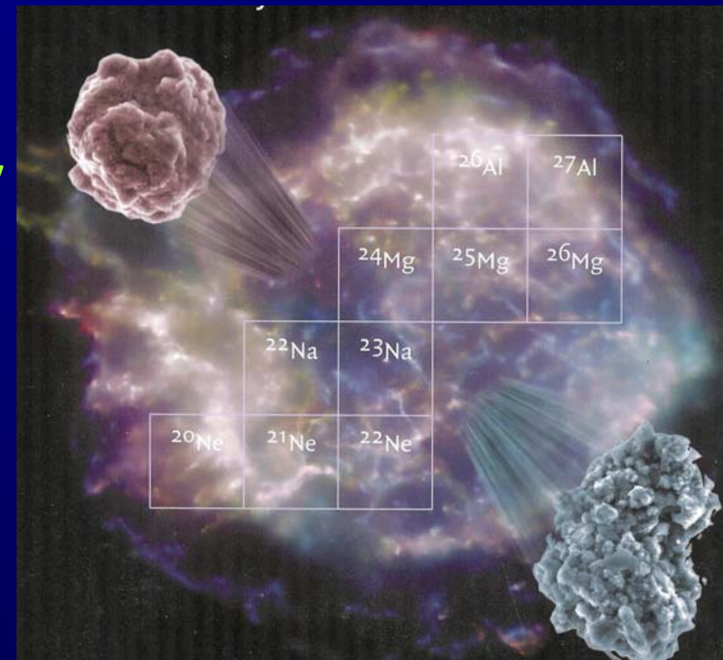
Neutron Stars and other Science Results with INTEGRAL

Roland Diehl

MPE Garching



- Faces of Neutron Stars, Physics Issues and Observables
- INTEGRAL Mission Status
- Science Results from INTEGRAL

Faces of Observable Neutron Stars

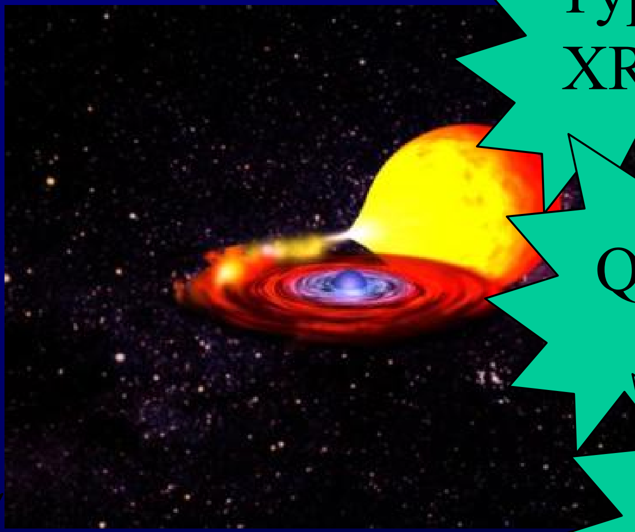
- Radio/HE Pulsars

glitches

AXPs

SGRs

- Accreting NS



Type I XRBs

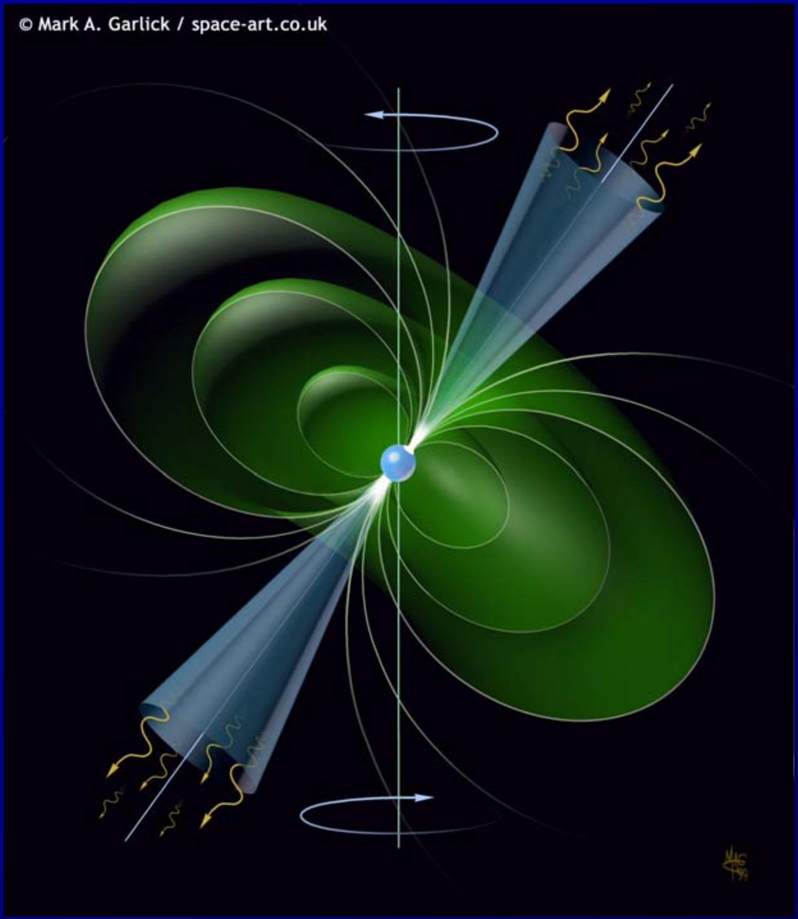
States,Jets, B(e) Systems…

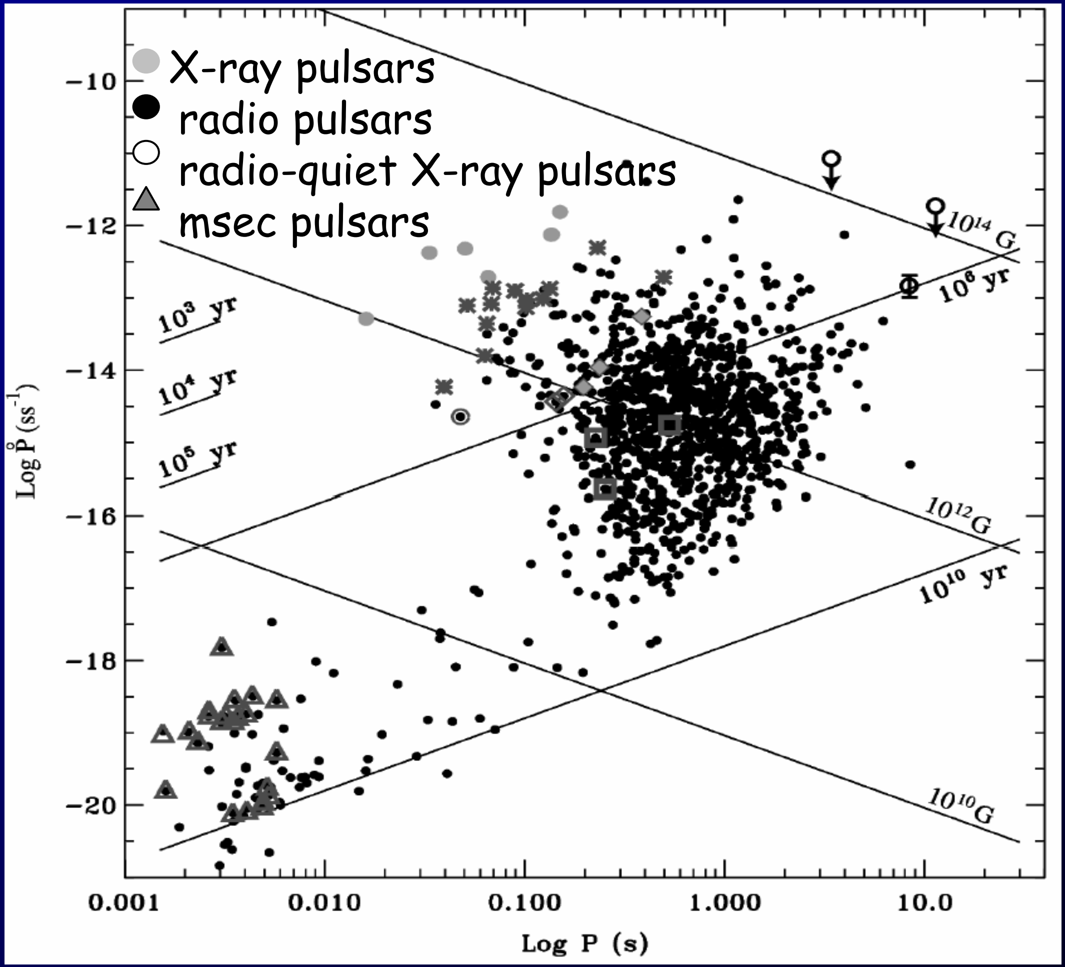
QPOs

ms Pulsars

- Cooling N

Pulsars: From NS Birth to Grave

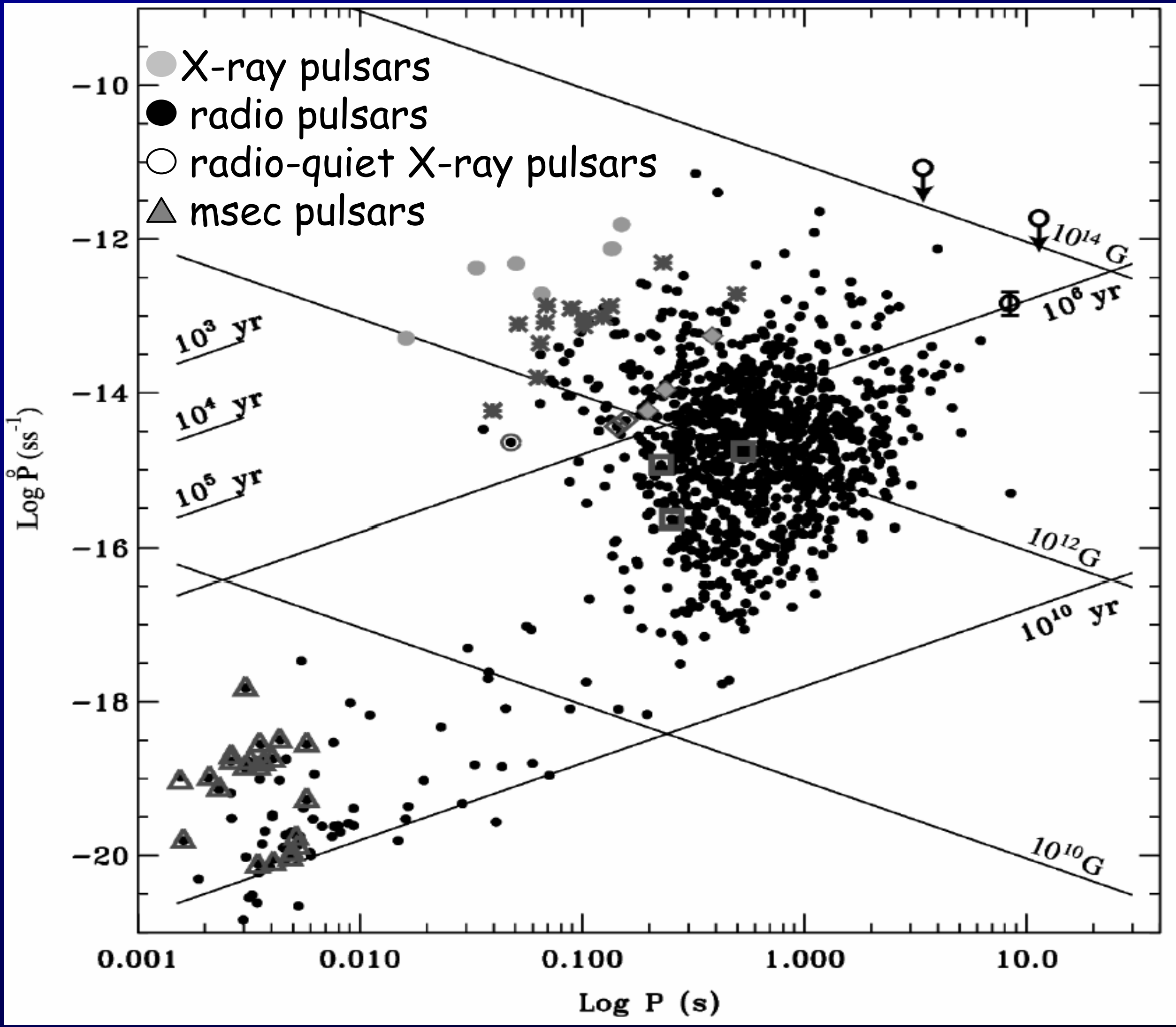




- Magnetic Field + Fast Rotation -> Pulsating Emission
- Slowing-Down + Magnetic-Field Decay with Time

Pulsar Variety and Populations

- Radio and Gamma-Ray Emission while Fastly-spinning and Highly Magnetic
- X-ray Emission from Accretion Hot Spots
- Re-Birth After Spin-up from Accretion



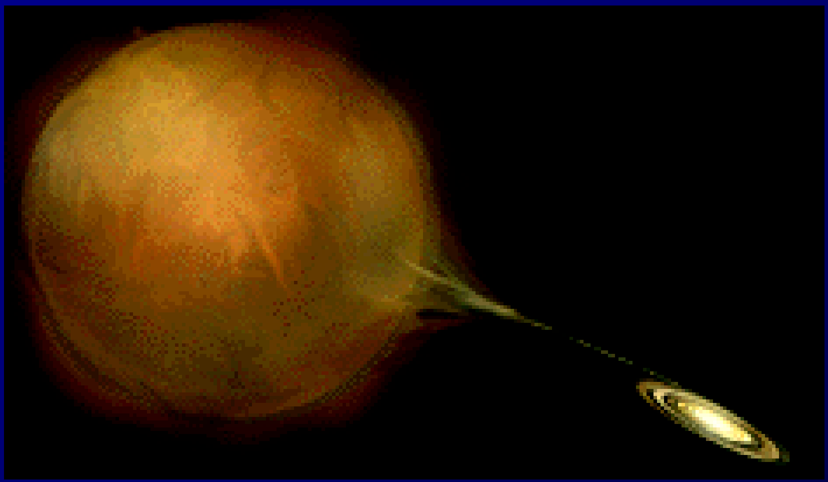
- Note: Pulsar Birth from
  - Core Collapse
  - WD Accretion-Induced Collapse

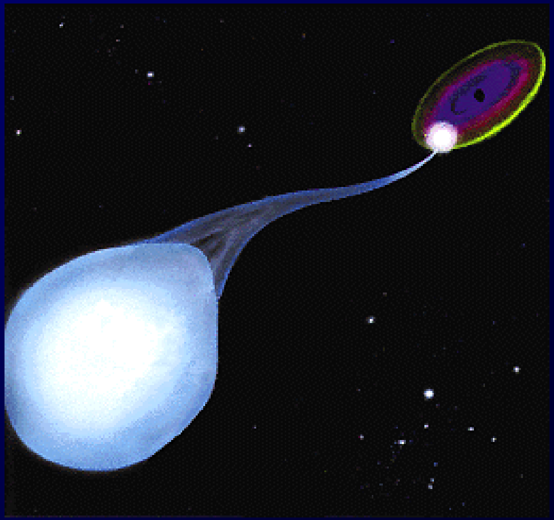
(very different ages…)

Accreting Binaries

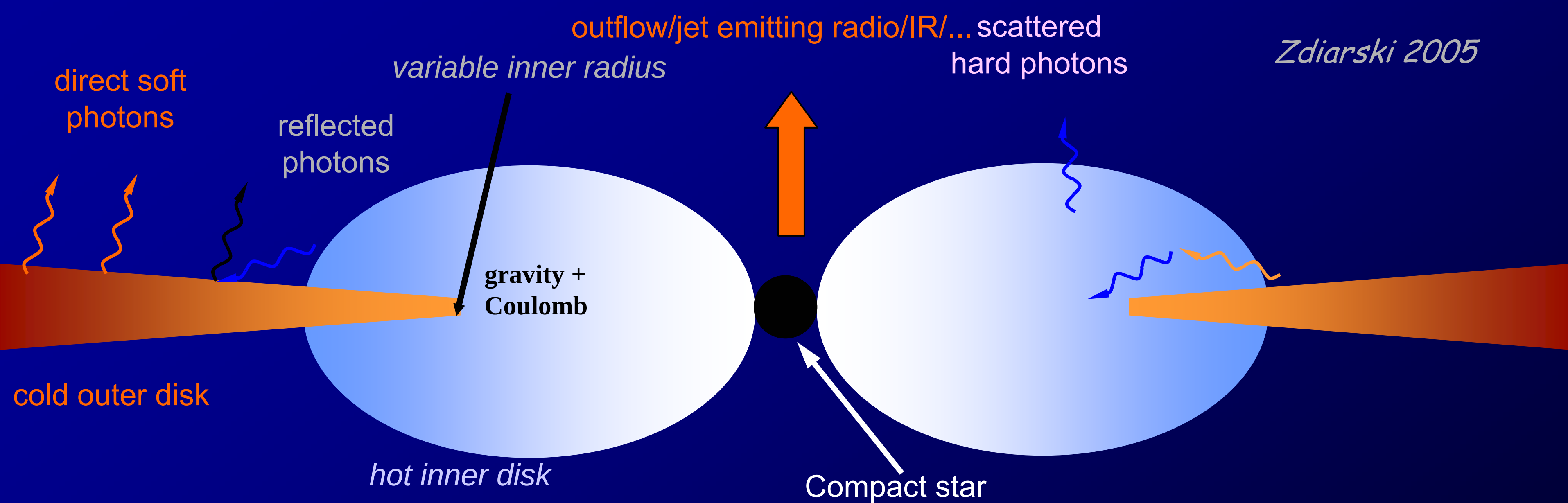
Variety of Configurations

- ☆ Mass Ratio of Donating-to-Compact Star
  - ☞ LMXB
  - ☞ HMXB
- ☆ Binary Orbit and Separation
  - ☞ B(e) Systems
- ☆ … *(not in this talk)*

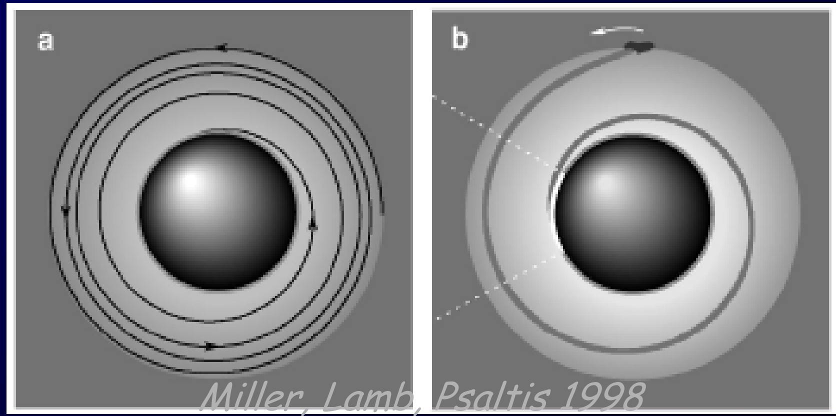




Accretion Phenomena in Accreting Binaries



thermal plasma with kT_e 🕐 50–150 keV in hot accretion solutions



- Interactions Between Accretion Disk and Compact Star -> Instabilities -> Variability of Emission from These Objects

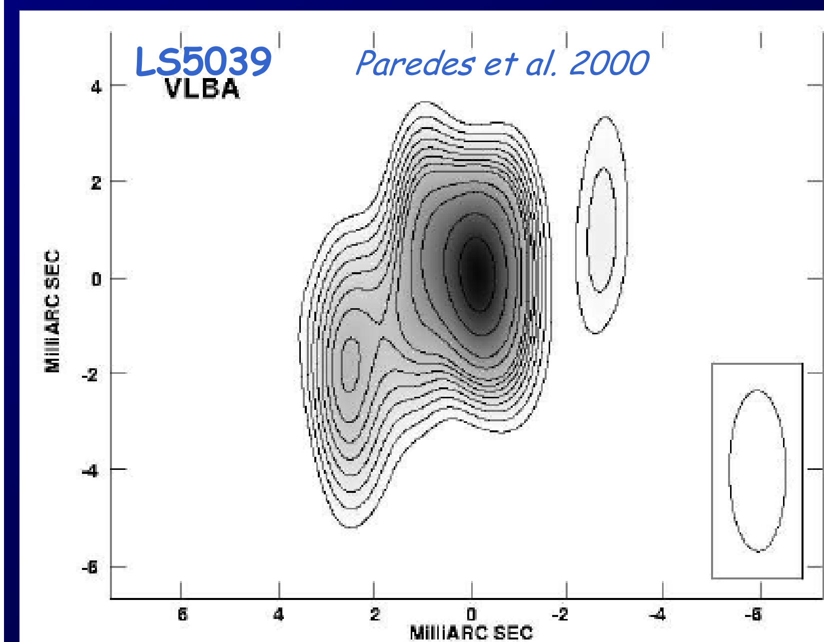
Micro-Quasars: Origins of Plasma Jets

XRB's with Relativistic Radio Jets

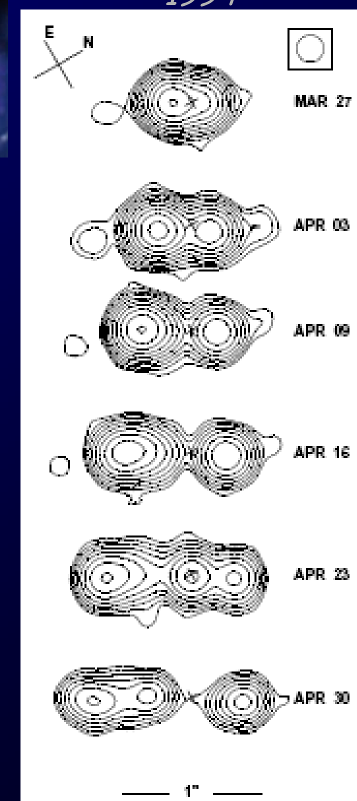
- 8 HMXB, 35 LMXB show radio emission
- 15 of 43 radio-emitting XRB's reveal jets

TABLE 1. Microquasars in our Galaxy

Name	System type*	D (kpc)	P_{orb} (d)	$M_{compact}$ $M_\odot$	Activity radio†	β_{apar}
High Mass X-ray Binaries (HMXB)						
LS I +61 303	B0V +NS?	2.0	26.5	–	p	≥0.4
V4641 Sgr	B9III +BH	~ 10	2.8	9.6	t	≥ 9.5
LS 5039	O6.5V((f)) +NS?	2.9	4.4	1–3	p	≥ 0.15
SS 433	evolved A? +BH?	4.8	13.1	11±5?	p	0.26
Cygnus X-1	O9.7Iab +BH	2.5	5.6	10.1	p	
Cygnus X-3	WNe +BH?	9	0.2	–	p	0.69
Low Mass X-ray Binaries (LMXB)						
Circinus X-1	Subgiant +NS	5.5	16.6	–	t	> 15
XTE J1550–564	G8–K5V +BH	5.3	1.5	9.4	t	> 2
Scorpius X-1	Subgiant +NS	2.8	0.8	1.4	p	
GRO J1655–40	F5IV +BH	3.2	2.6	7.02	t	1.1
GX 339–4	– +BH	> 6	1.76	5.8±0.5	t	–
1E 1740.7–2942	– +BH ?	8.5?	12.5?	–	p	–
XTE J1748–288	– +BH?	≥ 8	?	> 4.5?	t	1.3
GRS 1758–258	– +BH ?	8.5?	18.5?	–	p	–
GRS 1915+105	K–M III +BH	12.5	33.5	14±4	t	1.2–1.7

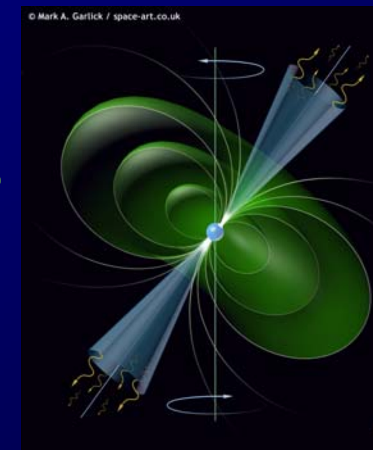


GRS1915
Mirabel & Rodriguez 1994

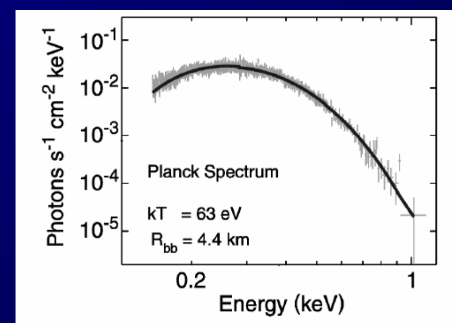


Neutron Star Observables

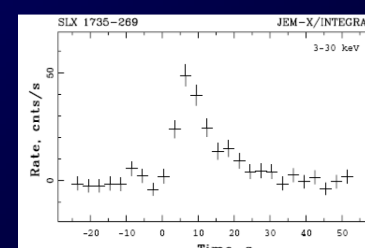
- Magnetospheric Emission
  - ☆ Non-thermal; magnetosphere as particle accelerator

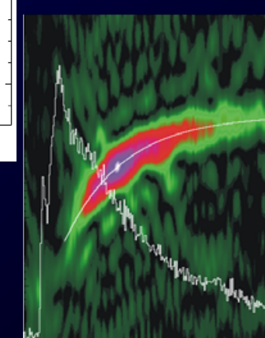


- Thermal Emission
  - ☆ Radiative Cooling, T~X-rays
  - ☆ Heating from Internal Energy
  - ☆ Heating from Matter Accretion
  - ☆ Heating from Nuclear Burning



- Temporal Modulations
  - ☆ NS Spin
  - ☆ Accretion Flow Irregularities
  - ☆ Nuclear Ignition: Type I X-ray Bursts
  - ☆ Structural Rearrangements: Glitches, Bursts
  - ☆ Relativistic Distortions of Radiation





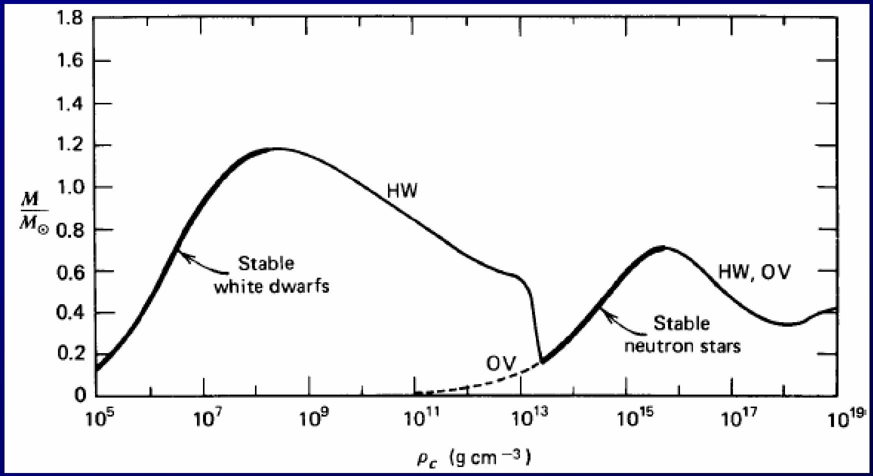
High-Density Matter and Stellar Configurations

Matter at Higher Densities

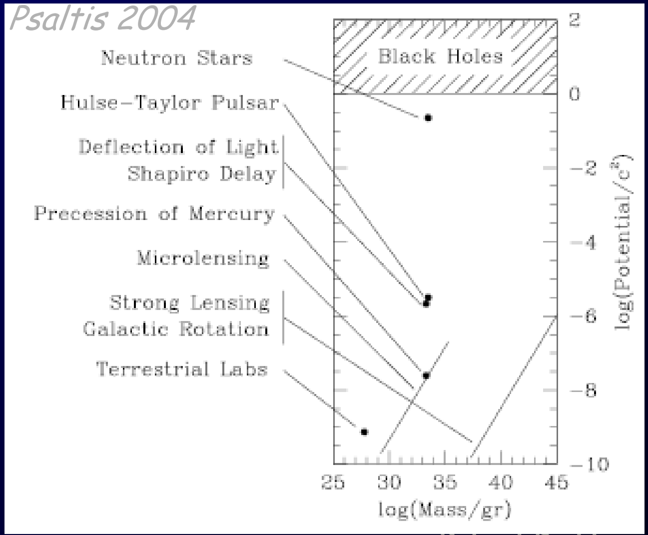
- ☆ Degeneracy Pressure

Stars

- ☆ Gravitationally-bound Matter in Hydrostatic Equilibrium



- ☆ Solutions
  (with “reasonable Equation of State” <-> p(E))
  - ☞ e pressure; 0.2 $M_\odot$ < M < ~1.5 $M_\odot$ (WD)
  - ☞ n pressure; 0.1 $M_\odot$ < M < ~3.2 $M_\odot$ (NS)



Neutron Stars: Probing Matter at High Gravity

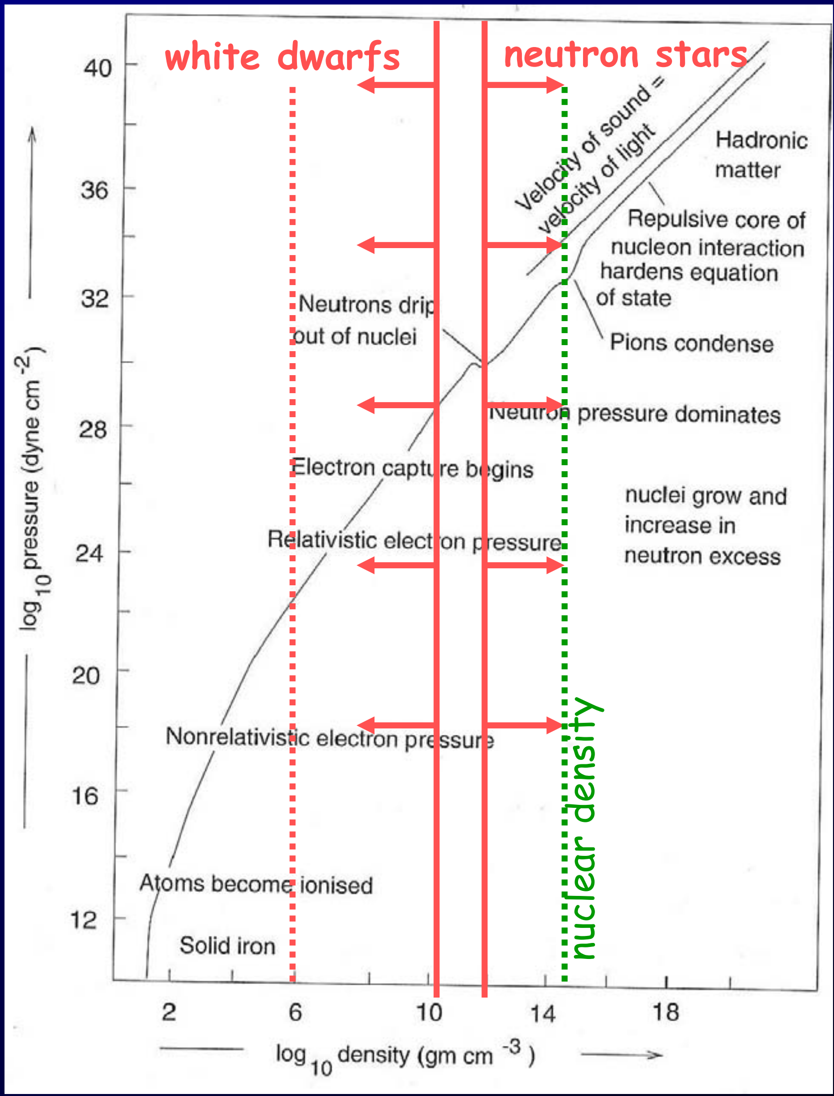
High-Density Stars: Regions of Interest for Nuclear Interactions

High Density Stars

- ☆ e^- Degeneracy Pressure ->WD
- ☆ n Degeneracy Pressure ->NS

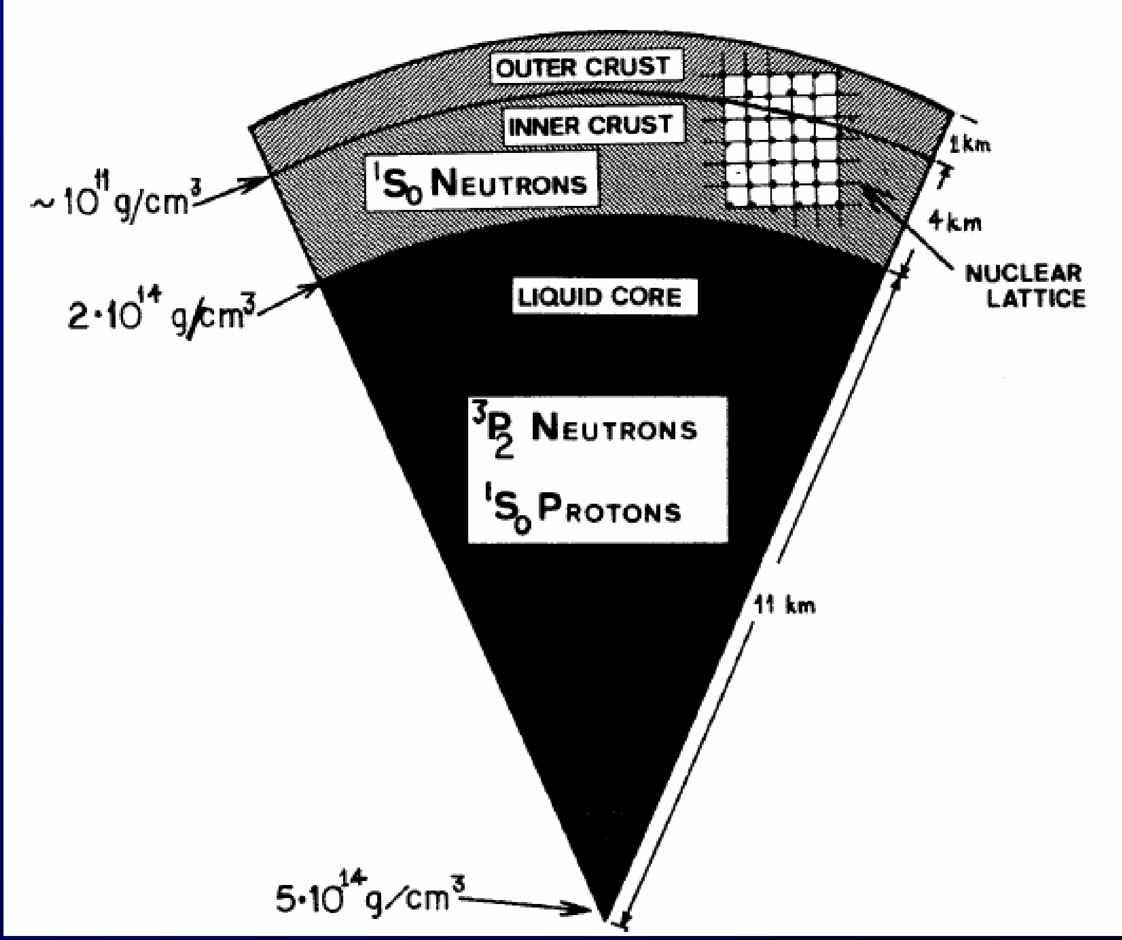
Transitions

- ☆ Relativistic e^- -> EC
- ☆ Nuclei -> n Drip -> n Fluid
- ☆ Hyperons ?
- ☆ Fermion Pairings -> Bosons ?



Neutron Stars

- ☆ Birth at T~10 MeV, Rapid Cooling to < MeV -> "cold" nucleons
- ☆ Structural Layers:
  - ☞ Atmosphere (ions, $\rho < 10^4$ g cm^{-3})
  - ☞ Outer Crust (Neutronized Nuclei, $\rho < 4.3\ 10^{11}$ g cm^{-3})
  - ☞ Inner Crust (Nuclei & n Fluid, $\rho < 2.5\ 10^{14}$ g cm^{-3})
  - ☞ Core (nucleonic fluid in β equilibrium, 5%p)



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- Thermal Emission
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  - NS Spin
  - Accretion Flow Irregularities
  - Nuclear Ignition
  - Structural Rearrangements
  - Relativistic Distortions

NS Interior / EoS

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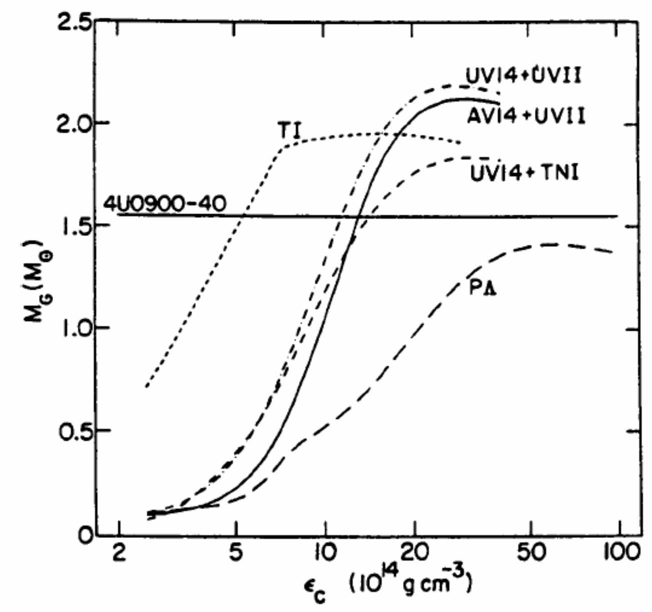
NS Interior / EoS

NS Crust

Neutron Star Matter

- Properties ~Unknown from Nuclear Physics
  - Normal Nuclear Matter: X_p~0.5
  - Neutron Star Matter: X_p~0.0x
  - $$E(\rho, X_p) = E(\rho, X_p = 0.5) + S(\rho) \cdot (1 - 2X_p)$$
    - Bulk and Surface Contributions of Symmetry Energy *S* Uncertain
      - Bulk: ~A ; Surface: ~$A^{2/3}$
      - Laboratory Range of A and X_p too small for Separation of Components
      - Need to Extrapolate in Huge Range of ρ
  - Factor ~6 Uncertainty in Nuclear-Matter Pressure
- Additional Phases
  - Superfluidity
  - Hyperons
  - Pairings -> Boson Condensates (?)

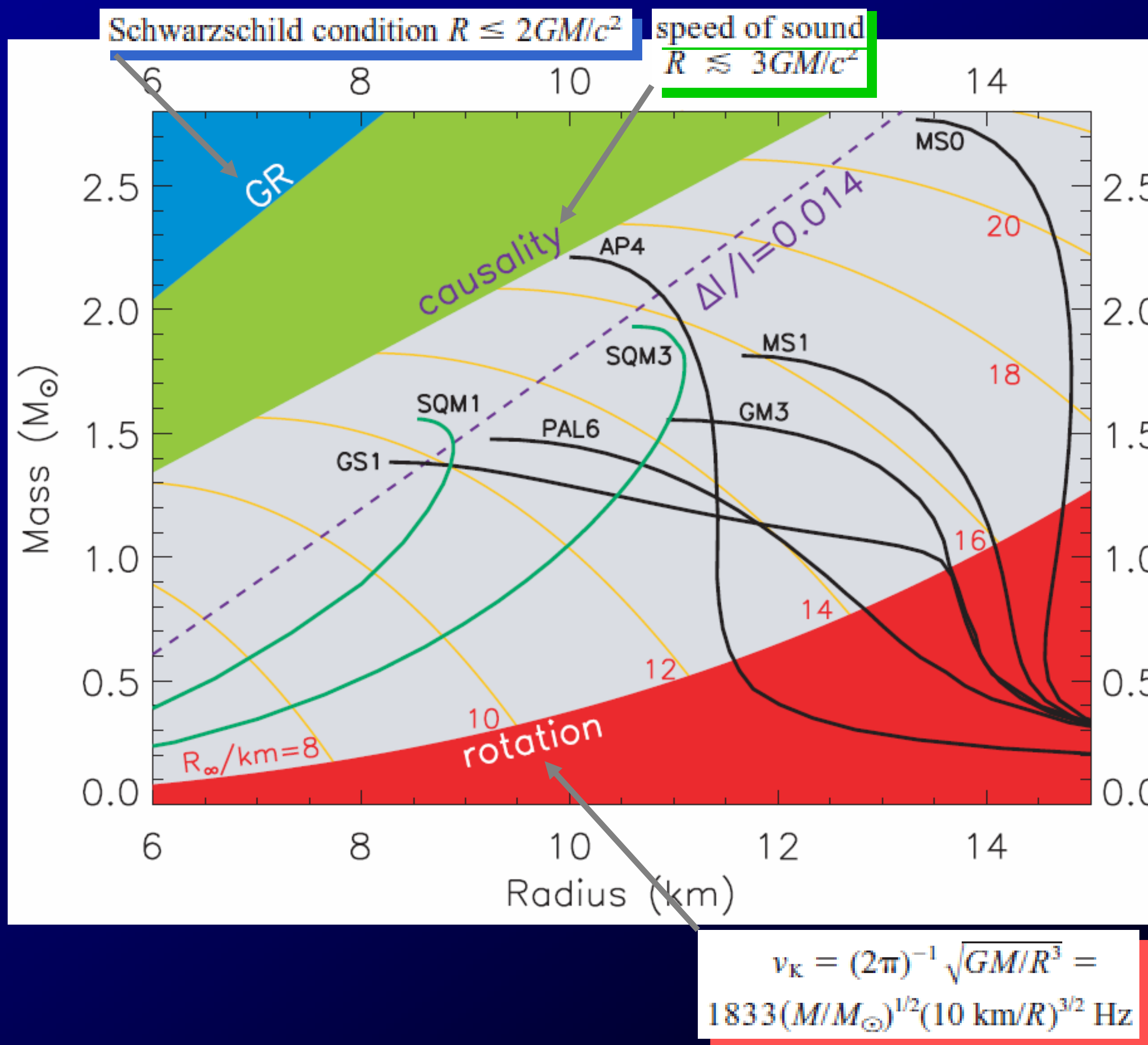


Equation of State for NS

- Nuclear Interaction
  (alternatives)
  - Nonrelativistic Potential
  - Effective Field
  - Relativistic Dirac-Brueckner-Hartree-Fock
- Plus: Softening Components
  - Hyperons
  - Bose Condensates
  - Quark Matter
- Plus:
  - Superfluidity
  - Pasta Phases

Mass-Radius Relation for NS

- Stability
  - ☆ Pressure from Degenerated n
  - ☆ Rotation
- Constraints
  - ☆ $v_{Fermi} < c$
  - ☆ $v_{Sound} < c$
  - ☆ $v_{Surf} < v_{Kepler}$
- Issues
  - ☆ n Phases
    - Lattices/Rods
    - Hyperons
    - Pairings, Condensates

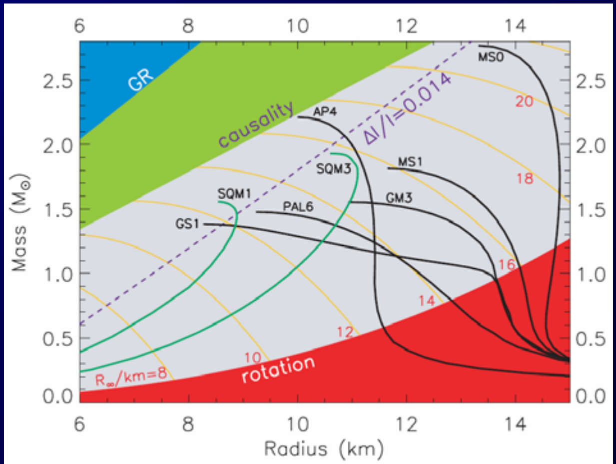


Neutron Stars and Properties of Nuclear Matter

- Key Issue:

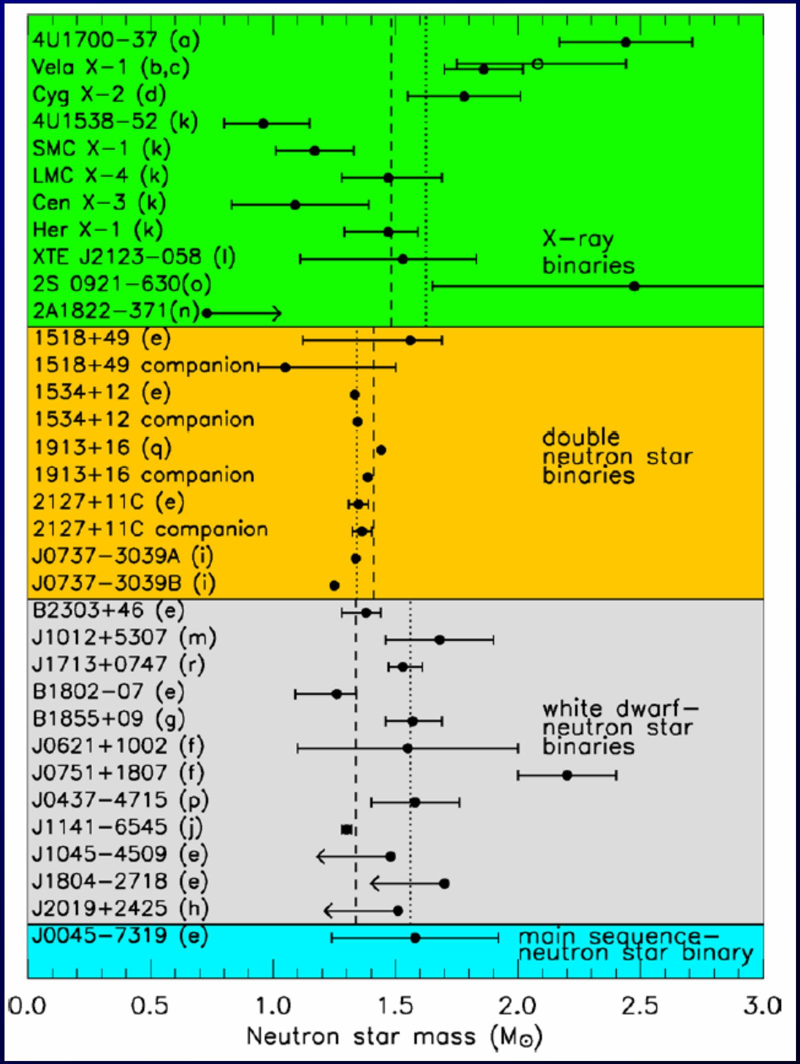
  How Densely-Packed are Nucleons inside Neutron Stars?

  - Sizes of NS (M-R)
  - Thermal Properties (Cooling)
  - Moments of Inertia (Spin, Glitches, Braking, QPOs)



Pulsars in Binaries: Neutron Star Masses

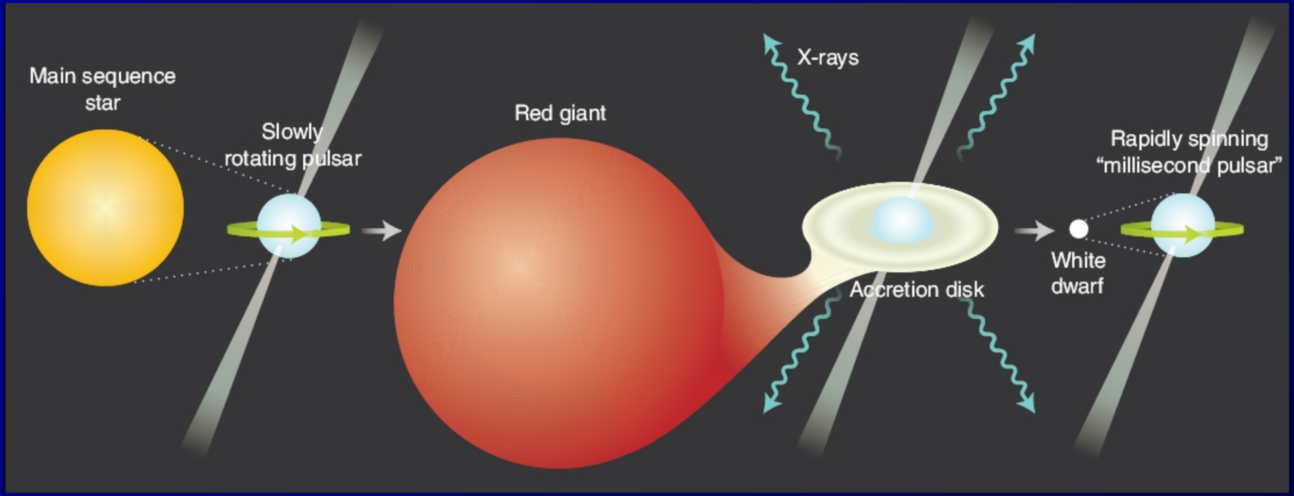
- ☆ Doppler Analysis of Pulsations
  - ☞ Orbit Size & Period -> Mass Function
- ☆ Typical Masses ~1.5 $M_{\odot}$



Pulsars in Globular Clusters

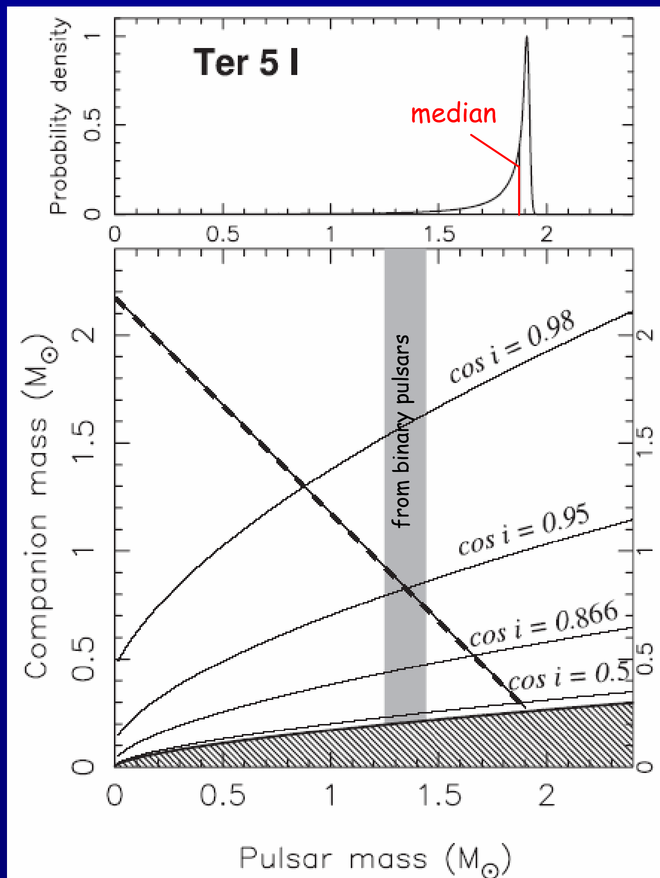
Globular Clusters:

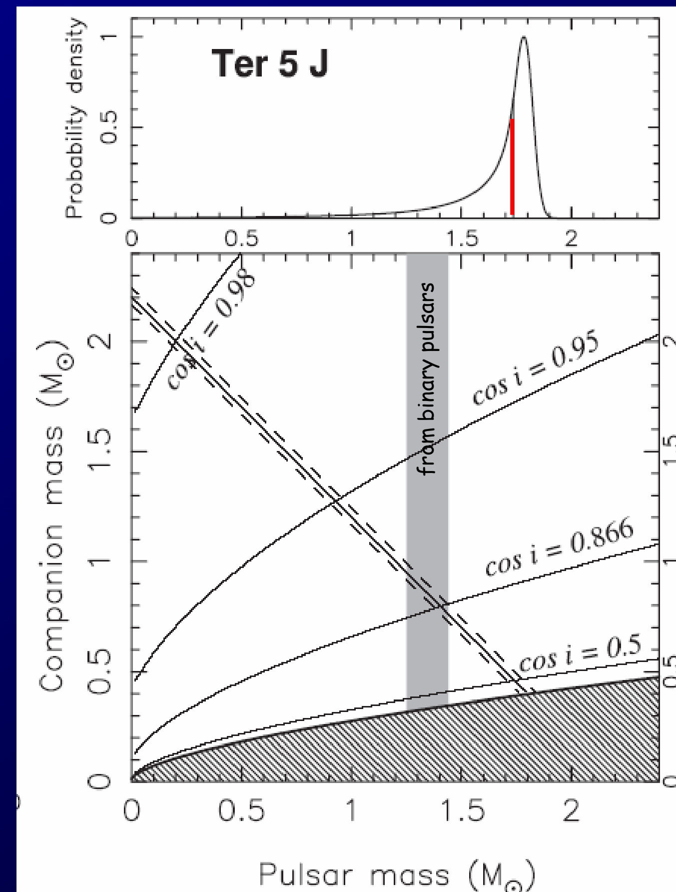
- ☆ Stellar Density ~200* Galactic Stellar Density
  - ☞ Much Increased Binary Encounters
  - ☞ Much Increased Probability for Formation of msec Pulsars



- ☆ ~100 Known Milli-Second Pulsars in Globular Clusters
  - ☞ 47Tuc: 24 pulsars
  - ☞ Ter5: 22 pulsars
    - – e.g. Lorimer, Science 2005

Neutron Star Mass Limits from msec Pulsars





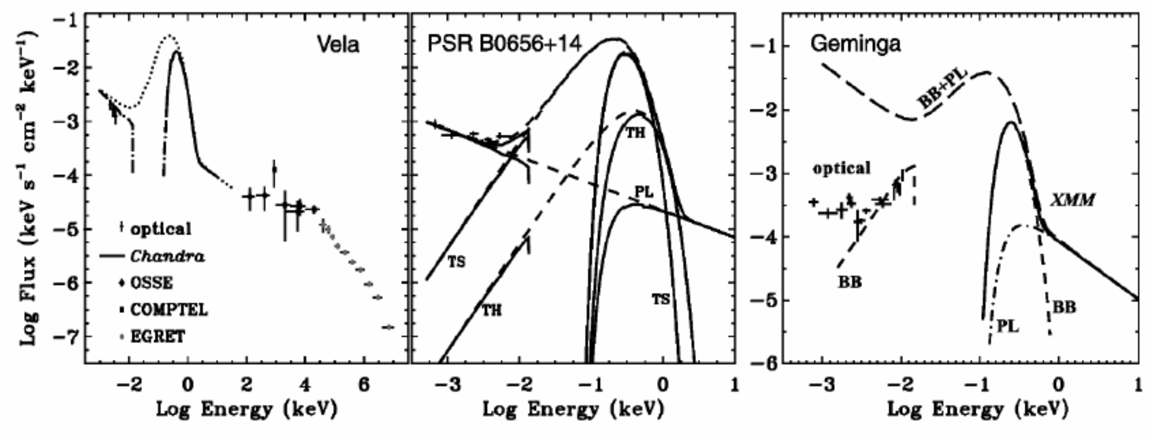
☞ *Ransom et al., Science 2005:*

☆ NS Masses > 1.7 M_o, Upper Limit 1.96 M_o

Radiation from Neutron Stars

ref. Trümper 2005

- ☆ **Magnetospheric Emission**
  - Non-Thermal, Beamed; Decay with Age; Origin: Accelerated Particles
- ☆ **Polar-Cap Emission**
  - Thermal; Origin: Heating from Material Infall
- ☆ **Bulk Surface Emission**
  - Thermal; Origin: Radiative Cooling



Inference of NS Sizes: Atmosphere Model & Pulsar Distance

☞PSR0656+14:	d~ 288 pc	R_{mH}~13-20 km
☞Vela:	d~ 290 pc	R_{mH}~17-20 km
☞Geminga:	d~ 157 pc	R_{bb} ~ 9 km

- ☆ NS Radii ~10-20 km

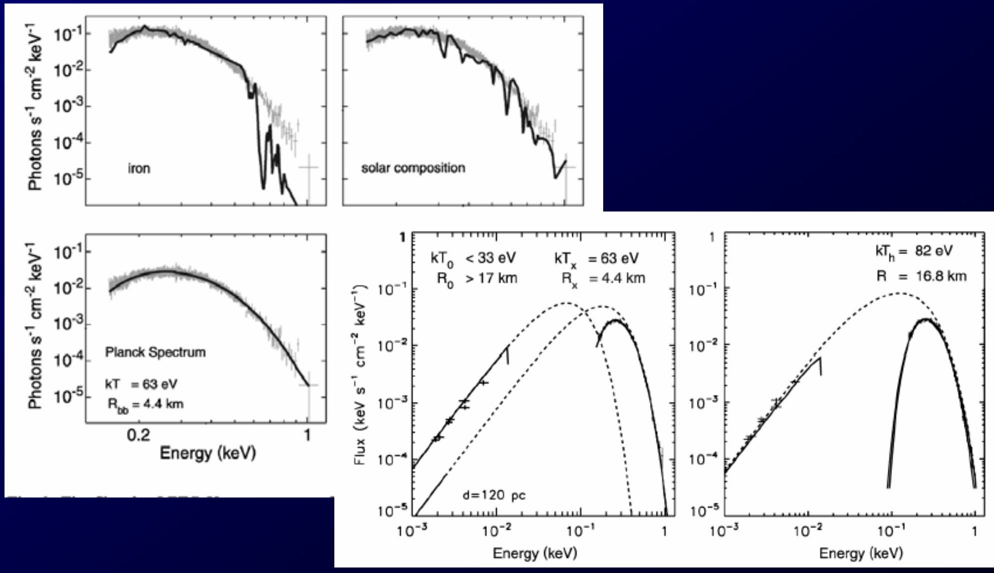
Thermal Neutron Star Radiation

☆ Radio-quiet X-ray-emitting Isolated Neutron Stars (->thermal-only)

Source	P (s)	$\dot{P}$ (s s^{-1})	L_x (erg s^{-1})	kT_{BB} (eV)	d (pc)	Opt.	Comments
RX J0420.0-5022	22.69	–	2.7×10^{30}	57	100	$B > 25.5$	(1)
RX J0720.4-3125	8.39	$(3–6) \times 10^{-14}$	2.6×10^{31}	85	100	$B = 26.6$	(2, 3, 4, 5)
RX J0806.4-4123	11.37	–	5.7×10^{30}	95	100	$B > 24$	(6, 7)
1RXS J130848.6+212708	10.31	$< 6 \times 10^{-12}$	5.1×10^{30}	90	100	$m_{50CCD} = 28.6$	RBS 1223 (8, 9, 10)
RX J1605.3+3249	–	–	1.1×10^{31}	92	100	$B > 27$	RBS 1556 (11)
RX J1836.2+5925?	–	–	5.4×10^{30}	43	400	$V > 25.2$	Variable? (12)
RX J1856.5-3754	–	–	1.5×10^{31}	62	117	$V = 25.7$	(13, 14, 15, 16)
1RXS J214303.7+065419	–	–	1.1×10^{31}	90	100	$R > 23$	RBS 1774 (17)

☆ Issue: Nature of X-ray Emission

- Blackbody
- Multiple Emission Regions
- Magnetic-Field Smeared Atomic-Line Superposition
- Centrifugal Corrections (gravity(latitude)->T(b))
- Composition



☆ Inferred Lower Limits to R_{NS}

- RXJ 1856.5: R > 14 km

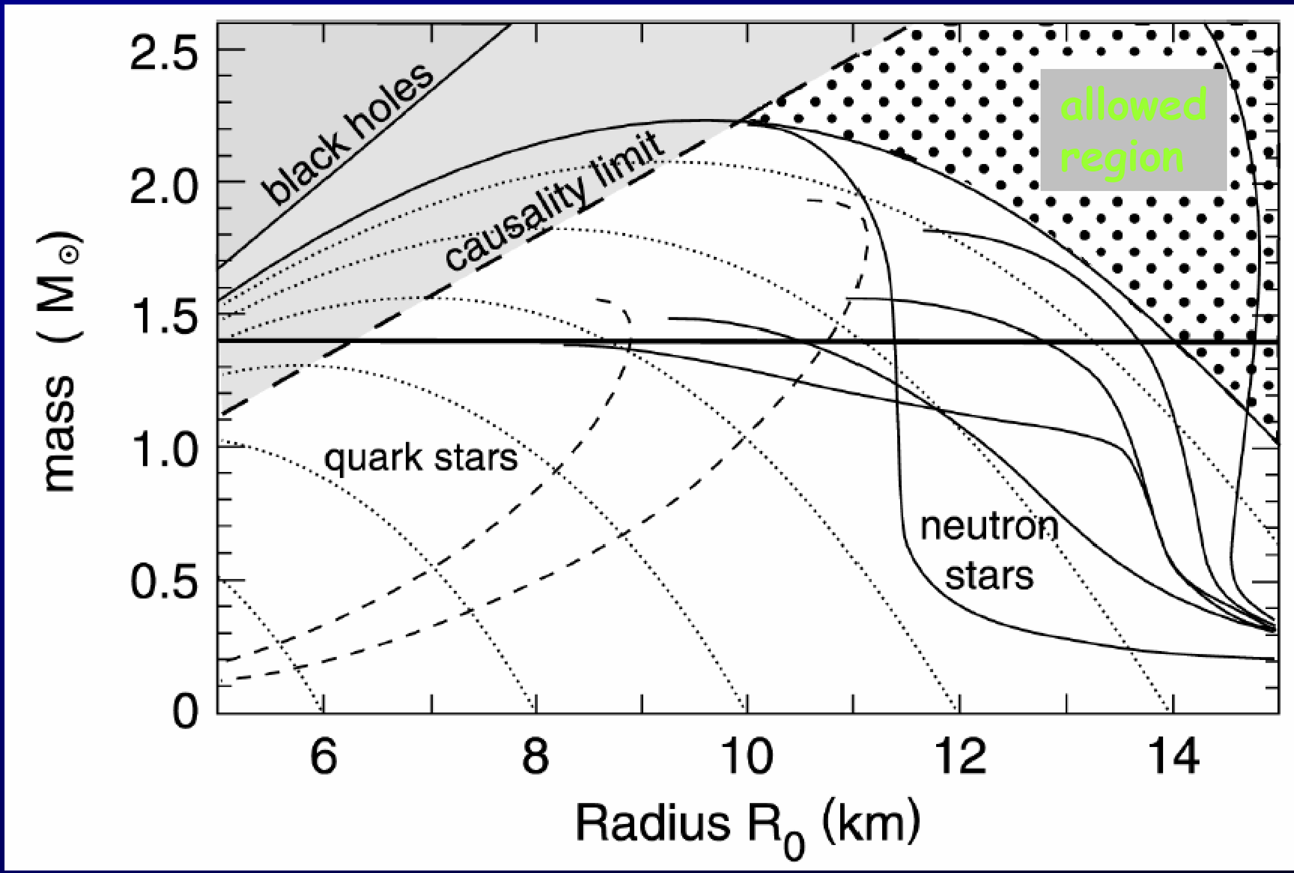
Thermal Radiation from NS: Issues

- Gravitational Redshifts
  - "Effective" Temperature -> Corrected using NS Mass
- Magnetic-Field Effects
  - Strong Zeeman Effects -> Level-Structures of Matter
  - Smearing of Atomic Lines with Effective B Range
  - $B \sim 10^{12}$G
  - Dependence on Elemental Composition
- NS Rotation
  - Effective Gravity Weaker at Equator -> Inhomogeneous Temp

- Needs:
  - Sensitive Pulsation Searches -> P (-> age, origin)
  - Spectroscopy -> Cyclotron Features, ...

Thermal Radiation from NS: Implications

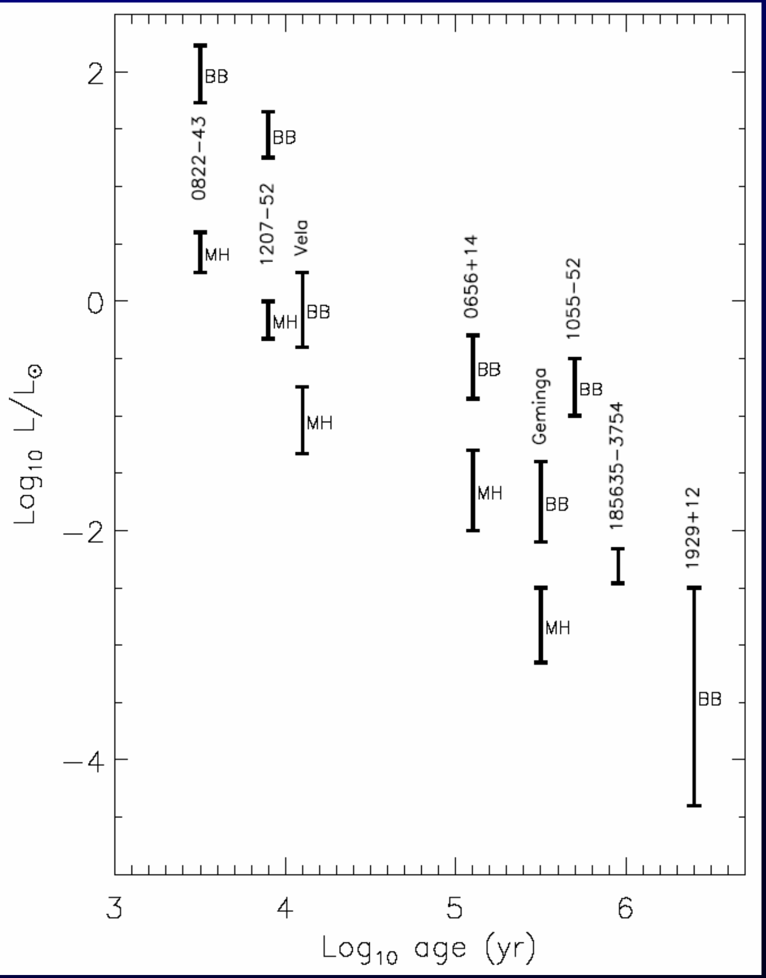
- ☆ RXJ 1856.5-3754:
  - ☞ $R_{apparent}$=16.5 km
  - ☞ Quark Star Excluded?



☞ *Pons et al. 2002, Trümper 2005*

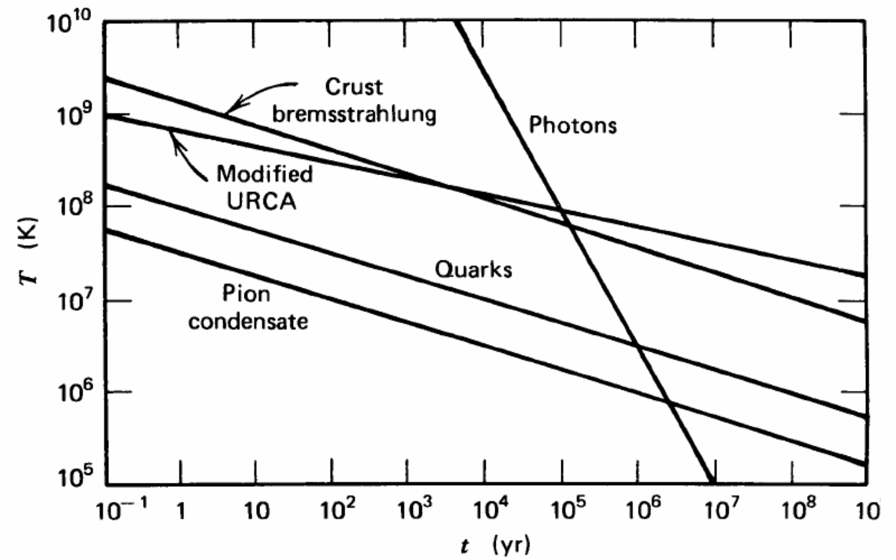
Neutron Star Cooling: Observations

- Different NS's and their Thermal Luminosities
  - ☆ Ages Poorly Constrained
  - ☆ Distances Uncertain



- Interpretation of Observed Luminosity
  - ☆ Thermal Surface Radiation
  - ☆ Radiation: BB or Less Efficient?
  - ☆ Heat Sources?
    - ☞ Rotational Slowdown Heating / Vortex Creep
    - ☞ ISM Matter-Accretion Heating
    - ☞ Pycnonuclear Reactions

Neutron Star Cooling: Interpretations

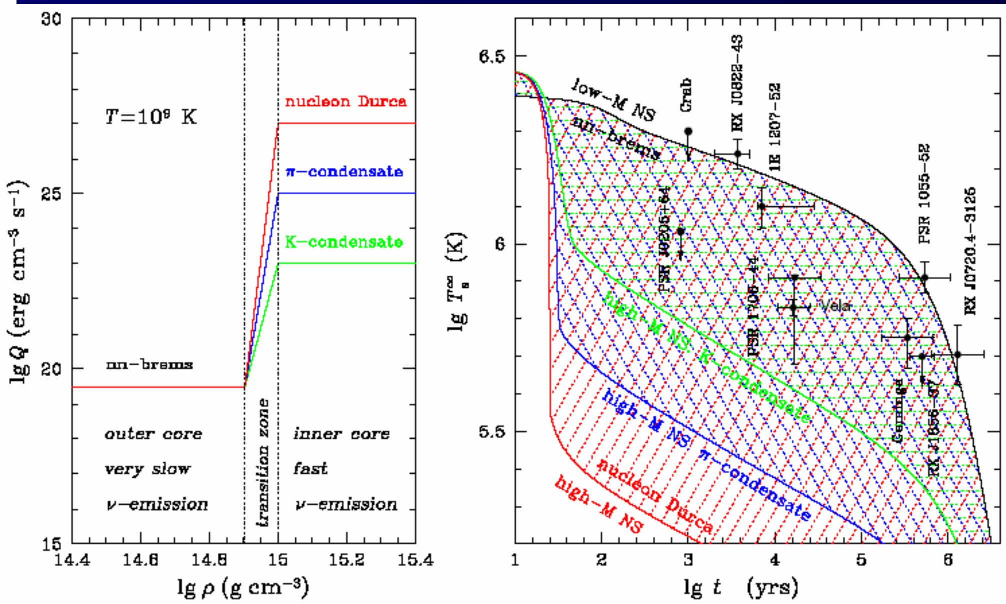


- Modified URCA Cooling Dominates at t<10^5y; Momentum Problem: $E_{fermi,n}$

Process			Q_s, erg cm^{-3} s^{-1}
Modified Urca	$nN \to pNe\bar{\nu}$	$pNe \to nN\nu$	$10^{20} - 3 \times 10^{21}$
Bremsstrahlung	$NN \to NN\nu\bar{\nu}$		$10^{19} - 10^{20}$

- Condensates Would Provide Momentum Sink -> Much More Efficient Cooling

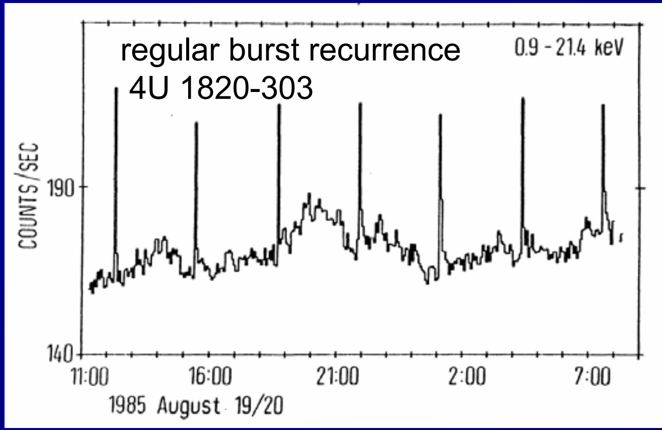
- Observations ~Agree with Normal EoS Coolings
- No Requirement for Exotic Phases

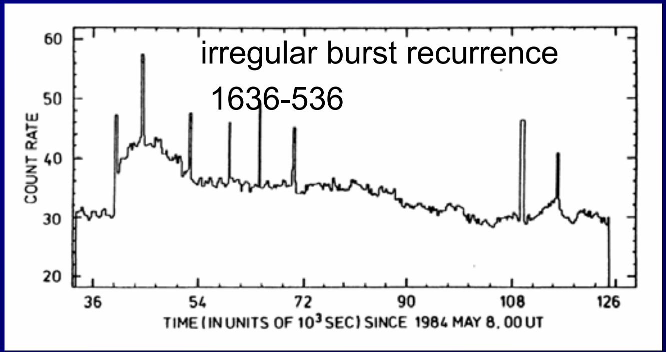


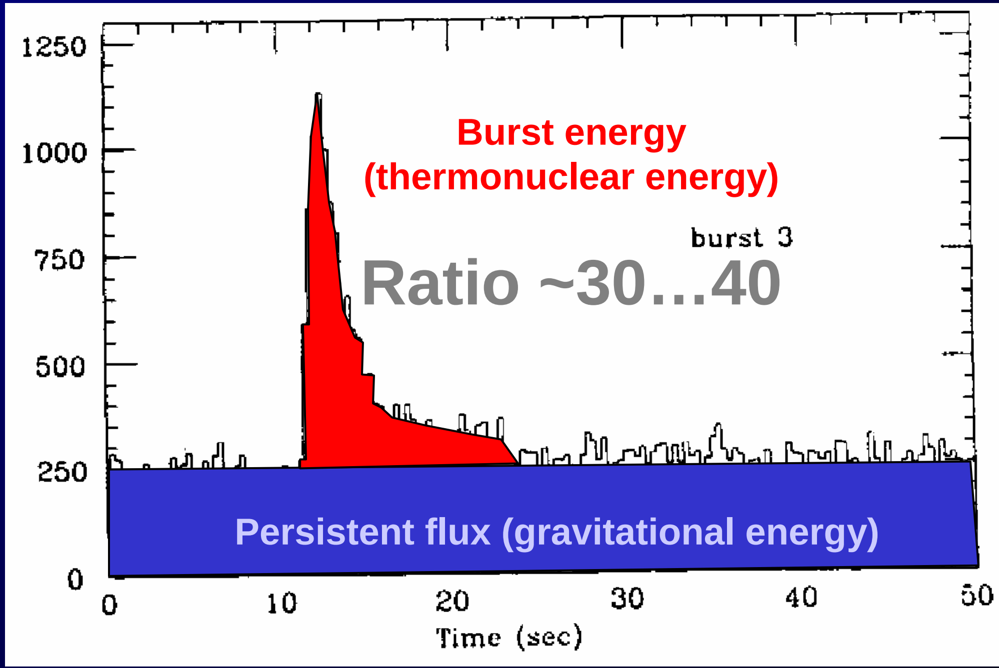
X-ray Bursts from Accreting Binaries

- Duration: 10…100 sec
- Energy release: 10^{36}…10^{38} erg/s
- Recurrence: hours - days

☆ Number of known bursters: about 70 (2001) (of ~160 LMXB's)

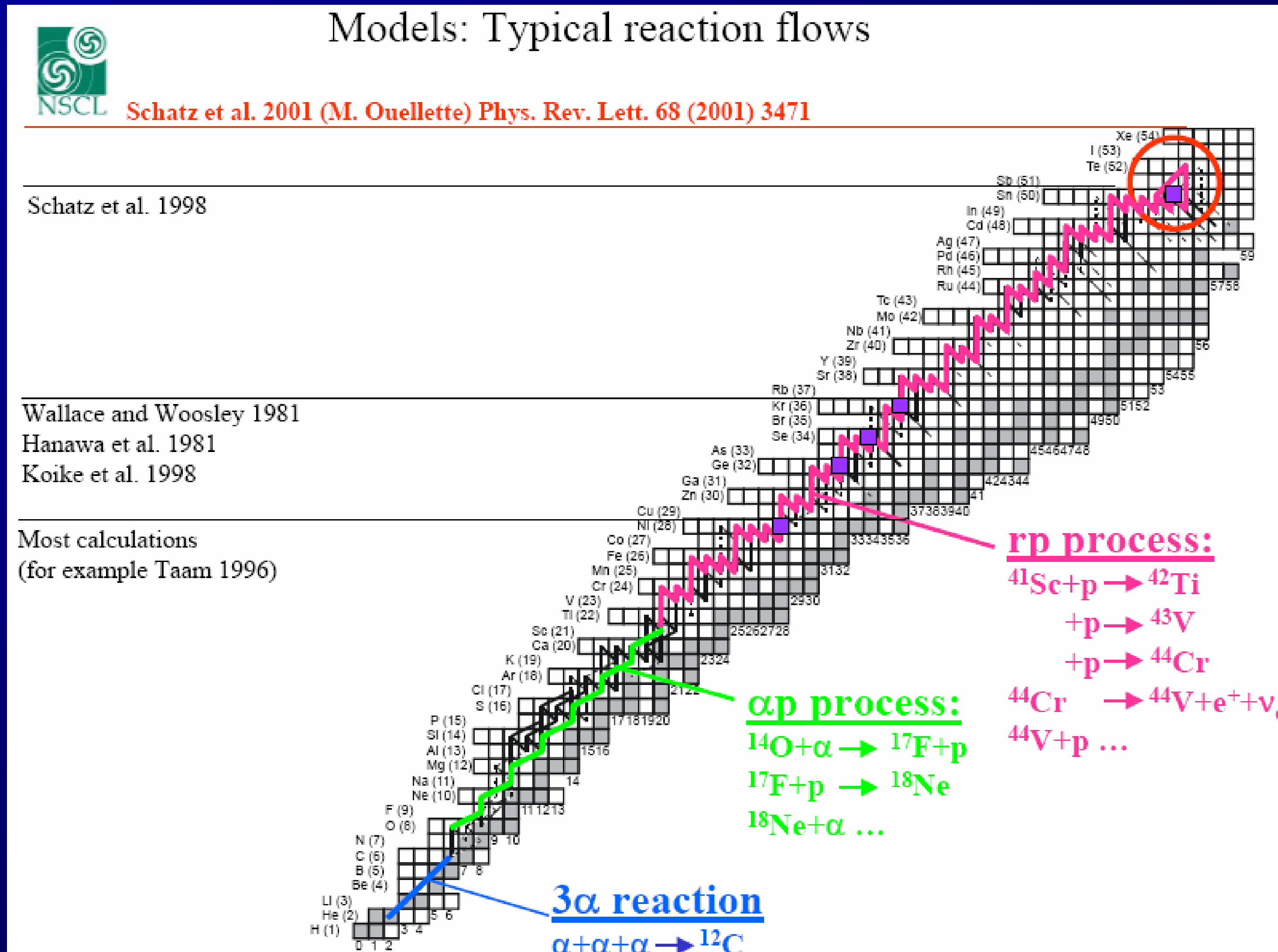






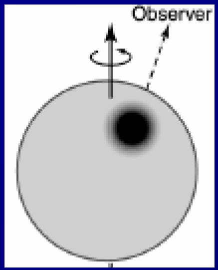
Nuclear Reactions During Type-I XRB

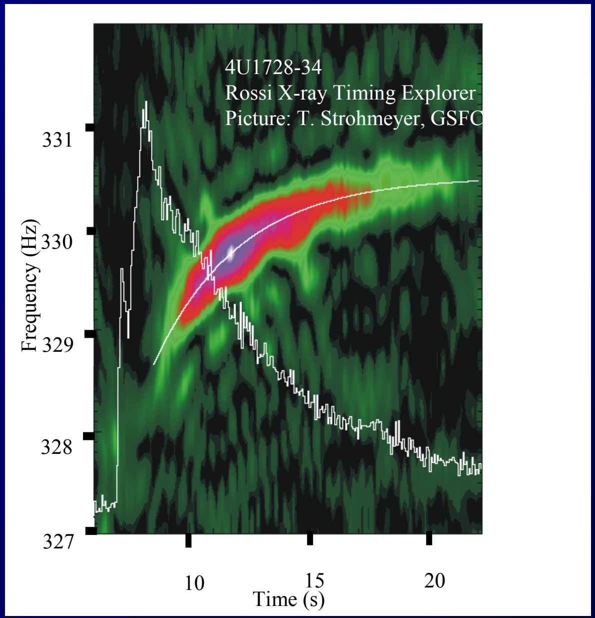
- Network -> Nuclear Energy Release

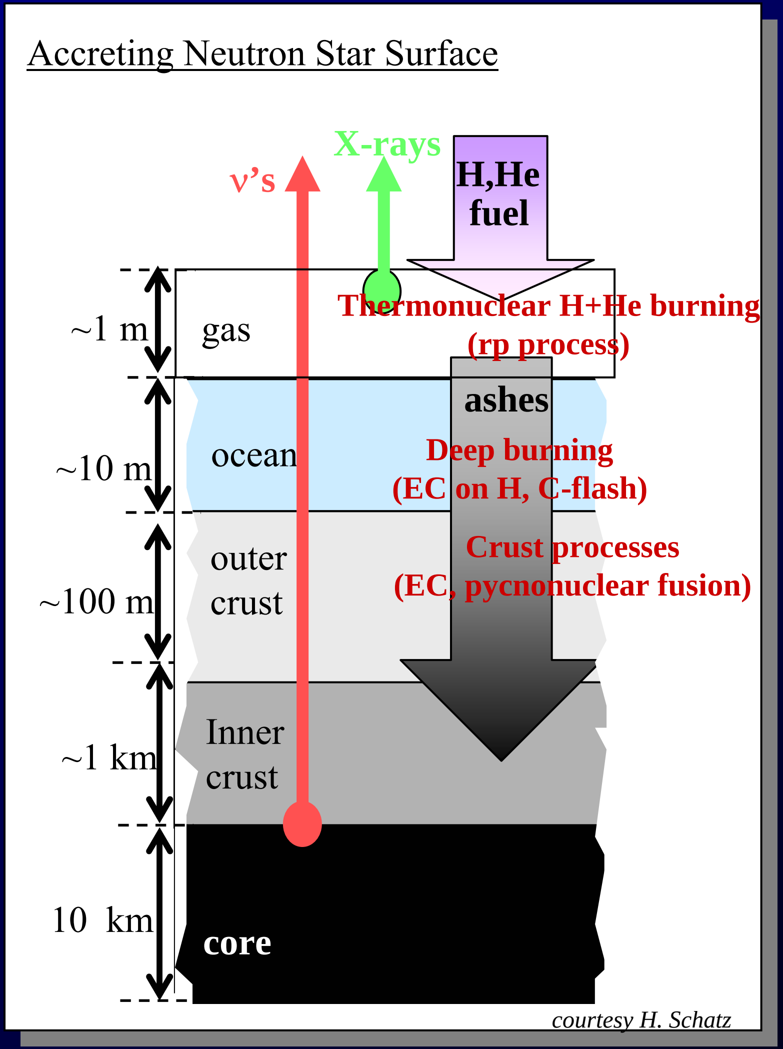


NS Nuclear-Reaction Layers

- Model for Type-I X-ray Bursts
  - Nuclear Burning of Accreted Material in NS Atmosphere
    - Ignition Spot -> Flame Front Propagation on NS Surface
    - Shearing of Burning Layer Above NS
    - Time-Variable 'Spin' Frequencies





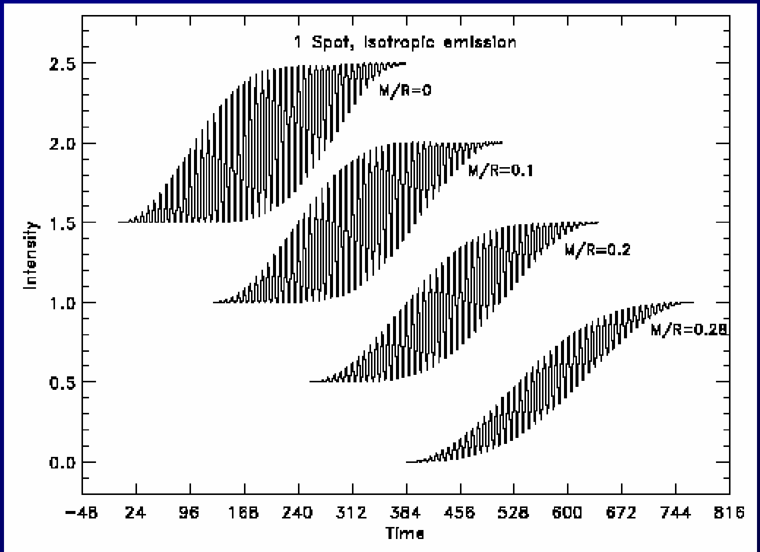


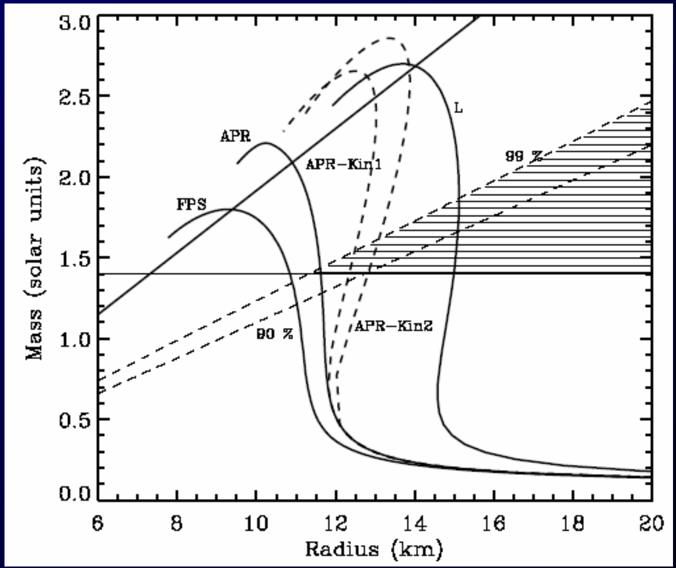
NS Compactness:
Modelling Oscillation Profiles at XRB Rise

☆ NS Rapid Rotation
-> Light Propagation Influenced by GR Effects
- Burst Rise Unaffected by Shear ->
- Light Deflection ~ "compactness"

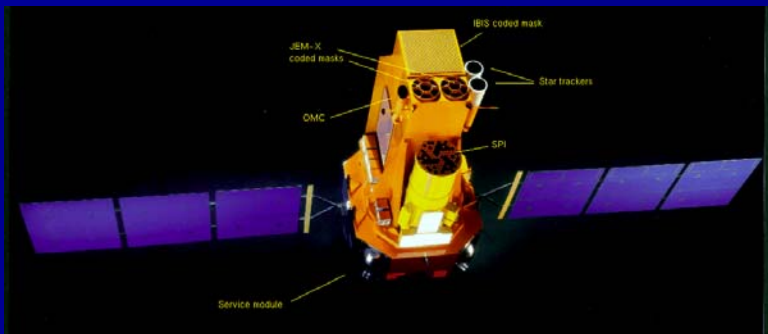
$$m/r \equiv \frac{GM}{c^2 R}$$

- Weaker rotational modulations in more compact stars ('smearing')
- Asymmetry of hot-spot peak from caustics
- *Nath, Strohmeyer, Swank 2002*





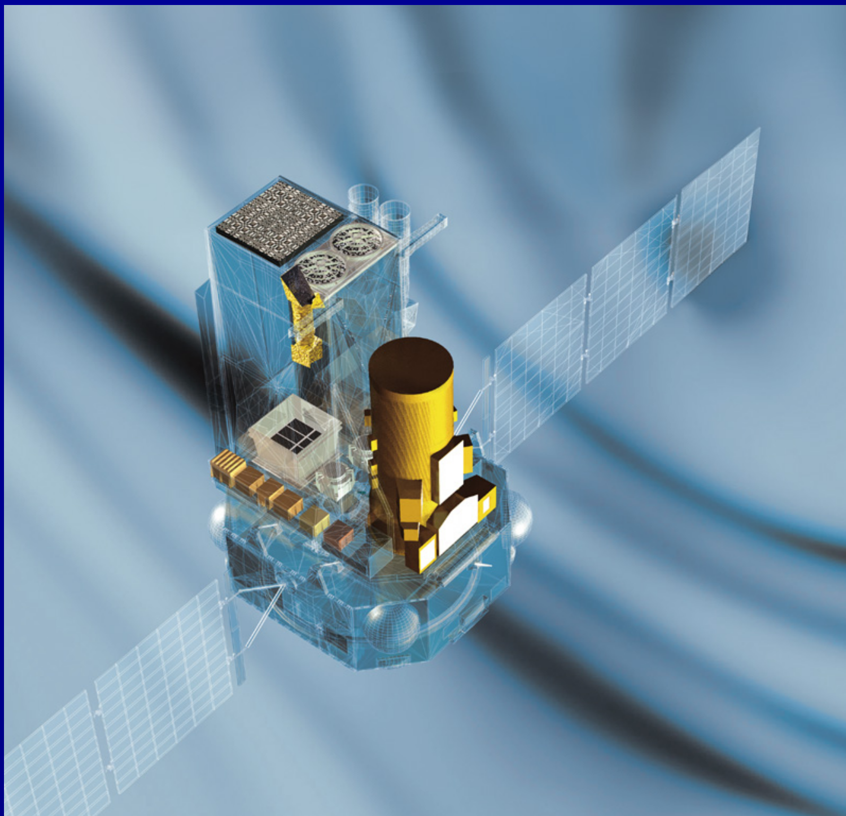
INTEGRAL Successfully Launched!

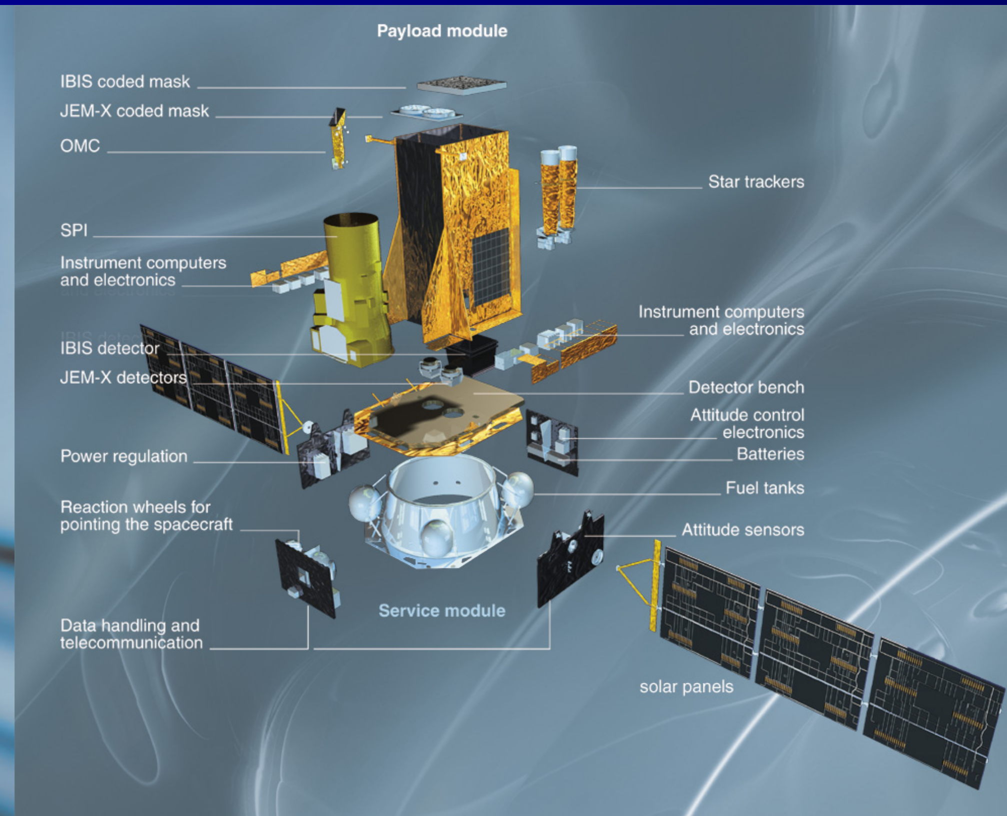


17 October 2002: INTEGRAL on its way (as planned)

12:00 INTEGRAL safely on its way, all systems normal
06:41 Launch of Integral from Baikonur / Kasachstan

The INTEGRAL Spacecraft

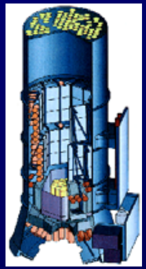




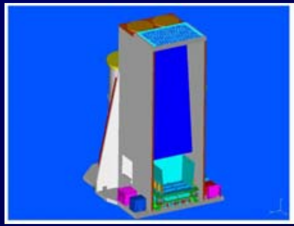
- Spacecraft Service Module (common with XMM)
- Two Coded-Mask Telescopes Side-by-Side
- Monitors and Auxilliary Sensors at Periphery

INTEGRAL Scientific Payload ("Instruments")

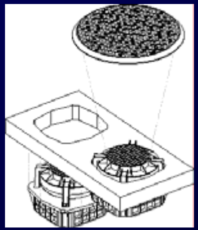
- SPECTROMETER SPI
  - Co-PI's: Jean-Pierre Roques (CESR Toulouse, France) and Roland Diehl (MPE Garching, Germany).



- IMAGER IBIS
  - PI: Pietro Ubertini (IAS Frascati, Italy), Co-PI's: Guido DiCocco (ITESRE Bologna, Italy), and Francois Lebrun (CE-Saclay, France).



- X-RAY MONITOR JEM-X
  - PI: Niels Lund (DSRI Copenhagen)

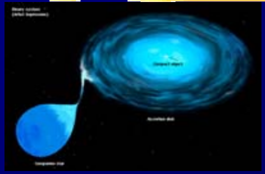
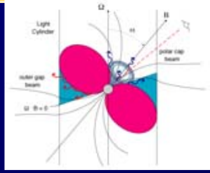


- OPTICAL MONITORING CAMERA OMC
  - PI: Alvaro Gimenez (INTA Madrid, Spain).

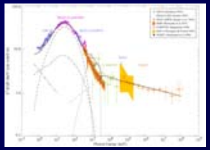
- INTEGRAL SCIENCE DATA CENTRE ISDC
  - PI: Thierry Courvoisier (Obs. Geneva, Switzerland)

INTEGRAL Science Targets

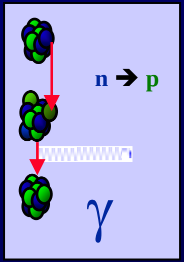
- Compact Objects
  - *White Dwarfs, Neutron Stars, Black Hole Candidates*
  - *High Energy Transients and Gamma-Ray Bursts*

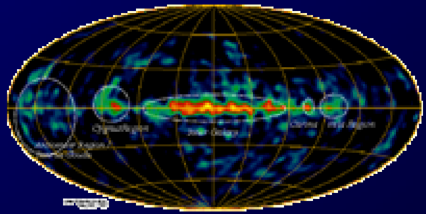



- Extragalactic Astronomy
  - *Galaxies, Clusters*
  - *AGN, Seyferts, Blazars*
  - *Cosmic Diffuse Background*

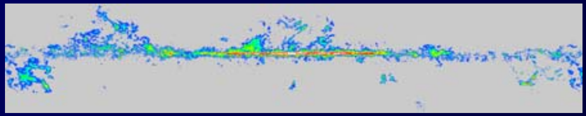
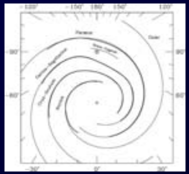



- Stellar Nucleosynthesis
  - *Hydrostatic Nucleosynthesis (AGB, WR Stars)*
  - *Explosive Nucleosynthesis (Supernovae, Novae)*

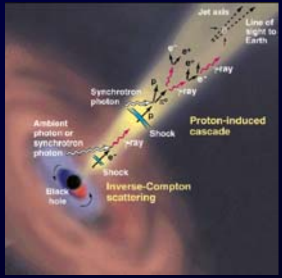




- Galactic Structure
  - *Cloud Complex Regions*
  - *Mapping of continuum and line emission*
  - *ISM distribution*
  - *CR distribution*


- The Galactic Centre
- Particle Processes and Acceleration
  - *Transrelativistic Pair Plasmas, Beams, Jets*
- Identification of High Energy Sources



INTEGRAL Mission

Mission Phases

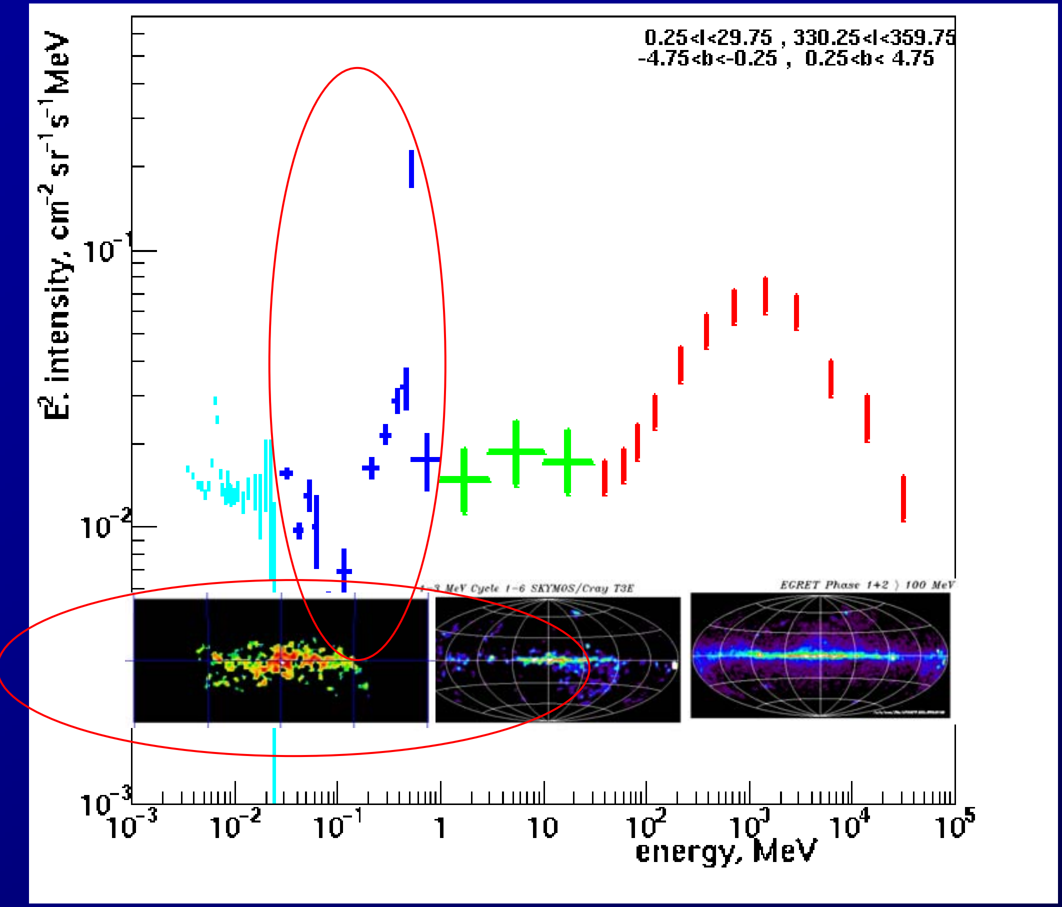
- Launch & Early-Orbit Checkout ~35 days
- Commissioning 2 months
- Nominal Operations 2 years
- Extended Operations 3 years+

(Nov 2003: ESA SPC Approval of 2-year-rolling extension till Dec 2008)

Science Operations Program

- Core Program (35% in year-1, 30% in year-2, 25% beyond)
- Open Program (65% in year-1, 70% in year- 2, 75% beyond)

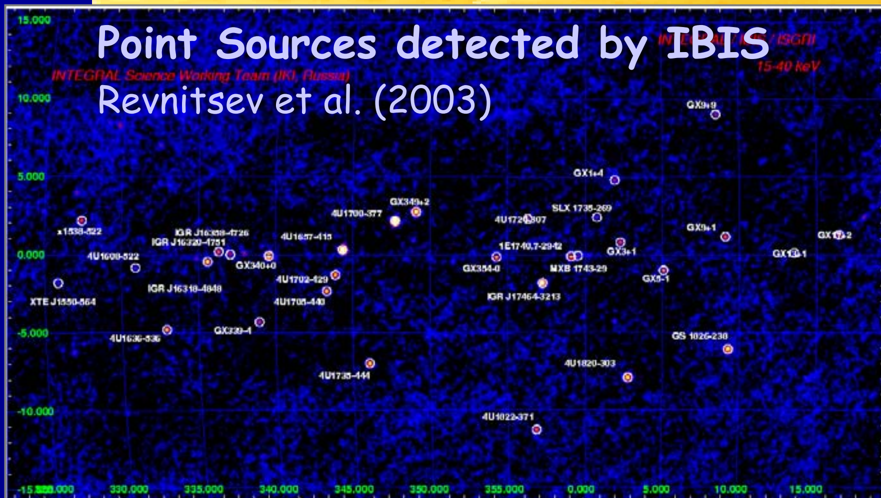
The Galactic Ridge in X/Gamma-Rays



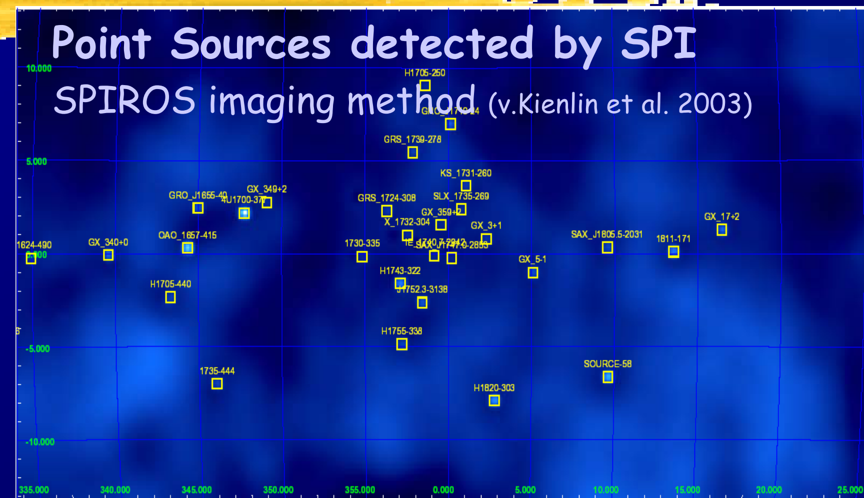
- Over 8 Decades in Energy
  - Spectra
  - Images

- A "Mine" of Information about High-Energy Processes in
  - ISM
  - Point-like Sources

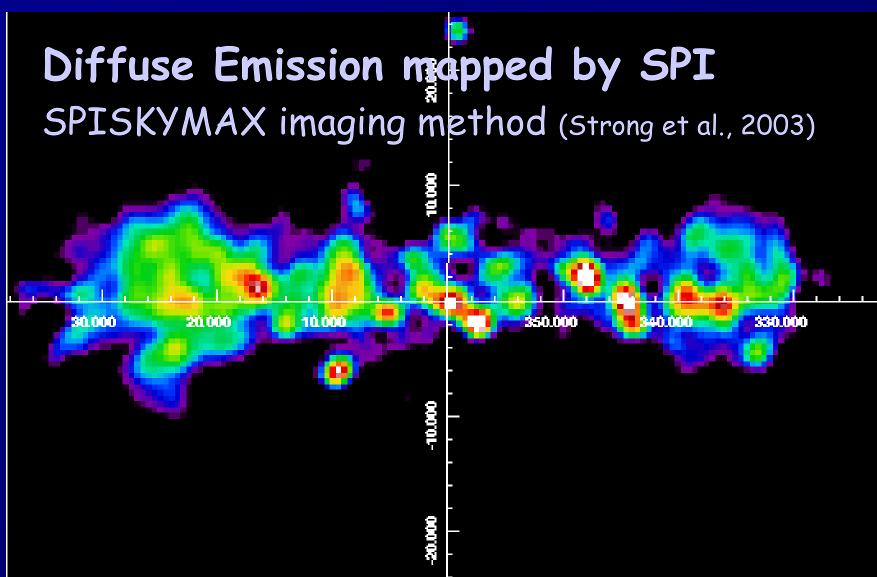
INTEGRAL's Gamma-Ray Source Survey



Point Sources detected by IBIS
Revnitsev et al. (2003)



Point Sources detected by SPI
SPIROS imaging method (v.Kienlin et al. 2003)

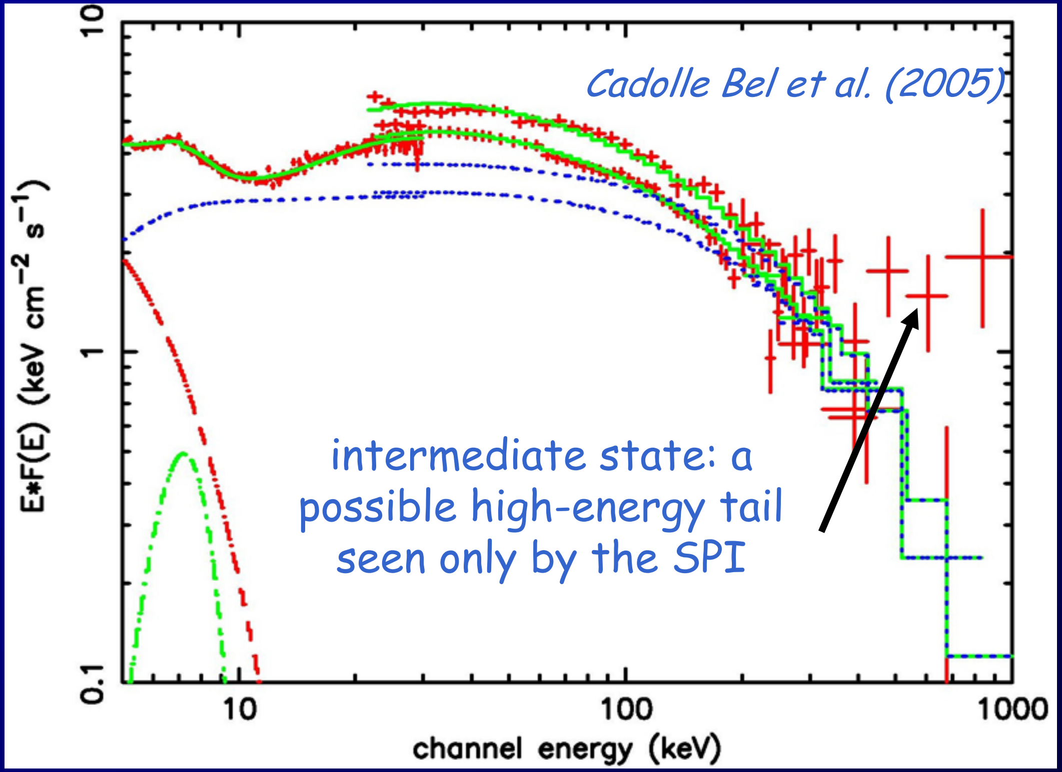


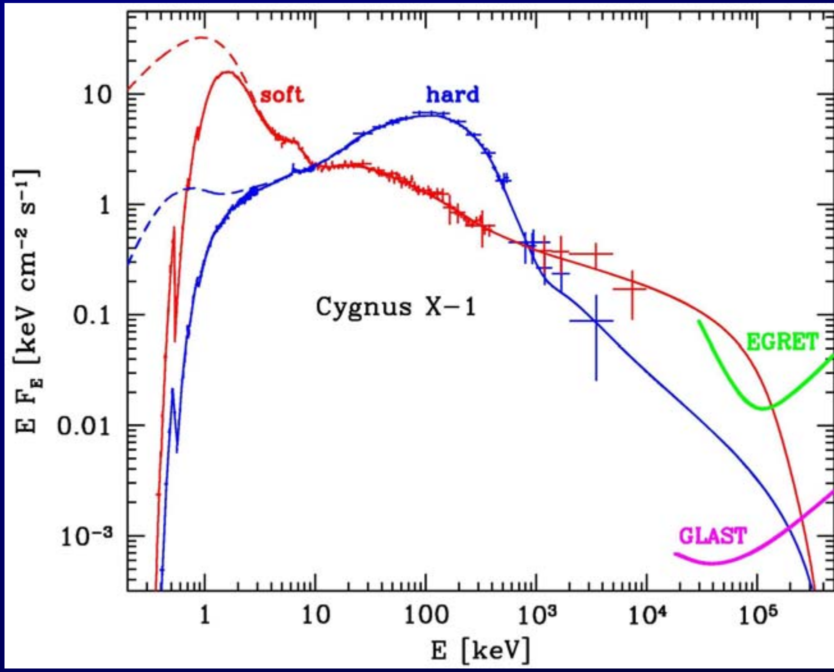
Diffuse Emission mapped by SPI
SPISKYMAX imaging method (Strong et al., 2003)

- Galactic Point Sources:
  - ☆ Accreting Binaries (Black-hole, NS)
  - ☆ Pulsars
  - ☆ ???
- Diffuse Galactic Emission
  - ☆ from Cosmic-ray / Gas Interactions
  - ☆ from Ensembles of Sources
  - ☆ from Galactic Nucleosynthesis
- AGN

INTEGRAL spectra of Cyg X-1

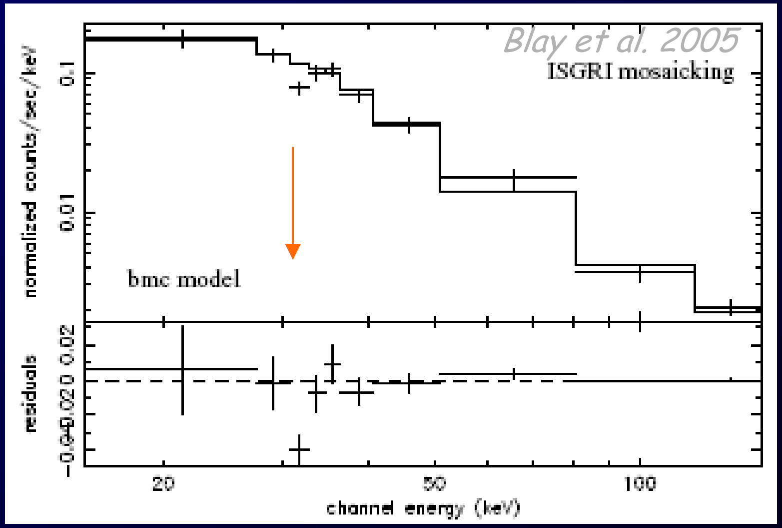
- Cyg X-1 State Changes
  - ☆ High-Energy Emission seen with SPI in Intermediate State





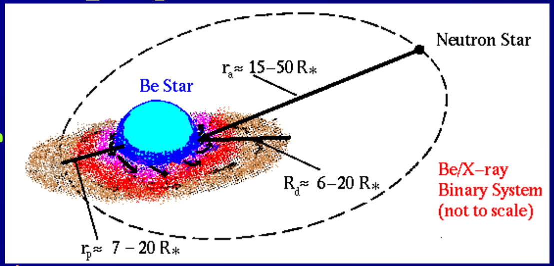
Diagnostics of HMXB's: WD, NS or BH?

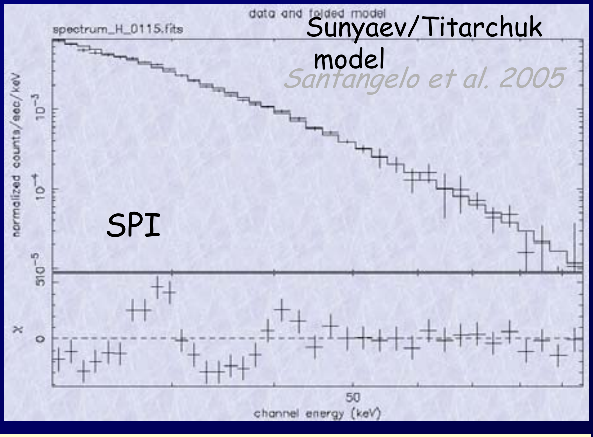
- HMXB's without Pulsations -> Nature of Compact Star?
- 4U2206+54:
  - ☆ Non-Periodical Variability -> Accretion-Powered System
  - ☆ L_X, HE Extent of Spectrum -> WD Unlikely
  - ☆ Evidence for Cyclotron Line at 32 keV (-> 3.6 10^{12}G NS?)
    - ☞ *Blay et al. 2005*



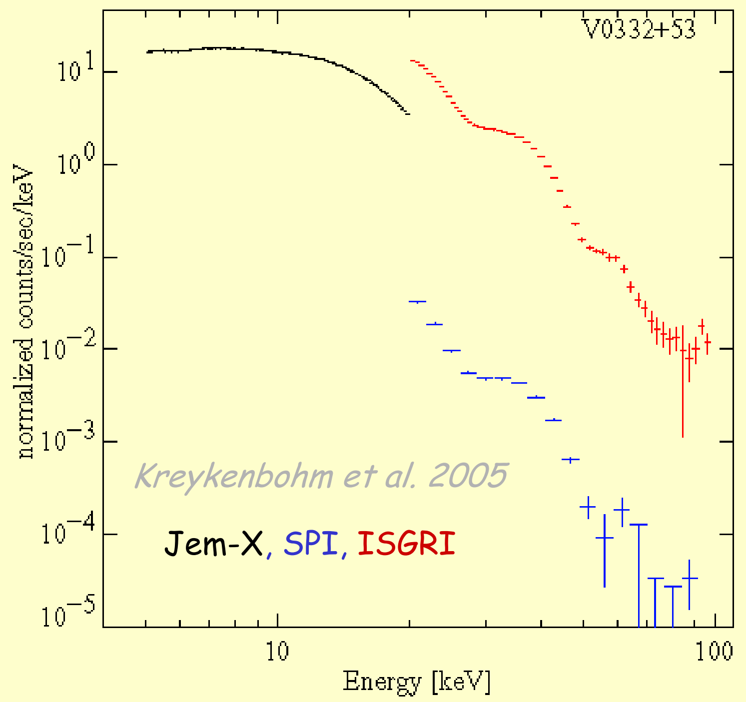
Measuring NS-Magnetic Fields in Hard-X-ray Pulsars

- Be / X-ray Binaries
  - ☆ Compact Star orbits around Massive Main-Sequence Star
    - NS-Wind/Disk Interactions -> High-Energy Radiation
    - Episodic Mass Transfers -> Transient





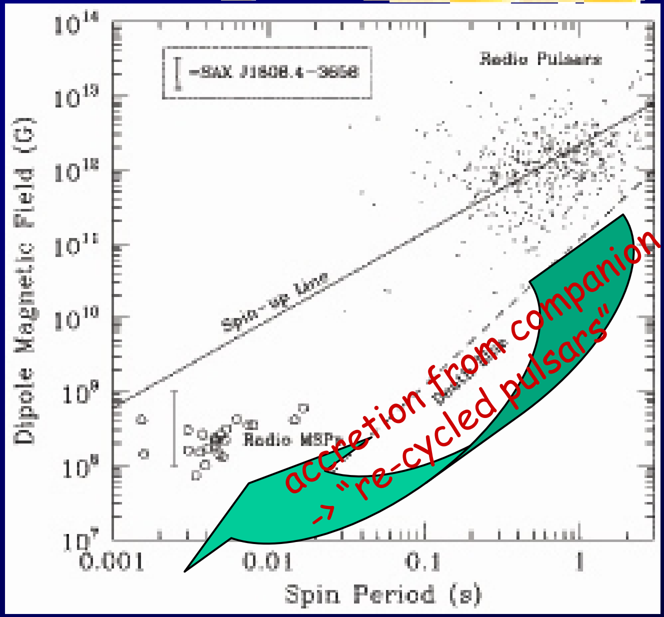
- ~11 Systems Detetced with INTEGRAL
  - X0115+63
  - ☆ NS+O Star System, d~7 kpc
    - Orbital Period 24.3 d (e=0.34), Pulsar Spin Period 3.61 s
    - Recurring Transient (~10^{38} ergs, i.e. ~L_{Edd}) (1978...2004)
  - ☆ 2004: (RXTE, INTEGRAL) Cyclotron lines
    - Lines at 22.3, 33.8, 44, 56 keV
  - V0332+58
  - ☆ NS+O Supergiant System, d~7 kpc
    - Orbital Period 34.297 d (e=0.31), Pulsar Period 4.375 s
  - ☆ 2004: (RXTE, INTEGRAL) Cyclotron lines with fundamental frequency ~25 keV
    - Lines at 24.9, 50.5, 71.7 keV
    - Magnetic Field ~2.7 10^{12}G



- Precise Magnetic-Field Measurements!

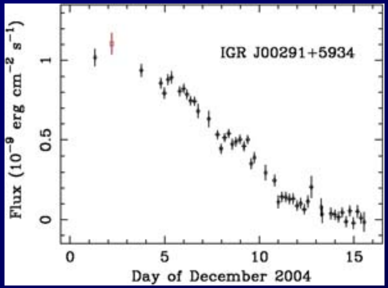
IGR J00291+5934: fastest-known X-ray msec Pulsar

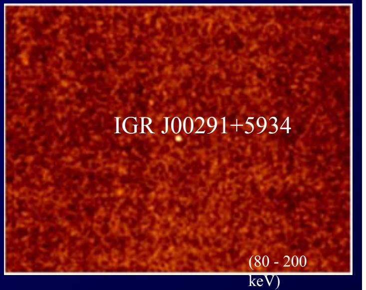
- New X-ray transient discovered with INTEGRAL on Dec 2, 2004 (Eckert et al. ATel 352)
  - ☆ Location: R.A.= 00h 29.1', Dec.= +59d 34m (=Cas region)
  - ☆ I ~ 55 mCrab (20-60 keV; ISGRI); 35 mCrab (2-10 keV; RXTE)
  - ☆ $I \sim E^{-1.7}$, $N_H \sim 7\ 10^{21}\ cm^{-2}$, pulsations seen up to 150 keV
  - ☆ 598 Hz X-ray Pulsar (RXTE, Marqwardt, Swank and Strohmeyer ATel 353)
  - ☆ No Evidence of any Harmonics -> fundamental NS Rotation Period~600Hz!
  - ☆ No X-ray Eclipses, No X-ray Bursts
  - ☆ Frequency drifts 36 mHz -> Doppler orbital modulation -> orbital period ~147.412 min, sin(i)~0.65, Companion > 0.038 $M_\odot$
  - ☆ Counterparts found: Optical at ~ 17.4 mag, Radio at ~1.1 mJy
  - ☆ Optical Spectra: Broad Emission Lines in HeII, Hα
  - ☆ Similar X-ray outbursts Nov. 26-28 1998, Sept. 11-21 2001 (from RXTE 1996-2004)
- -> fastest-known *X-ray* msec Pulsar! (2.67 msec)
- -> 3-year periodicity?

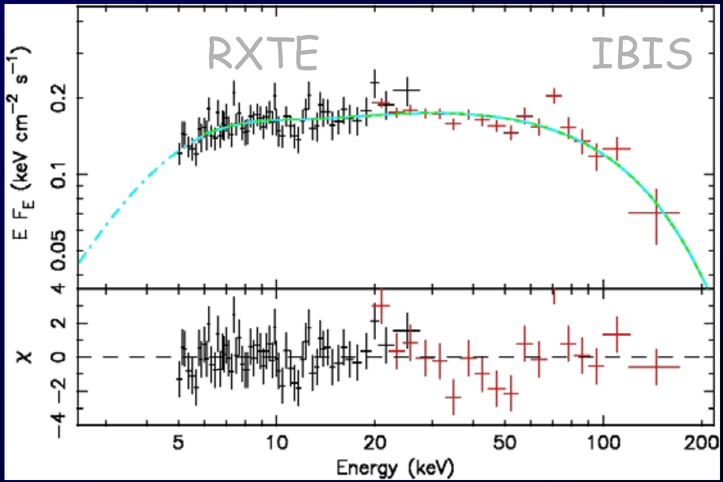


Falanga et al, 2005

- ~6 LMXBs known as msec pulsars now
- Comptonization model, seed ph from hot spot

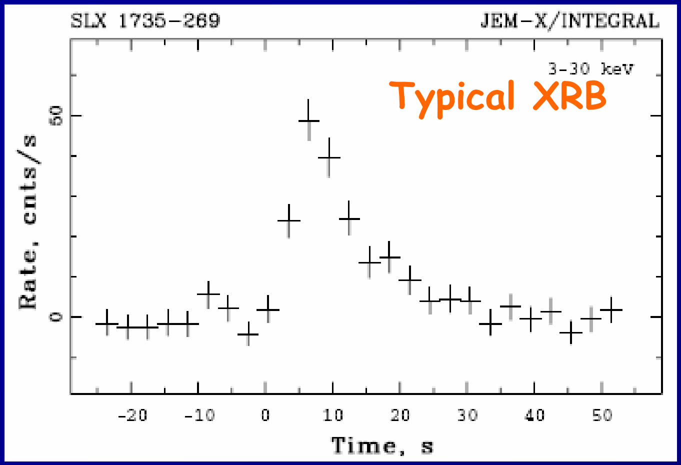


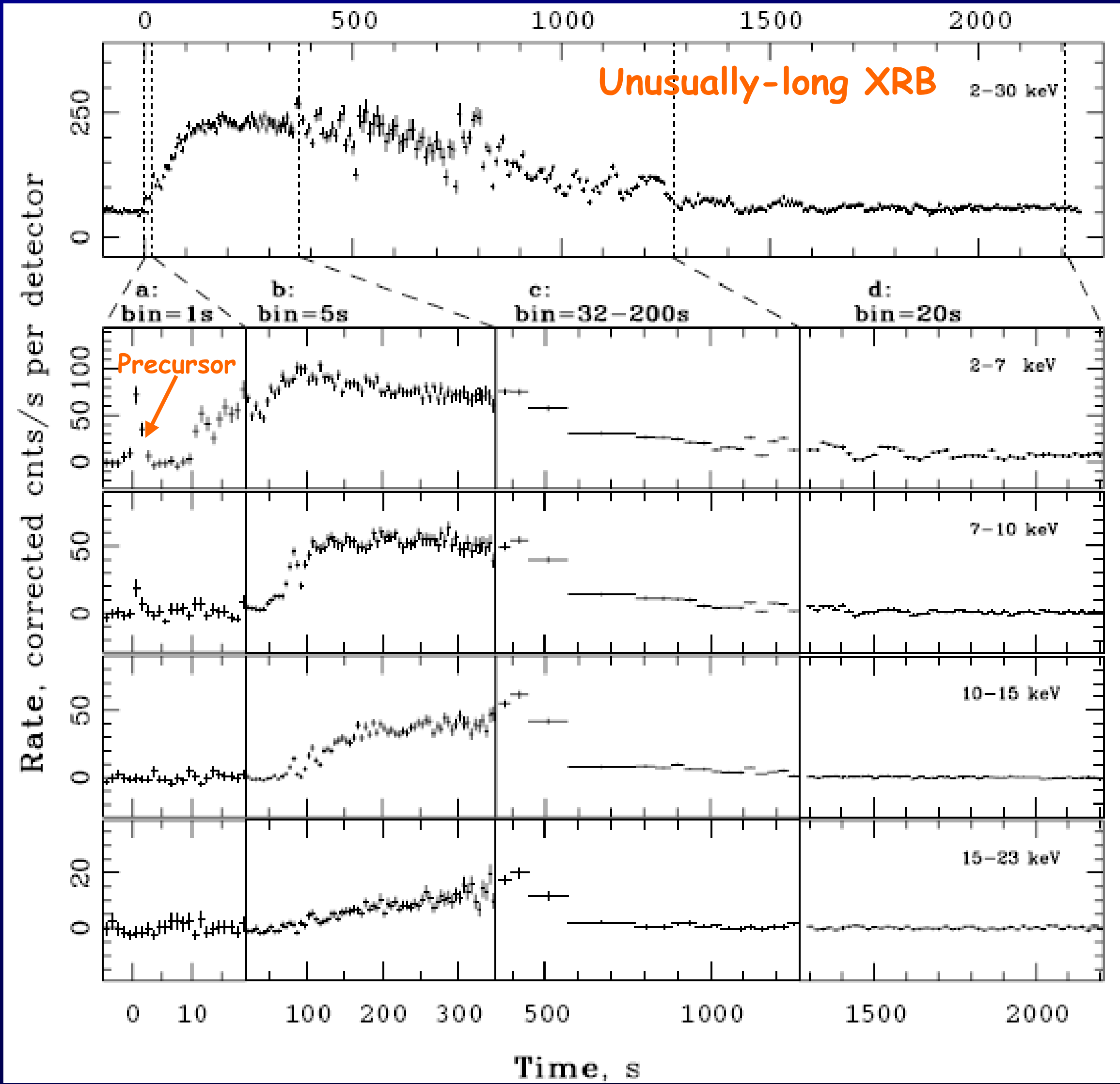




Type-I X-ray Bursts: SLX 1735-269

Molkov et al. 2005



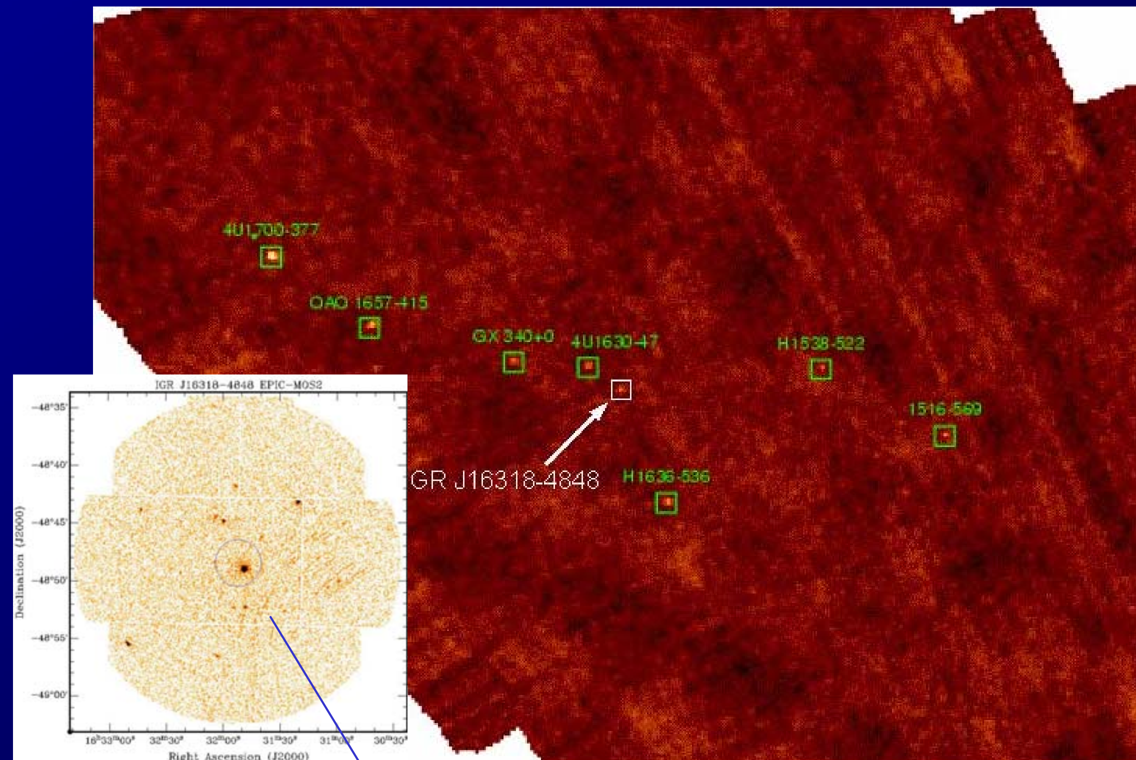


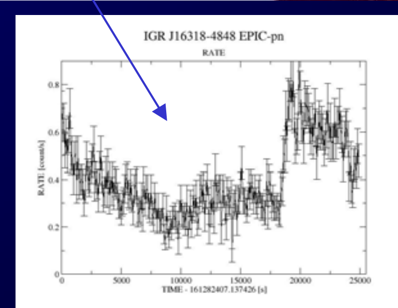
- SLX1735-269: 'Typical' XRBurster
- One Unusually-long XRB:
  - ☆ "Superburst"? No:
    - ☞ dM/dt to small for Steady He Burning
    - ☞ C Accretion Time 10^9y
  - ☆ He/H Flash?
  - ☆ Multiple Bursts?

New "INTEGRAL Gamma-Ray Sources" - Binaries

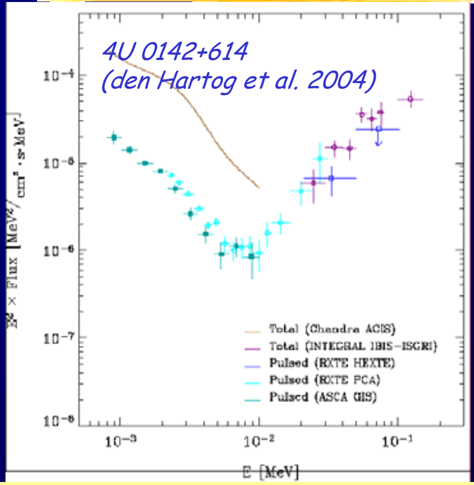
- **IGR J16318-4848**
  - ☆ Discovery Jan 2003 15-40 keV (ISGRI)
  - ☆ I~.05-.1 Crab, Variability δt~1000s
  - ☆ XMM/Newton ToO Discovers Weak X-ray Source
  - ☆ Highly Absorbed!
  - ☆ ...
- **IGR Sources:** (~2/month)
  - ☆ Mostly Soft Spectra, but Some Hard at >100 keV -> Pulsars, BH Candidates
  - ☞ Some Highly Absorbed (N_H~2 10^{24} cm^2)

-> New Class of Embedded Sources?

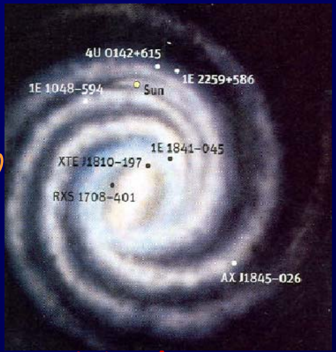




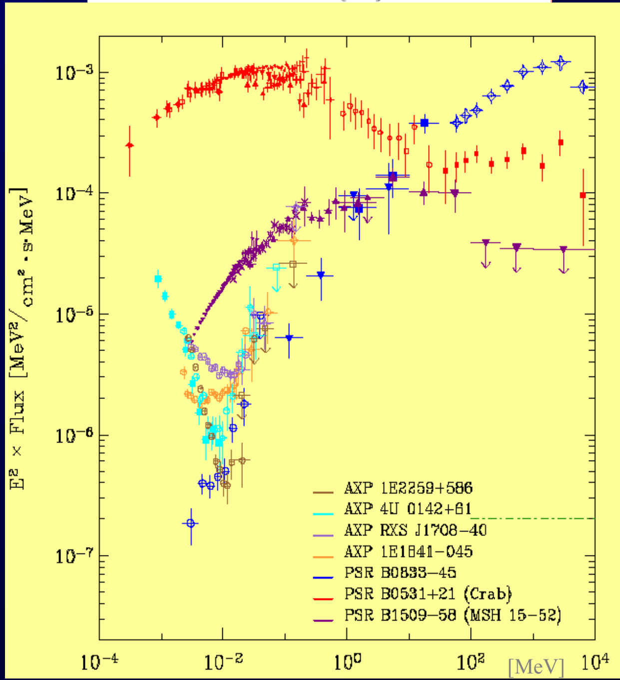
Gamma-Ray Emission from Neutron Stars: AXP's



- **Anomalous X-ray Pulsars:** *(e.g. Kaspi 2004)*
  - Periods in 5-12 sec range, spinning down
  - Located in young disk of Galaxy
  - Very soft spectra (kT~keV), L_x~10^{35} erg s^{-1}.
  - Not powered by rotation:
    X-ray power L_x > rotational energy loss
  - Not powered by accretion: steady spin down, no variability of emission, exept: SGR-like outbursts
- **INTEGRAL Discovers More Such Sources, Surprisingly, at >10 keV**



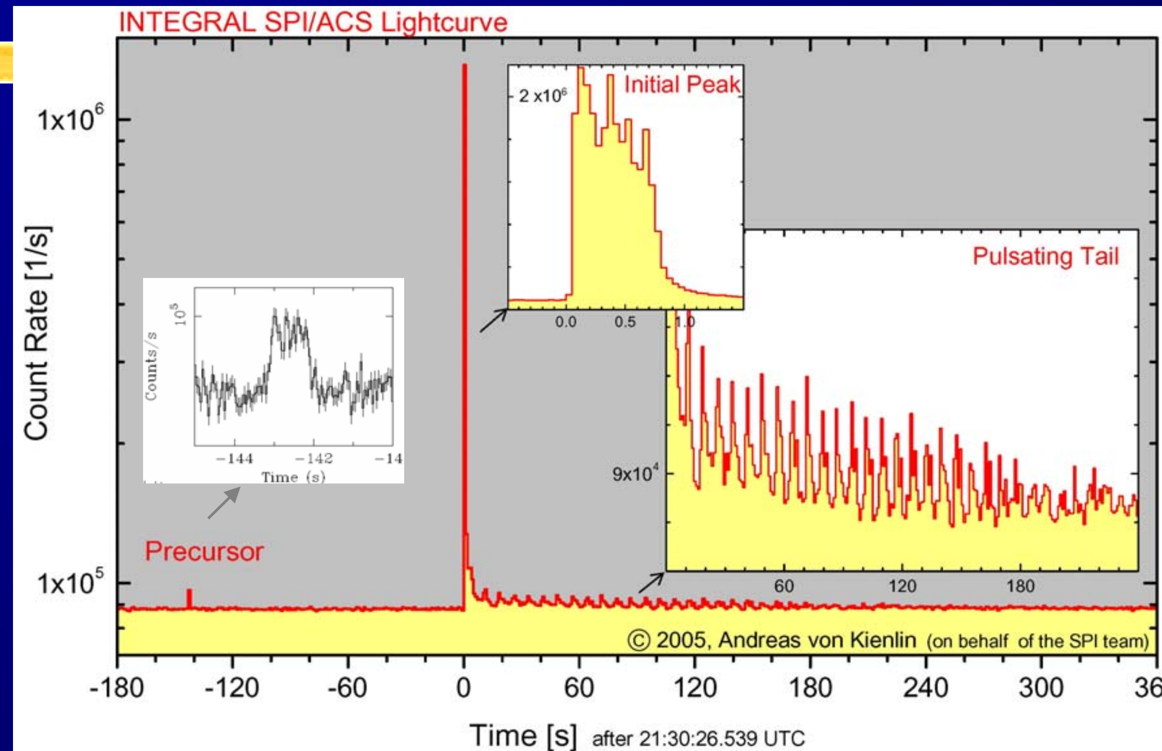
  - 1E 1841-045 *(Molkov et al. 2004, Bassani et al. 2004)*
  - 1RXS J170849-400910 *(Revnivtsev et al. 2004)*
  - 4U 0142+614 *(den Hartog et al. 2004)*
  - IGR J00234+6141 *(den Hartog et al. 2005)*
- **AXP's Spectra Now Show Significant High-energy Emission Tail with Hard Spectrum**
  - New Window to Study Magnetars B~$10^{14...15}$G!



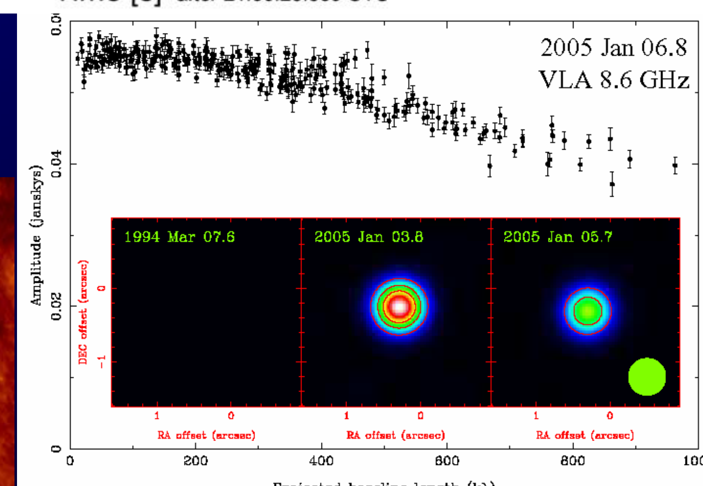
Soft Gamma-Ray Repeaters / SGR 1806-20

SGR 1806-20

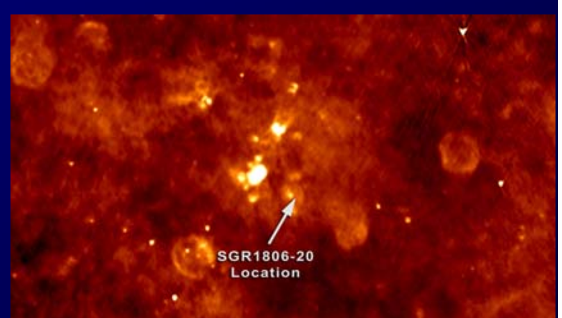
- ☆ Giant Flare 27 Dec '04
  - ☞ INTEGRAL/SPI-ACS, RHESSI, SWIFT, Mars-Odyssee…
  - ☞ 7.56 sec pulsations (NS rotation?)
  - ☞ Precursor at -143 s
  - ☞ $E_{total, flare} \sim 10^{46}$ erg! (100* other SGRs)
  - ☞ E_{peak}/E_{tail} >> other SGRs



- ☆ IR and Radio Afterglows
  - *(VLT, Israel et al. 2005; VLA, Gaensler et al. 2005;)*
  - ☞ *Expanding polarized radio nebula (v_{exp}~0.3 c)*
  - ☞ *~4 10^{43} erg in particles*

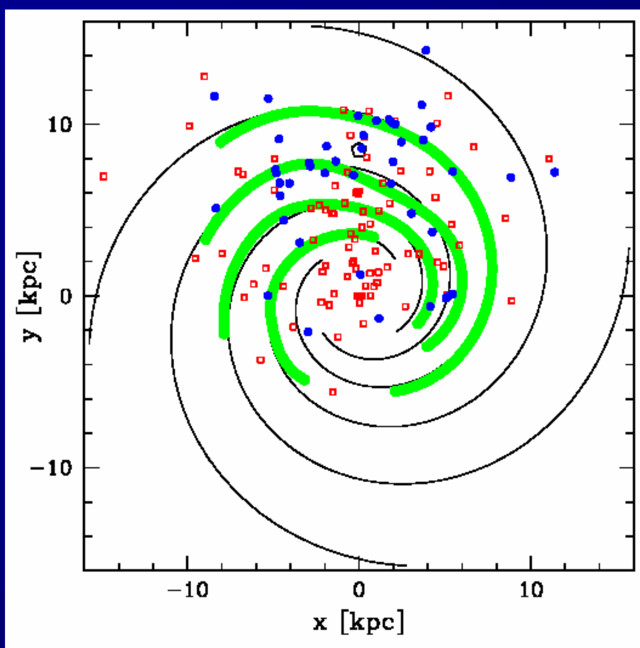


- ☆ *Example of a "Short-Duration" GRB??*



Galactic Distribution of X-ray Binaries

- ☆ Largely Incomplete Sample
- ☆ HMXBs Follow Distribution of Star-Forming Regions
- ☆ LMXB's Concentrate in Galactic Bulge
  - ☞ Grimm et al. A&A 2002
  - ☞ Lutovinov et al. 2005



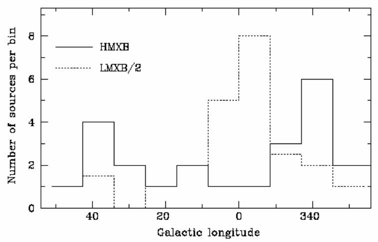


Fig. 7. Angular distribution of high mass X-ray binaries (HMXBs) and low mass X-ray binaries (LMXBs) in the inner Galaxy. The number of LMXB is devided by 2.

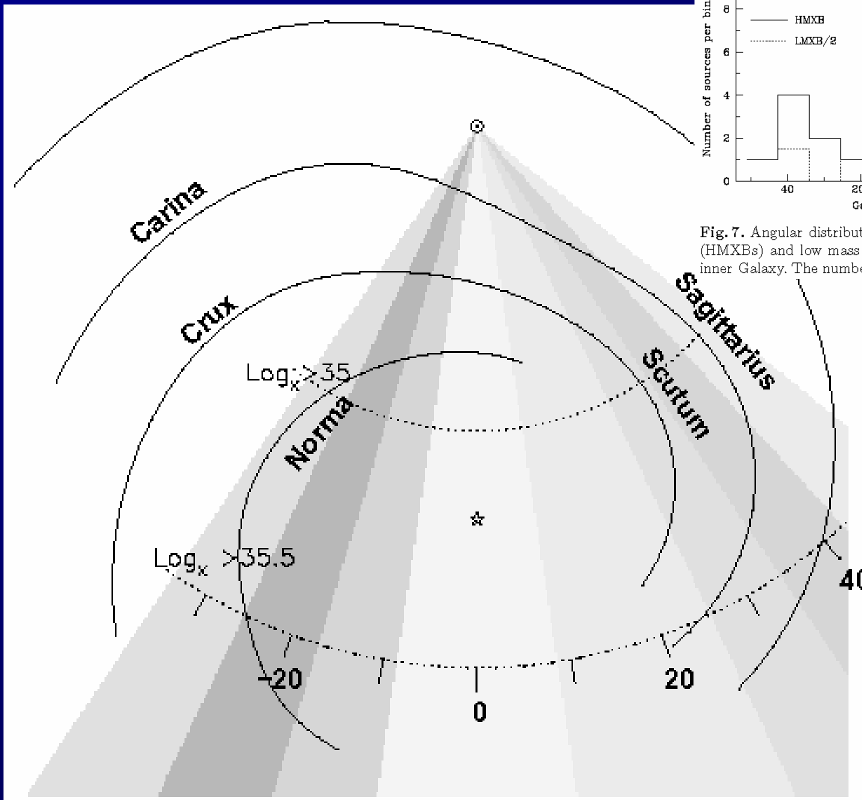
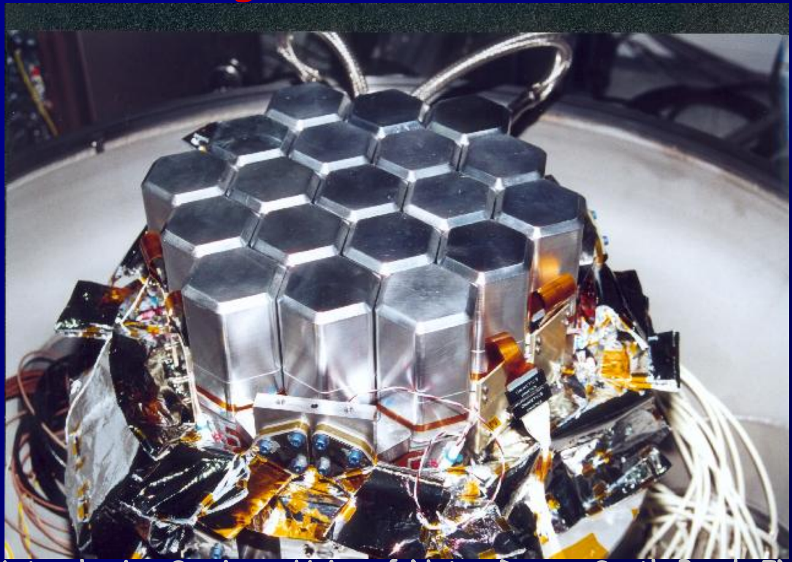
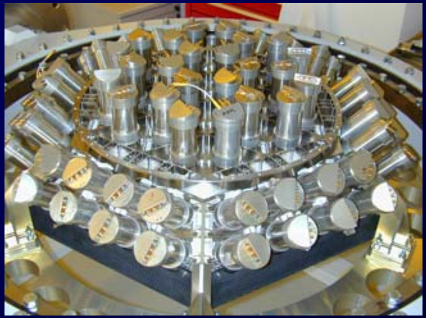


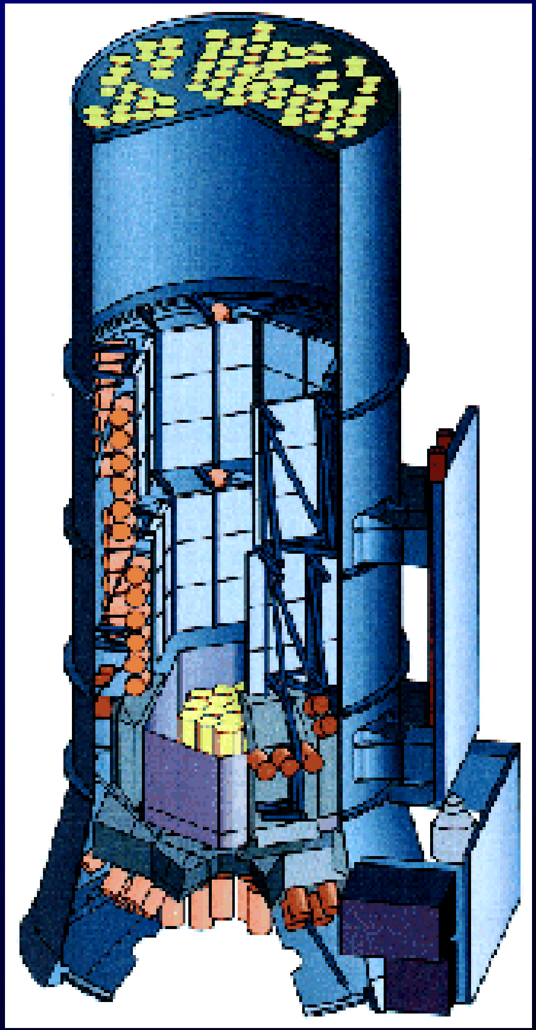
Fig. 8. Face-on view of the Galaxy with overlayed densities of HMXBs shown by gray scale (from 0 to 7, see Fig. 7). The distance 8.5 kpc of the Galactic Center from the Sun is assumed. The star denotes the position of the Galactic Center. Open circle with the dot denotes the position of the Sun.

The INTEGRAL Spectrometer (SPI)

- Coded-Mask Telescope
- 19 Ge Detectors (5.5x5.5x7cm)
- BGO Anticoincidence Detector & Shield
- Stirling Cryocooler
- Energy Range 15-8000 keV
- Energy Resolution ~2.2 keV @ 662 keV
- Angular Resolution ~2 arcmin
- Field-of-View 16x16°
- Timing Resolution 52 μs

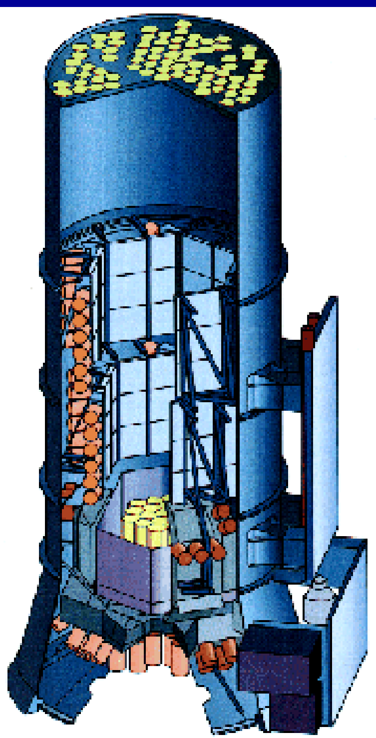


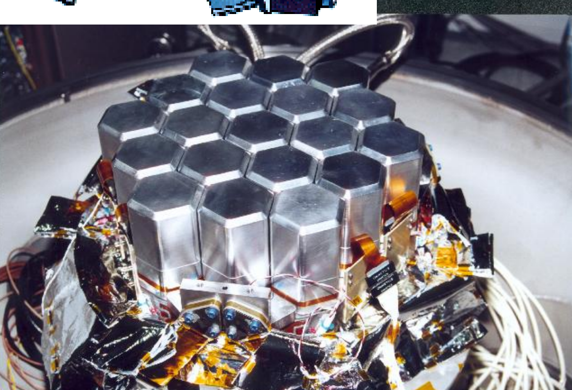


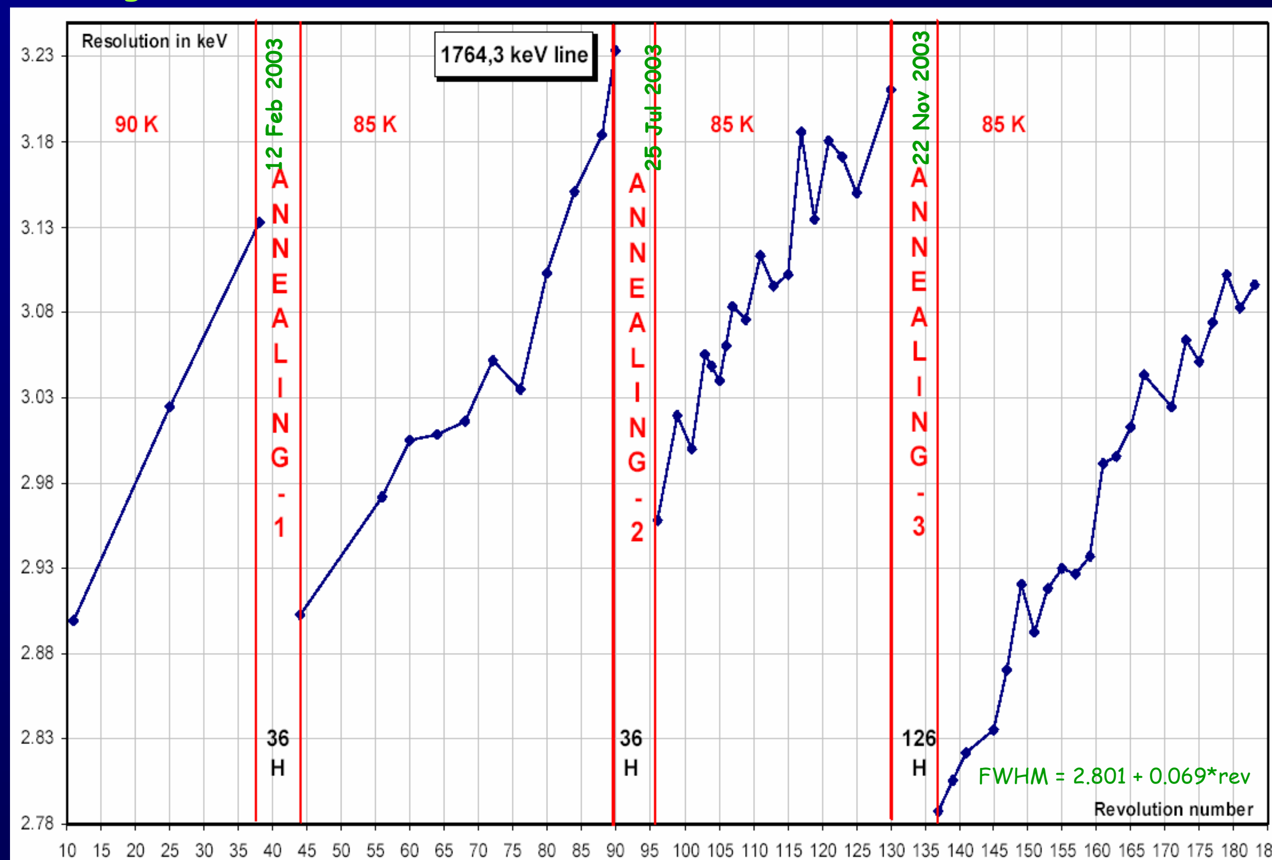


High-Resolution Gamma-Ray Spectroscopy in Space: SPI on INTEGRAL

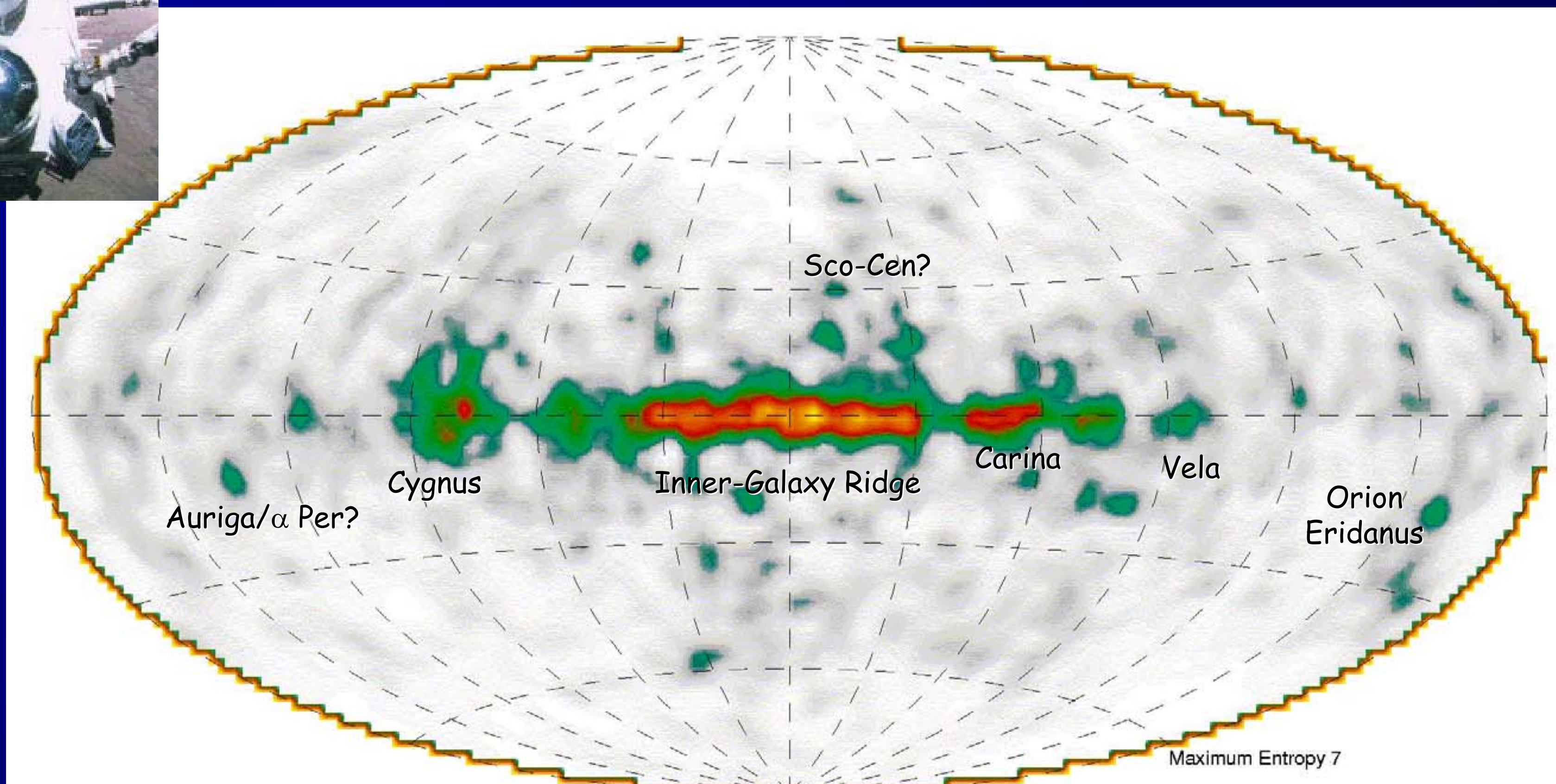
- Detector Elements: 2 Failures (of 19), Resolution ~ok
  - #2 6 Dec 2003, #17 17 Jul 2004
- Degradation from Cosmic Rays Rectified by Annealing
  - ~2% per Orbit, ~20% in 6 Months (@1 MeV)
  - Annealing: 126(36) hrs at 105C, few hrs at 90K; 5 times successful so far





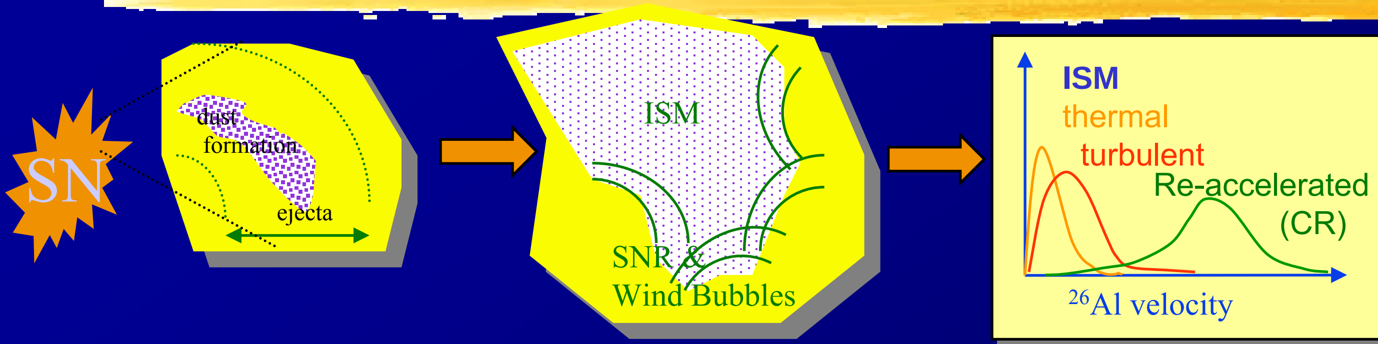


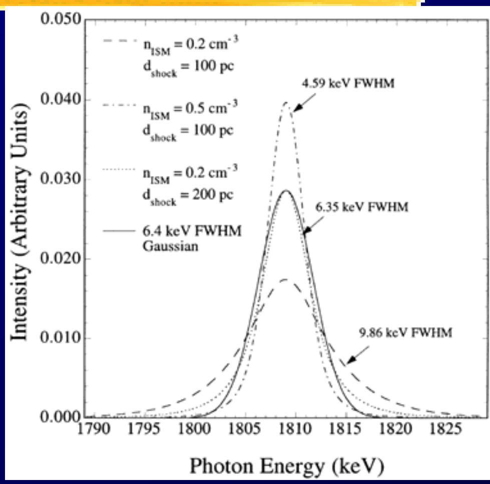
The Sky at 1809 keV: ^{26}Al



Complete CGRO Mission
(Plüschke et al. 2001)

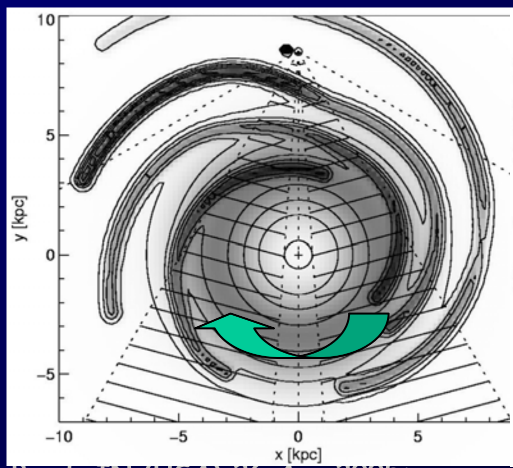
^{26}Al Line Shape Astrophysics

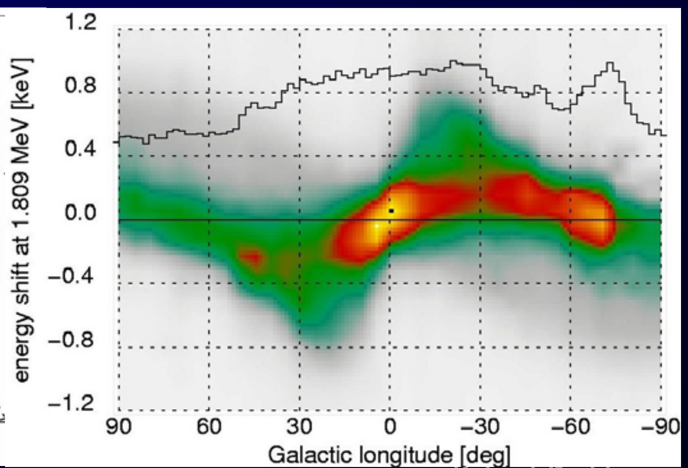




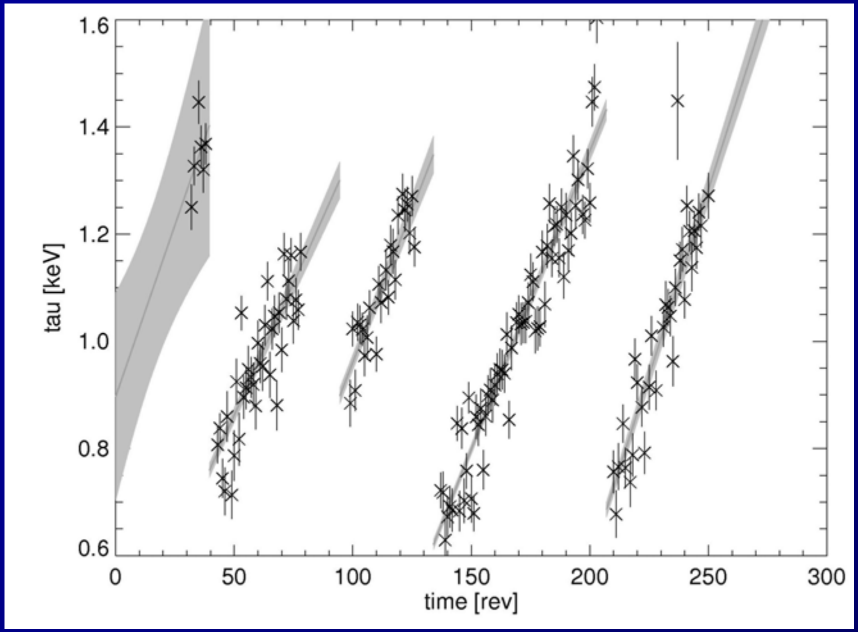
- Ejection and Slowing-Down of ^{26}Al from Sources
  - ☆ ^{26}Al Ejected into Hot Cavities (WR Winds, …)
    -> ISM Turbulence <-> Line Width
  - ☆ ^{26}Al Condensed on Dust, Re-accelerated -> High-Velocity Tail?
    - ☞ *Chen et al. 1997; Sturner & Naya 1999*

- Galactic Rotation
  - ☆ ^{26}Al Sources
    in Spiral Arms,
    Along Line-of-Sight
    -> ^{26}Al Source
    Location Along LoS
    - ☞ *Gehrels et al. 1996;*
      Kretschmer et al. 2003





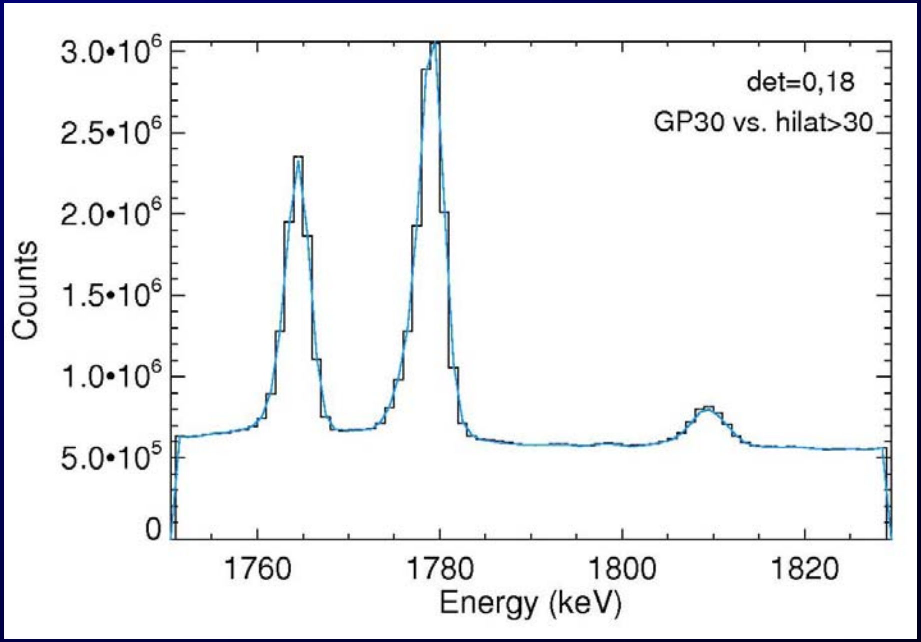
^{26}Al Line Spectroscopy from SPI Observations



- Variable Instrumental Resolution

☆ Underlying Broad Background Feature

  ☆ ^{26}Al Signal ~ 1% of total



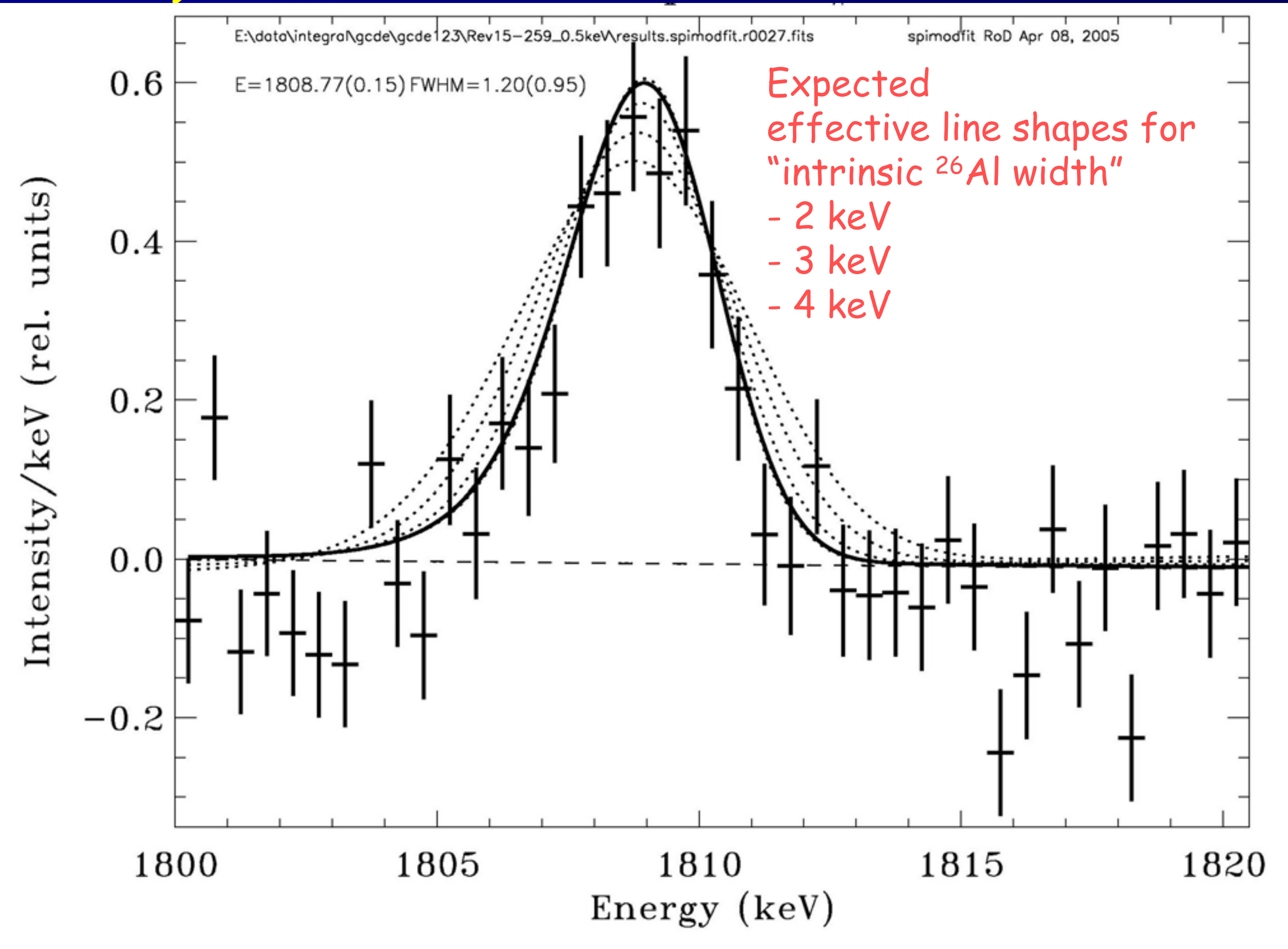
➢ Analysis Method:

☆ Fitting of Background and Sky Distribution Models in Fine E Bins

☆ Comparisons to "predicted" Features/Shapes

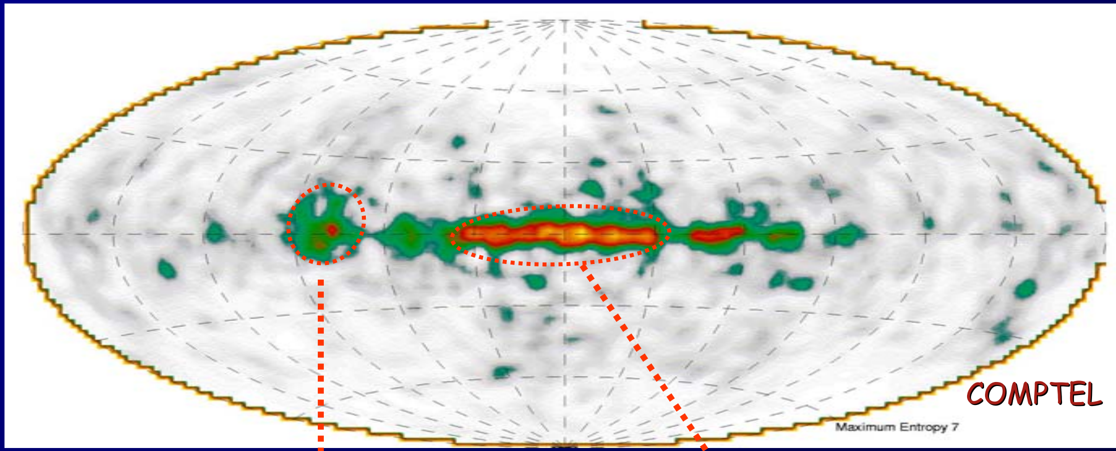
^{26}Al in the Inner Galaxy

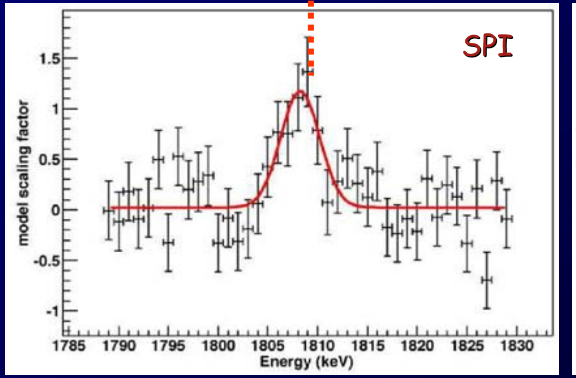
- Generally, the ^{26}Al Line is "Narrow" (~instrumental width)
  - SPI: 1.2 ± 0.9 keV

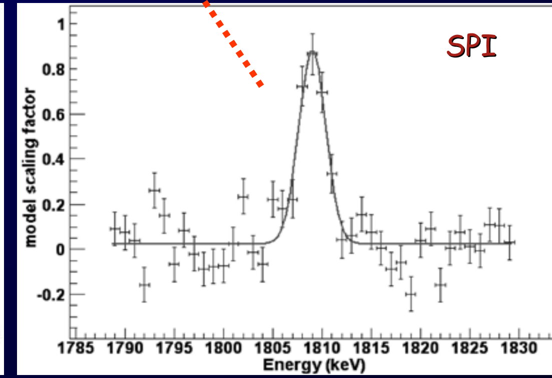


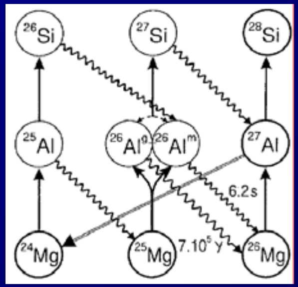
Nucleosynthesis in the Current Galaxy: ^{26}Al

- ^{26}Al Reflects Sources of Nucleosynthesis (τ~10^6y)
- COMPTEL Imaging -> Massive Stars are Dominating Sources
- Decay in ISM -> narrow line
- Large Cavities -> broad line
- Young Clusters -> broad line









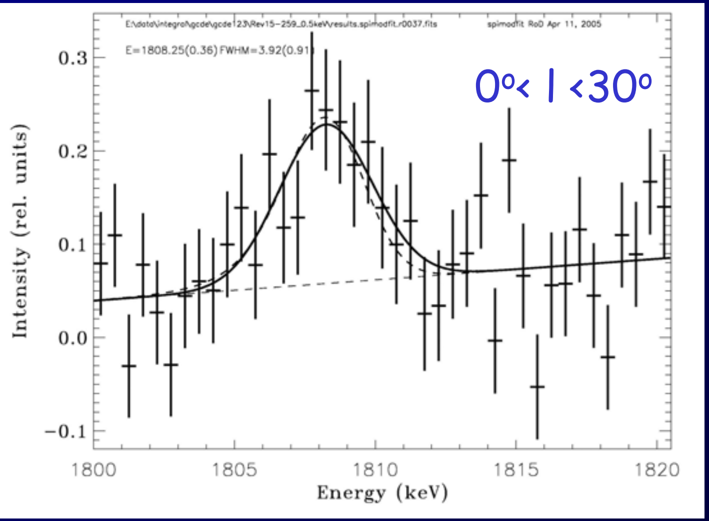
H Burning

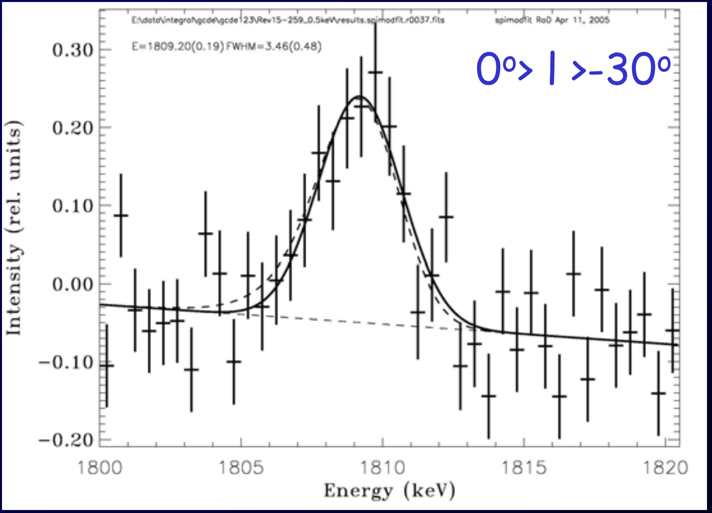
INTEGRAL/SPI: Add Fine Spectroscopy!

^{26}Al Spectroscopy Science: Inner Galaxy

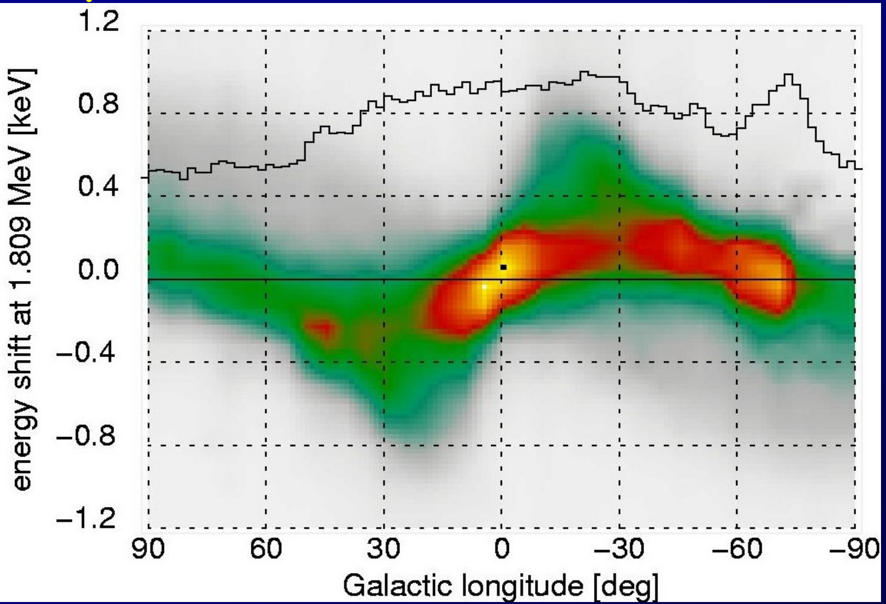
- ☆ Line Width -> Doppler Broadening
  - ☞ Galactic Rotation
  - ☞ Interstellar Turbulences

SPI:





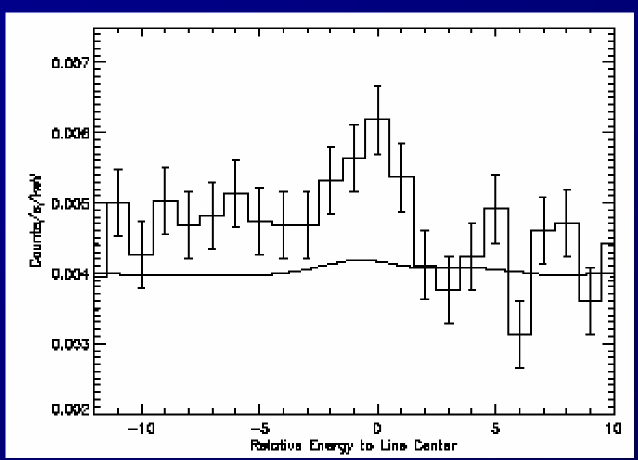
Expectations:

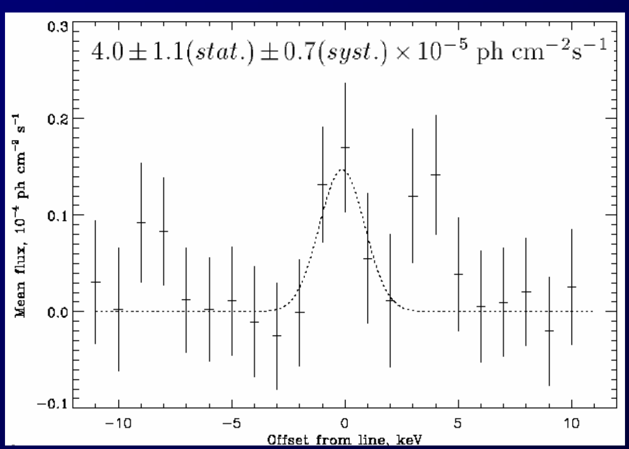


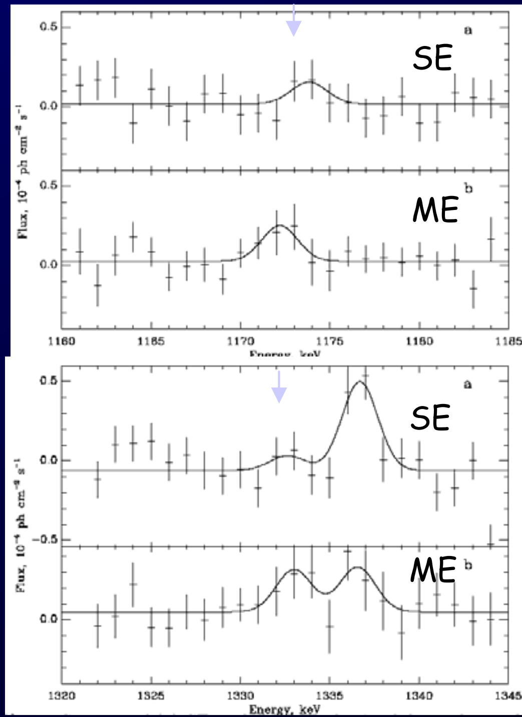
^{60}Fe Detections with RHESSI & SPI/INTEGRAL

- RHESSI
  - ☆ 2.6 σ Detection
  - ☆ I=0.91 ± 0.31 10^{-4} ph cm^{-2} s^{-1}
    - ☞ *Smith 2004*

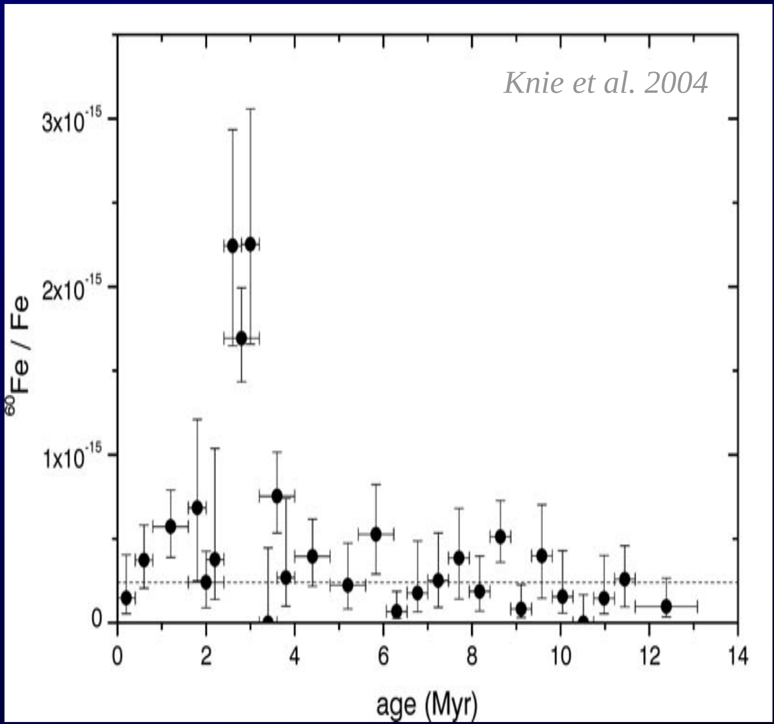
- SPI
  - ☆ 3 σ Detection
  - ☆ I=0.4 ± 0.2 10^{-4} ph cm^{-2} s^{-1}
    - ☞ *Harris et al. 2005*





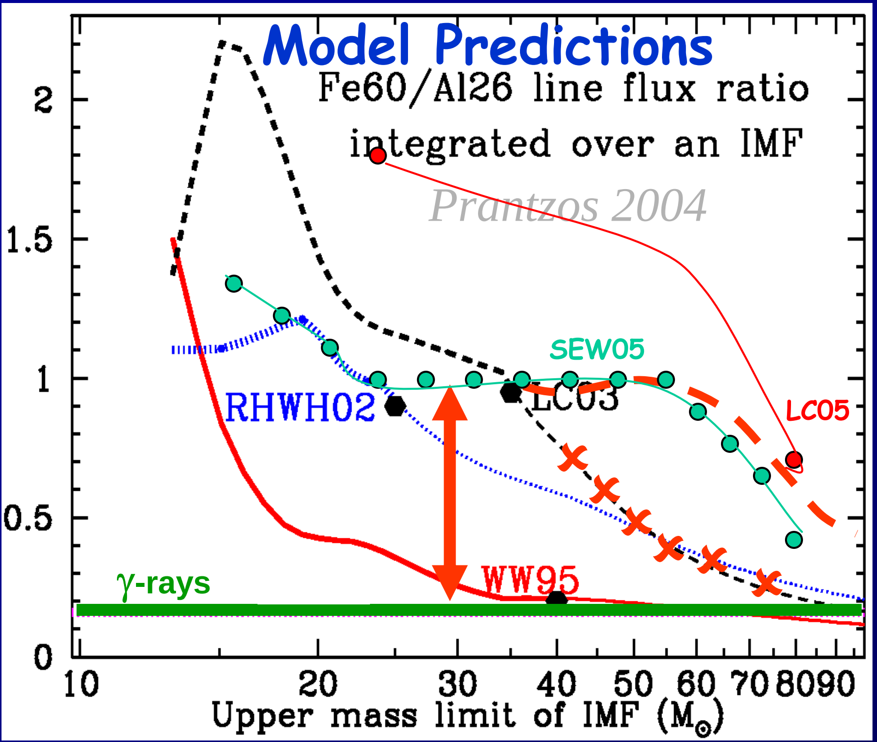


Terrestrial ^{60}Fe Detection



- Current Terrestrial Record:
  - ☆ Ocean Crust Analysis
    - ☞ Slow, Fe-rich Growth (2mm/My)
    - ☞ Dating with CR-Produced ^{10}Be
    - ☞ AMS Atom Counting
  - ☆ Nearby SN 2.8 My ago?
  - ☆ *NB: This is NOT the ^{60}Fe we see in the Galactic ISM in γ-rays!*

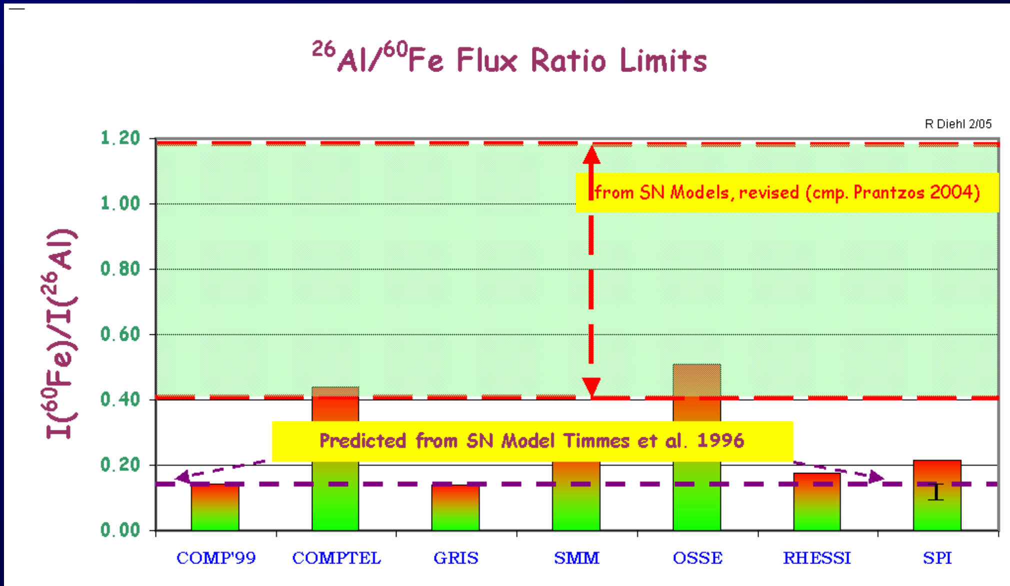
The ^{60}Fe Puzzle



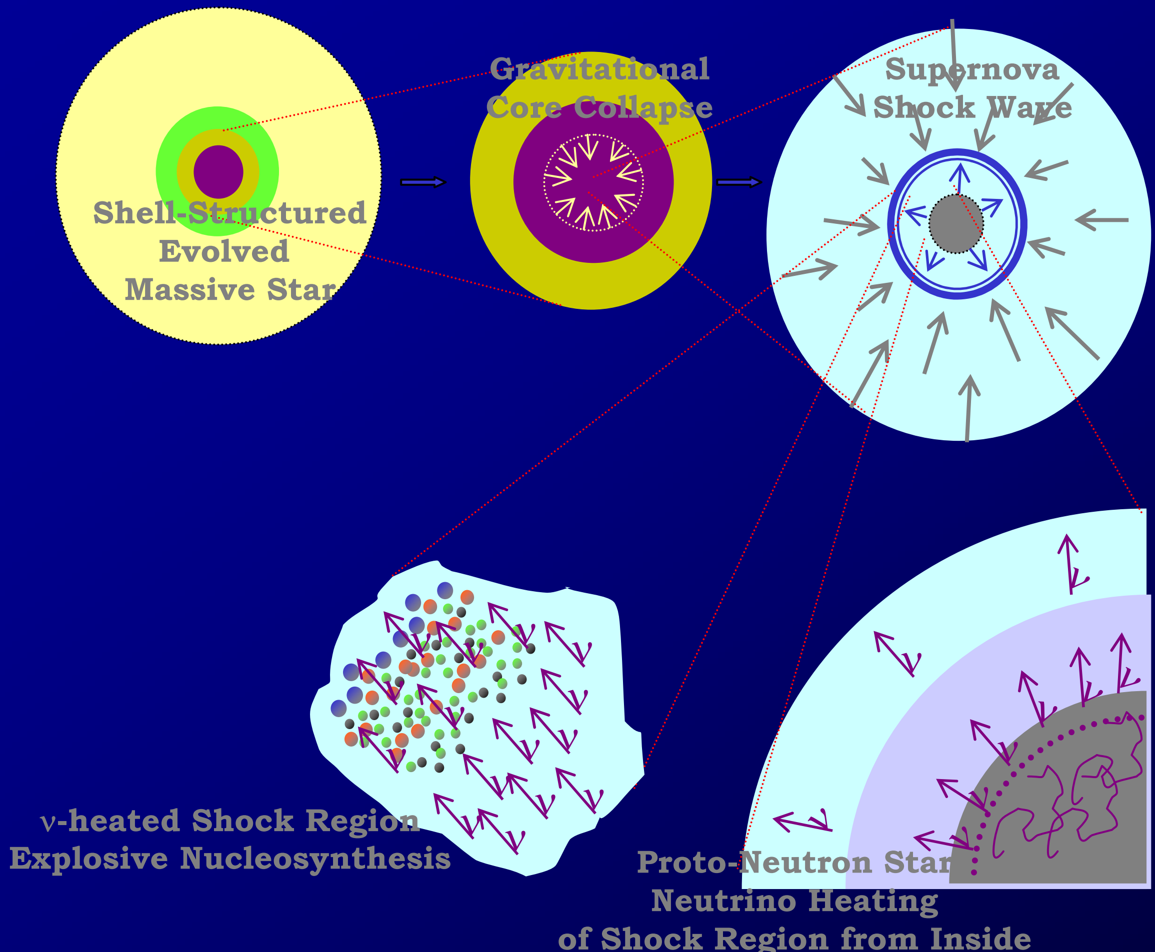
- ☆ No Source Would Bring the ^{60}Fe/^{26}Al Gamma-Ray Intensity Ratio Close to Measurement Constraints! (~Factor 3…5!)
  - Model Sample Statistics (LC)?
  - SN not a Significant ^{26}Al Source?
  - Nuclear Physics?

Uncertainties:

- n Capture Cross Sections for Fe Isotopes ^{59}Fe, ^{60}Fe
- β Decay Rate for ^{59}Fe
- Development of Hot-Base He Shell, C Shell
- n Source Activation



Core Collapse-Supernovae: The Model



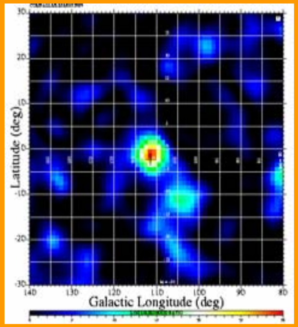
Empirical / Parametrized Models for Explosion (Explosion Energy, Mass Cut)

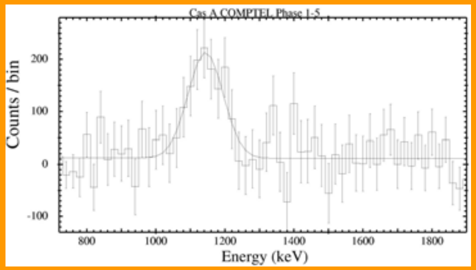
Nuclear Physics:

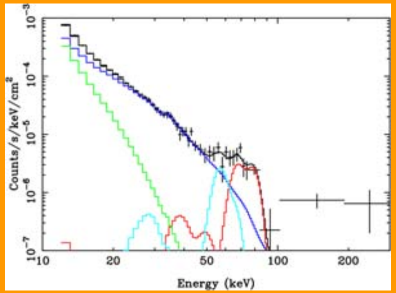
- ν Luminosities
  - PNS EoS, Pasta Phases
- Nucleosynthesis
  - Shock Region
  - Explosive

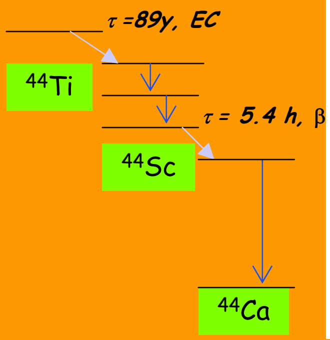
- Explosion Mechanism = Competition Between Infall and Neutrino Heating
- 3D-Effects Important for Energy Budget AND Nucleosynthesis

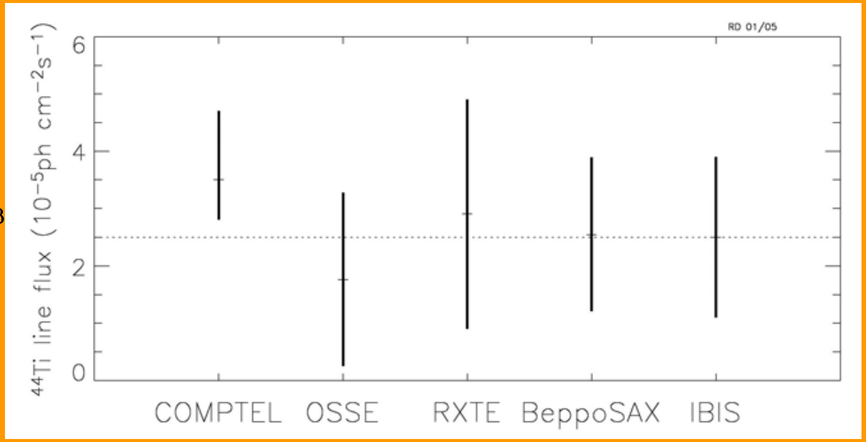
Core-Collapse Supernovae: ^{44}Ti from Cas A

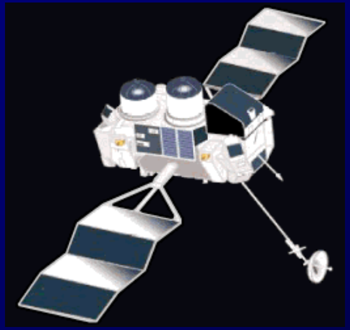












Detections:
- Iyudin et al. 1994: COMPTEL 1.157 MeV
- Vink et al. 2001; 2005: SAX & IBIS 68/78 keV

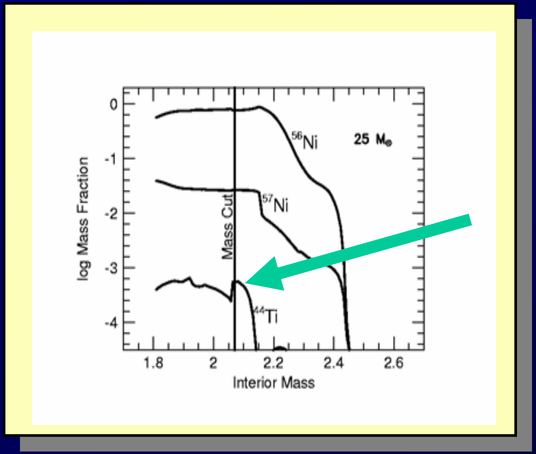
Comparable Upper Limits by RXTE, OSSE

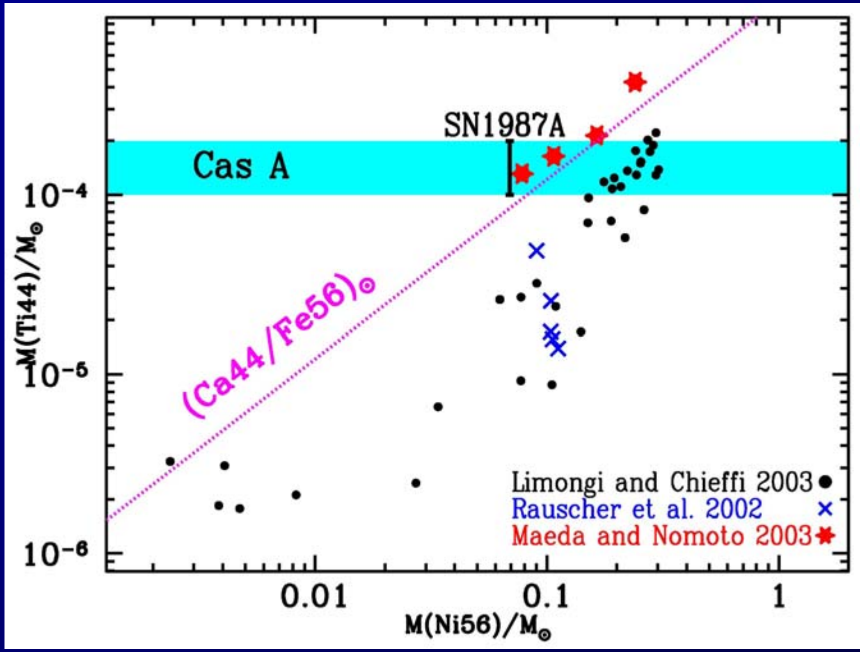
- ^{44}Ti Decay: τ~89y -> Young SNR
- Difficult γ-Ray Region (78, 68, 1157 keV) -> Uncertain I_γ , I_X

-> ^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} M_o

Core Collapse Supernovae: ^{56}Ni and ^{44}Ti

- Consistency of cc-SN Model: Cas A vs. ...
  - ^{44}Ti from Models/SN1987A/γ-Rays, vs. ^{56}Ni
  - Only Non-Spherical Models Reproduce Observed Ratios



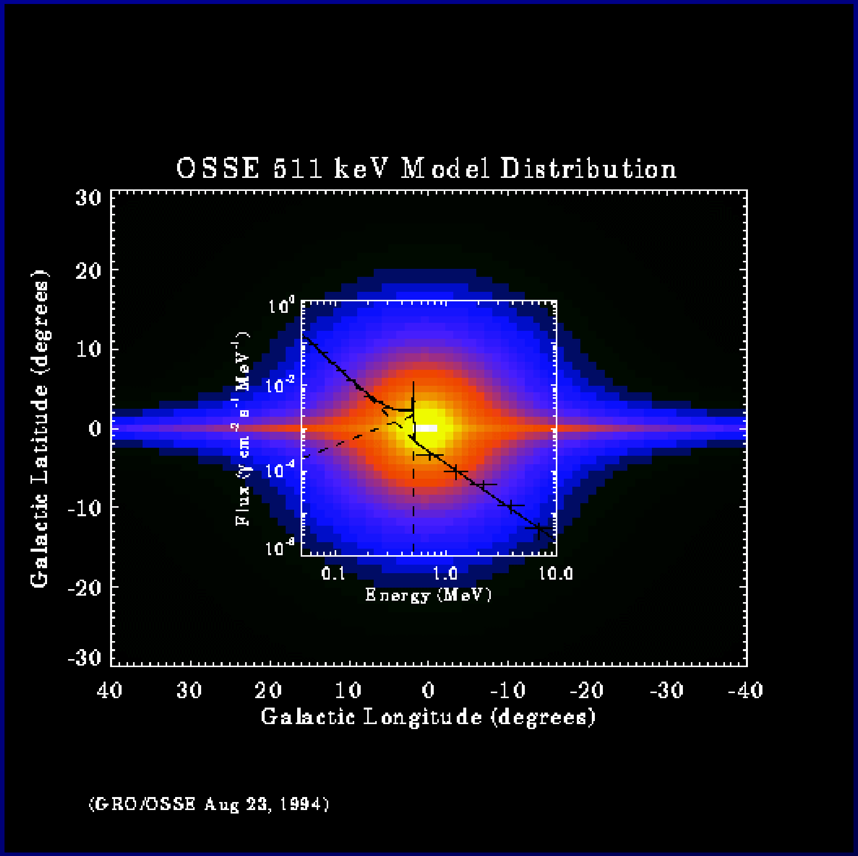


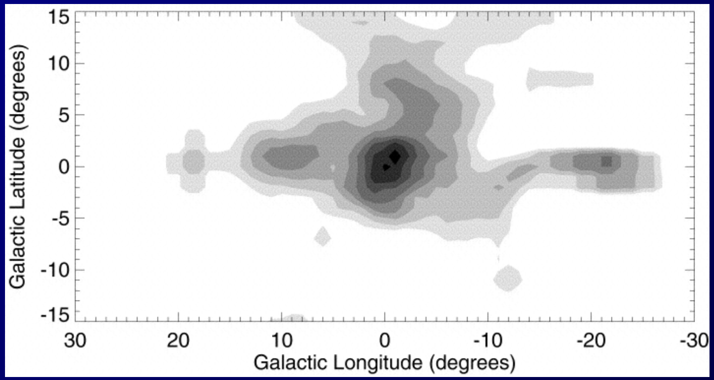
Aspherical explosions?? (->GRB)

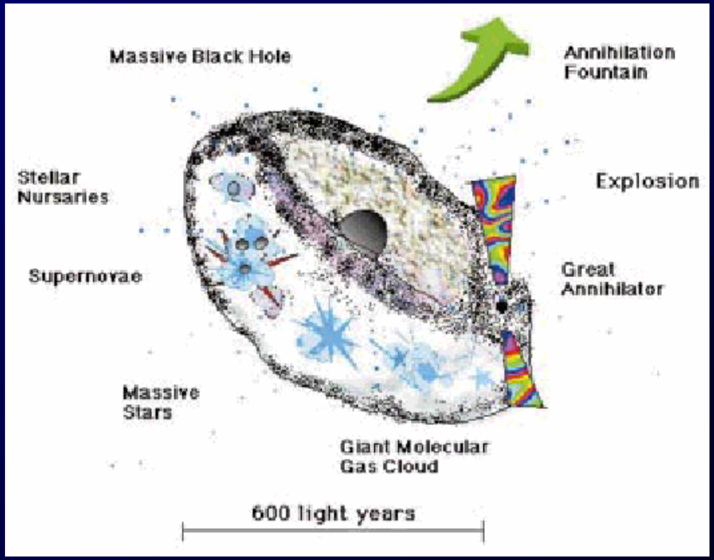
Need Event Statistics, ^{44}Ti Spectra

Measurements of Galactic e⁺ Annihilation

- "Imaging" with OSSE





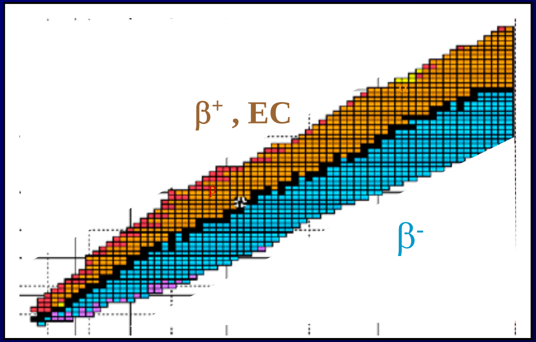


Sources of Positrons

Nucleosynthesis

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \nu_e$$

- ☆ e.g. $^{56}Ni(\beta^+)$, $^{44}Ti(\beta^+)$, $^{26}Al(\beta^+)$, $^{22}Na(\beta^+)$, $^{13}N(\beta^+)$, $^{14}O(\beta^+)$, $^{15}O(\beta^+)$, $^{17}F(\beta^+)$



Cosmic-Ray Nuclear Reactions

- ☆ e.g. $^{12}C(p,pn)^{11}C(\beta^+)$, or $^{16}O(p,\alpha)^{13}N(\beta^+)$
- ☆ Pion Production

$$p + p \rightarrow \pi^{+} + X$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \quad (\tau = 2{,}6 \cdot 10^{-8}\ s)$$
$$\hookrightarrow e^{+} + \nu_e + \bar{\nu}_{\mu} \quad (\tau = 2{,}2 \cdot 10^{-6}\ s)$$

Pair Production

- ☆ Hot (=Pair) Plasma

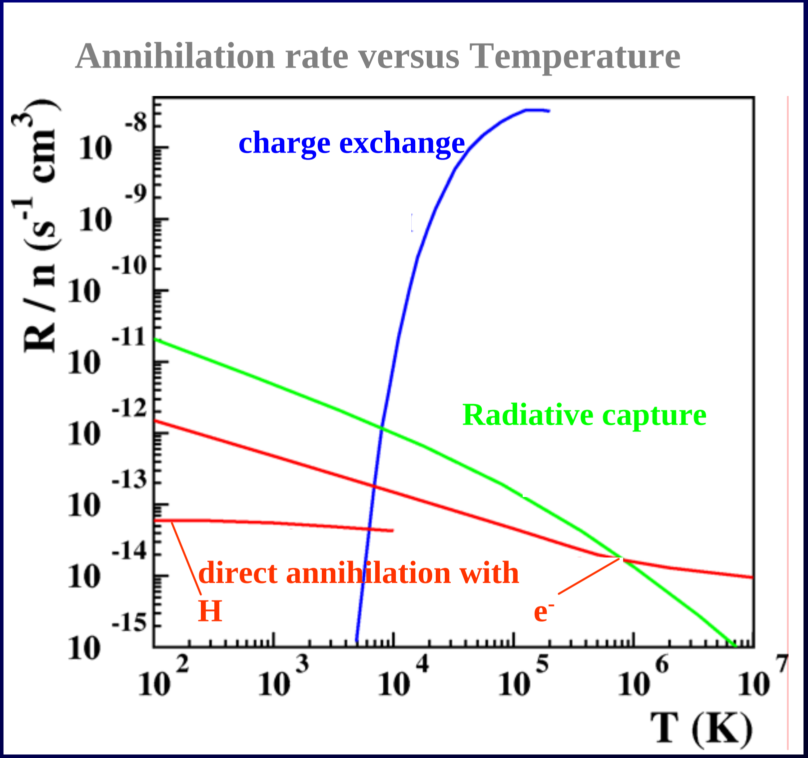
$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

- ☆ Strong Magnetic Fields

$$\gamma + B \rightarrow e^{+} + e^{-}$$

Positron Annihilation

- Charge Exchange with H Atoms
  - Coulomb Attraction, $p + e^- + e^+ \rightarrow Ps + p$
  - Most Efficient <50 eV
  - Threshold Energy 6.8 eV
  - In Neutral H, After Slowing-Down by Ionization and Excitation
- Radiative Capture of Free e^-
  - Momentum Balance: $e^- + e^+ \rightarrow Ps + h\nu$
  - In (partly-)Ionized ISM, After Thermalization by Coulomb Interactions
- Direct Annihilation
  - $e^- + e^+ \rightarrow 2h\nu$ (511 keV)
- Annihilation Rate Depends on Phase
  - $10^3 \ldots 10^5 \ldots 10^8$ y

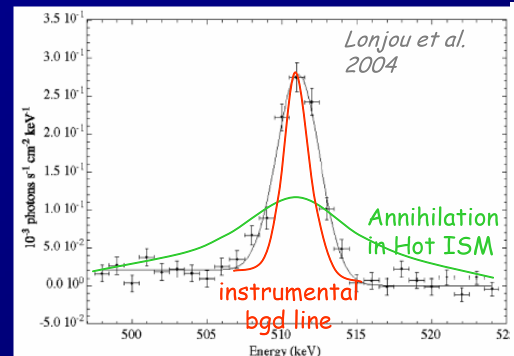


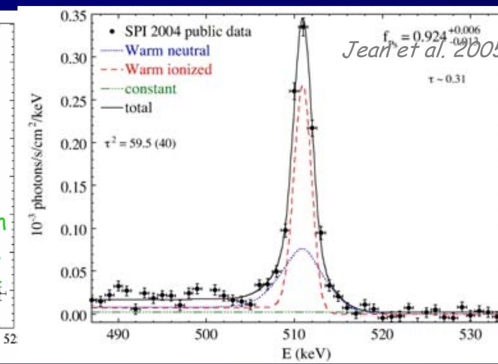
Annihilation of Positrons in the Galaxy

☞ See talk J.P.Roques

Astrophysics:

- Positron-Source Variety in Inner Galaxy
  - Nucleosynthesis Sources (SNIa, …)
  - Pulsars, Binaries, Jet Sources
  - Light Dark Matter Annihilations
- Annihilation in Diluted ISM ($\tau \sim 10^5$y)





Results (INTEGRAL / SPI) :

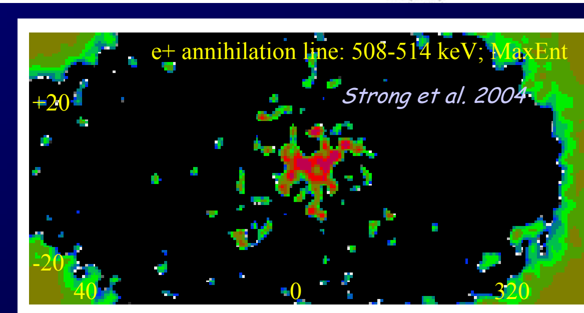
511 keV Line Characteristics :

- I = 0.96 10^{-3} ph cm^{-2} s^{-1}

-> **Annihilation Rate** (@GC) **1.4 10^{43} s^{-1}**

- Broadened Line: Deconvolved FWHM = 2.76 keV
- Expectation: Hot-ISM->~4 keV, Grains->~2 keV

-> **Annihilation in Warm ISM Phase**

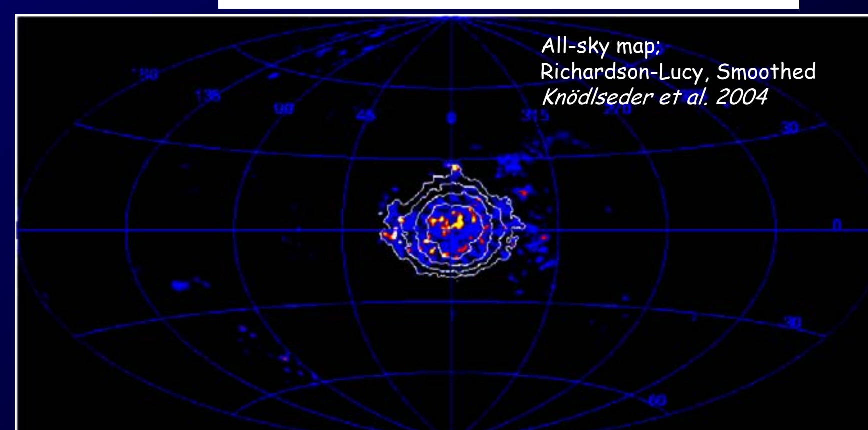


511 keV Line Emission Morphology:

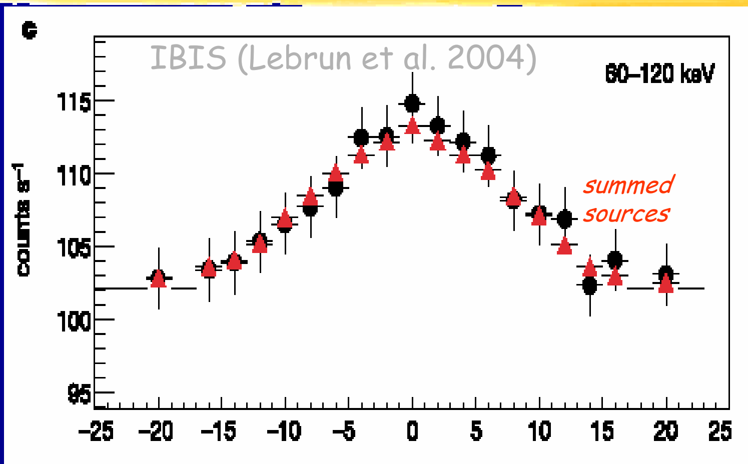
- **Extended, ~bulge-like Emission** (δl~8°,δb~8°)
- **No/Weak Disk Emission Seen; No "Fountain"**

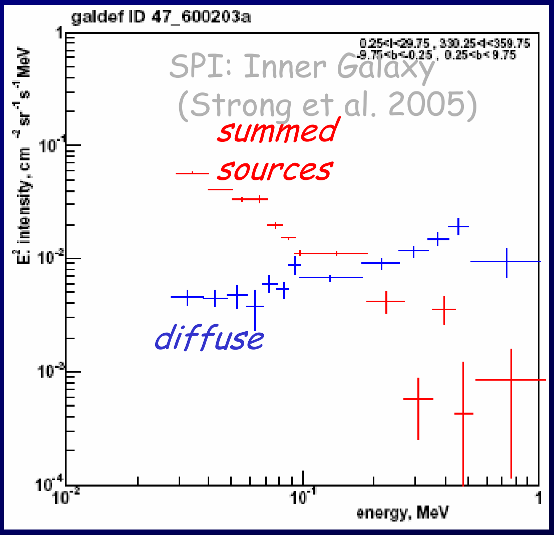
-> **Young Stars make Minor Contribution**

- **Old stellar population! Dark-Matter Annihilations?**

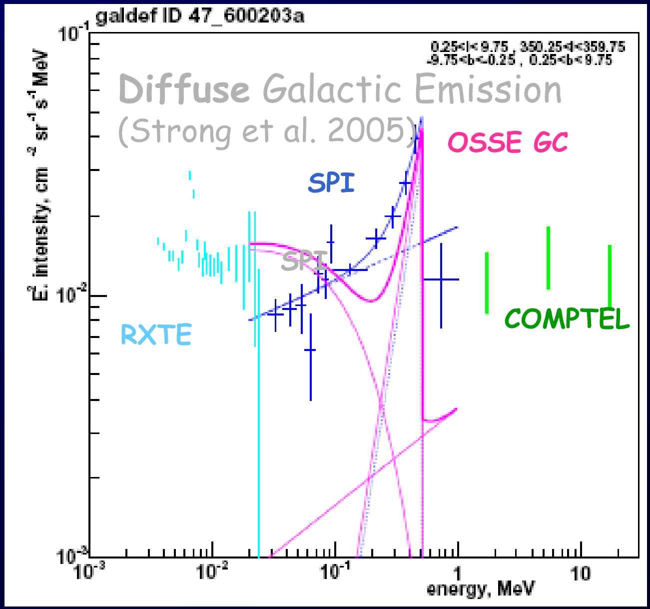


Diffuse Emission and Galactic Sources

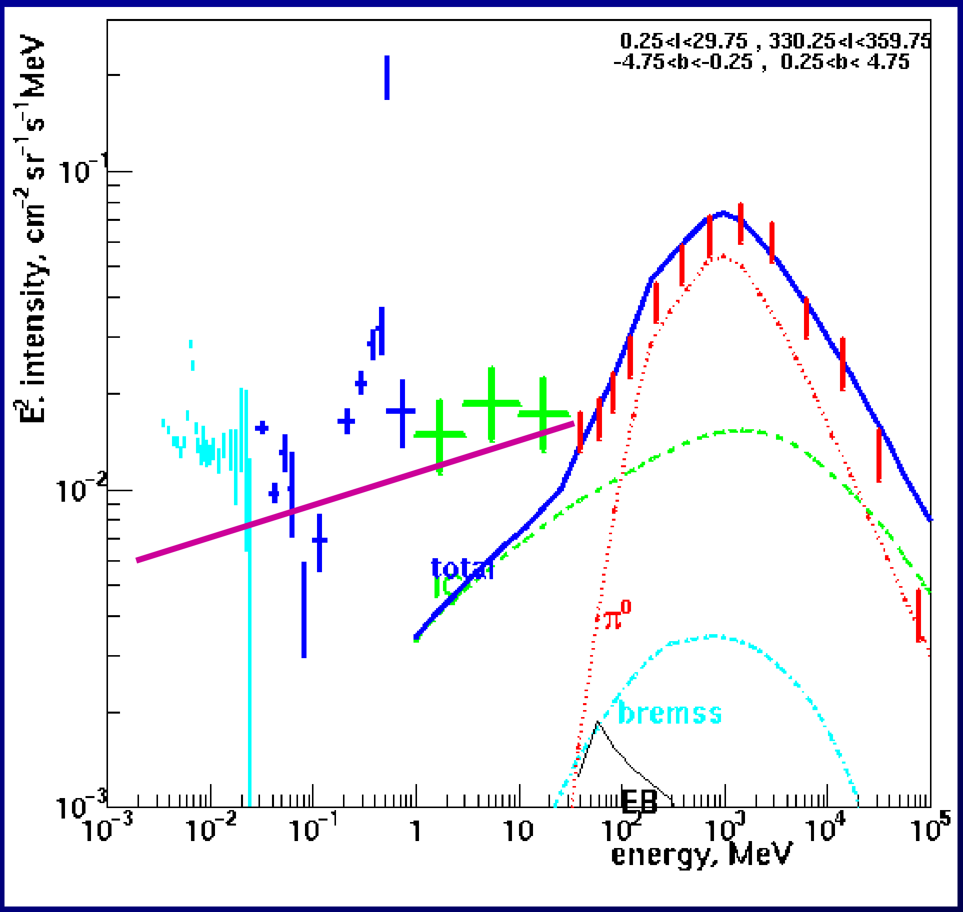




- ☆ Diffuse Emission ??
  - ☞ Large in Soft X-rays (~80%, Chandra)
  - ☞ Negligable/Absent in hard X-rays (IBIS)
  - ☞ Significant in harder X-rays (SPI)
  - ☞ Evident in γ-rays (CGRO; Sources??)
- ☆ Origin?
  - ☞ Non-Thermal Bremsstrahlung? Too Inefficient
  - ☞ Inverse-Compton? Insufficient; Steepened e- Spectrum would Violate HE Data (EGRET)
  - ☞ Positron Annihilation? Yes. But there is more.
  - ☞ Unresolved Sources?



Low-Energy Gamma-Rays from Inner Galaxy



- ☆ CR Interactions with ISM
  - ☆ Pion Production
- ☆ CR Interactions with Starlight
  - ☆ Inverse Compton
- ☆ Positron Annihilation
  - ☆ 511 keV Line, Ps Continuum
- ☆ Compact Accreting Sources
  - ☆ Thermal Hot Plasma
  - ☆ Non-thermal Tails
- ☆ **New Sort of Hard Sources ?**
  - ☆ Particle Accelerators
    - ☆ AXP's
    - ☆ In-situ CR e- Acceleration

The Galactic Plane with SPI

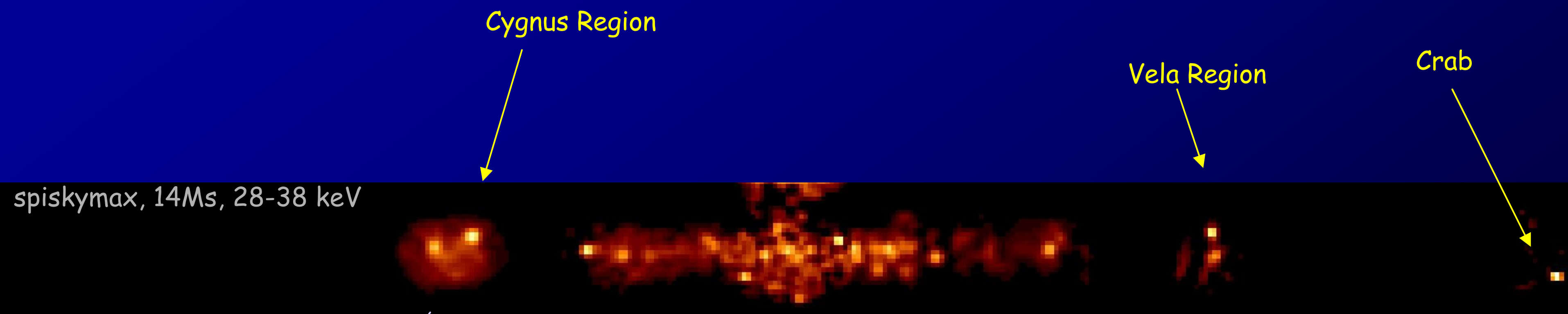
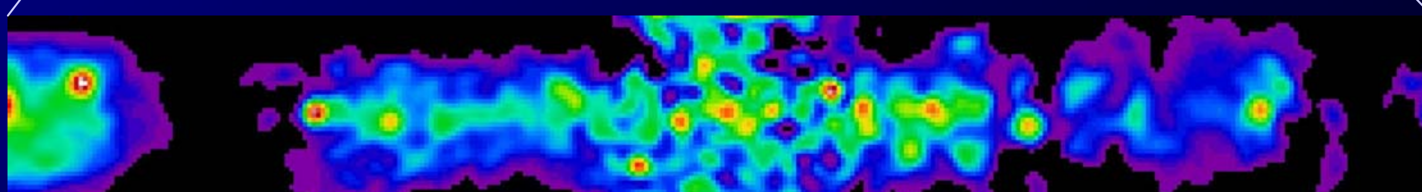


Image from 2 years of SPI Galactic-Plane Survey
(A. Strong et al., 2005)



Summary: INTEGRAL and Nuclear Physics

- High-Energy Astronomy -> "Nuclear" Information from Cosmic Objects
- Neutron Star Matter States Are Constrained by X-ray Emission from Variety of Objects with NS
- Core-Collapse Inner-Region Nucleosynthesis are Constrained by ^{44}Ti γ-rays
- Diffuse Radioactivities (^{60}Fe and ^{26}Al) are a Diagnostic for Explosive Nucleosynthesis