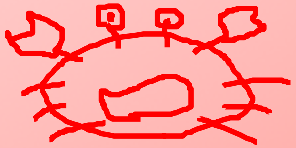
Broadband Emission of Magnetar Wind Nebulae



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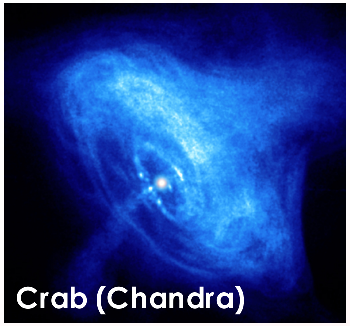


Pulsars in PWNe

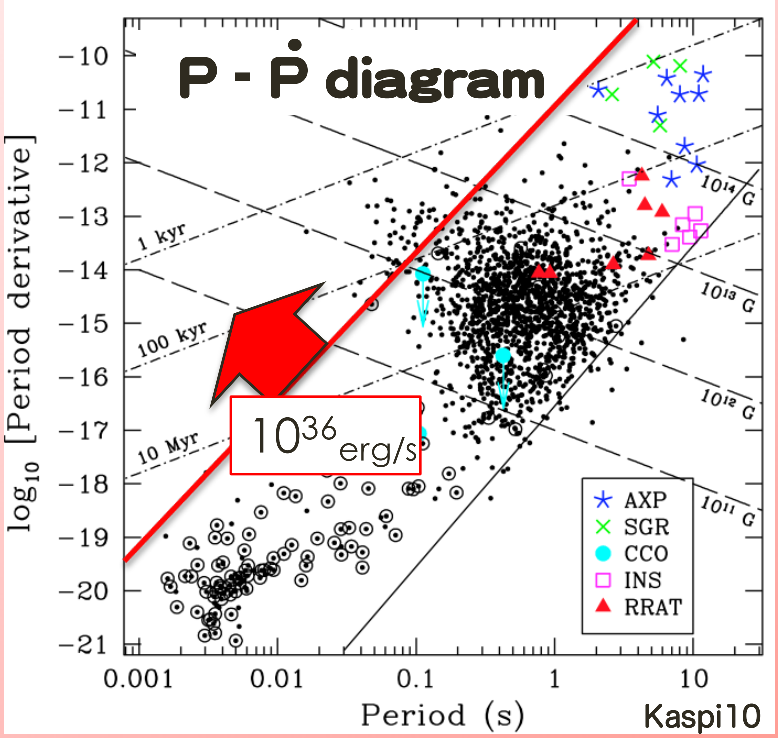
3C58 (Chandra + VLA)

$L_{spin} = I\Omega\dot{\Omega}$

- Pulse lumi. ~ a few % × L_{spin}

  Most of L_{spin} releases as pulsar wind!

- ~ 50 of 2000 pulsars have **observable** PWNe. ($L_{spin} > 10^{36}$erg/s)
- Bow-shock PWNe are around MSP of $L_{spin} < 10^{36}$erg/s



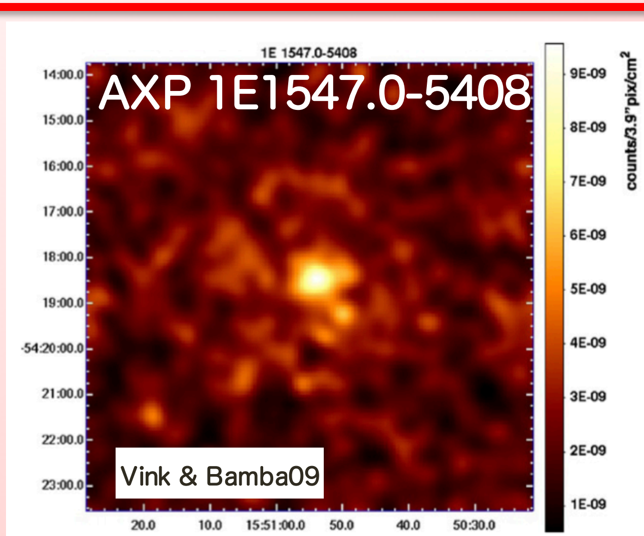
How about other classes of pulsar?

Magnetar Wind Nebulae?

PWNe are found around High-B radio pulsar.

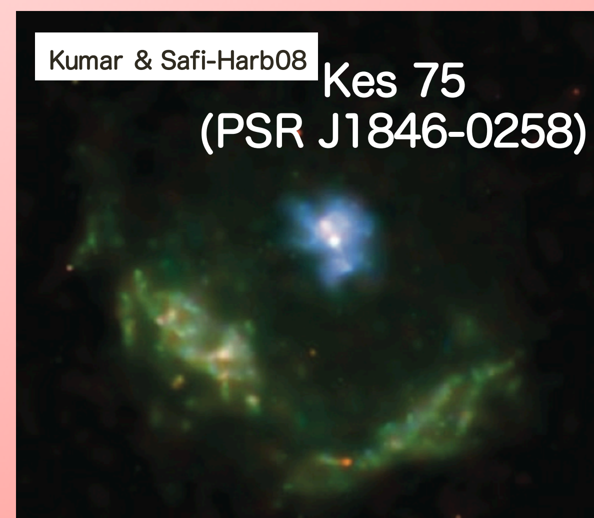
	PSR	SNR?	P[s]	$\dot{P}$[s/s]	B[G]	$L_{\rm spin}$[erg/s]	τ_c[kyr]	Extent
MWN candidate	1E 1547.0-5408	G327.2-0.1	2.07	2.32×10^{-11}	2.2×10^{14}	1.0×10^{35}	1.4	45″
MWN candidate	J1834.9-0846	W41 ?	2.482	8.06×10^{-12}	1.4×10^{14}	2.1×10^{34}	4.9	70 × 150″
HBPs detected	J1819-1458	–	4.26	5.76×10^{-13}	5.0×10^{13}	2.9×10^{32}	117	∼ 13″
HBPs detected	J1846-0258	Kes 75	0.324	7.1×10^{-12}	4.8×10^{13}	8.3×10^{36}	0.7	40″
HBPs detected	J1119-6127	G292.2-0.5	0.408	4.02×10^{-12}	4.1×10^{13}	2.3×10^{36}	1.7	6 × 15″

Safi-Harb13



Observed extended emission may be dust-scattering halo for 1E1547.0 ↑(e.g., Olausen+11)

One of young TeV PWN around high-B radio pulsar



Magnetar Wind

- Magnetars have large surface B-field (> 3×10^{14}G) and some have $L_x > L_{spin}$ ➡ B-powered emission?

e.g., Thompson & Duncan 95

- Magnetars have $\dot{P}$ ➡ Angular momentum loss!!

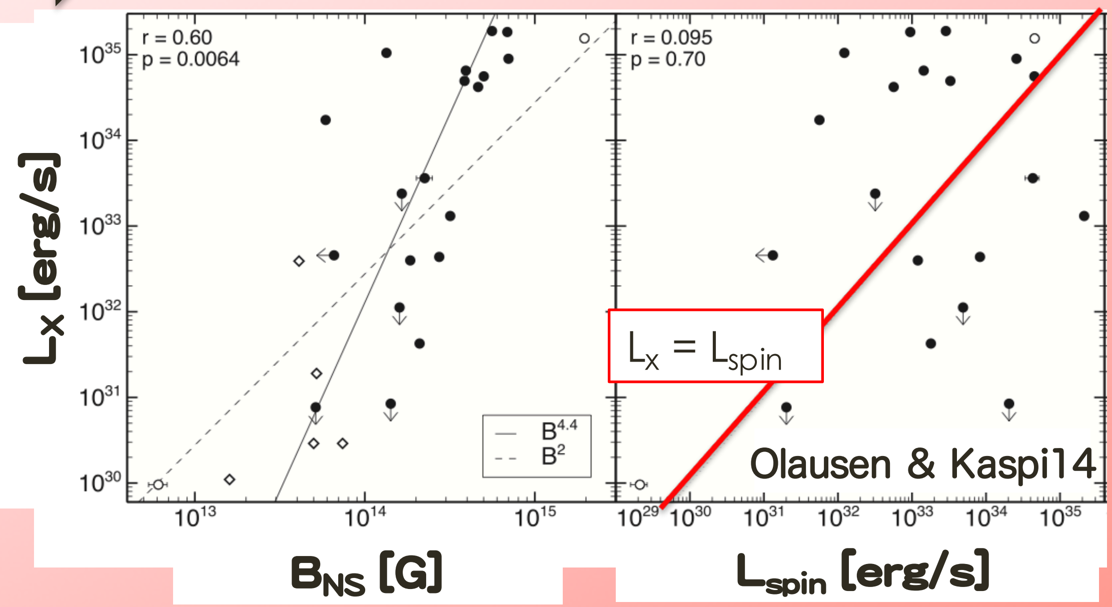
Wind loss

$$\dot{M}_{\rm wind} \approx R_{\rm LC}\frac{L_{\rm wind}}{c}$$

$$\left(= \frac{L_{\rm spin}}{\Omega} \text{ for RPP}\right)$$

Photon loss

$$\dot{M}_{\rm ph} \approx (R_{\rm NS}+\lambda)\frac{L_{\rm ph}}{c}$$



Even $L_x > L_{spin}$, wind angular momentum loss would dominate for magnetars from this simple estimate.

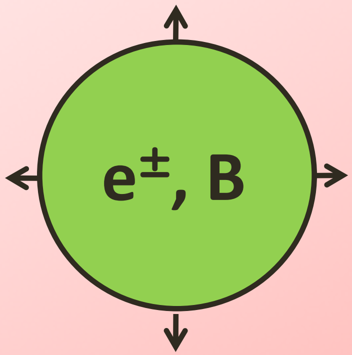
What We Learn from MWN

- PWN spectrum tells us spin evolution of pulsar
  => How about MWN?
  - Does a millisecond magnetar exist? e.g.) Thompson & Duncan 1993 Rea et al. arXiv:1510.01430
- Difference of wind properties from rotation powered pulsar (RPP).
  - magnetization: σ? pair multiplicity: κ?
- Testing fall-back disk model of magnetar. e.g., Chatterjee+00
  - Disk model does not produce MWN because no wind flows out from magnetosphere.

Contents

Spectral Evolution Model

- PWN as uniform sphere
- Constant rate of Expansion
  → applicable to young (<<10kyr) PWN



$$R_{PWN} = V_{PWN} \times t$$

- Introduce a parameter η satisfies (no hadron)

$$L_{spin} = L_{e\pm} + L_B = (1-\eta)\, L_{spin} + \eta\, L_{spin}$$

- B-field evolution as energy conservation

$$\int_0^t L_B(t')\,dt' = \frac{4\pi}{3} R_{PWN}^3 \frac{B^2(t)}{8\pi}$$

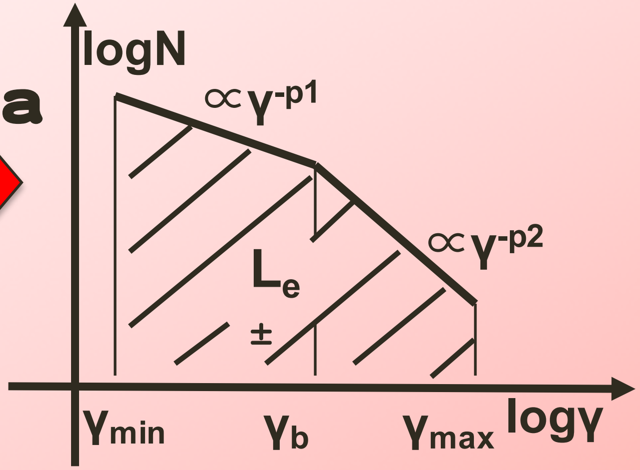
Total magnetic energy injected

Magnetic energy inside PWN

Spectral Evolution Model

- Injection of non-thermal $e^{\pm}$ plasma (broken power-law)

$$(1-\eta)L_{spin} = L_{e\pm} = \int Q_{inj}\,\gamma\, mc^2 d\gamma$$



- Evolution of energy distribution of $e^{\pm}$

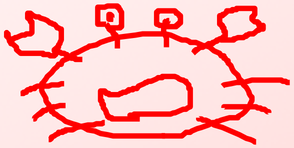
Radiative & adiabatic cooling

Injection from pulsar

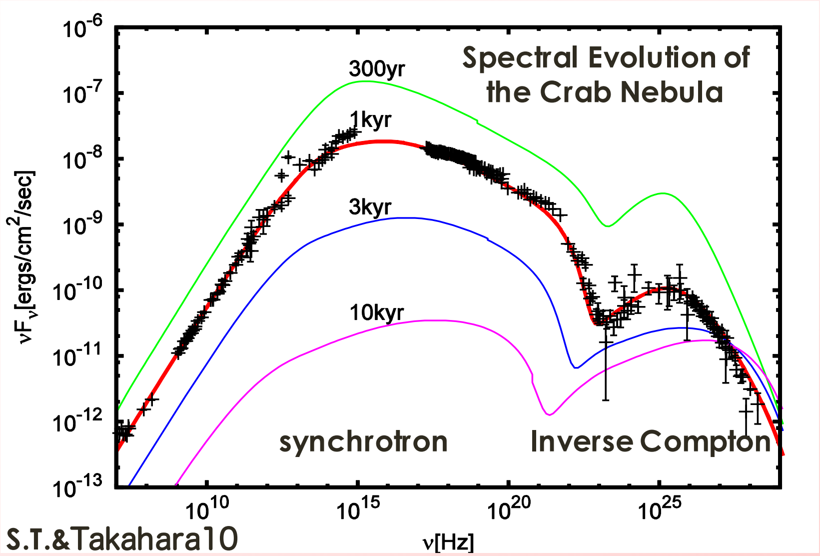
$$\frac{\partial}{\partial t}N(\gamma,t) + \frac{\partial}{\partial \gamma}\dot{\gamma}(\gamma,t)N(\gamma,t) = Q_{\rm inj}(\gamma,t)$$

Calculate Syn. & IC spectral evolution

Crab



Most observed & studied object (one parameter η)

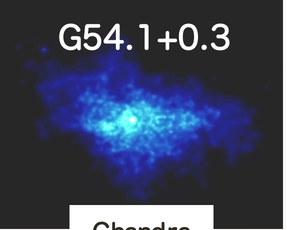


	radio[%/yr]	Opt.[%/yr]
Model	-0.16	-0.24
Obs.	-0.17	-0.55

- Observed flux@1kyr
  $\eta \sim 5 \times 10^{-3}$ (85μG)
- SSC dominates in γ-rays.
- Flux evolution is consistent.

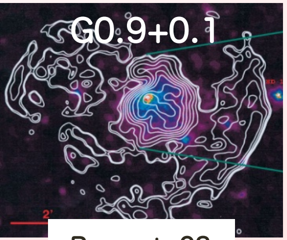
Model can reproduce observations

Young PWNe

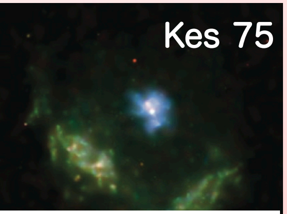


Chandra

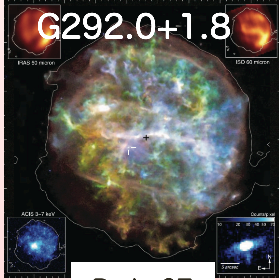
Chandra



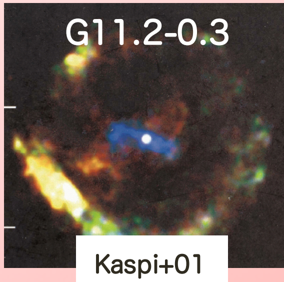
Porquet+03



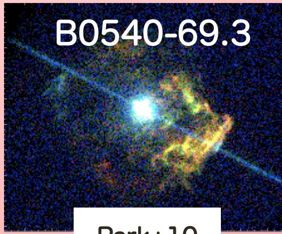
Kumar & Safi-Harb08



Park+07

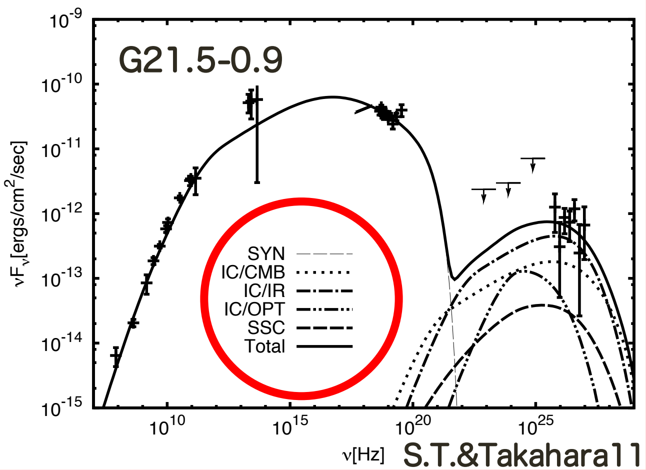


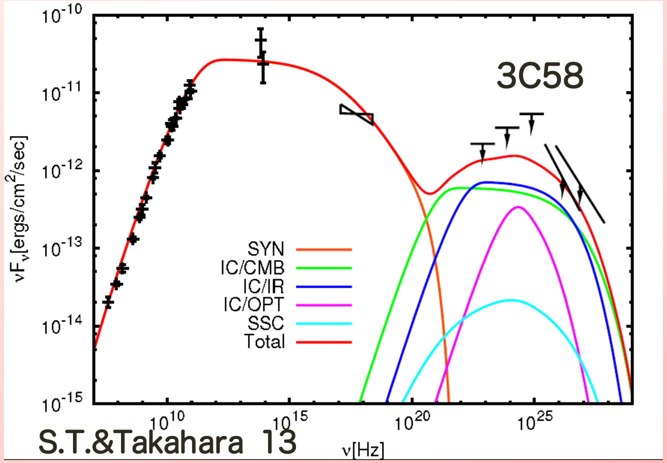
Kaspi+01



Park+10

Applicable to other young PWNe < 10kyr





3C58 (Chandra + VLA)

One-zone model is enough to get

- mean B-field inside PWN.
- spin-evolution of central pulsars
- predictions to γ-ray flux
- $\eta \sim 10^{-3}$ for all except for Kes 75

Contents

Simplified One-zone Model

- **Spin-down evolution**

$$t_c = \frac{n-1}{2}(t_{age} + \tau_0) \approx \frac{n-1}{2} t_{age}$$

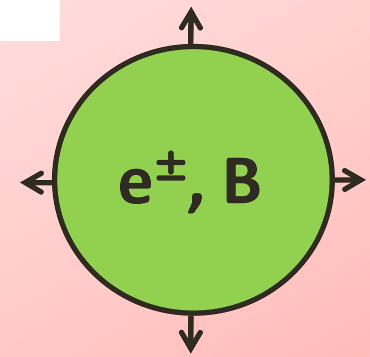
$$L_{spin}(t) \approx L_{spin,now} \left(\frac{t}{t_{age}}\right)^{-\frac{n+1}{n-1}}$$

- **Expansion of MWN**

$$R(t) = R_{now} \left(\frac{t}{t_{age}}\right)^{\alpha_R}$$

- **B-field inside MWN**

$$B(t) = B_{now} \left(\frac{t}{t_{age}}\right)^{\frac{\alpha_B}{2}}$$

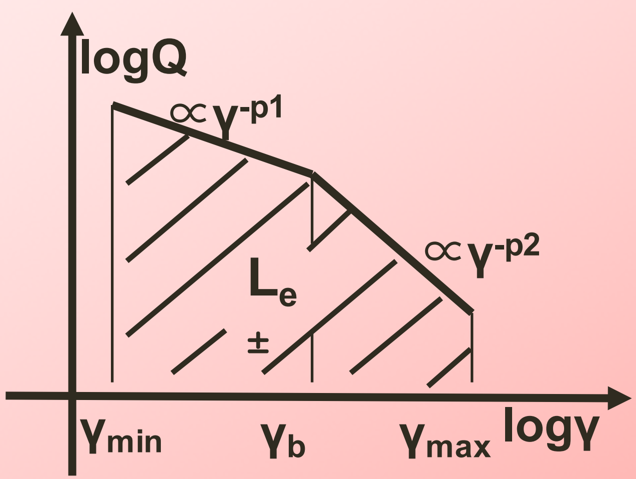


$-1.2 < \alpha_R < -1.0$, $-5 < \alpha_B < -3$ from past studies

e.g., Gelfand+09, Tanaka&Takahara10, 11, 13, Bucciantini+11

- **$e^{\pm}$ injection**

$$L_{e^{\pm}}(t) \sim L_{spin}(t)$$



$e^{\pm}$ energy distribution

$$\frac{\partial}{\partial t} n(\gamma, t) + \frac{\partial}{\partial \gamma} \dot{\gamma} n(\gamma, t) = Q(\gamma, t)$$

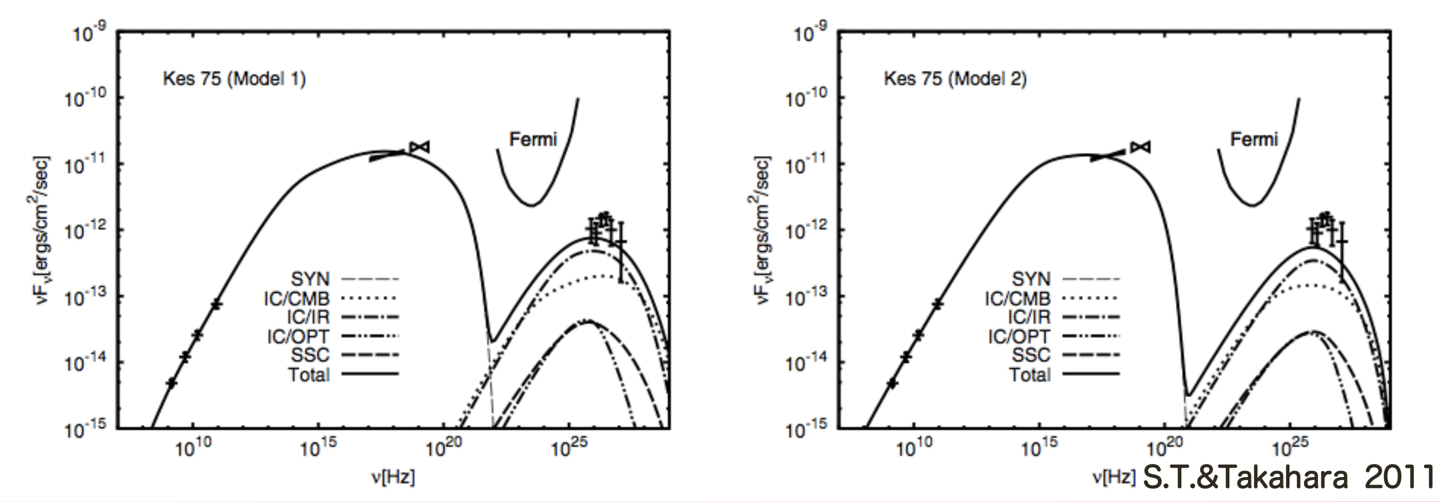
adiabatic + synchrotron
+ inverse Compton coolings

Kes 75

Young RPP with magnetar-like activity

Gavriil+08Sci

$L_{spin} = 8 \times 10^{36}$ erg/s, $B_{NS} = 4.8 \times 10^{13}$ G, $\tau_c = 0.7$ kyr

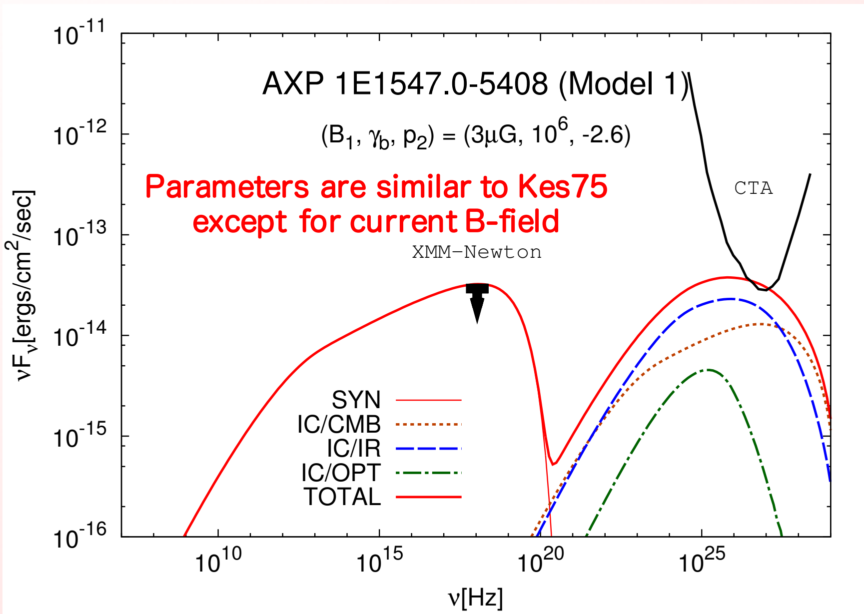


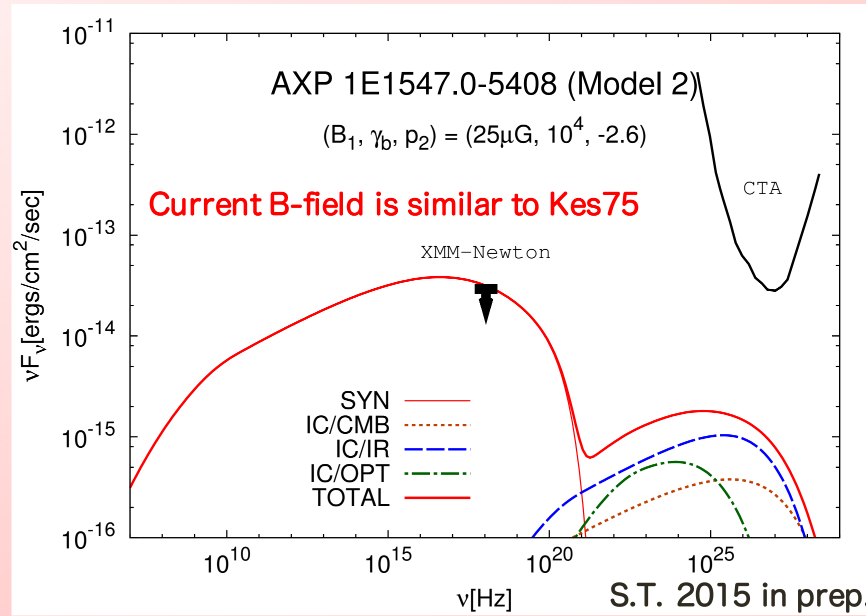
S.T.&Takahara 2011

	model 1	model 2
d	6kpc	10.6kpc
τ_0	0.2kyr	3yr
E_{rot}	1.5×10^{48} erg	2.1×10^{50} erg
B_{PWN}	20 μG	24 μG
η	5×10^{-5}	6×10^{-6}

AXP 1E1547.0-5408

Assuming $(u_{IR}, u_{opt}) = (1.0, 2.0)$ [eV/cc]
$L_{spin} = 1\times10^{35}$erg, $B_{NS} = 2.2\times10^{14}$G, $\tau_c = 1.4$kyr





- Results are insensitive to α_B & α_R.
- X-ray upper limit gives constraints $B_{now} < 25\mu$G.
- CTA would detect MWN around 1E1547.0 when $B_{now} < 3\ \mu$G & $u_{IR} > 1.0$eV/cc <= larger value is expected
- $\eta \ll 10^{-3}$ is consistent with Kes 75.
- $P_0 < 100$msec is presumed.

Summary

- Pulsar & Pulsar Wind Nebula
  - Most of L_{spin} lost by pulsar wind
  - σ- & κ- problem about physics of pulsar magnetosphere
  - One-zone model of PWNe tells us spin-evolution of central pulsars

- A Spectral model of MWNe
  - Angular momentum loss of magnetar => magnetar wind?
  - Deep obs. of 1E1547.0 by CTA can examine the hypothesis.
  - $\eta \ll 10^{-3}$ is consistent with High-B radio pulsars.
  - Constraint on P_0 is not strong < 100msec
  - Detections of MWN in multi-wavelength are required to constrain magnetar evolution properties.