Hotter is more luminous at same size
- Rate of fading, s: Slower-brighter relation
  - More luminous have more highly ionized, more opaque atmospheres
- $M_B = M_s + \alpha(s-1)+\beta c$
- Fit 2 (or 3) cosmology parameters plus 3 supernova parameters: leaves chi^2 per dof about 2. X^2=1 requires σ_{int} = 0.14 magnitudes (i.e. last 14% jitter not yet understood)


$(\Omega_m,\Omega_\Lambda)=(0.26,0.74)$
$(\Omega_m,\Omega_\Lambda)=(1.00,0.00)$
SNLS 1st Year
μ_B
44
42
40
38
36
34
0.2
0.4
0.6
0.8
1
SN Redshift
$\mu_B - 5\log_{10}(d_L c^{-1} H_0)$
1
0.5
0
-0.5
-1
0.2
0.4
0.6
0.8
1

The Baryon Acoustic Oscillation scale



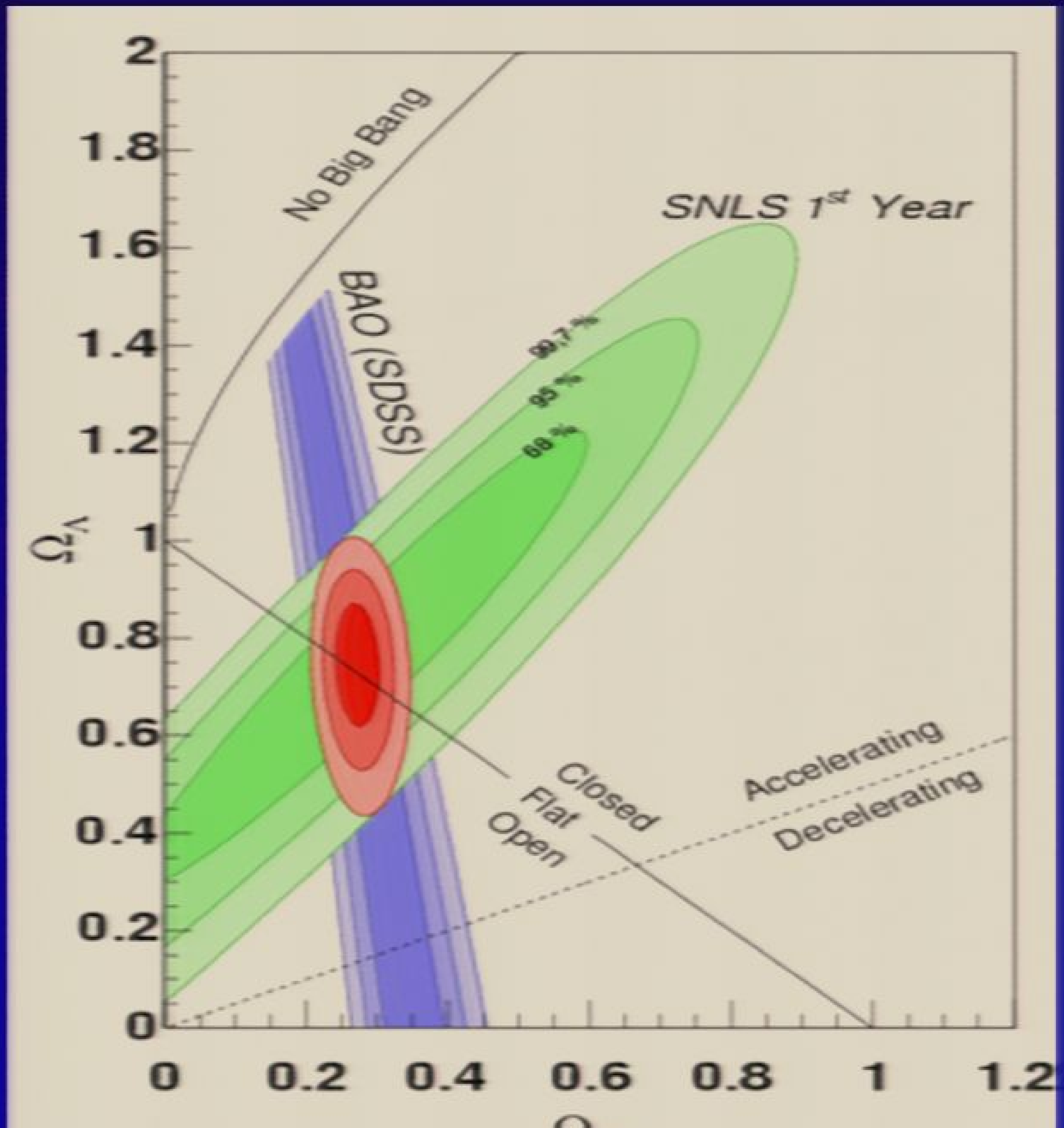
Data provides an angular scale which measures the ratio of the distances to the SDSS galaxies at z=0.35 and the CMB at z=1089

We use A=0.469±0.017

$$R_{0.35} \equiv \frac{D_V(0.35)}{D_M(1089)}.$$

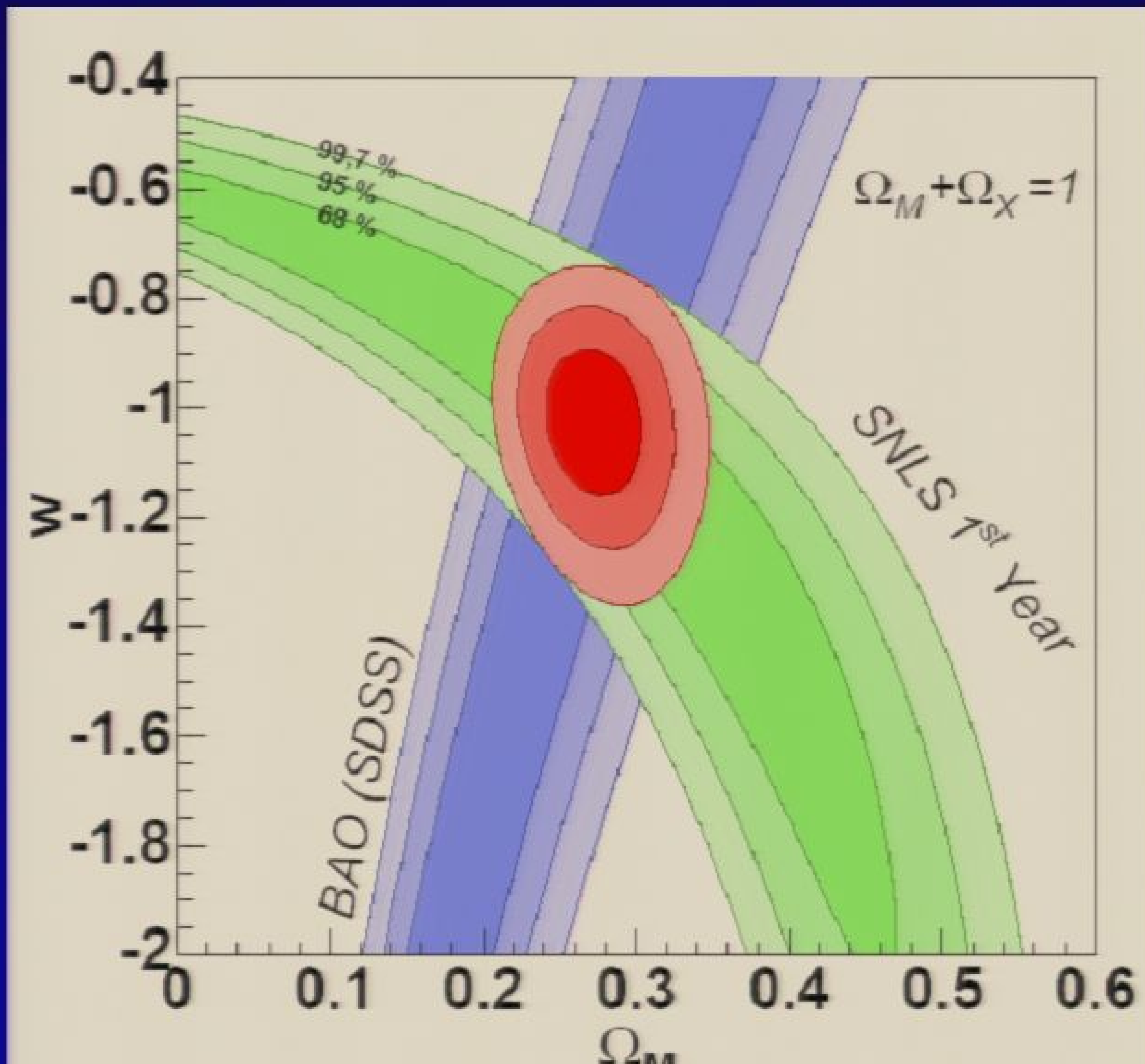
$$A = \sqrt{\Omega_m} E(z_1)^{-1/3} \left[\frac{1}{z_1} \int^{z_1} \frac{dz}{E(z)} \right]^{2/3}$$

Cosmology

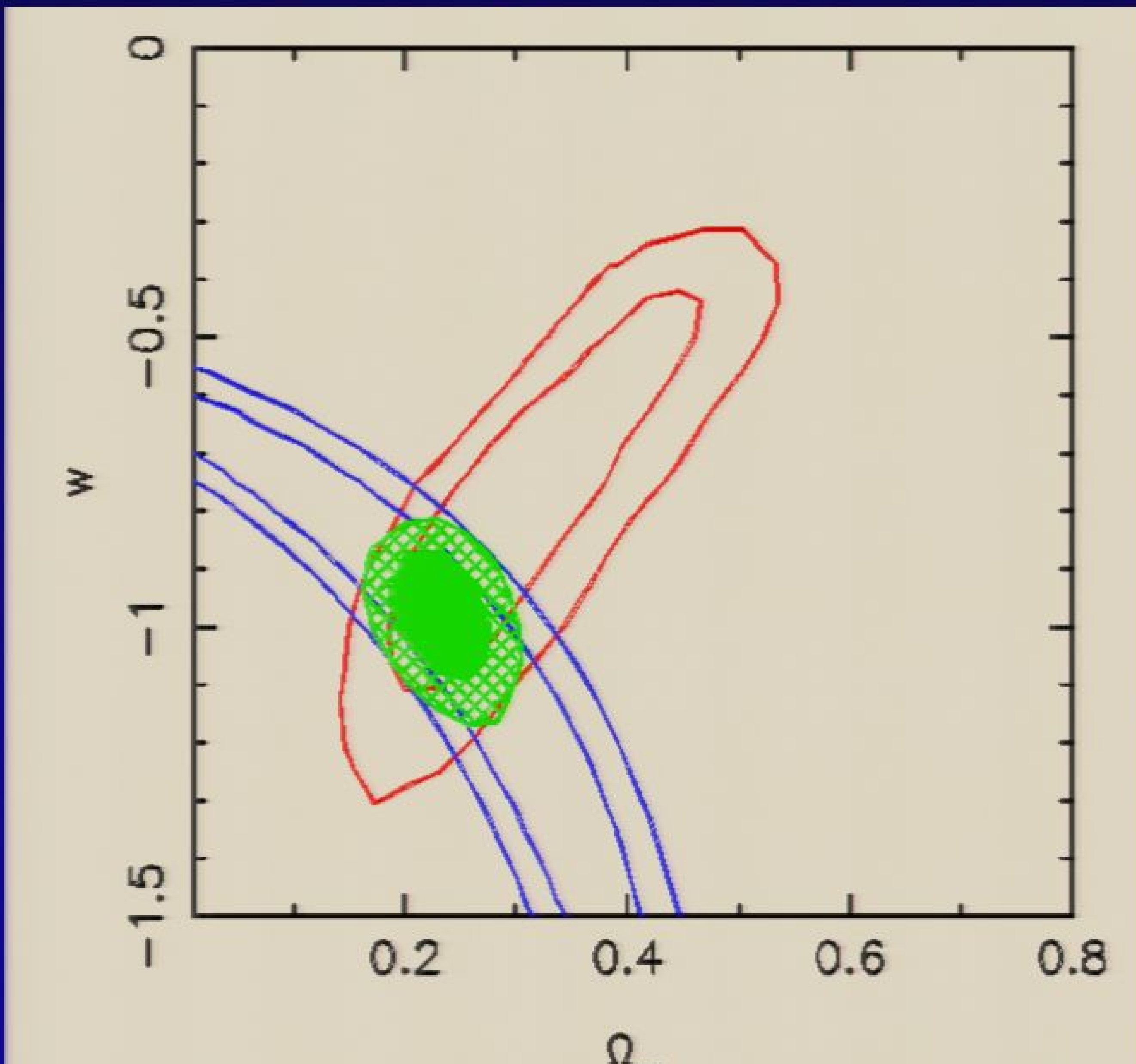


No Big Bang
SNLS 1st Year
BAO (SDSS)
99.7 %
95 %
68 %
Closed
Flat
Open
Accelerating
Decelerating
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2

Sne Ia plus BAO
w = -1.02 ± 0.09 (stat)



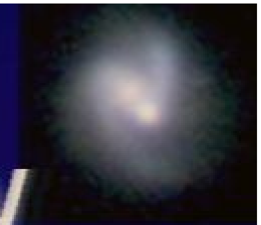
With 3rd year WMAP



Systematic Errors Checks

- No colour residual
  - (there is a distance-colour relation at z>0.8)
  - (very noisy photometry at z>0.8)
- No "stretch" residual, yet
- No significant malmquist bias
- Independent analyses confirm "clean" data
- But, upcoming data is much better.
  - Better sampling in time and colour
  - Lower noise for z band
  - Calibration improvements

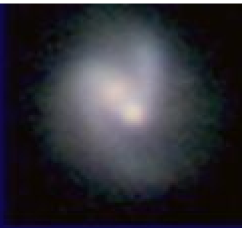
The Motivation for variable w



- Widely used model for Dark Energy (and inflation) is a quantum scalar field, φ(x,t).
- Energy density, ρ = ½ [dφ/dt]^2 + V(φ).
- Pressure, P = ½ [dφ/dt]^2 - V(φ).
- w = P/ρ is near -1 for slowly varying φ.

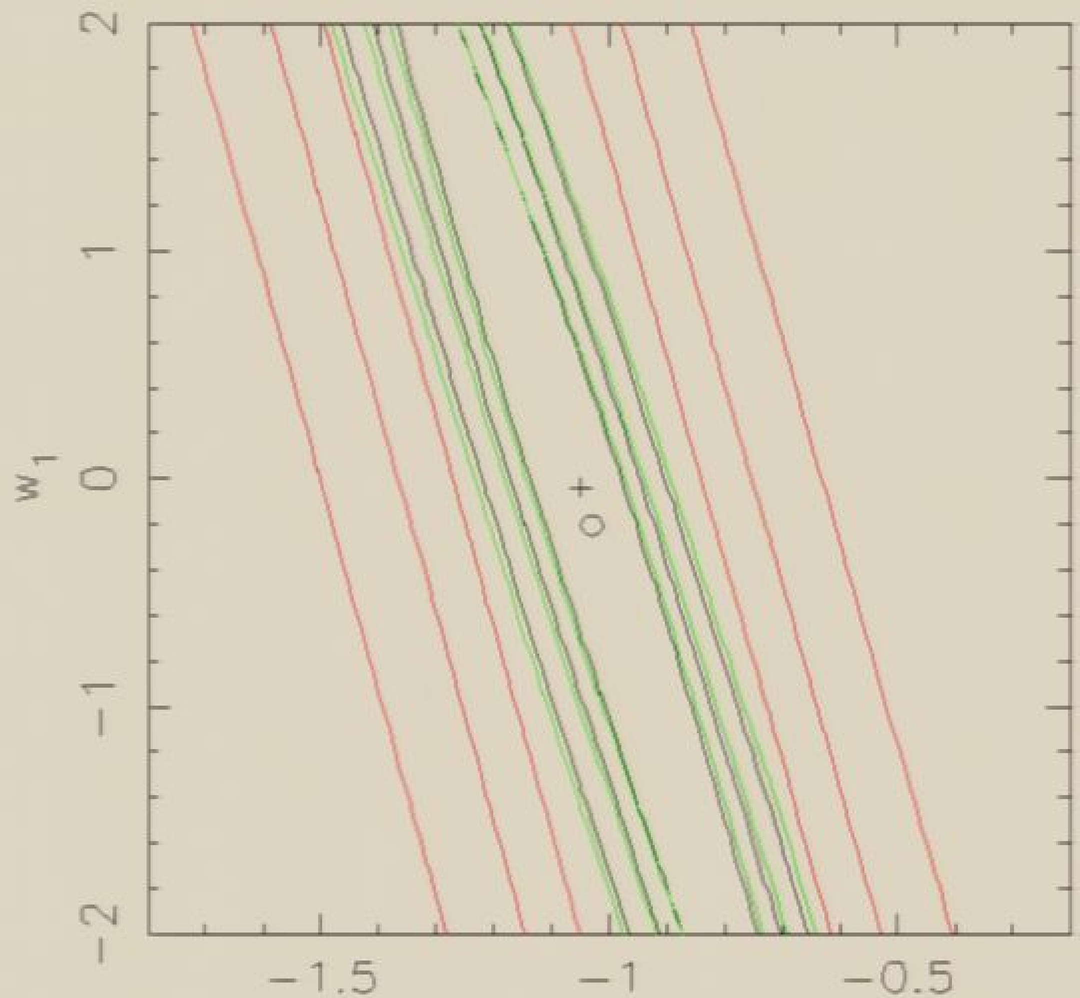
$$w = \frac{\frac{1}{2}\dot{\varphi}^2 - V(\varphi)}{\frac{1}{2}\dot{\varphi}^2 + V(\varphi)}$$

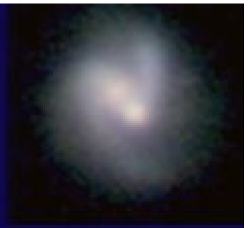
Empirical fit for w(z)



- $w(a) = w_0 + w_1 (1-a)$, $a = 1/(1+z)$
  - Integrated in Friedmann equation

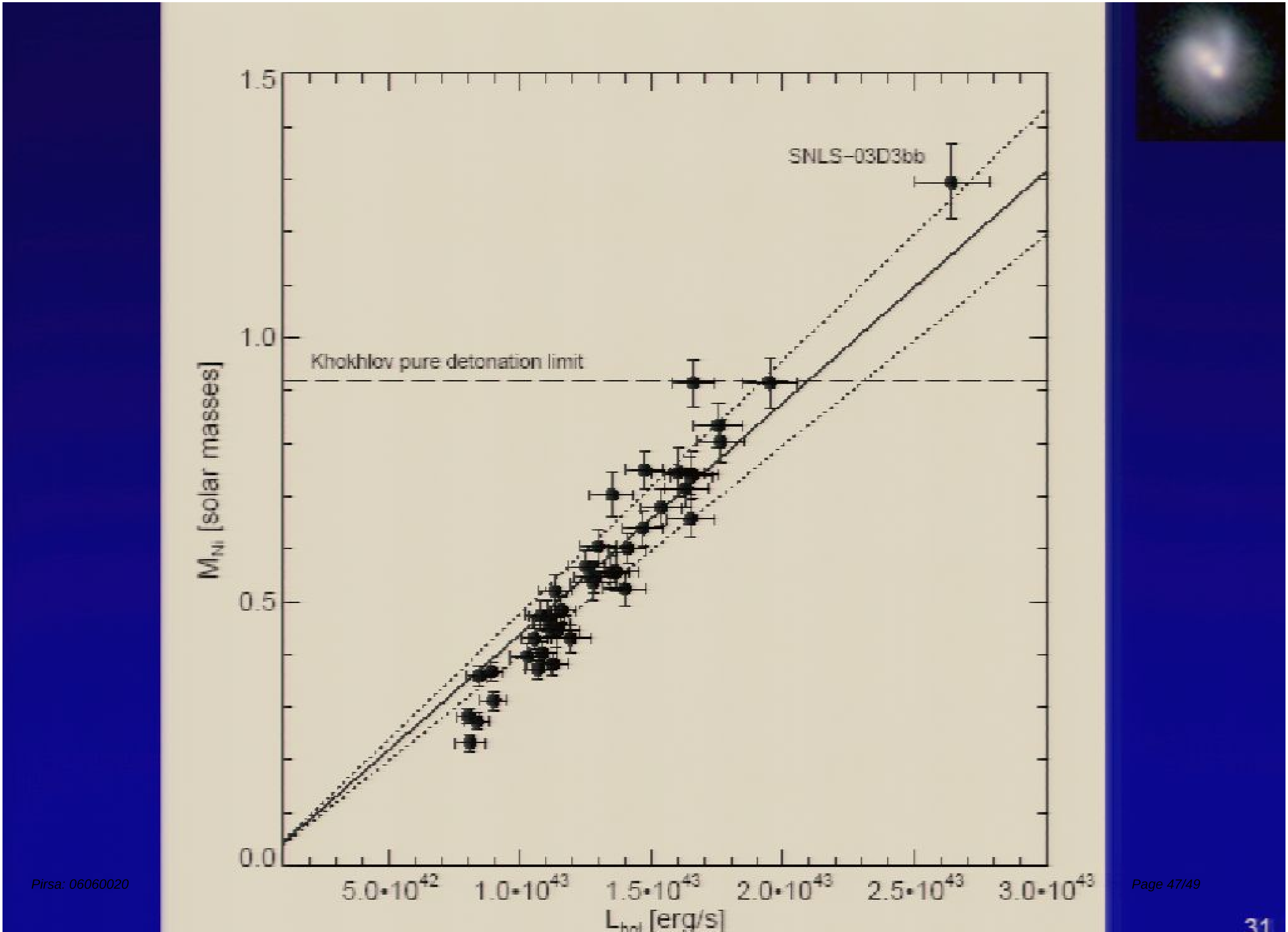
$w = w_o + w_1(1\text{-}a)$ Linder





Supernova themselves

- Many supernovae from young, small galaxies:
  - Linear model
  - Rate = A * (Stellar Mass) + B * (Star formation rate)
  - "B term" dominates beyond about z~0.5
  - Suggests many high z Ia.



SNLS-03D3bb
Khokhlov pure detonation limit
M_Ni [solar masses]
L_bol [erg/s]
1.5
1.0
0.5
0.0
5.0•10^42
1.0•10^43
1.5•10^43
2.0•10^43
2.5•10^43
3.0•10^43
31

Where do we go from here?

- Third year results should be prepared in the early fall (data acquisition continues to July)
- Better BAO constraints (next year)
  - SDSS spectroscopy (x2)
  - SDSS/2dF photometric (~x1)
- Future photometric surveys 2011 reports?
  - Variable w_1 to ~0.3?

Conclusions

- Current data consistent with constant DE
  - $w = -1.02 \pm 0.09$
- Systematic errors are the challenge.
- New results coming: "3rd year" analysis