HIGH ENERGY RELATIVISTIC COMPACT COSMIC OBJECTS

by Jean HEYVAERTS (ULP)

COMPACT STARS ARE THE END POINTS OF STELLAR EVOLUTION

FOR AN EQUILIBRIUM STAR, THERE IS A RELATION MASS / PRESSURE / DENSITY

$$\frac{dP}{dr} = -G\,\frac{\rho(r)M(r)}{r^2}$$

$dP/dr \approx P_c/R \qquad M \approx \rho_c R^3$

$\Rightarrow$ **« Virial » Relation**

$$P_c \approx k\; GM^{2/3}\rho_c^{4/3}$$

LIMITS TO CENTRAL PRESSURE

Central density increases

with evolution until..... ??

either $\Rightarrow$ degeneracy

a) Electron degeneracy

b) Neutronization + nucleon degeneracy

or $\Rightarrow$ occlusion

c) Black Hole

OCCLUSION LIMIT

$$m\frac{v^2}{2} - G\,\frac{mM}{R} = E$$

$$E > 0 \qquad \text{to escape}$$

NO ESCAPE POSSIBLE IF $R < 2GM/c^2$

Virial Relation for $R = GM/c^2$ $\Rightarrow$

$$P_c = \rho_c\, c^2$$

THE NULL ISOTHERM

At « small » T,

electrons degenerate

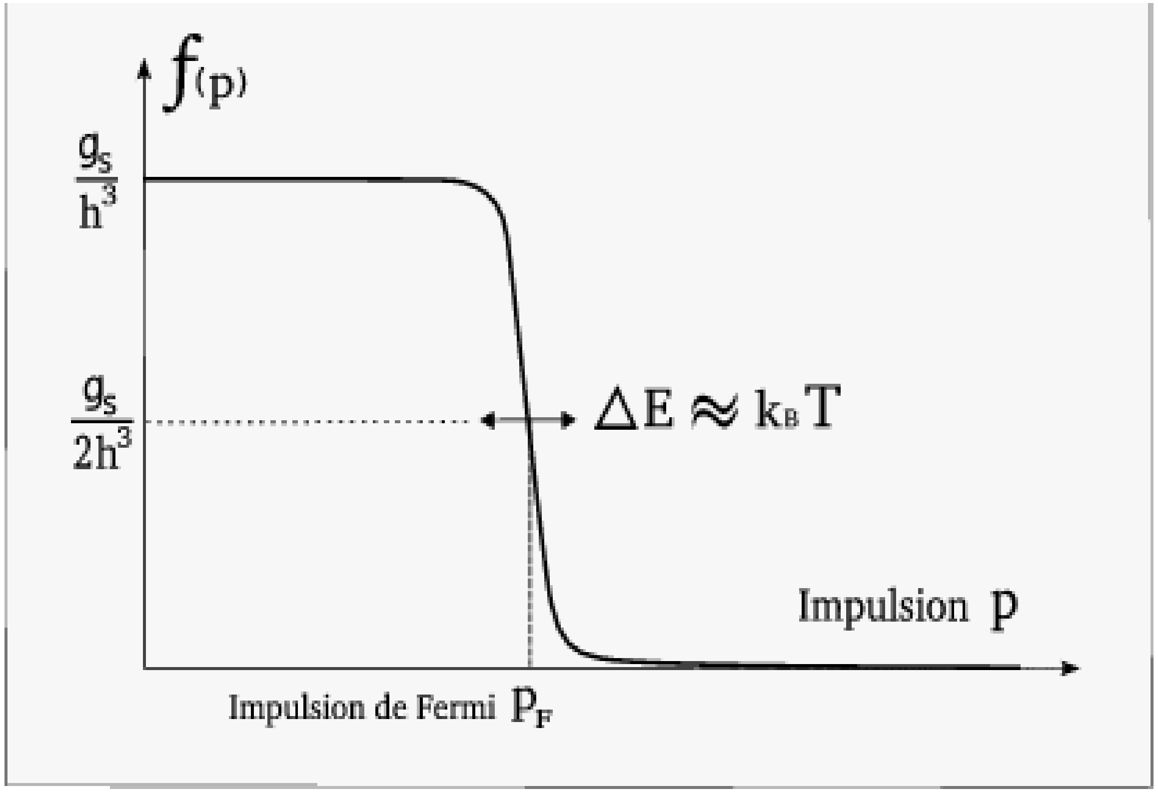
Fermi Dirac distribution

Fermi momentum p_F

$$\mathbf{P} \approx n(p_F)\, E(p_F)$$

$p_F < mc$ $\quad \mathbf{P} \approx \rho^{5/3}$

$p_F > mc$ $\quad \mathbf{P} \approx \rho^{4/3}$



NEUTRONIZATION

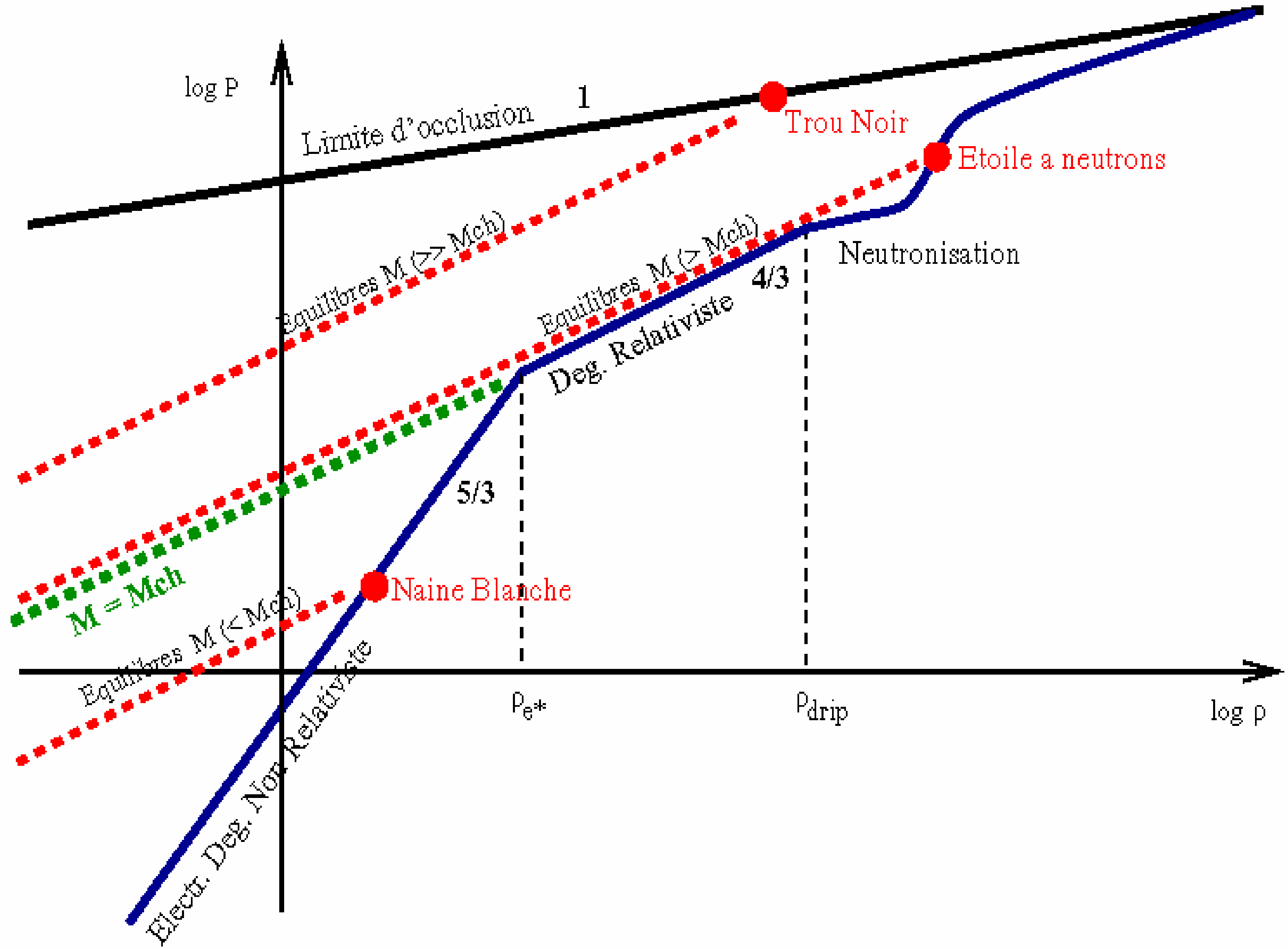
$$n \longrightarrow p + e^- + \overline{\nu}_e$$

$$(m_n - m_p)\, c^2 = \qquad 1.293 \;\; \text{MeV}$$

BUT, when $E_F > (m_n - m_p)c^2$
the system lowers its energy
by β creation of neutrons

$$p + e^- \longrightarrow n + \nu_e$$

$$n \leftrightarrow p + e$$



log P
1
Limite d'occlusion
Trou Noir
Etoile a neutrons
Equilibres M (>> Mch)
Equilibres M (> Mch)
Neutronisation
4/3
Deg. Relativiste
5/3
M = Mch
Naine Blanche
Equilibres M (< Mch)
Electr. Deg. Non Relativiste
ρ_{e*}
ρ_{drip}
log ρ

REALISTIC NEUTRONIZATION

$$(A, Z) + e^- \leftrightarrow (A, Z-1) + \nu_e$$

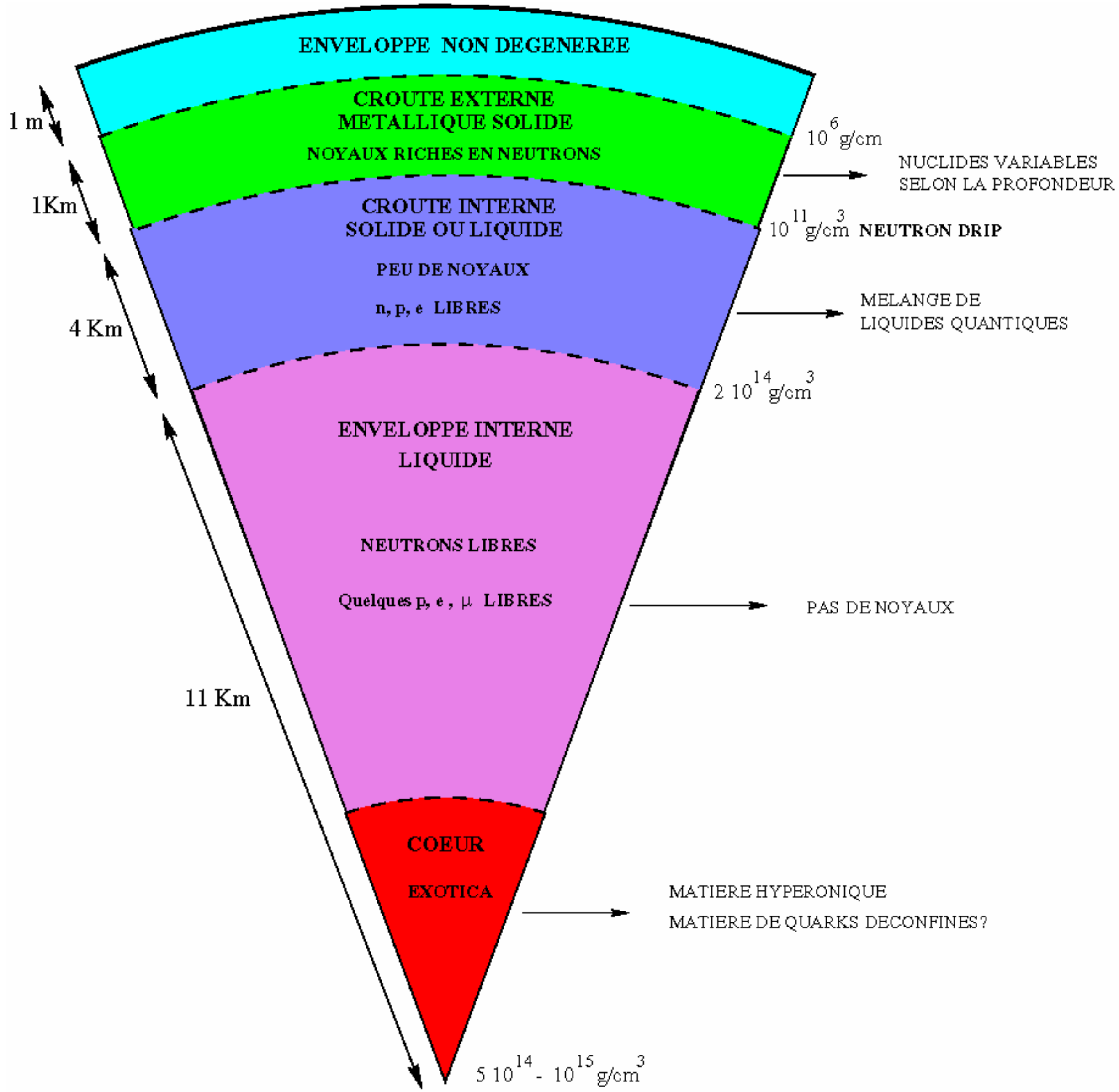
Creation of exotic neutron-rich nuclei

NEUTRON DRIP at about 4.5 10^{11} g/cm^3

More β reactions at even higher density

$$e^- \leftrightarrow \mu^- + \overline{\nu}_\mu + \nu_e$$

$$n + e^- \leftrightarrow \Sigma^- + \nu_e$$



ENVELOPPE NON DEGENEREE
CROUTE EXTERNE
METALLIQUE SOLIDE
NOYAUX RICHES EN NEUTRONS
CROUTE INTERNE
SOLIDE OU LIQUIDE
PEU DE NOYAUX
n, p, e LIBRES
ENVELOPPE INTERNE
LIQUIDE
NEUTRONS LIBRES
Quelques p, e , μ LIBRES
COEUR
EXOTICA
1 m
1Km
4 Km
11 Km
10^6 g/cm
NUCLIDES VARIABLES
SELON LA PROFONDEUR
10^{11} g/cm^3 NEUTRON DRIP
MELANGE DE
LIQUIDES QUANTIQUES
2 10^{14} g/cm^3
PAS DE NOYAUX
MATIERE HYPERONIQUE
MATIERE DE QUARKS DECONFINES?
5 10^{14} - 10^{15} g/cm^3

HOW DOES A STAR BECOMES A COMPACT STAR ?

WHITE DWARFS : Continuous transition ;

Planetary Nebula + Long radiative cooling

NEUTRON STARS and BLACK HOLES :

Super Nova II cataclysm :

No exothermic nuclear reactions from Fe.

Core collapse + detonation wave = explosion

+ « fast » neutrinic cooling

A Super-Nova Remnant nebula is left

+ the dense star

t=15

DEAD STARS

ARE STILL ALIVE !

because they may …

- **tap on residual thermal energy** : Isolated n*
- **tap on rotational enegy** : **Pulsars**
- **tap on magnetic energy** : Magnetars
- **energize their environment by their large gravitational field :**

  Accreting X-Ray Binaries,

  Galactic Nuclei,

  Short Gamma Ray Bursts

POWERED BY ROTATION :

PULSARS

Radio discovery (late 1960's) ; CP1919 :

$P = 1.33730113$ s $P \uparrow$ $dP/dt = 10^{-15}$

Pulsars are « radio beacons » =
rotating neutron stars
+ anisotropic radio emission

1982: ∃ millisecond pulsars!! (Old !! Not young!)

Near breakup!!

$dP/dt = 10^{-19}$
Often in dble systems , like
PSR 1913+16 (n* + pulsar 59 millisec 7h 45mn orb.)
or double pulsar PSR J0737-3039 A B
(2.8 s + 23 millisec, 2hr24mn orbital)

THE CRAB PULSAR

- A pulsar found in the Crab Nebula ,

  = Super Nova Remnant from the SN 1054

  P = 33 millisec

  $dP/dt = 3\ 10^{-13}$

- Pulsed Optical emission found by stroboscopy

  Coincides with the mysterious « Baade Star »

- Also pulsed X ray and γ ray emission

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)

The Crab Nebula and its Pulsar

- Puzzling energy budget of the Crab Nebula:

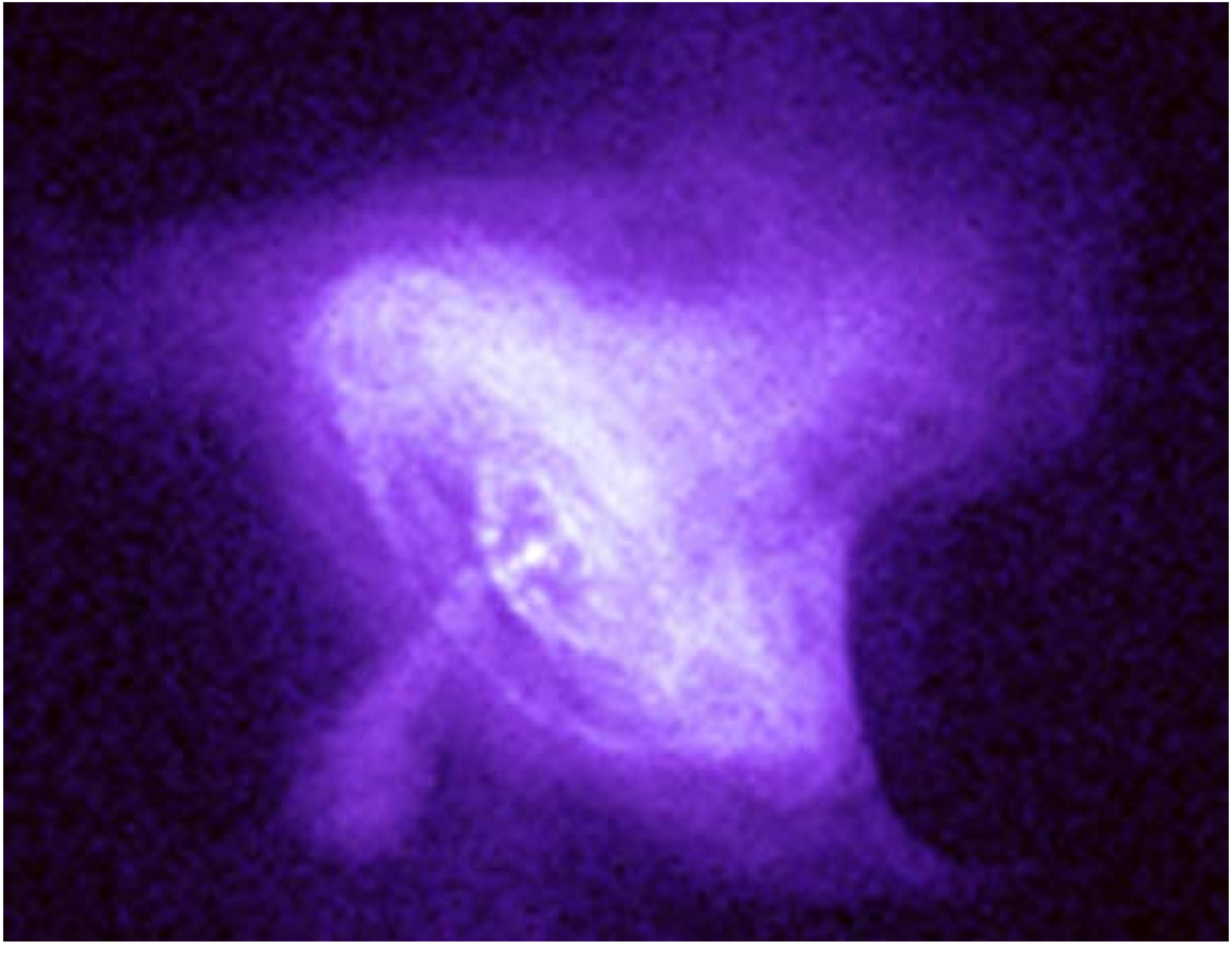
  Optical Synchrotron radiation by electrons of life time = years !!

- **What feeds the nebula with energy ??**
  - **The pulsar !!**

Indeed, $dE_{rot}/dt =$ 5 10^{38} ergs/s $\approx$ Radiation of Nebula.

- **Crab Nebula = a pulsar-powered SNR**

  About 50 such « plerions » known in Milky Way



γ RAY PULSARS

A handful of short period pulsars (= young)

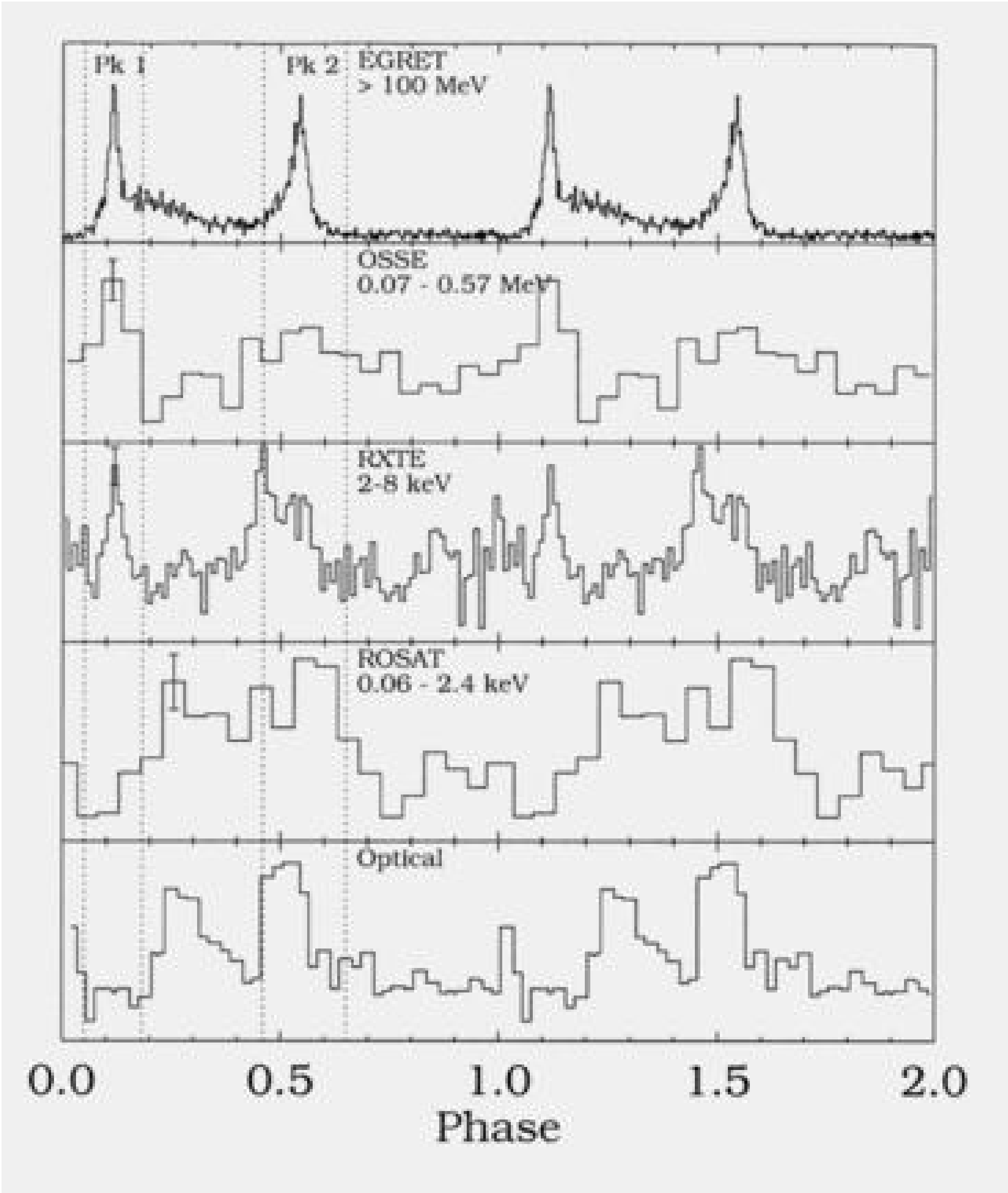
Large dP/dt

$10^{-3} – 10^{-1}$ of rotational power in γ's

Range : MeV-GeV pulsed

Some TeV non-pulsed (= from nebula).

VELA PULSAR LIGHT CURVES



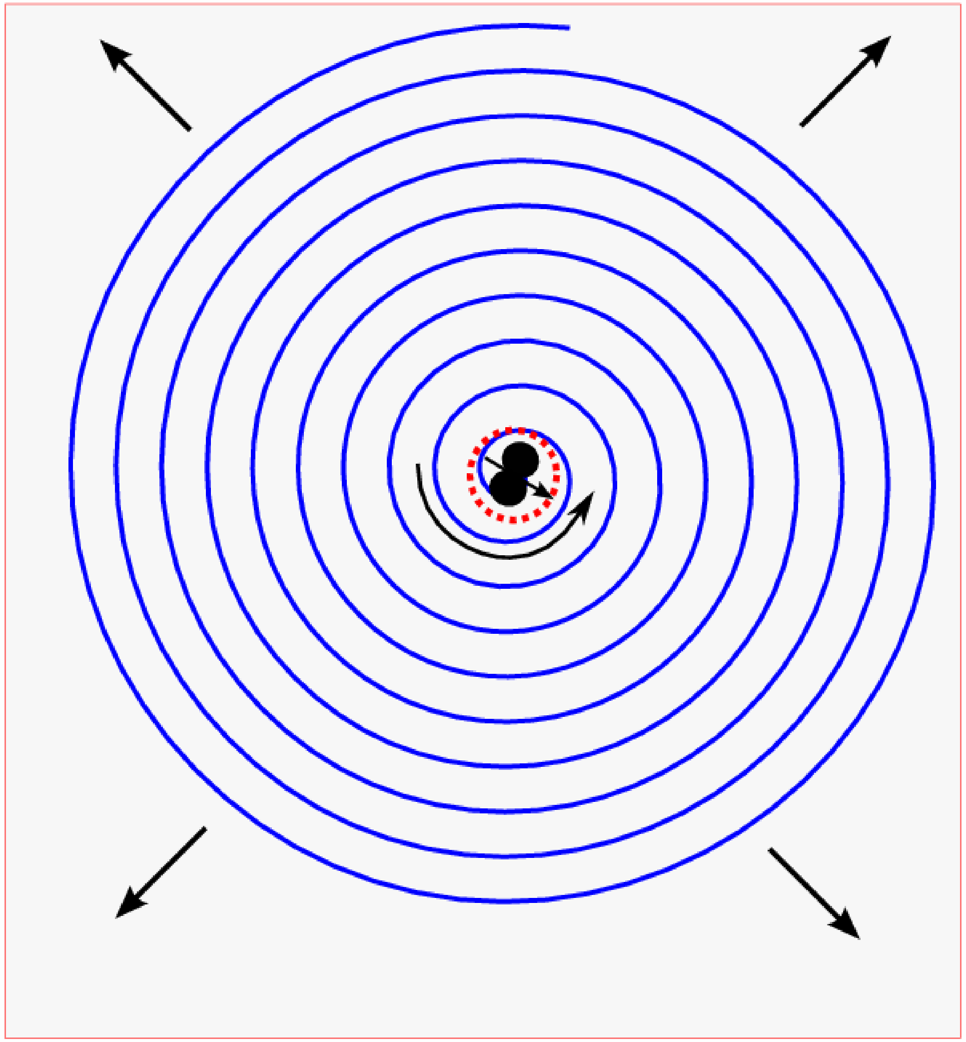
OBLIQUE ROTATOR PULSARS
emit a large electromagnetic wave

Magnetic dipole radiation from rotating dipole

Wave zone at

$$R_L = c/\Omega$$

t=30



MAGNETIC DIPOLE LOSSES

EMITTED POWER:

$$\mathcal{P}_{em} = \frac{2\pi}{3\mu_o c^3} B_*^2 R_*^6 \sin^2\chi \; \Omega^4$$

$$\mathcal{P}_{em} = -\frac{1}{2}\frac{d}{dt}\left(I_*\Omega^2\right) \qquad \text{[measured]}$$

B* = 10^{12} Gauss for radio pulsars

= 10^{9} Gauss for millisec pulsars

= 10^{15} Gauss AXP's

FROM WAVE TO WIND

- Interaction large amplitude wave / particles

Particles set in relativistic motion by wave :

Some of the Poynting flux into particle energy flux

$\Rightarrow$ Evacuating relativistic wind

- Origin of persistent wind ?

$\Rightarrow$ Physics in vicinity of neutron star

CHARGES EXTRACTED

Aligned rotator as a model

= an unipolar dynamo

$$\mathbf{E} + (\Omega \times \mathbf{r}) \times \mathbf{B} = 0$$

∃ Surface charges . . .

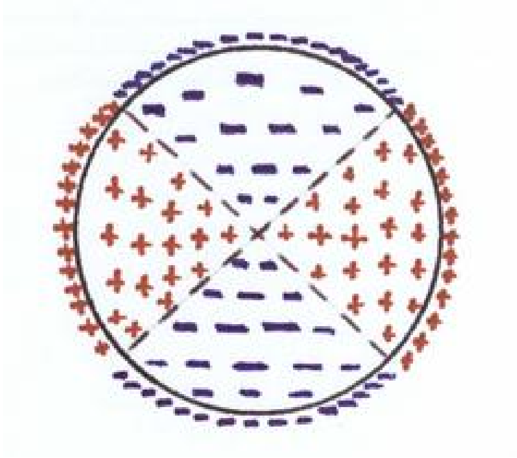
which however

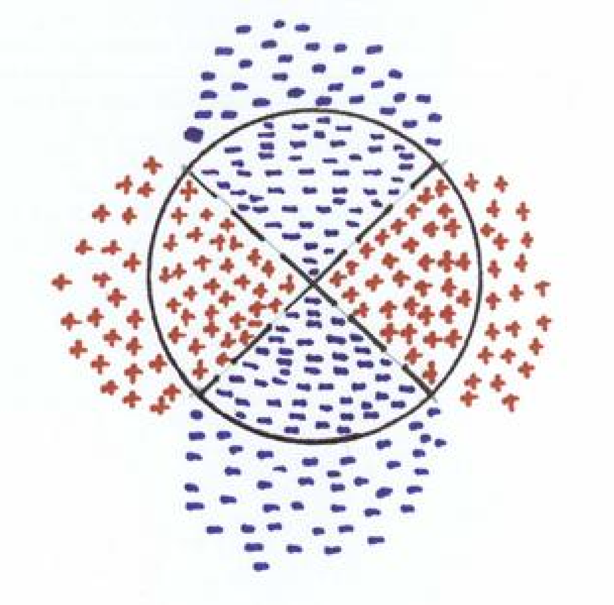
can be extracted

from the star by

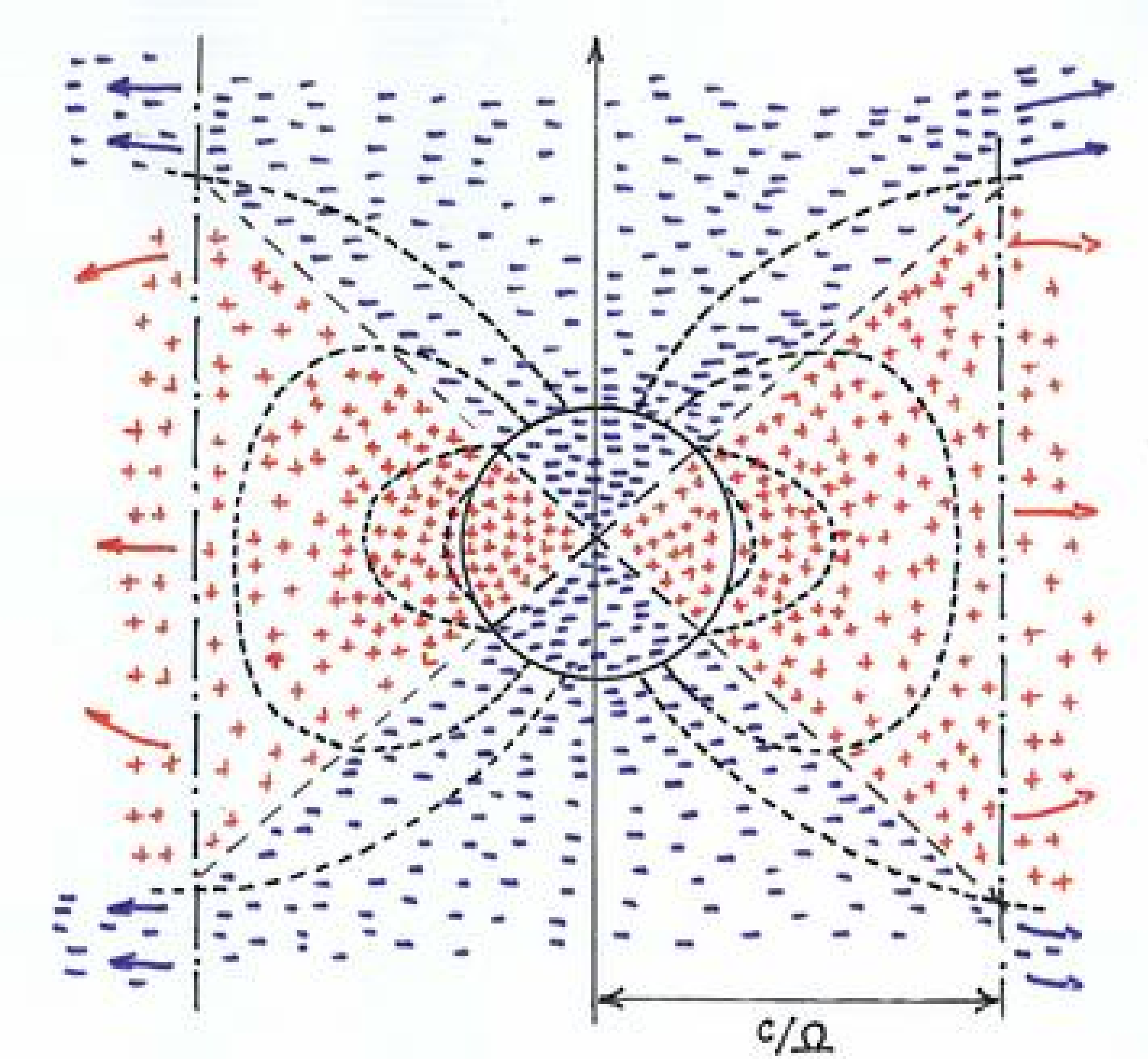
strong E at the

star's surface

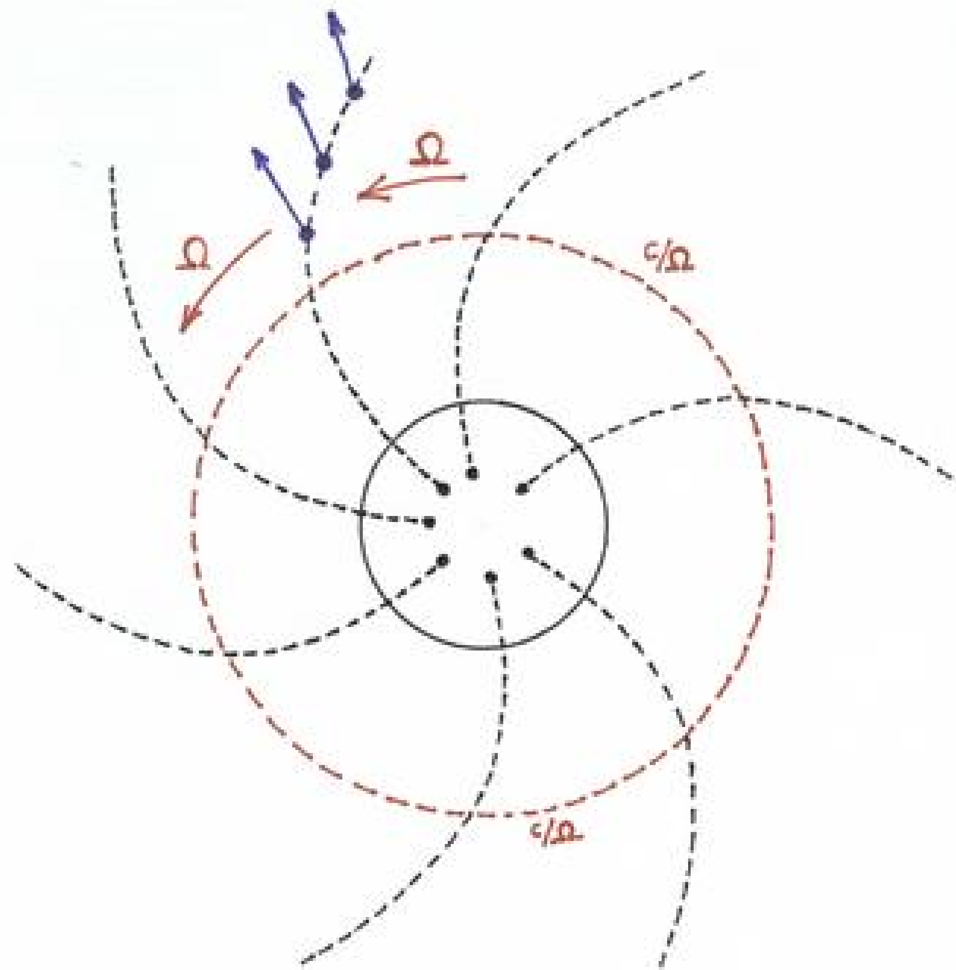




A FILLED ELECTROSPHERE ?



WITH CENTRIFUGALLY DRIVEN CHARGED OUTFLOW ?



PULSAR WIND NEBULAE

At a few R_L's,

Wind = Large Poynting Flux

+ Small Relativistic Particles Energy Flux (σ >>1)

γ of order 10^2 near R_L.

Far from R_L, rams into nebular material

Forward + reverse (= ring) **shocks**

Non spherical (wind anisotropy)

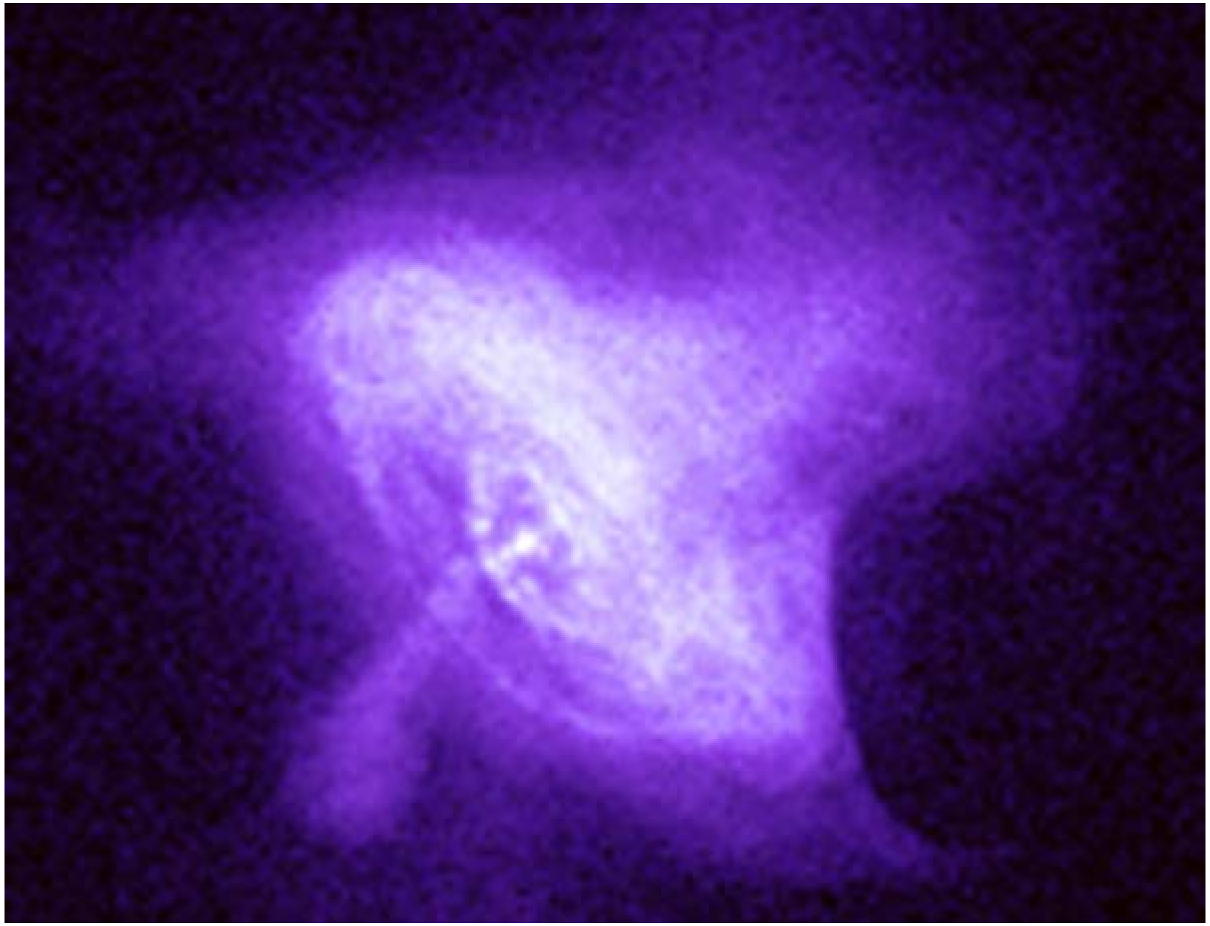
Poynting **energy $\Rightarrow$ entirely into particle's (σ << 1)**

$\Rightarrow$ Synchrotron-emitting torus after shock

Implies CR electrons with γ factors > 10^6

$\Rightarrow$ TeV gamma rays by IC of these e^- on

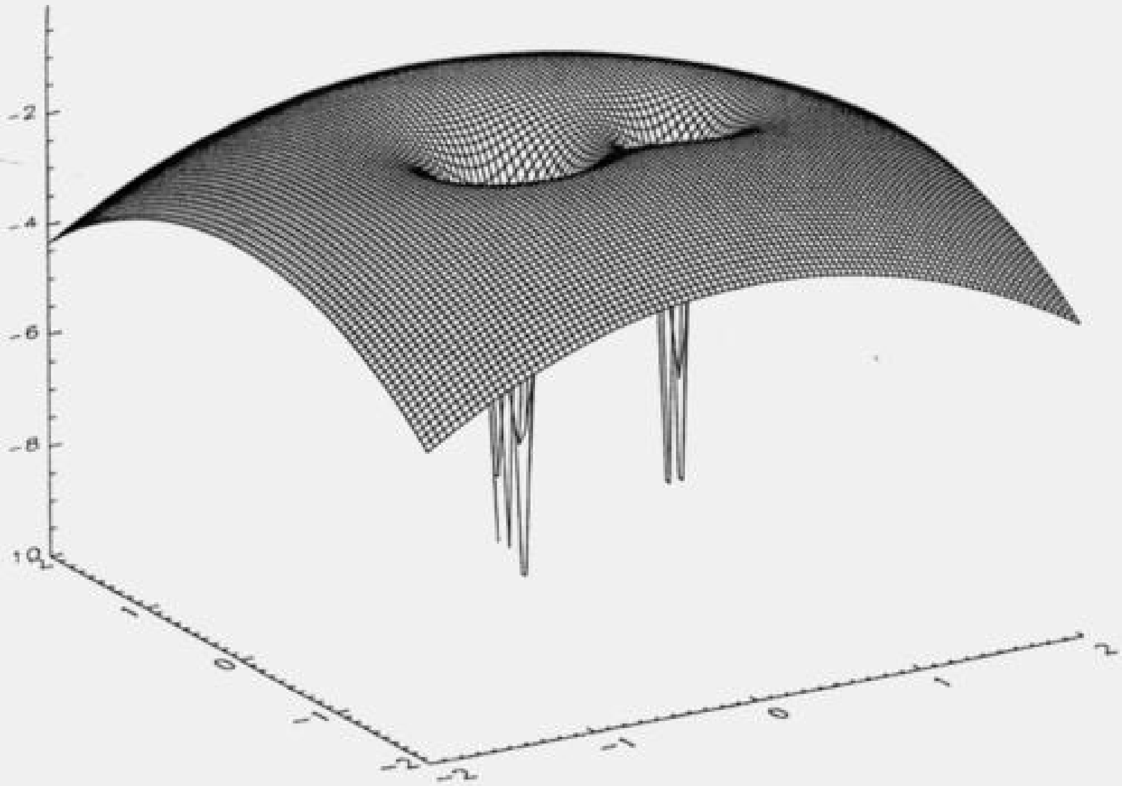
« local » IR , Opt, UV photons (syncho self emitted)



GRAVITATIONALLY POWERED:

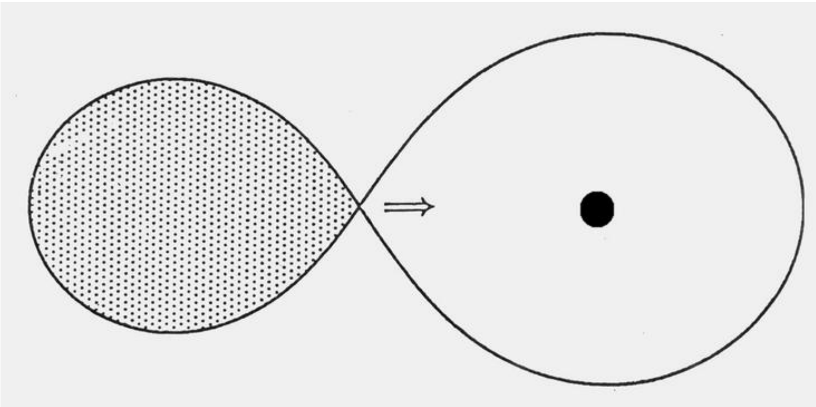
BINARY X RAY SOURCES

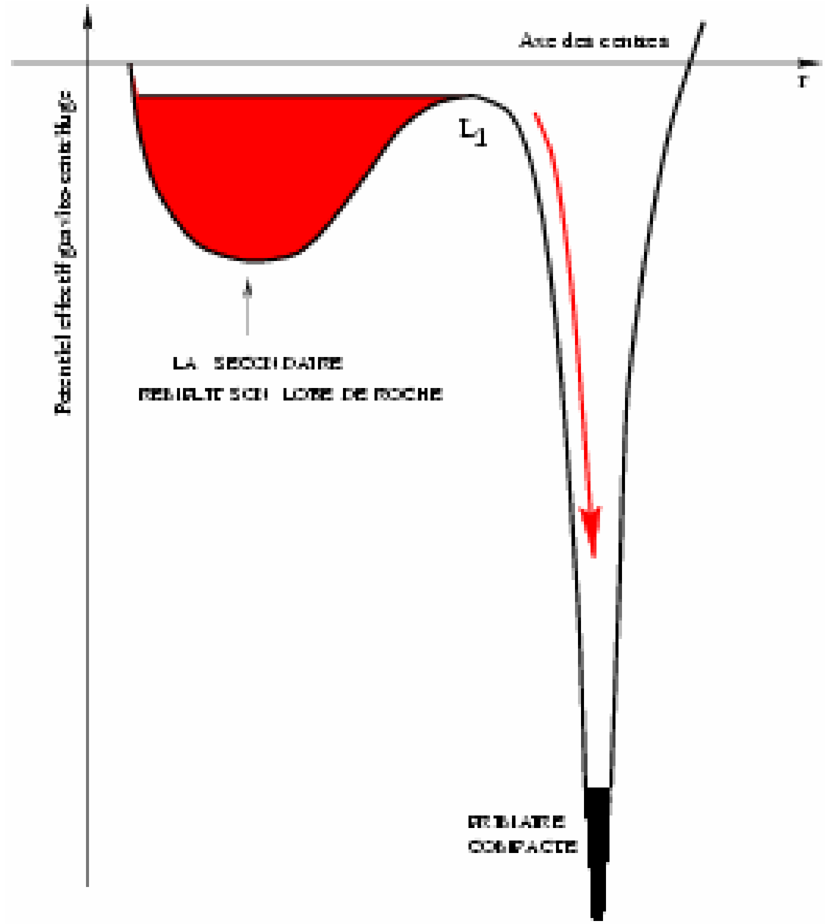
ROCHE POTENTIAL



$$\Phi = -\frac{GM_1}{|r - r_1|} - \frac{GM_2}{|r - r_2|} - \frac{1}{2}|\omega \times r|^2$$

ROCHE LOBE OVERFLOW





GLOBAL PHYSICS of XRB

1kg falling to R_* frees **GM_*/R_*** of Pot. Energy :

$$L = G\,M'M_*/R_*$$

$$L = 4\pi R_*^2\,\sigma_B T^4$$

Neutron stars and stellar-mass BH $\Rightarrow$ **X Rays**

∃ different types of XR Binaries :

If magnetosphere : Polar caps, XRpulsars

Mass measurements possible from Döppler on spin period

t=45

ACCRETING BLACK HOLES EXIST !

- **High Mass** companions (≈ 7 – 20 $M_{\odot}$)
  = **persistent** sources, soft X

- **Low Mass** companions (≈1 $M_{\odot}$)
  = **transients** sources

Soft XRT or XRNovae ; short orbital period

Shine high in soft X Rays for weeks

Then fall into a low state for years emitting hard X

∃ also XRNovae with n*

PHYSICS OF ACCRETION

Falling fluid elements have angular momentum
(= suffer Coriolis force in frame of line of centers)

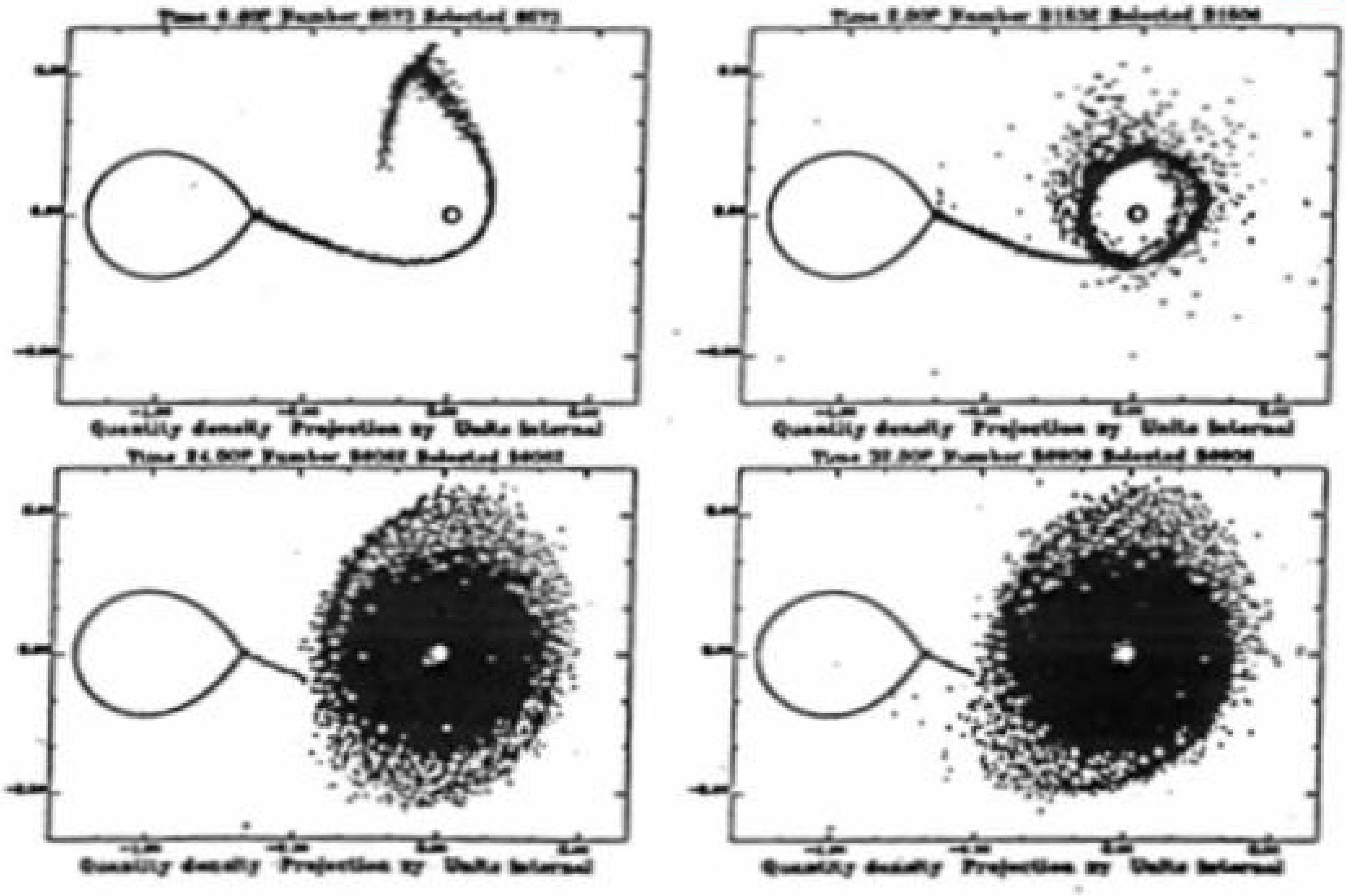
THE MAIN PROBLEM :
TO LOSE ANGULAR MOMENTUM

- Viscous stresses
- Lorentz torques

$\Rightarrow$ Formation of an ACCRETION DISK

VISCOSITY-DRIVEN ACCRETION

FORMATION OF A DISK BY VISCOUS STRESSES



CONSEQUENSES OF ACCRETION

- **Changes in properties of the system :**

Center of mass. Individual star evolution.

Roche geometry.

Sometimes ∃ net loss of mass or ang. mom.

- **Spin-up of the accreting object :**

… with or without a magnetopause

⇒ **Origin of millisec. pulsars**

VISCOUS DISK STRUCTURE

Shakura-Sunyaev : $\nu_{turb} = \alpha H c_S$

Disk locally described algebraically if

- ➢Stationary
- ➢Radiative local energy balance
- ➢Driven by turbulent viscosity

Parameters : α and M'

NON RADIATIVE SOLUTIONS @ SMALL M'

ADAF's : ADVECTION -DOMINATED

VISCOUS DISK STABILITY

BISTABILITY for

SOME OPACITY REGIMES

LOCAL LIMIT CYCLES

COMMUNICATED TO

ALL DISK

RECURENT CYCLES

AVALANCHES/

REPLENISHMENT

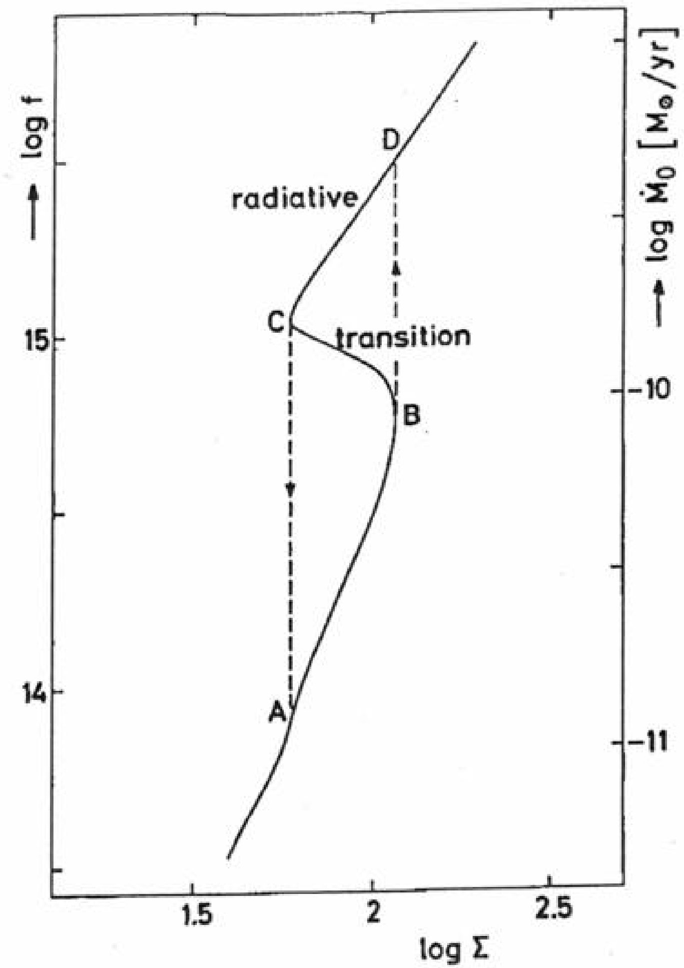


Figure 2. Viscosity integral f as a function of surface density Σ at log r = 10 (cgs units except $\dot{M}_o$).

ACCRETION AVALANCHES

1- M' in disk < $M'_{injected}$

Mass accumulates

2- Avalanche episode

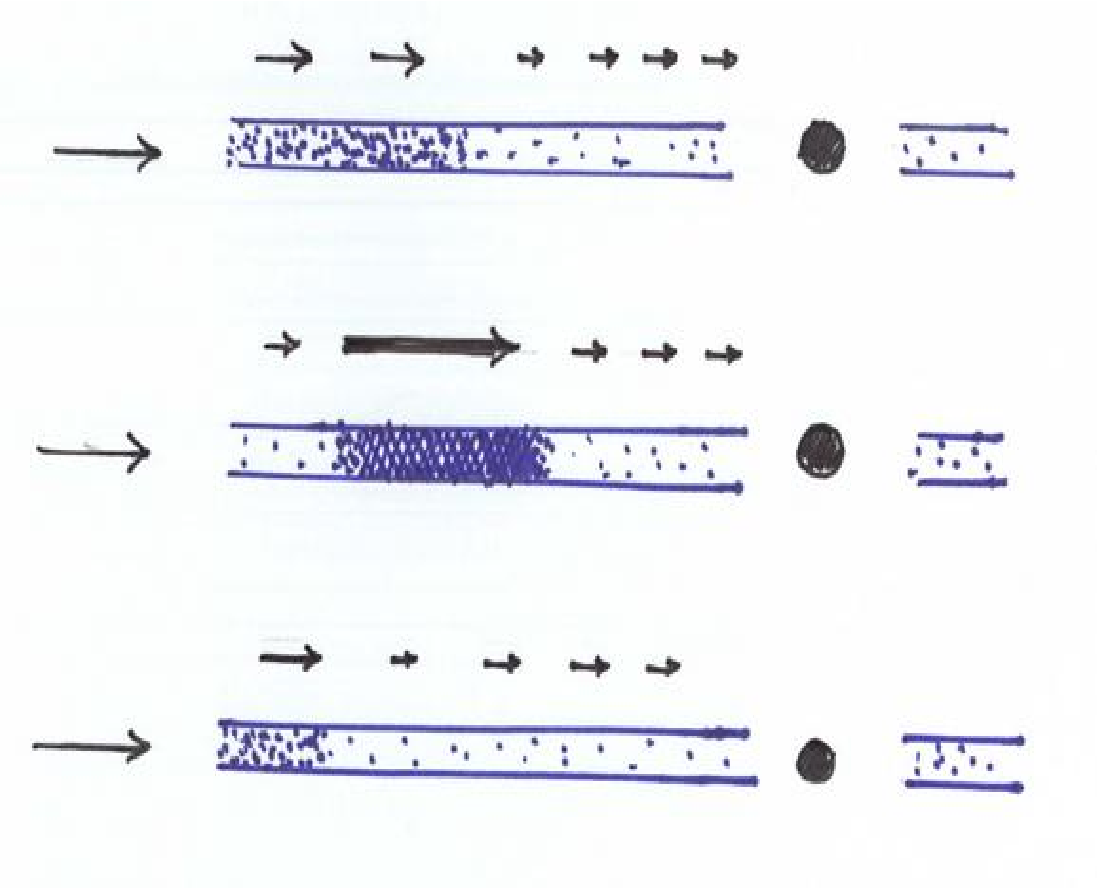
M' in (part of) disk > M'_{inj}

A wave of high matter flux travels through the disk, almost emptying it

3- Back to

M' in disk < M'_{inj}

Disk replenishes again



LORENTZ-FORCE-DRIVEN ACCRETION

JETTING OBJECTS

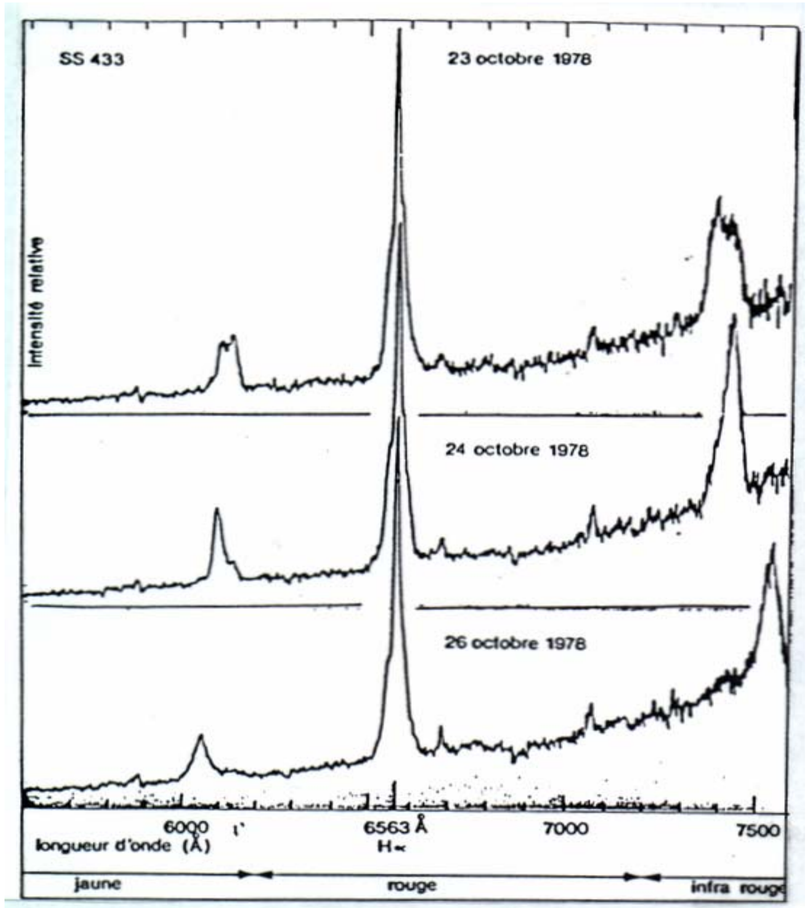
ACCRETION AND EJECTION ARE RELATED PHENOMENA

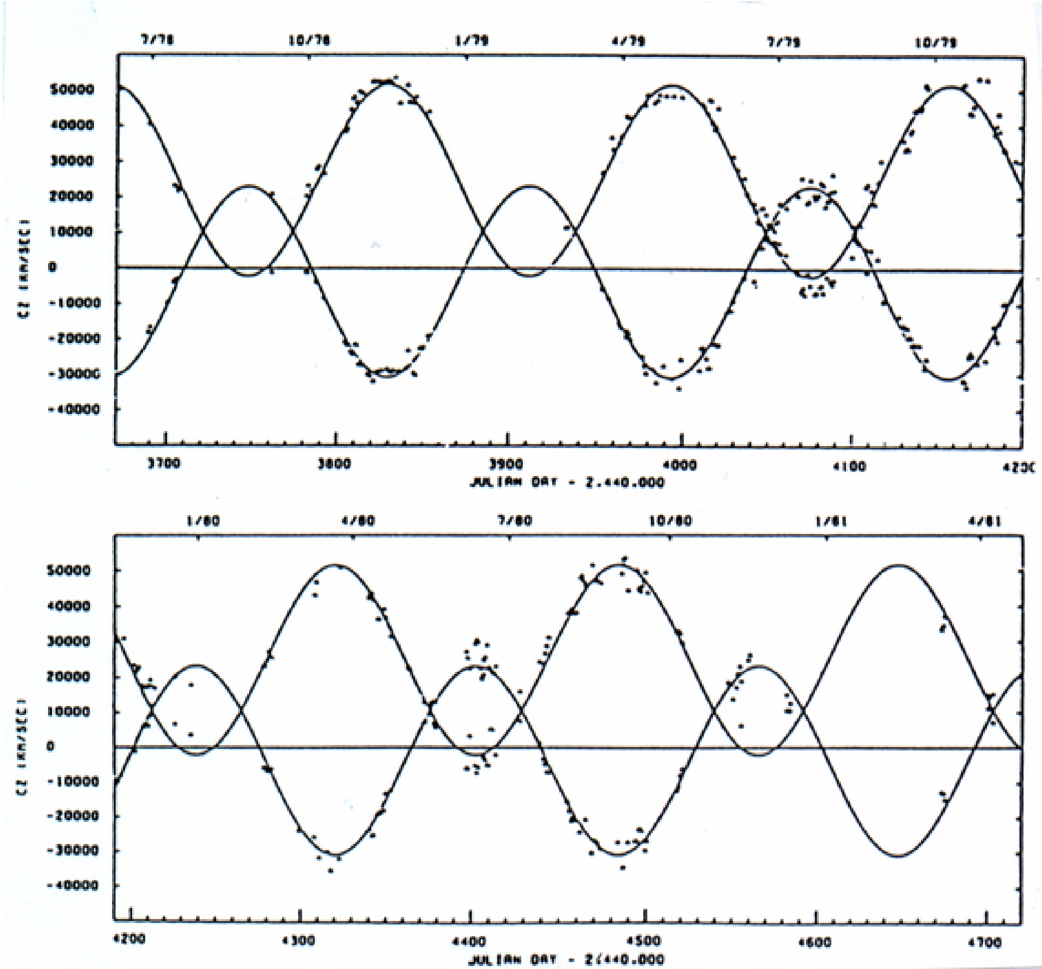
Observed in different objects, like

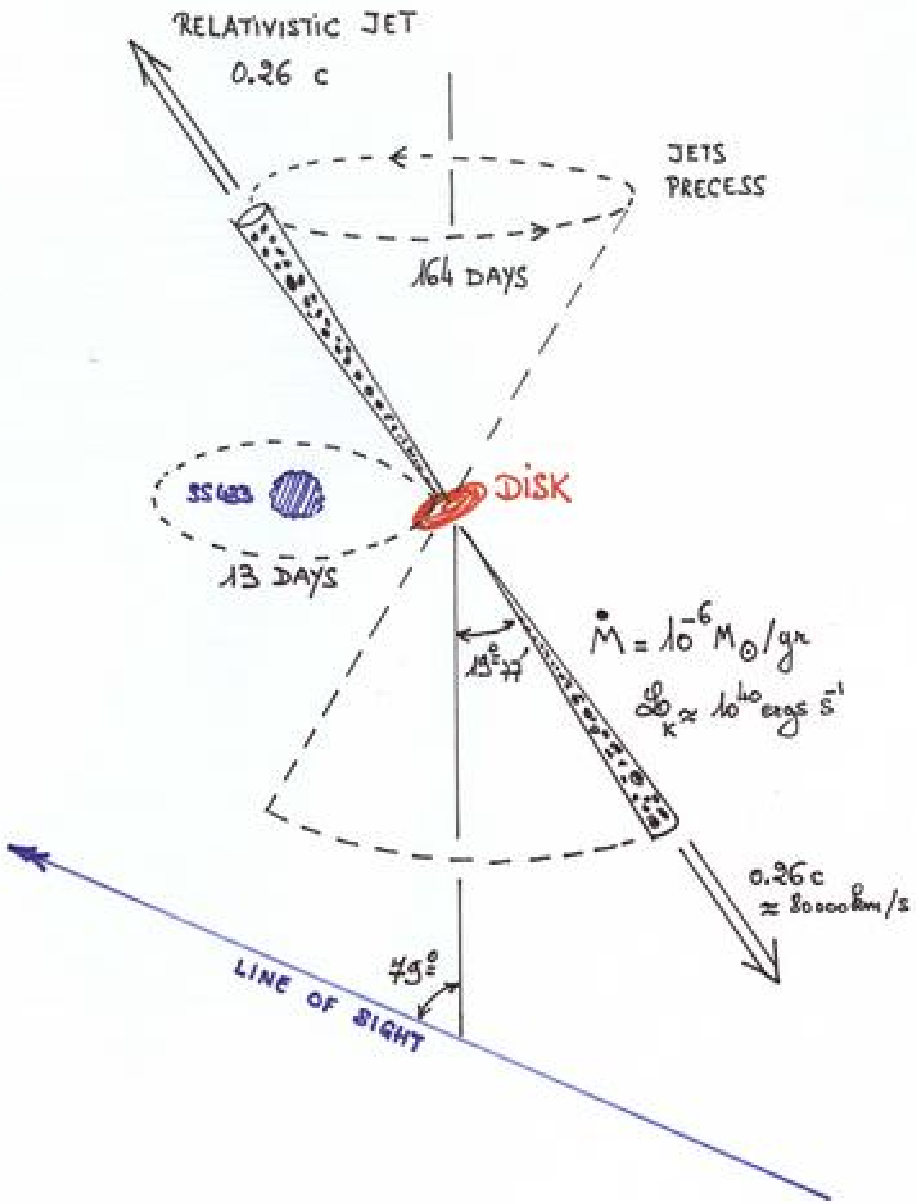
- **JET BINARY X RAY SOURCES**
- **YOUNG STARS IN FORMATION**
- **ACTIVE GALACTIC NUCLEI**

t=1h

SS 433: THE DISCOVERY







RELATIVISTIC JET
0.26 c
JETS
PRECESS
164 DAYS
SS433
DISK
13 DAYS
$\dot{M} = 10^{-6} M_\odot/yr$
$\mathcal{L}_K \simeq 10^{40}$ ergs s^{-1}
19°47'
0.26 c
≃ 80000 km/s
79°
LINE OF SIGHT

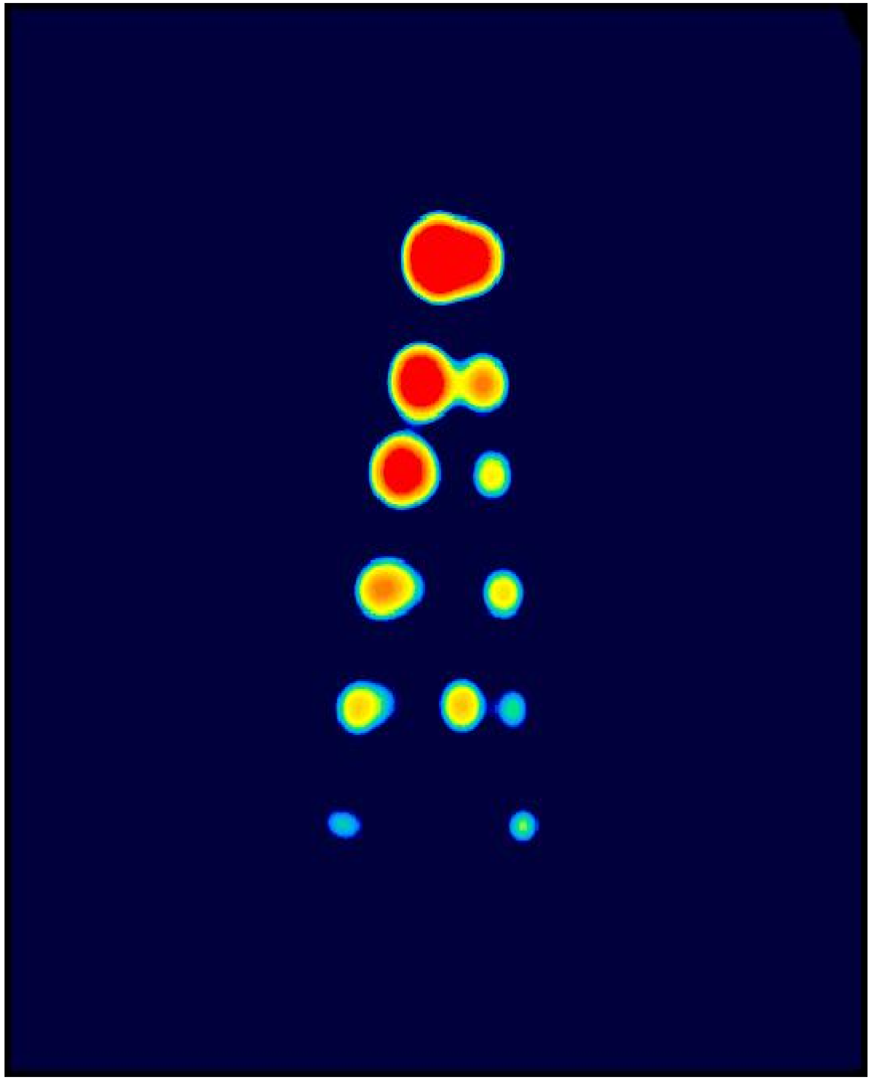
GRS 1915+105: a JET at 0,92 c

Some X ray sources
= transient or variable

Superluminic
apparent motion
of radio-emitting gas
= geometric illusion

GRS 1915:

v_{app} = 1.25 c
v_{real} = 0.92 c



ACTIVE GALACTIC NUCLEI

Some galaxies have « **Active Galactic Nuclei** »

Nebular emission spectrum; $v = 10^4$ km / s

Quasars = nuclei overshining their host galaxy

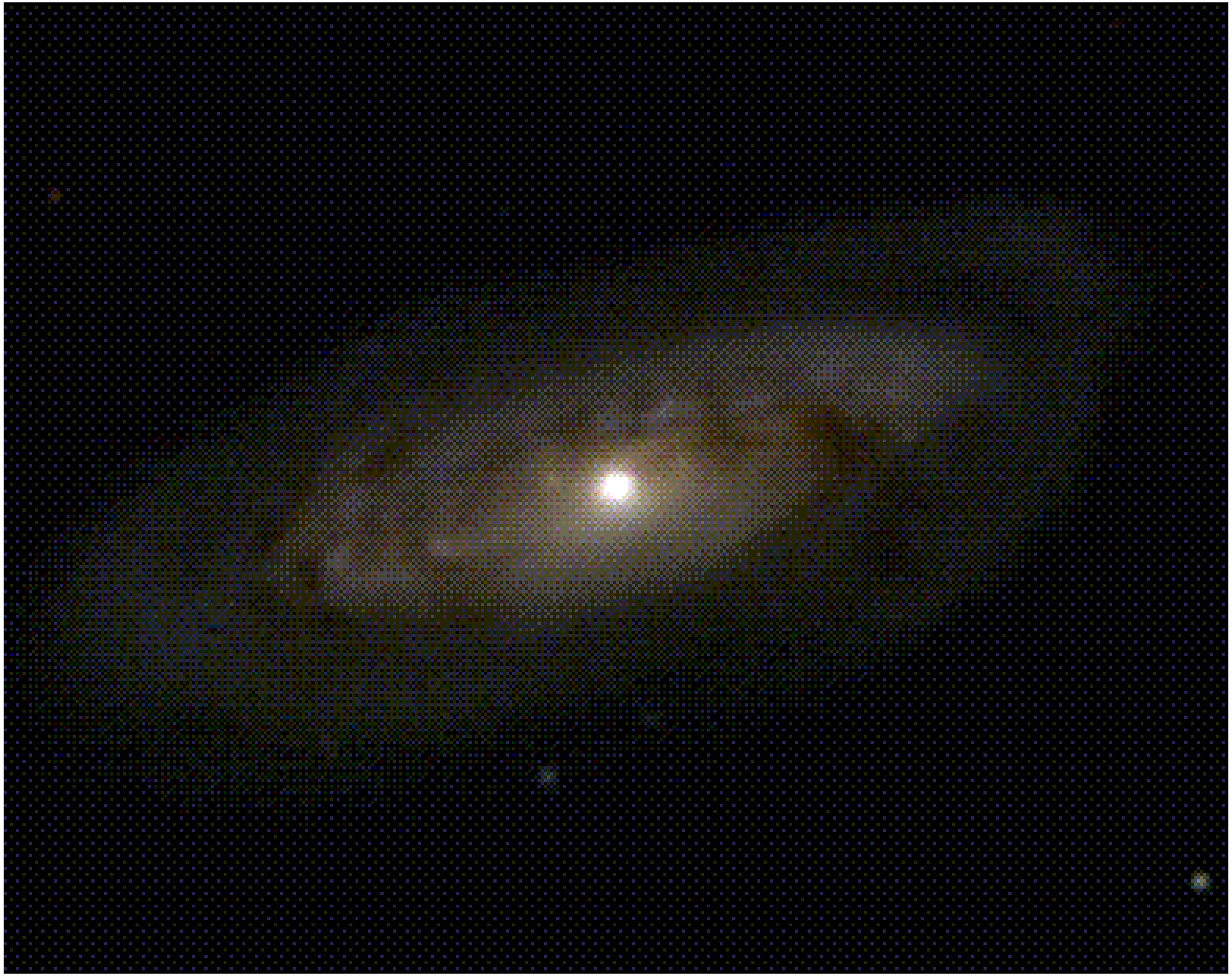
@ cosmological distances

Extragalactic radio sources

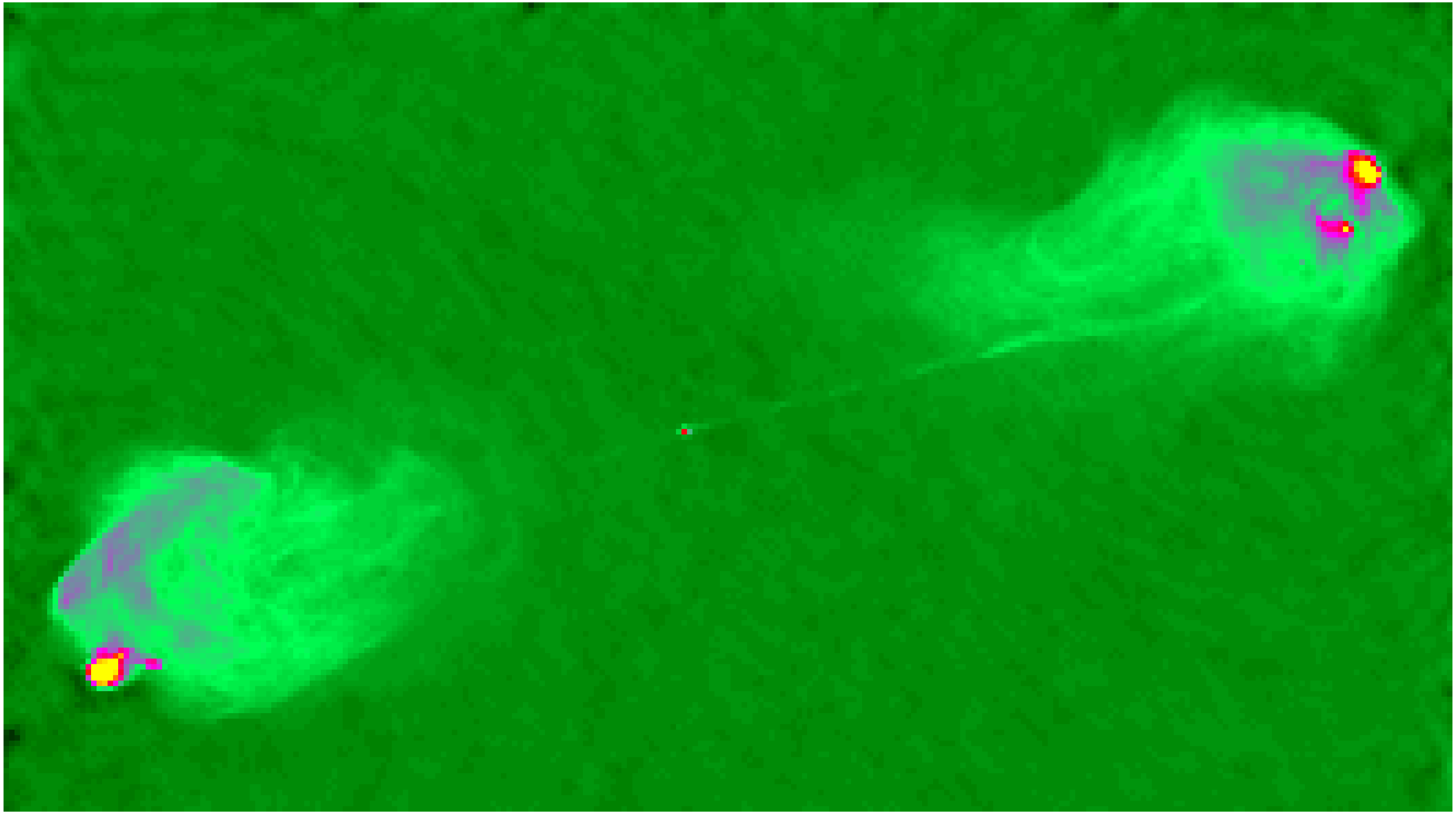
originate in galactic nuclei

= compact sources + **jets** + hot spots + lobes

Superluminic phenomenon observed for some



CYGNUS A



NATURE OF AGN's ?

- Variability in X ray < days
  - ⇒ Source < light days = size of solar syst.

- Enormous luminosity 10^{42} ergs/s
  - ⇒ very efficient energy transformation

⇒ Accreting Black Holes 10^8-10^9 $M_\odot$

Supported by fitting Opt UV spectrum
fitting broad line profiles (Opt, K_α)
variability constraints + other checks

SgrA*, our nucleus

- 10% of galaxies have a « presently » active nucleus
- But some nuclei may be inactive !!

DOES ANY GALAXY HAS A NUCLEUS ?

OUR GALAXY ? Precise IR obs. (adapt. optics) of central radio source

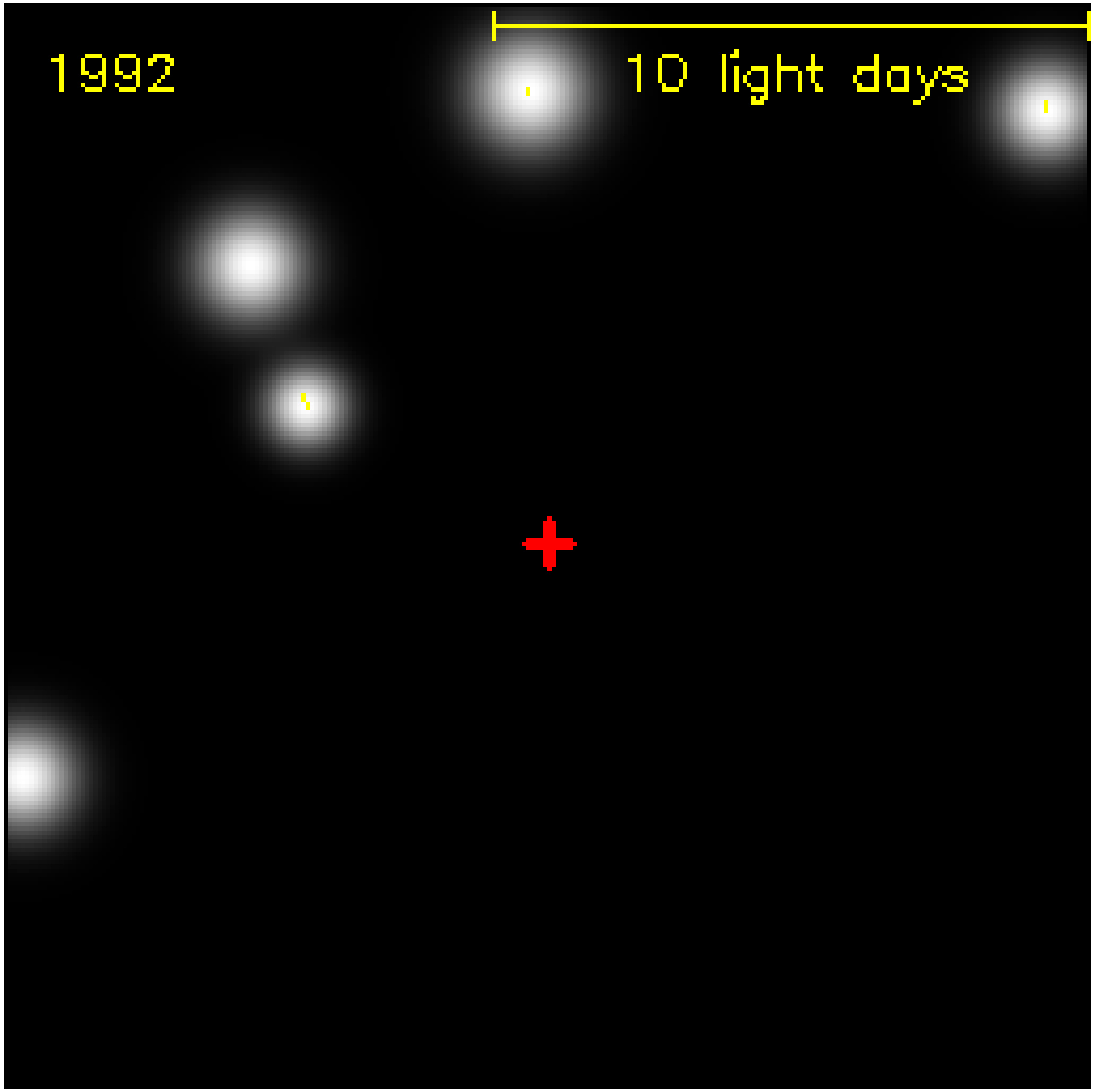
$\Rightarrow$ **SgrA* = CENTRAL MASS CONCENTRATION**

3.6 10^6 M_O in 20 light days = a BH !!

SgrA* is in a low luminosity ADAF state

= « starved » BH

PROBING THE GALACTIC CENTER's POTENTIAL



JETS ARE MHD WINDS

VxB electromotive field

generates currents in moving conductor

JxB Lorentz force **acts** on moving conductor

MHD WIND = A MOTOR THAT IS ITS OWN DYNAMO

E+VxB = 0 for a very good conductor.

$\Rightarrow$ field and matter stuck to eachother

(flux freezing theorem)

t=1h15

STRUCTURE OF AN MHD WIND

Axisymmetric + Stationary

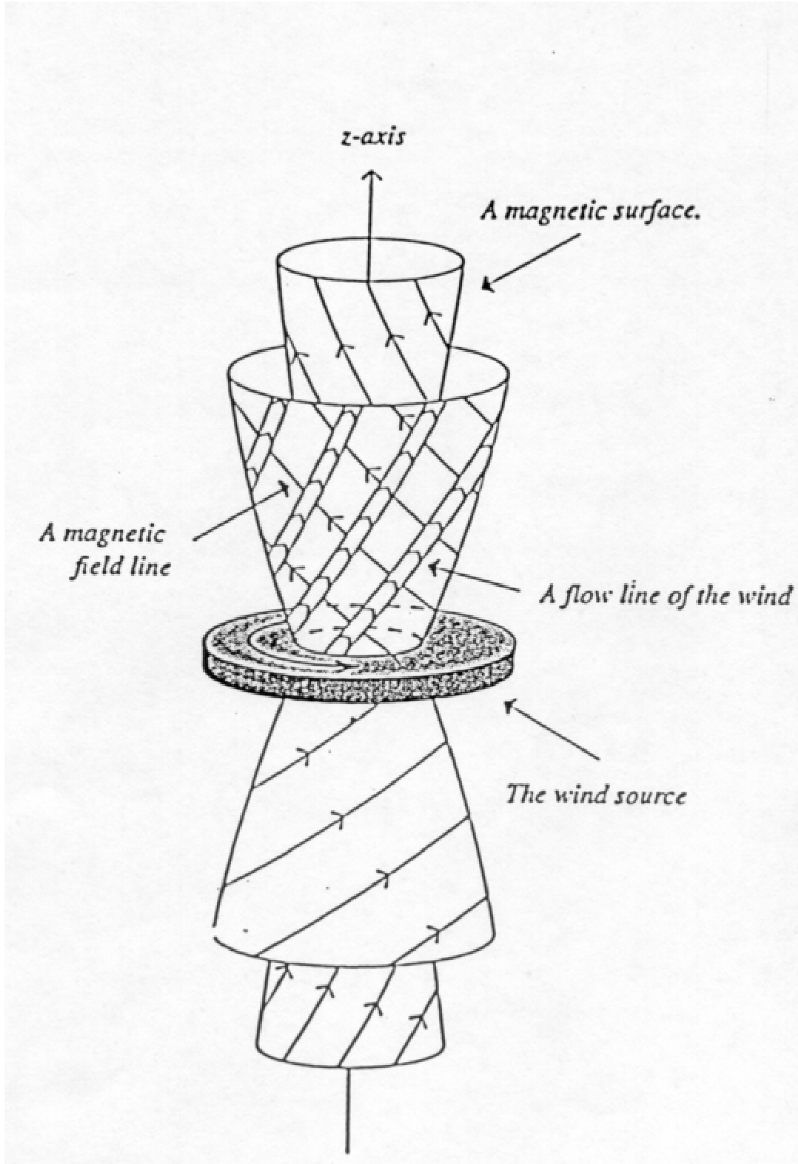
Magnetic surfaces

$a(r,z) = a$

= Flow surfaces

Foot point entrained by fluid motion on source $\Rightarrow$ Helical field lines

$$\mathbf{v} = r\,\Omega(a)\,\mathbf{e}_\phi + k\,\mathbf{B}$$

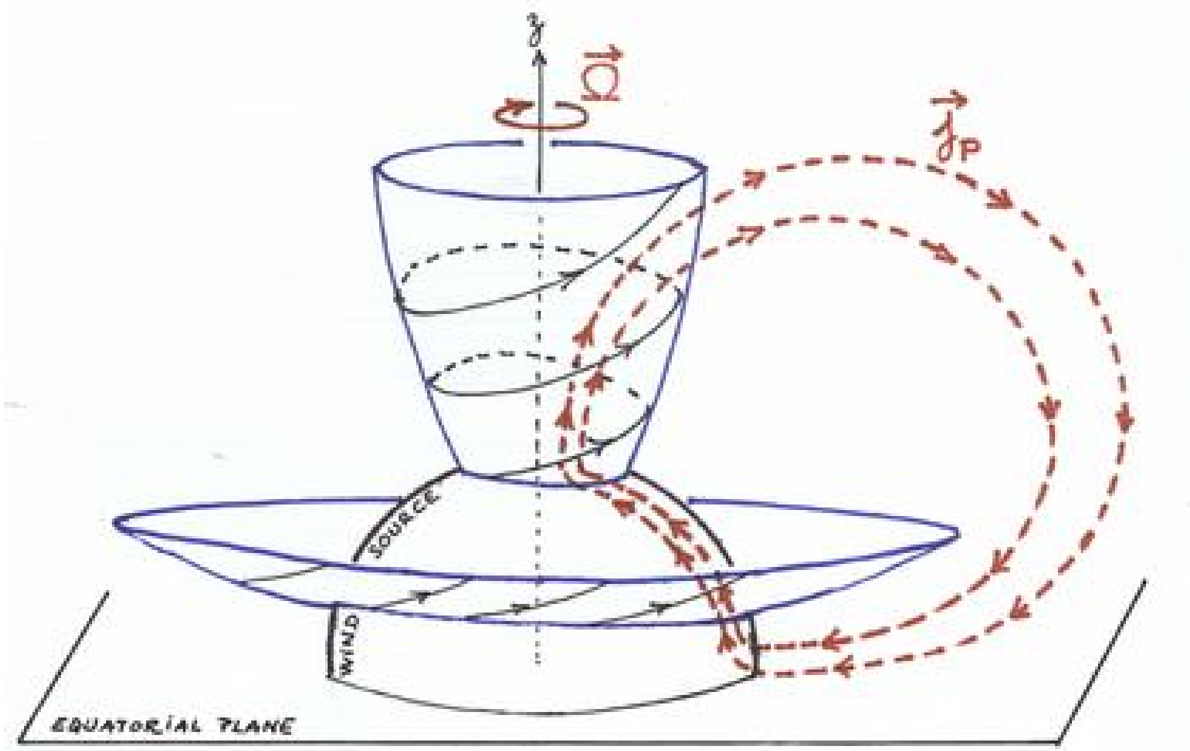


THE BRAKING LORENTZ TORQUE

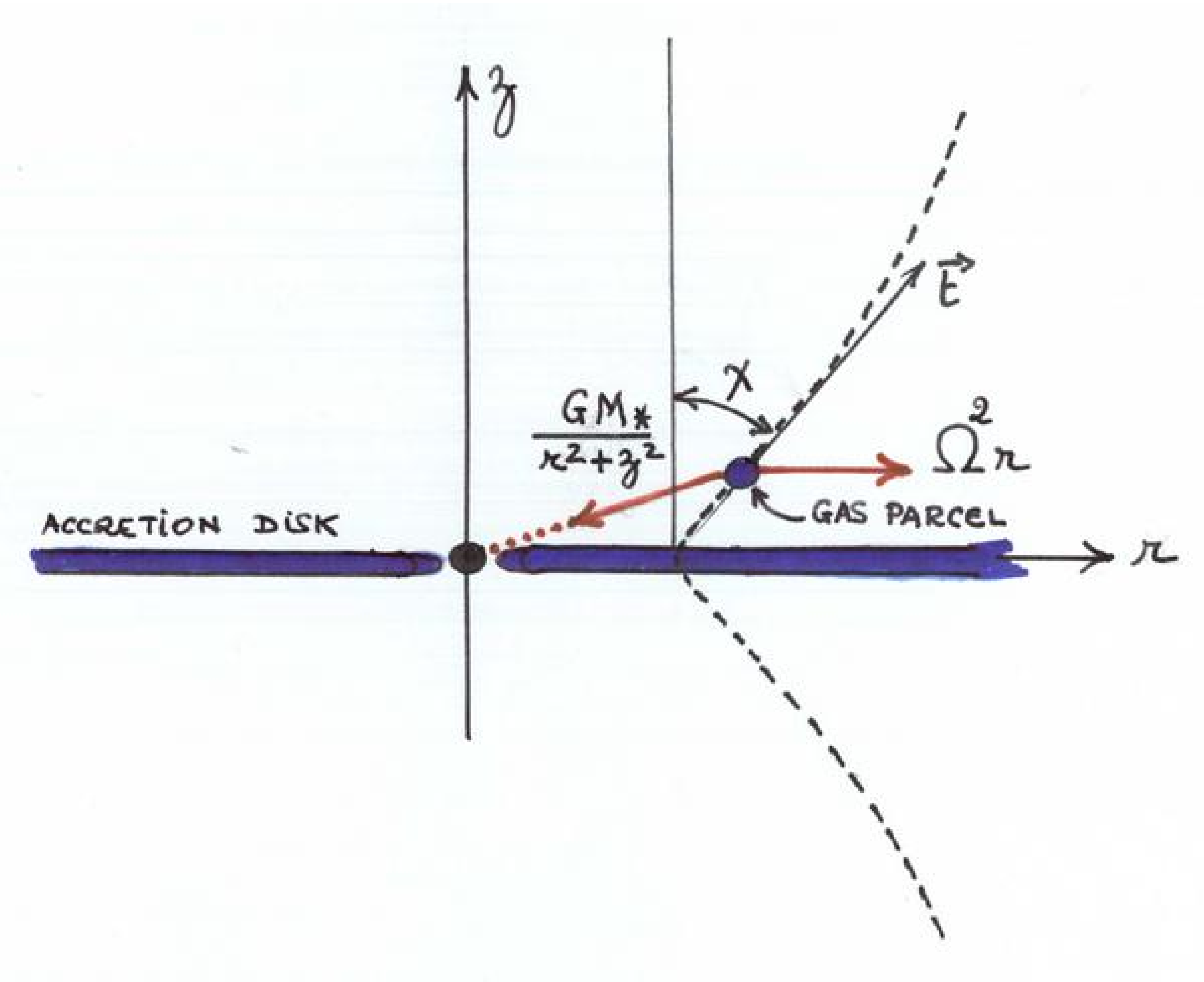
WIND-CURRENT CLOSES IN THE WIND-SOURCE.

$\mathbf{j}_P \times \mathbf{B}_P$

in the source exerts a BRAKING TORQUE allowing accretion



CENTRIFUGAL WIND EJECTION



CENTRIFUGAL WIND PROPERTIES

$\chi > 30°$ $\Rightarrow$ matter at foot point in unstable position

Centrifugal ejection

ACCRETION CAUSES
WIND EJECTION !

WIND EJECTION
CAUSES ACCRETION !

Velocity at ∞ $\approx$ escape velocity

PRESSURE AND RADIATIVE FORCE HELP!

DIFFERENT LORENTZ FORCES

$$JxB = (J_P+J_\phi)x(B_P+B_\phi) = (J_PxB_P) + J_PxB_\phi + J_\phi x B_P$$

1 **2** **3**

1 = Toroidal torquing force (direction ϕ)

2 = $\mathbf{J}_{P//}$ x $\mathbf{B}_\phi$: « pinch » poloidal force $\perp$ to $\mathbf{B}_P$

$\mathbf{J}_{P\perp}$x $\mathbf{B}_\phi$: field-aligned « coiled spring » force

3 = Poloidal magn. pressure and tension force

Shapes magnetic surfaces

FOCUSING

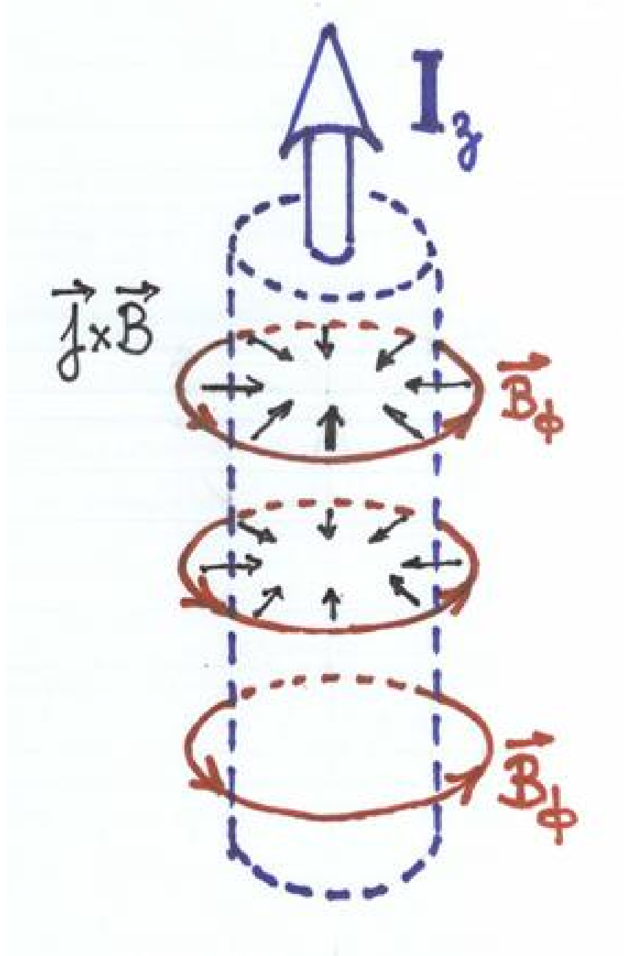
Focusing from pinch force :

Ampère near axis :

$$2\pi r\, B_\phi = \mu_o\, I_z$$

$$\mathbf{j}_z \times \mathbf{B}_\phi = \mathbf{-}\, (\mu_o /2\pi r)\;\; j_z\, I_z\, \mathbf{e}_r$$

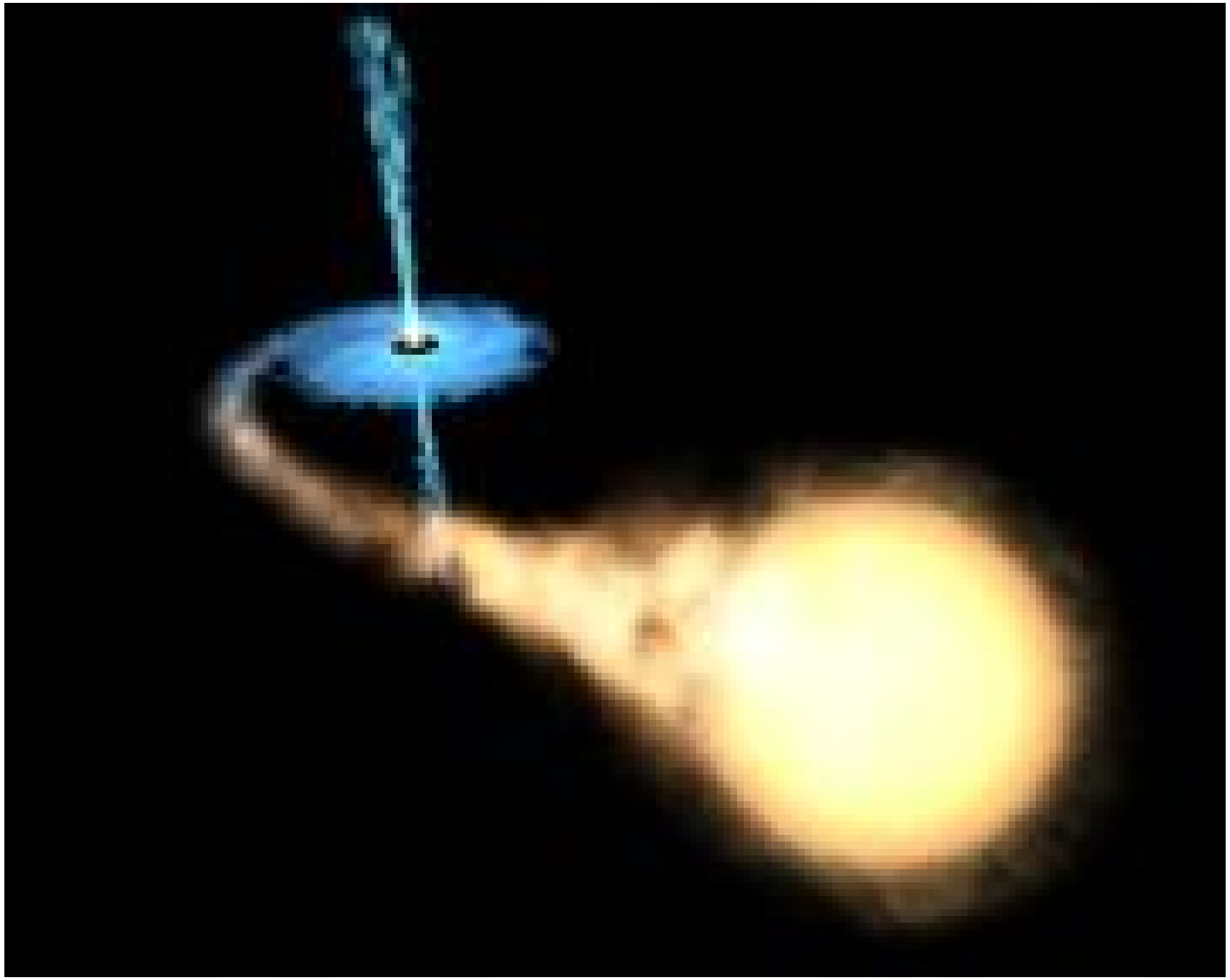
Theorem : the pinching force focuses the wind asymptotically

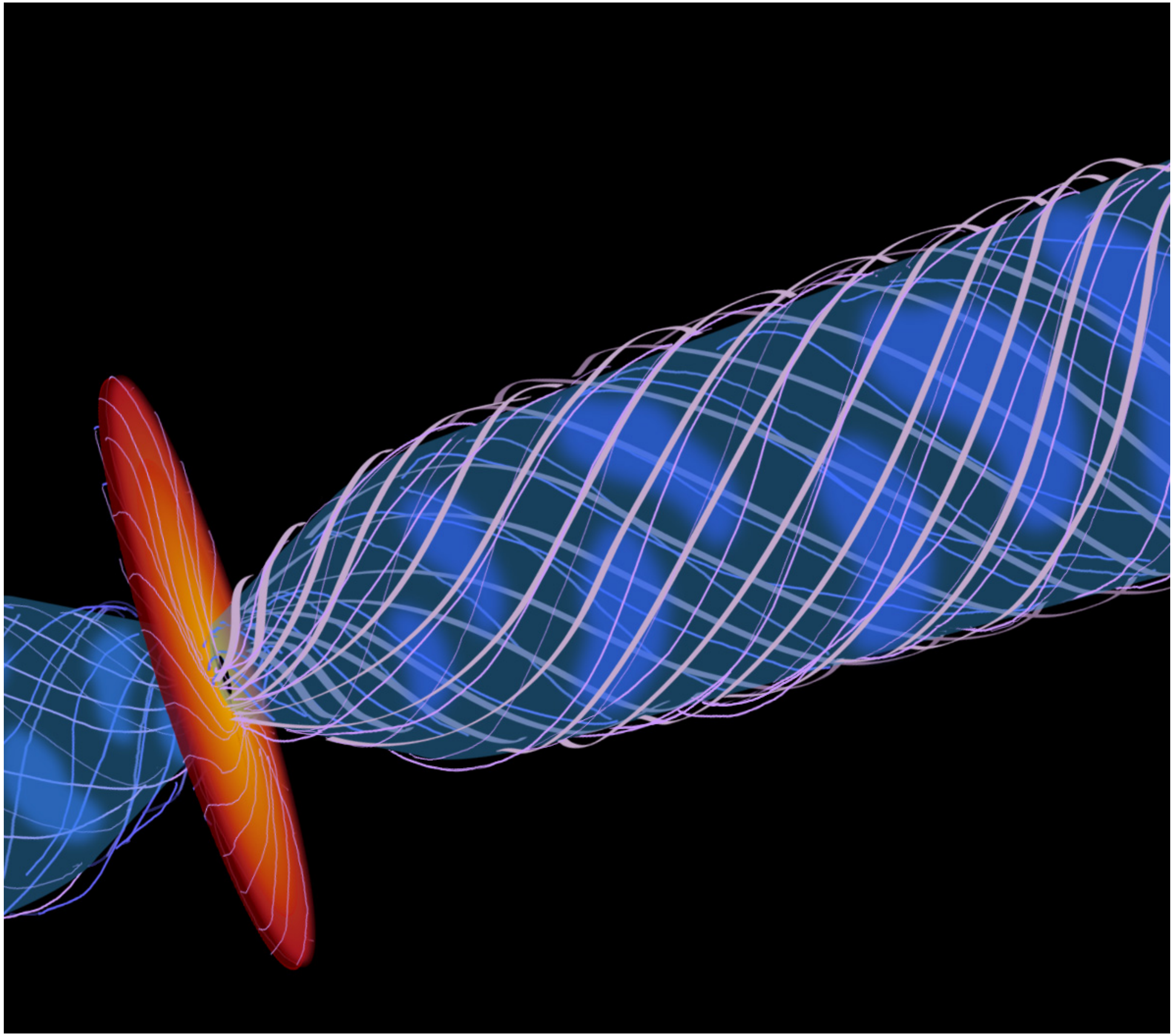


Wind is forced to the axis

near pole

to form a « jet »





GAMMA RAY BURSTS

WHAT IS A GAMMA RAY BURST?

Serendipitous military discovery (1967, revealed 1973)

Short, strong γ ray emission ($\tau = 10^{-3} – 10^{3}$ s.)

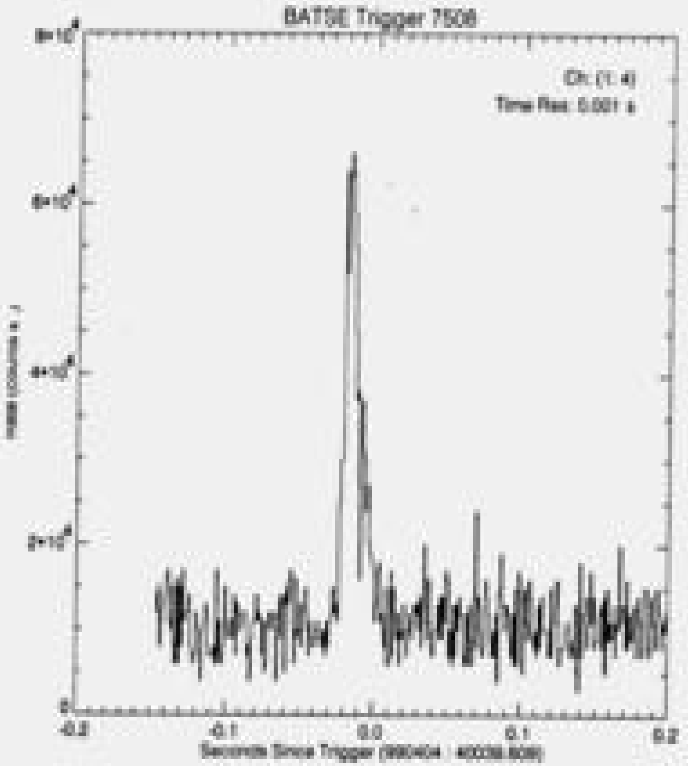
Hard X – MeV gammas, sometimes GeV's.

Frequent (about one per day) @ present sensitivity

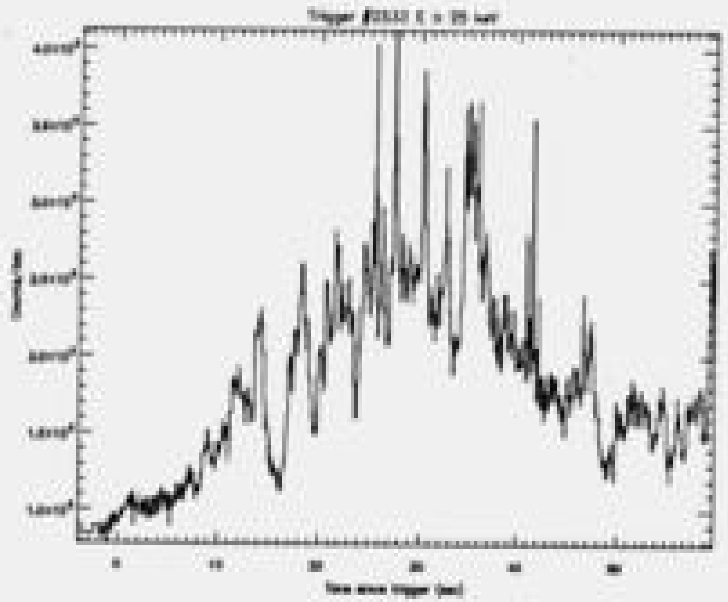
No obvious counterpart, **excpt. March 5th 1979 in SNR N49 (30 Doradus LMC)**

No recurence, except a few « repeaters »

GAMMA RAY BURST LIGHT CURVES

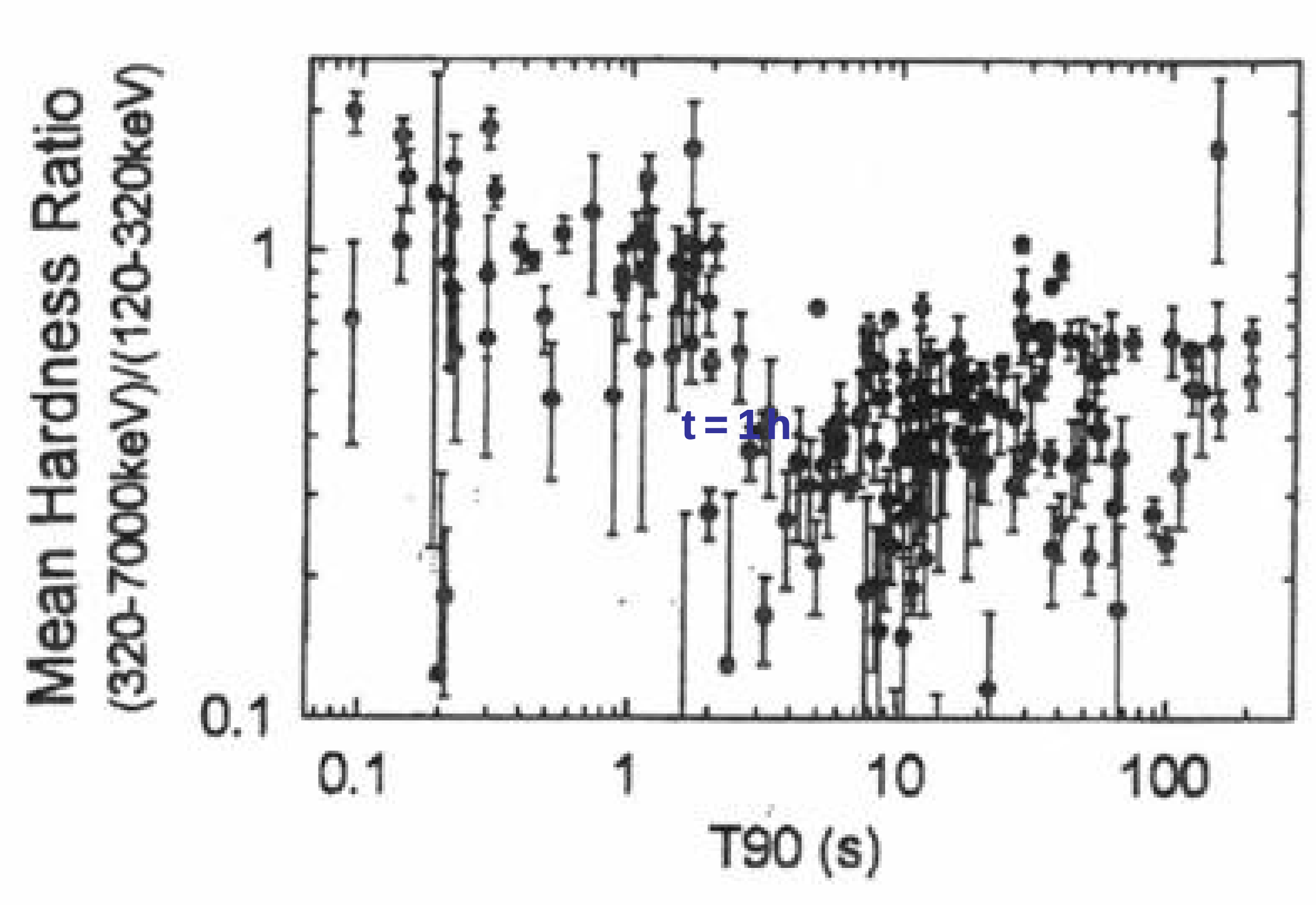


1 graduation = 0.01 sec



1 graduation = 1 sec

LONG AND SHORT BURSTS



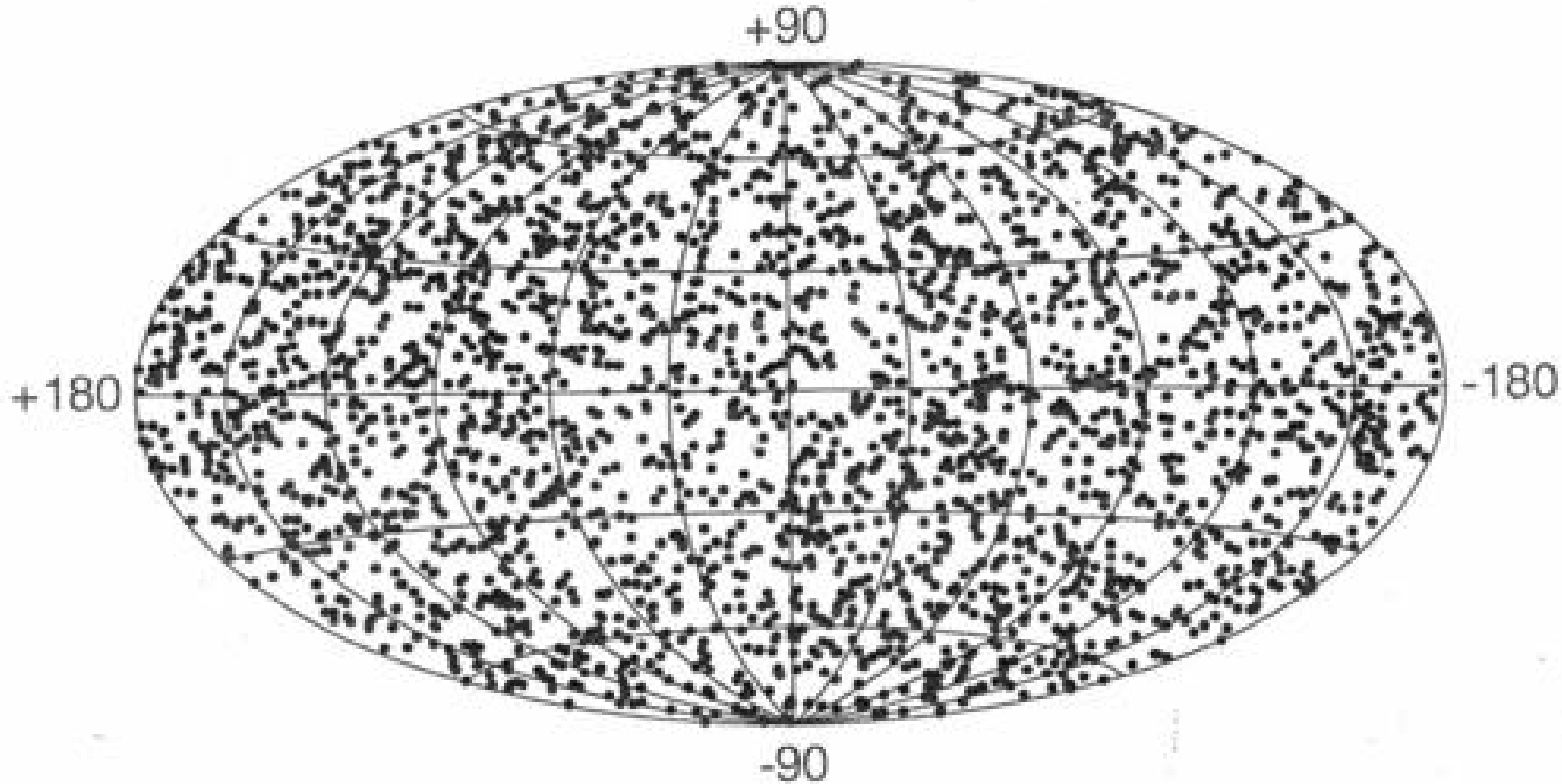
∃ **3d class : Soft Gamm a ray Repeaters (galactic)**

t=1h30

WHERE ARE GAMMA RAY BURSTS?

VERY ISOTROPIC DISTRIBUTION

$\Rightarrow$ VERY LOCAL OR @ COSMOLOGICAL DISTANCES !!



THE FIRST OPTICAL AFTERGLOW

08 May 1997 : GRB 970508

X RAY COUNTERPART IN REAL TIME

BY BEPPO SAX

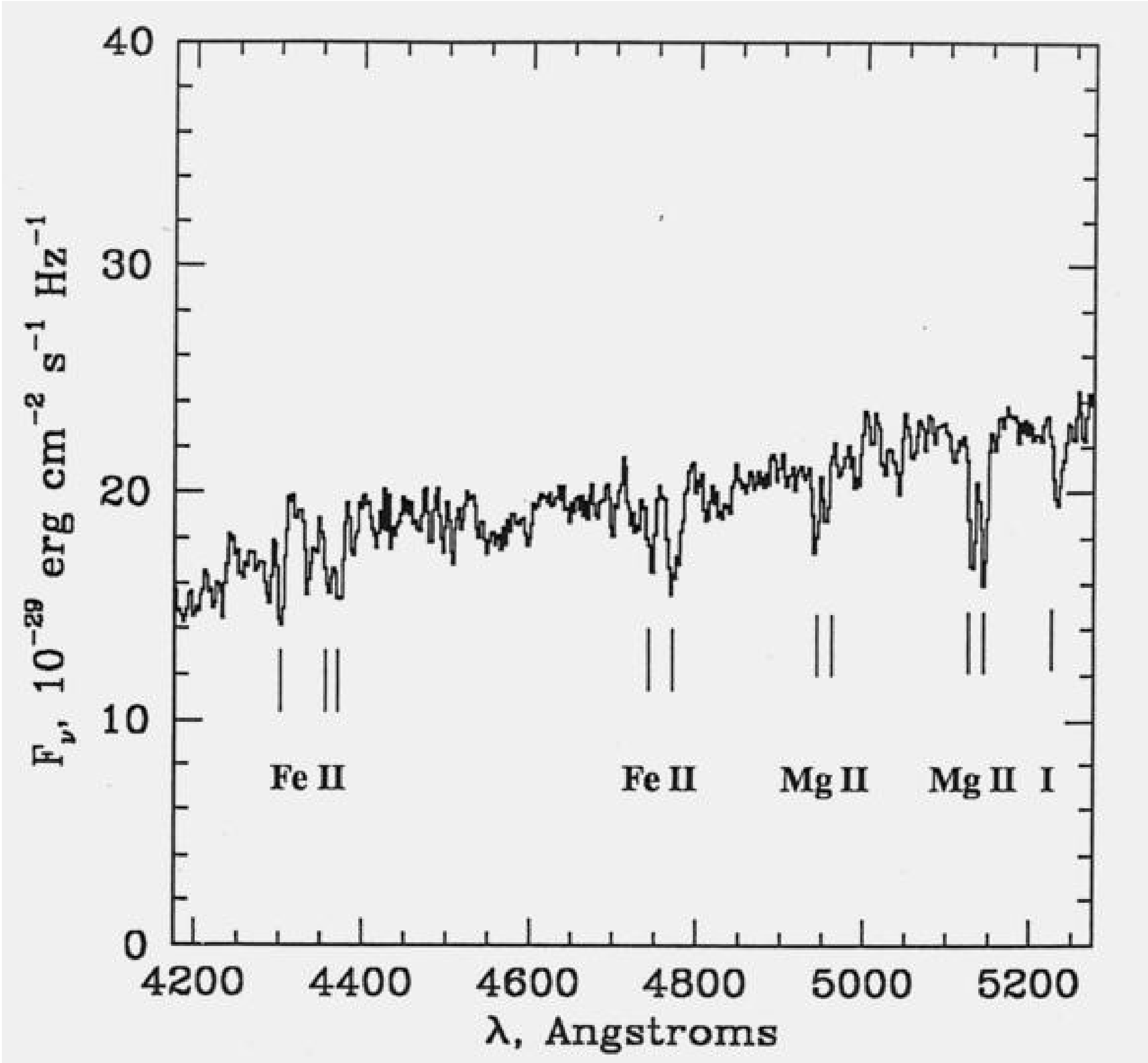
OPTICAL OBSERVATIONS
FEW HOURS AFTER

OPTICAL COUNTERPART VISIBLE FOR 5 DAYS.

KECK SPECTRUM ON MAY 11TH $\Rightarrow$

FEII AND MGII ABSORPTION
SYSTEMS @ Z = 0.835!!
In a star-forming Dwarf Galaxy

THE FIRST OPTICAL COUNTERPART



MORE COUNTERPARTS

40 X-optical-radio afterglows

obs[d] in 2 years with **Z = 0.4 - 4.5**

All in the « **long class** » and in Dwarf Galaxies

(Beppo Sax misses the ones < 5 sec)

Afterglow = synchrotron emission

by an expanding source in relativistic motion

In one case ROTSE detects

prompt optical emission

Fades out in about 700 sec.

THIS PROMPT OPTICAL SOURCE

MUCH BRIGHTER THAN A QUASAR!

EVEN MORE COUNTERPARTS

SWIFT MISSION (launched November 2004)

detects soft X ray counterpart of

GRB 050506 (40 millisec duration)

Since then, a handful of others

@ edge of an

old, red host Galaxy.

No star forming regions.

Not really at cosmological distances.

NATURE OF GAMMA RAY BURSTS

LONG BURSTS :

Probably a rare type of supernova (hypernovae)

A star should end as an hypernova with probability 10^{-6}.
$M > 40\ M_{O}$ (?)
Massive star core collapse when merging with a companion ?

Propulsion by radiation (?) Neutrinos : efficiency pb.
If centrifugal MHD wind from collapsing core,
10^{15} Gauss required to accomodate the short time scales.

Duration: accretion time of fall-back material

AFTERGLOW = « SNR » emission in relativistic regime

NATURE OF GAMMA RAY BURSTS

SHORT BURSTS :

Probably merging of compact objects

2 neutron stars $\Rightarrow$ 1 Black Hole

- Accomodates very short time scales
- Observ. tells PSR 1913+16 will merge in about 10^9 years
- Enough such events to sustain observed number of events per year
- Concept supported by SWIFT counterpart observations (at edge of galaxies because of kick by last SN event in couple)

A FIREBALL FORMS

Enormous energy freed in very small volume

must induce lepton/photon cascade,

$\gamma + \gamma \leftrightarrow e^+ + e^-$

independently of how energy is « freed »

(provided it is fast enough)

Opacity for observed γ ray luminosity

from $\approx$ a neutron star volume :

$$\tau_{\gamma\gamma} = n_\gamma \, \sigma_T \, R^* = (L_\gamma \, / \, 4\pi R_*^2 \, h\nu \, c) \, \sigma_T \, R^* \approx 10^{15} \, !!$$

FIREBALL INITIAL EXPANSION

- **Very opaque**, hot fireball with little radiation by
  a gamma ray photosphere: ≈ adiabatic (4/3)

- **Fireball free expansion phase :**
  Expands (isotropically ?) at relativistic speed.
  Thermal energy converted into kinetic
  Opacity ↓ (because $n_\gamma \downarrow$, $\theta_{\gamma\gamma} \downarrow$, $<E_\gamma>_{rest\ fr} \downarrow$)

- **Eventually reaches :**
  1- **Energy almost all in kinetic form**
  bulk Lorentz factor $\gamma \approx 100$
  (depending on degree of «baryonic pollution»)
  2- **Transparency** for GeV-MeV $\gamma\gamma$ collision

TRANSPARENT PHASE

When transparent
⇒ prompt non-thermal radiation appears.

Non thermal radiation attributed to
Synchro-Self Compton by CR $e^- e^+$ at shocks, …
…otherwise…
….radiation too weak, too thermal, too smooth
Complicated light curve of long events
due to multiple internal shock events .

1st order Fermi acceleration of baryons at shocks.
Max^m energy limited by losses suffered by protons
(not by residence time near shock).
E_{max}(protons) = 10^{20}eV (? Number ??)

AFTERGLOW PHASE

Free expansion relayed by a « Sedov » phase **as**

mass of external matter met by head shock

becomes comparable to mass of ejecta.

Front shock splits into forward / reverse shock

Afterglow from vicinity of forward shock….

… lepton acceleration

+ optical synchrotron photons

+ inverse Compton on those, producing GeV γ's

Shifts progressively to lower frequency

and fades out slowly

t=1h45

THANKS

SUPPLEMENTS

Neutrinos from GRB's

Invisible large flux of MeV neutrinos from the cooling of merger or collapse (σ too small)

High energy neutrinos from high energy CR protons by photo-pion production at threshhold of Δ resonance in very radiative environment

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \quad \text{or} \quad p + \gamma \rightarrow \Delta^+ \rightarrow \rightarrow p + \pi_o$$

Alternatively, **high energy CR, p or n, may inelastically collide on dense cold gas** and generate pions

Charged pions emit neutrinos by

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad ; \quad \mu^+ \rightarrow e^+ + \text{anti } \nu_\mu + \nu_e$$

If protons are @ **energy < 10^{14}eV , pair photo-production** $p + \gamma \rightarrow p + e^+ + e^-$ dominates and starts a lepton / photon cascade

High energy neutral pions start a lepton/photon cascade too by

$$\pi_o \rightarrow \rightarrow \gamma + \gamma \text{, followed by} \quad (\text{high energy } \gamma) + \gamma \rightarrow e^+ + e^- \text{, etc..}$$

Escaping high energy γ should have $E\gamma$ = TeV (to be observed in 20 MeV-300 GeV range by GLAST, launched Sept 2007)

For protons colliding on MeV γ rays, E_p>10^{16} eV needed, ν's then expected @ $E\nu = 10^{14}$ eV
For protons colliding on optical photons, E_p>10^{20} eV needed and ν's @ $E\nu = 10^{17}$ eV
For protons colliding on cold gas, E_p>10^{14} eV needed and ν's @ $E\nu = 10^{10}$ eV

Neutrinos from AGN's

High energy photons **from blazars** only (jet-associated) CGRO 66 blazars at GeV's.

Leptonic Model : Origin in Inverse Compton of 100 TeV cosmic ray electron-positrons on optical UV photons, either self radiated by synchrotron or on ambiant photons from accretion disk

There is a pb with accelerating leptons to these energies against these IC losses.

Very small neutrino emission (much less probable than $e^+ + e^- \rightarrow \gamma + \gamma$) by $e^+ + e^- \rightarrow \nu +$ **anti** ν

Hadronic model : Cascades initiated by postulated hadrons 10^{17}-10^{19} eV **by photo-pion production at Δ resonance** in very radiative environment. .

$$\mathbf{p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \qquad or \qquad p + \gamma \rightarrow \Delta^+ \rightarrow \rightarrow p + \pi_o}$$

Pb with accelerating baryons to such energies against these losses. Secondary very high energy baryons may go on with photo-pion production

High energy CR p or n inelastically colliding on dense cold gas unlikely (very little such gas).

High energy charged pions emit neutrinos by

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad ; \quad \mu^+ \rightarrow e^+ + \text{anti } \nu_\mu + \nu_e$$

In this environment , pair photo-production by protons, $p + \gamma \rightarrow p + e^+ + e^-$ dominates and starts a lepton / photon cascade when $E_p < 10^{17}$eV

High energy neutral pions start a lepton / photon cascade by

$$\pi_o \rightarrow \rightarrow \gamma + \gamma, \qquad \text{followed by} \qquad (\text{high energy } \gamma) + \gamma \rightarrow e^+ + e^-, \text{ etc..}$$

Neutronized Nuclei

$B(A,Z) / m_u c^2 = a_{vol} A - a_{surf} A^{2/3}$
$- a_{antisym} A (Z/A - ½)^2 - a_{Coulb} Z^2/A^{1/3}$

Minimize en. density @ given baryon density

$\varepsilon = \varepsilon_{degenerate\ elect} (n_e) + \varepsilon_{degenerate\ free\ n} (n_n) +$
$n_{nuclei} ((A-Z) m_n c^2 + Z m_p c^2 - B(A,Z))$

Exotic neutron-rich nuclei formed:

@ 8 10^6 g/cm^3 Fe^{56}

@ 1.5 10^9 g/cm^3 Ni^{66} (natural Ni = Ni^{58})

@ 4.3 10^{11} g/cm^3 Kr^{118} (natural Kr = Kr^{84})

Isolated neutron star cooling

Neutron*: born 10^{11} K. Early neutrino cooling, then conduction + rad.

Isolated n* X Ray observation:

Surface T from satellite X ray obs. If age derivable for a number of them, can construct a « cooling history curve ».

Observation of X ray shine reveals internal state of matter, conduction in crust, strong B (10^{14} G) atomic physics.. etc..

Neutrino cooling by URCA process:

$$p + e^- \rightarrow n + \nu \; ; \; n \rightarrow p + e^- + \text{anti } \nu \; ; \; \text{etc}$$

Always a ν loss !!!

At T = 0 does not occur when β eq^m is established. Active for particles near the Fermi surface. Neutrino emitted of order kT.

Influenced by neutron and proton superfluidity because of « gap » near the Fermi surface (hampers transitions, reduces ν emission)

Strange Stars

- **At high density** (4 to 15 n_{nucl}; n_{nucl} = 0.16 fm^{-3}) **quarks deconfined** (partially rather than totally in a n*)
- Quark β equilibrium for

$$d \rightarrow u + e^- + \text{anti } \nu_e \qquad u + e^- \rightarrow d + \nu_e$$
$$s \rightarrow u + e^- + \text{anti } \nu_e \qquad u + e^- \rightarrow s + \nu_e$$

$$\mu_d = \mu_u + \mu_e = \mu_s$$

- If quark masses = 0 solution is **strange matter**

  no leptons and $\mu_d = \mu_u = \mu_s$

  In this case Fermi momenta equal, density equal and strange matter neutral without leptons.

- Speculation that such matter, once formed, is more stable than ordinary nucleonic matter, even at low pressure

- May exist stars made of such matter ?? Similar to n*, but with a lesser radius.

AN ELECTROSPHERE with GAPS?

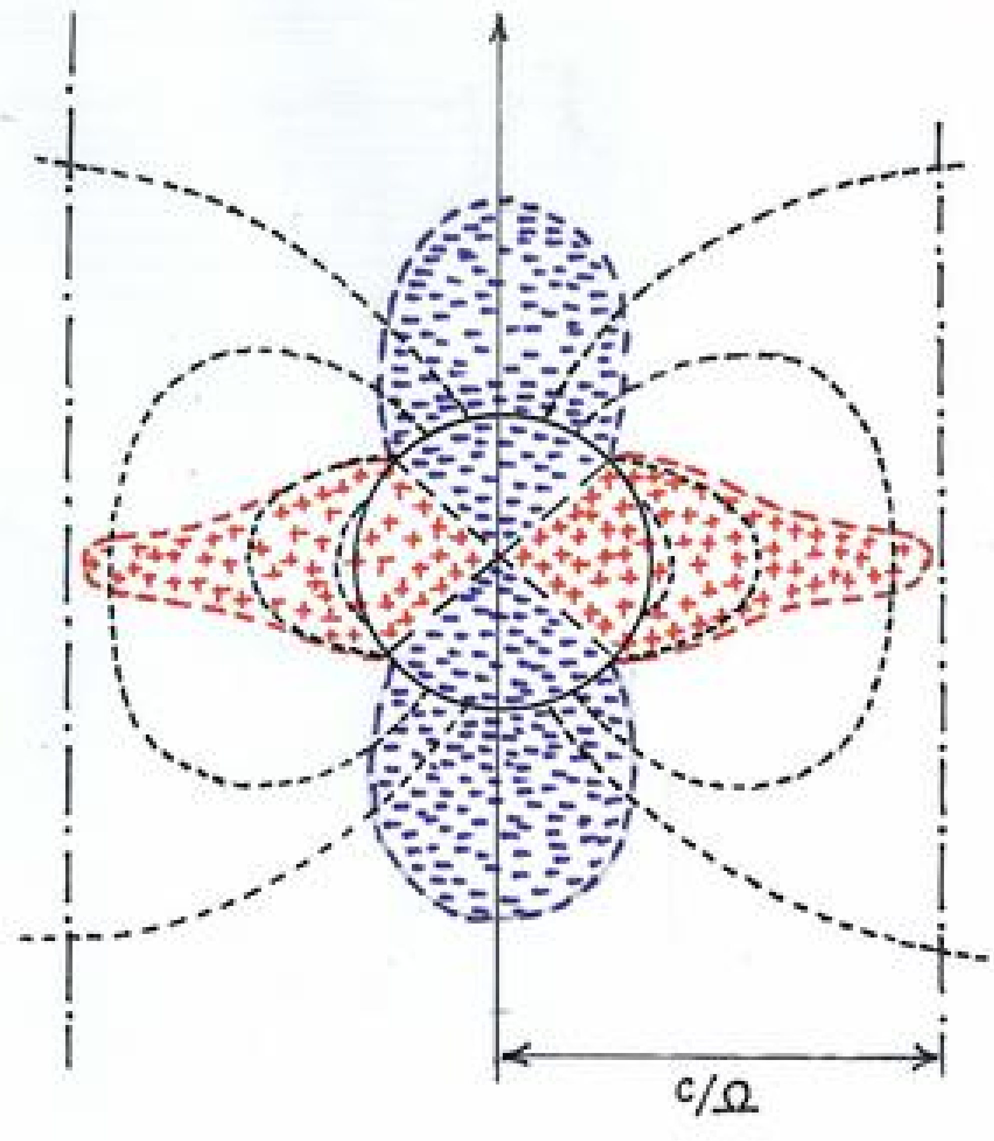
For dipolar field, the 2 poles lose charges of the same sign

Star gets charged until charges of opposite sign can also be shot from equator at R_L by pair creation activity

When star gets charged, a partially filled, limited, electrosphere with large vacuum gaps develops.

Potential drop in the gaps of order

$$V = \Omega^* R^{*2} B^* = 6 \; 10^{12} \text{ Volts}$$


c/Ω

Blandford Znajek

B.H. threaded by magnetic field of external origin

Inertial frame dragging create an electric field,
partly field-aligned.

Field-aligned electric field may accelerate any local lepton at high energy and generate e^+e^- - $\gamma\gamma$ avalanche.

Once lepton plasma created, behaves as an el^{o}magnetic (similar to MHD) wind.

Less efficient than disk wind, but taps on hole directly.

Cyg X1 is a black hole

Companion of Cyg X1 is HDE 226868 (index 1) O9*, spectro binary with a sin i = 72 km/s in 5.6 day orbit, which gives

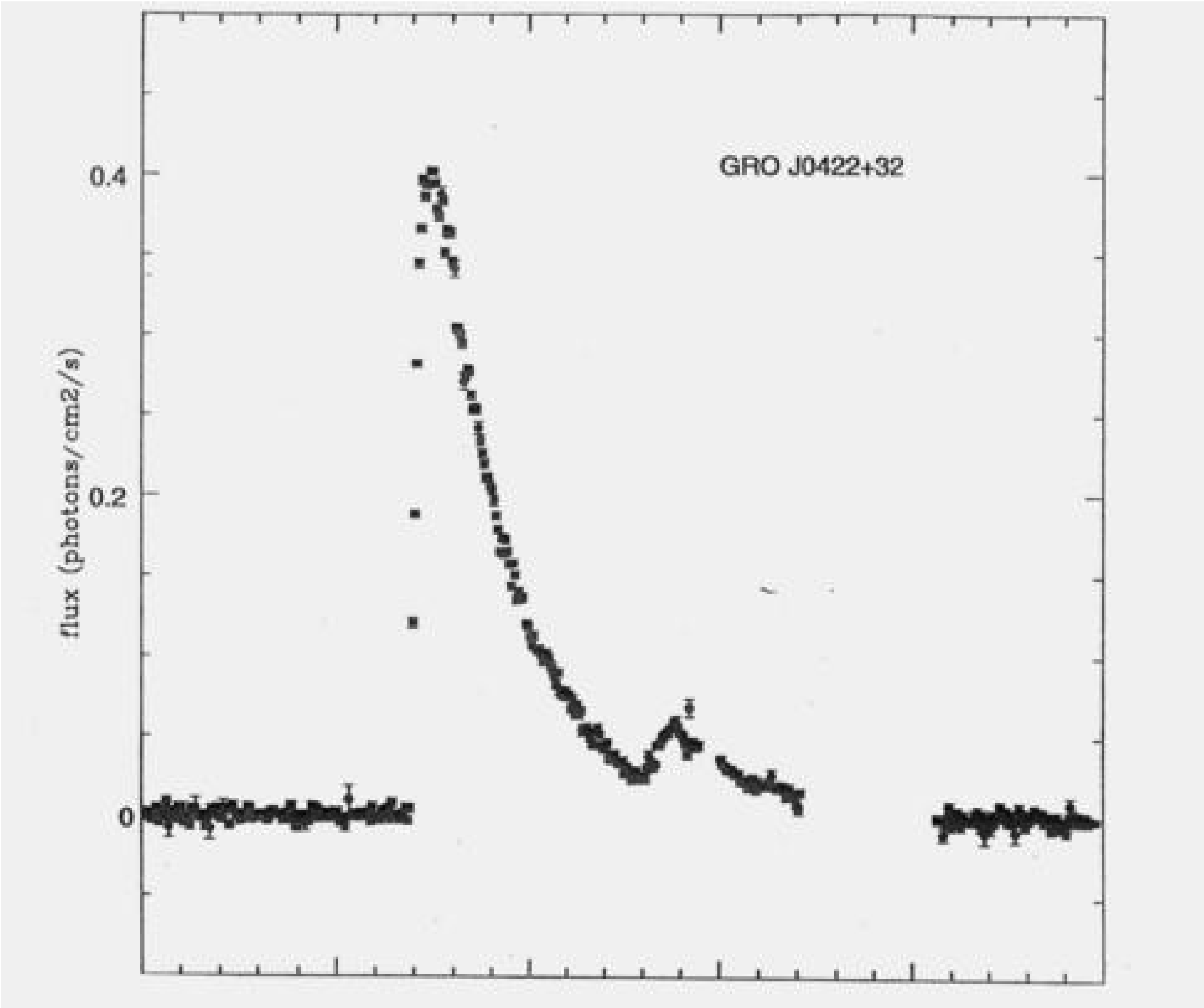
$$\mathbf{m_2^3 \sin^3 i / (m_1 + m_2)^2 = 0.25\ M_O}$$

No X ray eclipses implies $(a_1 + a_2) \cos i > R_{HDE} = 21R_O$, so (Kepler)

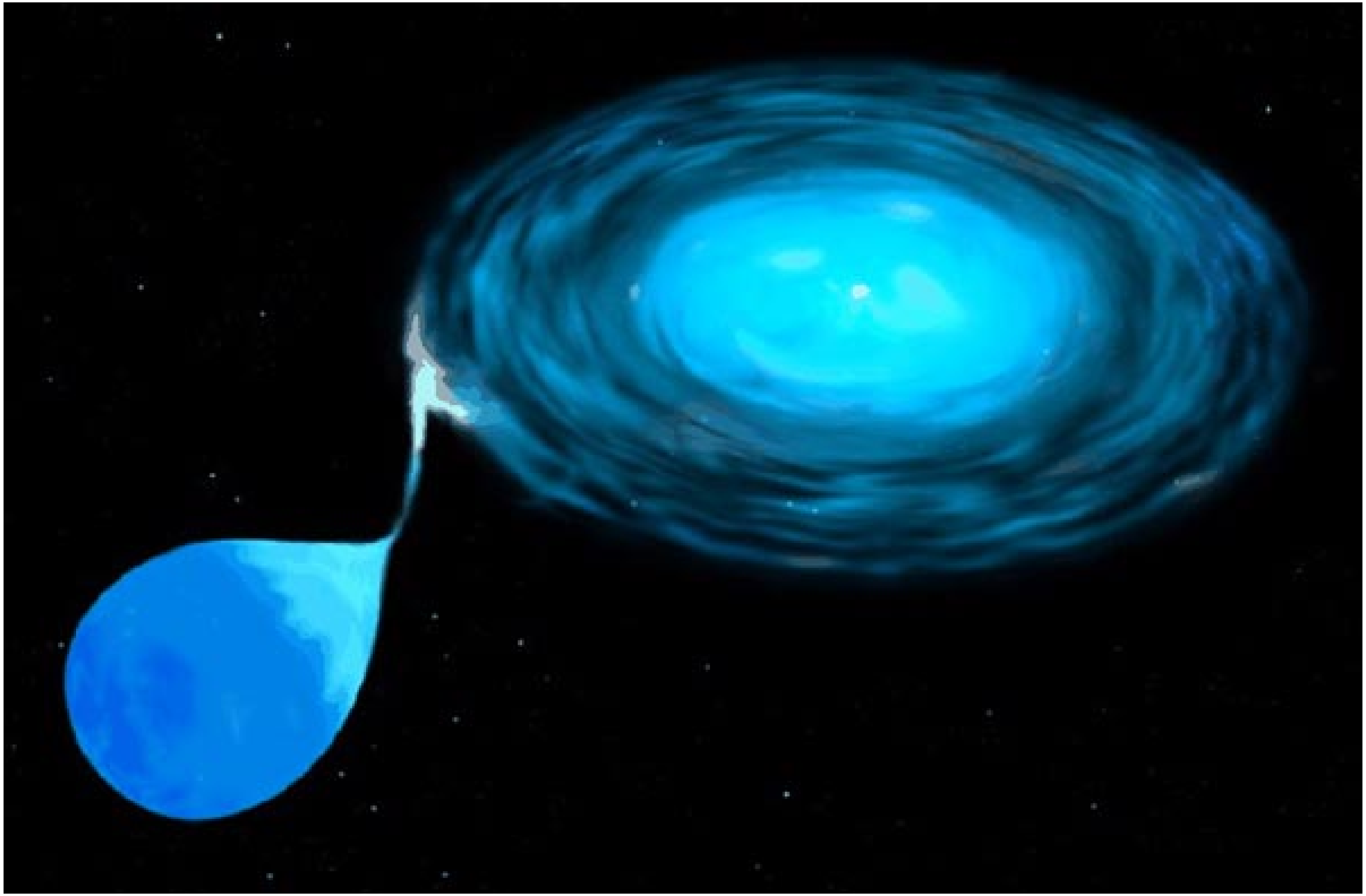
$$\mathbf{(m_1 + m_2)^{1/3} \cos i > 1.6}$$

Implies $\mathbf{m_2 > 1.6 /(\sin i \cos^2 i)}$

As a result $\mathbf{m_2 > 4M_O}$, cqfd



Time: 1 graduation = 20 days



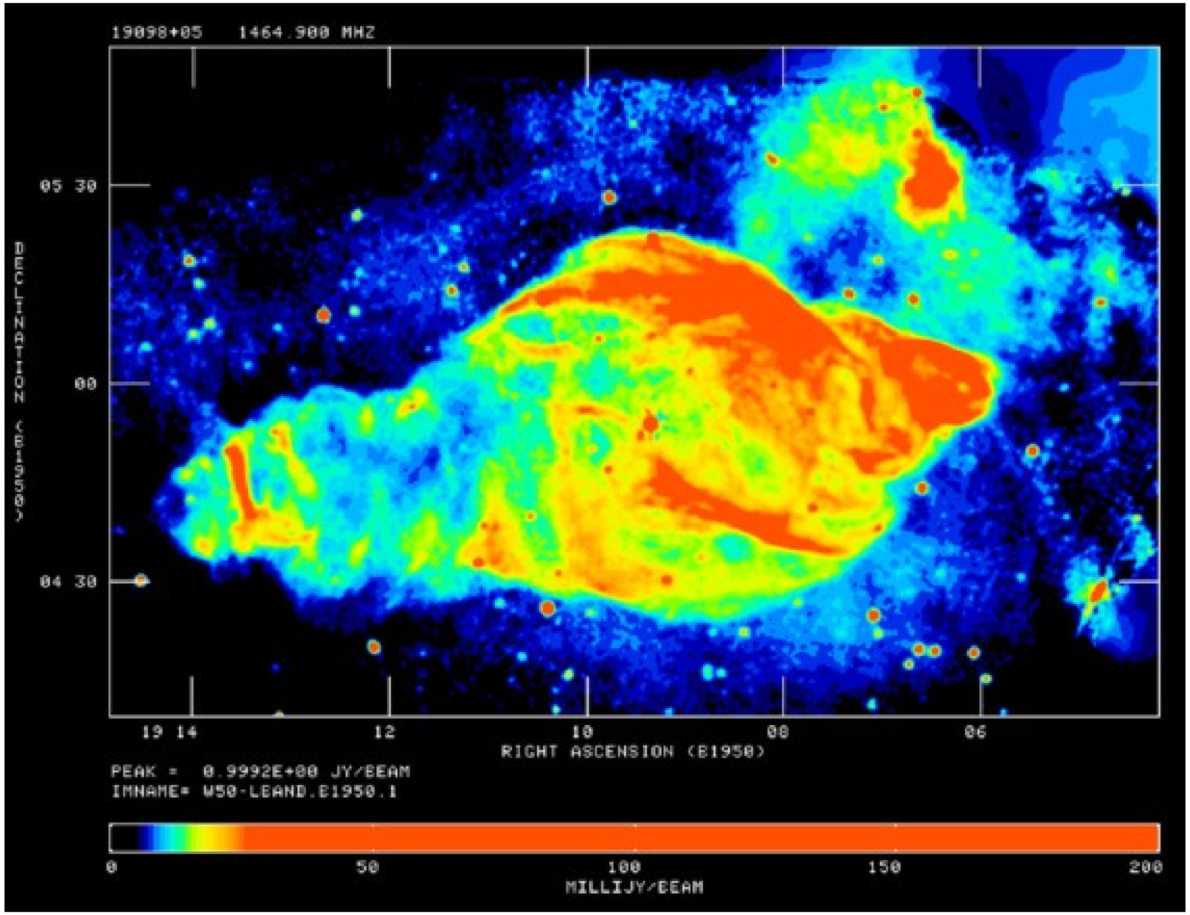
W50 : A JET BAG

Age = 2000 years

$M' = 10^{-6}\ M_O/yr$

$L_{kin} = 10^{40}$ ergs/s

Total energy emitted = 1 Super Nova



$\exists$ **First integrals** like [PEUT ETRE INUTILE]

$$\mathbf{E(a)} = E_M + E_B$$

E_M = Matter energy flux per escaping kg on surface « a ».

E_B = Poynting flux per escaping kg on surface « a ».

$$\mathbf{L(a)} = L_M + L_B$$

L_M = Matter Ang. Mom. flux per esc. kg on surface « a »

L_B = Ang. Mom. flux per escaping kg on surface « a »

of the e.m. momentum density $\varepsilon_o \mathbf{E} \times \mathbf{B}$.

THE WIND CARRIES AWAY ANGULAR MOMENTUM

Magnetars

- 13 known (either SGR's or AXP's)
- **Recurent** gamma bursts with periodic modulation @ a few sec.
- Ex: SGR 1806-20 gave 40 flares in 1 year.
- **Extremely large dP/dt of order 10^{-10}**
- **Hard XR at a low level in quiescence** (10^{35} ergs/s).
- During flares 10^{41} ergs/s.
- **Flares local to n*** because of rotational modulation. Imply large B for lepton flare plasma confinement
- In **young** plerions (rotational ages = a few 10^{3} years).
- All properties imply very **large B = 10^{14}-10^{15} Gauss**
- **Not rotationally powered** (rotation 8 sec of 5 March 1979 cannot power the quiescence X ray emission)
- Model : slow dissip of internal magnetic energy, modification of Lorentz stresses on crust, produce occasional starquake with flares.

GRAVITATIONAL WAVES