Nearby, Thermally Emitting Isolated Neutron Stars

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Physics of Neutron Stars
St. Petersburg
July 15, 2011

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Passenger bound and gagged and flight diverted after violent clash on United Airlines plane

- **Passengers said they found wires in bathroom after man refused to come out**

By RACHEL QUIGLEY

Last updated at 4:05 PM on 10th July 2011

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This was not me.

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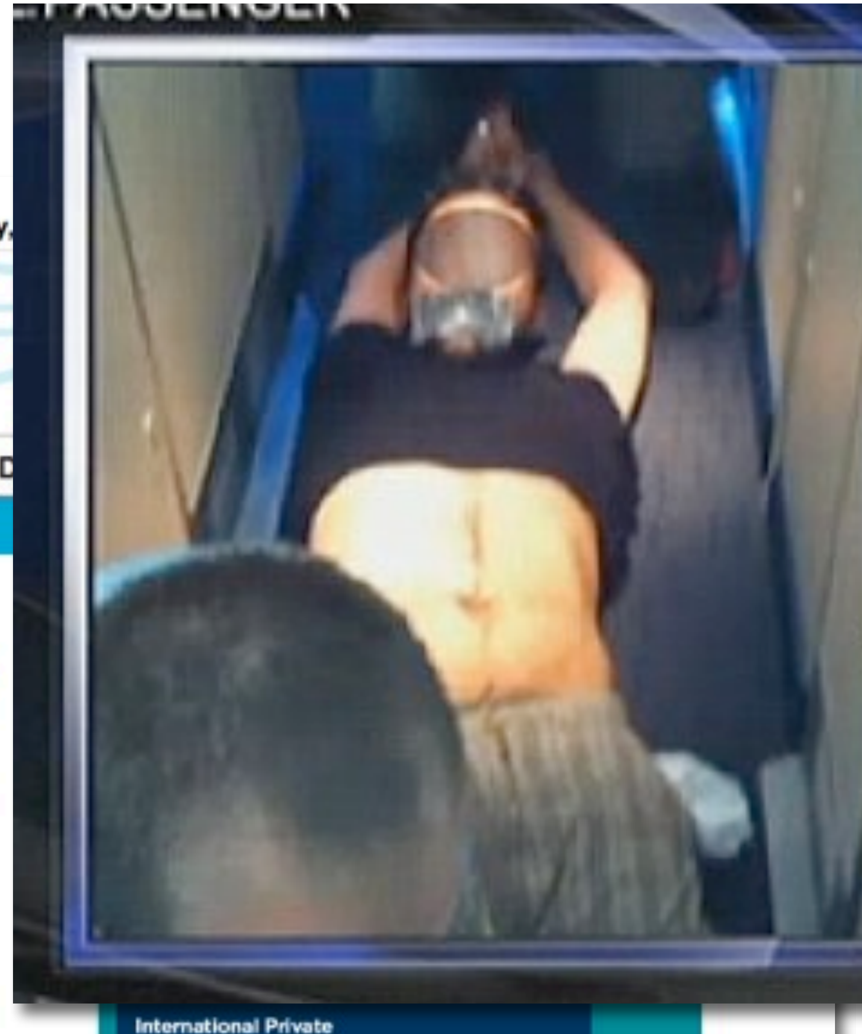

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Joe Shulfer, of Woodstock, told Newsradio 780: 'The flight attendant just ran up to me and literally grabbed me by the shirt and said, "You need to come with me now".'

By then three men were already wrestling with him and they managed to handcuff him and tie up his feet. Then he started spitting and swearing.

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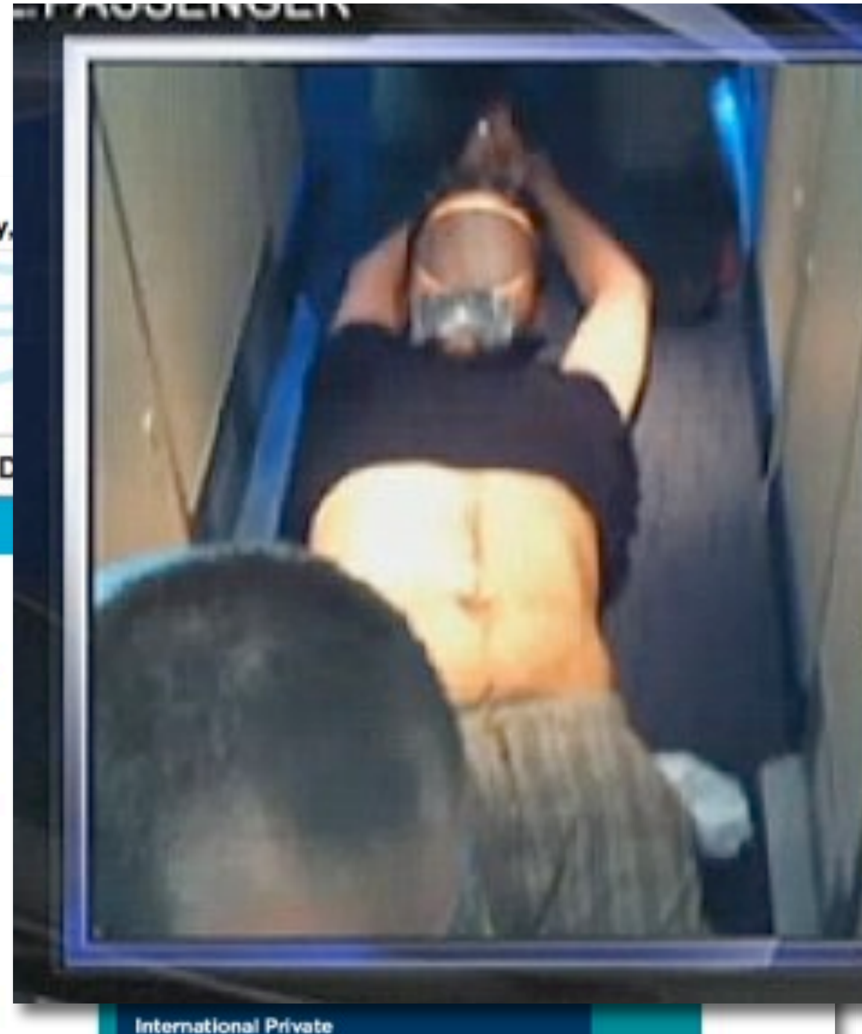

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This was not me.

This was not me either.

Introduction

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- Exploit neutron stars to learn about matter:
  - extreme densities
  - extreme magnetic fields

- Exploit soft X-rays to learn about neutron stars

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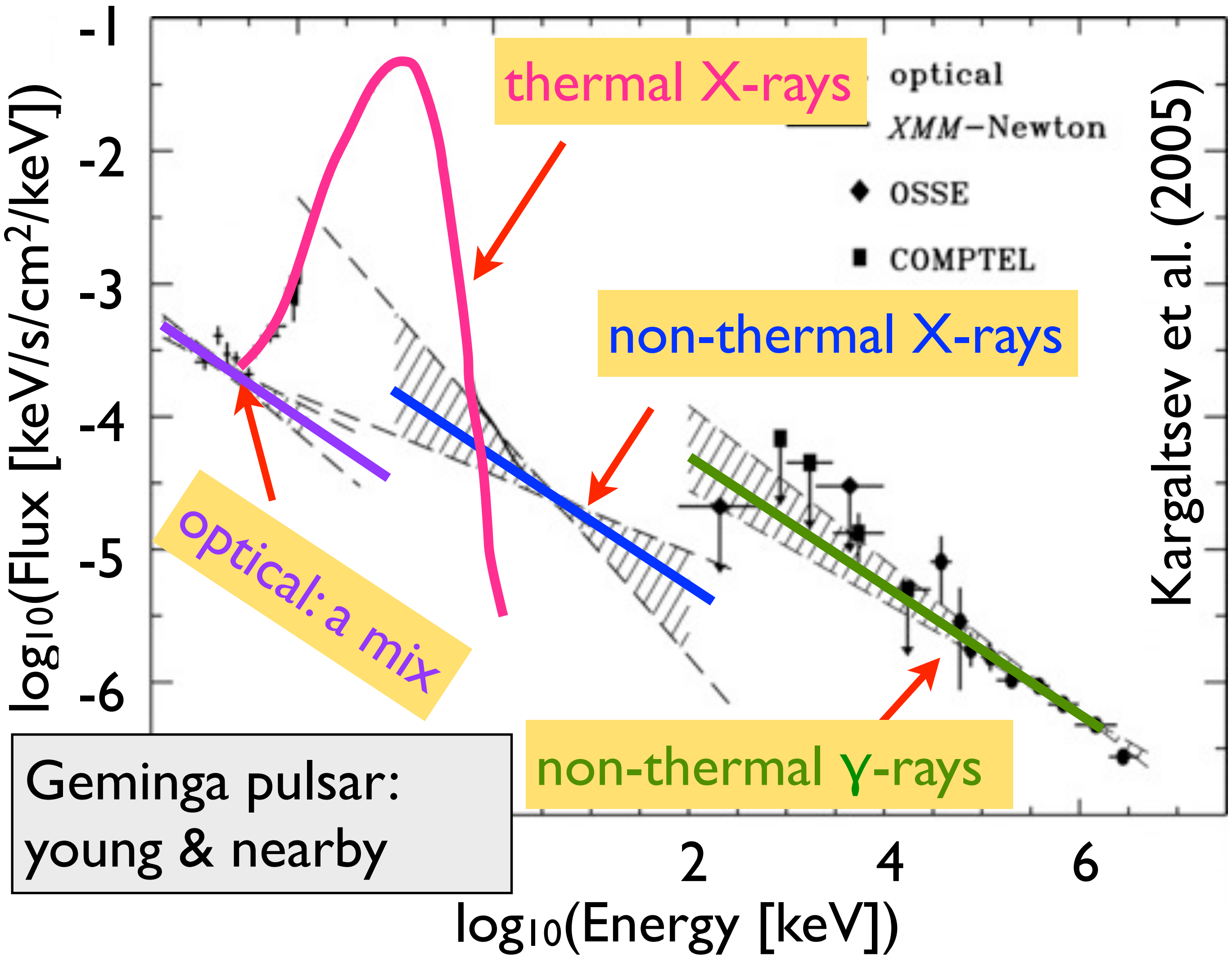
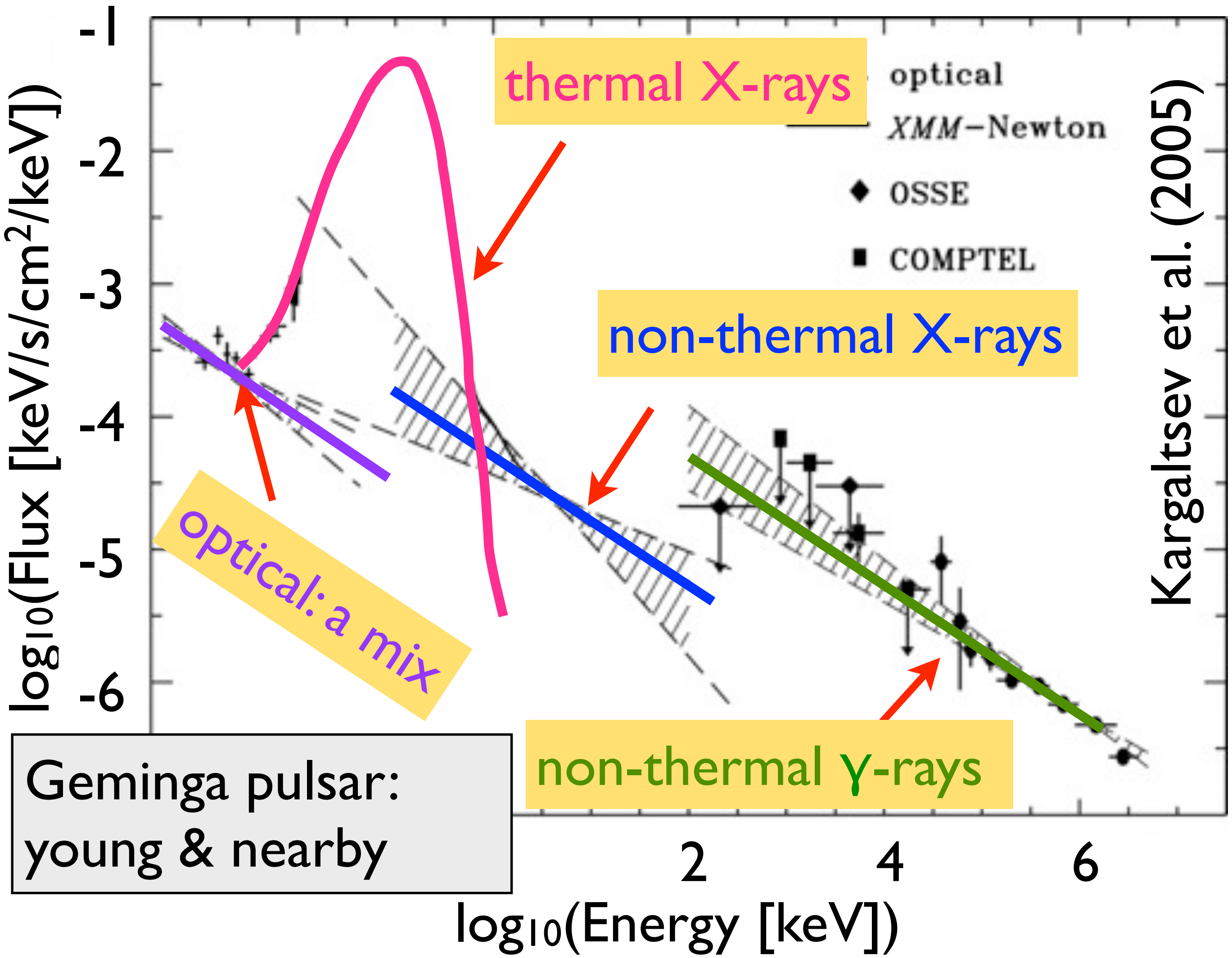
- Exploit soft X-rays to learn about neutron stars
- Cooling: need distances, ages
- Radius measurements: need ages
- <u>Both need real understanding of surfaces!</u>

The Problem With Pulsars



The Problem With Pulsars

- Strong, complicated non-thermal emission
- Makes radius estimation difficult
- Also heats surface: cooling compromised
- Need a new sample



Geminga pulsar: young & nearby

The Problem With Pulsars

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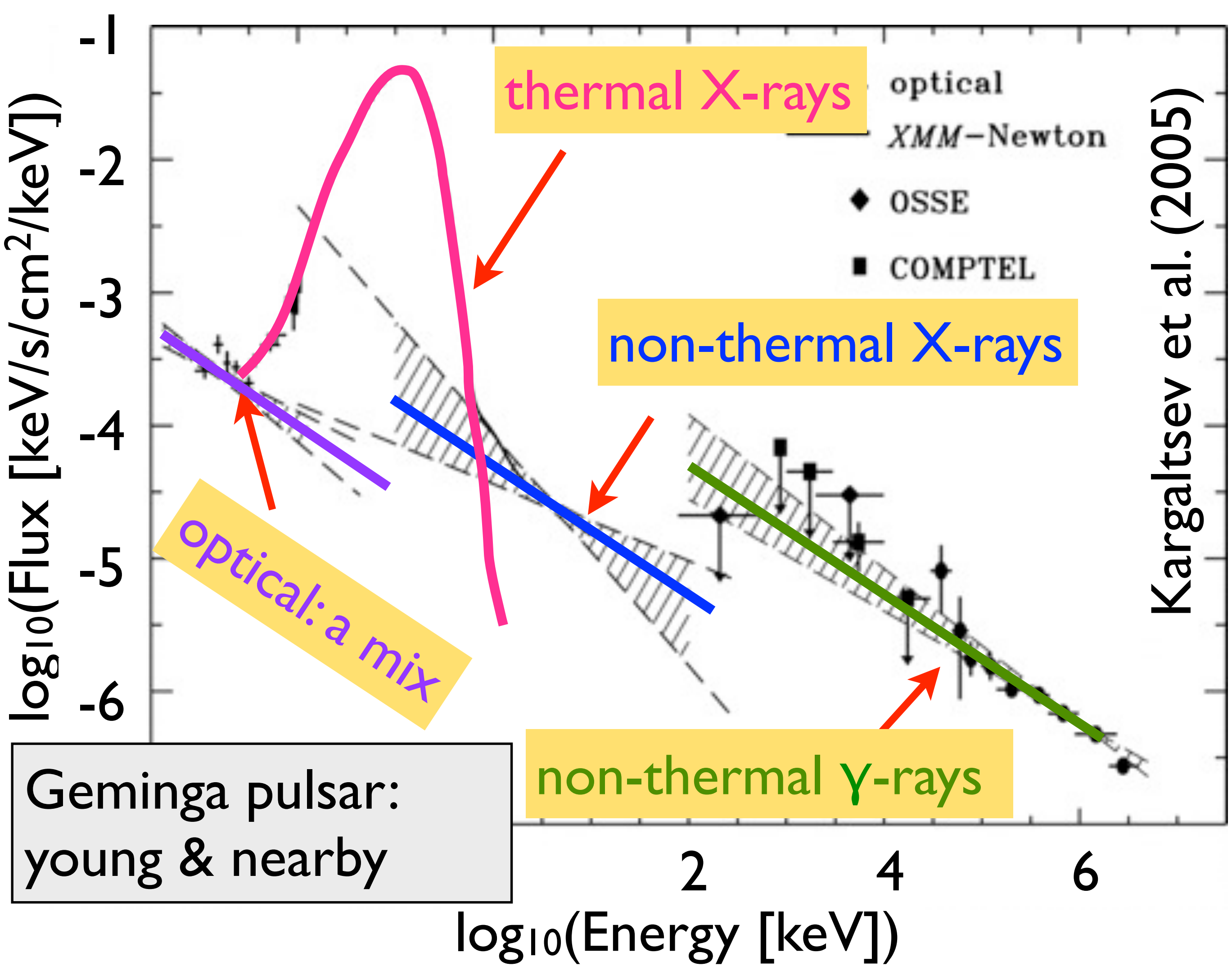
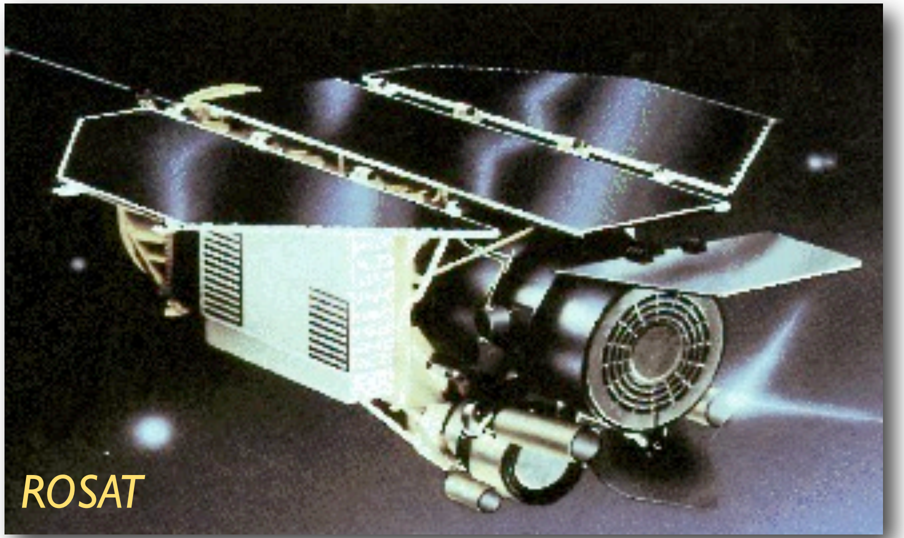
- Makes radius estimation difficult
- Also heats surface: cooling compromised
- Need a new sample
- Look in Soft X-rays:
    - All neutron stars cool



Isolated Neutron Stars



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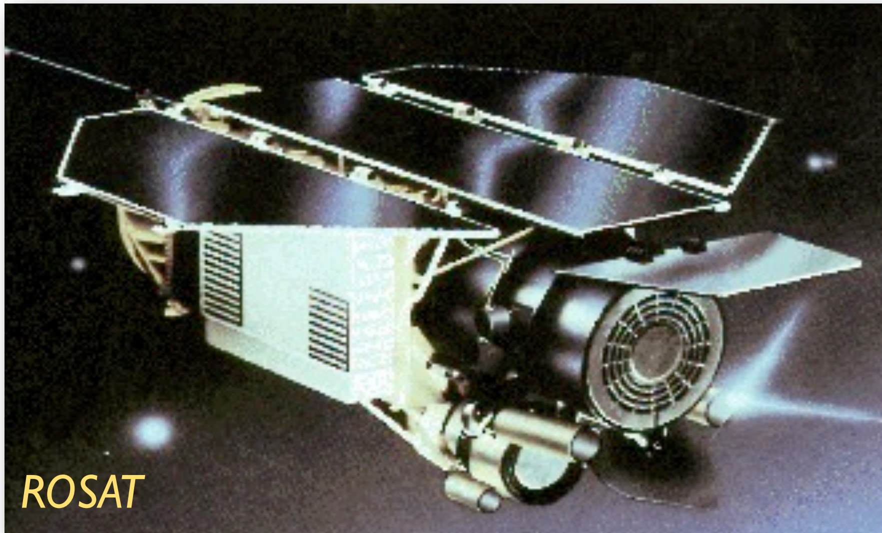

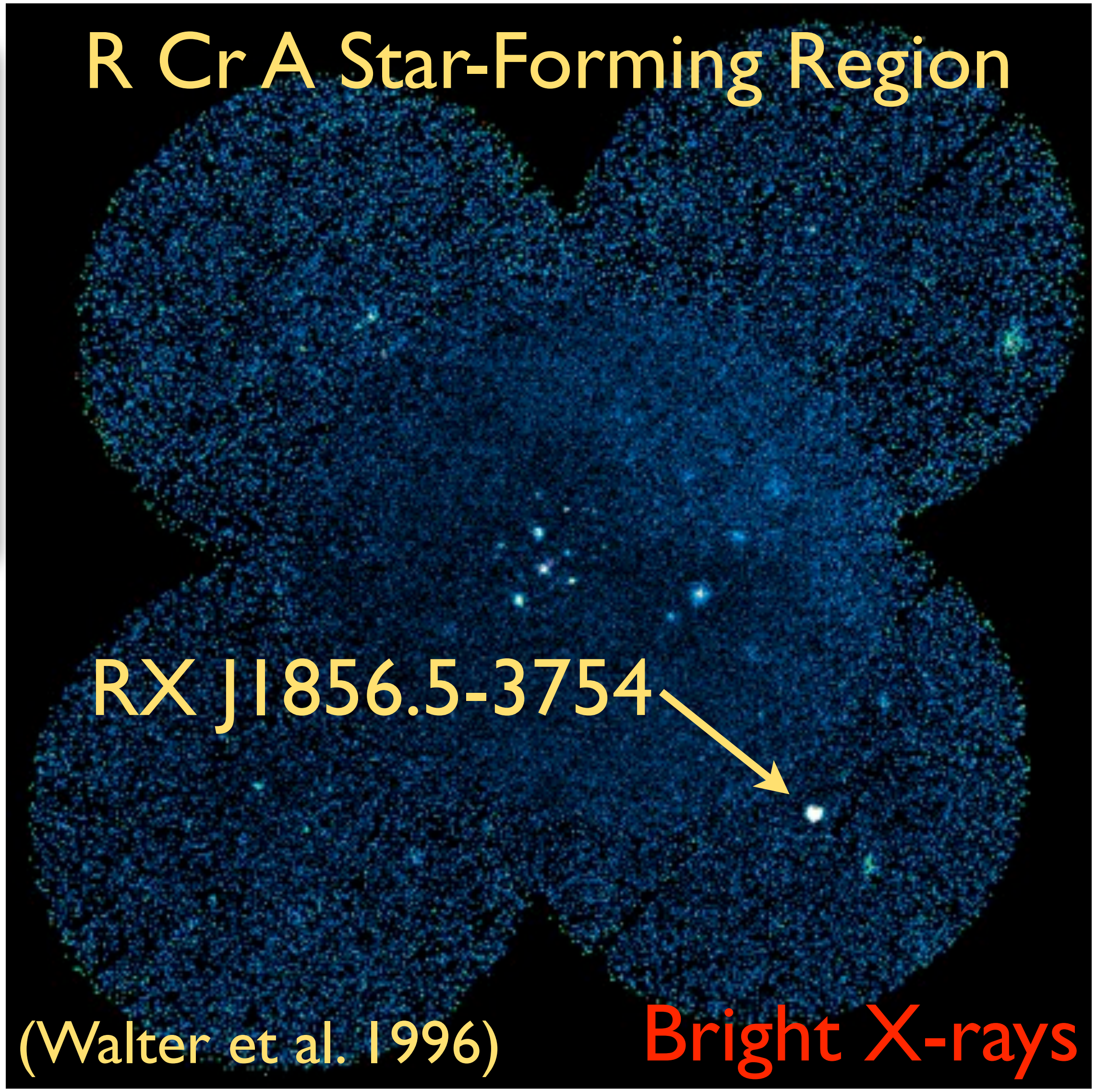

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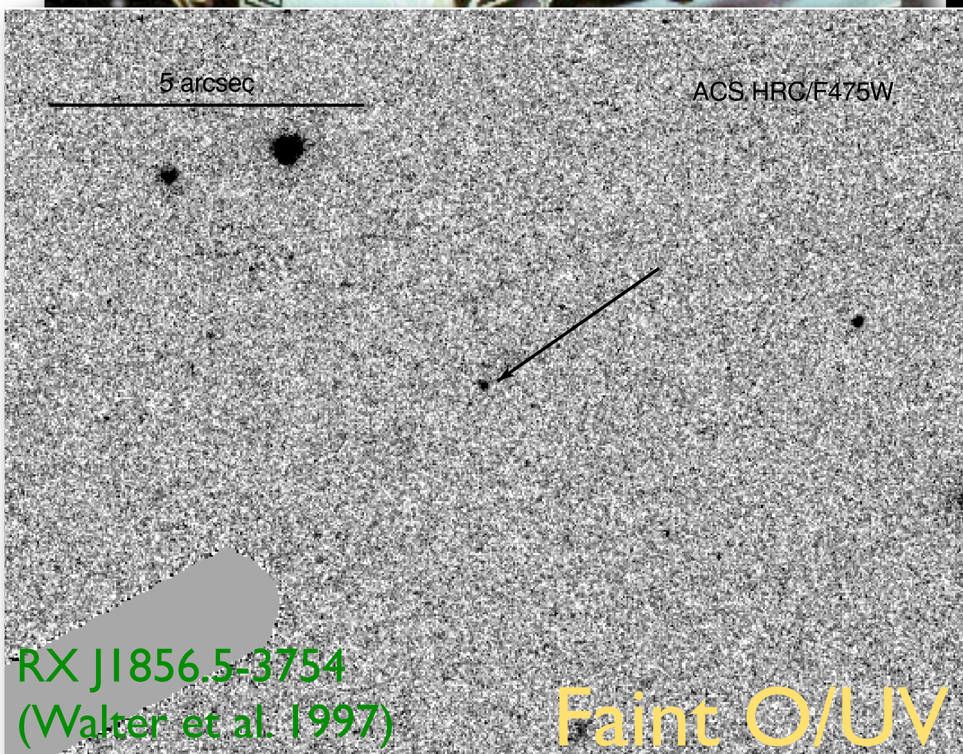

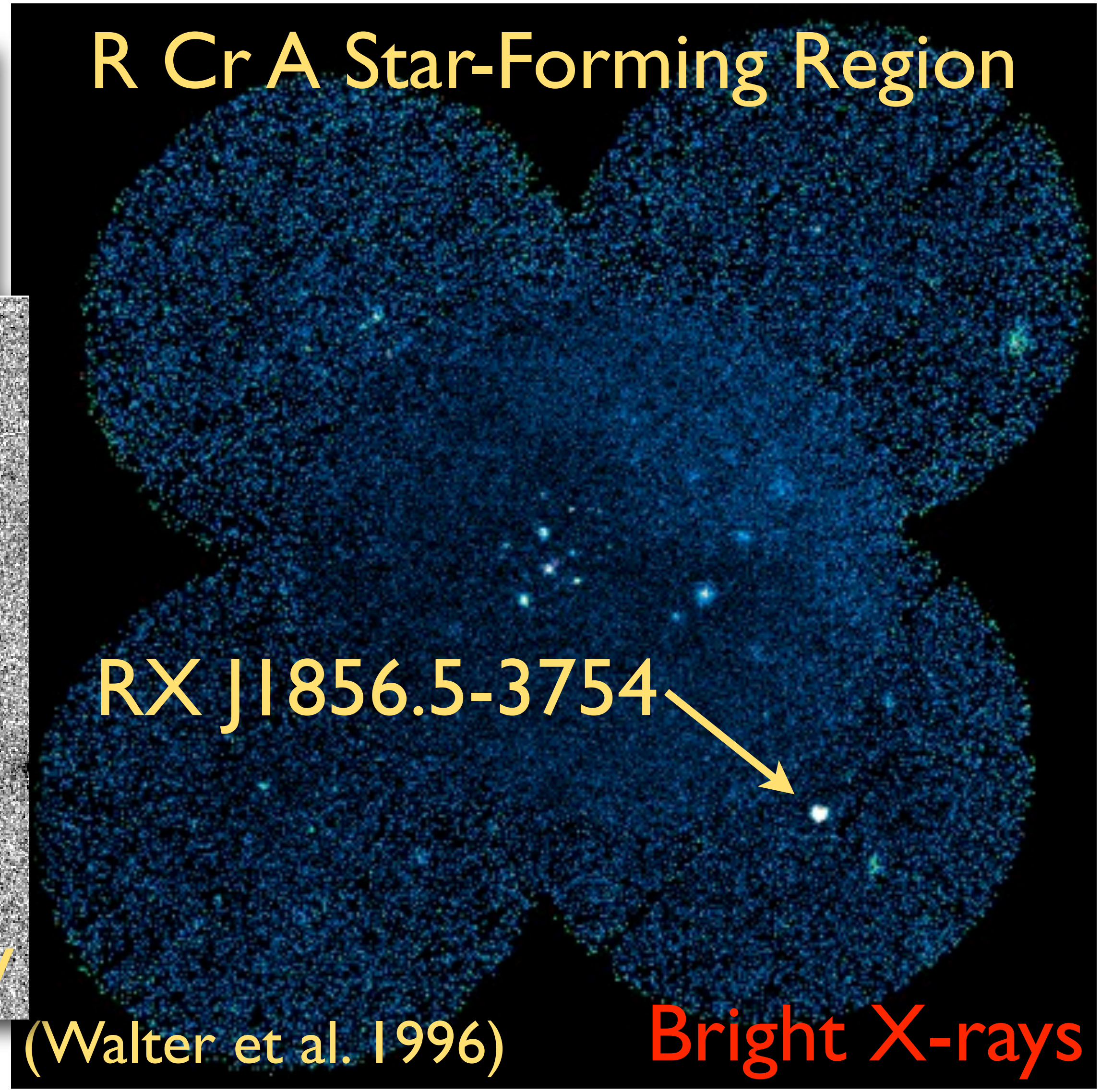

Isolated Neutron Stars

- Bright, cool X-ray sources w/ very faint optical counterparts
- Currently 7 (review: Kaplan 2008, arXiv:0801.1143)
- Properties:
  - temperatures ~ 1 million degrees (peak at ~100 eV=124 Å)
  - spin periods 3-10 sec.
  - no confirmed radio (bursts or continuous: limits sub-mJy)
  - nearby, < 1 kpc
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- Why this sample?
  - Nearby → bright
  - Relatively young → can use for cooling curves
  - Emission is thermal → comes only from surface

Isolated Neutron Stars

- Bright ... nterparts
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  - ter ... 0 eV=124 Å)
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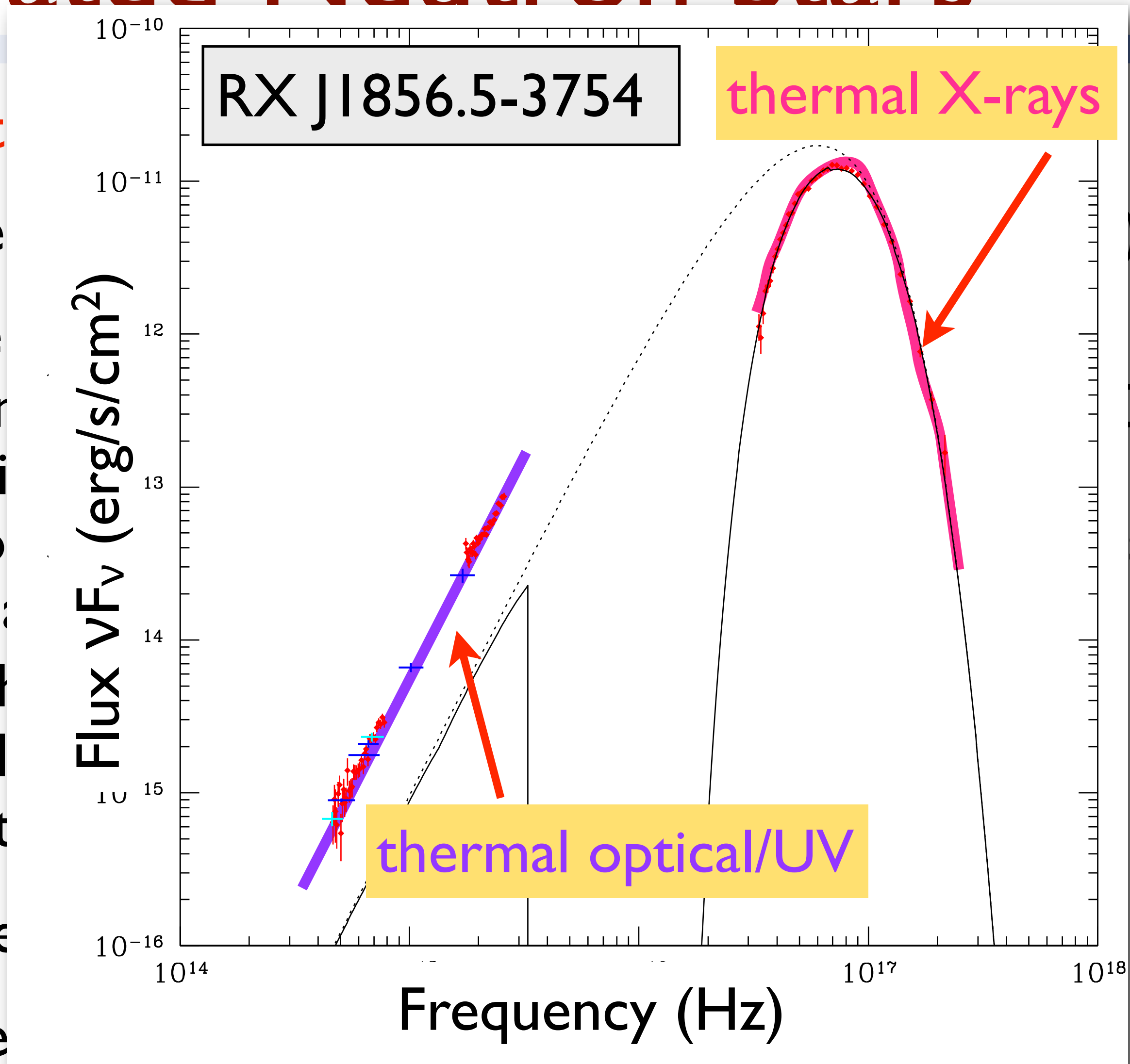


What We Know from X-rays

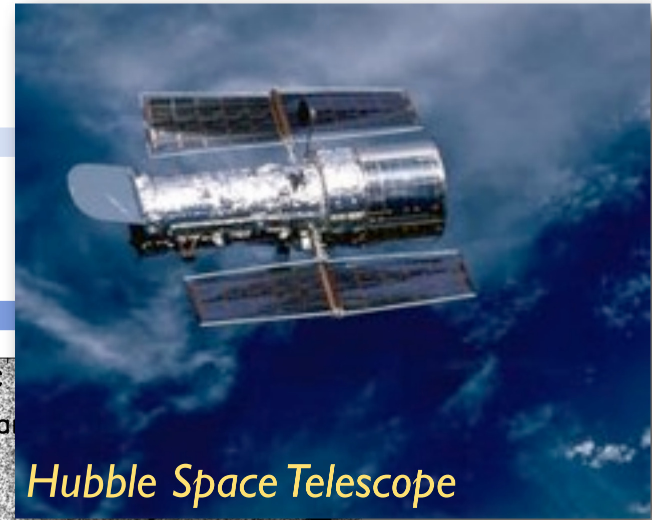
- *ROSAT* All-Sky Survey (>0.05 count/sec):
  - Soft X-rays (0.1-2.4 keV)
  - Efficient way to find young/energetic/nearby neutron stars

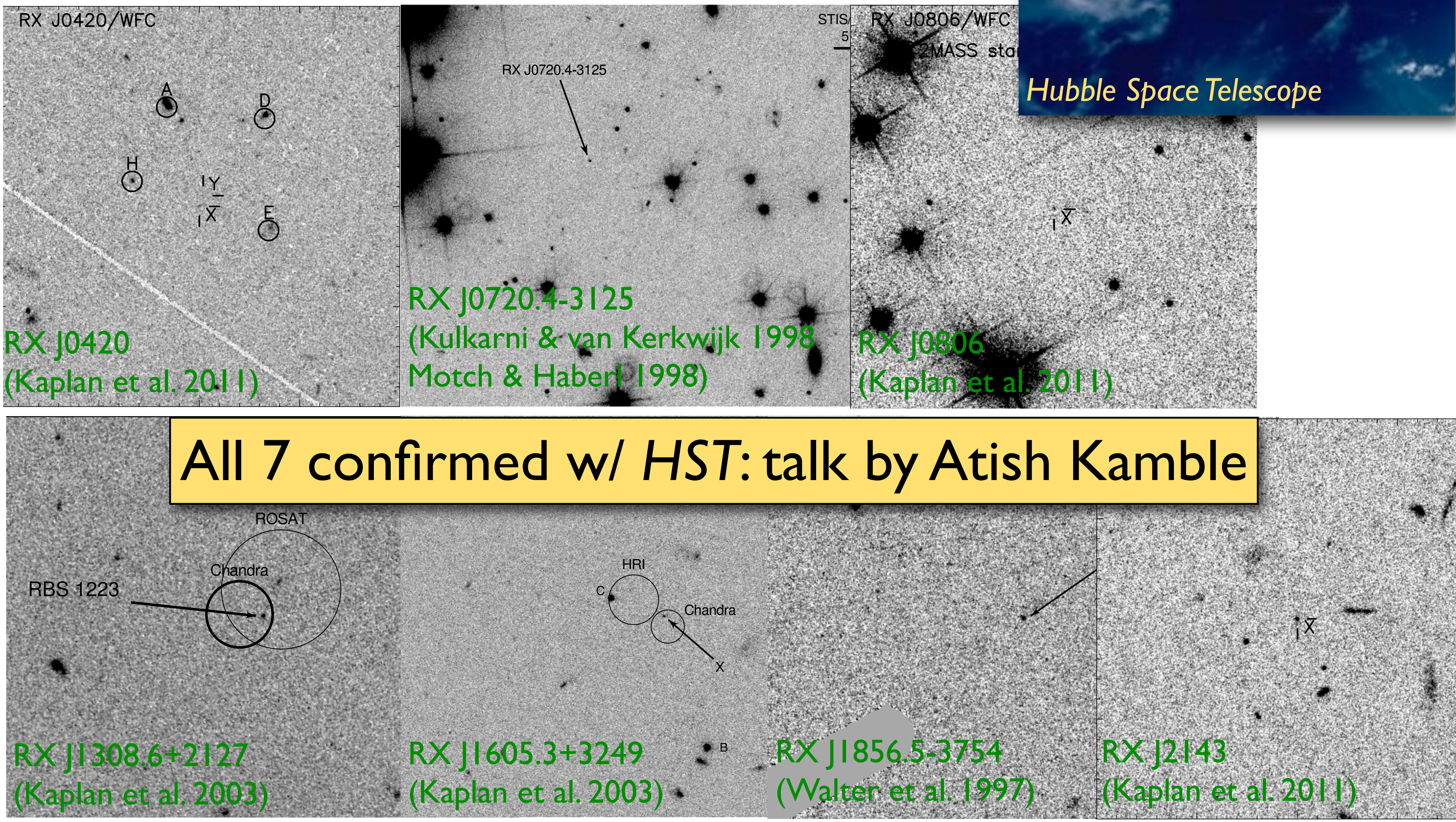
=no radio

Pulsars (non-thermal, P<400 ms)	INS (thermal, P>3 s)
v. young! Crab (48.4 s^{-1})	RX J1856.5-3754 (3.64 s^{-1})
Vela (3.4 s^{-1})	RX J0720.4-3125 (1.64 s^{-1})
PSR B0656+14 (1.92 s^{-1})	RX J1605.3+3249 (0.90 s^{-1})
Geminga (0.54 s^{-1})	RX J0806.4-4123 (0.38 s^{-1})
PSR B1055-52 (0.35 s^{-1})	RX J1308.6+2127 (0.29 s^{-1})
old! PSR J0437-4715 (0.20 s^{-1})	RX J2143.0+0654 (0.18 s^{-1})
old or young? Calvera (0.08 s^{-1})	RX J0420.0-5022 (0.14 s^{-1})
PSR J0538+2817 (0.06 s^{-1})	No Beaming!
PSR B1951+32 (0.07 s^{-1})	

Kaplan (arXiv:0801.1143); Kaplan and van Kerkwijk (2009, ApJ, 705, 798);
Zane et al. (2011, MNRAS, 410, 2428)

Optical Counterparts



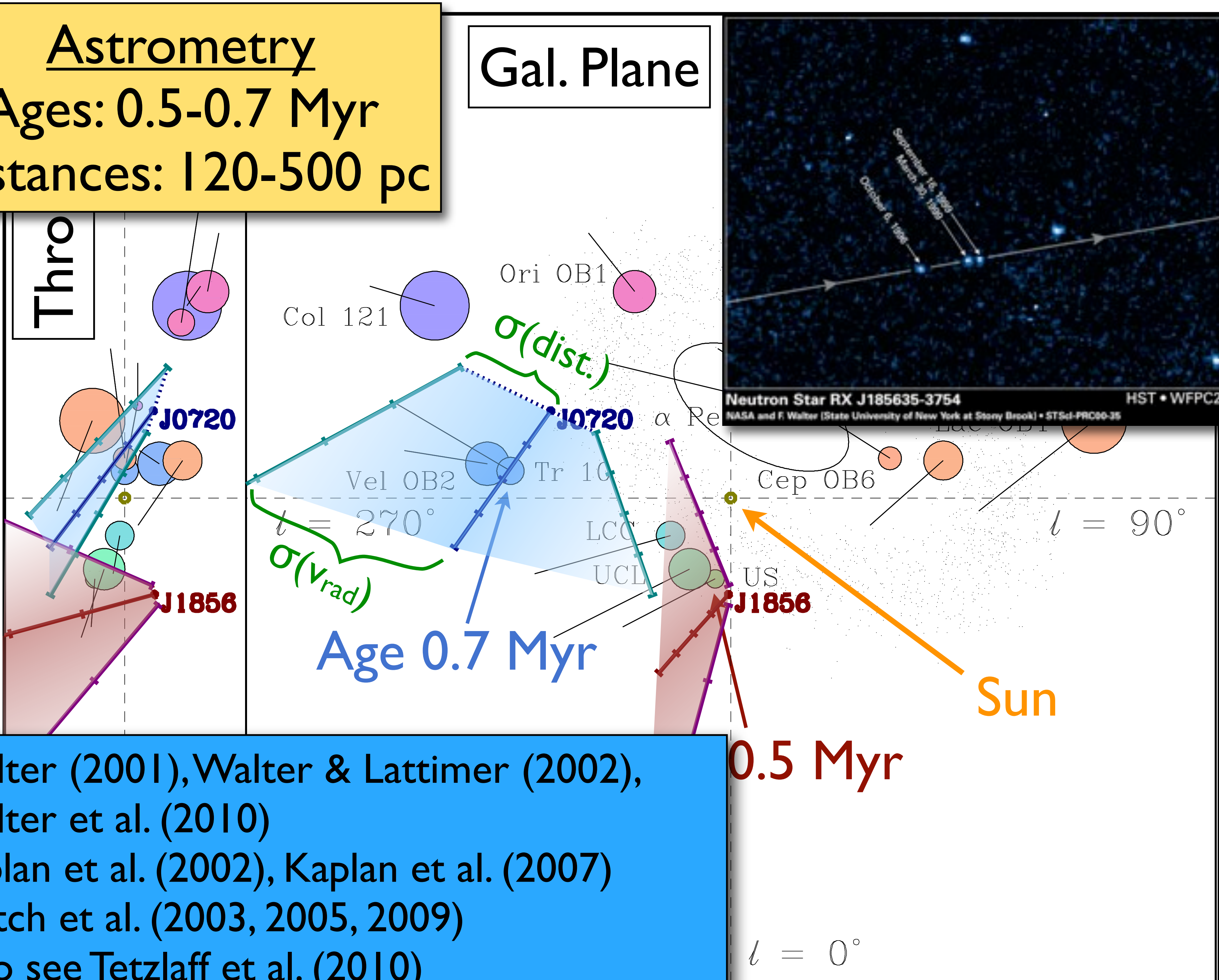


All 7 confirmed w/ *HST*: talk by Atish Kamble

Astrometry

Ages: 0.5-0.7 Myr

Distances: 120-500 pc



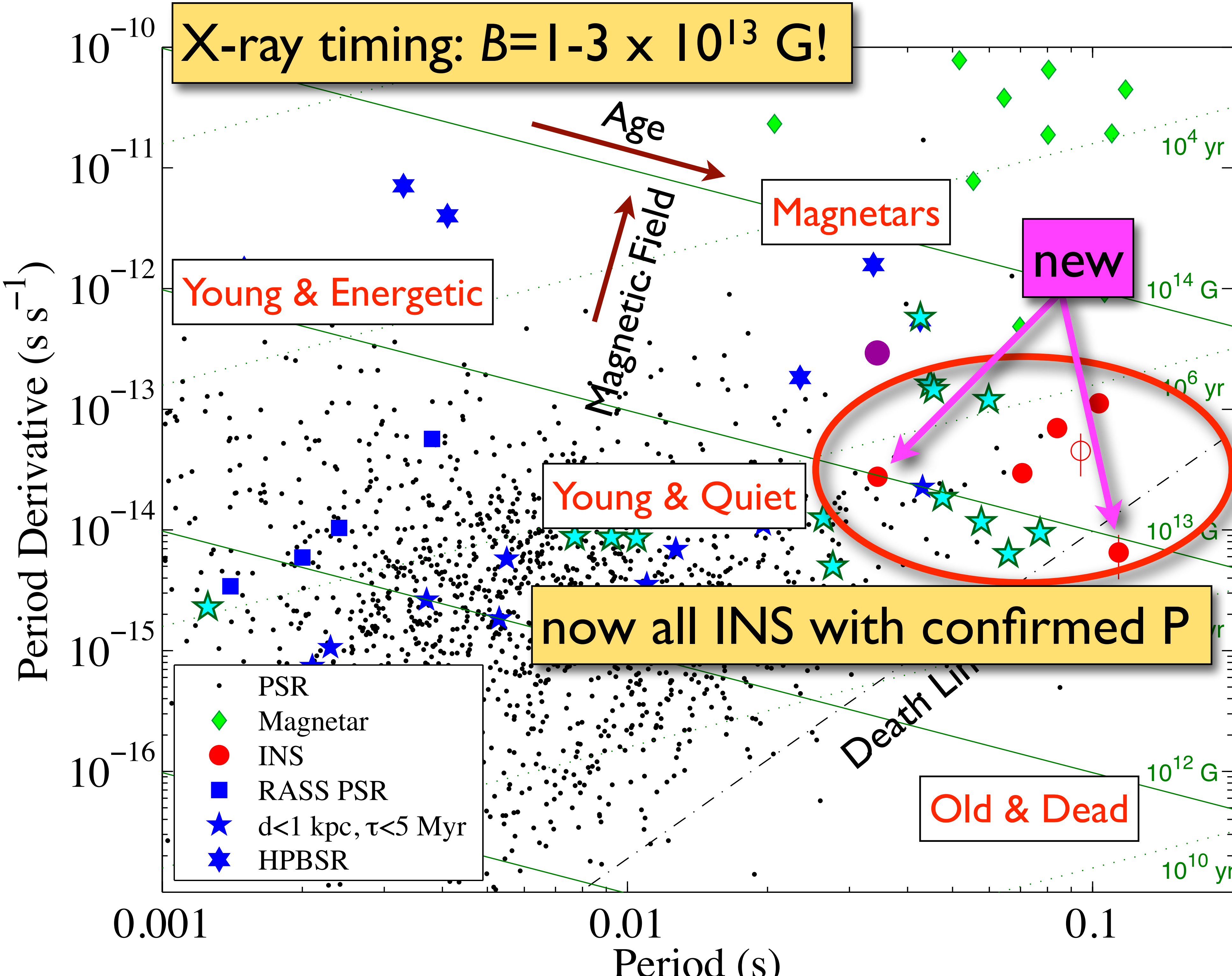
Walter (2001), Walter & Lattimer (2002), Walter et al. (2010)

Kaplan et al. (2002), Kaplan et al. (2007)

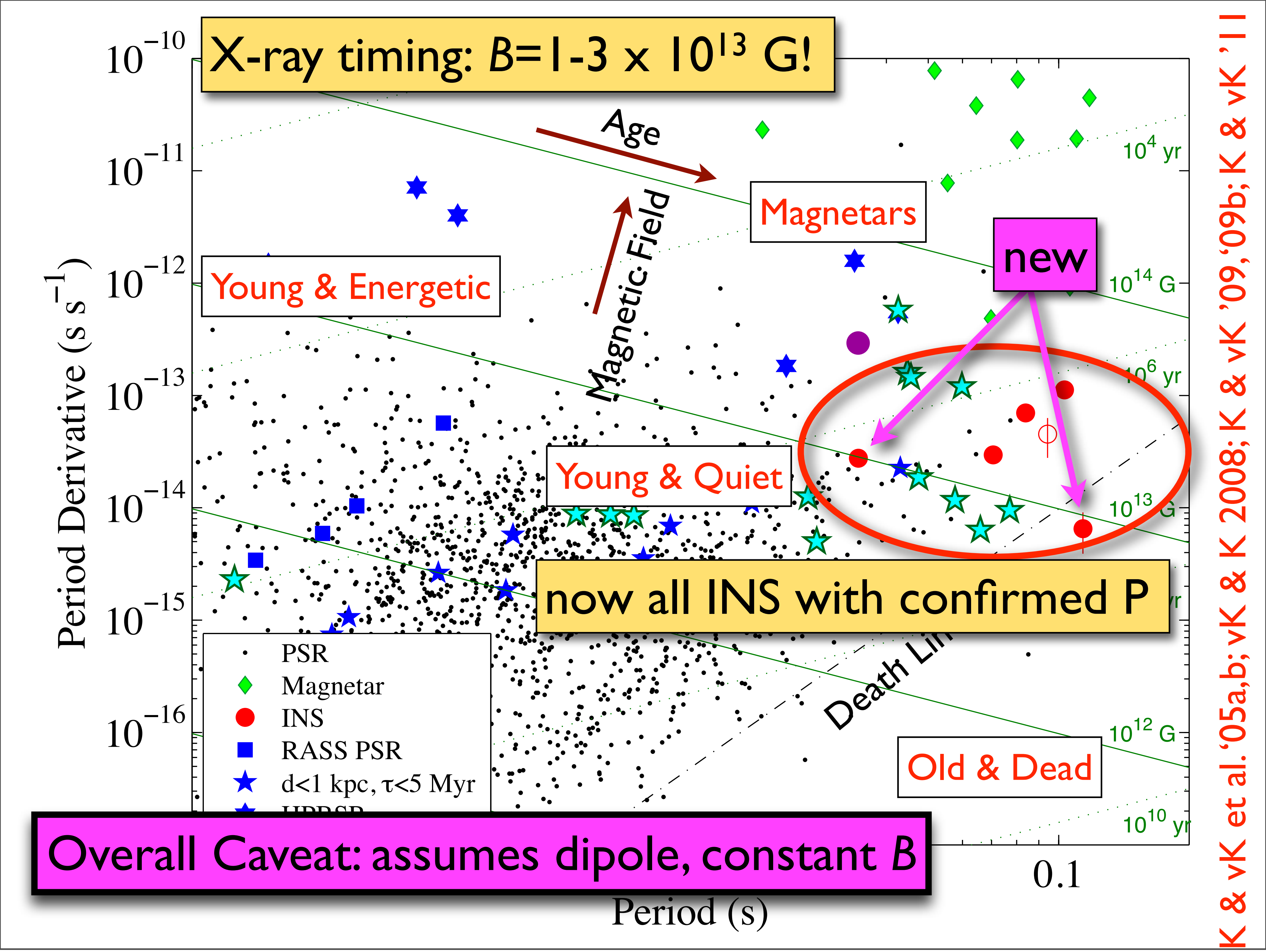
Motch et al. (2003, 2005, 2009)

Also see Tetzlaff et al. (2010)

(OB assns adapted from de Zeeuw et al. '99)



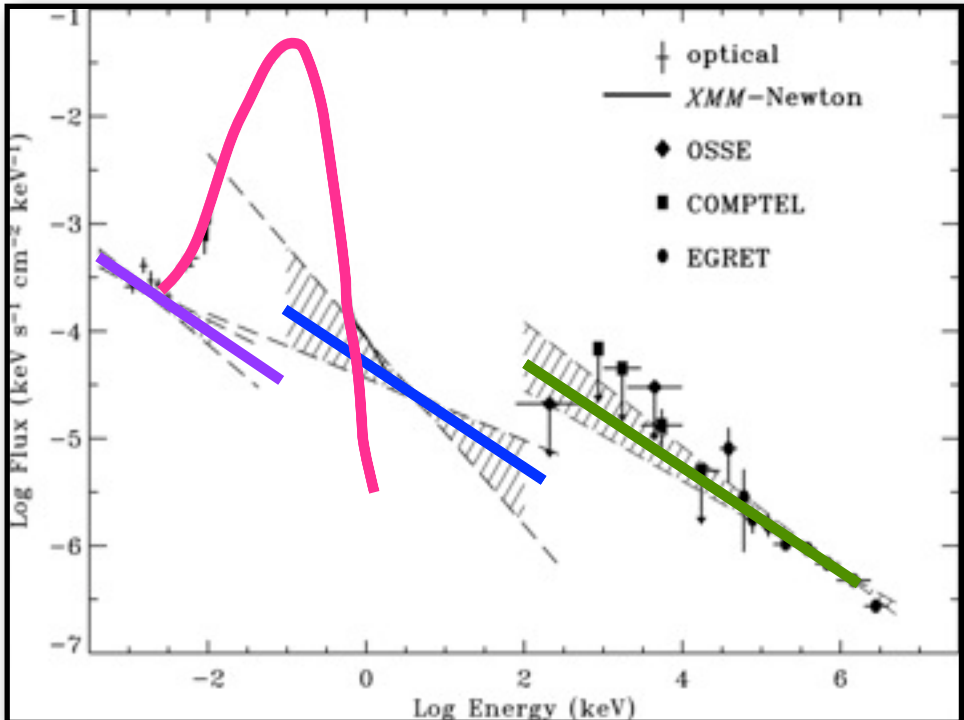
K & vK et al. '05a,b; vK & K 2008; K & vK '09,'09b; K & vK '11

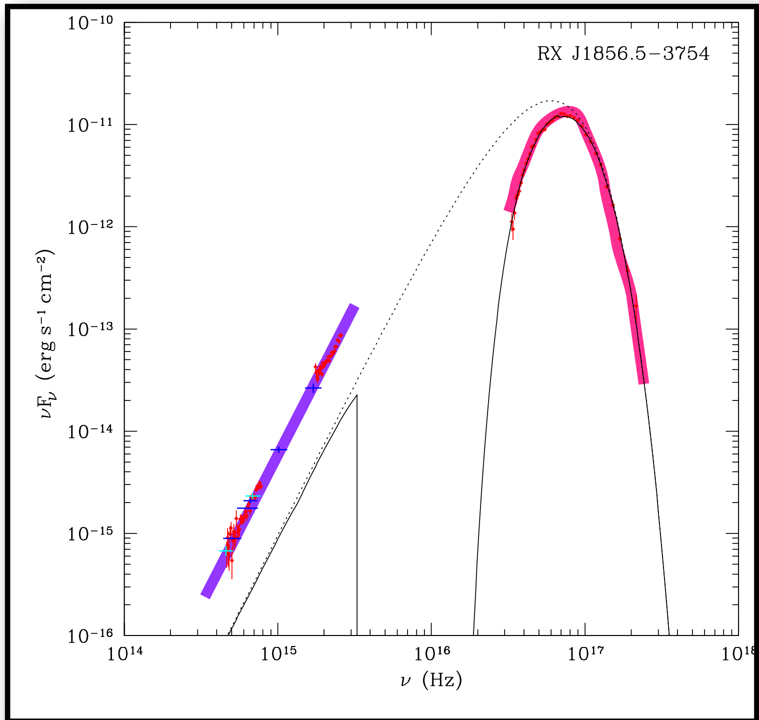

X-ray timing: B=1-3 x 10^13 G!
Young & Energetic
Magnetars
Young & Quiet
Old & Dead
new
now all INS with confirmed P
Overall Caveat: assumes dipole, constant B
Age
Magnetic Field
Death Line
Period Derivative (s s^-1)
Period (s)
0.1
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^4 yr
10^14 G
10^6 yr
10^13 G
10^12 G
10^10 yr
PSR
Magnetar
INS
RASS PSR
d<1 kpc, τ<5 Myr
K & vK et al.'05a,b; vK & K 2008; K & vK '09,'09b; K & vK '11

Is Emission Thermal?

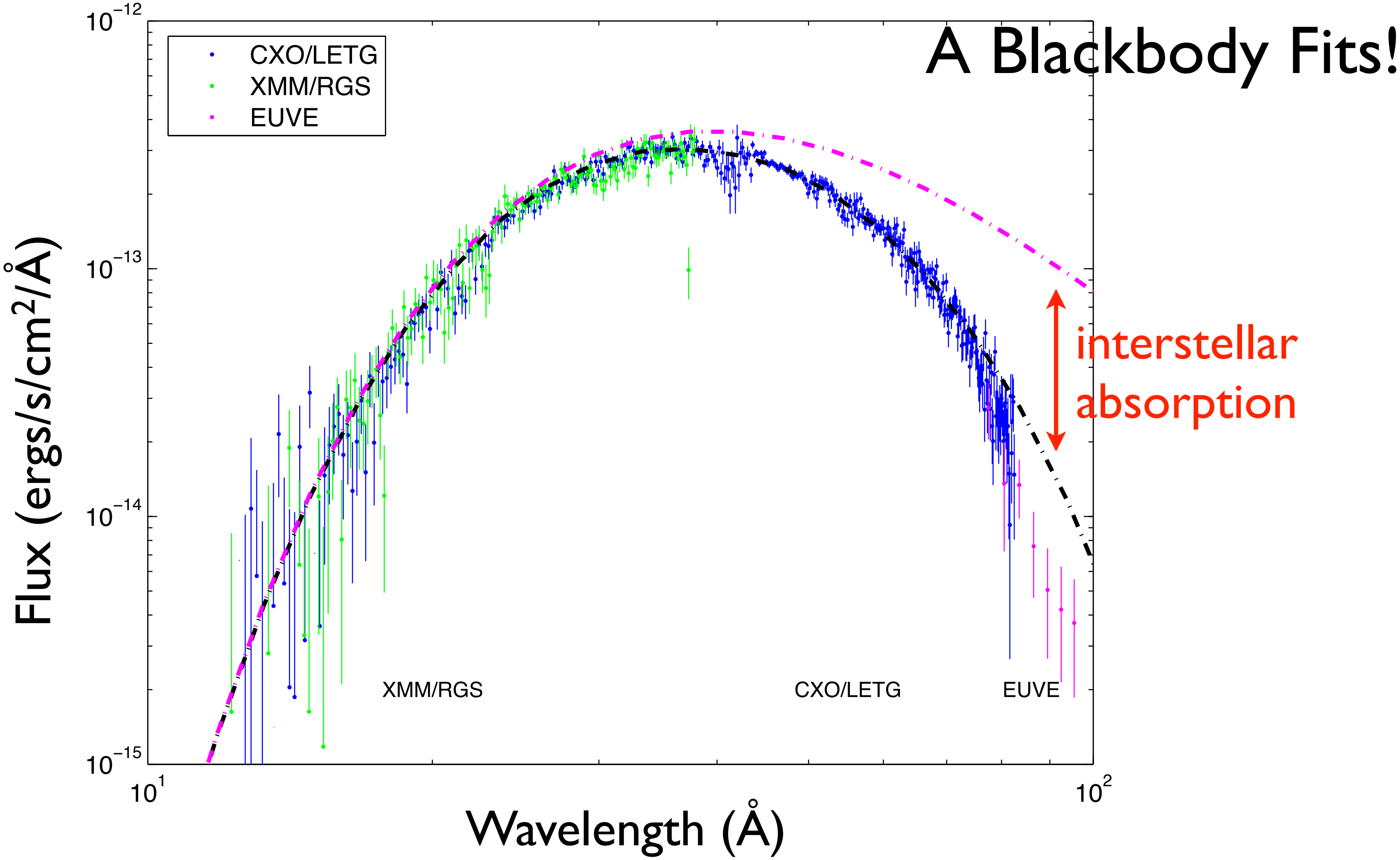
- Compare:
  - X-ray luminosity $L_X=4\pi d^2 F_X$
  - Spin-down luminosity $\dot{E}=d(\frac{1}{2}I\Omega^2)/dt$

- Radio pulsars:
  - $L_X \ll \dot{E}$
  - Much non-thermal emission
- INS
  - $L_X/\dot{E} \sim (10^{32}/10^{30}) \sim 100$
  - Little non-thermal emission





RX J1856: Optical to X-rays



(Drake et al. '02; Pons et al. '02; Burwitz et al. '03; Kaplan et al. 2002, 2003, 2003b)

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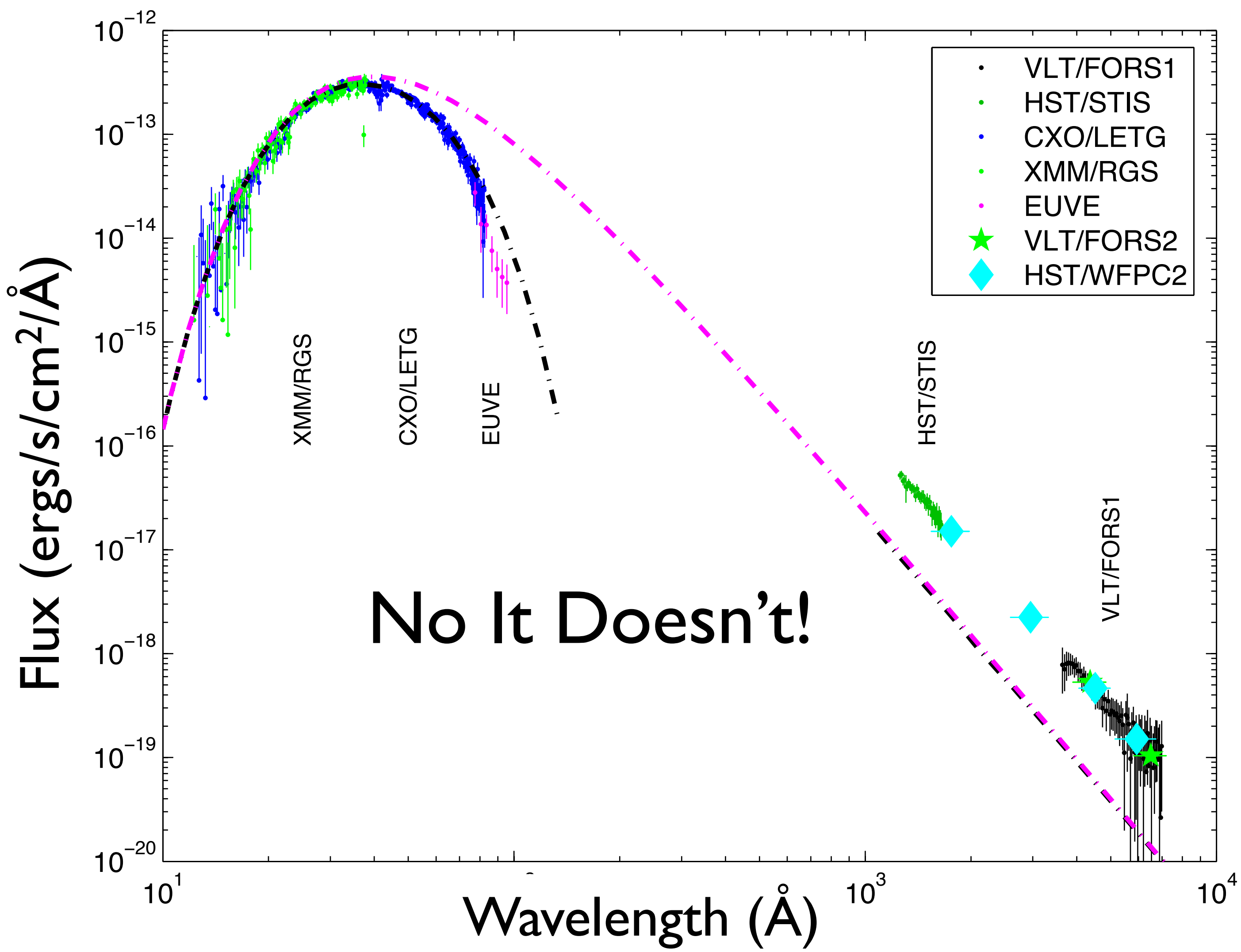


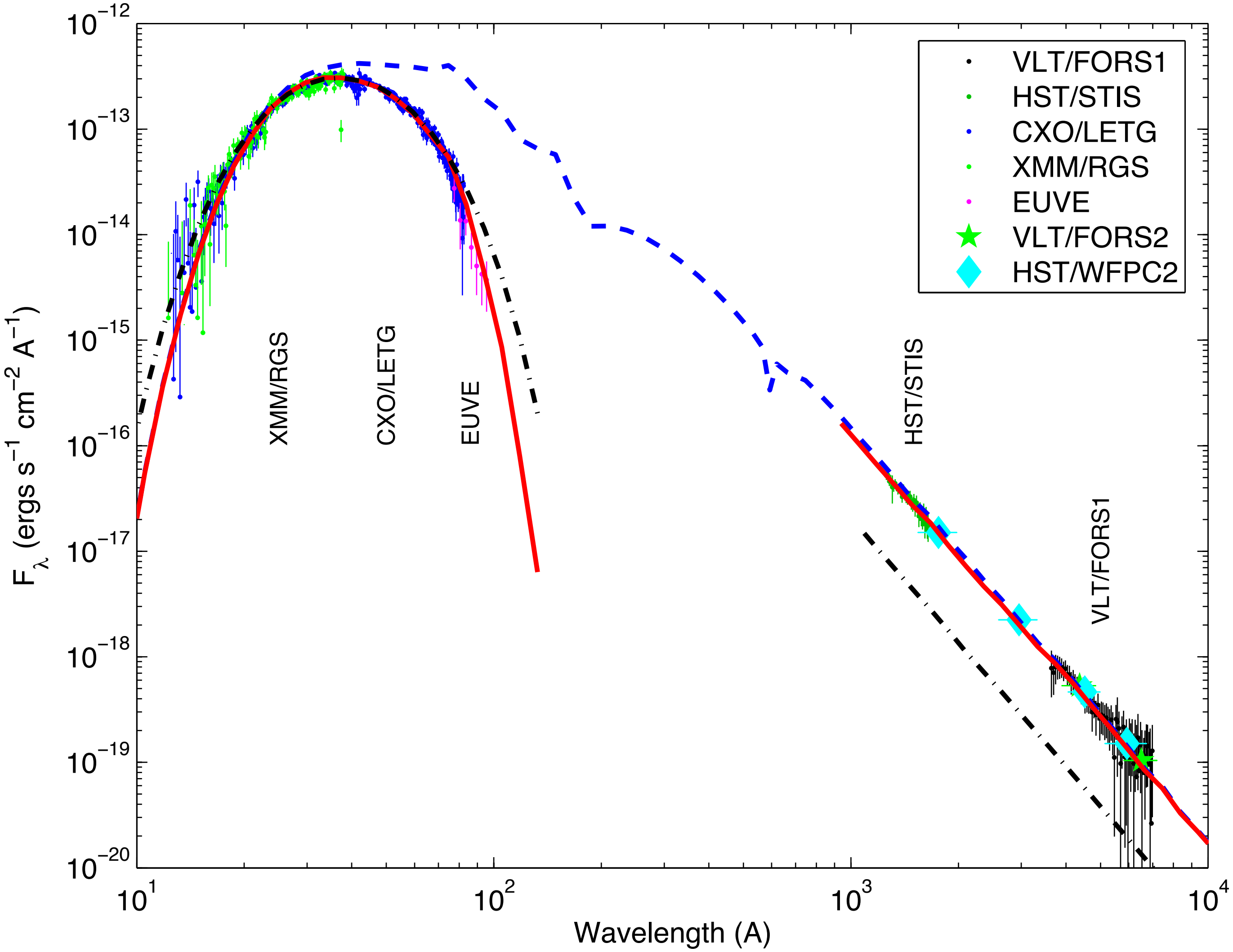
(Drake et al. '02; Pons et al. '02; Burwitz et al. '03; Kaplan et al. 2002, 2003, 2003b)

Puzzles

- X-ray blackbody does not match O/UV
- O/UV not the same across objects (talk by Kamble)
- Spectra are not blackbodies (talk by Potekhin)
- Magnetic field is high: standard atmosphere models not valid, might decay (talk by Popov)
- Hα nebula from RX J1856
- Variability

RX J1856.5-3754

a more realistic model



- Thin (~1 g/cm^2) layer of partially ionized H
- On top of condensed surface

(Ho, Kaplan et al. 2007; Ho 2007; also see Motch et al. '03, Zane et al. '04)

RX J1856.5-3754

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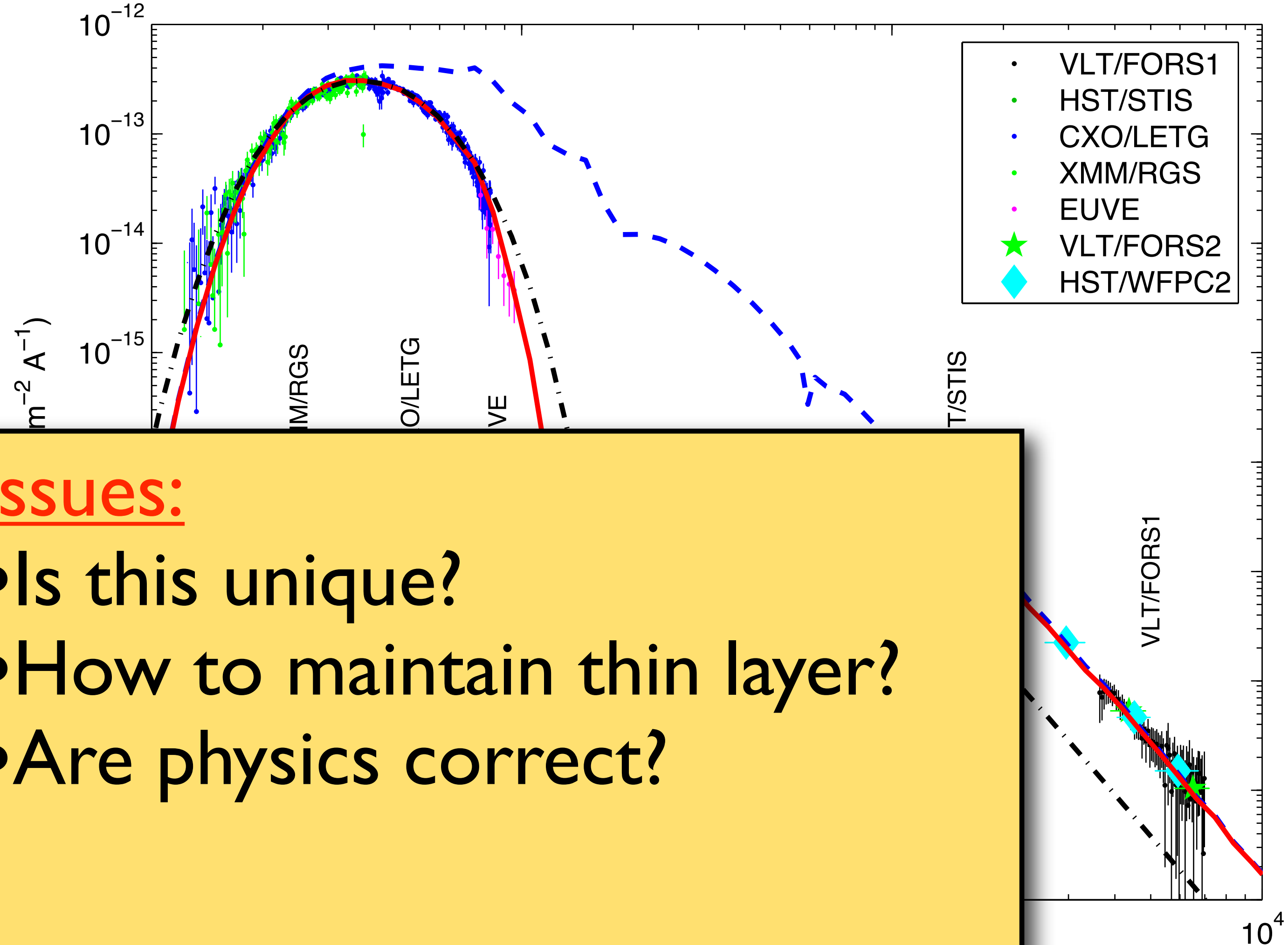

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<u>Issues:</u>
- Is this unique?
- How to maintain thin layer?
- Are physics correct?

Motch et al. '03, Zane et al. '04)

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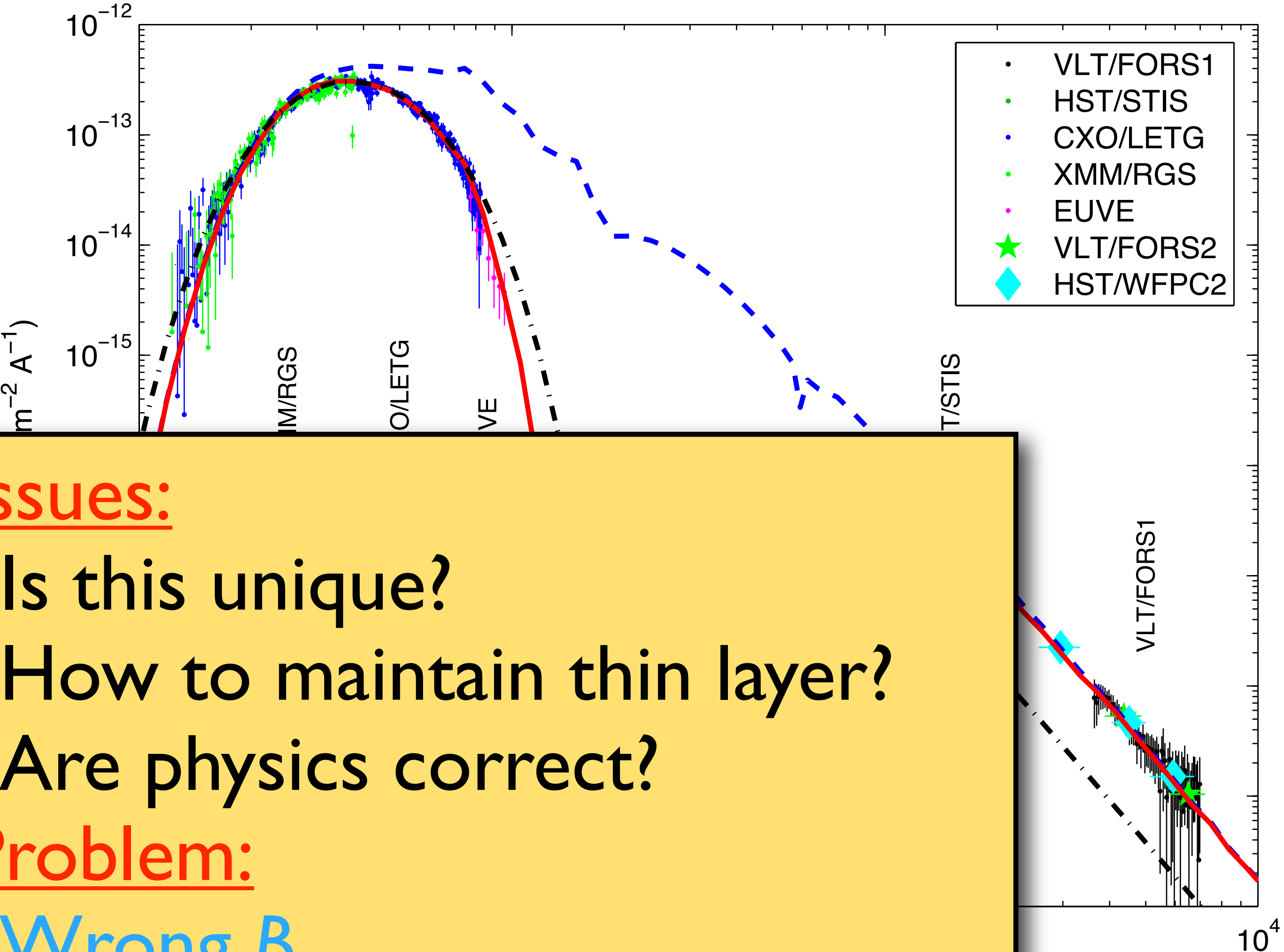

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- Wrong *B*

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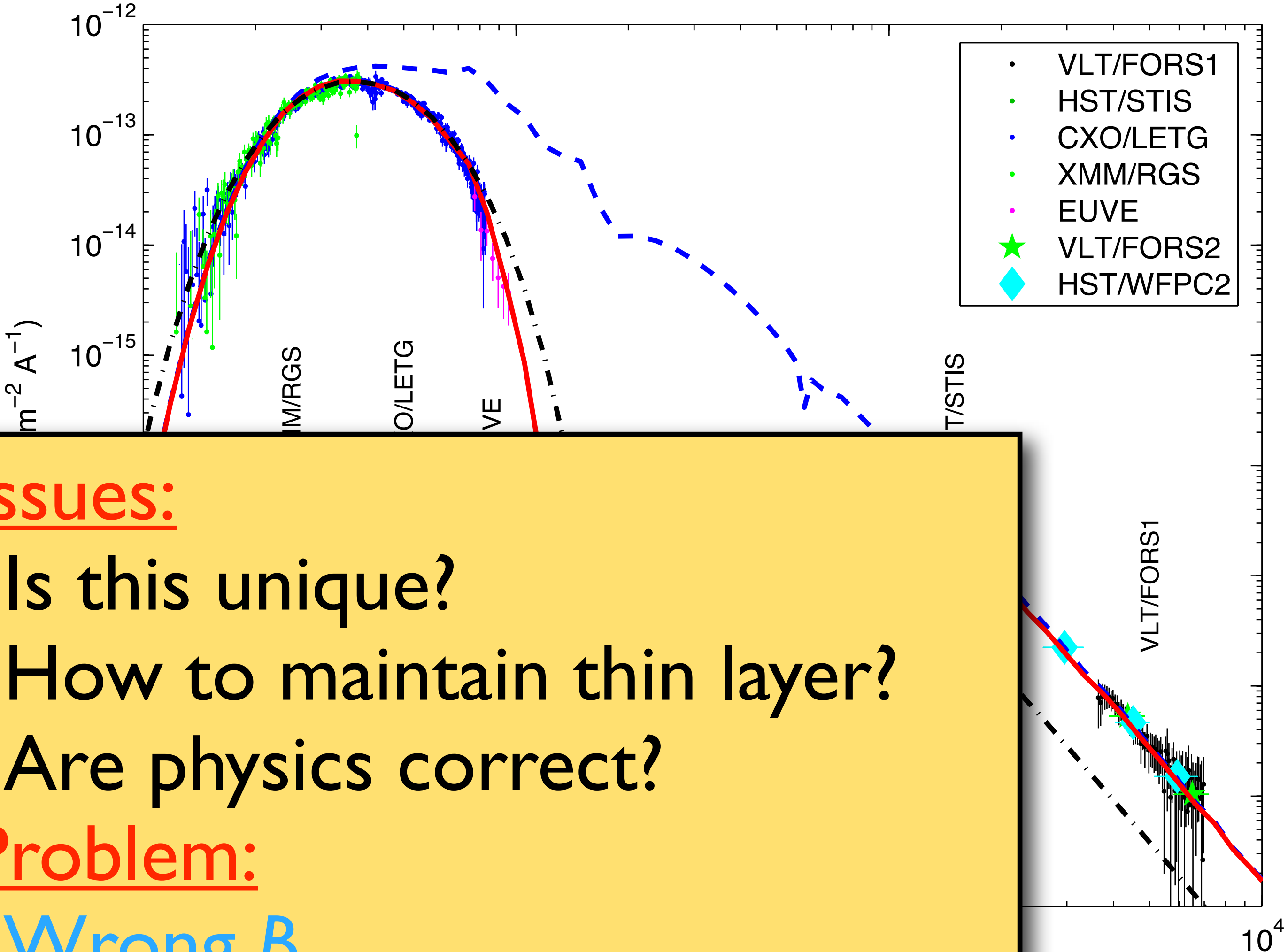

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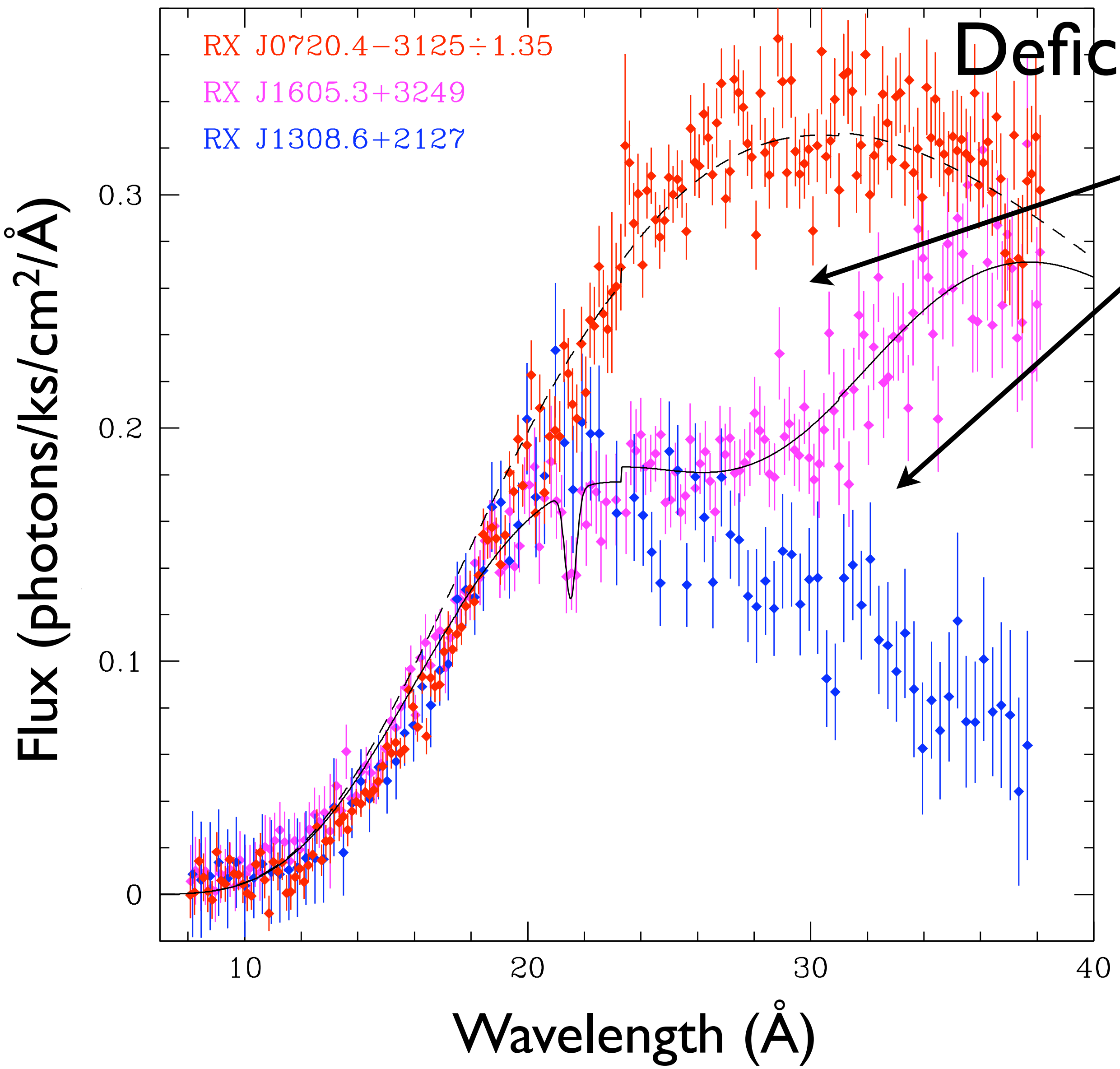
- See talks by Potekhin, Kamble

(Motch et al. '03, Zane et al. '04)

Spectral Absorption Features

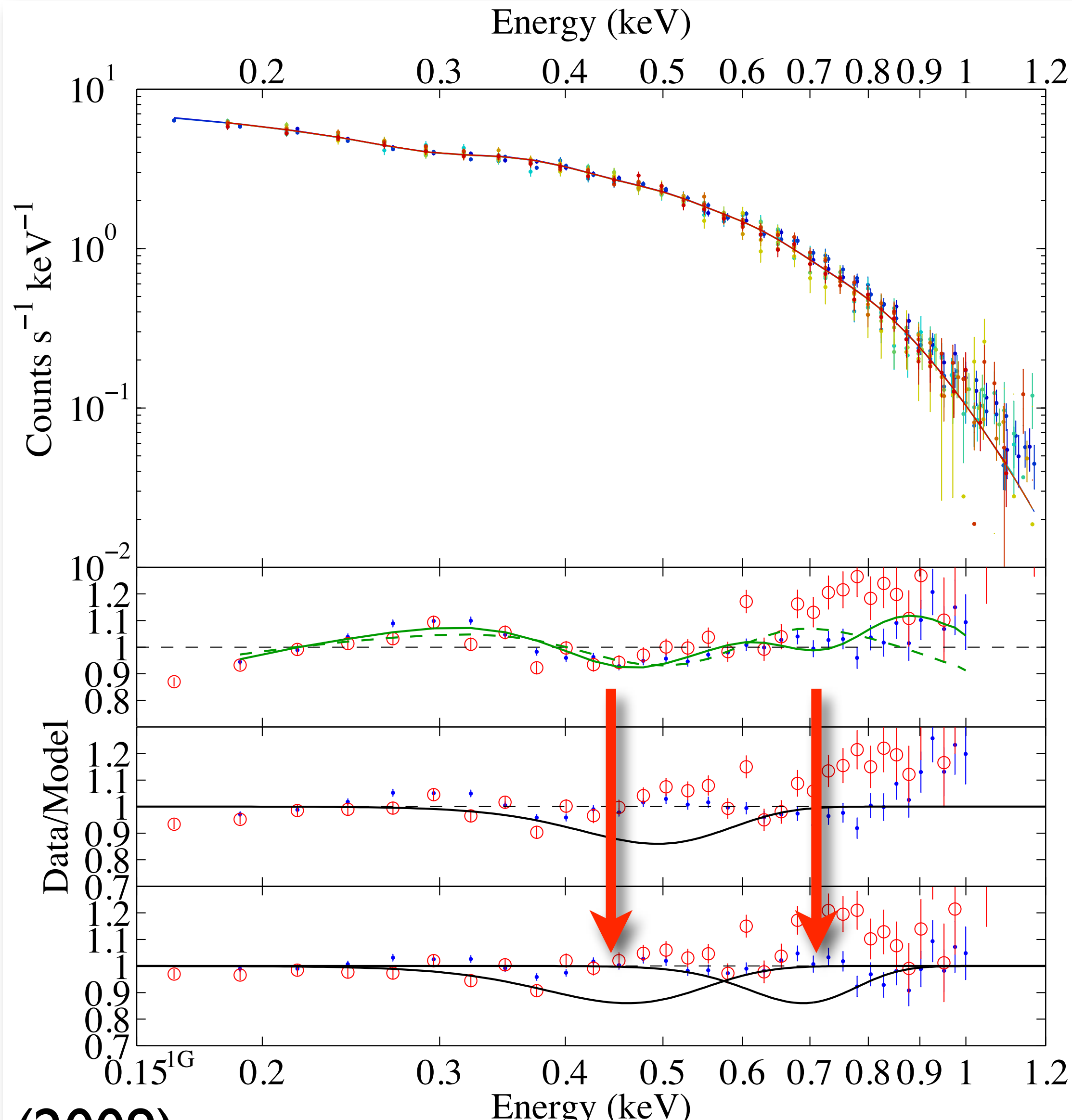


Deficits=X-ray absorption

Haberl et al. (2003, 2004)
van Kerkwijk et al. (2004)
Zane et al. (2005)

Complex Absorption

- A number of objects:
  - absorption is complex, not a single line
  - multiple lines?
  - harmonic relation between line energies (1:2, 2:3, ?)



Haberl (2007), Kaplan & van Kerkwijk (2009)

What Causes Features?

- Cyclotron (proton)
- Neutral hydrogen
- Molecular H
- He (neutral, ionized, molecular,...)
- Other species
- See Haberl (2007)

Need to consider:

•vacuum resonance suppression (Ho & Lai 2003)

    •high *B*: absorption weaker

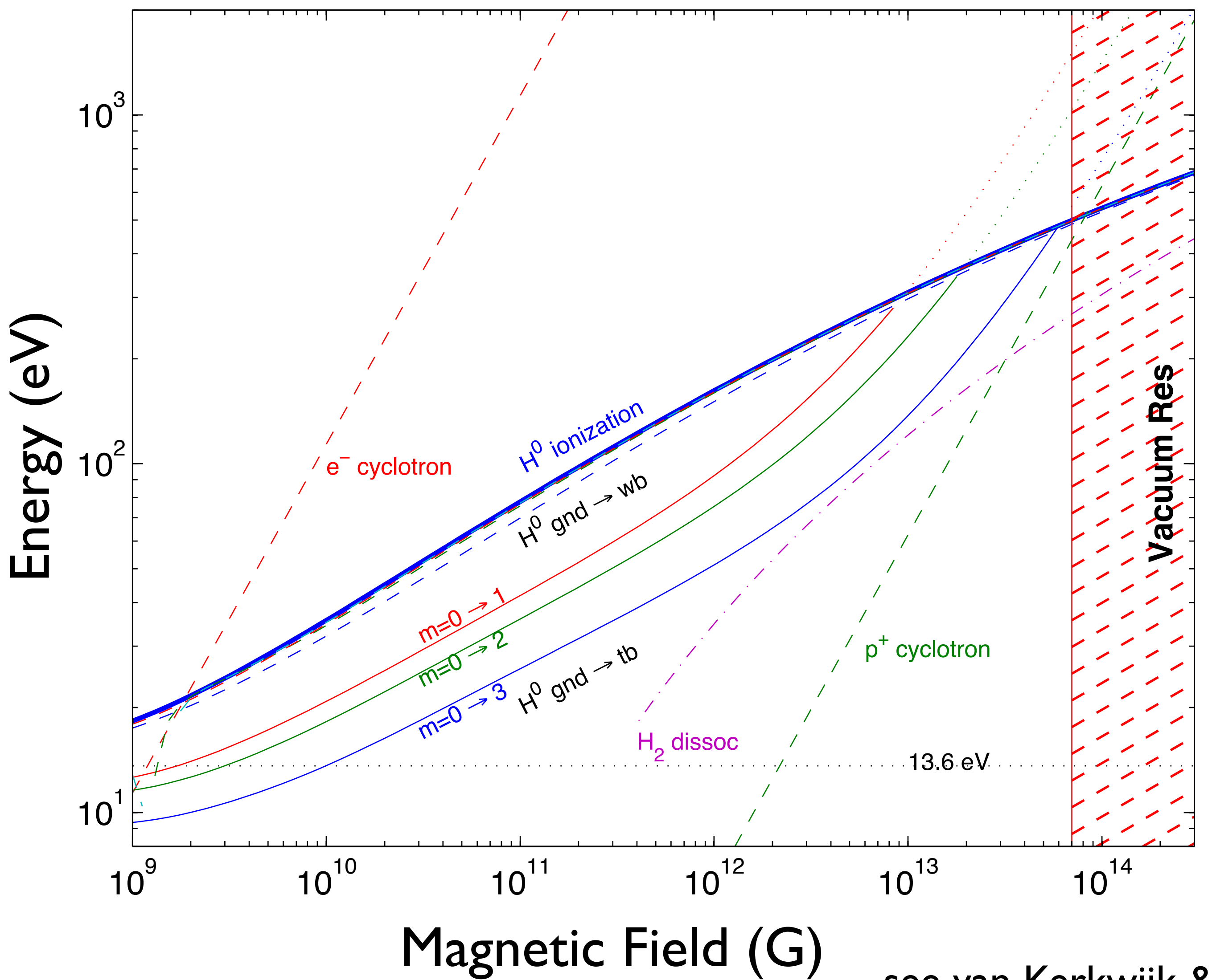
•role of condensation (Medin & Lai 2007)

    •high *B*/low T: solid surface

•Multiple lines in some sources

    •Cyclotron harmonics not possible (Potekhin; Suleimanov+ ’10)

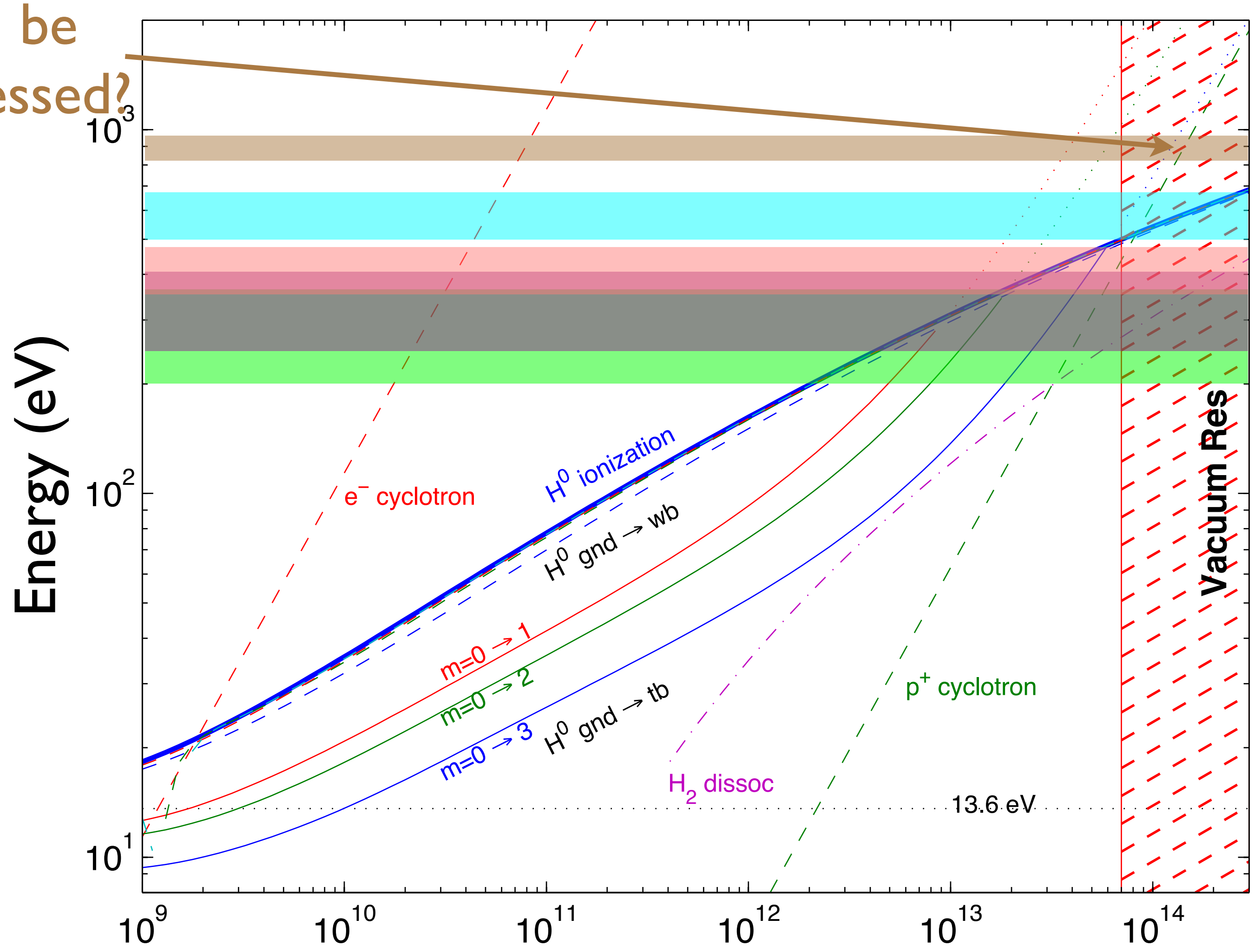
What Causes Features?



see van Kerkwijk & Kaplan (2007), K & vK '09

What Causes Features?

should be suppressed?



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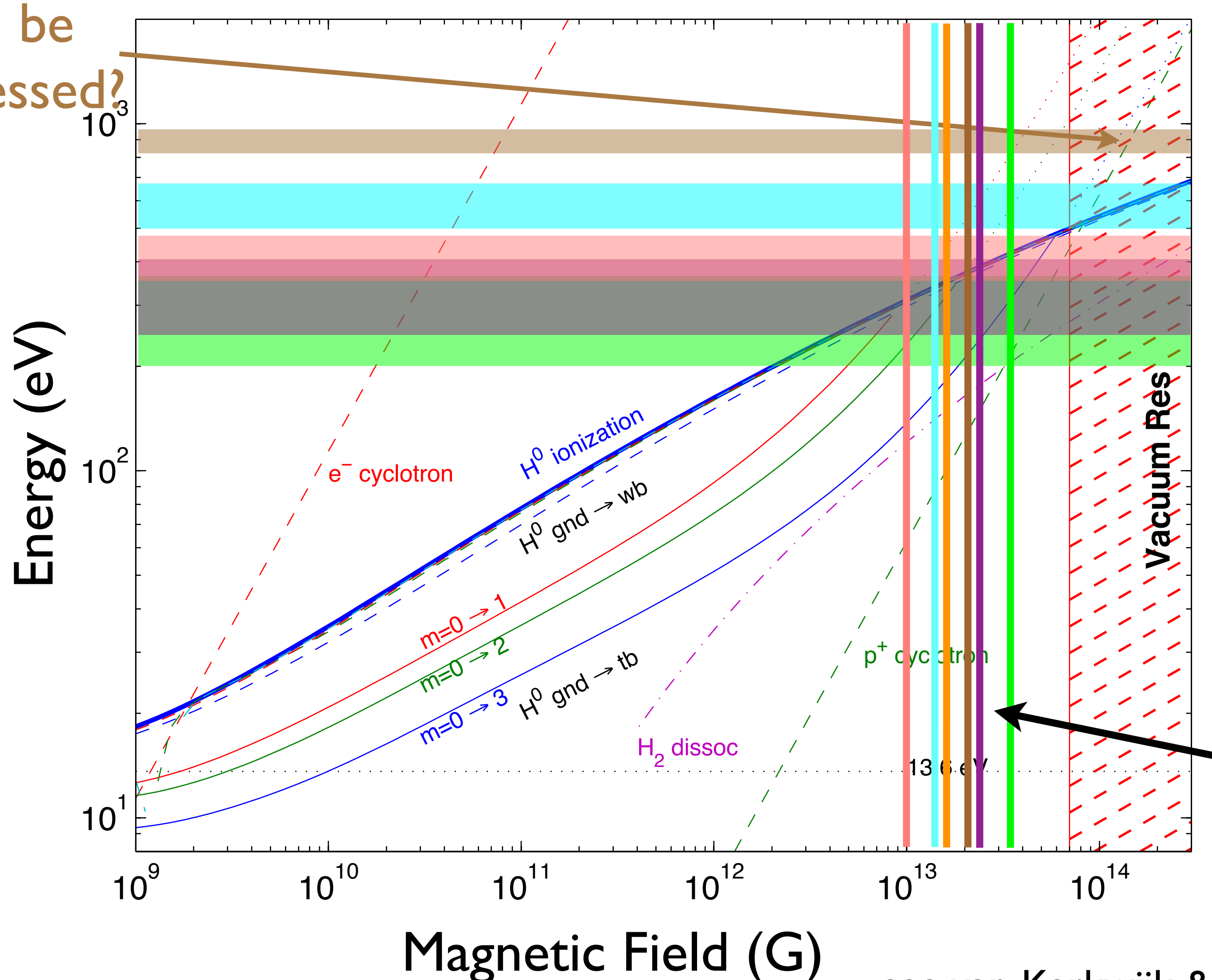

Timing results

see van Kerkwijk & Kaplan (2007), K & vK ‘09

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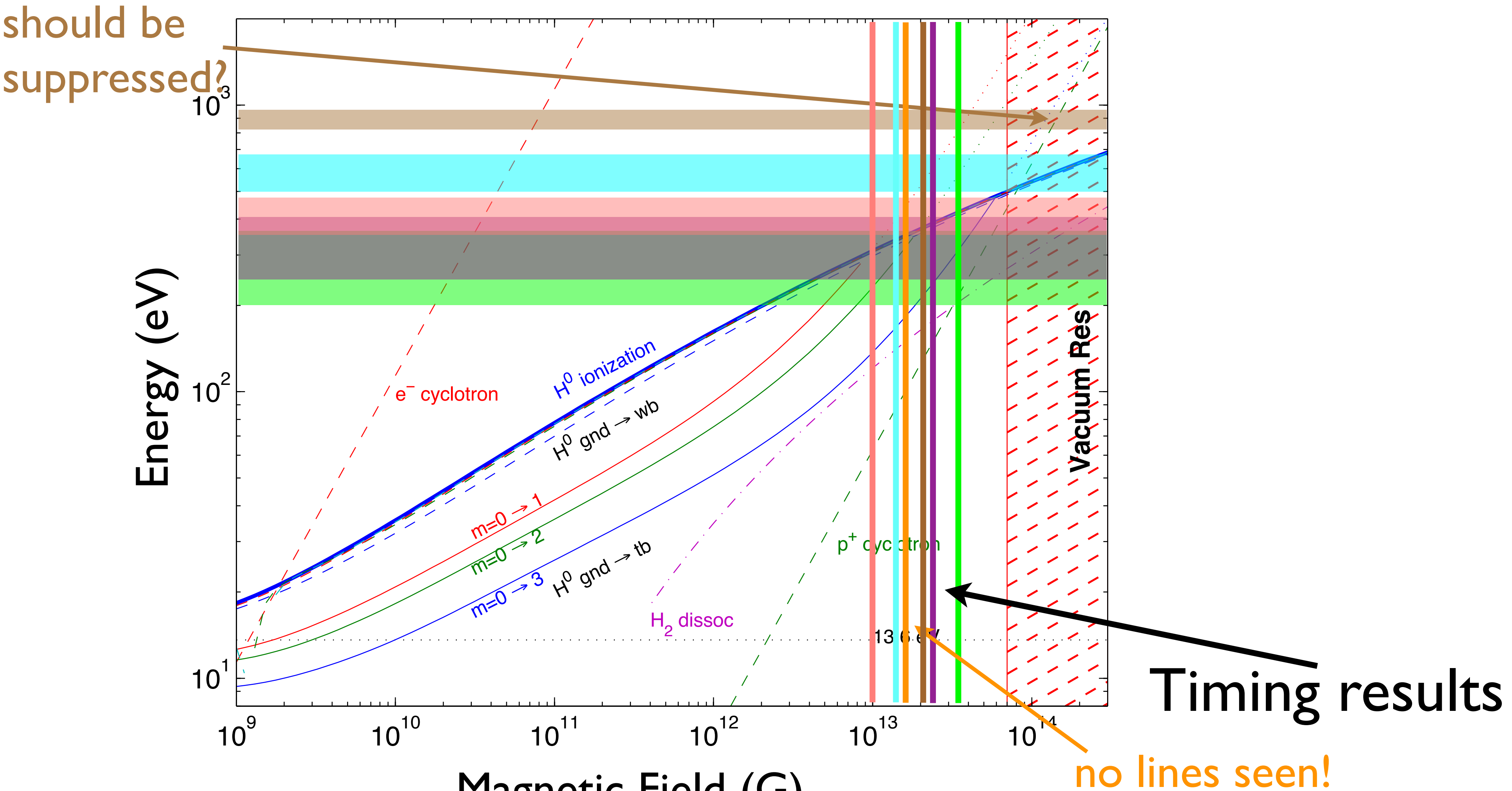

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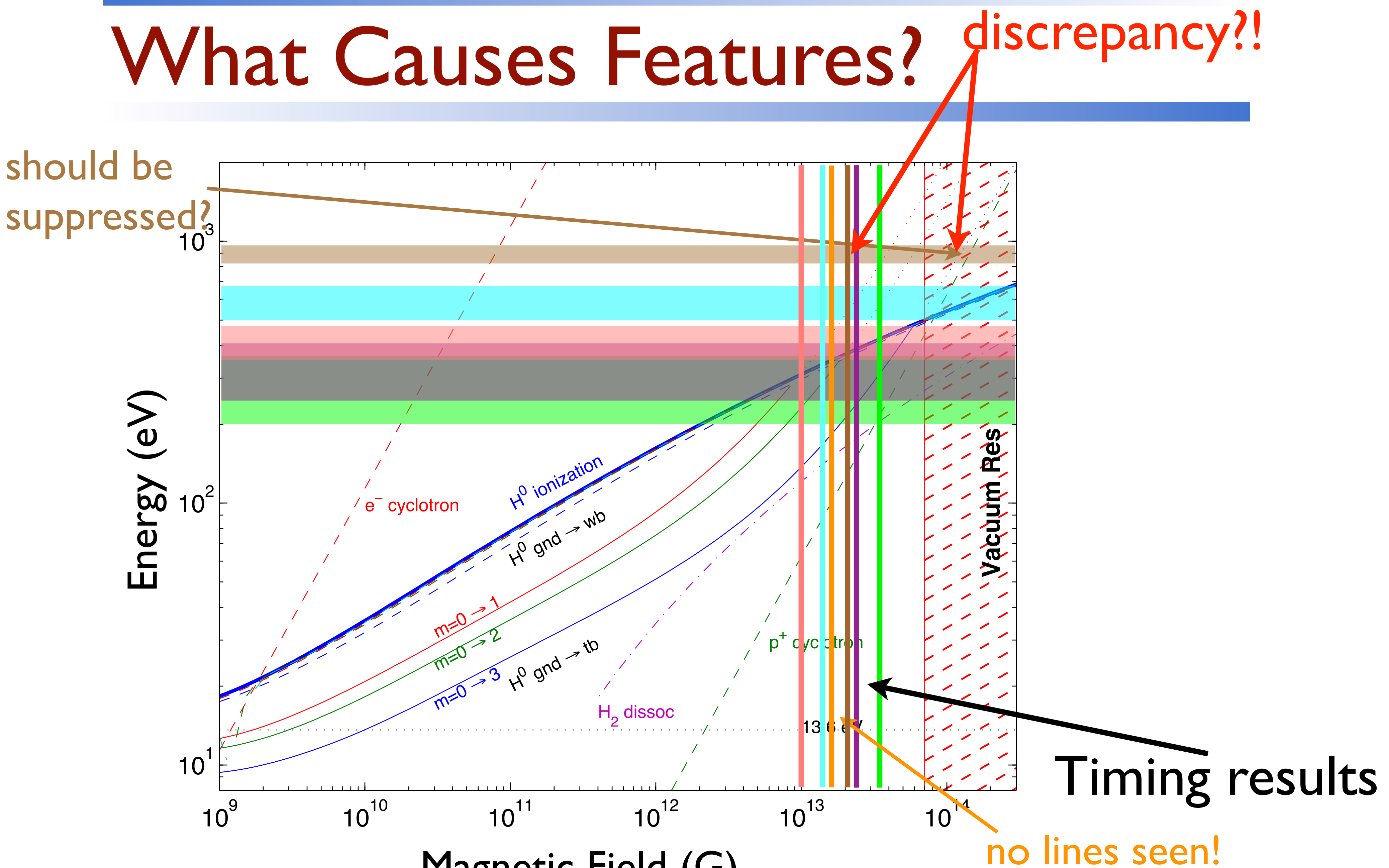

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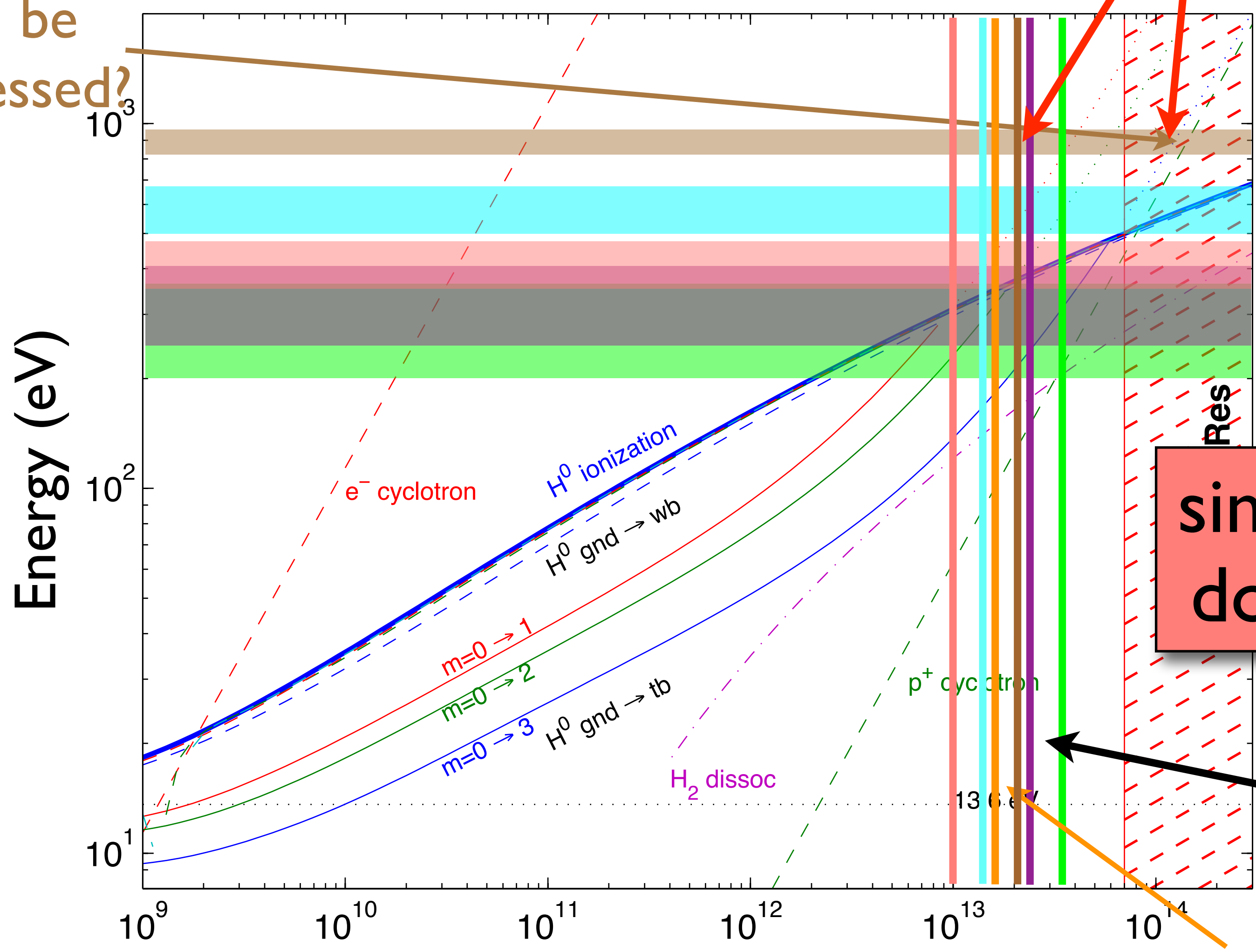
What Causes Features?

discrepancy?!

should be suppressed?



simple ordering does not work

Timing results

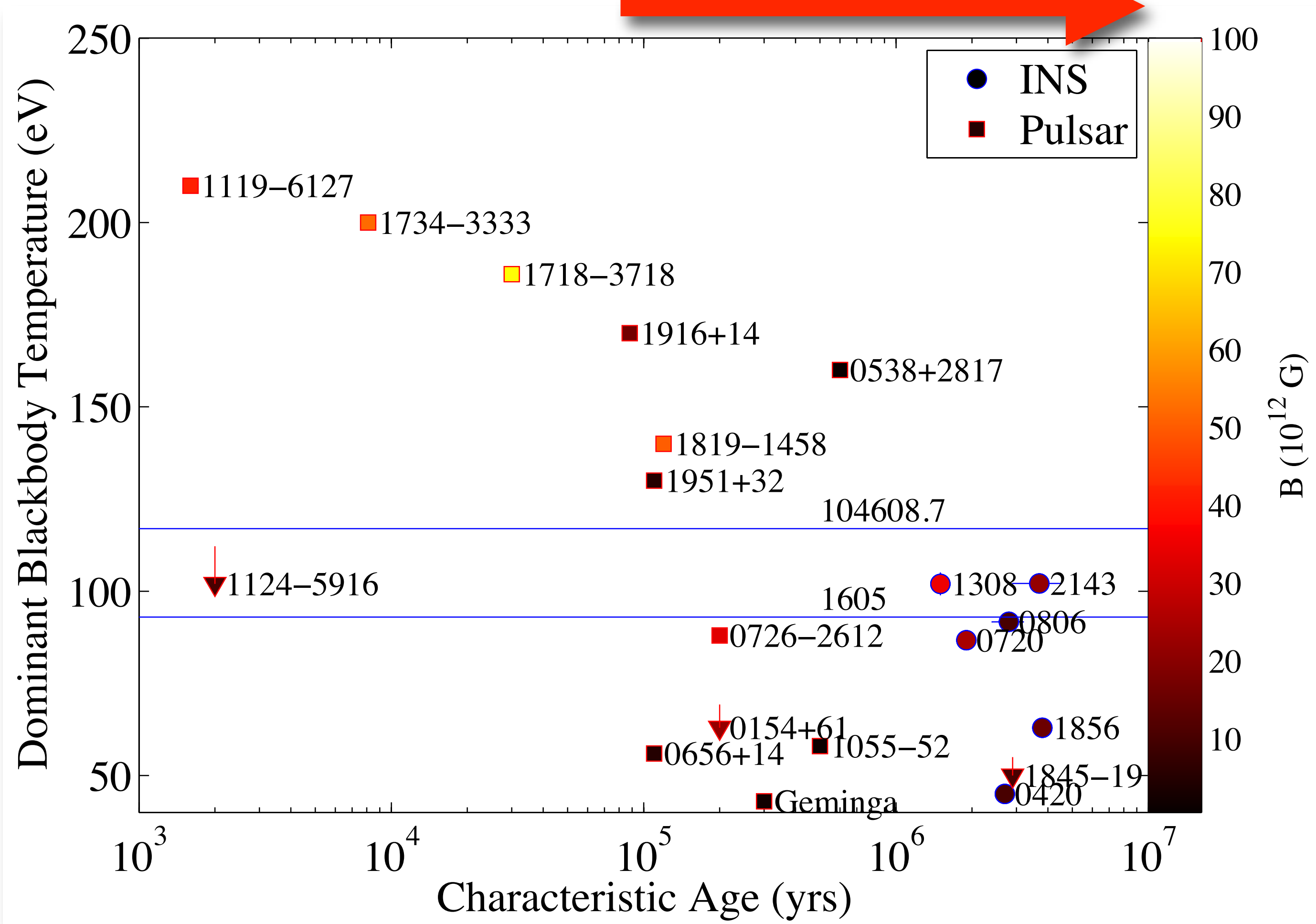
no lines seen!

see van Kerkwijk & Kaplan (2007), K & vK '09

This is *Not* A Cooling Curve

- Temperature represents at least *most* of surface, blackbody model
  - For > 1 Myr, most pulsars have polar cap and/or PL
- Systematic offset: τ(INS)~10*τ(PSR) for same *kT*
- What about composition? Radio?
- ISM "bias": cooler sources not visible

focus here



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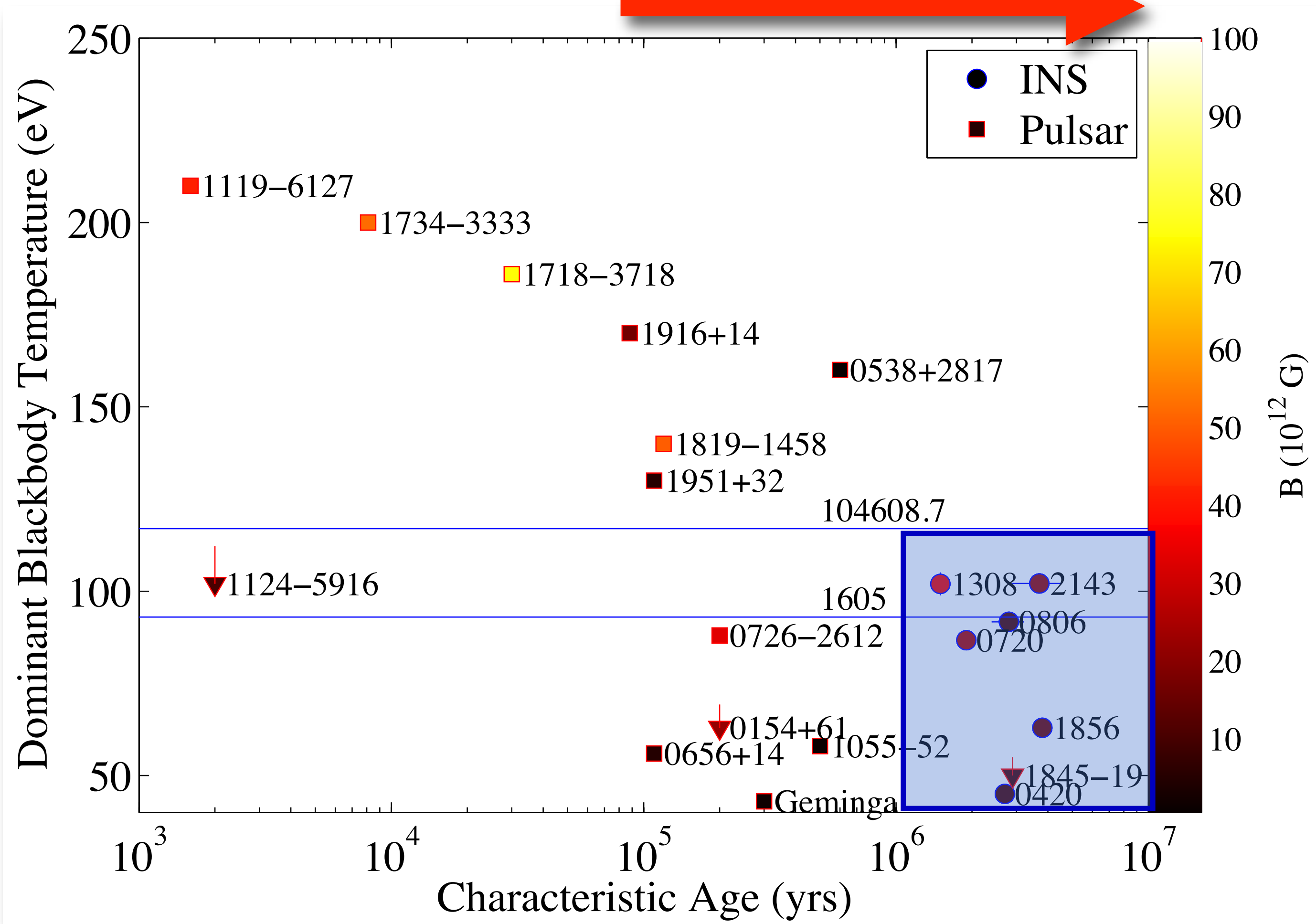

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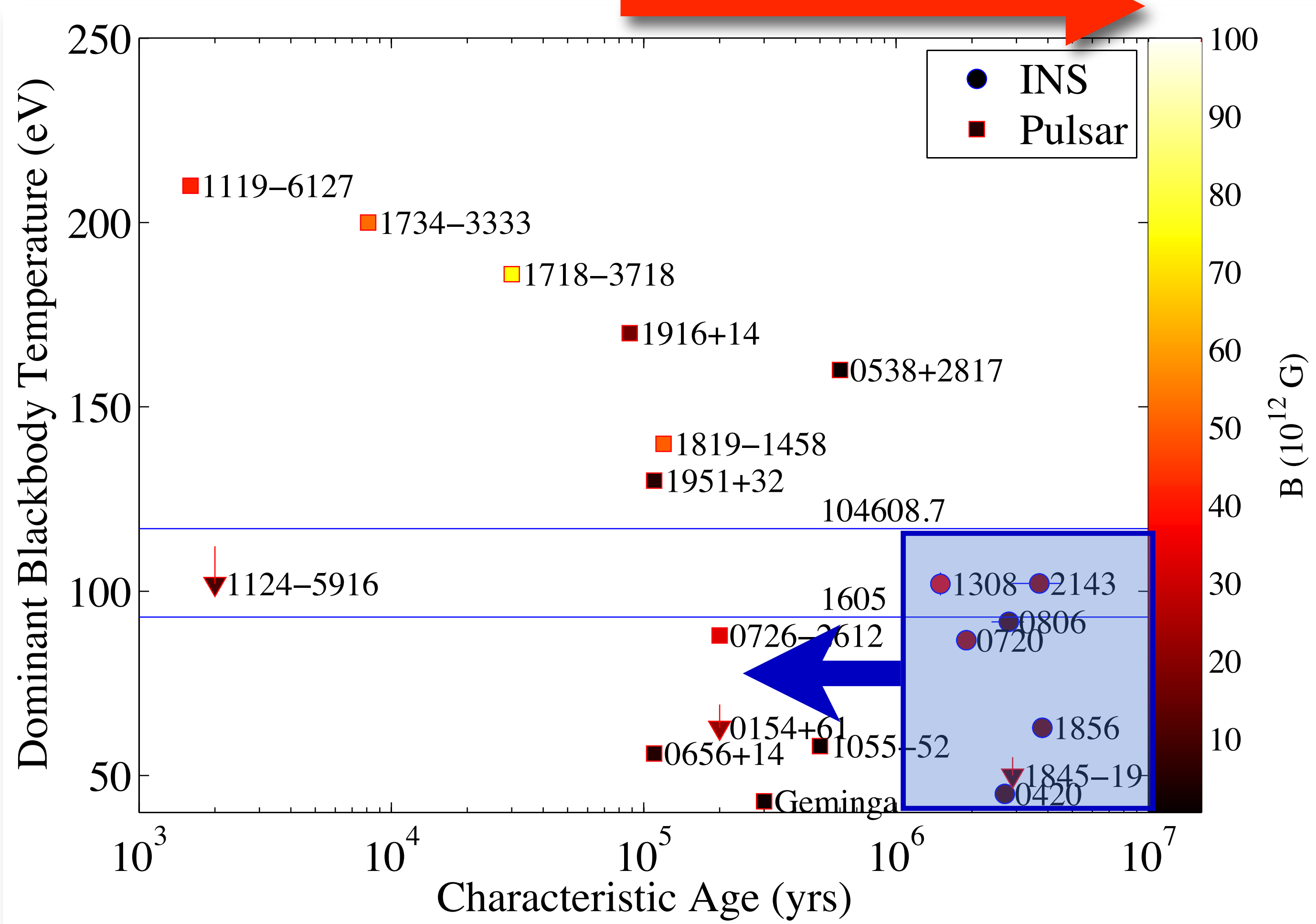

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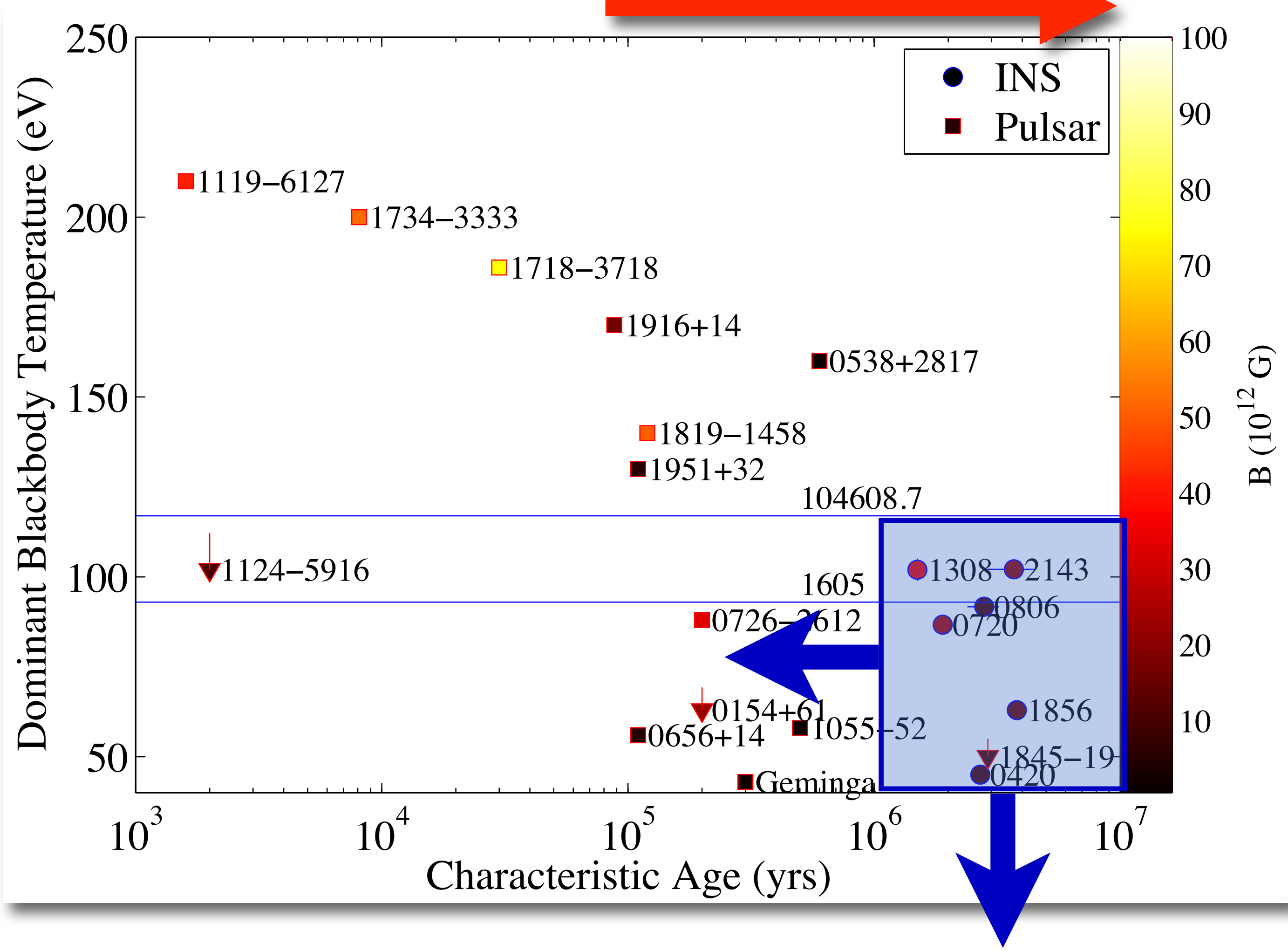

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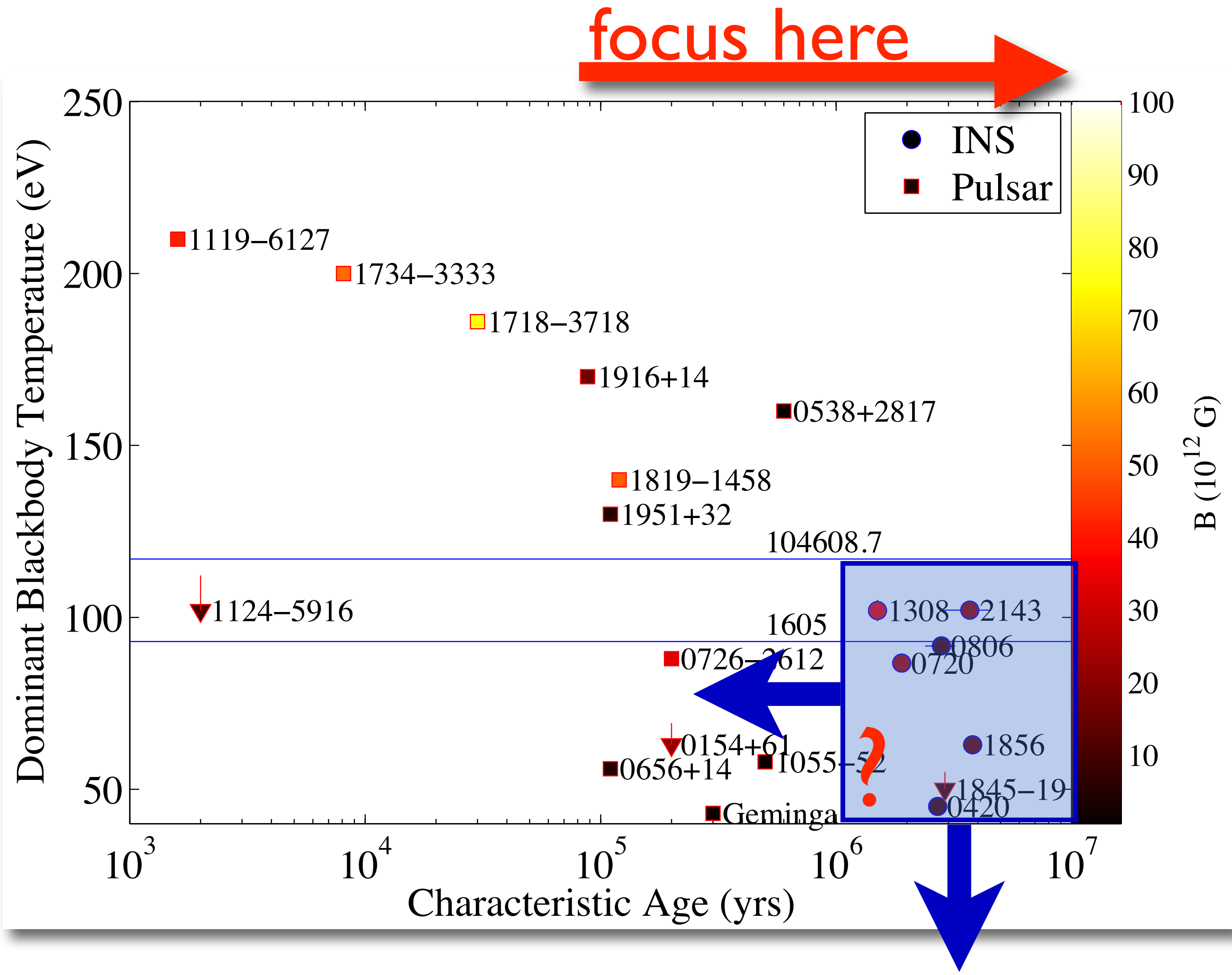

Also see Zhu et al. (2009, 2011), talk by Kaspi (that Canadian woman)

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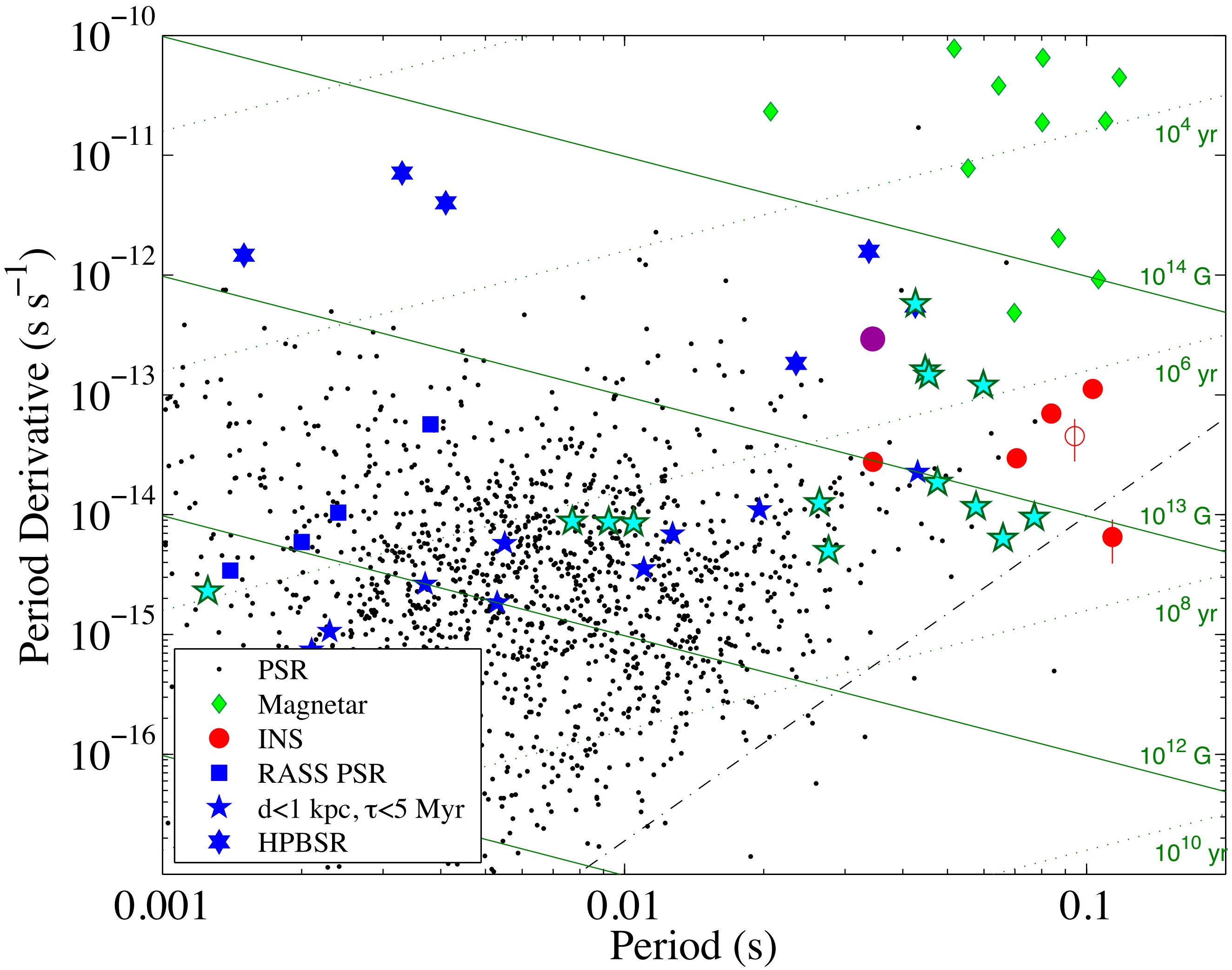

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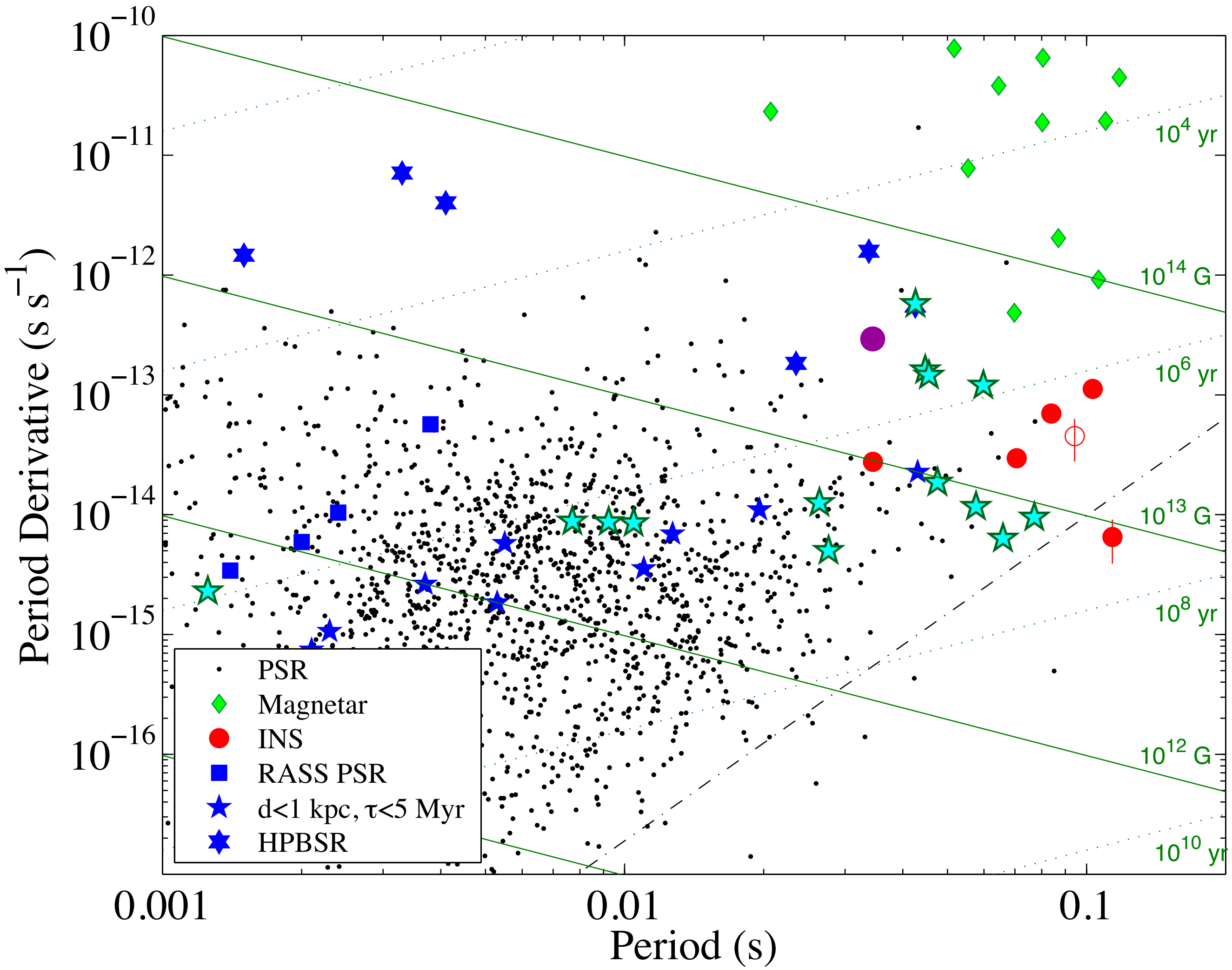

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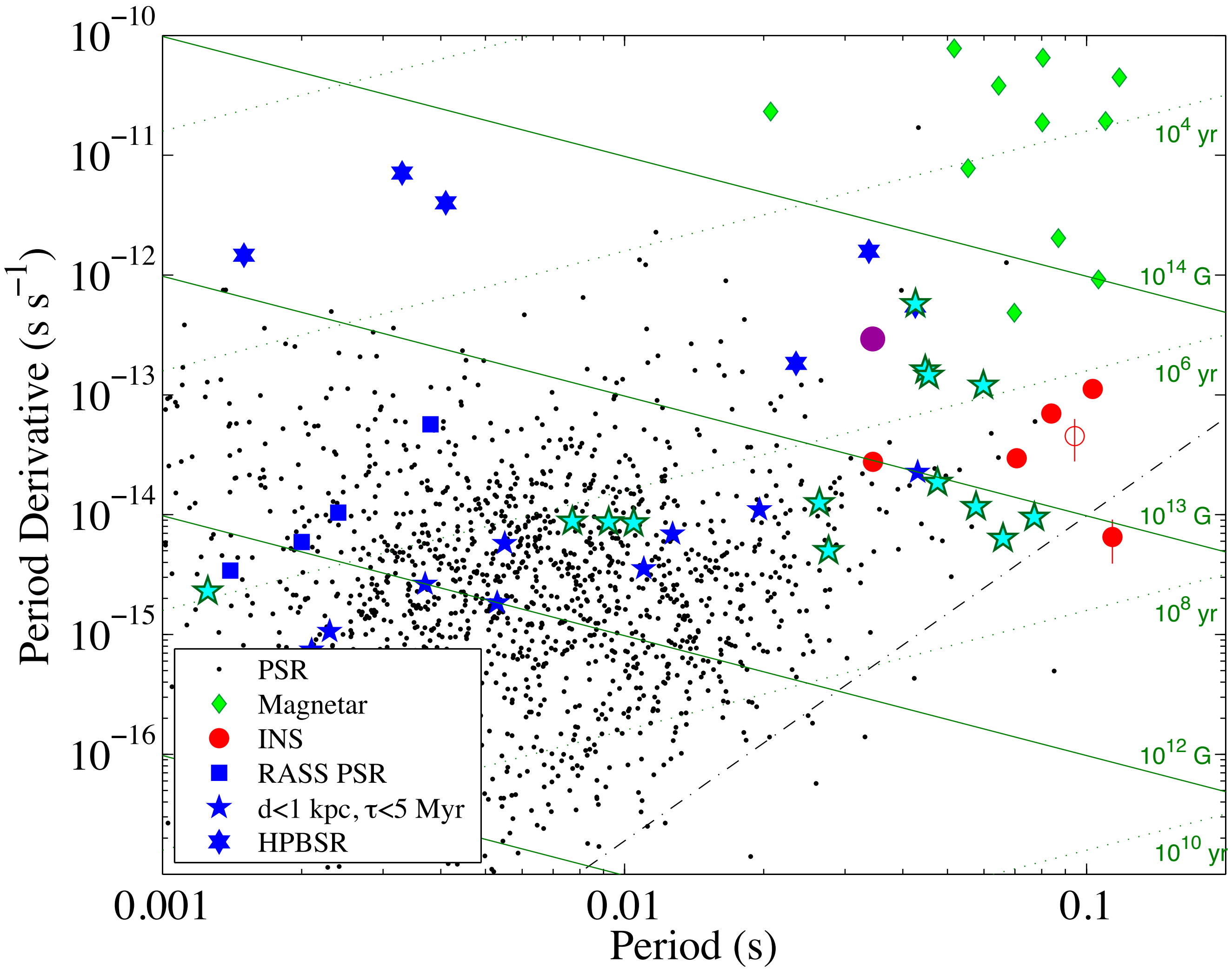

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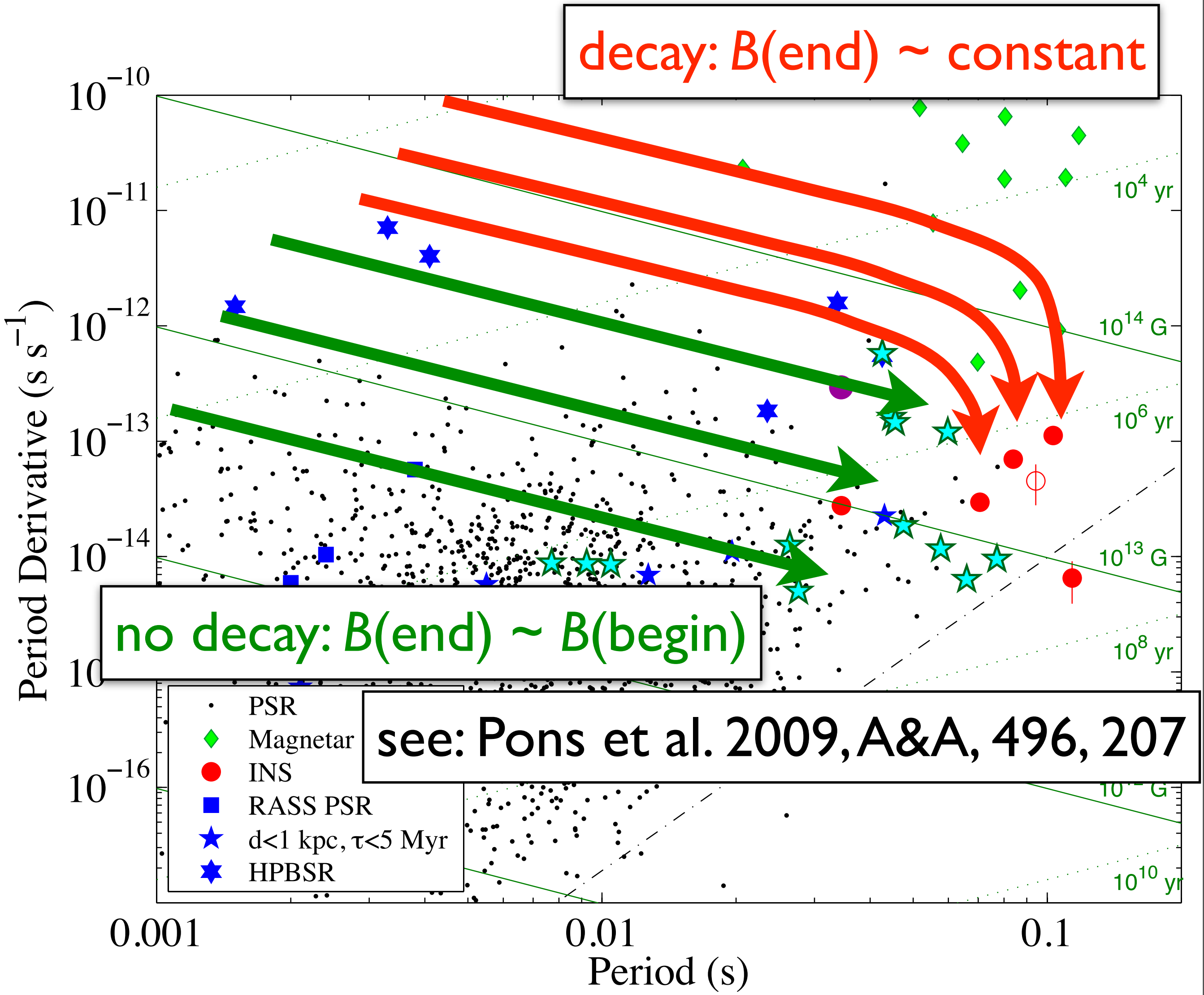

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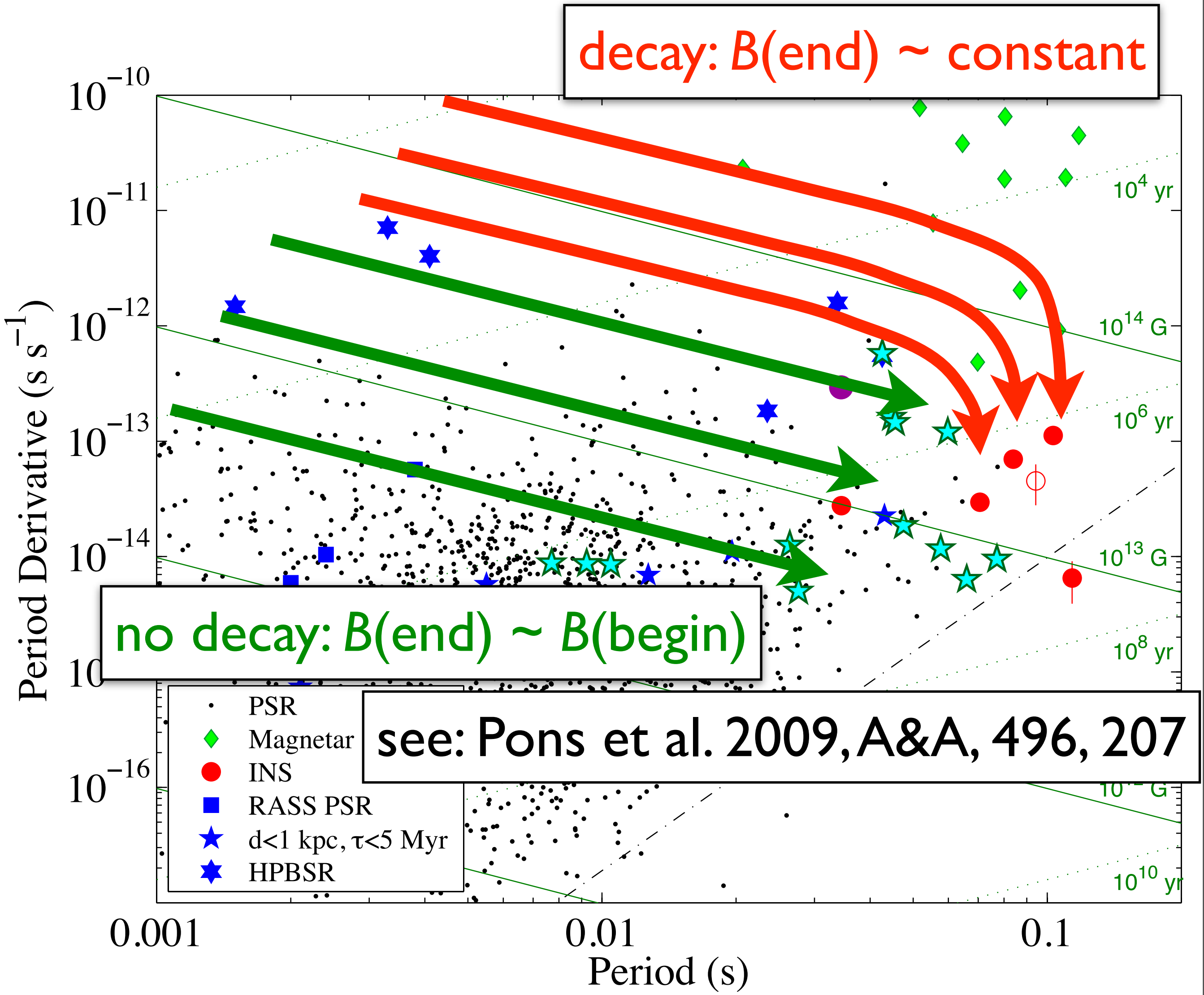

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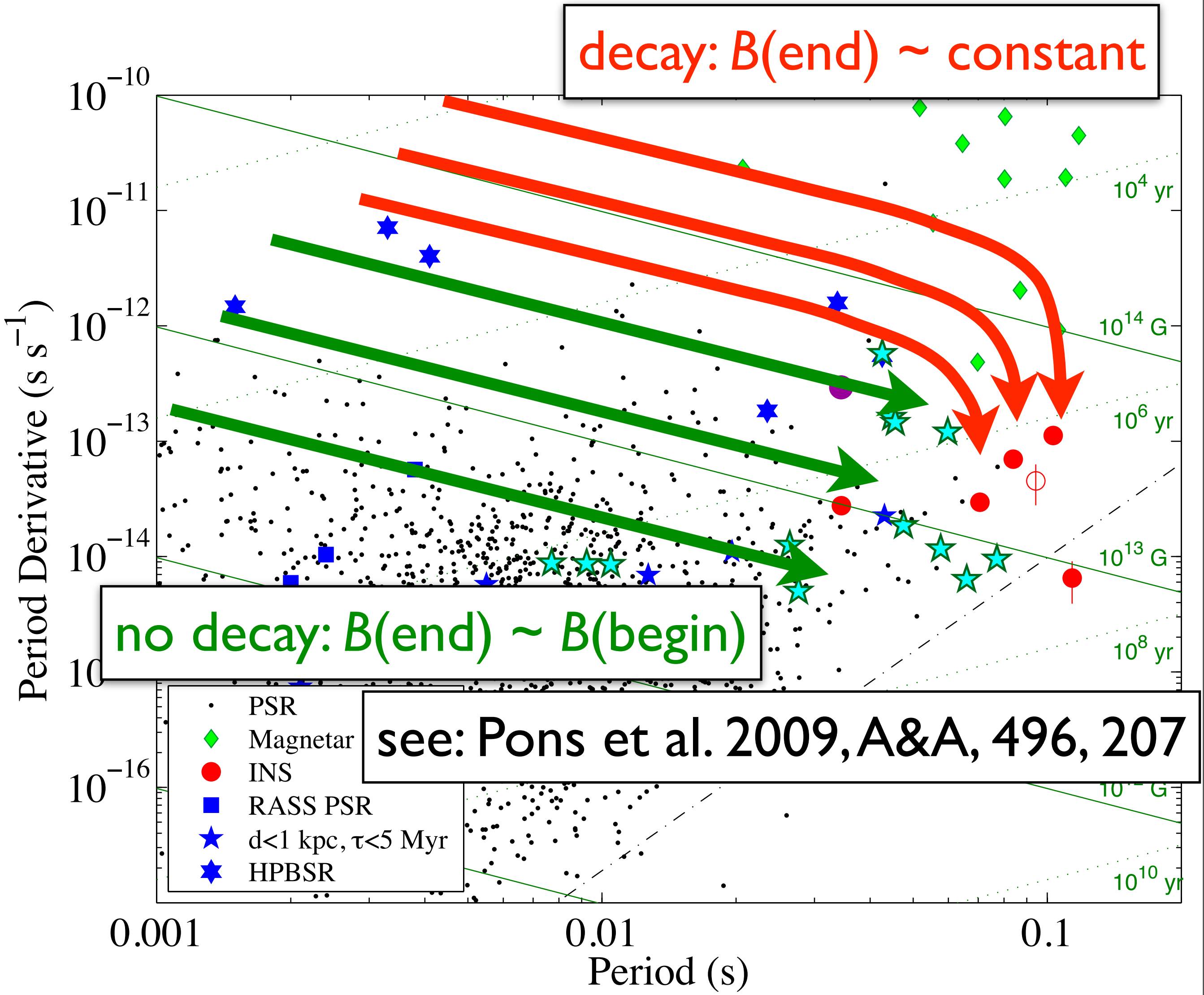

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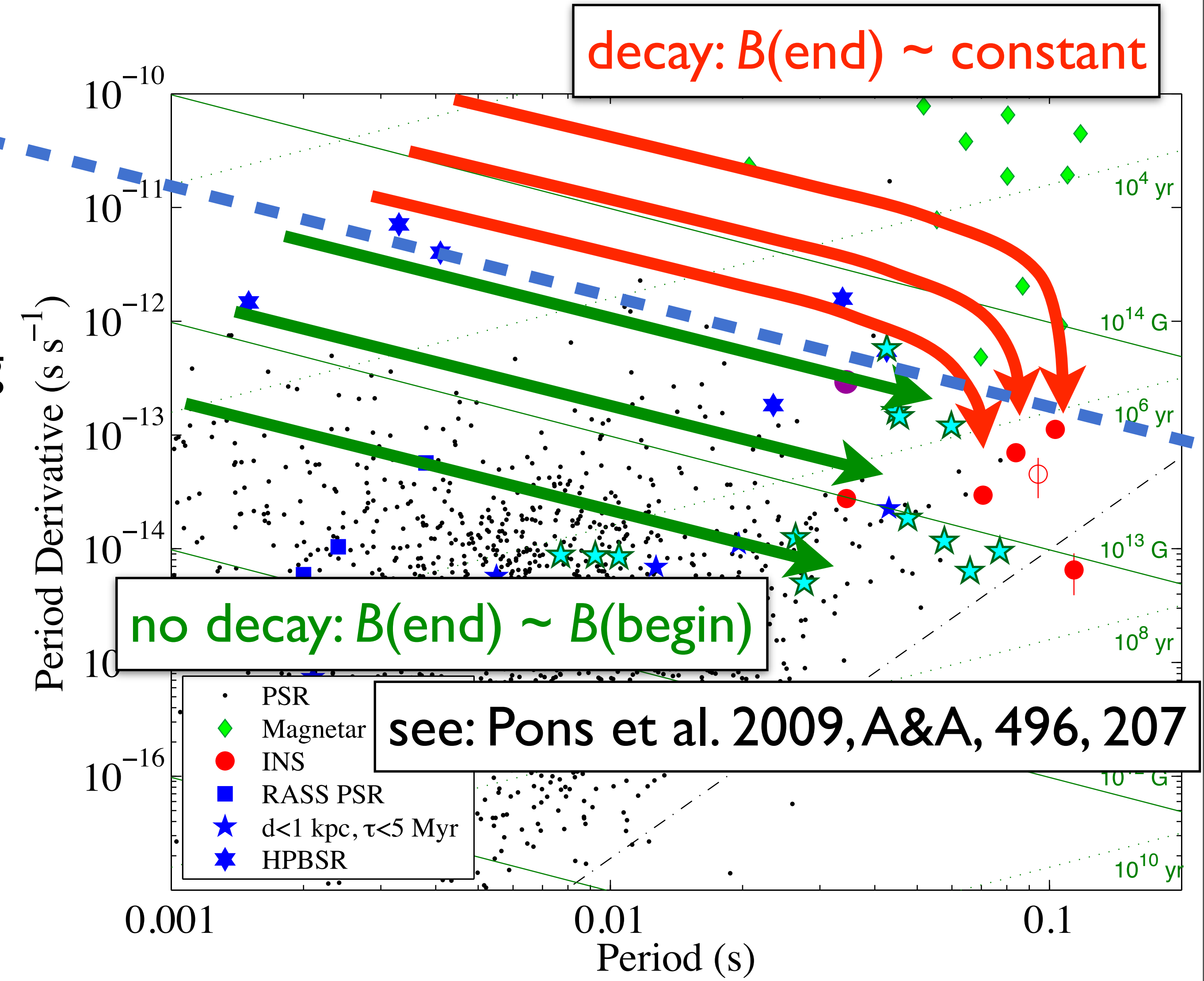

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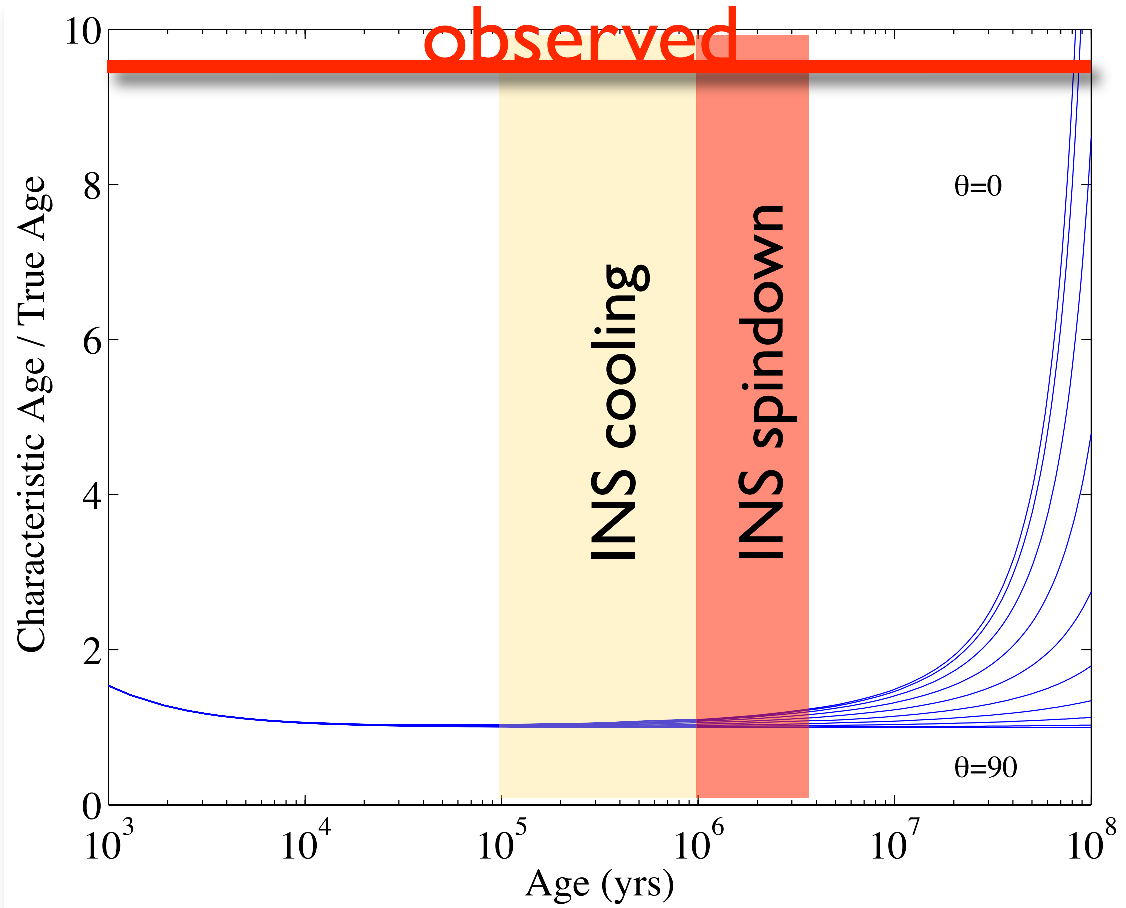

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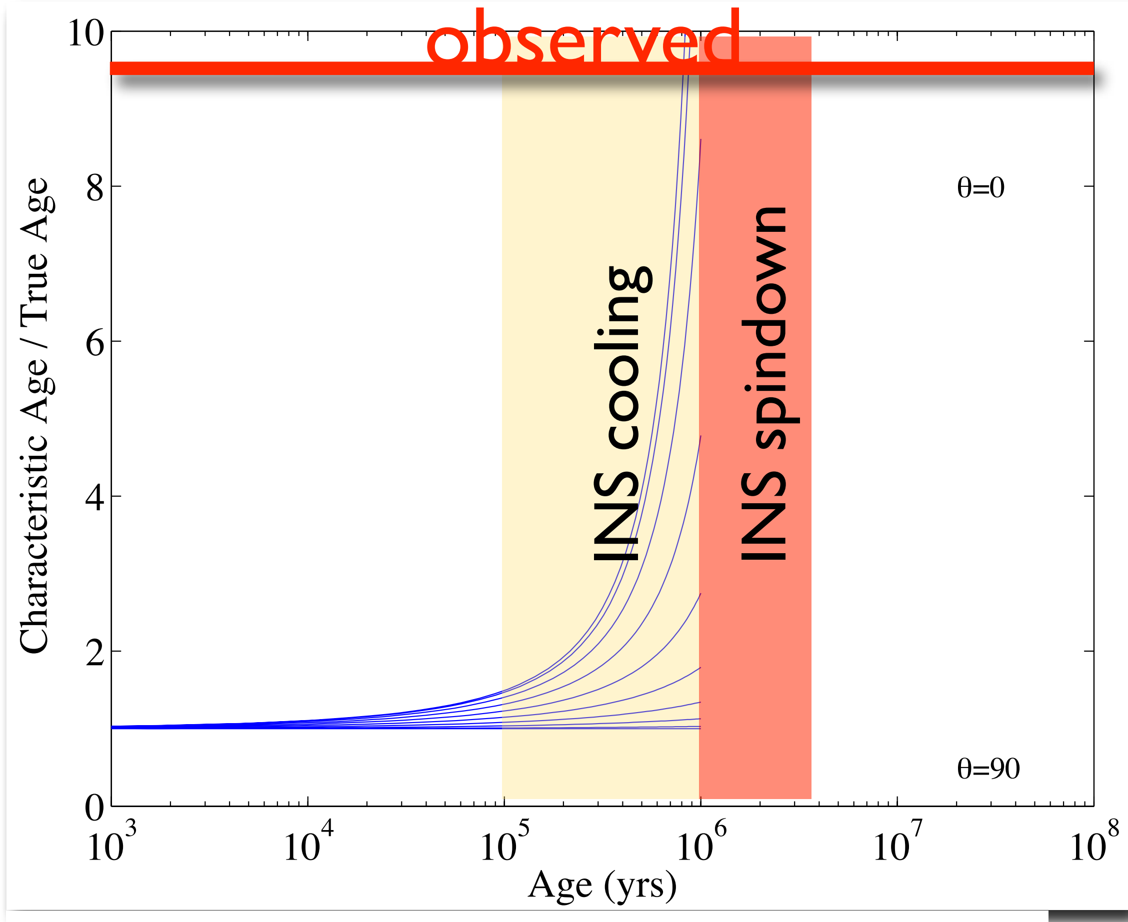

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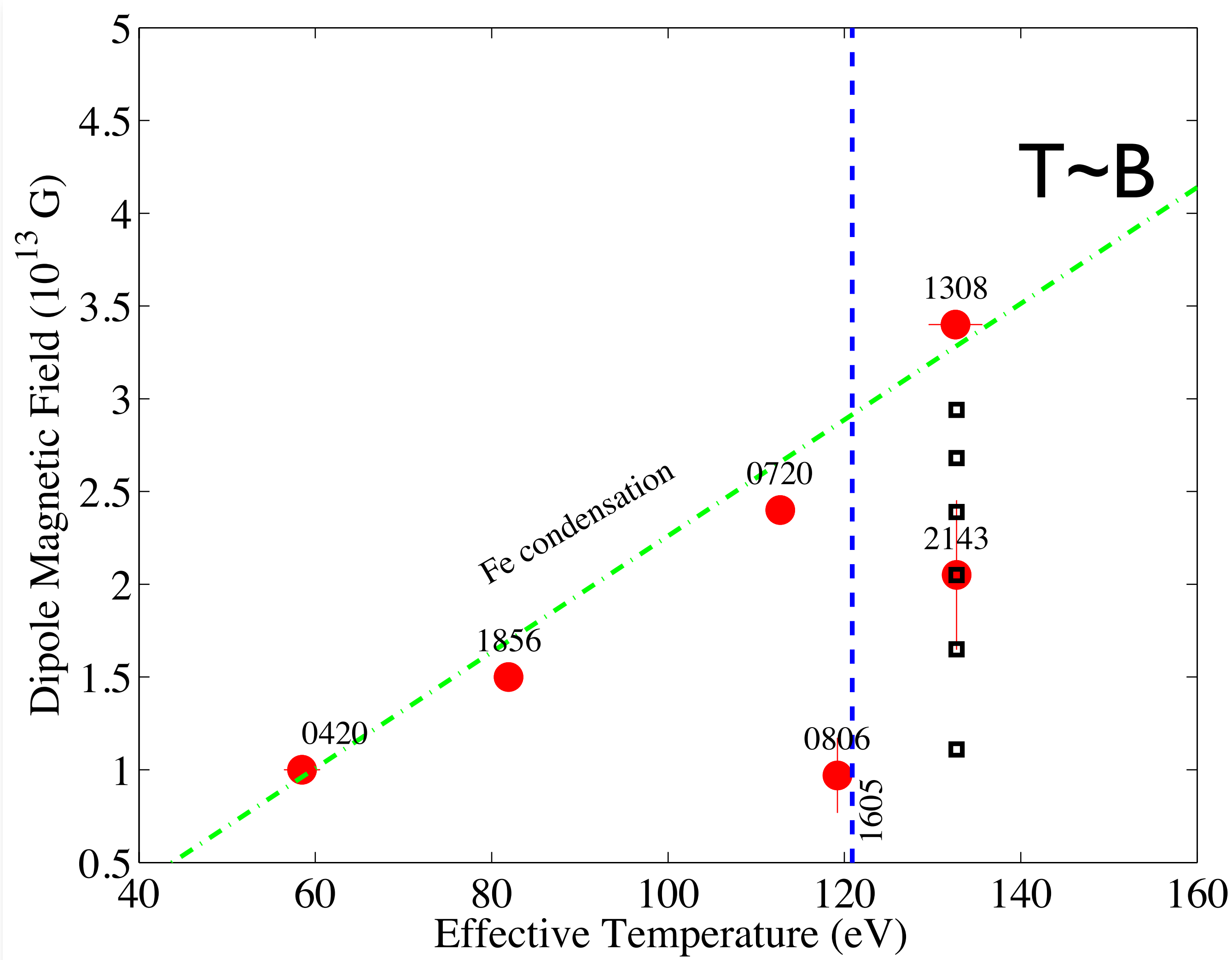

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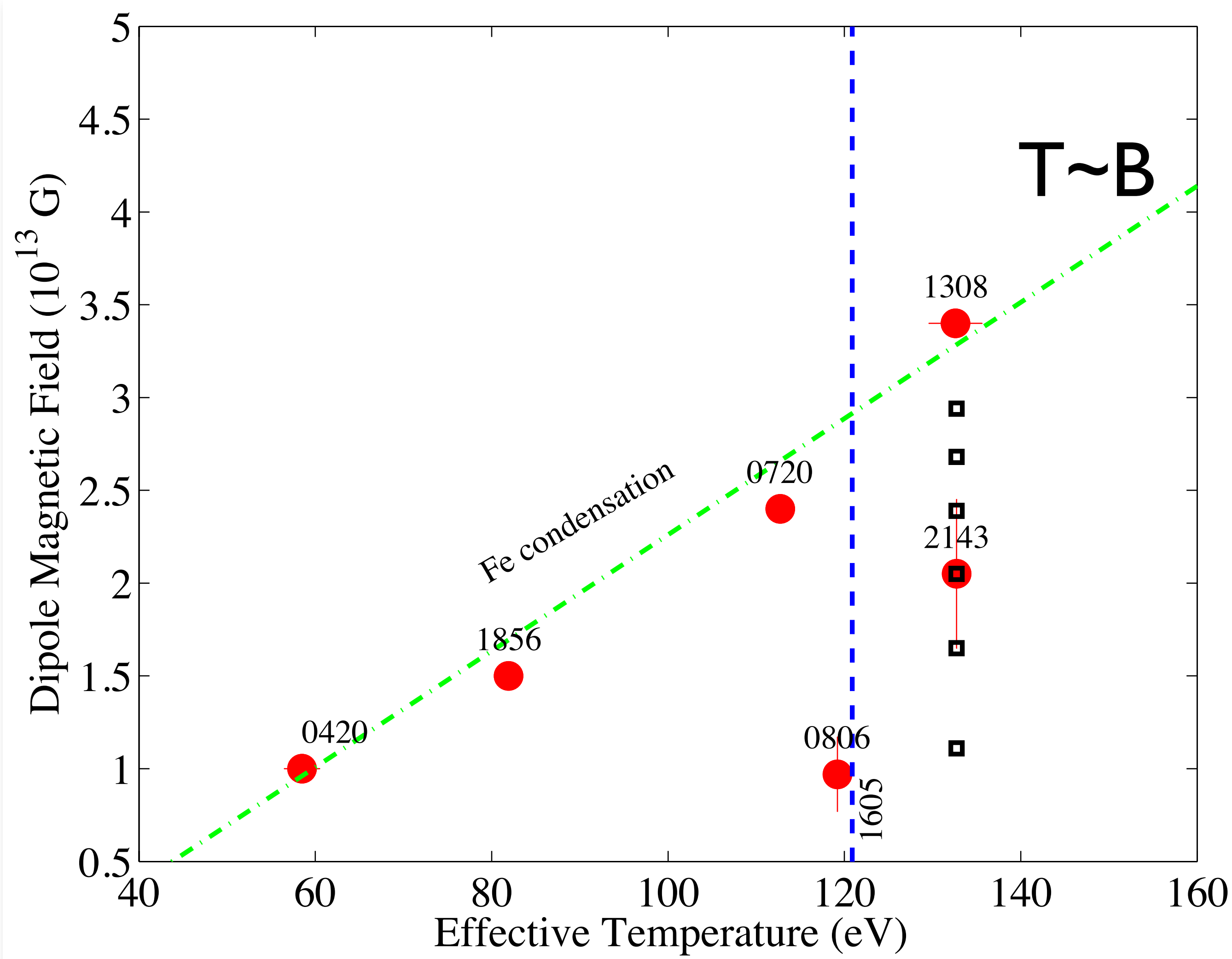

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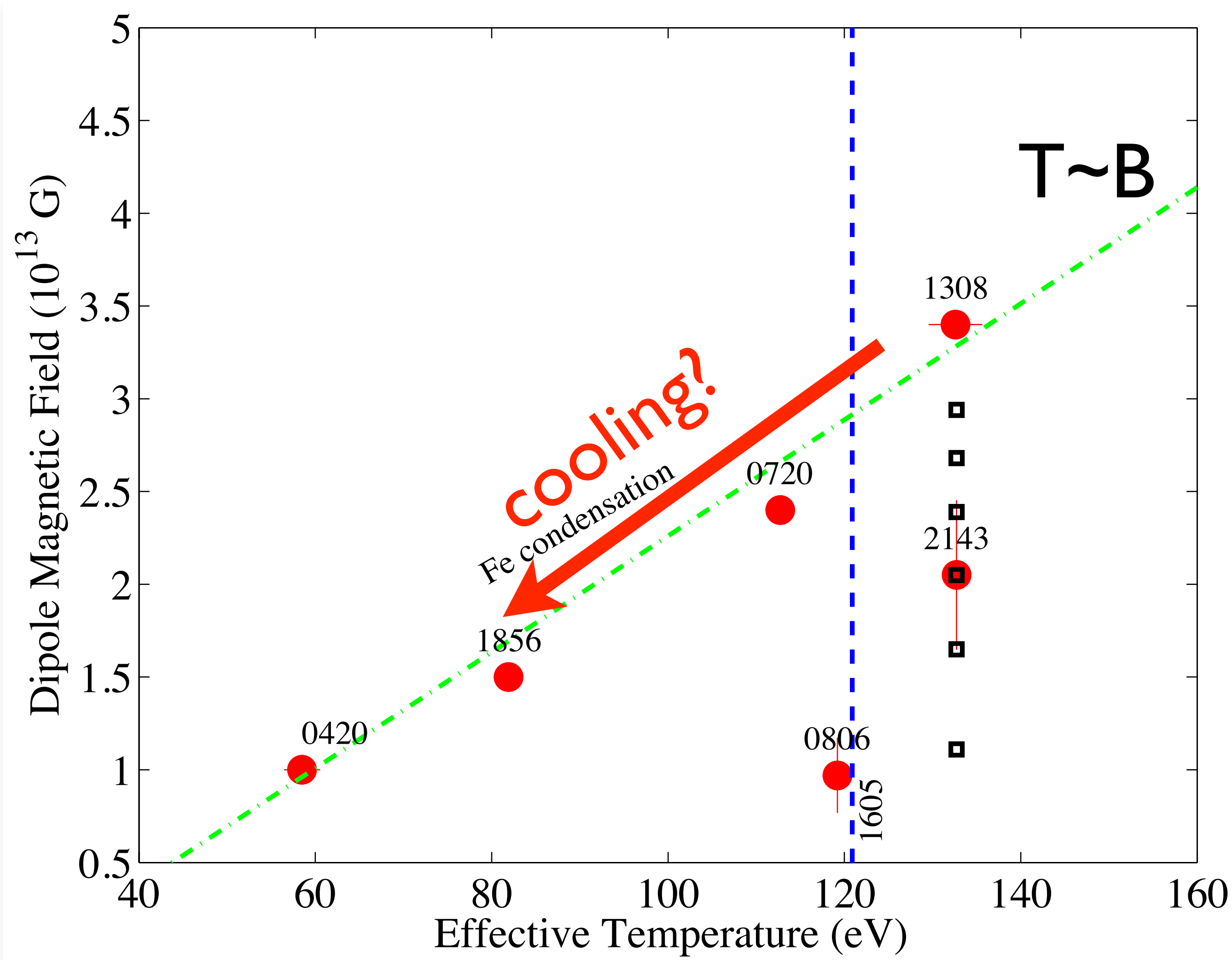

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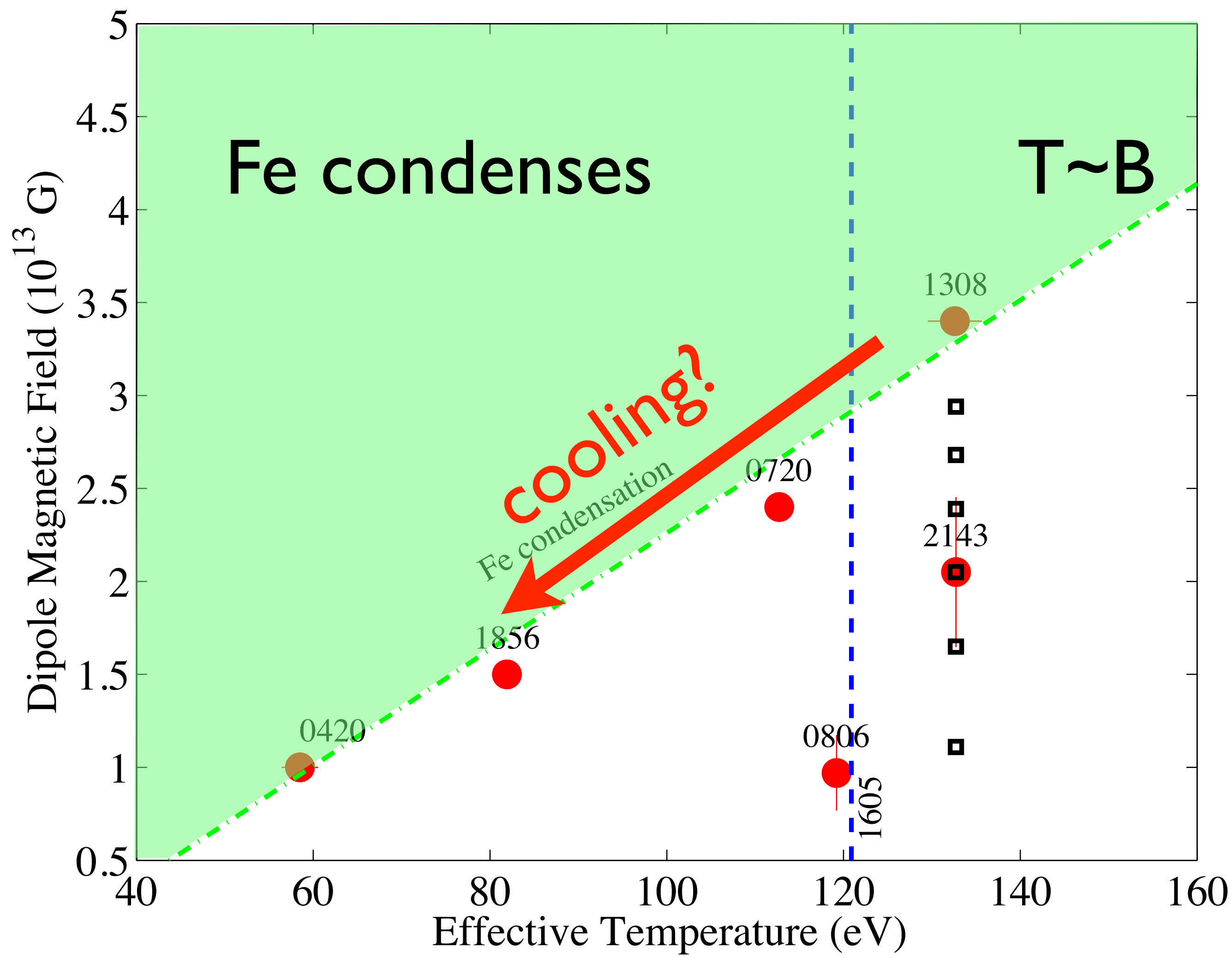

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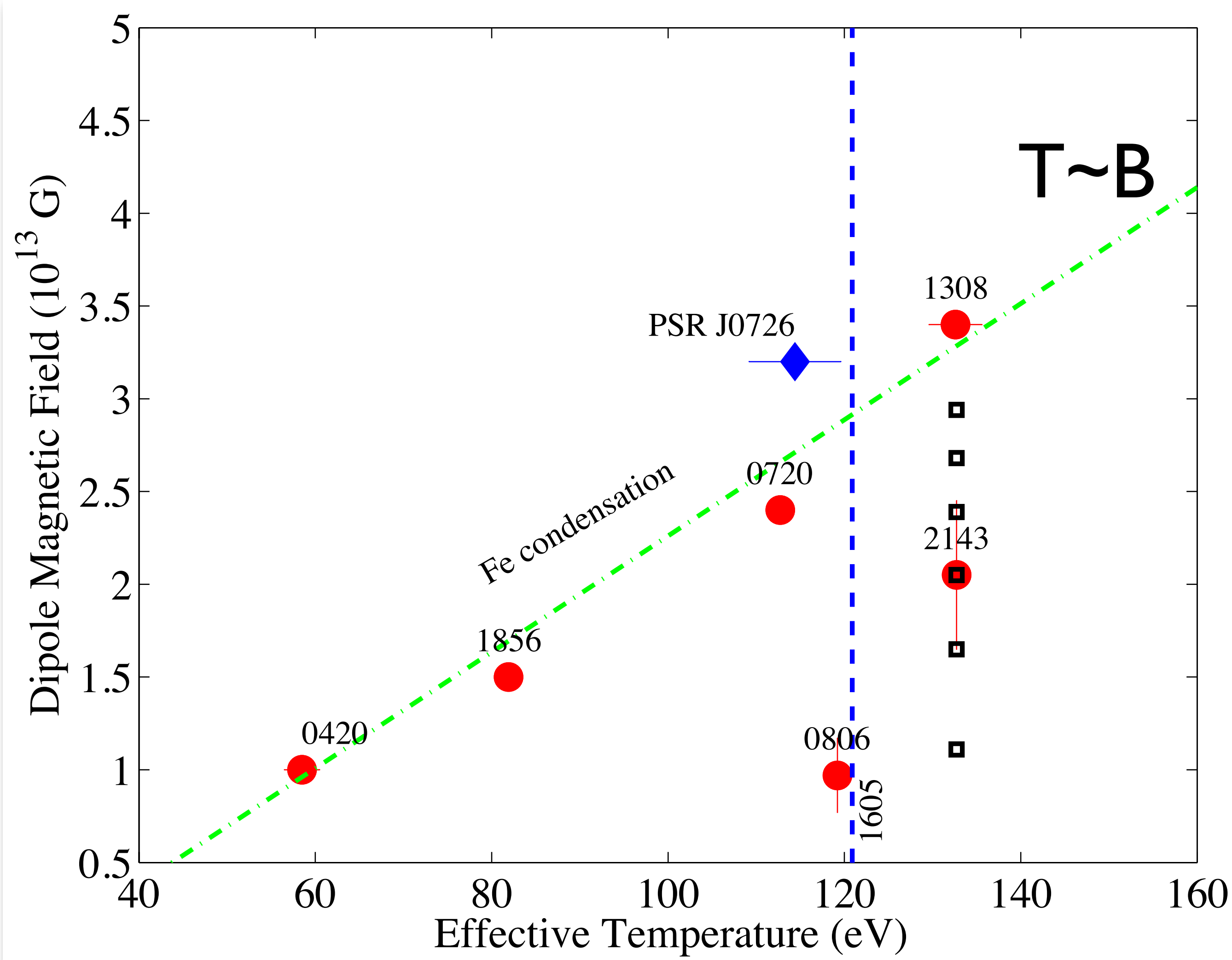

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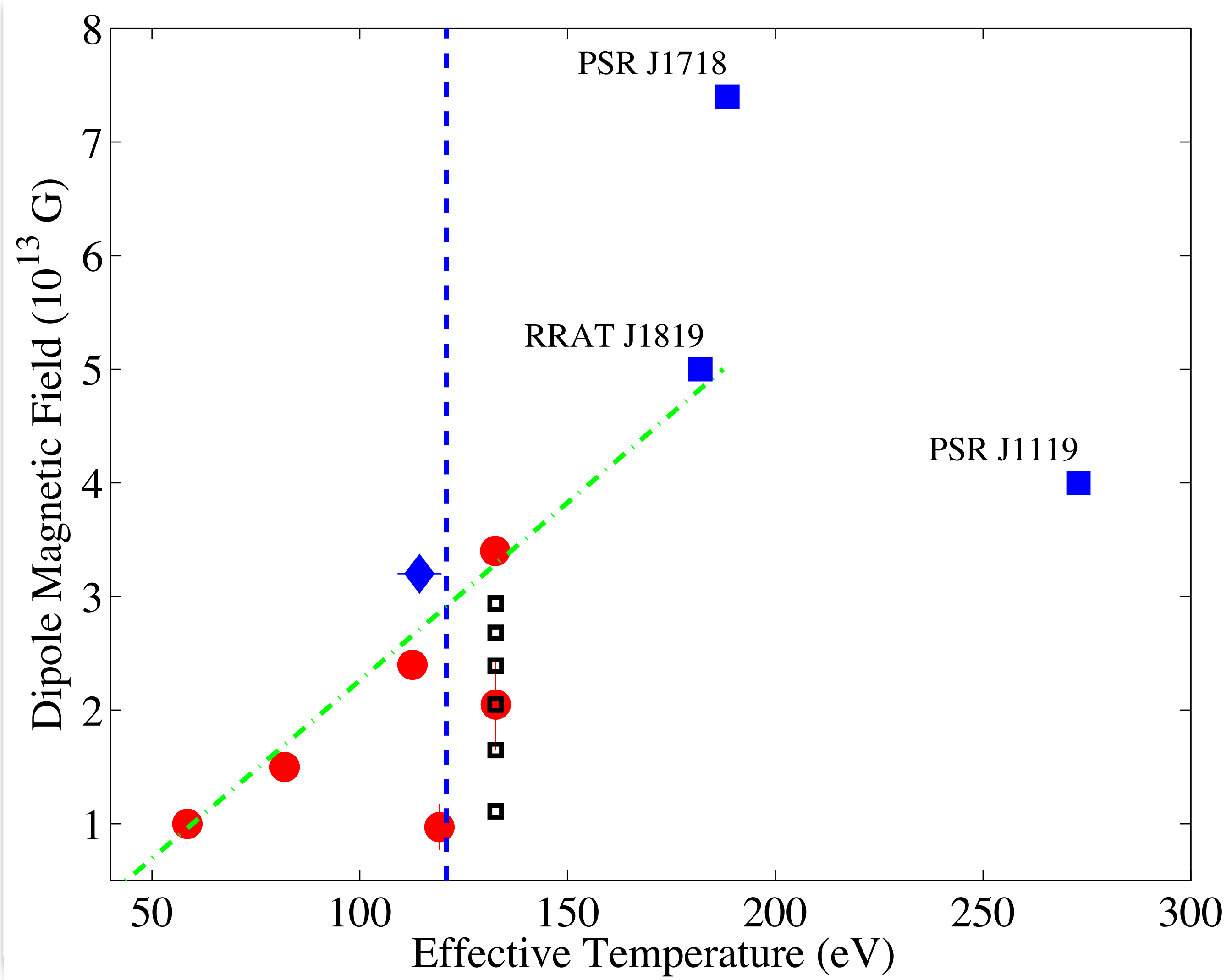

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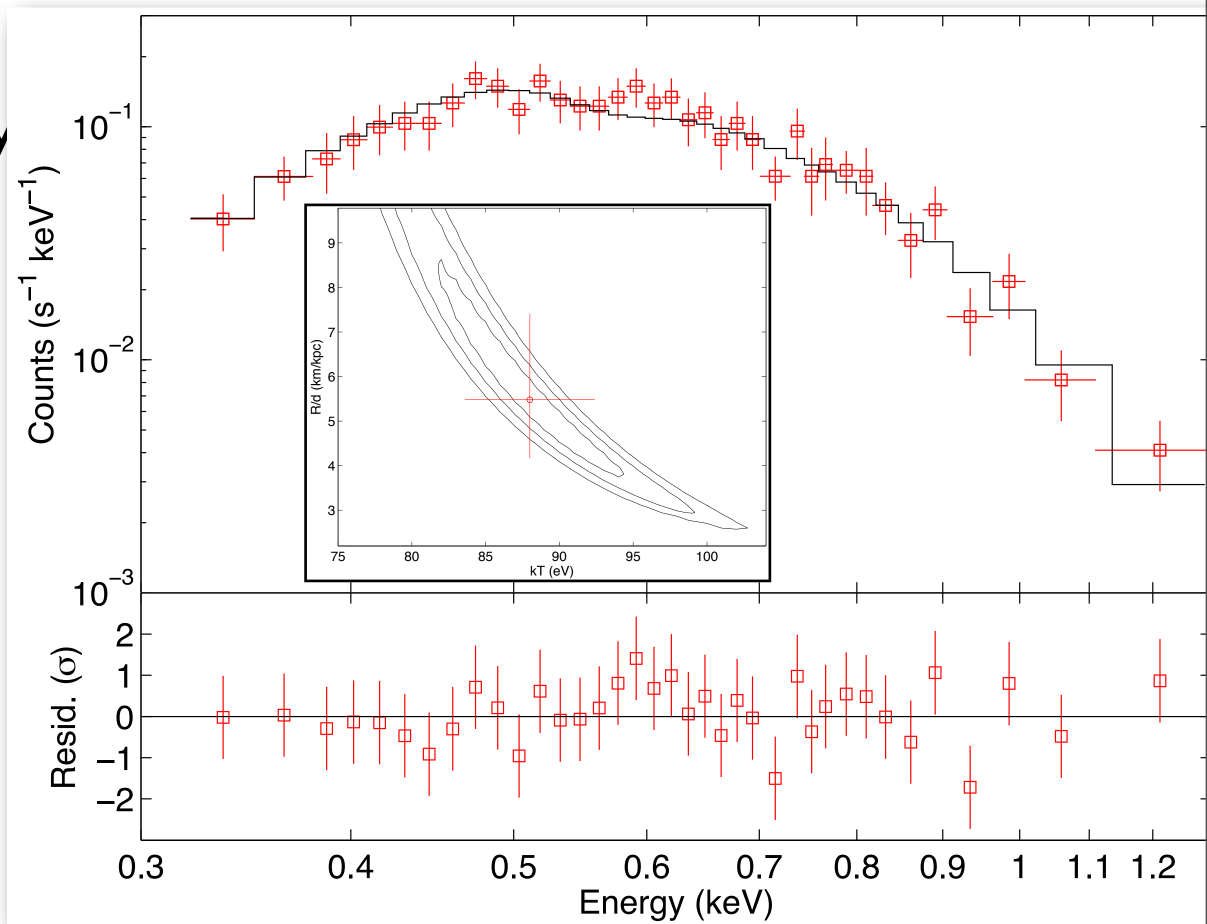

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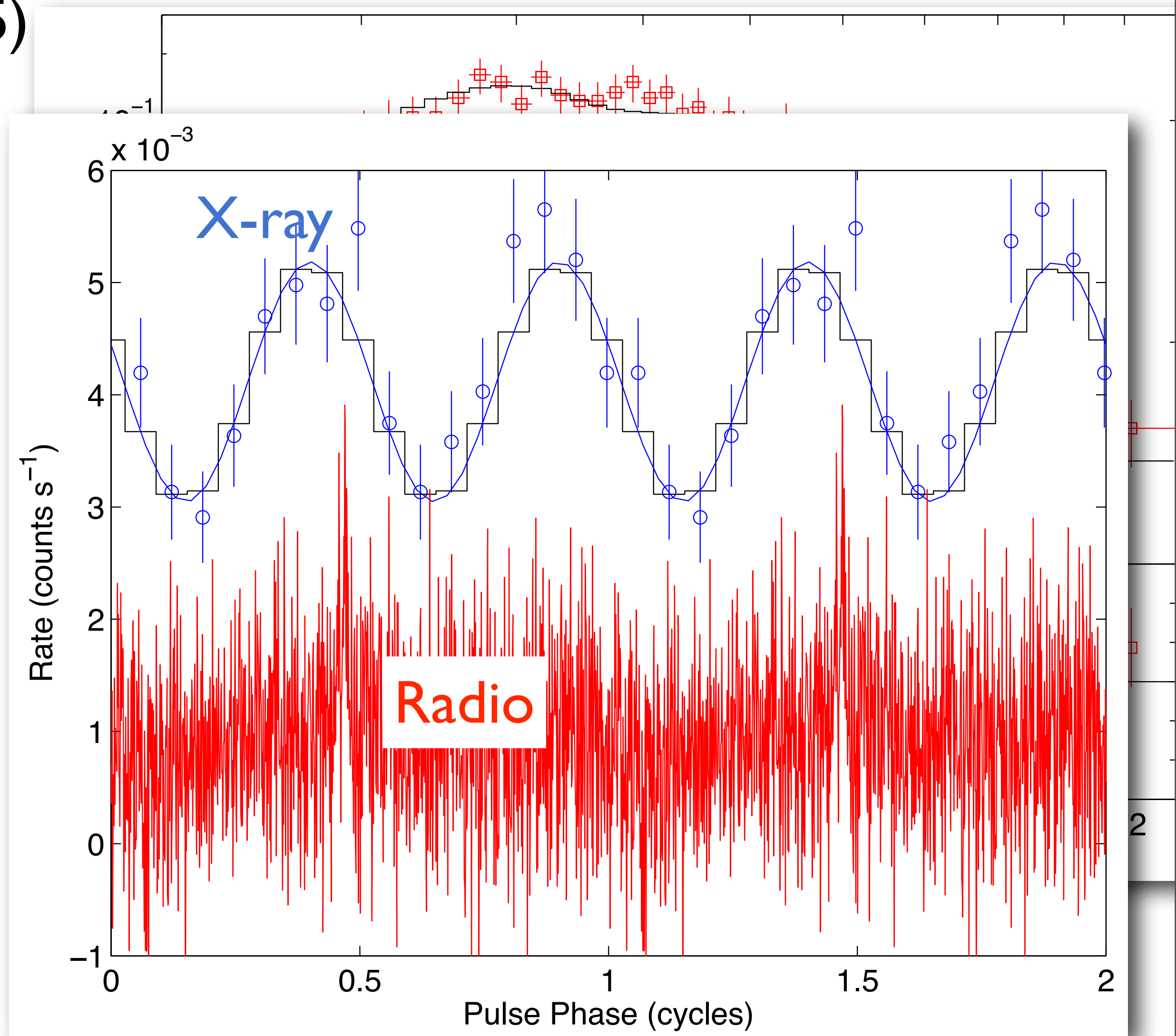

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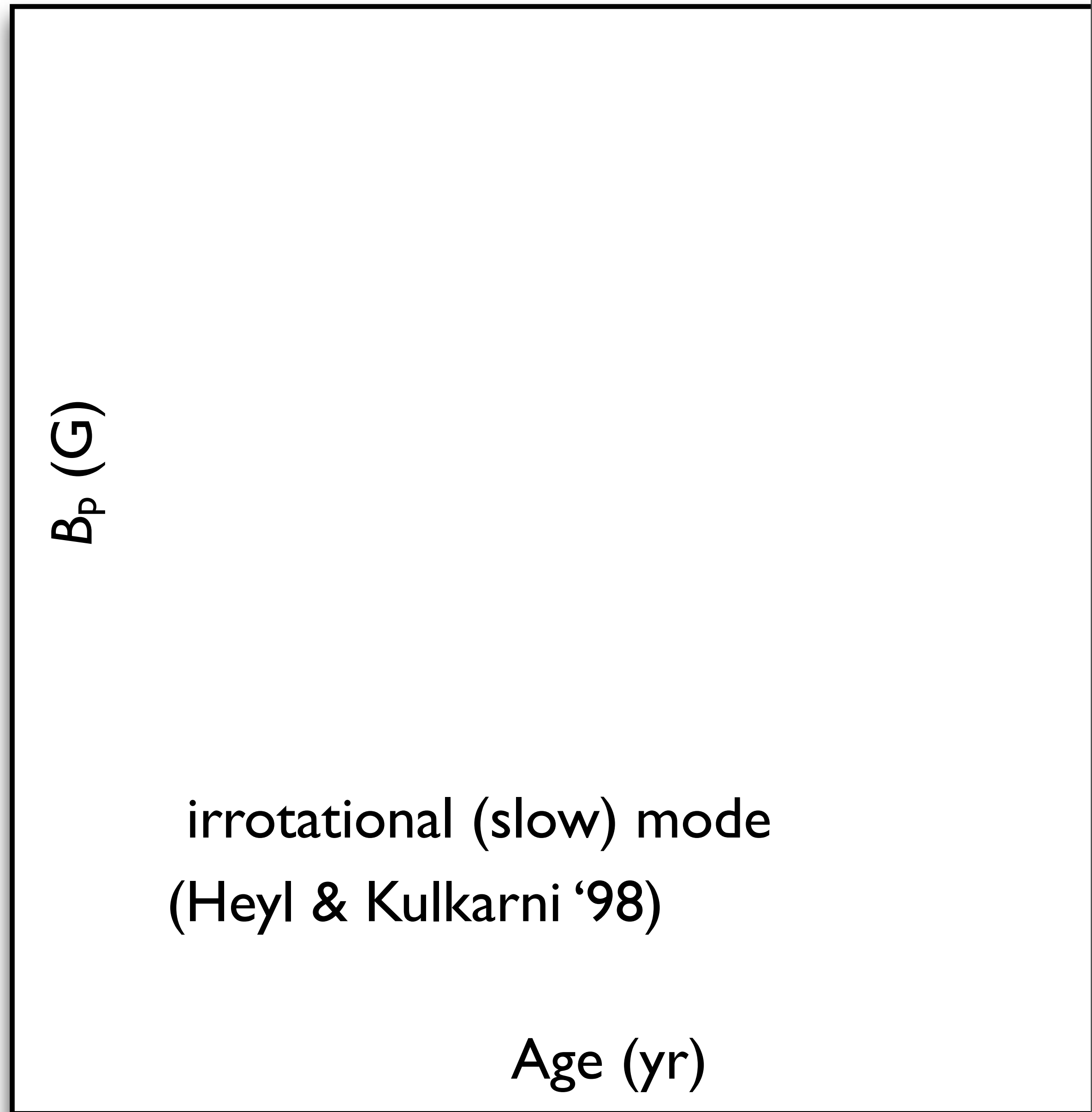

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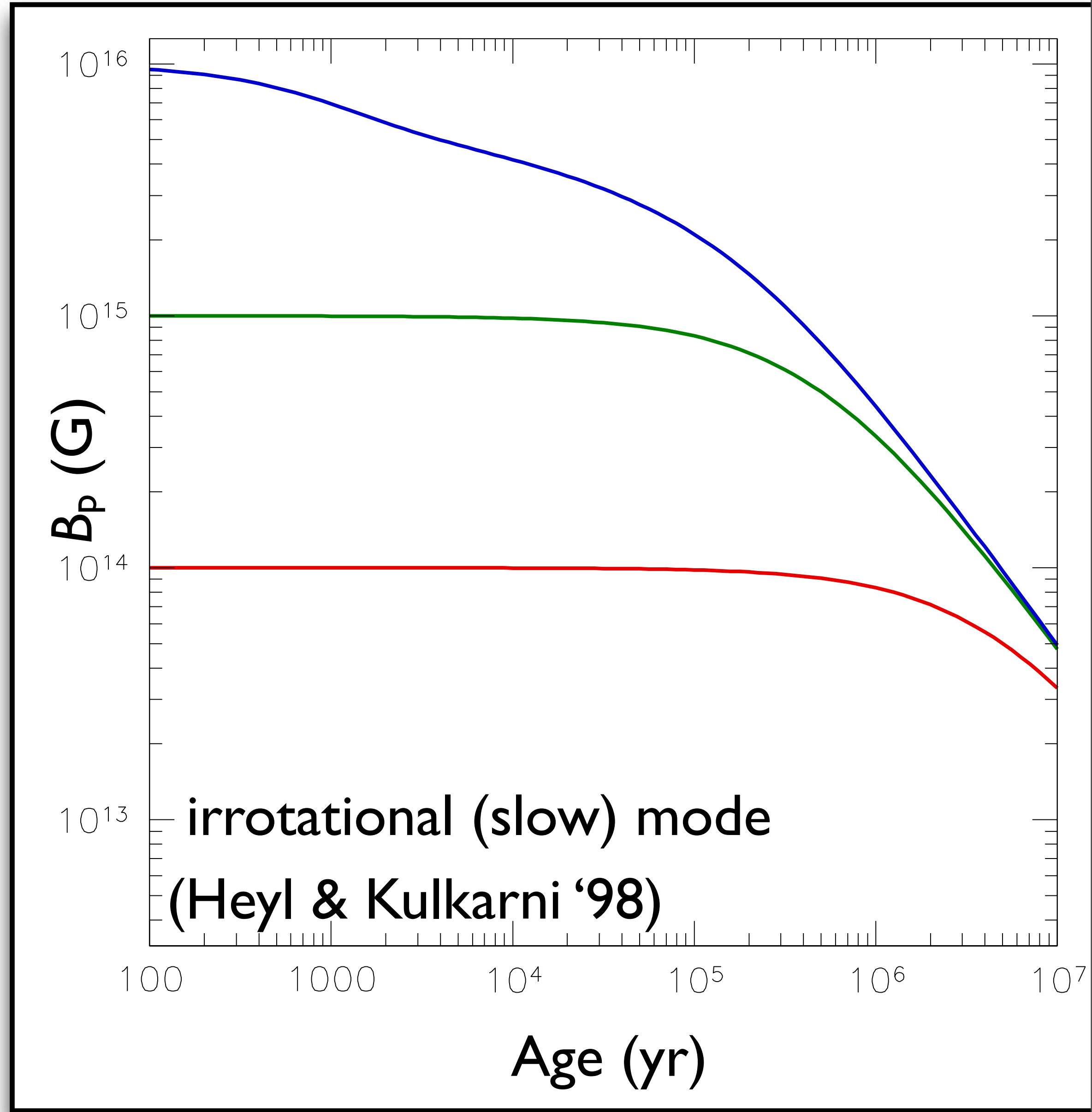

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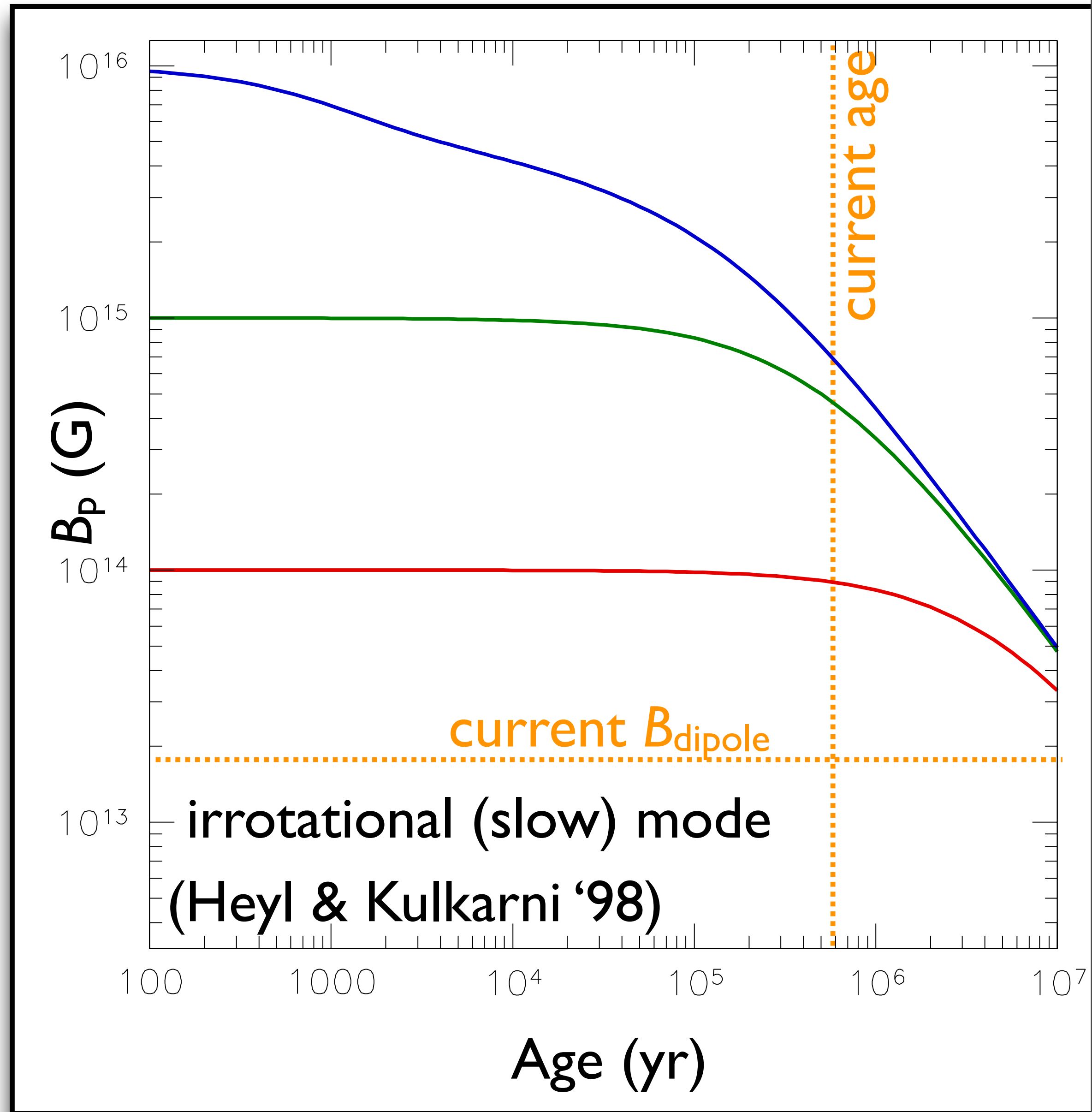

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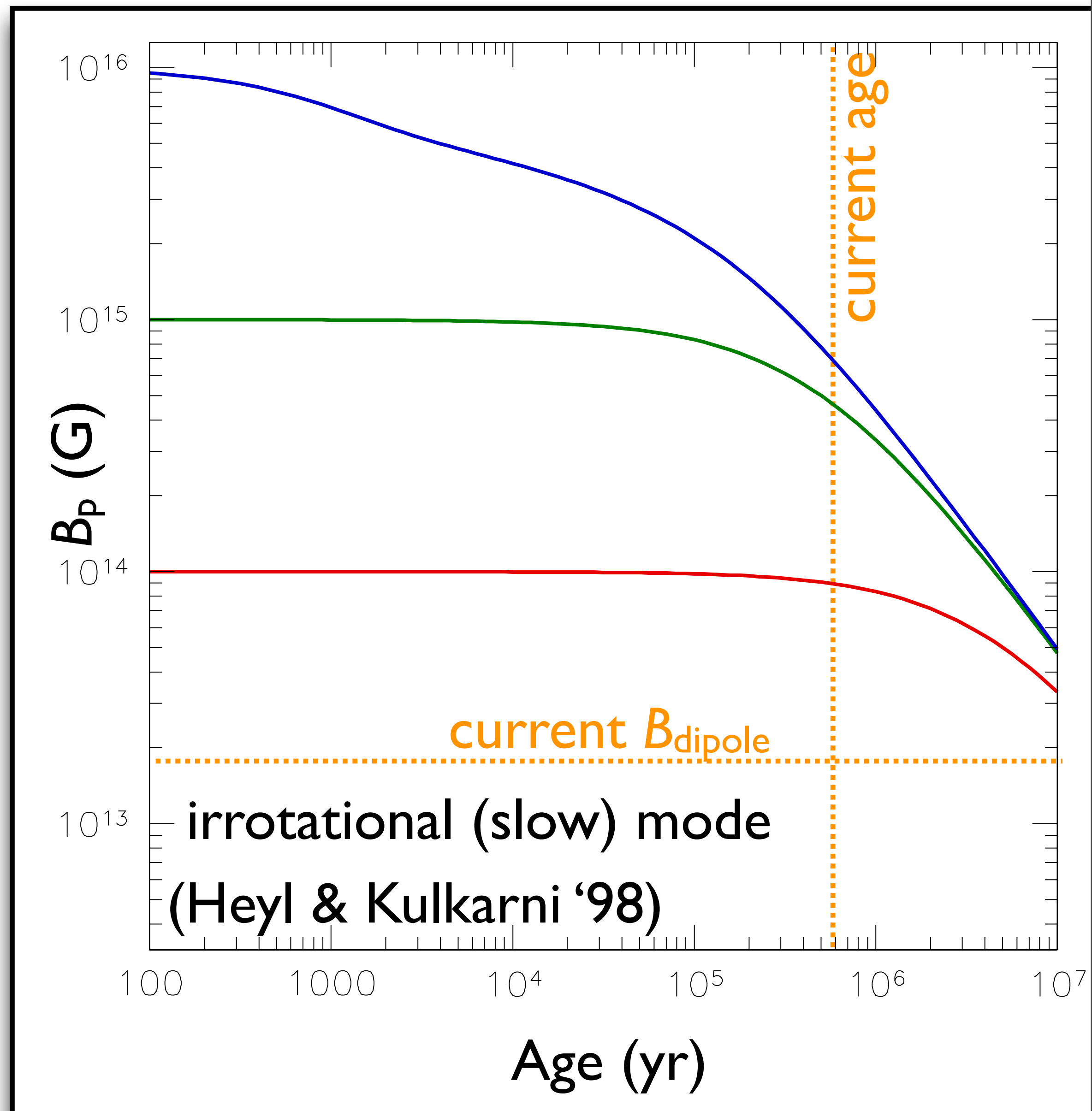

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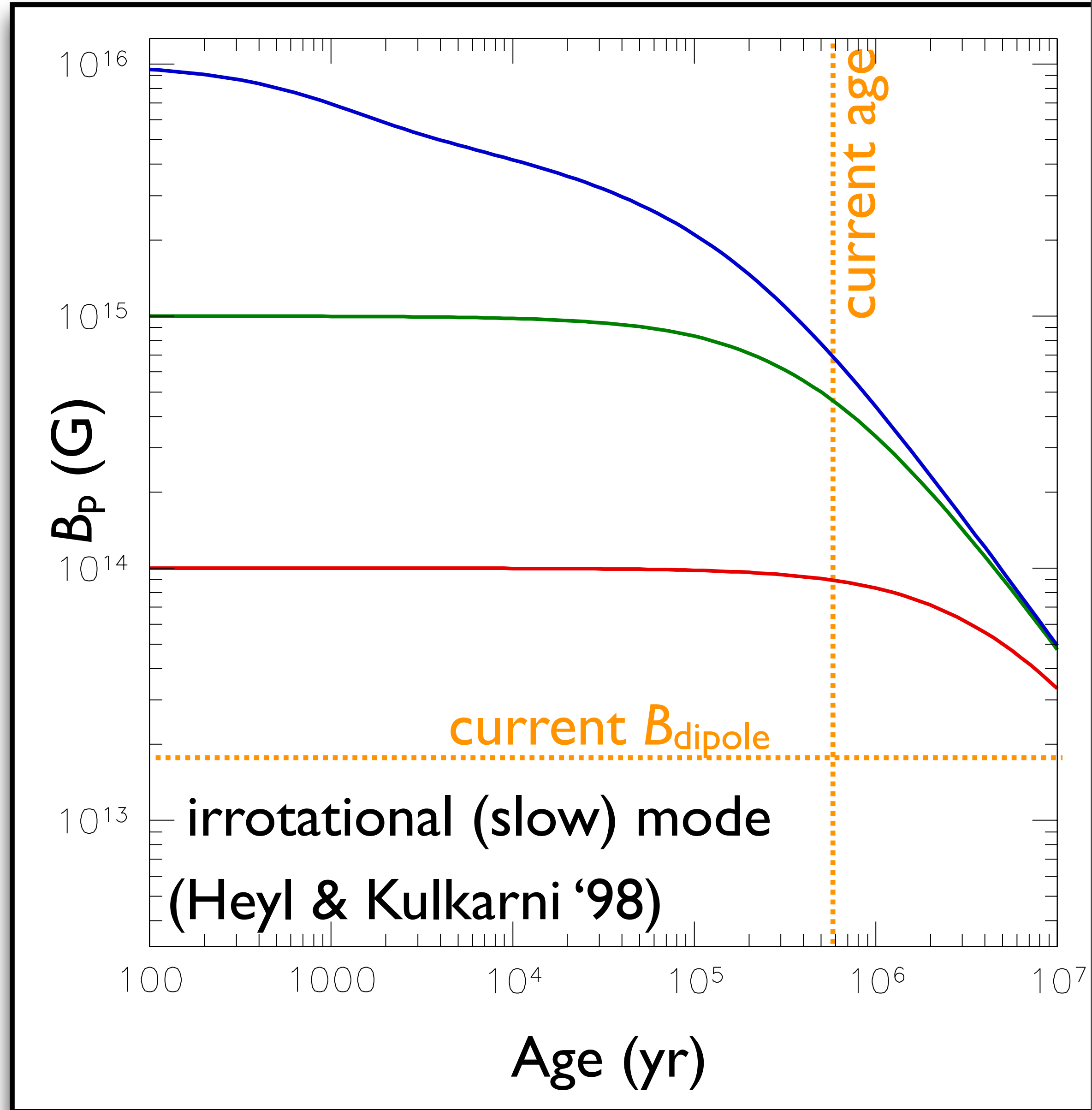

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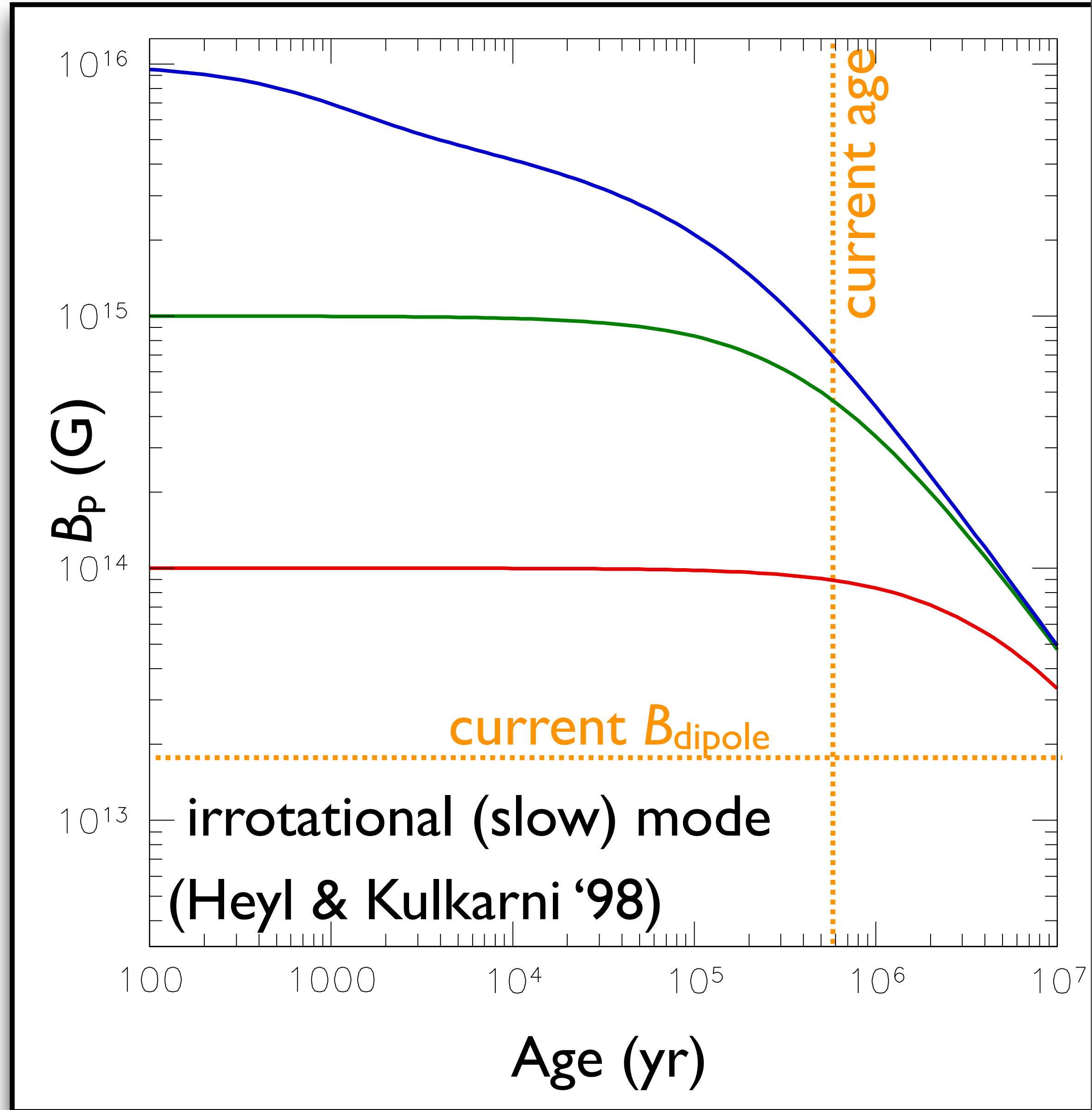

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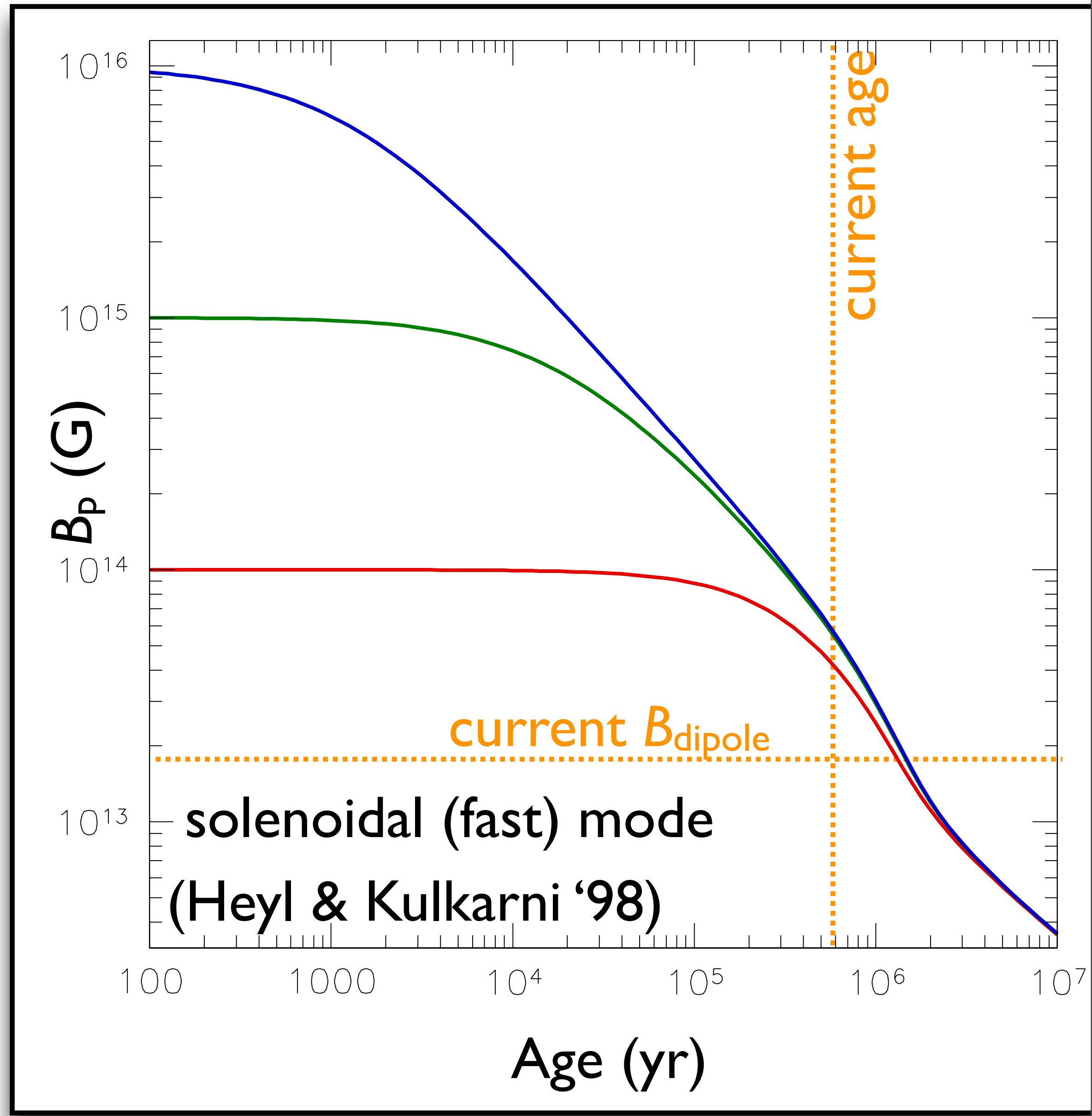

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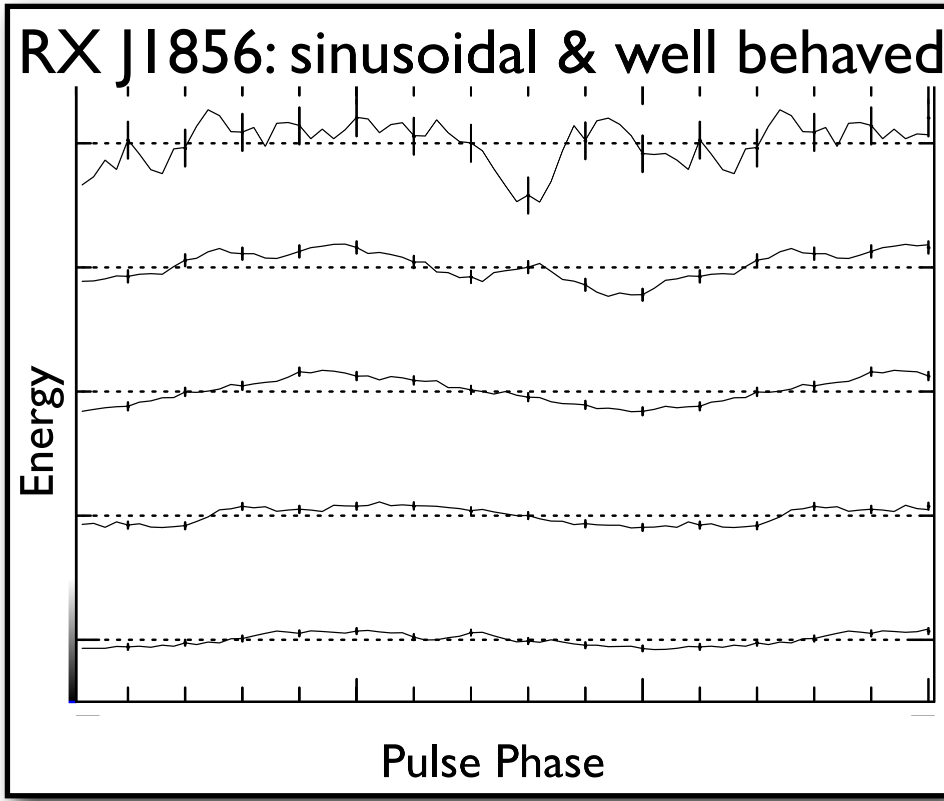

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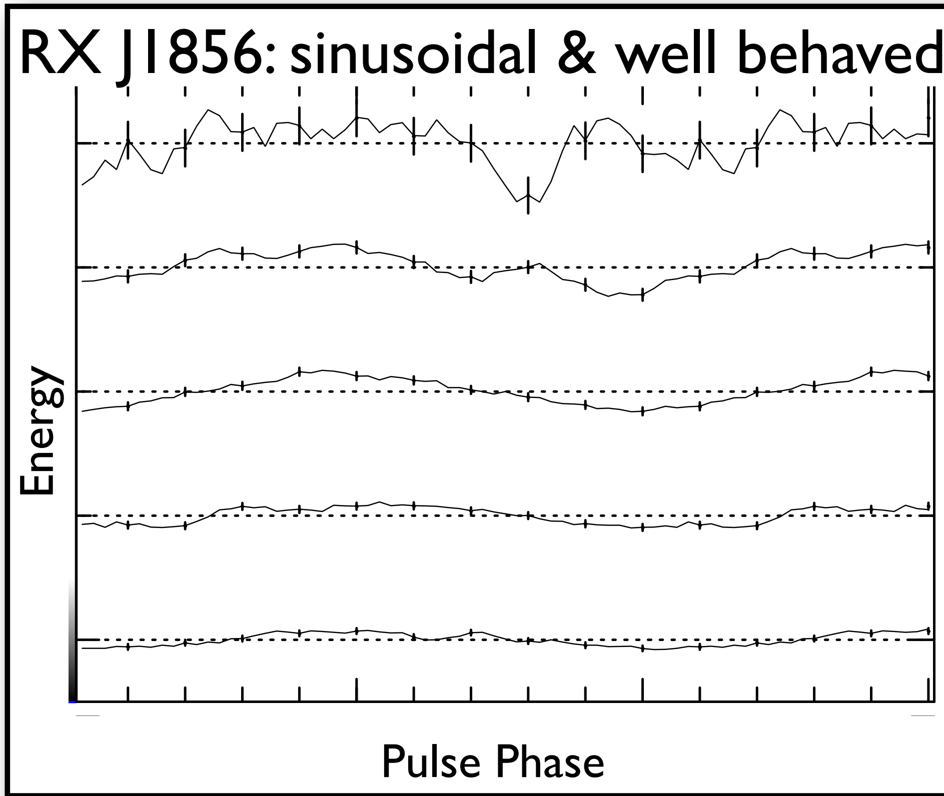

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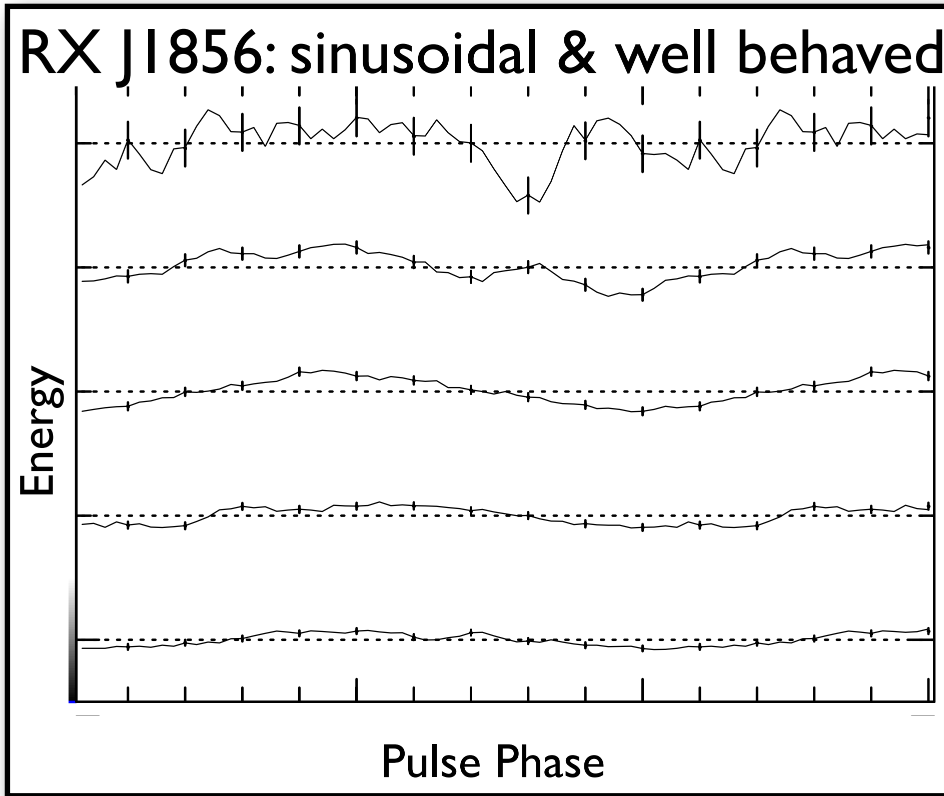

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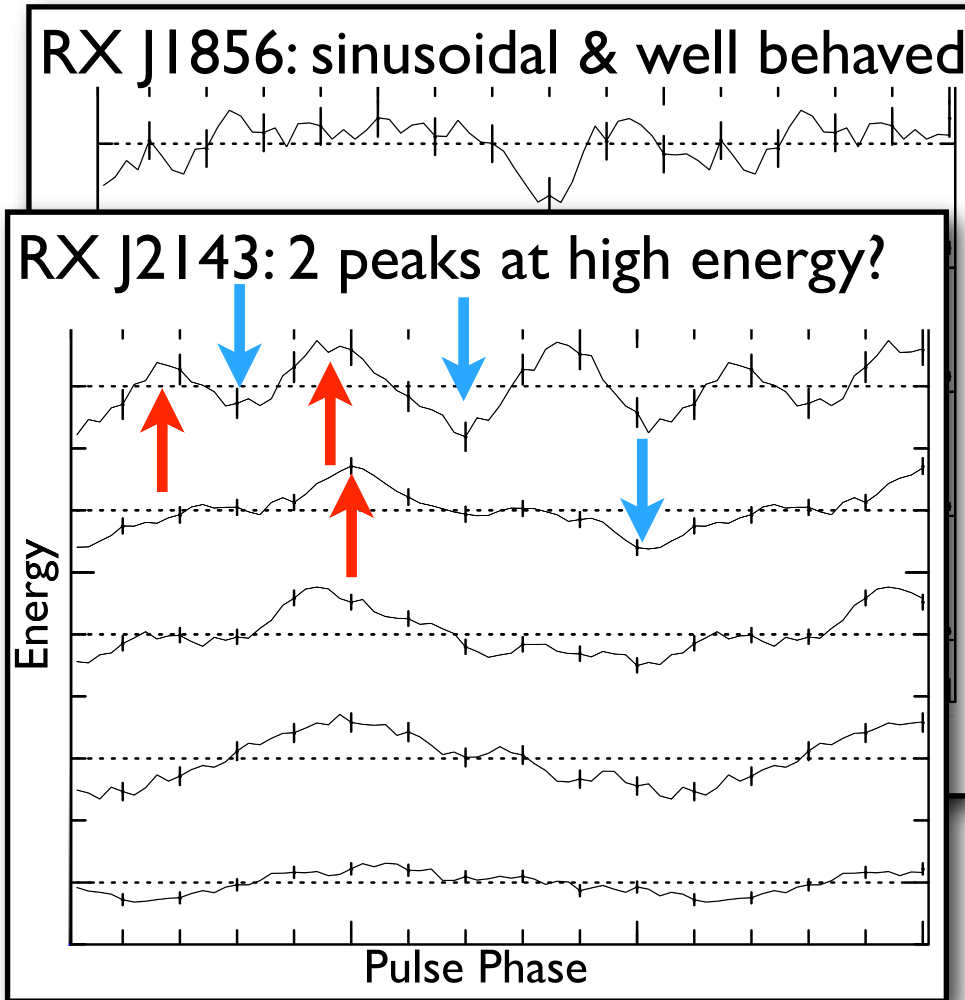

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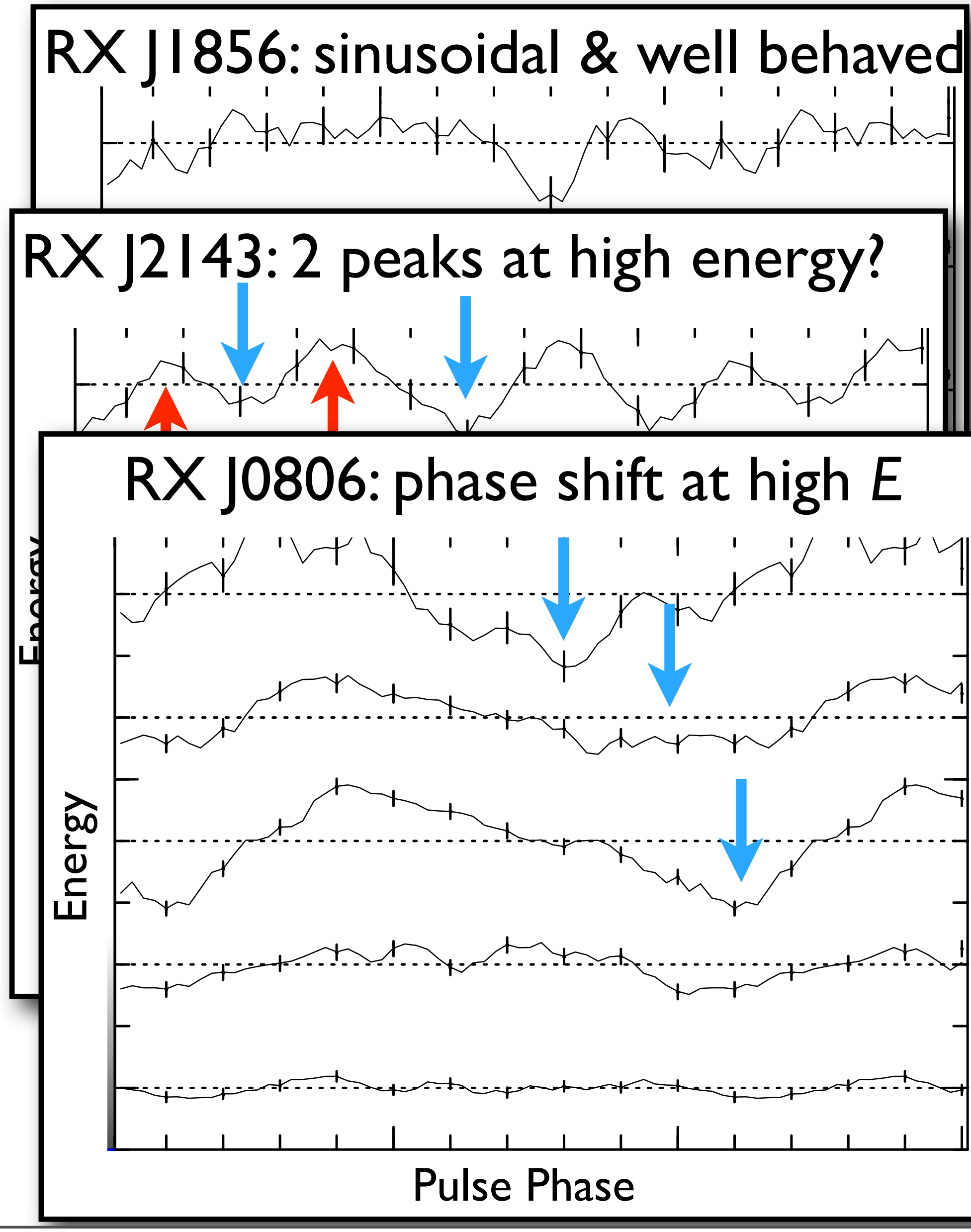

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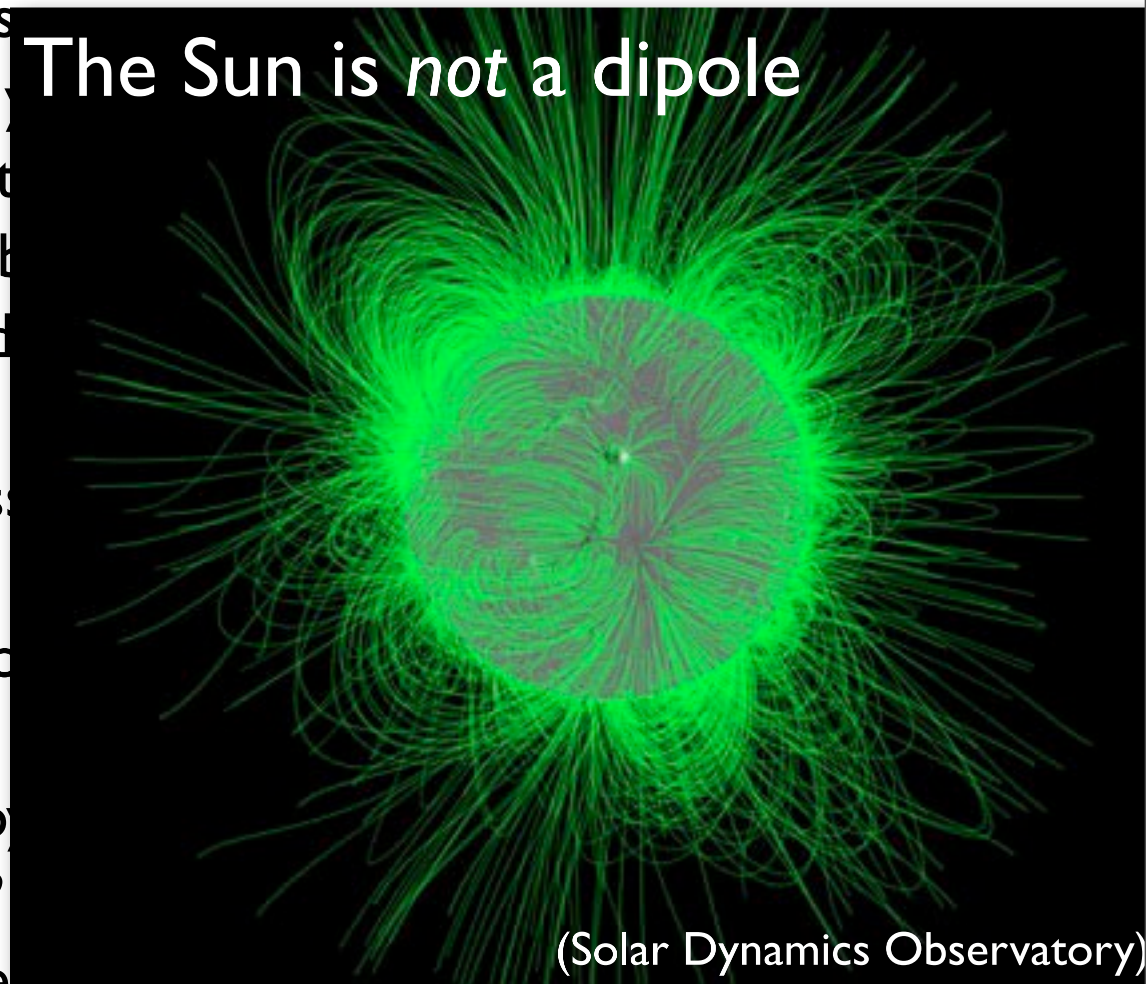

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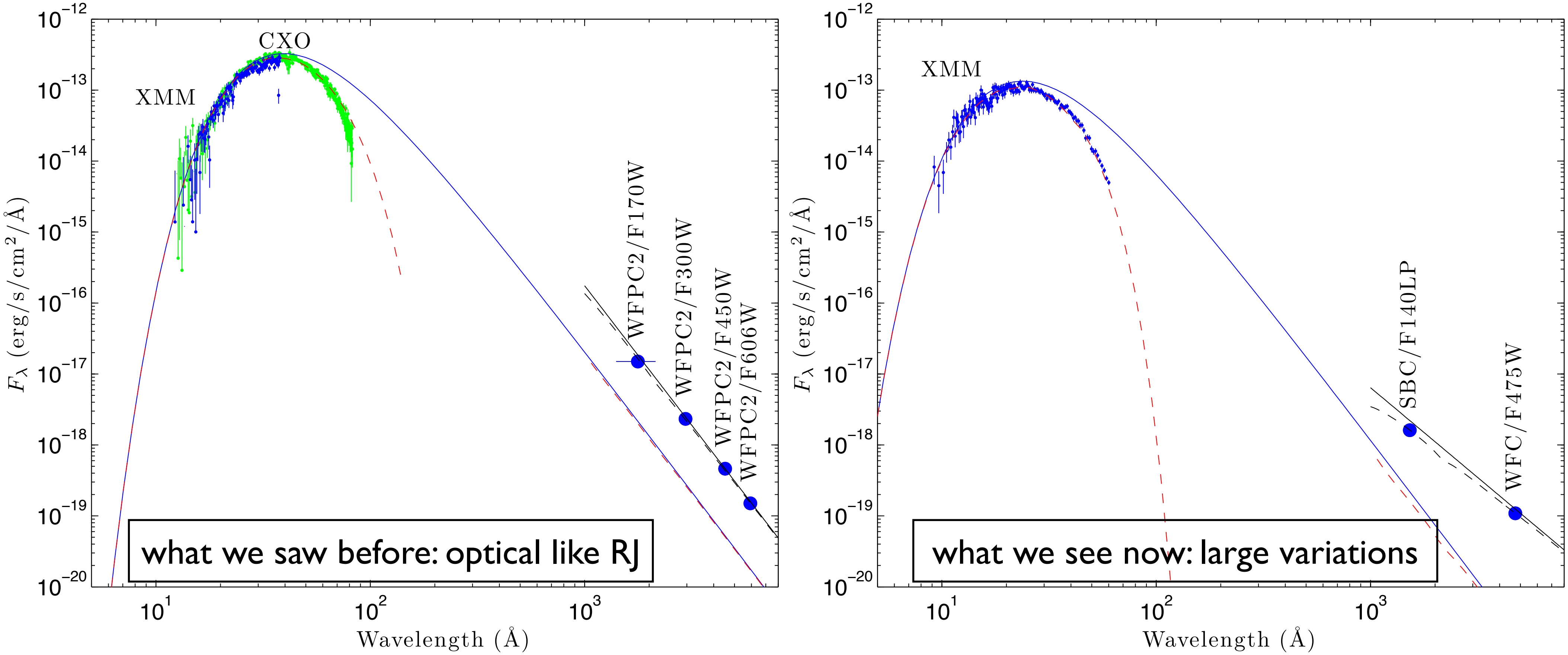
	(keV)	(s)	(s/s)	(keV)	(c/s)	(%)	(mag)	(mas/yr)
1856	60	7.06	3E-14	...	2.1	1	25.8	333
0720	85	8.39	7E-14	0.3	1.4	11	26.5	108
1605	93	6.88?	...	0.5	1.0	<3	26.9	144
1308	90	10.31	1E-13	0.3	0.5	18	28.5	200
2143	101	9.44	4E-14	0.7	0.6	4	26.3	?
0806	96	11.37	9E-15	0.5	0.5	6	27.9	?
0420	45	3.45	3E-14	0.3	0.05	13	27.9	?

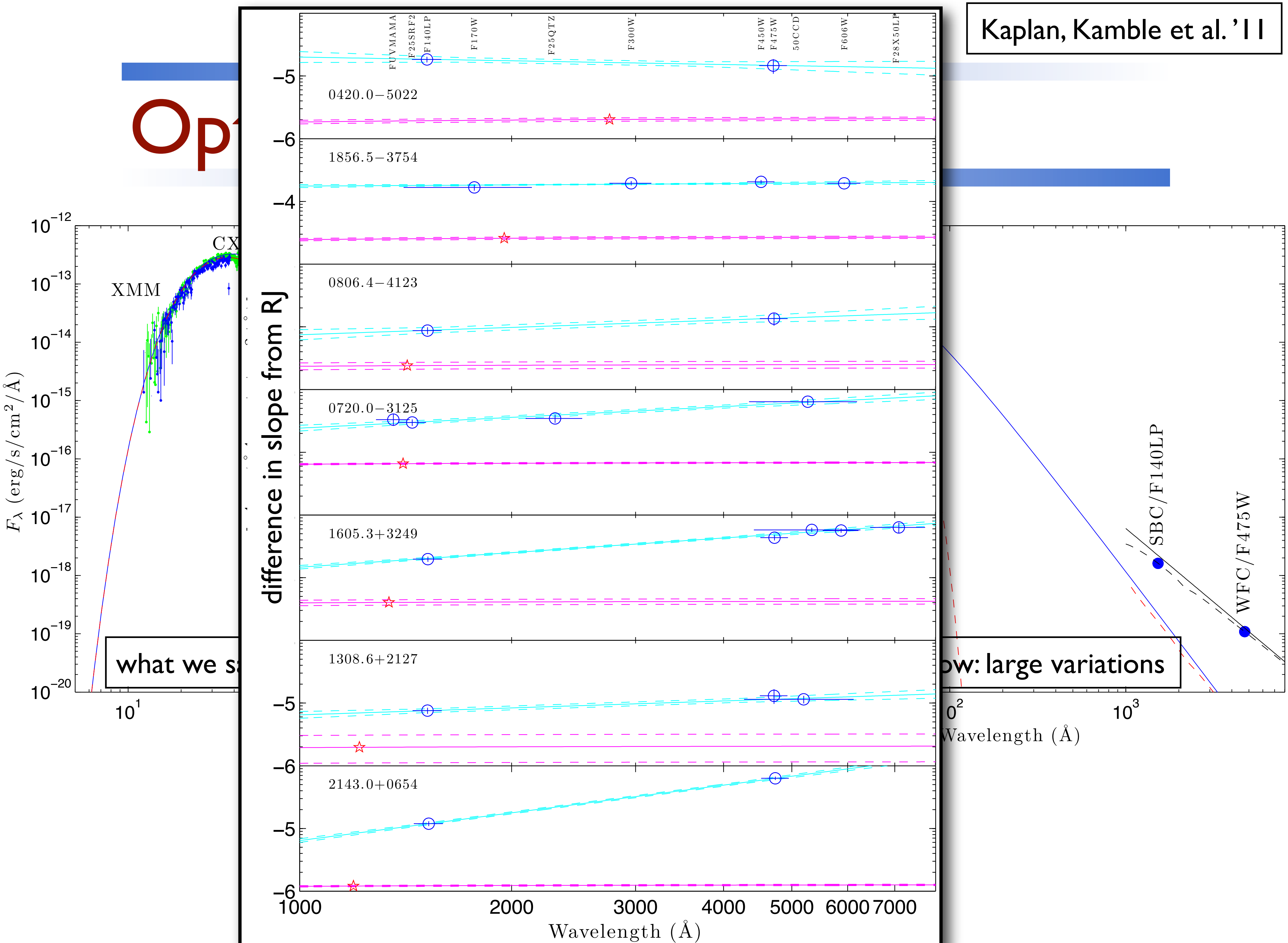
Kaplan, Kamble et al. '11

Optical In Detail

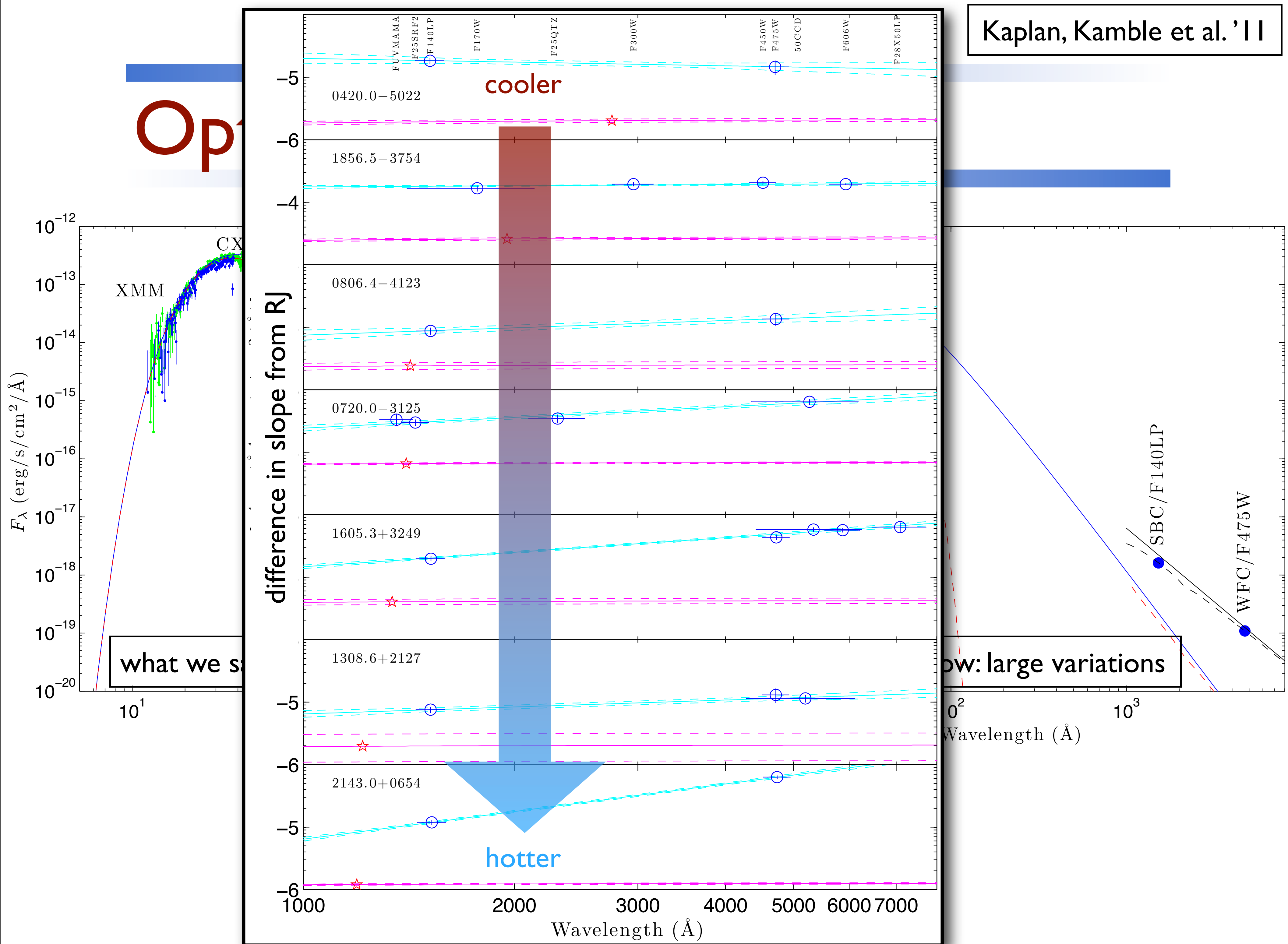


Kaplan, Kamble et al. '11

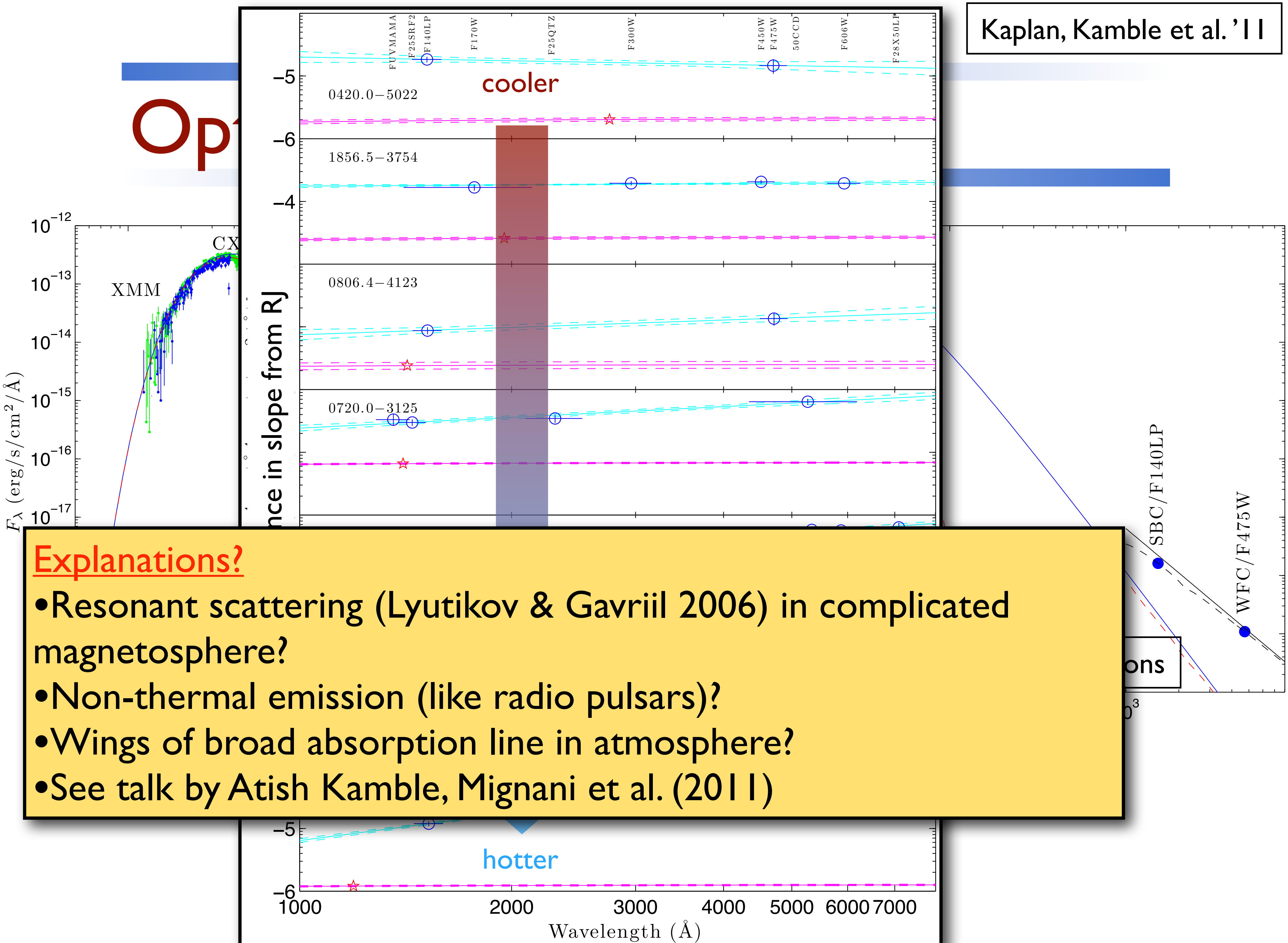
Op



what we s... ...w: large variations


Kaplan, Kamble et al. '11
Op
what we s
ow: large variations
XMM
CX
F_λ (erg/s/cm^2/Å)
Wavelength (Å)
SBC/F140LP
WFC/F475W
difference in slope from RJ
cooler
hotter
FUVMAMA
F25SRF2
F140LP
F170W
F25QTZ
F300W
F450W
F475W
50CCD
F606W
F28X50LP
0420.0−5022
1856.5−3754
0806.4−4123
0720.0−3125
1605.3+3249
1308.6+2127
2143.0+0654
Wavelength (Å)

Kaplan, Kamble et al. '11



Explanations?

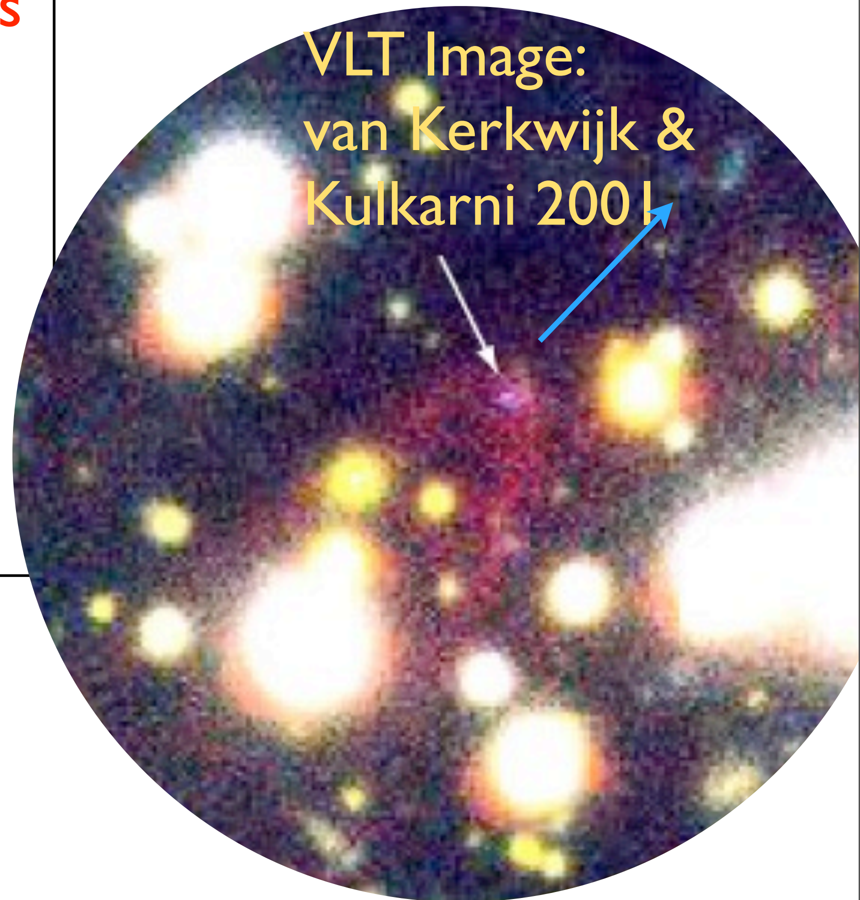
- Resonant scattering (Lyutikov & Gavriil 2006) in complicated magnetosphere?
- Non-thermal emission (like radio pulsars)?
- Wings of broad absorption line in atmosphere?
- See talk by Atish Kamble, Mignani et al. (2011)

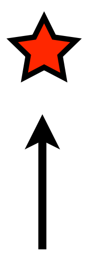
A Hα Nebula Around RX J1856

- Hα nebulae around pulsars: usually "bowshocks"
  - Size R_0 comes from pressure balance:
  - ISM ram pressure = pulsar wind pressure

$$\rho_{ISM} v_{NS}^2 = \dot{E}/4\pi c R_0^2$$

  - Additional constraint: match photon flux to number of incoming atoms ($n_\gamma < n_H$)





Neutron Star

(van Kerkwijk & Kulkarni 2001; van Kerkwijk & Kaplan 2008)

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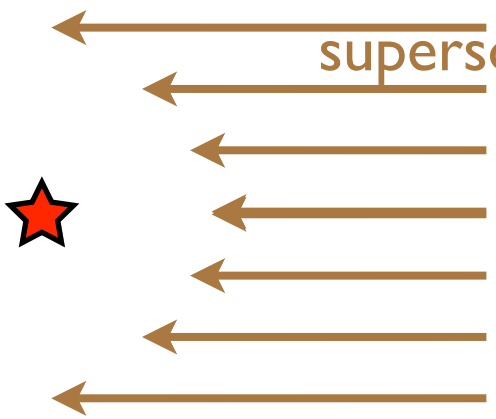

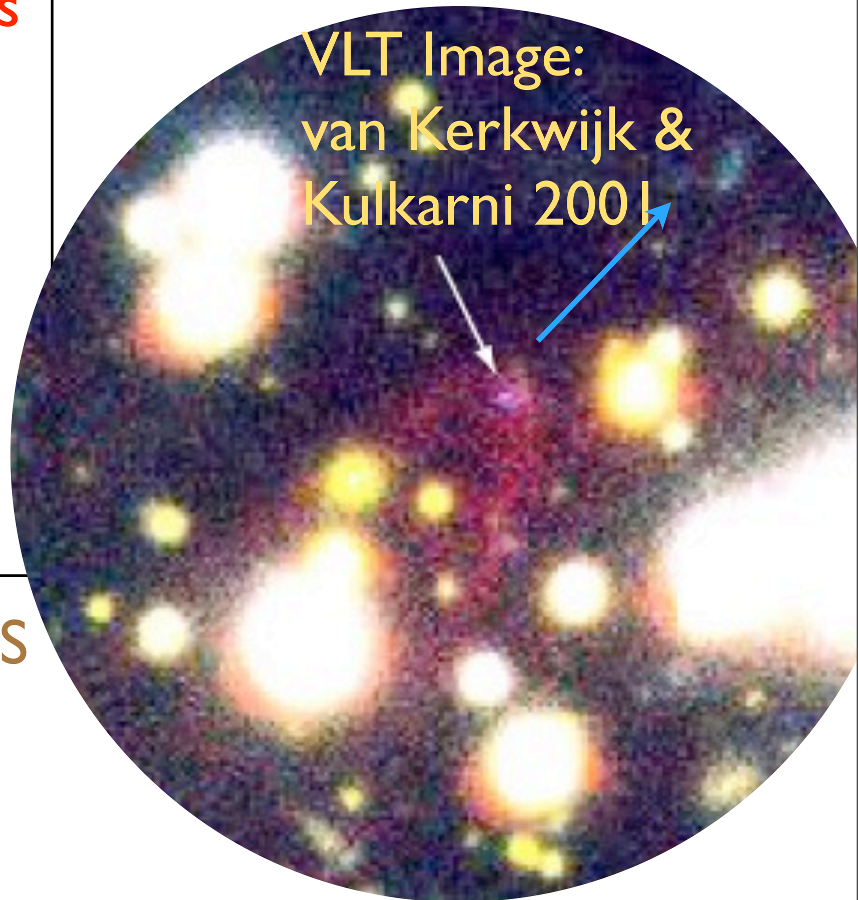

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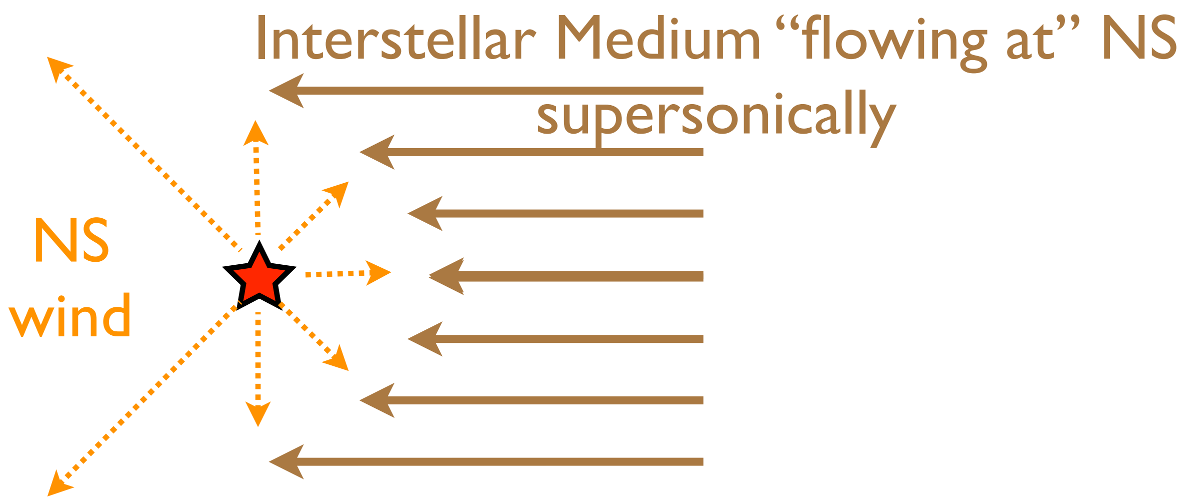

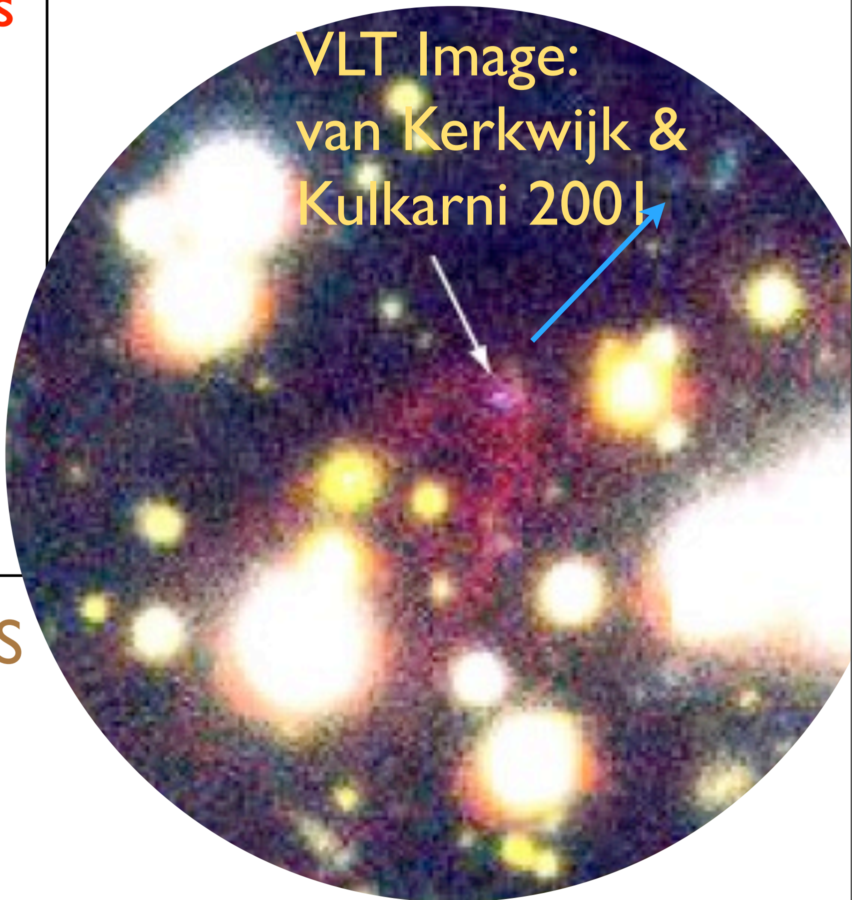

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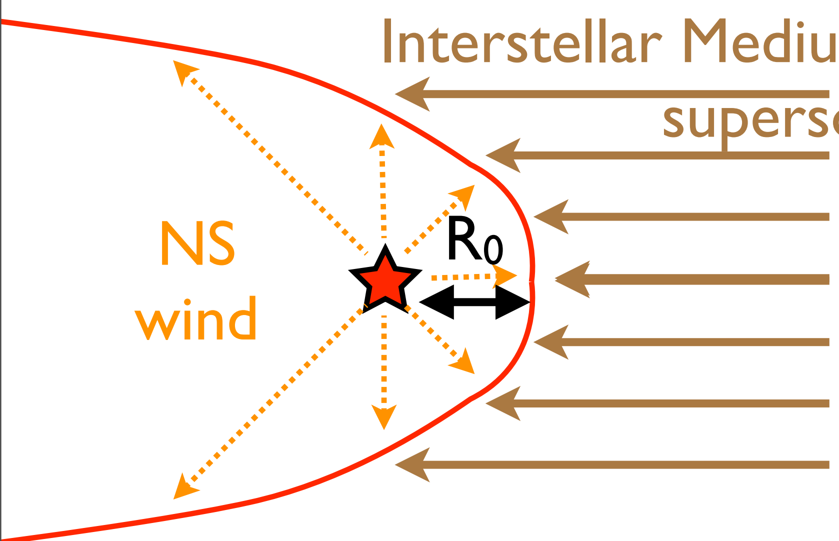

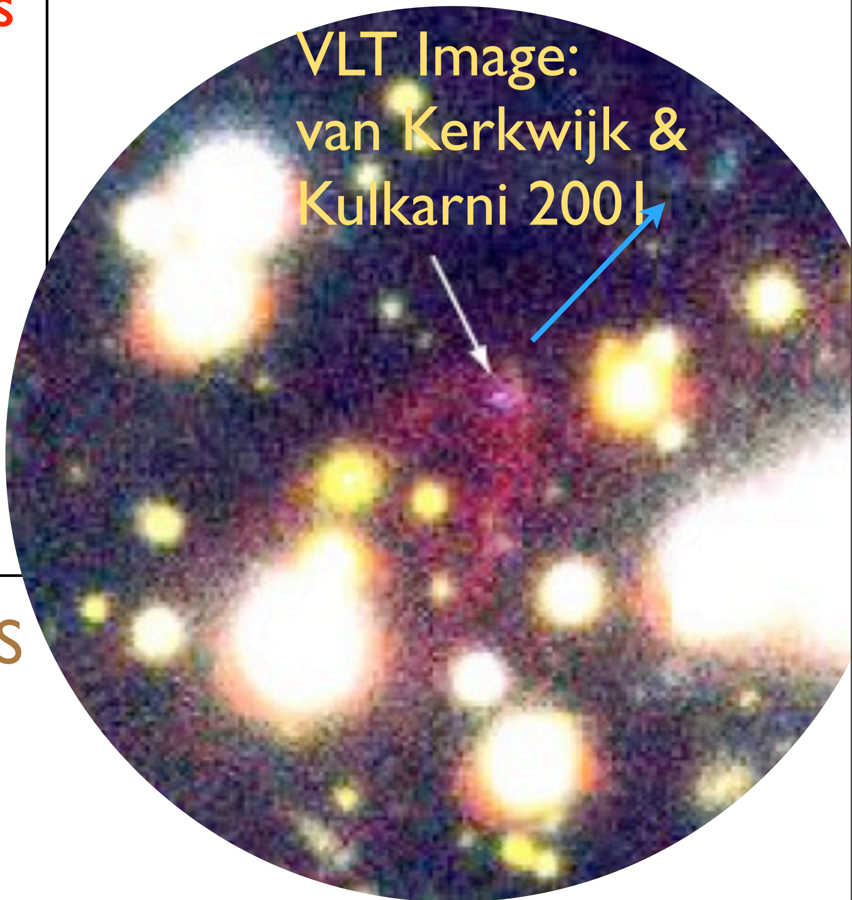

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unknown   known (with $\dot{P}$,μ,d)

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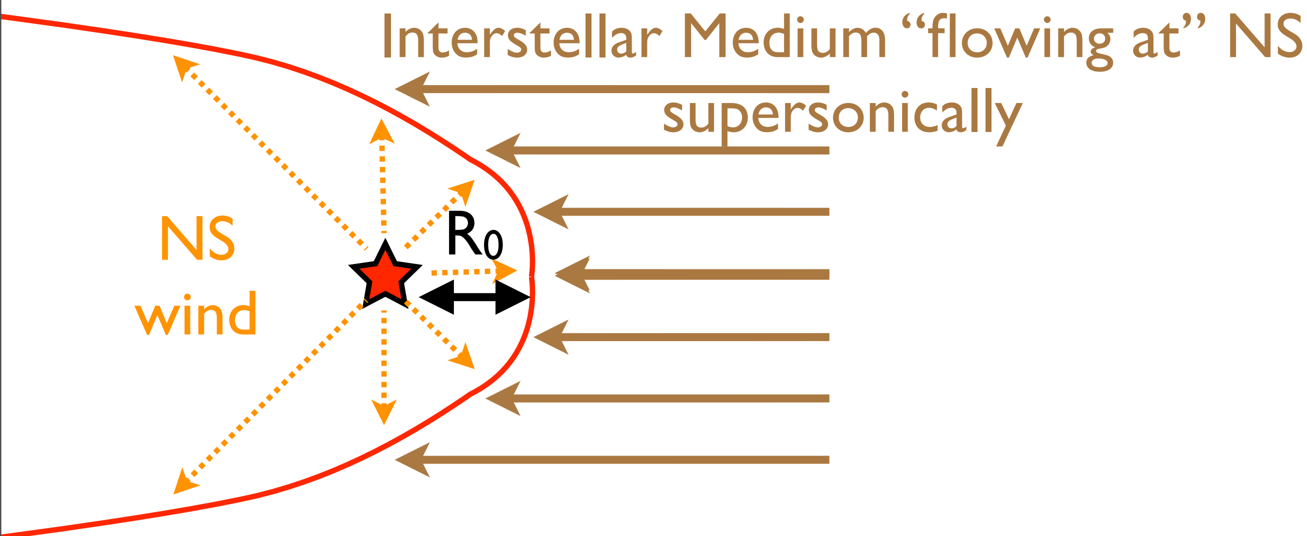

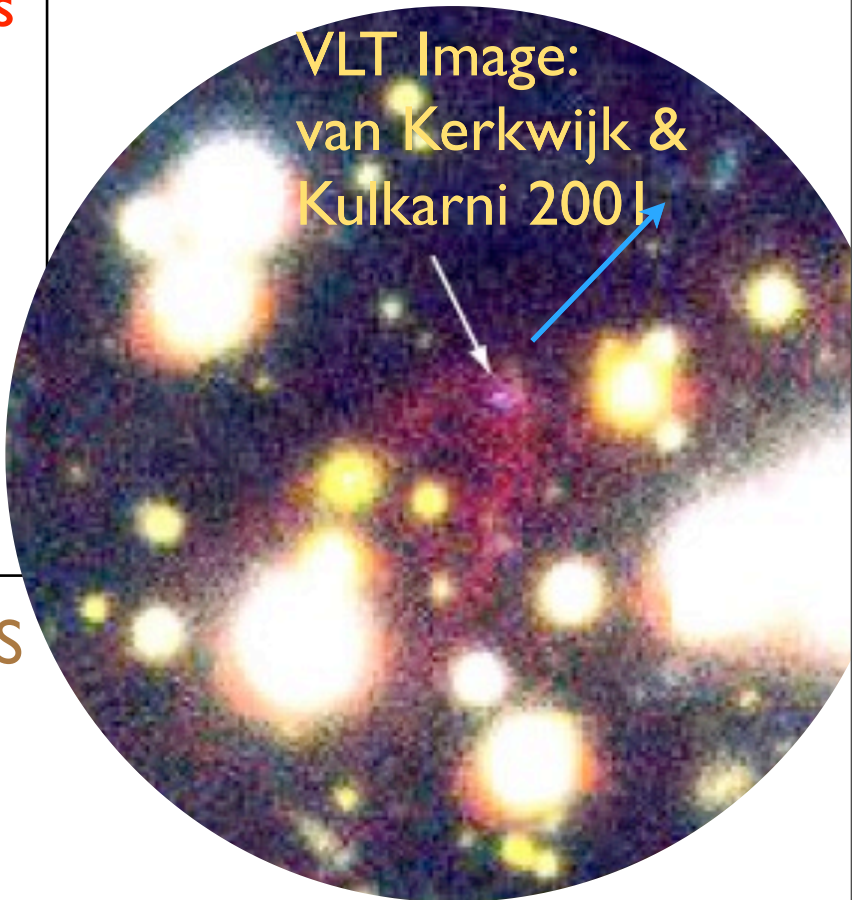

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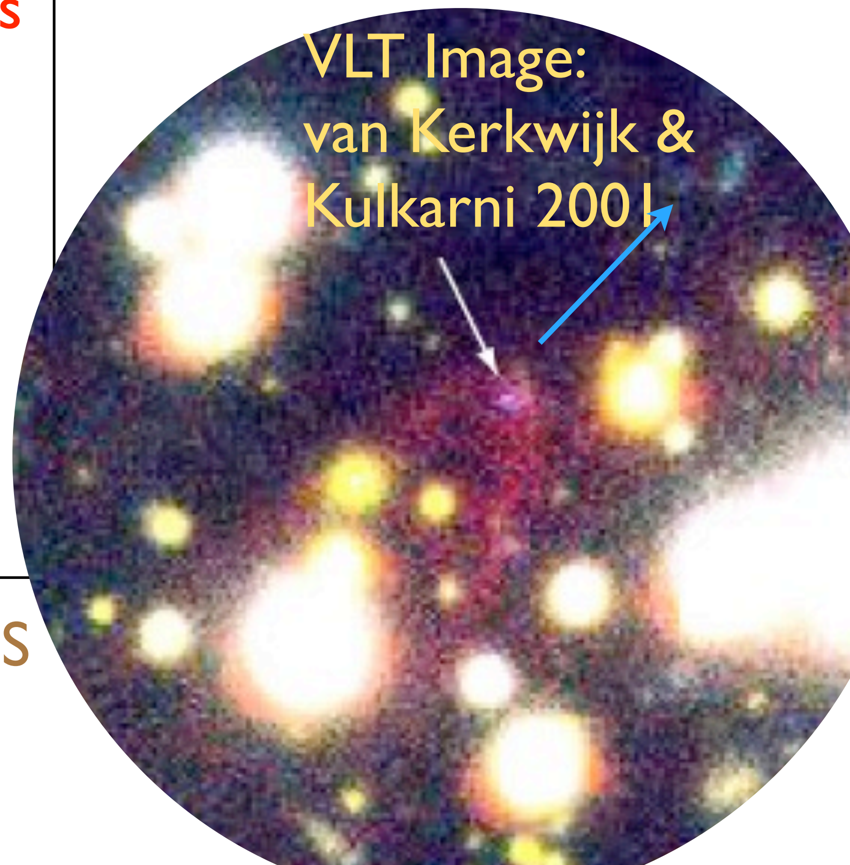
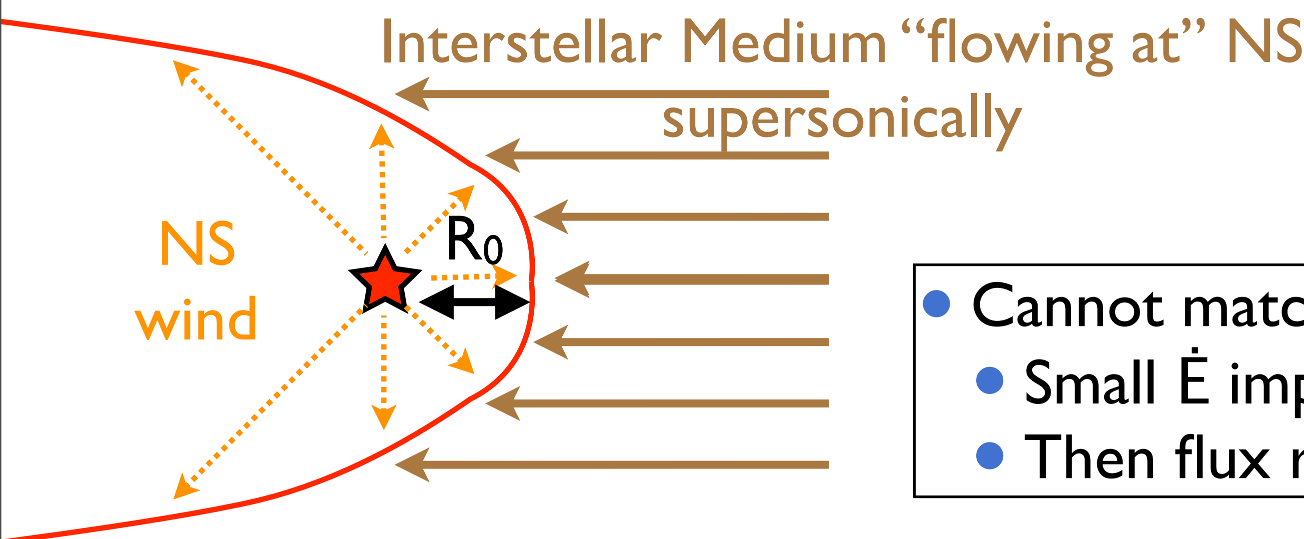
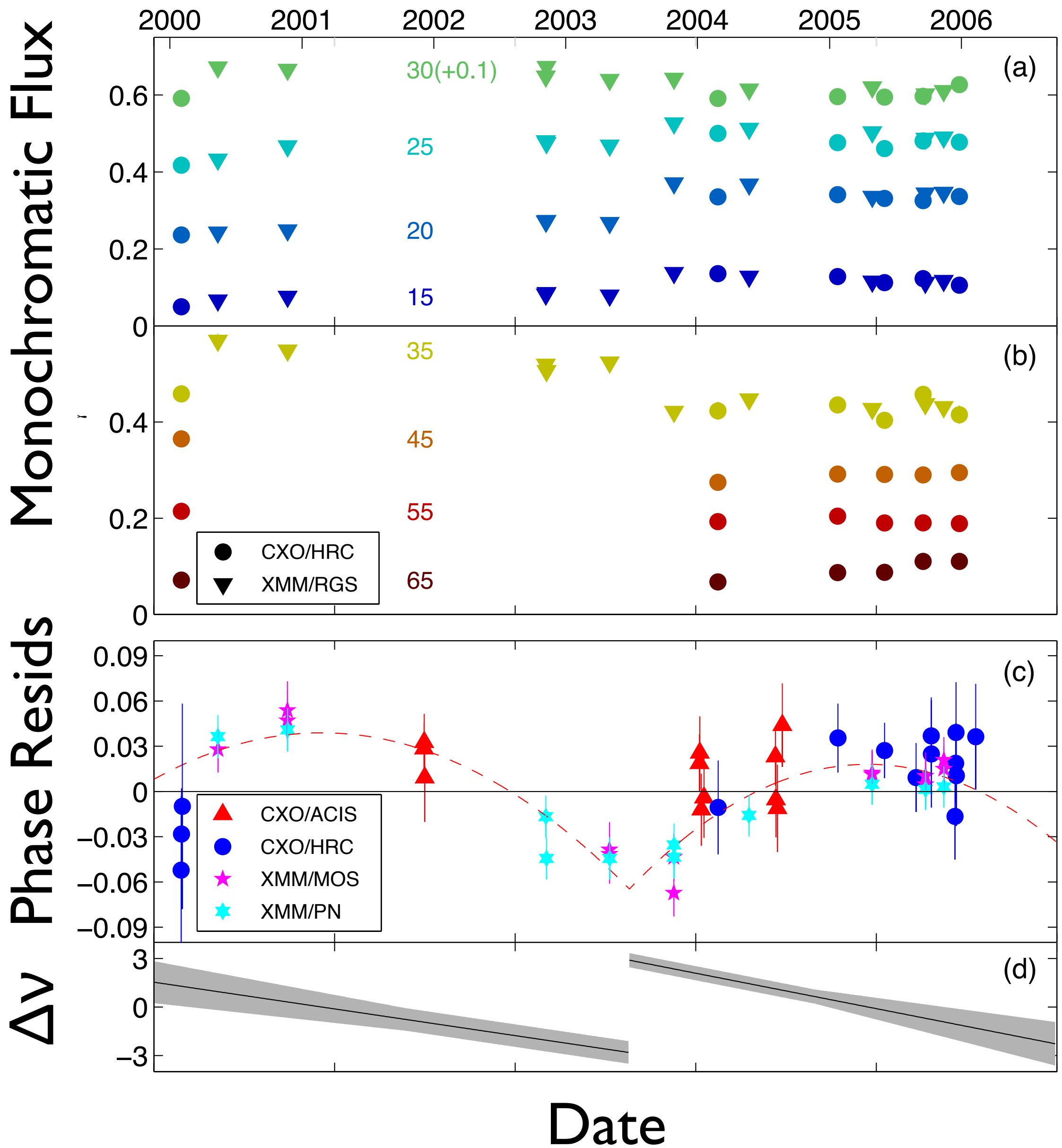




- Cannot match data
  - Small $\dot{E}$ implies tiny density
  - Then flux requires ~30 photons/atom!

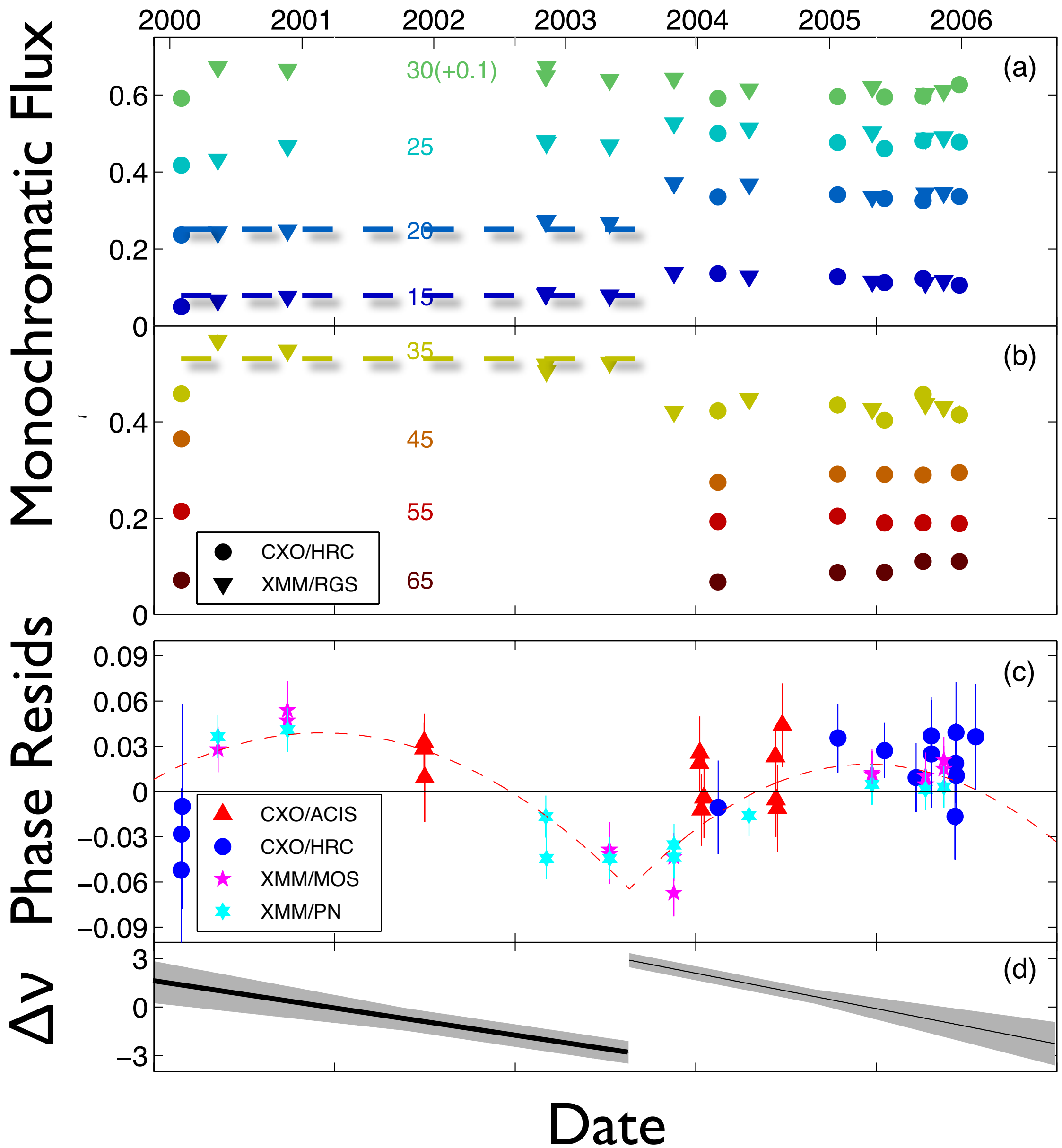
(van Kerkwijk & Kulkarni 2001; van Kerkwijk & Kaplan 2008)

RX J0720: Variability



van Kerkwijk, Kaplan et al. '07

RX J0720: Variability



van Kerkwijk, Kaplan et al. '07

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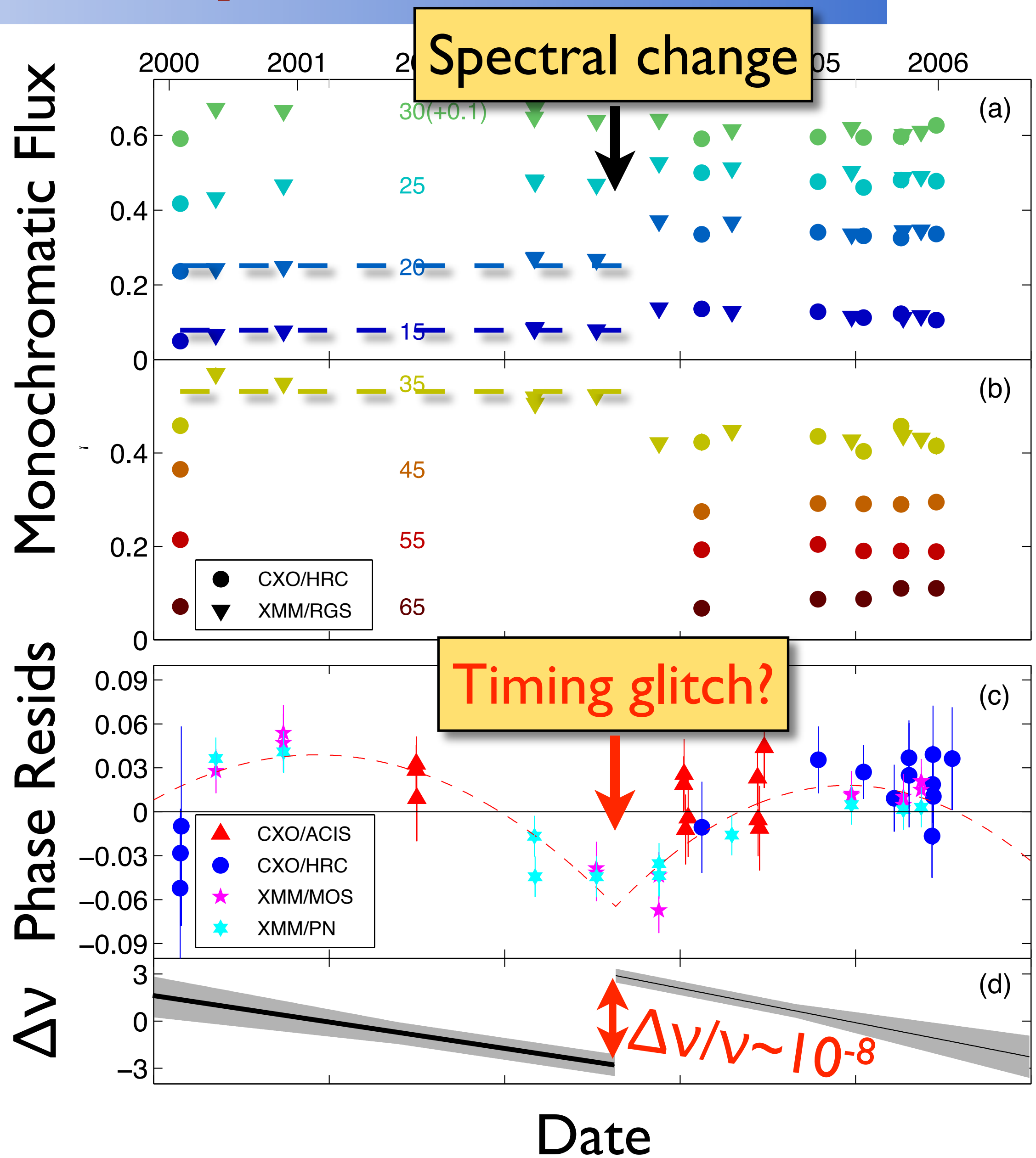
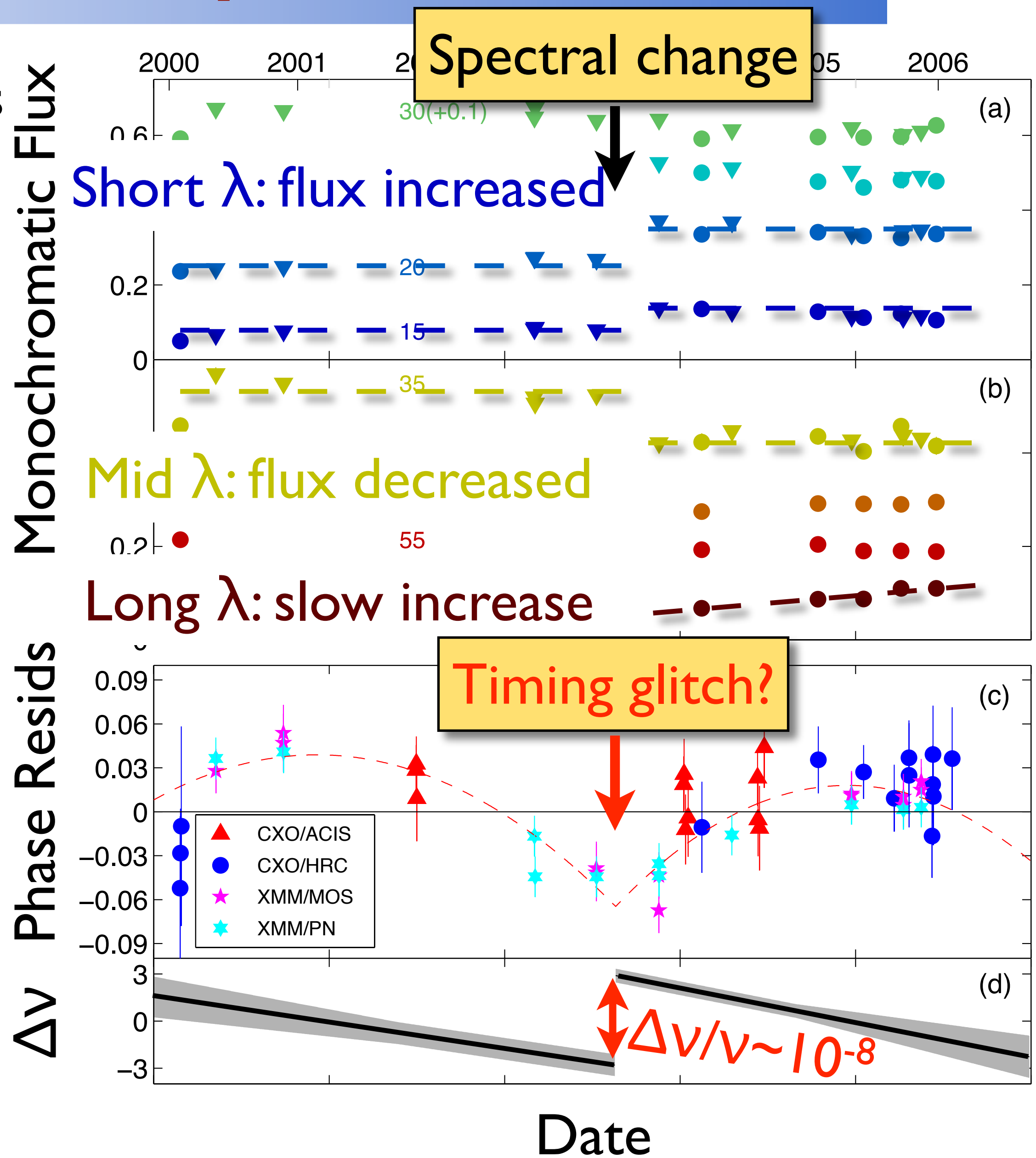


van Kerkwijk, Kaplan et al. '07

RX J0720: Variability

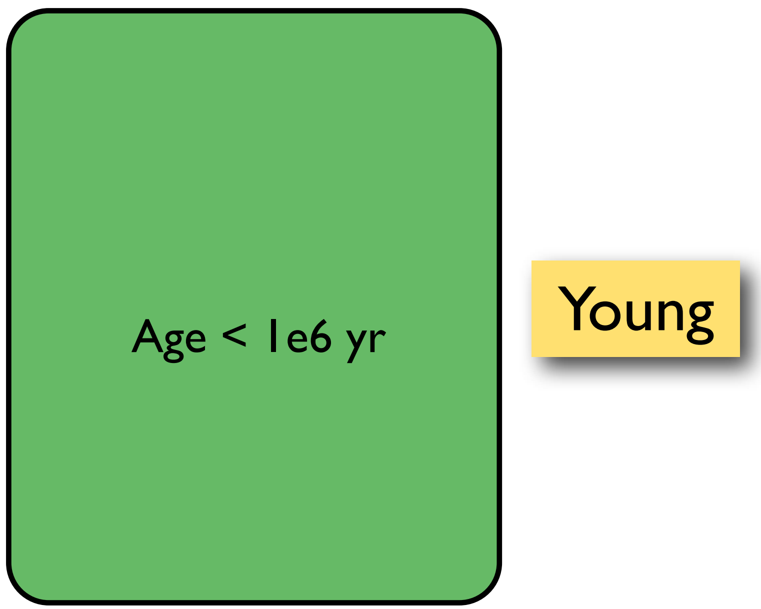
- Spectrum changed over ~months (de Vries et al. '04)
- Same with pulse profile, phase
- Affected ~40% of surface

- Still working on nature of change:
  - Free precession?
  - Glitch related to coupling of superfluid core to crust via *B*?
  - Change in *B* topology or currents?
  - Accretion of debris/dust?
- Also see Hohle et al. 2009



van Kerkwijk, Kaplan et al. '07

Demographics: PSRs vs. INS



- INS are significant fraction (up to 50%) of nearby sources
- But no PSRs resemble INS
- Radio quiet:
  - Old pulsar: non-thermal emission has shut off?
  - Expect narrow radio beams for long P
- Extends B dist'n upward (as with pulsars; Vranesevic et al., Faucher-Giguère & Kaspi)

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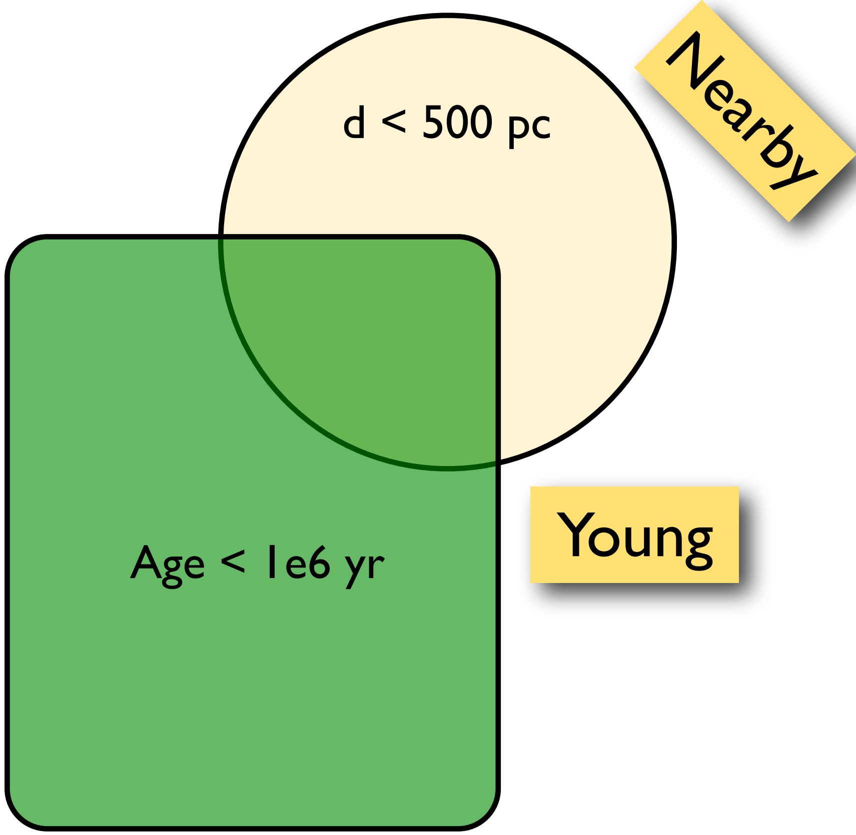

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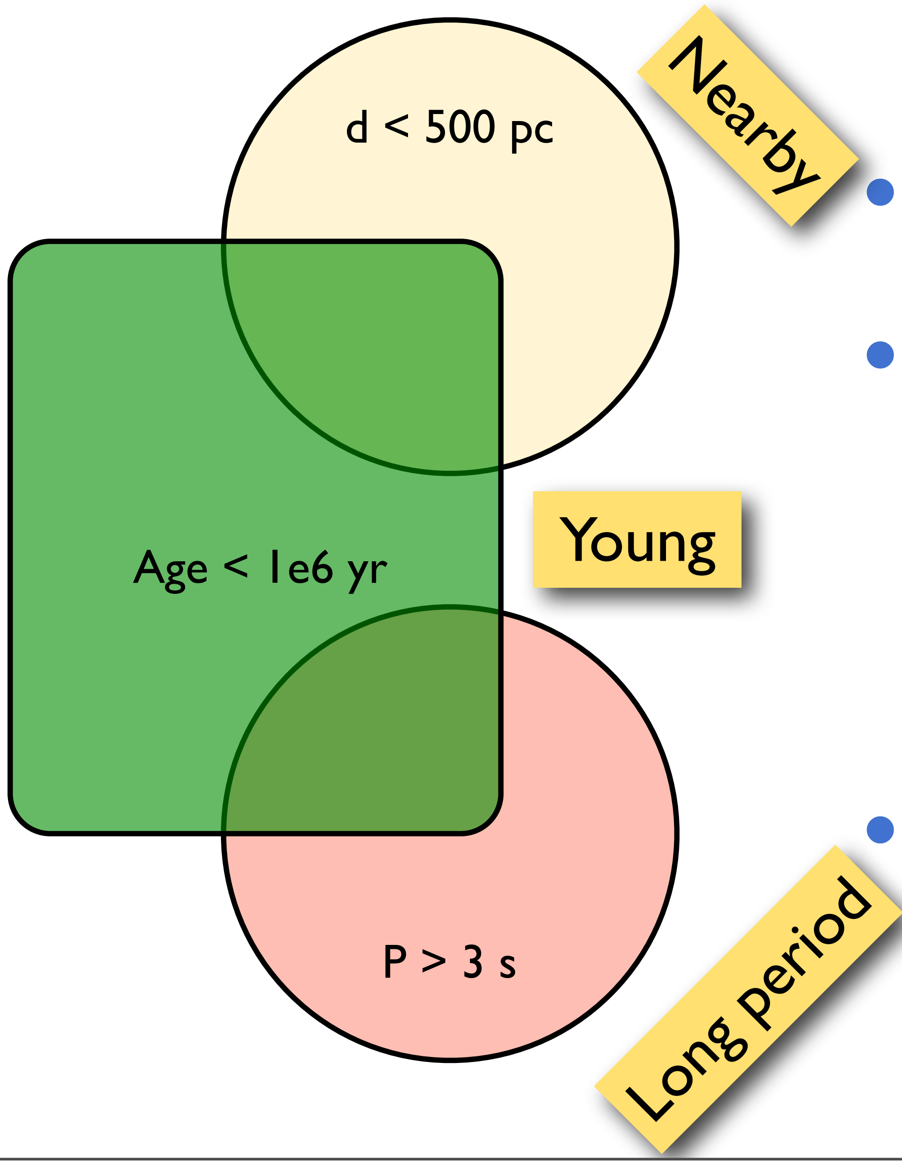

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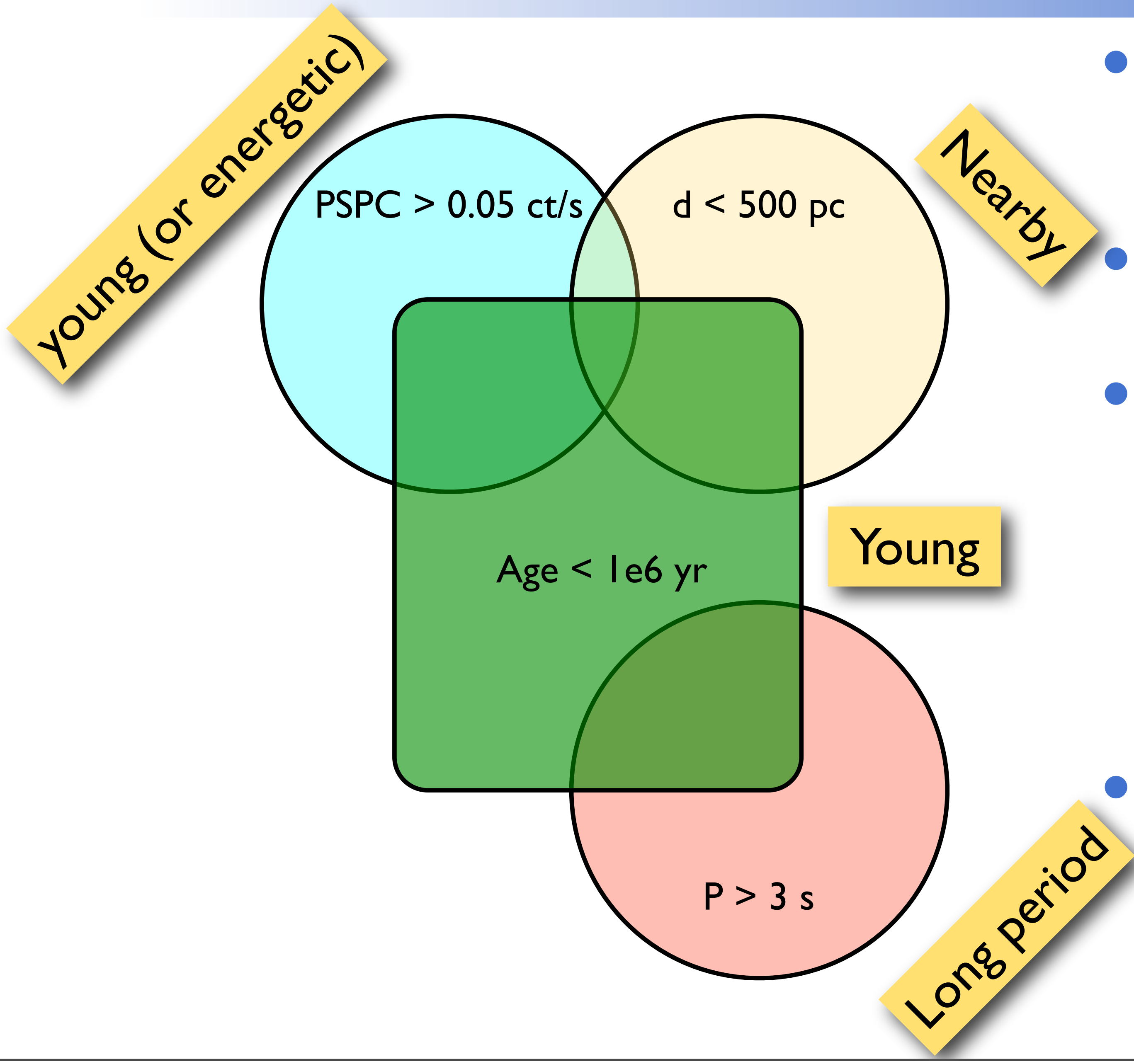

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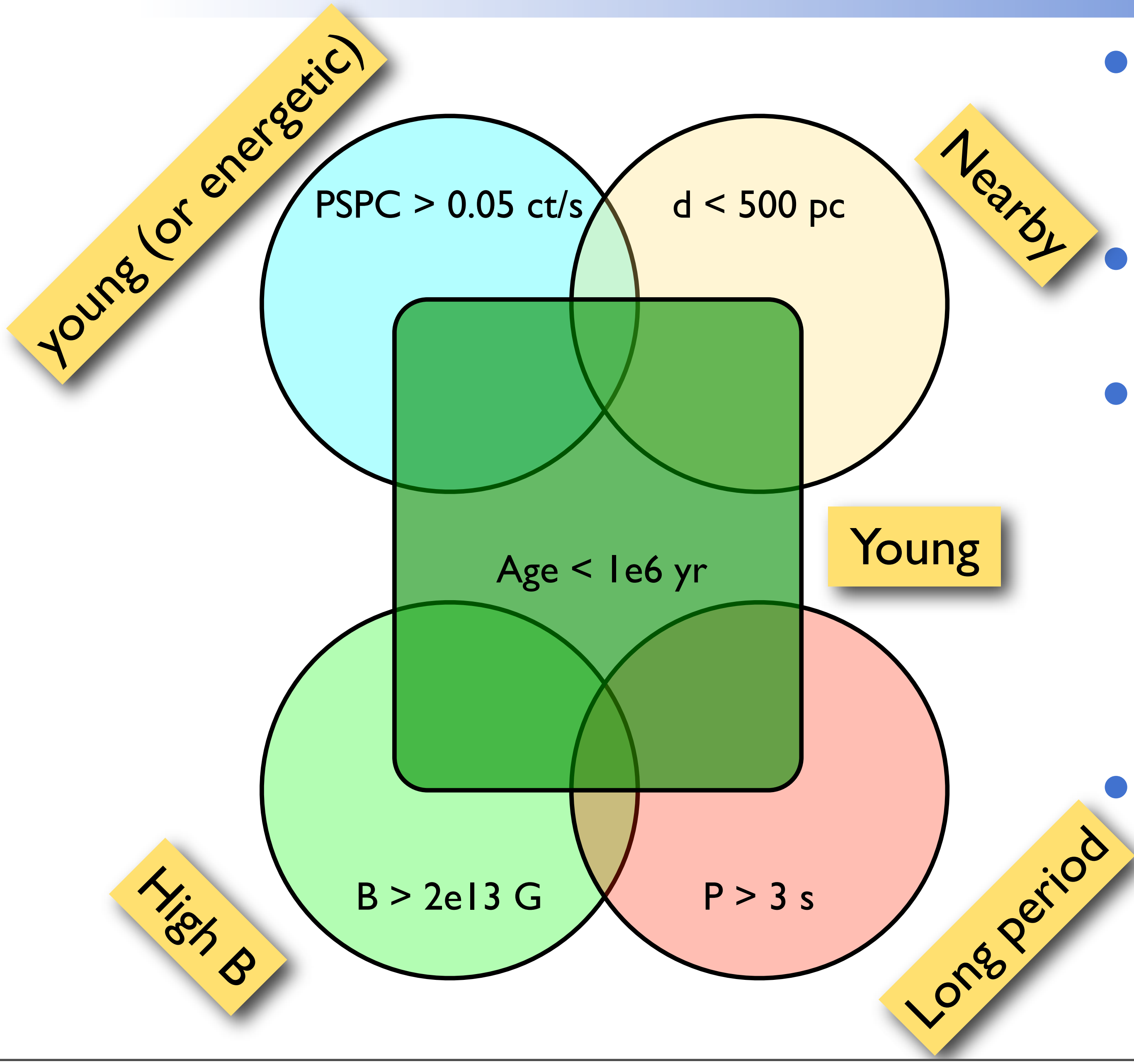

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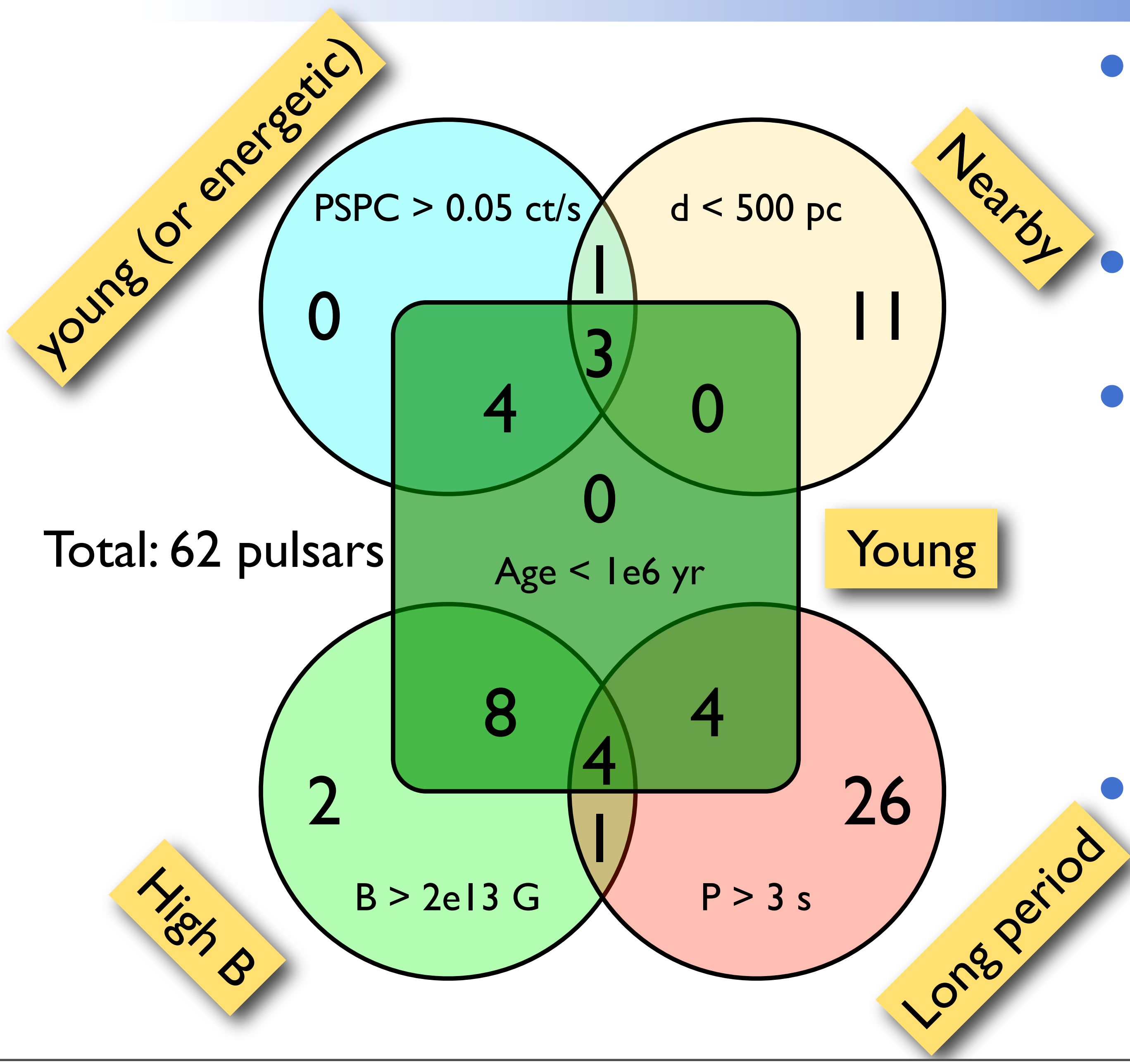

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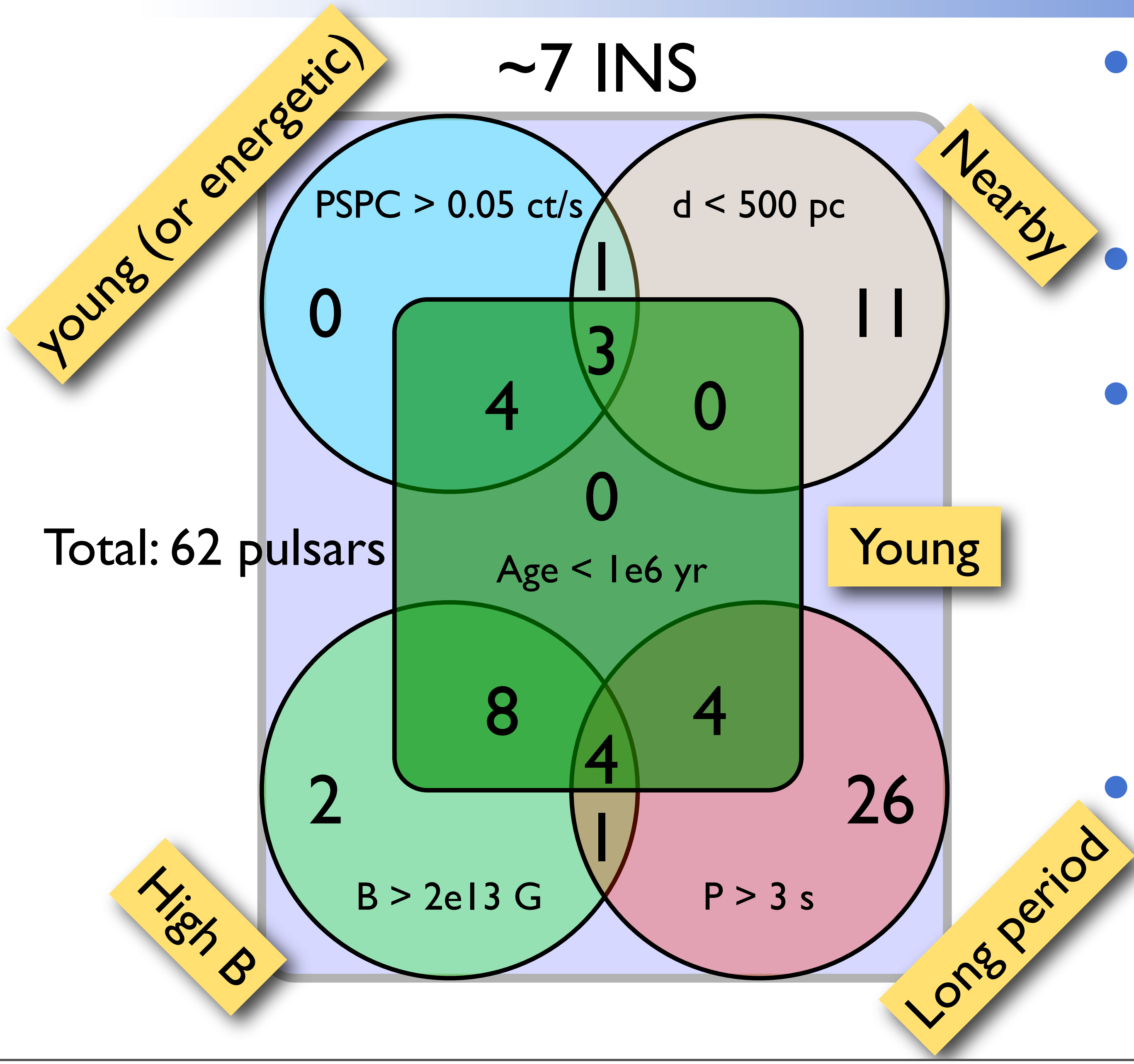

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