

Insight into Dark Energy from
SNe

+

Baryon/Dark Matter Inventory
of the Universe

Layout of the Course

Feb 3: Introduction / Overview / General Concepts

Feb 5: Age of Universe / Distance Ladder / Hubble Constant

Feb 10: Distance Ladder / Hubble Constant Distant Measures

This Week

Feb 12: SNe science / Baryonic Content / Dark Matter Content of Universe

Feb 17: Dark Matter + Cosmic Microwave Background

Feb 19: Cosmic Microwave Background

Feb 26: Large Scale Structure / Baryon Acoustic Oscillations

Mar 5: Dark Energy / Clusters

Mar 12: Cosmic Shear / Dark Energy Missions

Mar 19: No Class

Mar 26: Review for Final Exam

Apr 11: Final Exam

Problem Set #1

Available on Bright Space
already (and also mailed it to
you)!

Due Monday, February 17, 2025

Review Material from Last Week

Deriving the Hubble constant

In principle, this is very straightforward:

$$H_0 = v / d$$

Measure the relative velocities to galaxies from their
Doppler shifts and distances...

Because of the “noise” introduced by peculiar velocities (from local gravitational forces) into the overall velocity field governed by the Hubble expansion, we need to reach greater distance to
measure H_0

Need to reach distances of $>50-100$ Mpc

Primary Methods

(local, primarily geometric)

Radar Echo

Parallax (Trigonometric, Secular,
Statistical)

Moving Cluster

Main Sequence Fitting to Star Clusters

Eclipsing Star

Light Echo

Wasselink-Baade Method

Secondary methods

(calibrated based on primary methods)

Cepheids and RR Lyraes

Planetary Nebula LF

Globular Cluster LF

Brightest Stars

Type Ia Supernovae

Tully-Fisher and Faber Jackson

$D_n - \sigma$

Surface Brightness Fluctuations

Methods Bypassing Distance Ladder

Gravitational lens time delays

Sunyaev-Zeldovich effect (from galaxy clusters)

Water Masers

Why is Hubble constant important?

Establishes basic measures of distance and time in all extragalactic cosmological measurements

$$\text{Age of Universe} \sim 1/H_0$$

$$\text{Distance to Faraway Galaxy} \sim cz/H_0 \sim 1/H_0$$

$$\begin{aligned} \text{Luminosity of Faraway Galaxy} &\sim \text{flux} \times (4\pi D^2) \\ &\sim \text{flux} \times 4\pi (cz/H_0)^2 \\ &\sim 1/H_0^2 \end{aligned}$$

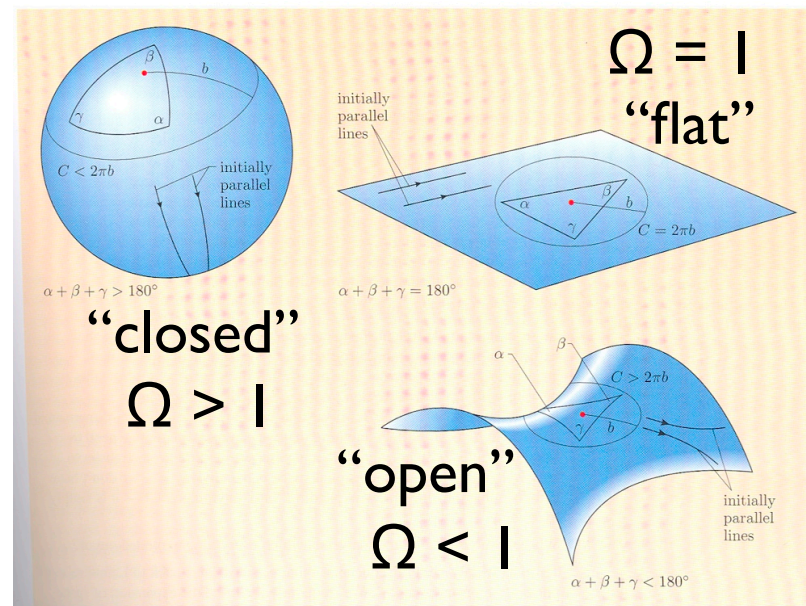
In constructing the distance ladder and deriving the Hubble constant, we've effectively treated space as Euclidean:

$$\text{flux} = L / 4\pi D^2$$

$$\theta_{\text{galaxy}} = \text{Radius}_{\text{galaxy}} / D$$

“Angular size”

But in reality it is not
(at sufficiently large distances)



To determine the topology of the universe on larger scales, we need to move beyond the Hubble constant and derive other parameters.

H_0 Hubble Constant

Ω_M Matter Density in Matter

Ω_Λ Density of Dark Energy

Ω_b Matter Density in Baryons

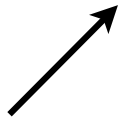
Ω_r Energy Density in Radiation

n_s Slope of Primordial Power Spectrum

σ_8 RMS fluctuations of the mass density in spheres of $8h^{-1}$ Mpc

w 'w' parameter

determine
these



How to determine these parameters?

We take advantage of two things we can observe:

I. Redshift of Far-Away Sources

Determine from the position of emission or absorption lines

Redshift immediately tells the relative size of the universe when the source emitted its light to what it is now

$$1 + \underset{\substack{\nearrow \\ \text{redshift}}}{z} = \frac{\lambda_0}{\lambda_{emitted}} = \frac{R(t_0)}{R(t_{emitted})}$$

2. Distances to Far-Away Sources

We can measure the distances to far-away sources as in this lecture by taking advantage of standard candles or standard rods.

Then, we determine how the distance we measure to sources compares with their measured redshifts...

Different densities in matter and dark energy predict different relationships between these quantities

Discussed four different distance measures:

Proper distance

$$t_p = D_p/c$$

“light travel path”

$$D_P = \int ds = R(t) \begin{cases} \sin^{-1} r, & k = +1 \\ r, & k = 0 \\ \sinh^{-1} r, & k = -1 \end{cases}$$

Luminosity distance

$$\text{flux} = L / 4\pi D_L^2$$

$$D_L = R_0 r (1+z)$$

$$r = f_k \left(\frac{c}{R_0 H_0} \int \frac{dz}{E(z)} \right) \text{ where } f_k(x) = \begin{cases} \sin x, & k = +1 \\ x, & k = 0 \\ \sinh x, & k = -1 \end{cases}$$

comoving coordinate r

Angular-diameter distance

$$\theta = \text{Radius}_{\text{galaxy}} / D_A$$

$$D_A = R_0 r / (1+z)$$

$$R_0 = (c/H_0) \Omega_k^{-1/2}$$

Proper Motion distance

$$d\theta/dt = dx/dt / D_M$$

$$D_M = R_0 r$$

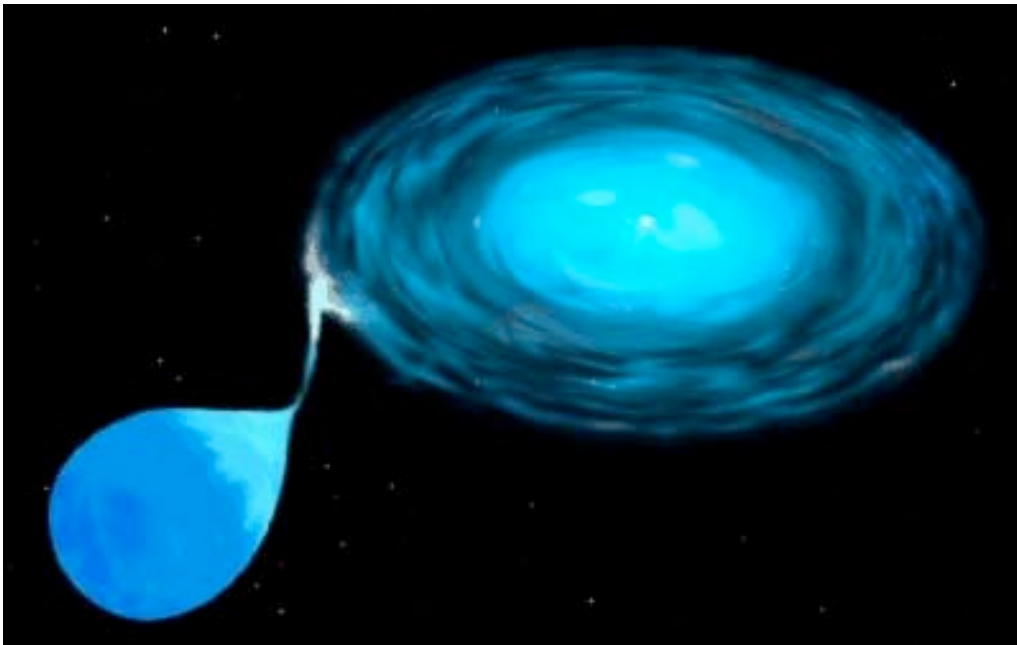
Now onto new material...

One particularly fruitful approach is rely on the sensitivity of distance measures to cosmology

Identify standard candles in early universe and use those to constrain cosmology

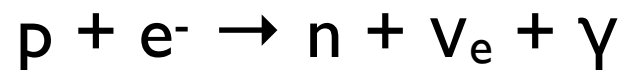
Supernovae Ia

Accretion of matter from a nearby companion onto a white dwarf



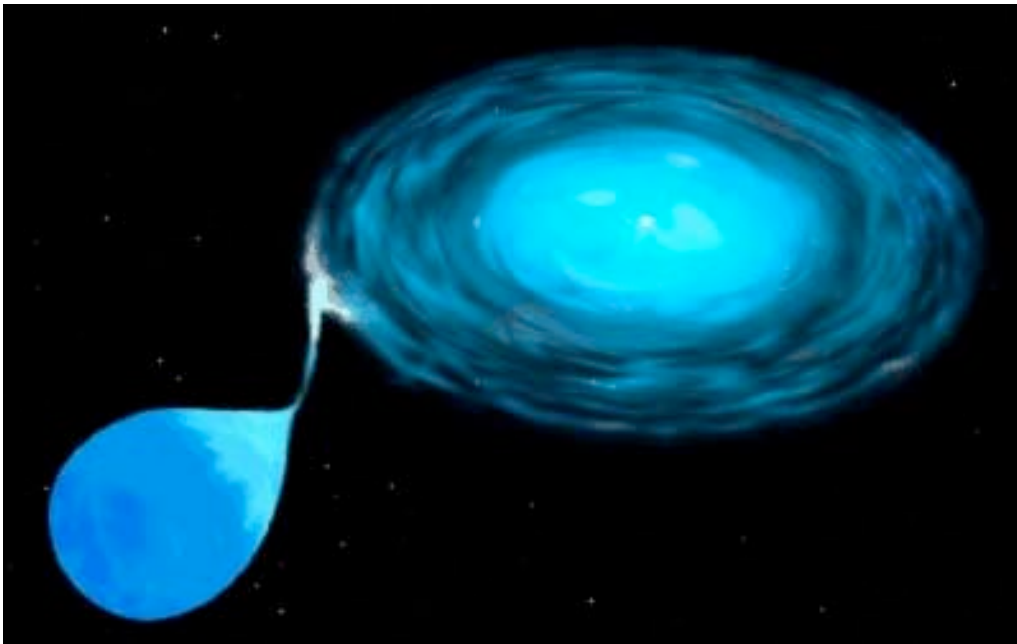
-- Likely occurs when a white dwarf is pushed over the Chandrasekhar limit of $> 1.4 M_{\text{solar}}$ by accretion from a nearby companion

Exceeding the Fermi pressure, inverse beta decay occurs:



Supernovae Ia

Accretion of matter from a nearby companion onto a white dwarf

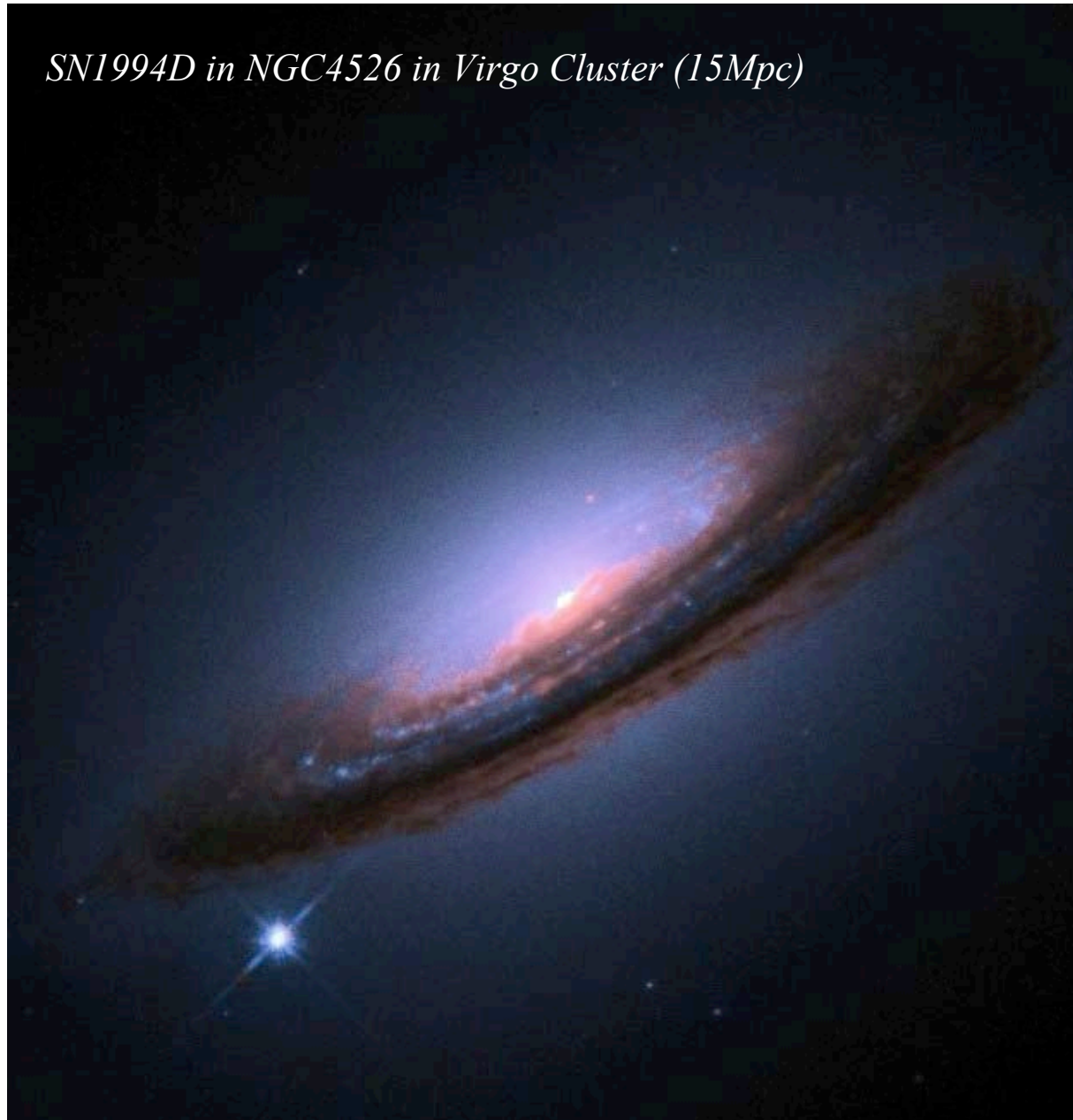


-- Likely occurs when a white dwarf is pushed over the Chandrasekhar limit of $> 1.4 M_{\text{solar}}$ by accretion from a nearby companion

Instead of collapsing, material in the star ignites in fusion type reactions producing a huge amount of Ni^{56} ($0.5 M_{\text{sol}}$) and a very luminous supernovae explosion

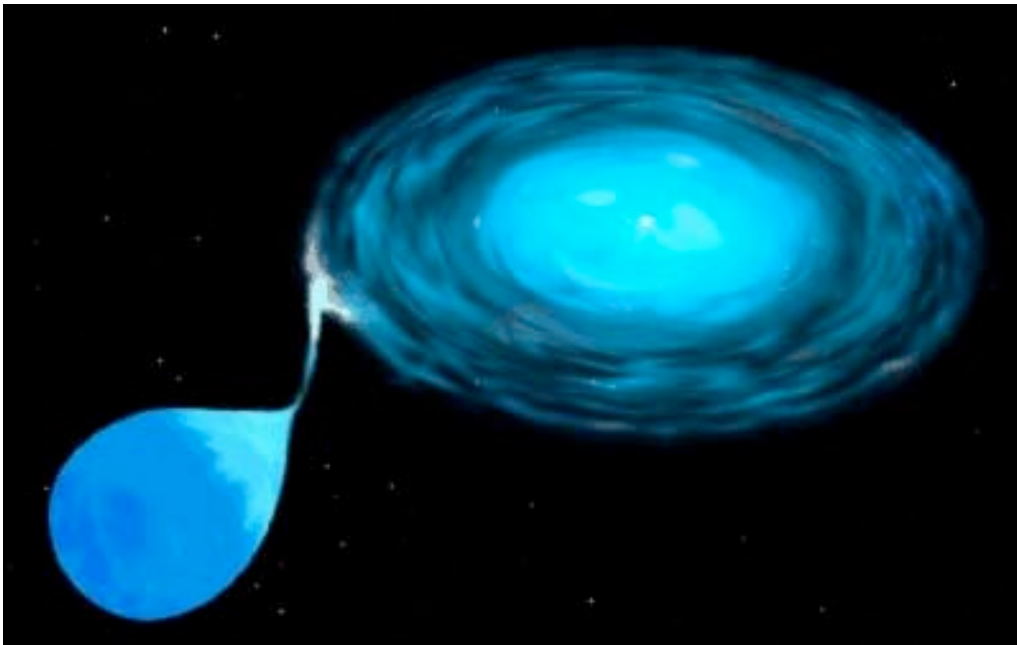
Supernovae Ia have same luminosity as an entire galaxy
(but only for ~ 1 month)

SN1994D in NGC4526 in Virgo Cluster (15Mpc)



Supernovae Ia

Accretion of matter from a nearby companion onto a white dwarf



Are found in both elliptical galaxies and spiral galaxies

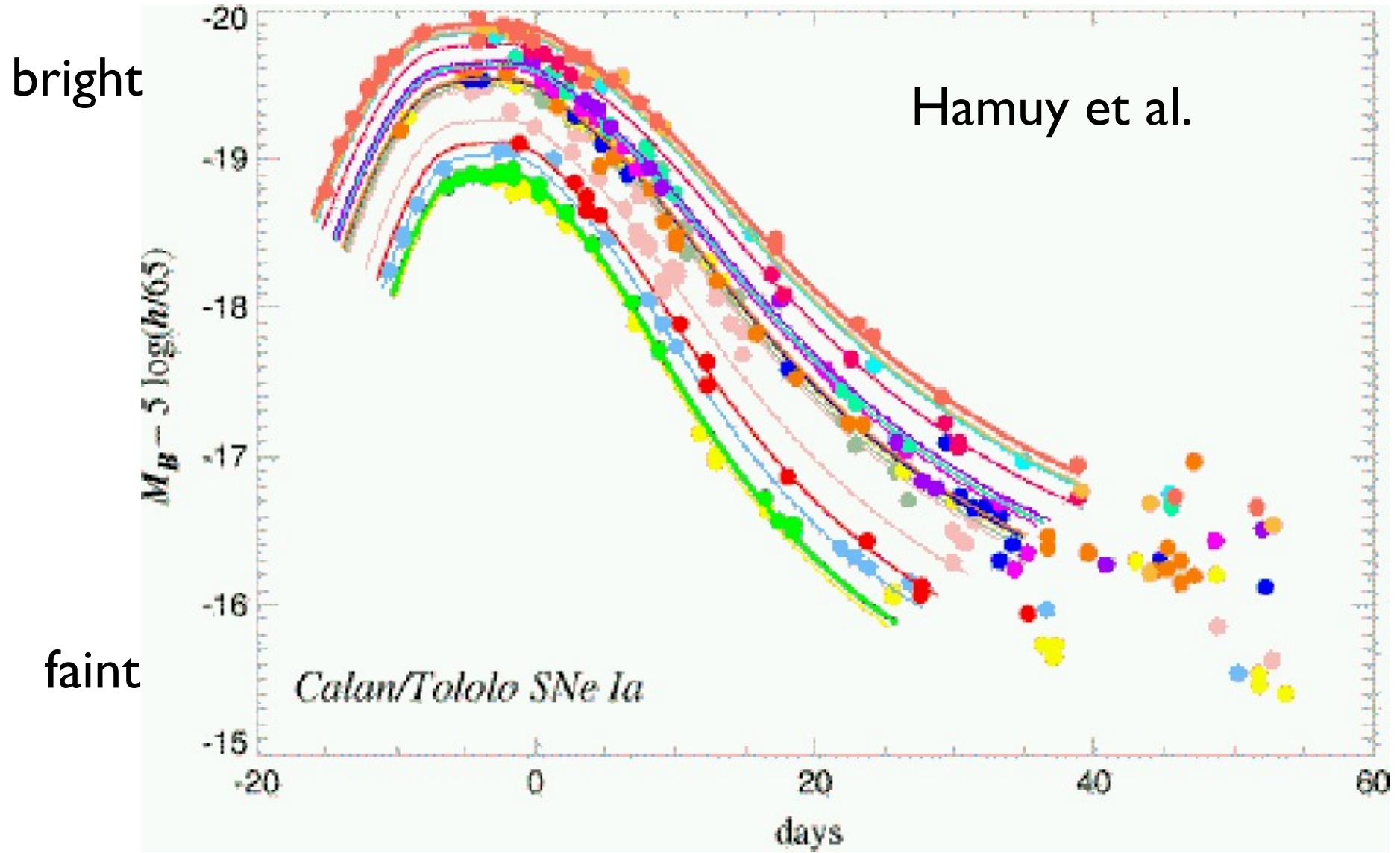
10-100 times brighter than other supernovae

Can be seen to great distance, >2000 Mpc

To derive luminosity distances, SN Ia must be a standard candle?

Are they standard candles?

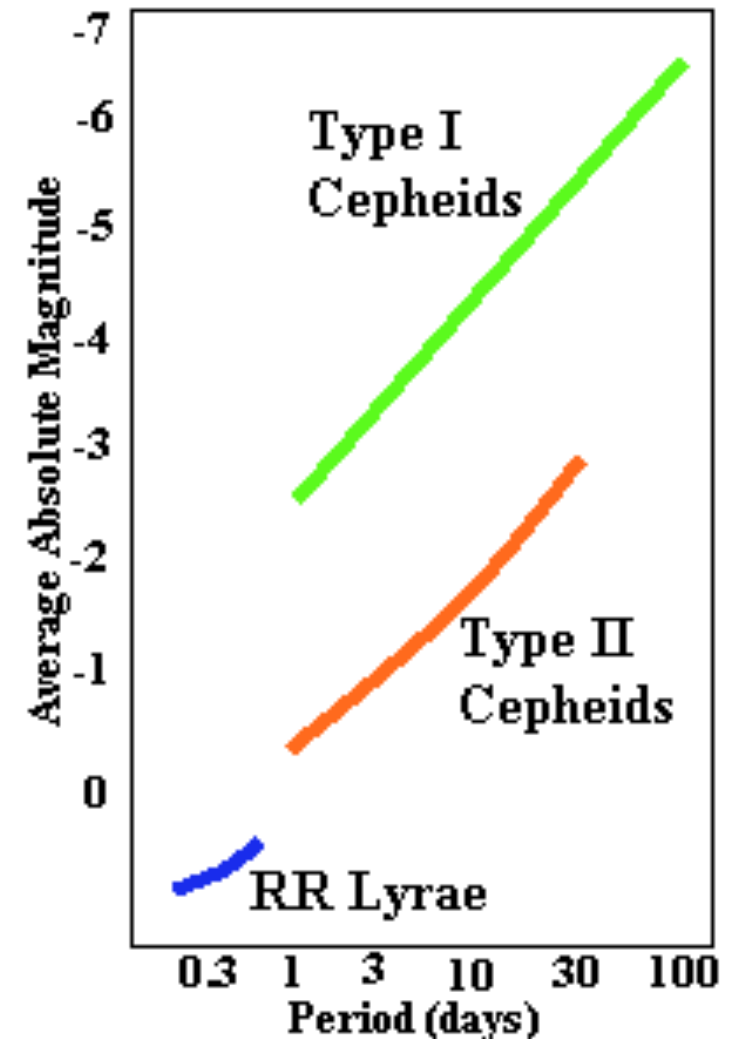
The luminosity of Supernovae Ia varies somewhat depending upon the decay time for the light curve



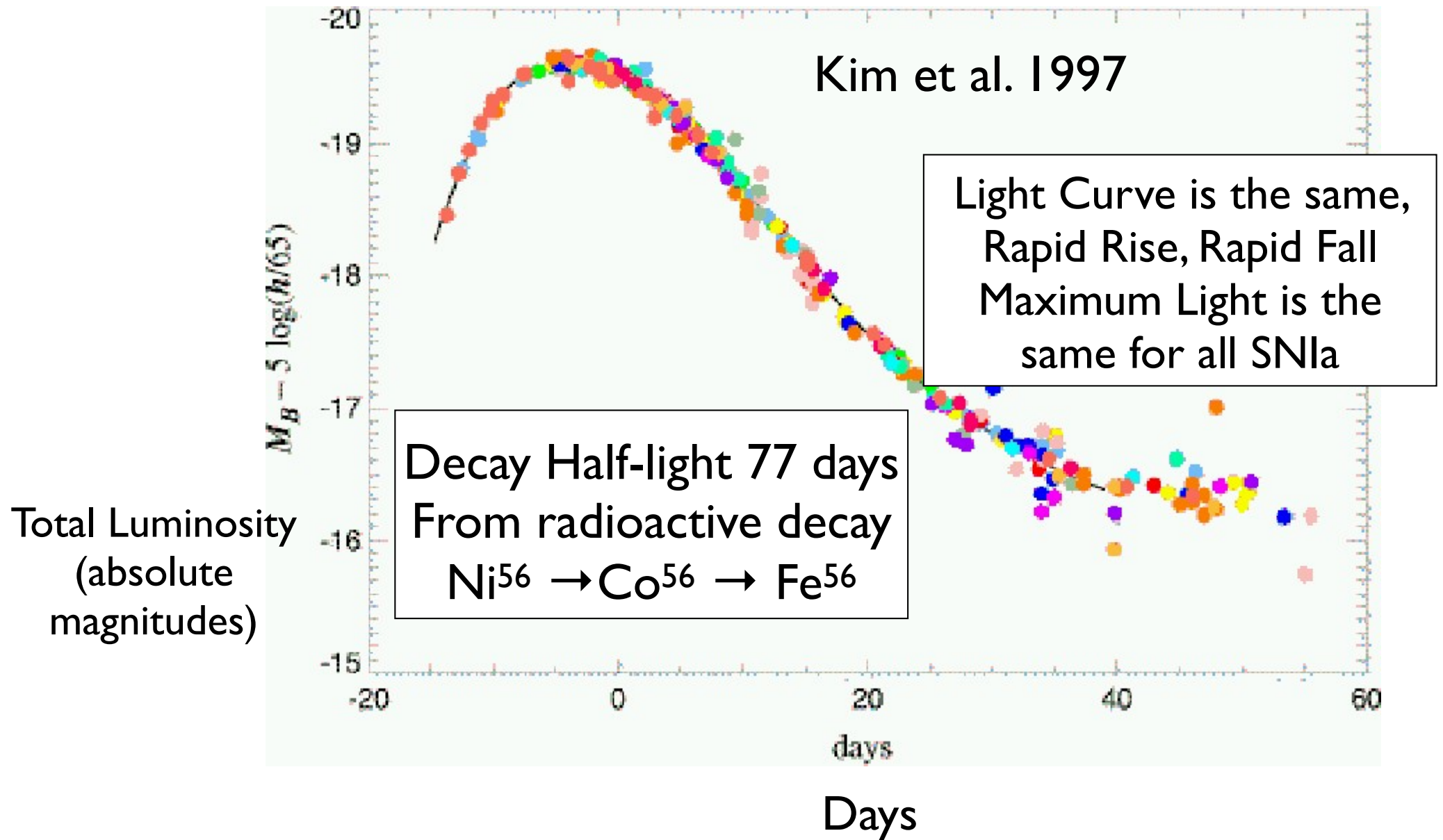
Phillips relation (Phillips et al. 1996)

No they are not *standard* candles, but
they are *standardizable*

Similar to situation for
variable stars



How does its brightness vary with time?



Before continuing, it is worthwhile remarking that we only require that SNe Ia's be standardizable candles...

Establishing the actual luminosity of SNe Ia is important for H_0

For determining Ω_m, Ω_Λ , we only need to know the relative distances

However, even after correcting for this effect, the luminosity of SNe Ia still varies by 10% (depending on which SNe Ia event one examines)

However, because this variation appears to be random, by observing multiple SNe Ia at the same point in cosmic time, one can reduce this source of error

1 SNe \rightarrow 10% error

10 SNe \rightarrow $10\% / 10^{1/2} \sim 3\%$ error

100 SNe $\sim 1\%$ error

\Rightarrow Because of this, only makes sense to measure the fluxes so well...

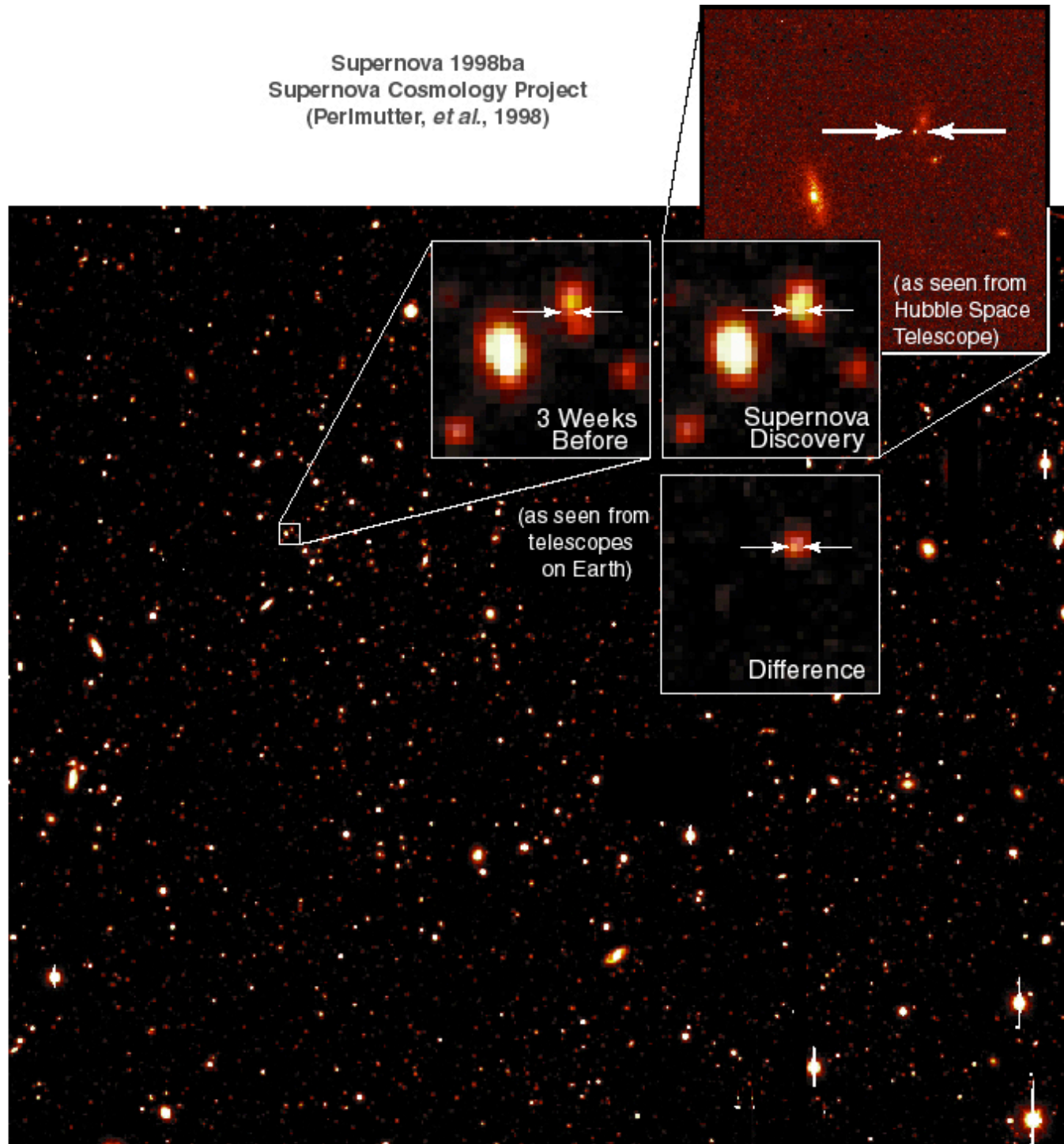
How do we find SNe Ia?

I. Construct a survey

- image the same part of the sky repeatedly looking for them
(monitoring required every few days)
- subtract current image from image earlier to time to look for
time variable event

(this can be a challenge with ground-based telescopes since smoothing from turbulent sky conditions may change from night to night)

Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)



How do we find SNe Ia?

I. Construct a survey

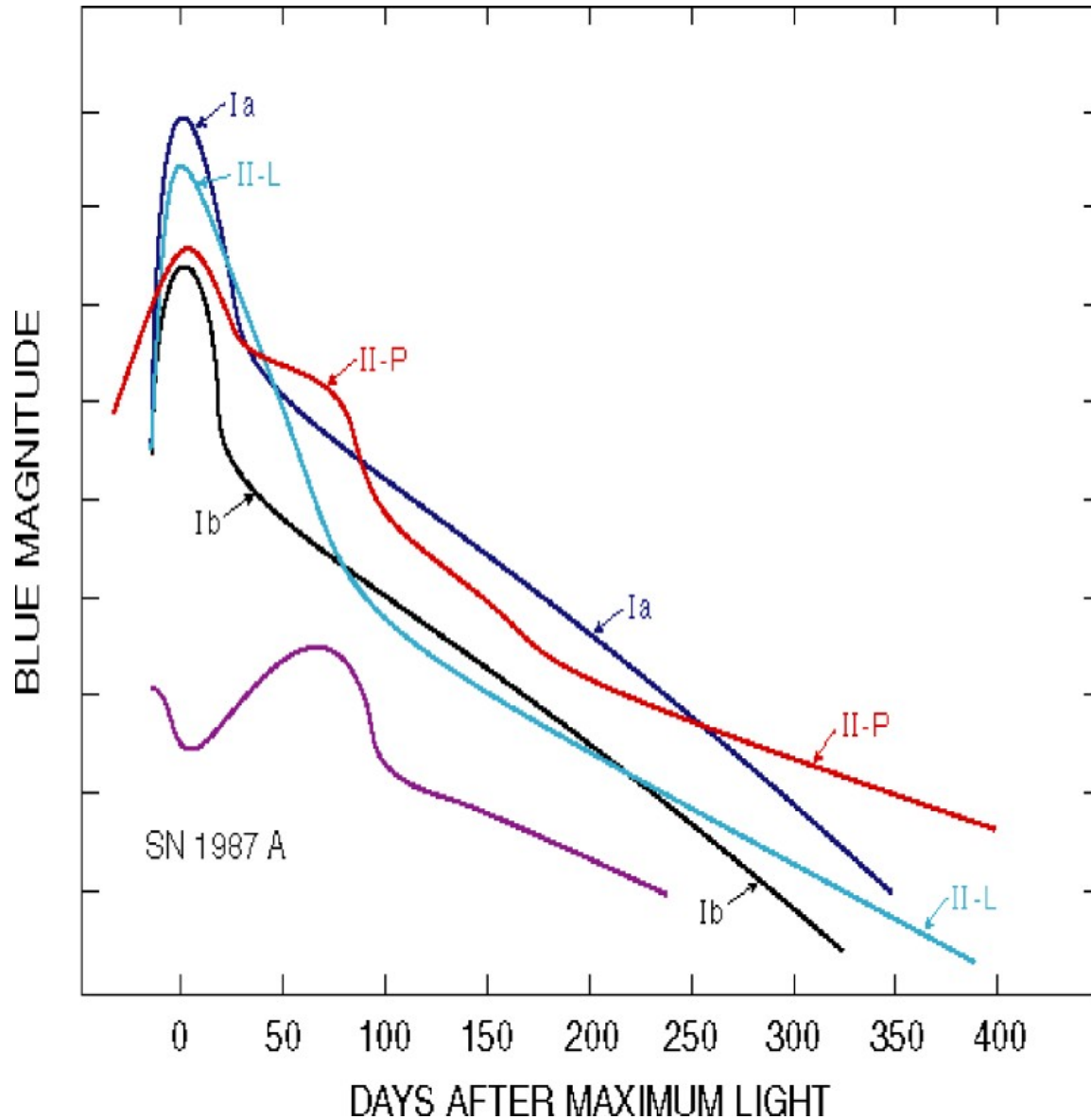
- image the same part of the sky repeatedly looking for them
(monitoring required every few days)
- subtract current image from image earlier to time to look for
time variable event

(this can be a challenge with ground-based telescopes since smoothing from turbulent sky conditions may change from night to night)

2. Determine that source is not variable star or quasar

- are the colors of the source consistent with its being a SNe Ia?
- is the light curve consistent with its being a SNe Ia?

Light Curves for different types of SNe



Core-collapse of stars with initial masses $> 30 M_{\text{sol}}$ \rightarrow SNe II

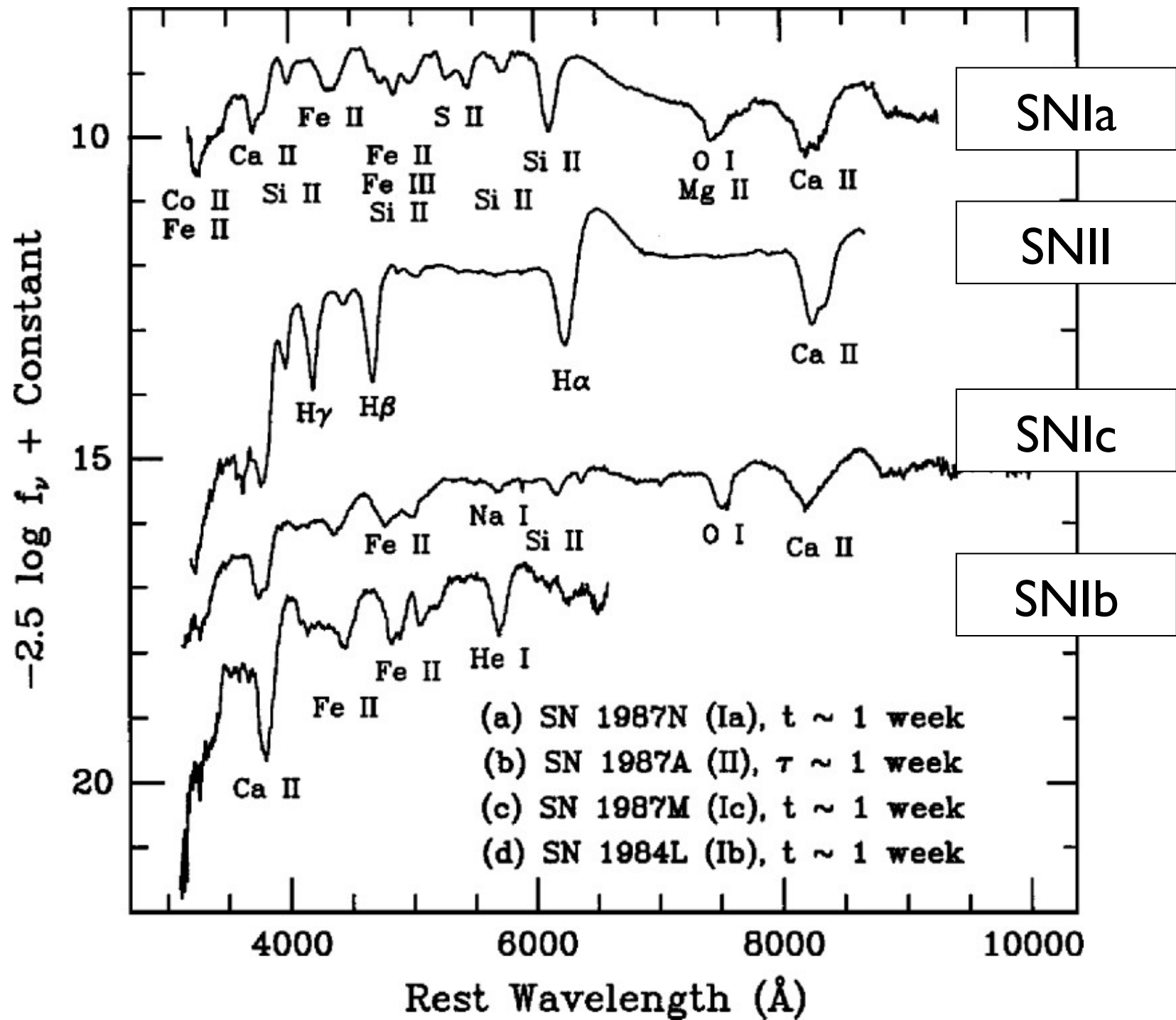
Core-collapse of stars with initial masses $8 - 30 M_{\text{sol}}$ \rightarrow SNe Ib/Ic

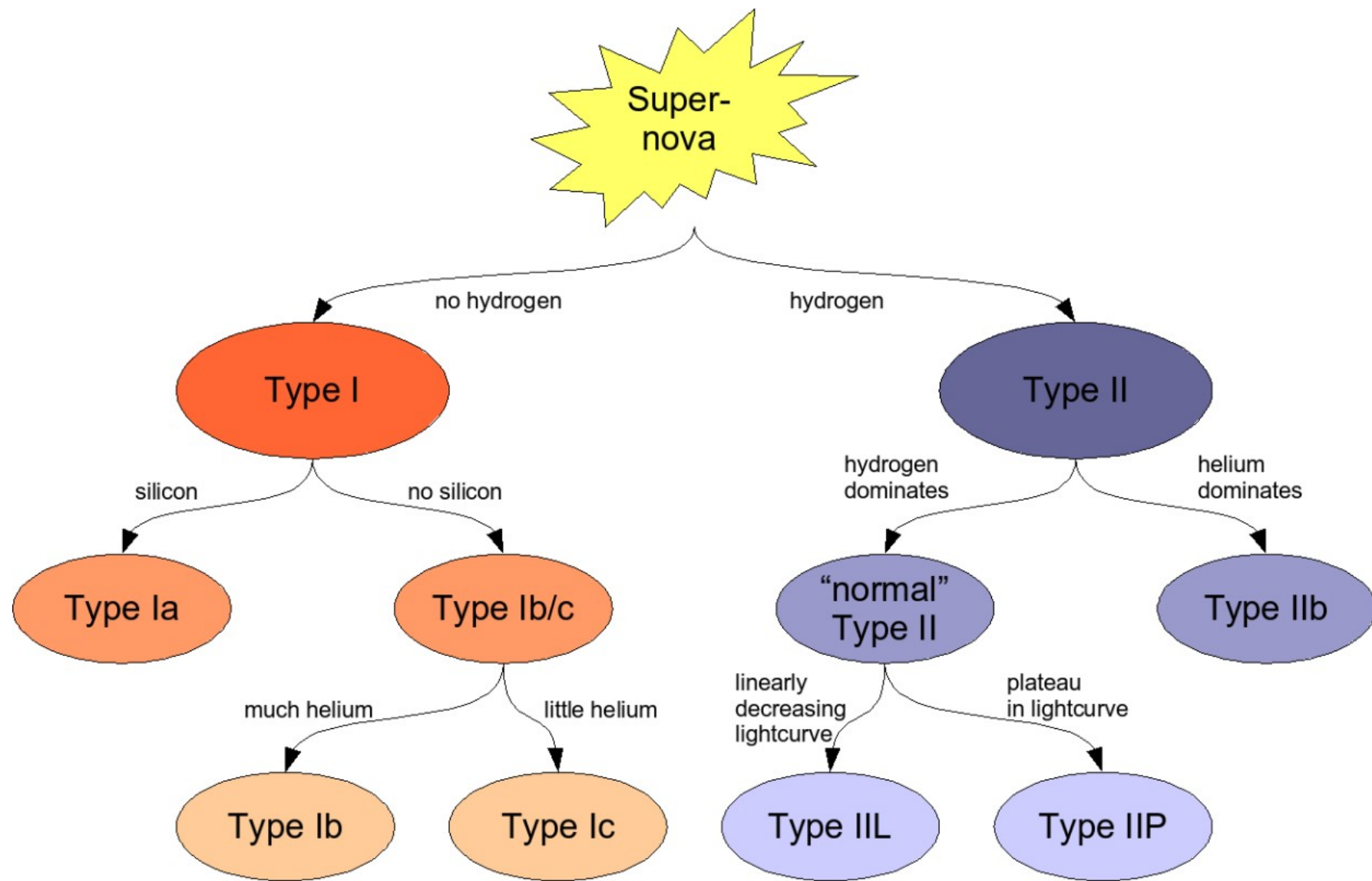
How do we find SNe Ia?

3. Obtain a spectrum of the SNe candidate to determine if it is a SNe Ia

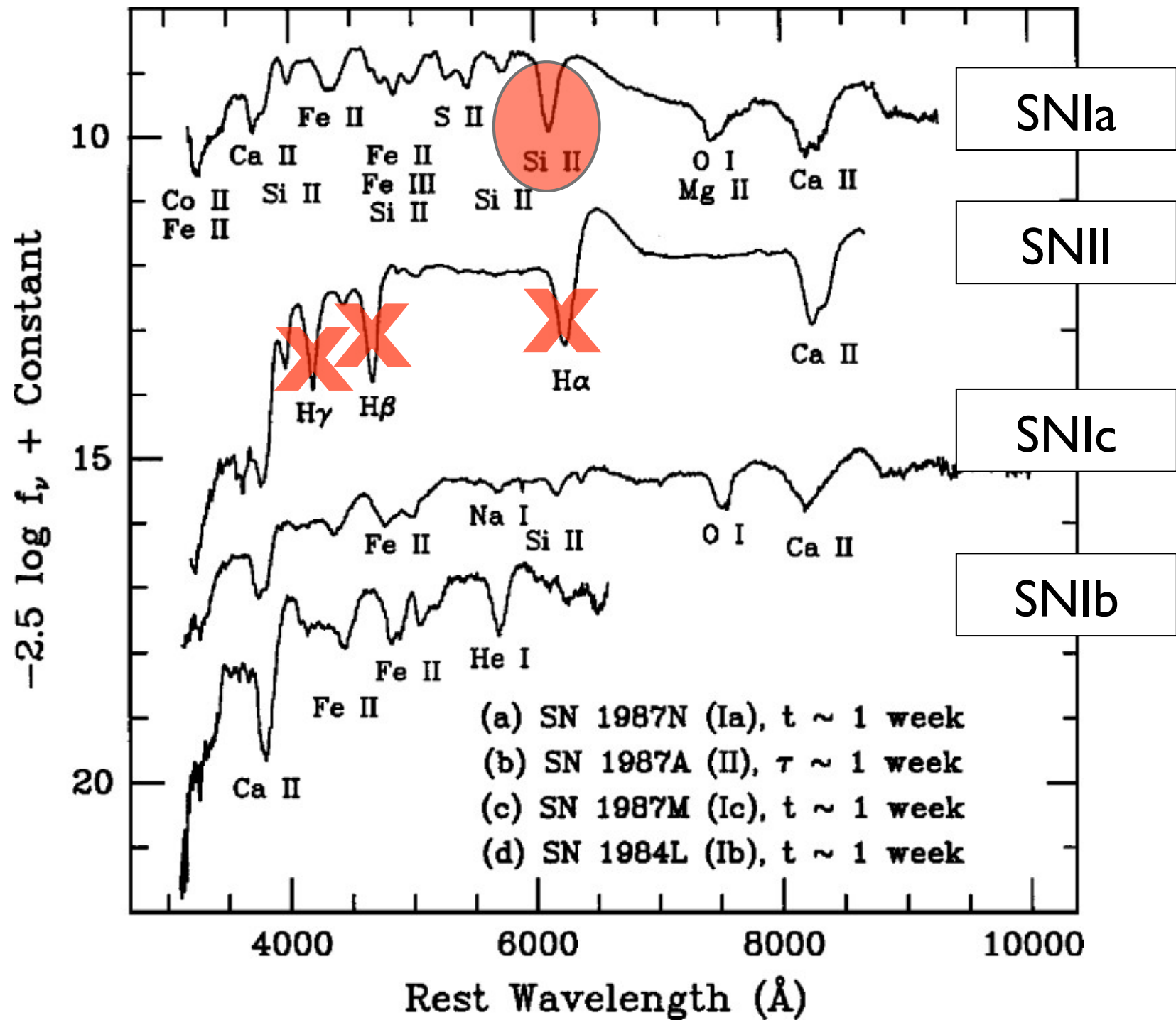
This is challenging for very distant SNe -- since they can have magnitudes of > 23 - 24 mag and requires large telescopes

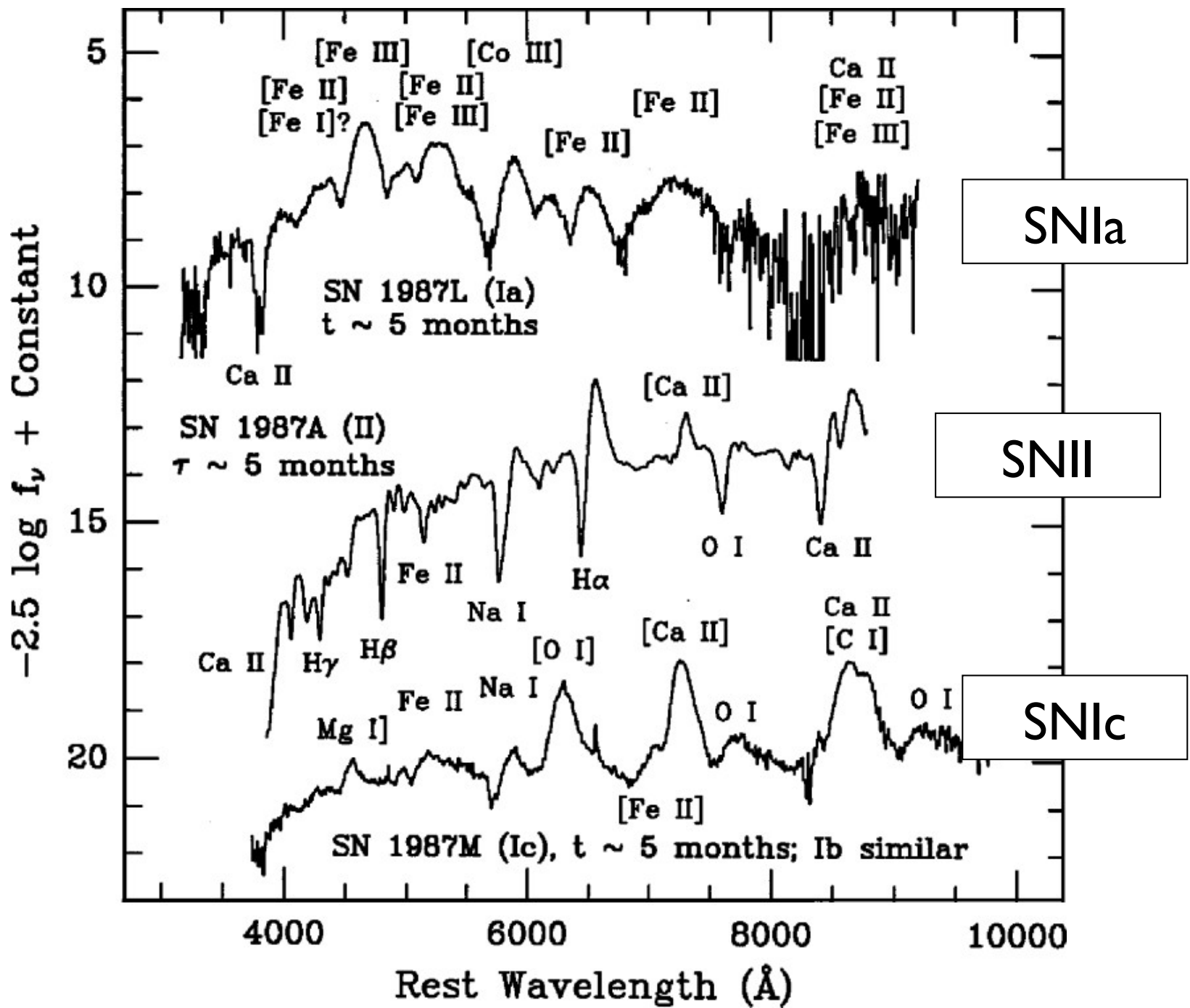
To distinguish SNe Ia from SNe Ib/Ic, need to check for the presence of Silicon lines (at ~ 6500 Angstroms rest-frame), so need spectroscopy in near-IR





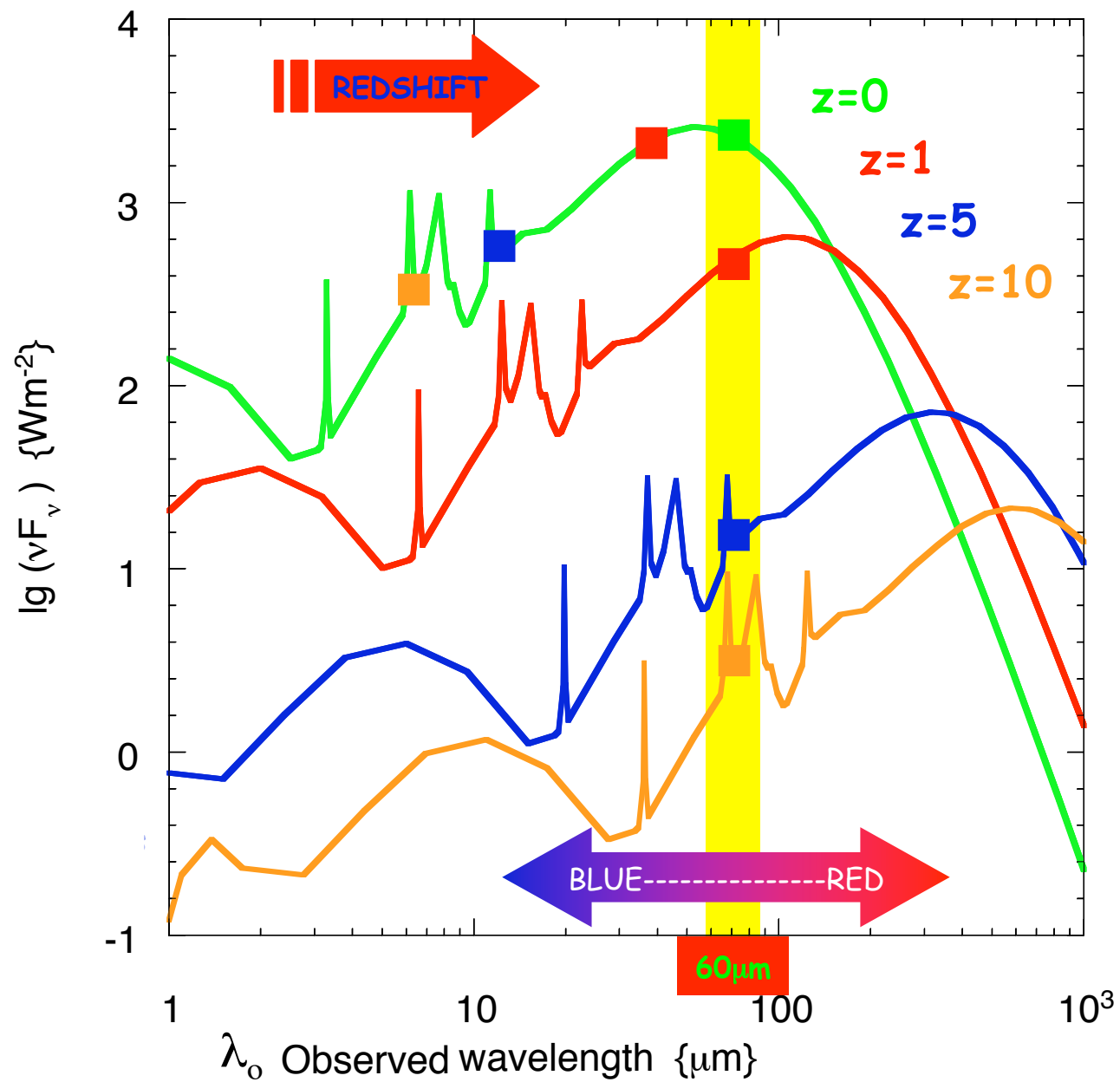
Supernova classification.





What do we do with the SNe Ia after we find them?

- I. Correct the observed light for the fact that light is redshifted (and therefore the wavelength we're examining a SNe Ia depends on its redshift)
(called a "k-correction")



What do we do with the SNe Ia after we find them?

2. Correct for dust extinction in the galaxy hosting the supernovae.

-- since SNe have a very distinctive spectral energy distribution, can perform this correction fairly well

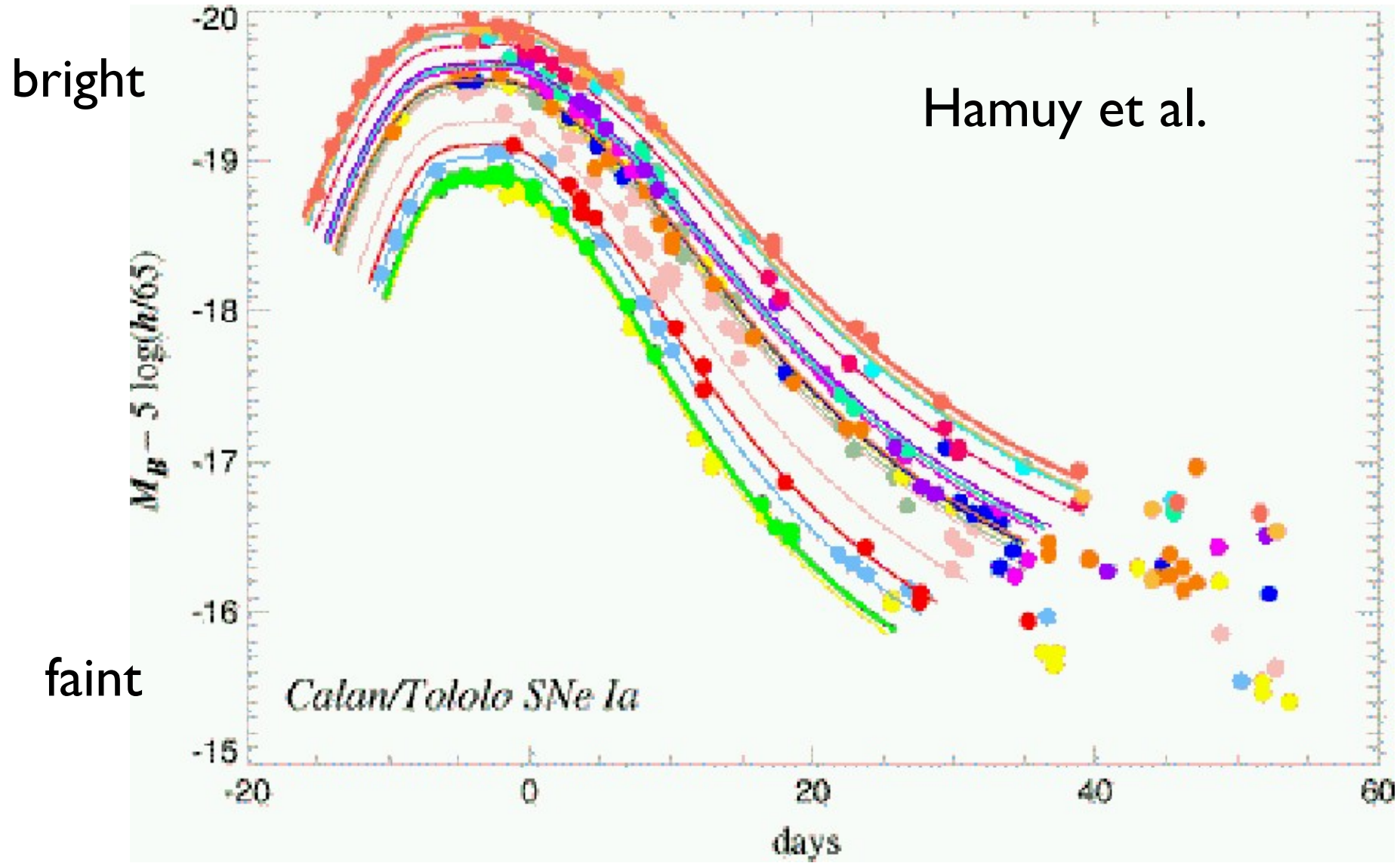
What do we do with the SNe Ia after we find them?

3. Correct brightness based on decay time of SNe Ia light curve...

Also must correct for cosmological time delay!

Time scale at which SNe Ia decays is slower by a factor of $(1+z)$!

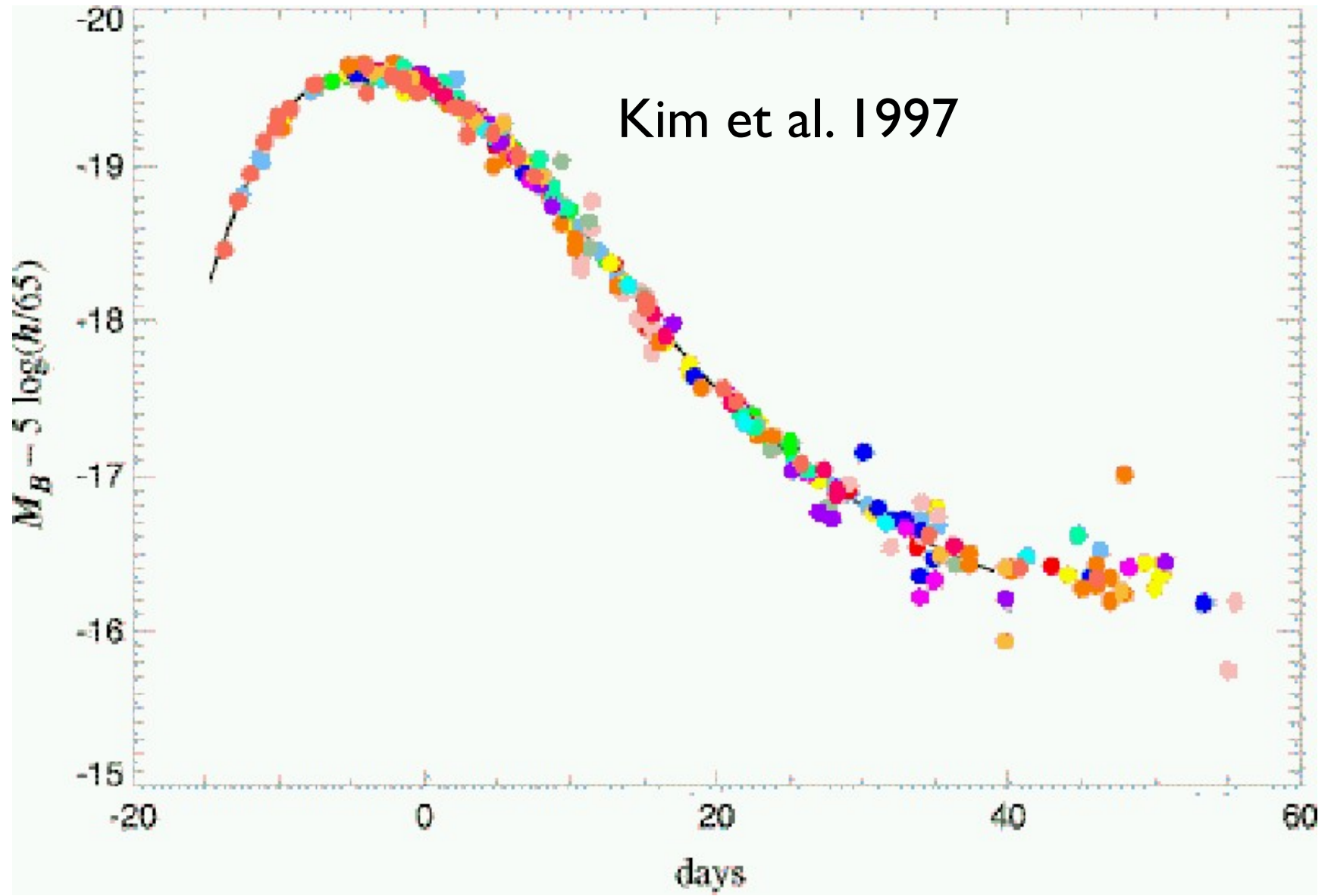
The luminosity of Supernovae Ia varies somewhat depending upon the decay time for the light curve



Philips relation (Philips et al. 1996)

SNe light curve (after correction)

bright



What do we do with the SNe Ia after we find them?

3. Correct brightness based on decay time of SNe Ia light curve...

Also must correct for cosmological time delay!

Time scale at which SNe Ia decays is slower by a factor of $(1+z)$!

4. Calculate luminosity distance for each SNe Ia.

$$D_L = (L_{\text{candle}} / (4\pi f))^{1/2}$$

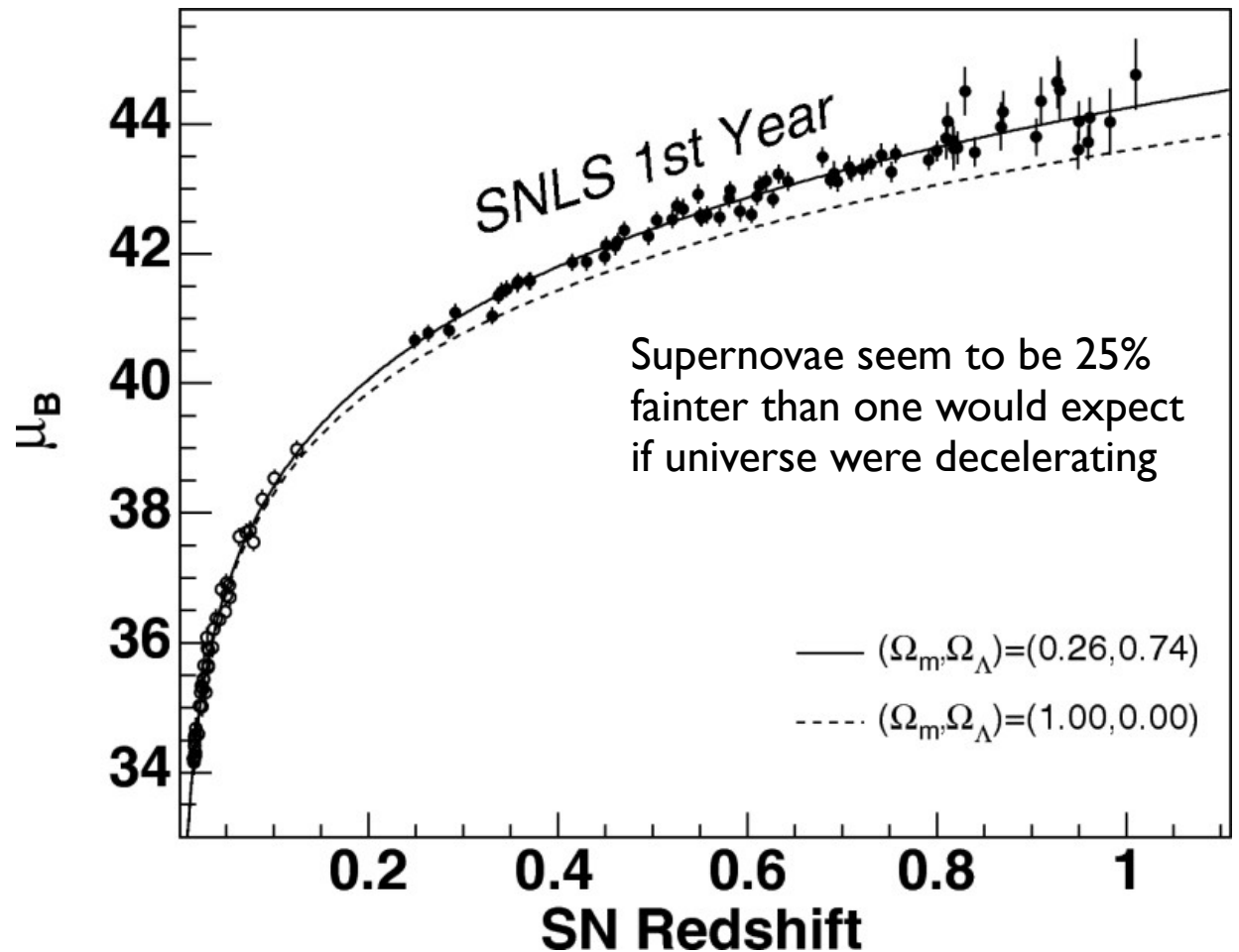
f = flux

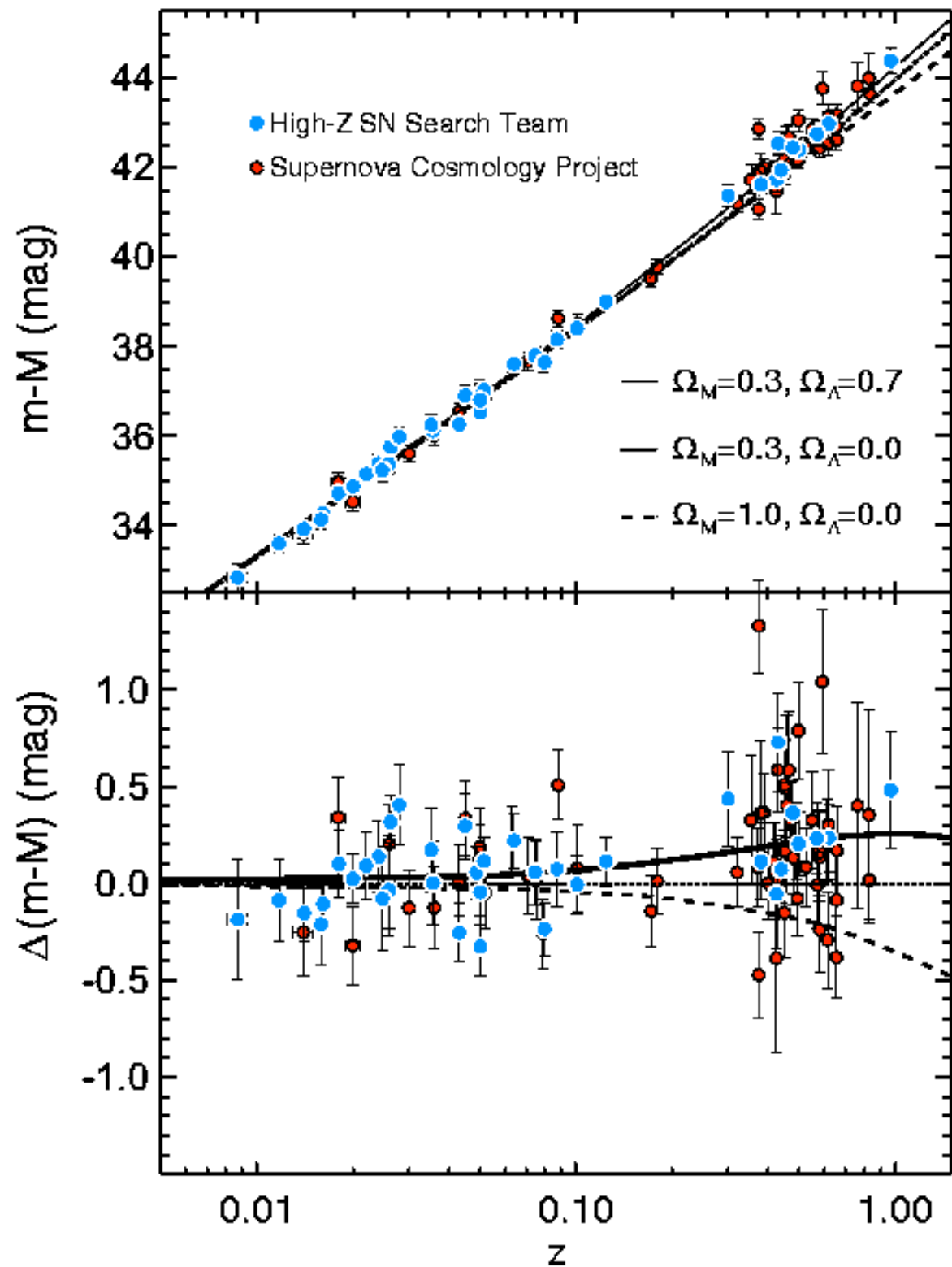
What do we do with the SNe Ia after we find them?

5. Plot luminosity distance versus redshift

Distance modulus

$$\Delta m = m - M = 5 \log_{10}(D / 10 \text{ pc})$$



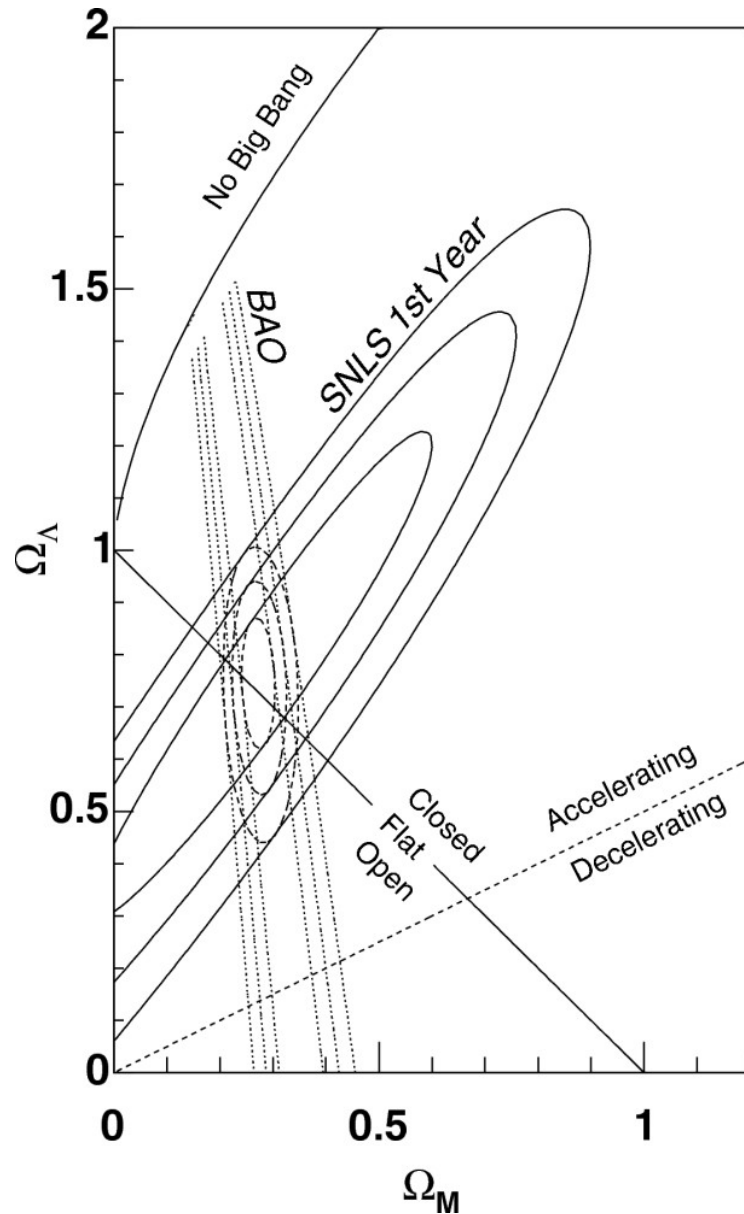


Riess et al. 1998

Supernovae seem to be 25% fainter than one would expect if universe were decelerating

Since it is relative distance measurements for SNe at $z \sim 0.8$ and $z \sim 0.02$, this cannot be due to a miscalibration of SNIa luminosities.

What constraints can one set?



Two different ways of increasing luminosity distance:

- 1) Increase Ω_Λ
- 2) Decrease Ω_m

This causes the degeneracy between Ω_Λ and Ω_m

But even with this degeneracy, the error contours clearly prefer Ω_Λ values greater than 0

Cosmological parameter constraints derived from the same data.

Two Main Teams found this result:

High-Z SNe search
team

Supernovae Cosmology
Project

Adam Riess

Brian Schmidt

Saul Perlmutter



Photo: Scanpix/AFP

Adam G. Riess



Photo: Belinda Pratten, Australian National University

Brian P. Schmidt



Photo: Lawrence Berkeley National Lab

Saul Perlmutter

Nobel Prize in 2011

Potential Problems with SNe experiments

-- Main challenge in dust in the host galaxy

Two solutions:

1) Observe SNIa over very wide wavelength range
to ensure understand dust extinction well

2) Only consider SNe in galaxies known to lack
dust

-- Difficult to correct for the effects of “grey” dust, i.e., dust
that has no effect on the colors of the SN Ia

-- Especially distant SNIa will be affected by gravitational lensing
from sources along line of sight

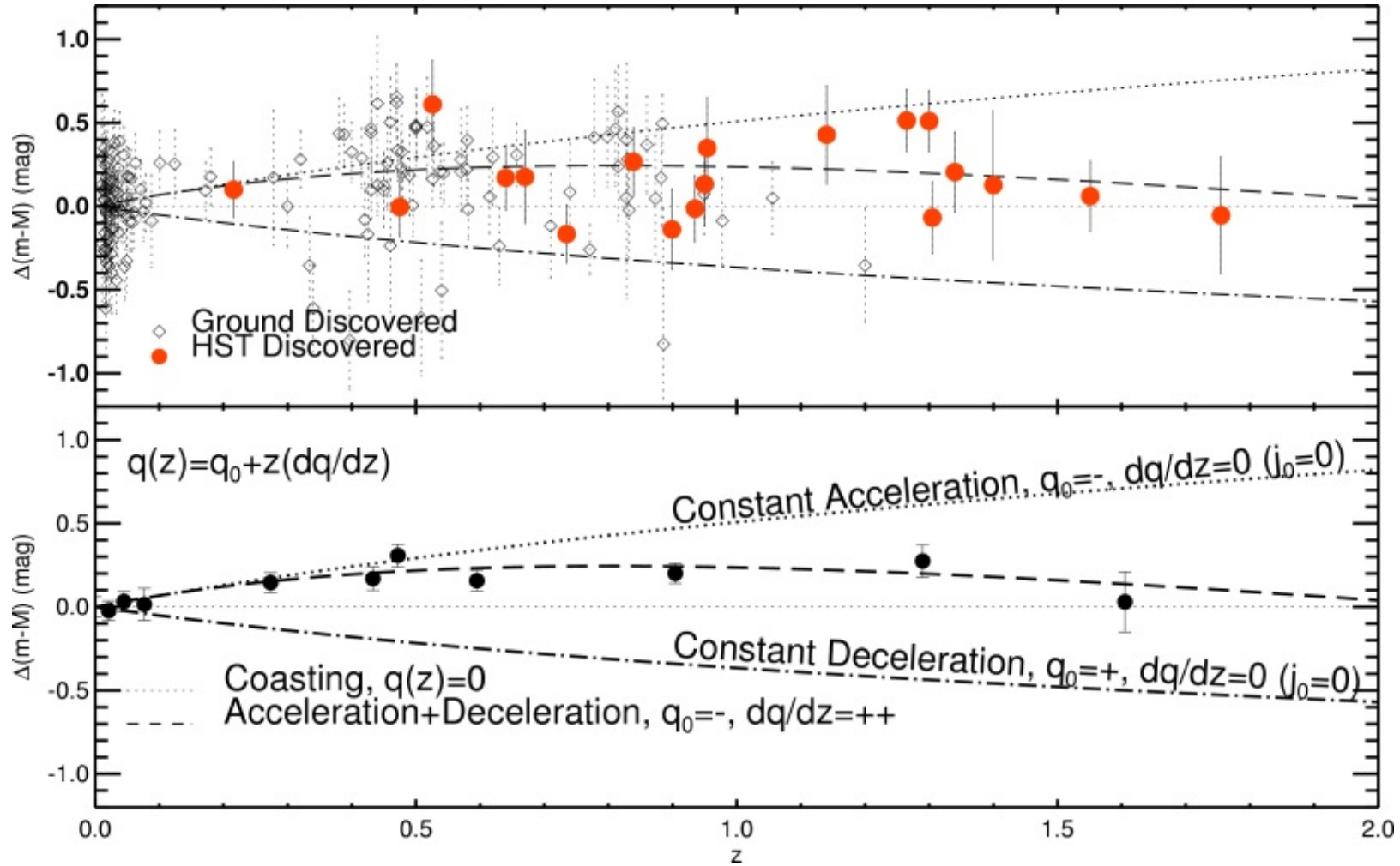
* Will change the apparent luminosity of the SNIa

* Some sources will be brighter, some fainter
(on average no large change)

Potential Problems with SNe experiments

- Are SNe at high redshift the same as at lower redshift?
(their metal content may be different!)
(no evidence for this from theoretical simulations)
- Possible to mistake SNIb's and SNIc's for SNIa's
(if there is problem with identifying Silicon feature)

Note that at $z \sim 1$, there is a change in shape and cosmic acceleration turns into deceleration



What other evidence for dark energy were there in the late 1990s?

-- there was a big tension between the age of universe from globular clusters + radiometric dating

i.e., > 13 Gyr

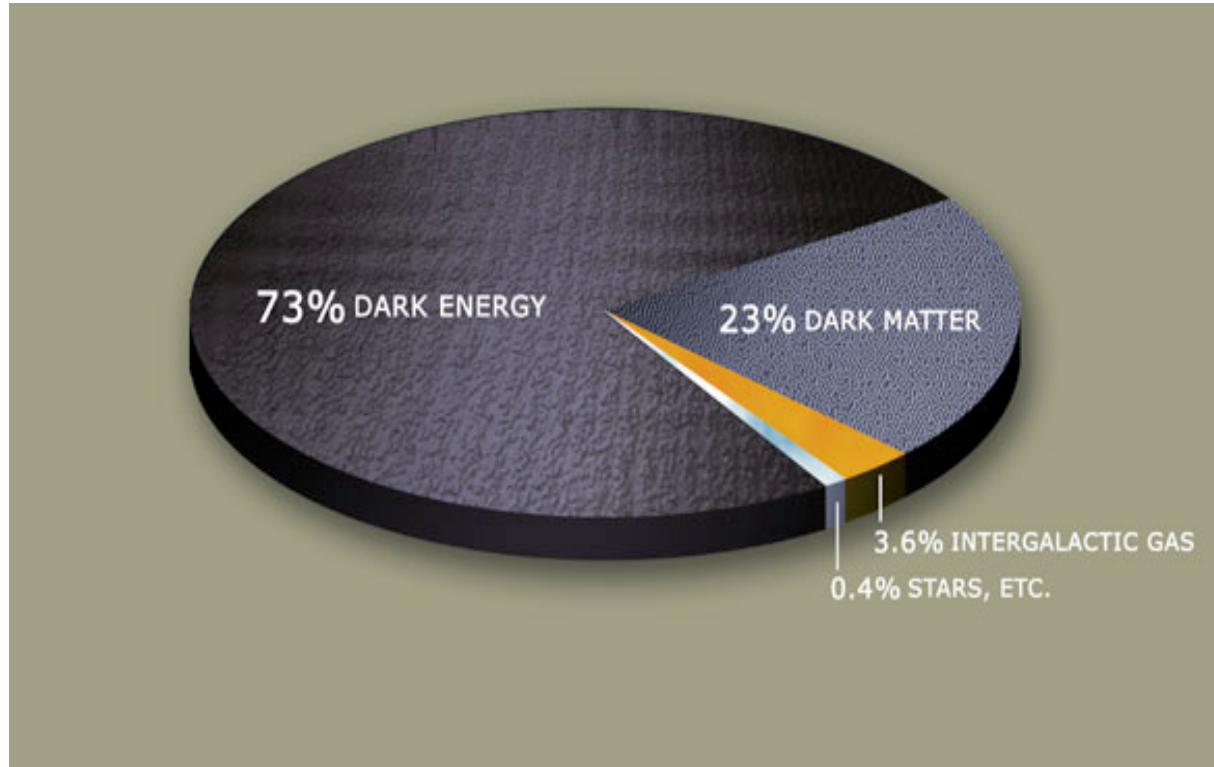
and the age of the universe from $H_0 \sim 70$ km/s/Mpc and measured value $\Omega_m \sim 0.3$ (evidence from galaxy clusters and peculiar velocities)

i.e., ~ 11 Gyr

(but which is ~ 13.6 Gyr including dark energy)

**What are the contents of the
universe?**

Earlier in this lecture, we argued based on the measured fluxes of SNe in the distant universe that today most of the mass-energy density in the universe is in the form of dark energy.



Leaving $\sim 27\%$ of mass-energy density of the universe in the form of normal matter

(we will present convincing evidence that $\Omega = 1$ next week)

How can we determine the matter density in the present day universe from the observations?

(you are almost certainly aware that matter comes in two flavors: dark matter and baryonic matter)

First the baryonic content...

Let's do an inventory!

THE COSMIC BARYON BUDGET

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Received 1997 December 2; accepted 1998 March 26

ABSTRACT

We present an estimate of the global budget of baryons in all states, with conservative estimates of the uncertainties, based on all relevant information we have been able to marshal. Most of the baryons today are still in the form of ionized gas, which contributes a mean density uncertain by a factor of about 4. Stars and their remnants are a relatively minor component, comprising for our best-guess plasma density only about 17% of the baryons, while populations contributing most of the blue starlight comprise less than 5%. The formation of galaxies and of stars within them appears to be a globally inefficient process. The sum over our budget, expressed as a fraction of the critical Einstein–de Sitter density, is in the range $0.007 \lesssim \Omega_B \lesssim 0.041$, with a best guess of $\Omega_B \sim 0.021$ (at Hubble constant $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$). The central value agrees with the prediction from the theory of light element production and with measures of the density of intergalactic plasma at redshift $z \sim 3$. This apparent concordance suggests that we may be close to a complete survey of the major states of the baryons.

Subject headings: cosmology: observations — elementary particles — galaxies: fundamental parameters

**Classic Paper on this subject
Fukugita, Hogan, Peebles 1998**

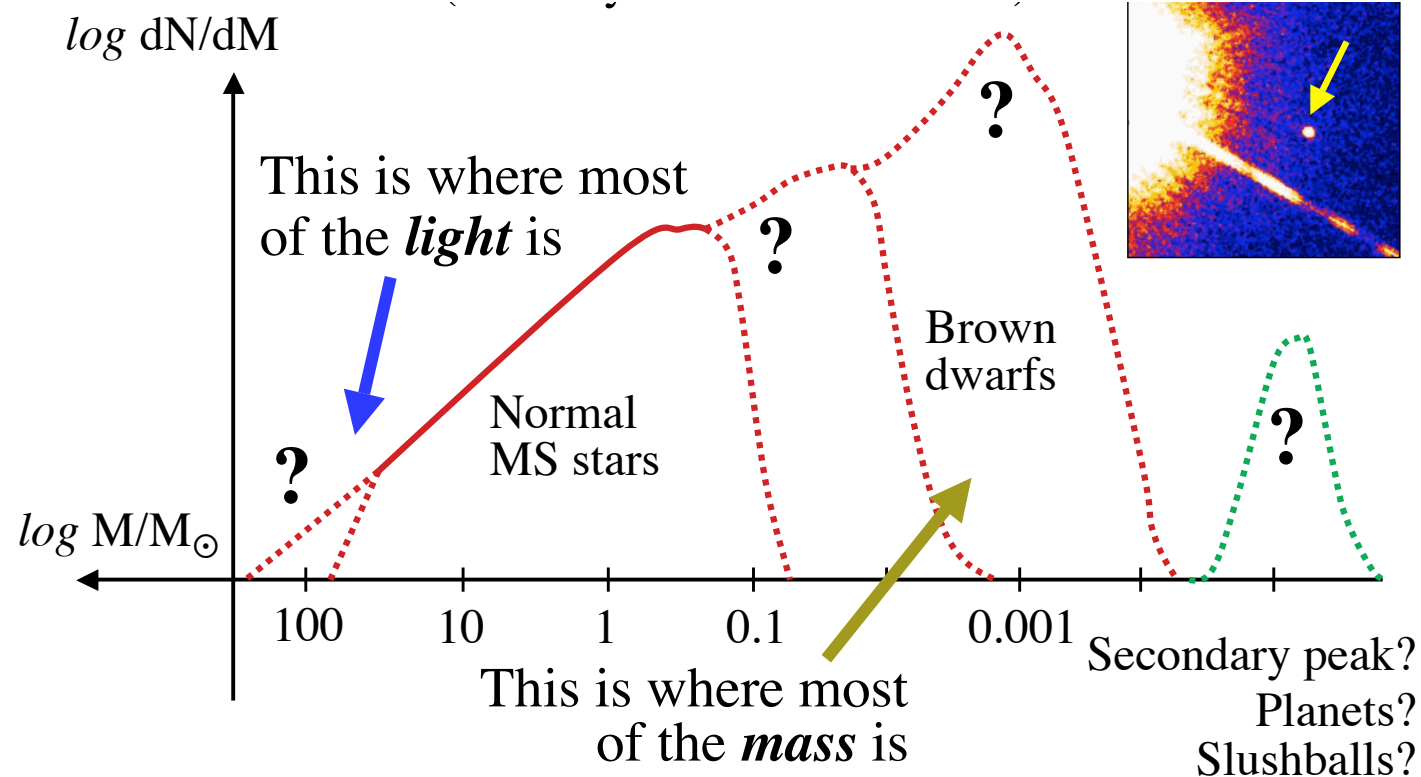
**What is the mass density in
stars?**

Since it is very easy to measure the light
coming from stars...

The challenge, of course, is in going from
light to mass

What is the mass density in stars?

The question can be challenging since stars have a wide range of masses: while most of light comes from the most massive stars, most of the mass comes from lower mass stars



So, an important assumption in measuring the mass in stars to make assumptions about the relative number of stars formed at all masses, i.e., the initial mass function

Credit: Djorgovski

What is the mass density in stars?

Assume that stars have always form with a certain distribution of masses

This is important since M/L ratio of stars depend on the mass

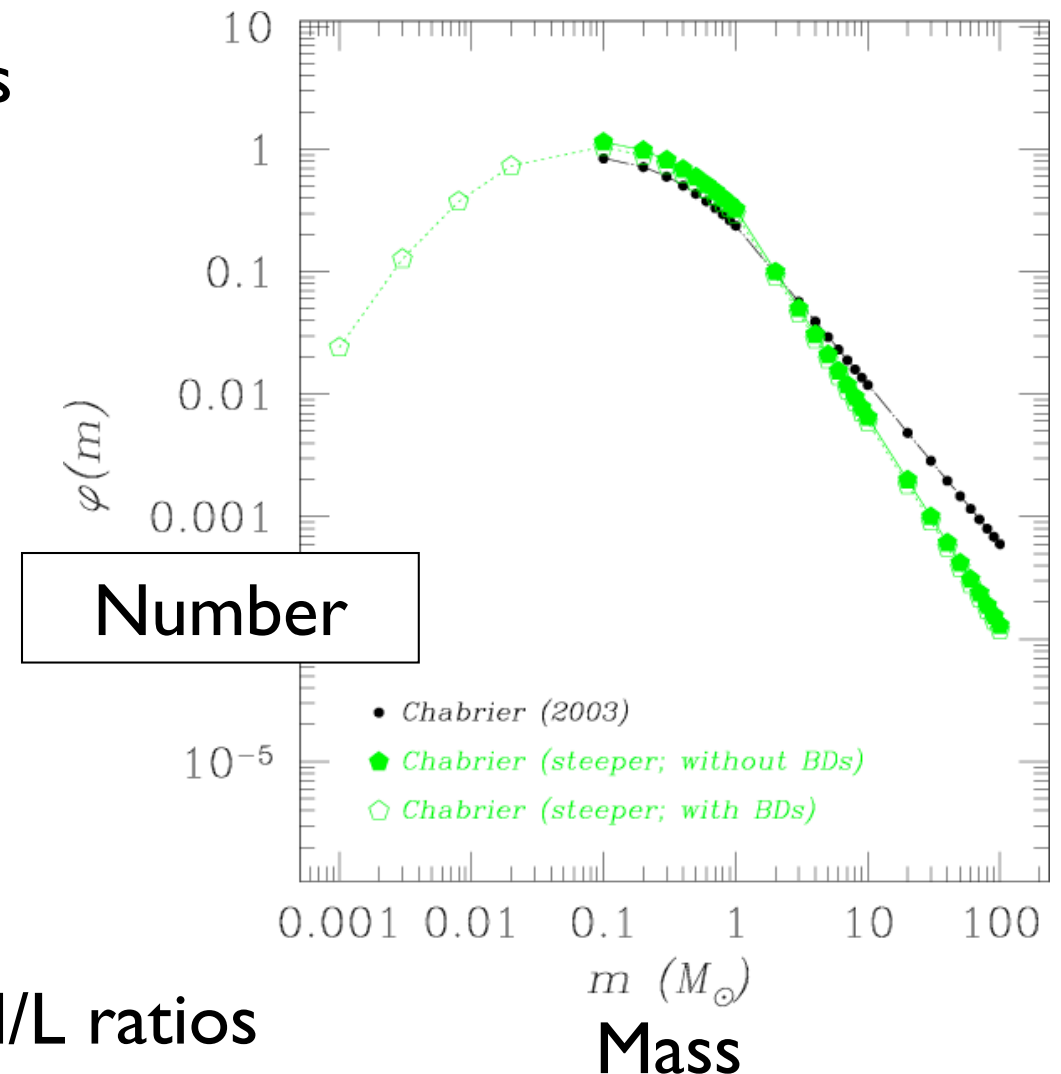
i.e., since $L \propto M^3$

then $M/L \propto M^{-2}$

low mass stars \rightarrow high M/L ratios

high mass stars \rightarrow low M/L ratios

Stellar Initial Mass Function



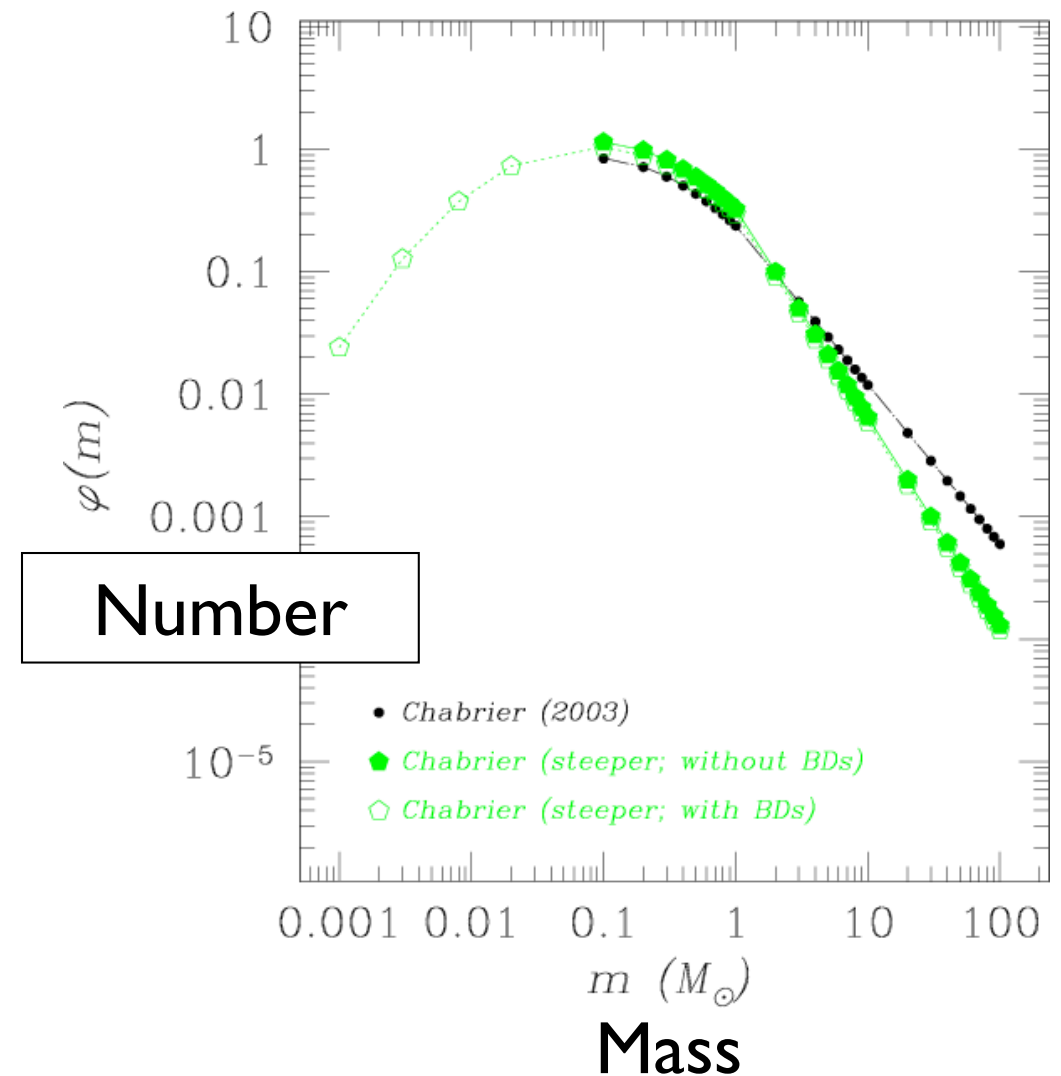
What is the mass density in stars?

Integrating over the Initial Mass Function, we can compute an average M/L ratio

But stars age...
the high mass stars use their fuel first

so the M/L ratio for a population of stars depends on its age

Stellar Initial Mass Function



What is the mass density in stars?

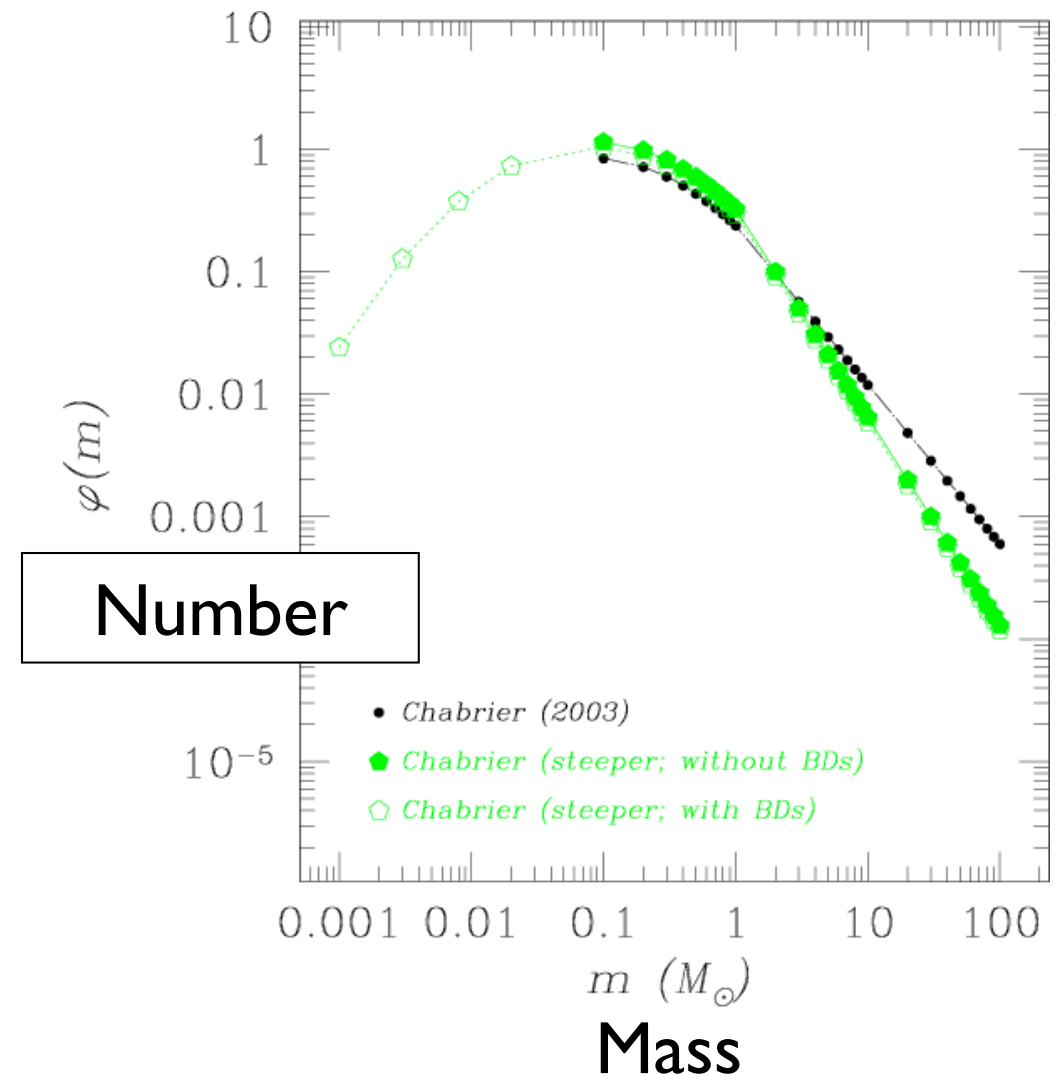
so the M/L ratio for a population of stars depends on its age

but we can estimate the age of a population from its colors

red galaxies → old

blue galaxies → young

Stellar Initial Mass Function



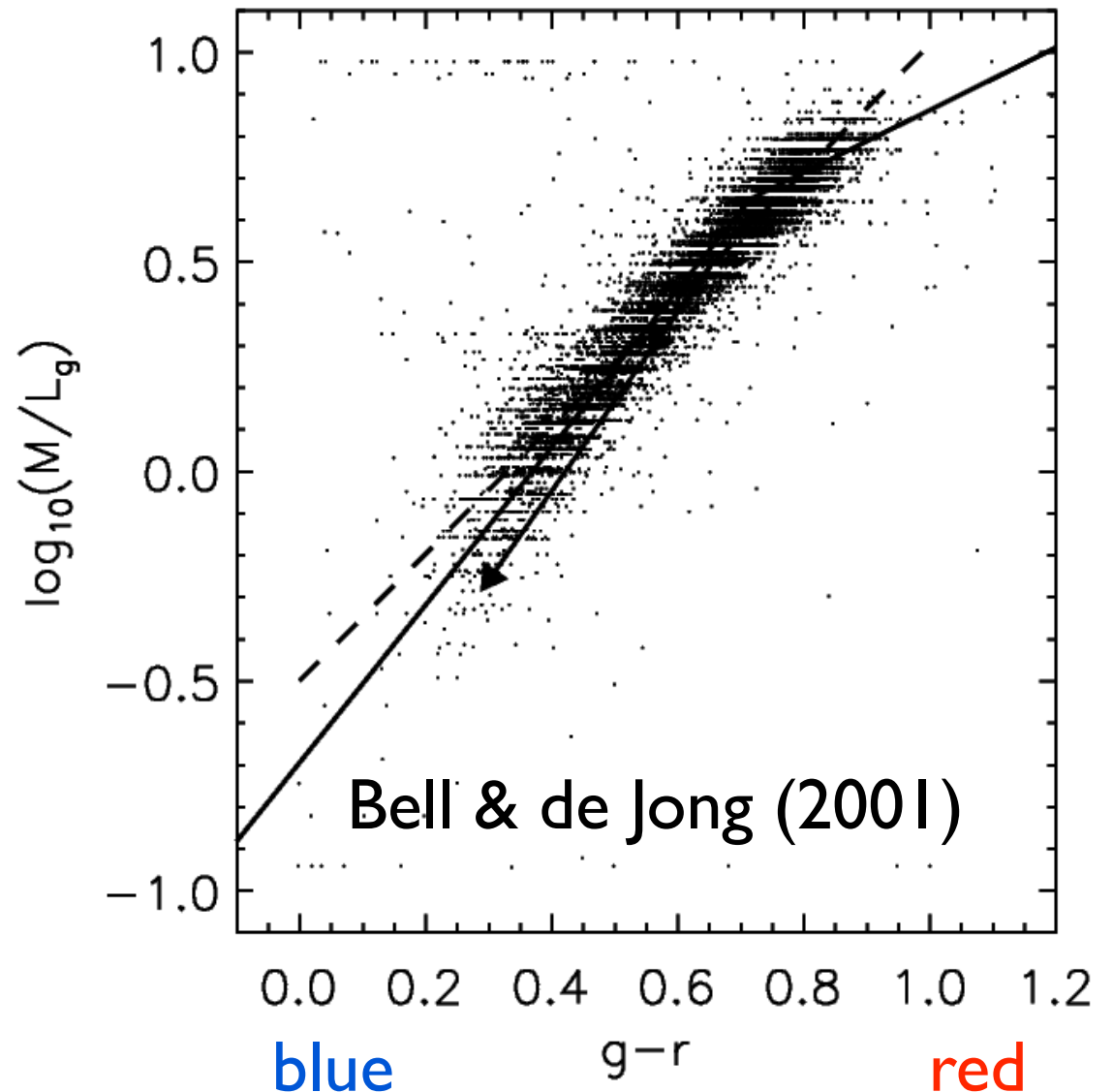
What is the mass density in stars?

M/L ratio vs. color

possible to relate
the M/L ratio to
the observed color of a
galaxy

$$\log_{10} M/L \sim -0.4 + 1.1 (g-r)$$

⇒ this allows us to
estimate the mass for
one galaxy at a time



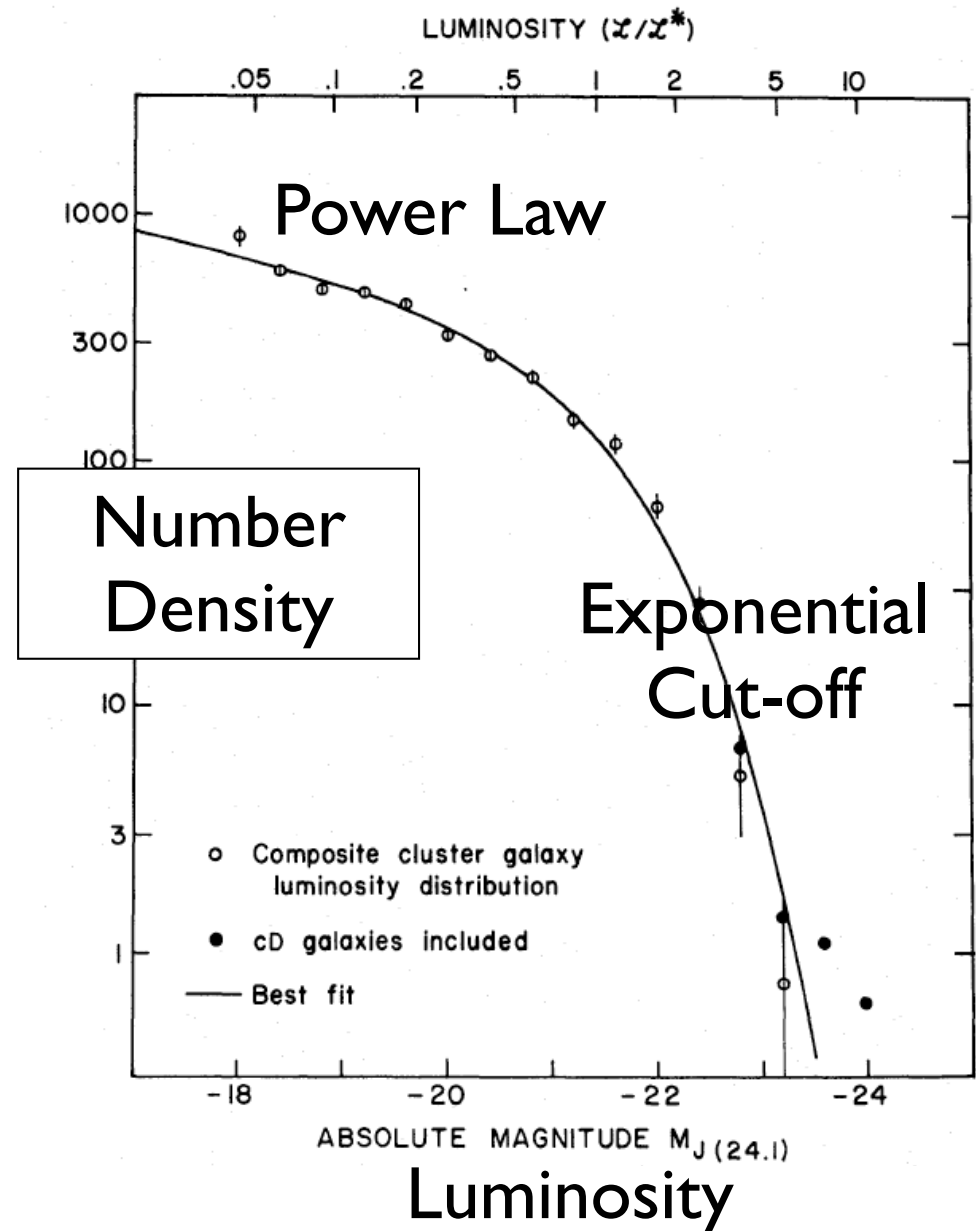
What is the mass density in stars?

Need to integrate up many from many galaxies using the observed luminosity function

Luminosity Function is found to have a Schechter distribution:

$$dN/dL = \Phi(L/L^*)^\alpha e^{-L/L^*}$$

Integrate over this function:

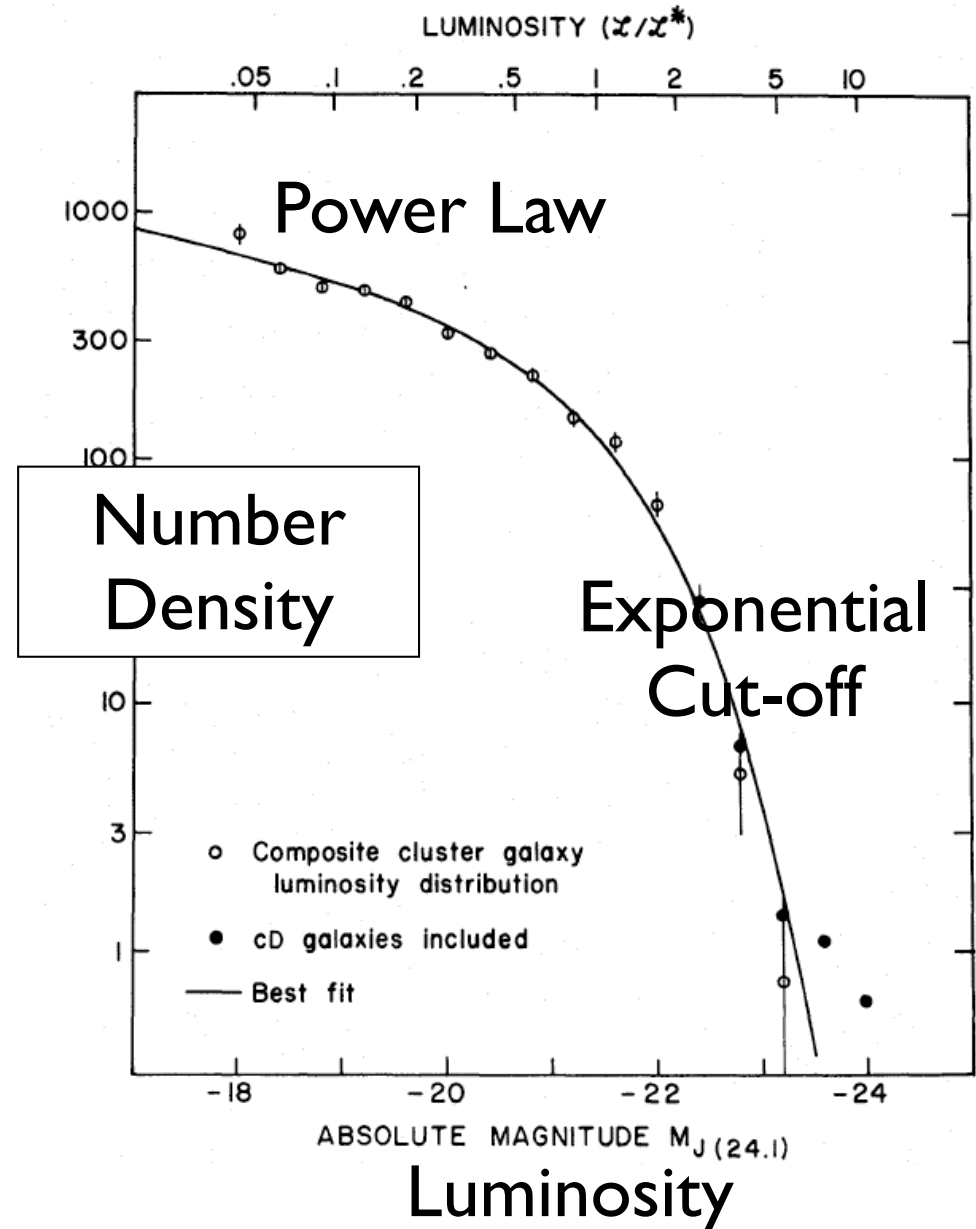


What is the mass density in stars?

Integrate over this function:

$$M_{\text{stars}} = 3 \times 10^8 M_{\text{sol}}/\text{Mpc}^3$$

$$\Omega_{\text{stars}} = 0.002$$



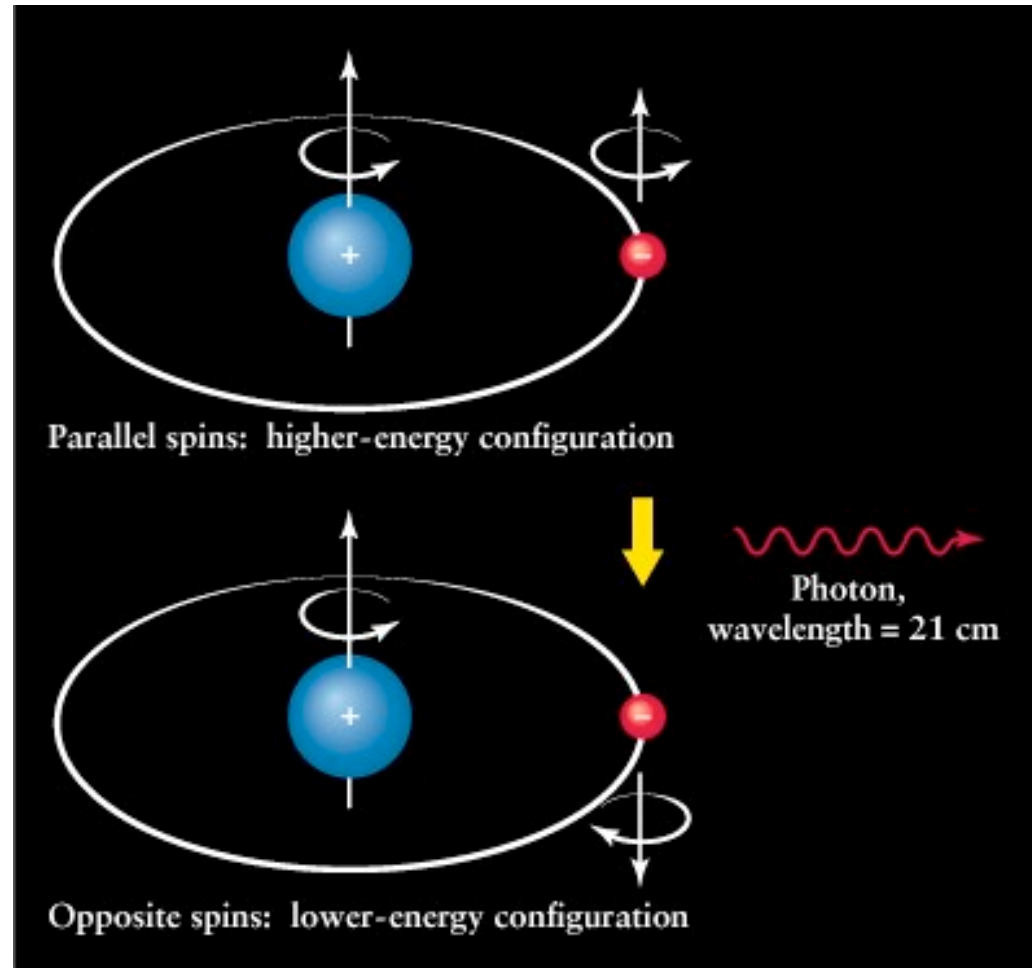
What is the mass density in
cold gas?

neutral atomic hydrogen
molecular hydrogen H_2

What about the mass density in neutral atomic hydrogen?

We can take advantage of the fact that neutral hydrogen has two different states that differ by a very small amount of energy.

Since the upper state is low enough energy that it is populated even at very low temperatures, one can observe quite a significant amount of light coming from galaxies at these frequencies.



b

What about the mass density in neutral atomic hydrogen?

Conduct blind surveys at
21 cm with radio
telescopes

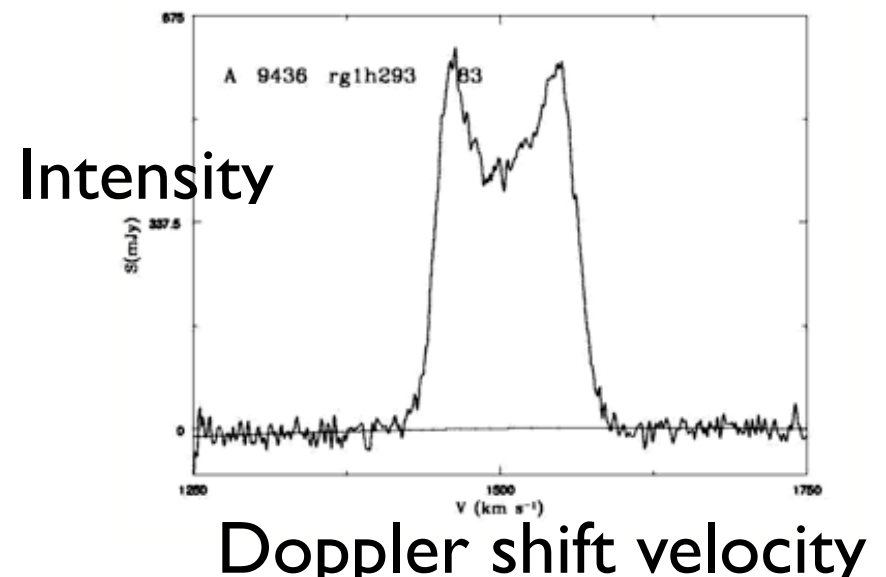


Arecibo or Parkes
(64 m dish)

$$\Omega_{\text{HI gas}} = 0.0003$$

Rao & Briggs (1993)

Here's what an
observation of a spiral
galaxy looks like at ~21
cm



What about the mass density in molecular hydrogen H₂?

Difficult to go out and search for H₂ since no
observable transitions (has no dipole)

To make progress, assume CO emission is a good tracer of
H₂ (CO emission caused by H₂ molecules colliding with CO)

Quantify ratio of atomic hydrogen to molecular hydrogen in
galaxies and then use this to convert from atomic hydrogen mass
density

$$\Omega_{\text{H}_2} = 0.0003$$

Fukugita et al. (1998)

Baryonic mass density

$$\Omega_{\text{stars}} = 0.002$$

$$\Omega_{\text{cold gas, HI}} = 0.0003$$

$$\Omega_{\text{cold gas, molecular hydrogen}} = 0.0003$$

$$\Omega_{\text{stars+gas}} = 0.0026$$

Baryonic mass density

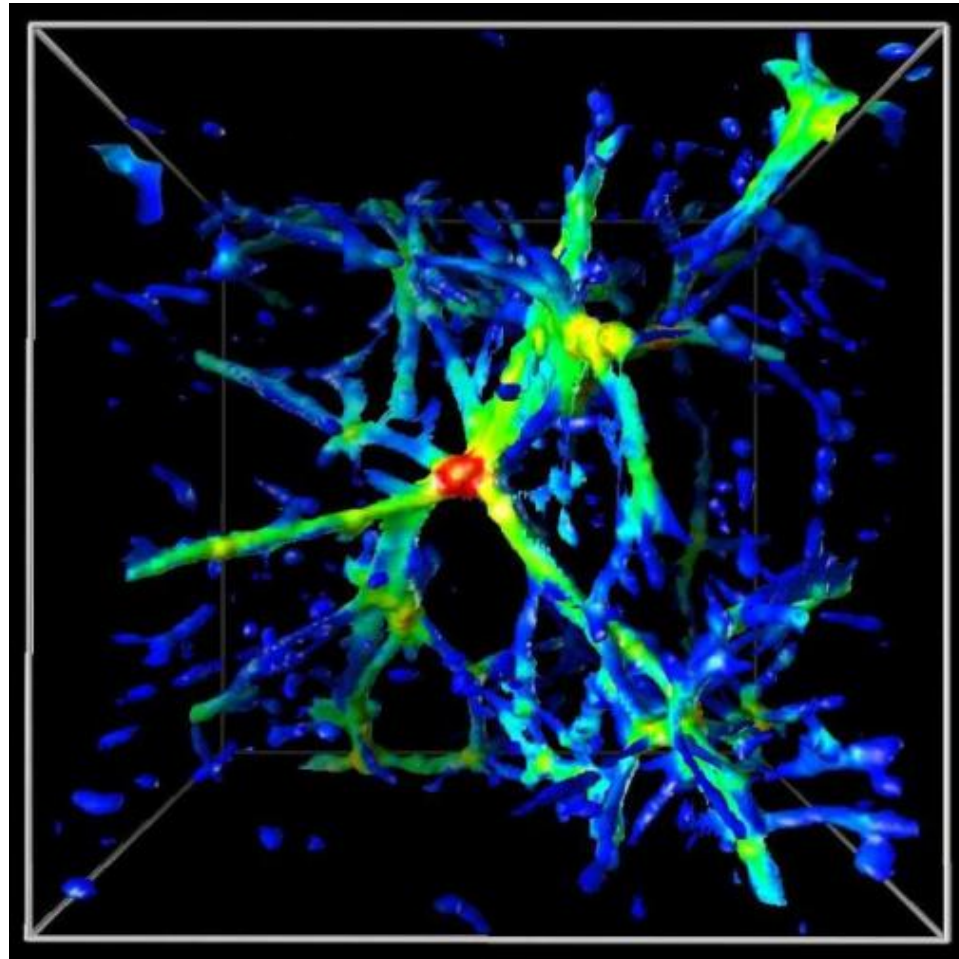
$$\Omega_{\text{stars+gas}} = 0.0026$$

(what we can easily detect)

but this is a small fraction (<10%) of
the value we prefer today $\Omega_{\text{baryons}} = 0.04$

where are the rest?

Missing baryons are thought to be a warm/hot ionized gas

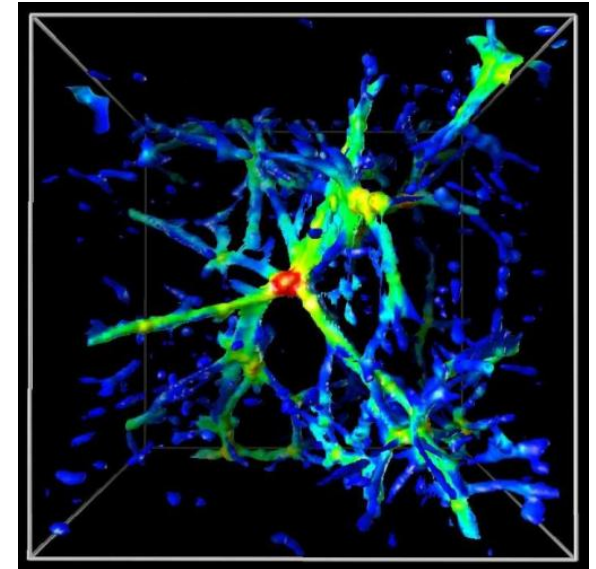


Can we measure the total mass density in this warm, hot ionized material?

Would expect ionized material to emit thermal bremsstrahlung radiation, but neither dense enough or hot enough to produce enough flux to observe with x-ray satellites

Therefore need to detect the material by looking for evidence for absorption in light from bright background source

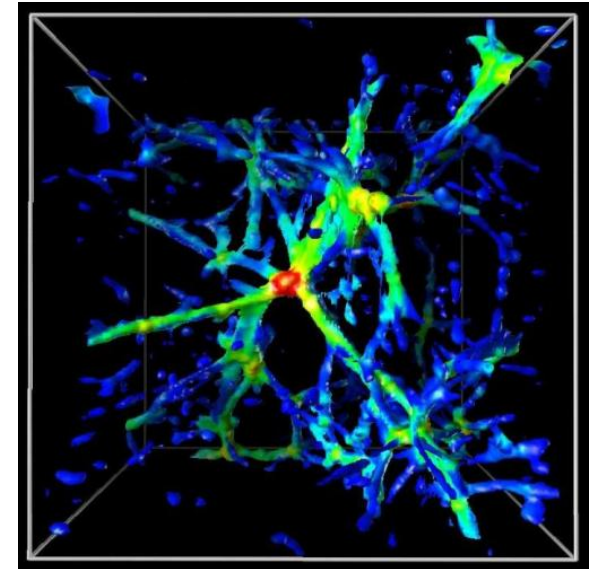
Note: This is different than large galaxy clusters -- where the ionized gas is hotter and denser!



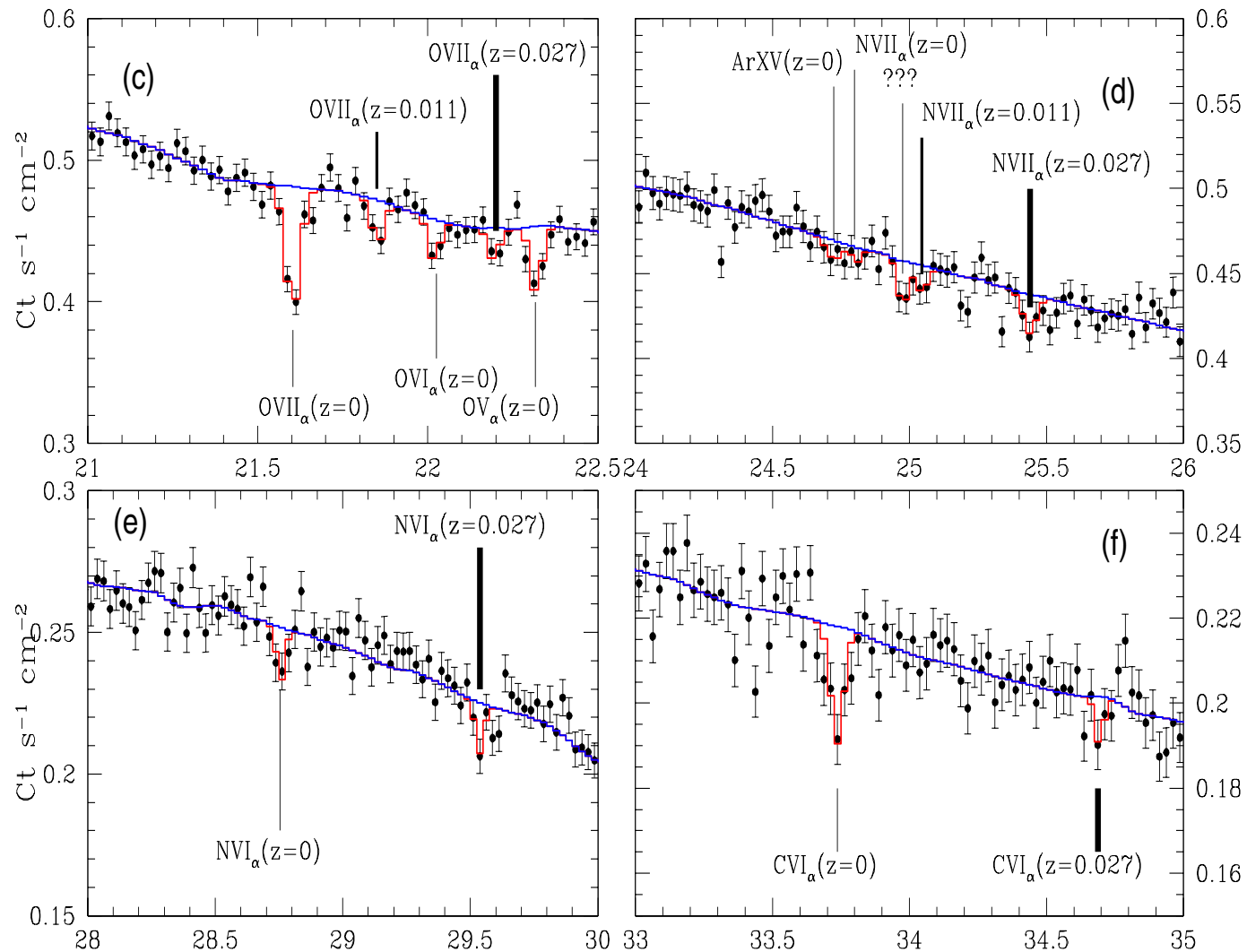
Can we measure the total mass density in this warm, hot ionized material?

However it is not sufficient to just look for absorption in a normal bright x-ray source.

We need to wait for a flare up in activity of a blazar (active galactic nucleus with radio jet pointed towards us) to have something bright enough to find these lines



Example of such an attempt to find absorption lines through absorption in an x-ray spectrum

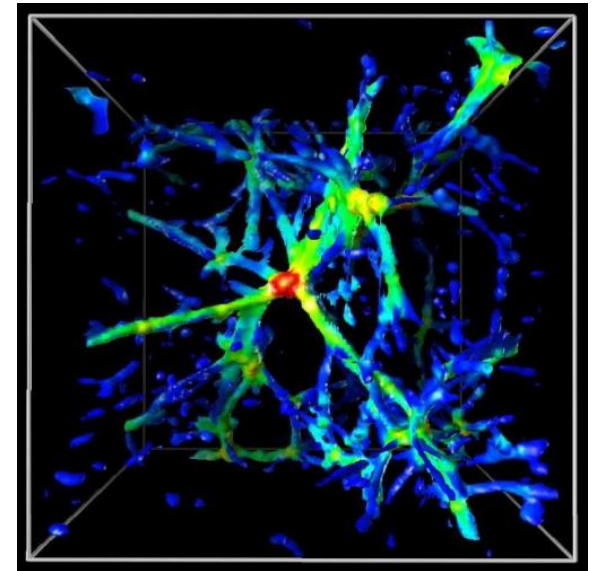


Can we measure the total mass density in this warm, hot ionized material?

Based on these absorption lines in the blazar, estimates for the mass in the WHIM are

$$\Omega_{\text{WHIM}} = 0.02$$

Nicastro et al. (2004)



For all but the most energetic and radiative materials in the distant universe, it is often easier to infer the presence of a substance through absorption rather than emission

The total mass density in the warm-hot IGM was supposed to be measured quite definitively with a future satellite Constellation X:

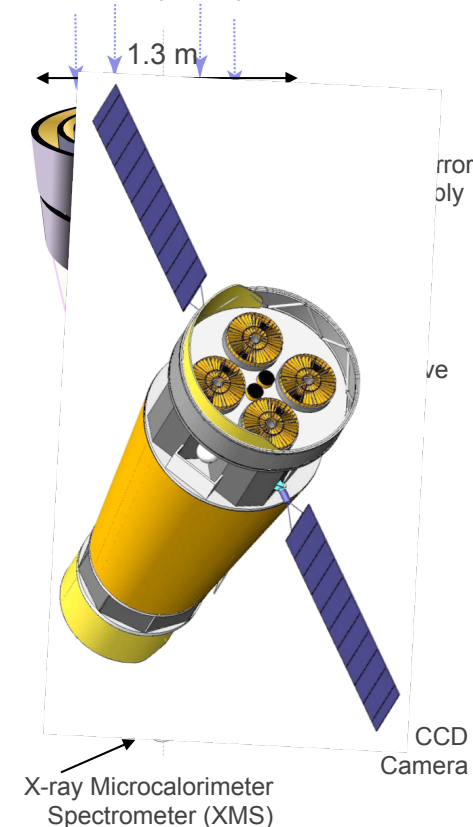
Beyond Einstein: From the Big Bang to Black Holes

Constellation X
The Constellation X-ray Mission

Mission Implementation

- 4 Spectroscopy X-ray Telescopes (SXTs) each consisting of a Flight Mirror Assembly and a X-ray Microcalorimeter Spectrometer (XMS)
 - Covers the band-pass from 0.6 to 10 keV
 - Angular resolution requirement of 15 arc sec (goal of 5 arc sec HPD)
 - Field of View 5 x 5 arc min (64x64 pixels, goal of 10 x 10 arc min FOV)
 - Count rates: 1/4 crab or 1,000 ct/sec/pixel
- Two additional systems extend the bandpass:
 - X-ray Grating Spectrometer (XGS) covers from 0.3 to 1 keV (included in one or two SXT's)
 - Hard X-ray Telescope (HXT) band-pass covers from 6 to 40 keV (not shown)
- All instruments operate **simultaneously**

4 Spectroscopy X-ray Telescopes



Where are the Baryons: Searching in the UV and X-ray Bands

Many of the predicted baryons have **not** been detected in the local Universe

- Most are thought to reside in a hot $10^6 - 10^7$ K intergalactic medium

Terminated by NASA due to
a lack of funding

There is an effort to see if a
cheaper alternative exists that can
accomplish same science goals

Baryonic mass density

$$\Omega_{\text{stars}} = 0.002$$

$$\Omega_{\text{cold gas, HI}} = 0.0003$$

$$\Omega_{\text{cold gas, molecular hydrogen}} = 0.0003$$

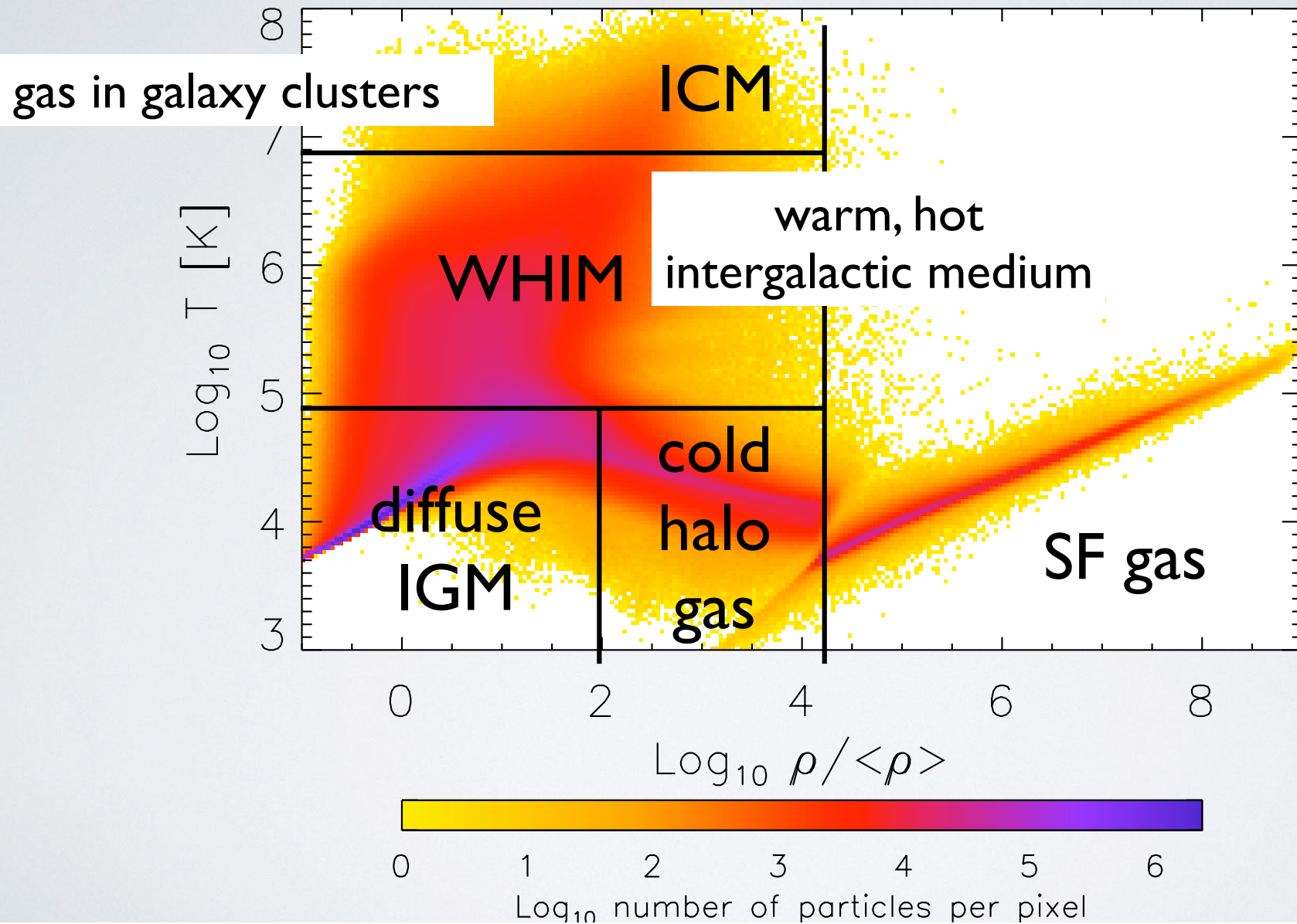
$$\Omega_{\text{ionized hydrogen}} = 0.02$$

$$\Omega_{\text{total}} = 0.0226$$

Multi-phase Diagram from Cosmological Hydrodynamical Simulation

Showing where the Baryons Are Predicted to be:

$z = 2$



van der Voort et al. 2011 (was a student of Joop Schaye here)

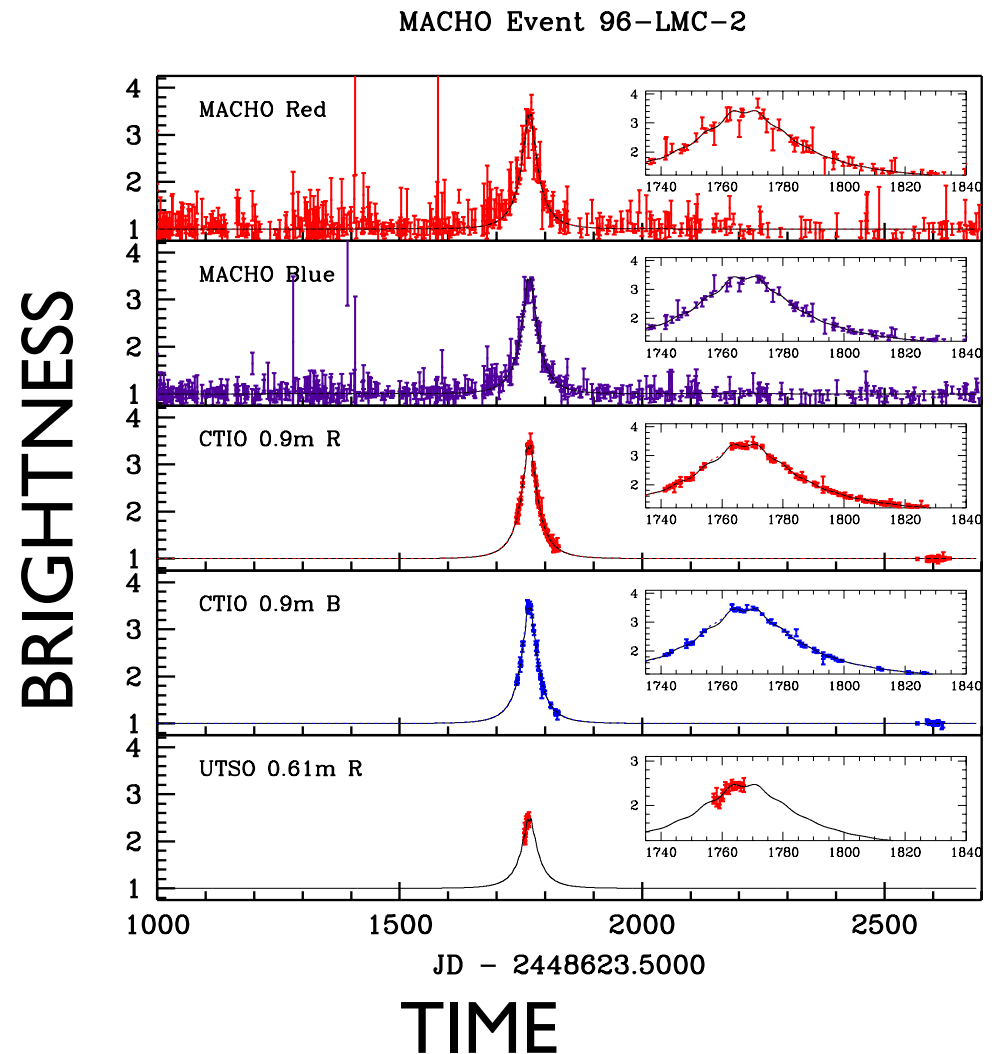
Missing baryons were thought
to possibly be in MACHOs
(massive compact halo objects)

i.e., white dwarfs, neutron stars, black holes, Jupiter
mass sources

(investigated extensively in
mid 1990s)

How did people search for MACHOs?

- observe millions of stars in the Large Magellanic Cloud...
- wait for some star to brighten because compact object passes in front of it
- a few events are found in such experiments, but seem to be consistent with self lensing
- no evidence MACHOs contribute significantly to baryonic matter density



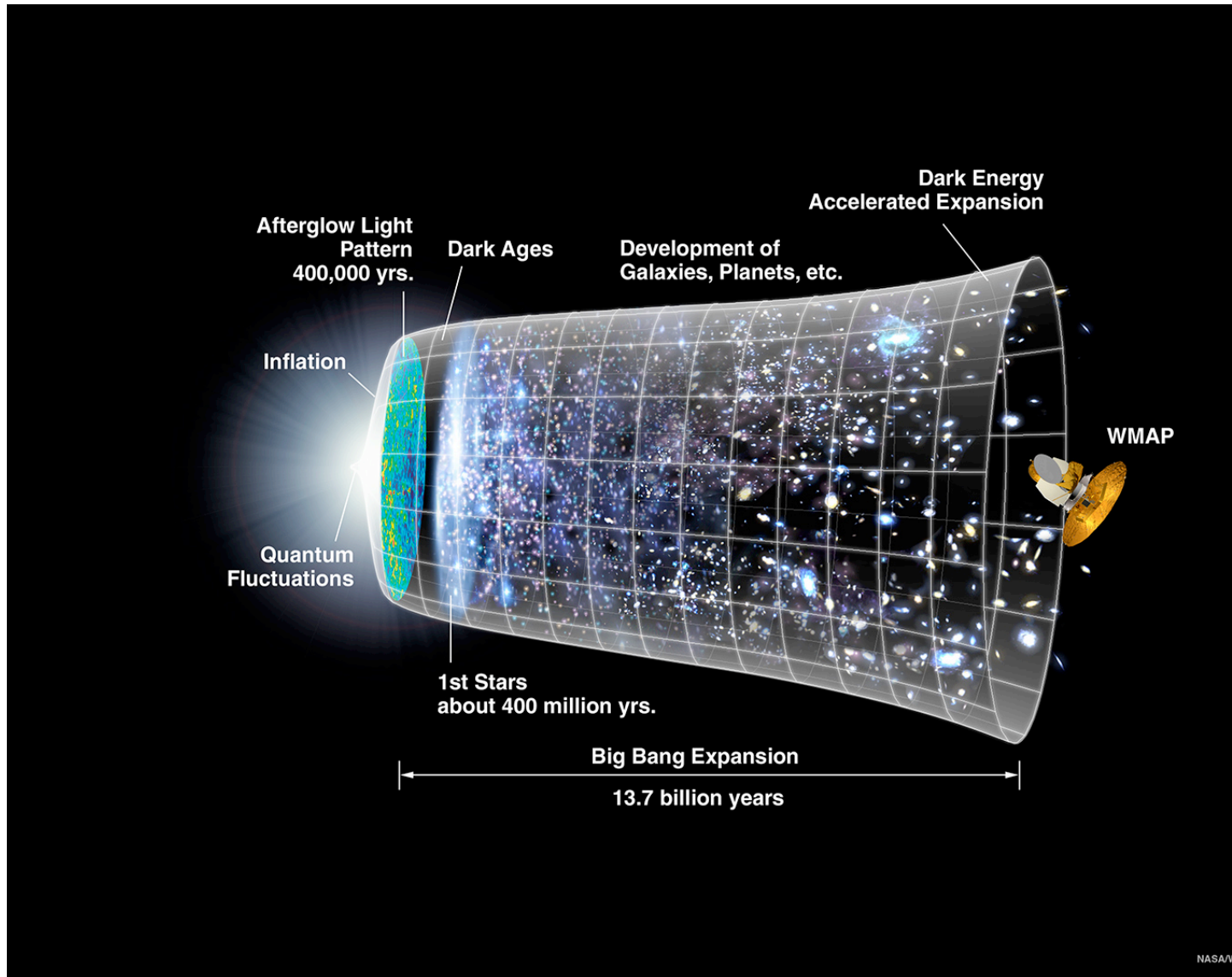
But where does this
number $\Omega_{\text{baryon}} = 0.04$
come from?

Big Bang Nucleosynthesis

“Nuclear fusion in early Big Bang”

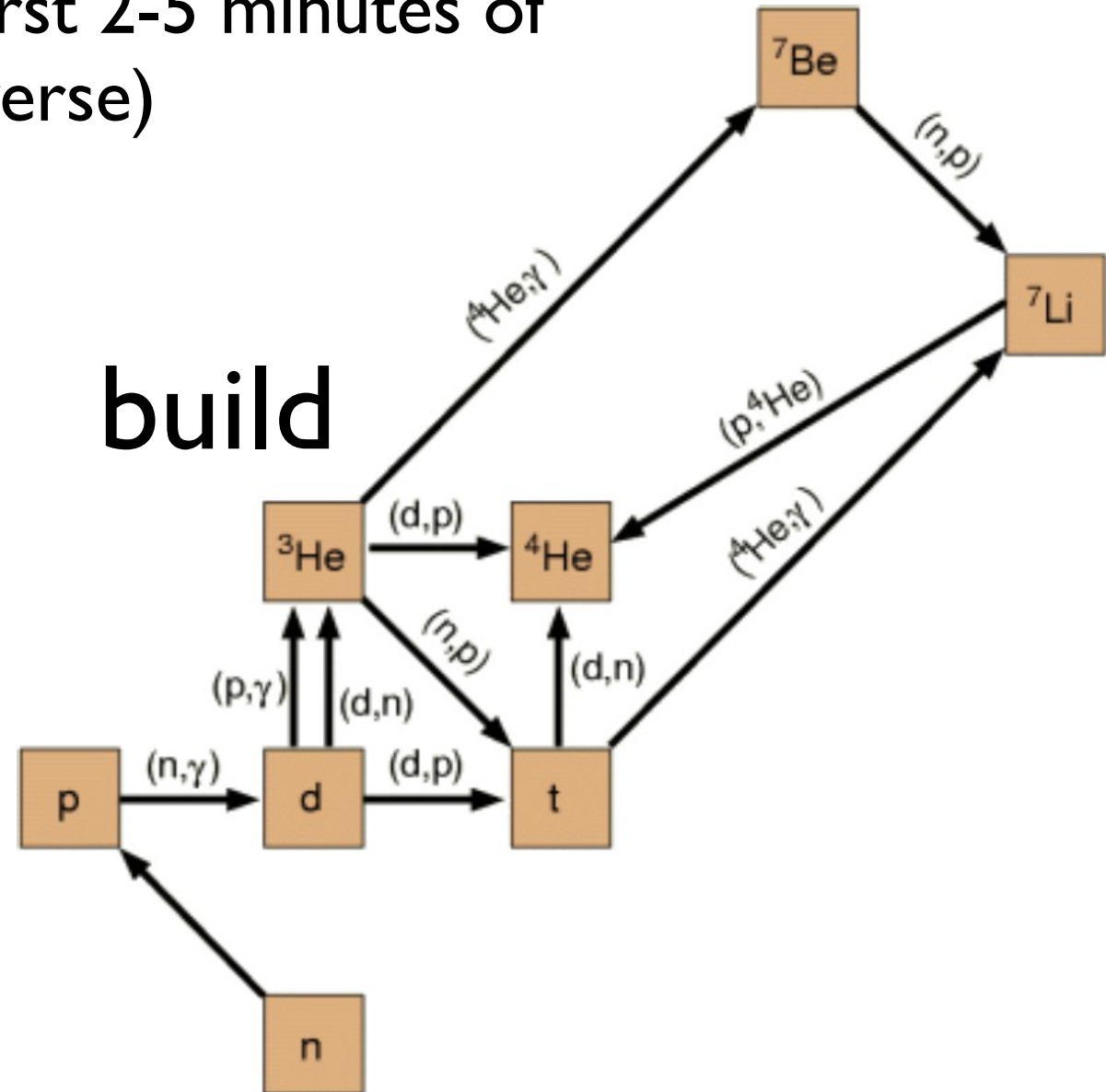
(though we can also derive it using the CMB observations)

You all probably have a rough idea about the approximate history of the universe



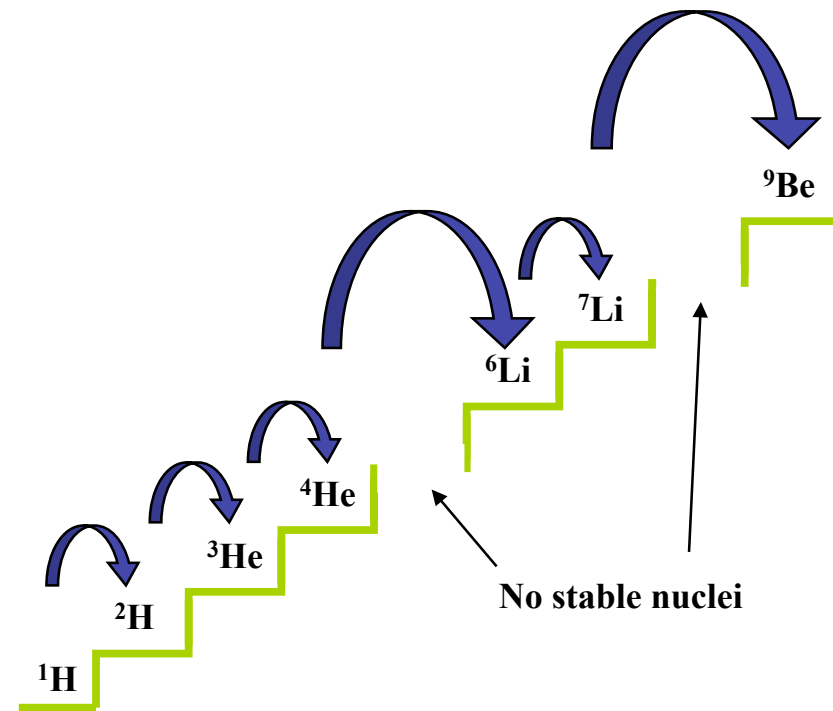
How do heavier elements build up?

(occurs during first 2-5 minutes of universe)



Stable mass gaps in the periodic table

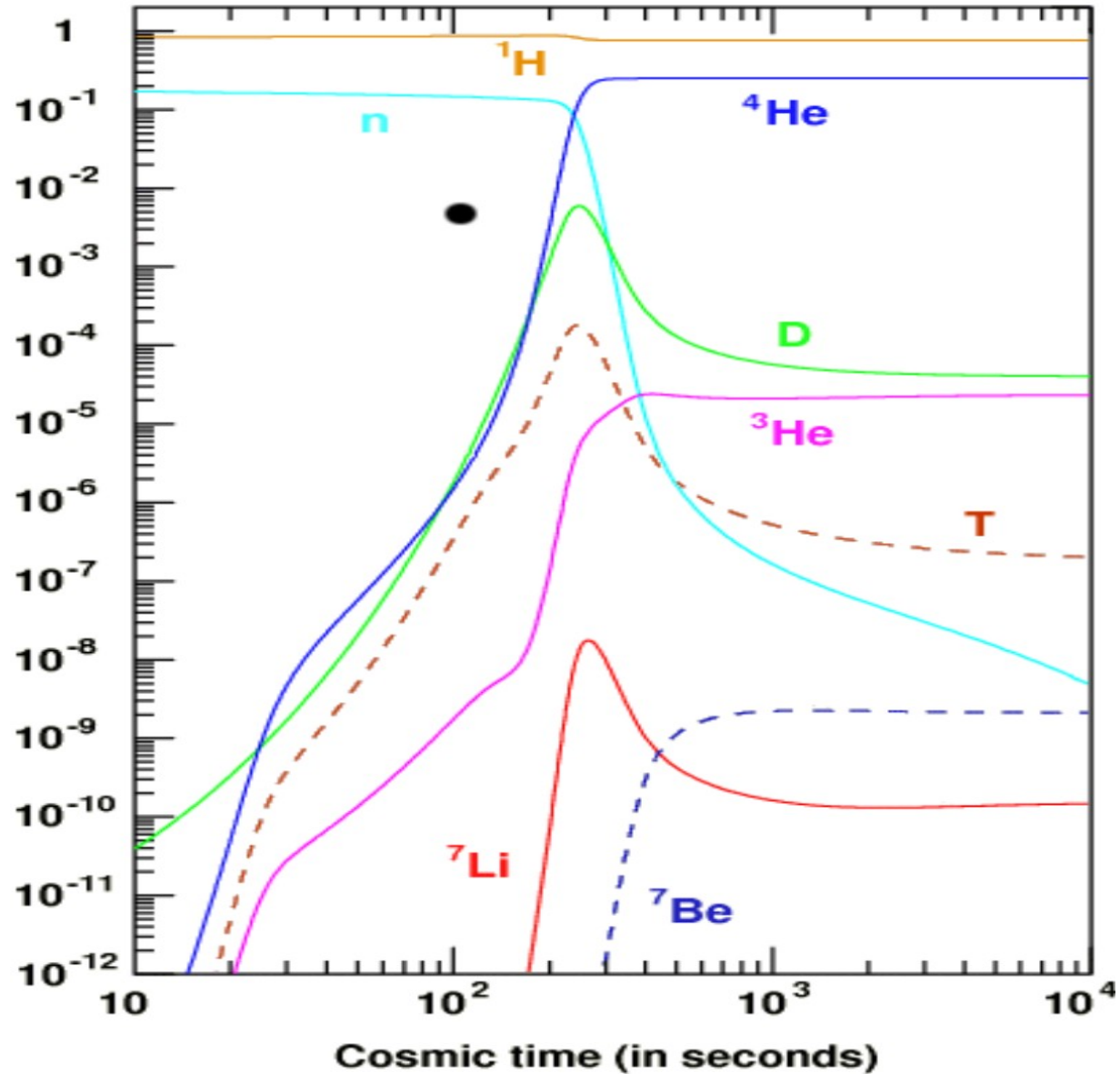
1																	2							
H																	He							
3	4											5	6	7	8	9	10							
Li	Be											B	C	N	O	F	Ne							
11	12											13	14	15	16	17	18							
Na	Mg											Al	Si	P	S	Cl	Ar							
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36							
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr							
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54							
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe							
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86							
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn							
87	88	89	104	105	106	107	108	109	110															
Fr	Ra	Ac	Unq	Unp	Unh	Uns	Uno	Une	Umn															
											58	59	60	61	62	63	64	65	66	67	68	69	70	71
											Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
											90	91	92	93	94	95	96	97	98	99	100	101	102	103
											Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



The lack of stable elements with masses 5 and 8 make it more difficult for cosmic nucleosynthesis to progress beyond Lithium and even Helium.

How do abundances depend on time?

Fraction of Mass
Density



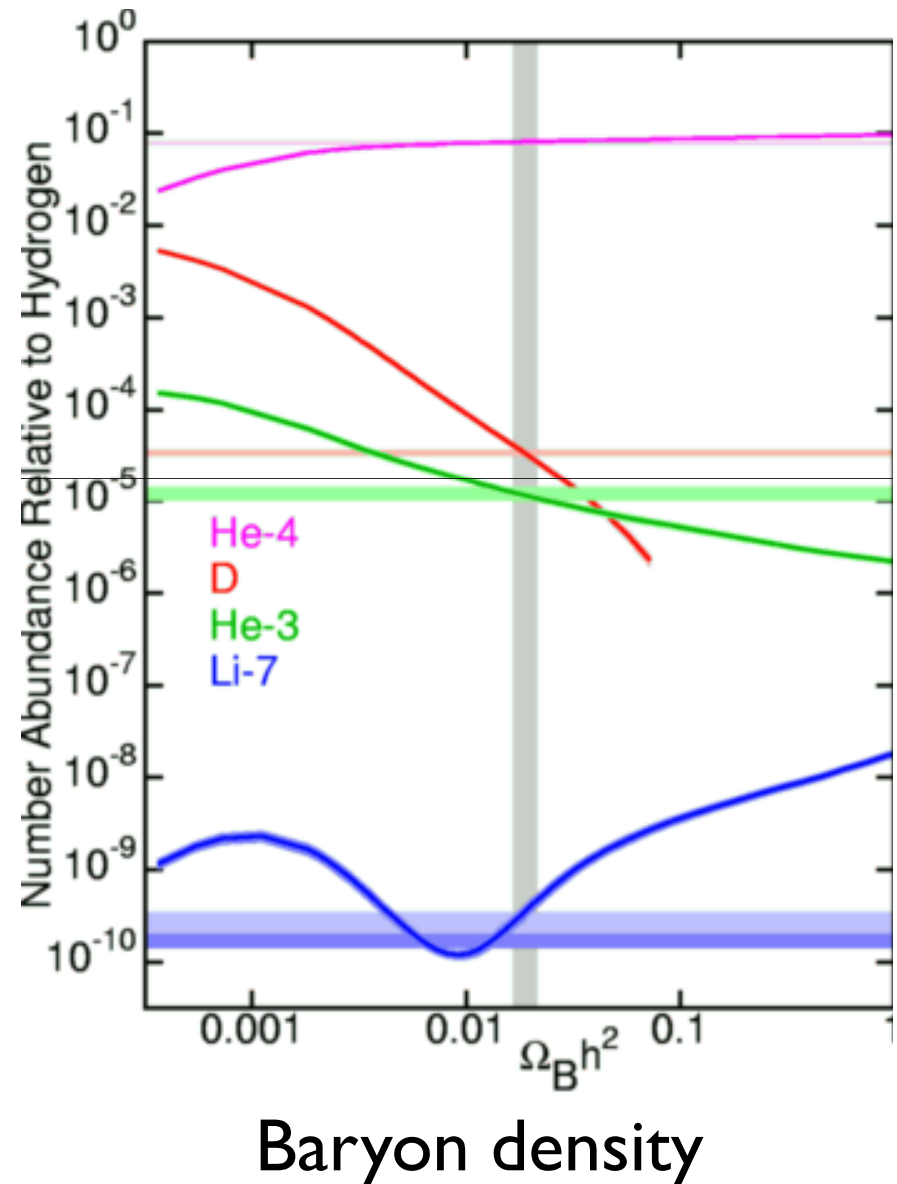
But what does this teach us
about the matter density in
baryons?

Abundance of heavier elements synthesized depends on baryon density

Reaction Rate \propto baryon density

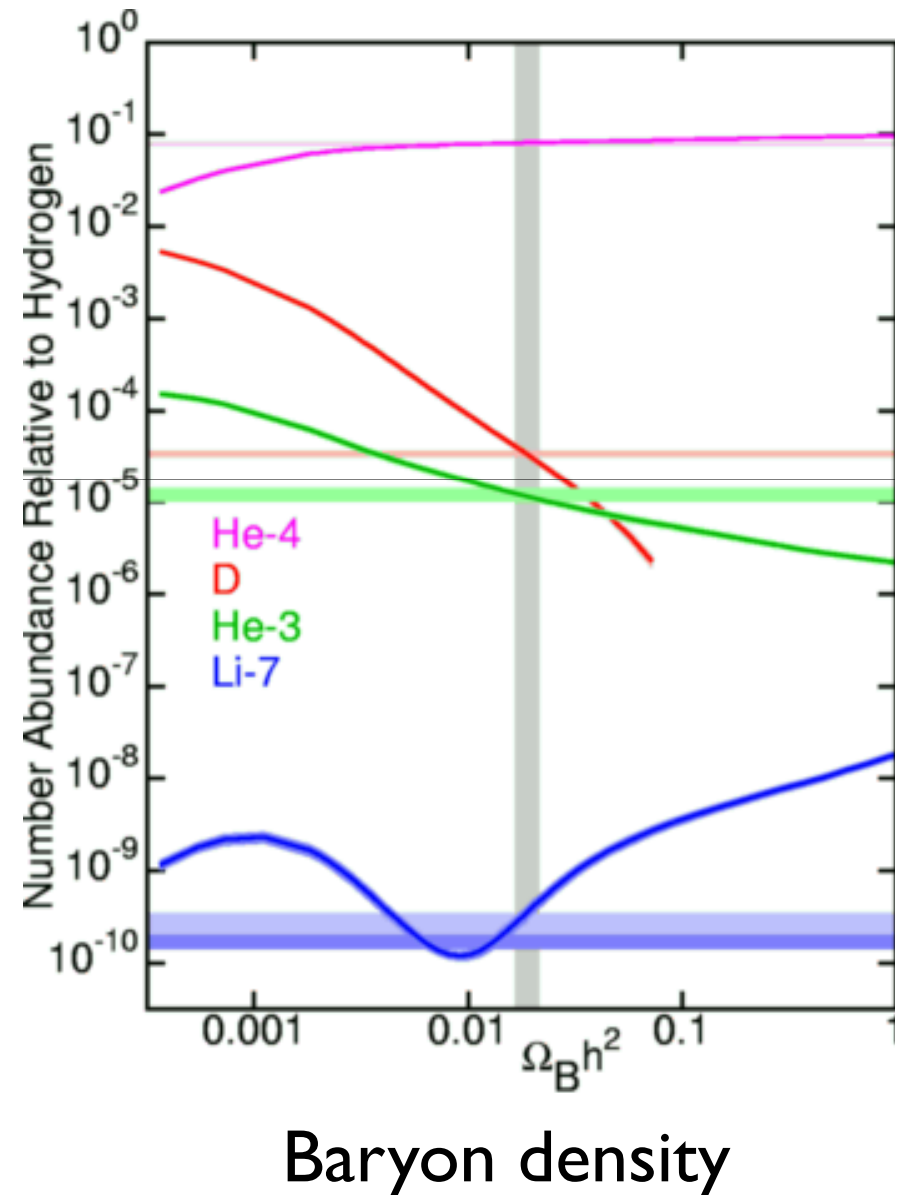
He⁴ is much more stable species, so it increases in proportion to baryon density

Note: The time scale during which nucleosynthesis can occur is almost independent of the baryon density -- since the energy density of the universe dominated by radiation at early times



Abundance of heavier elements synthesized depends on baryon density

IMPLICATION: If we can determine what the abundance of the above elements is relative to hydrogen, we can determine the baryon density in the universe at early times...



So how can we go out and determine what the abundance of these heavier elements is relative to hydrogen?

The challenge is that the universe has not been held in a constant state, there are stars, and they destroy some elements and create others...

Challenge is that:

D → readily destroyed in stars from fusion

He^4 → easily produced from fusion

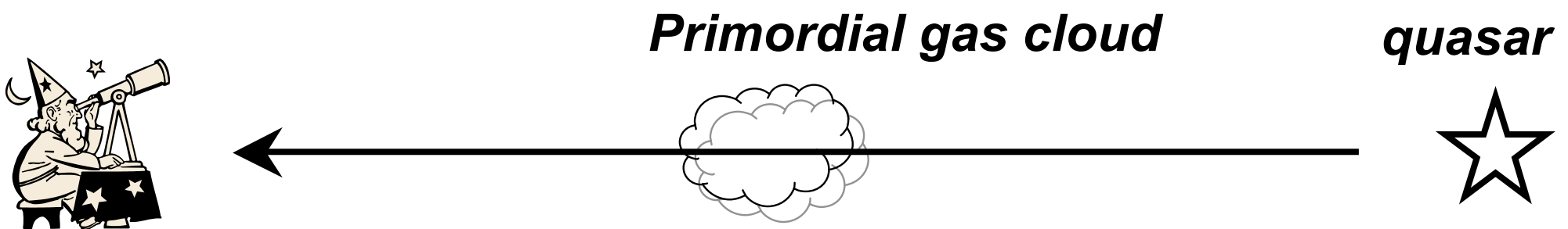
Li^7 → easily destroyed in stars from fusion
→ may be created by cosmic-ray spallation in the
interstellar medium

He^3 → produced by burning deuterium
→ destroyed to produce He^4

How might we determine the primordial abundances then?

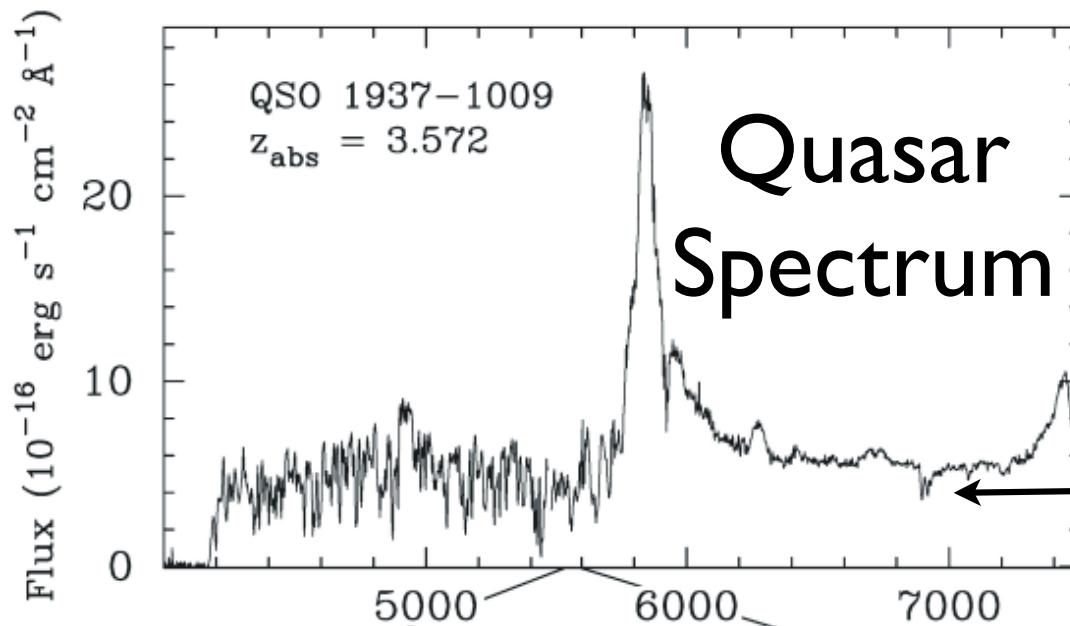
For deuterium:

Observe some gas cloud in early universe where stars have not yet formed and look for absorption by hydrogen and deuterium:

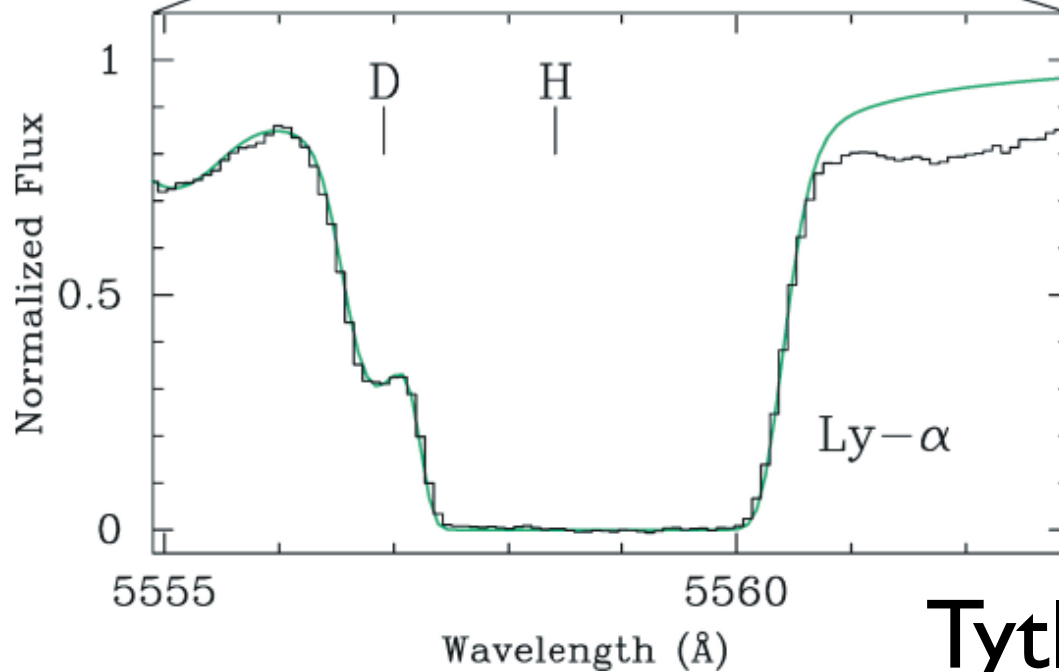


Very bright sources like quasars needed so we infer the presence of rare elements in gas clouds through weak absorption features

What do these spectra look like?

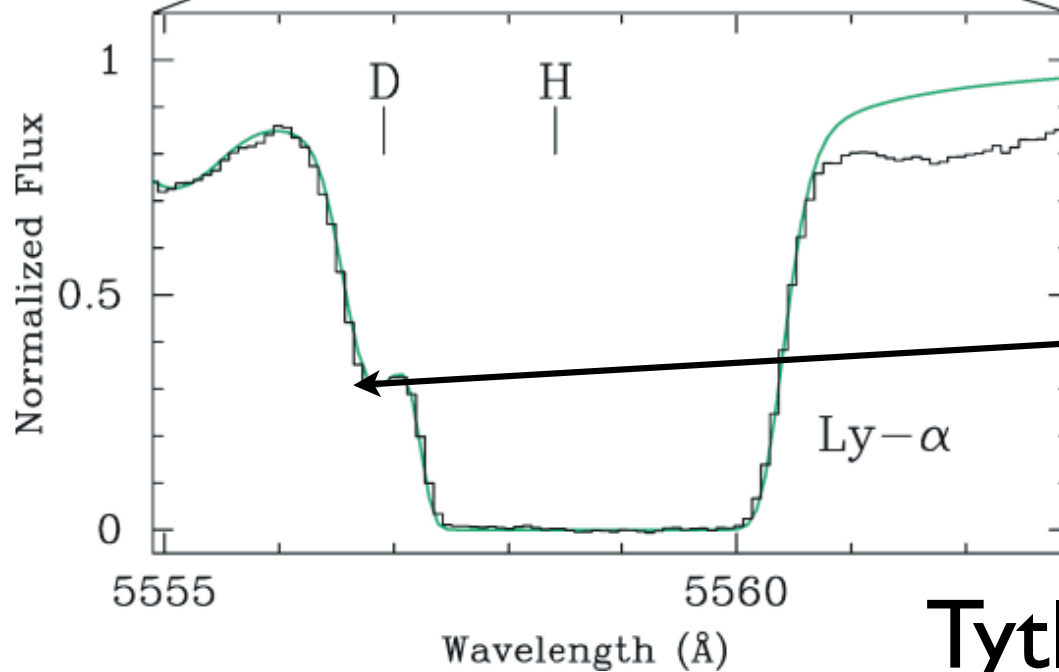
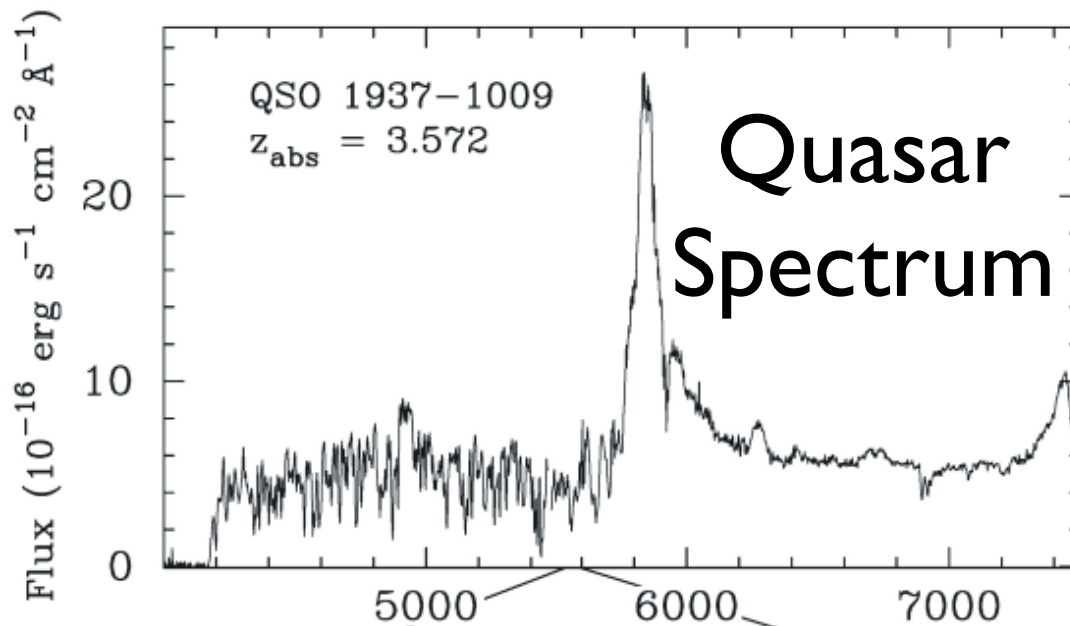


Verify that the gas cloud shows no evidence for being polluted by heavier elements (this ensures deuterium abundance not affected)



Tytler & Burles

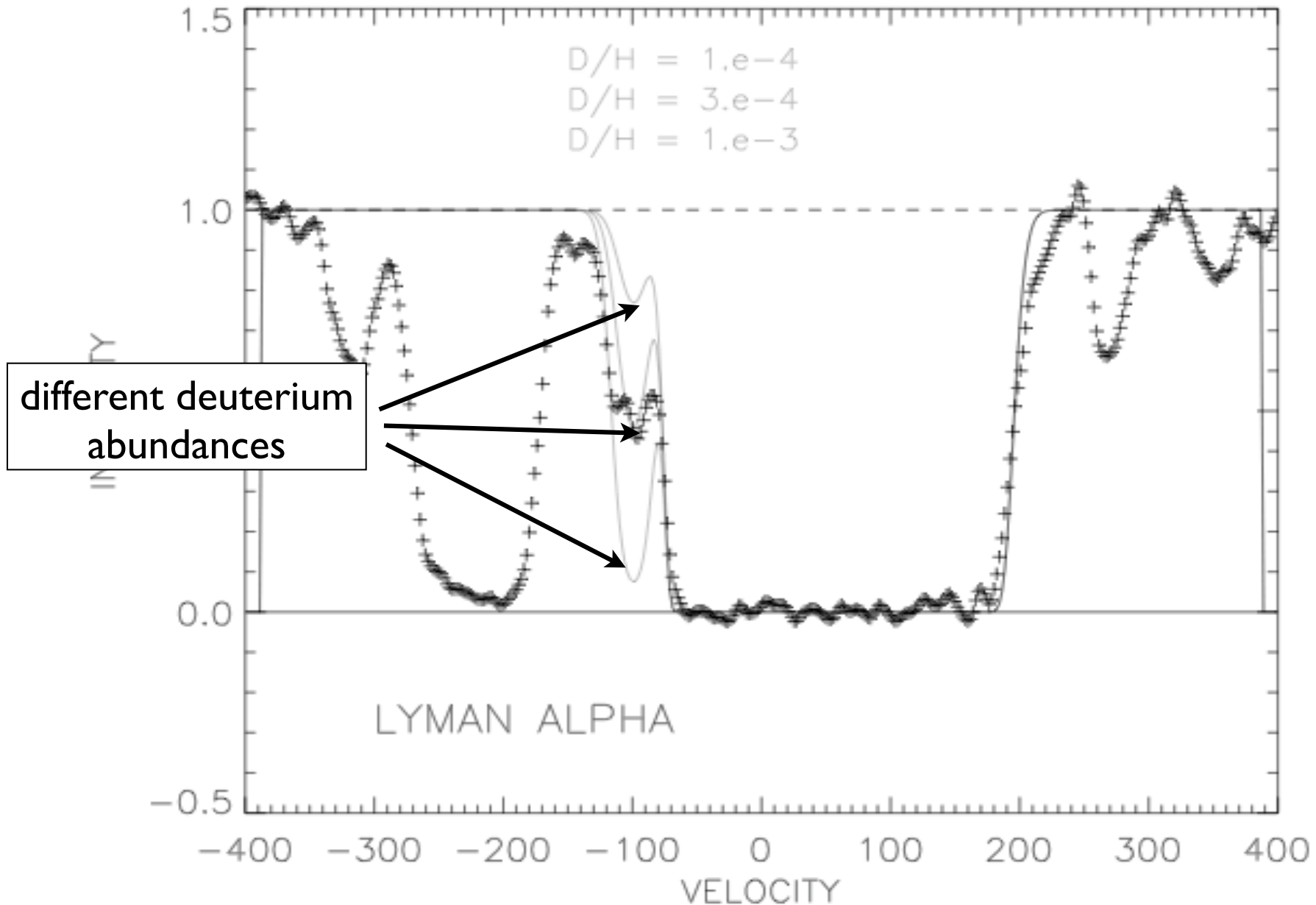
What do these spectra look like?



Need to be sure this isn't just another cloud of cold gas at different redshift

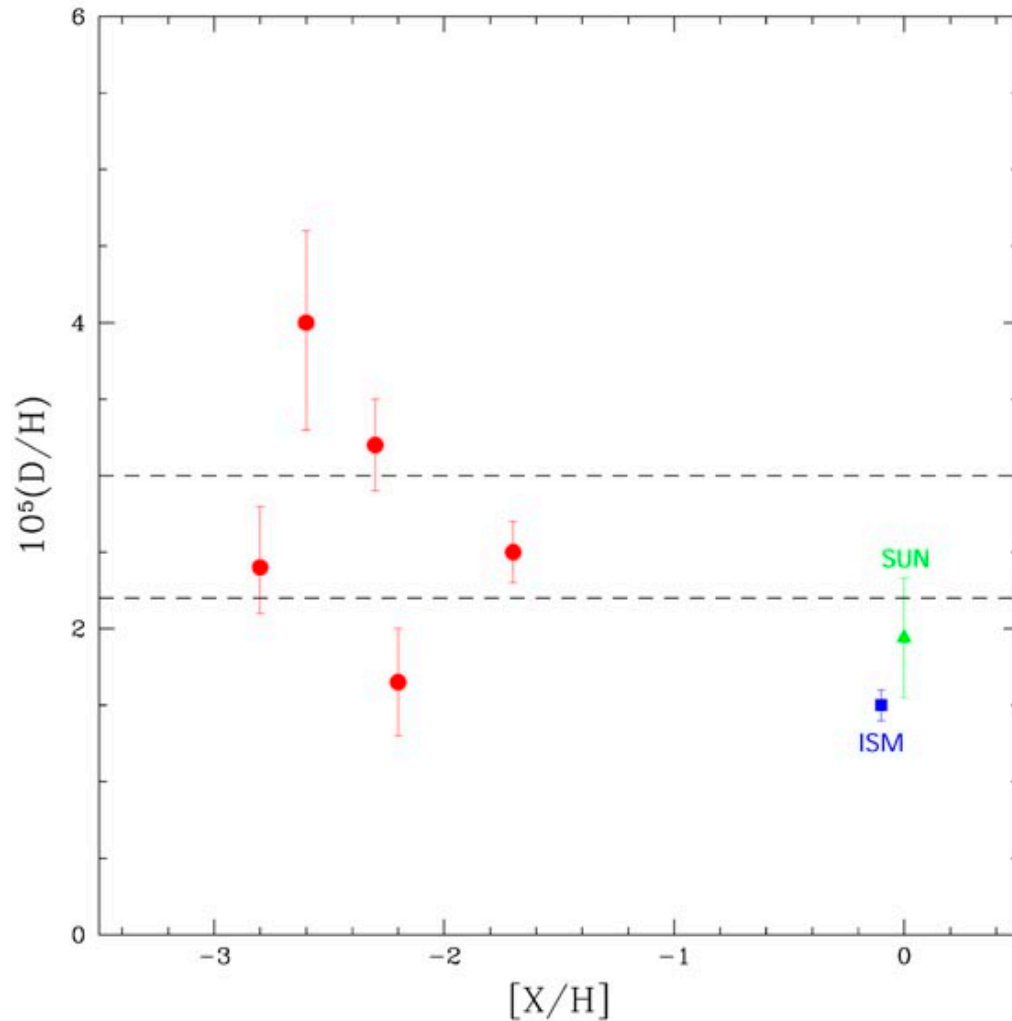
Tytler & Burles

How might the observations look different with another deuterium abundance?



What results have been found for deuterium?

For deuterium:



$$[D/H] \sim 3 \times 10^{-5}$$

How might we determine the
primordial abundances then?

For He⁴

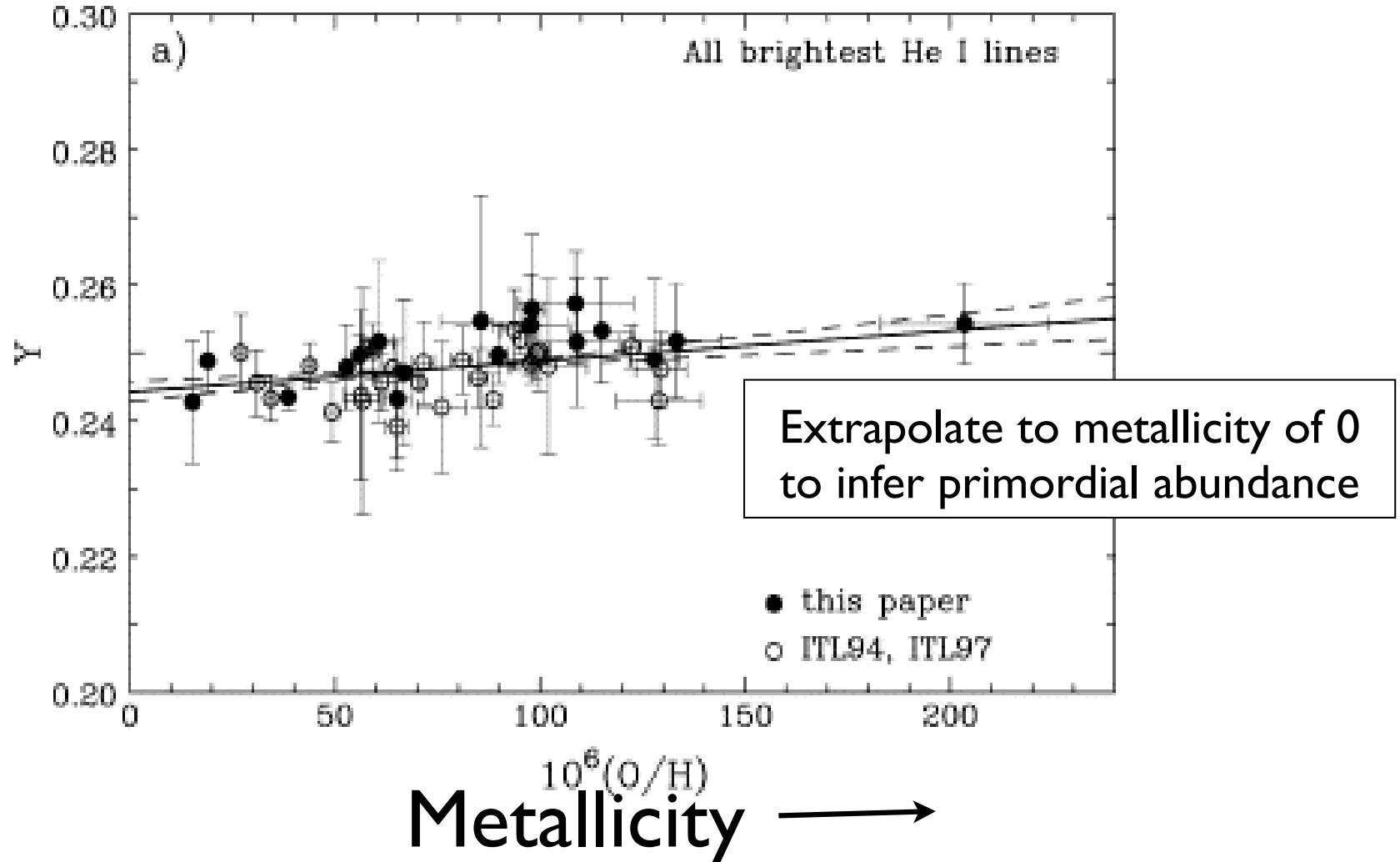
Recombination lines from HII
regions in low metallicity galaxies

Measure abundance ratios of many
elements He, O, N, H

How might we determine the primordial abundances then?

For He⁴

mass
fraction
of
baryons
in He⁴



How might we determine the primordial abundances then?

For Li^7

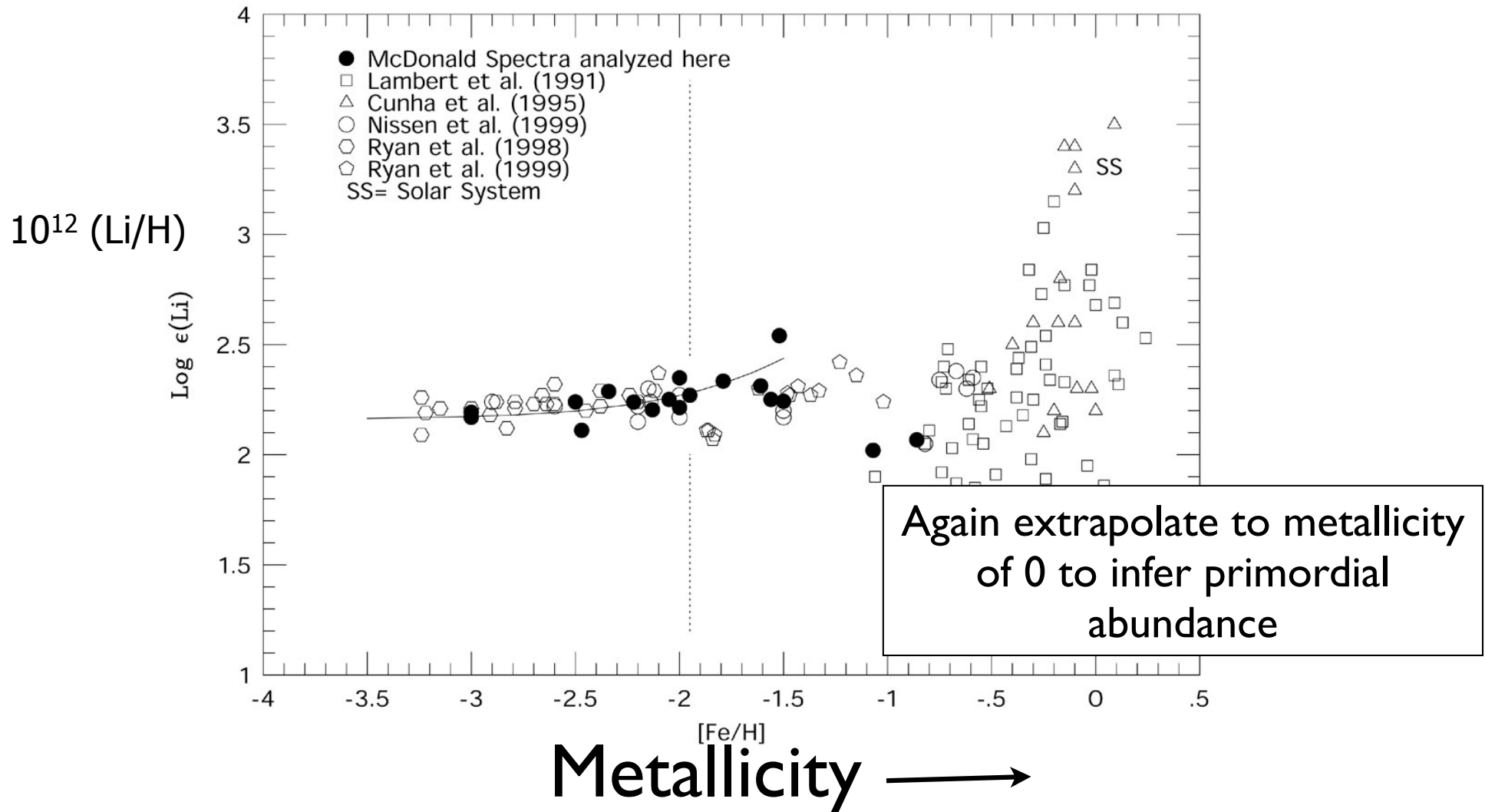
observed by absorption in the atmospheres of cool, metal poor population II halo stars

but difficult to infer since it can both be destroyed and created

inferring its abundance also difficult due to uncertainties in modeling the atmosphere of stars

How might we determine the primordial abundances then?

For Li^7



How might we determine the primordial abundances then?

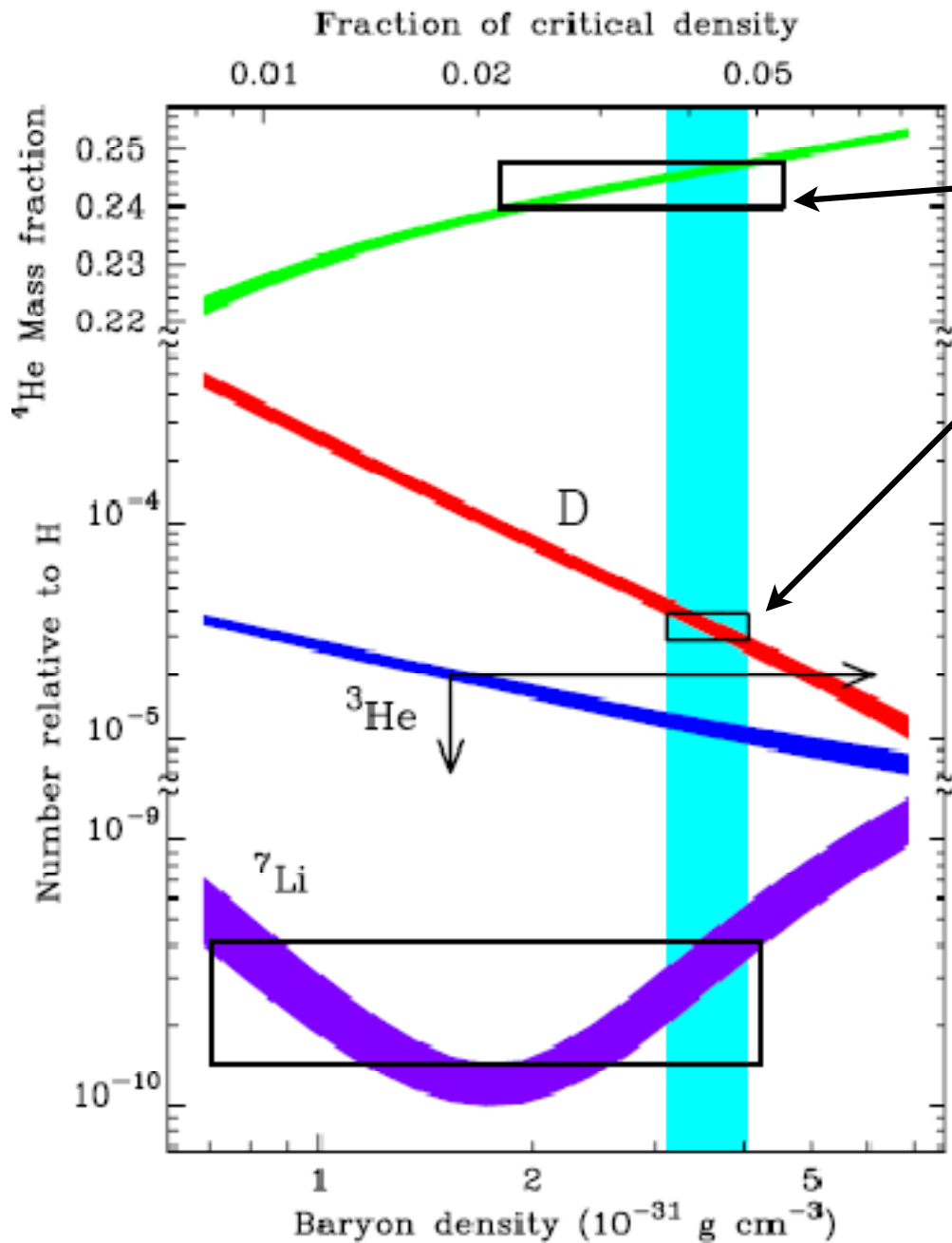
For He³

Has been found in some galactic HII regions

In principle, not burned in outer layers of stars -- though convection in stars could mix outer layers with inner layers.

Somewhat model dependent, so not especially reliable

What is bottom line putting together constraints?



Boxes show constraints on abundances relative to hydrogen

Best Fit Baryon Density

$$\Omega_{\text{B}} h^2 = 0.019 \pm 0.0024$$

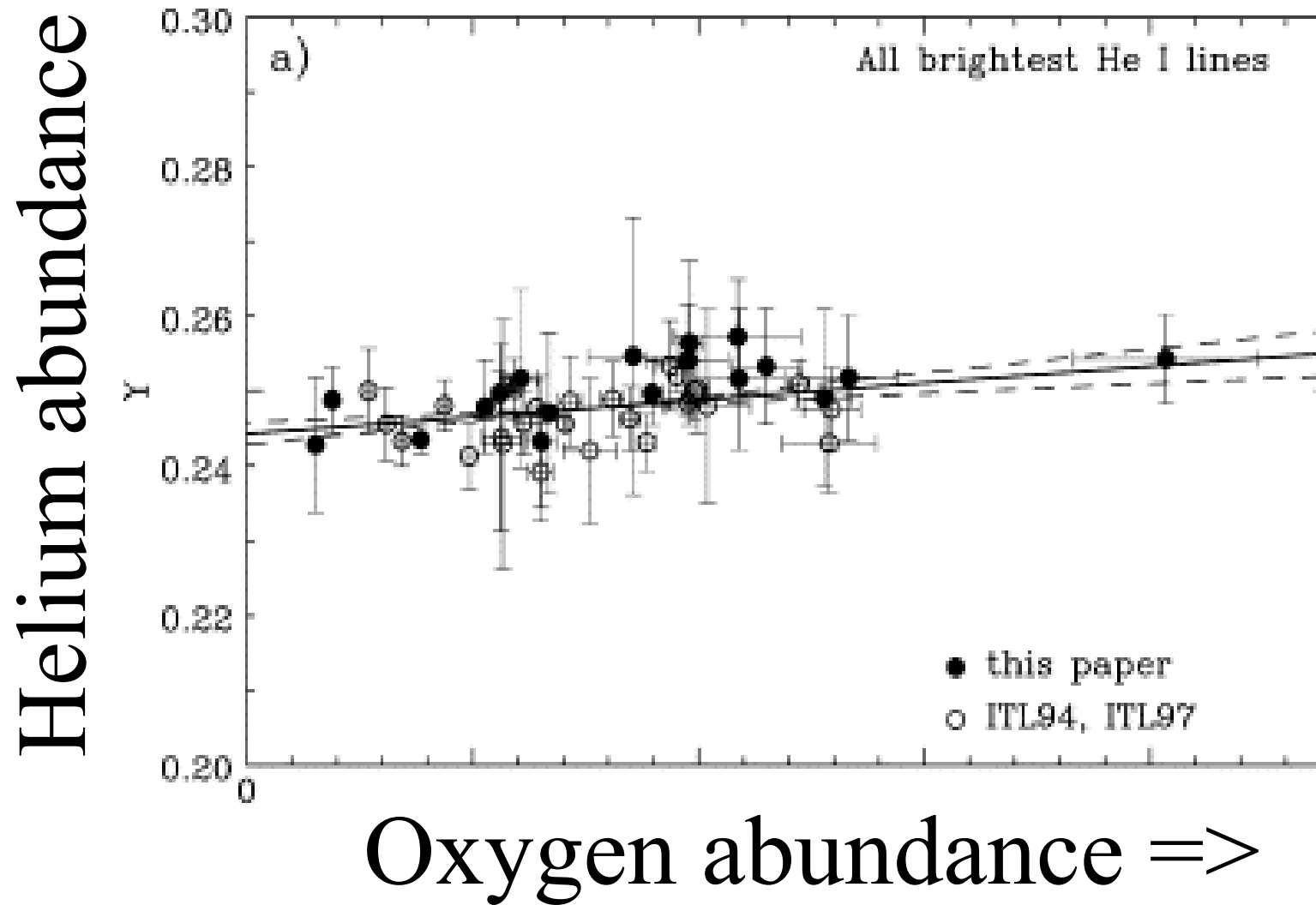
$$\Omega_{\text{B}} = 0.037 \pm 0.009$$

Most useful constraint is from deuterium abundances given steep dependence on $\Omega_{\text{b}} h^2$

Worthwhile, noting that
this gives us another
strong piece of evidence
for big bang

Maybe helium just formed
during fusion in stars?

Here is the evidence:



Helium could not just have
formed from fusion in stars

(since one would expect other heavier
elements to be produced)

Evidence for Big Bang

1. Age of “Stuff” in Universe $\sim 1/H_0$

Radioactive Decay,
White Dwarf Cooling,
Globular Clusters

$\sim 13 \pm 1$ Gyr

“Expansion Rate
of Universe”

~ 13.8 Gyr

2. Helium Abundance of Universe

cannot be explained by fusion in
stars, but easily explained as
happening in Big Bang, but

Baryonic mass density

$$\Omega_{\text{stars}} = 0.002$$

$$\Omega_{\text{cold gas, HI}} = 0.0003$$

$$\Omega_{\text{cold gas, molecular hydrogen}} = 0.0003$$

$$\Omega_{\text{ionized hydrogen}} = 0.02$$

$$\Omega_{\text{total}} = 0.0226$$

$$\text{vs. } \Omega_{\text{baryons}} = 0.04 \text{ (from BBN)}$$

Taking an Inventory of the Dark Matter Content of the Universe

How can establish the dark matter content of universe directly from observations?

First of all, what is dark matter?

Dark Matter:

Baryonic dark matter: black holes, compact objects (not typically what one refers to as “dark matter”)

Hot dark matter (HDM): low-mass particles such as neutrinos (since they have low mass, they can erase small scale density fluctuations)

Cold dark matter (CDM): much heavier particles such as WIMPs. Since these particles are much heavier, this matter tends to preserve density small-scale density fluctuations)

How can establish the dark matter content of universe directly from observations?

First of all, what is dark matter?

Evidence from the Rotation Curves of Galaxies

Dark matter in galaxies

- One technique for estimating the mass inside a circularly symmetric rotating object is from the rotation speed

$$\frac{GM(\leq r)}{r^2} = \frac{v_{\text{rot}}^2(r)}{r}$$

force per unit mass

acceleration

r = radius,

v = rotation speed,

$M(<r)$ = mass inside radius r ,

G = gravitational constant

Dark matter in galaxies

- One technique for estimating the mass inside a circularly symmetric rotating object is from the rotation speed

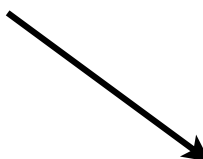
$$\frac{GM(\leq r)}{r^2} = \frac{v_{\text{rot}}^2(r)}{r}$$

r = radius,

v = rotation speed,

$M(<r)$ = mass inside radius r ,

G = gravitational constant

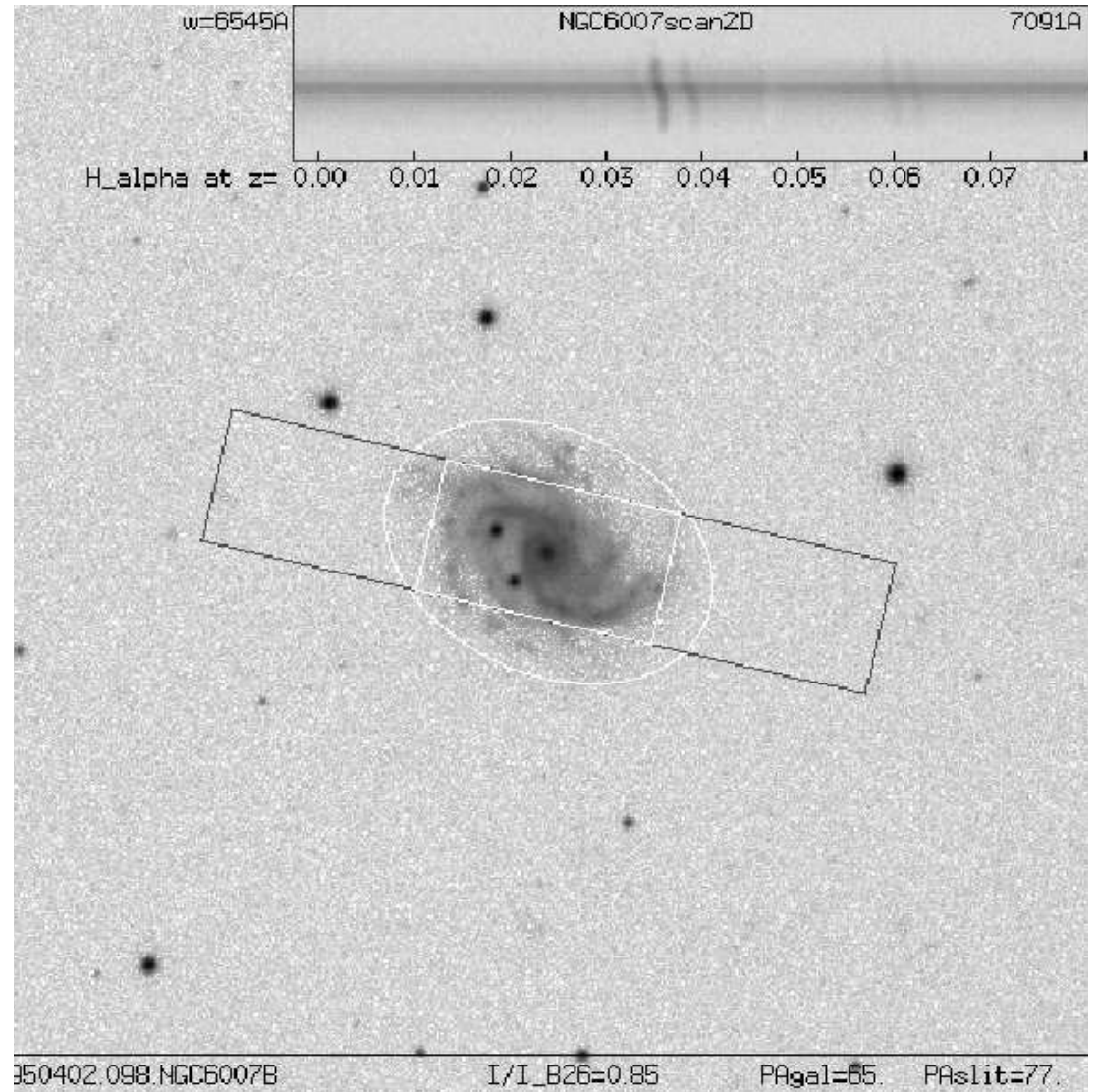

$$M(\leq r) = \frac{v_{\text{rot}}^2 r}{G}$$

Dark matter in galaxies

-- How are galaxies observed to rotate?

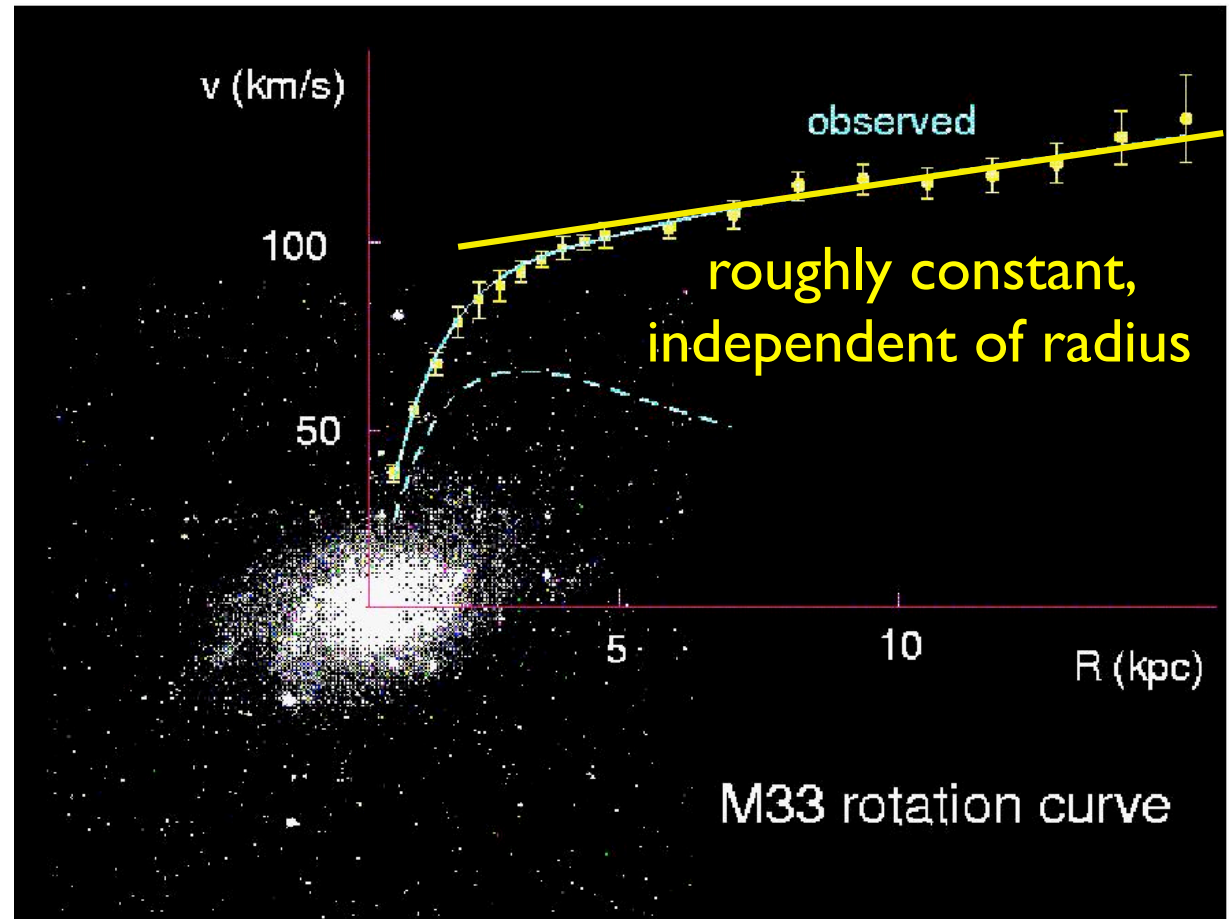
-- The rotation rate of galaxies can be measured by letting light pass through a slit along the axis of a galaxy and taking a spectrum

-- It is easiest if we observe a spiral galaxy edge-on. Otherwise we need to apply an inclination angle correction



Dark matter in galaxies

- Rotation velocities of spiral galaxies increase rapidly from their centers to their outer radii
- Rotation velocities tend to asymptote towards some constant value



$$M(\leq r) = \frac{v_{\text{rot}}^2 r}{G}$$

$$\Rightarrow M(\leq r) \propto r$$

Dark matter in galaxies

- By contrast, light in galaxies decreases exponentially with radius:

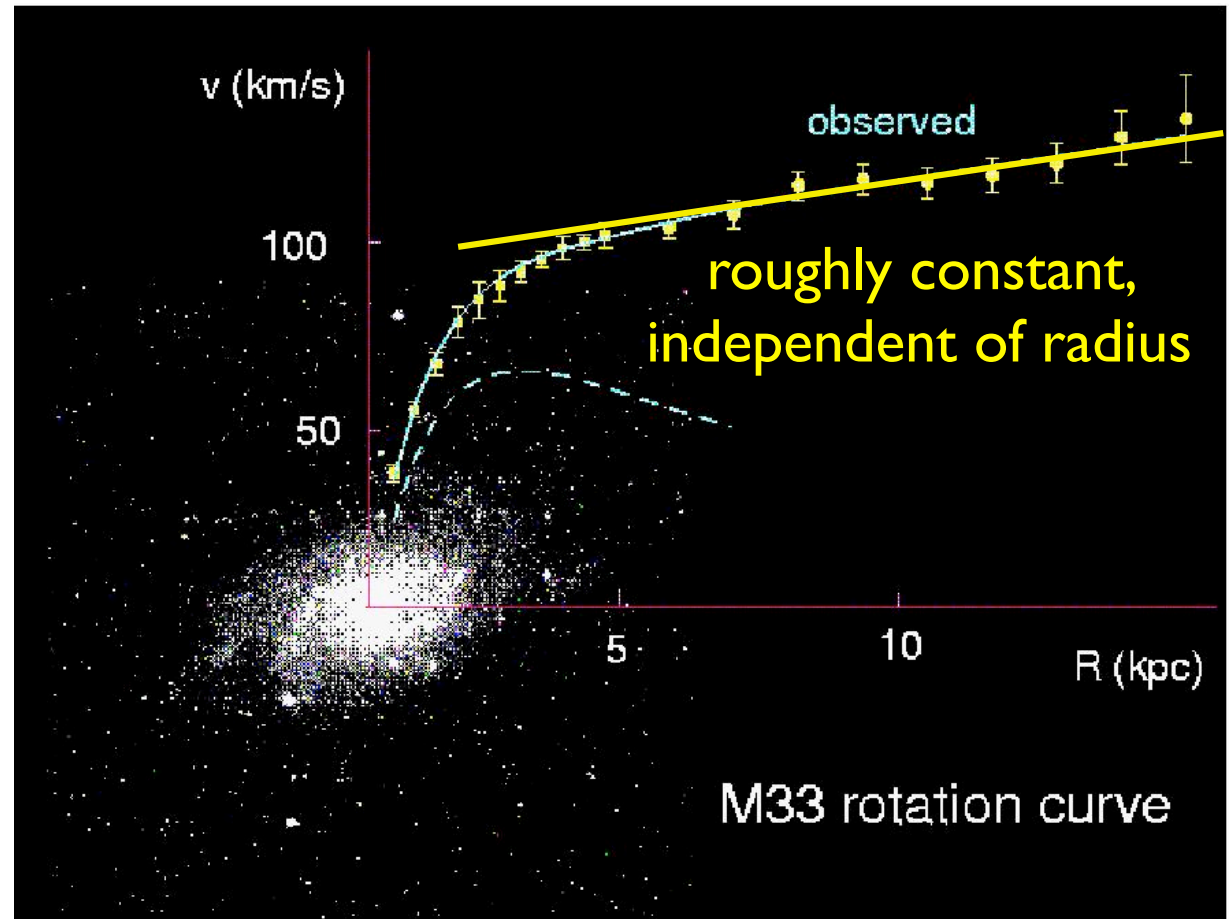
$$I(r) = I_0 \exp(-r/h)$$

h = scale length of galaxies

- Integrating up the total light in a galaxy to some radius r_0 :

$$I_0 \int_0^{r_0} 2\pi r \exp(-r/h) dr$$
$$\propto h^2 - h(r + h) \exp(-r/h)$$

- Equals a constant at large radii

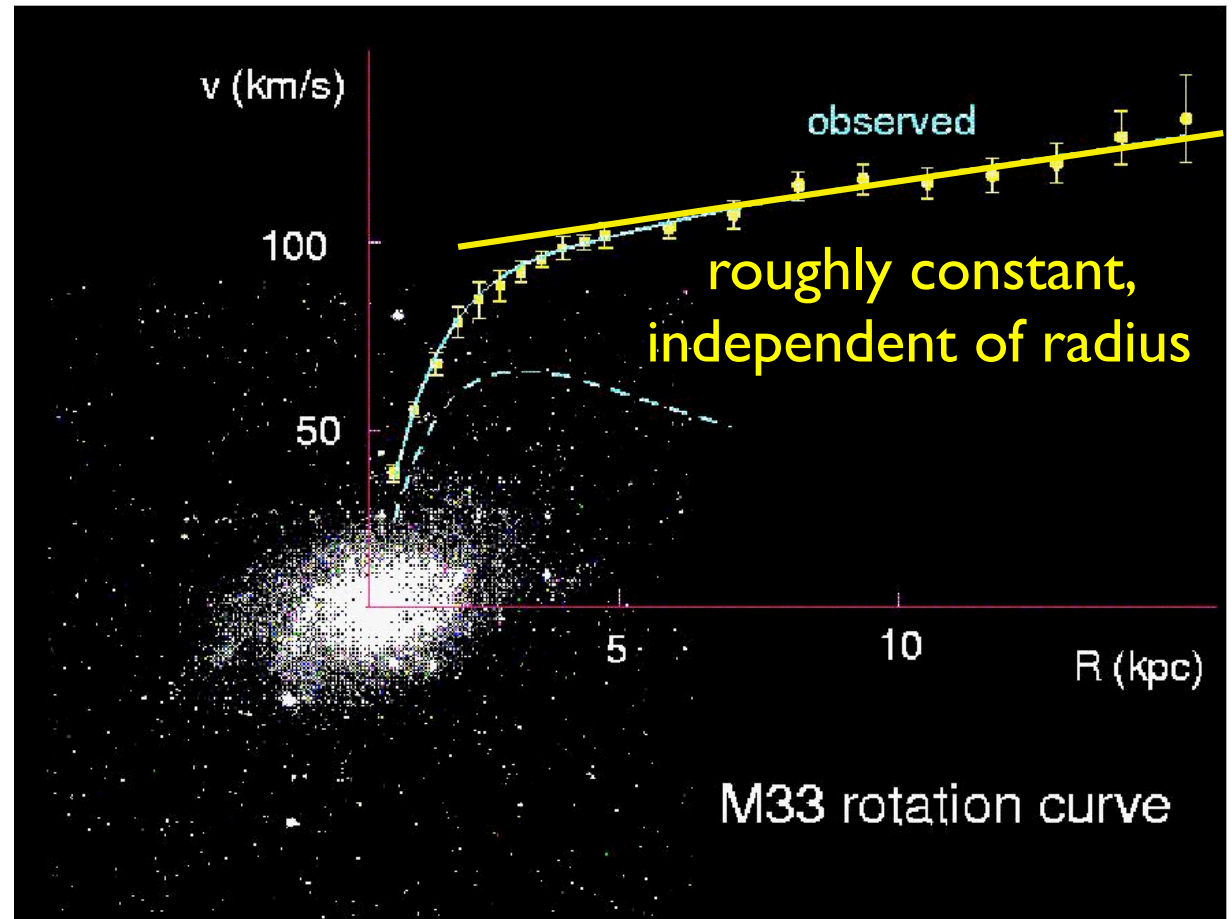


- The implication is that the light and also baryons in galaxy are restricted to very center

Dark matter in galaxies

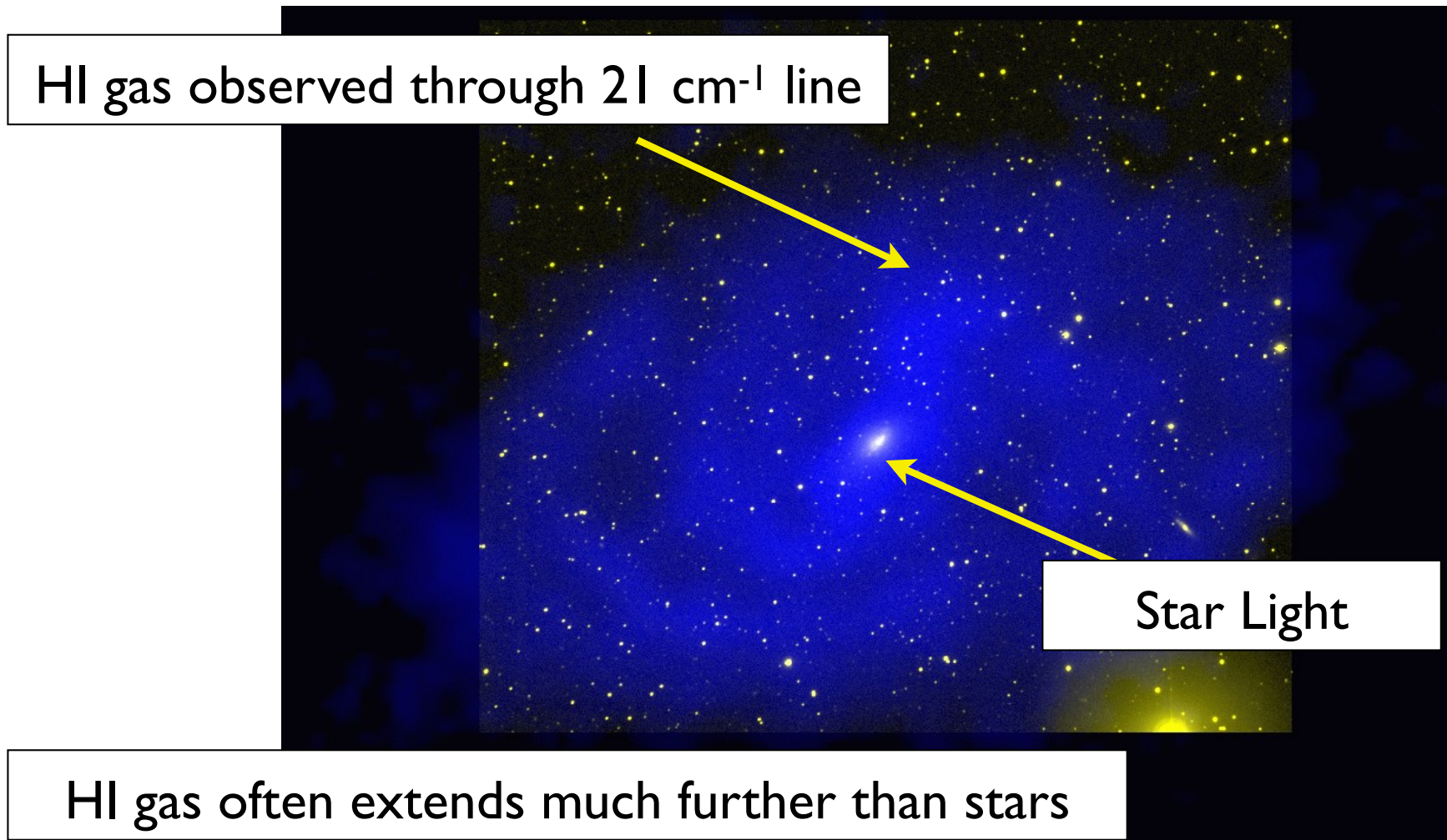
-- This restriction of the baryonic mass to the center of galaxies is in contrast to the monotonic increase seen in the gravitational mass

-- So if gravity works the same on large scales as small scales, then there must be some other matter in universe we do not see!



Dark matter in galaxies

- In many case, one can measure the velocity of rotation out to very large radii by observing the HI gas (neutron hydrogen) through the 21 cm^{-1} line

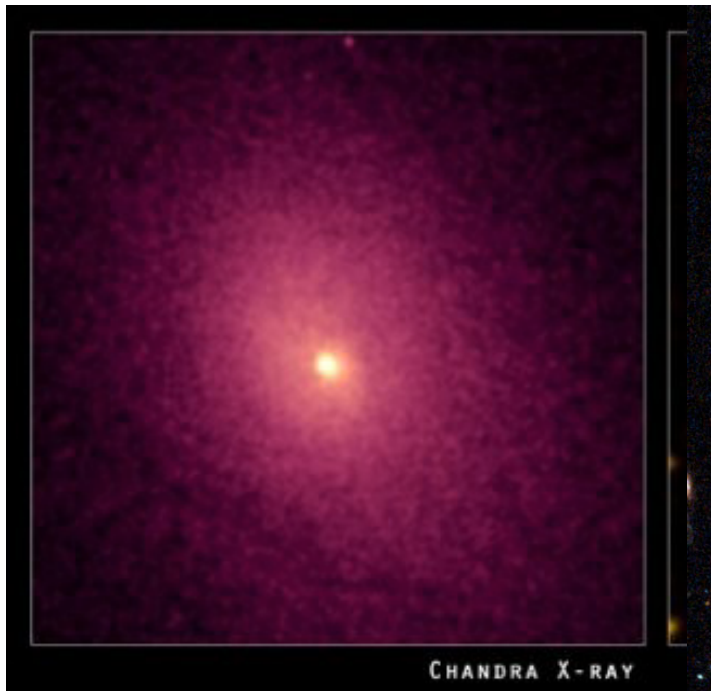


Evidence from the Observations of Colliding Galaxy Clusters

Evidence from the Observations of Colliding Clusters

First a few words to orient you a little more about what a galaxy cluster is

Galaxy clusters are regions of the universe that have collapsed (due to gravity)



Approximate mass budget:

~2% galaxies

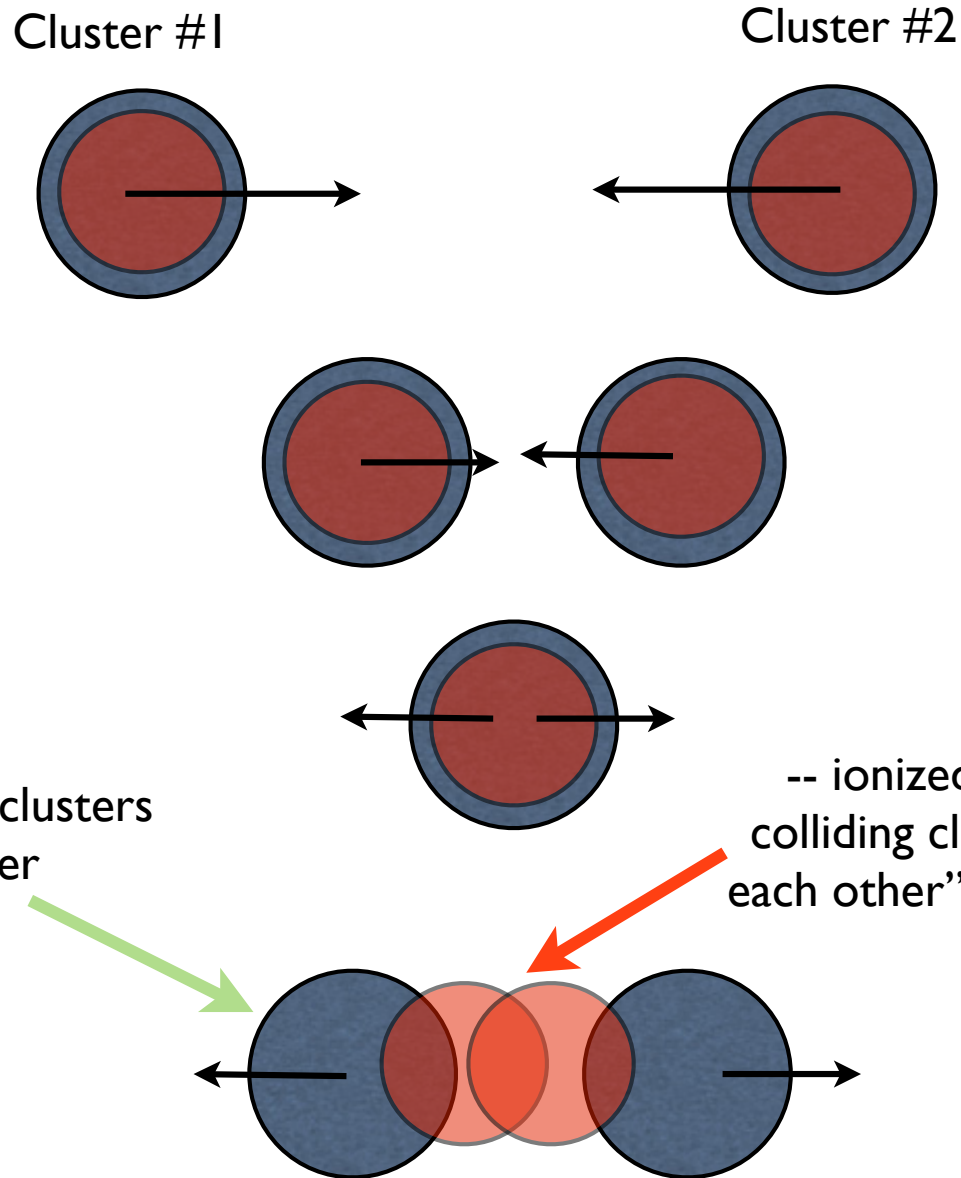
~13% in a very hot ionized gas

~85% in dark matter

Most of the baryons are in the ionized gas!

Evidence from the Observations of Colliding Clusters

Reason it is useful
can be seen from
the following
“simulation”:



-- dark matter from the colliding clusters
pass right through each other

-- ionized gas from the
colliding clusters “run into
each other” forming a shock

this presents us with a situation where the light (from baryons) and
mass (from dark matter) are in different places

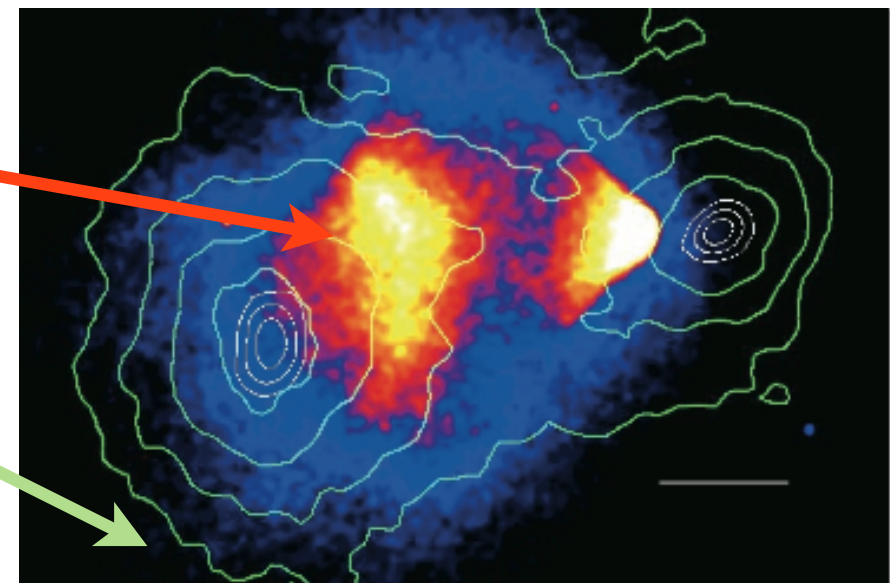
Evidence from the Observations of Colliding Clusters

“Bullet Cluster” Clowe et al. 2006

- how can we use the observations to see that baryons do not provide most of the mass
- x-ray light shows us where the ionized gas (i.e., baryons) is
- gravitational lensing shows us where the mass is (mostly dark matter)



- ionized gas from the colliding clusters “run into each other” forming a shock
- dark matter from the colliding clusters pass right through each other



The Bullet Cluster

Credit: Papovich for layout



Orange: stars

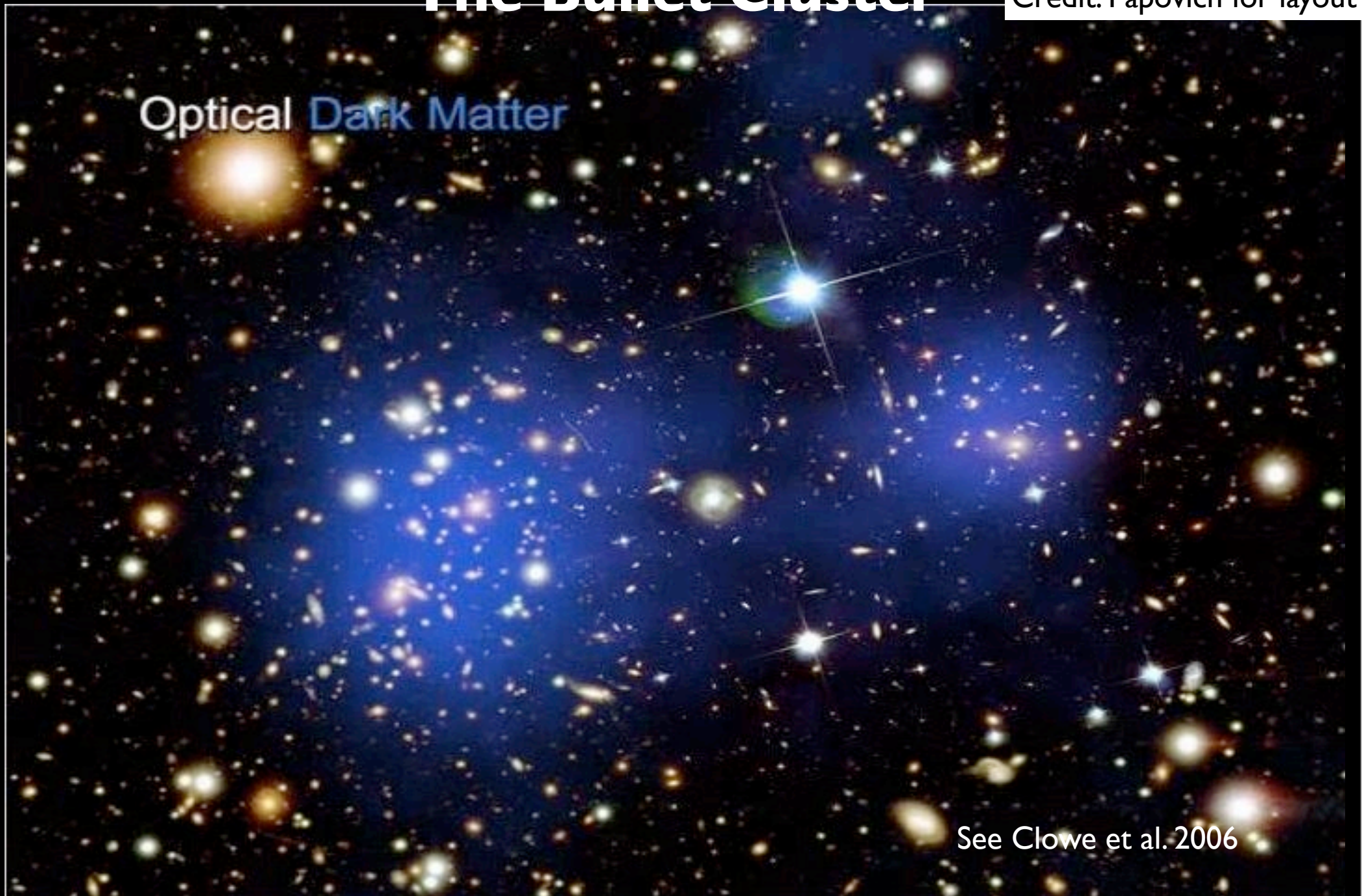
Red : X-ray gas

Blue : Mass from lensing measurements

The Bullet Cluster

Credit: Papovich for layout

Optical Dark Matter



See Clowe et al. 2006

Orange: stars

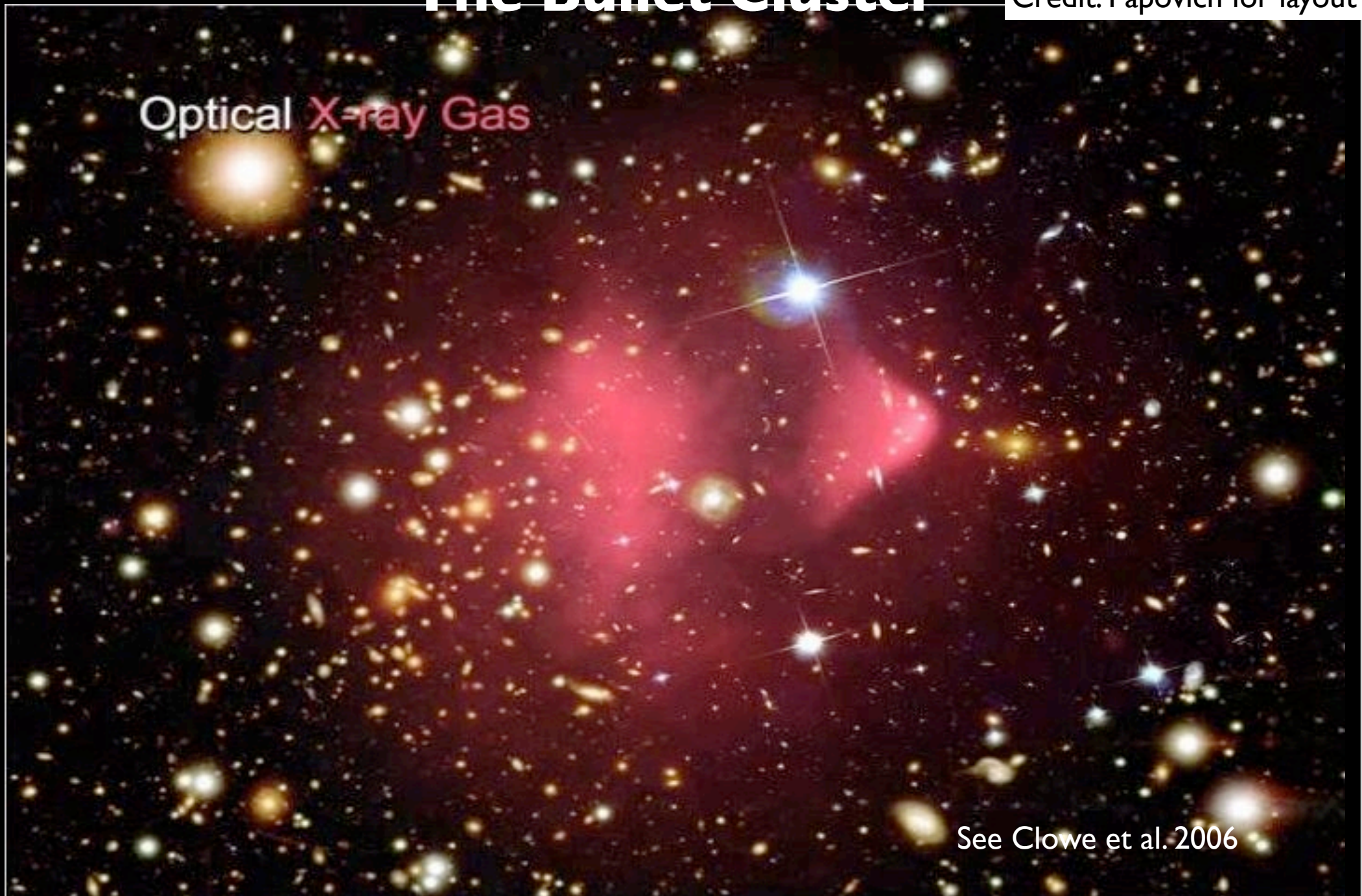
Red : X-ray gas

Blue : Mass from lensing measurements

The Bullet Cluster

Credit: Papovich for layout

Optical X-ray Gas



See Clowe et al. 2006

Orange: stars

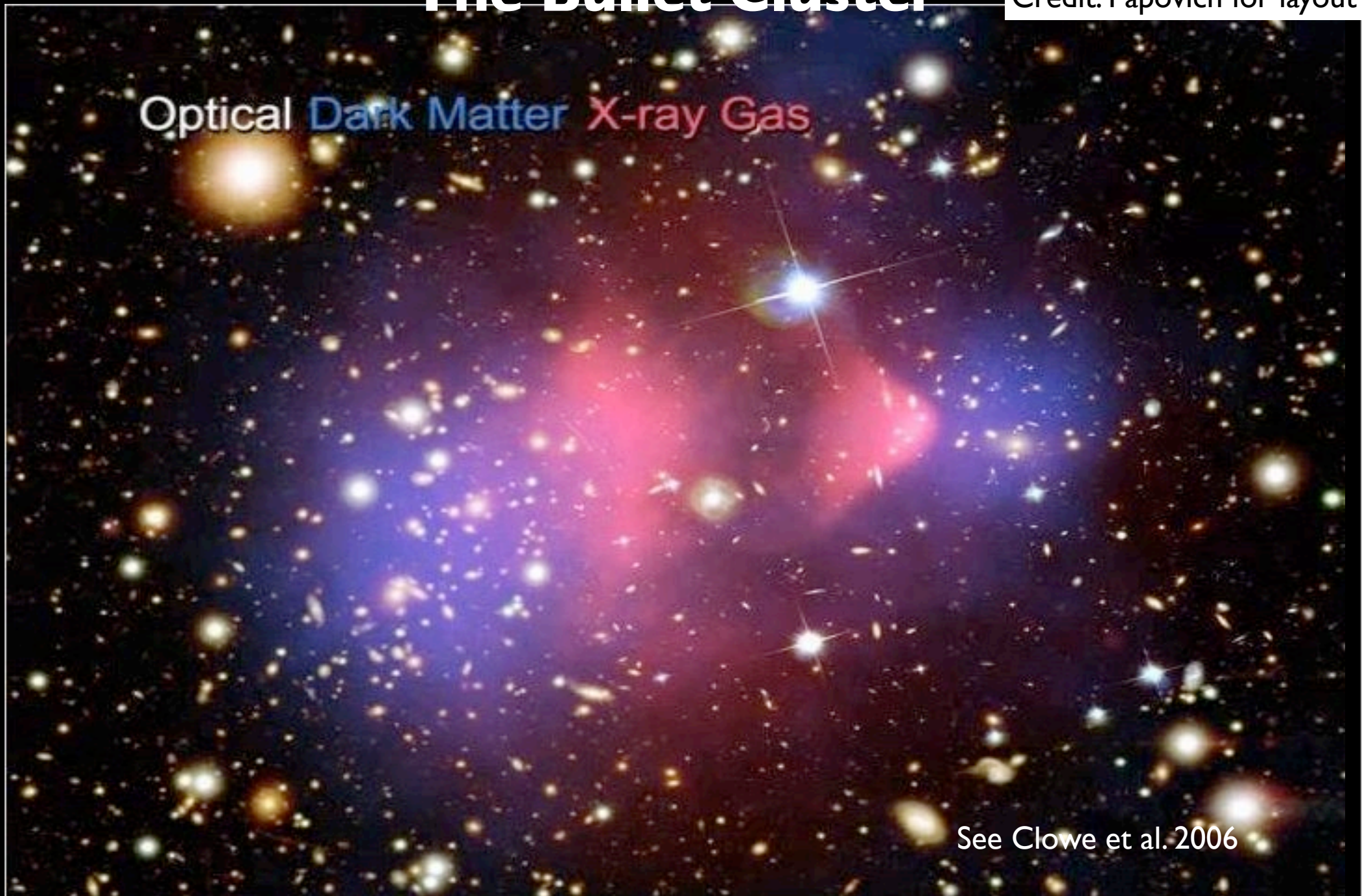
Red : X-ray gas

Blue : Mass from lensing measurements

The Bullet Cluster

Credit: Papovich for layout

Optical Dark Matter X-ray Gas



See Clowe et al. 2006

Orange: stars

Red : X-ray gas

Blue : Mass from lensing measurements