First things....then

Summary of Last Lecture Next 5 Slides

See **Supernova remnants: the X-ray perspective for an excellent review article**
JaccoVink, 2012 A&ARv..20...49

The rest of the lecture
Part I Supernova remnants, particle acceleration and cosmic rays
- shock acceleration
- how do we know that SNR actually accelerate cosmic rays

Part II Use of Supernova for cosmology
Part III Discussion of how to conduct the rest of the class

First Phase of SNR- Free Expansion

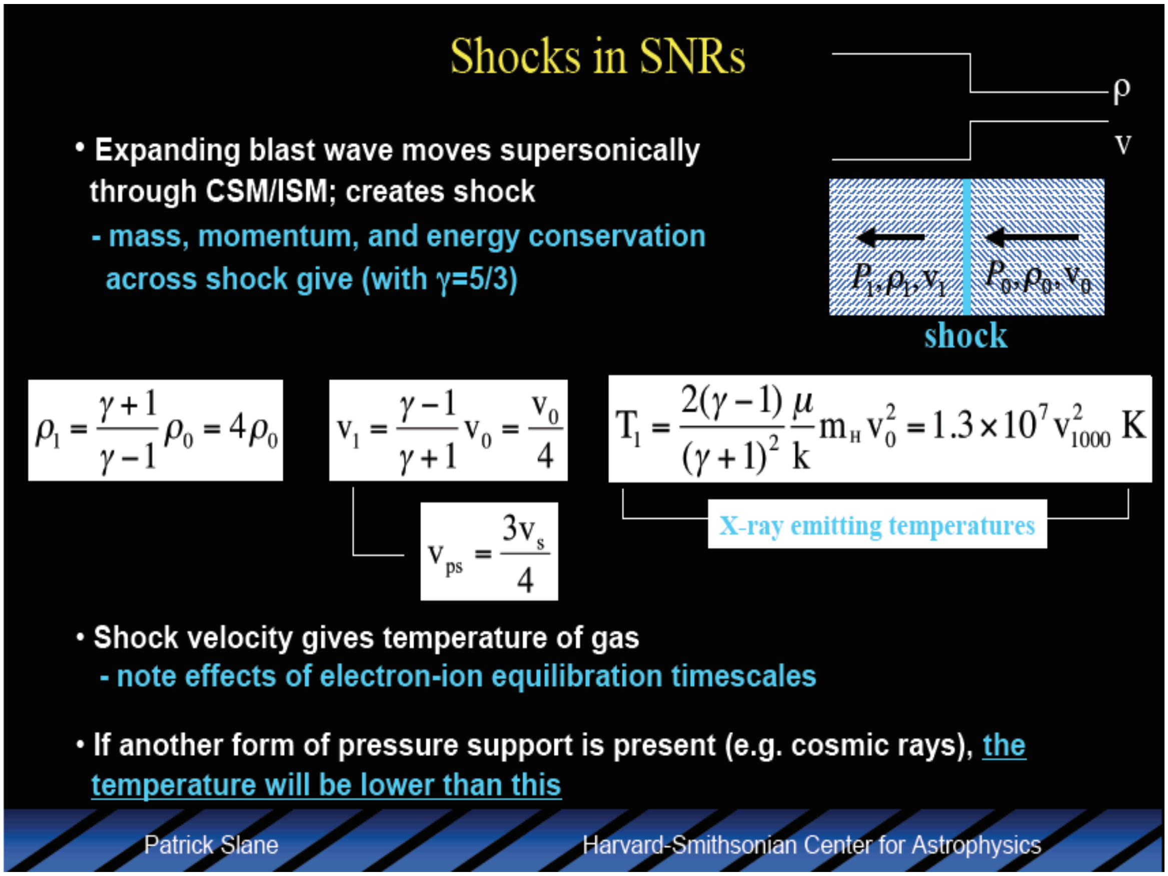
Useful units

$$r = \left(\frac{3}{4\,\pi}\,\frac{M_{ej}}{n_{ism}\,\mu\,m_H}\right)^{\frac{1}{3}} = 1.9\,pc\,\left(\frac{M_{ej}(M_\odot)}{n_{ism}}\right)^{\frac{1}{3}}$$

$$t = 200\,yrs\,\left(\frac{M_{ej}(M_\odot)}{n_{ism}}\right)^{\frac{1}{3}}\frac{1}{v_s(10{,}000\,km\,s^{-1})}$$

M_{ej}= mass of ejecta in solar masses
v_{shock} in units of 10,000km/sec
n_{ism}= number density of gas

K. Long



Shocks in SNRs

- Expanding blast wave moves supersonically through CSM/ISM; creates shock
  - mass, momentum, and energy conservation across shock give (with γ=5/3)

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 = 4\rho_0$$

$$v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4}$$

$$v_{ps} = \frac{3v_s}{4}$$

$$T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{\mu}{k}m_H v_0^2 = 1.3\times10^7 v_{1000}^2 \text{ K}$$

X-ray emitting temperatures

- Shock velocity gives temperature of gas
  - note effects of electron-ion equilibration timescales
- If another form of pressure support is present (e.g. cosmic rays), the temperature will be lower than this

Patrick Slane

Harvard-Smithsonian Center for Astrophysics

- Kinetic energy of expansion (KE) is transferred into internal energy - total energy remains roughly the same (e.g. radiative losses are small)
- The temperature of the gas is related to the internal energy

$$\boxed{T\sim10^{6}\text{k } E_{51}^{1/2} n^{-2/5}(t/2\text{x}10^4\text{yr})^{-6/5}}$$

for typical explosion energies and life times the gas emits in the x-ray band

- measuring the size (r), velocity (v) and temperature T allows an estimate of the age

$$\boxed{\tau_{Sedov} \sim 3\text{x}10^4 T_6^{-5/6} E_{51}^{1/3} n^{-1/3}\text{yr}}$$

- at T ~10^6-10^7 k the x-ray spectrum is line dominated
- $R\sim(E/\rho)^{2/5}t^{2/5}$
- $v\sim(2/5)(E/\rho)^{1/5}t^{-3/5}$

Sedov-Taylor Solution

- nice discussion in Draine sec 39.1.2
- assume a spherical shock of radius R and it has a a power law dependence on energy of the explosion, E, time since explosion,t, and density of the medium into which it is running ρ.
- $R=AE^{\alpha}\rho^{\beta}t^{\eta}$
- with dimensional analysis (e.g. the powers to which mass length and time appear to get
- mass $\alpha+\beta=0$, length $1-2\alpha-3\beta=0$, $-2\alpha+\eta=0$ time

one solves this to get $\alpha=1/5$, $\beta=-1/5$, $\eta=2/5$

or $R=AE^{1/5}\rho^{-1/5}\, t^{2/5}$

putting in the physics and numbers

$R=1.54\text{x}10^{19}\text{cm}\ E_{51}^{1/5}n^{-1/5}\, t_3^{2/5}$

(we have switched units, n is particle density, t_3 is in units of 10^3 years, E_{51} is in units of 10^{51} ergs.

$v_s=1950\text{km/s}\ E_{51}^{1/5}n^{-1/5}\, t_3^{-3/5}$

$T=5.25\text{x}10^7\text{k}\ E_5^{2/5}n^{-2/5}\, t_3^{-6/5}$

Sedov-Taylor Solution

- In more useful units (K. Long)

Radius of shock front: $R_{shock}\sim5(E_{51}/n)^{1/5}(t_{kyr})^{2/5}$ pc

Velocity of shock front: $v_{shock}\sim2000\ (E_{51}/n)^{1/5}(t_{kyr})^{-3/5}$ km/sec

Temperature of gas: $T_{shock}\sim4.9\ (E_{51}/n)^{2/5}(t_{kyr})^{-6/5}$ keV

- Free Expansion Phase

the ejecta expands freely into the interstellar medium. The expanding envelope compresses the ISM, creates a shock wave because of its high velocity, and sweeps up the ISM. During this initial phase, the mass of gas swept up is <<mass of the ejecta and the expansion of the envelope is not affected by the outer interstellar gas andit keeps its initial speed and energy.

- Adiabatic Expansion Phase

When mass of gas swept up > mass of ejecta the kinetic energy of the original exploded envelope is transferred to the swept up gas, and the swept up gas is heated up by the shock wave roughly independent of the physics of the explosion. The radiative losses from the swept up gas are low (energy is conserved) - adiabatic expansion phase.

The evolution during this phase is determined only by the energy of explosion E_0, the density of interstellar gas, and the elapsed time from the explosion t. A self similar solution relating the density, pressure, and temperature of the gas, and the distribution of the expansion velocity exists (Sedov-Taylor)

Next 2 Phases

- Constant Temperature Expanding Phase

The expansion velocity decreases with time and, radiative cooling behind the shock front becomes important. When the radiative cooling time of the gas becomes shorter than the expansion time, the evolution deviates from the self similar one. In this phase, the SNR evolves, conserving momentum at a more or less constant temperature and the radius of the shell expands in proportion to the 1/4 power ($r \sim t^{1/4}$)of the elapsed time since the explosion.

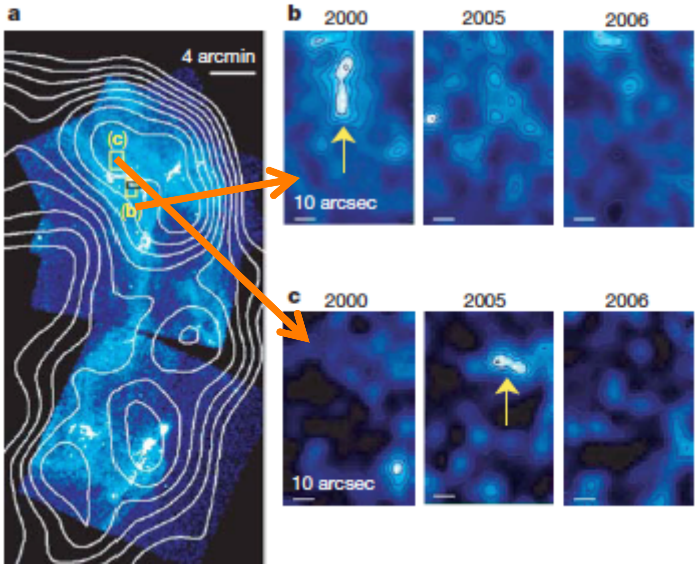
In useful units

$$r_{rad} = 25\ pc\ \left(\frac{E_{51}}{n_h}\right)^{\frac{1}{5}}$$

$$t_{rad} = 47\ kyr\ \left(\frac{E_{51}}{n_h}\right)^{\frac{1}{3}}$$

SNR are Thought to Be the Source of Galactic cosmic rays See Longair sec 17.3

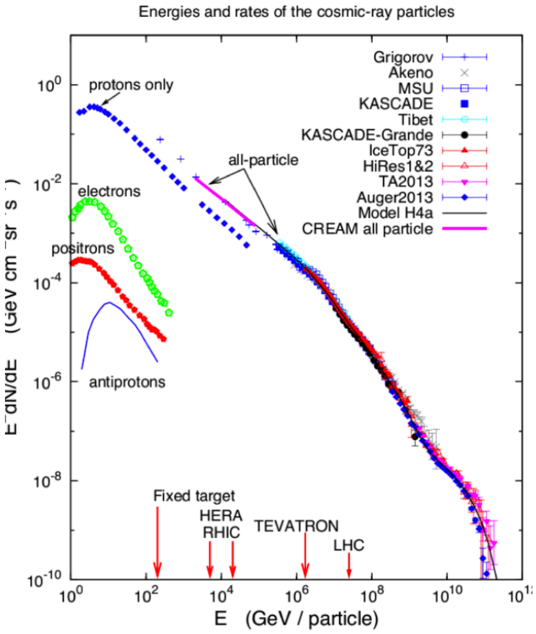
- SNR need to put ~ 5-20% of their energy into cosmic rays in order to explain the cosmic-ray energy density in the Galaxy (~2 eV/cm^3 or 3x10^{38} erg/s/kpc^2) , the supernova rate (1-2/100yrs), the energy density in SN (1.5x10^{41} ergs/sec~2x10^{39} erg/s/kpc^2)



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

SNR are Thought to Be the Source of Galactic cosmic rays See Longair sec 17.3

- 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
- see **The Origin of Galactic Cosmic Rays** Pasquale Blasi **arXiv: 1311.7346**for a recent review



(Tom Gaisser).

Cosmic Rays- Some Numbers

- Cosmic rays have a mean interstellar energy density of U~ 10^{-12} ergs cm^{-3}
- They "fill" the Galactic volume, V, and have a mean Galactic residence time, τ~90x10^{6} (H/3kpc)yrs, and require (e.g. Lingenfelter 2013) a power Q ~ UV/τ, ~10^{41} ergs s^{-1} of continuous energy injection (H is height of halo)
- Galactic cosmic rays can be produced by supernova shocks, if they have gained~ 10% of the shock energy, consistent with theoretical expectations.
- Cosmic rays are enriched in heavy elements by factors of ~20 to 200 times wrt solar system values, consistent with a composition mix of swept-up ISM and the ejecta of the CCSNe (SN II & Ib/c) and with little or no contribution from type Ias.
  - Elemental ratios suggest that acceleration occurs in the early periods of the supernova remnant expansion, ending well before the end of the Sedov phase (Prantzos 2012).

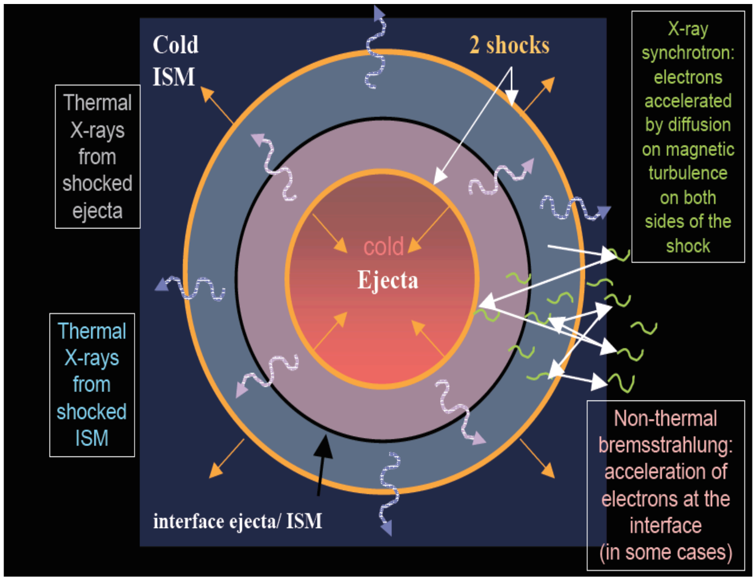
Lingenfelter 2019

The Nine Lives of Cosmic Rays in Galaxies Isabelle A. Grenier,John H. Black,and Andrew W. Strong ARAA 2015

SN Movie Cosmic Ray Origin

See Melia sec 4.3 Longair 17.3

- 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 v_{shock}/c
- particle spectrum is a power law



DeCourchelle 2007

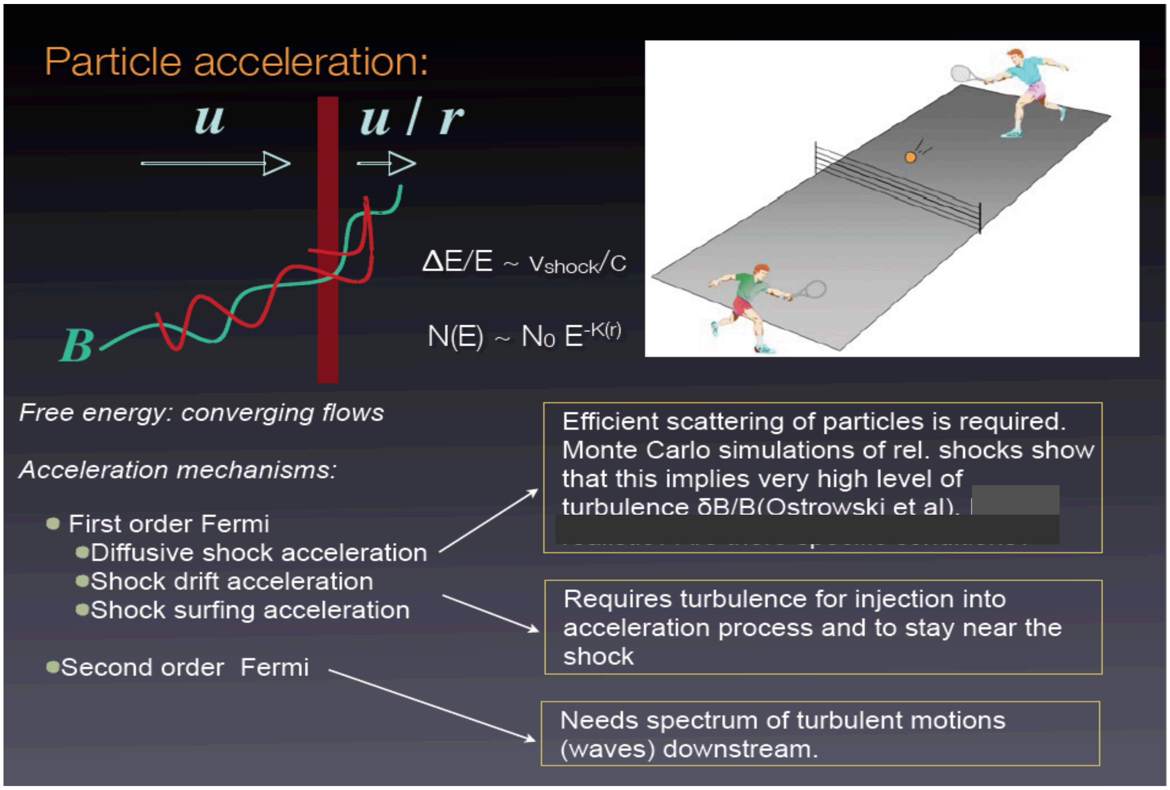
Nice analogy- ping pong ball bouncing between descending paddle and table

Fermi Acceleration- Longair 17.3

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** - produces a power law spectrum
- The derivation in Longair is clear and includes an update in sec 17.4

Spitovsky 2008



Particle acceleration:

$\Delta E/E \sim v_{shock}/c$

$N(E) \sim N_0 E^{-K(r)}$

Free energy: converging flows

Acceleration mechanisms:

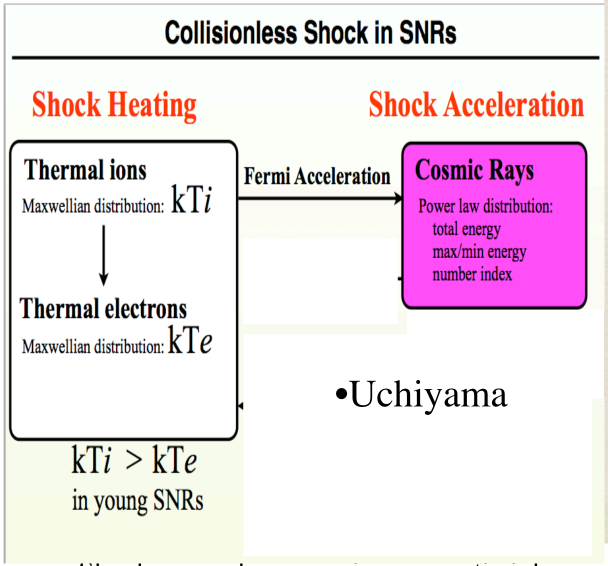
- First order Fermi
  - Diffusive shock acceleration
  - Shock drift acceleration
  - Shock surfing acceleration
- Second order Fermi

Efficient scattering of particles is required. Monte Carlo simulations of rel. shocks show that this implies very high level of turbulence δB/B(Ostrowski et al). [redacted]

Requires turbulence for injection into acceleration process and to stay near the shock

Needs spectrum of turbulent motions (waves) downstream.

Test of Fermi Acceleration Hypothesis



Collisionless Shock in SNRs

Shock Heating

Shock Acceleration

Thermal ions
Maxwellian distribution: kT*i*

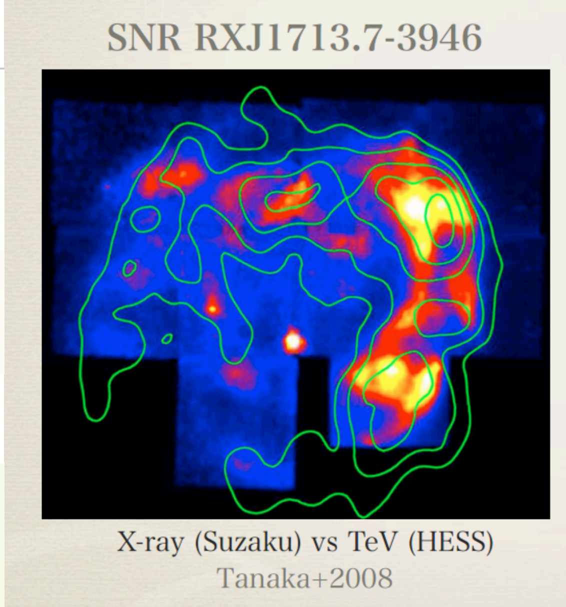
Thermal electrons
Maxwellian distribution: kT*e*

Fermi Acceleration

Cosmic Rays
Power law distribution:
total energy
max/min energy
number index

kT*i* > kT*e*
in young SNRs

•Uchiyama



SNR RXJ1713.7-3946

X-ray (Suzaku) vs TeV (HESS)
Tanaka+2008

- 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:

Fermi Mechanism

$<\Delta E/E> = 8/3\ (V/c)^2$. 17.15- see the detailed derivation in Longair

- the average increase in energy is second-order in V/c.
- leads to an exponential increase in the energy of the particle since the same fractional increase occurs per collision
- average rate of energy increase $dE/dt = 4/3(V^2/cL)E = \alpha E$.
- Following the derivation in Longair this leads to a spectrum of the form
  - $N(E) = \text{constant} * E^{-x}$, (eq 17.20) where $x = 1 + (\alpha\tau_{esc})^{-1}$; a power-law energy spectrum for the particles
- the scattering mechanism is interaction with plasma waves and the particles gain energy by being scattered stochastically by them.

But...Longair 17.4, Vink sec 5.5

- The acceleration mechanism which has dominated much astrophysical thinking since the late 1970s is associated with particle acceleration in strong shock waves, often referred to as diffusive shock acceleration.
- first-order Fermi acceleration (eg energy gain is on the order of v/c) in the presence of strong shock waves
- $\Delta E/E \approx (4/3)(v_1 - v_2)/c = 4/3(\chi-1)/\chi)V_s/c$
  - V_1 and V_2 the velocities upstream and downstream and $V_1 = \chi V_2$
  - The chance that a particle will be scattered up and down at least k-times is $P(n \geq k) = (1 - Pesc)^k$
  - Assuming a shock compression ratio of χ
- Produces a particle spectrum of $n(E)dE \propto E^{-q}dE, q = (\chi+2)/(\chi-1)$.

But...Longair 17.4, Vink sec 5.5

a compression ratio of 4 corresponds to a particle index of q=2 this result is independent of the diffusion properties (slow or fast) as long as the diffusion is isotropic. This slope is close to what is needed to explain the cosmic-ray spectrum observed on Earth.

an upper limit to the energy to which particles can be accelerated by this mechanism since The particles have to diffuse back and forth across the shock wave many times and, in the case of the shells of supernova remnants, their energies increase by about one part in 100 at each crossing

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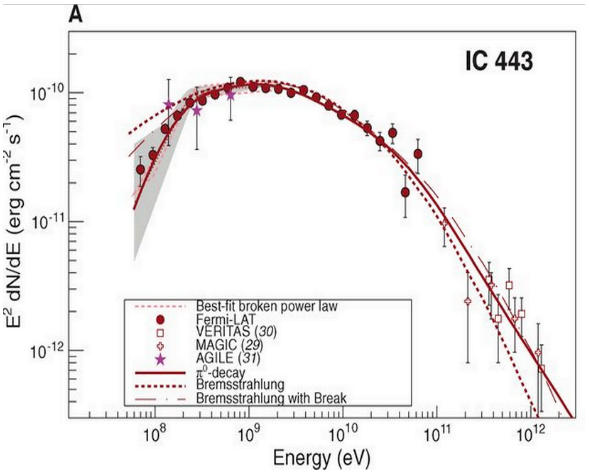
How Does the Fermi γ-ray Signal 'Prove' CRs are Accelerated ?

<u>High energy (GeV)</u> γ-rays can originate in SNR in 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(1/2 of π^0 mass)- need to convolve with energy distribution of CR protons

When cosmic-ray protons accelerated by SNRs penetrate into high-density clouds, π_0-decay γ-ray emission is expected to be enhanced because of more frequent pp interactions (p+p $\Rightarrow$ $p+p+\pi_0$ $\Rightarrow$ $2p+2\gamma$



How Gamma-Rays Trace Cosmic Ray Interaction with ISM

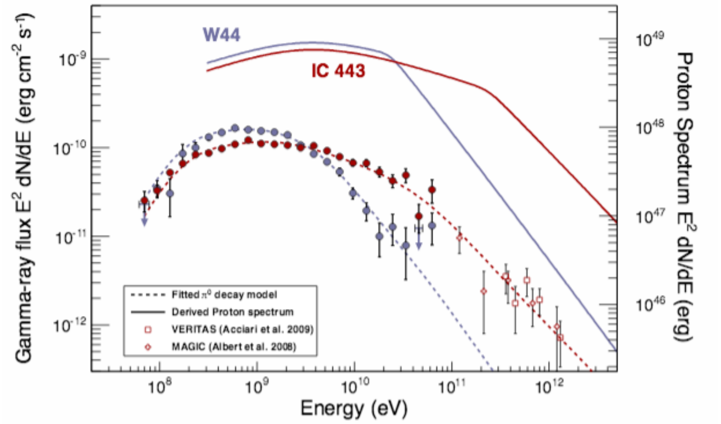
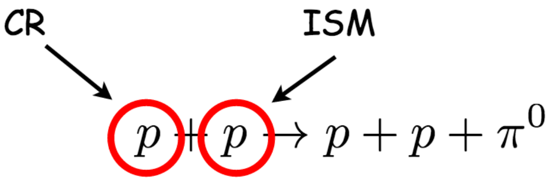


Figure 5. Proton and gamma-ray spectra determin

IC 443 and W44

Supernova remnant W44: a case of cosmic-ray reacceleration A&A595,A58

- The gamma ray emission traces the gas distribution (times the CR distribution)
- Fermi detection of π_0 decay in 2 SNR- **proof** that some CRs are produced in SNR (incoming proton has to have enough energy to create a π_0



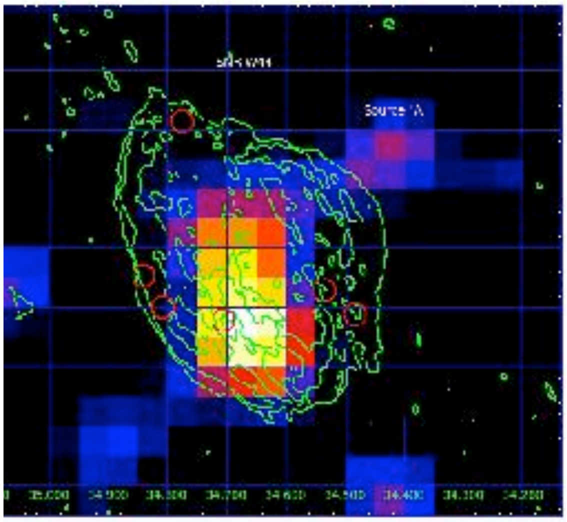
$$p + p \to p + p + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

- consider two protons are moving towards each other with equal and opposite velocities, (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.
- if the relativistic mass of the incoming protons in the center of mass frame is m, the total energy $E=2m_pc^2+m_{\pi0}c^2$ and using total energy $=m_p/\mathrm{sqrt}(1-v^2/c^2)$
- energy of proton is 931 meV gives v/c=0.36c ; use relativistic velocity addition to get total velocity or a needed 280Mev of additional energy-- threshold for π_0 production

W44

- γ-ray image superimposed on 324 MHz radio continuum
- the average gas density of the regions emitting 100 MeV–10 GeV gamma-rays is high ($n \sim 250–300\ \mathrm{cm}^{-3}$)



Reynolds Gaensler Bocchino 2011

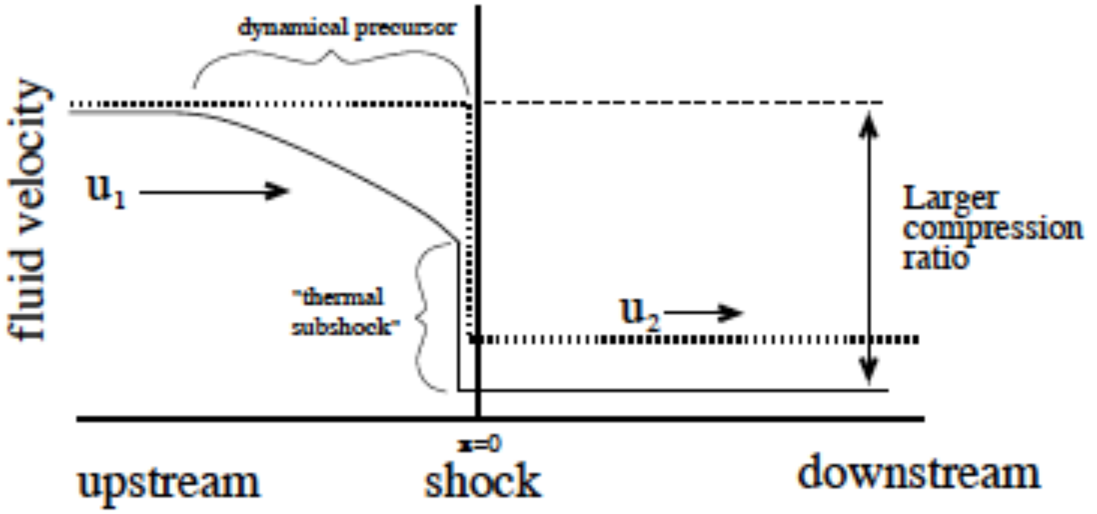
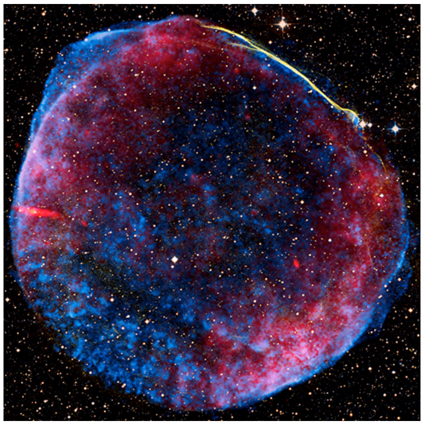
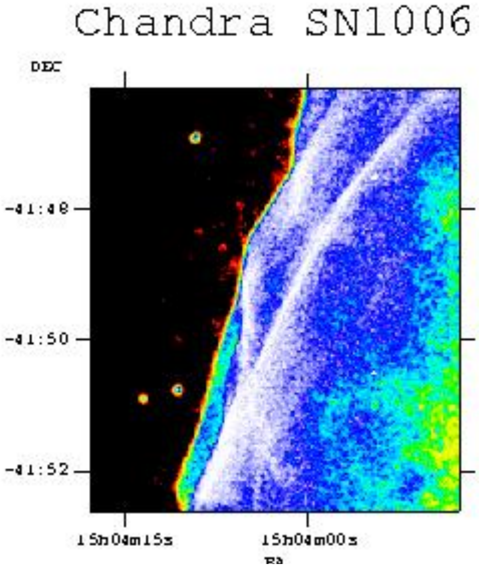


Fig. 2 Schematic velocity profile of a shock wave with upstream velocity u_1 and downstream u_2. Dotted line: test-particle shock (velocity discontinuity). Solid line: shock modified by cosmic rays.

Sn1006

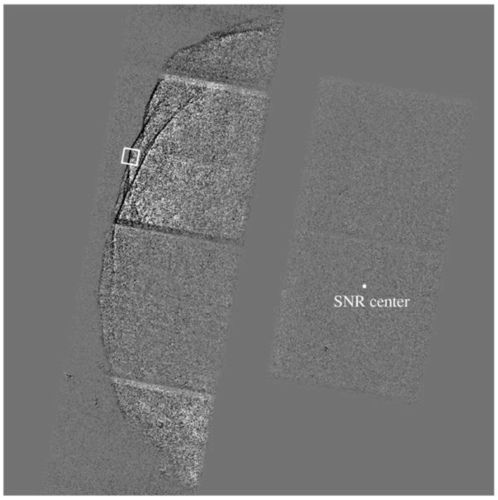
- The first SN where synchrotron radiation from a 'thermal' remnant was detected- direct evidence for very high energy particles



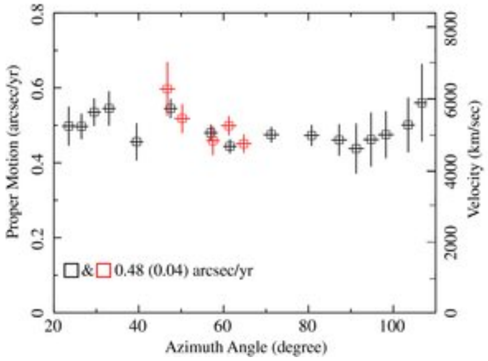


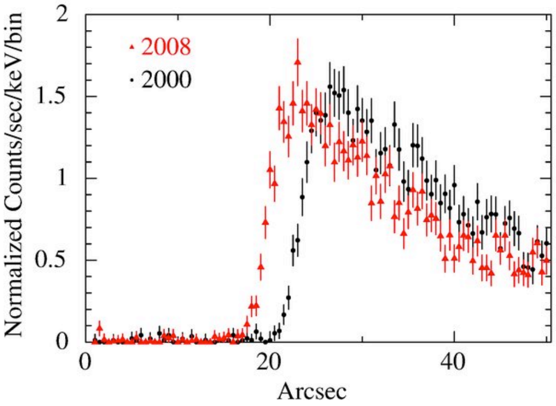
Enlarged SN filaments

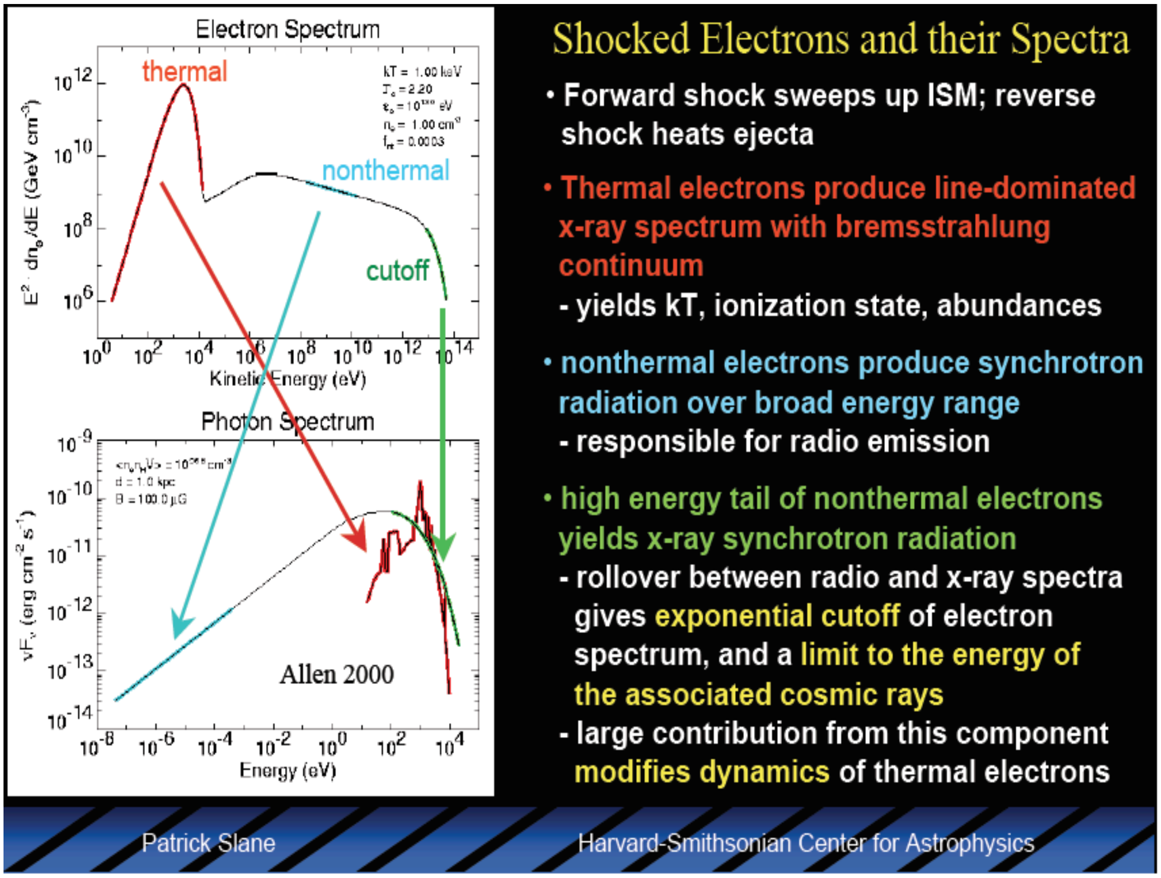
SN1006



Difference Image







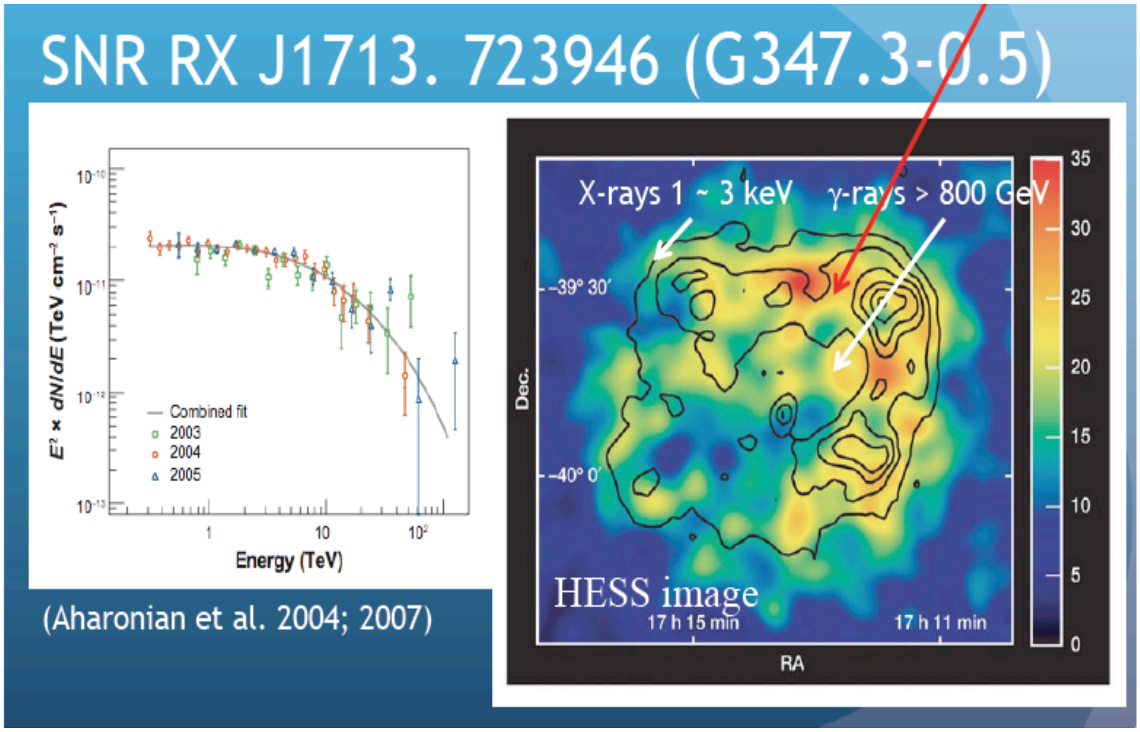
Shocked Electrons and their Spectra

- Forward shock sweeps up ISM; reverse shock heats ejecta
- Thermal electrons produce line-dominated x-ray spectrum with bremsstrahlung continuum
  - yields kT, ionization state, abundances
- nonthermal electrons produce synchrotron radiation over broad energy range
  - responsible for radio emission
- high energy tail of nonthermal electrons yields x-ray synchrotron radiation
  - rollover between radio and x-ray spectra gives exponential cutoff of electron spectrum, and a limit to the energy of the associated cosmic rays
  - large contribution from this component modifies dynamics of thermal electrons

Patrick Slane

Harvard-Smithsonian Center for Astrophysics

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



SNR RX J1713. 723946 (G347.3-0.5)

(Aharonian et al. 2004; 2007)

HESS image

Where Else May This Process Operate?

- Fermi Bubbles in the MW and other galaxies
- Chandra Press release http://chandra.si.edu/photo/2019/ngc3079/
- NGC 3079's superbubbles are younger cousins of "Fermi bubbles," Li et al 1901.10536

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
- In General relativity there are 3 distances of relevance
  - The proper distance D_P that we measure to an object is the distance we would get if we were to take a snapshot of the universe and directly measure the distance between where we are and where the object is, at some fixed time
  - The luminosity distance D_L is how far an object of known luminosity L (measured in energy per time) would have to be in Euclidean space so that we measure a total flux F (measured in energy per area per time), $D_L = \mathrm{sqrt}(L/(4\pi F))$.
  - The angular diameter distance D_A is the distance an object of known size L would have to be in Euclidean space so that it appeared to be its measured angular size θ; $D_A=L/\theta$.

More Cosmology

- Each of 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
    - And 'cosmological constant' Λ or alternatively the equation of state parameter $w=P/\rho$; where P and ρ are the pressure and energy density of the universe (in GR the scale factor a and $d^2a/d^2t\{(da/dt)/a\}^2=\{8\pi G\rho/3-k/a^2\}$
- 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

- Use of SN Ia as 'standardizable candles'
- What we want to know is the absolute distance to the source (luminosity distance)

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

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

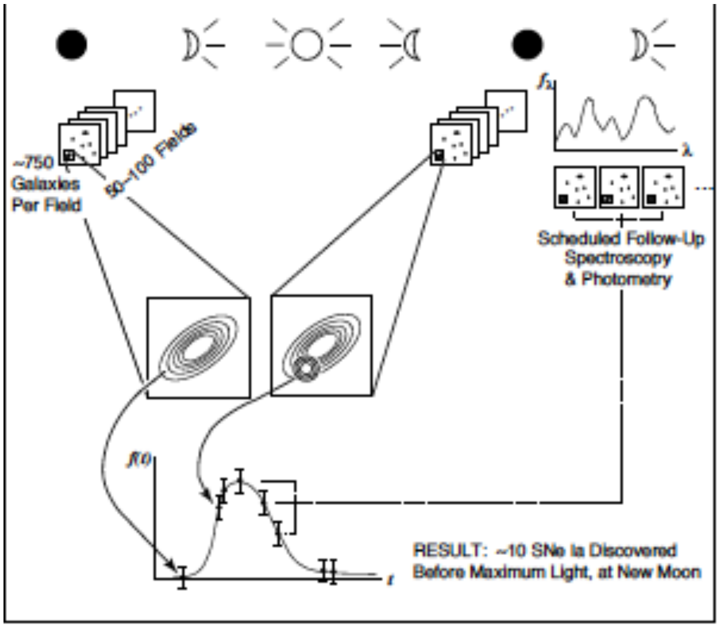
$k=1-\Omega_m-\Omega_{\Lambda;}$

the luminosity distance, d_L, **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**

Type I SN and Cosmology

- how old is the universe, how fast is it expanding, how much material and of what type is in it, what is its fate?
- Need to determine the relationship between distance and redshift
  - Redshift (‘z’) is the measure of Doppler shift by the expansion of the universe- (1+z)~v/c
  - In General relativity there are 3 distances of relevance
  - The proper distance D_P that we measure to an object is the distance we would get if we were to take a snapshot of the universe and directly measure (e.g., pace off) the distance between where we are and where the object is, at some fixed time
  - .•The luminosity distance D_L is how far an object of known luminosity L (measured in energy per time) would have to be in Euclidean space so that we measure a total flux F (measured in energy per area per time), $D_L = \mathrm{sqrt}(L/(4\pi F))$.
  - The angular diameter distance D_A is the distance an object of known size l (say, one meter) would have to be in Euclidean space so that it appeared to be its measured angular size θ;

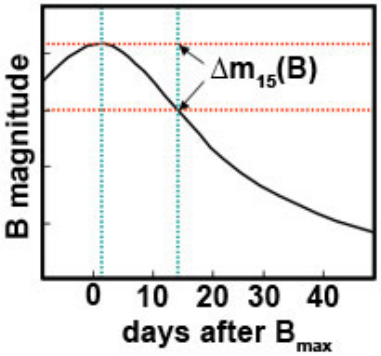
- Supernova on demand-
  - we know the average SNIa rate per galaxy/yr (1/100 yrs for a L(*) galaxy)
  - To obtain ~10 SN Ia per 1 week of observing have to observe ~50,000 galaxies about ~2 weeks apart and see what has changed

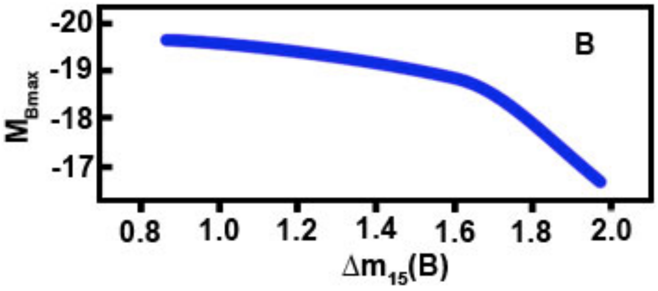


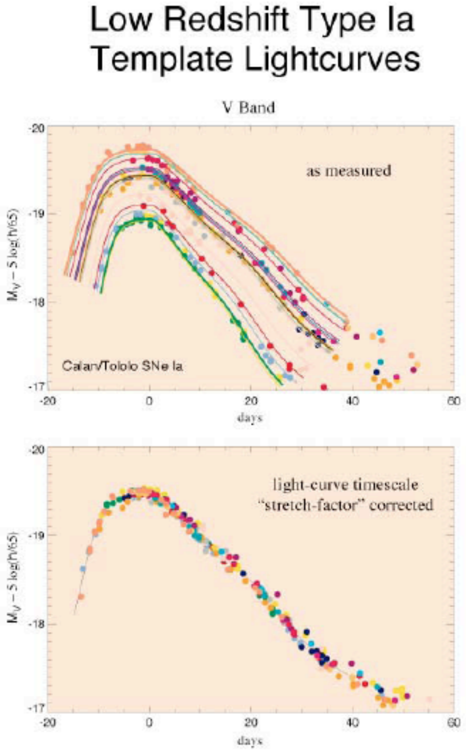
Perlmuter et al 1997

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







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

Standardizing Them

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

Riess,Press and Kirshner 1995)

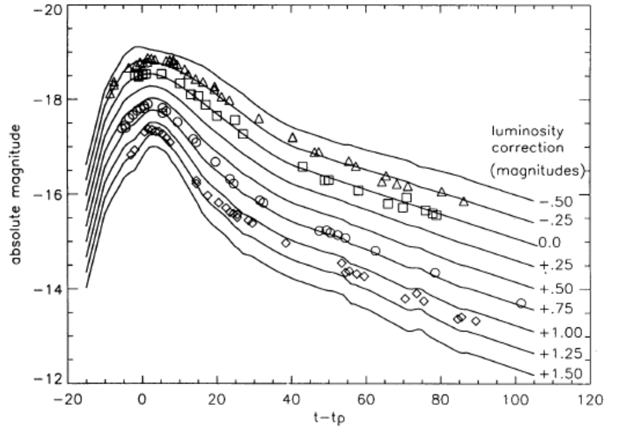
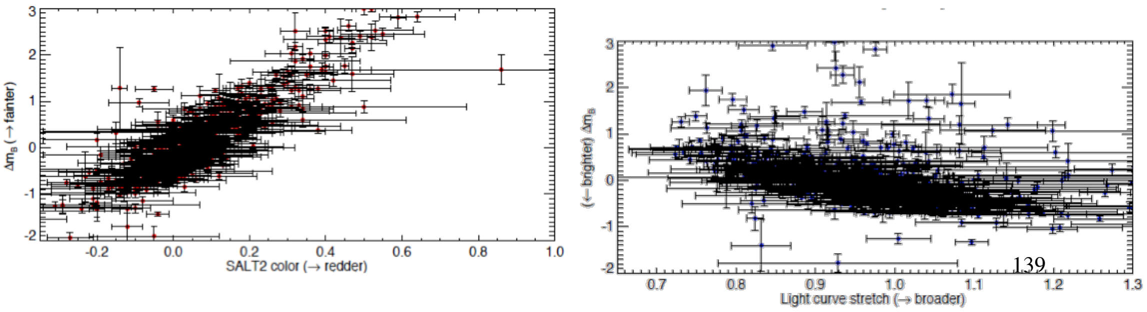
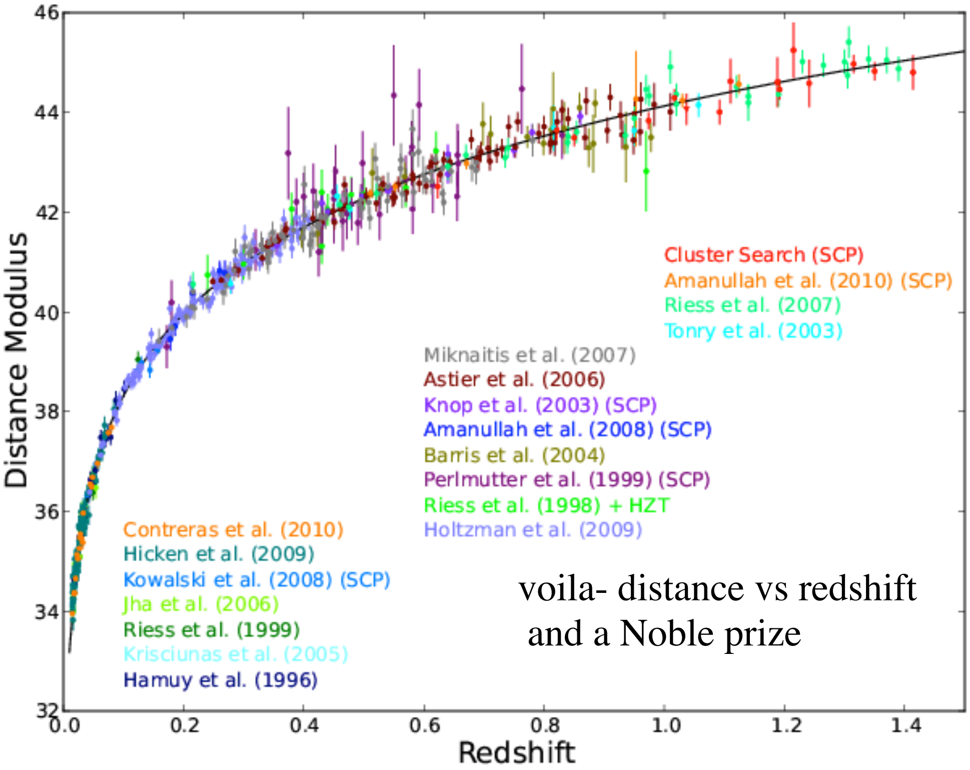


FIG. 1.—Empirical family of visual band SN Ia light curves. This sample of

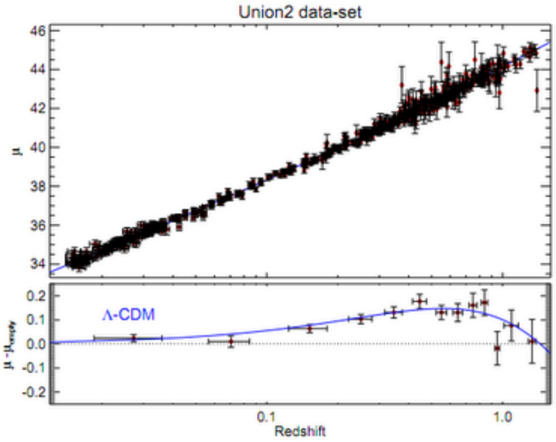


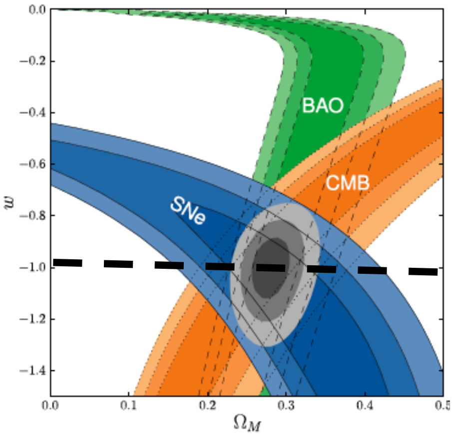


voila- distance vs redshift
and a Noble prize

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)



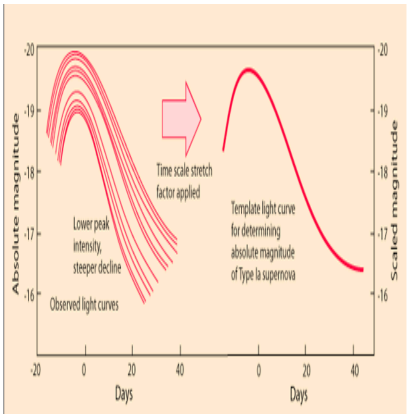


Ω_m

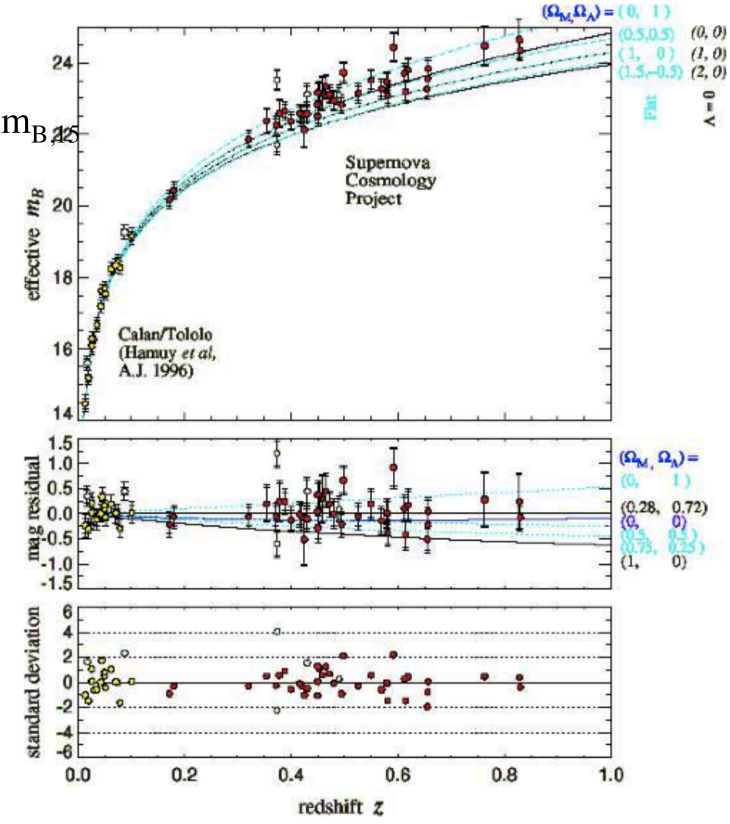
w=-1 is equivalent to a cosmological constant

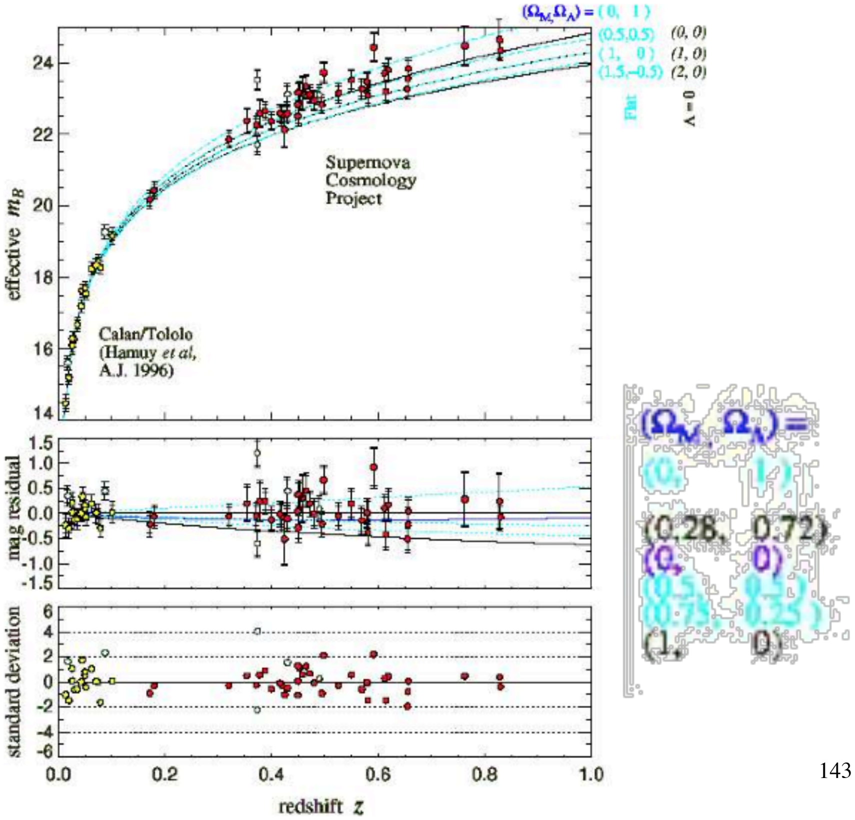
$M_{B,max} = -19.3+5 (\log H_{60})$

$M_{B,max} = -21.726 + 2.698\Delta m_{B,15}$

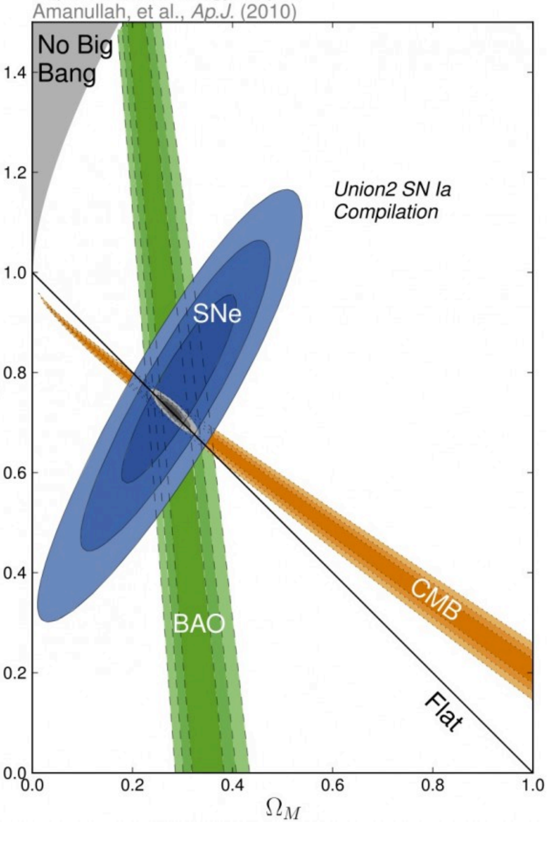


Perlmutter 2003





Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)



- Remember Project
- Due the week before finals May 17
- Discussion of grading, presentation and project.