Sources of Cosmic Rays

Galactic sources

Supernovae

We have seen already that SN produce enough energy

And shock fronts are observed at SNRs

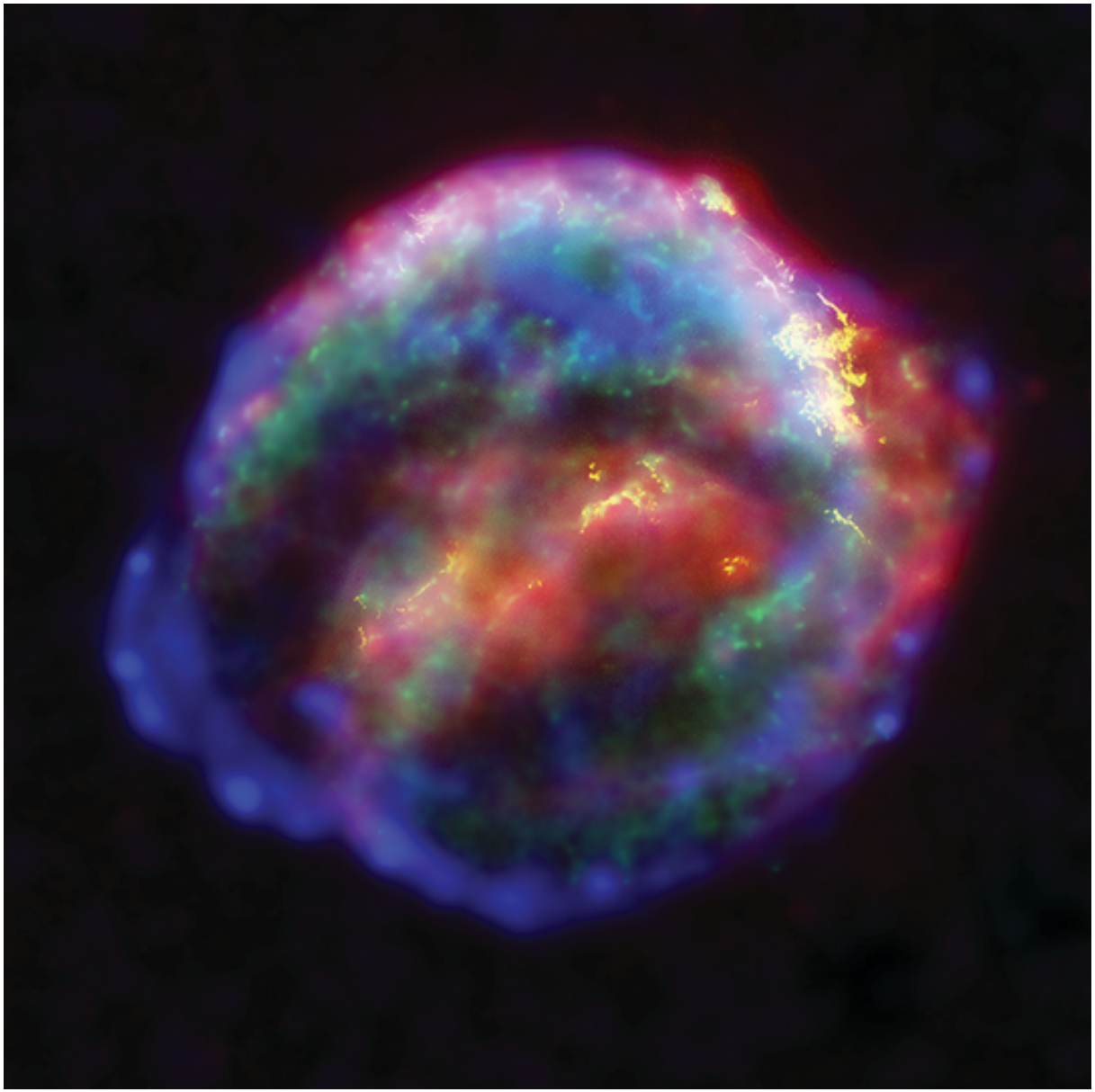
expansion velocity of shock front

up to $20-30 \cdot 10^3 \frac{km}{s}$ $(M >> 1)$

duration up to 100 000 a

↳ diameter of ~ 2-3 kpc

Kepler’s supernova 1604, d ~ 8 kpc



X-ray, Optical & Infrared Composite of Kepler's SNR

SN emits radiation in X-ray regime

high plasma temperatures

radio emission through synchrotron radiation of electrons

remark: synchrotron radiation

$$-\frac{dE}{dt} \propto \left(\frac{E}{m_0}\right)^4 \propto \gamma^4 \qquad (R \text{ fixed})$$

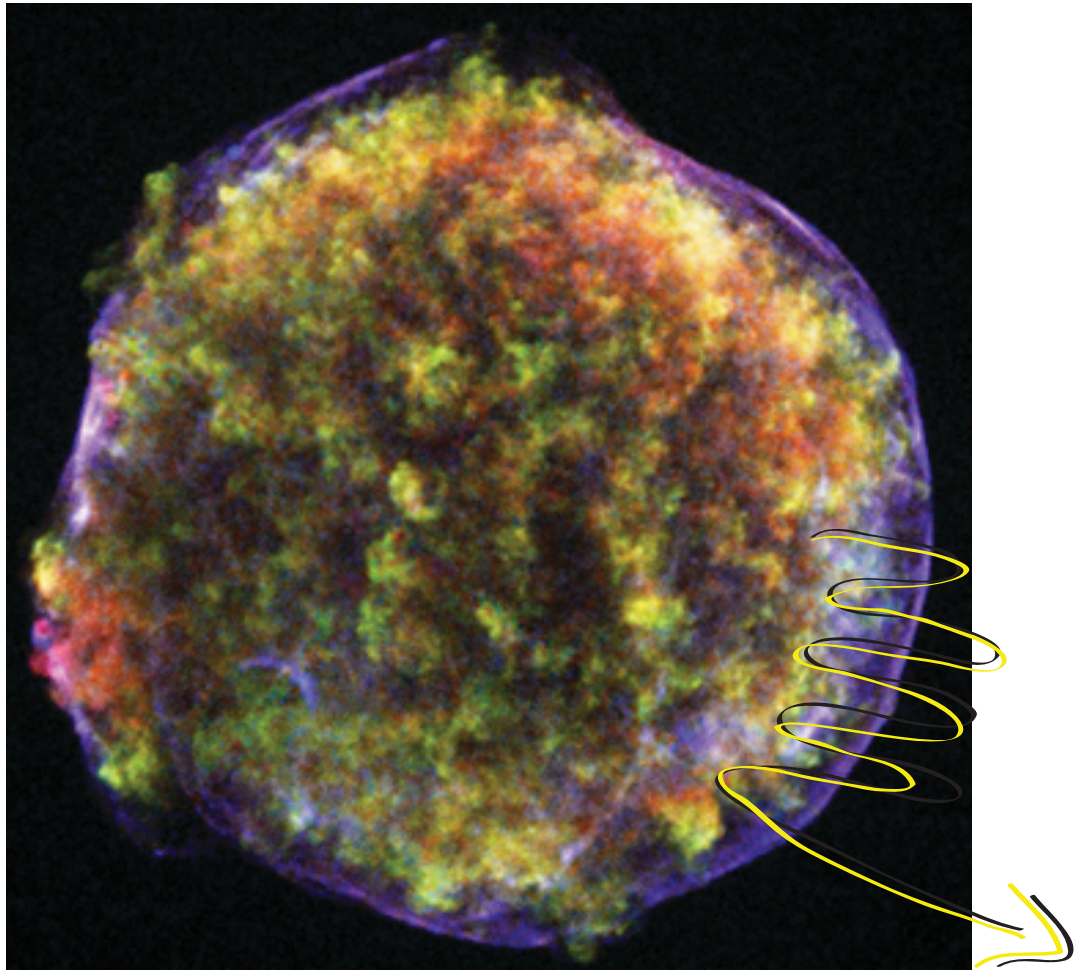
$$-\frac{dE}{dt} \propto B^2 \gamma^2$$

$\rightarrow$ important for electrons (10^4 compared to protons)

$\rightarrow$ confirmation of shock acceleration of particles

(strictly speaking only for electrons)

Tycho's supernova 1572, d ~ 2.3 kpc
v_S ~ 4600 +/- 400 km/s
E_{kin} ~ $5*10^{50}$ erg

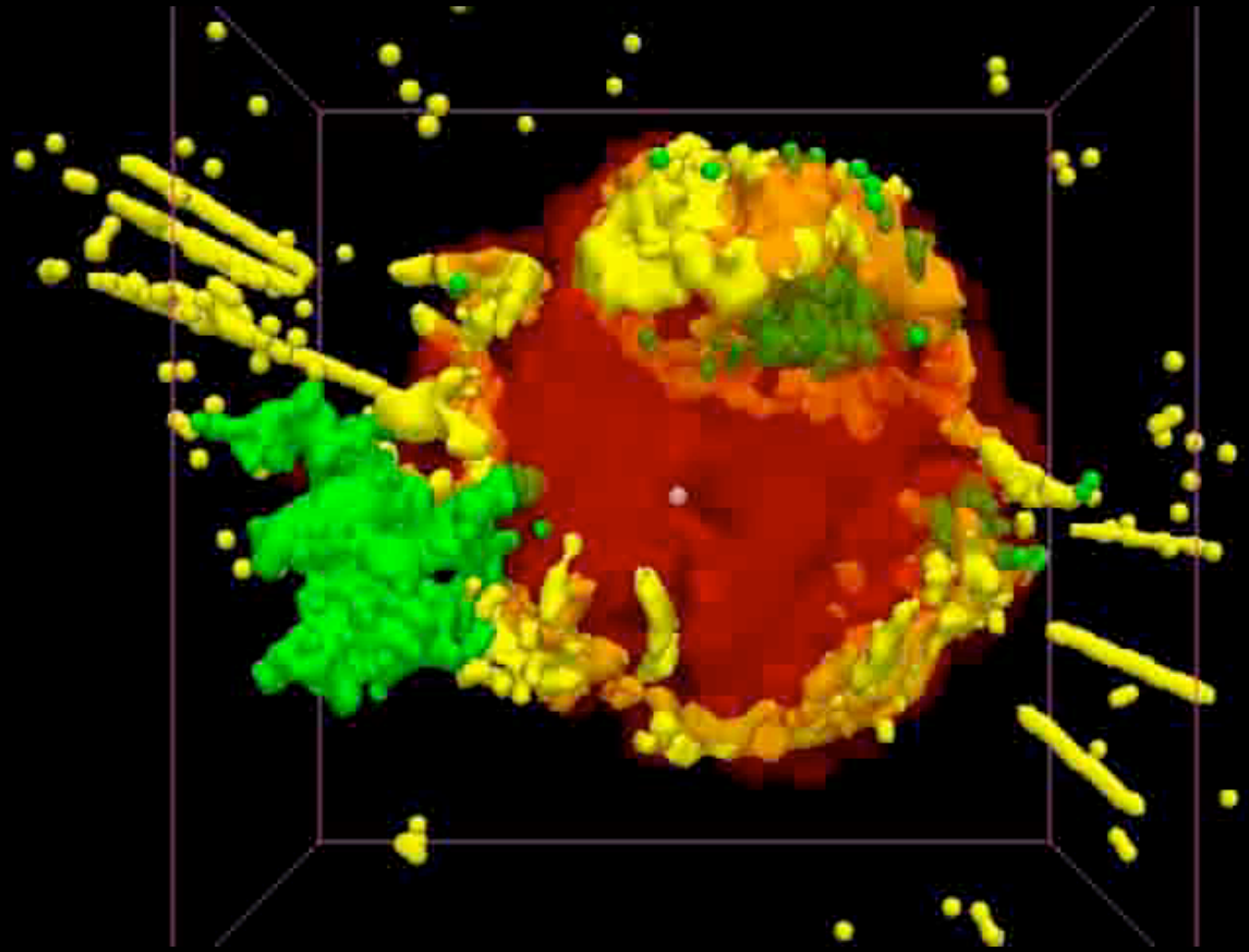


Chandra x-ray image

Cassiopeia A

This visualization shows a fly-through of Cas A based on the 3-D representation constructed from Chandra and Spitzer data. It begins with an artists rendition of the neutron star previously detected by Chandra. Next, new features unseen in traditional 2-D data sets are visible, including details of how the parent star exploded. The green region is mostly iron observed in X-rays; the yellow region is mostly argon and silicon seen in X-rays, optical and infared; the red region is cooler debris seen in the infared and the blue region is the outer blast wave, most prominent in X-rays.

Cassiopeia A



A research team has released a unique look of the supernova remnant Cassiopeia A (Cas A). By combining data from Chandra, the Spitzer Space Telescope, and ground- based optical observations, astronomers have been able to construct the first three-dimensional fly-through of a supernova remnant. This visualization (shown here as a still image) was made possible by importing the data into a medical imaging program that has been adapted for astronomical use. The green region shown in the image is mostly iron observed in X-rays; the yellow region is mostly argon and silicon seen in X-rays, optical and infared and the red region is cooler debris seen in the infared. The positions of these points in three-dimensional space were found by using the Doppler effect and simple assumptions about the supernova explosion.

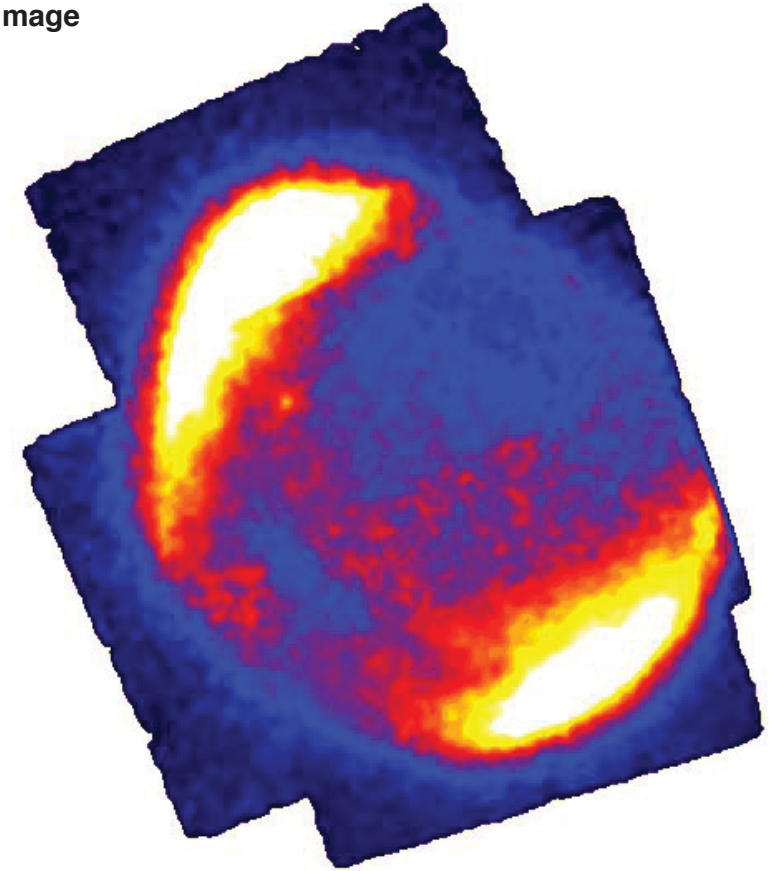
List of supernova remnants

From Wikipedia, the free encyclopedia

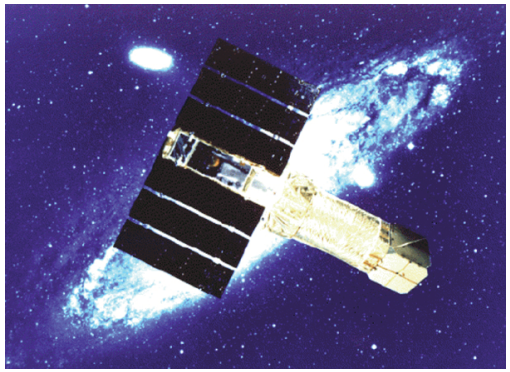
This is a list of observed supernova remnants.

Name	Date of Arrival of Supernova's Light at Earth	Apparent Magnitude	Distance (ly)	Type	Remnant
Sagittarius A East	?	?	26,000	?	Sagittarius A East
Simeis 147	>100,000 BC	?	3,000	?	Simeis 147 or Sharpless 2-240
W49B	?	?	35,000	?	GRB remnant?
W50	?	?	16,000	?	SS 433
Vela Supernova	11th-9th millennium BC	?	800	?	Vela Supernova Remnant
Veil Nebula	>3600 BC	?	1,400-2,600	?	NGC 6992-95, NGC 6979, NGC 6960
Puppis A	?	?	?	?	
SN 185	December 7, 185	-8?	3,000	Ia?	Possibly RCW 86
SN 1006	May 1, 1006	-7.5	7,200	Ia[1]	SNR 1006
SN 1054	1054	-6	6,300	II	Crab Nebula
G350.1-0.3	about 1100	?	approx. 15,000	?	G350.1-0.3
SN 1181	1181	-1	?	?	Possibly 3C58
RX J0852.0-4622	about 1250	?	700	?	G266.2−1.2
SN 1572	November 11, 1572	-4	7,500	Ia[1]	Tycho's Supernova Remnant
SN 1604	October 8, 1604	-2.5	20,000	Ia	Kepler's Supernova Remnant
Cassiopeia A	mid 17th century	+6	10,000	IIb[2]	Cassiopeia A Supernova Remnant
G1.9+0.3	about 1868	?	approx. 25,000	?	Supernova remnant G1.9+0.3
SN 1885A	August 20, 1885	+6	2,500,000	?	SNR 1885A
SN 1987A	February 24, 1987	+3	168,000	II-P	SNR 1987A

SN 1006
x-ray image



ASCA (Advanced Satellite for Cosmology and Astrophysics)



Maximum energy obtained during acceleration at SNR

$$E_{max} \propto Z \cdot B \cdot R \cdot \beta_s$$

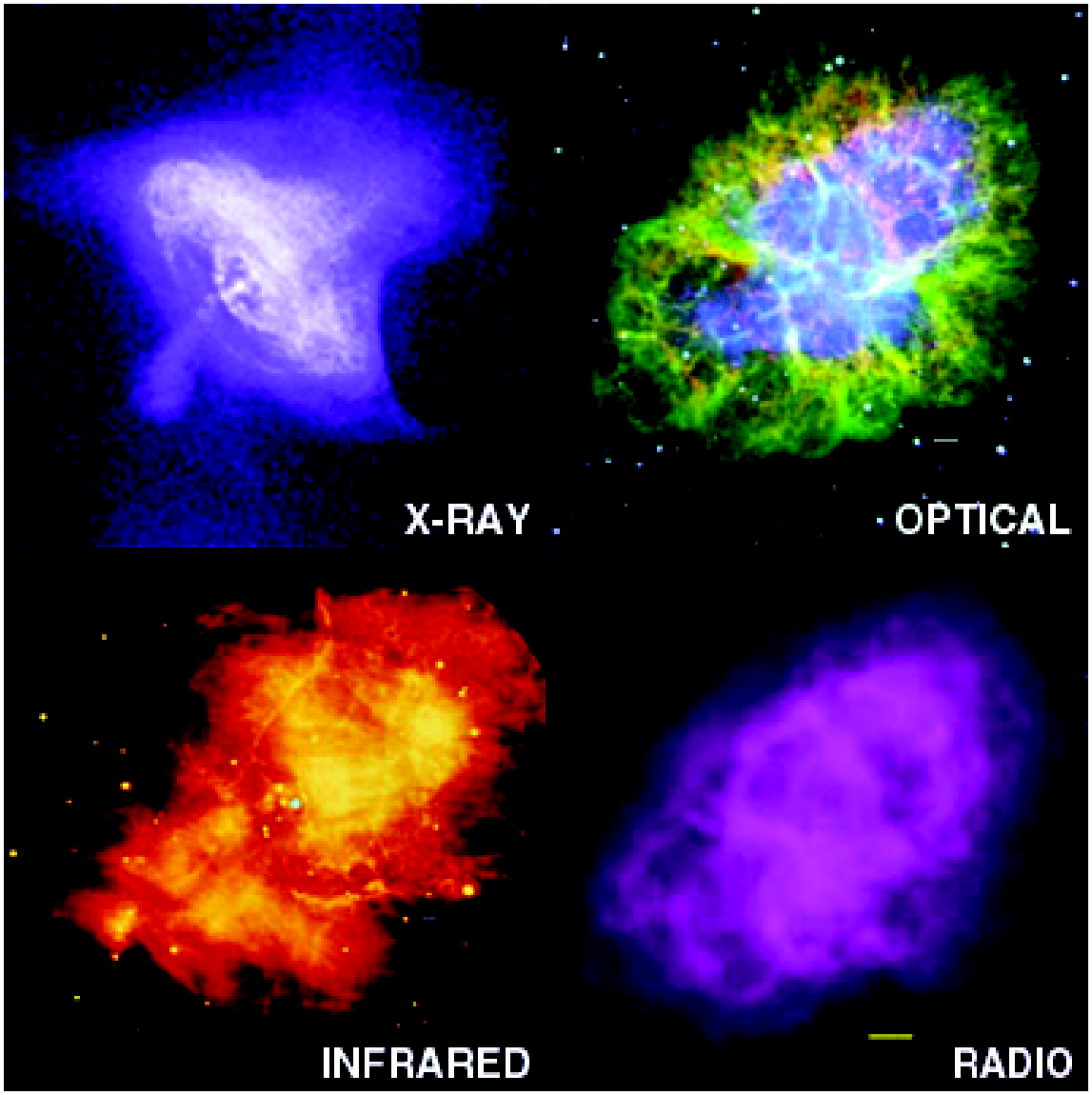
$$E_{15} \lesssim Z \cdot B_{\mu G} \cdot R_{pc} \cdot \beta_s$$

$$\sim 5 \quad \sim 1 \quad \sim 0{,}1$$

$$\Rightarrow E_{max} \simeq Z \cdot 10^{15}\ eV \pm 1 \text{ order of magnitude}$$

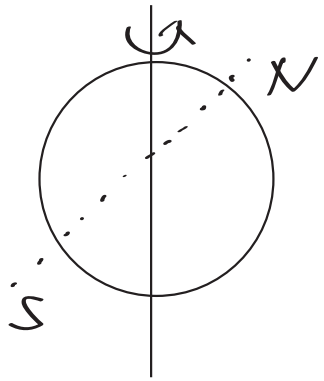
In addition to shell-type SNRs there are also filled-center SNRs

Crab Nebula - supernova of 1054



Pulsars

rotating neutron star, left over from a SN



$B \sim 10^{12}$ G

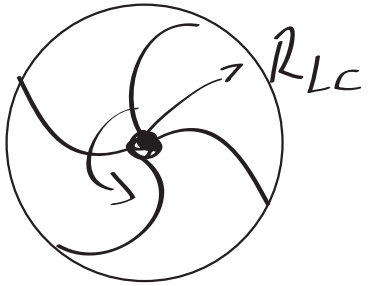
$M \sim 1{,}5\ M_\odot$

$\nu \sim 10 - 1000\ 1/s$

$E_{rot} \sim 10^{53}$ erg

$e^+ e^-$ are produced at high B-field regions around the poles

particles move along B field lines out to the light cylinder



$$v_{max} = c = \frac{2\pi R_{Lc}}{2\pi}\,\omega$$

$$\Rightarrow R_{Lc} = \frac{c}{\omega}$$

$$\text{e.g. } R_{Lc} = \frac{3\cdot 10^8\ \frac{m}{s}}{1000\ \frac{1}{s}} = 300\ km$$

second possible process

high electric fields between poles & equator

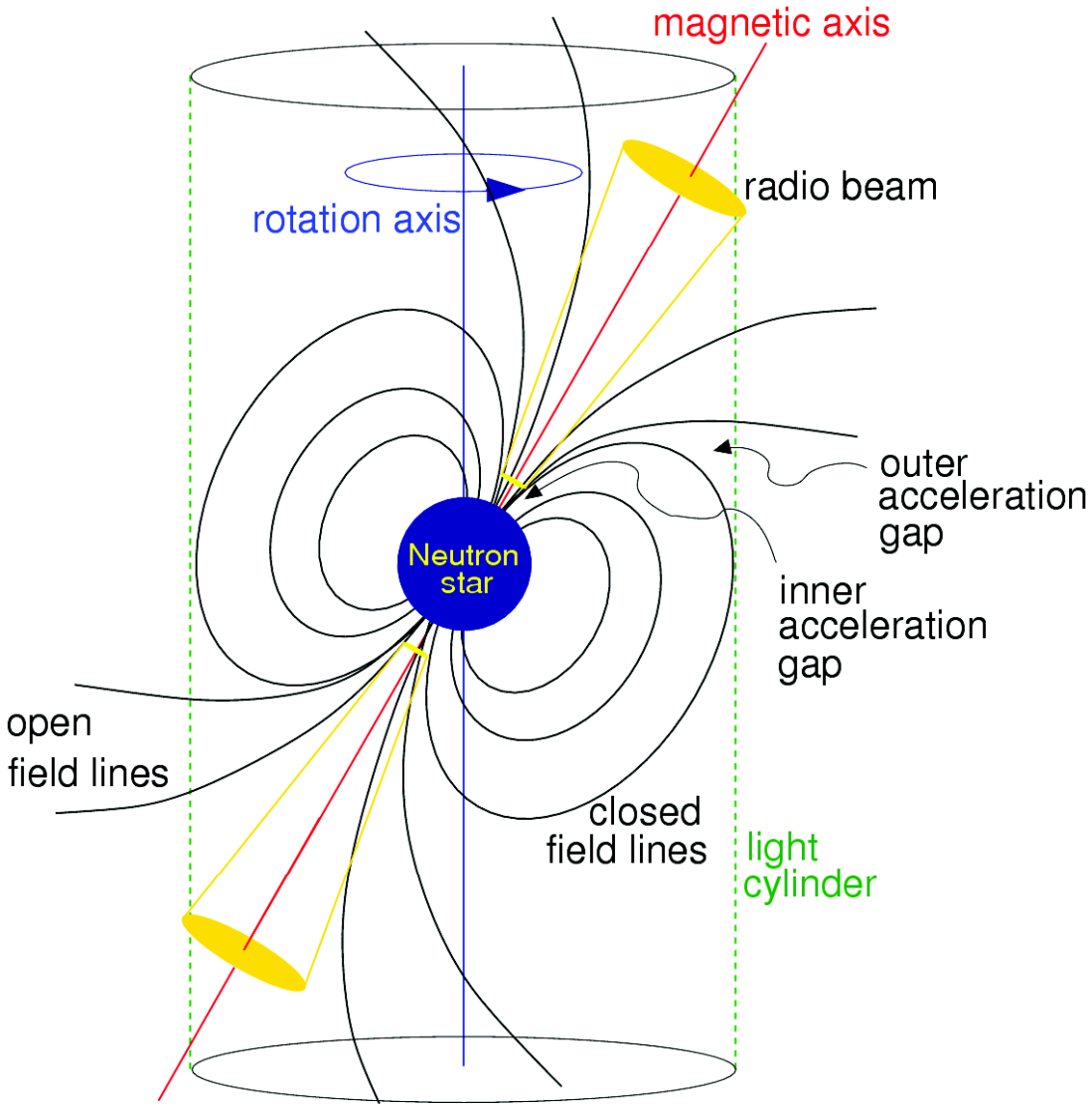
$$E = v \times B / c \cdot z$$

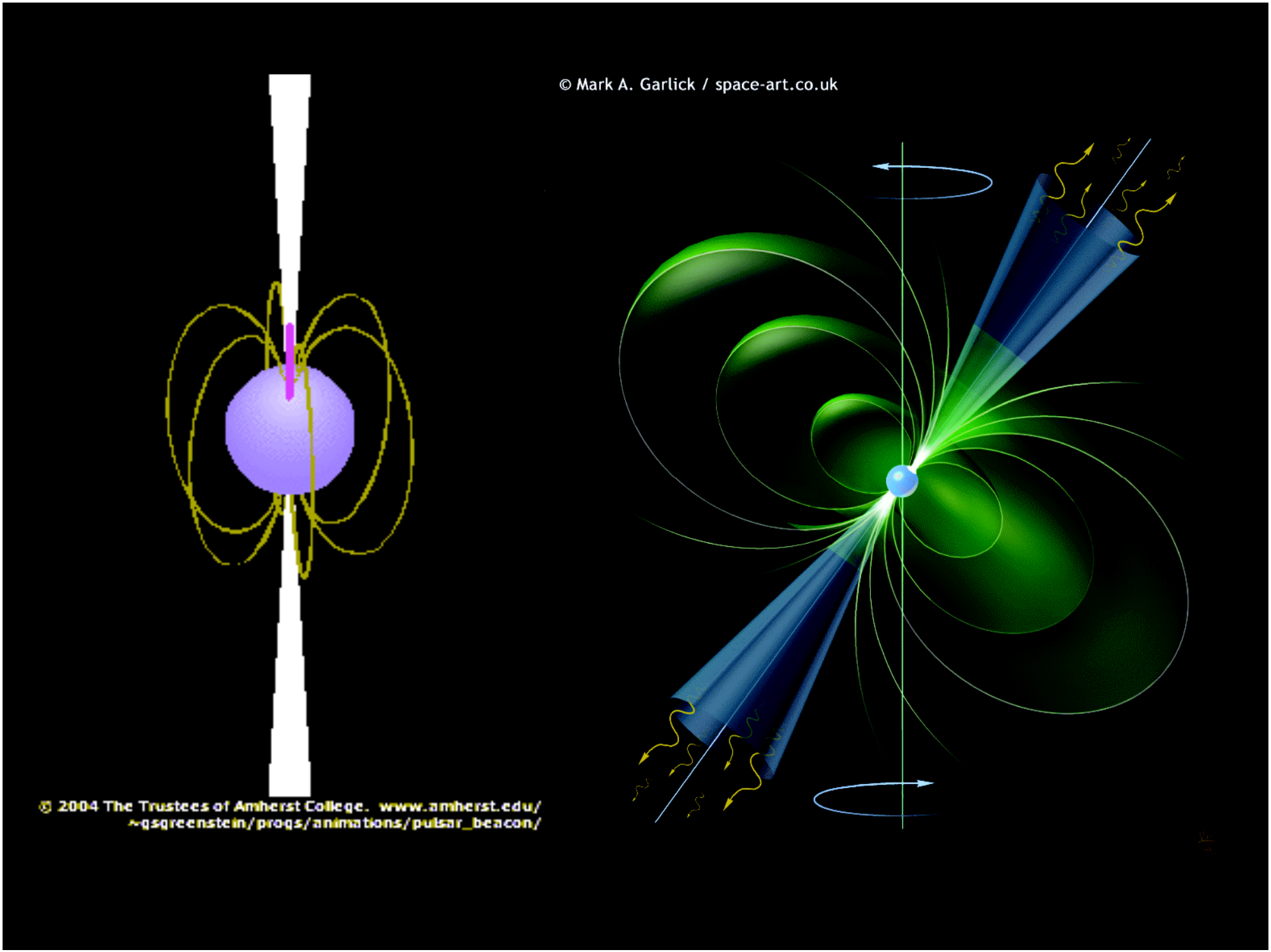
$$\sim \omega \cdot R \cdot B \cdot z$$

$$\sim 100\ \frac{1}{s} \cdot 1000\ m \cdot 10^8\ T$$

$$\sim 10^{13}\ \frac{V}{m}$$

$$E_{max} \sim z \cdot \omega \cdot R^2 \cdot B \sim 10^{16}\ eV$$


magnetic axis
rotation axis
radio beam
outer
acceleration
gap
Neutron
star
inner
acceleration
gap
open
field lines
closed
field lines
light
cylinder


© Mark A. Garlick / space-art.co.uk
© 2004 The Trustees of Amherst College. www.amherst.edu/~gsgreenstein/progs/animations/pulsar_beacon/

Problems:

1) strong fields are "shorted" through e^+e^- pairs

2) both processes yield single energies
but no power law

=> SNRs are regarded as most plausible
accelerators of cosmic rays

Extragalactic sources

Important for high-E astrophysics

active galaxies and their cores: AGN

1940 Mt. Wilson 1st observation of AGN

Karl Seyfert

a few % of spiral galaxies have bright cores

with strong & wide emission lines

widths are caused by Doppler effect

-> turbulent gas with high velocities

-> v a few % of c

=> Seyfert galaxies

spiral galaxies

M31 Andromeda

M 74 Gemini galaxy

1954 1st observation in radio astronomy

bright radio source in a galaxy

at $z = 0{,}05 \rightarrow d = \frac{c \cdot z}{H_0} \sim 300$ Mpc

Cygnus A

later with better resolution:

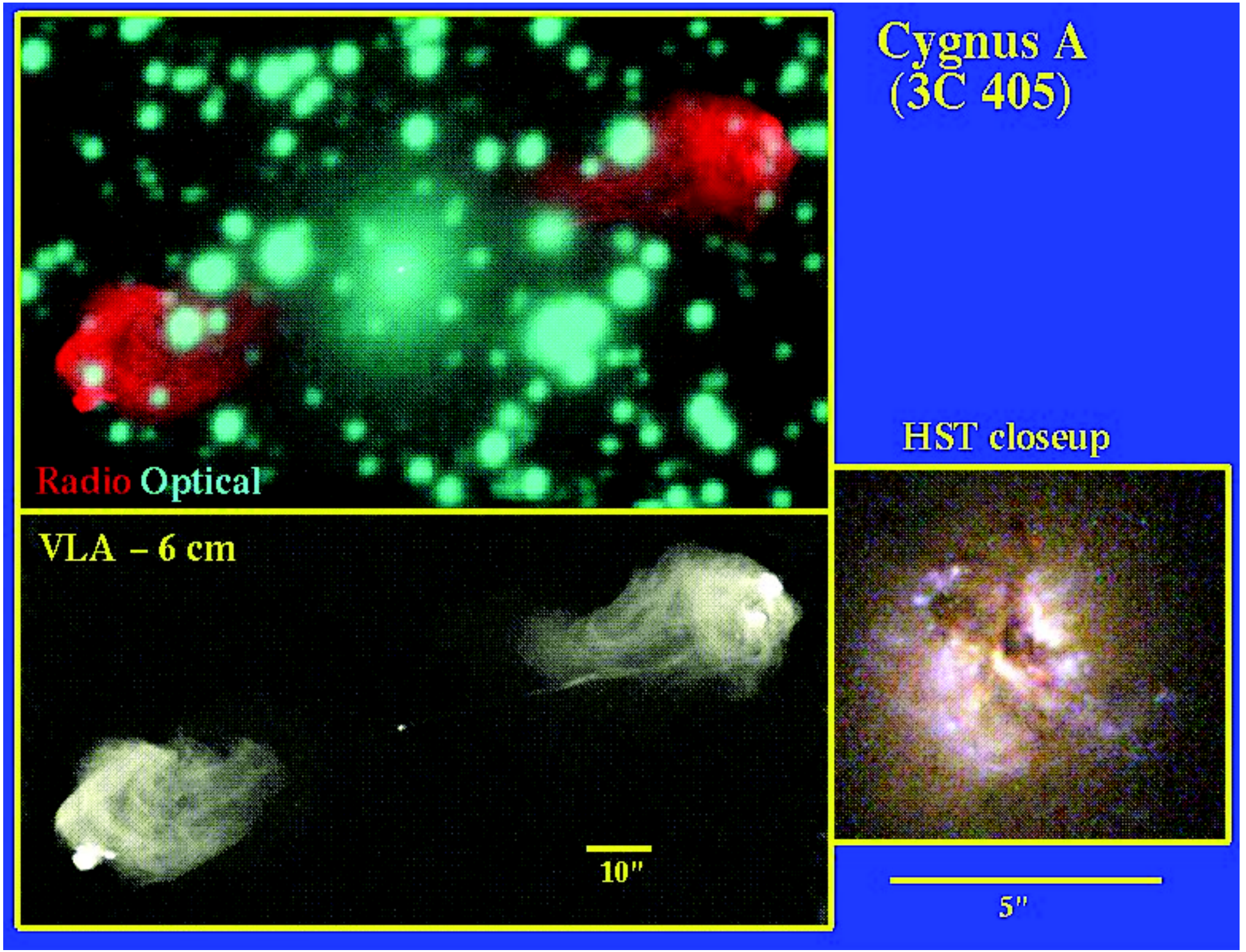
radio emission originates in two regions

~100 kpc away from center

explanation: radio emission is generated

through electrons in B fields

→ synchrotron radiation

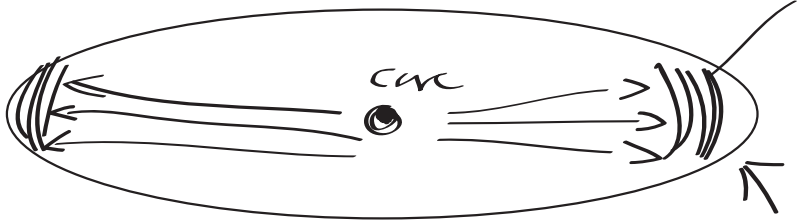

Cygnus A
(3C 405)
Radio Optical
HST closeup
VLA – 6 cm
10"
5"

radiated energy is significantly larger as compared to SNRs

energy originates in the core (AGN) in a black hole

~ up to 40% of the rest mass can be converted to radiation

origin of jets & radio lobes



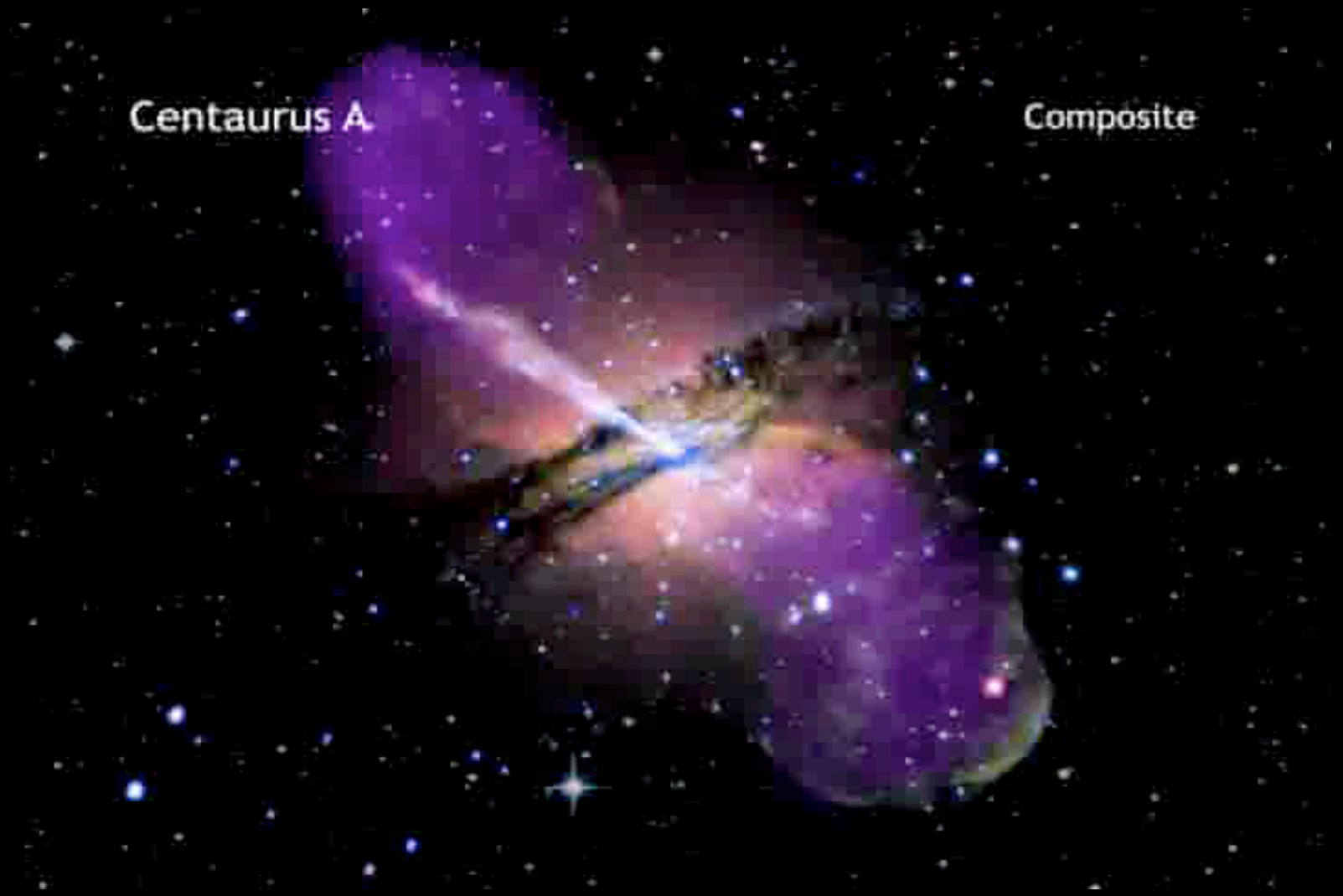
hot spot radio lobe

shocked intergalactic medium

energy is delivered to lobes from AGN

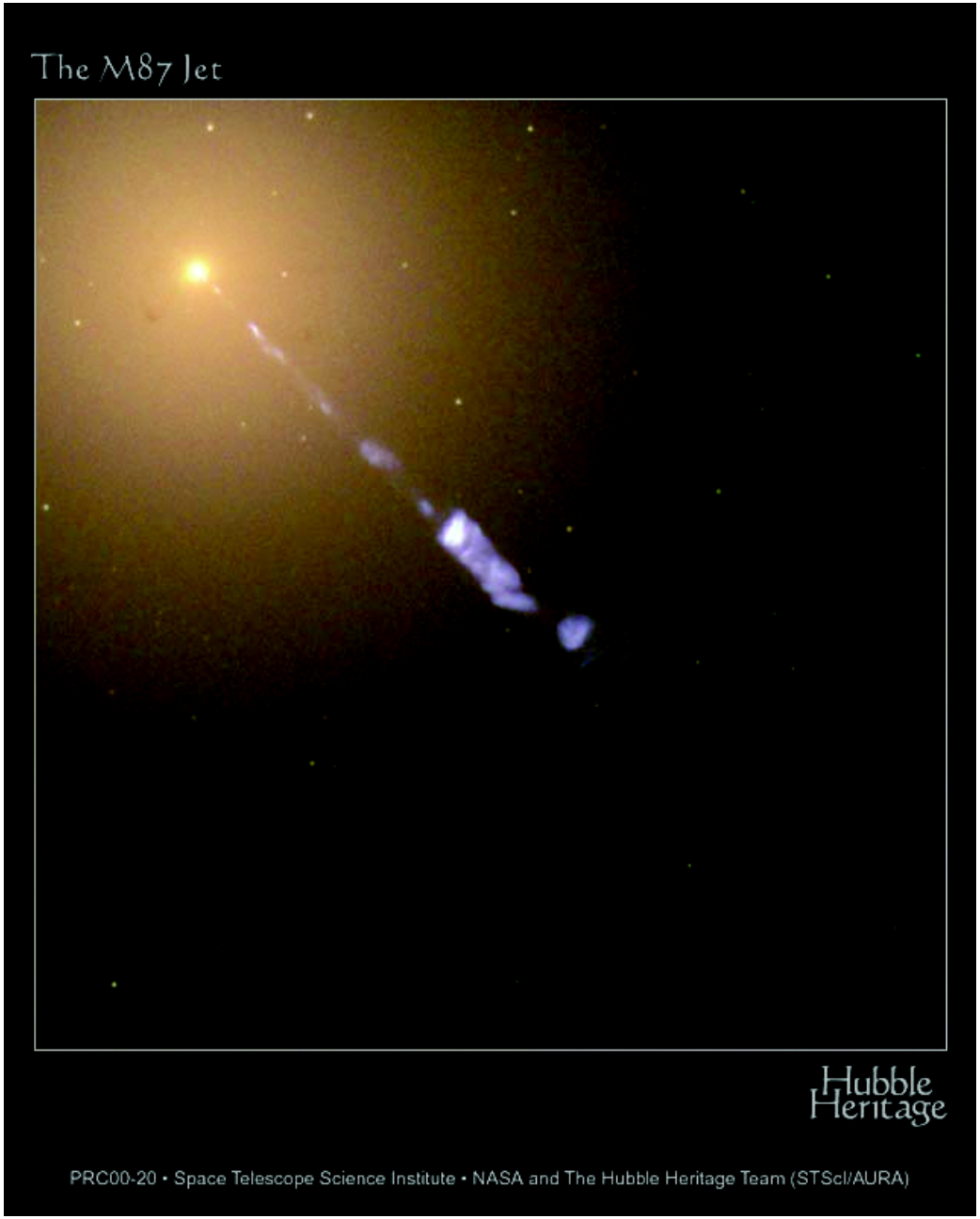
Cen A

Centaurus A



There is nothing subtle about the black hole in the galaxy Centaurus A. First off, it's about 10 million times more massive than the sun, and Chandra's X-ray image shows it's not just sitting quietly as a bright point in the middle. Instead, the monster black hole is responsible for powering massive jets, including one that extends to the upper left for some 13,000 light years. Radio data also show the effect of these jets far beyond the plane of the galaxy. An image in optical light shows the elliptical galaxy and the dark bands running almost perpendicular to the jet. These are caused by dust lanes created when Centaurus A merged with another galaxy, perhaps 100 million years ago. The combination from all of these telescopes shows us just how much is really going on in Centaurus A.

M 87


The M87 Jet
Hubble Heritage
PRC00-20 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)

fast stream of gas → jet

ISM close to galaxy
IGM further out } resistance for jet

→ end of jet is slowed down

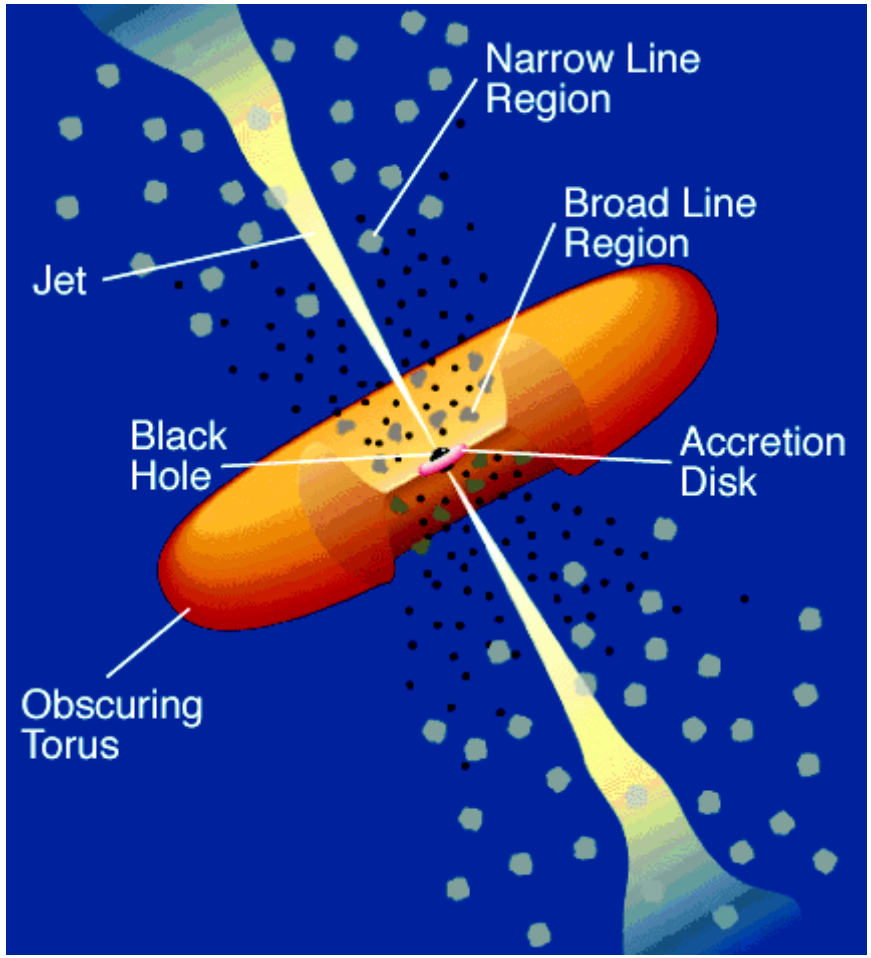
→ energy is concentrated at end of jet

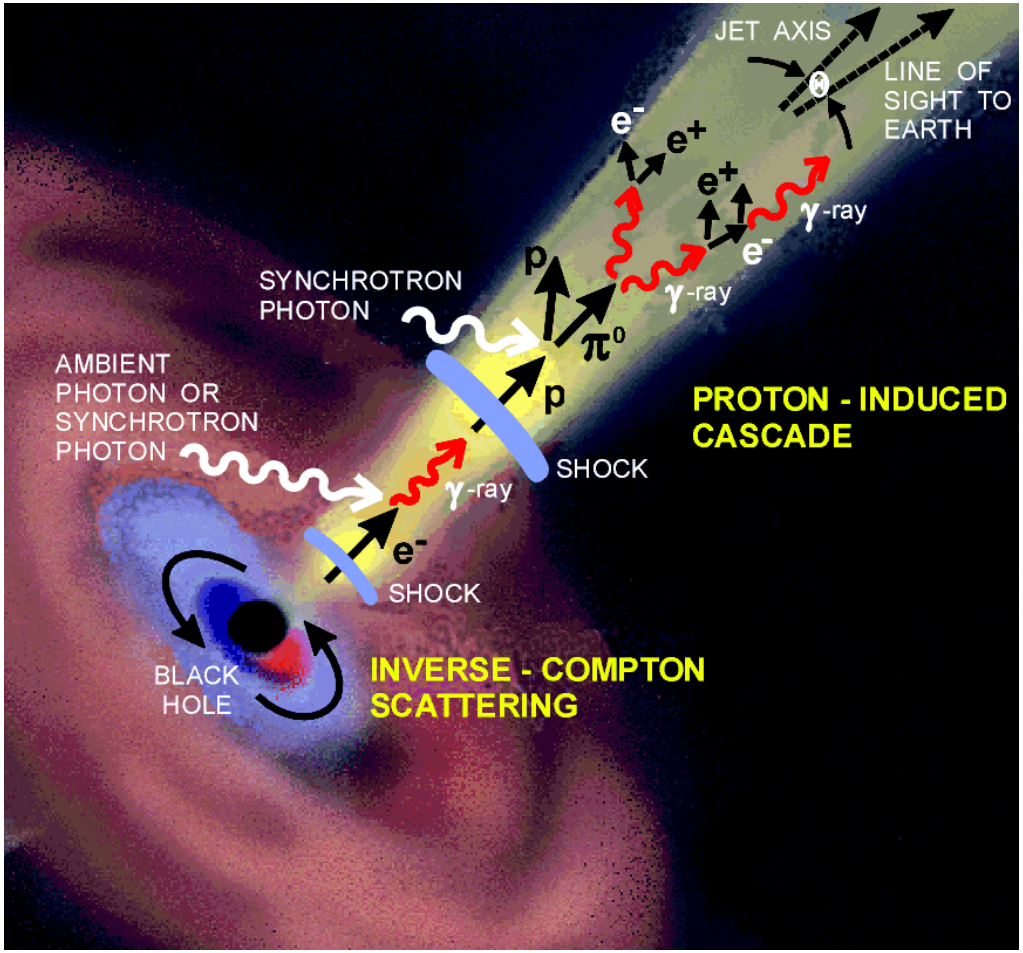
→ hot spot

gas in jet moves close to c and is slowed down at hot spot

→ shock wave

→ convert kinetic energy in jet to acceleration of particles up to energies of 10^{20} eV


Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus


JET AXIS
LINE OF SIGHT TO EARTH
θ
e-
e+
e+
e-
γ-ray
γ-ray
SYNCHROTRON PHOTON
p
π0
p
AMBIENT PHOTON OR SYNCHROTRON PHOTON
PROTON - INDUCED CASCADE
SHOCK
γ-ray
e-
SHOCK
BLACK HOLE
INVERSE - COMPTON SCATTERING

general considerations about accelerators

trajectory of particle in B field

centripetal force = Lorentz force

$$m \frac{v^2}{r} = q \cdot v \times B \qquad m \cdot v = p \text{ momentum}$$

$$\frac{p}{r} = z \cdot e \cdot B$$

$$r_L = \frac{p}{z \cdot e \cdot B}$$ Larmor radius

L dimension of accelerator

$$L > 2 r_L$$

closer look (Hillas 1984)

$$L > \frac{2 r_L}{\beta} \qquad \beta = \frac{v}{c}$$ velocity of scattering centers

$$L > \frac{2 \cdot \rho}{z \cdot e \cdot B \cdot \beta}$$

$$\boxed{B \cdot L > \frac{2 \cdot \rho}{z \cdot e \cdot \beta}}$$

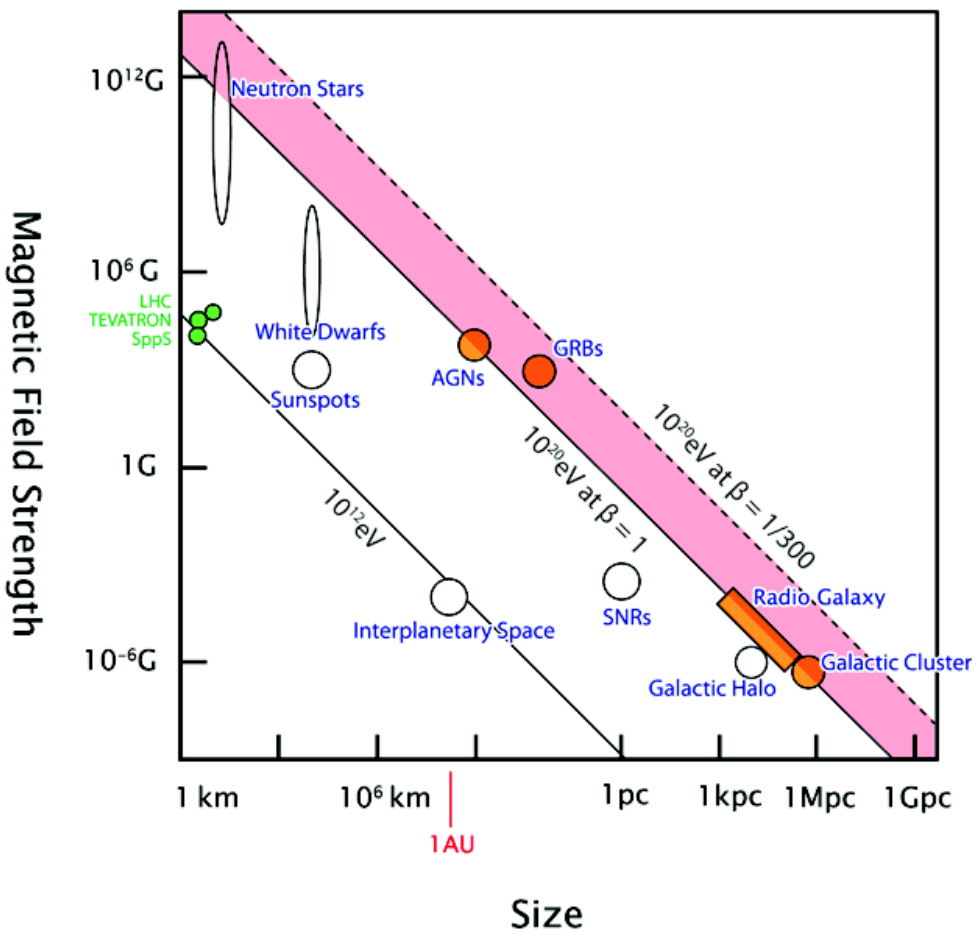
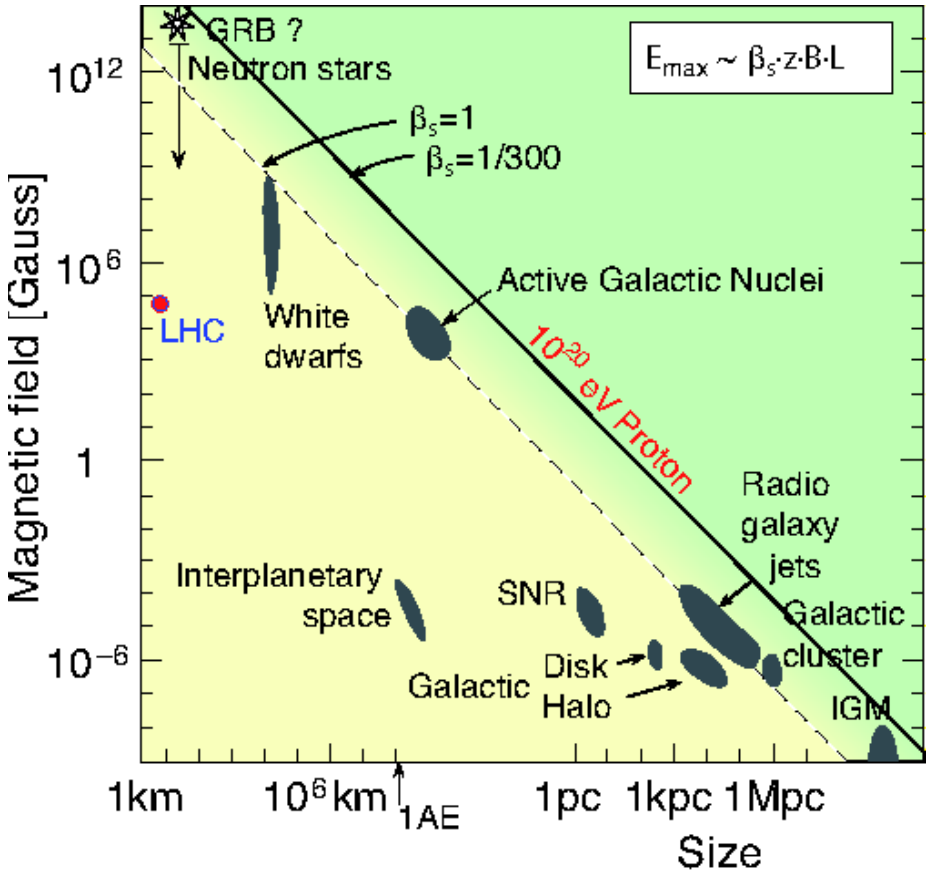
Hillas criterion

in astrophysical units

$$r_L = 1{,}08\,\mathrm{pc}\,\frac{E_{15}}{z \cdot B_{\mu G}}$$

$$\boxed{B_{\mu G} \cdot L_{\mathrm{pc}} > \frac{2 \cdot E_{15}}{z \cdot \beta}}$$

necessary condition

not sufficient

Hillas diagram