Астрометрия, космография, решения Фридмана

С.И.Блинников

sergei.blinnikov@itep.ru, sblinnikov@gmail.com

ИТЭФ, ГАИШ, НГУ

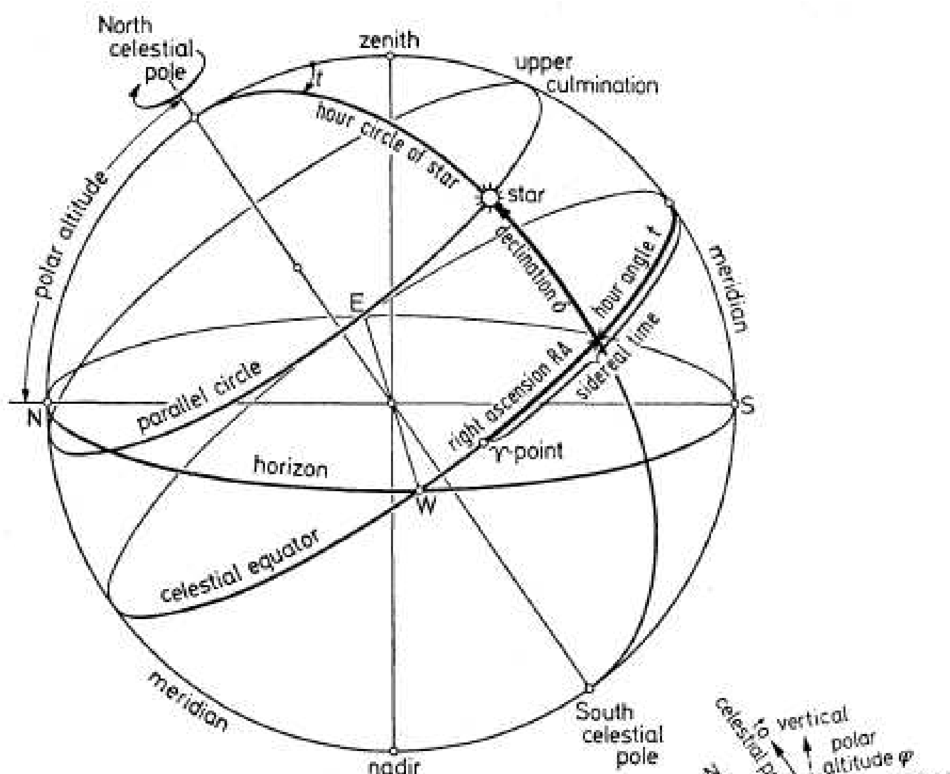
S.I.Blinnikov[1,2]

[1] *ИТЭФ = ITEP = Institute for Theoretical and Experimental Physics, Moscow*

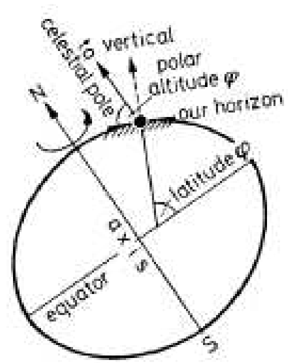
[2] *ГАИШ = SAI = Sternberg Astronomical Institute, Moscow*

НГУ 26 сентября 2012

Элементы астрономии: Небесные координаты



Celestial coordinates



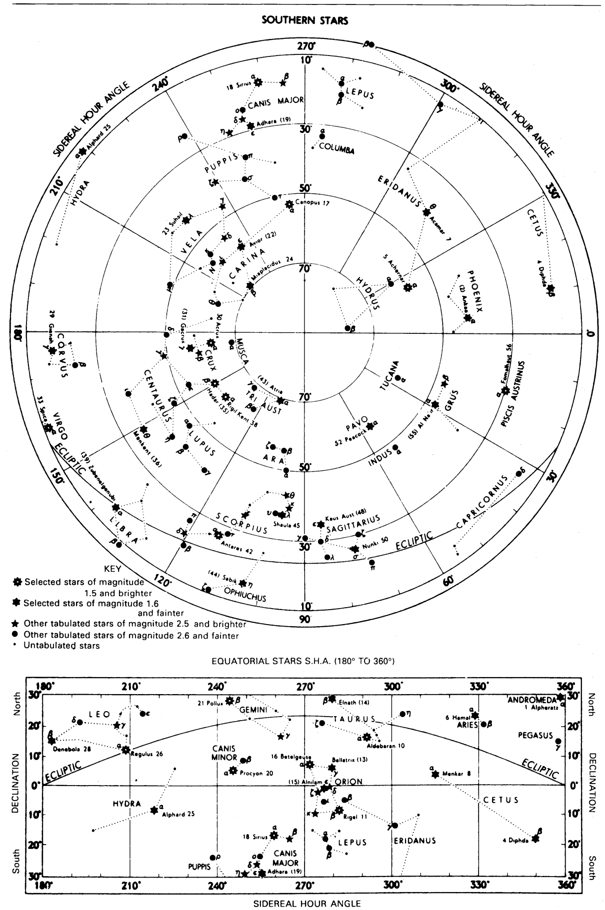
Экваториальные координаты

Экваториальные координаты, по существу, являются проекциями земных географических координат: прямое восхождение RA или α, аналогично долготе, — но измеряется в часах, а не в градусах! — а склонение δ — аналог широты.

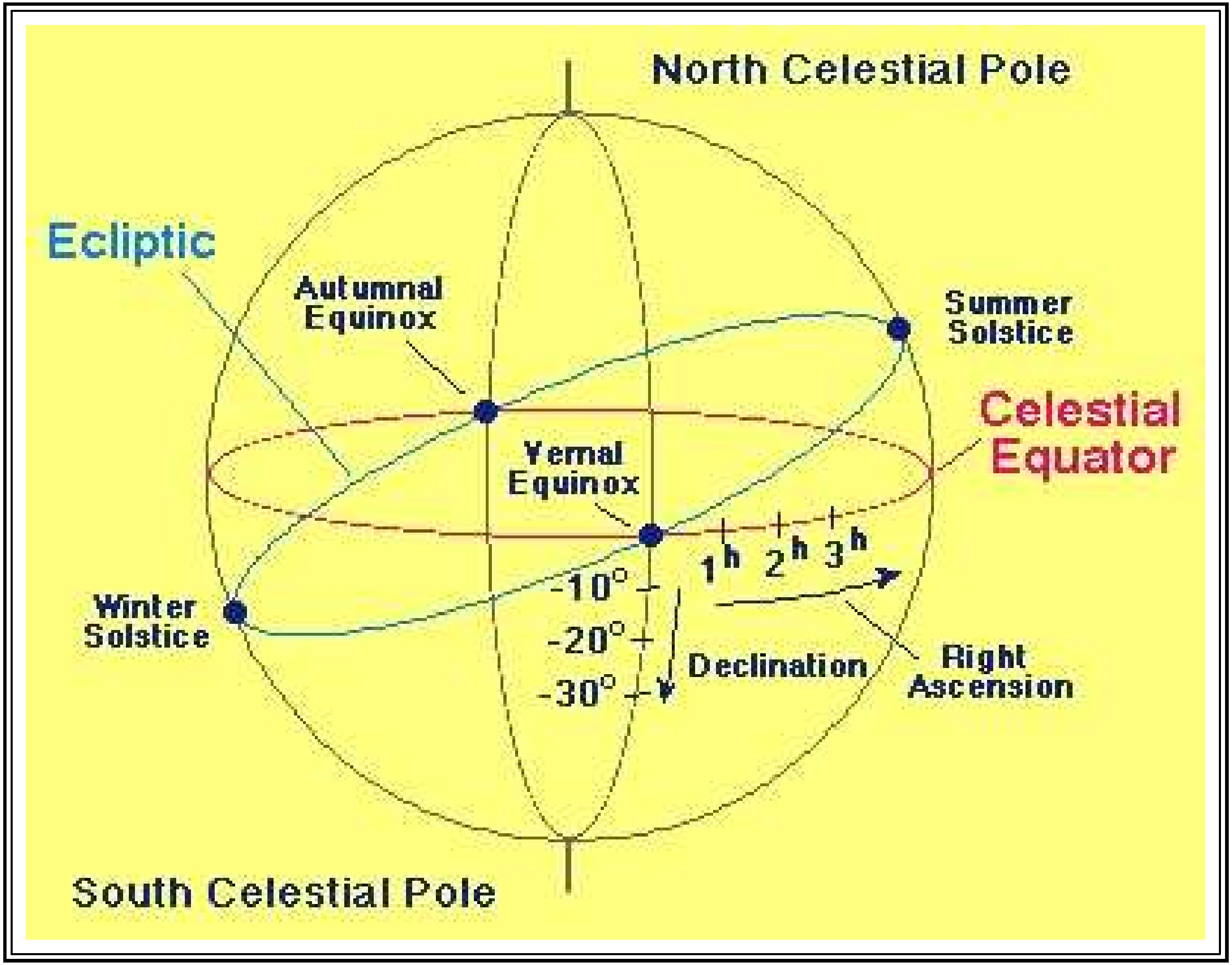
38

Stars

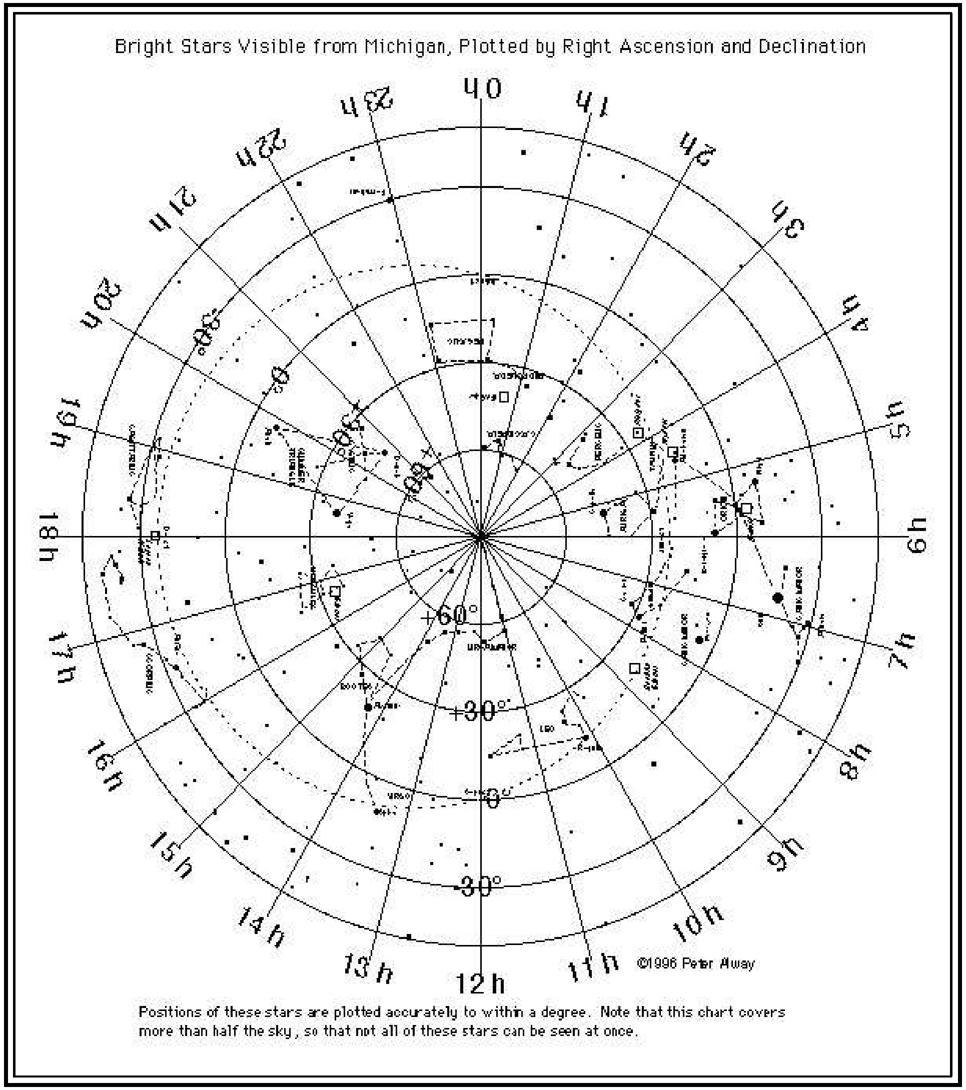
Star charts



Equatorial coordinates-2

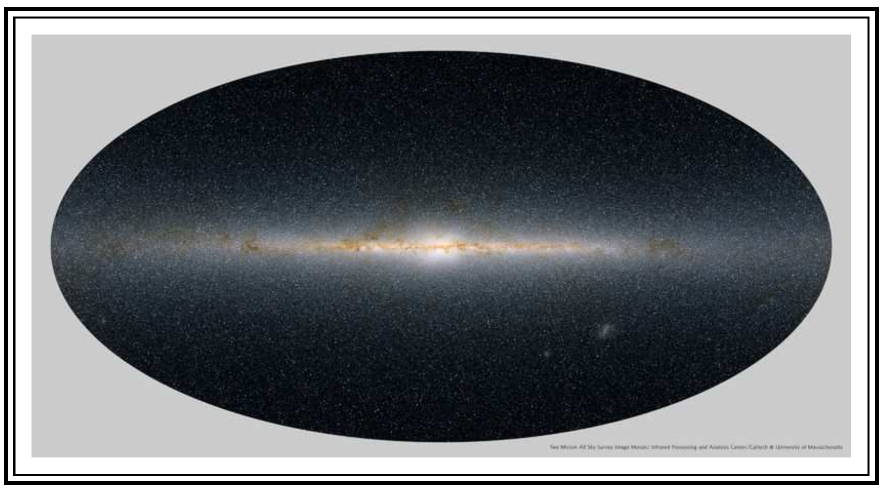


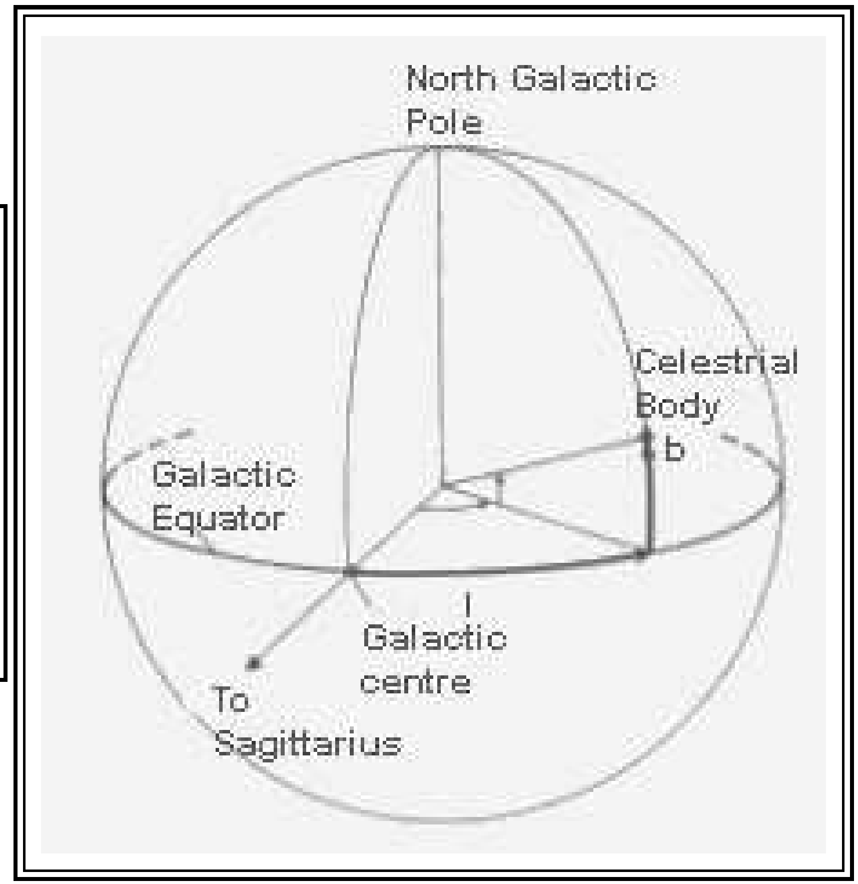
Equatorial coordinates-3



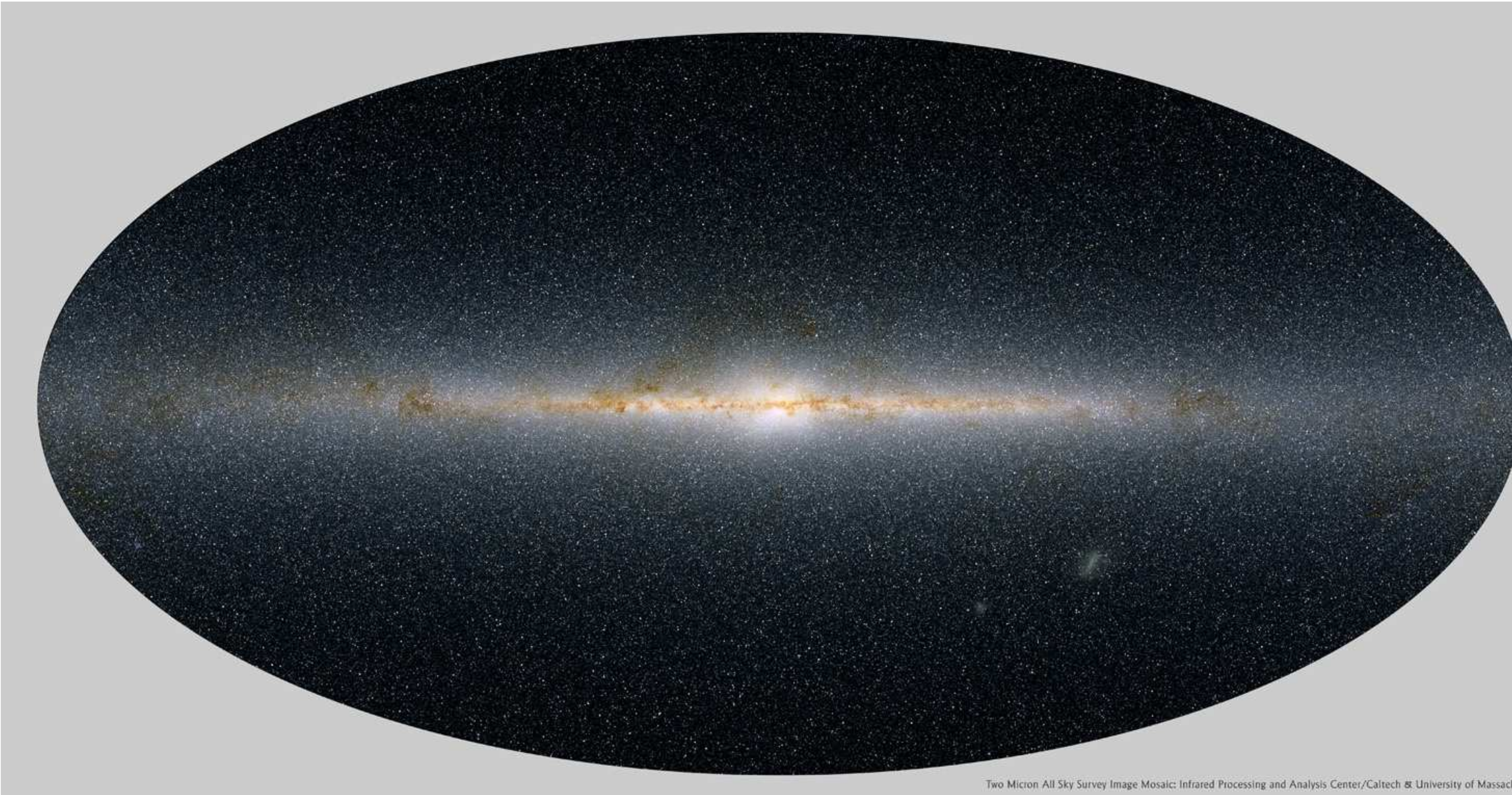
Galactic coordinates

For more distant objects more natural system is the Galactic one: longitude (measures from the center of our Galaxy – Milky Way) and latitude (from the plane drawn in the ‘middle’ of Milky Way).





Milky Way infrared



Measuring radiation

Luminosity L is just the power emitted by an object: $L = \frac{d\mathcal{E}}{dt}$.
Flux S in astrophysics is the power coming per unit time per unit area of a detector $S = \frac{d\mathcal{E}}{dtdA}$ (called *illumination* in some branches of laboratory physics).
Exposition (fluence) F – the integral energy coming per unit area of a detector, $F = \frac{d\mathcal{E}}{dA}$ useful for bursting objects.

Forms used for describing spectra

1) The photon number spectrum $N(E)$, or $N(\nu)$, with $E = h\nu$, units of photons per second per cm^2 per unit energy.
2) The differential energy flux density $S(E) = EN(E)$, written also as $S_\nu = h\nu N(\nu)$. The notation F_ν is often used for the flux instead of S_ν, but I will use the letter F for the fluence.
3) The second moment of $N(E)$ is the so called νS_ν distribution, (or νF_ν distribution), $\nu S_\nu \propto E^2 N(E)$, which peaks where the maximum radiation power comes (per decade of the photon energy).

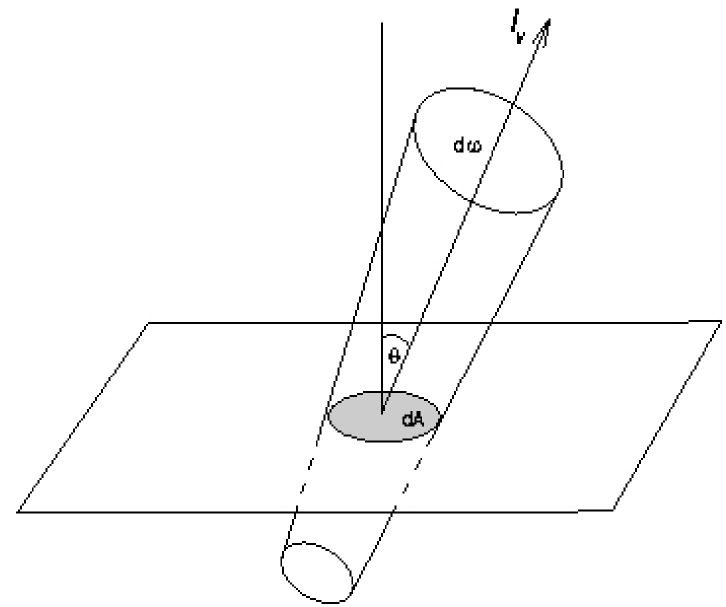
Intensity

A very important quantity is *intensity* (brightness) I it is the flux density per solid angle:

$$I = \frac{d\mathcal{E}}{dt\,dA\,d\Omega}$$

or spectral intensity

$$I_\nu = \frac{d\mathcal{E}}{d\nu dt\ dA\ d\Omega}$$



Intensity

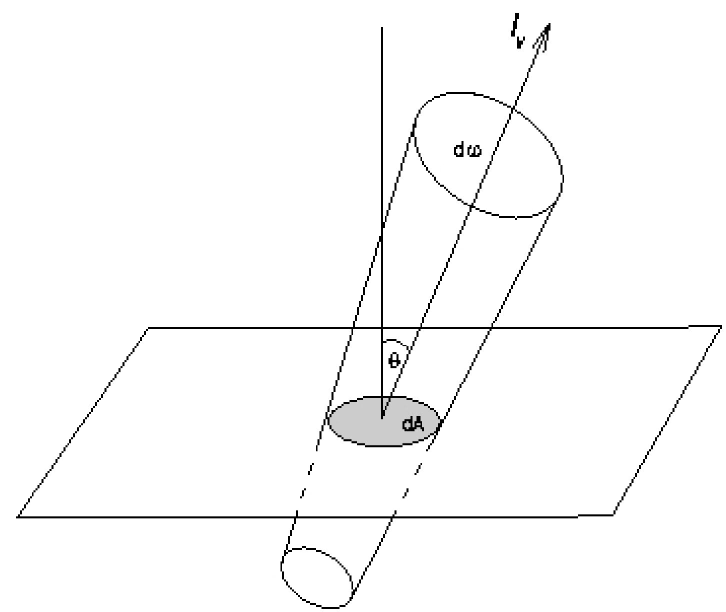
A very important quantity is *intensity* (brightness) I it is the flux density per solid angle:

$$I = \frac{d\mathcal{E}}{dt\,dA\,d\Omega}$$

or spectral intensity

$$I_\nu = \frac{d\mathcal{E}}{d\nu\,dt\,dA\,d\Omega}$$

OK for dA normal to beam



Intensity

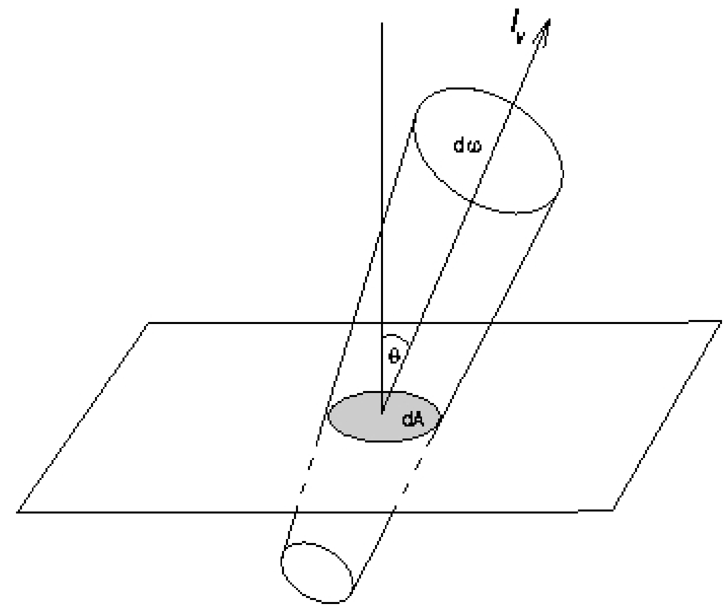
A very important quantity is *intensity* (brightness) I it is the flux density per solid angle:

$$I = \frac{d\mathcal{E}}{dt\,dA\,d\Omega}$$

or spectral intensity

$$I_\nu = \frac{d\mathcal{E}}{d\nu\,dt\,dA\,d\Omega}$$

OK for dA normal to beam, else $dA\cos\theta$



Intensity-2

I_ν . Here the subscript ν refers to frequency. The observations and experiments always work with I_ν, but the physics is actually described by the occupation number $f(\mathbf{p})$.

One can see that I_ν and f are simply connected:

$$I_\nu = \frac{gc}{(2\pi\,\hbar)^3}\, fp^2\, \frac{dp}{d\,\nu}\, cp = \frac{g f p^3 c}{(2\pi\,\hbar)^2} = \frac{g f h\,\nu}{\lambda^2}$$

(here $dp/d\,\nu = 2\pi\hbar/c$, and $g = 2$ for photons). I_ν has the meaning of energy coming through the area λ^2 in unit time per unit frequency interval, so

$[I_\nu] = \mathrm{erg}/\mathrm{cm}^2\,\mathrm{s}\,\mathrm{Hz} = \mathrm{erg}/\mathrm{cm}^2$.

Stellar magnitudes

A traditional way of measuring fluxes in astronomy is the stellar magnitude (mag):

$$m_1 - m_0 = -2.5(\lg S_1 - \lg S_0) = -2.5\lg(S_1/S_0)$$

– a zero point (ZP) m_0 must be defined at some standard star (usually Vega $= \alpha$ Lyrae). All m's and S's here may have subscripts (ν, or U, B, V etc. for filters).
Absolute stellar magnitude $\mathcal{M}$ is mag at the standard distance d of 10 parsecs. Since $S \propto d^{-2}$ the *distance modulus* is

$$m - \mathcal{M} \equiv -2.5[\lg S(d) - \lg S(10\,\text{pc})]$$

$$= +5[\lg(d/10\,\text{pc})] = 5\lg d_{\rm pc} - 5\ .$$

Importance of units

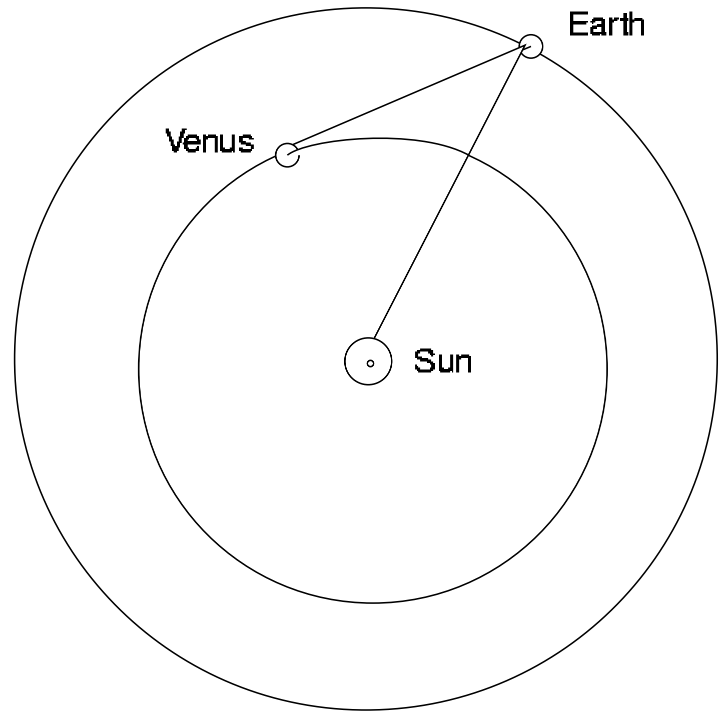
The role of units used for measuring distances and other physical parameters of celestial objects is very important.

Let us consider one example from old astronomy

One astronomical unit 1 AU $\approx 1.5 \times 10^{13}$ cm – the mean distance of Earth from Sun.

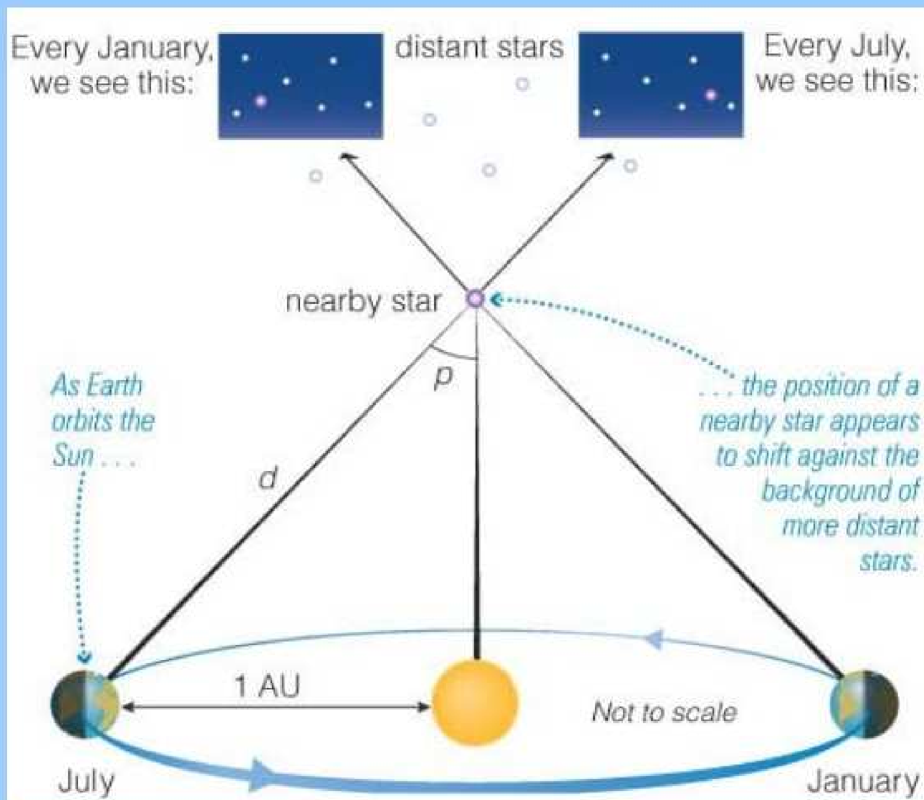
Measuring angles

Ancient astronomers knew distance of Venus from the Sun in AU with a reasonable accuracy, because in AU everything reduces to measuring angles and time, but in terrestrial units they were wrong by orders of magnitude.



So if you measure the angle α between the Sun and Venus at the moment of their maximum departure (elongation) you have the distance Sun-Venus equal to $\sin\alpha$ AU.

Parallax



By measuring stellar parallaxes we can determine the distances to the nearby stars. The Hipparcos satellite measured many thousands of parallaxes.

Trigonometric Parallax

Measure the change in the apparent position of the star as the viewers position changes

$$d = 1\text{AU}/\tan(\theta)$$

If $\theta = 1''$ then d= 206265 AU = 1pc

One can measure up to 40 pc from Earth

Up to 100 pc with Hipparcos satellite

Astronomical Unit, AU

Modern determinations
Very precise measurements of the relative positions of the inner planets can be made by radar and by telemetry from space probes. As with all radar measurements, these rely on measuring the time taken for light to be reflected from an object.
The International Astronomical Union (IAU) currently accepted best estimate (2009) of the value of the astronomical unit in metres is

$$\text{AU} = 149597870700(3)\ \text{m} \approx 1.5 \times 10^{13}\ \text{cm}.$$

Parsecs

The unit for interstellar distances, parsec: 1 pc = 206265 AU$\approx 3 \times 10^{18}$ cm, is again derived from measuring angles (parallax), it is the distance from which 1 AU is visible at the angle of 1 sec of arc (since 1 radian = 206265 arcsecs).

Eventually this leads to *angular* and *parallactic* distances.

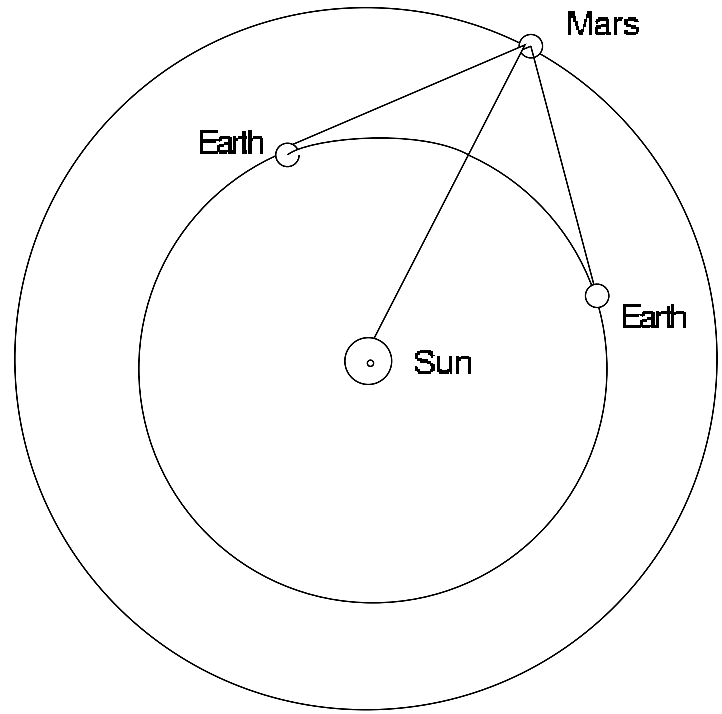
Kepler-Einstein

Discovery of Kepler's laws and hence of the Newton's gravity.

In one of his popular papers, Einstein gave the most brilliant account of that story.

Kepler: use Mars as a lighthouse

One cannot directly measure the distance Sun-Mars, because Mars moves outside the terrestrial orbit. The idea of Kepler essentially was to use a rotating frame of reference where Mars is at rest and to find from terrestrial observations (made by Tycho Brahe)



the position of Earth corresponding to two elongations of our planet as viewed from Mars - then one can find all angles and the distance Sun-Mars in AU.

Kepler's laws

This resulted in the great Kepler's laws. The most important is the 3rd Kepler's law, that the square of the period of planet's revolution around the Sun is proportional to the cube of its orbit semimajor axis. This great discovery led Newton to the formulation of classical dynamics and to the law of gravity.

For a circular orbit of the radius r around a star of mass M we have for the speed u:

$$u^2 = G_{\mathrm{N}} M/r,$$

from Newton's mechanics.

Kepler's laws-2

This derivation is OK while $u^2 \sim |\phi| \ll c^2$. If the period is $\mathcal{P}$, then $u = 2\pi r/\mathcal{P}$ and

$$r^3/\mathcal{P}^2 = M/M_\odot$$

if r is in AU, $\mathcal{P}$ in years. And this is the 3rd Kepler's law. Note that $G_{\rm N}$ does not enter in the units that we used, and it is convenient to take the solar mass $M_\odot$ as a unit of mass M.

Solar mass in grams

How accurate is the mass of the Sun $M_\odot \approx 1.9884 \times 10^{33}$ in grams? We get it from 1 AU in cm (radar location of planets and asteroids with a very high accuracy, better than 10^{-11}) and $\mathcal{P} = 1$ year $\approx 3.16 \times 10^7$ in seconds (accuracy is much higher than 3 digits in 3.16).

1) Laboratory measurements of $G_{\rm N} = (6.6742 \pm 0.0010) \times 10^{-8}$ cm^3/(g$\cdot$s^2), according to Particle Data Group (2004): it is the lowest accuracy among fundamental constants.

So we cannot get $M_\odot$ in grams (or kg) with accuracy higher than $\sim 0.2 \times 10^{-3}$ which is absolutely not sufficient for computing the orbits of interplanetary missions etc. But everything is OK in the units AU, year, $M_\odot$.

Fifth force?

2) Yukawa type deviations from Newton's law of gravity are possible in principle: instead of

$$\phi = G_{\mathrm{N}} M / r$$

one can have

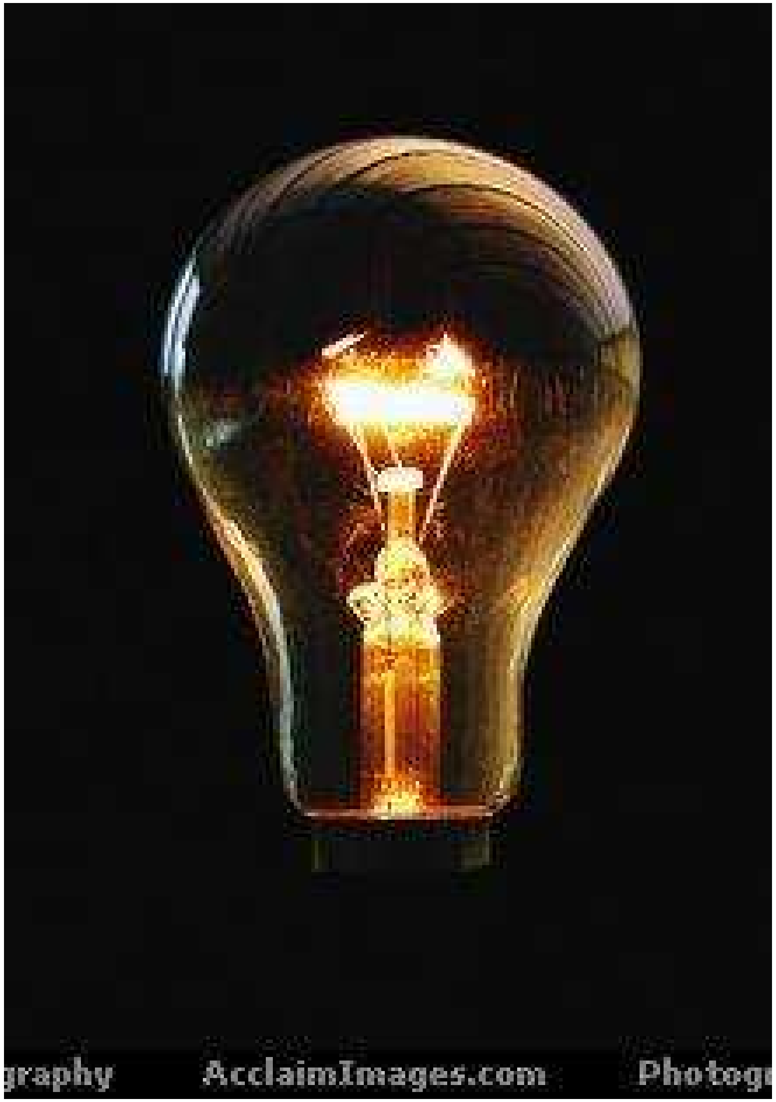
$$\phi = \frac{G_{\mathrm{N}} M}{r} \big(1 + \alpha \exp(-\mu r)\big)$$

and α can be as high 0.1 - 0.3 if μ is $\sim 1\,\mathrm{km}^{-1}$! (See, e.g. Sugimoto 1972, Blinnikov 1978, Hoskins et al. 1985.)

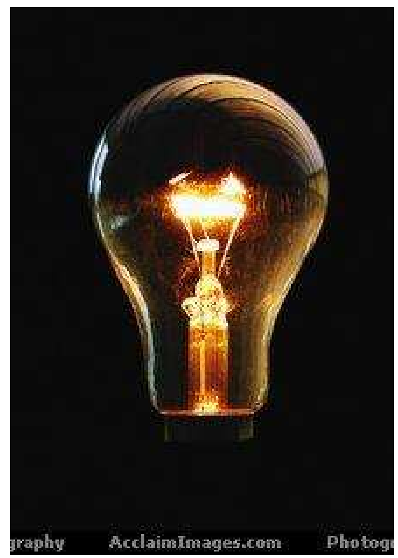
$M_\odot$ accurate ~ 20% ?

Astrophysics is a science for testing models: in the General Relativity (GR) model (which reduces to pure Newtonian gravity for small speeds u) we know $M_\odot$ in grams with accuracy of laboratory G_{N}. In the model-free case we know $M_\odot$ with accuracy ~ 20 % (the same is true for the mass of Earth!).

Elementary Cosmography

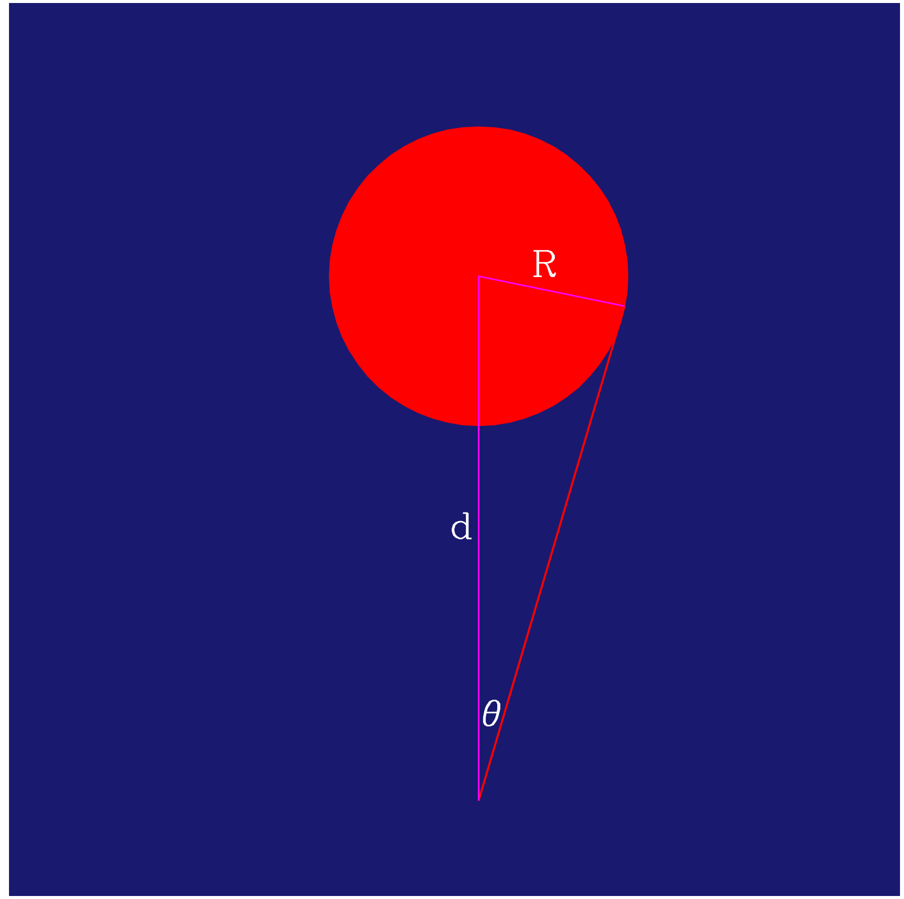


Angular size halved – distance doubled. Flux 1/4, brightness not changed.



Distances: angular diameter

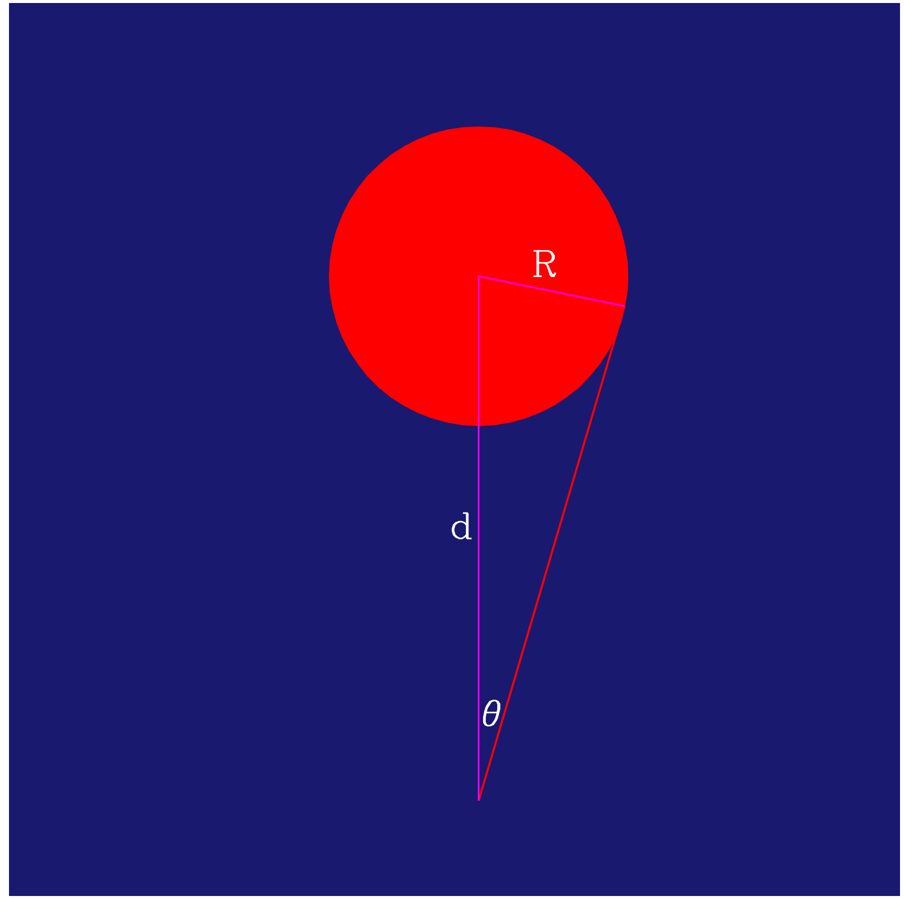
Standard ruler length R: $\theta = R/d \rightarrow d_A = R/\theta$ (for small θ)



Distances: photometric

Standard candle power L: $F = \frac{L}{4\pi d^2} \to d_{\mathrm{ph}}^2 = \frac{L}{4\pi F}$.

The same flux if the brightness is I: $F = \pi\theta^2 I = \pi I R^2/d_A^2$.



Distances

The photometric or luminosity distance is defined as

$$d_{\mathrm{ph}}^2 = \frac{L}{4\pi F} \; ,$$

where L is the absolute luminosity of the source and F is the flux measured by the observer (the energy per unit time per unit area of some detector).
The angular diameter distance $d_A = d_{\mathrm{ph}}$ only in a static flat space. They differ in an expanding universe.

Luminosity L is crucial

Светимость должна быть высокой. А самые мощные звёзды – сверхновые. Что это такое?

В нашей Галактике, около 10^{11} звёзд.

Каждый год заканчивает эволюцию примерно одна звезда.

Почему далеко не все из них (а только $\sim 1/50$) взрываются как сверхновые?

Что остаётся после взрыва?

Как объяснить свечение самых мощных сверхновых?

Взрывающиеся звезды

— новые и сверхновые.

НОВАЯ звезда (nova) — это яркая вспышка на $\sim 10 - 12$ mag, причём светимость достигает $\mathrm{L} \sim 10^5 \mathrm{L}_\odot$, где $\mathrm{L}_\odot$ – светимость Солнца.

Звёздные величины

По традиции, чем меньше m (mag, magnitude), тем выше блеск звезды. Например Вега $m = 0$. Слабые звёзды, видные глазу $m \approx 5$. Разница $m_1 - m_2 = 5$ – это различие в потоках в 100 раз.

Звёздная величина является логарифмической мерой светового потока.

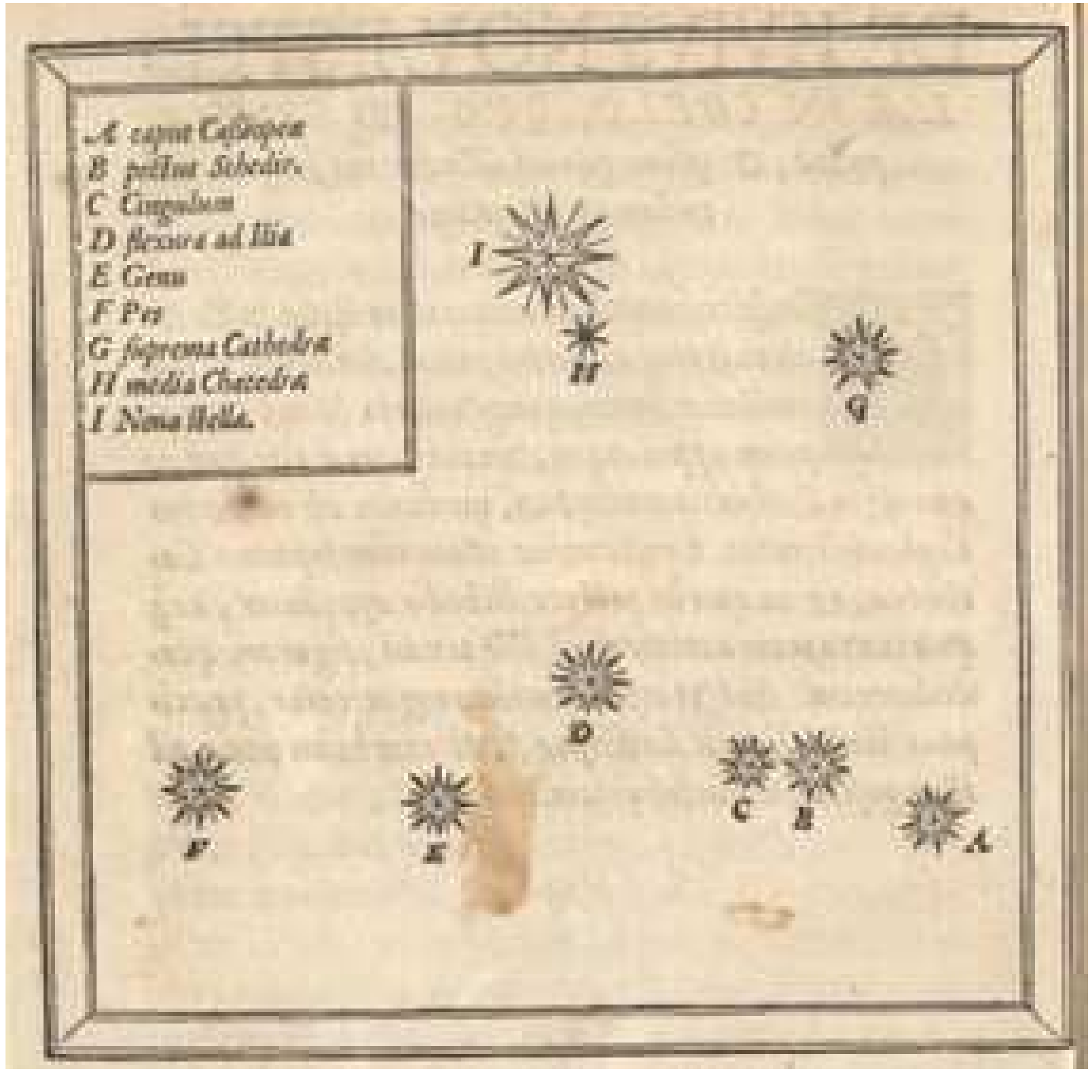
Вспышки новых

— это взрыв водорода на поверхности белого карлика в двойной системе.

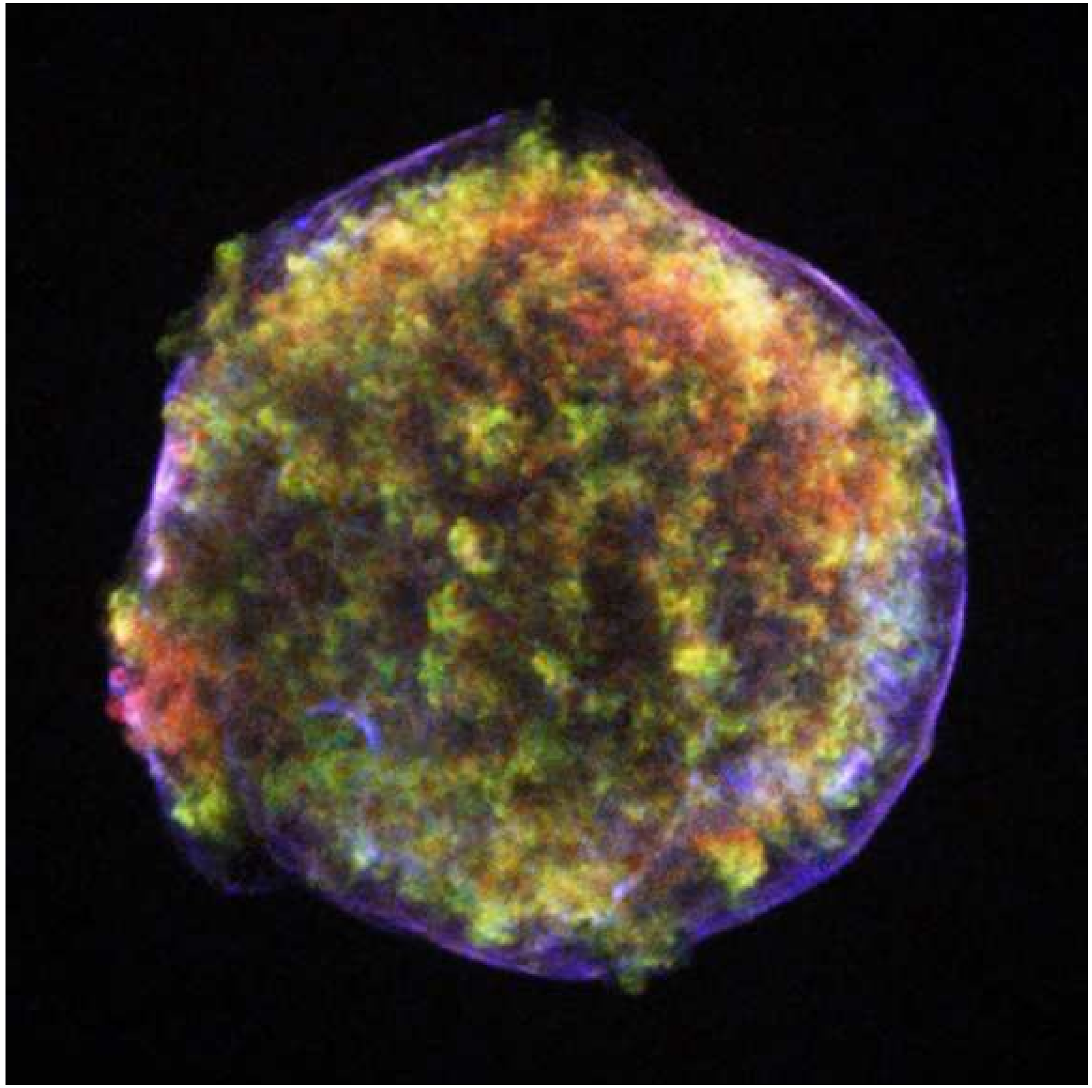
Выбрасывается малая доля массы звезды $\lesssim 10^{-4} M_\odot$.

“Stella Nova” по Латыни значит “новая звезда” — так думали древние увидев вспышку, но на самом деле звезда старая.

Tycho “Nova” 1572



SNR Tycho in X-rays (Chandra)



СВЕРХНОВЫЕ

(Supernova = SN, Supernovae = SNe) — светимость $\mathbf{L \sim 10^{10} L_{\odot}}$ и выше.

Это одни из наиболее сильных взрывов во Вселенной.

Разрушается и выбрасывается *бóльшая* часть массы звезды.

Открытие сверхновых

SN2005cs in M51 (see center of right image).
Discovered by Wolfgang Kloehr, June 28, 2005

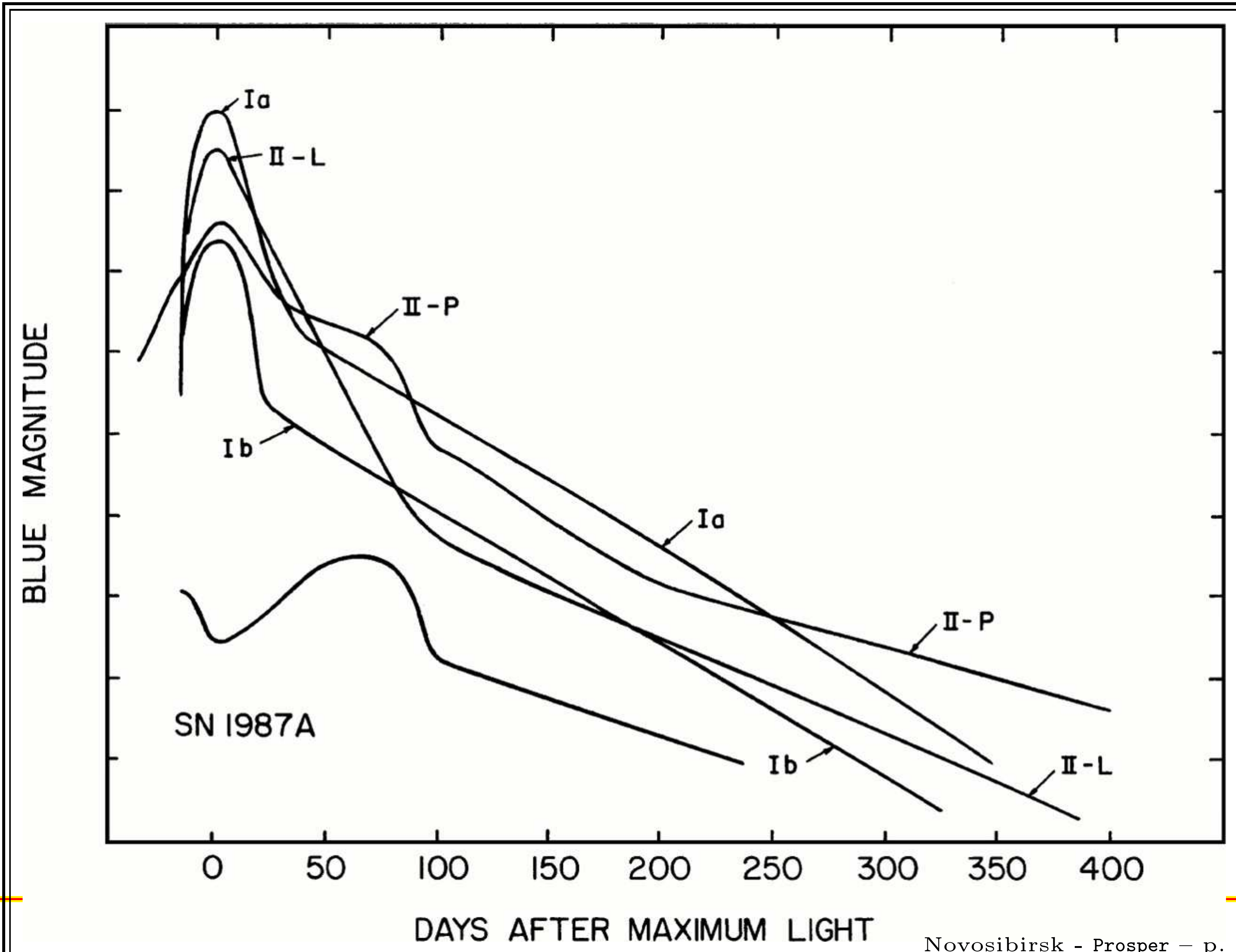
Сверхновая в галактике Centaurus-A

Click below for web:

Фото, кривая блеска, спектры, © S.Perlmutter

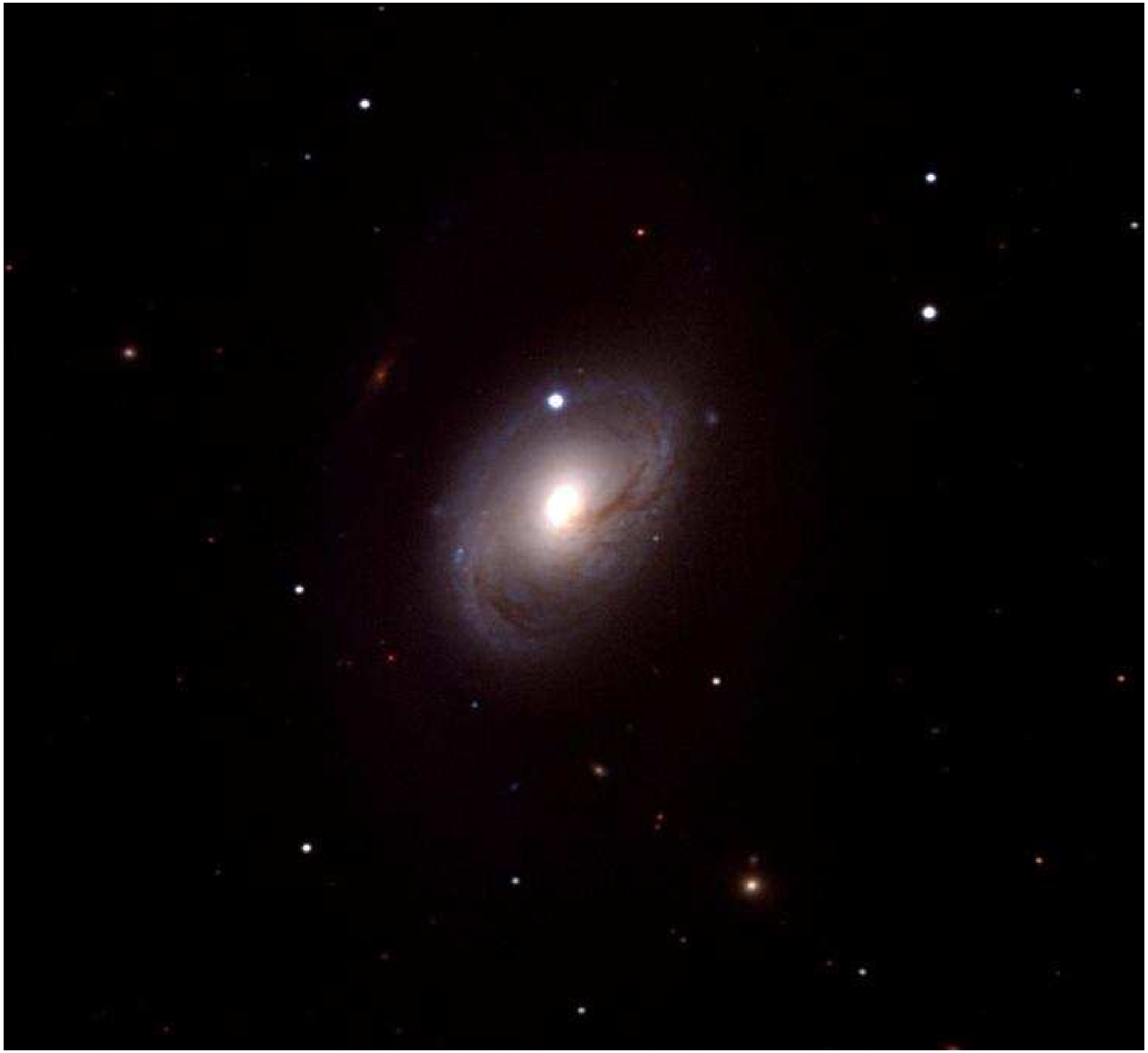
SN Movie: for files saved locally, © S.Perlmutter

SN Light Curves - Кривые блеска



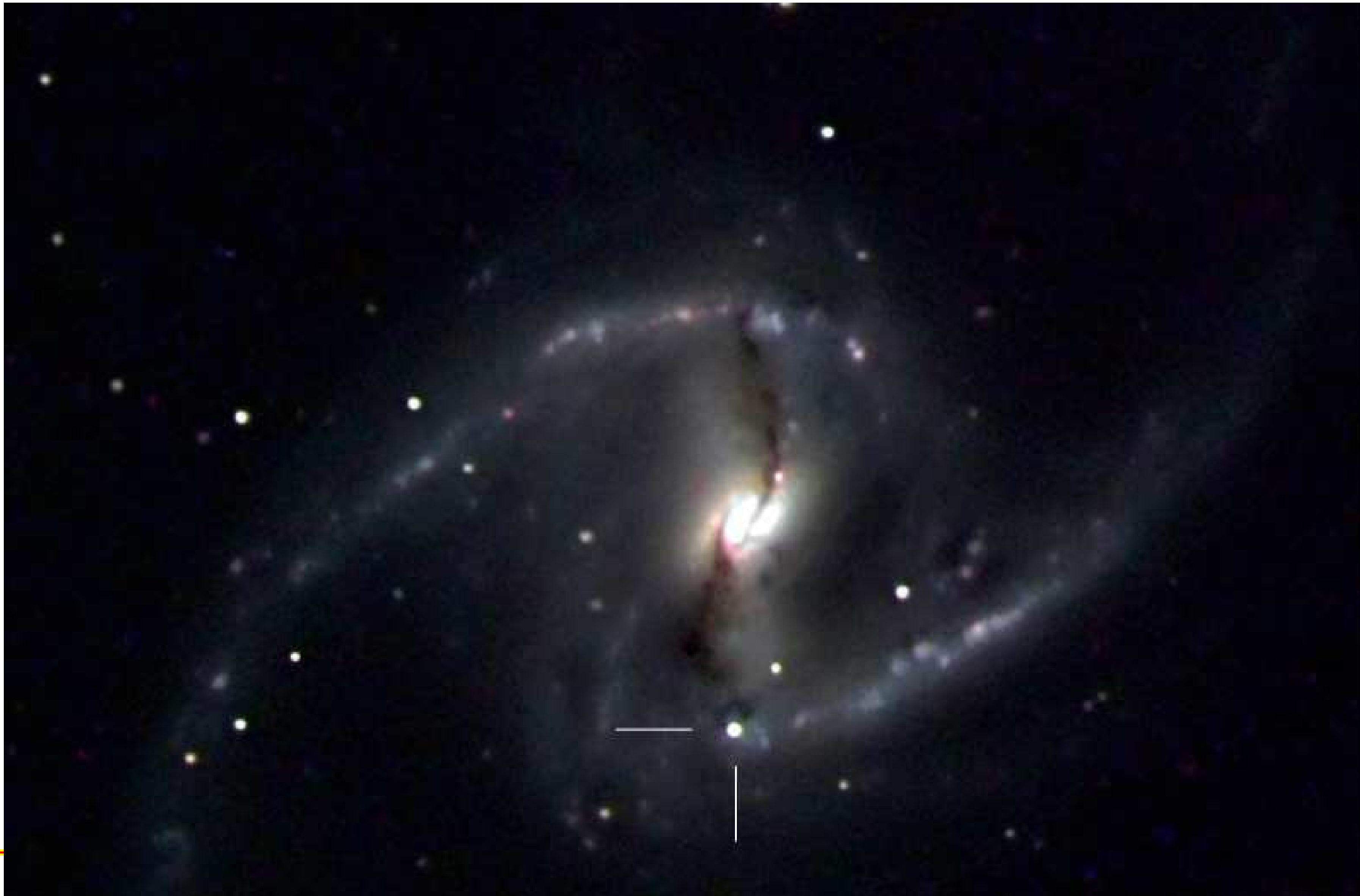
SN1987A в БМО

SN1998bu in M96



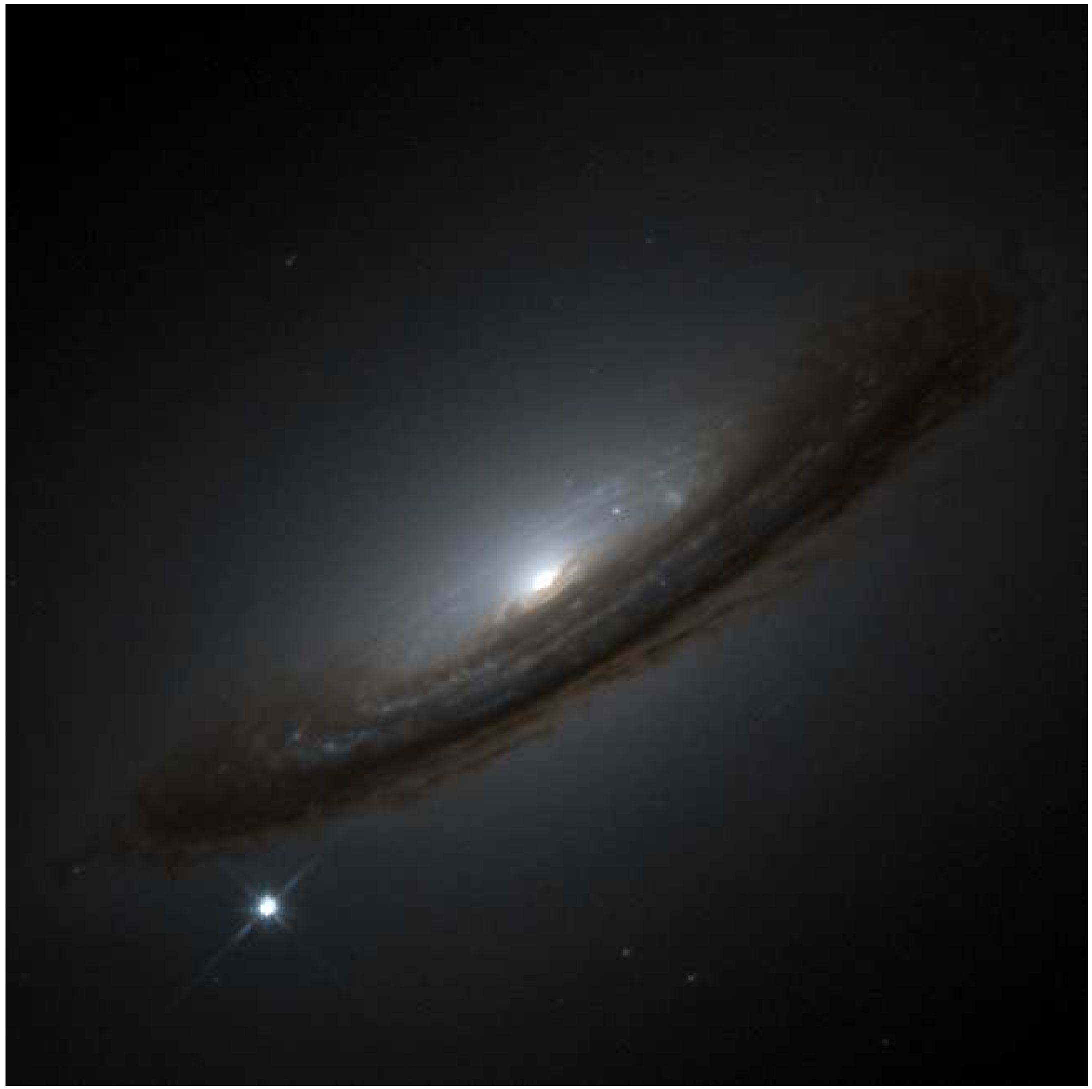
SNII 2001du in NGC1365

SNeII are close to spiral arms

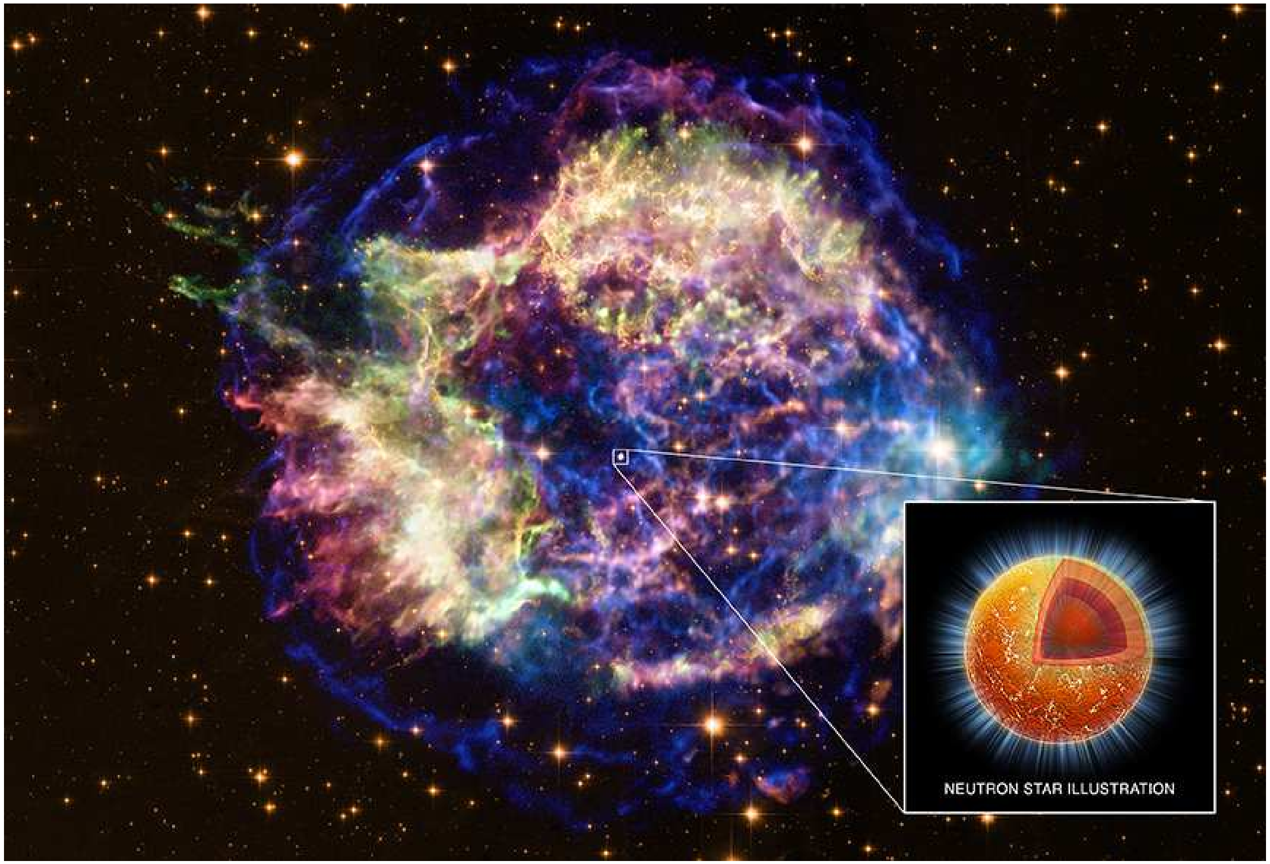


SNIa 1994D in NGC4526

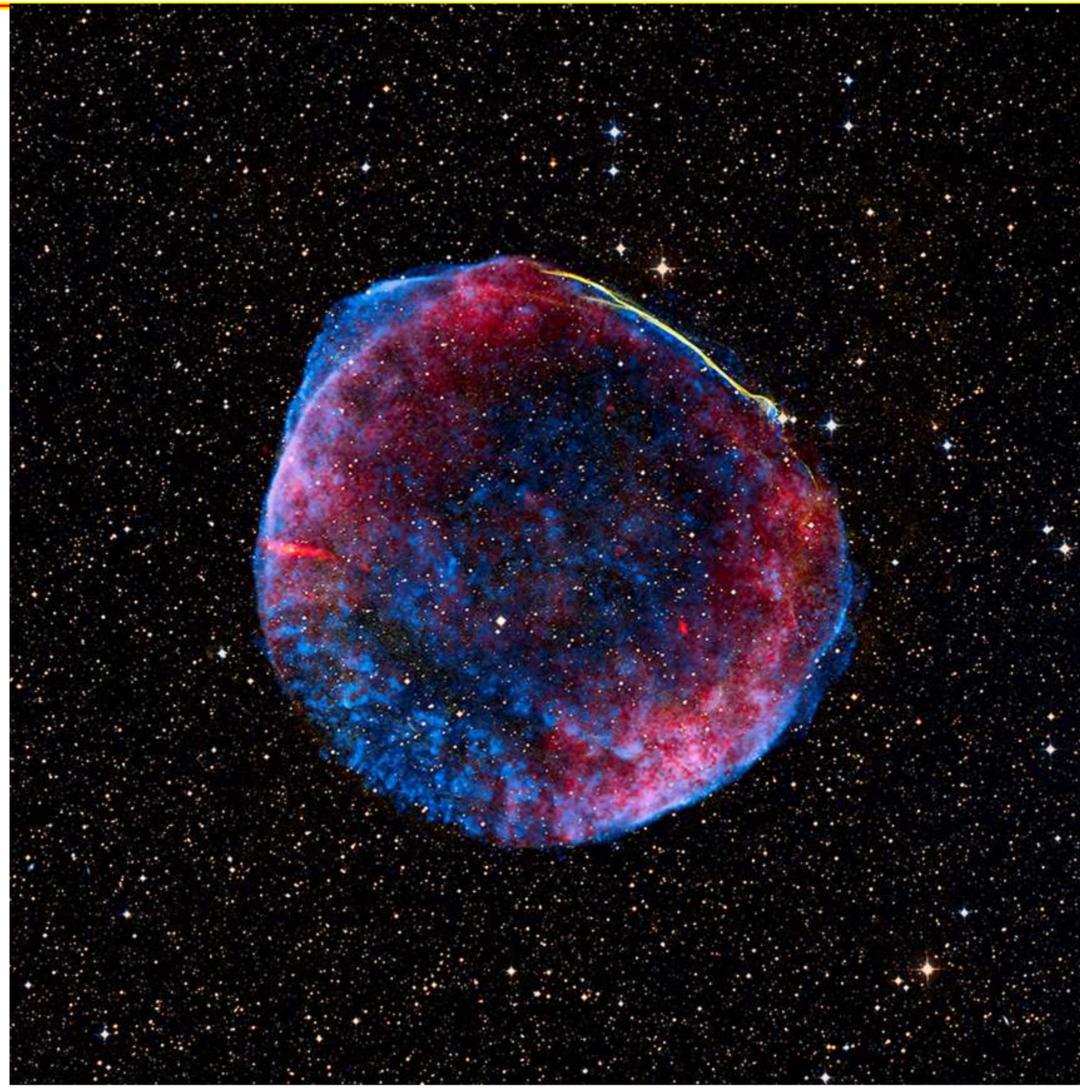
SNeIa may be away of spiral arms



SNR Cas A Chandra

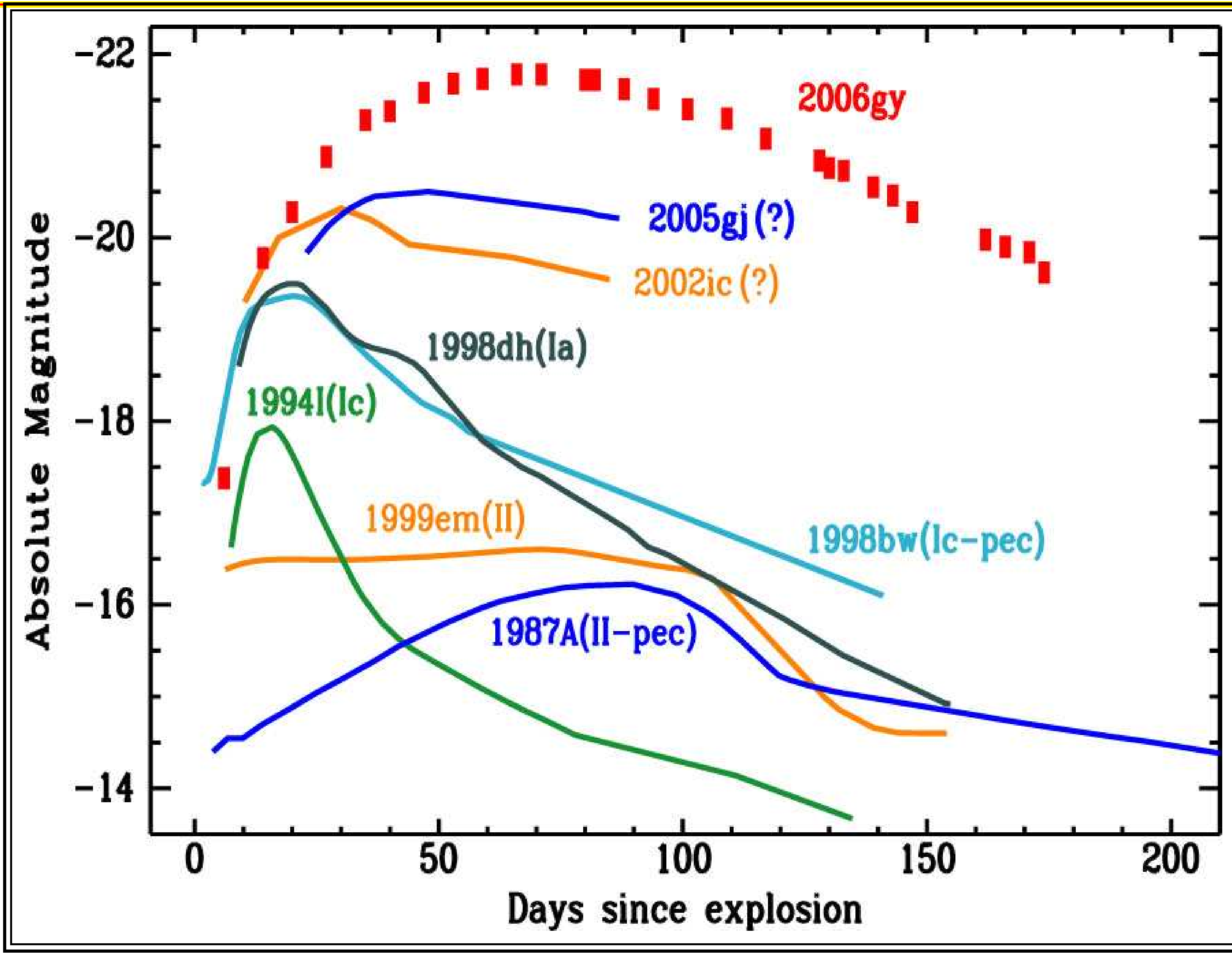


SNR 1006



movie – click here for web | movie – for files saved locally

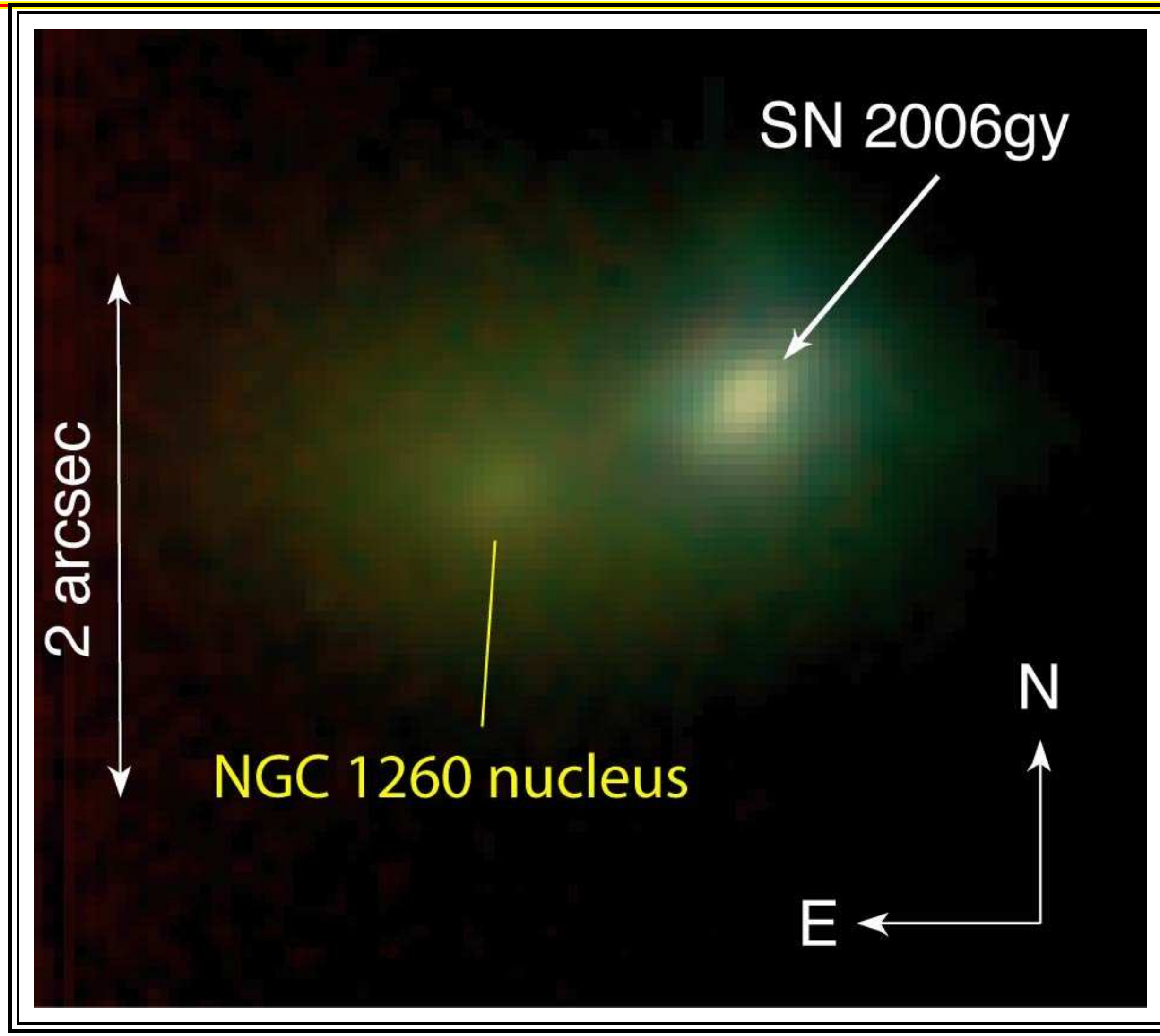
Most Luminous SNe

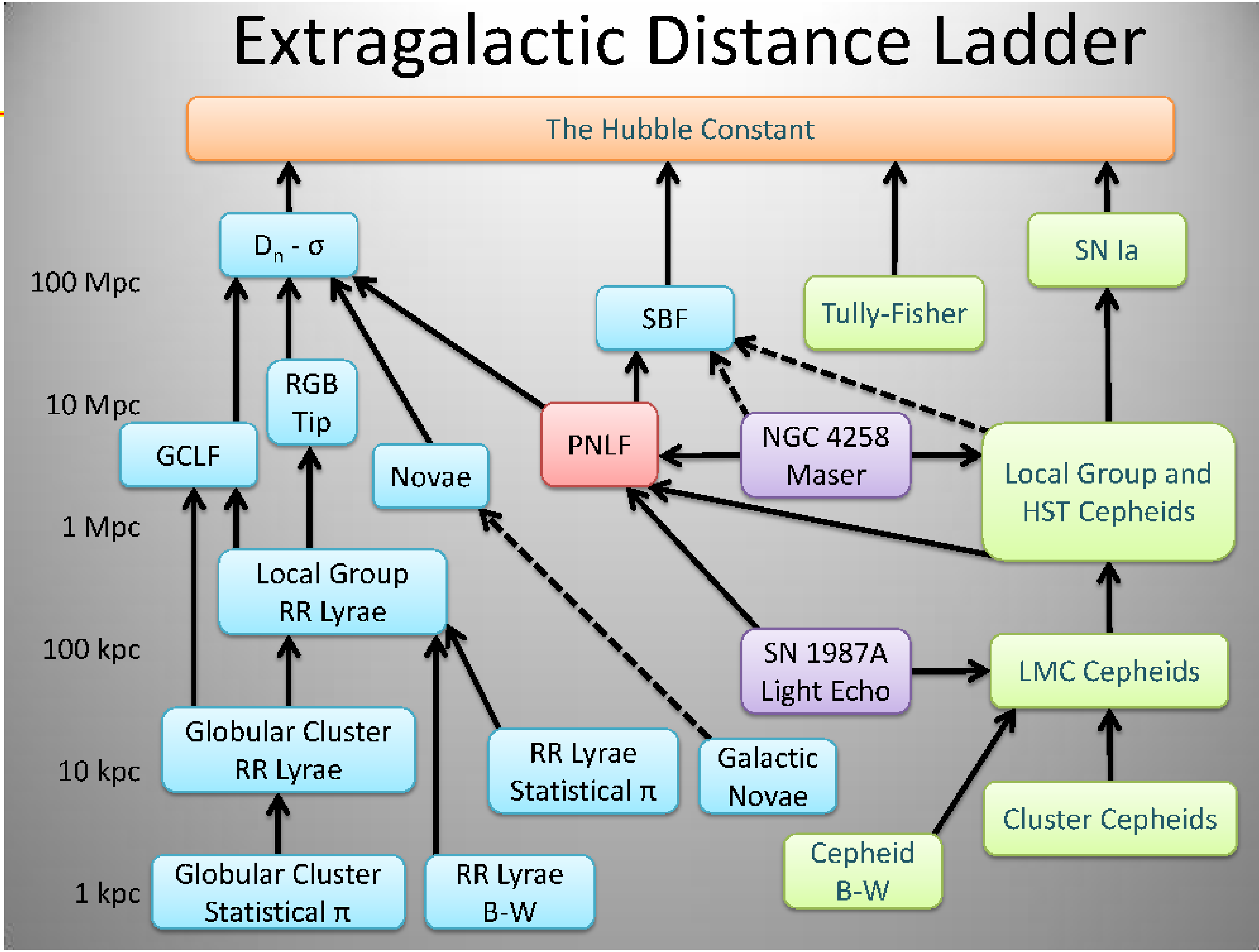


SN 2006gy – сверхмощная сверхновая

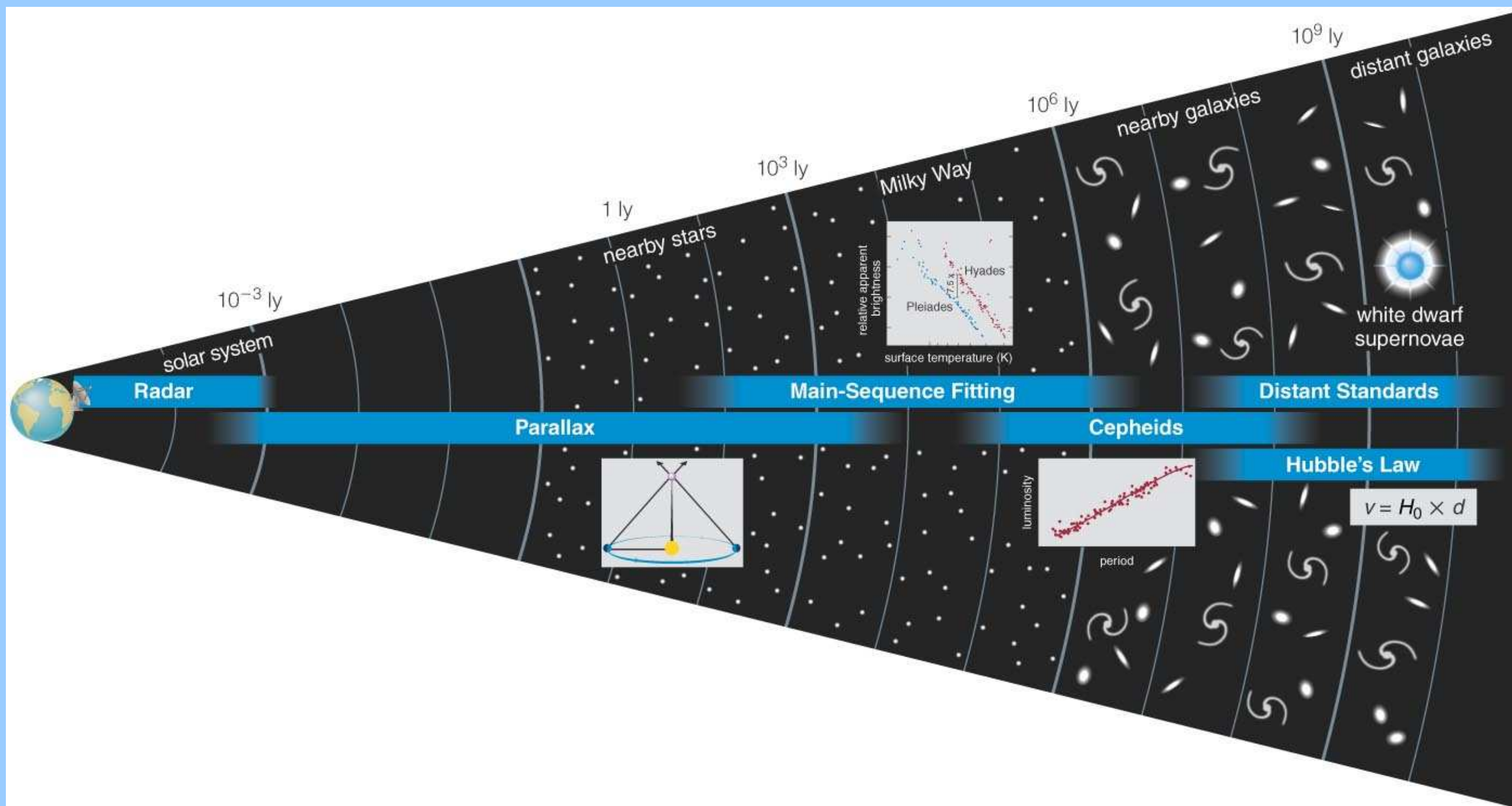
Ofek et al. 2007, ApJL, astro-ph/0612408)

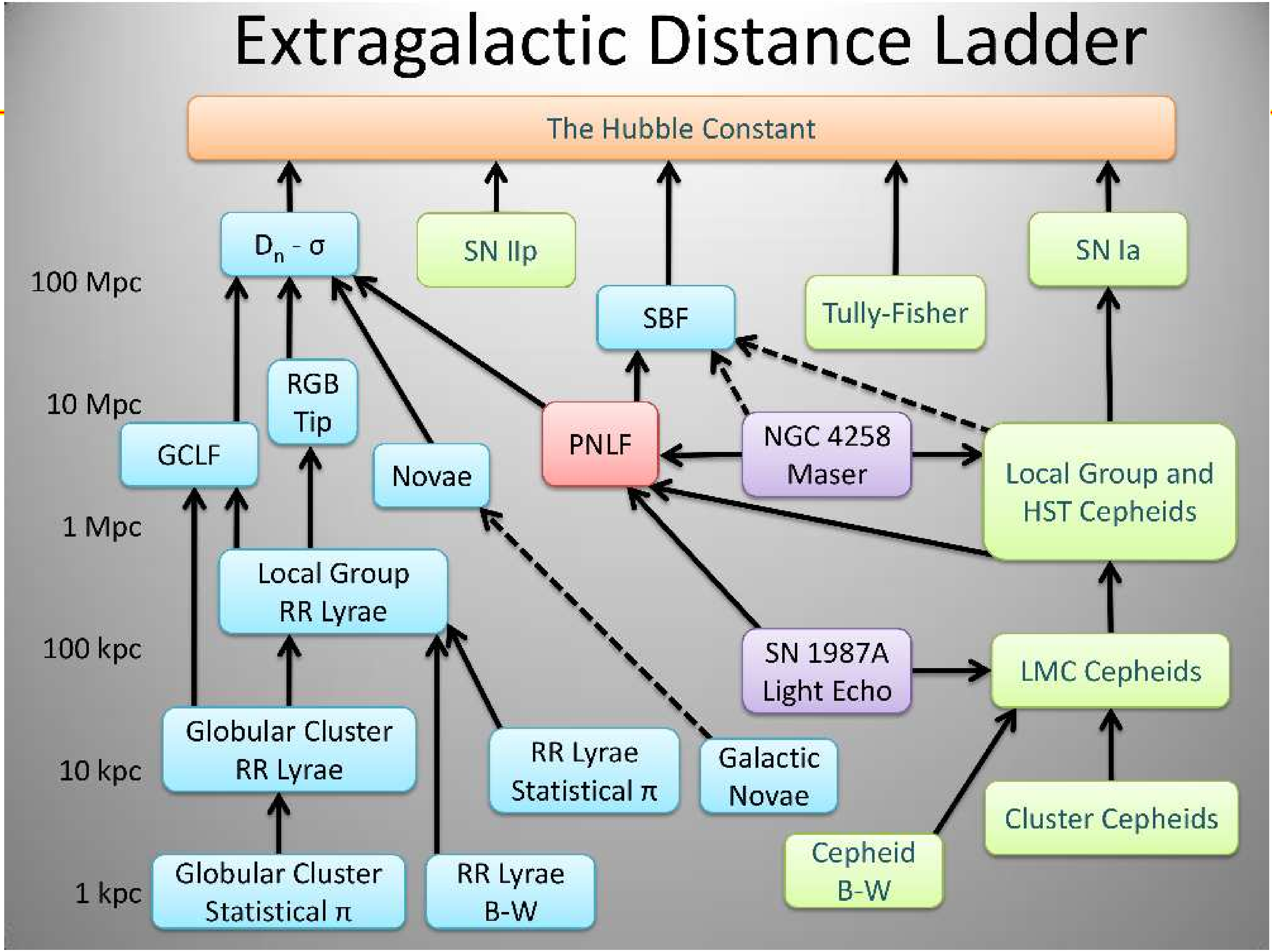
Smith et al. 2007, Sep. 10 ApJ, astro-ph/0612617)



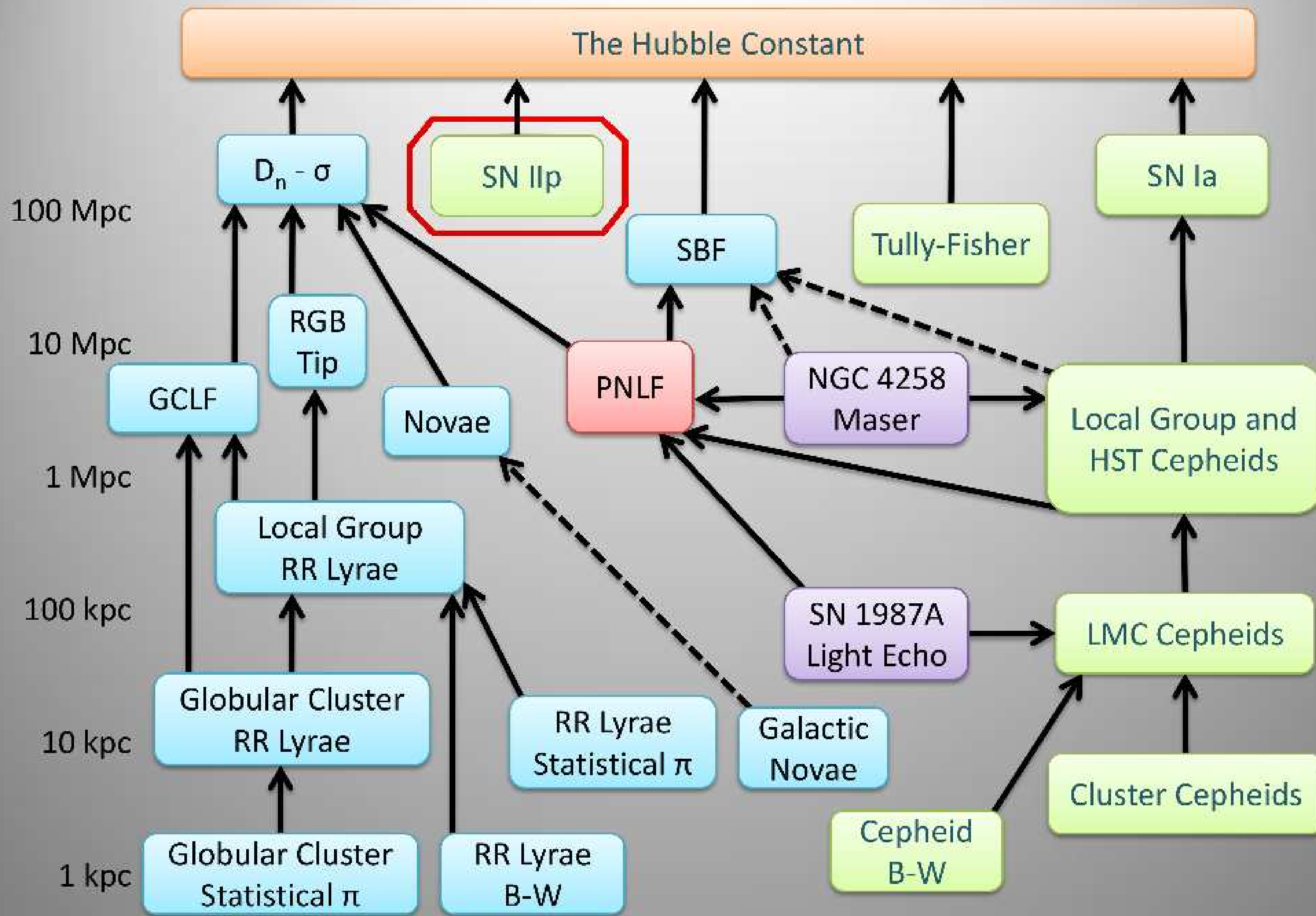

Extragalactic Distance Ladder
The Hubble Constant
D$_n$ - σ
SBF
Tully-Fisher
SN Ia
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
1 kpc
RGB Tip
GCLF
Novae
PNLF
NGC 4258 Maser
Local Group and HST Cepheids
Local Group RR Lyrae
SN 1987A Light Echo
LMC Cepheids
Globular Cluster RR Lyrae
RR Lyrae Statistical π
Galactic Novae
Cluster Cepheids
Cepheid B-W
Globular Cluster Statistical π
RR Lyrae B-W

Distance Ladder Cone



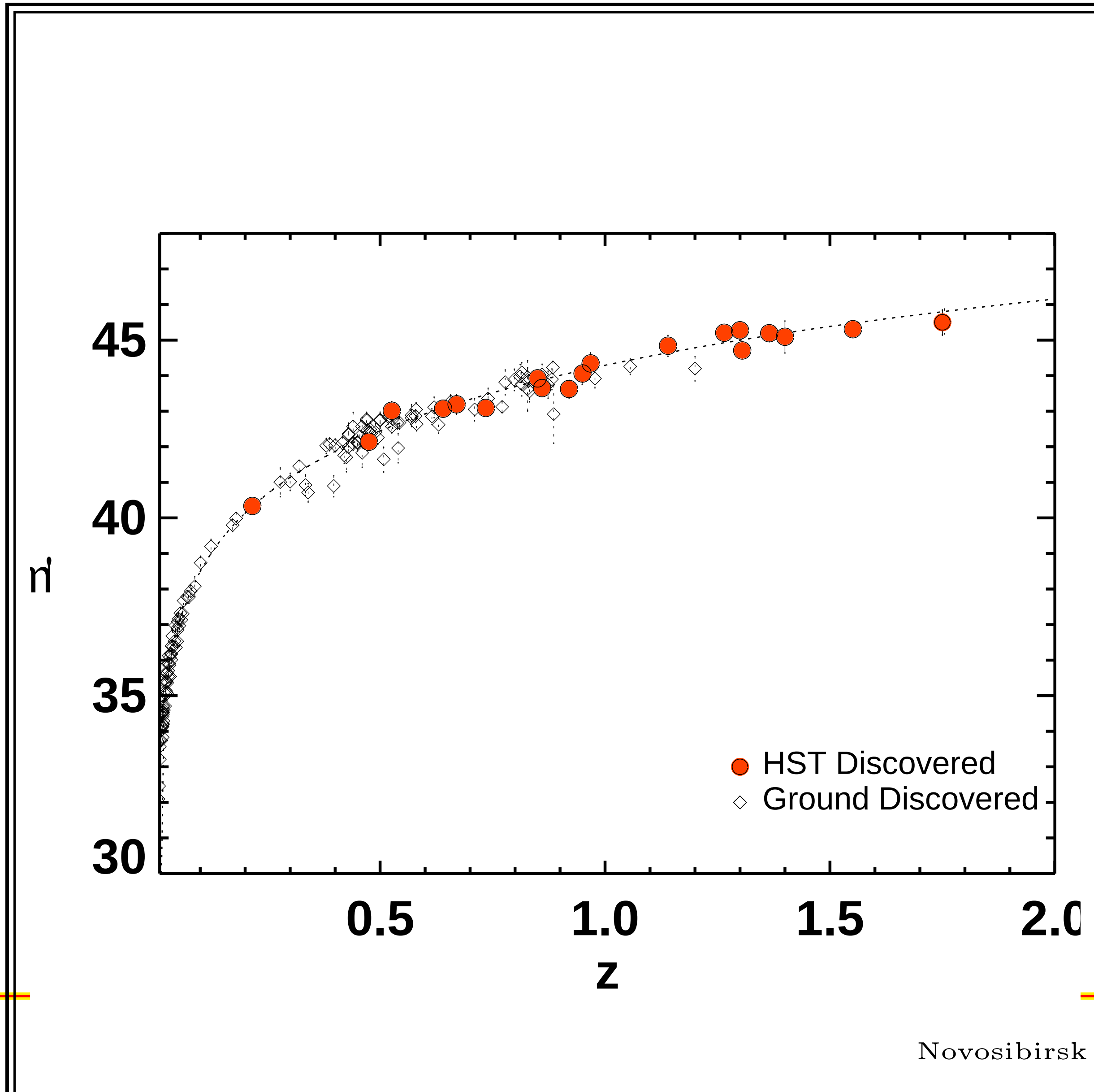

Extragalactic Distance Ladder
The Hubble Constant
D_n - σ
SN IIp
SBF
Tully-Fisher
SN Ia
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
1 kpc
RGB Tip
GCLF
Novae
PNLF
NGC 4258 Maser
Local Group and HST Cepheids
Local Group RR Lyrae
SN 1987A Light Echo
LMC Cepheids
Globular Cluster RR Lyrae
RR Lyrae Statistical π
Galactic Novae
Cluster Cepheids
Cepheid B-W
Globular Cluster Statistical π
RR Lyrae B-W

Extragalactic Distance Ladder

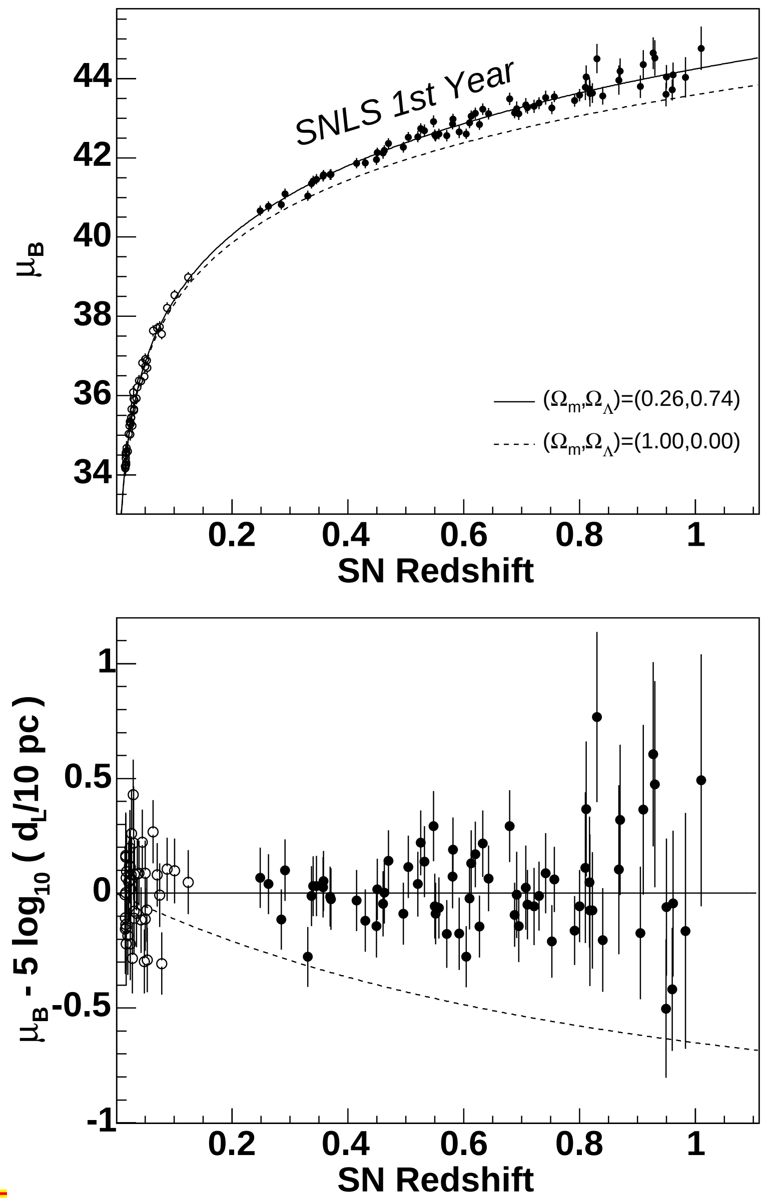


Hubble diagram, Feb 2004

for SN Ia (A.Riess et al.)

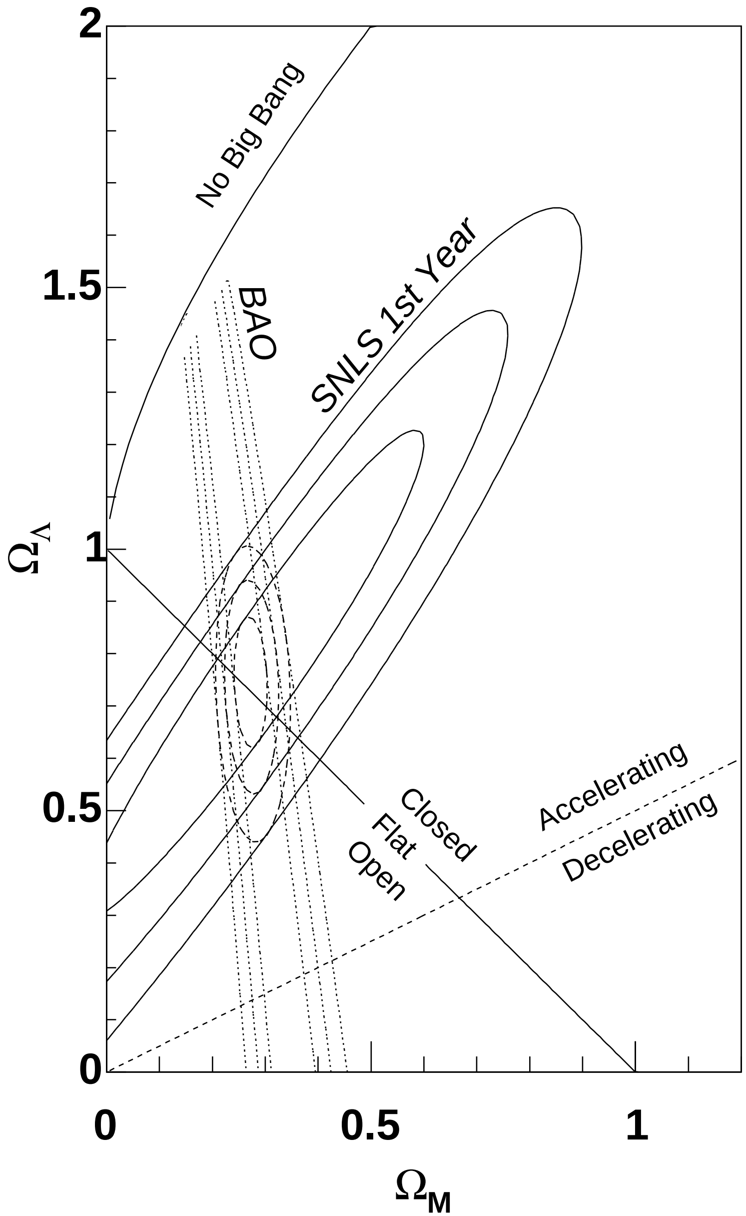


Hubble diagram SNLS



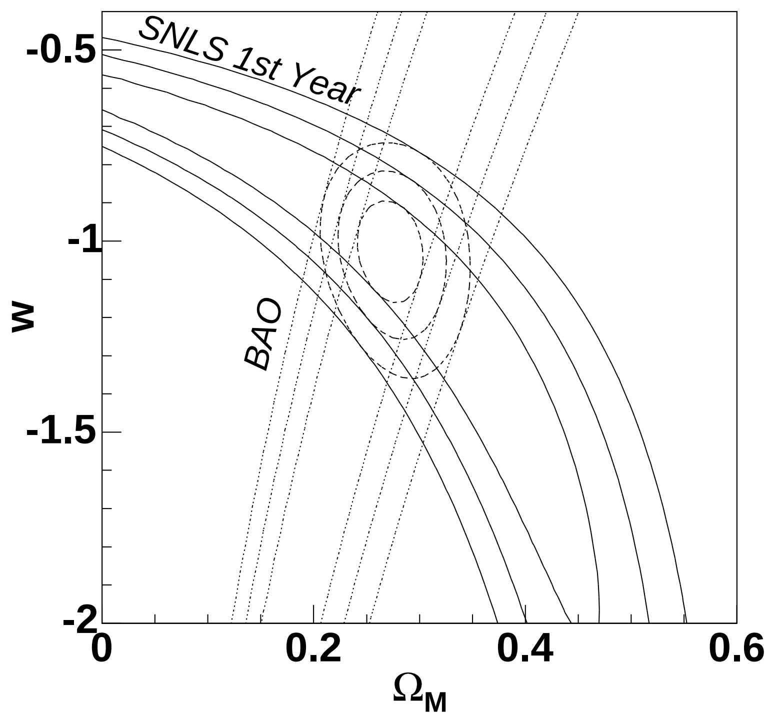
The bottom plot shows the residuals for μ_B when $d_{\mathrm{ph}}(z)$ is for the best fit flat Λ-cosmology ($\Omega_M = 0.26,\ \Omega_\Lambda = 0.74$). Dashed line is for the flat zero Λ model. Adopted with corrections from (Astier et al., 2006).

$(\Omega_m, \Omega_\Lambda)$ cosmology, SNLS



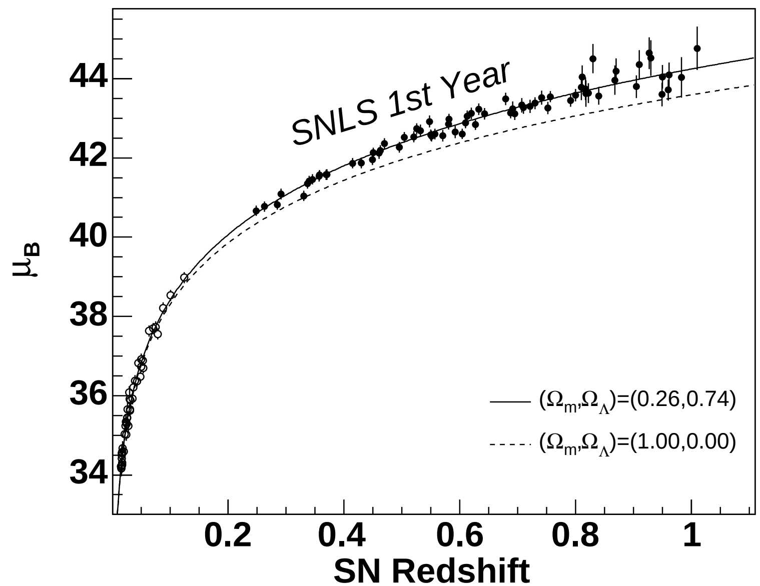
68.3%, 95.5% and 99.7% confidence levels for the SNLS Hubble diagram (solid contours), the SDSS baryon acoustic oscillations (Eisenstein et al. 2005, dotted lines), and the joint confidence contours (dashed lines). (Astier et al., 2006).

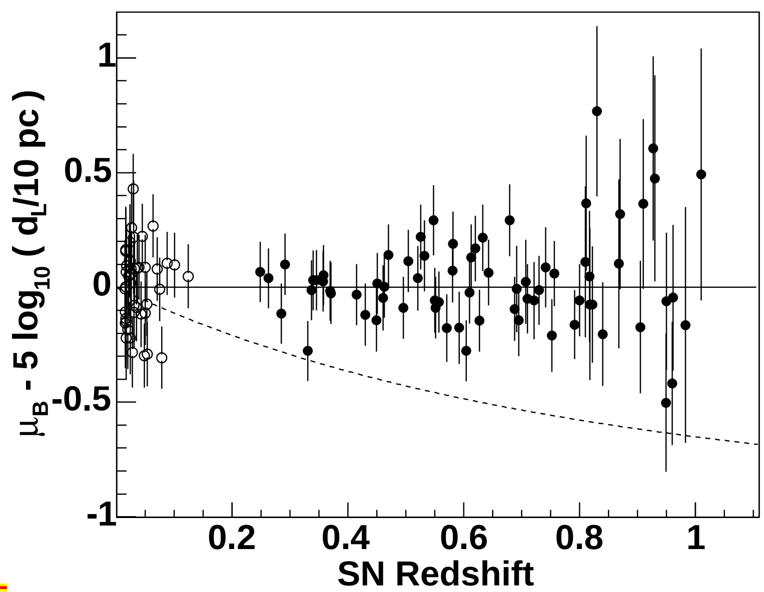
(Ω_m, w) cosmology



Contours at 68.3%, 95.5% and 99.7% confidence levels for the fit to cosmology with equation of state $P = w\mathcal{E}$ for flat 3D space, from the SNLS Hubble diagram alone, from the SDSS baryon acoustic oscillations alone (Eisenstein et al. 2005), and the joint confidence contours. From (Astier et al., 2006).

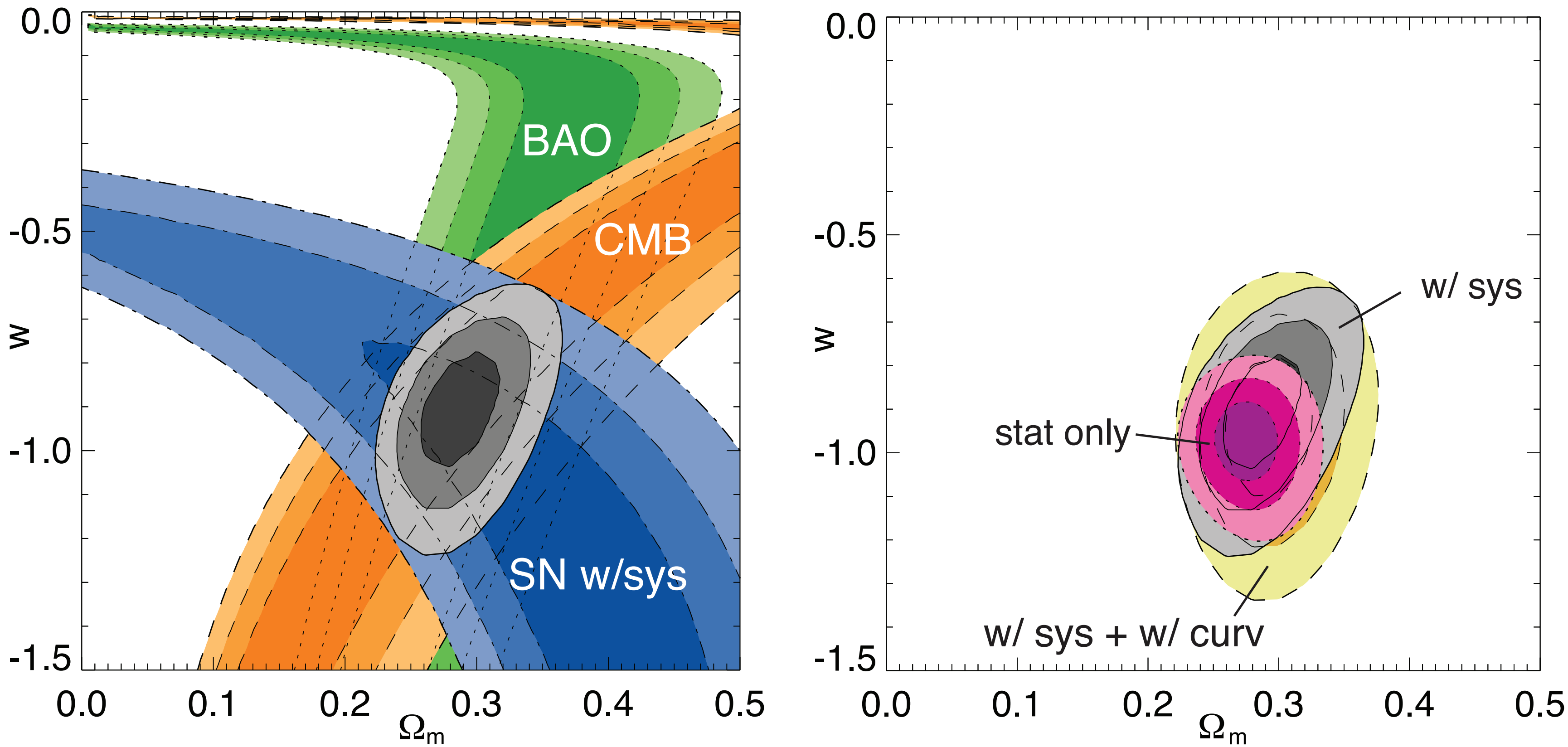
Hubble diagram SNLS





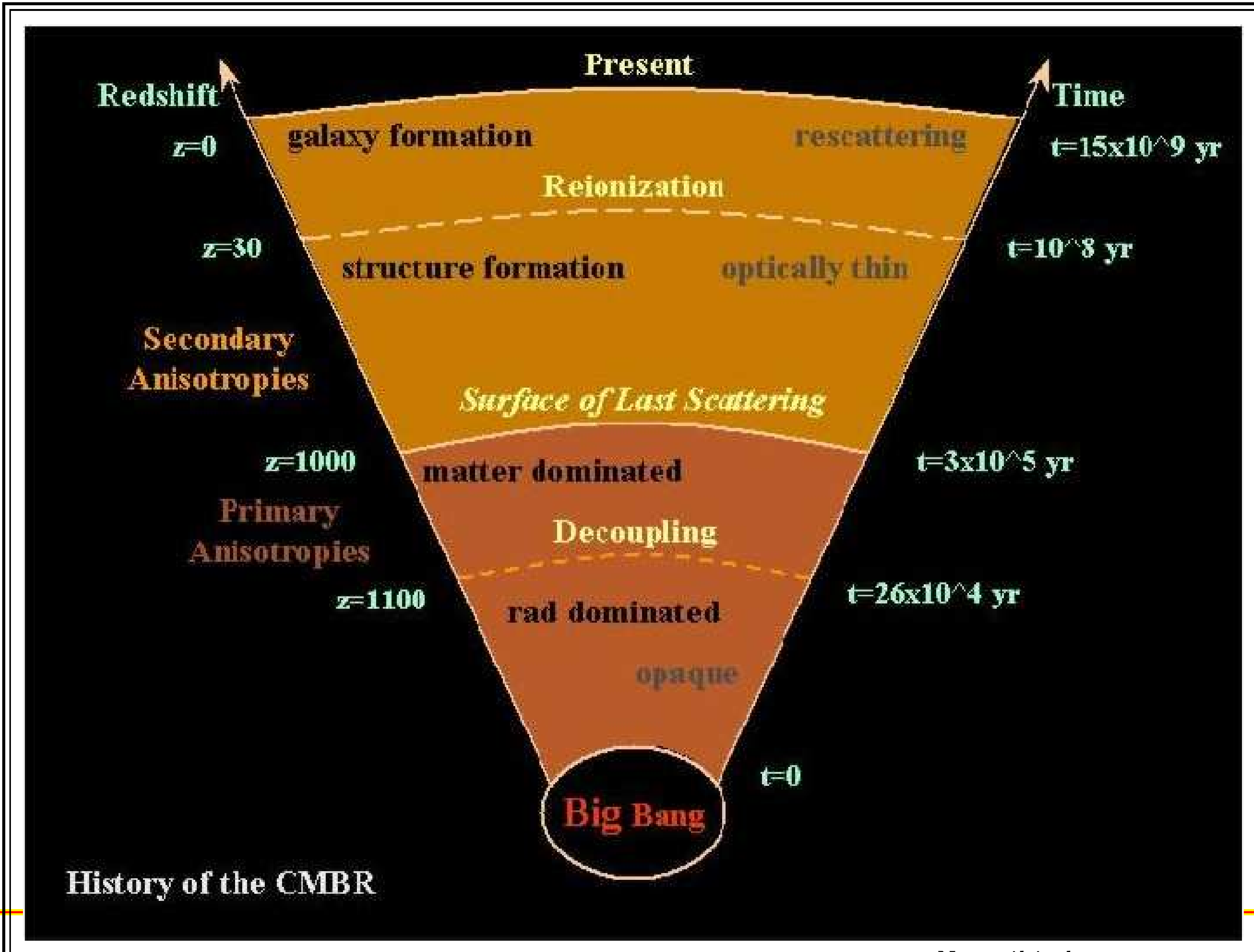
The bottom plot shows the residuals for μ_B when $d_{\rm ph}(z)$ is for the best fit flat Λ-cosmology ($\Omega_M = 0.26,\ \Omega_\Lambda = 0.74$). Dashed line is for the flat zero Λ model. Adopted with corrections from (Astier et al., 2006).

D.Rubin, E.V.Linder, M.Kowalski et al. ApJ 2009



68.3%, 95.4%, and 99.7% conf. levels on a constant EOS w and Ω_m for the individual and combined data sets. The left panel shows individual and combined probes in the flat universe case; the right panel repeats the combined systematics contour, and also compares to the statistical only contour, and to the systematics contour when simultaneously fitting for spatial curvature.

Surface of Last Scattering



Structure formation simulations

`http://www.mpa-garching.mpg.de/galform/data_vis/S2_960x640.avi`

Что нас окружает: SDSS

SDSS = Sloan Digital Sky Survey, проект на Apache Point обсерватории с аккуратными измерениями положений (угловых координат) и спектров (т.е. и красных смещений z) сотен тысяч галактик и квазаров. Данные выкладываются в открытый доступ. Угловые координаты и z позволяют построить трёхмерную картину распределения видимого вещества во Вселенной. Эта картина показана в фильме:

http://astro.uchicago.edu/cosmus/projects/sloanmovie/april18.mov

Конец 3-й лекции