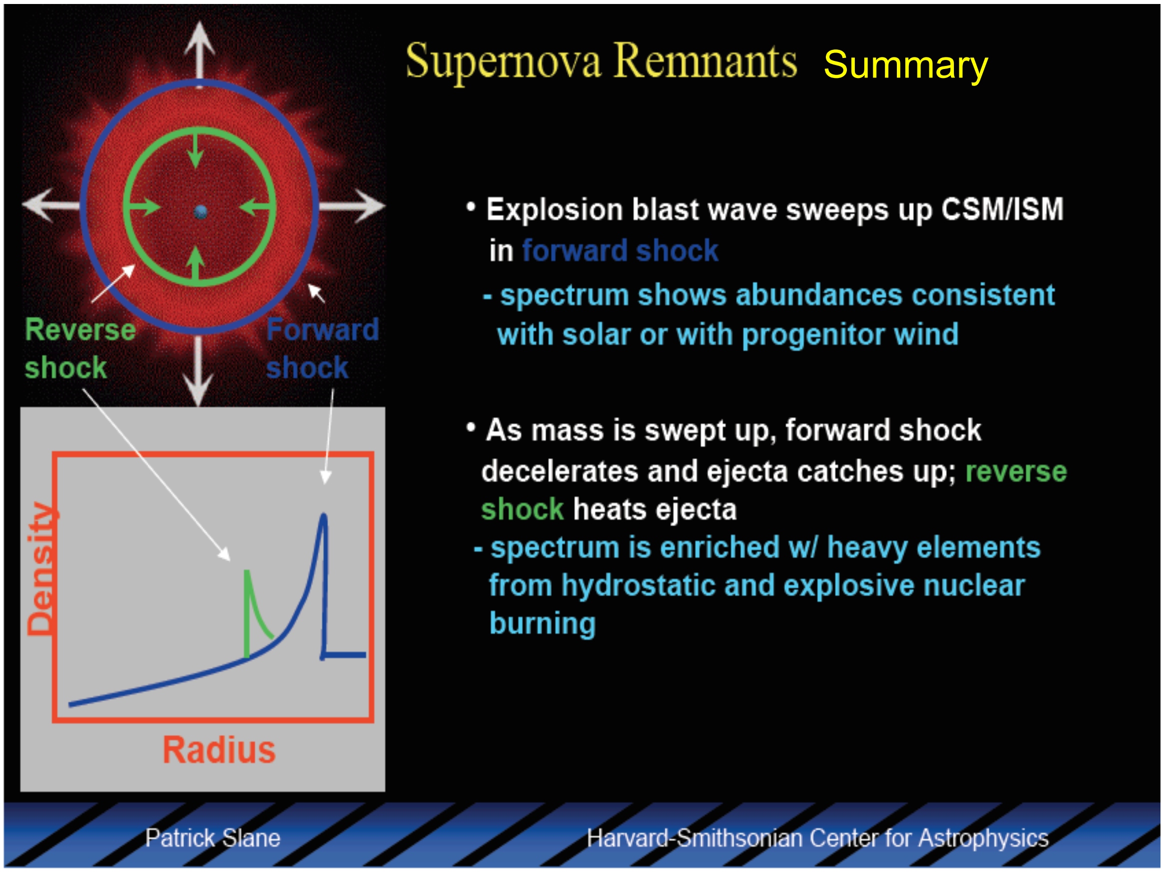
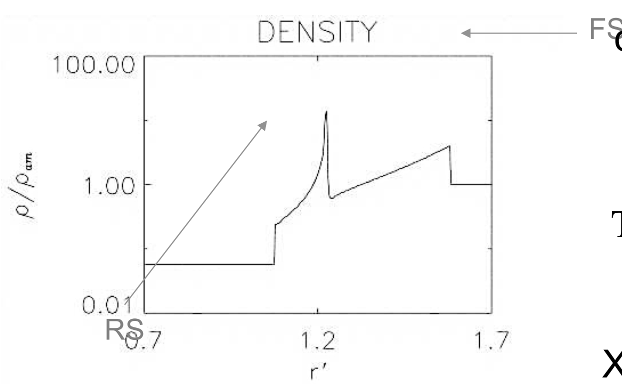


Summary of shocks



Shocks compress and heat gas

Mass, momentum, energy conservation give relations (for γ=5/3)

$\rho = 4\rho_0$

V = 3/4 v_{shock}

T=1.1 m/m_H $(v/1000\ km/s)^2$ keV

X-rays are the characteristic emission

The shock is "collisionless" because its size scale is much smaller than the mean-free-path for collisions (heating at the shock occurs by plasma processes) coupled through the structure of turbulence in shocks and acceleration

Collisions do mediate ionizations and excitations in the shocked gas

Plasma Physics

- the supernova remnant has more complex phenomena than clusters of galaxies
- most of the time the system is not in equilibrium

Plasma takes time to come into equilibrium

- particle ("Coulomb") collisions in the post-shock plasma will bring the temperature of all species, including the free electrons eventually to an equilibrium value: $kT = 3/16 \mu m_p v_s^2$
- **However it takes time for the system to come into equilibrium** and for a long time it is in non-equilibrium ionization (NEI)- to reach equilibrium need product of density and time to be >

  $\boldsymbol{\tau \sim n_e t \sim 3 \times 10^{12} cm^{-3} s}$

if the plasma has been shocked recently or is of low density it will not be in equilibrium

explain graph

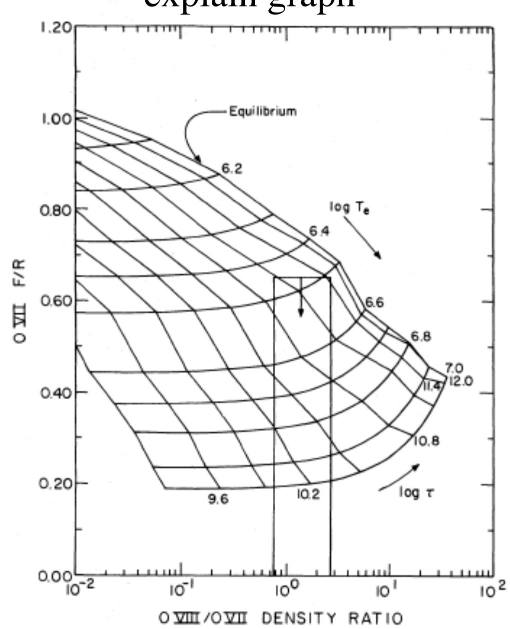
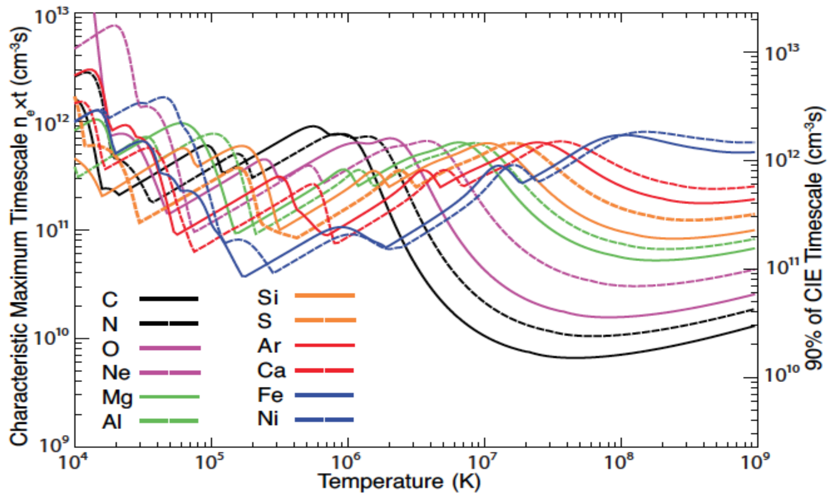


FIG. 3.—The results of our ionization nonequilibrium model (see text). The

- Timescale to reach equilibrium depends on ion and temperature- solution of coupled differential equations.
- Relevant parameter is $n_e t$ (density x time)



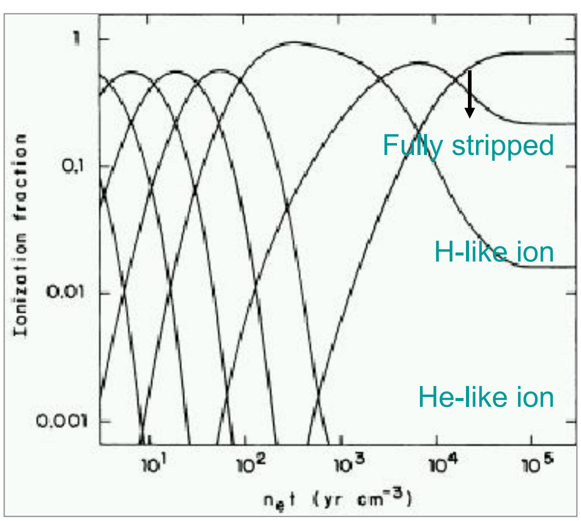
axis] Density-weighted timescales (in units of cm^{-3} s) for C, N, O, Ne, Mg, Al, S, Si, Ar, Ca, Fe, and Ni owards ionization equilibrium in a constant temperature plasma. [Right axis] Density-weighted timescale f eir equilibrium value.

Smith and Hughes 2010

Time-Dependent Ionization

Oxygen heated to 0.3 keV
(Hughes & Helfand 1985)

Impulsive Shock Heating Equilibrium



nt (in units of yr cm^{-3})

Ionization is effected by electron-ion collisions, which are relatively rare in the ~1 cm^{-3} densities of SNRs

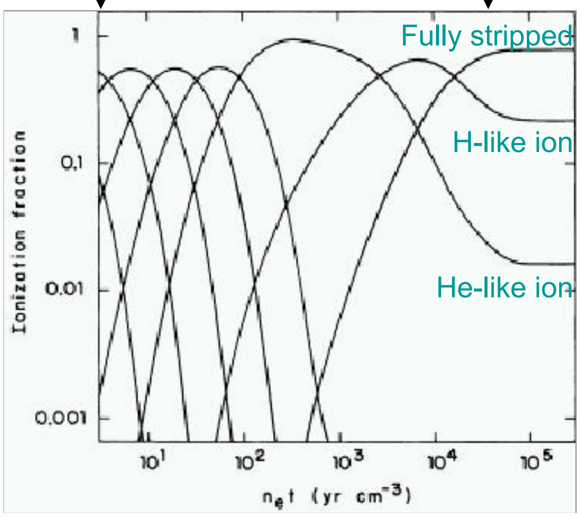
Ionization is time-dependent

Ionization timescale = $n_e t$
electron density x time since impulsively heated by shock

Time-Dependent Ionization

Oxygen heated to 0.3 keV
(Hughes & Helfand 1985)

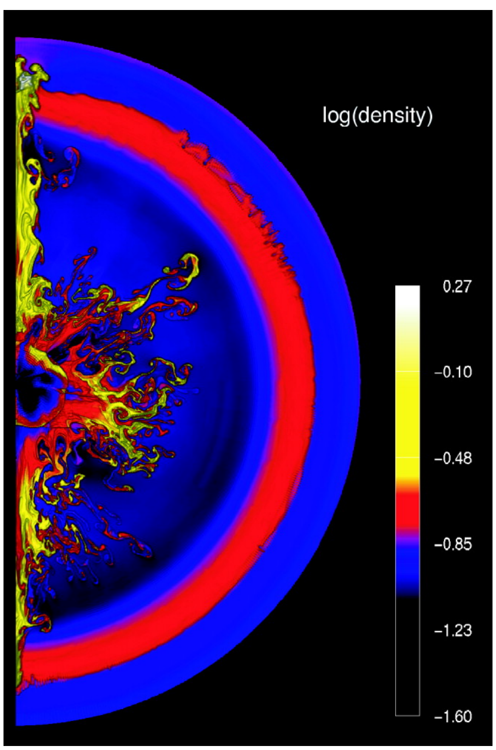
Impulsive Shock Heating   Equilibrium



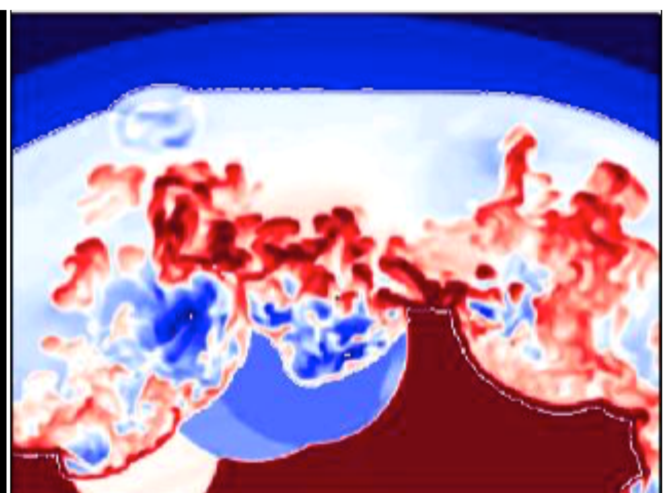
Ionization equilibrium attained at $n_e t \sim 10^4$ cm^{-3} yr

Ionizing gas can have many more H- and He- like ions, which then enhances the X-ray line emission

Inferred element abundances will be too high if ionization equilibrium is inappropriately assumed for an ionizing gas



Kifonidis et al. 2000



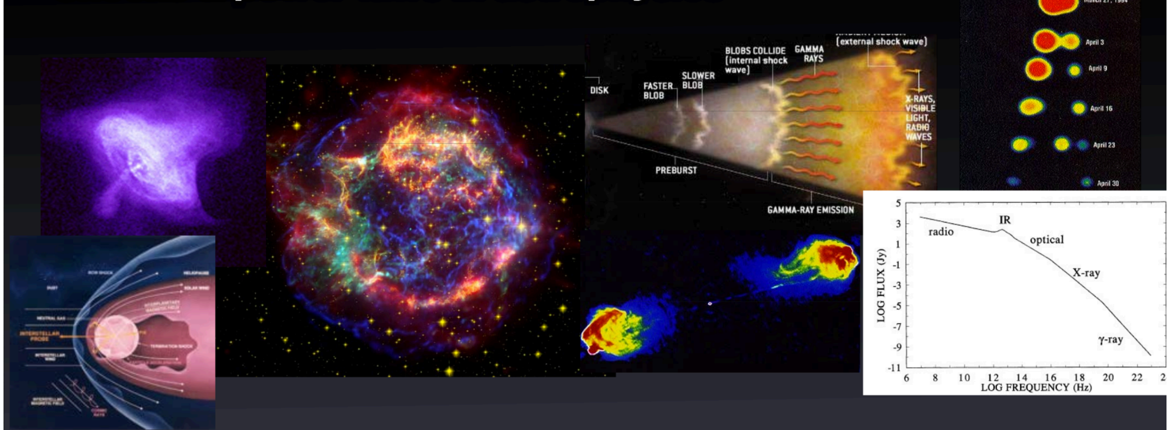
Fe bubbles Blondin et al. 2001

Instabilities

irregular shock boundaries
mixing between ejecta layers
mixing between ejecta and ISM

What it really looks like

Shocks & power-laws in astrophysics



Astrophysical shocks are typically collisionless (mfp >> shock scales).
Many astrophysical shocks are inferred to:

1) accelerate particles to power-laws
2) amplify magnetic fields
3) exchange energy between electrons and ions

Spitkovsky

How do they do this? Mechanisms, efficiencies, conditions?…

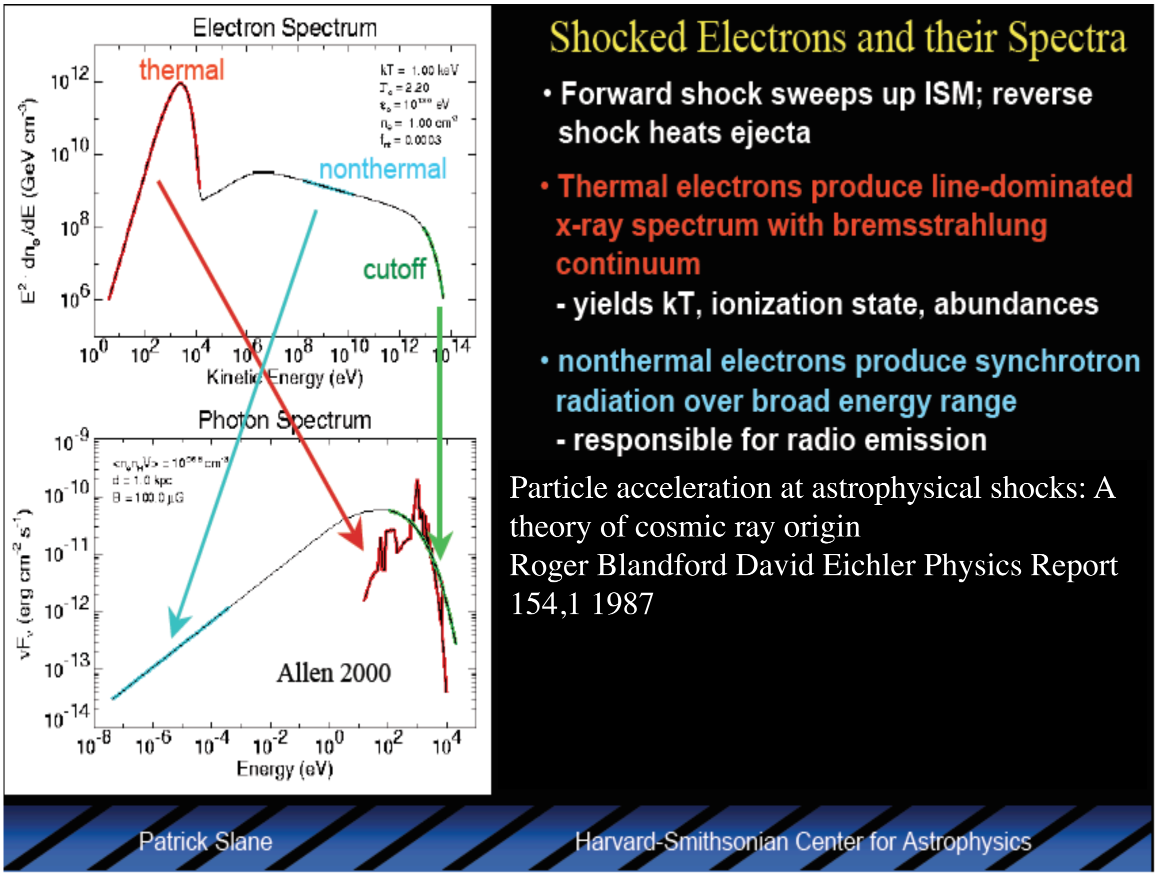
Particle Acceleration

Supernova remnants are thought to be the site of acceleration of cosmic rays

Why?
Only need to tap ~5% of SN energy to produce observed energy of CRs (E. A. Helder et al ., Science 325, 719 (2009))

Strong shocks can accelerate particles

The Nine Lives of Cosmic Rays in Galaxies
Grenier, Black and Strong
2015ARA&A..53..199



SNR are Thought to Be the Source of Galactic cosmic rays

- SNR need to put ~ 5-20% of their energy into cosmic rays in order to explain the cosmic-ray energy density in the Galaxy (~2 eV/cm^3 or 3x10^{38} erg/s/kpc^2) ,
- This is based on using the supernova rate (1-2/100yrs), the energy density due to SN is ~1.5x10^{41} ergs/sec~2x10^{39} erg/s/kpc^2

many young SNRs are actively accelerating electrons up to 10-100TeV, based on modeling their synchrotron radiation

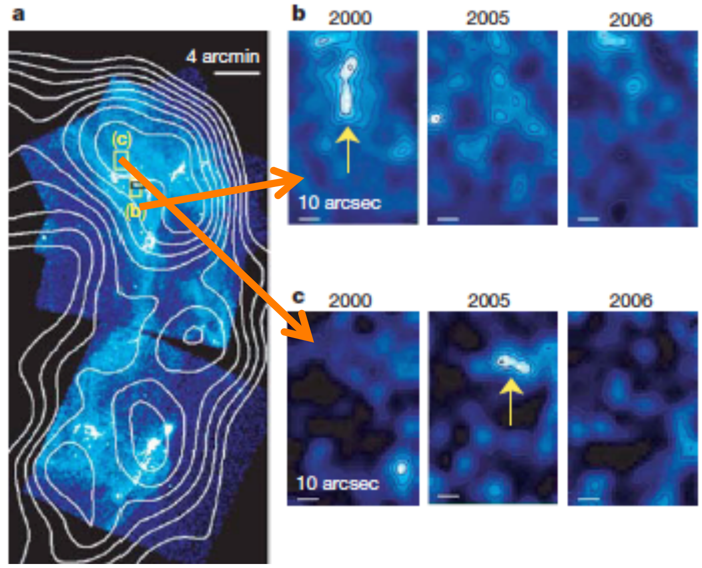
SNR are Thought to Be the Source of Galactic cosmic rays

- Particles are scattered across the shock fronts of a SNR, gaining energy at each crossing (Fermi acceleration)

- Particles can travel the Larmor radius

$R_L \sim E_{17}/B_{10\mu G}\ Z$ kpc

Z is the charge on the particle

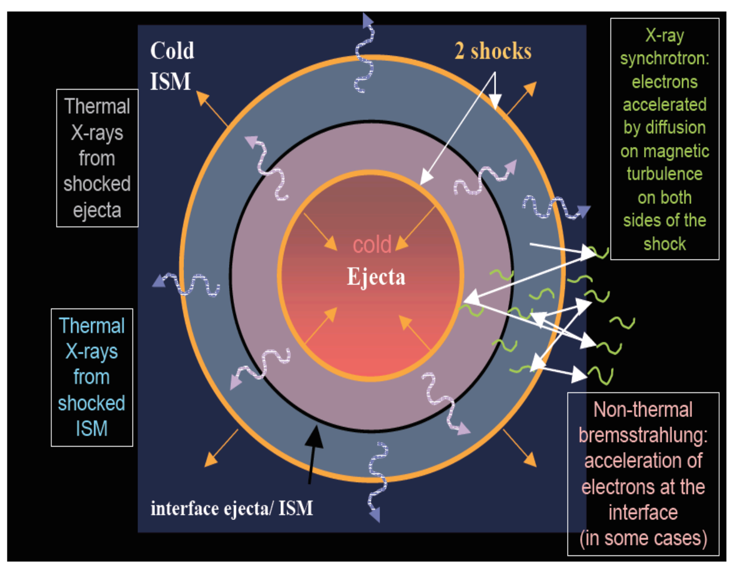


Changes in synchrotron emission in a SNR on timescales of years- short loss times and acceleration times

- Fermi acceleration- 1949:
- charged particles being reflected by the moving interstellar magnetic field and either gaining or losing energy, depending on whether the "magnetic mirror" is approaching or receding.
- energy gain per shock crossing is proportional to velocity of shock/ speed of light
- CR spectrum is a power law

See Longair 17.3

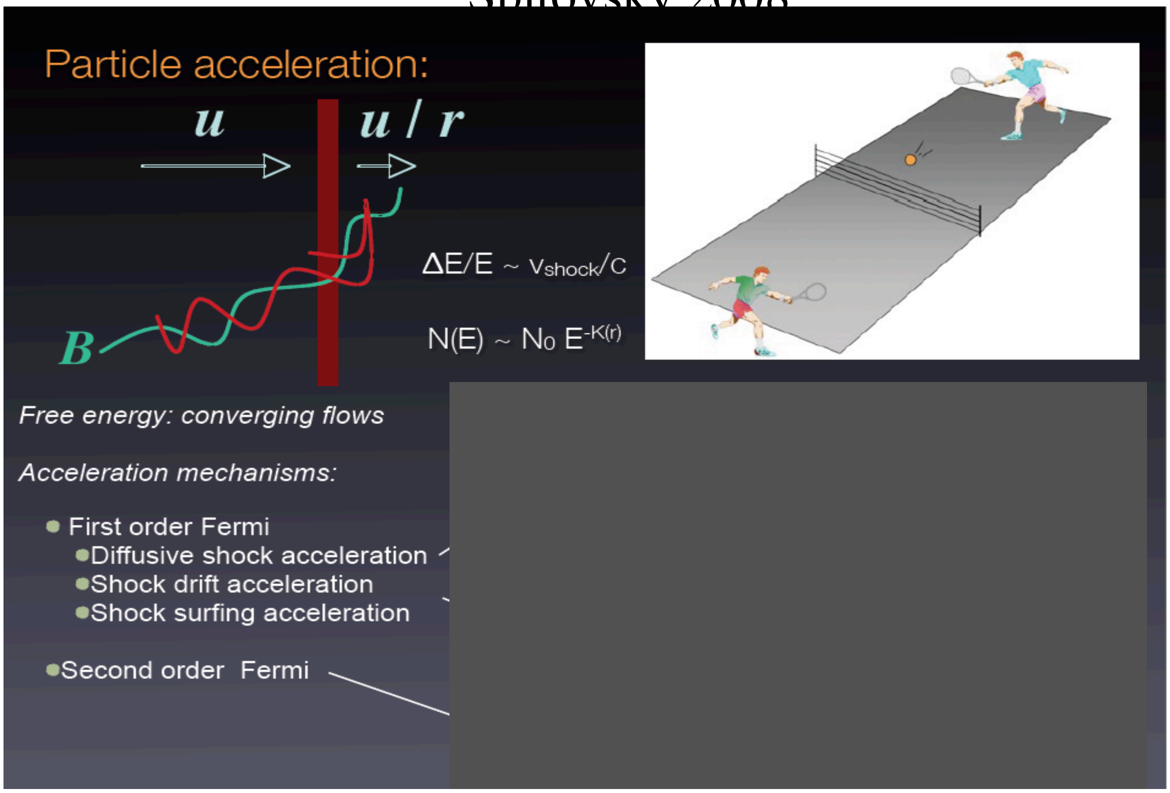
DeCourchelle 2007



Nice analogy- ping pong ball bouncing between descending paddle and table

Particle Acceleration sec 4.4.2 in R+B

Spitovsky 2008



Fermi Acceleration

2nd Order energy gained during the motion of a charged particle in the presence of randomly moving "magnetic mirrors". So, if the magnetic mirror is moving towards the particle, the particle will end up with increased energy upon reflection.

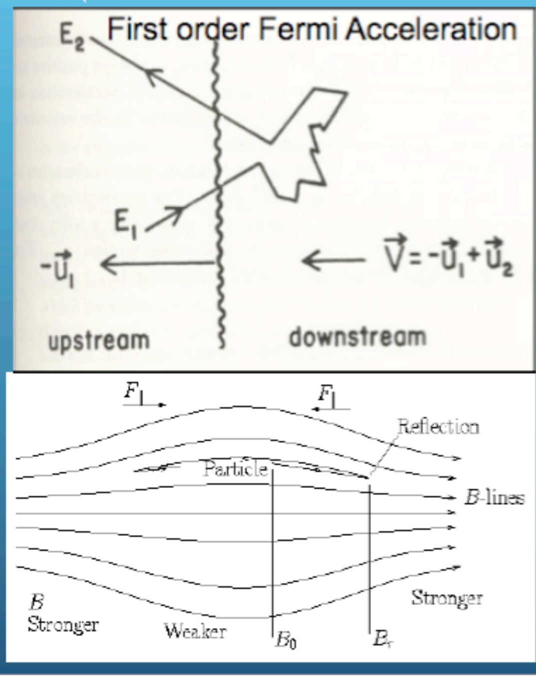
- energy gained by particle depends on the mirror velocity squared. - also produces a power law spectrum

- the average increase in energy is

only *second-order* in *V*/*c*. This result leads to an exponential increase in the energy of the particle since the same fractional increase occurs per collision. Longair 17.15

Diffusive Shock Acceleration (Fermi Mechanism)

Fermi 1949;
Spitkovsky 2008;



V_s V_e

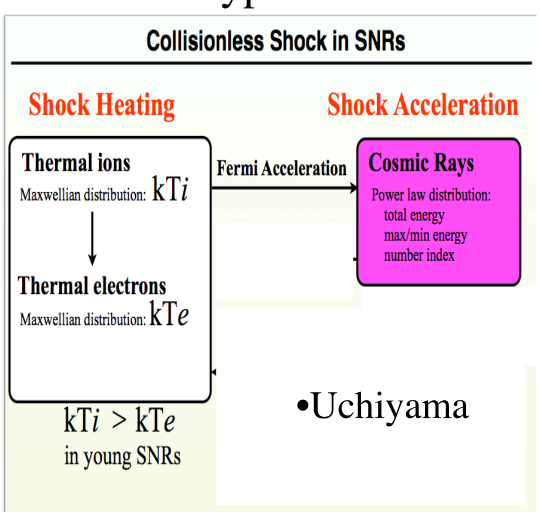
$V_s > 0$ gain energy

$V_s < 0$ lose energy

$\Delta\varepsilon \sim \beta$

Janfei Jang

Fermi Acceleration Hypothesis



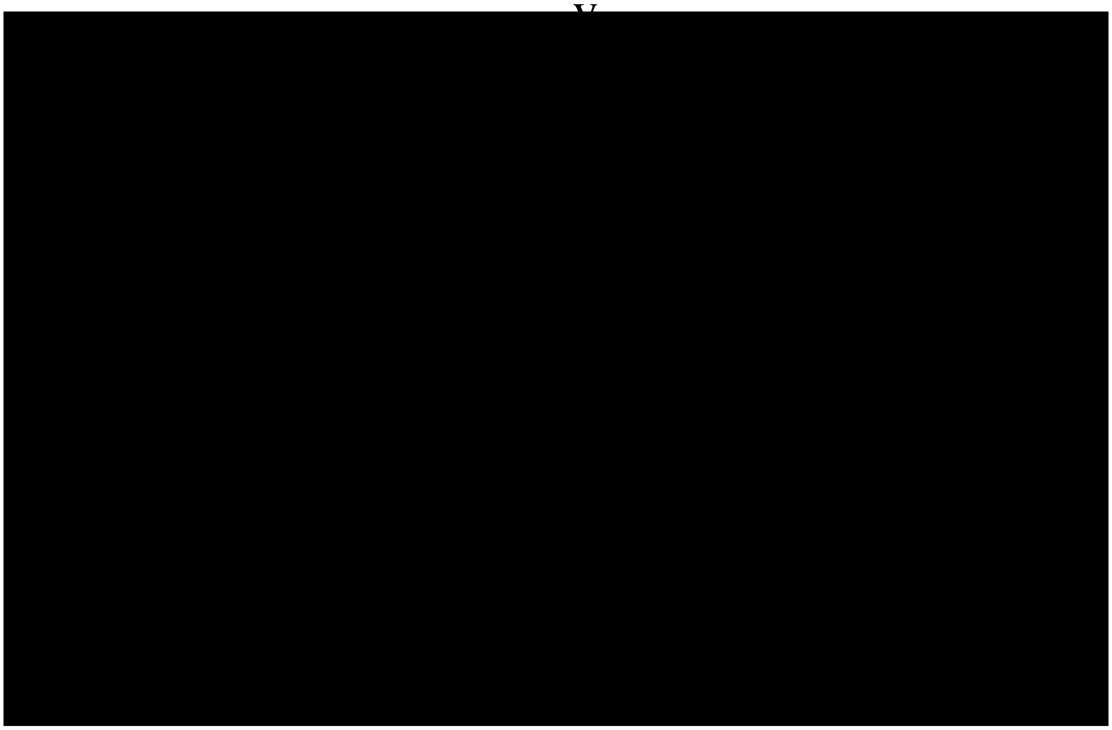
Shock waves have moving magnetic inhomogeneities – Consider a charged particle traveling through the shock wave (from upstream to downstream).

If it encounters a moving change in the magnetic field, it can reflect it back through the shock (downstream to upstream) at increased velocity.

- If a similar process occurs upstream, the particle will again gain energy. These multiple reflections greatly increase its energy. The resulting energy spectrum of many particles undergoing this process turns out to be a power law:

How Do we Know that Protons are Also Accelerated

- While synchrotron from electrons is visible in x-ray and radio and indicates short timescales most of the energy in CRs is in the protons
- Look for evidence of accelerated protons (gamma-rays)



How Does the Fermi γ-ray Signal 'Prove' CRs are Accelerated ?

γ-rays can originate in SNR in 3 separate ways

- Inverse Compton scattering of relativistic particles
- Non-thermal bremmstrahlung
- Decay of neutral pions into 2 γ-rays

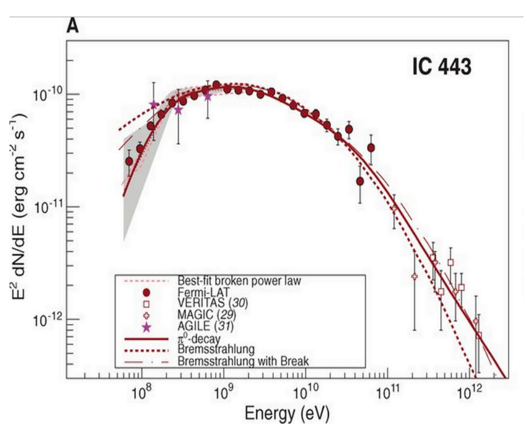
- the first 2 have broad band ~power law shapes
- pion decay has a characteristic energy E_γ=67.5 MeV- need to convolve with energy distribution of CR protons

The π_0 meson has a mass of 135.0 MeV/c^2 . The main π_0 decay mode is into two photons: $\pi 0 \rightarrow 2\ \gamma$.

How Does the Fermi γ-ray Signal 'Prove' CRs are Accelerated ?

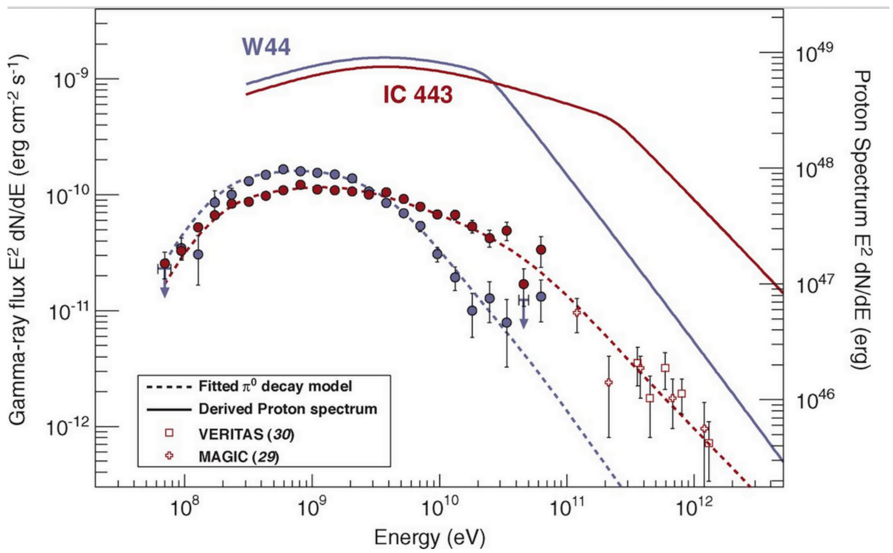
When cosmic-ray protons accelerated by SNRs penetrate into high-density clouds, π_0-decay γ-ray emission is expected to be produced

p+p → p+p+π_0 → 2p+2γ



Fit of Fermi γ-ray data to Pion model

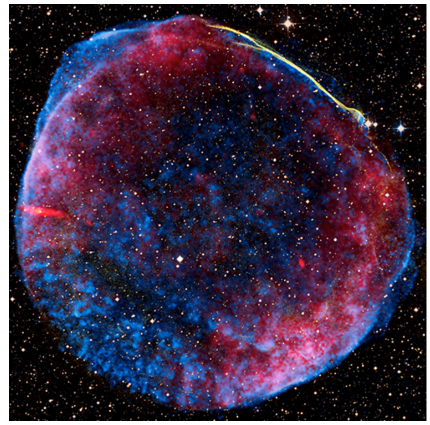
- One of the fitted parameters is the proton spectrum need to product the γ-ray spectrum via pion decay.
- Observed γ-rayspectrum is consistent with proton CR spectrum

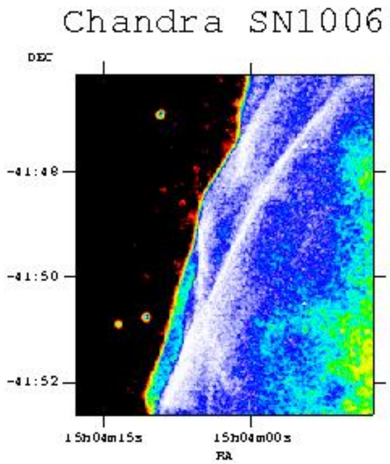


- Assume initially two protons are moving towards each other with equal and opposite velocities, thus there is no total momentum.
  - in this frame the least possible K.E. must be just enough to create the π_0 with all the final state particles (p,p,π_0) at rest.
  - Thus if the relativistic mass of the incoming protons in the center of mass frame is m, the total energy $E=2m_pc^2+m_{\pi 0}c^2$ and using total energy $=m_p/\text{sqrt}(1-v^2/c^2)$
- rest mass energy of proton is 931 meV gives v/c=0.36c ;
  - use relativistic velocity addition $[u=(v+u)/(1+(vu/c^2)]$ to get total velocity-
  - needed 280Mev of additional energy-- threshold for π_0 production

Sn1006

- The first SN where synchrotron radiation from a 'thermal' remnant was detected- direct evidence for very high energy particles via detection at TeV energies with HESS



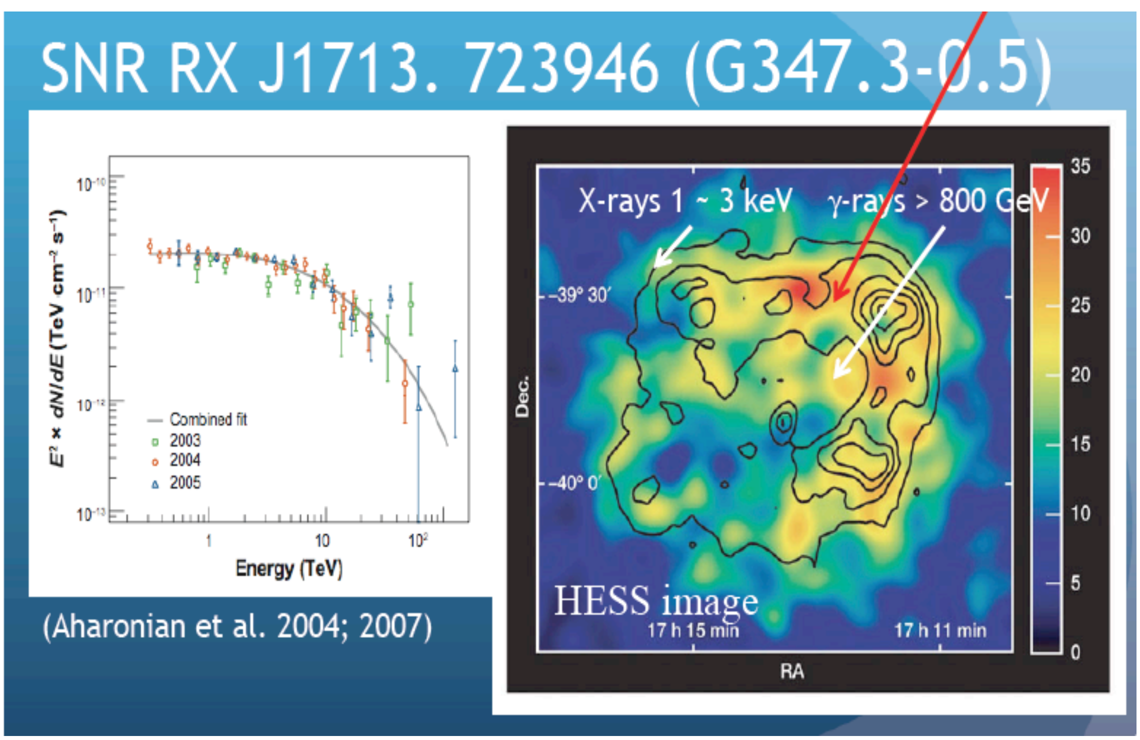


Enlarged SN filaments

direct evidence is the energy of the photons emitted (~TeV)+ the needed particle energies to produce synchrotron x-rays

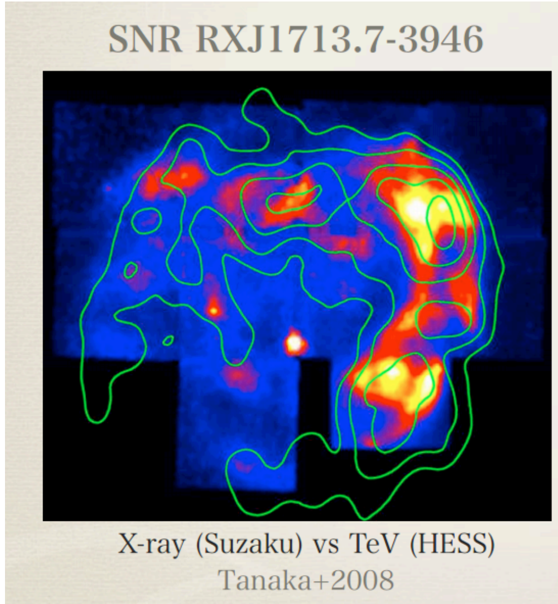
ν_{synch}~16keV(BE_{Tev}^2) Hz
loss time of the particles t_{synch}~400s B^{-2} E_{tev}^{-1}
for field of 100μG one gets
E~100Tev, **t_{synch}~15 years--** so need continual reacceleration

Evidence for Particle Acceleration- Tev Emission + X-ray Synch



Relation of γ-rays to X-rays in a Young SNR

- X-rays are synchrotron emission from relativistic particles
- γ-rays are inverse Compton
- Allows calculation of magnetic field B~10μG
- Short lifetimes argues for fast acceleration



•Uchiyama

Type I SN and Cosmology

- One of the main problems in astrophysics is understanding the origin and evolution of the universe: how old is the universe, how fast is it expanding, how much material and of what type is in it, what is its fate?

- A major step in this is to determine the relationship between distance and redshift

- Studies of distant supernova allow this measurement

See Supernova Cosmology:Legacy and Future Annu. Rev. Nucl. Part. Sci. 2011. 61:251–79

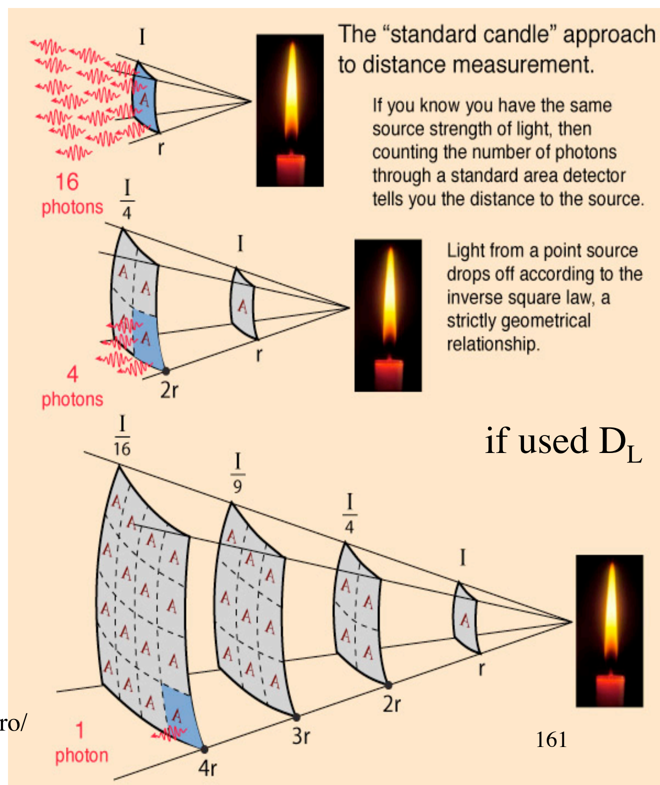
More Cosmology

- These distances depends on cosmological parameters* in a different way
  - * in classical cosmology -the Hubble constant (H_0)
  - The density of the universe in baryons Ω_B and total matter Ω_M
  - ‘cosmological constant’ Λ

Why a Standard Candle??

Need either a standard candle or a standard yardstick bright enough or large enough
to convert measurements of brightness or size into distances

$$L = 4\pi D^2 F \qquad F = \frac{L}{4\pi D^2}$$



http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/stdcand.html

Use SN Ia as 'standardizable candles'

- What we want to know is the absolute distance to the source (luminosity distance, d_L)

$$m(z)=M+5 \log d_L(z,H_{0,} \Omega_m,\Omega_\Lambda)+25$$

Einstein GR gives the following formula

$$d_L(z,H_{0,} \Omega_m,\Omega_\Lambda)=\{c(1+z)/H_0 \, \mathrm{sqrt}(k)\}x$$
$$\sin\{\mathrm{sqrt}(k)\int[(1+z')^2(1+\Omega_m z')-z'(2+z')\Omega_\Lambda]^{-1/2} dz'\}$$

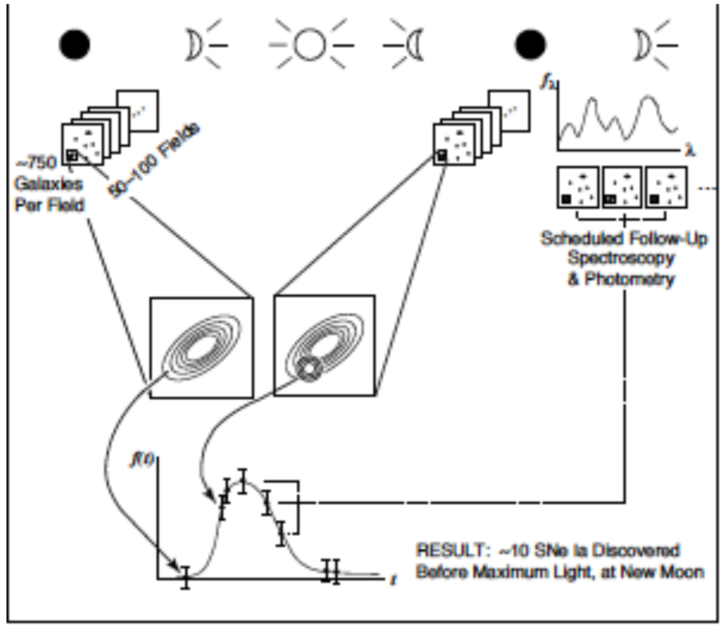
$k=1-\Omega_m-\Omega_\Lambda;$

the luminosity distance depends on z, Ω_m, Ω_Λ and H_0 and in principle seeing how it changes with redshift allows one to constrain these parameters

More Cosmology

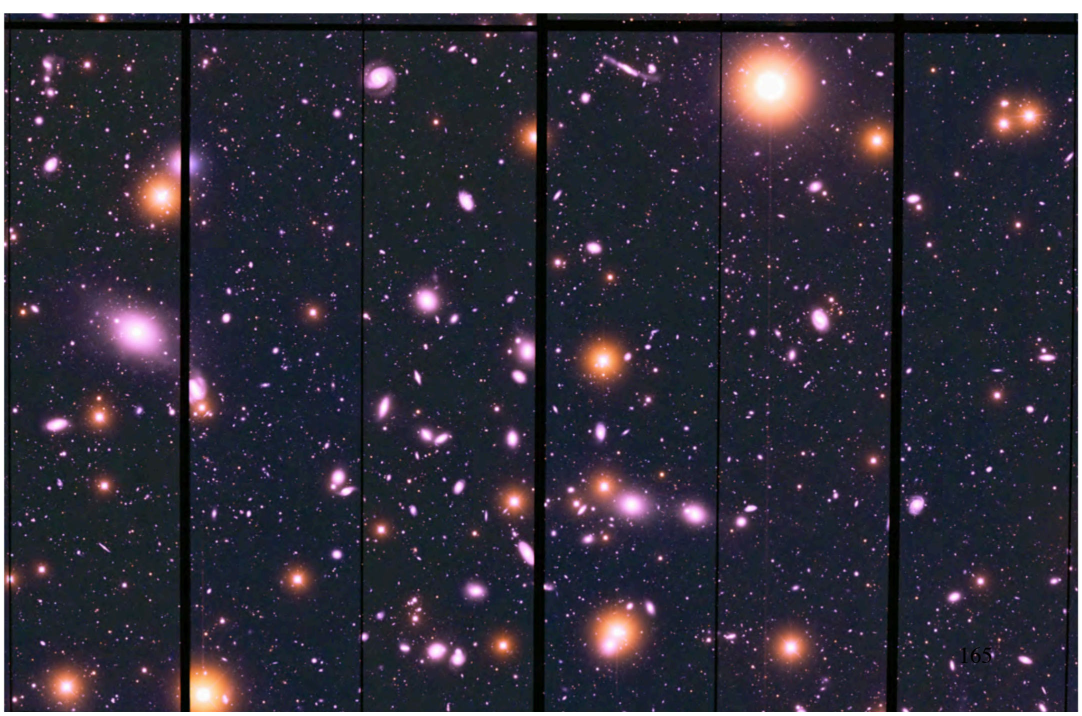
- Back to type Ia SN-
  - It turns out (when I say that it means a huge amount of work by many people over many years) that type Ia SN are 'standardizable candles' - one can use their brightness, color and speed of decay to determine an 'absolute' luminosity to ~10% accuracy.
  - With a measured redshift and absolute luminosity one can get the luminosity distance using values of $H_0,\Omega_M,\Omega_\Lambda$ and vary then to get the data to fit

- Supernova on demand-
  - we know the average SNIa rate per galaxy/yr (1/100 yrs for a L(*) galaxy)
  - To obtain ~10 SN Ia per 1 week of observing have to observe ~50,000 galaxies about ~2 weeks apart and see what has changed



Perlmuter et al 1997

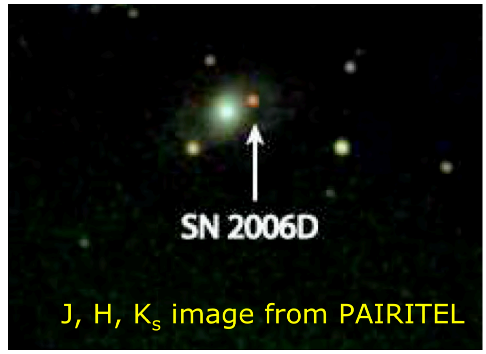
1/100 years ~ 1/5000 weeks => 5000 galaxies



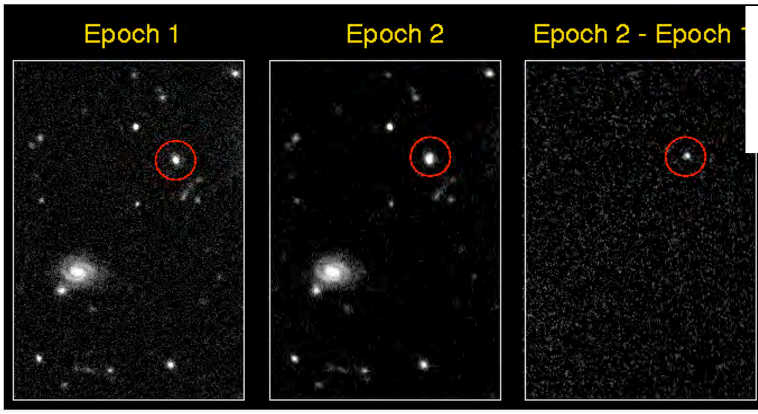
Finding the SN

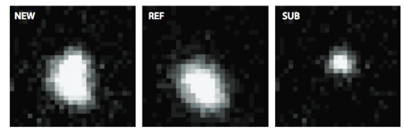
z= 0.00853, in a catalogued galaxy "obvious"

Not so obvious ones subtract out the constant galaxy



Searching by Subtraction

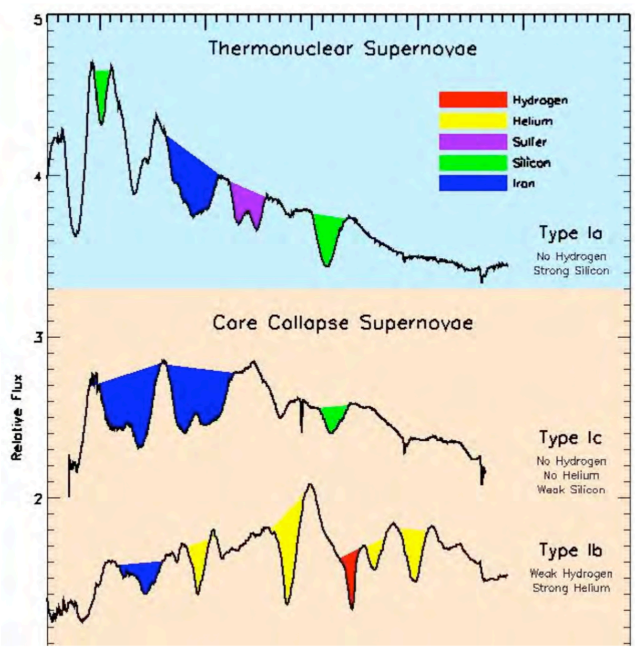




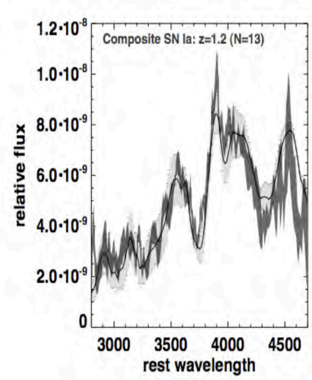
Need to Figure Out Which Are SNIa

- Take spectra to figure out which are the Ia's (light curves too)

: Dan Kasen

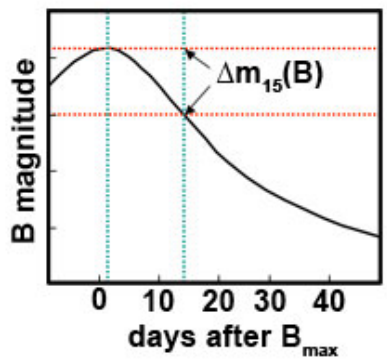


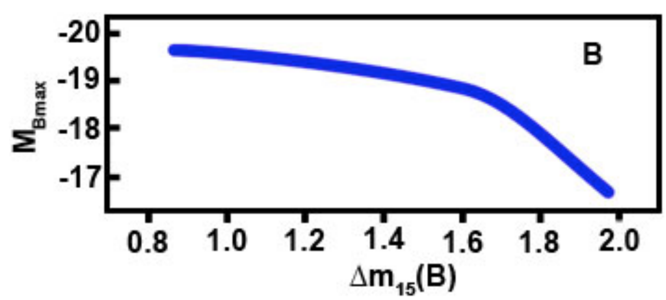
No difference between nearby and distant supernovae



Several Correlations Allow A Standard Candle to be Created

- Phillips et al 1993 notce that the change in brightness of the SN Ia light curve at a fixed timescale was related to the absolute brightness of the SN

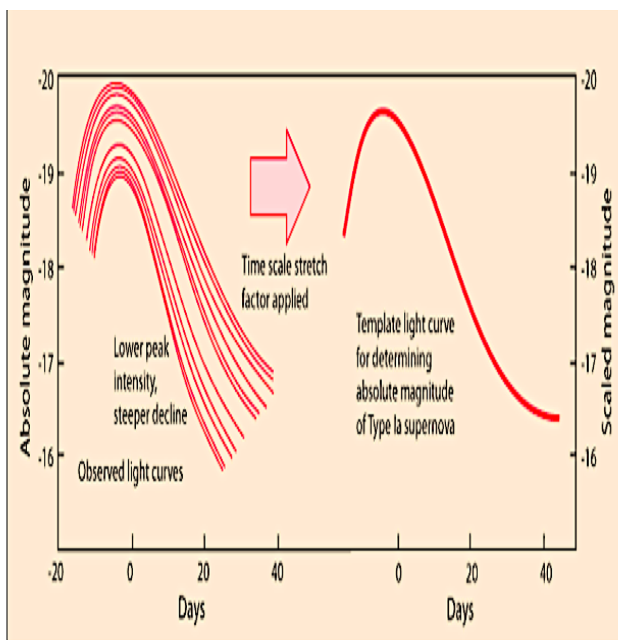




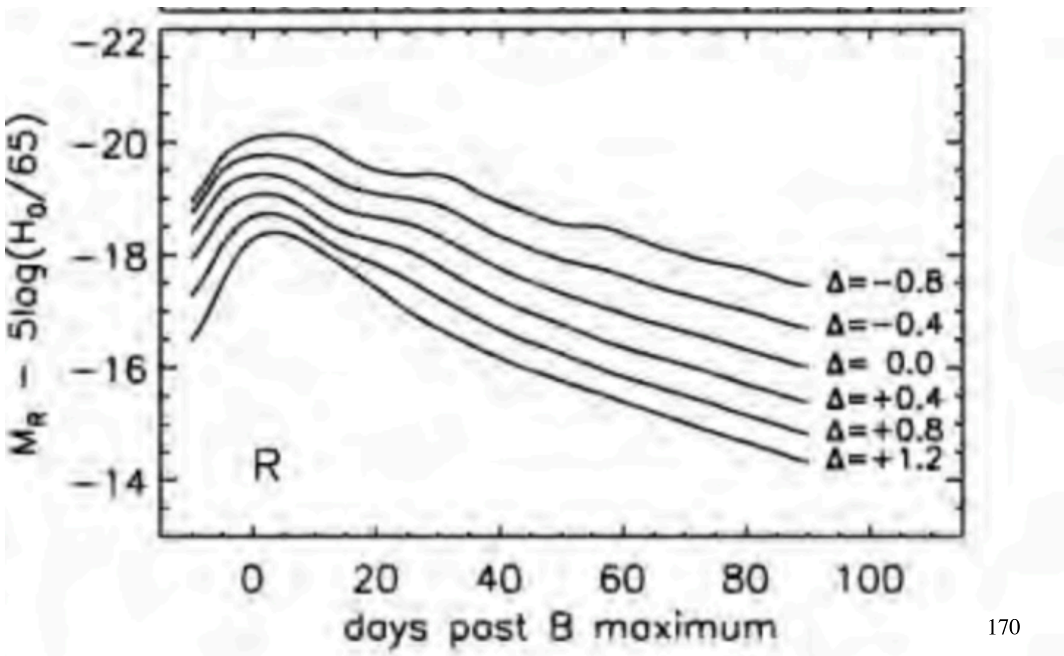
$$M_{B,max} = -19.3+5 (\log H_{60})$$
$$M_{B,max} = -21.726 + 2.698 \Delta m_{B,15}$$

Interesting point- the stretch has to be converted to proper time

Perlmutter 2003



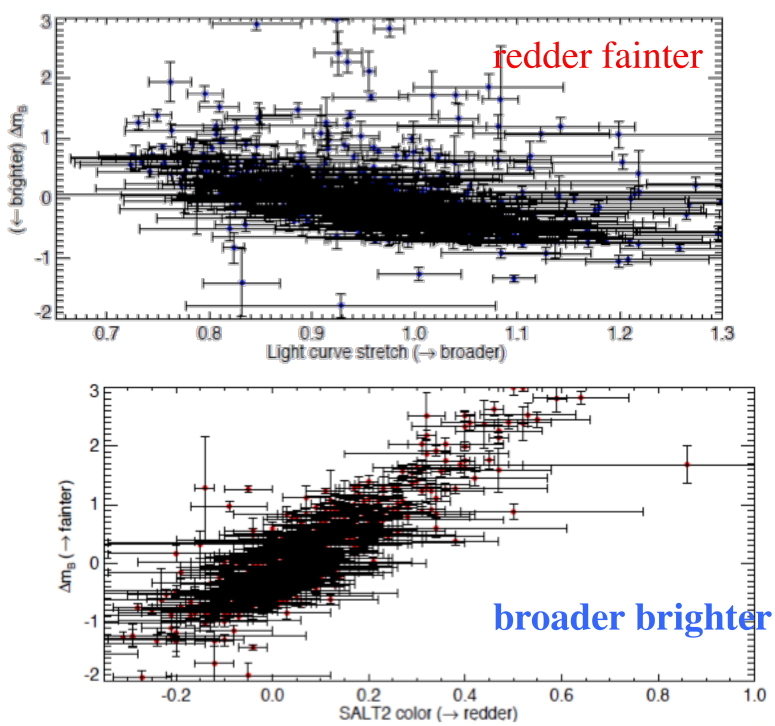
Brighter SN have slower declines

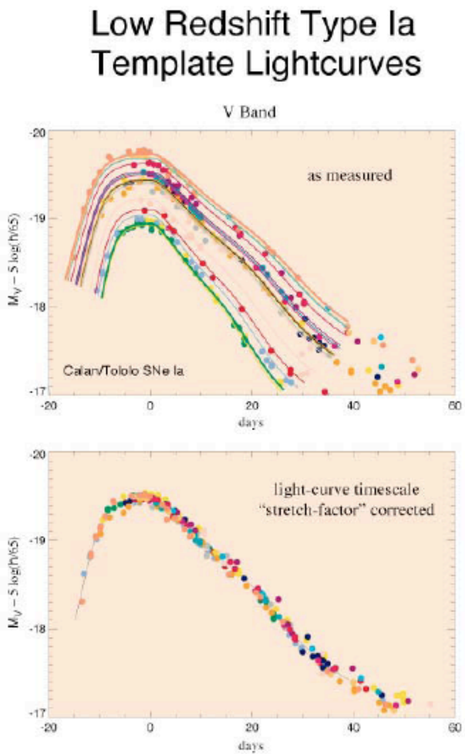


Standardizing Them

Riess,Press and Kirshner 1995)

- There are a variety of SNIa light curves and brightness-
- However - luminosity correlates strongly with light curve shape and color





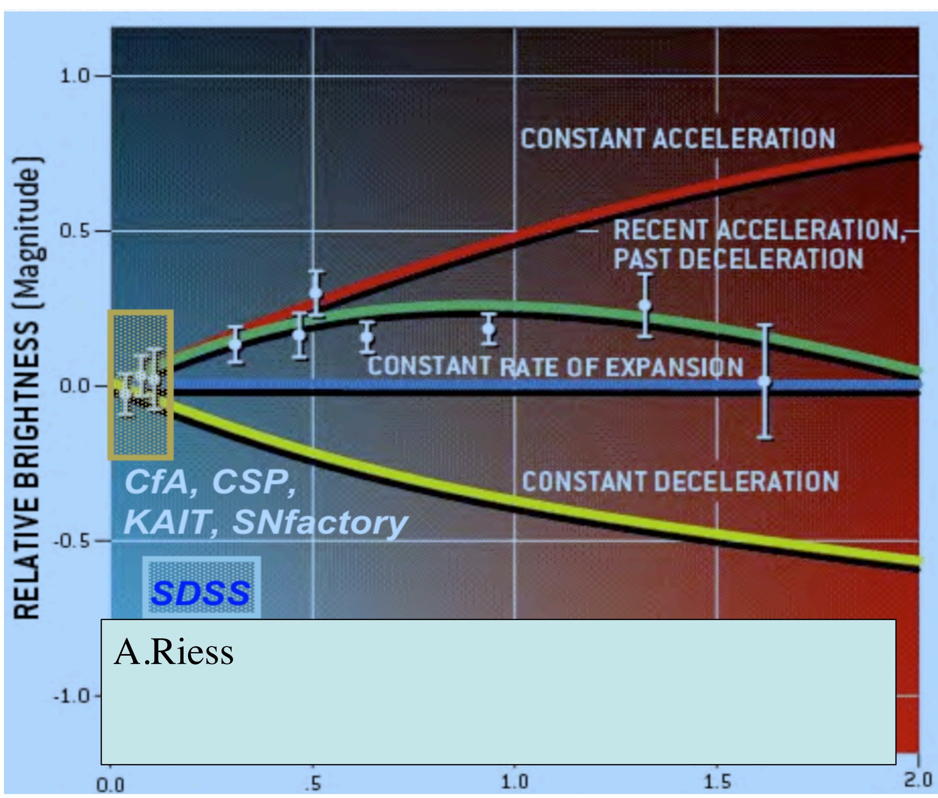
The Phillips Relation
(post 1993)

Broader = Brighter

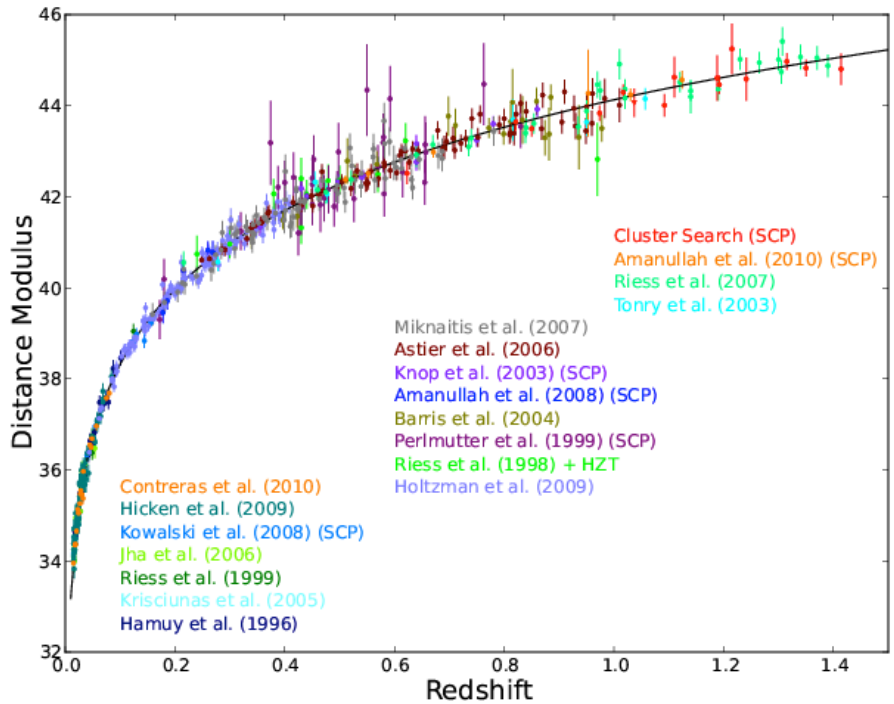
Can be used to compensate for the variation in observed SN Ia light curves to give a "calibrated standard candle".

Note that this makes the supernova luminosity at peak a function of a single parameter – e.g., the width.

Woosely 2010

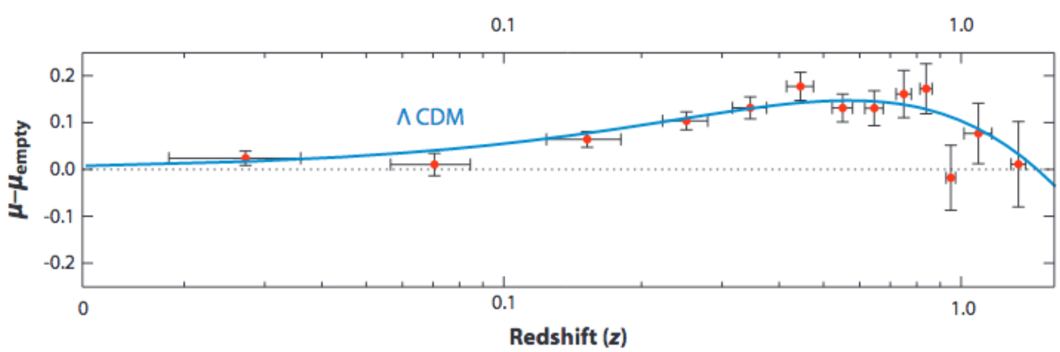


Z (redshift)



log H_0 can be read off from the intercept of the logcz−0.2m_B plot if one knows how to standardize the candle (explain to class)

What is found

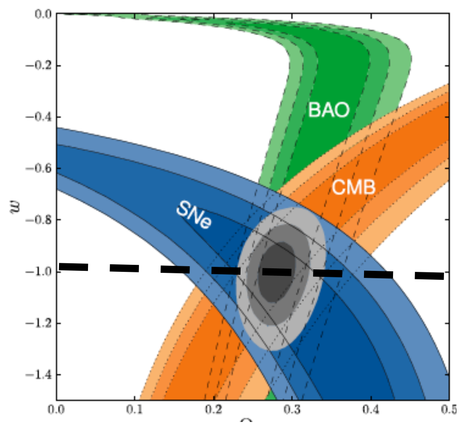


Blue line is fit of ΛCDM model with Ω_M=0.3, Ω_Λ=0.7

Goobar & Leibundgut

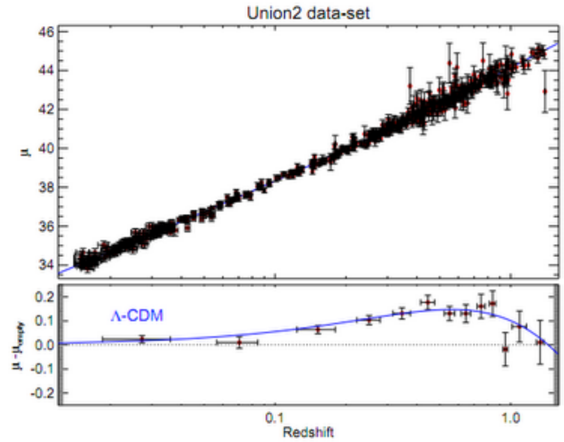
It Works Pretty Well

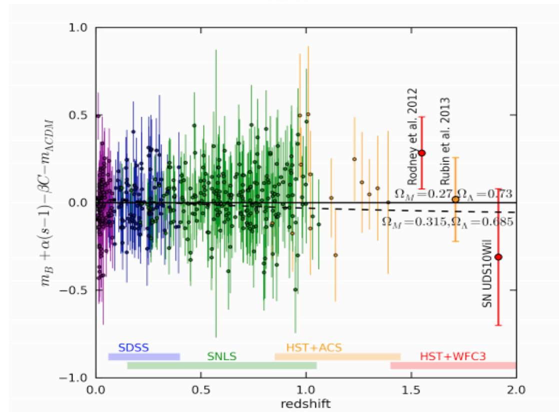
- The formal errors in the cosmological parameters for this method only are a good fit to Λ-CDM (cold dark matter)



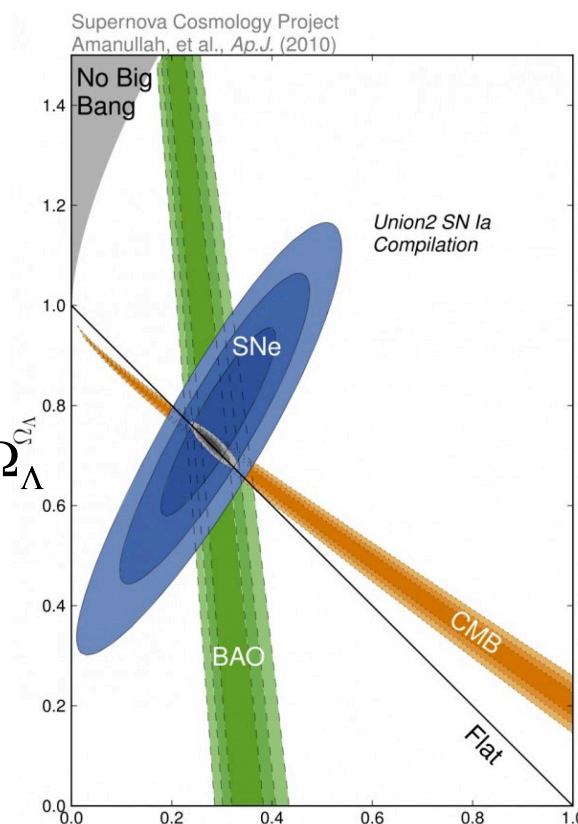
Ω_m

w=-1 ; a cosmological constant





Constraints on cosmological parameters from CMB and SN Ia – Nobel Prize



Ω_Λ

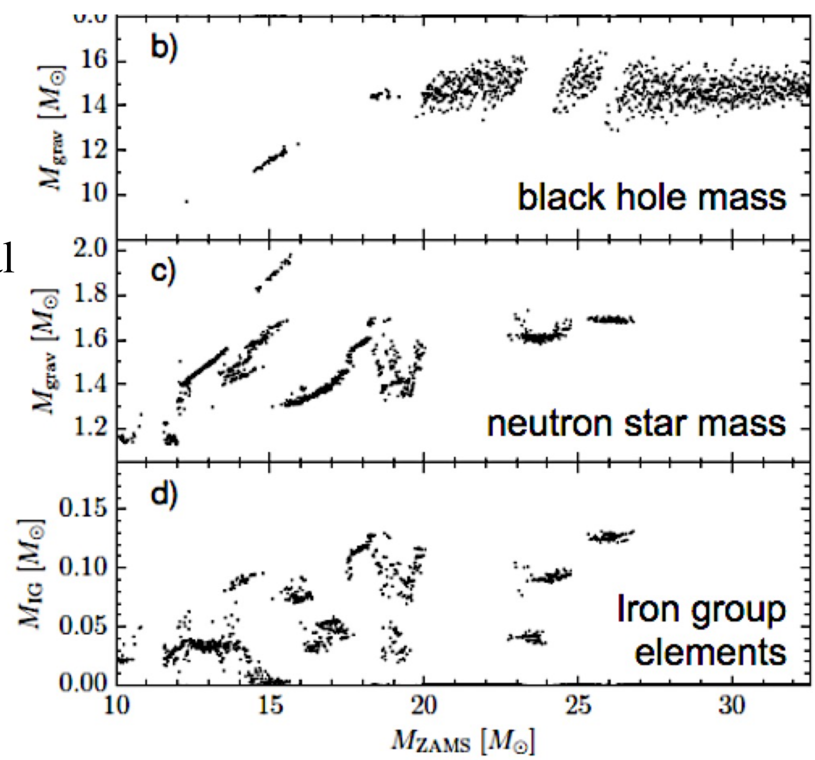
Ω_M

Formation of Black Holes and NS in SN Explosions

- The formation of NS/BHs occurs at the end of the nuclear burning phase in massive stars and can proceed via two routes.
  - For the lower mass end of BH formation, a meta-stable proto-neutron star (NS) is produced, followed by the formation of a BH through accretion of the part of the stellar envelope that was not expelled in the supernova explosion.
- Direct collapse (sometimes called failed supernova) into a BH occurs in the case of the most massive stars.
- NS are 'natural' products of massive star collapse

The mass of the remnant is determined by the mass of the star at the moment of collapse, and the explosion energy

when a NS or a BH forms is not so simple (Mueller et al 2017, Pejcha et al 2012))



now onto Neutron stars and black holes

A rich field with many many many parts...

- Remember Project
- Due the week before finals Dec 3
- Please send me your tentative titles