Insight into Dark Energy from SNe

+

Inventory of the Universe

Layout of the Course

This Week

Feb 5: Introduction / Overview / General Concepts
Feb 12: Age of Universe / Distance Ladder / Hubble Constant
Feb 19: Distance Ladder / Hubble Constant / Distance Measures
Feb 26: Distance Measures / SNe science / Baryonic Content
Mar 4: Dark Matter Content of Universe / Cosmic Microwave Background
Mar 11: Cosmic Microwave Background
Mar 18: Cosmic Microwave Background / Large Scale Structure
Mar 25: Baryon Acoustic Oscillations / Dark Energy / Clusters
Apr 1: No Class
Apr 8: Clusters / Cosmic Shear
Apr 15: Dark Energy Missions / Review for Final Exam

May 13: Final Exam

Problem Set #1

Due Wednesday, February 28, 2024

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-σ

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

Age of Universe ~ $1/H_0$

Distance to Faraway Galaxy ~ cz/H_0 ~ $1/H_0$

Luminosity of Faraway Galaxy ~ flux x $(4\pi D^2)$

~ flux x $4\pi(cz/H_0)^2$

~ $1/H_0^2$

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

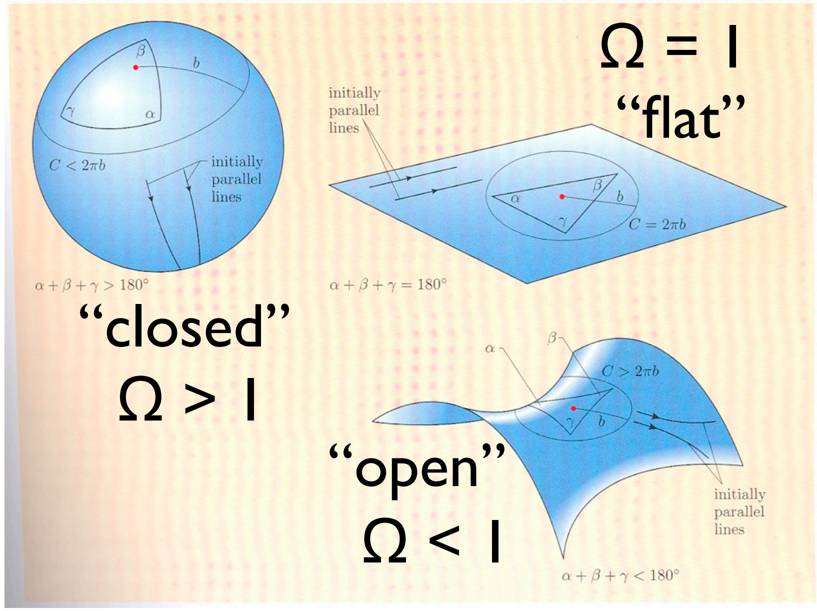
$$\text{flux} = L / 4\pi D^2$$

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

"Angular size"

But in reality it is not

(at sufficiently large distances)


Ω = 1
"flat"
initially parallel lines
α
β
γ
b
$C = 2\pi b$
$\alpha + \beta + \gamma = 180°$
$C < 2\pi b$
initially parallel lines
$\alpha + \beta + \gamma > 180°$
"closed"
Ω > 1
$C > 2\pi b$
"open"
Ω < 1
initially parallel lines
$\alpha + \beta + \gamma < 180°$

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:

1. 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

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

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

Now onto new material...

Cosmological Distances

-- Proper Distance

Start with the distance measure in Friedmann-Robertson Walker metric:

$$c^2dt^2 - R^2(t)\frac{dr^2}{1-kr^2} = ds^2$$

Consider dt = 0

$$D_P = \int ds = R(t)\int\frac{dr}{\sqrt{1-kr^2}}$$

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

Cosmological Distances

Proper Distances are not especially practical to measure for applications in observational cosmology!

More useful to manipulate equation as follows to come up with an expression expressing how far light would travel in terms of the comoving coordinate r in time t.

This expression will be useful for all other distance measures we will consider here.

Cosmological Distances

More useful to manipulate equation as follows

$$cdt - R(t)dr(1-kr^2)^{-1/2} = 0$$

$$\frac{cdt}{R(t)} = \frac{dr}{\sqrt{1-kr^2}}$$

$$c\int \frac{dt}{R(t)} = \int \frac{dr}{\sqrt{1-kr^2}}$$

$$= \frac{c}{R_0}\int \frac{R_0}{R(t)}dt$$

$$= \frac{c}{R_0}\int \frac{R_0}{R(t)}\frac{dt}{dz}dz$$

$$= \frac{c}{R_0}\int (1+z)\frac{1}{H_0E(z)(1+z)}dz = \frac{c}{R_0H_0}\int \frac{dz}{E(z)}$$

$$\frac{dR}{dt} = H_0RE(R)$$

dR/dz = $-R_0(1+z)^{-2}$

$$\frac{dt}{dz} = \frac{dt}{dR}\frac{dR}{dz}$$

$$= \frac{1}{HR}R_0(1+z)^{-2}$$

$$= \frac{1}{H_0E(z)(1+z)}$$

Cosmological Distances

More useful to manipulate equation as follows

$$\int \frac{dr}{\sqrt{1-kr^2}} = \frac{c}{R_0 H_0}\int \frac{dz}{E(z)}$$

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

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

This tells us to which comoving coordinate r light would travel, from the present day t = 0 to some time t (redshift z) in the past.

Now let's apply these to the three main distance measures people discuss:

Luminosity distance

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

Angular-diameter distance

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

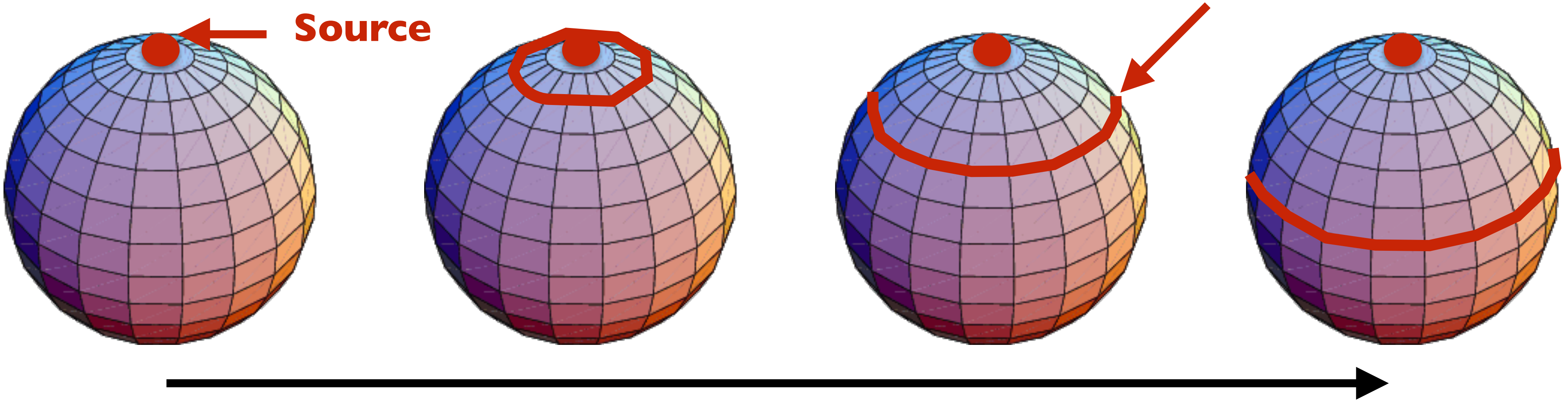
Proper Motion distance

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

All these distances are defined so that the standard formulas in Euclid geometry apply.

Let’s first look at the luminosity distance and look at this using illustrations to get a feel for it:

Example using a simple closed space time



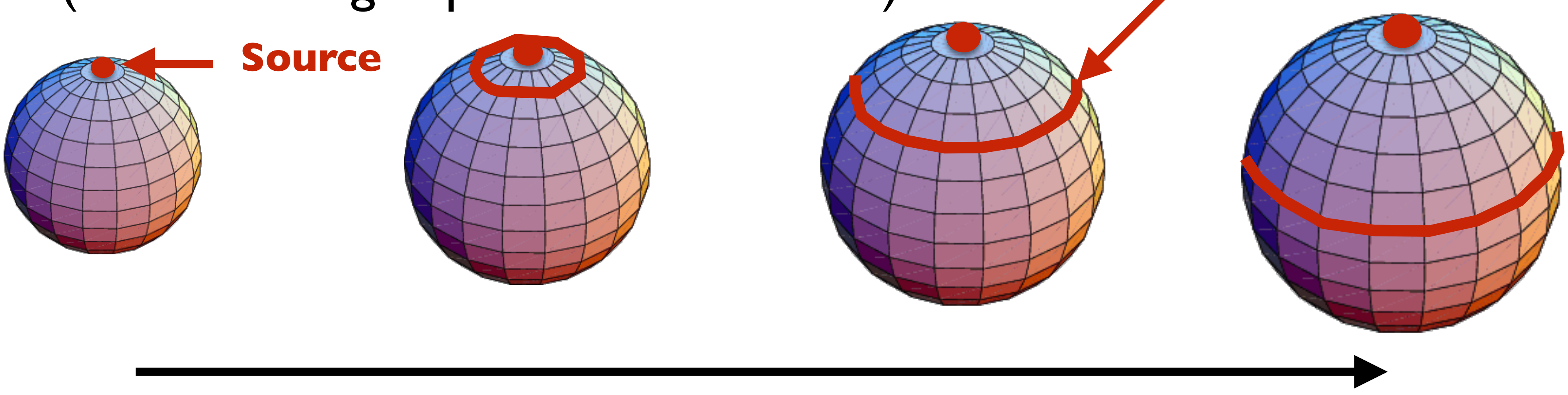
Source

Light cone eminating from source

time

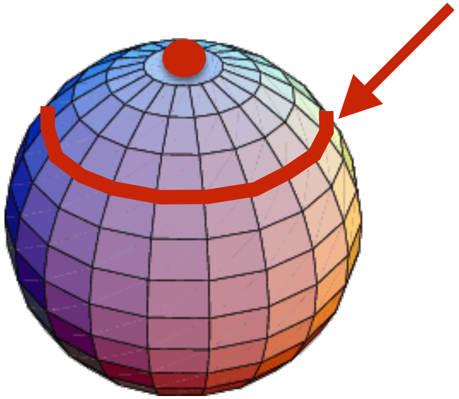
Let's first look at the luminosity distance and look at this using illustrations to get a feel for it:

Example using a simple closed space time (now showing expansion of universe)

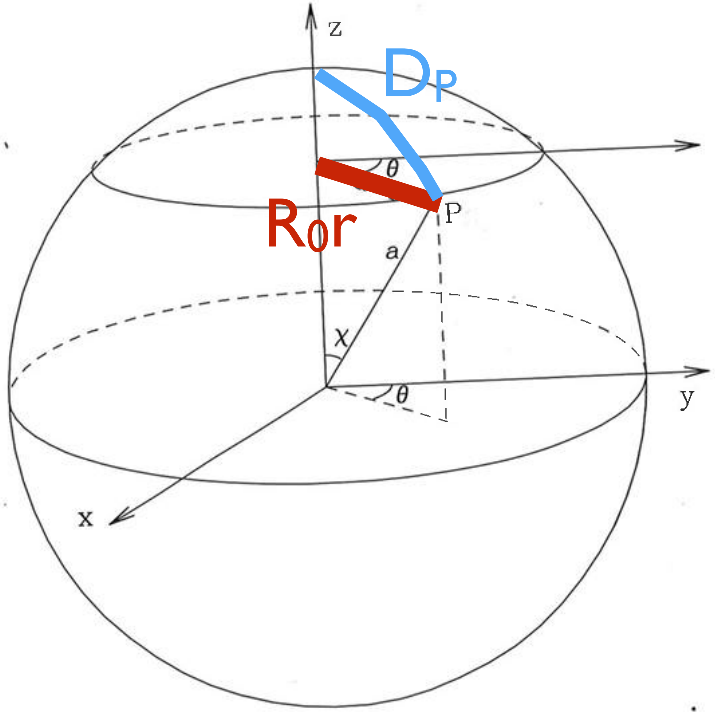

Source
Light cone eminating from source

time

Let's now work on the luminosity distance for the example



Light cone eminating from source (i.e., where we observe it)

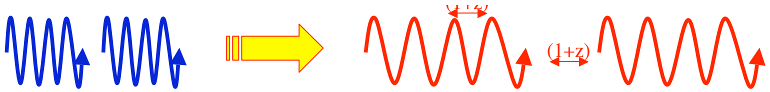

z
D_P
θ
R_0r
P
a
χ
θ
y
x

$f = L/4\pi(R_0r)^2 \times$ [effect of redshift/time delay]

r = comoving coordinate

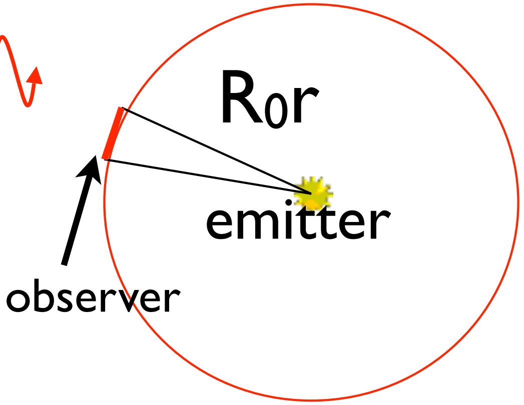
R_0: scale factor of universe: $(c/H_0)\Omega_k^{-1/2}$

Two factors of (1+z) for
(1) effect of redshifting on energy of photons
(2) time delay between photons



View from above

bolometric flux !


R_0r
emitter
observer

$f = L/4\pi(R_0r)^2 / (1+z)^2$

$L = f\,4\pi(R_0r)^2(1+z)^2$

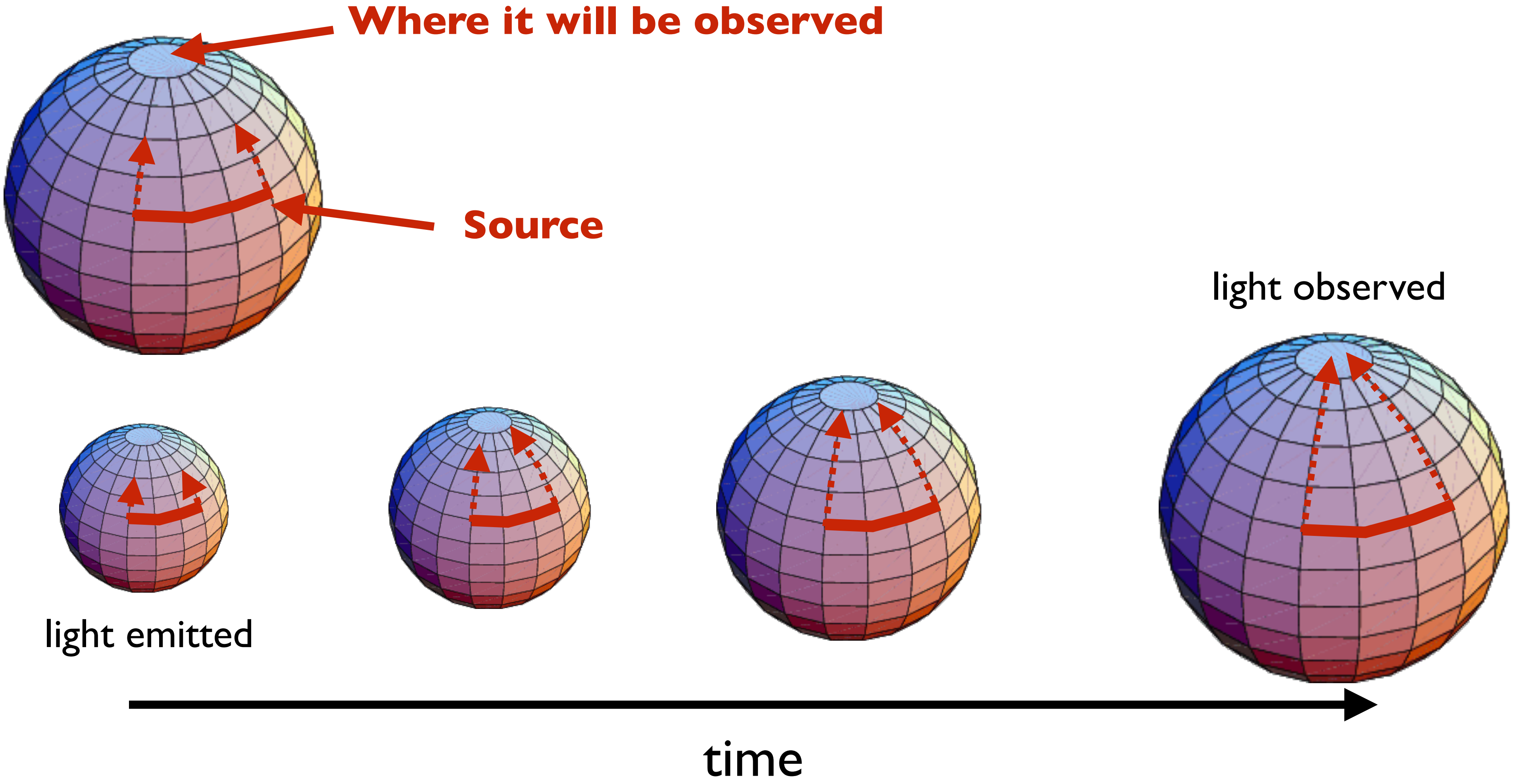
$\Rightarrow D_L = R_0r(1+z)$

Another way to assign a distance is to use the angular size $d\theta$

$$d\theta = L / D_A$$

since more distant objects
are smaller in general!

Example using a simple closed space time



Where it will be observed

Source

light observed

light emitted

time

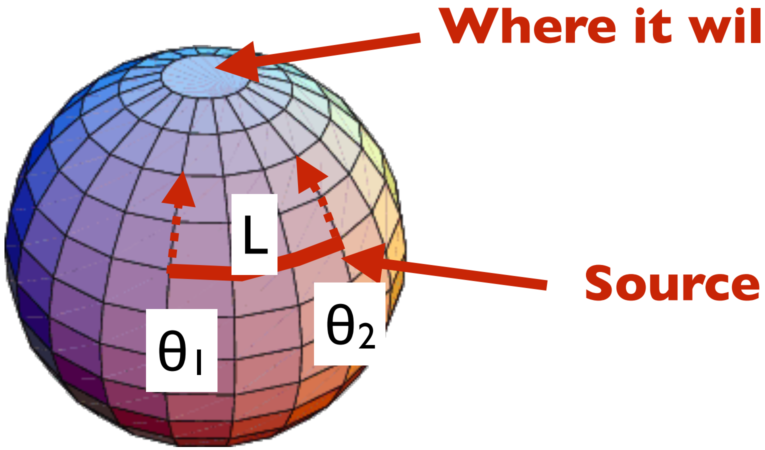
Note angle maintained as universe expands!

Another way to assign a distance is to use the angular size $d\theta$

$$d\theta = L / D_A$$

since more distant objects
are smaller in general!

Example using a simple closed space time



L
θ_1
θ_2

Where it will be observed

Source

Consider FRW metric again where the coordinates of the emitter are as follows:

one side of emitter: (r, θ_1, Φ)
other side of emitter: (r, θ_2, Φ)

$$d\theta = |\theta_1 - \theta_2|$$

What is $d\theta$?

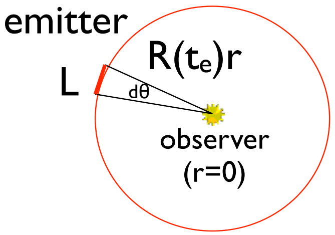
$$d\theta = L / (R(t_e)r)$$

$$\uparrow$$

$$D_A = R(t_e)r$$

$$D_A = (R(t_0)/(1+z))r$$

View from above



emitter
$R(t_e)r$
L
$d\theta$
observer
$(r=0)$

Another distance measure is a proper motion distance $d\theta/dt$, i.e., angle on sky per unit time.

$$D_M = (dL/dt_0) / (d\theta/dt_0)$$

As for angular diameter distance, angle on sky is determined by when a source emits its light… but then there is time delay…

So

$$D_M = D_A(t_0)\ (1+z)$$

Cosmological Distances

Comparison of Distance Measures:

Angular Diameter Distance: $D_A = R_0 r/(1+z)$

Luminosity Distance: $D_L = R_0 r(1+z)$

Proper Motion Distance: $D_M = R_0 r$

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

$D_L = D_M\,(1+z) = D_A\,(1+z)^2$

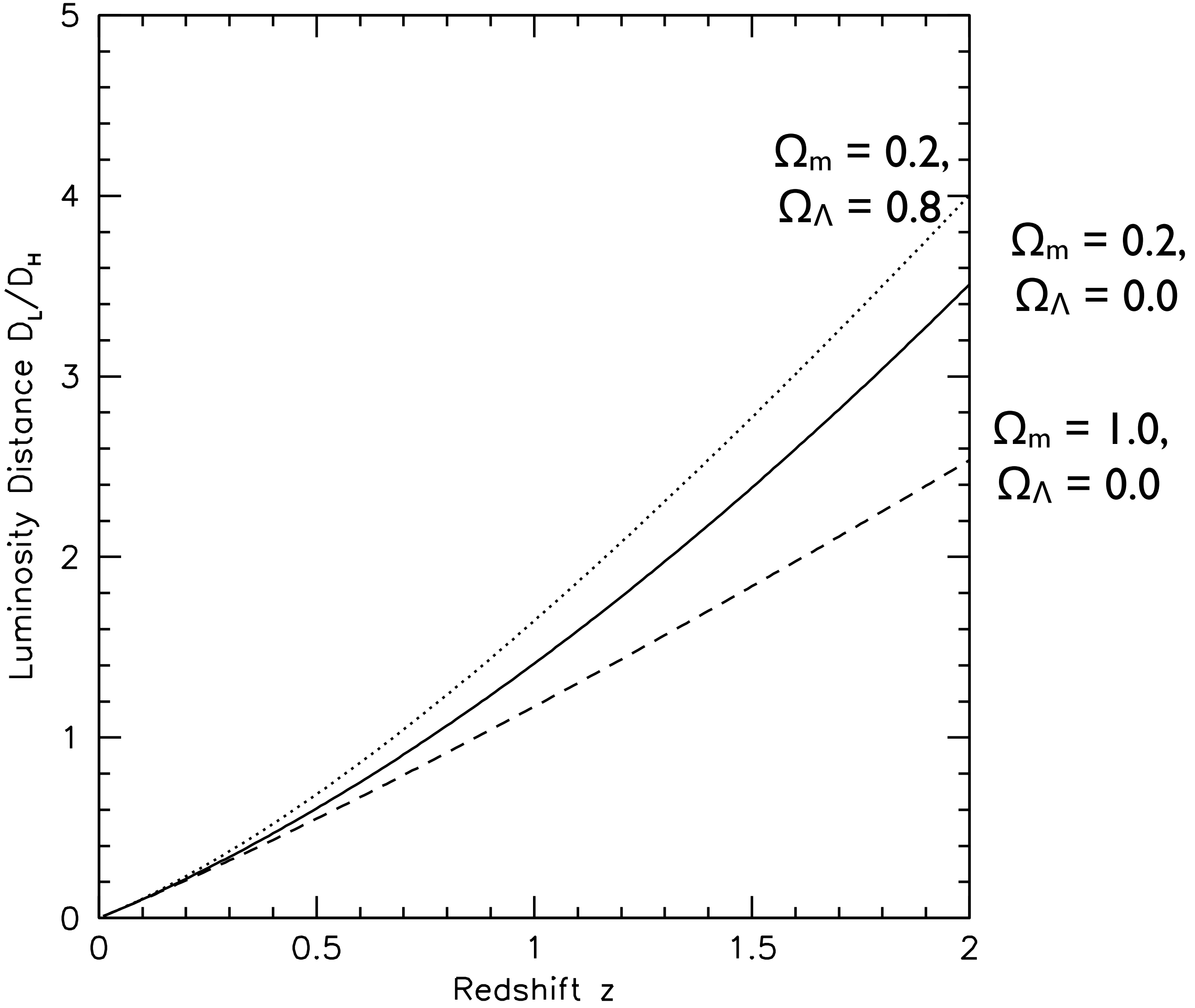
At close enough distances (where cosmological redshift $z \sim 0$)

$D_P = D_M = D_L = D_A$

What are the values of these distances for a given redshift in real cosmologies?

Different densities for matter and dark energy predict different relationships between distance and redshift

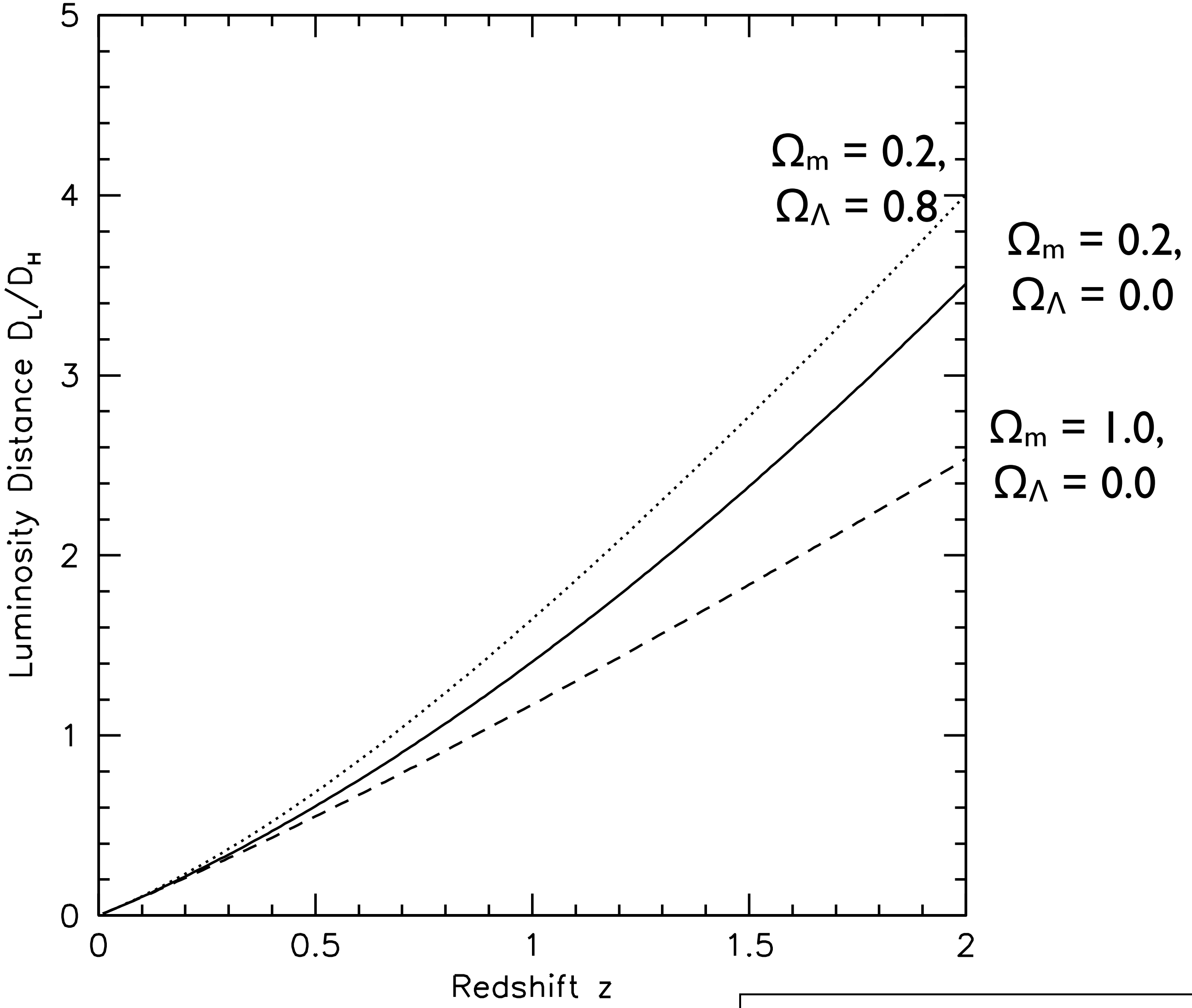
Luminosity Distance



The relationship between distance and redshift depends on the matter/dark energy density of the universe due to their impact on the expansion rate of the universe.

Different densities for matter and dark energy predict different relationships between distance and redshift

Luminosity Distance

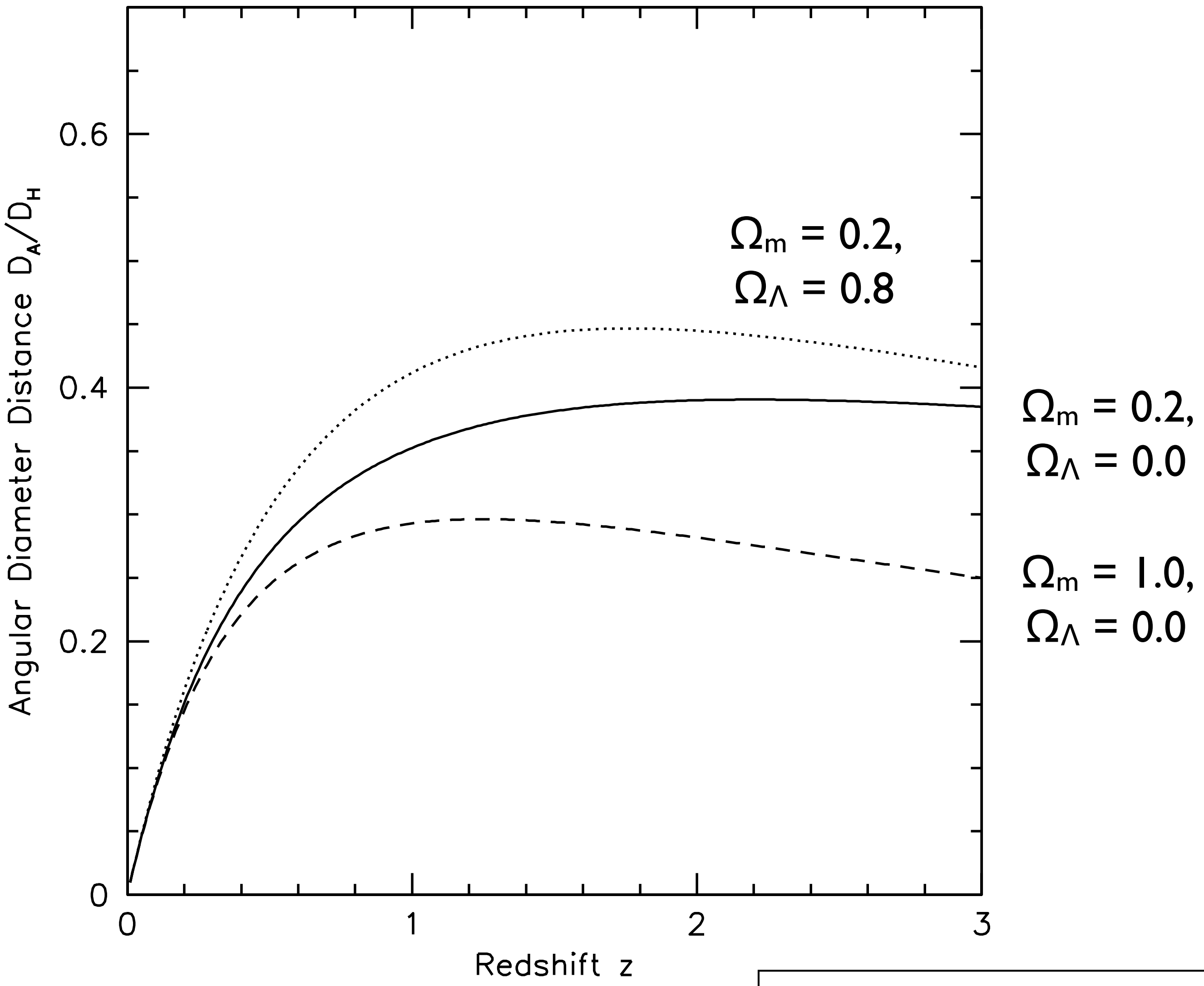


Two different ways of increasing the luminosity distance:

1) Increase Ω_Λ
2) Decrease Ω_m

Different densities for matter and dark energy predict different relationships between distance and redshift

Angular
Diameter
Distance

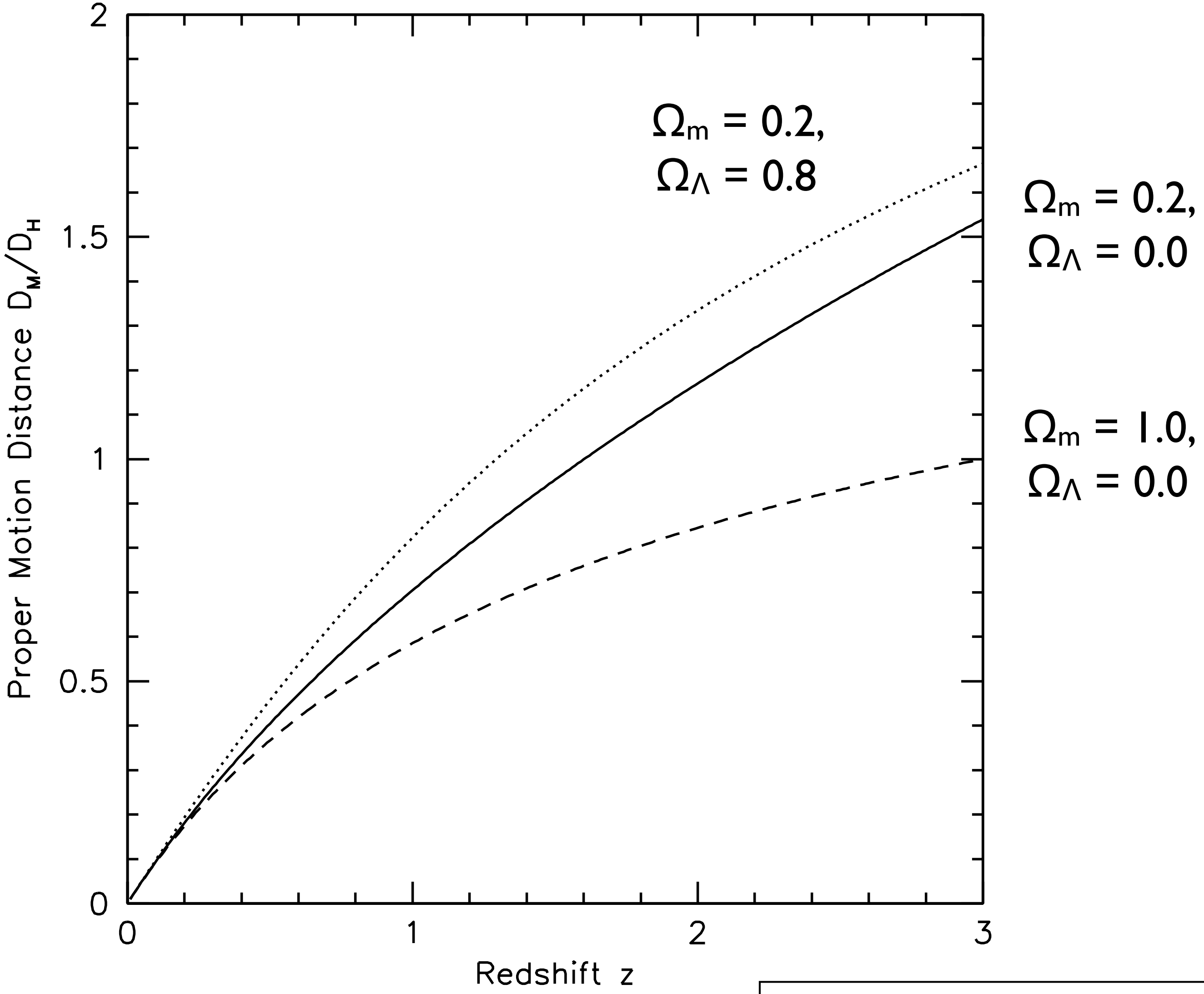


Two different ways of increasing the angular diameter distance:

1) Increase Ω_Λ
2) Decrease Ω_m

Different densities for matter and dark energy predict different relationships between distance and redshift

Proper
Motion
Distance

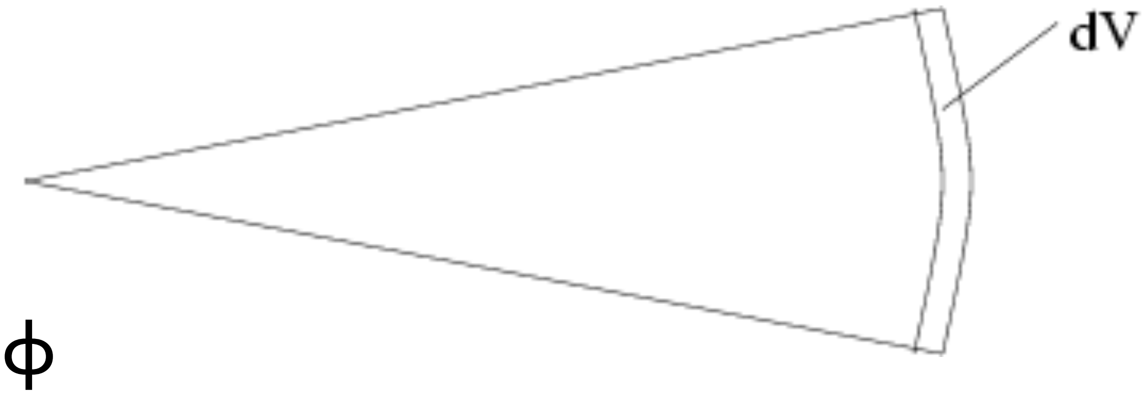


Two different ways of increasing the proper motion distance:

1) Increase Ω_Λ
2) Decrease Ω_m

Cosmological Volume Element

-- Also useful to know the differential volume element we're looking through as a function of distance (to quantify the volume density of galaxies, galaxy clusters we find in searches)

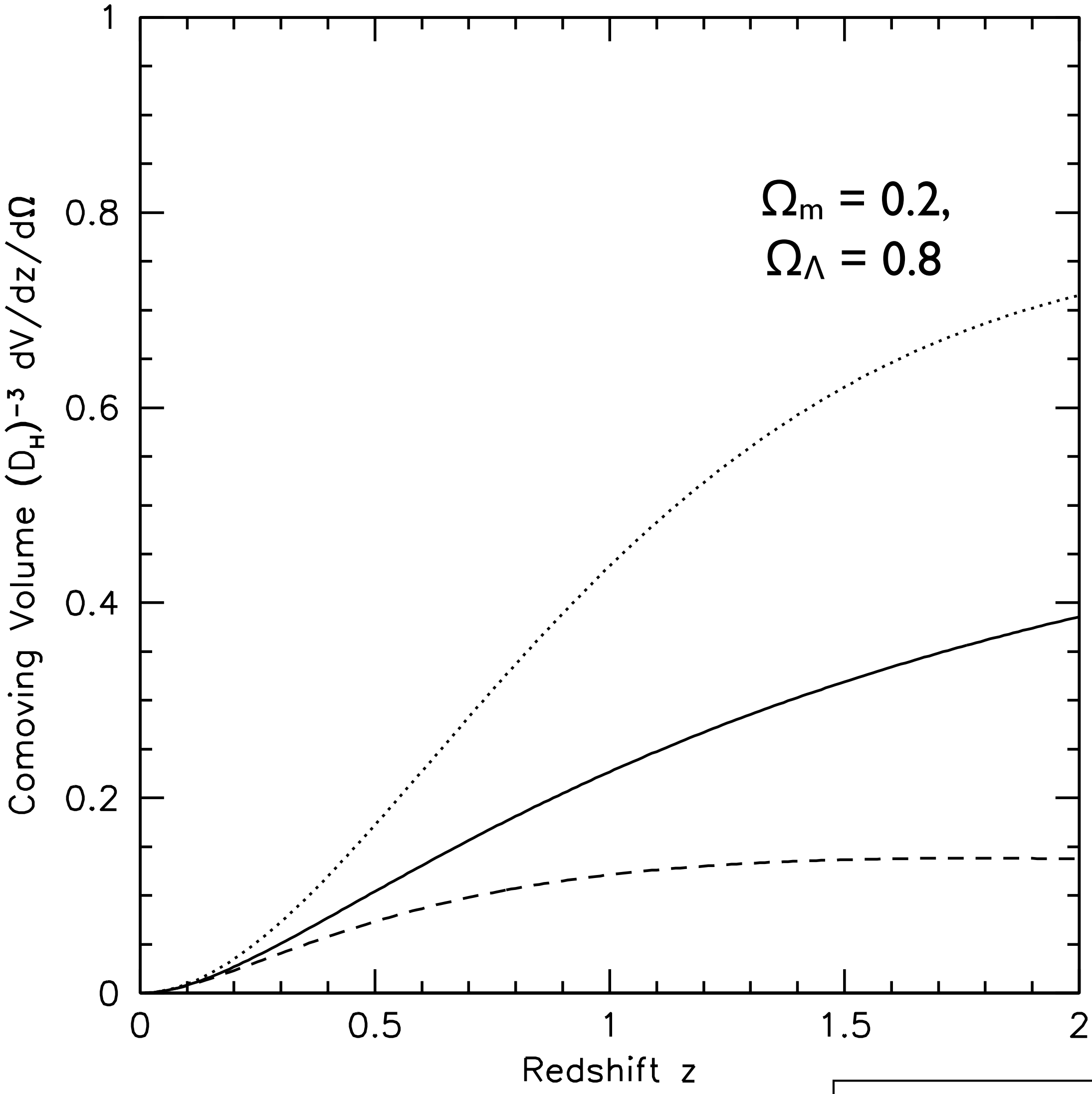


In Euclidean space:
$dV = r^2 \sin\theta \, dr \, d\theta \, d\phi$

Accounting for expansion and spacetime:
$dV = (c/H_0)\, 4\pi D_L^2 / [(1+z)^2 (H(z)/H_0)]dz$

Different densities for matter and dark energy predict different relationships between distance and redshift

Comoving volume



$\Omega_m = 0.2$, $\Omega_\Lambda = 0.8$

$\Omega_m = 0.2$, $\Omega_\Lambda = 0.0$

$\Omega_m = 1.0$, $\Omega_\Lambda = 0.0$

Two different ways of increasing the cosmological volume:

1) Increase Ω_Λ
2) Decrease Ω_m

As we can see, these distances and volumes for a given redshift depend very sensitively on the cosmological parameters

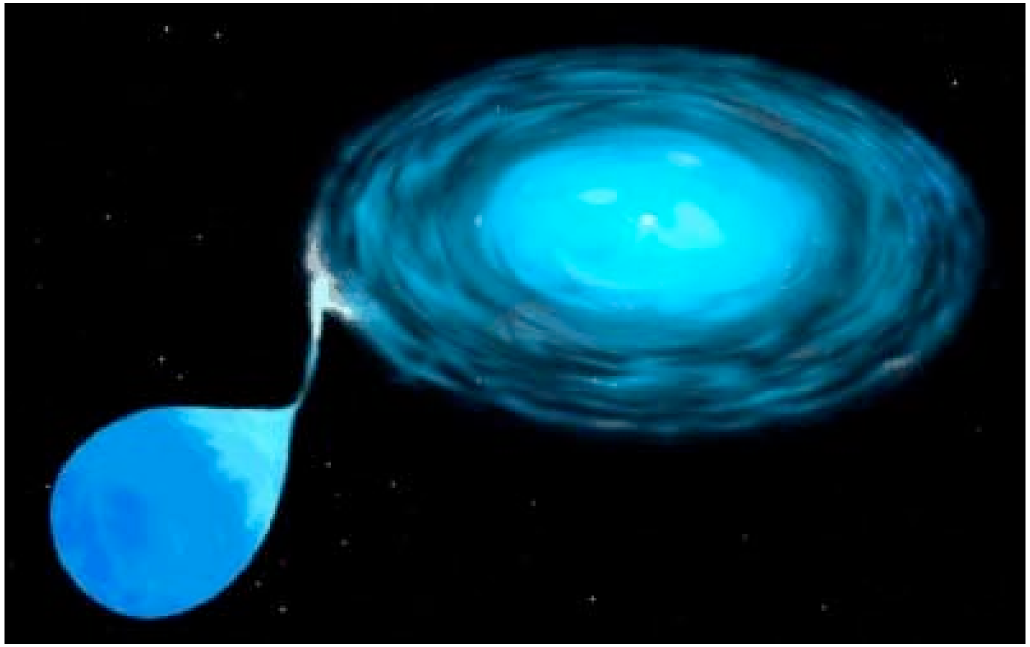
Because of this sensitivity, we can go out and try to measure each of these quantities as a function of redshift to derive Ω_m, Ω_Λ

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



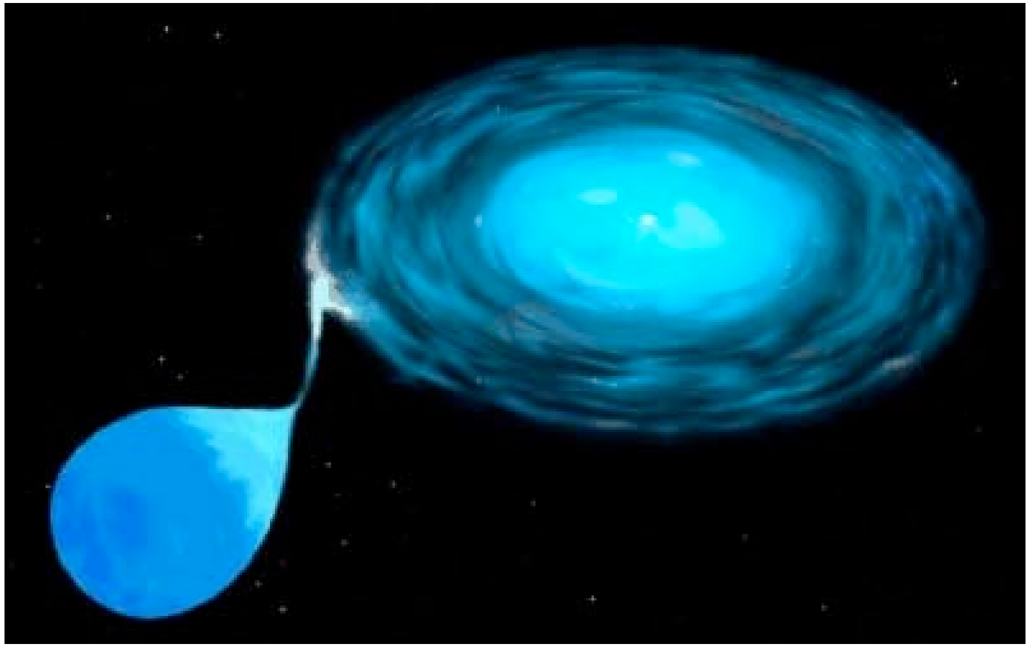
-- Likely occurs when a white dwarf is pushed over the Chandrashekhar limit of >1.4 M_{solar} by accretion from a nearby companion

Exceeding the Fermi pressure, inverse beta decay occurs:

$$p + e^- \rightarrow n + \nu_e + \gamma$$

Supernovae Ia

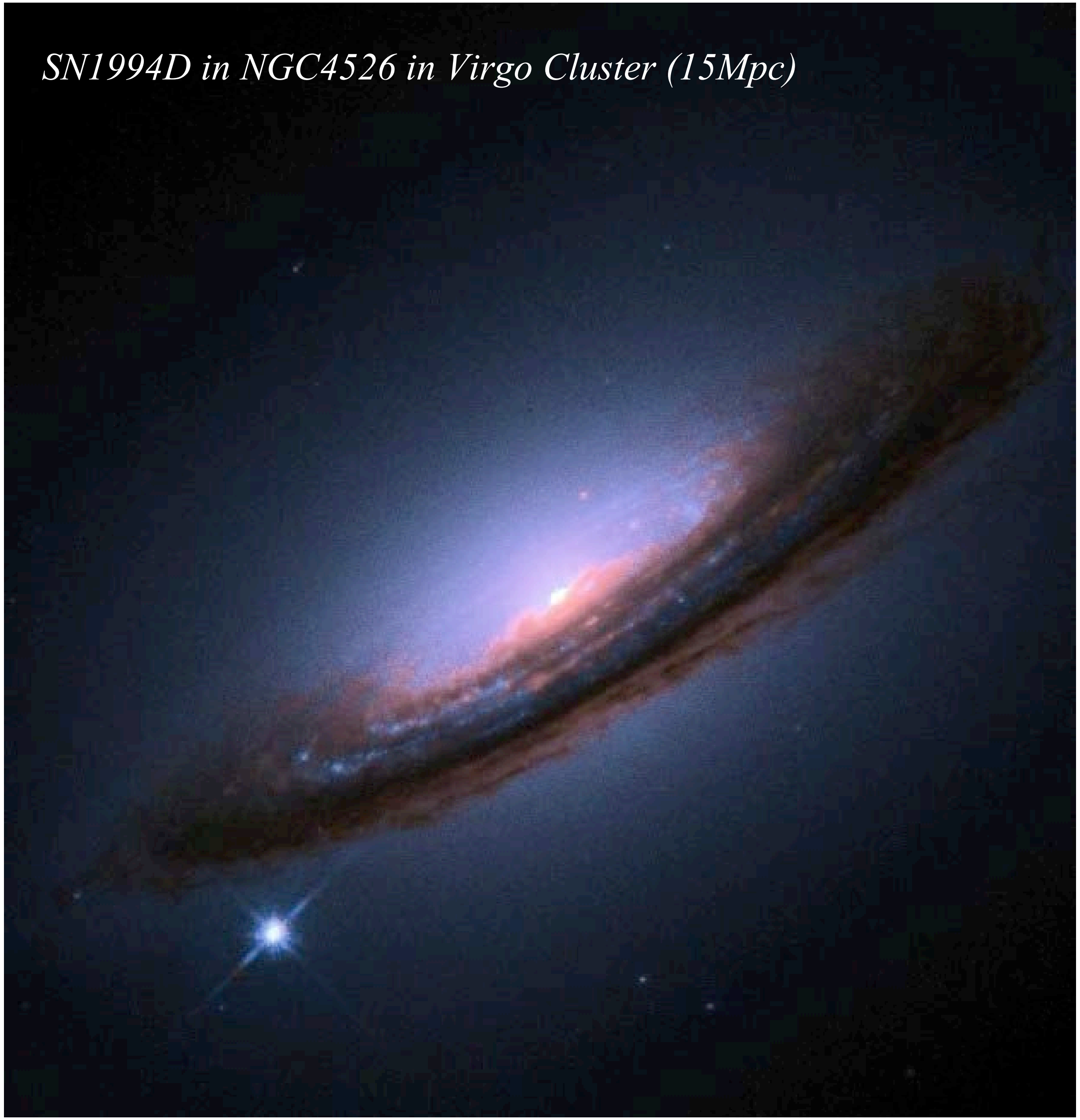
Accretion of matter from a nearby companion onto a white dwarf



-- Likely occurs when a white dwarf is pushed over the Chandrashekhar limit of >1.4 M_{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_{sol}) and a very luminous supernovae explosion

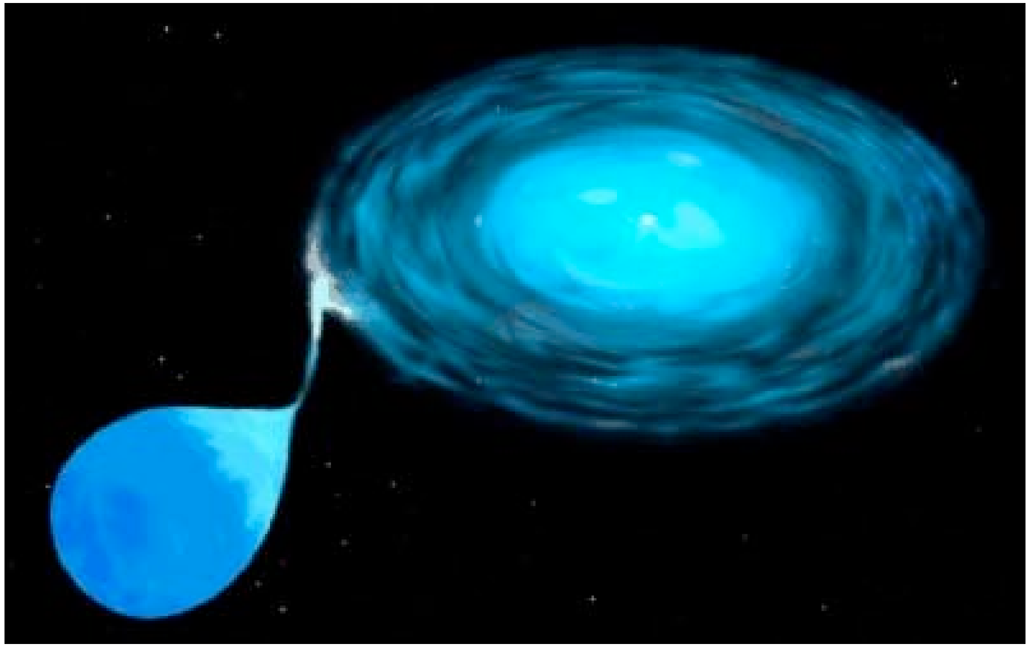
Supernovae Ia have same luminosity as an entire galaxy (but only for ~1 month)



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

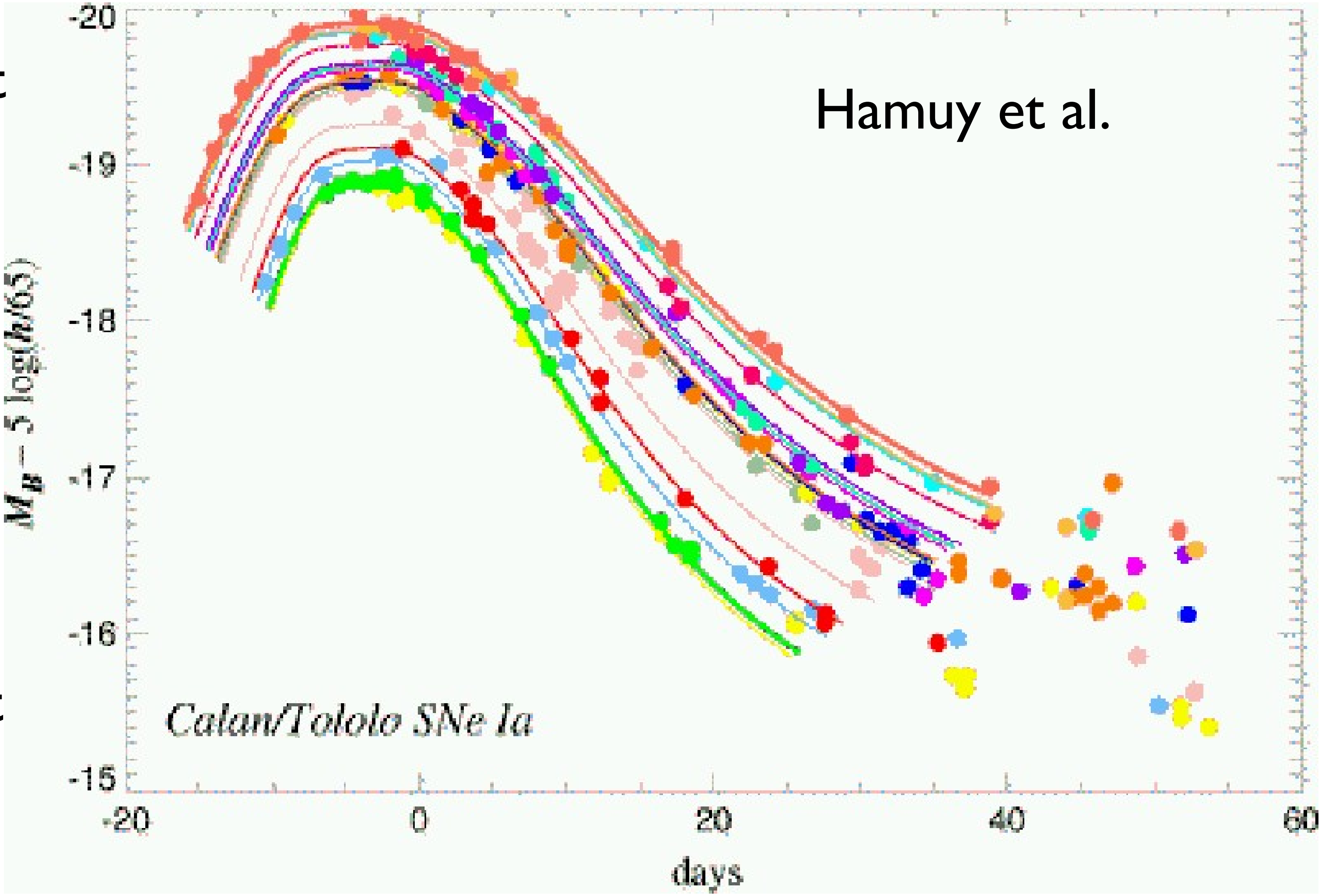
To derive luminosity distances, SN Ia must be a standard candle?

Are they standard candles?

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

bright

faint



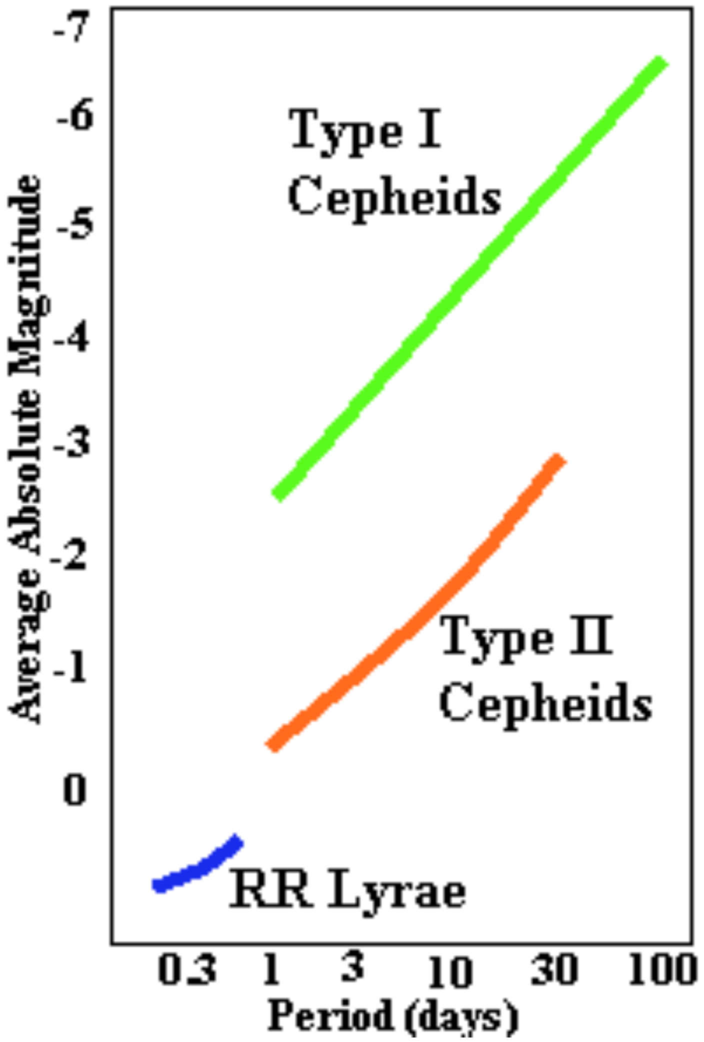
Hamuy et al.

Phillips relation (Phillips et al. 1996)

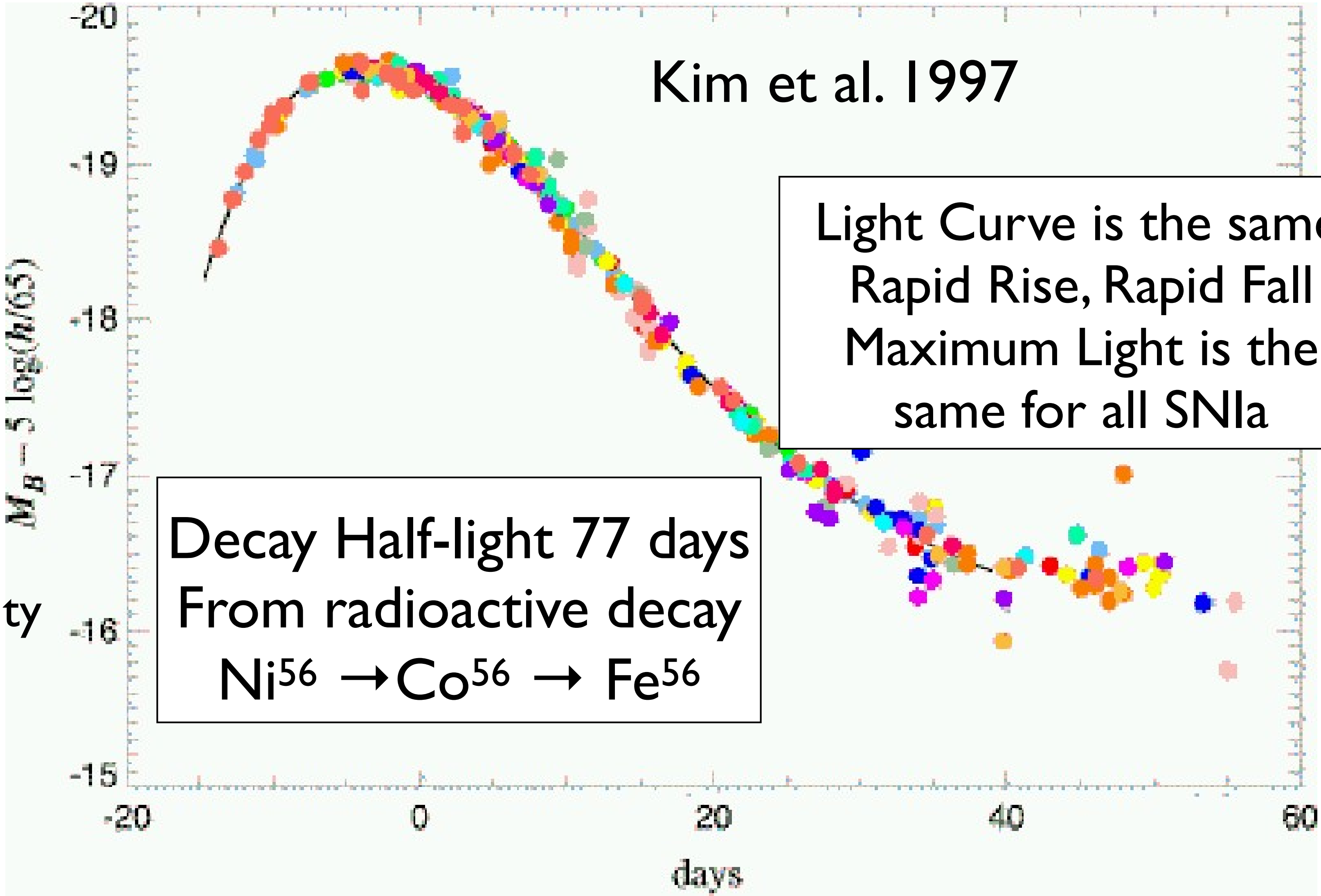
No they are not *standard* candles, but

they are *standardizable*

Similar to situation for variable stars →



How does it brightness vary with time?



Kim et al. 1997

Light Curve is the same,
Rapid Rise, Rapid Fall
Maximum Light is the
same for all SNIa

Decay Half-light 77 days
From radioactive decay
$Ni^{56} \rightarrow Co^{56} \rightarrow Fe^{56}$

Total Luminosity
(absolute
magnitudes)

Days

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

Establishing the actual luminosity of SNe are 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 → 10% error
10 SNe → 10% / $10^{1/2}$ ~ 3% error
100 SNe ~ 1% error

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

How do we find SNe Ia?

1. Construct a survey

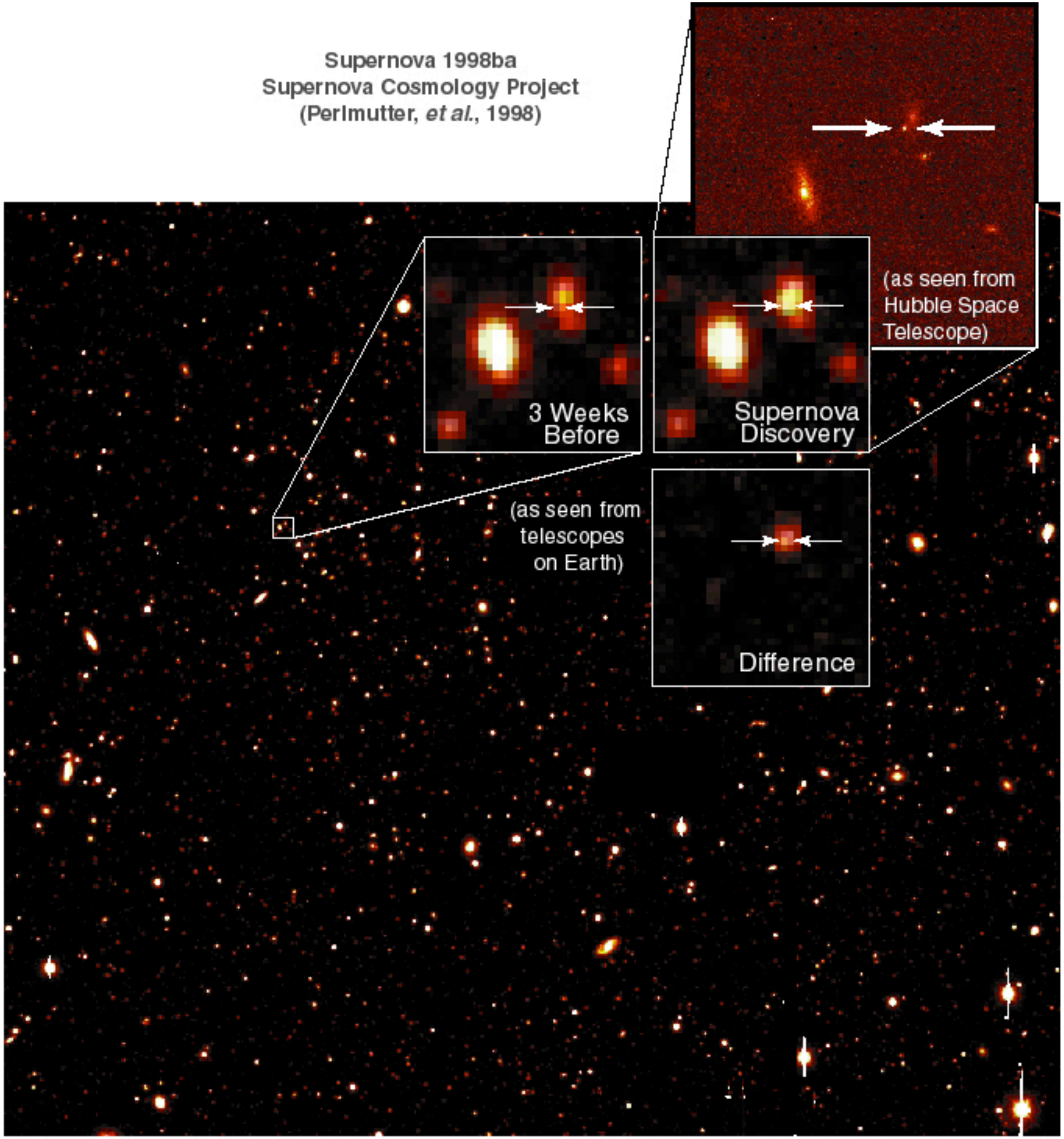
-- image the same part of the sky repeatedly looking for them

(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)


3 Weeks Before
Supernova Discovery
Difference
(as seen from Hubble Space Telescope)
(as seen from telescopes on Earth)

How do we find SNe Ia?

1. 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

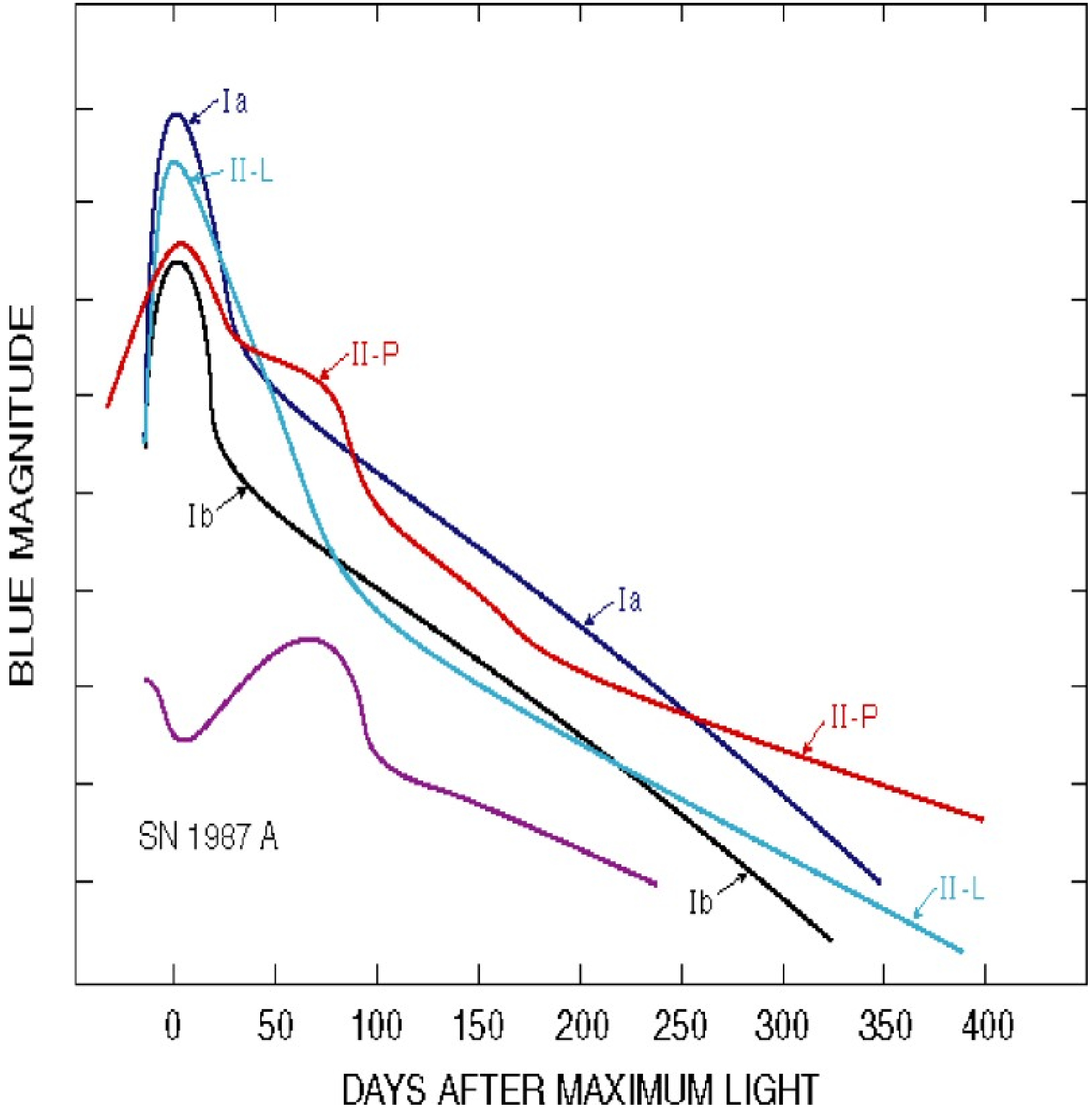
(this can be a challenge with ground-based telescopes since smoothing from turbulent sky conditions may change from night to night)

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_{sol} → SNe II

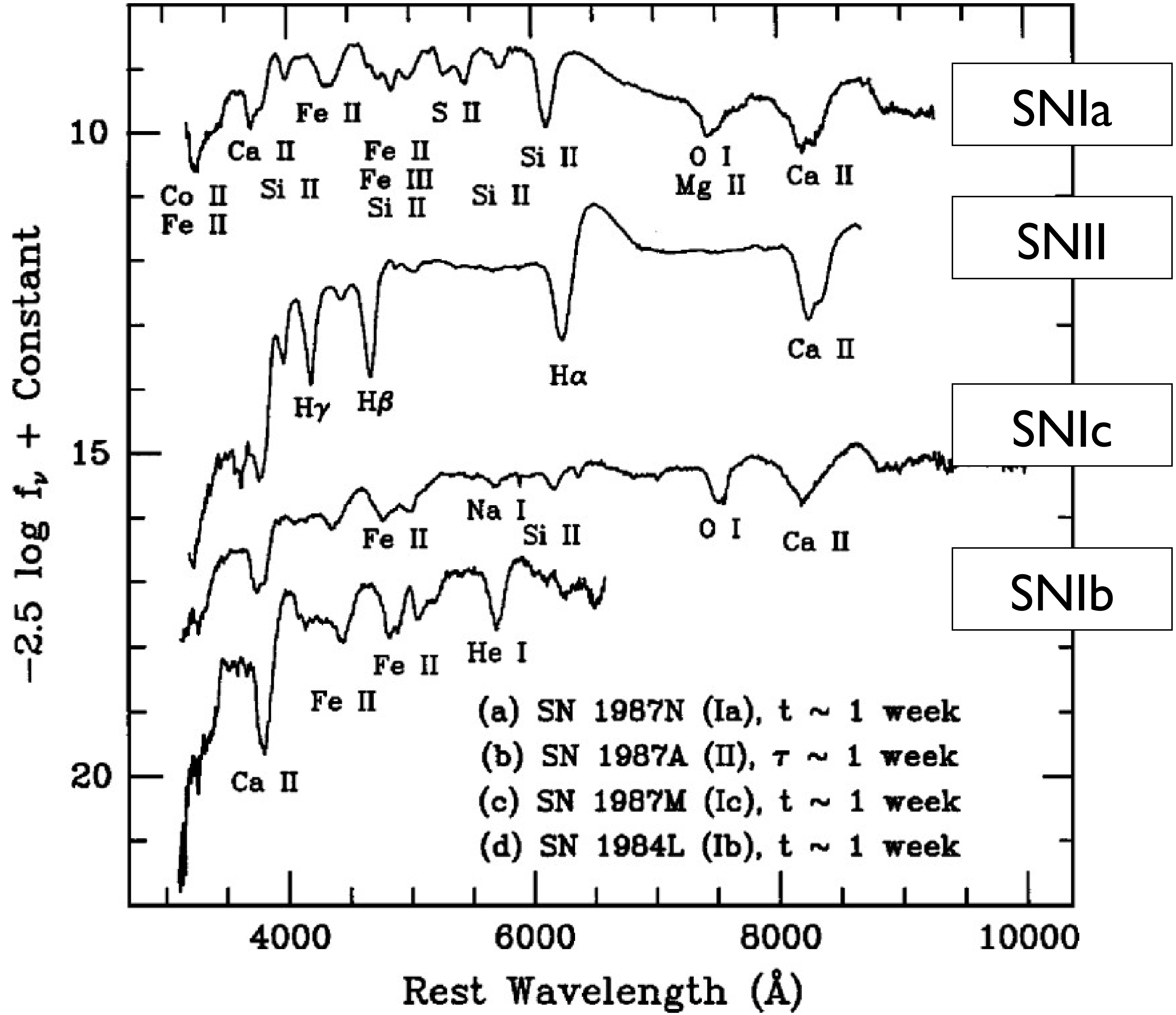
Core-collapse of stars with initial masses 8 - 30 M_{sol} → SNe Ib/Ic

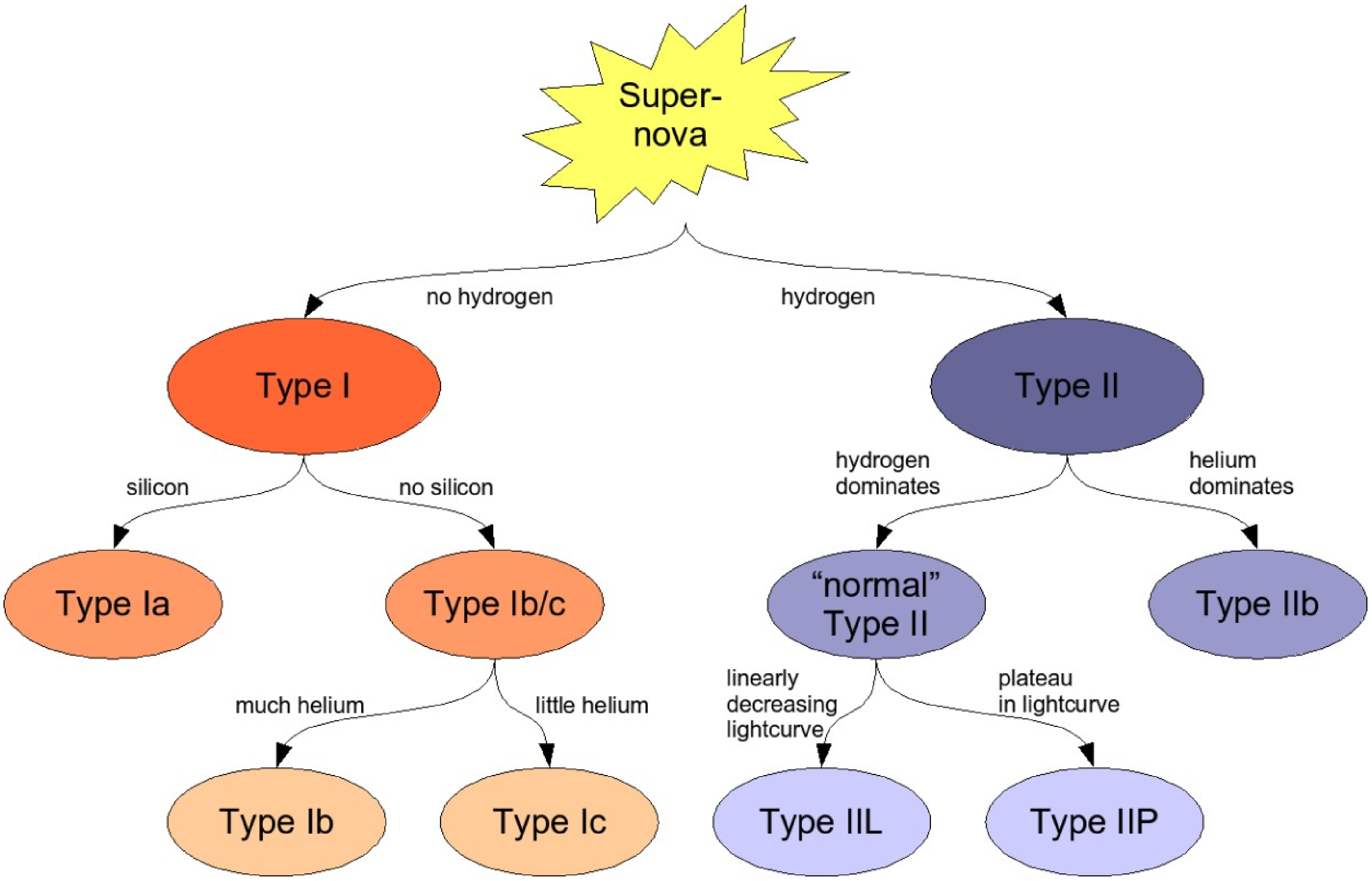
How do we find SNe Ia?

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

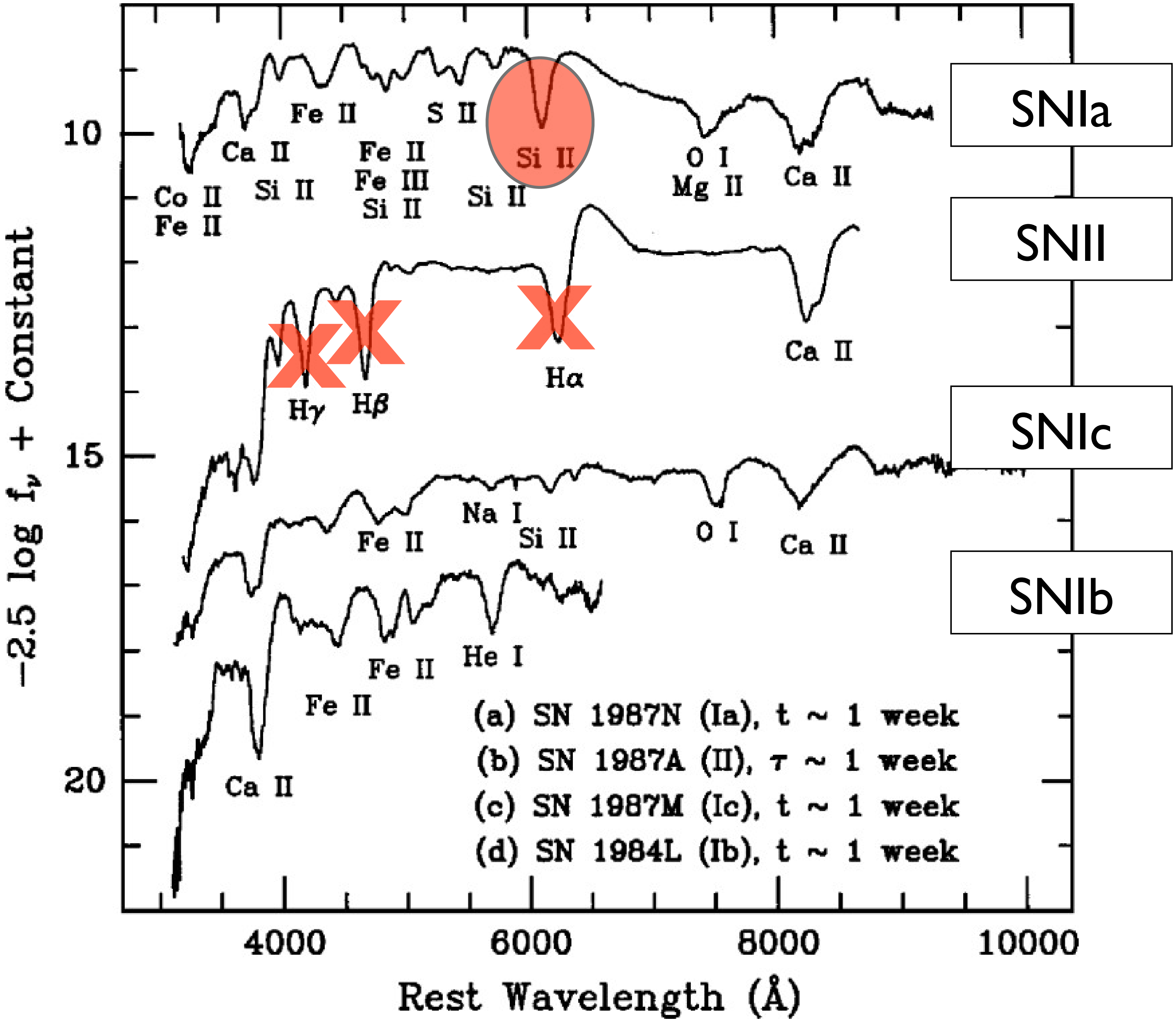
This is challenging for very distant SNe -- since they can have magnitudes of > 23-24 mag and requires large telescopes

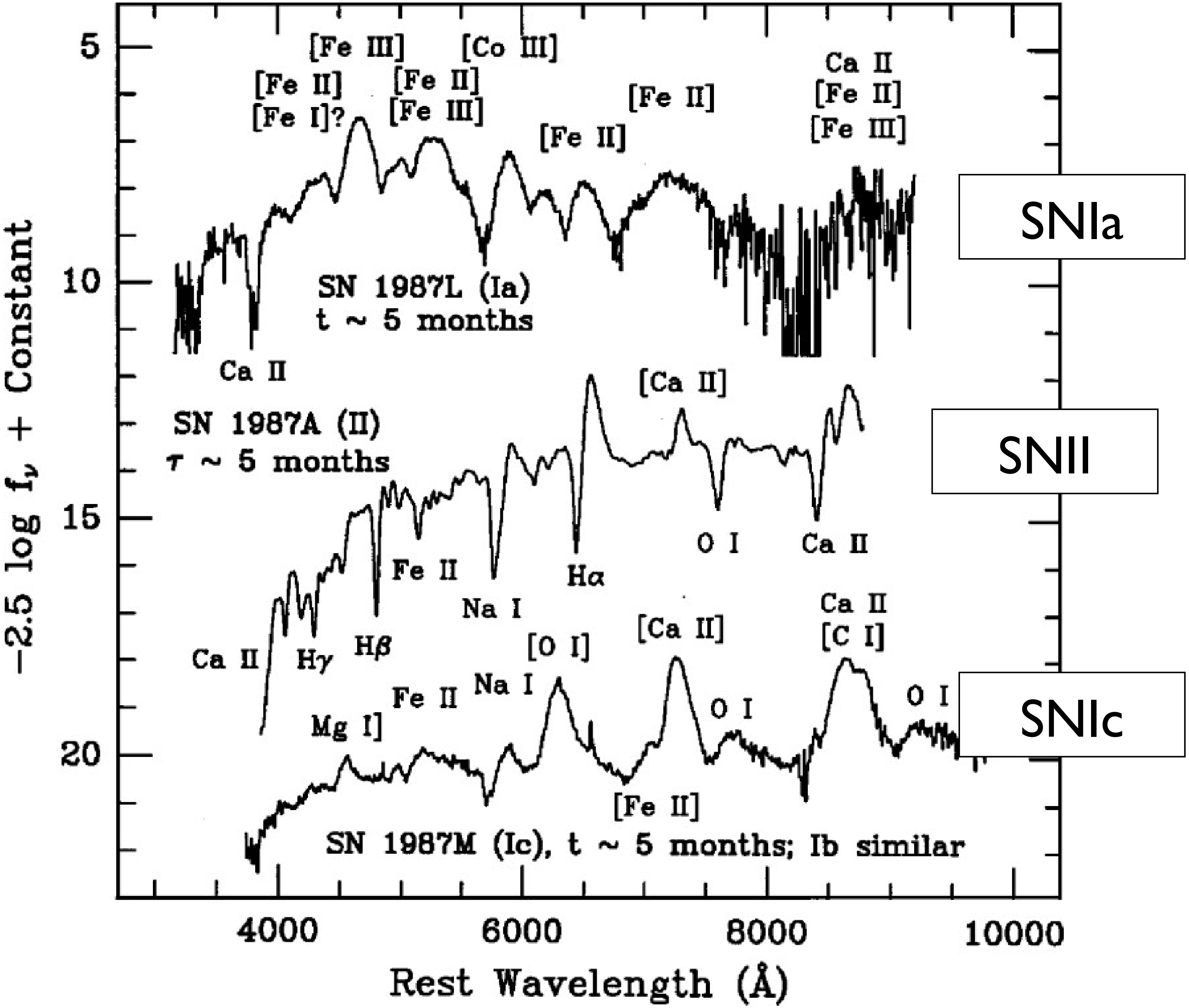
To distinguish SNe Ia from SNe Ib/Ic, need to check for the presence of Silicon lines (at ~6500 Angstroms rest-frame), so need spectroscopy in near-IR


SNIa
SNII
SNIc
SNIb
−2.5 log f_ν + Constant
10
15
20
4000
6000
8000
10000
Rest Wavelength (Å)
Co II
Fe II
Ca II
Si II
Fe II
Fe II
Fe III
Si II
S II
Si II
Si II
O I
Mg II
Ca II
Hγ
Hβ
Hα
Ca II
Fe II
Na I
Si II
O I
Ca II
Ca II
Fe II
Fe II
He I
(a) SN 1987N (Ia), t ~ 1 week
(b) SN 1987A (II), τ ~ 1 week
(c) SN 1987M (Ic), t ~ 1 week
(d) SN 1984L (Ib), t ~ 1 week


Super-
nova
no hydrogen
hydrogen
Type I
Type II
silicon
no silicon
hydrogen dominates
helium dominates
Type Ia
Type Ib/c
"normal" Type II
Type IIb
much helium
little helium
linearly decreasing lightcurve
plateau in lightcurve
Type Ib
Type Ic
Type IIL
Type IIP

Supernova classification.


SNIa
SNII
SNIc
SNIb
Fe II
S II
Si II
Ca II
Fe II
Fe III
Si II
Si II
Co II
Fe II
Si II
O I
Mg II
Ca II
Hγ
Hβ
Hα
Ca II
Na I
Si II
Fe II
O I
Ca II
Fe II
He I
Fe II
Ca II
(a) SN 1987N (Ia), t ~ 1 week
(b) SN 1987A (II), τ ~ 1 week
(c) SN 1987M (Ic), t ~ 1 week
(d) SN 1984L (Ib), t ~ 1 week
−2.5 log f_ν + Constant
10
15
20
4000
6000
8000
10000
Rest Wavelength (Å)



SNIa

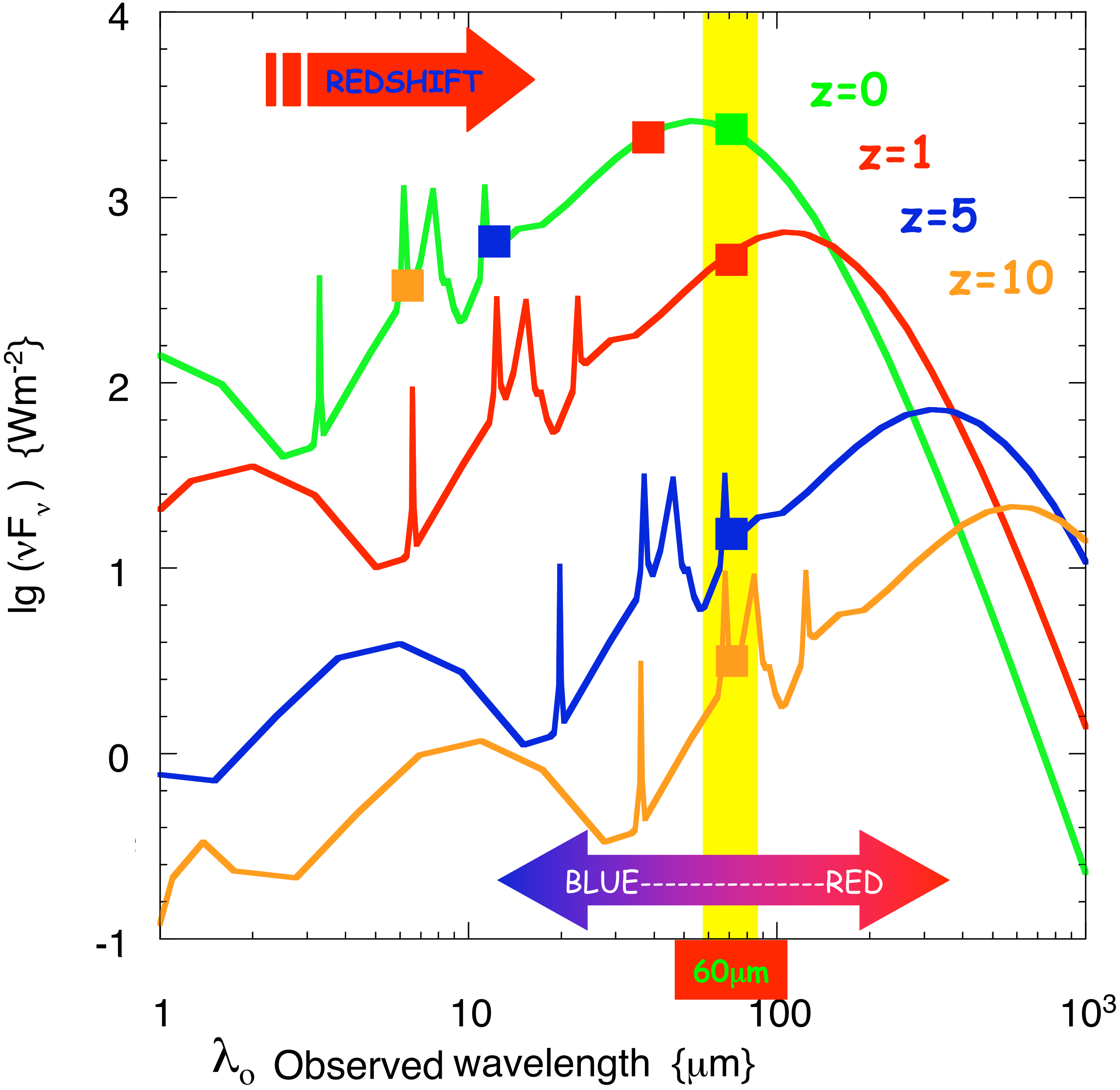
SNII

SNIc

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

1. 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")


REDSHIFT
z=0
z=1
z=5
z=10
BLUE--------------RED
60μm
4
3
2
1
0
-1
1
10
100
10^3
λ_o Observed wavelength {μm}
lg (νF_ν) {Wm^-2}

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...

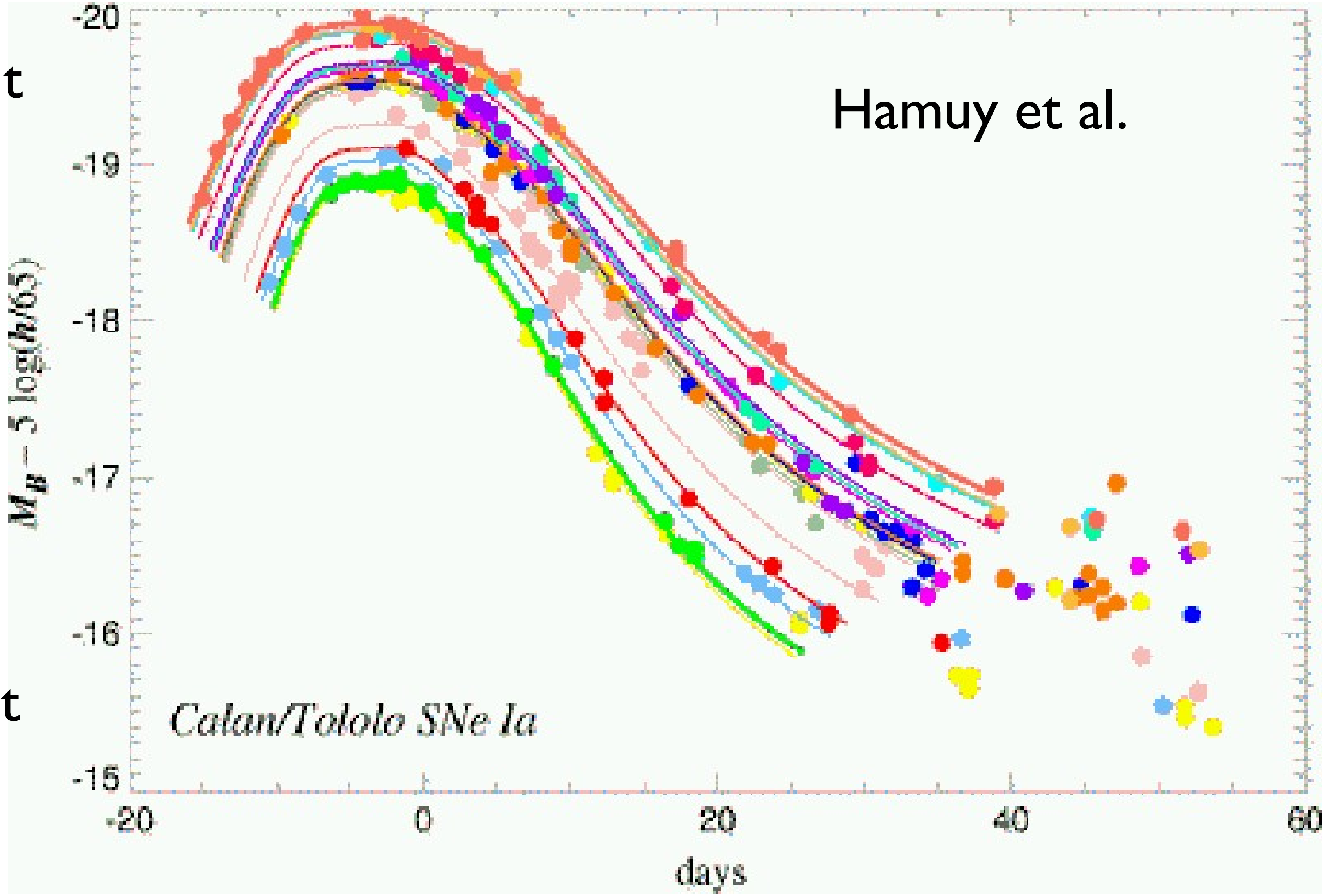
Also must correct for cosmological time delay!

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

bright

faint



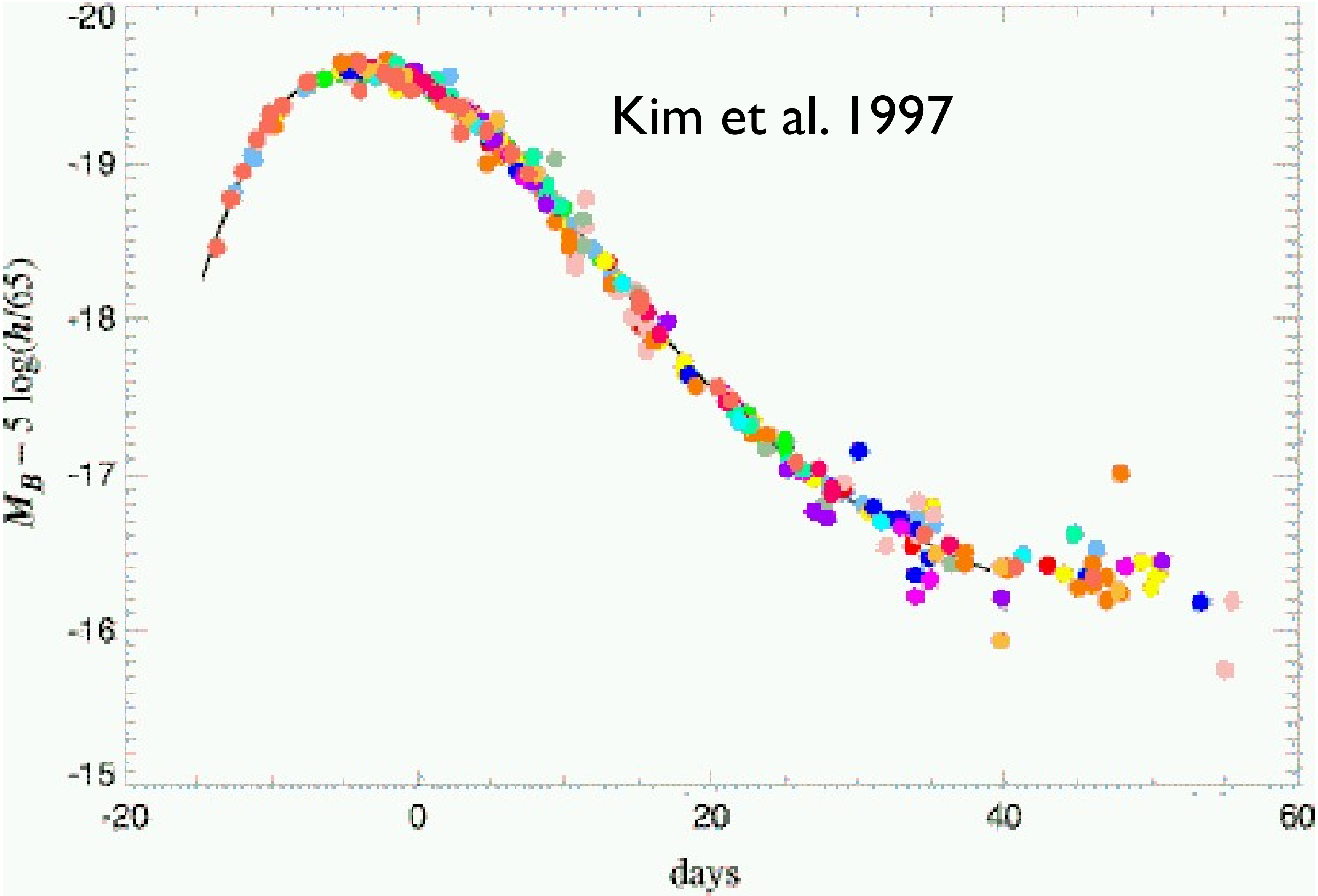
Hamuy et al.

Philips relation (Philips et al. 1996)

SNe light curve (after correction)

bright

faint



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.

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

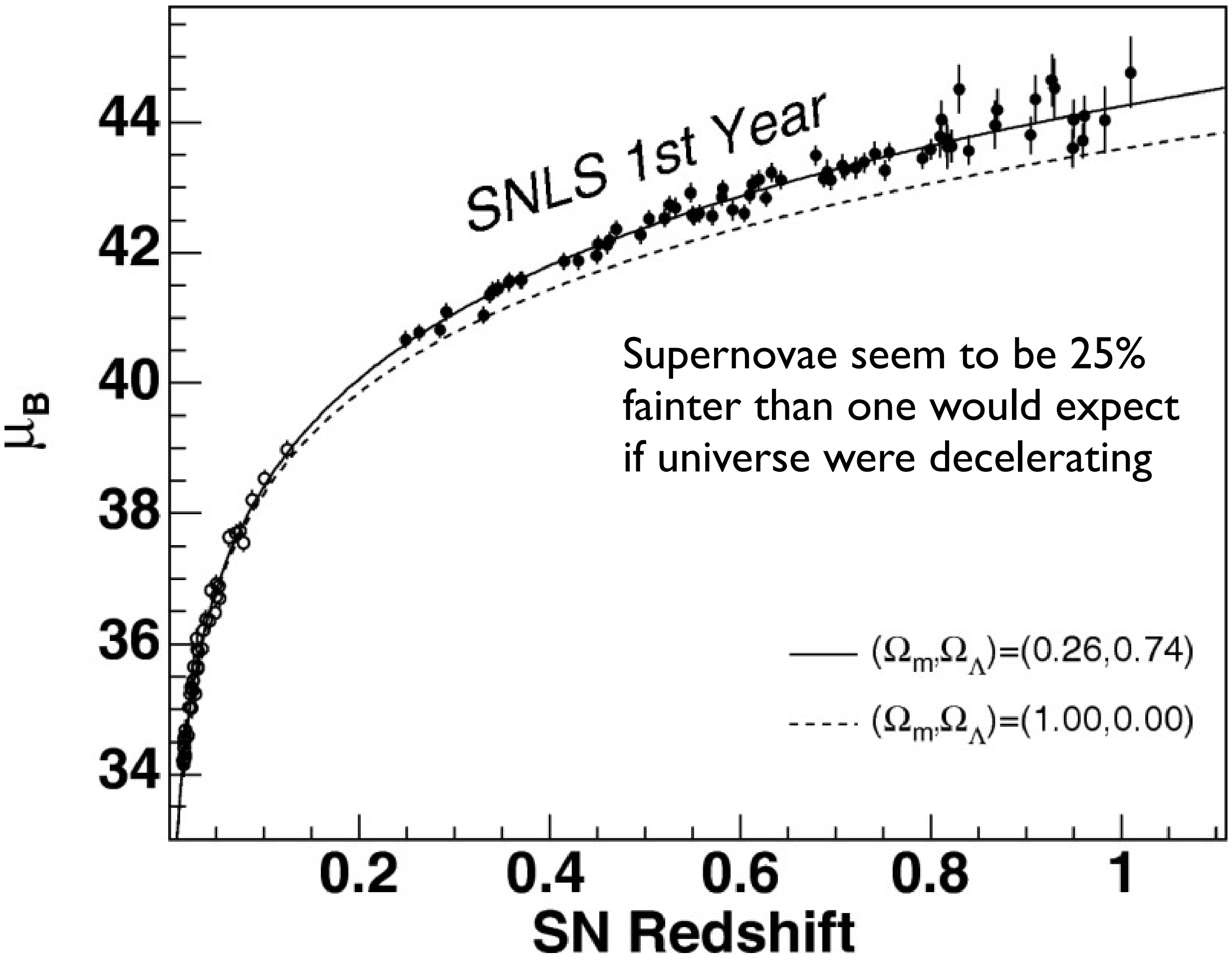
f = flux

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

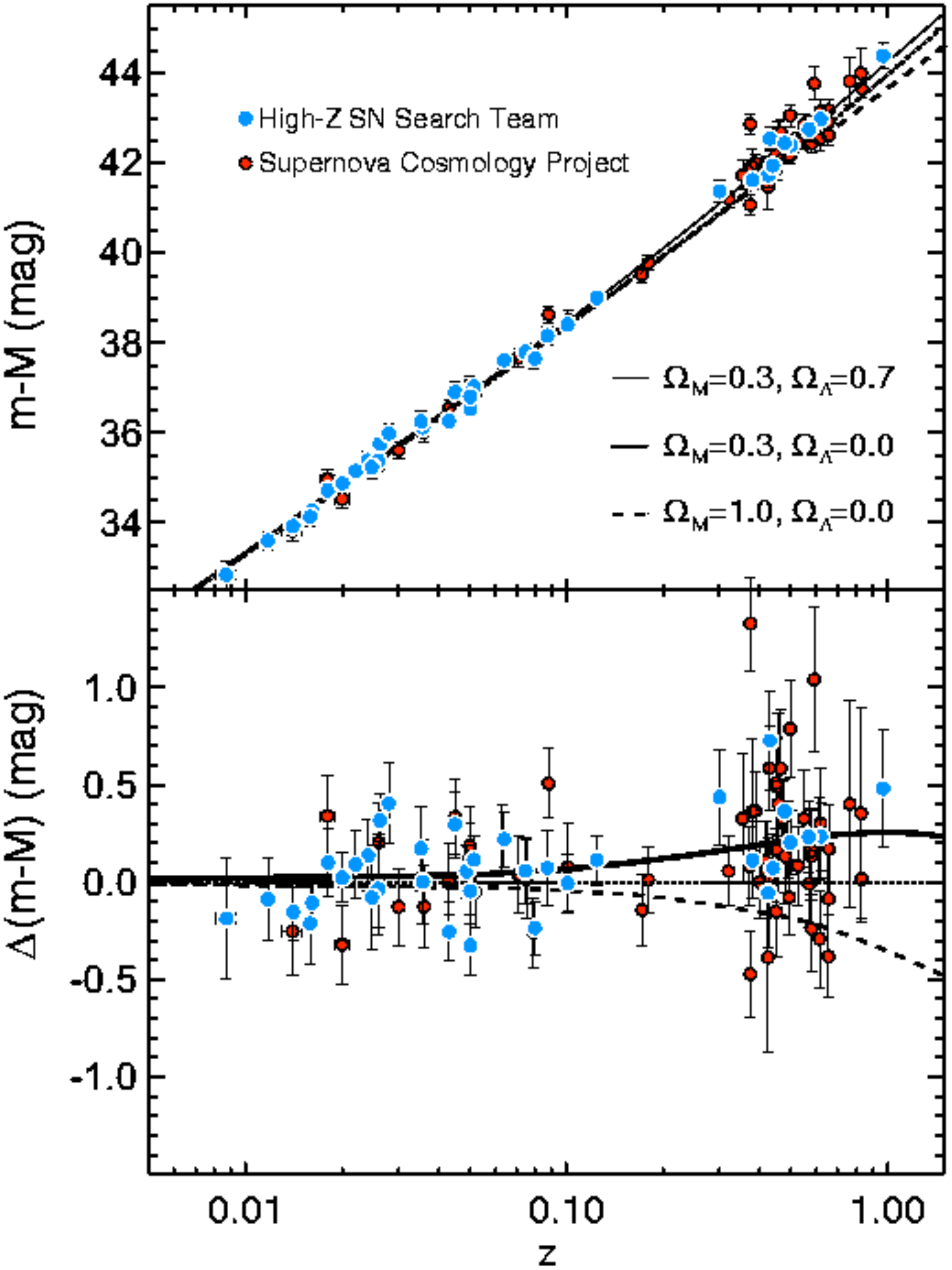
5. Plot luminosity distance versus redshift

Distance modulus

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



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

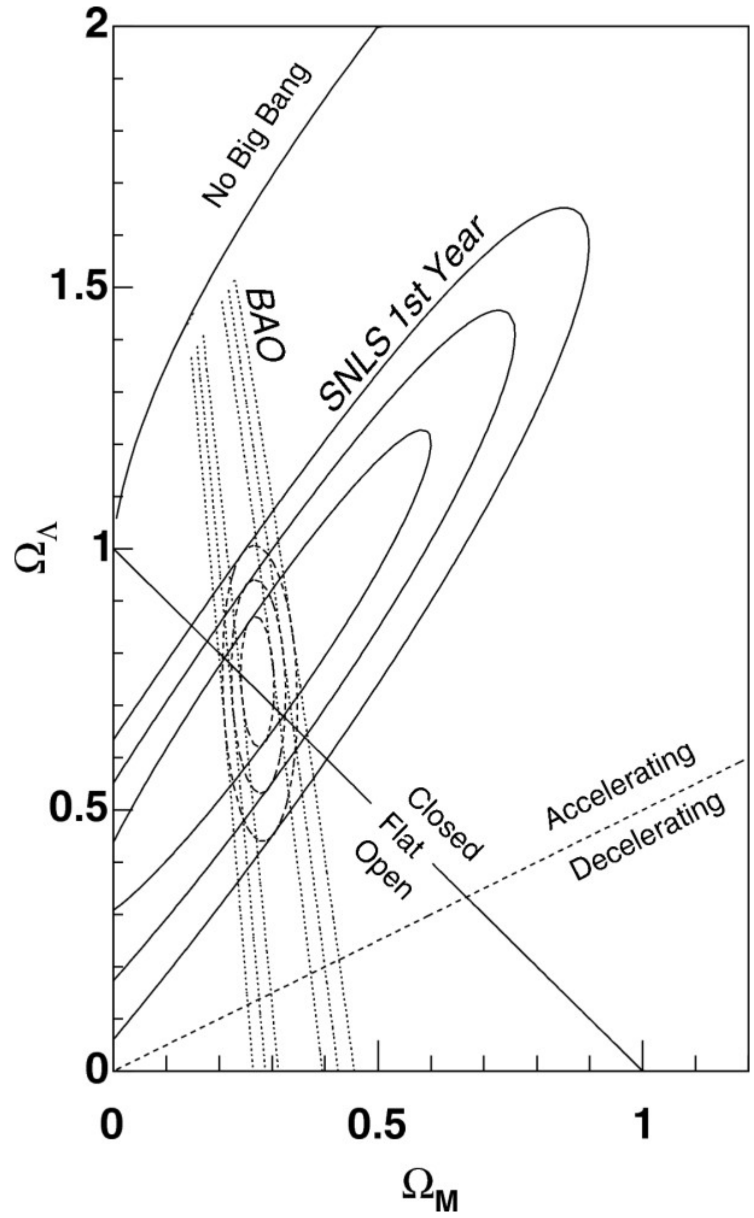


Riess et al. 1998

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

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

What constraints can one set?



Cosmological parameter constraints derived from the same data.

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

Two Main Teams found this result:

High-Z SNe search team

Supernovae Cosmology Project

Adam Riess

Photo: Scanpix/AFP

Adam G. Riess

Brian Schmidt

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Saul Perlmutter

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?

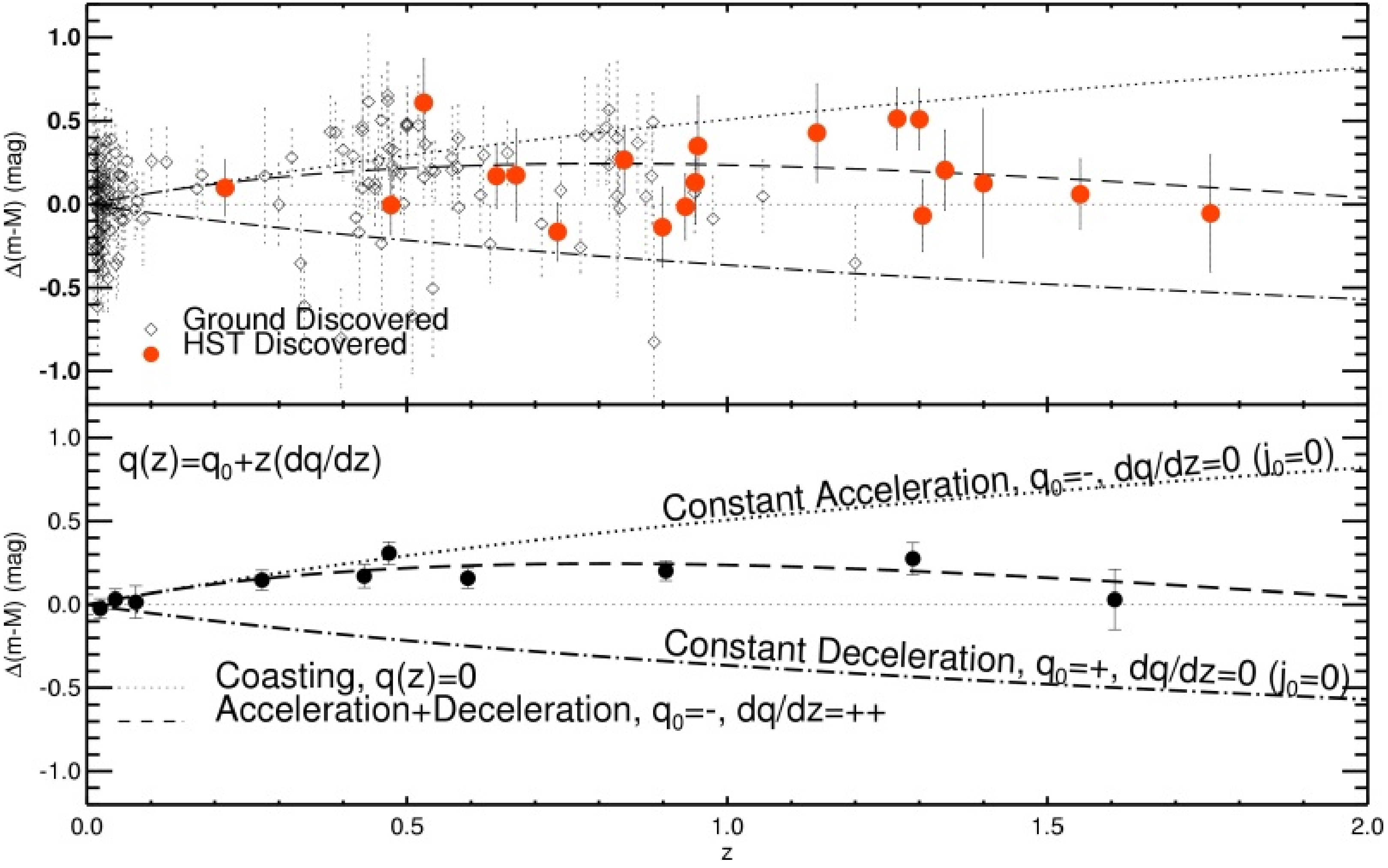
(their metal content may be different!)

(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 ~ 1, there is a change in shape and cosmic acceleration turns into deceleration



Riess et al. 2004

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)

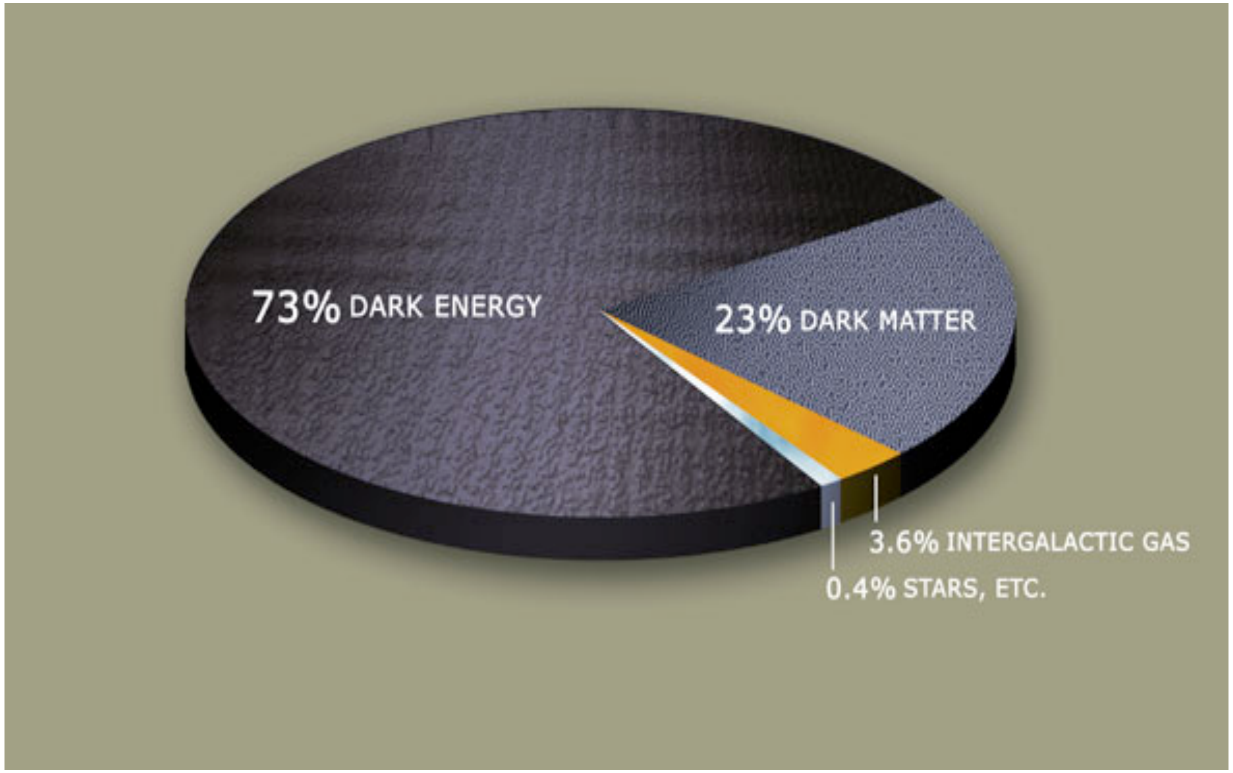
We will talk more about dark energy later in the course.... but it is interesting to consider why did no one notice it before ~1997?

- The measured value corresponds to a matter density of 0.000000000000000000000000006 kg per cubic meter (less than the mass of 4 protons)
- The best vacuum made in a physics laboratory has a density which is higher by a factor of a billion
- A cube stretching from Bonn to the Moon only contains 340 g of dark energy
- A cube stretching from Bonn to the Sun only contains 20 million Kg of dark energy, a fraction 0.00000000000000000000001 of the solar mass
- A cube enclosing the whole Galaxy contains nearly 1 trillion solar masses of dark matter but only 3 million solar masses of dark energy
- A cube as large as the visible universe contains 73% of the mass in dark energy

Credit: Porciano

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 ~27% of mass-energy density of the universe in the form of normal matter

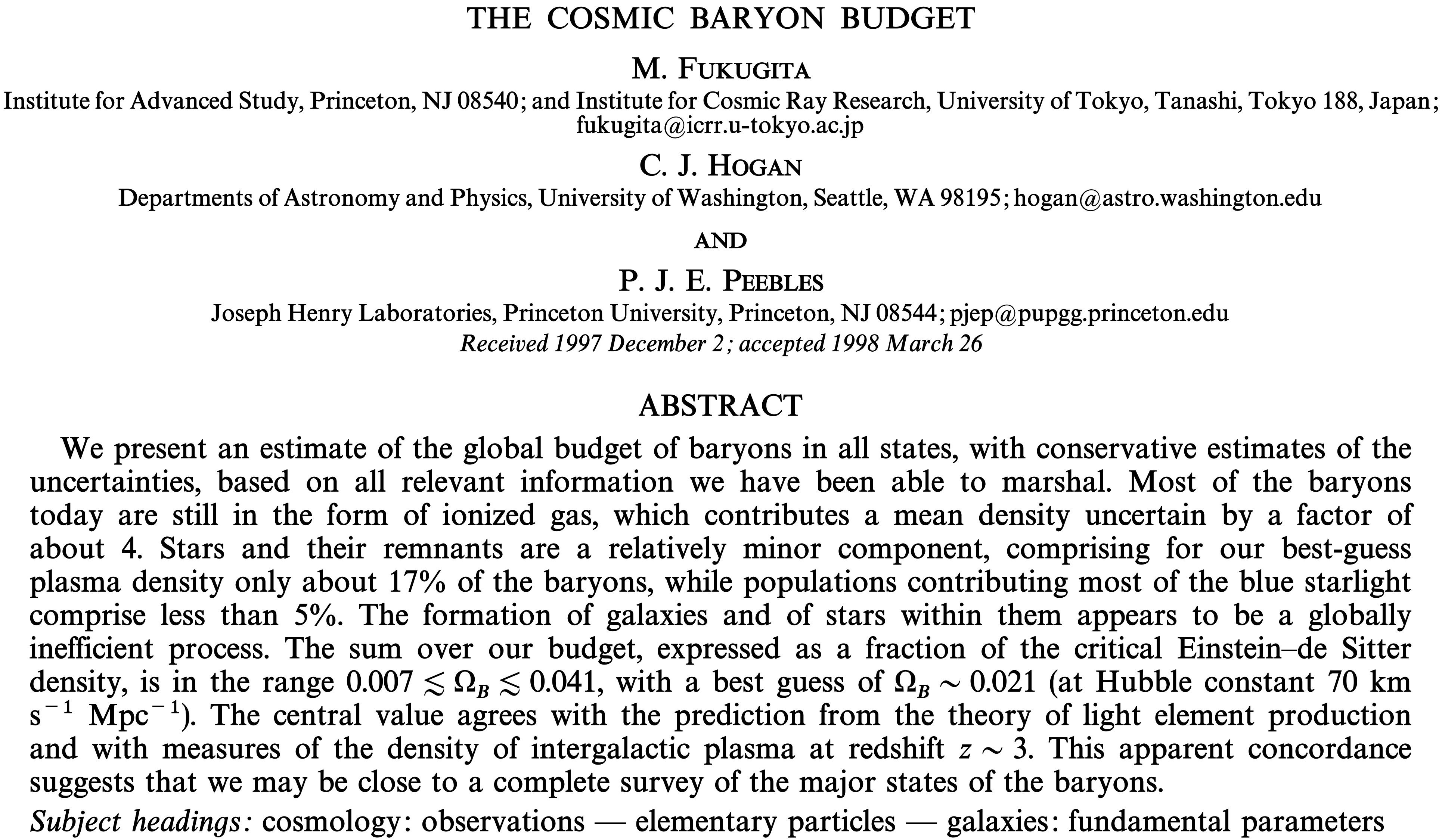
(we will present convincing evidence that $\Omega = 1$ next week)

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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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 km s^{-1} 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

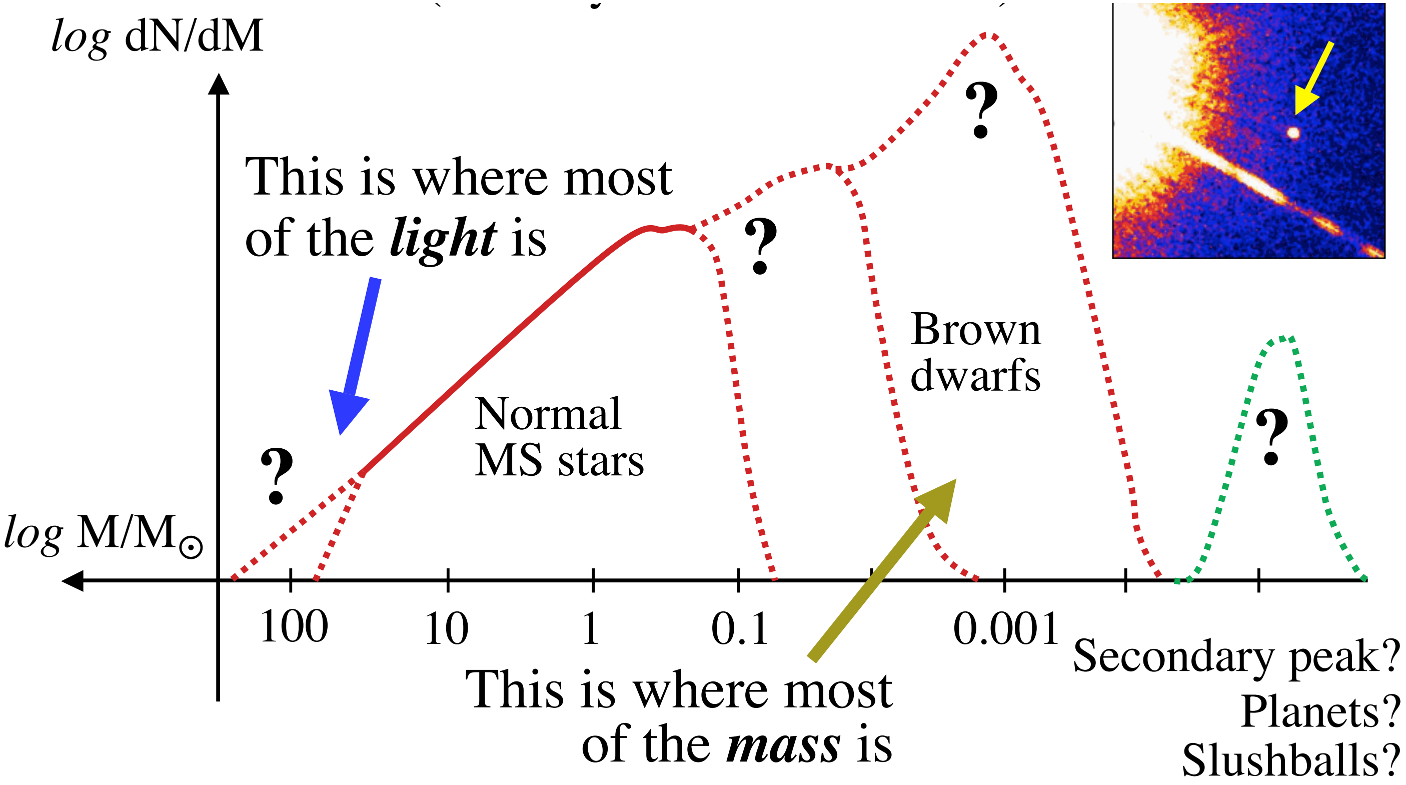
What is the mass density in stars?

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



This is where most of the ***light*** is

This is where most of the ***mass*** is

Secondary peak?
Planets?
Slushballs?

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

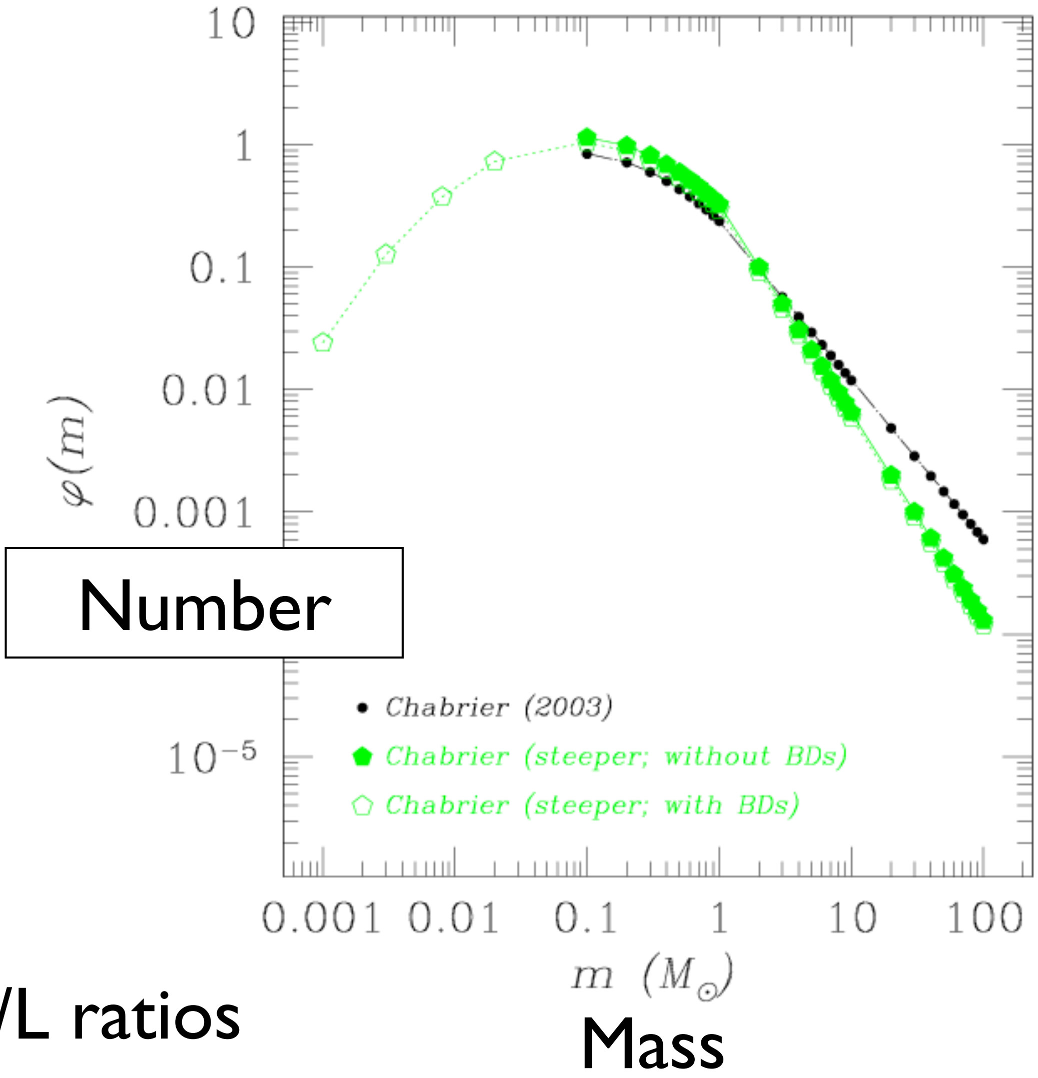
i.e., since L ∝ M^3

then M/L ∝ M^{-2}

low mass stars → high M/L ratios

high mass stars → low M/L ratios

Stellar Initial Mass Function



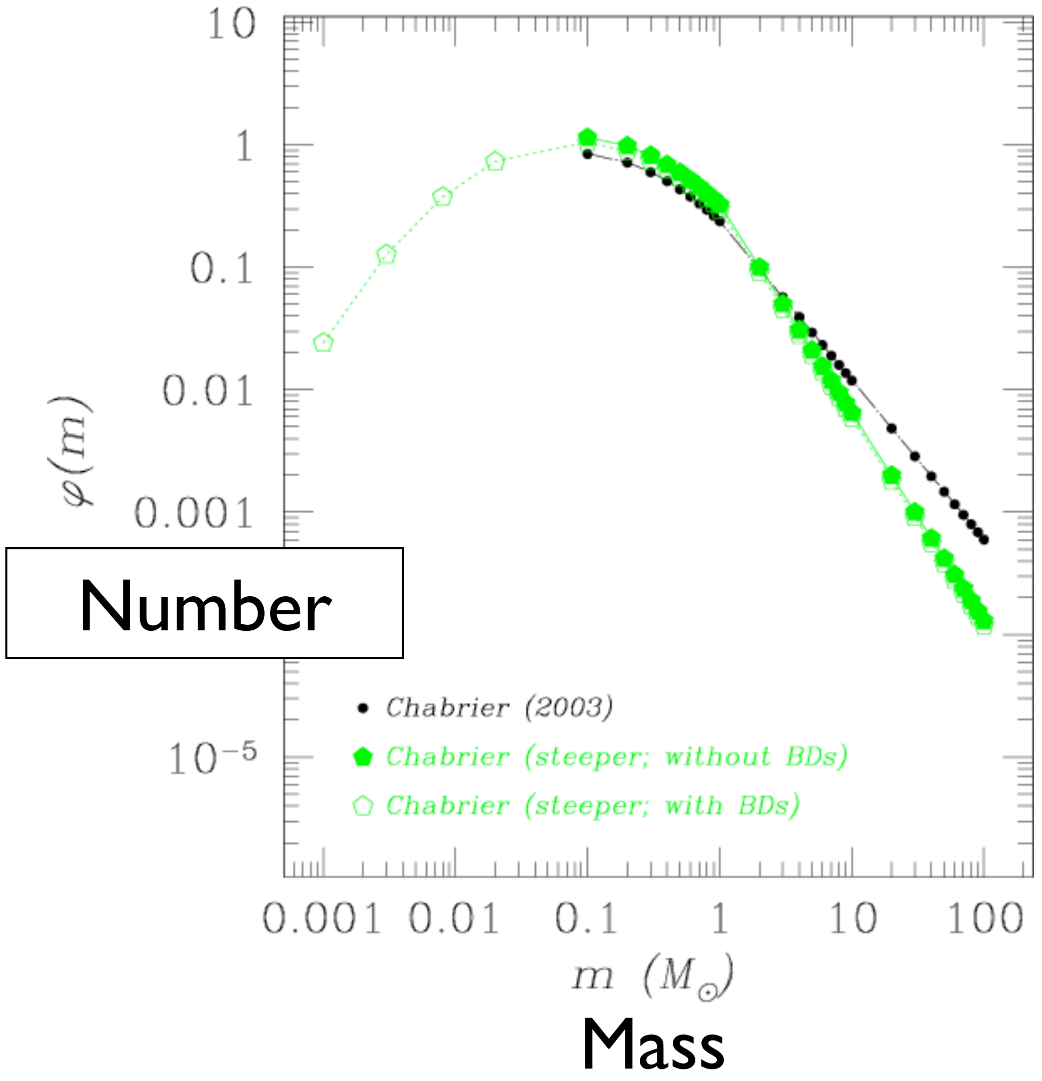
What is the mass density in stars?

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?

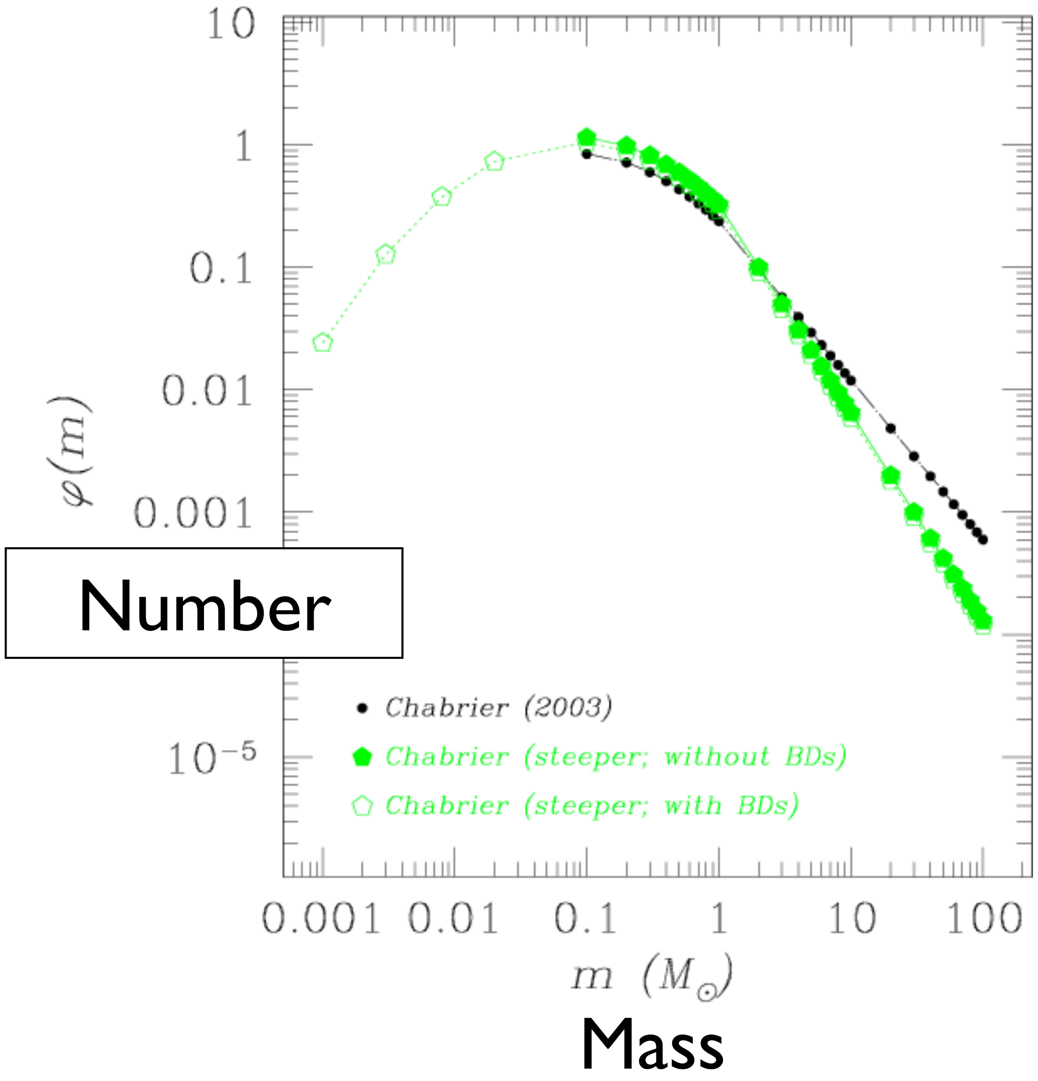
so the M/L ratio for a population of stars depends on its age

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?

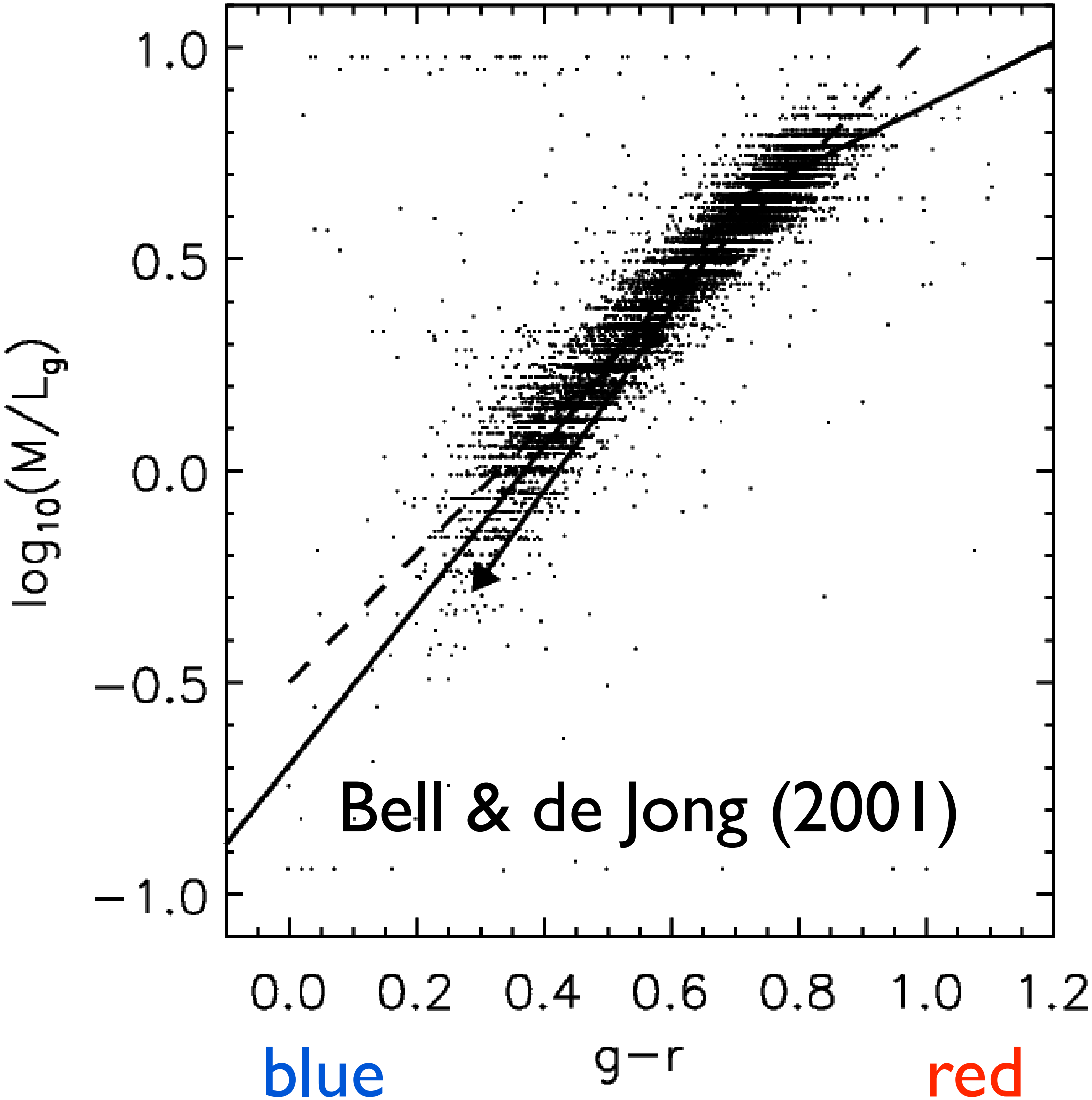
possible to relate
the M/L ratio to
the observed color of a
galaxy

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

⇒ this allows us to

estimate the mass for
one galaxy at a time

M/L ratio vs. color



Bell & de Jong (2001)

blue

red

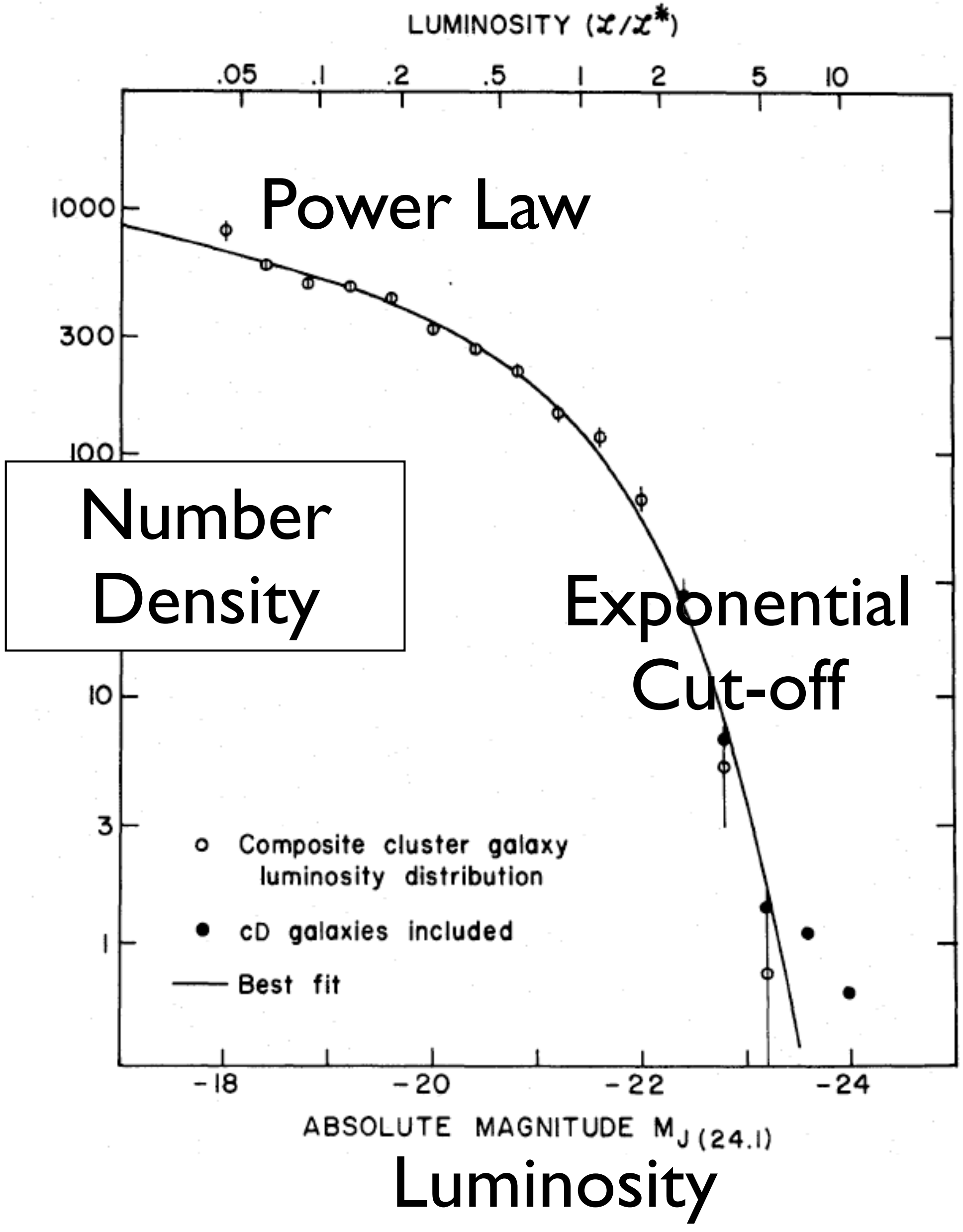
What is the mass density in stars?

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:

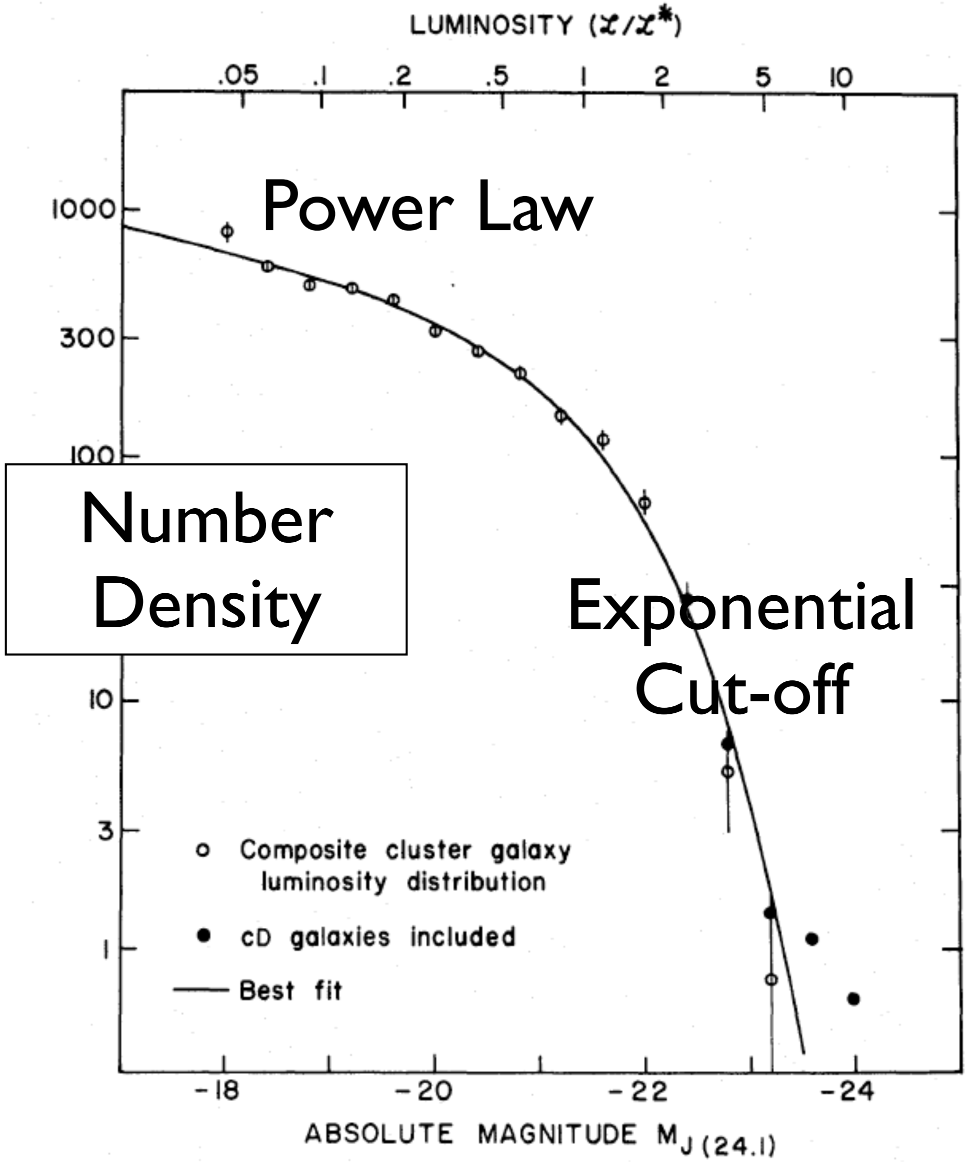


What is the mass density in stars?

Integrate over this function:

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

$\Omega_{stars} = 0.002$



Power Law

Number Density

Exponential Cut-off

Luminosity

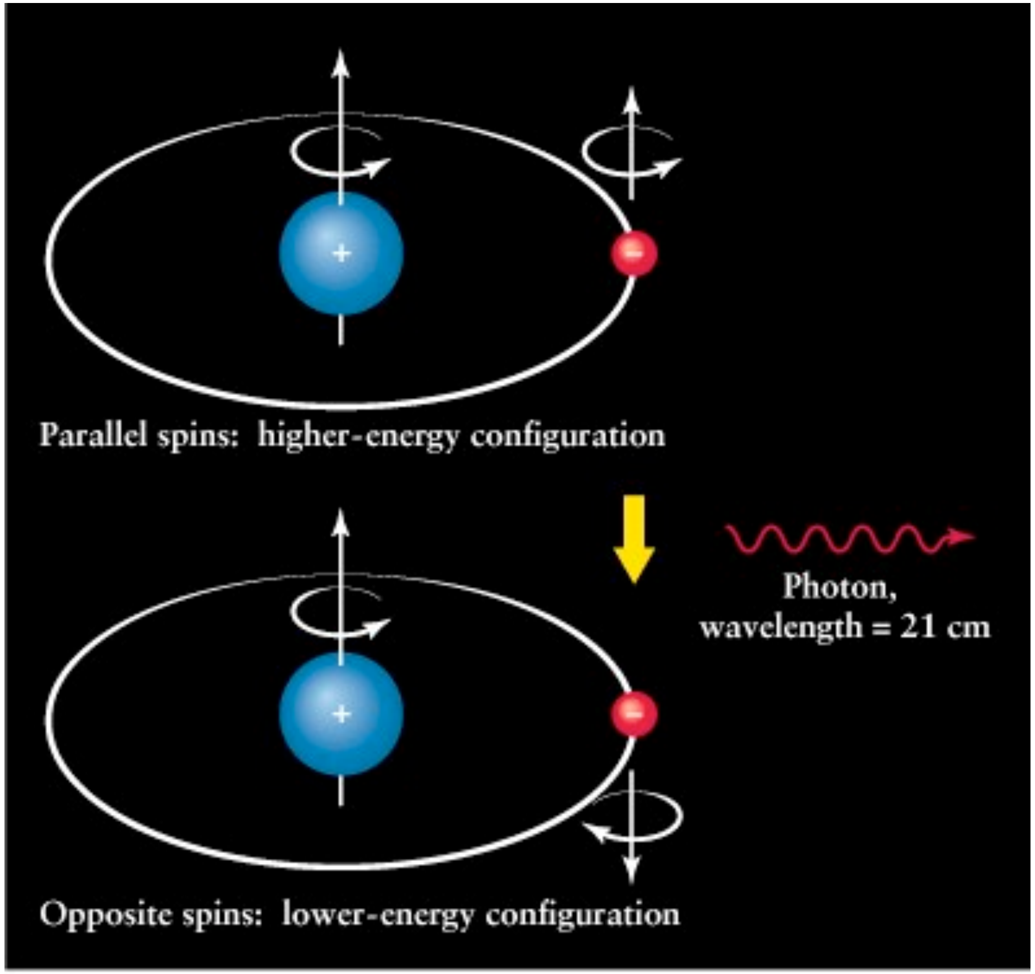
What is the mass density in cold gas?

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.


+
−
Parallel spins: higher-energy configuration
Photon,
wavelength = 21 cm
+
−
Opposite spins: lower-energy configuration

b

What about the mass density in neutral atomic hydrogen?

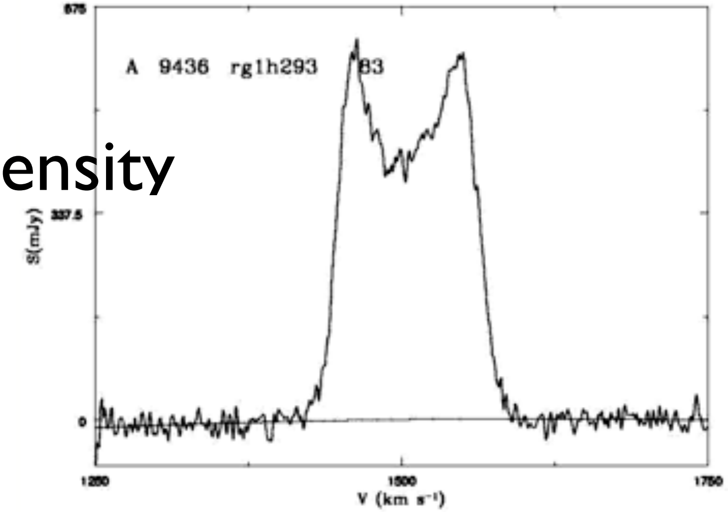
Conduct blind surveys at 21 cm with radio telescopes

Arecibo or Parkes
(64 m dish)

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

Rao & Briggs (1993)

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



Intensity

Doppler shift velocity

What about the mass density in molecular hydrogen H_2?

Difficult to go out and search for H_2 since no observable transitions (has no dipole)

To make progress, assume CO emission is a good tracer of H_2 (CO emission caused by H_2 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

$\Omega_{H2} = 0.0003$

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

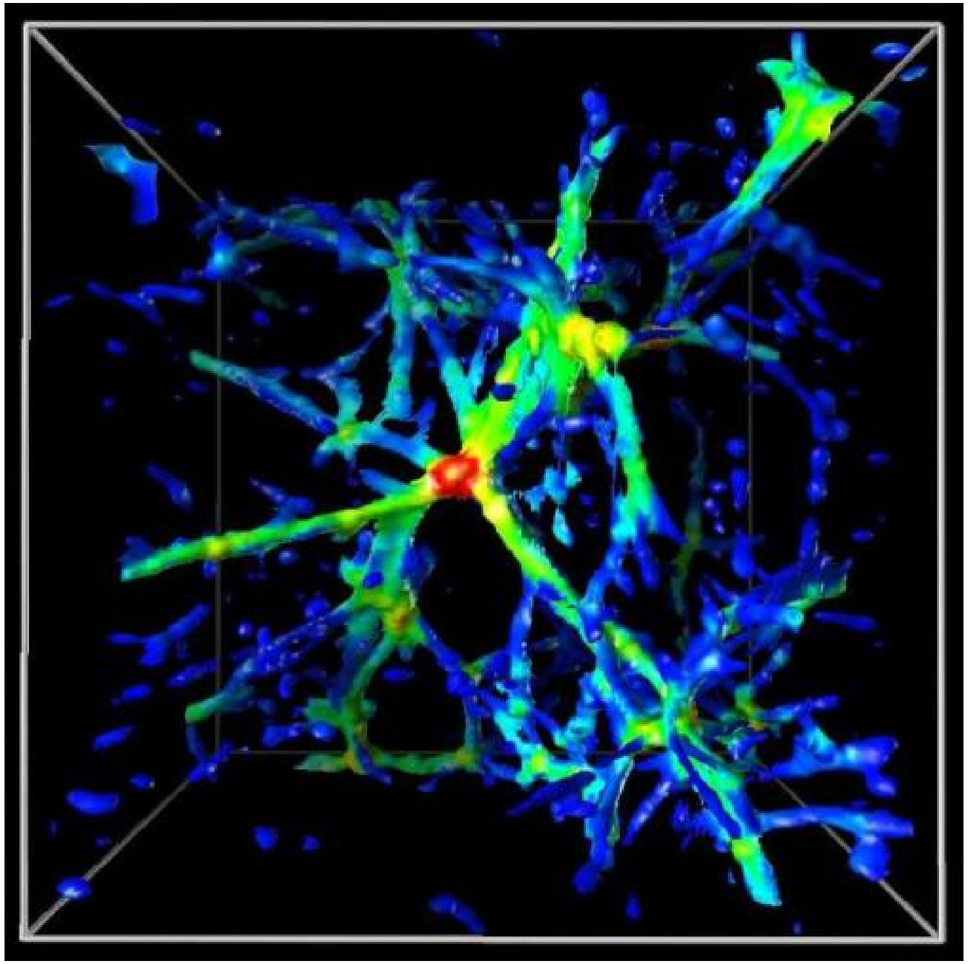
$$\Omega_{\mathrm{stars+gas}} = 0.0026$$

(what we can easily detect)

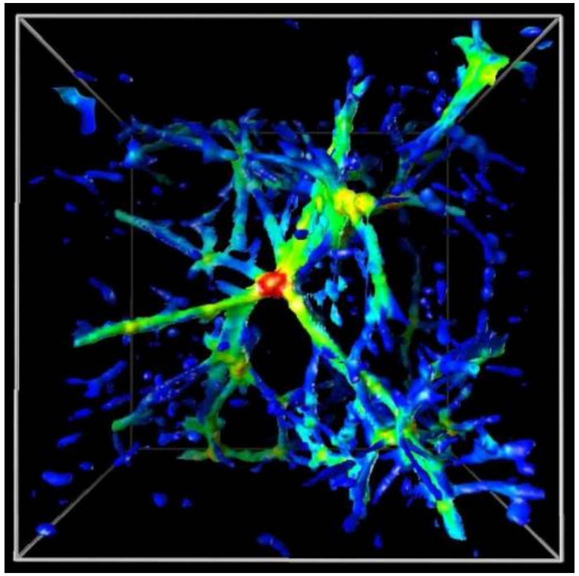
but this is a small fraction (<10%) of the value we prefer today $\Omega_{\mathrm{baryons}} = 0.04$

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?

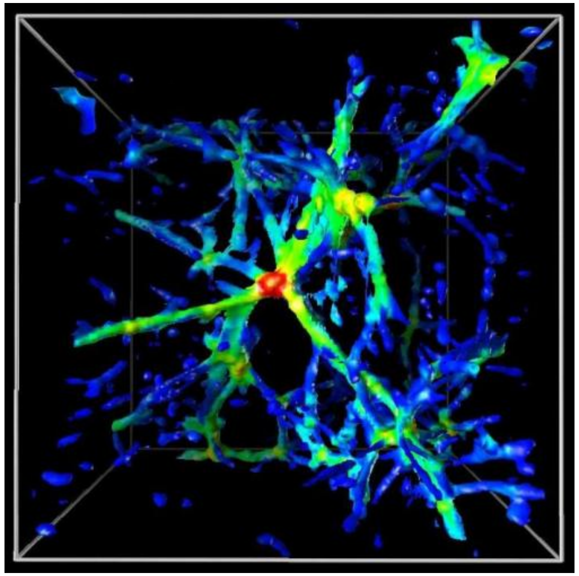


Would expect ionized material to emit thermal bremstrahlung radiation, but neither dense enough or hot enough to produce enough flux to observe with x-ray satellites

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!

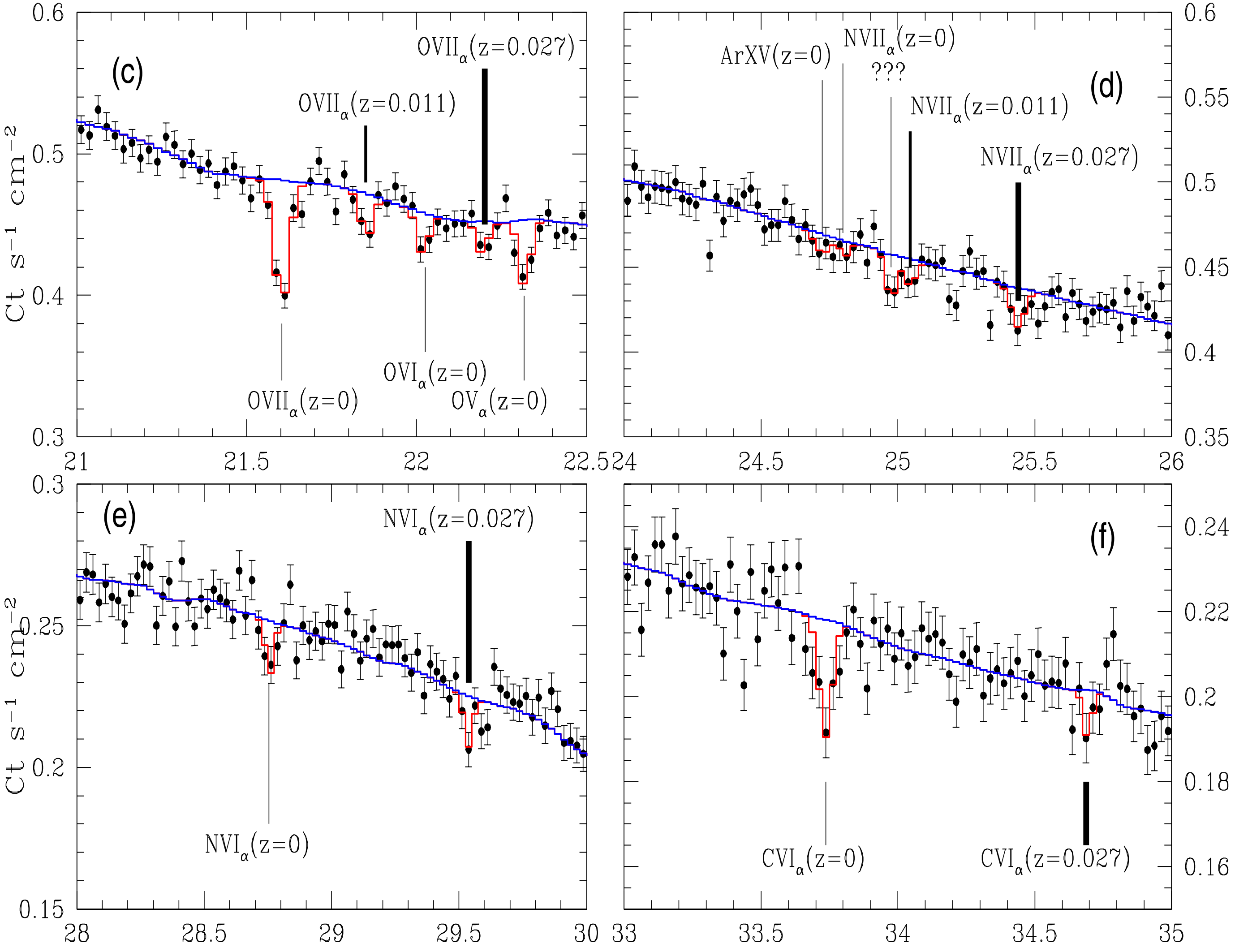
Can we measure the total mass density in this warm, hot ionized material?



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

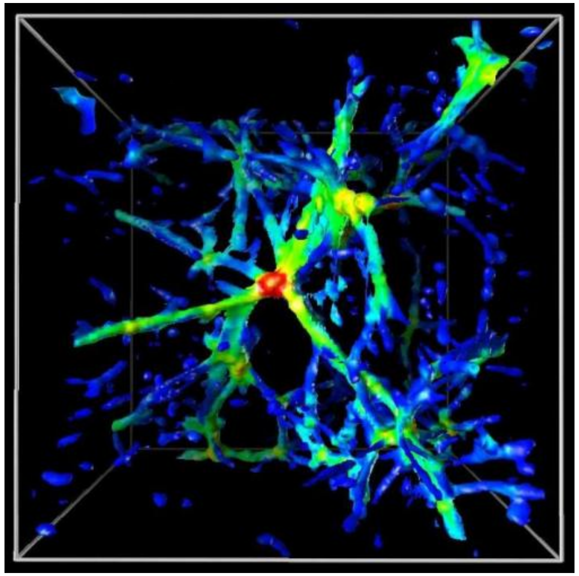
Example of such an attempt to find absorption lines through absorption in an x-ray spectrum



From Chandra x-ray telescope

Nicastro et al. 2004

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



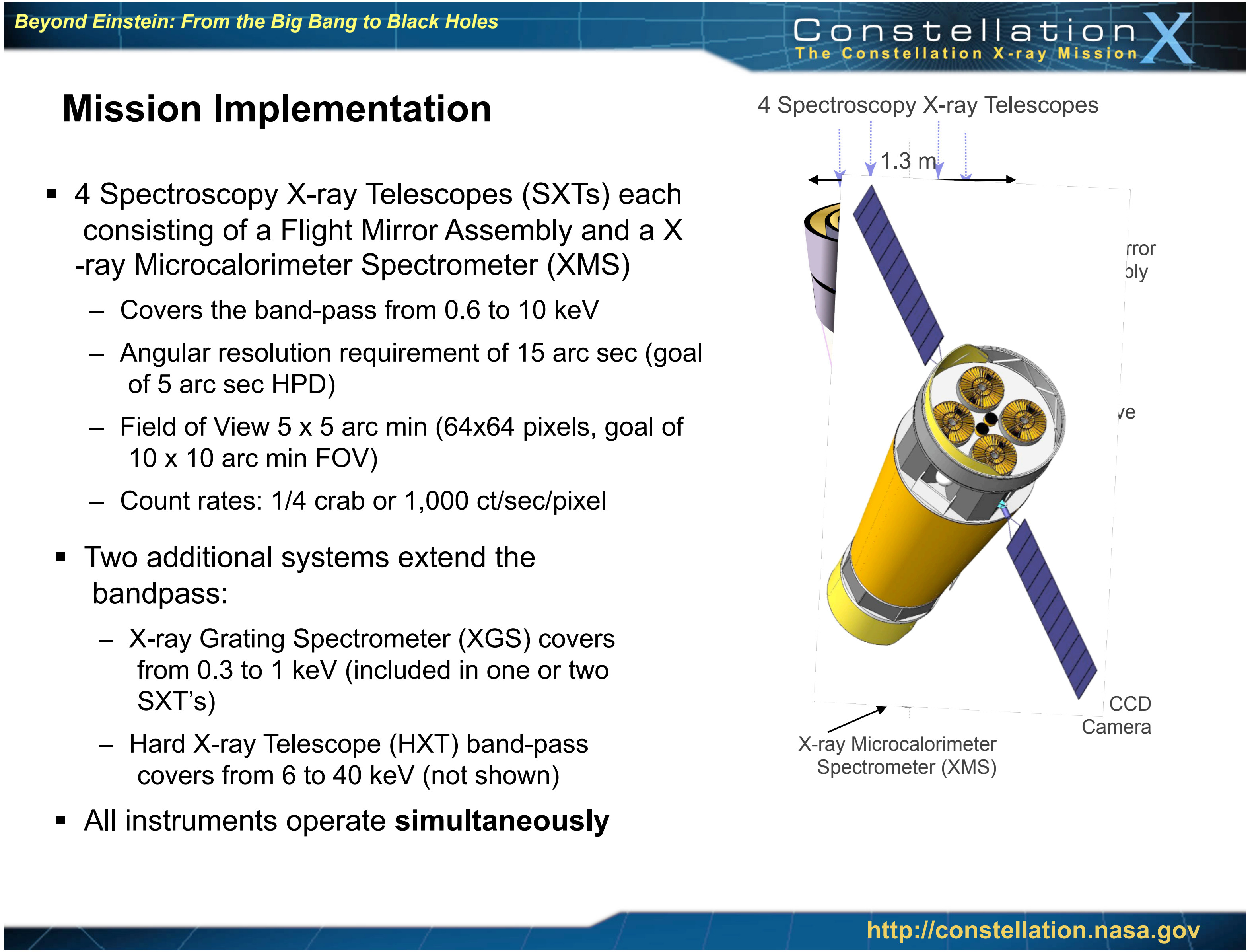
Based on these absorption lines in the blazar, estimates for the mass in the WHIM are

$$\Omega_{WHIM} = 0.02$$

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
1.3 m
rror
oly
ve
CCD Camera
X-ray Microcalorimeter Spectrometer (XMS)

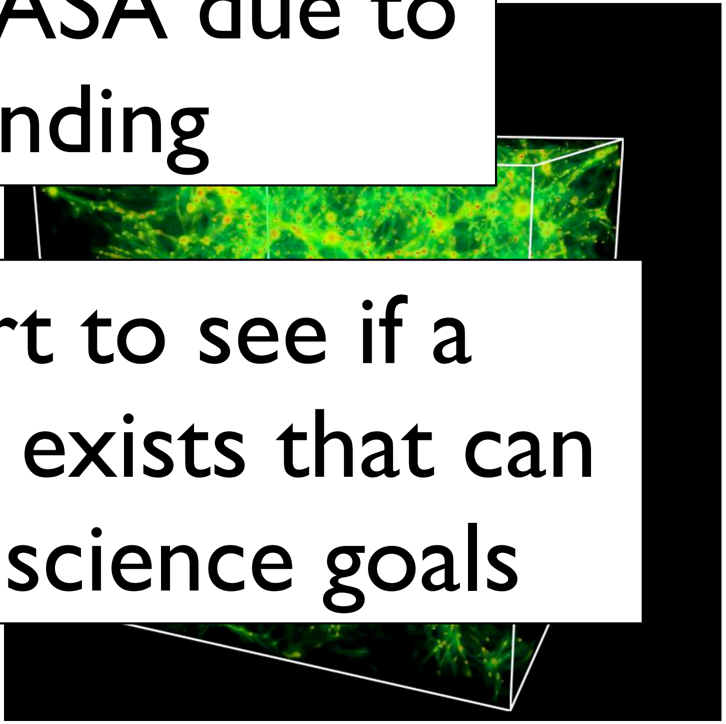
http://constellation.nasa.gov

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

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

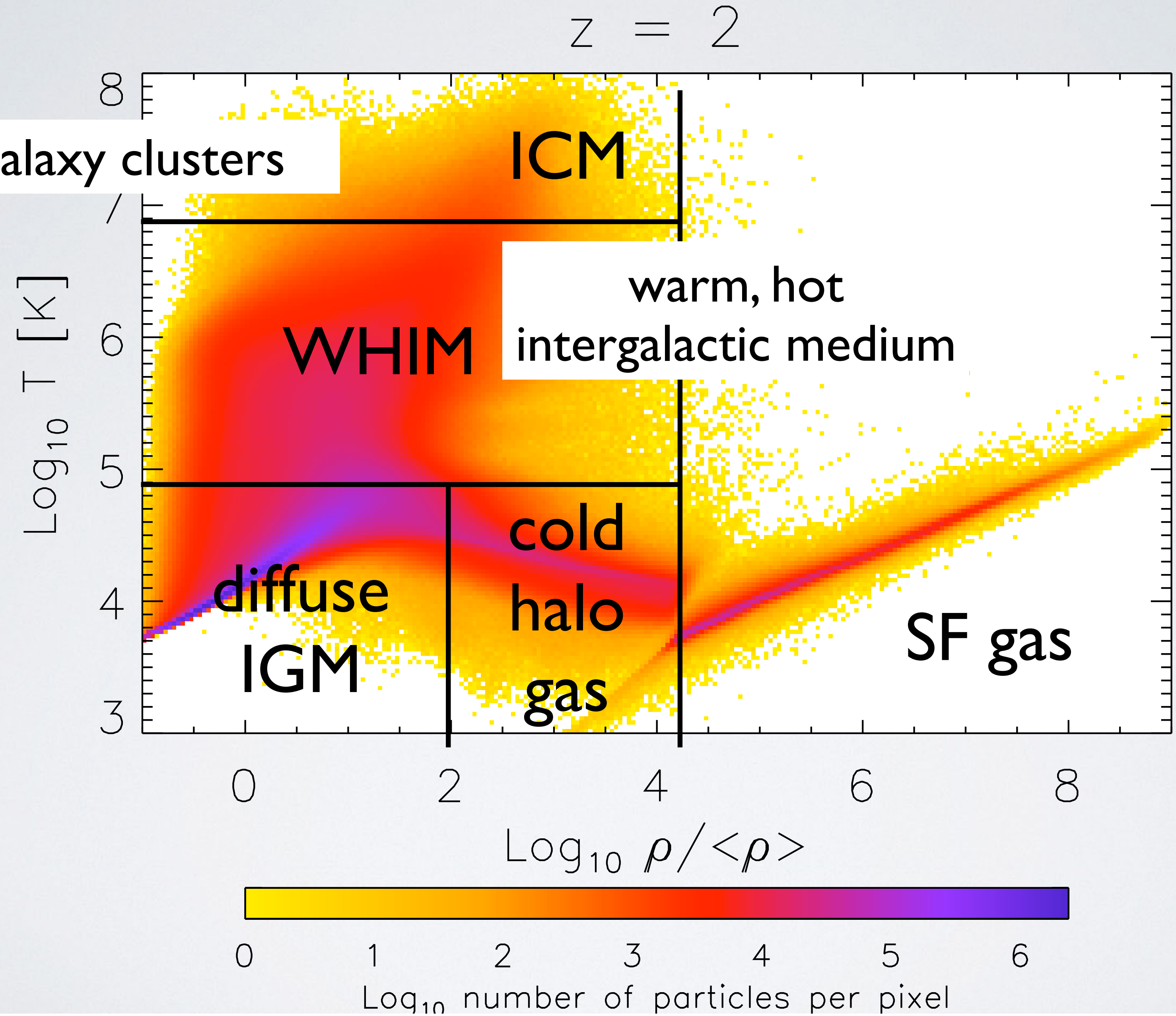
$$\Omega_{\text{cold gas, HI}} = 0.0003$$

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

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

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

Multi-phase Diagram from Cosmological Hydrodynamical Simulation Showing where the Baryons Are Predicted to be:



gas in galaxy clusters

warm, hot intergalactic medium

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)

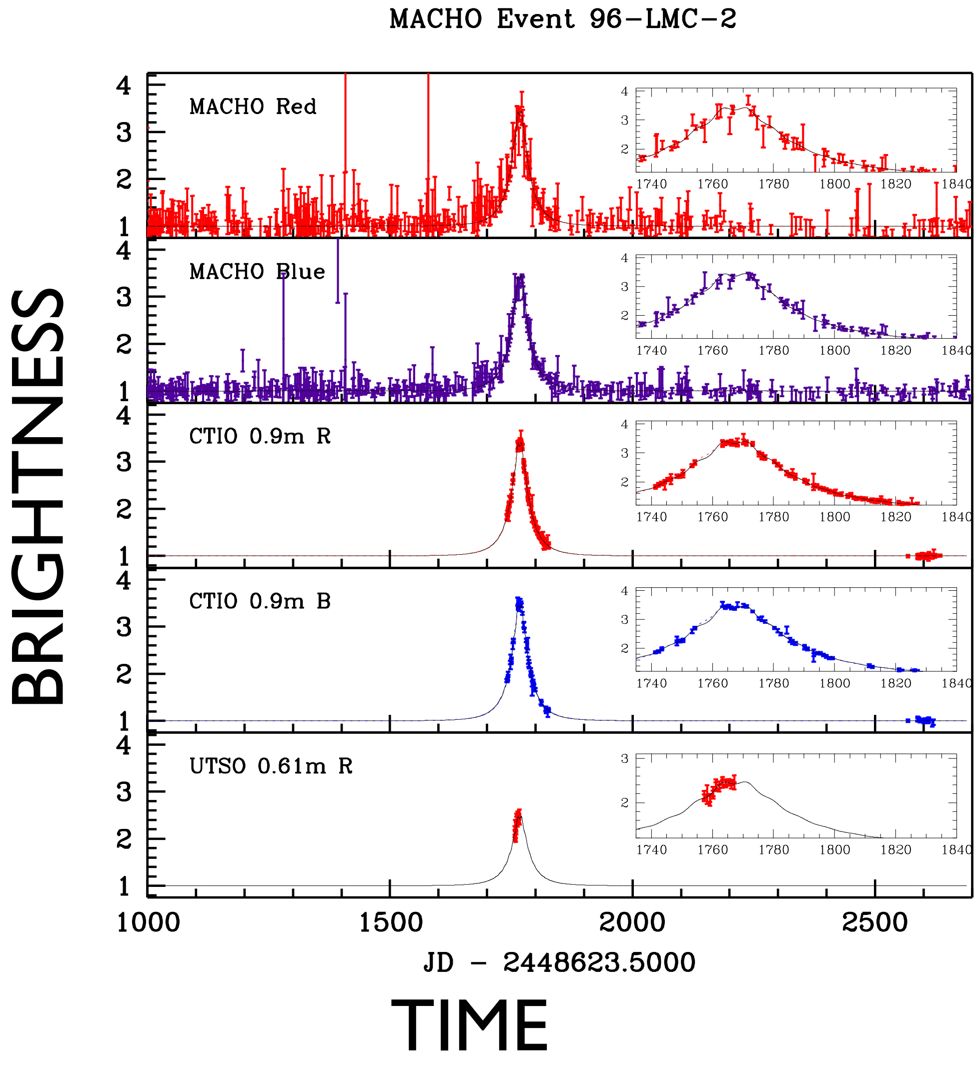
How did people search for MACHOs?

-- 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



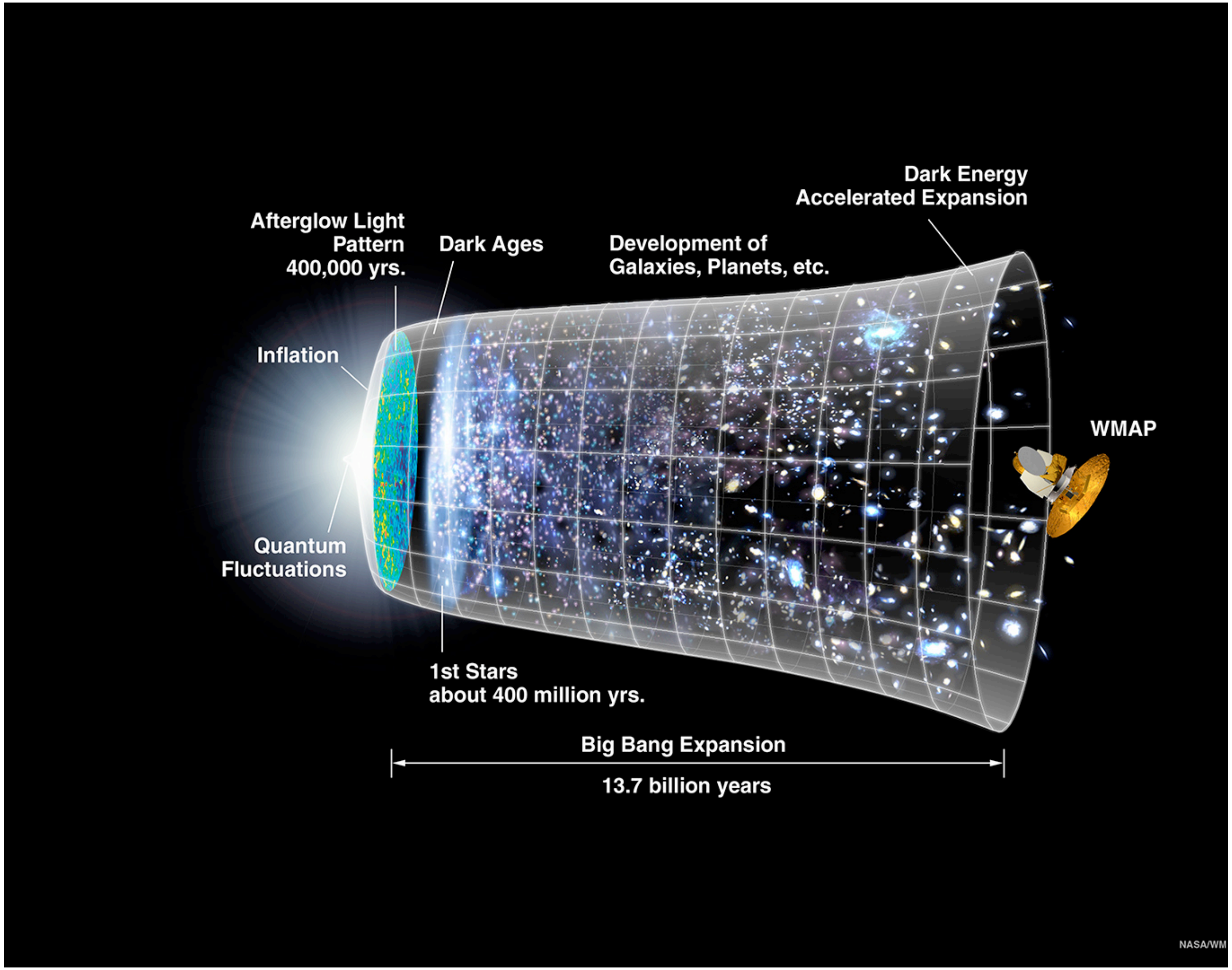
But where does this number $\Omega_{\text{baryon}} = 0.04$ come from?

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

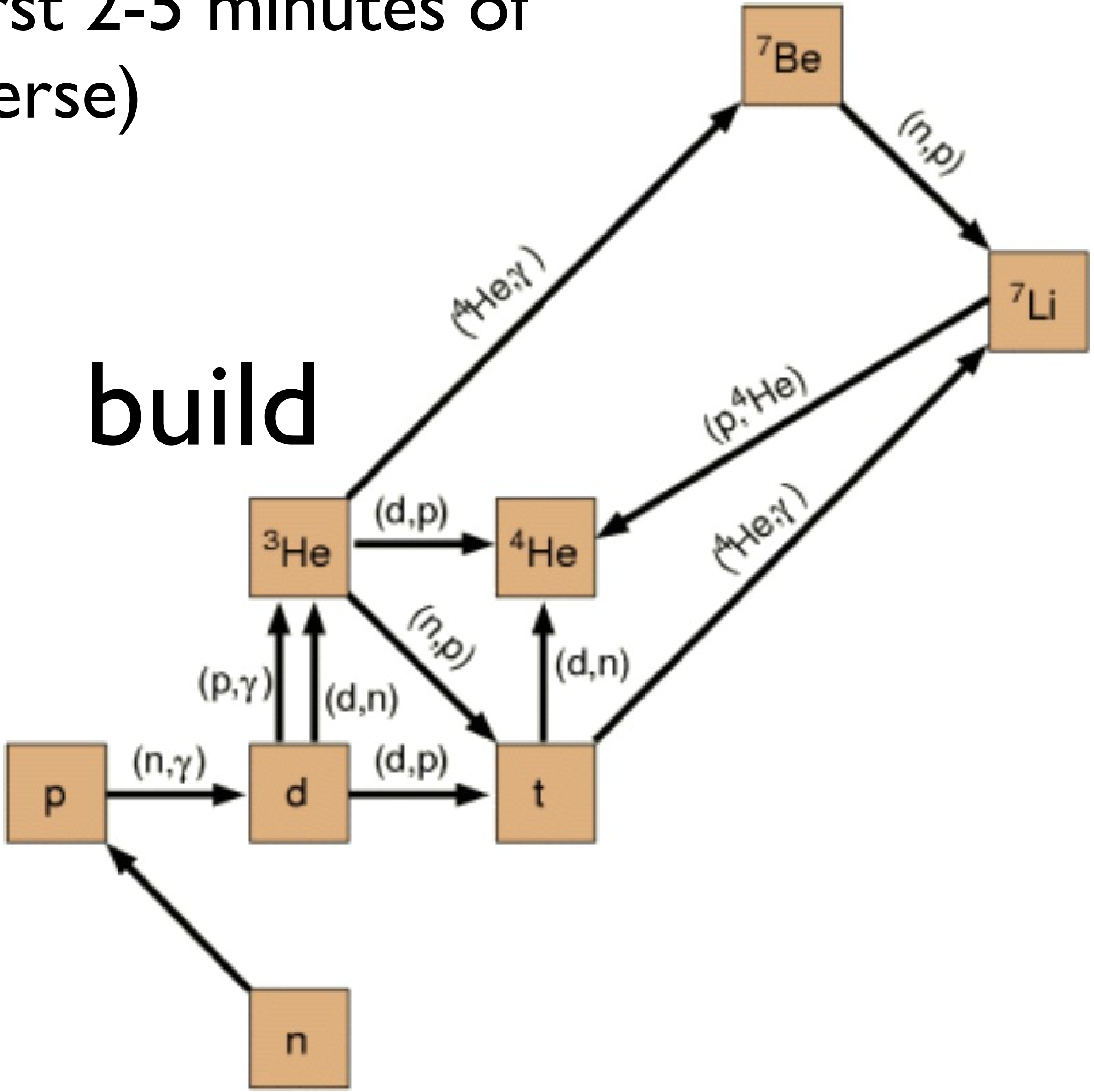

Dark Energy Accelerated Expansion
Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WM

How do heavier elements build up?

(occurs during first 2-5 minutes of universe)

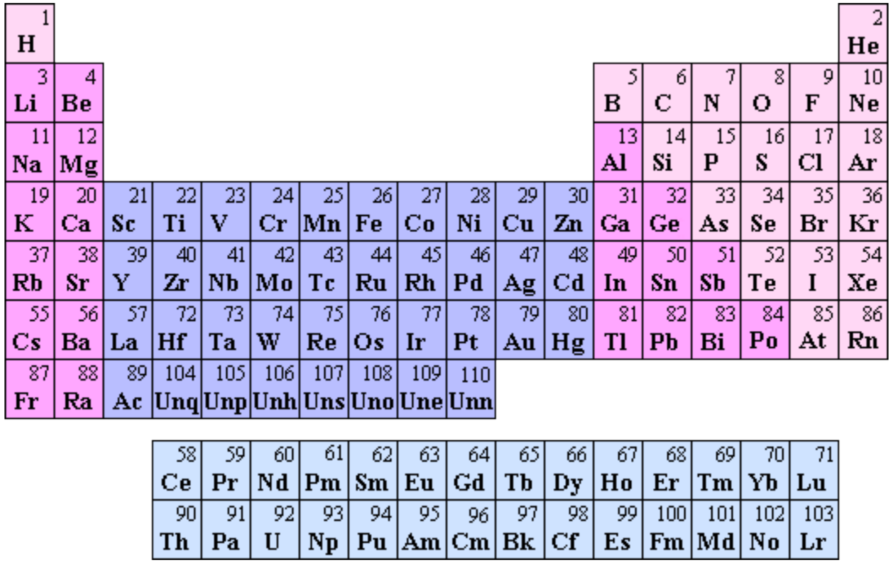
p + n →

build

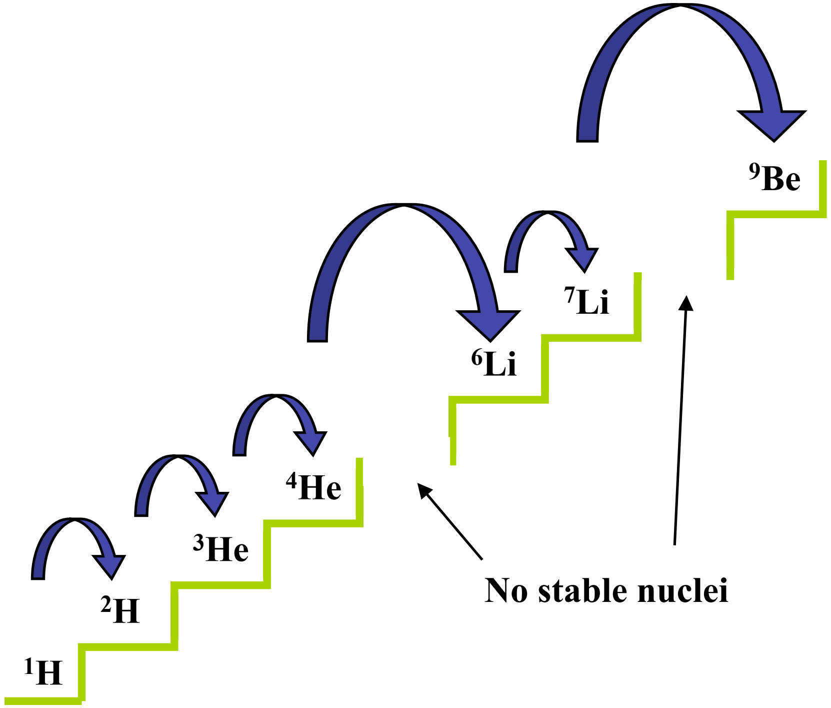


^{7}Be
(n,p)
^{7}Li
(^{4}He,γ)
(p,^{4}He)
^{3}He
(d,p)
^{4}He
(^{4}He,γ)
(n,p)
(p,γ)
(d,n)
(d,n)
p
(n,γ)
d
(d,p)
t
n

Stable mass gaps in the periodic table



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

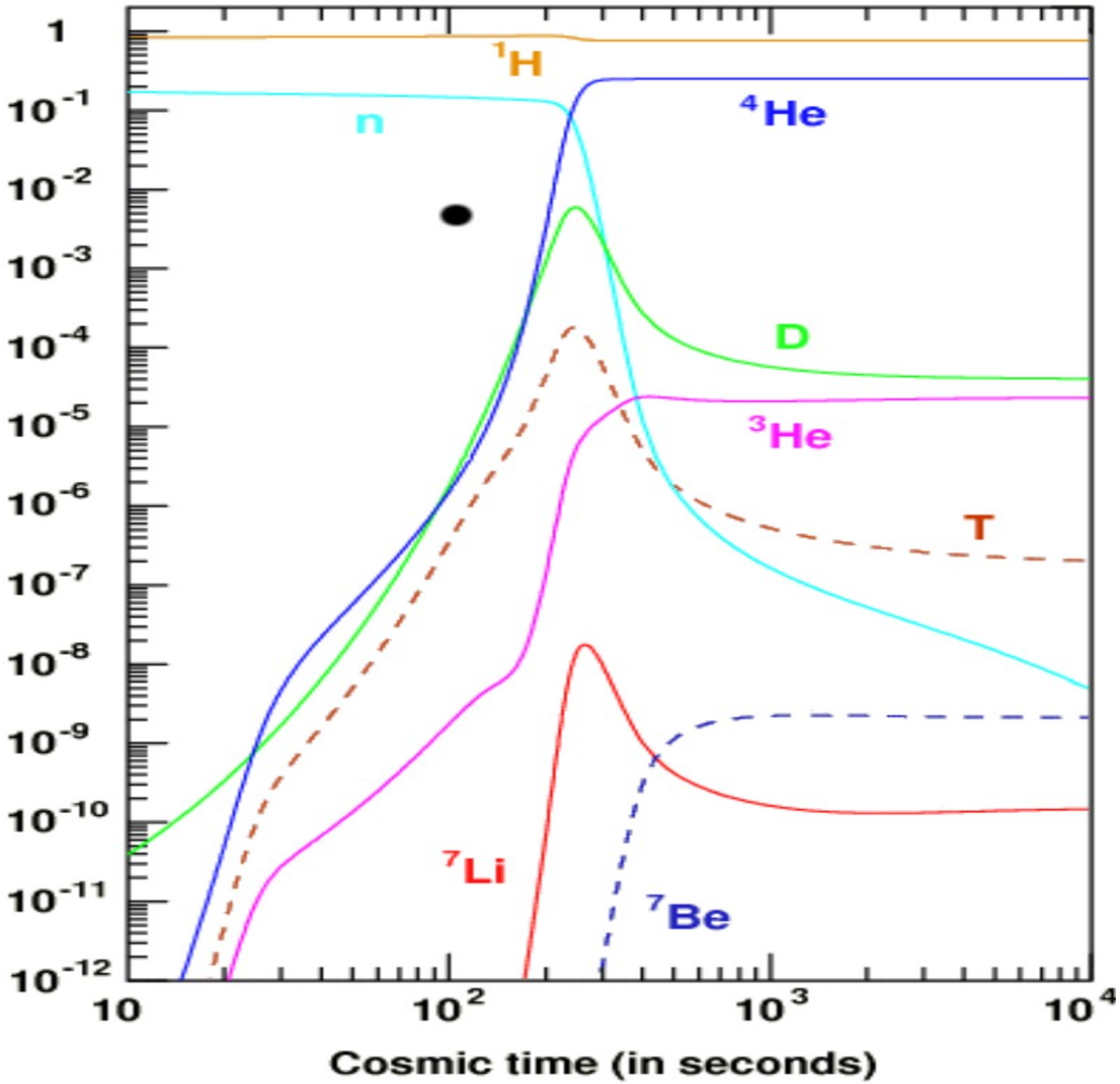


No stable nuclei

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



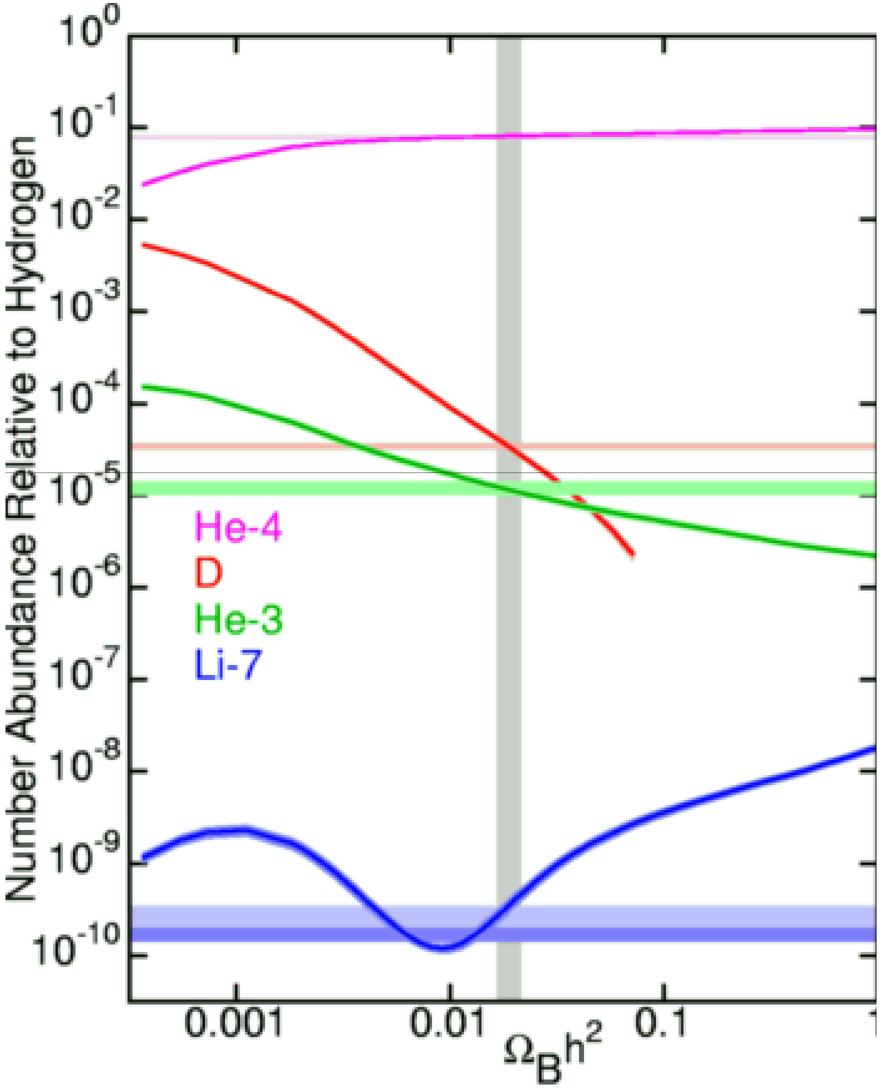
But what does this teach us about the matter density in baryons?

Abundance of heavier elements synthesized depends on baryon density

Reaction Rate ∝ baryon density

He^4 is much more stable species, so it increases in proportion to baryon density

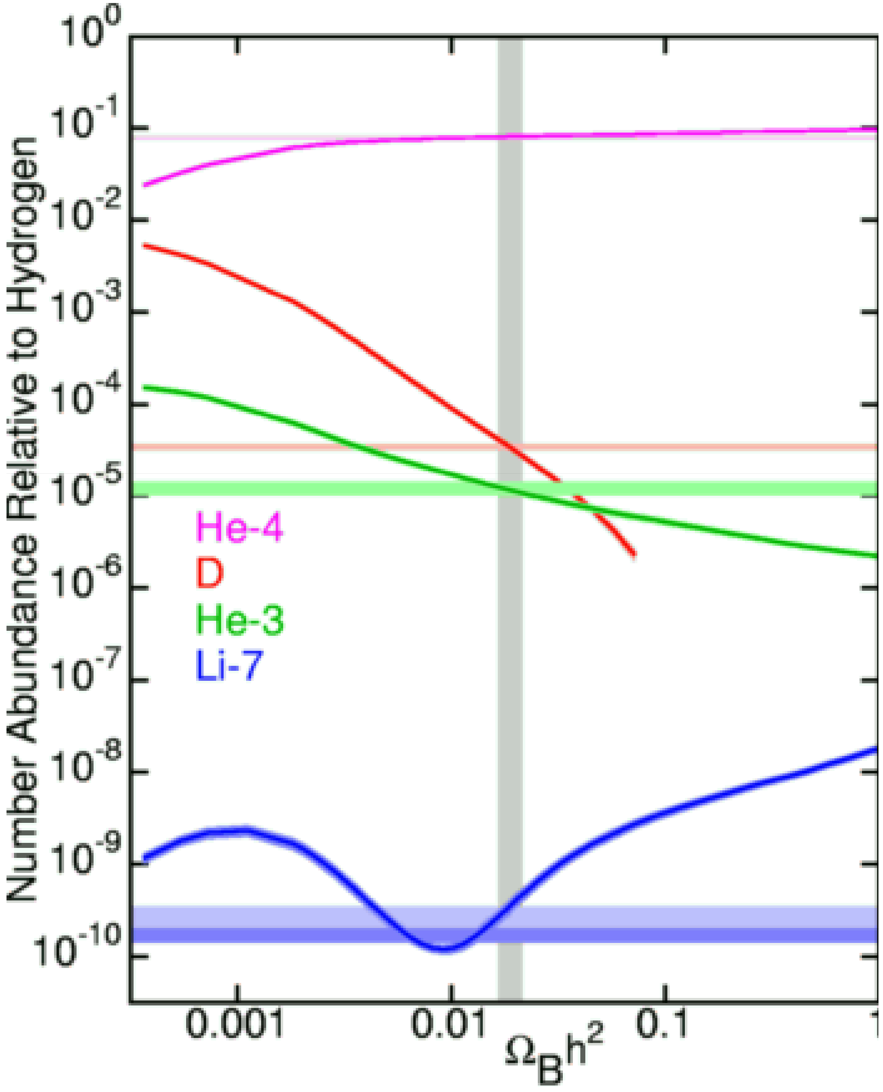
Note: The time scale during which nucleosynthesis can occur is almost independent of the baryon density -- since the energy density of the universe dominated by radiation at early times



Baryon density

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...



Baryon density

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 → readily produced from fusion

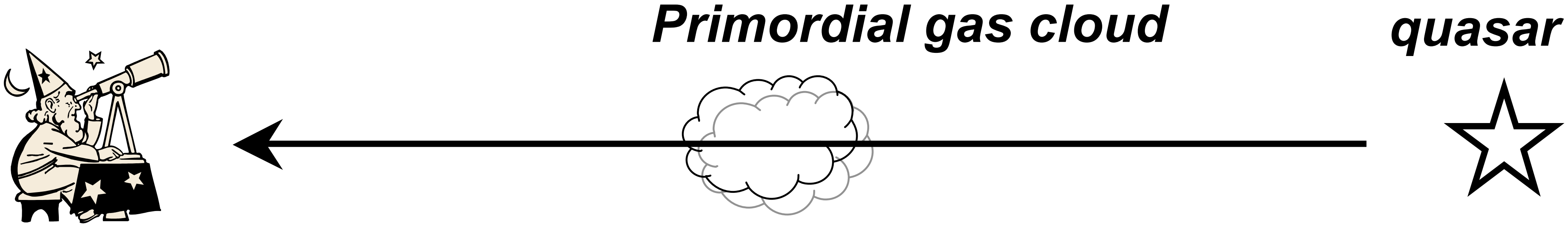
Li^7 → readily destroyed in stars from fusion
→ may be created by cosmic-ray spallation in the interstellar medium

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

How might we determine the primordial abundances then?

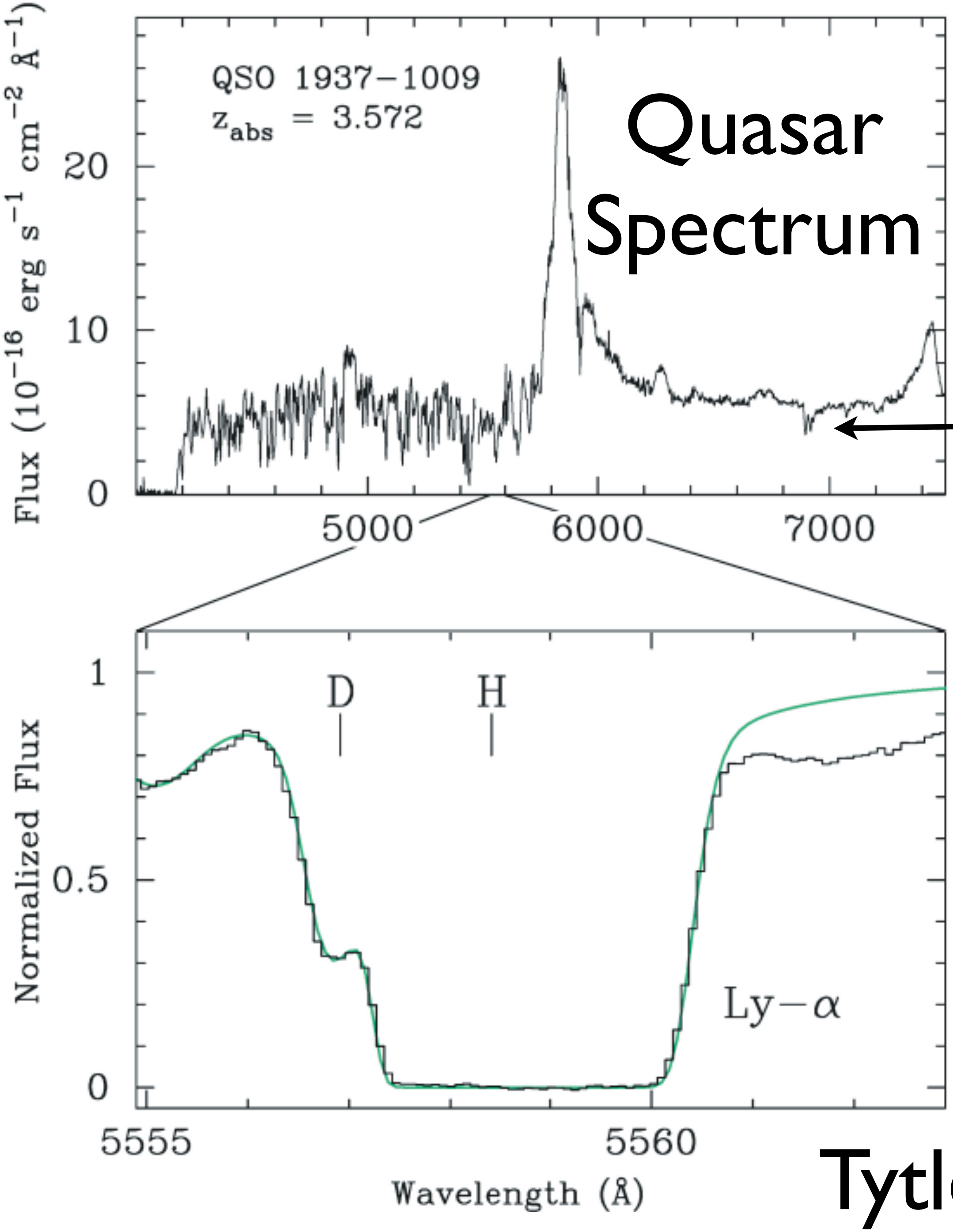
For deuterium:

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?

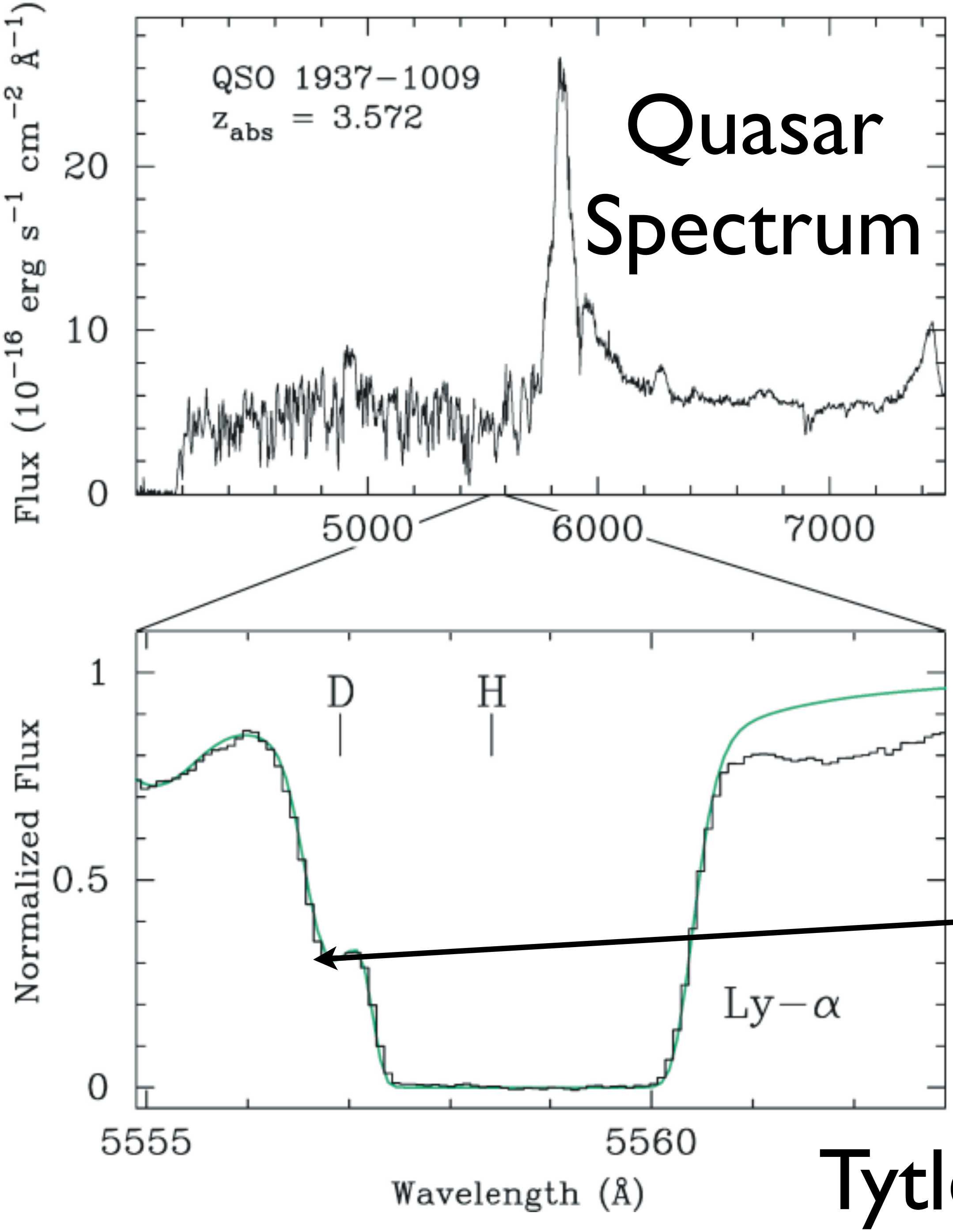


Quasar Spectrum

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?

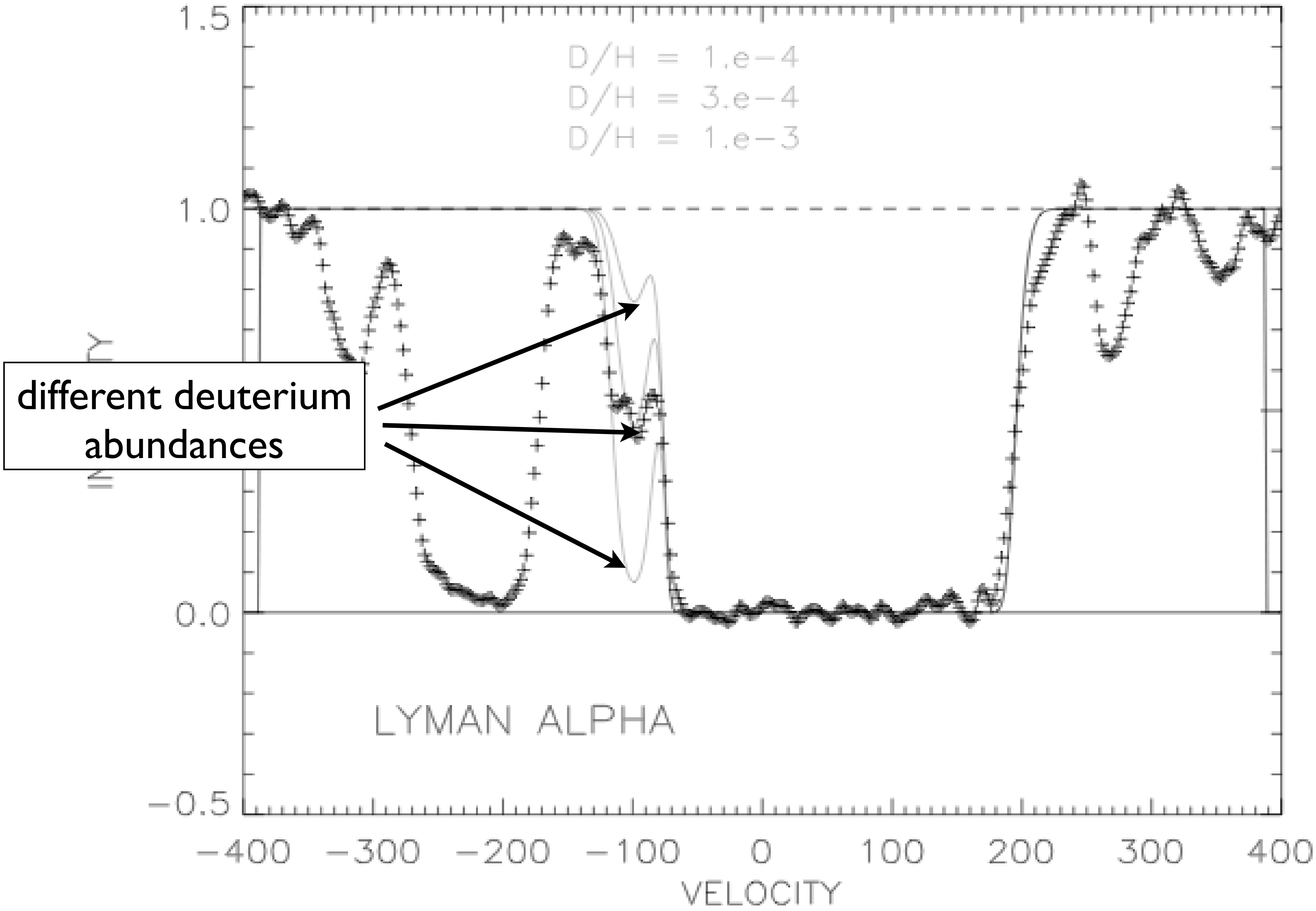


Quasar Spectrum

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

Tytler & Burles

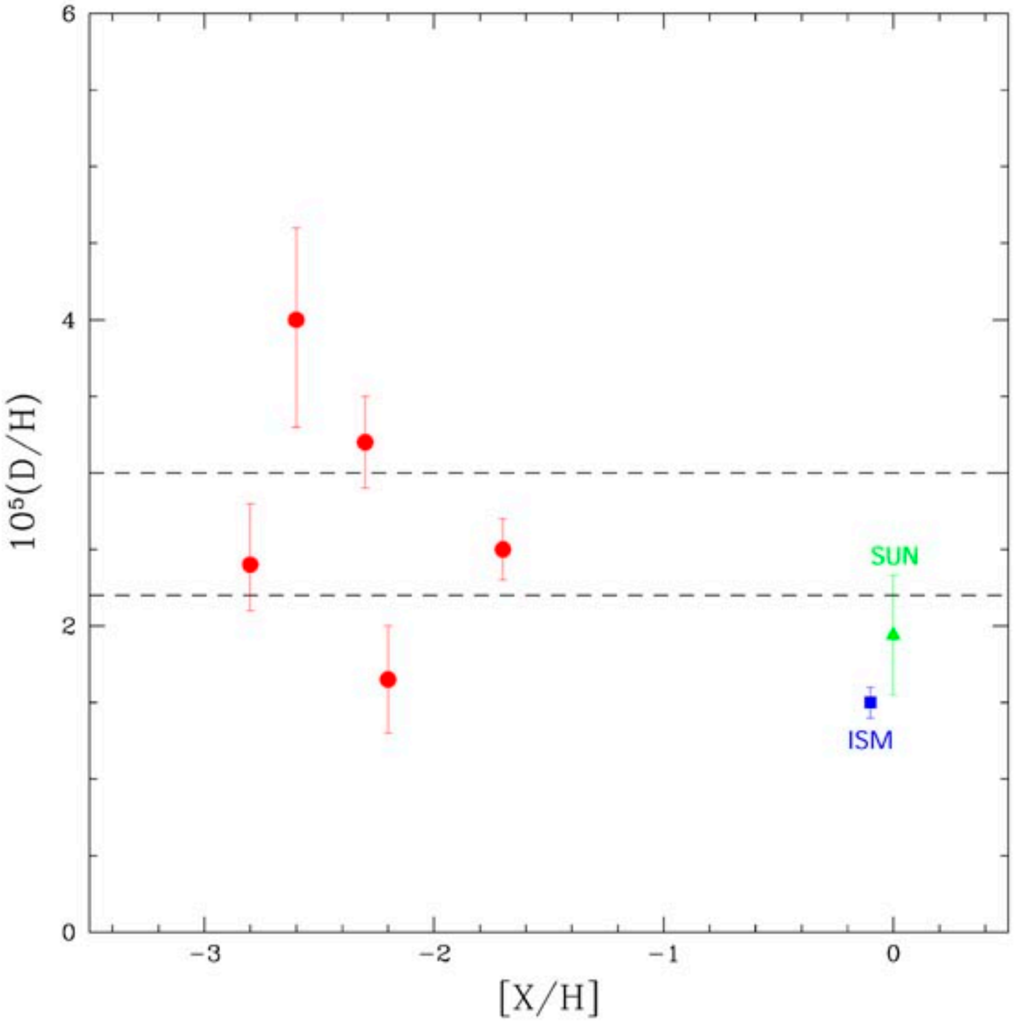
How might the observations look different with another deuterium abundance?



different deuterium abundances

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 He^4

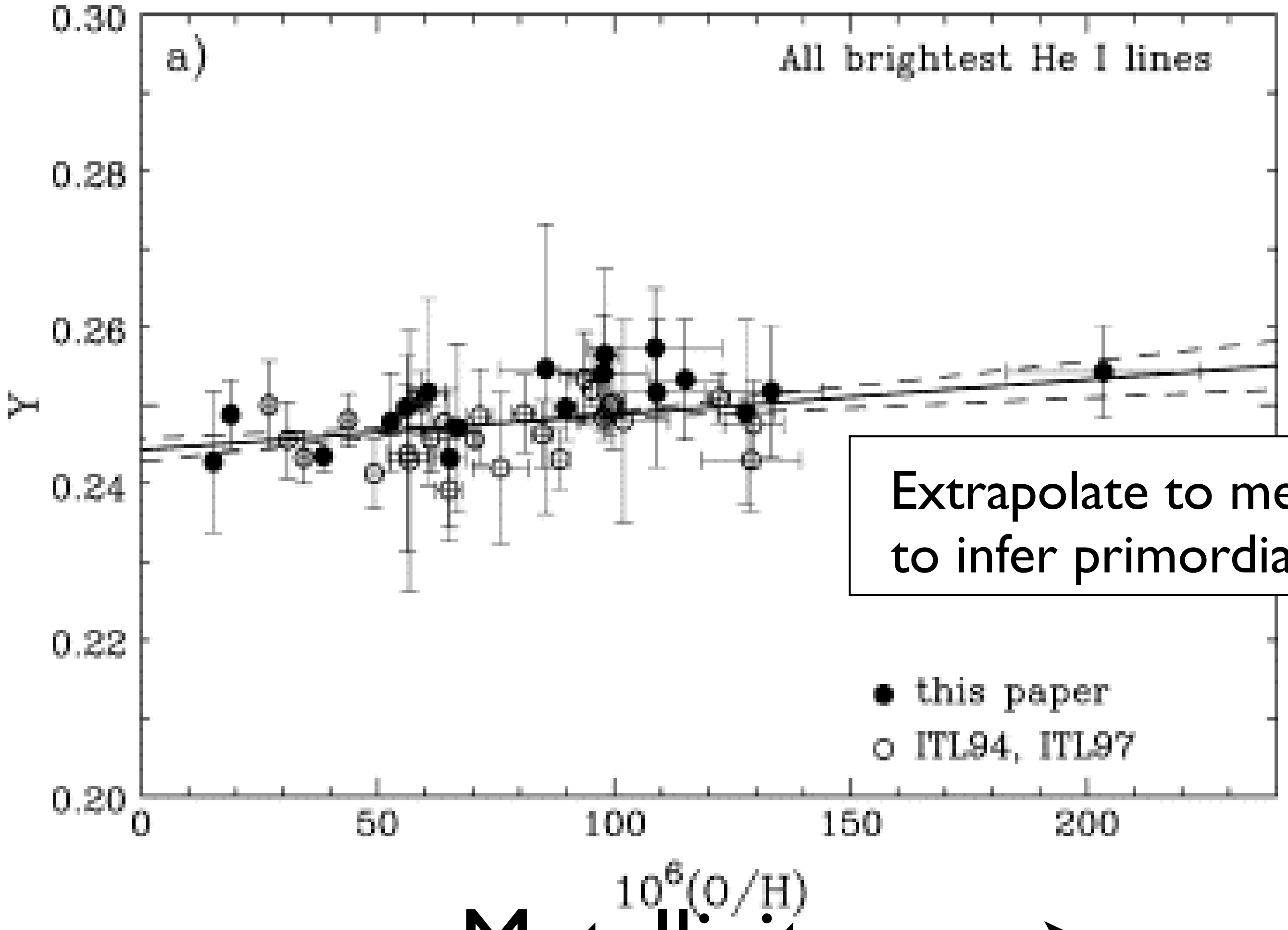
Recombination lines from HII regions in low metallicity galaxies

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

How might we determine the primordial abundances then?

For He^4

mass fraction of baryons in He^4



Extrapolate to metallicity of 0 to infer primordial abundance

Metallicity ⟶

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

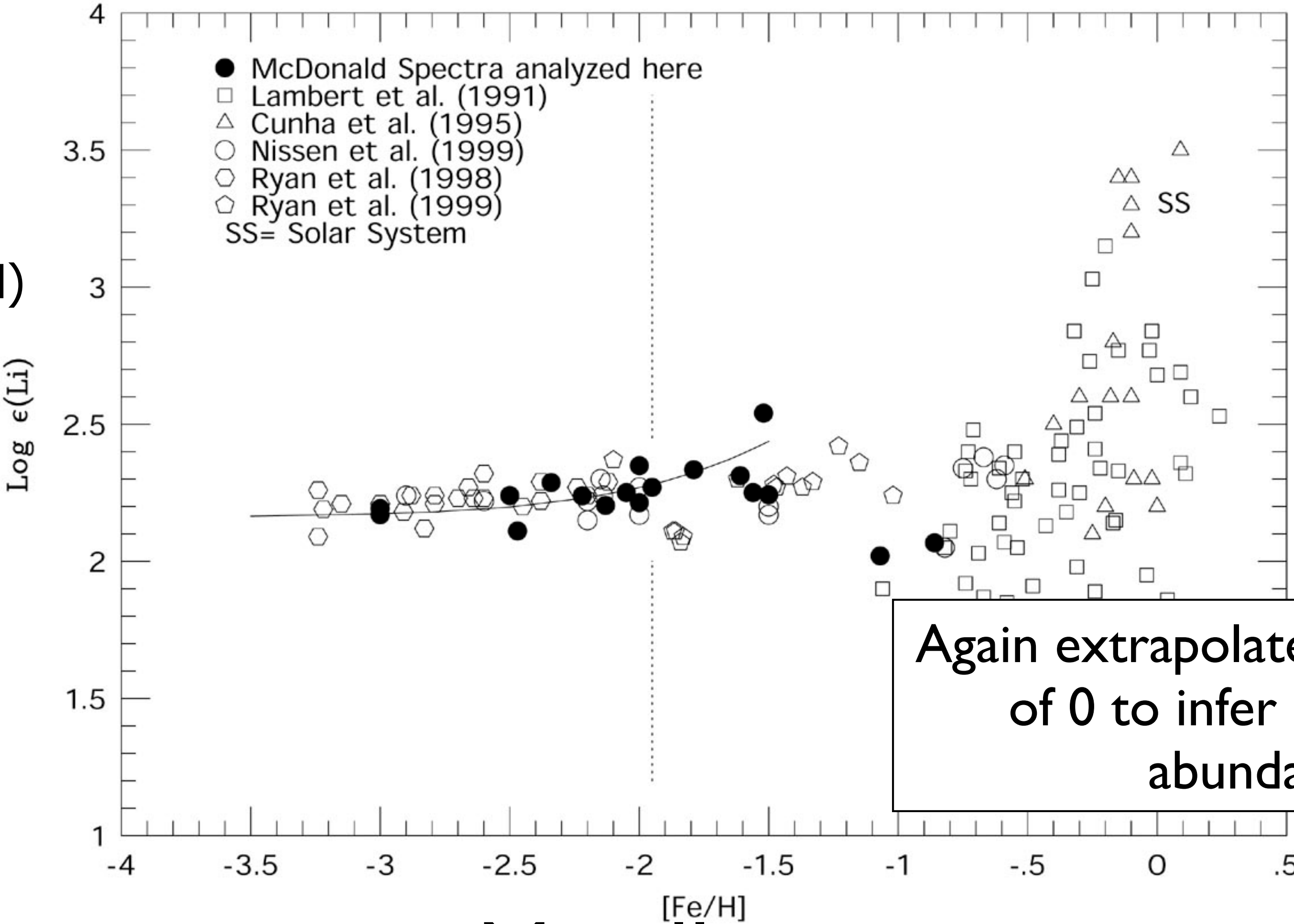
but difficult to infer since it can both be destroyed and created

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

10^{12} (Li/H)



Again extrapolate to metallicity of 0 to infer primordial abundance

Metallicity ⟶

How might we determine the primordial abundances then?

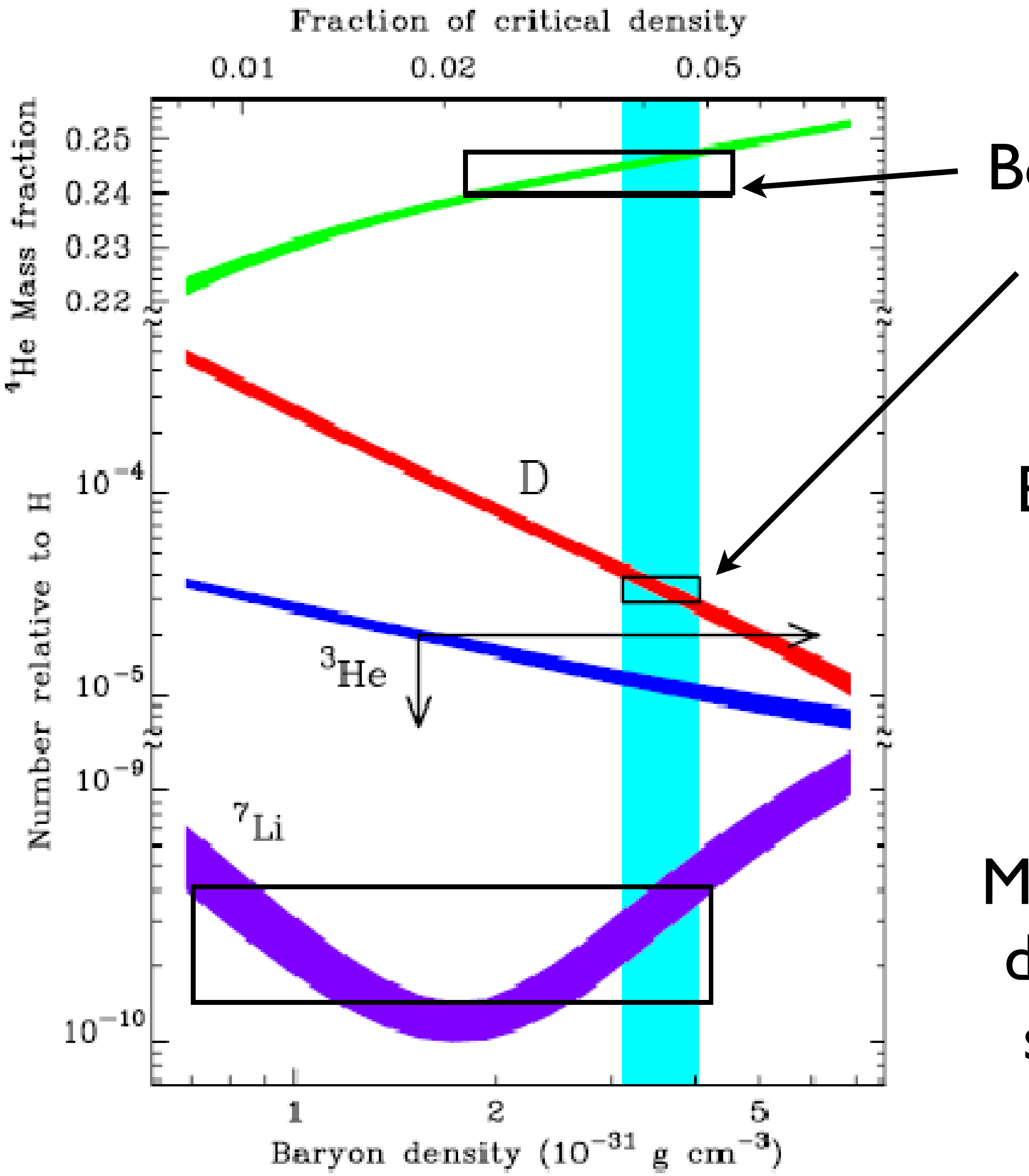
For He^3

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 will 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

$$\Omega_B h^2 = 0.019 \pm 0.0024$$

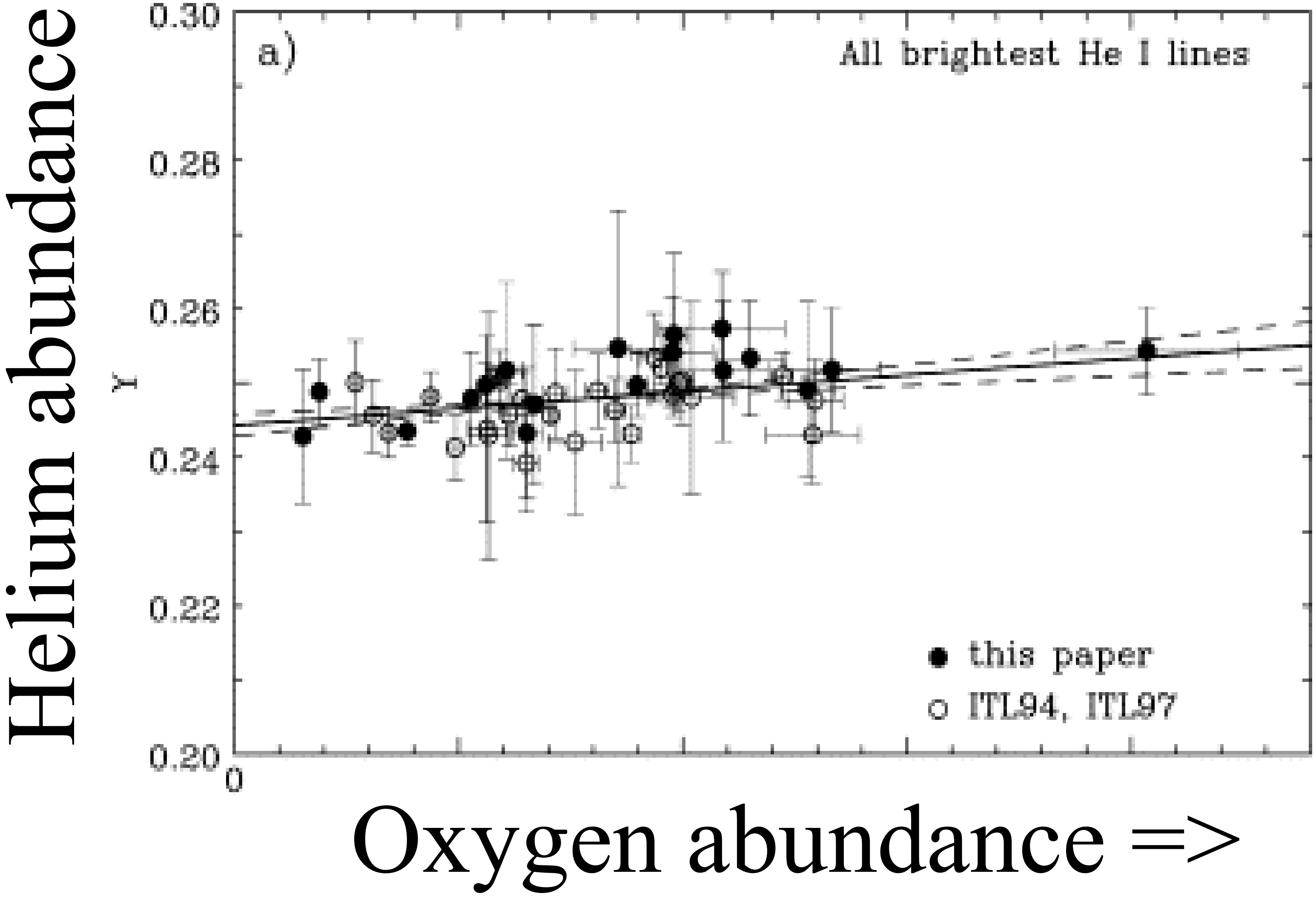
$$\Omega_B = 0.037 \pm 0.009$$

Most useful constraint is from deuterium abundances given steep dependence on $\Omega_b h^2$

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 ~ $1/H_0$

Radioactive Decay, White Dwarf Cooling, Globular Clusters	"Expansion Rate of Universe"
~13 ± 1 Gyr	~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

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

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

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

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

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

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