Physics and Astrophysics of Compact Stars

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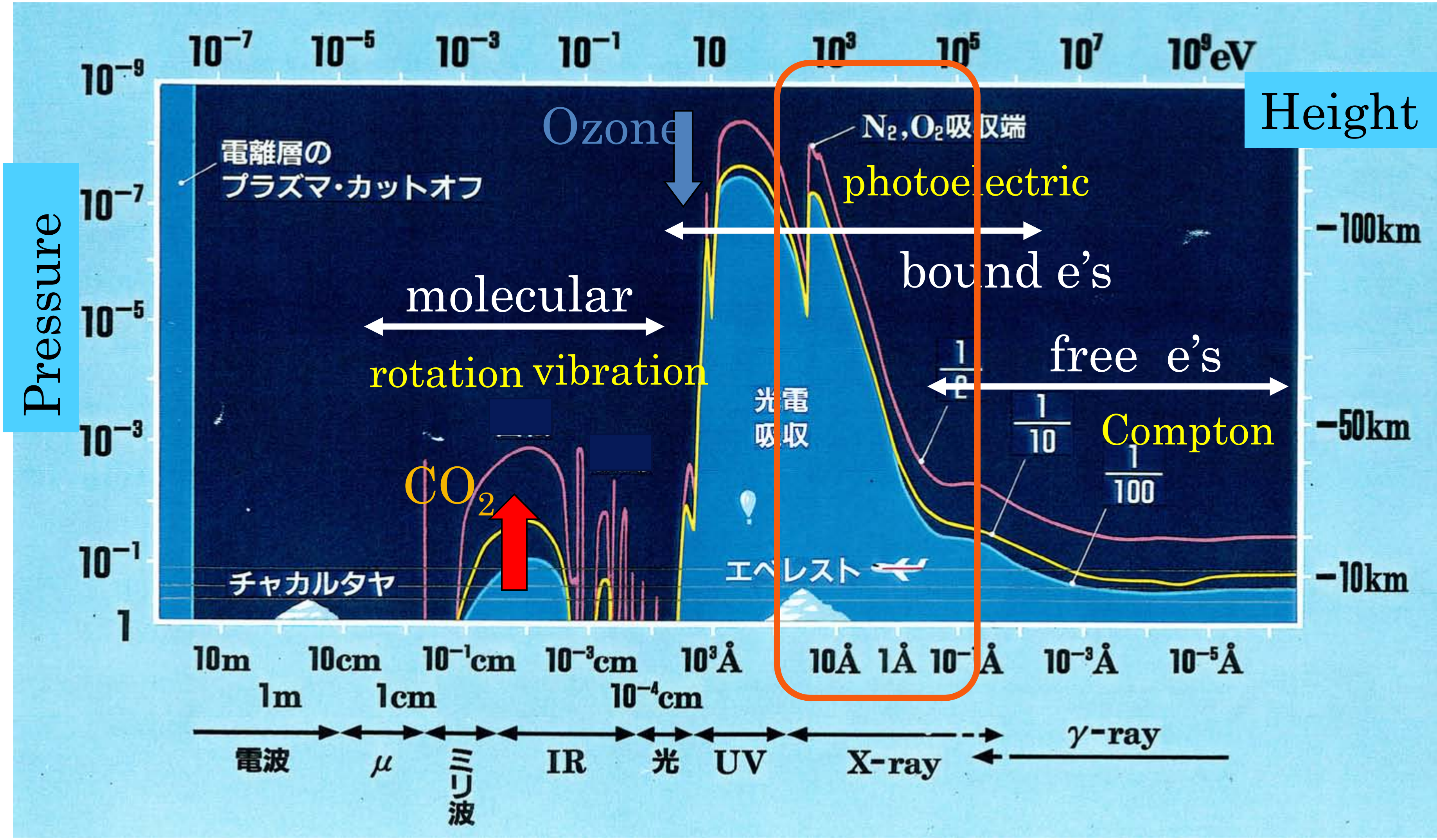
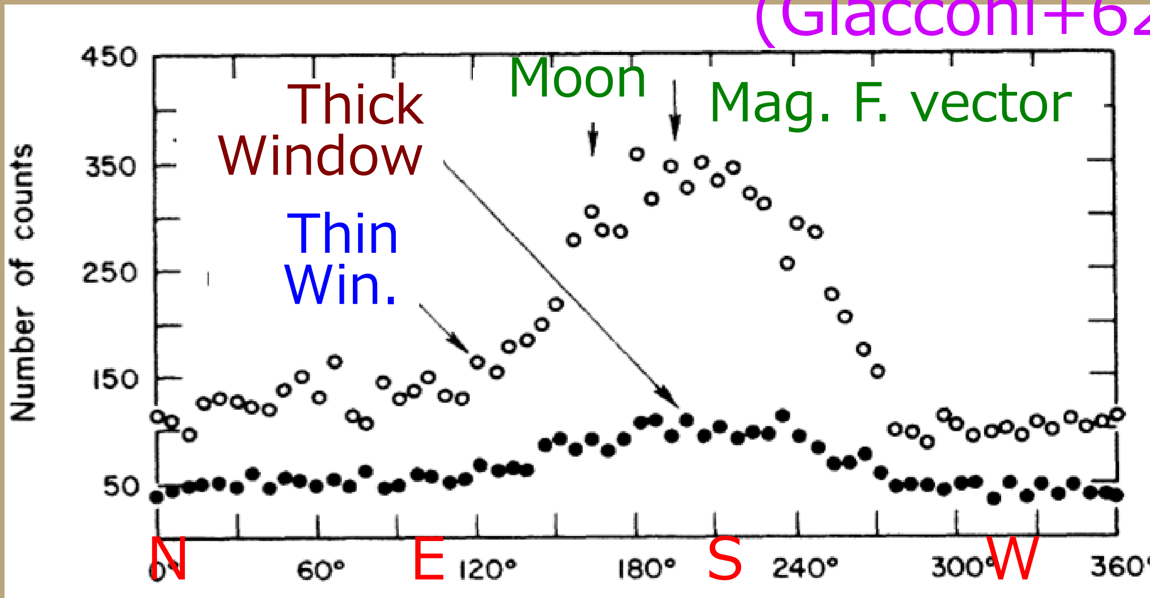
Experimental High energy Astrophysics using satellite-borne X-ray instruments

(1-1)Atmospheric Transparency

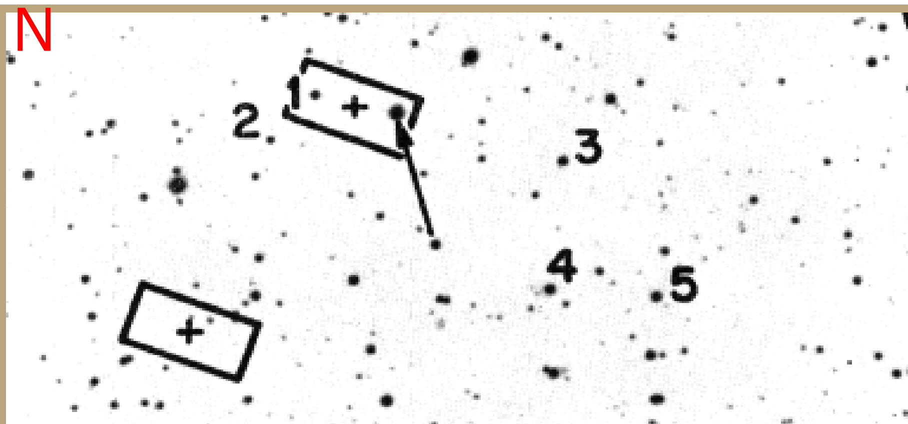


(1-2) Discovery of a Cosmic X-ray Source (1962)

(Giacconi+62)

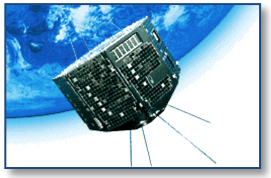
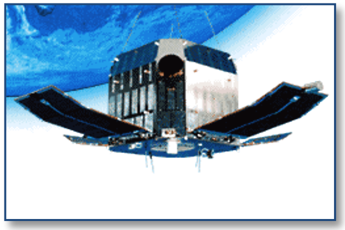
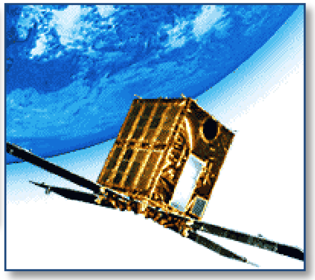


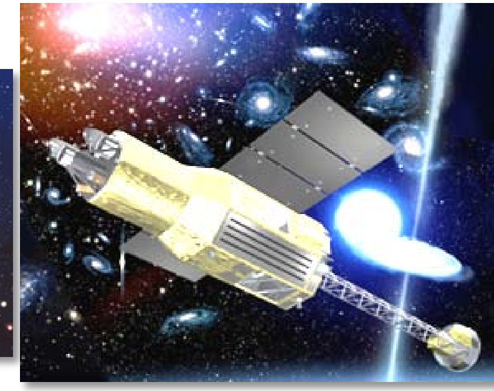
M. Oda (right) and his modulation collimator

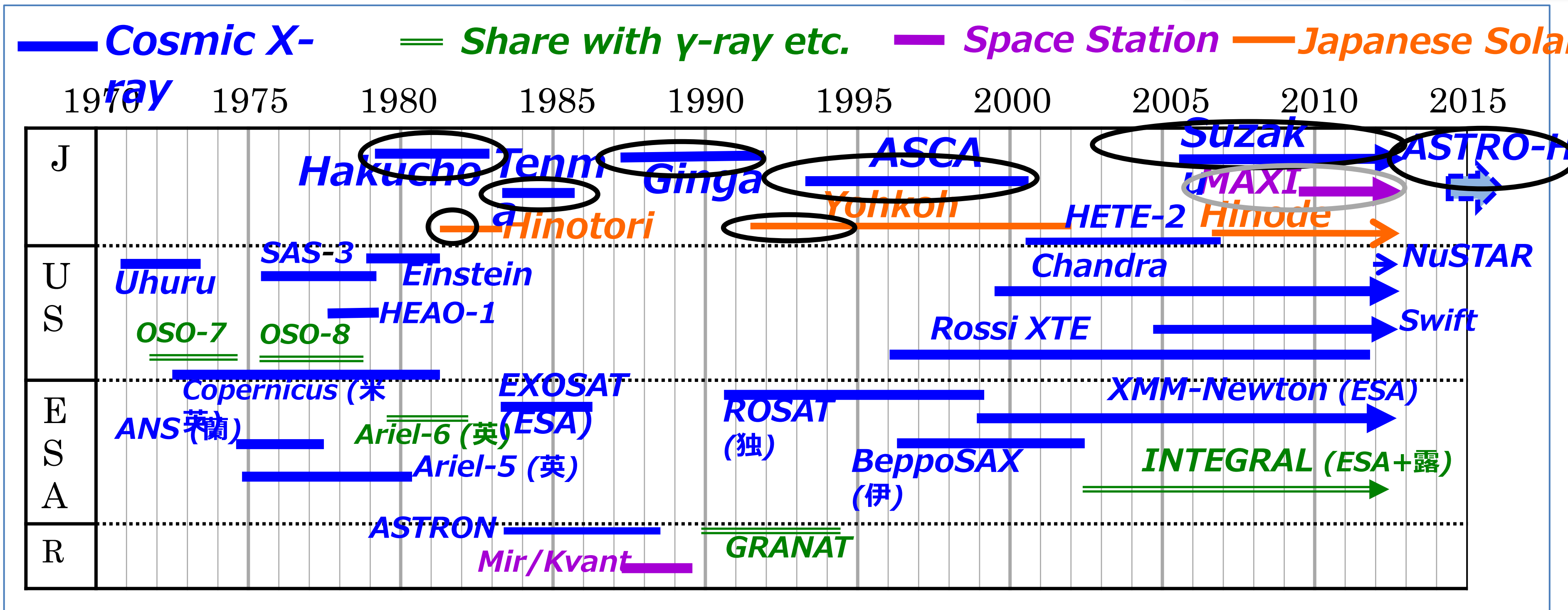


Optical ID, first in Japan, then at Palomar; (Sandage, Giacconi, ...,,, Oda, Osawa, Jugaku 66)

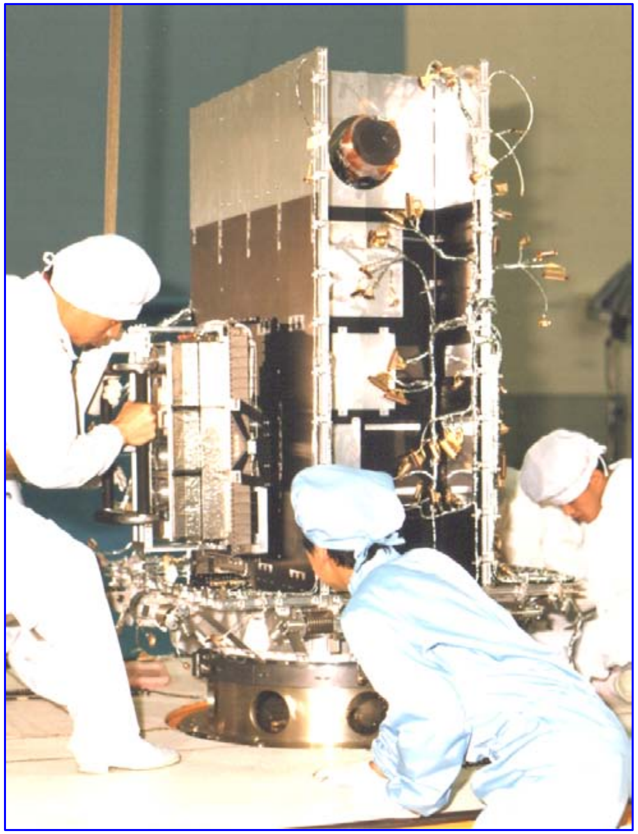
§2. X-ray Satellites



Some Pictures ..



Construction of *Ginga* (launched in 1987)

The Instrumentation Team for the HXD (Hard X-ray Detector) on-board *Suzaku* (launched in 2005)

§3. Beauty of Astrophysics

How macro properties of celestial objects described via first principle using fundamental constants

✧ c, e, h, m_p , m_e , G, (ε_0)

✧Two important dimensionless constants:

- Fine structure constant (EM interaction strength)

$$\alpha = e^2 / 4\pi\varepsilon_0 \hbar c = 1/137$$

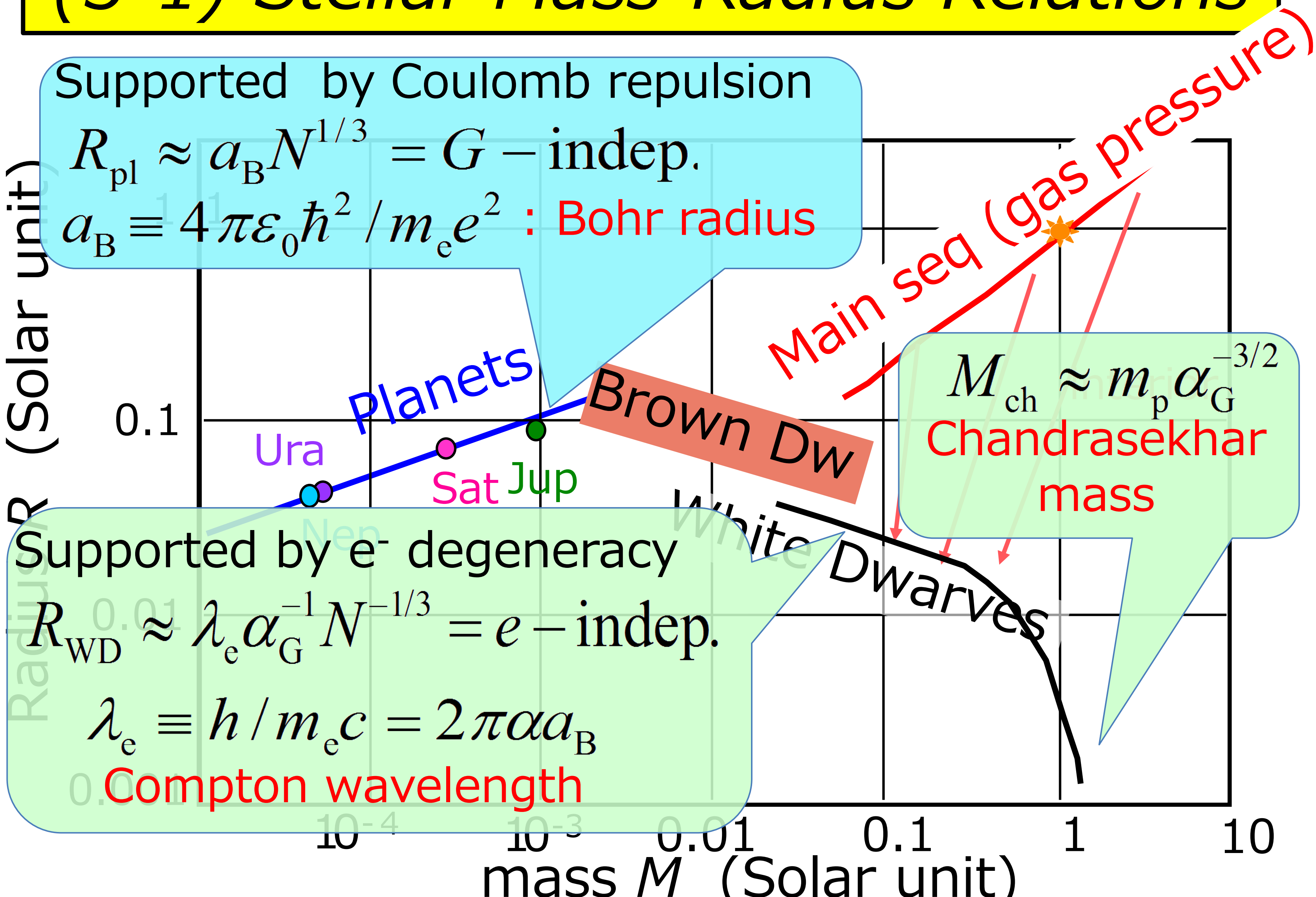
- Grav. f.s. const. (gravitational interaction strength)

$$\alpha_G = G m_p{}^2 / \hbar c = 5.90 \times 10^{-39}$$

- For any celestial object, α_G:α = self-gravitating energy : Coulomb repulsion energy (if not neutral)

✧The only macro variable: mass M (or $N \equiv M / m_p$)

(3-1) Stellar Mass-Radius Relations



Supported by Coulomb repulsion

$$R_{\rm pl} \approx a_{\rm B} N^{1/3} = G - \text{indep.}$$

$$a_{\rm B} \equiv 4\pi\varepsilon_0 \hbar^2 / m_{\rm e} e^2$$: Bohr radius

Supported by e⁻ degeneracy

$$R_{\rm WD} \approx \lambda_{\rm e} \alpha_{\rm G}^{-1} N^{-1/3} = e - \text{indep.}$$

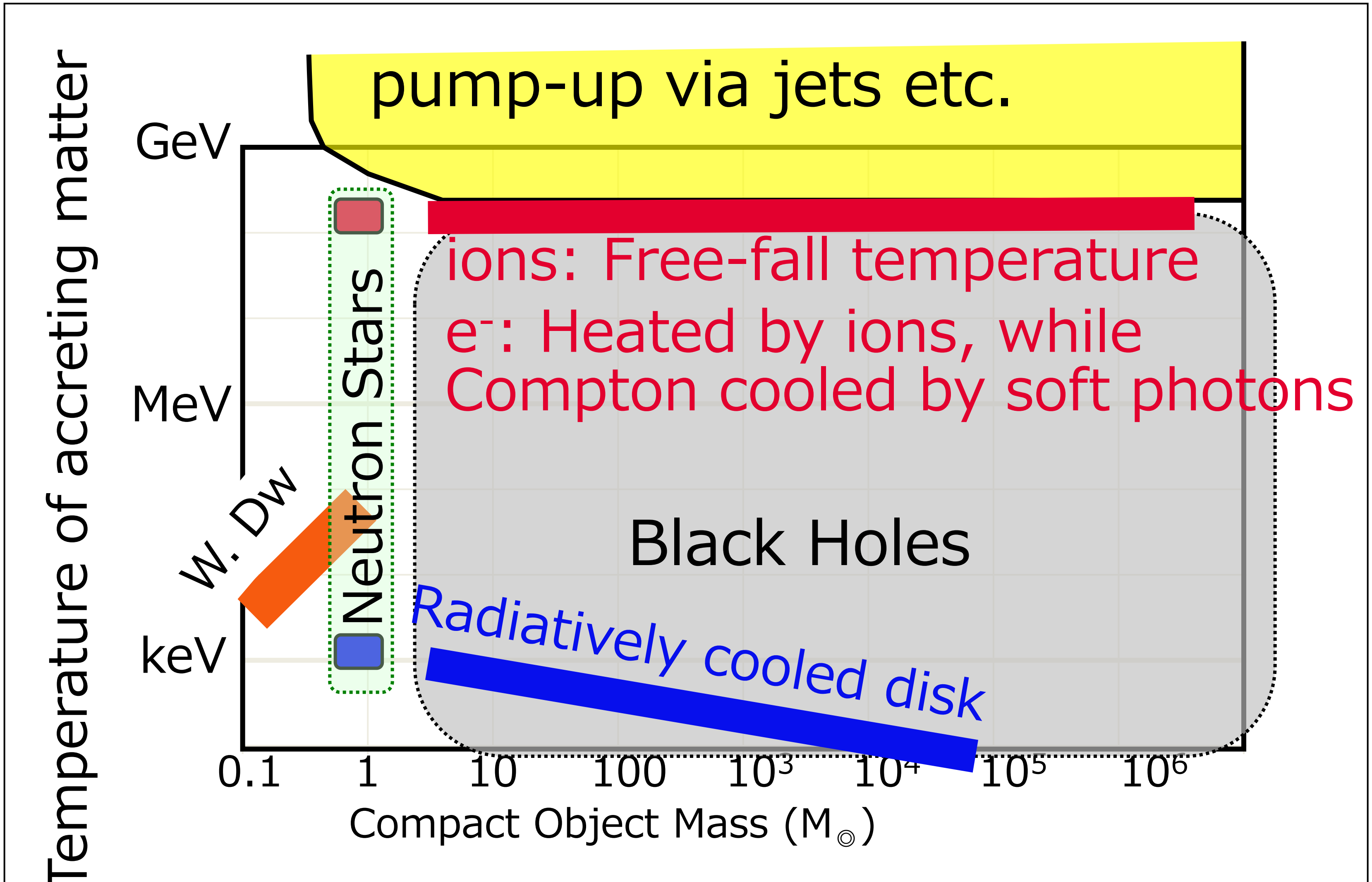
$$\lambda_{\rm e} \equiv h / m_{\rm e} c = 2\pi\alpha a_{\rm B}$$

Compton wavelength

$$M_{\rm ch} \approx m_{\rm p} \alpha_{\rm G}^{-3/2}$$

Chandrasekhar mass

(3-2) Temperature of Accreting Matter



(3-3) Temp. of accretion disks around BHs

(Shakura & Sunyaev 1973)

✧ A BH of mass *M* radiating at η(0<η<1) times the Eddington limit: $L = 4\pi\eta G M m_p c / \sigma_T$

✧ Thomson cross sect.: $\sigma_T = (8\pi/3)(e^2 / 4\pi\varepsilon_0 m_e c^2)^2$

✧ Stefan-Boltzmann's law: $L = 4\pi R^2 \sigma T^4$

S-B constant: $\sigma \equiv \pi^2 k^4 / 60 c^2 \hbar^3$

✧ Innermost radius (GR) : $R = 3R_s = 6GM/c^2$

✧ Disk temperature at the innermost radius:

$$kT = (5/8\pi^3)^{1/4} (\alpha_G \alpha^2)^{-1/4} [(m_e c^2)(m_p c^2)]^{1/2} (\eta / N)^{1/4}$$

$$= 1.0 \eta^{1/4} (M / 10 M_\oplus)^{-1/4} \mathrm{keV}$$

§4. Computational Astrophysics

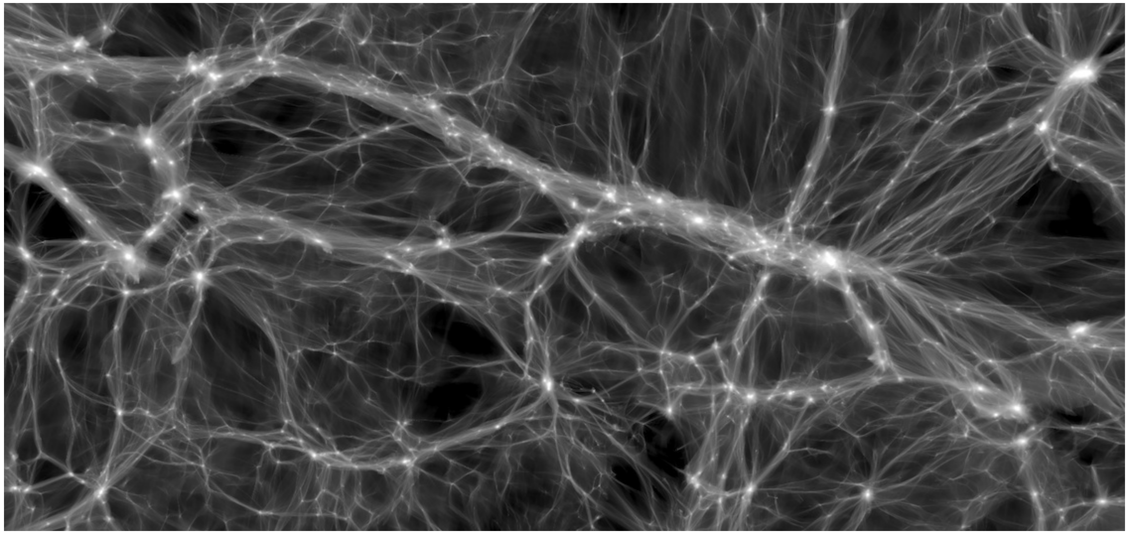
1. Physical settings cannot be chosen as you like
   Strong spatial gradients, Non steady-state, Explosive/Transient, Versatile processes, ⋯

2. Extreme (often exotic) physical conditions
   $\rho > \rho_{nuc}$, $kT > m_e c^2$, G.R., $B > 4.4\times10^{13}$ G, etc., where our knowledge may be insufficient⋯

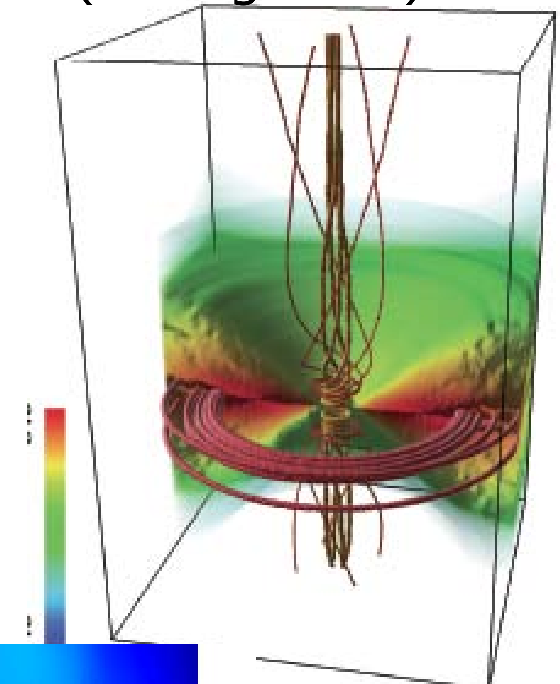
3. Long-range force (Grav, EM) + local interactions
   Strong non-linearity, Self-interaction, Energy non-equipartition, Spont. struct. formation, ⋯

Typical Results

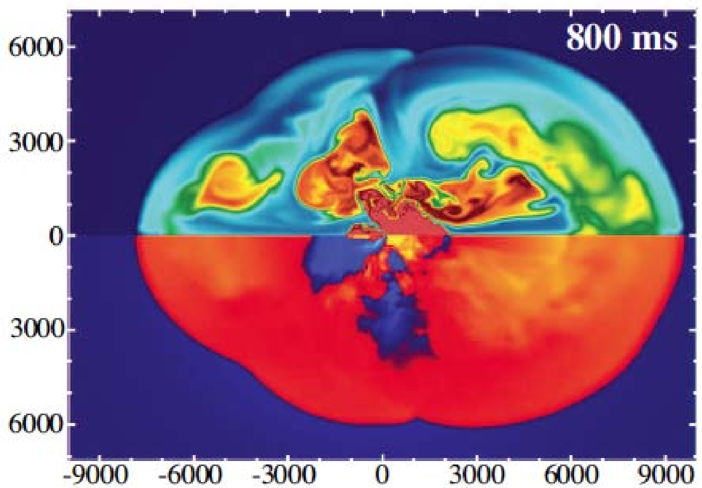
Structure formation in CDM universe (Abel+12)

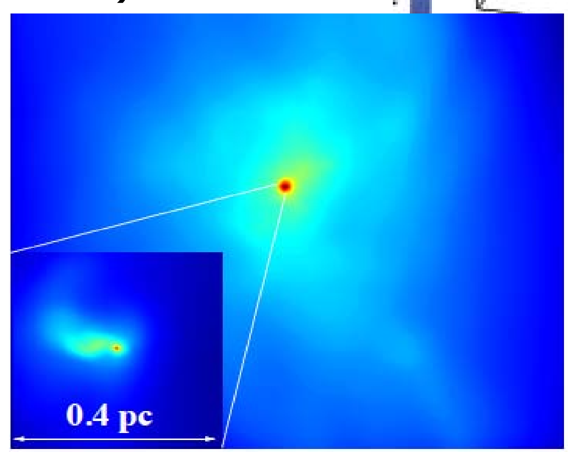


Matter accretion onto a black hole (Ohsuga+09)



Core-collapse supernovae (Bruenn+12)





Formation of a protostar in very early universe (Yoshida+07
)

§5. Neutron Stars (NSs)

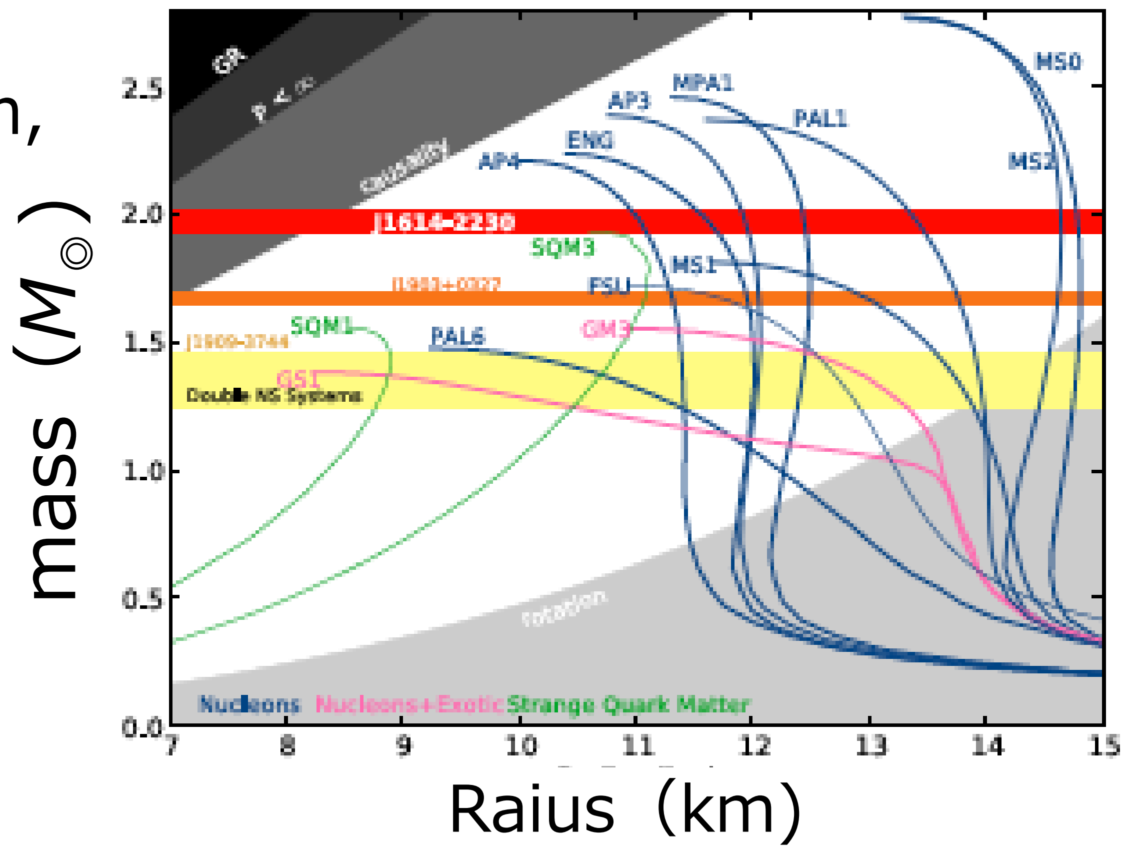
✧ An ultra-compact star, in which the extreme gravity ($10^9 g$) is supported by degenerate pressure of neutrons.

✧ Formed by core collapse of a massive star.

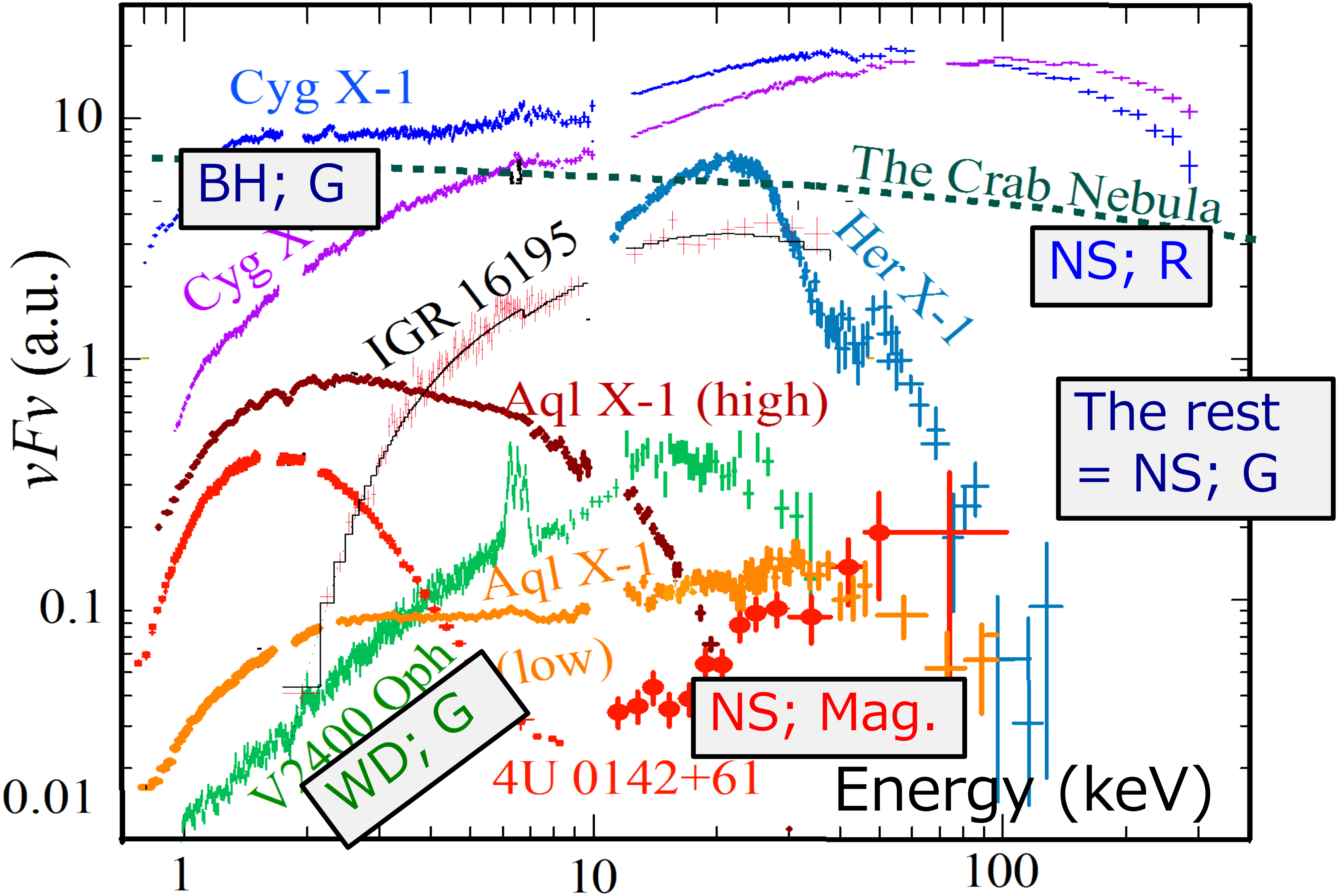
✧ $M_{NS} \sim 1.4\ M_{\odot}$, $R_{NS} \sim N^{1/3} r_{nuc} \sim 10$ km, $\rho \sim \rho_{nuc}$ or higher

✧ The M_{NS} vs. R_{NS} relation is sensitive to the nuclear EOS.

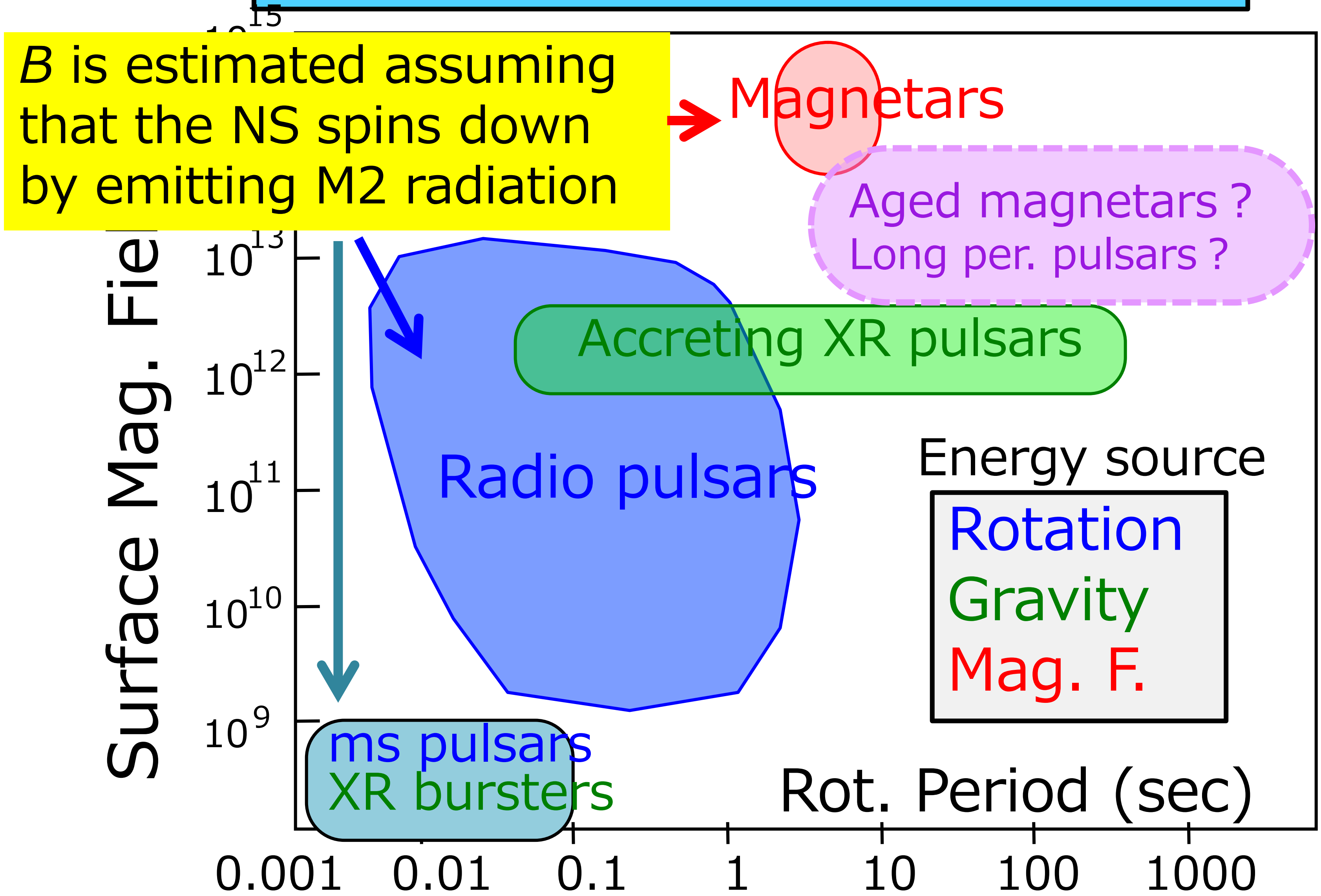
$$\frac{R_{WD}}{R_{NS}} \approx \frac{m_p}{m_e}\left(\frac{M_{WD}}{M_{NS}}\right)^{-1/3}$$



(5-2) Suzaku Spectra of Compact Objects

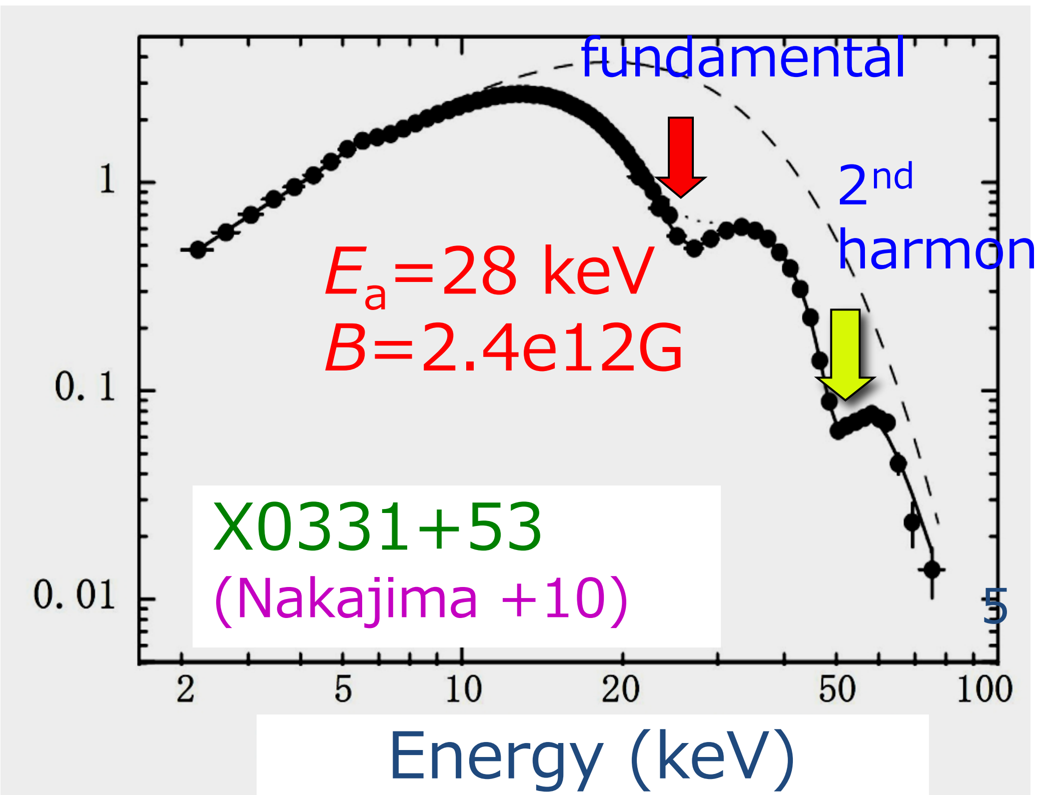


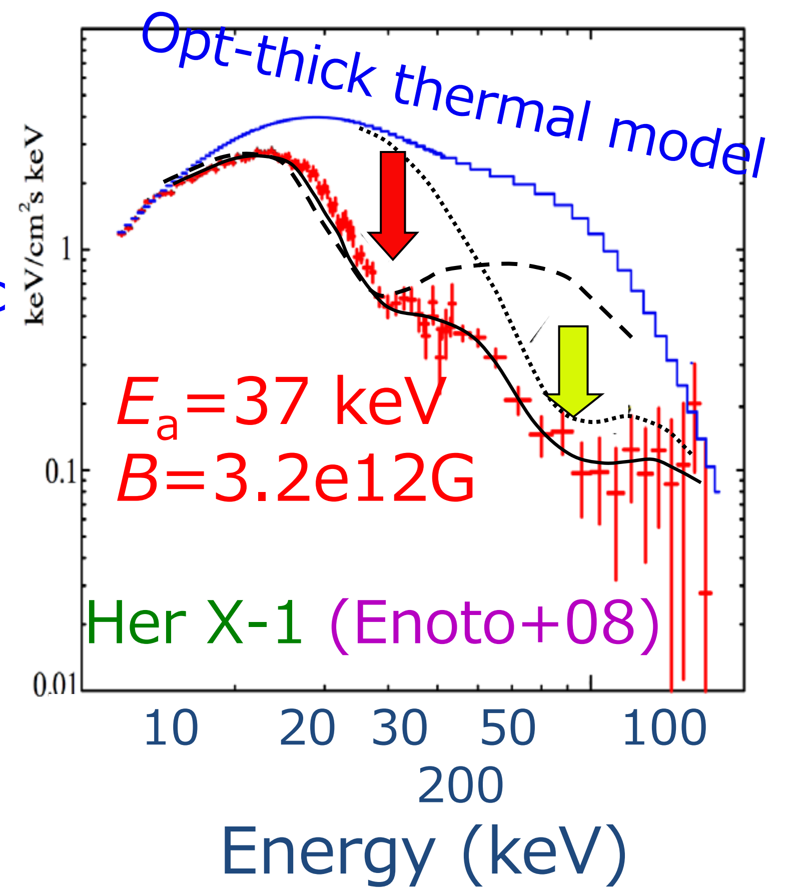
§6. NS Magnetism



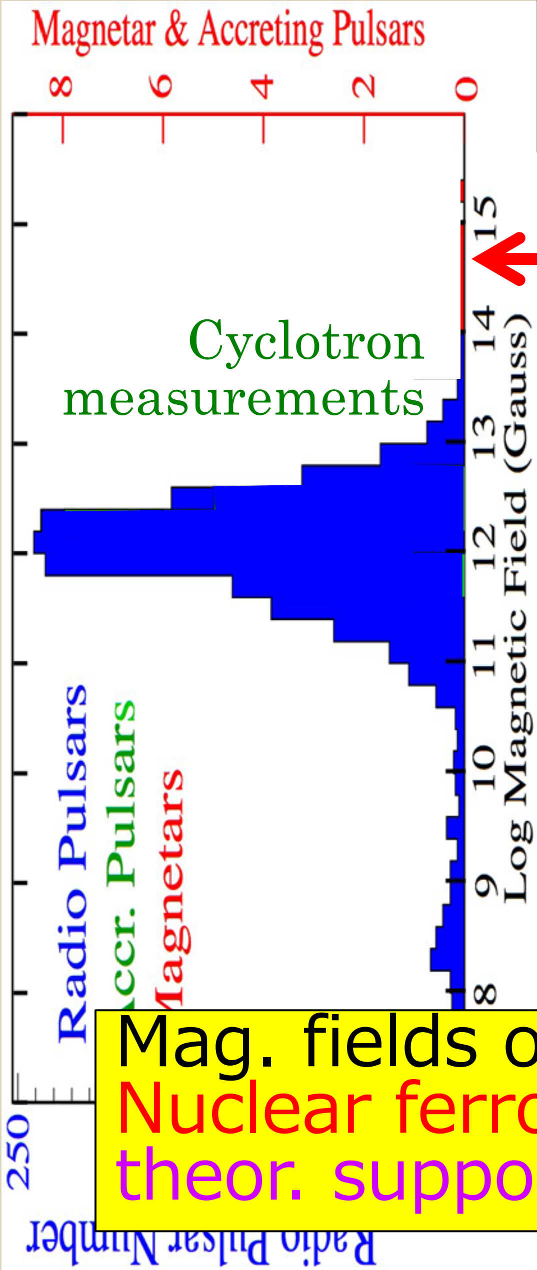
(6-1) Electron Cyclotron Resonances

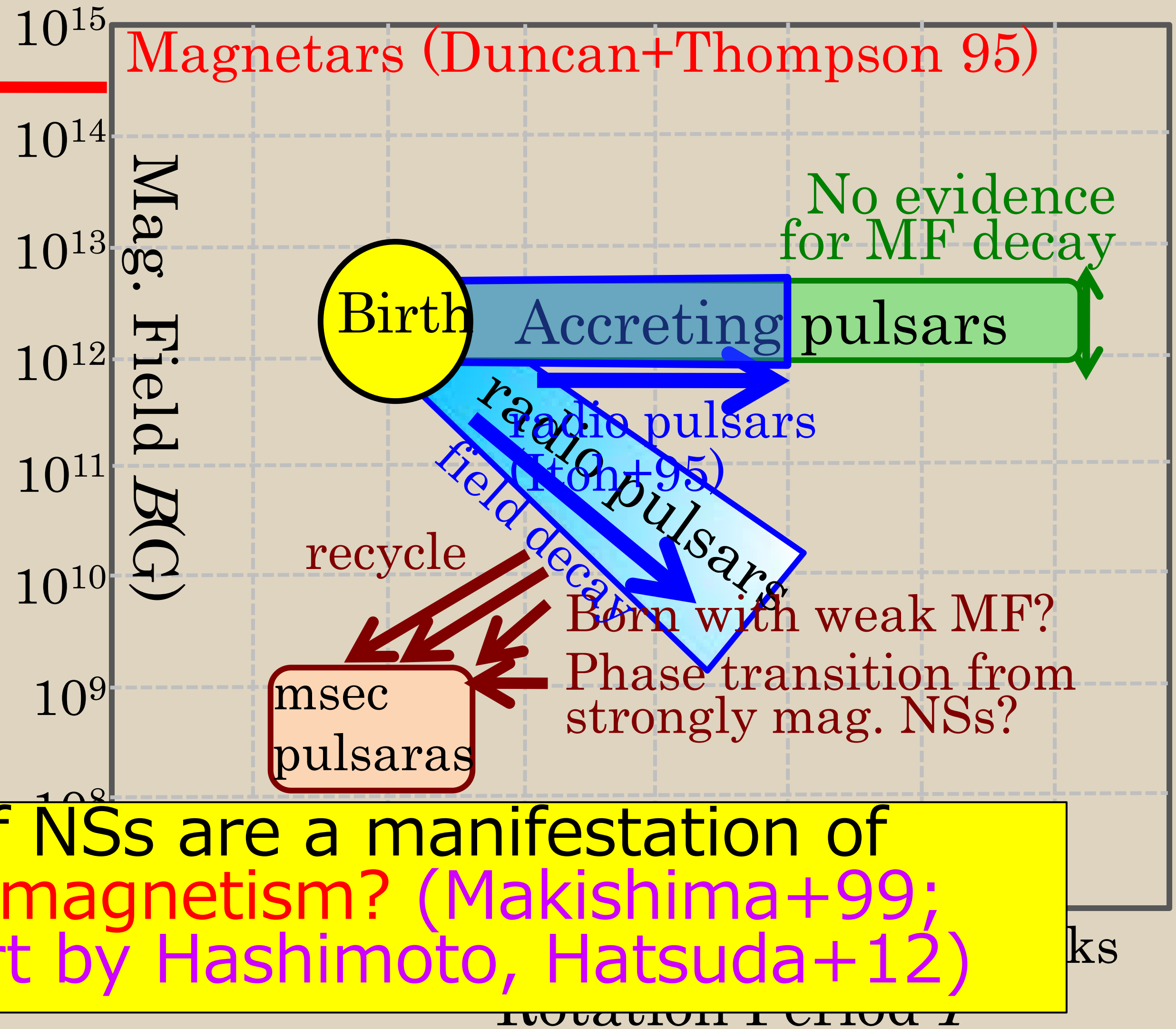
About half of ~40 known accreting binary X-ray pulsars have allowed detections of electron cyclotron resonance features (Landau level transisions) in their spectra (Makishima +99), at an energy of $E = \hbar eB / m_e = 11.6(B/10^{12}\,\mathrm{G})$ keV.





(6-2) Evolution of NS MFs: a revolution in the 1990’s

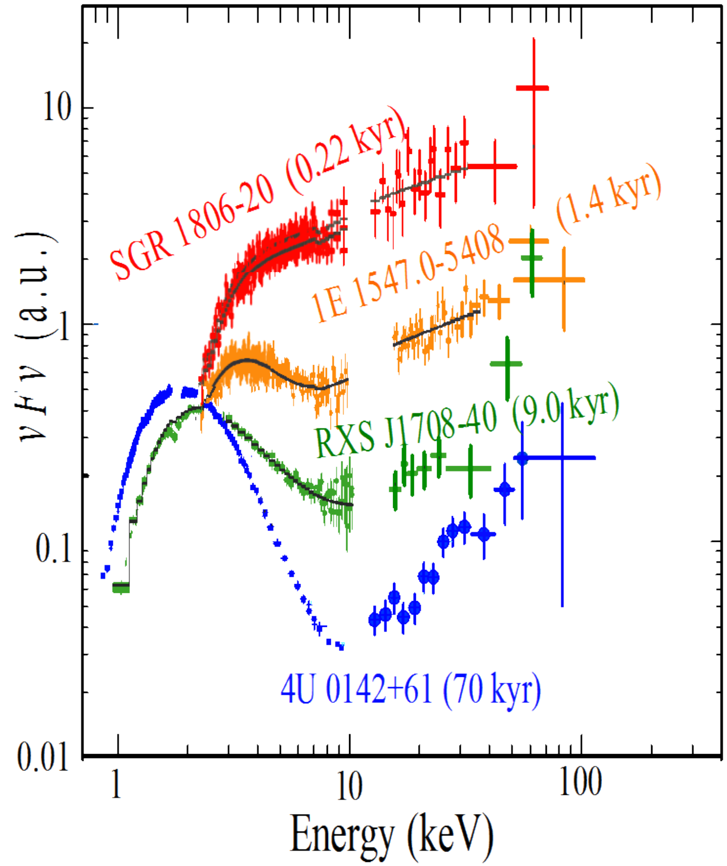




Mag. fields of NSs are a manifestation of Nuclear ferromagnetism? (Makishima+99; theor. support by Hashimoto, Hatsuda+12)

§7. Puzzles of Magnetars

- ✧ Isolated NSs with no evidence of mass accretion. Sometimes emitting repetitive intense soft gamma-ray flashes.
- ✧ About 25 known. From P and dP/dt, B=10 $^{14\text{-}15}$ G is suggested.
- ✧ X-ray lum. » spin-down lum.
  ➔not rotation powered.
- ✧ Radiating by consuming their magnetic energies.



- ✧ Suzaku → peculiar 2-comp. spectra.
- ✧ Emission mech. of hard component?
- ✧ With age, why the hard c. gets weaker but harder?

(7-1) Physics in ~10^{12} Gauss M.F.

Harding, A., & Lai, D. Rep. Prog. Phys. 69, 2631 (2006)

Particle acceleration by induced electric fields
$E = v \times B$ = 2e14 $(P/30\text{ms})^{-1}(B/1\text{e}12\text{G})(R/10\text{km})^2$ (V/m)
(still « Schwinger limit···)

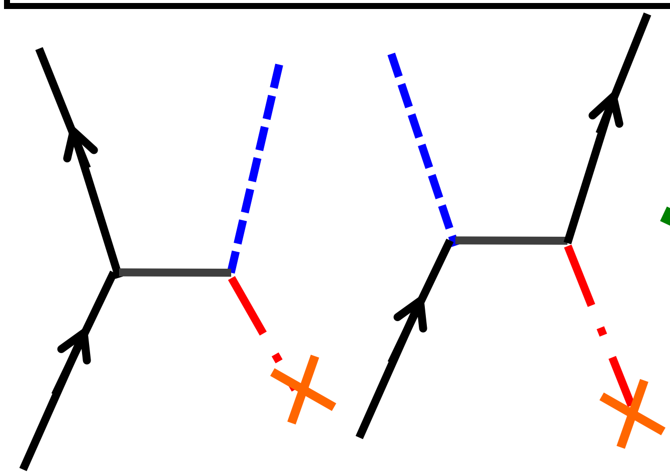
↓ energetic e's

Synchrotron/
curvature radiation

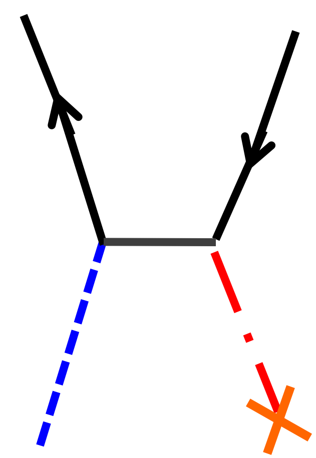
→ seed γ's (> 1 MeV) →

one-photon pair
production

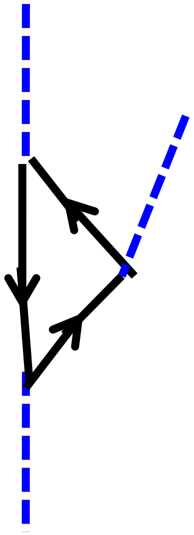
← many e^+e^- pairs



→ Strong synchrotron radio emission



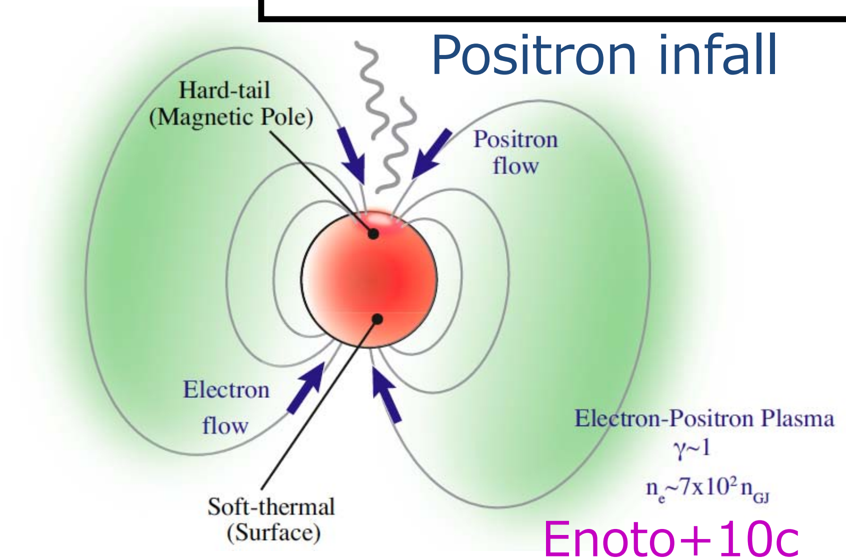
(7-2) Physics in $10^{14\text{-}15}$ Gauss M.F.



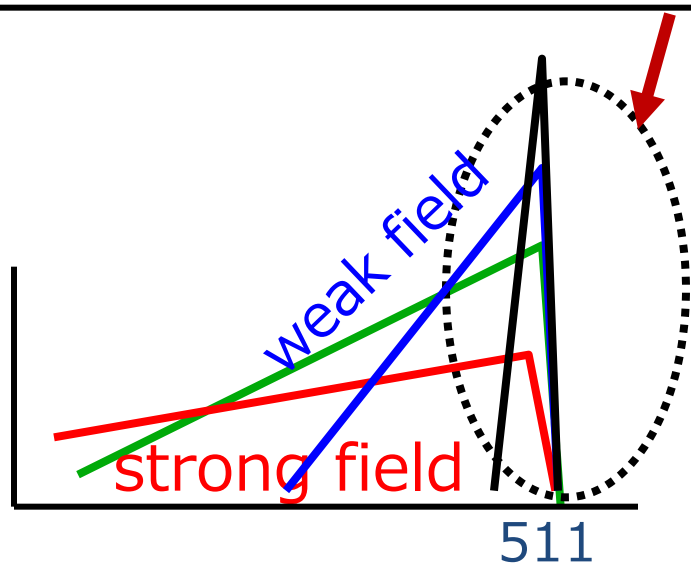
"Photon Splitting"

- ✧ A 3rd QED effect: a photon interact with *B*-field and splits into two with lower energies.
- ✧ Cross section $\propto (B/B_{cr})^6 (h\nu/m_ec^2)^5$, with photon-polarization dependence.

(Bialynicka-Birrla & Bialynicka-Birrla 70, Meszros & Ventura 79, Baring & Harding 01)



Enoto+10c



§8. *ASTRO-H*

A successor to *Suzaku*, to be launched in 2014

- ✧ Soft XR mirror＋Micro Calorimeter:
  0.5-12 keV, ΔE/E~0.1%
- ✧ Soft XR mirrror+ X R CCD camera :
  0.3-12 keV、Wide FOV of 40’
- ✧ Super Mirror + Hard XR Imager :
  5~80 keV, imaging spectroscopu
- ✧ Soft GR Detector :
  60~600 keV, Advance Compton camera