Nearby, Thermally Emitting Neutron Stars:

Laboratories for Extreme Physics

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UW INT
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Introduction

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- Physics goals:
  - cooling
  - extreme densities
  - extreme magnetic fields

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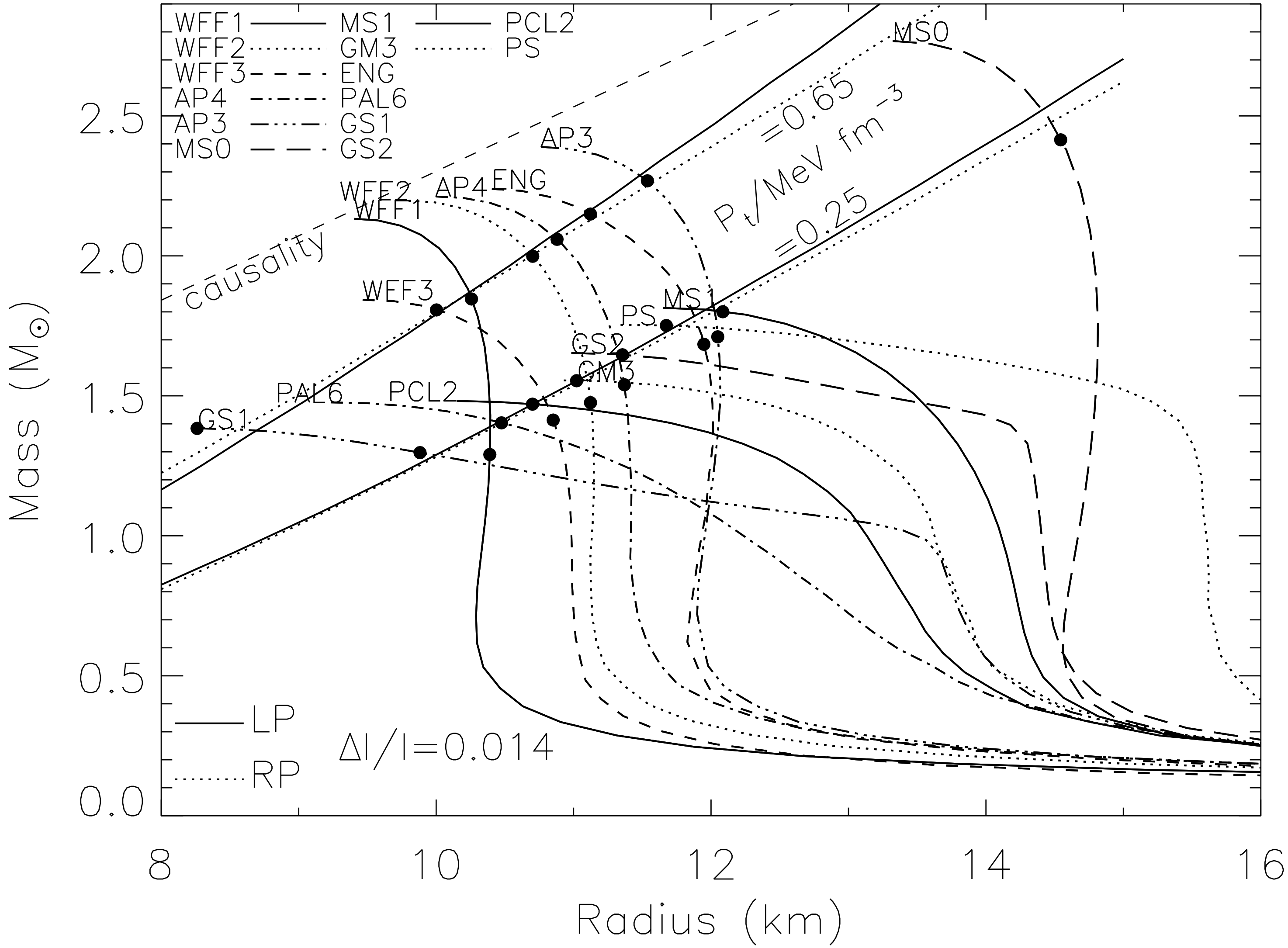
- Physics goals:
  - cooling
  - extreme densities
  - extreme magnetic fields
- What **observations** do we need?

Equation of State: Radius & Mass



(Lattimer & Prakash 2000)

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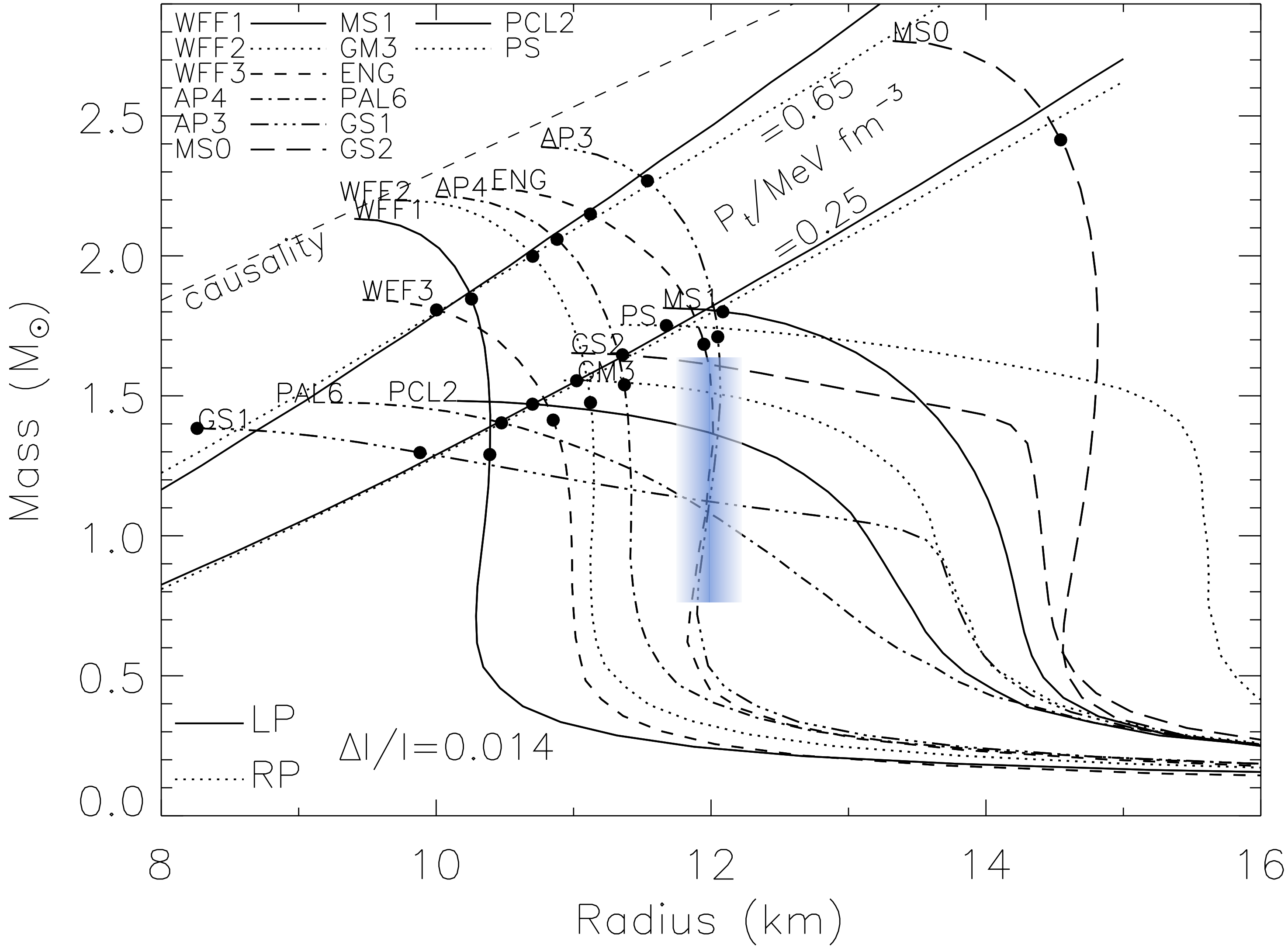

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Goal: Populate Cooling Diagram

- Models incorporate interior physics
- Include effects of:
    - Magnetic field
    - Elemental abundances
- **mass** can change cooling

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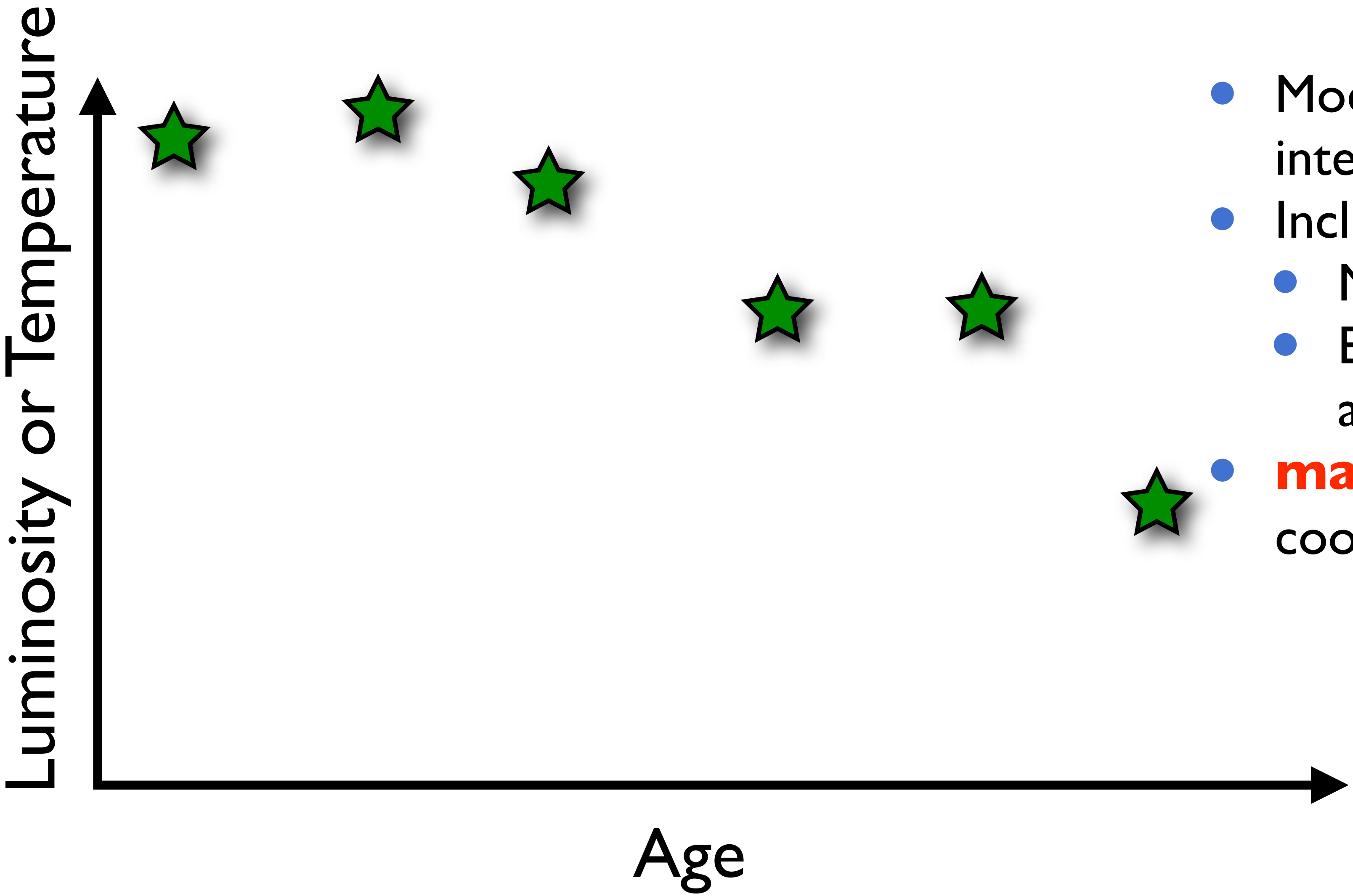

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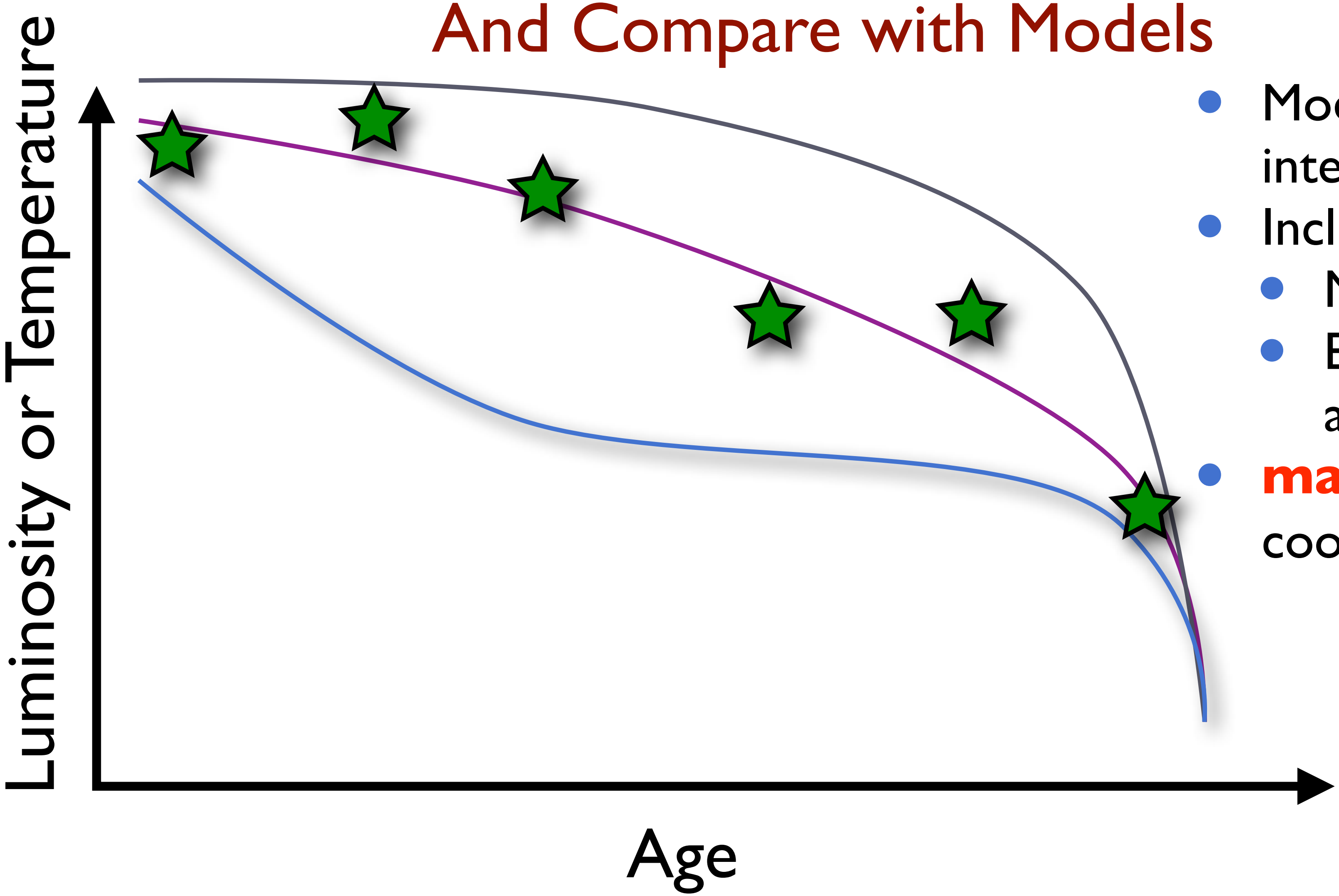

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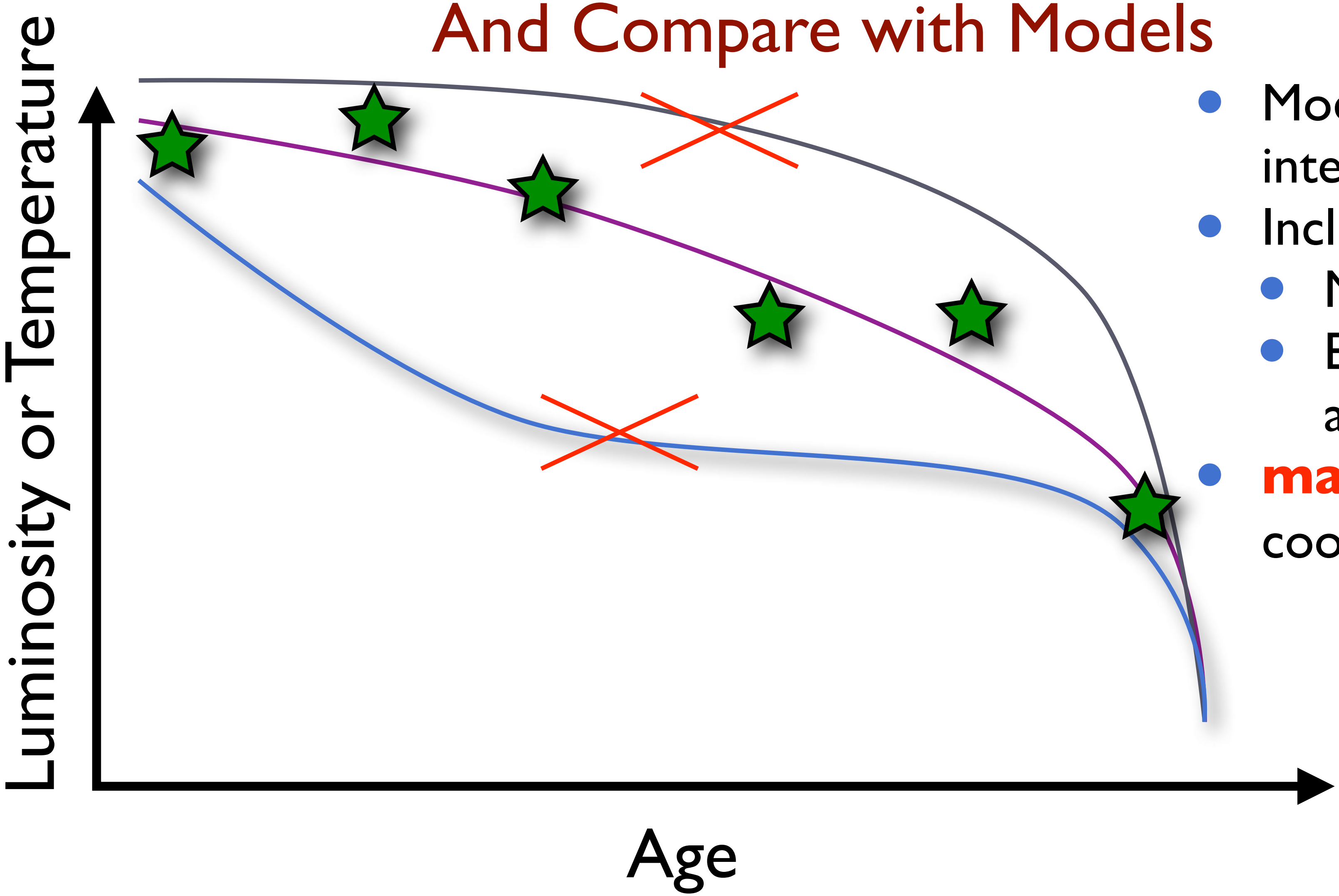

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Other Methods for EOS

- Fastest spin of millisecond pulsars (Chakrabarty): best limit does not constrain EOS (but see Kaaret et al. '06)
- Binary mass measurements (Thorsett & Chakrabarty): new measurements (Ransom; Nice) may be important
- Quiescent X-ray Binaries (Rutledge; Heinke): known distances, but *faint* & unknown physics
- Gravitational redshift (Cottam): one source, one observation (also see Özel '06)
- Moment of inertia of double pulsar (Kramer): may be possible in 5-10 years

Types of Cooling Isolated NSs

- Young ($<10^4$ yrs) in supernova remnants
  - active (radio) pulsars (Crab, Vela, 3C 58)
  - radio-quiet Central Compact Objects (Cas A, Puppis A)
- Middle-aged ($<10^6$ yrs)
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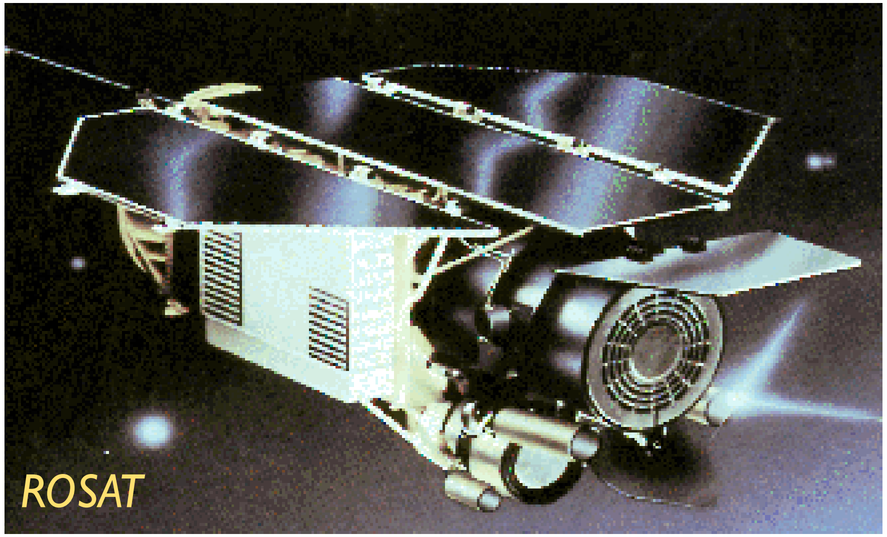

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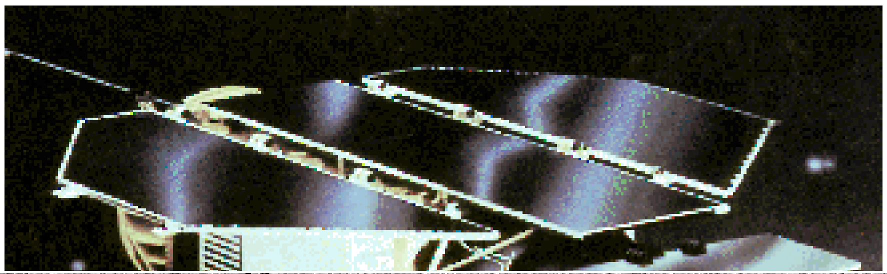

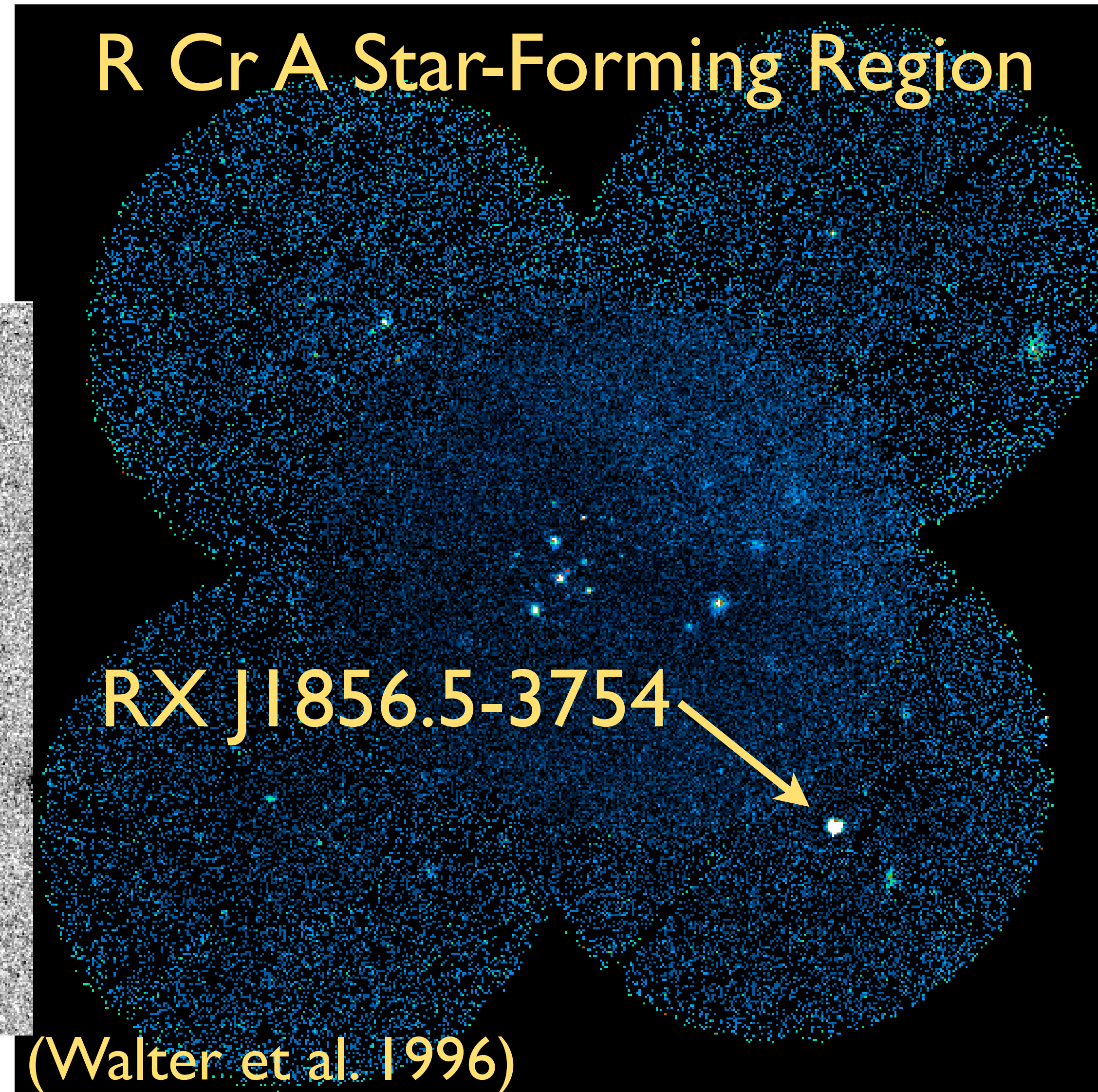

Isolated Neutron Stars

- Bright, cool X-ray sources w/ very faint optical counterparts
- Currently 7 with no extra complications
- Properties:
  - temperatures ~ 1 million degrees
  - spin periods > 3 sec.
  - nearby, < 1 kpc

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- Bright, cool X-ray sources w/ very faint optical counterparts
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- Properties:
  - temperatures ~ 1 million degrees
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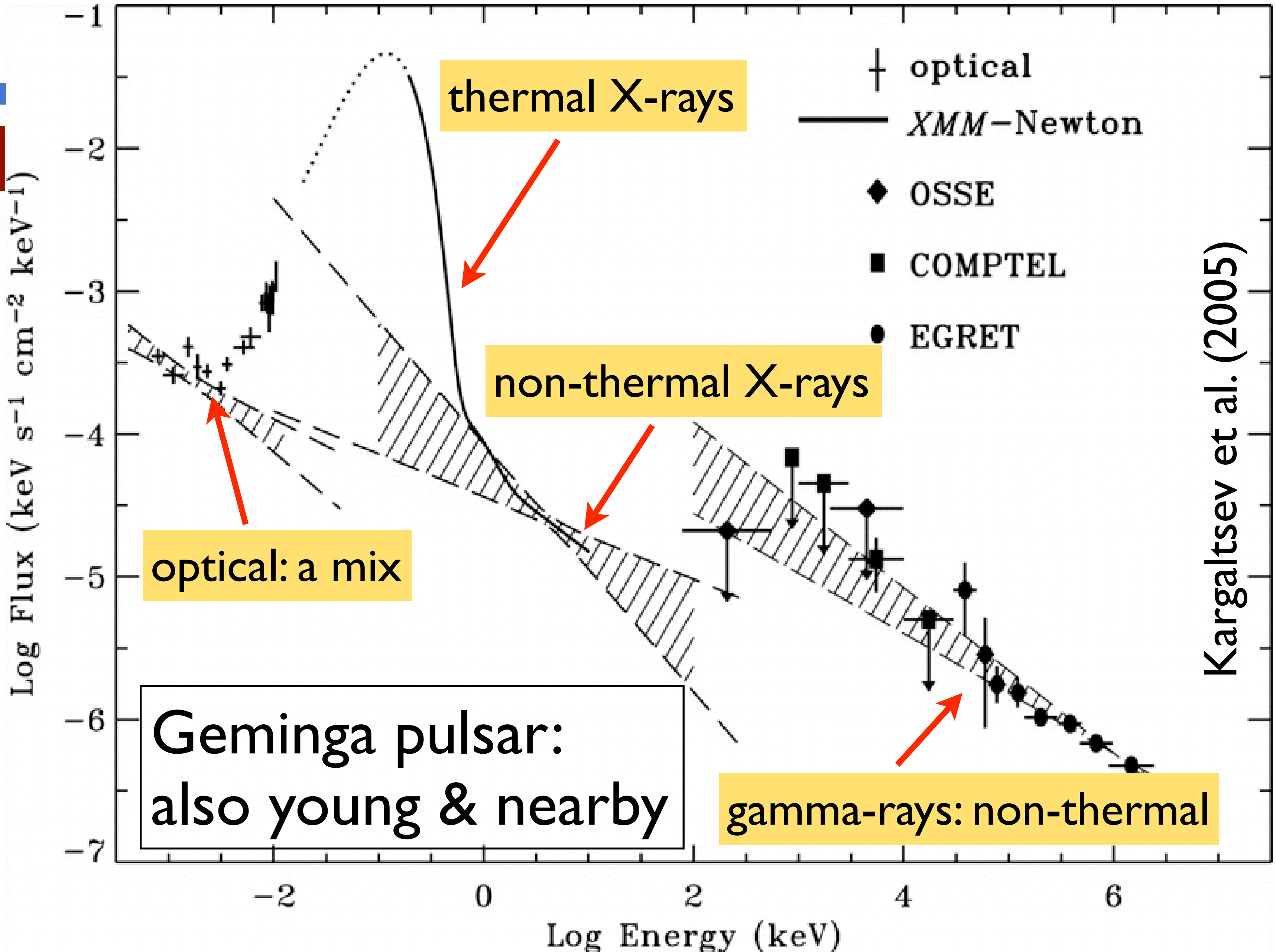
- Why this sample?
  - Nearby → bright
  - Relatively young → can use for cooling curves
  - Emission is thermal → comes only from surface



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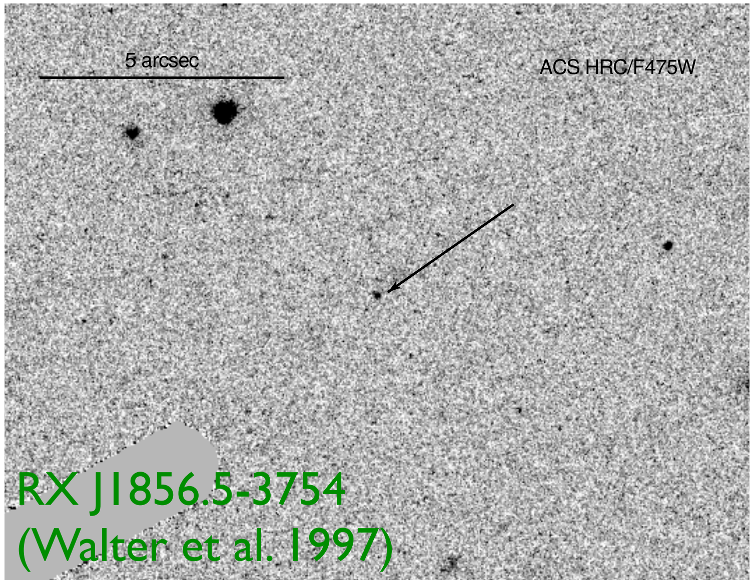
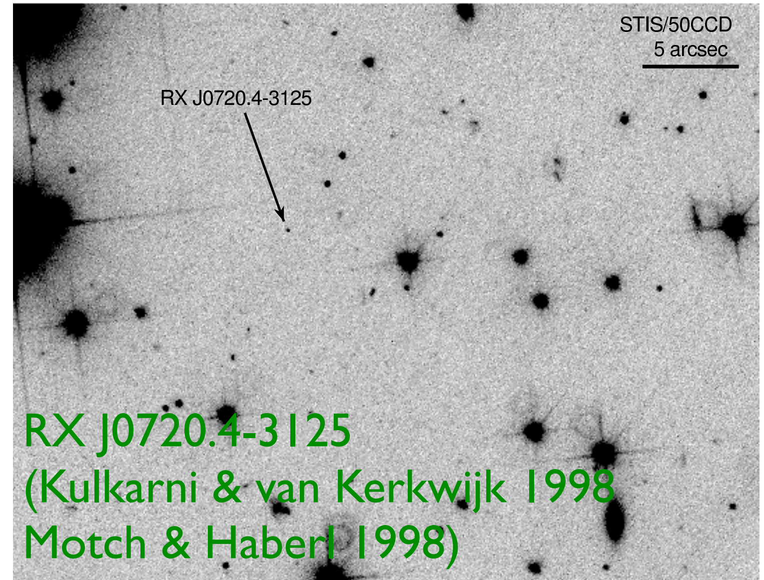
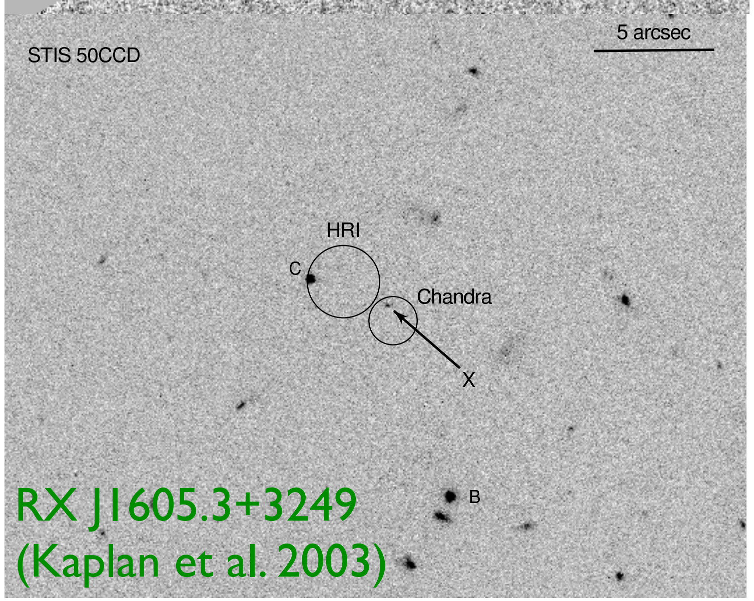
Optical Counterparts



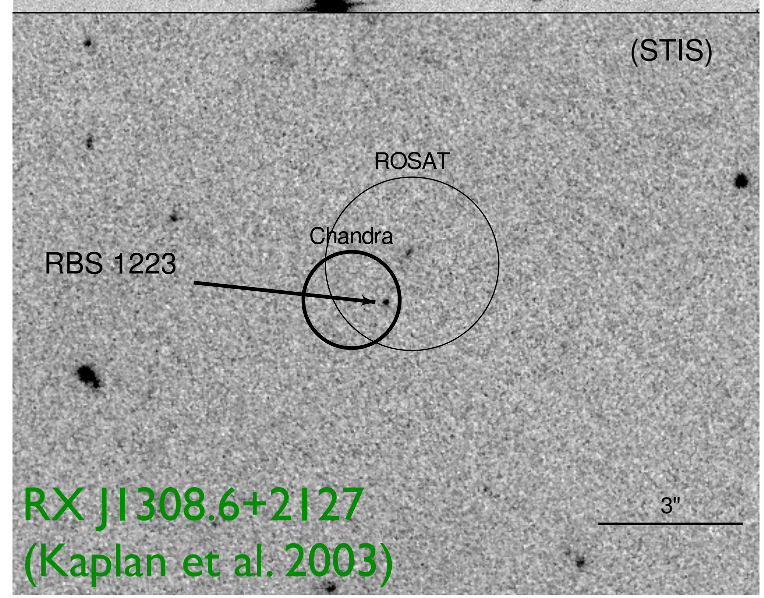
RX J1856.5-3754
(Walter et al. 1997)



RX J0720.4-3125
(Kulkarni & van Kerkwijk 1998
Motch & Haberl 1998)



RX J1605.3+3249
(Kaplan et al. 2003)



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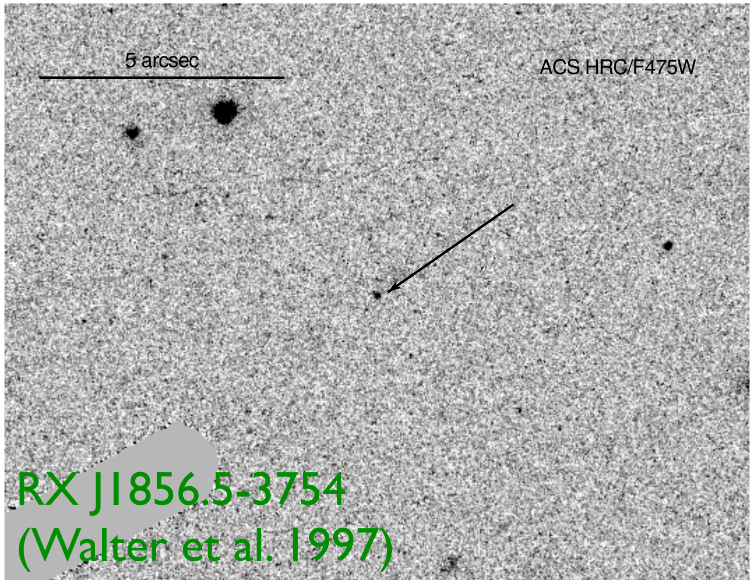

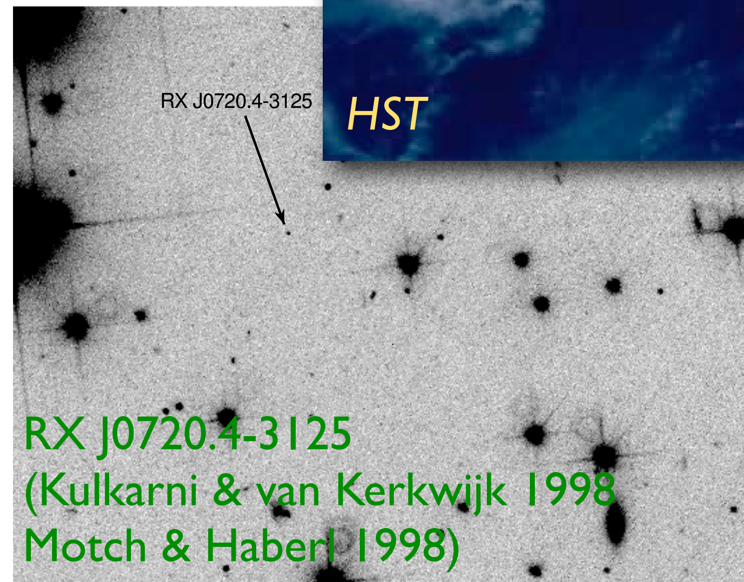

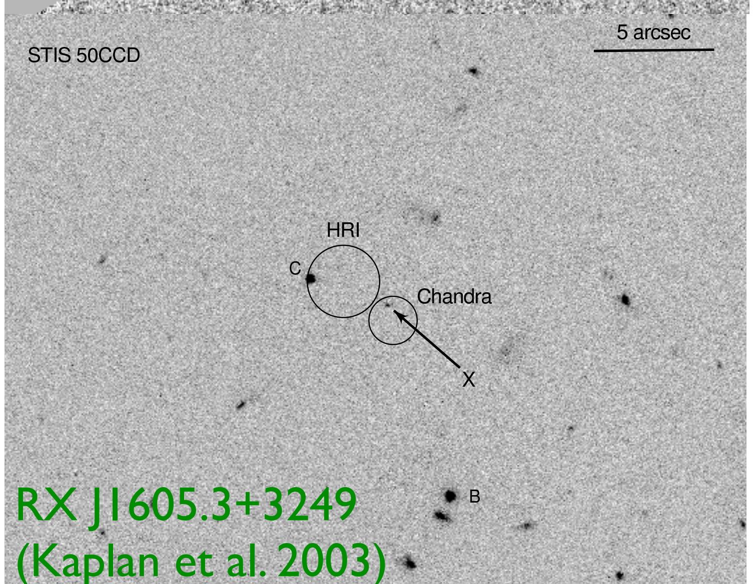

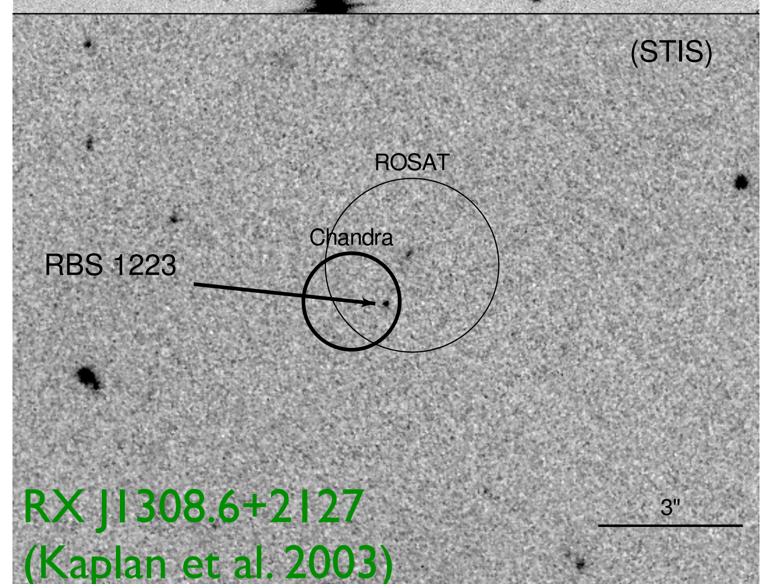

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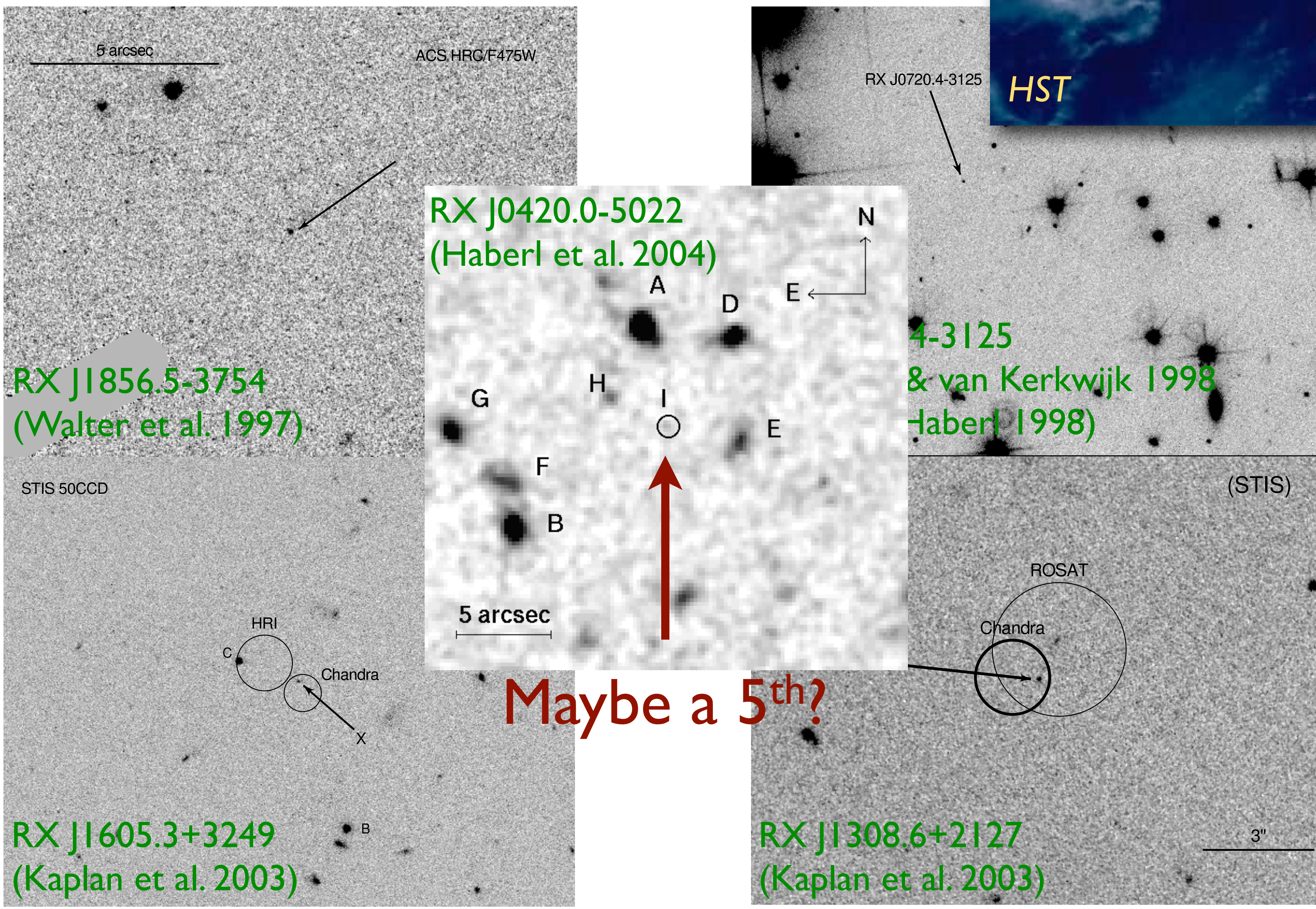

Maybe a 5th?

What Do We Need to Know?

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- For radius:
  - distance: angular size → true size
  - understanding of surface (abundances, *T* & *B* distributions): received flux → true flux

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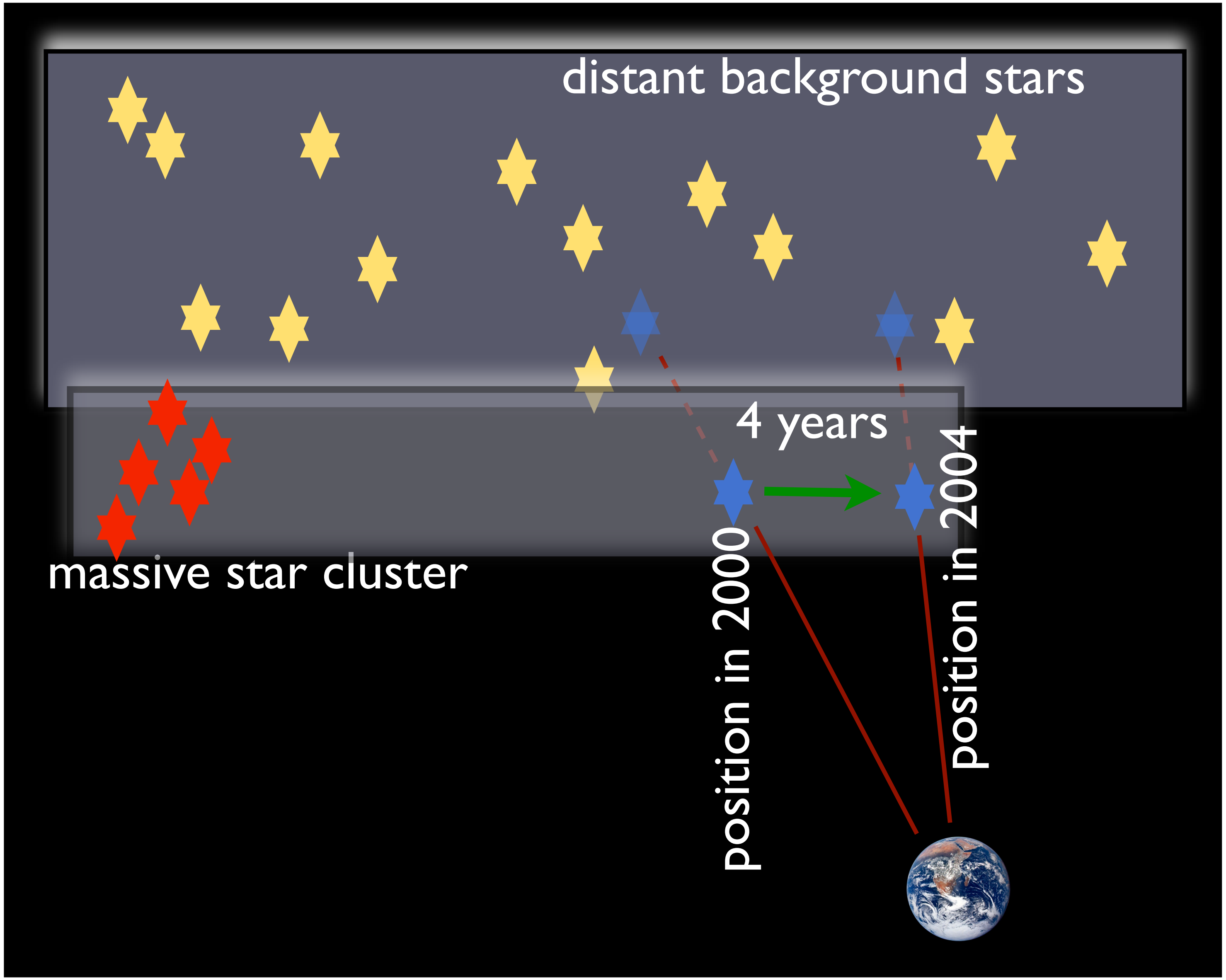
- For radius:
  - distance: angular size→true size
  - understanding of surface (abundances, *T* & *B* distributions): received flux→true flux
- For cooling:
  - age
  - distance: flux→observed luminosity
  - understanding of surface: observed luminosity → total luminosity

Proper Motions: Measuring Ages



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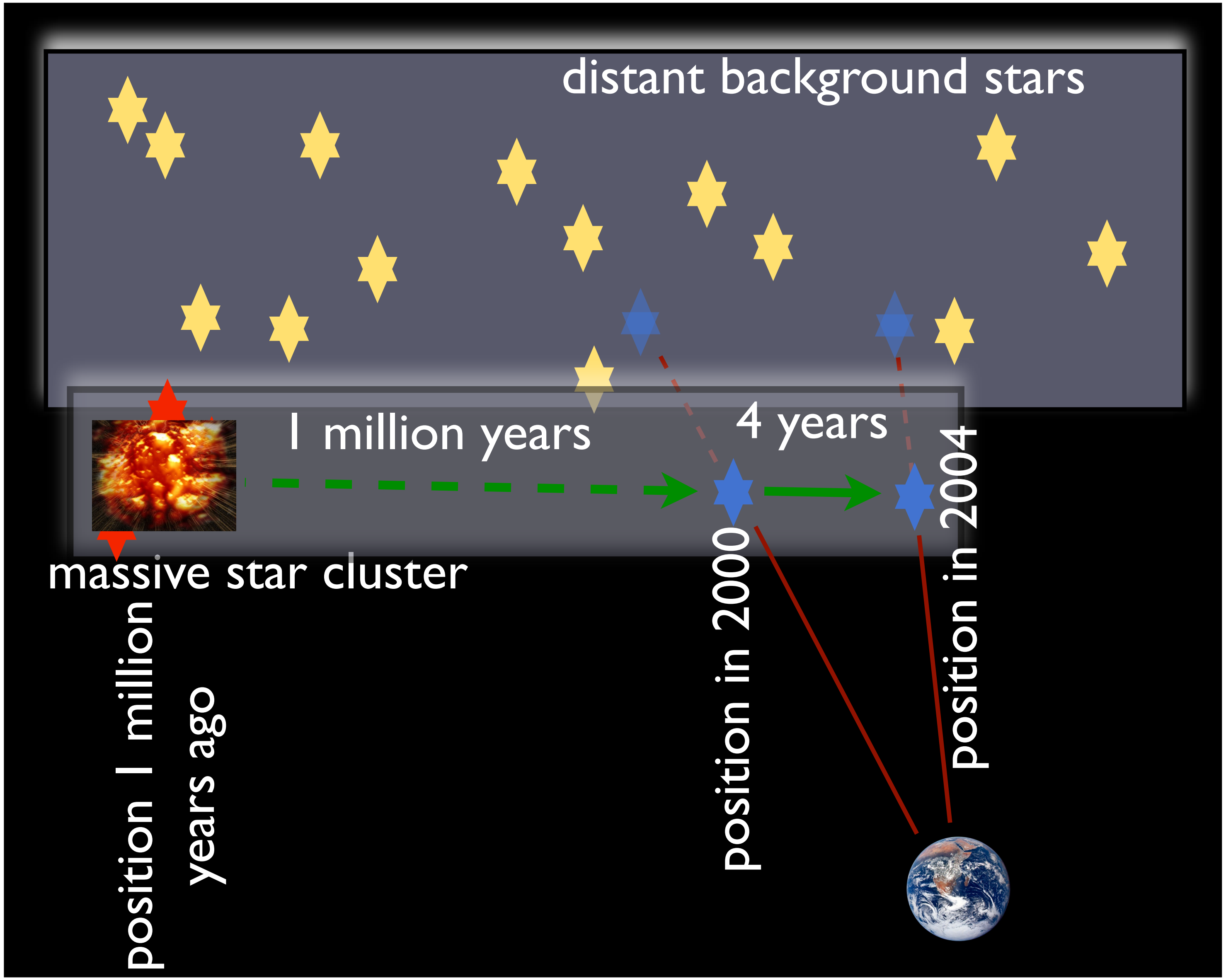
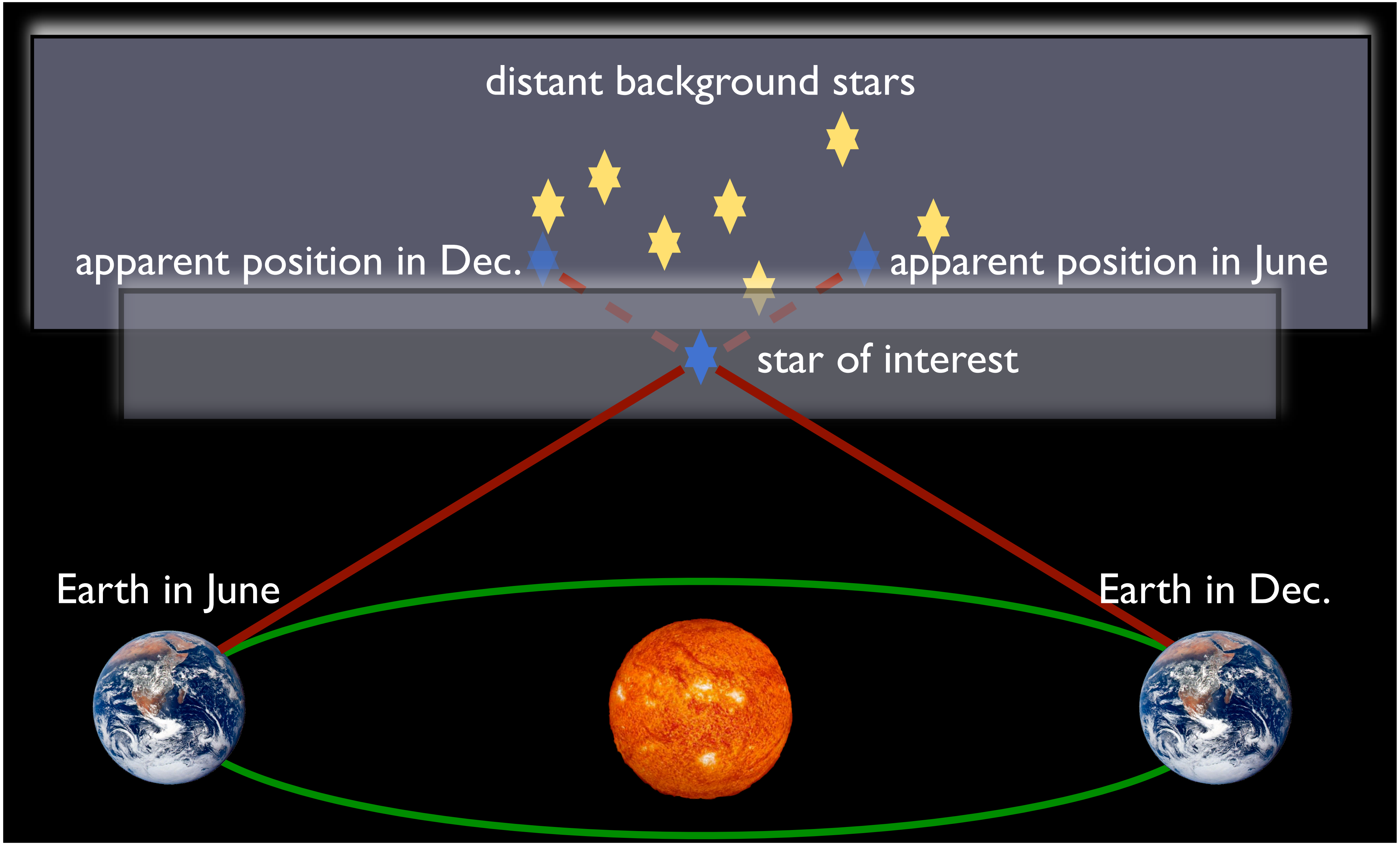


Parallaxes: Measuring Distances



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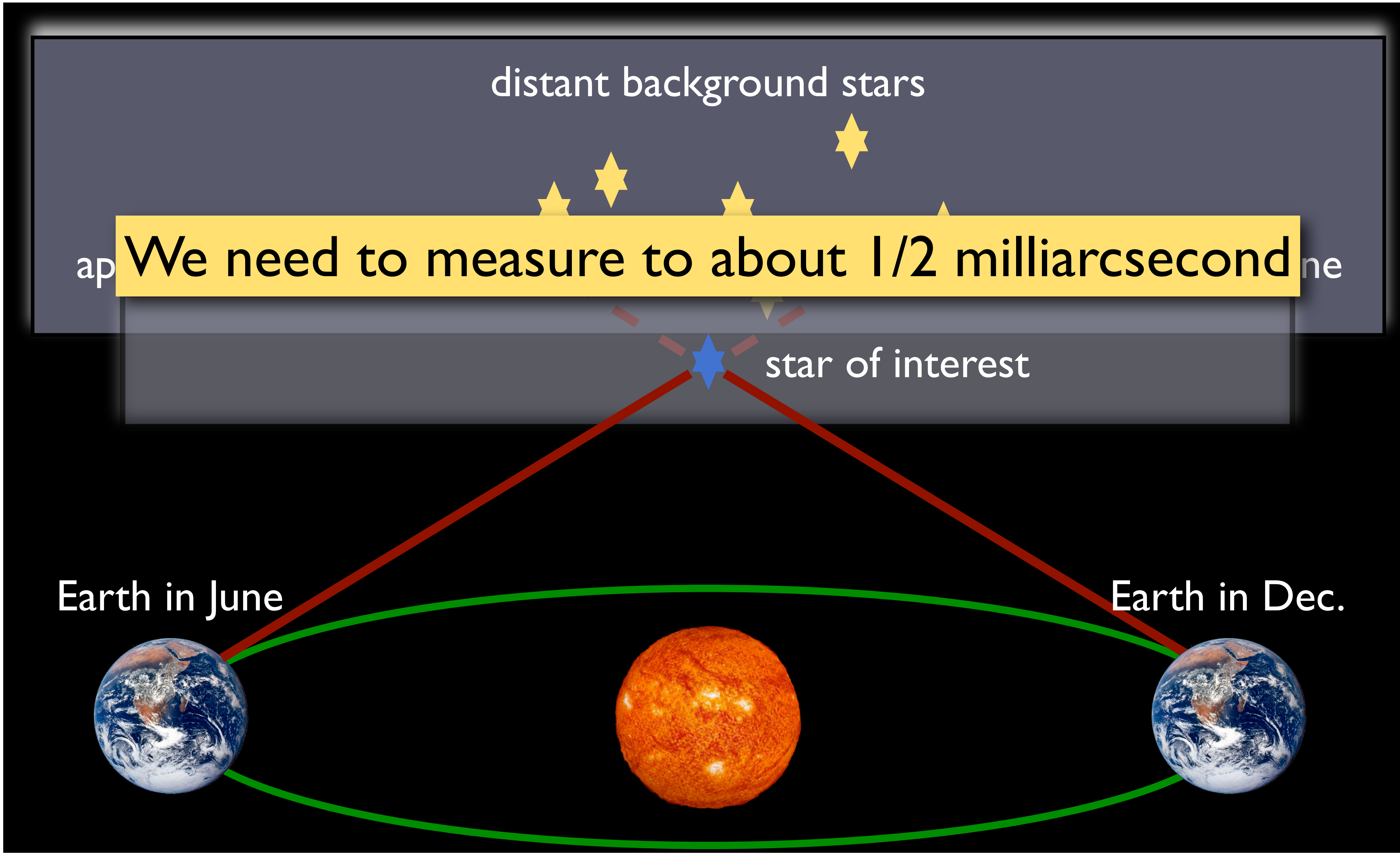

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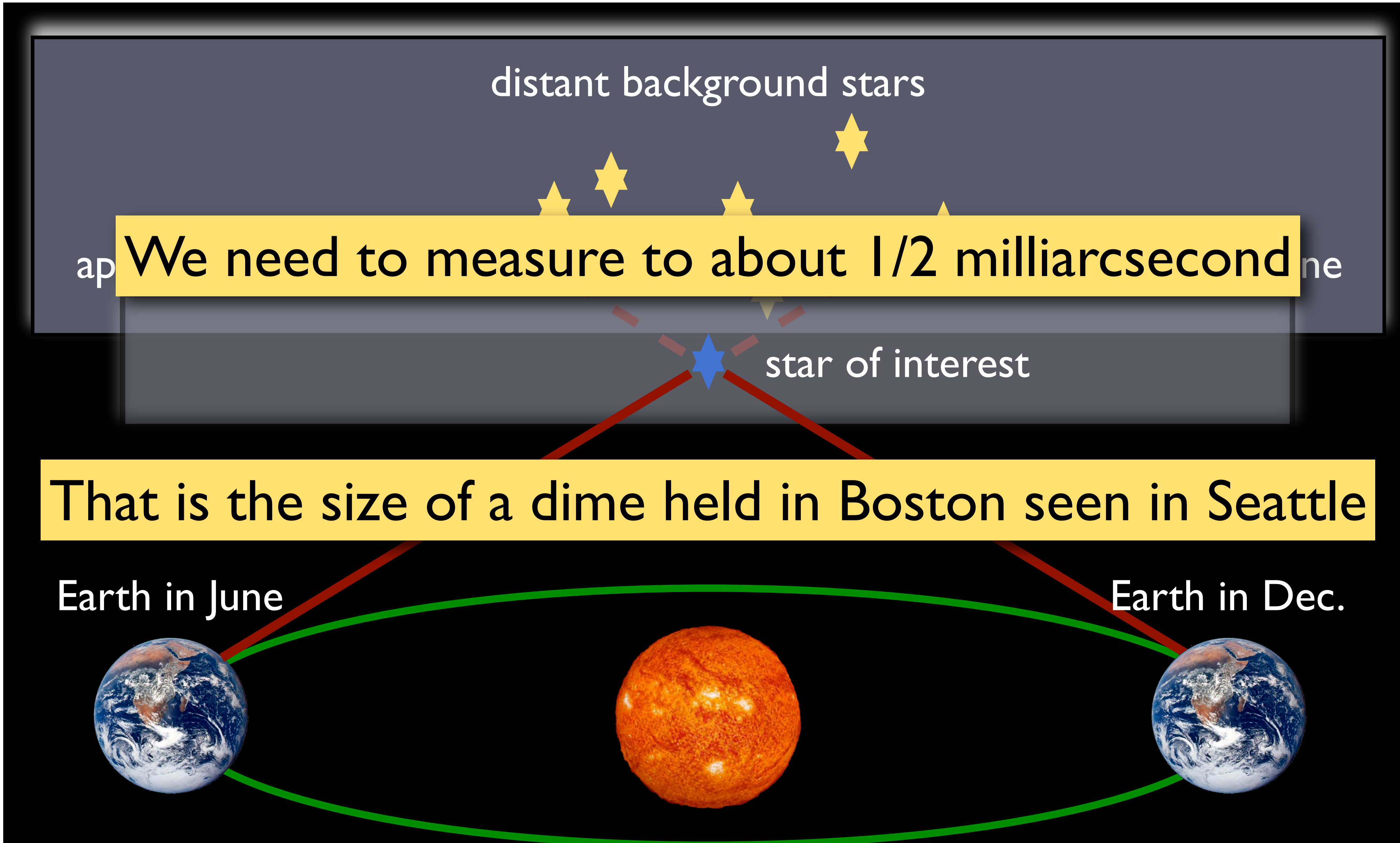
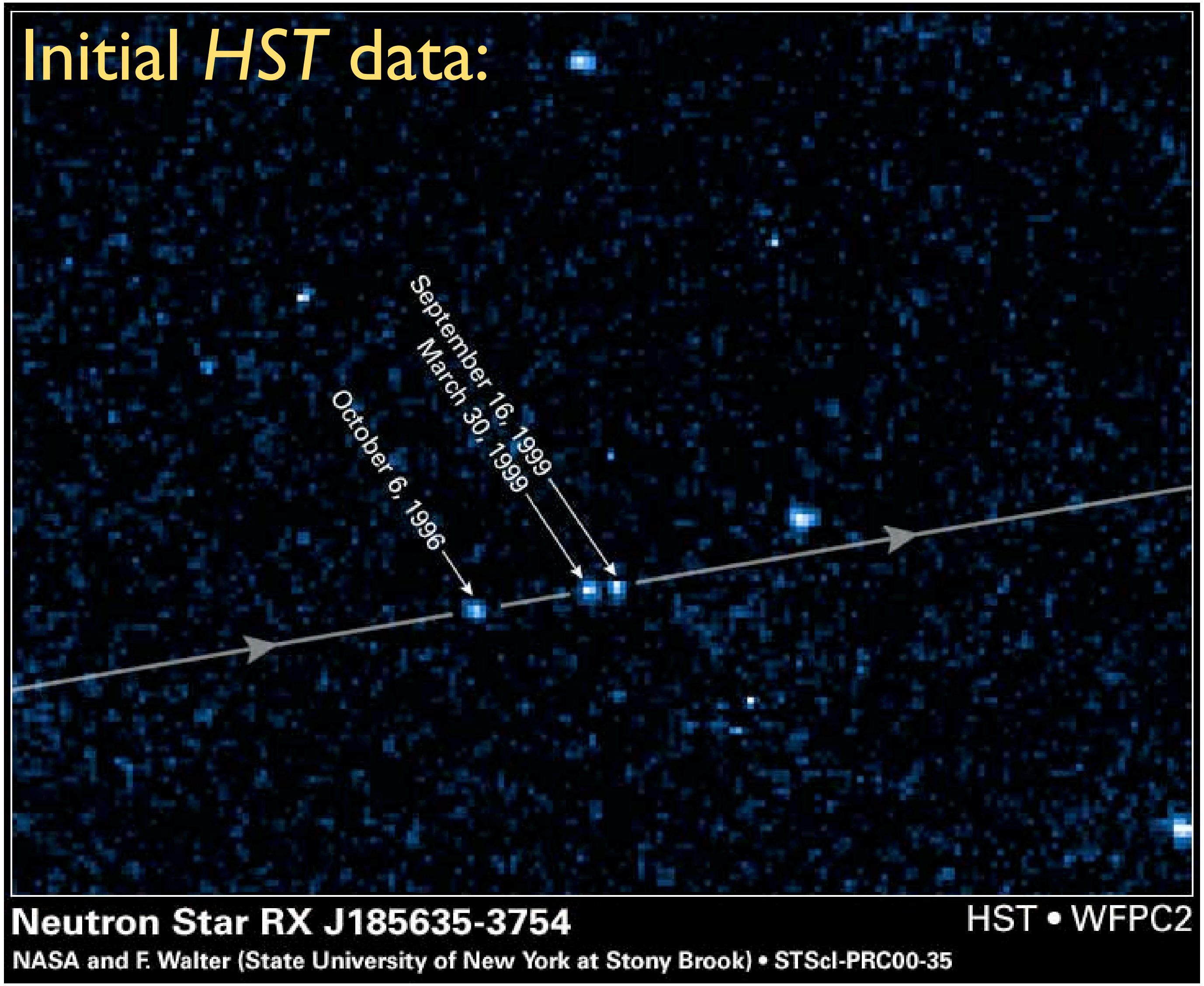


We need to measure to about 1/2 milliarcsecond

That is the size of a dime held in Boston seen in Seattle

Can We Do This? RX J1856:



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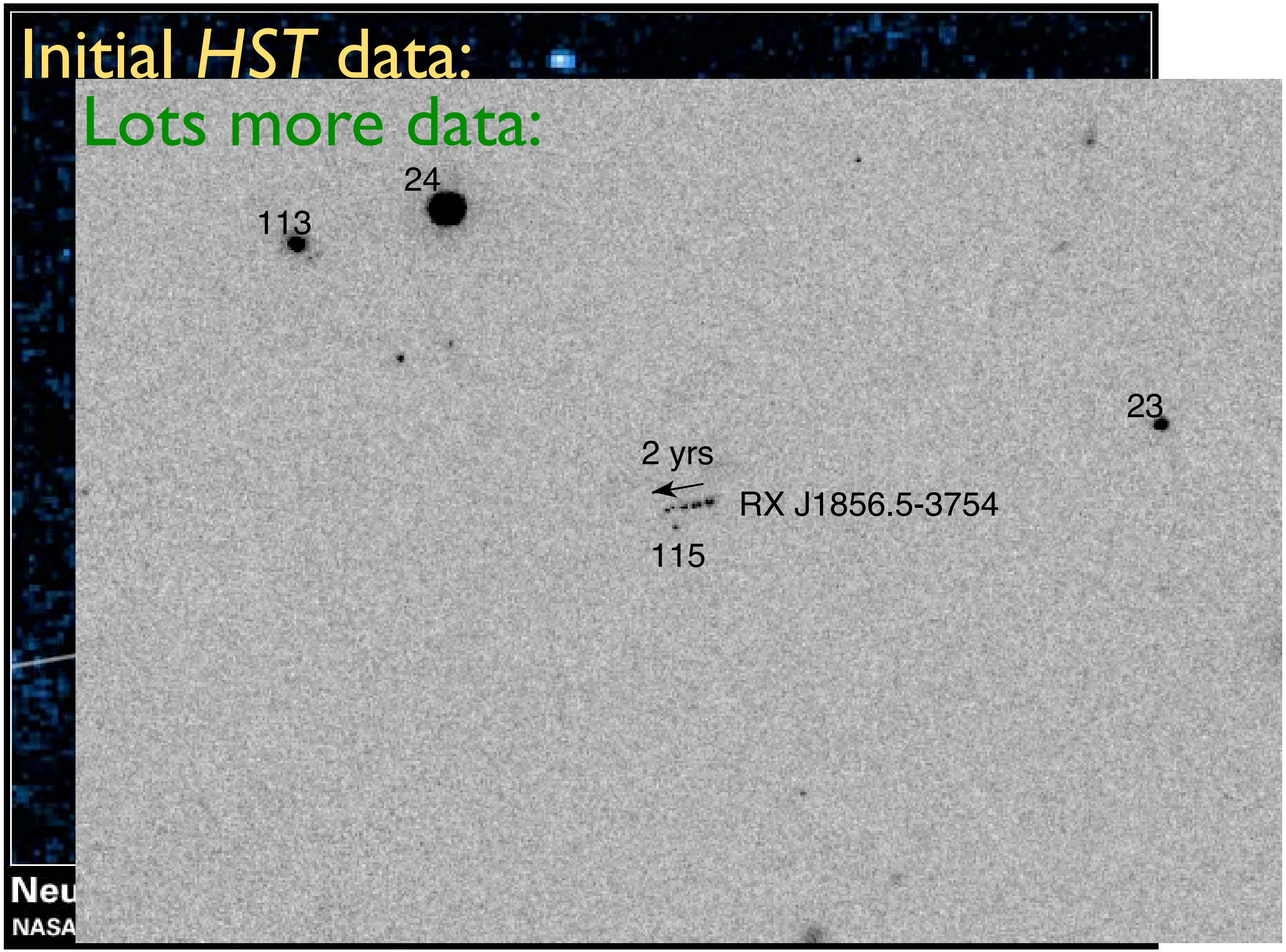

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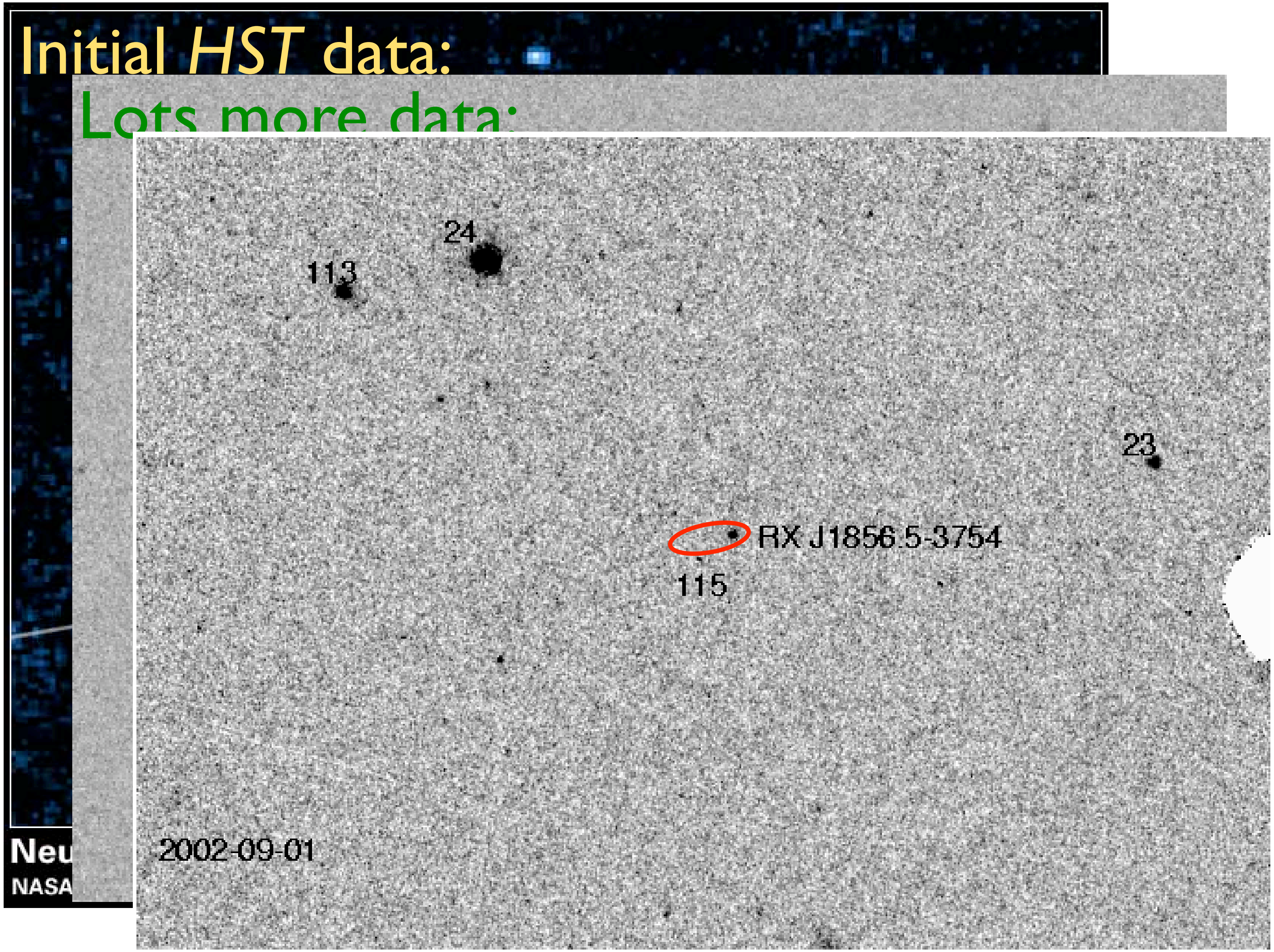

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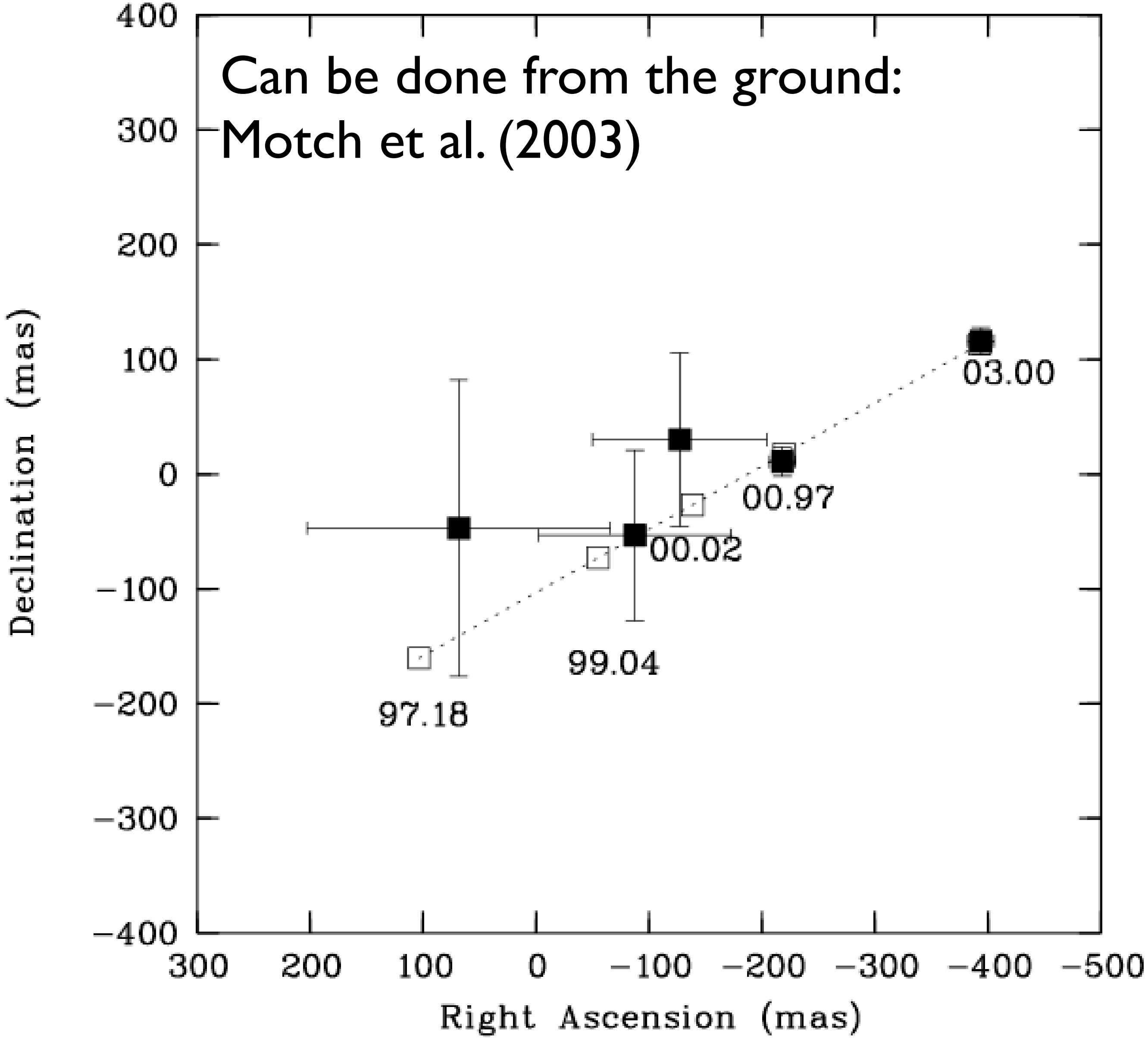
Another Case: RX J0720



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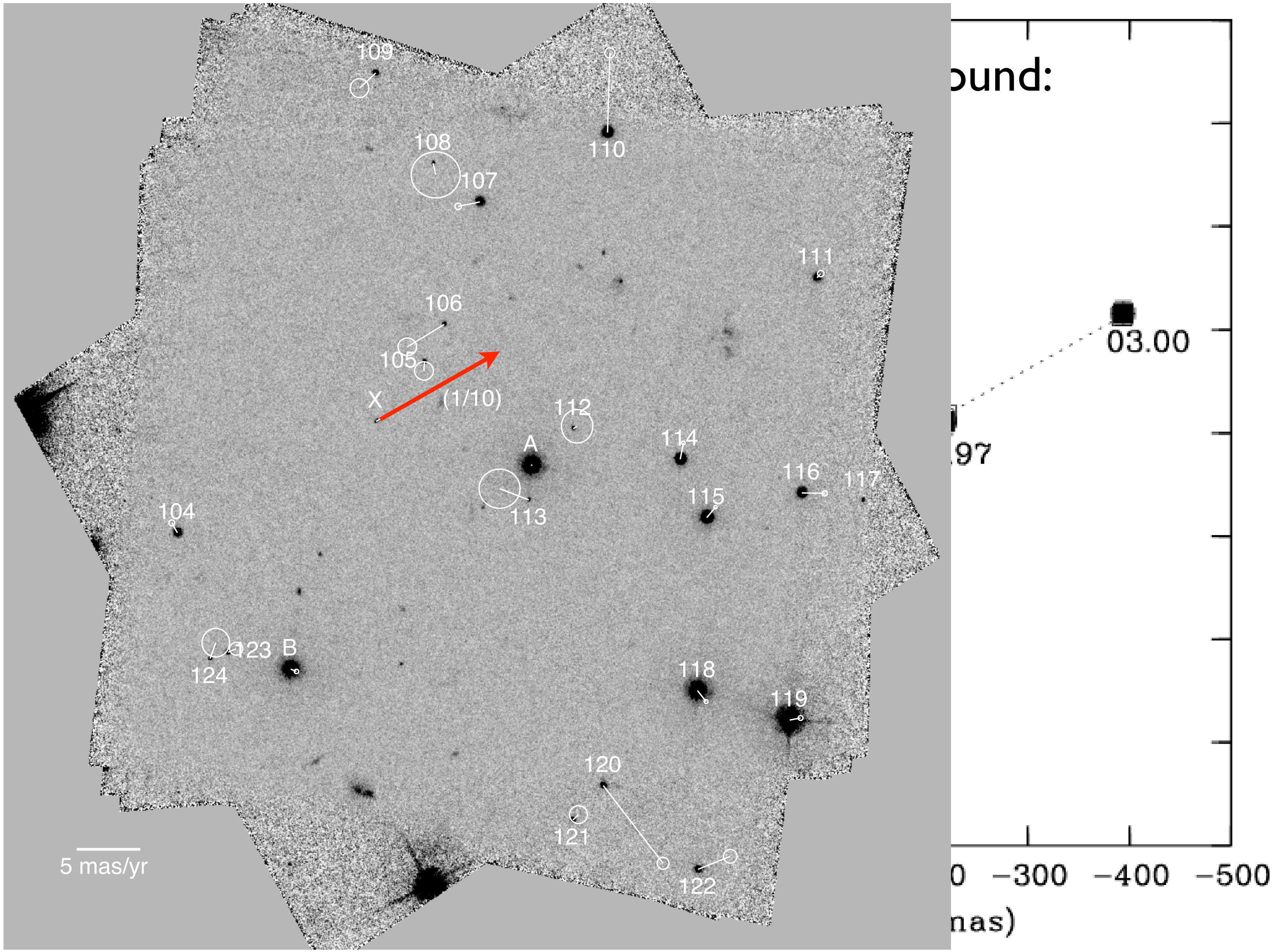

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also see Motch et al. 2005 for another object

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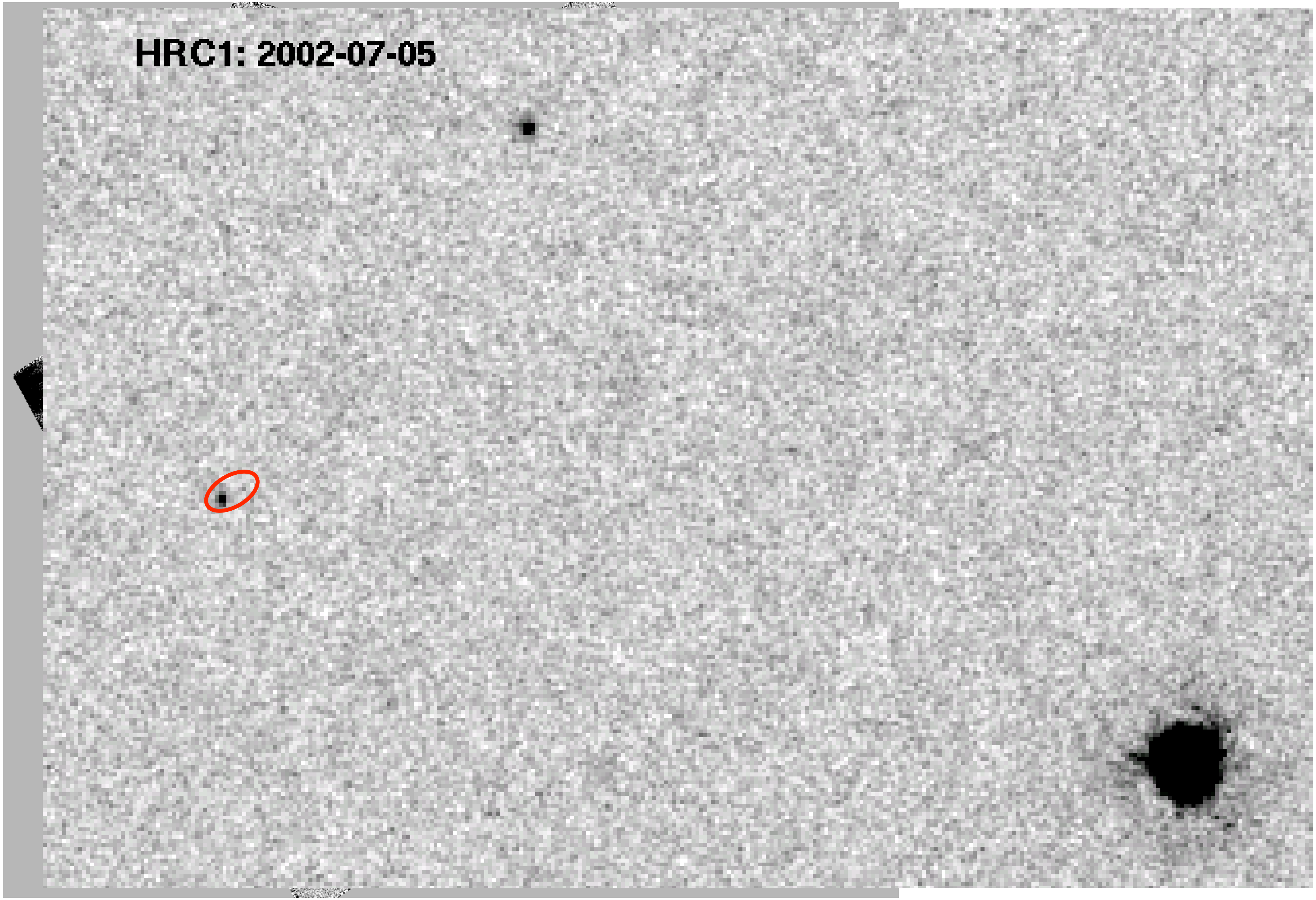

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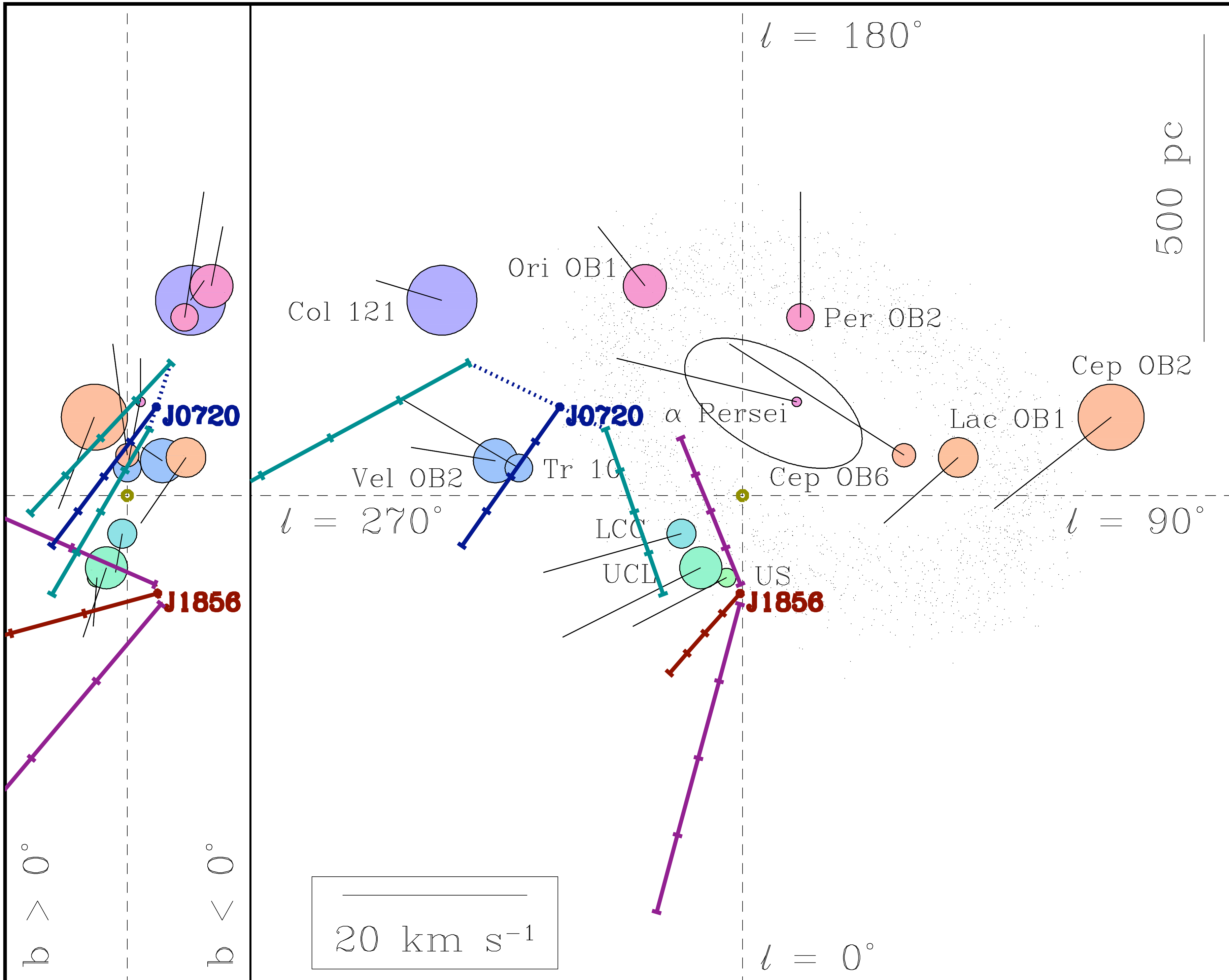
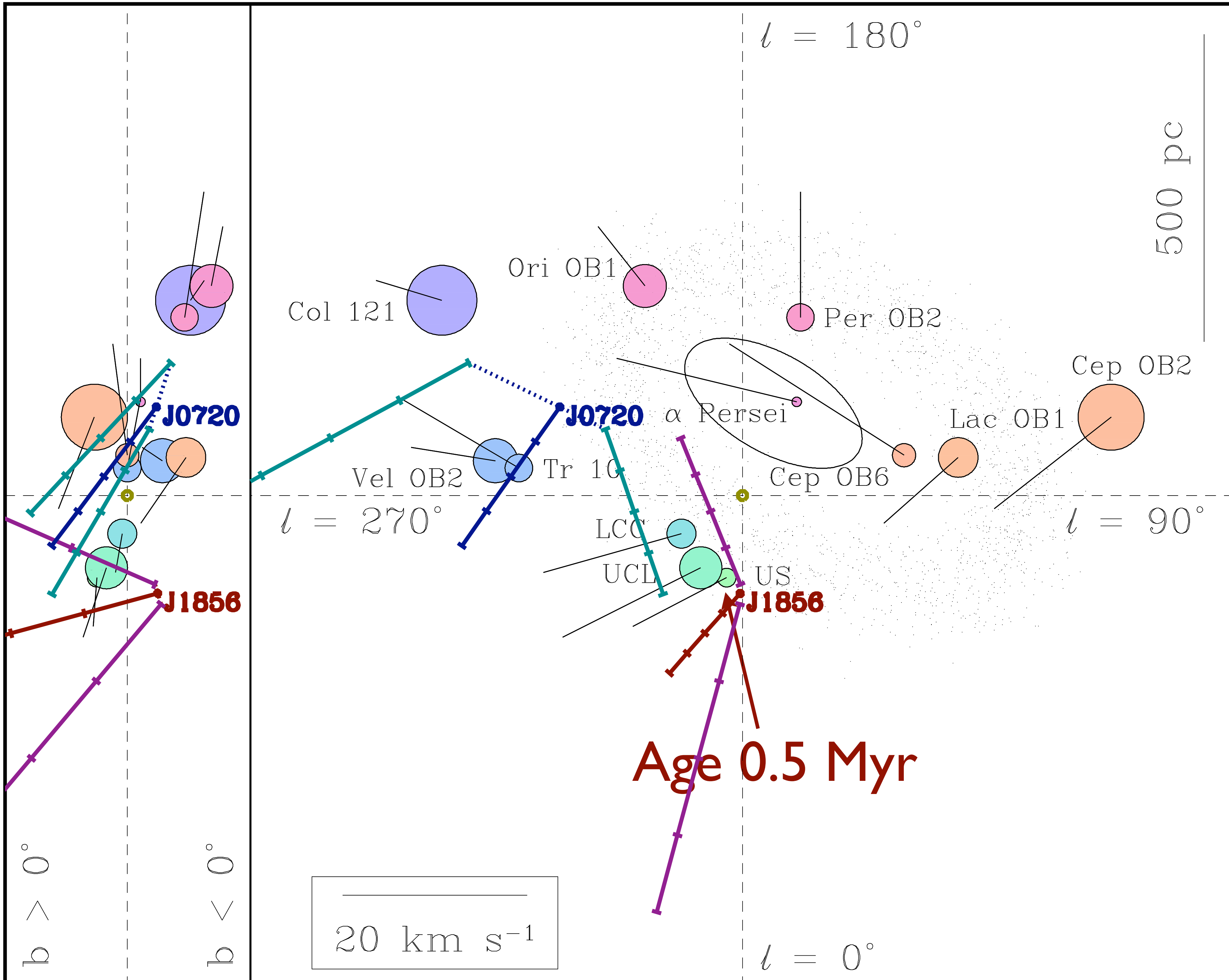


(OB assns adapted from de Zeeuw et al.'99)



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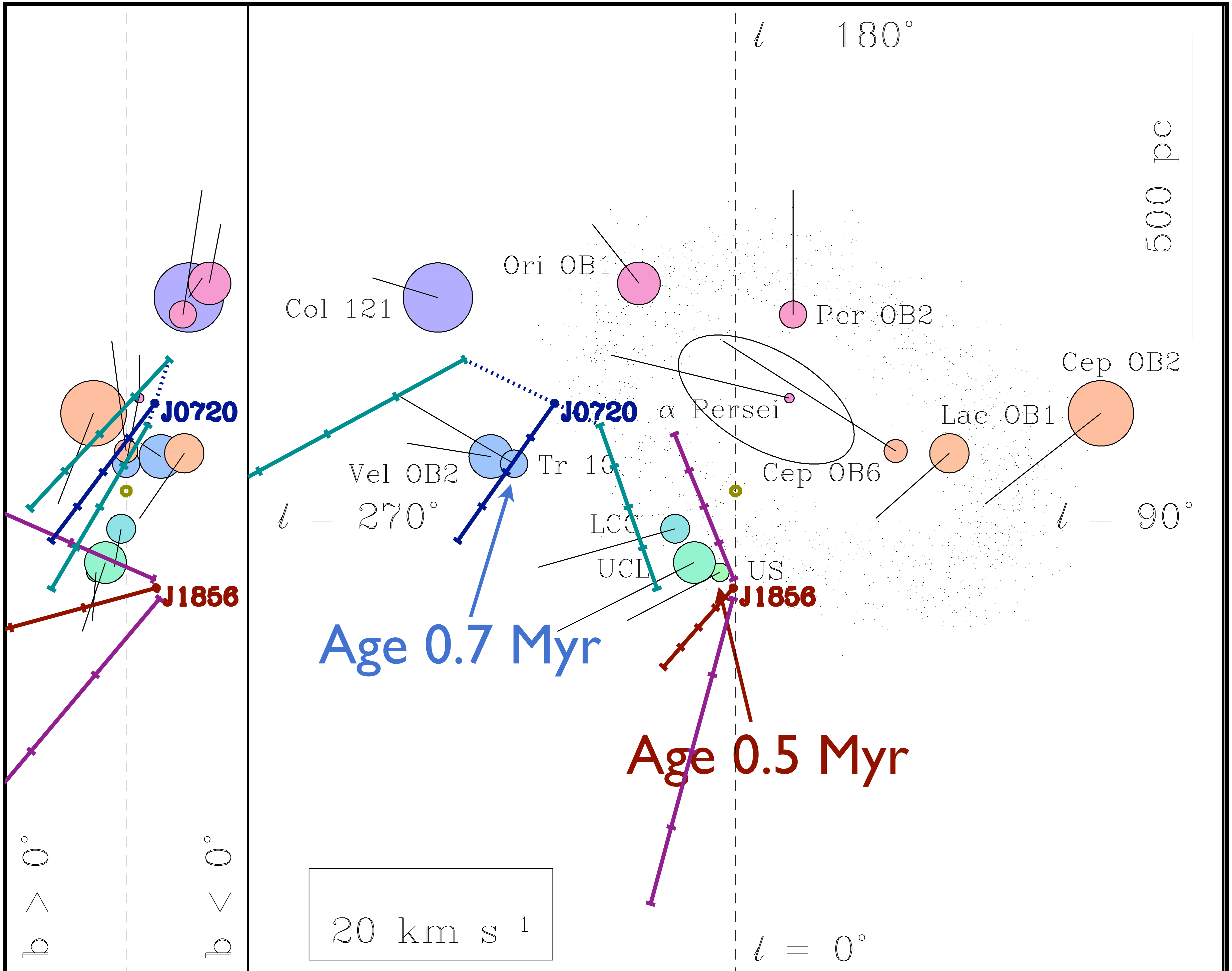

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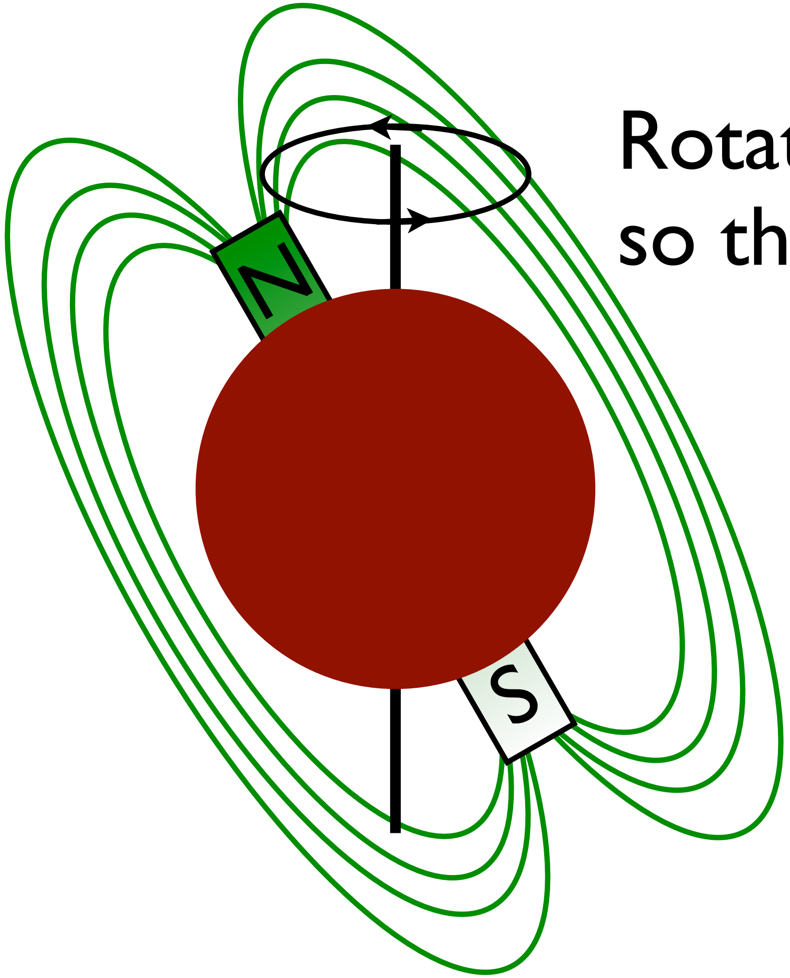
X-ray Timing: Magnetic Fields



Rotating dipoles lose energy, so they slow down

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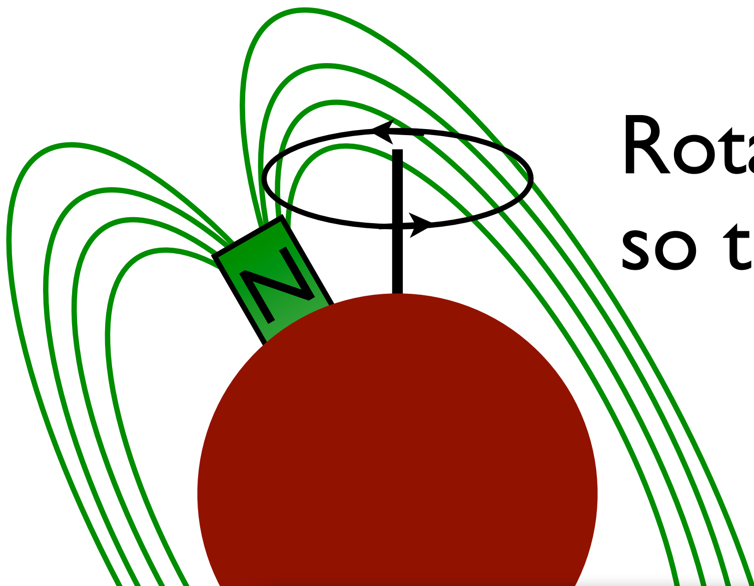

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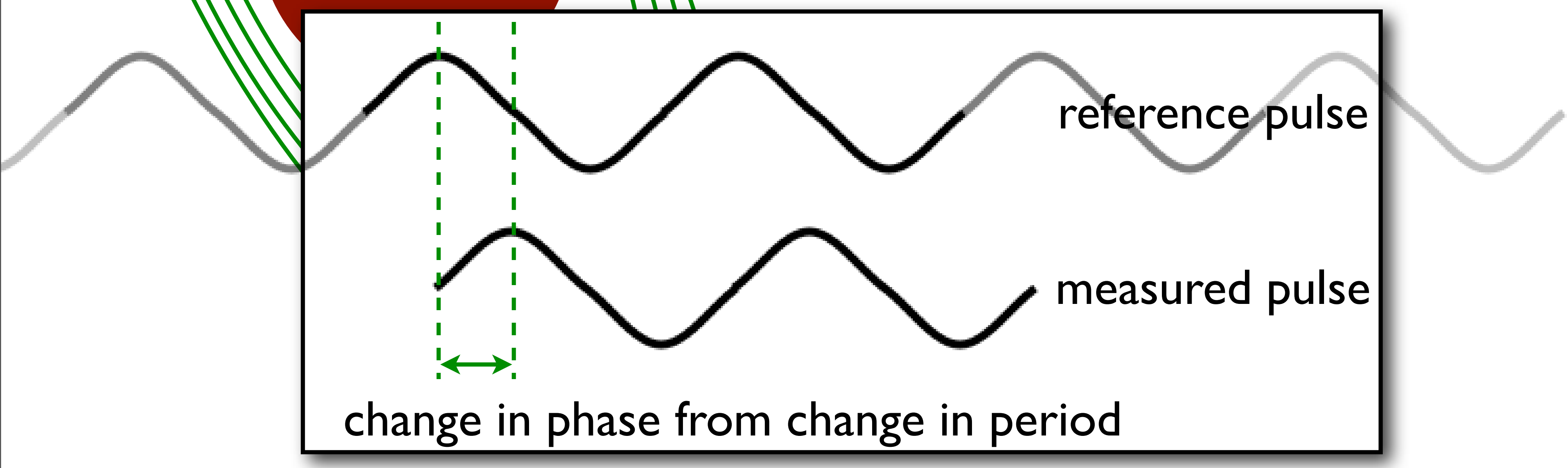
If we can measure the slow-down, we can measure the magnetic field



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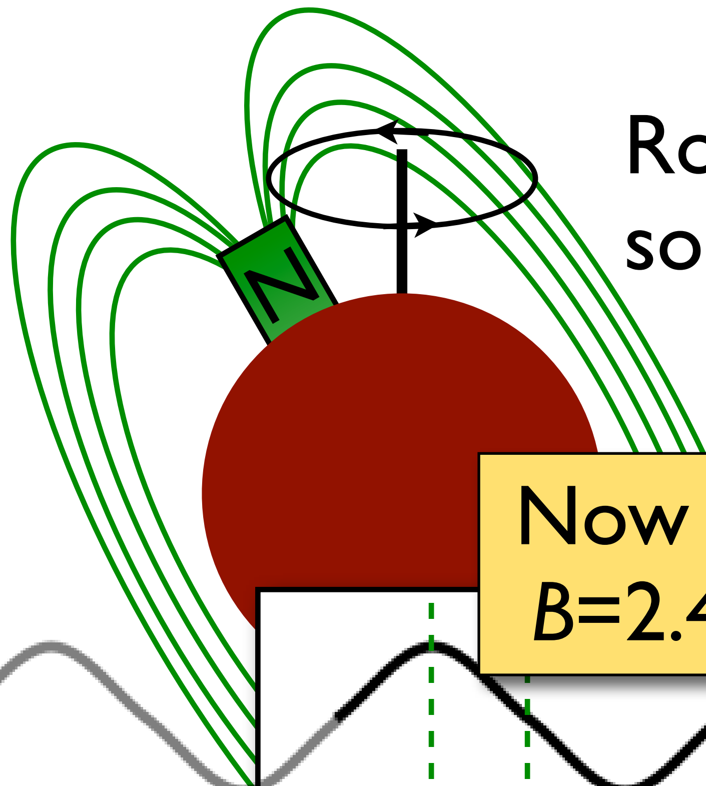

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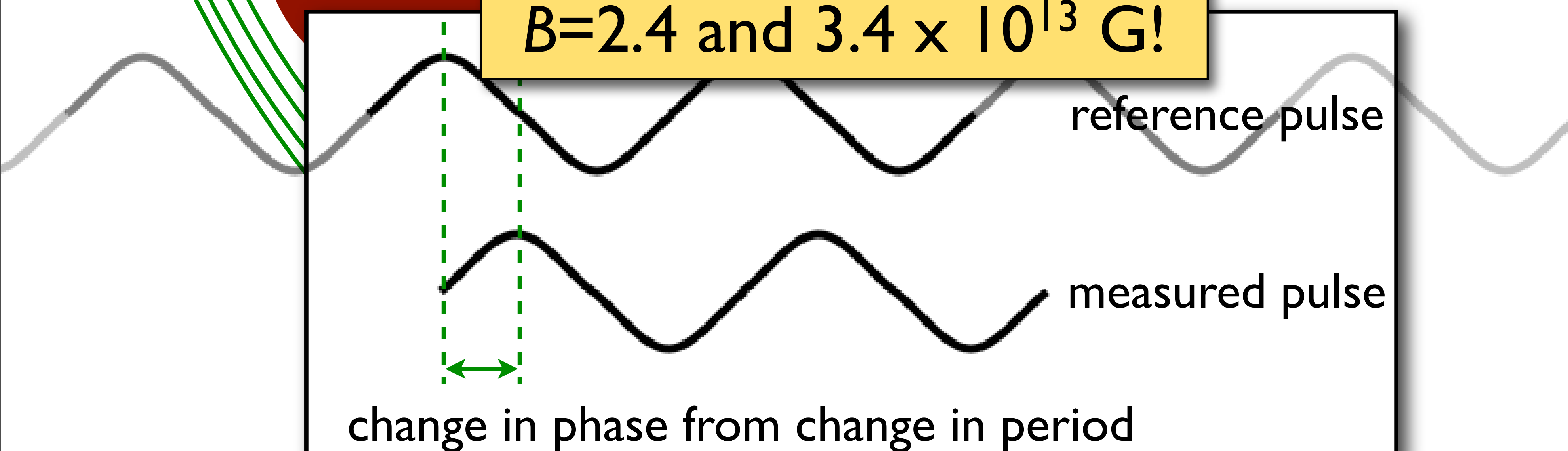
Now done for 2 objects: B=2.4 and 3.4 x 10^{13} G!



Is Emission Thermal?

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

- Radio pulsars:
  - $L_X \ll \dot{E}$
  - Significant non-thermal emission, driven by $\dot{E}$
- INS
  - $L_X/\dot{E} \sim (10^{32}/4e30) \sim 40$
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But: bowshock implies higher $\dot{E}$ (~10^{32} erg/s) for this source (RX J1856), although P is similar

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- Found: 0 (indicated by $\dot{P}$, v)
- Why?
  - Velocity too high for accretion (~200 km/s)
  - Magnetic field inhibits $\dot{M}$ too
  - See Perna et al. (2003)

Not Magnetars (?)

- X-ray emission we see is from cooling
- Could "normal" cooling be augmented by *B* decay?
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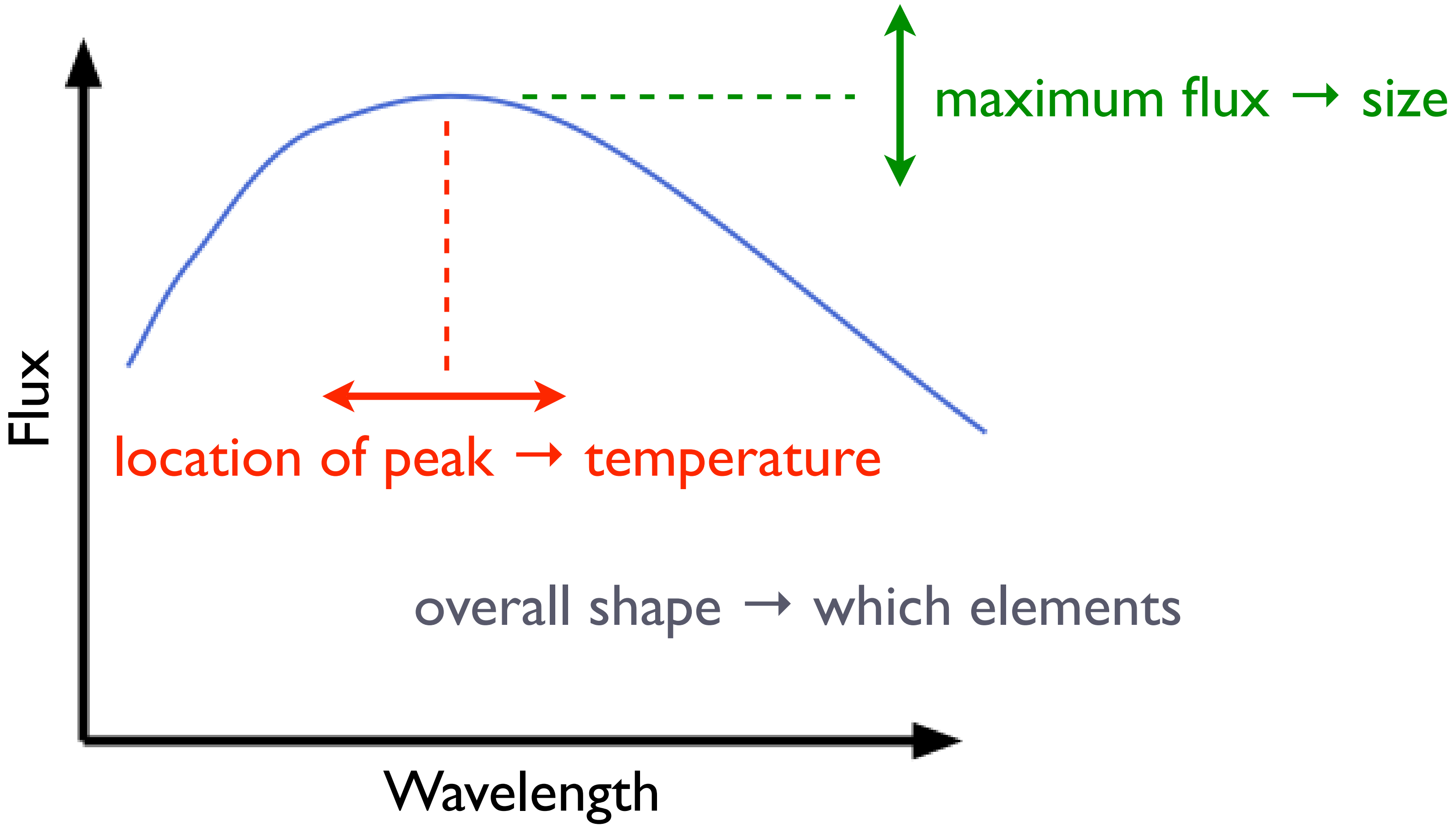
- X-ray emission we see is from cooling
- Could "normal" cooling be augmented by *B* decay?
  - i.e., is energy in *B* relevant?
- Answer: probably not (Zane et al. '02; Kaplan et al. '02)
  - Based on simple models of field decay (Heyl & Kulkarni '98)
  - Would need *B*(now)>2^{14} G to have decayed significantly in past
  - Compare to 2^{13} G from spin-down
  - Caveat: field decay is complicated

Spectroscopy: Measuring Surfaces



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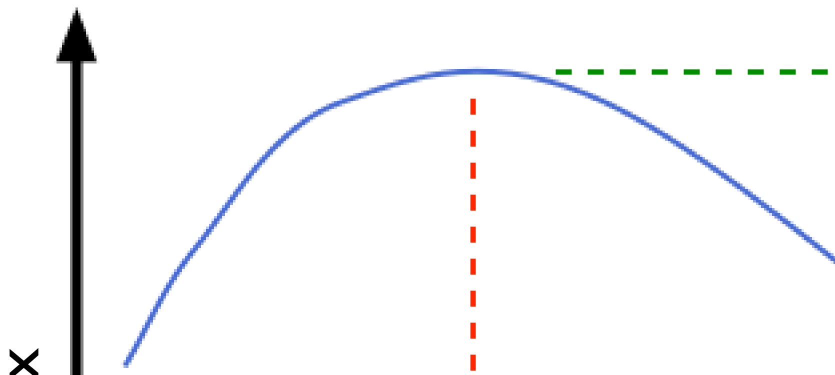

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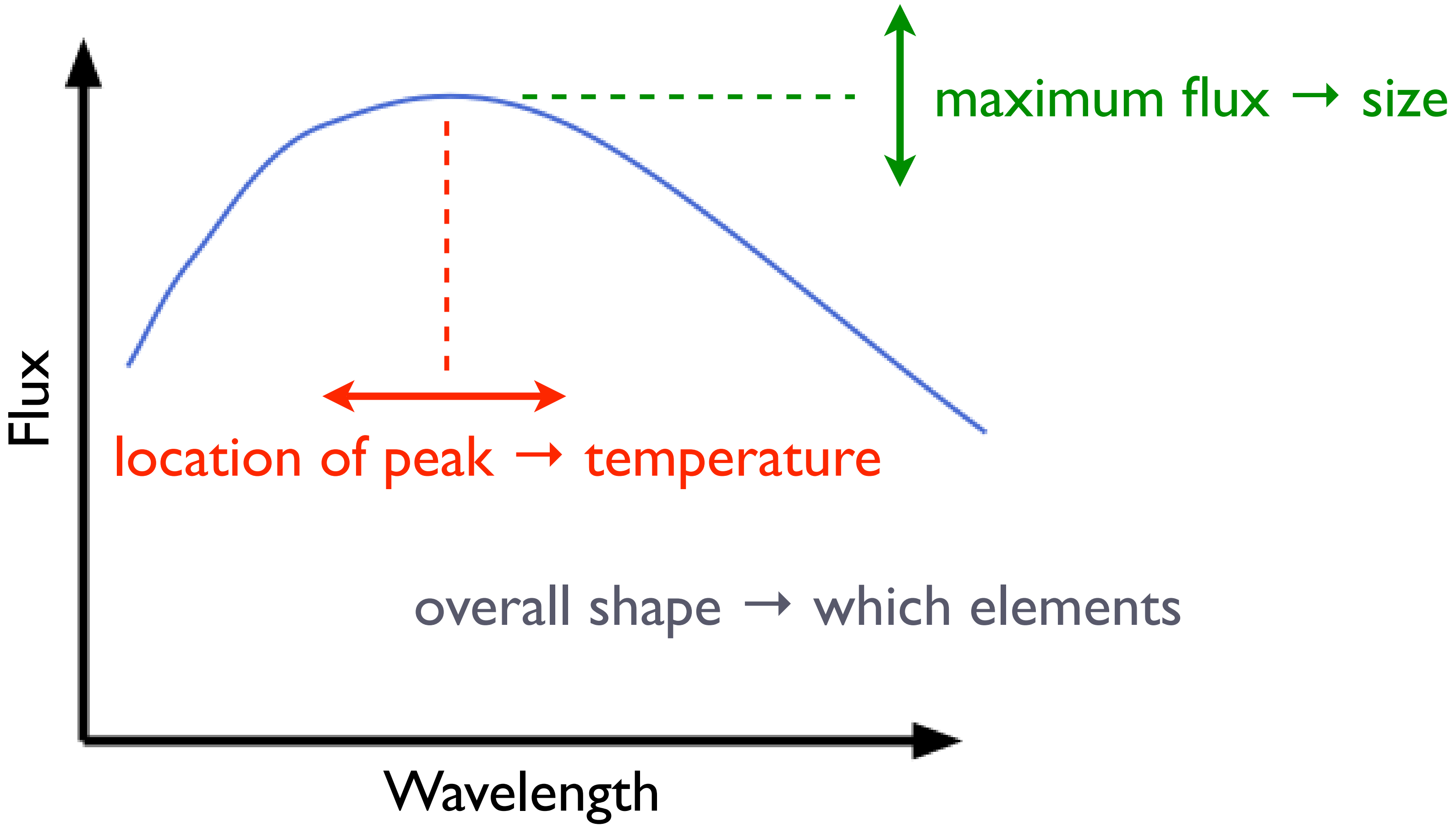

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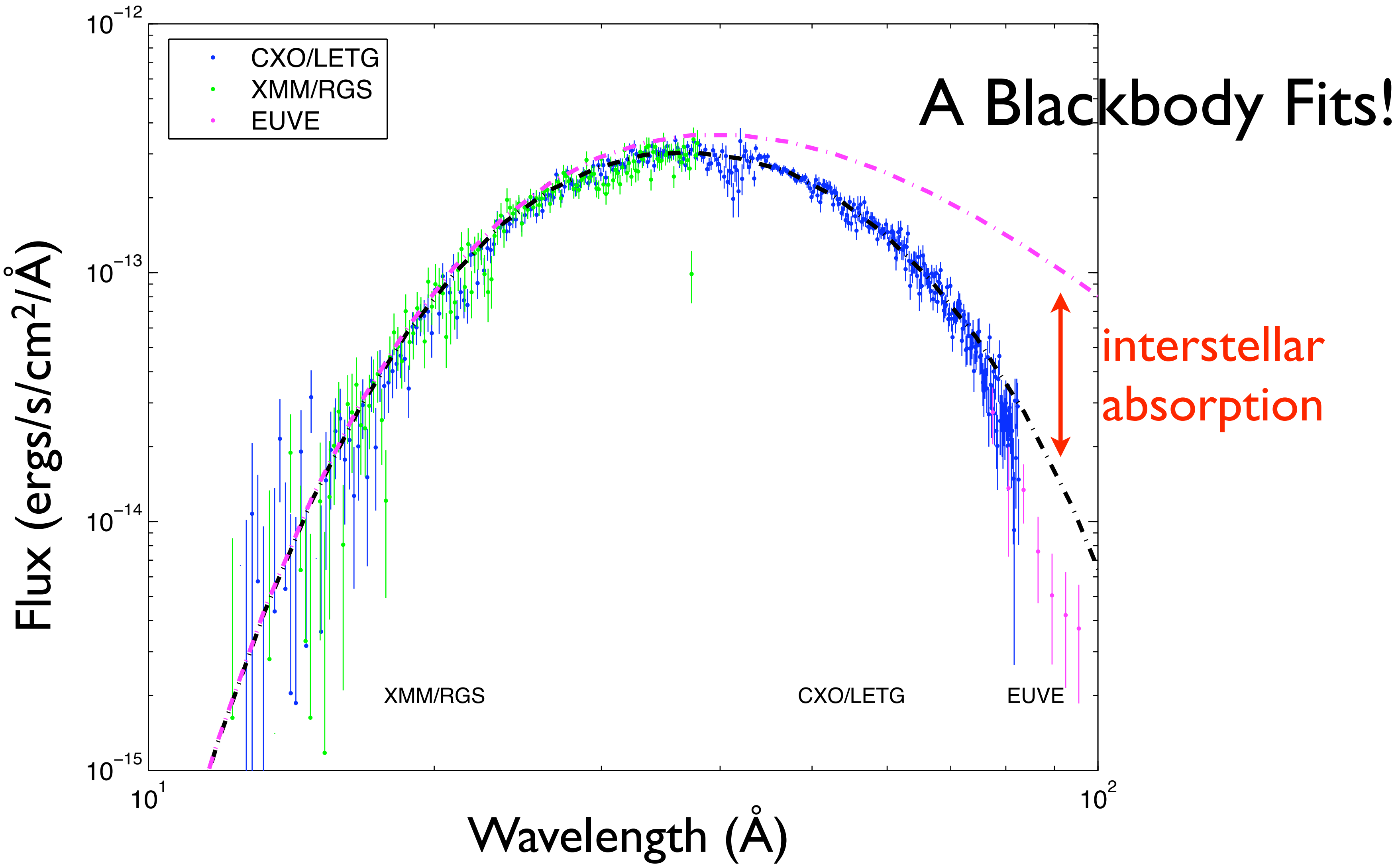

(Drake et al. '02; Pons et al. '02; Burwitz et al. '03)

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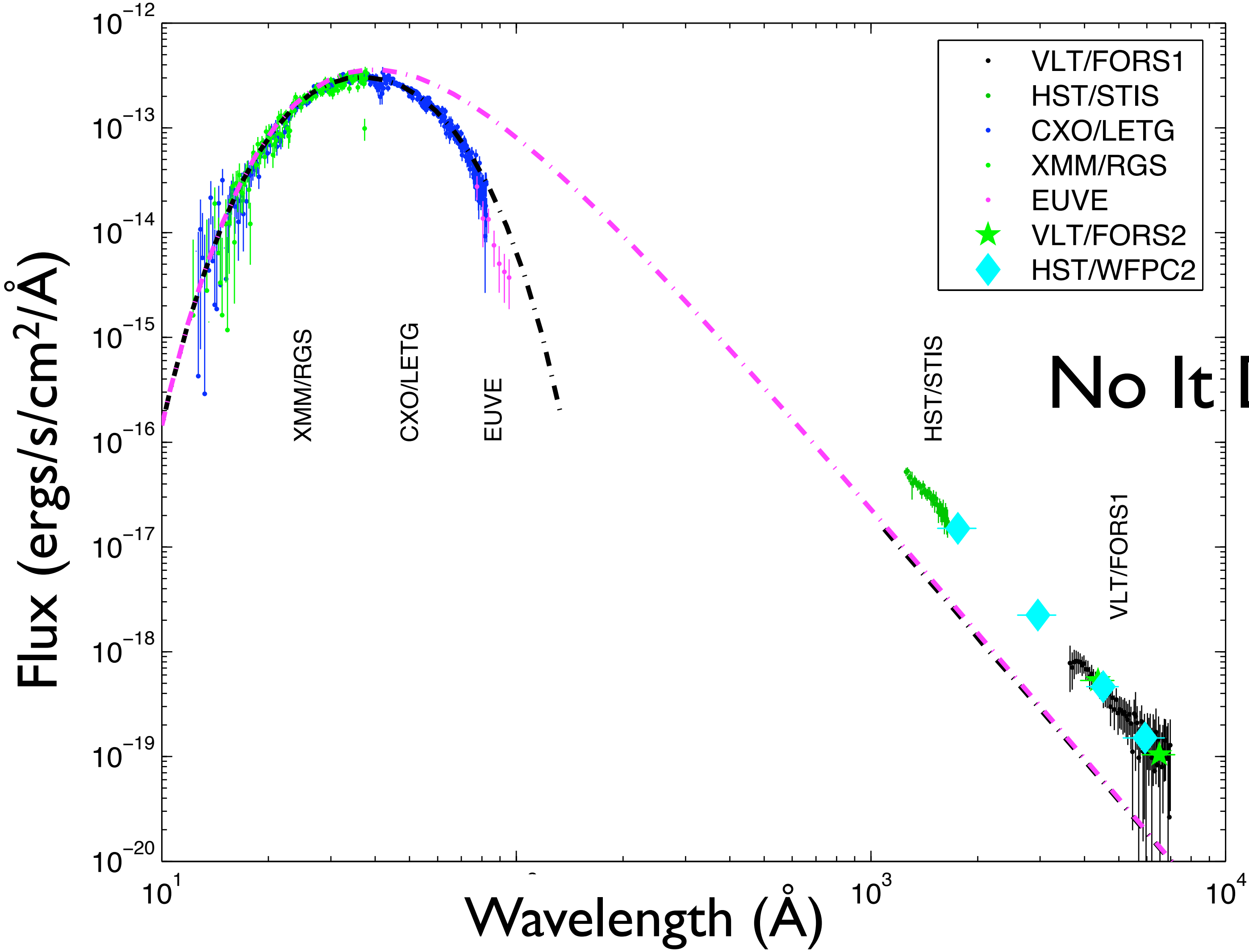

No It Doesn’t

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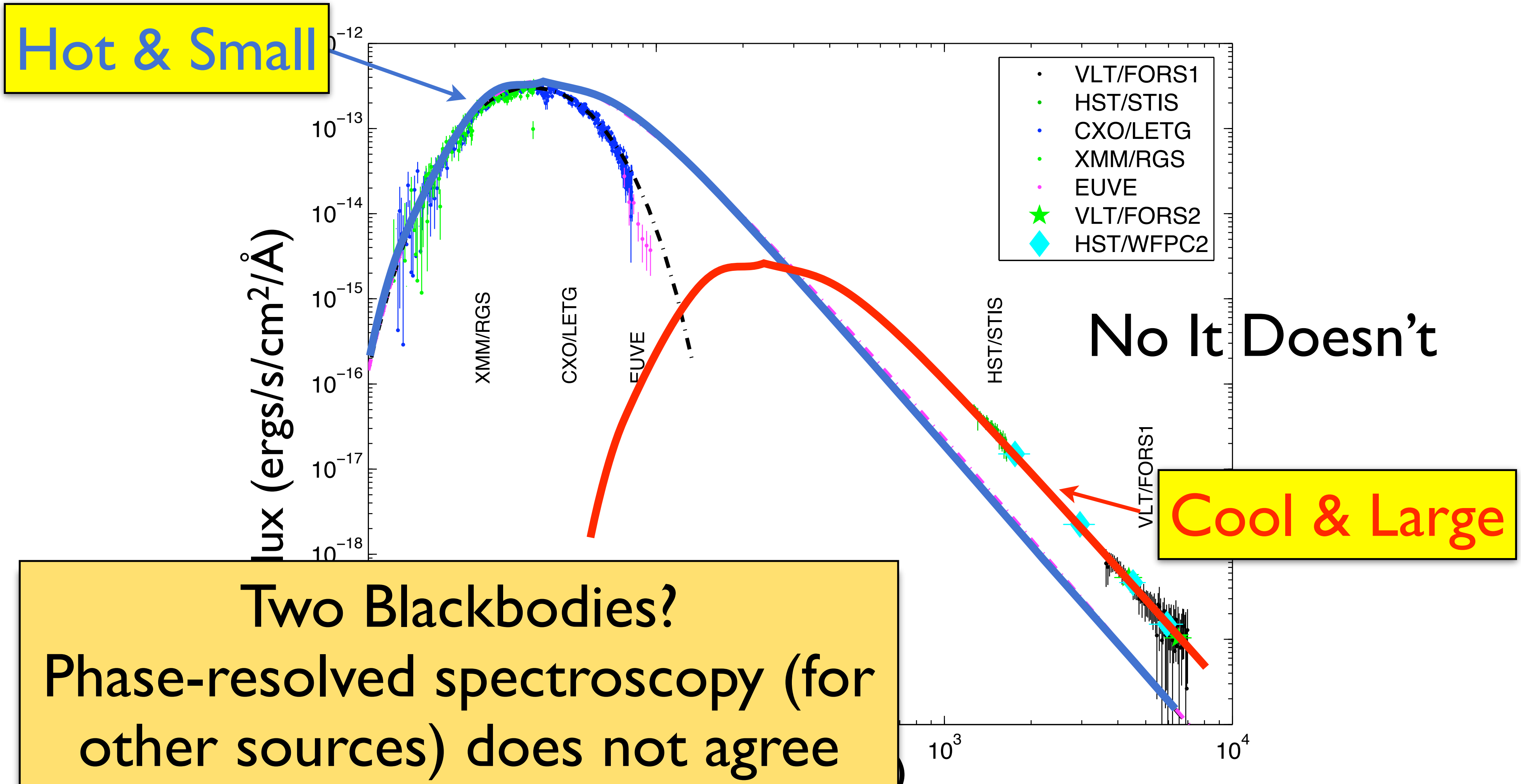


No It Doesn't

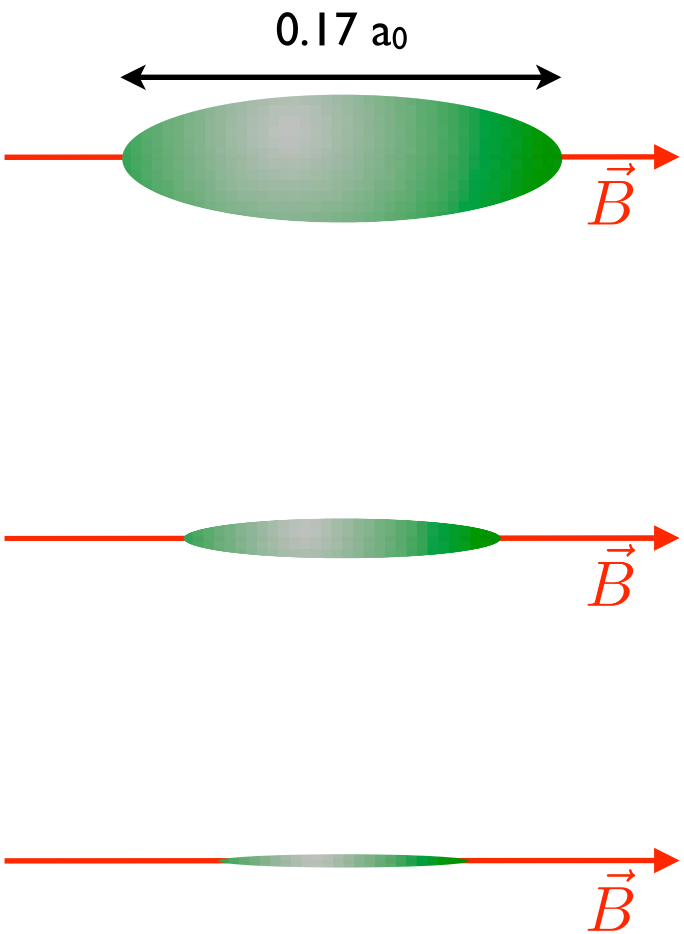
Two Blackbodies?
Phase-resolved spectroscopy (for other sources) does not agree

(Drake et al. '02; Pons et al. '02; Burwitz et al. '03)

Complications

- Magnetic field is high: standard atmosphere models not valid
- X-ray blackbody does not match O/UV
- For most sources, 1 or 2 blackbodies do not fit
- We see pulsations: surface not uniform
- Variability!

Effects of B on Hydrogen Atoms

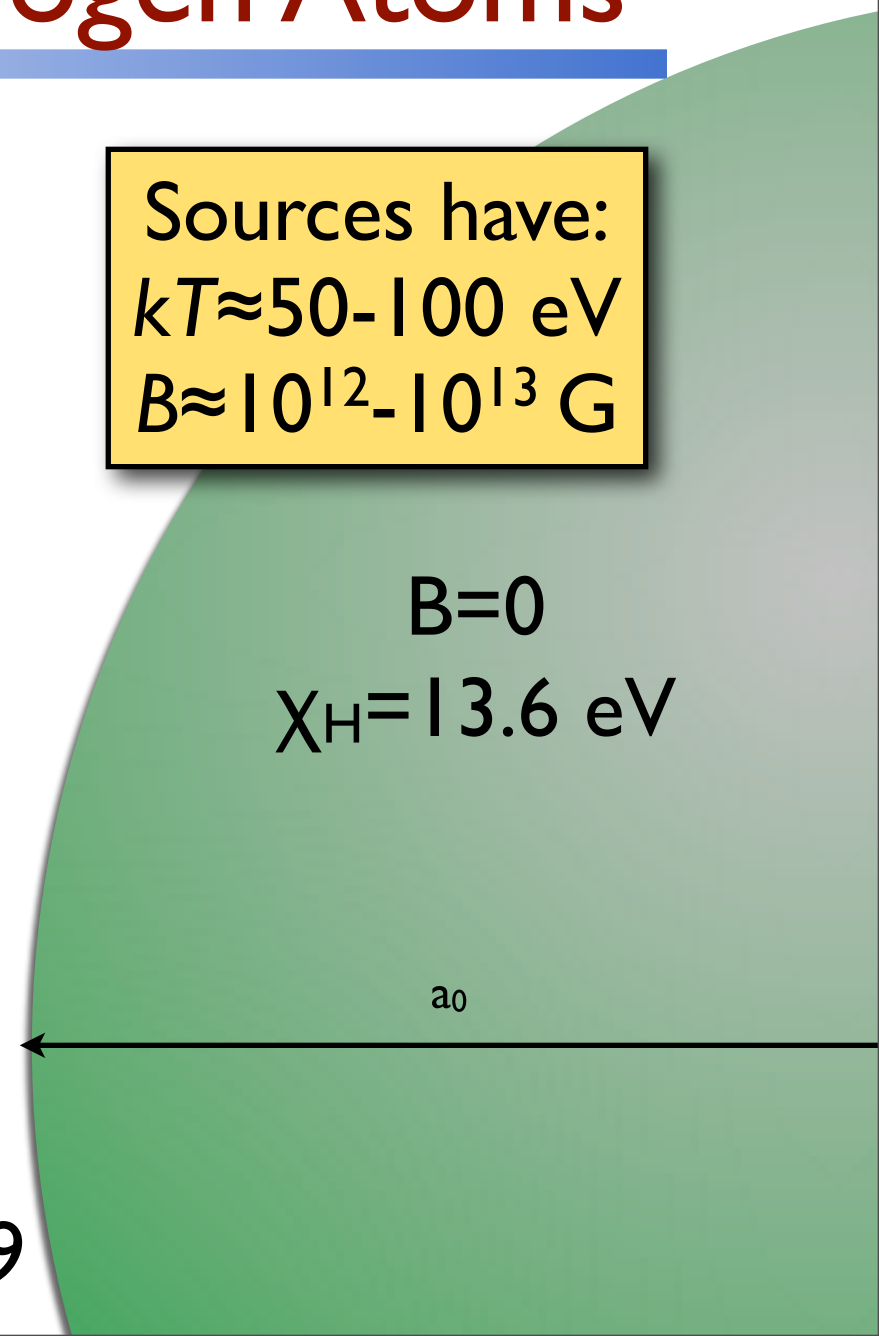


B=10^{12} G
χ_H=161 eV

B=10^{13} G
χ_H=310 eV

B=10^{14} G
χ_H=541 eV

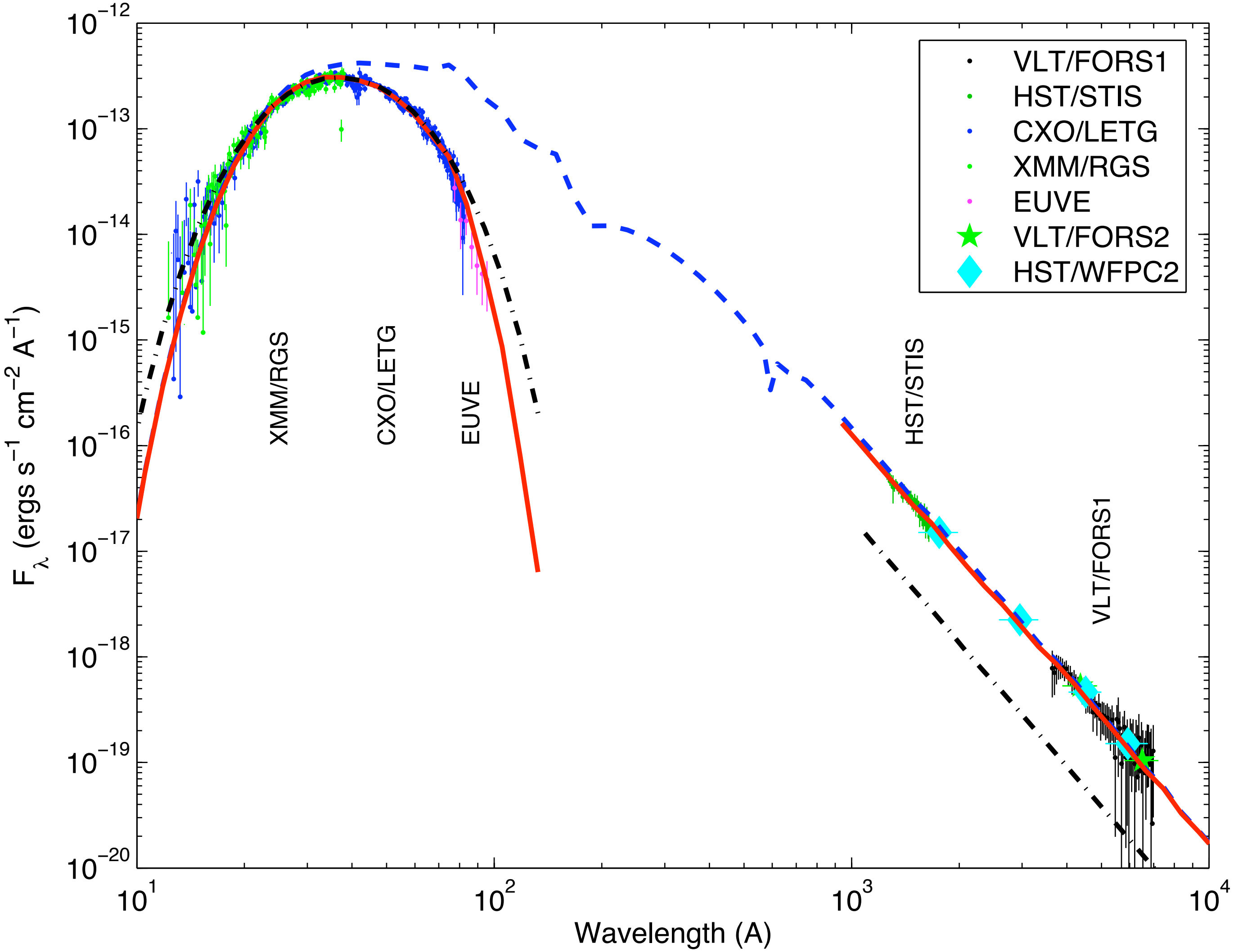
Sources have:
kT≈50-100 eV
B≈10^{12}-10^{13} G



see Lai 2001, Rev. Mod. Phys., 73, 629

RX J1856.5-3754

a more realistic model



- Thin (~1 g/cm^2) layer of partially ionized H
- On top of condensed surface
- Even w/ dipole *B* (& *T*), does not predict strong pulsations (see Ho 2007; Tiengo & Mereghetti '06)

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

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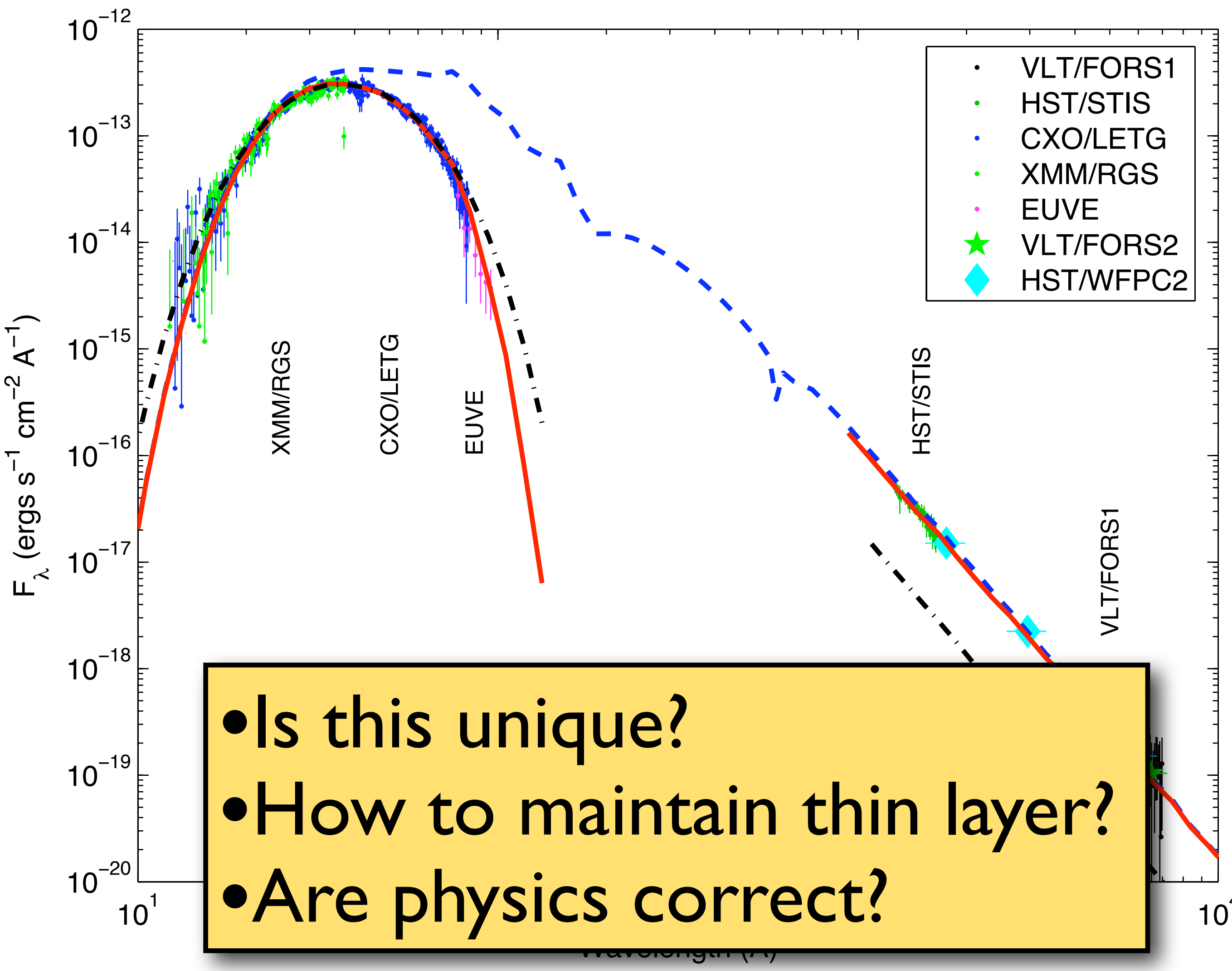

- Is this unique?
- How to maintain thin layer?
- Are physics correct?

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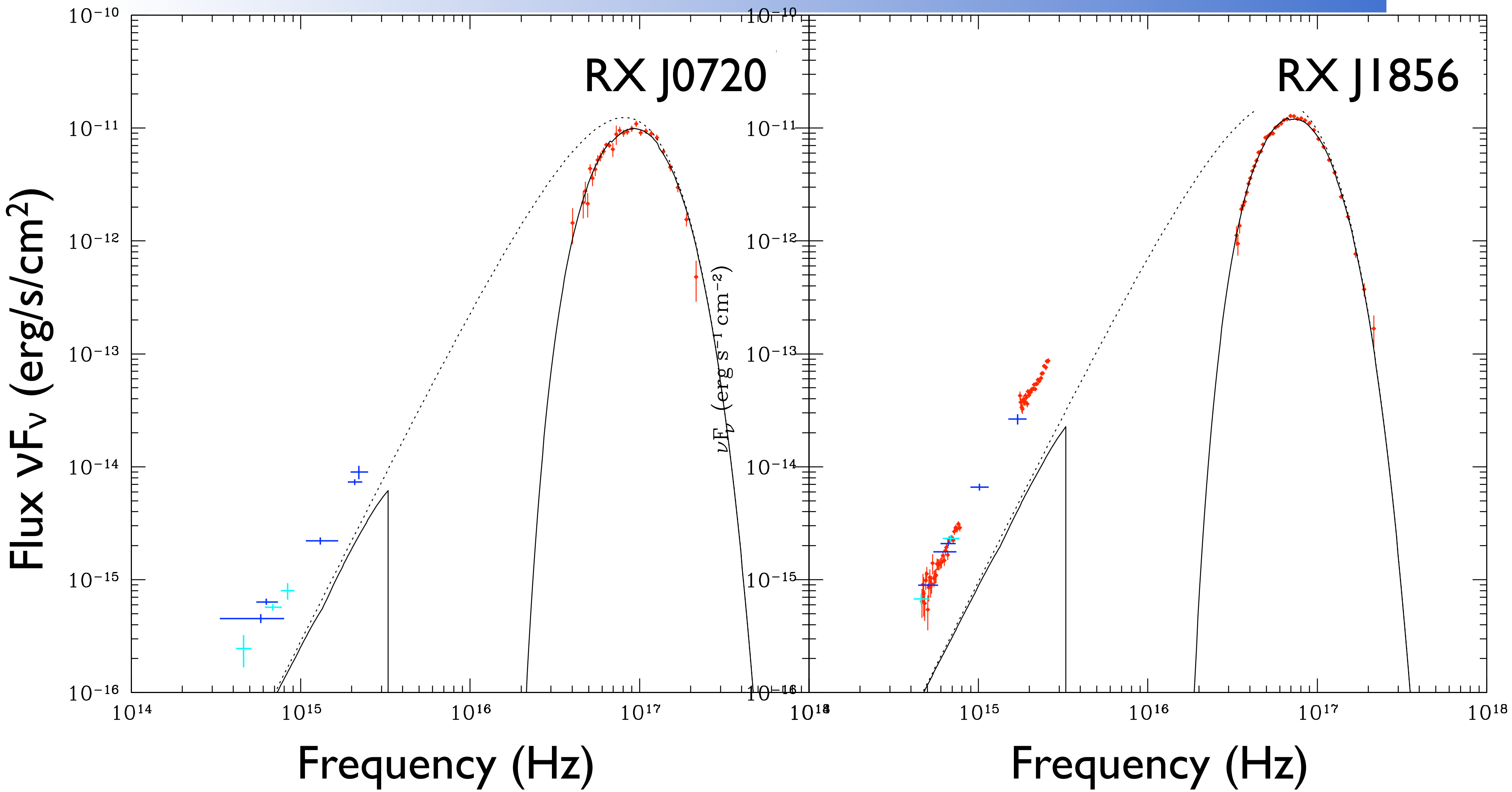

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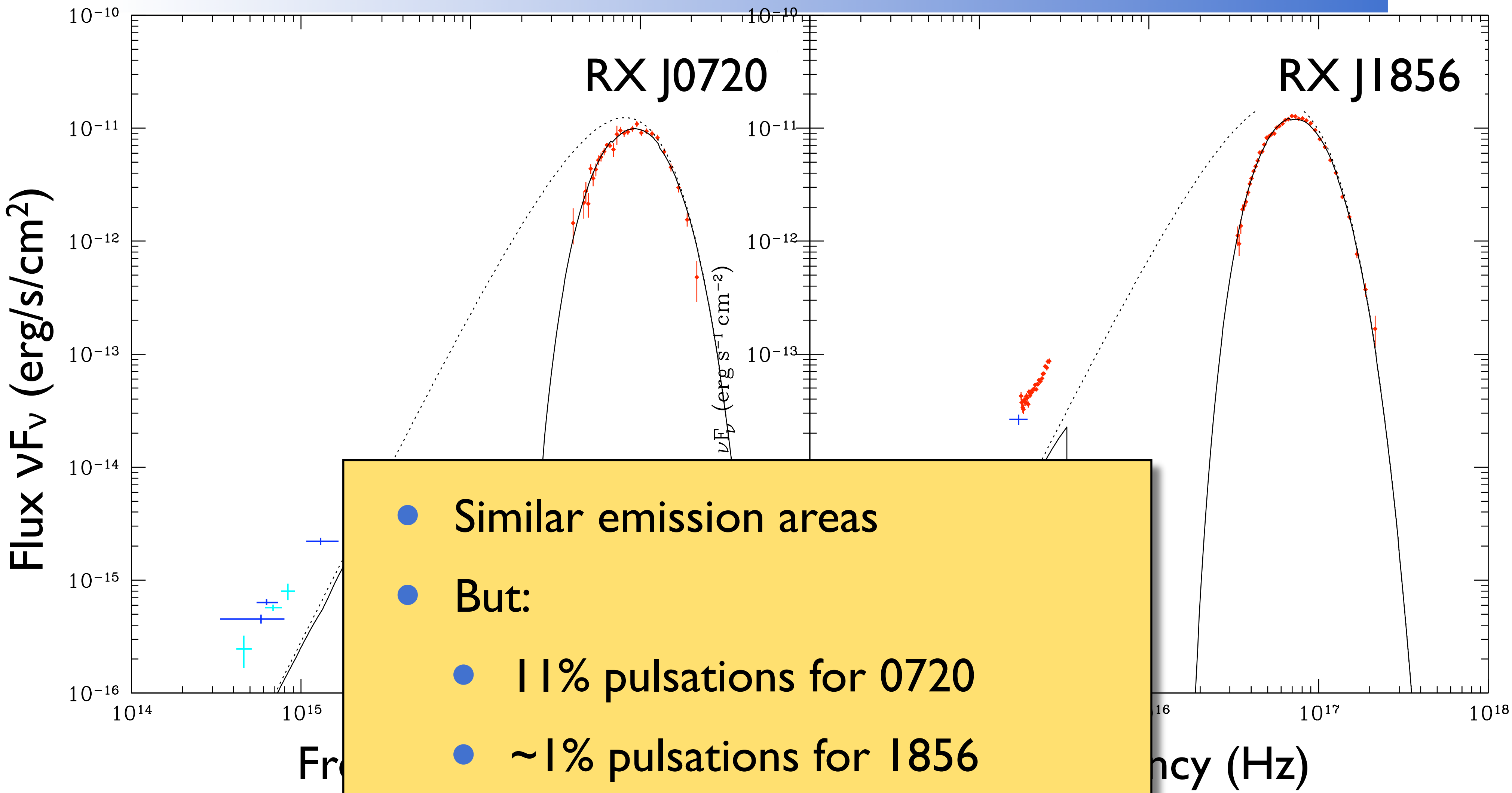
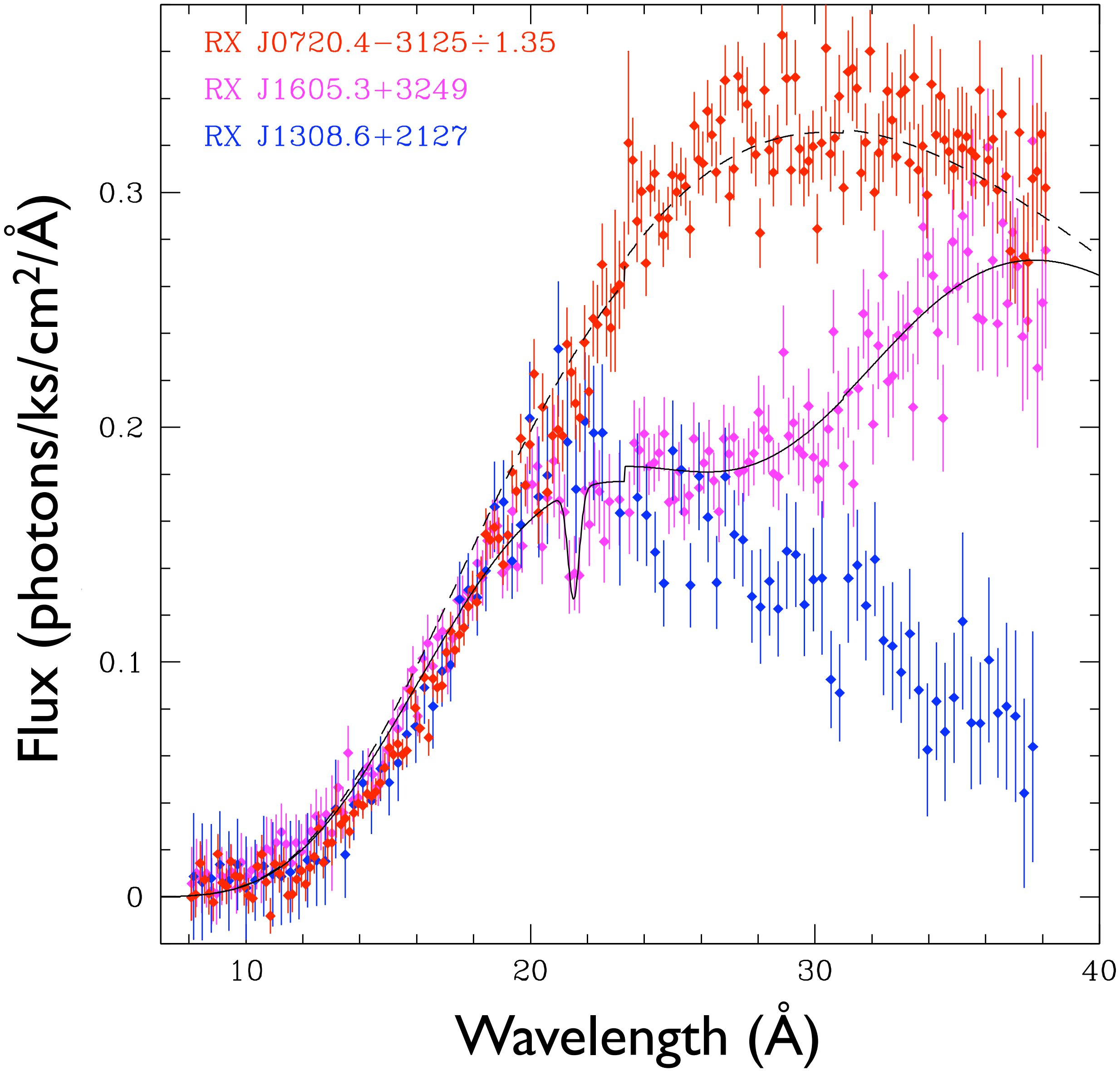


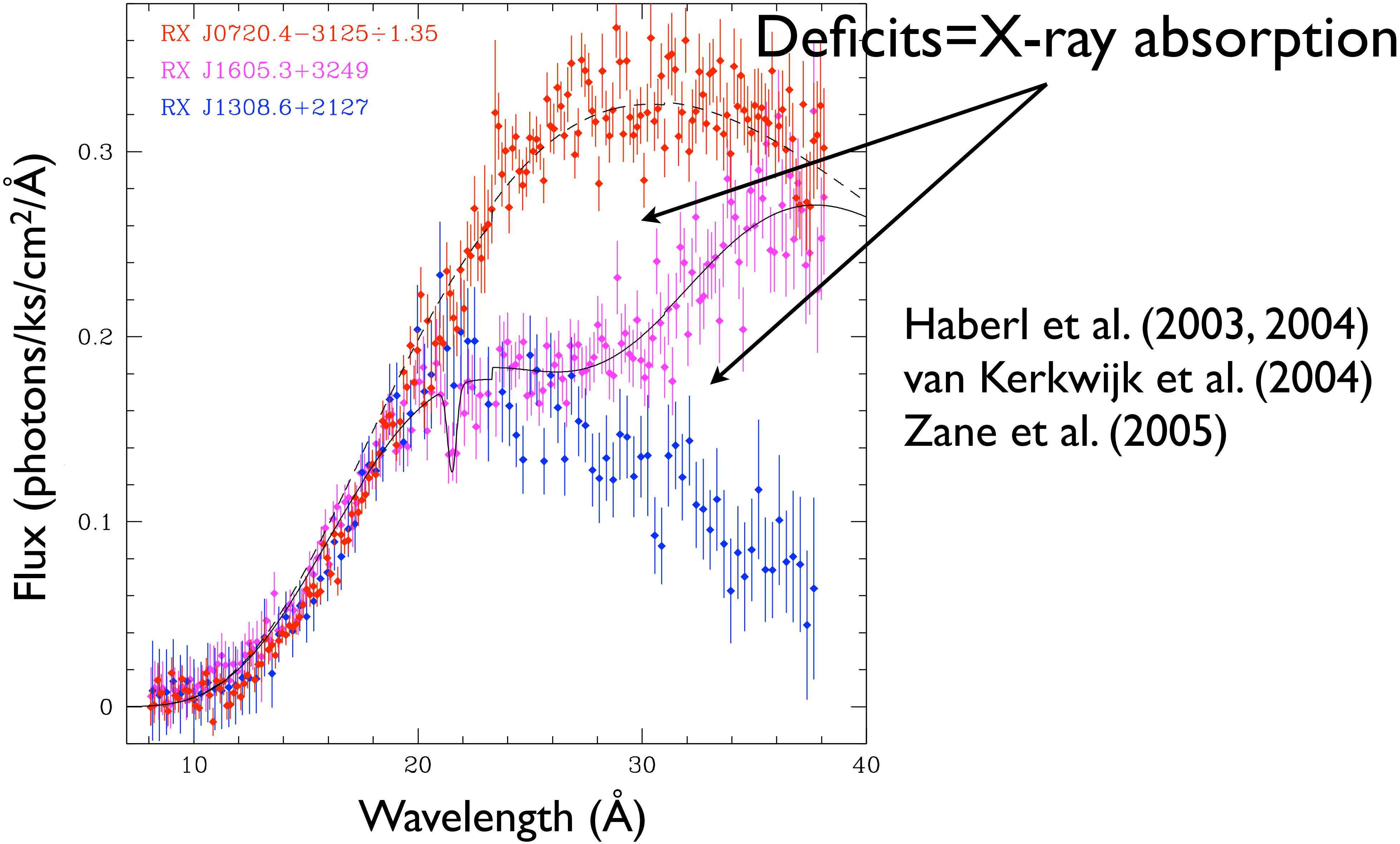
- Similar emission areas
- But:
  - 11% pulsations for 0720
  - ~1% pulsations for 1856

Spectral Absorption Features



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

Spectral Absorption Features



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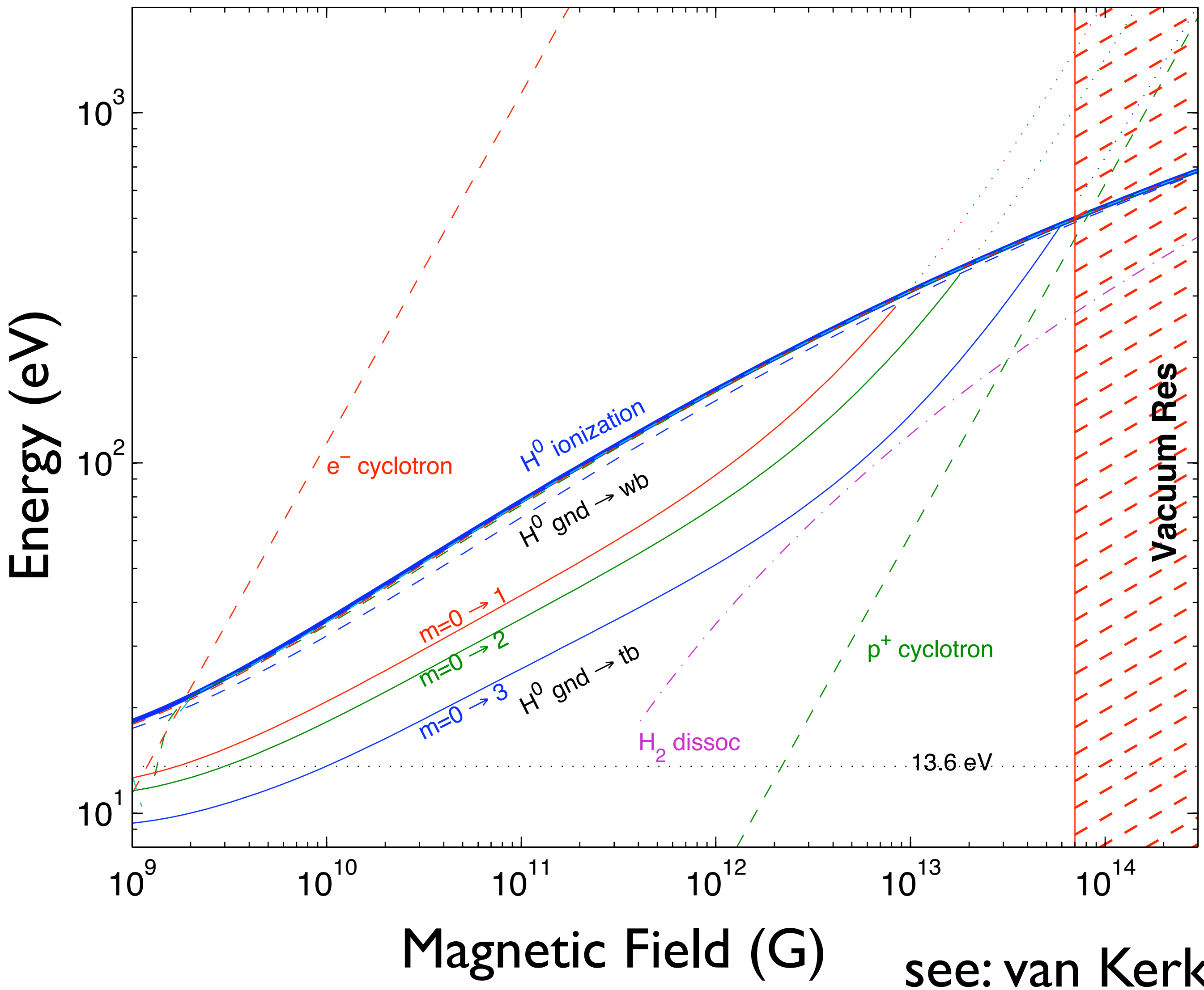
What Causes Features?

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

Need to consider vacuum resonance suppression

What Causes Features?



see: van Kerkwijk & Kaplan (2006)

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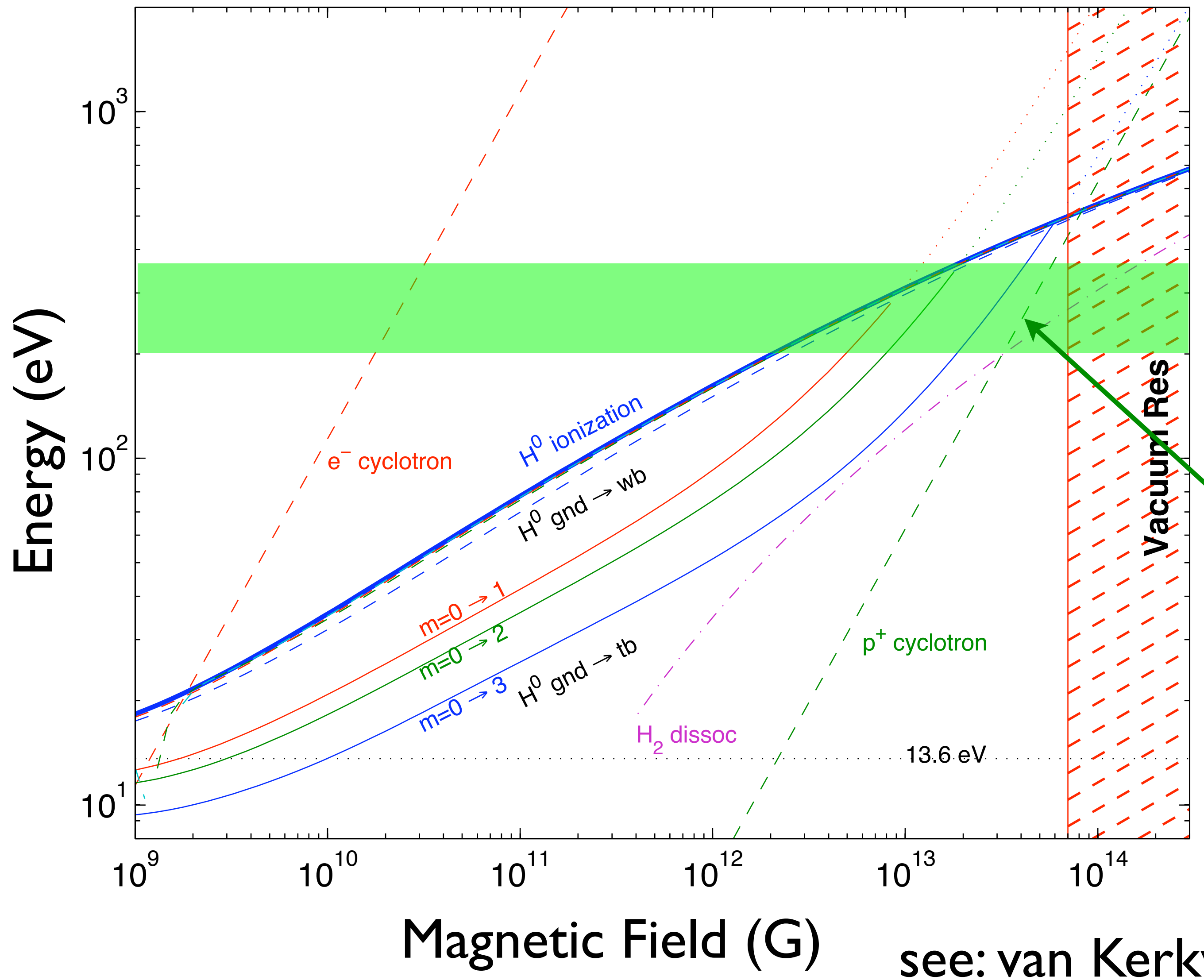
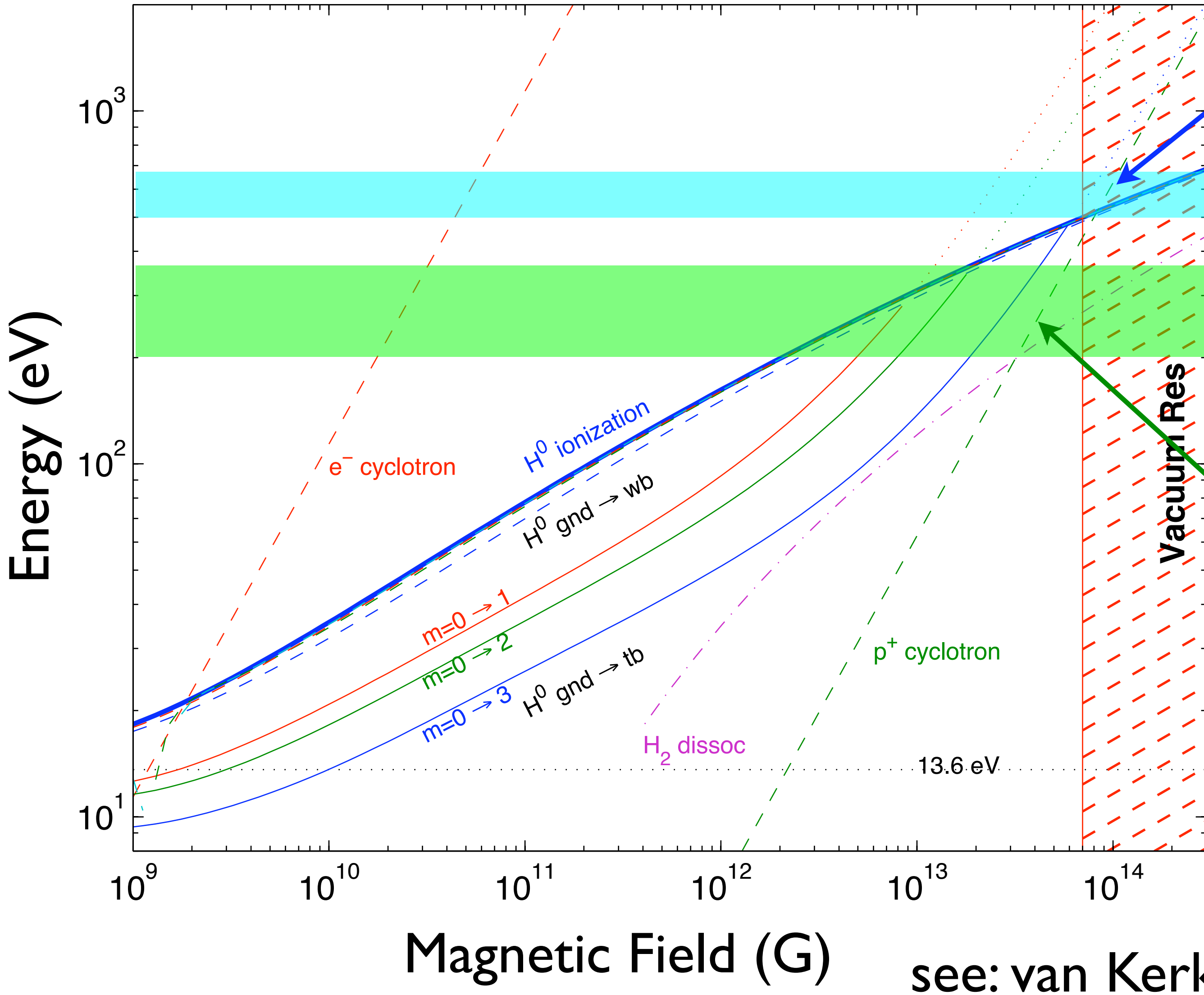


broad, strong:
cyclotron
B~4e13

see: van Kerkwijk & Kaplan (2006)

What Causes Features?

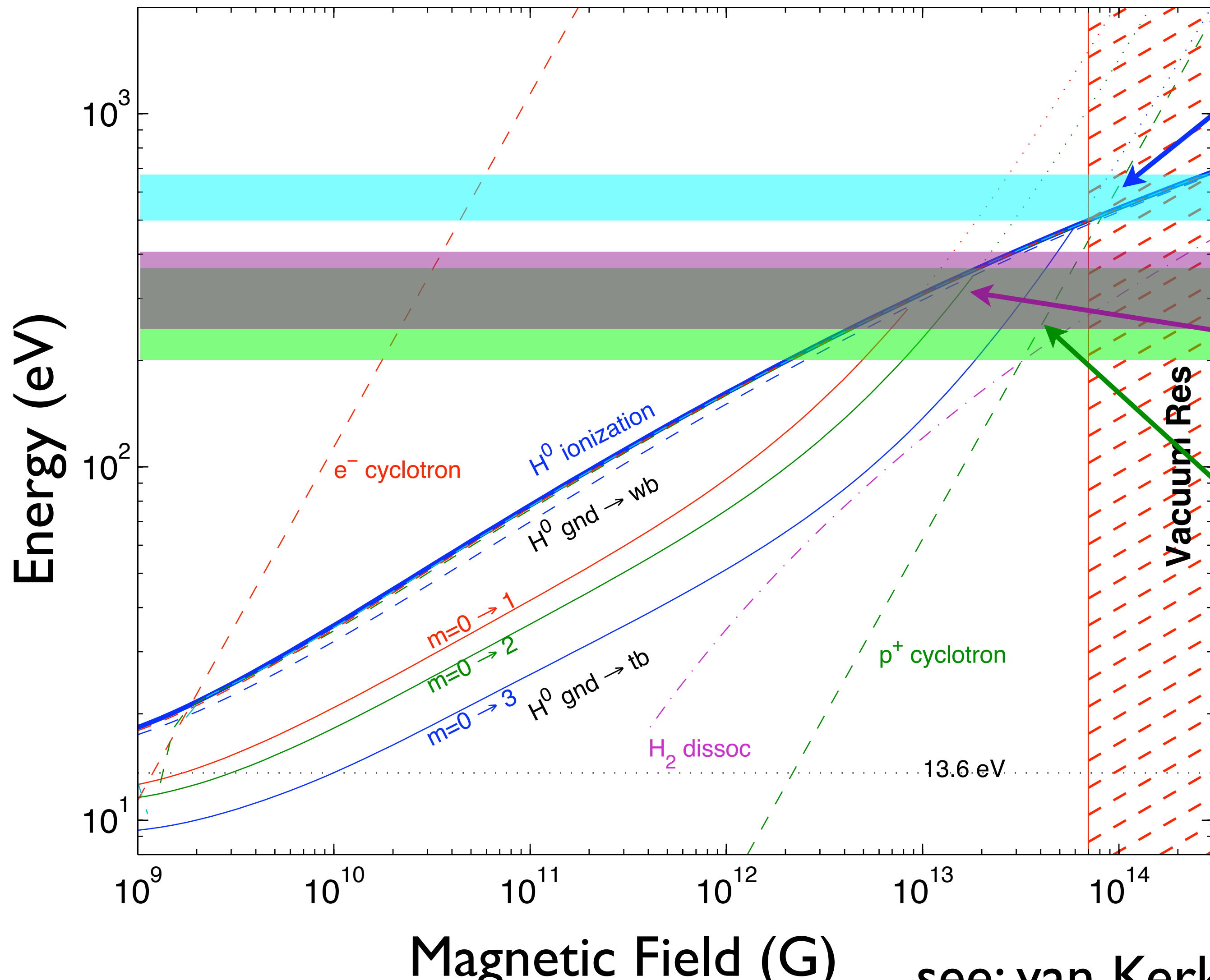


less broad, weaker: cycl. w/ vac. res. B~1e14

broad, strong: cyclotron B~4e13

see: van Kerkwijk & Kaplan (2006)

What Causes Features?



less broad, weaker: cycl. w/ vac. res. B~1e14

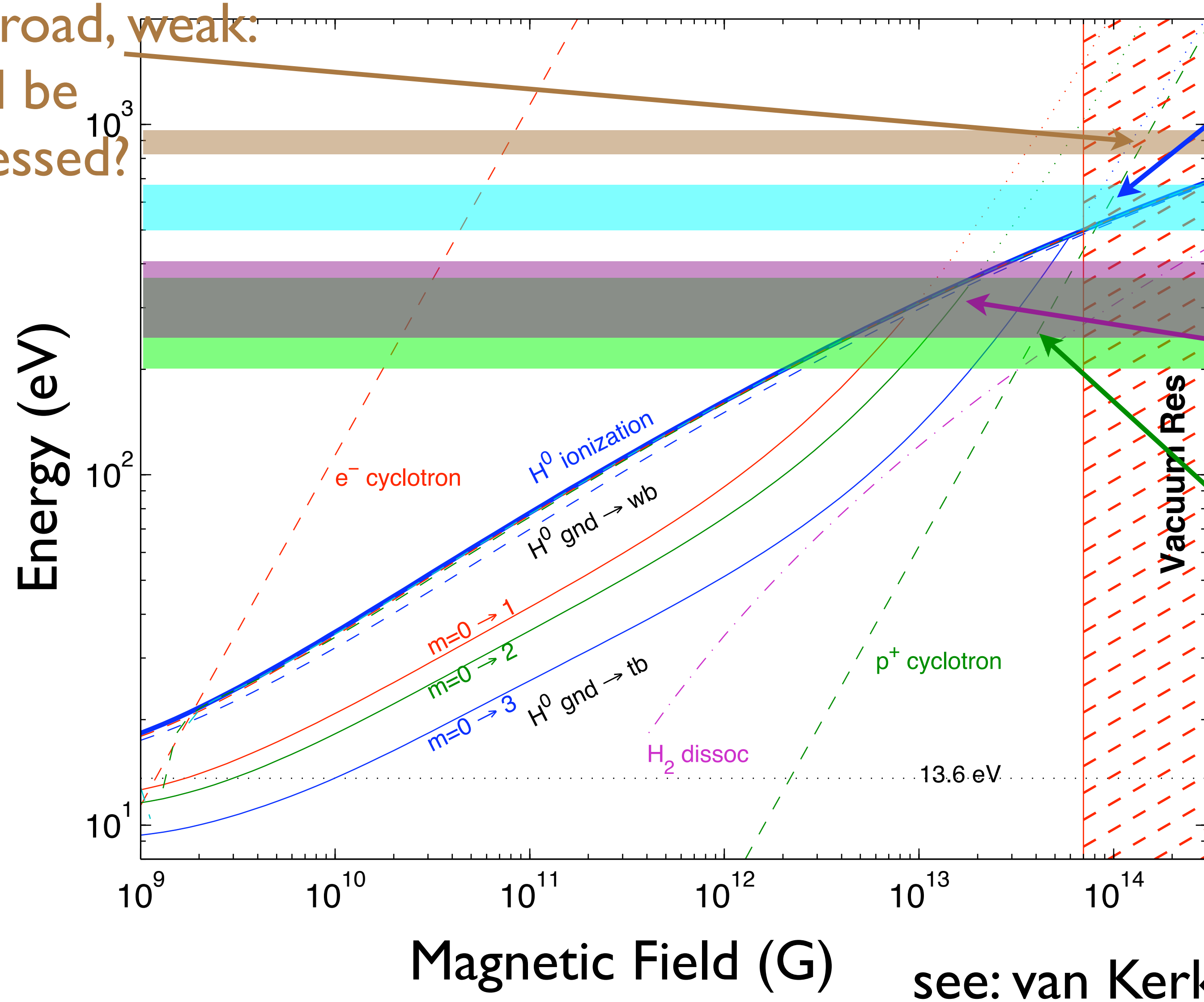
less broad, weak: H m=0→2 B~2e13

broad, strong: cyclotron B~4e13

see: van Kerkwijk & Kaplan (2006)

What Causes Features?

Less broad, weak: should be suppressed?



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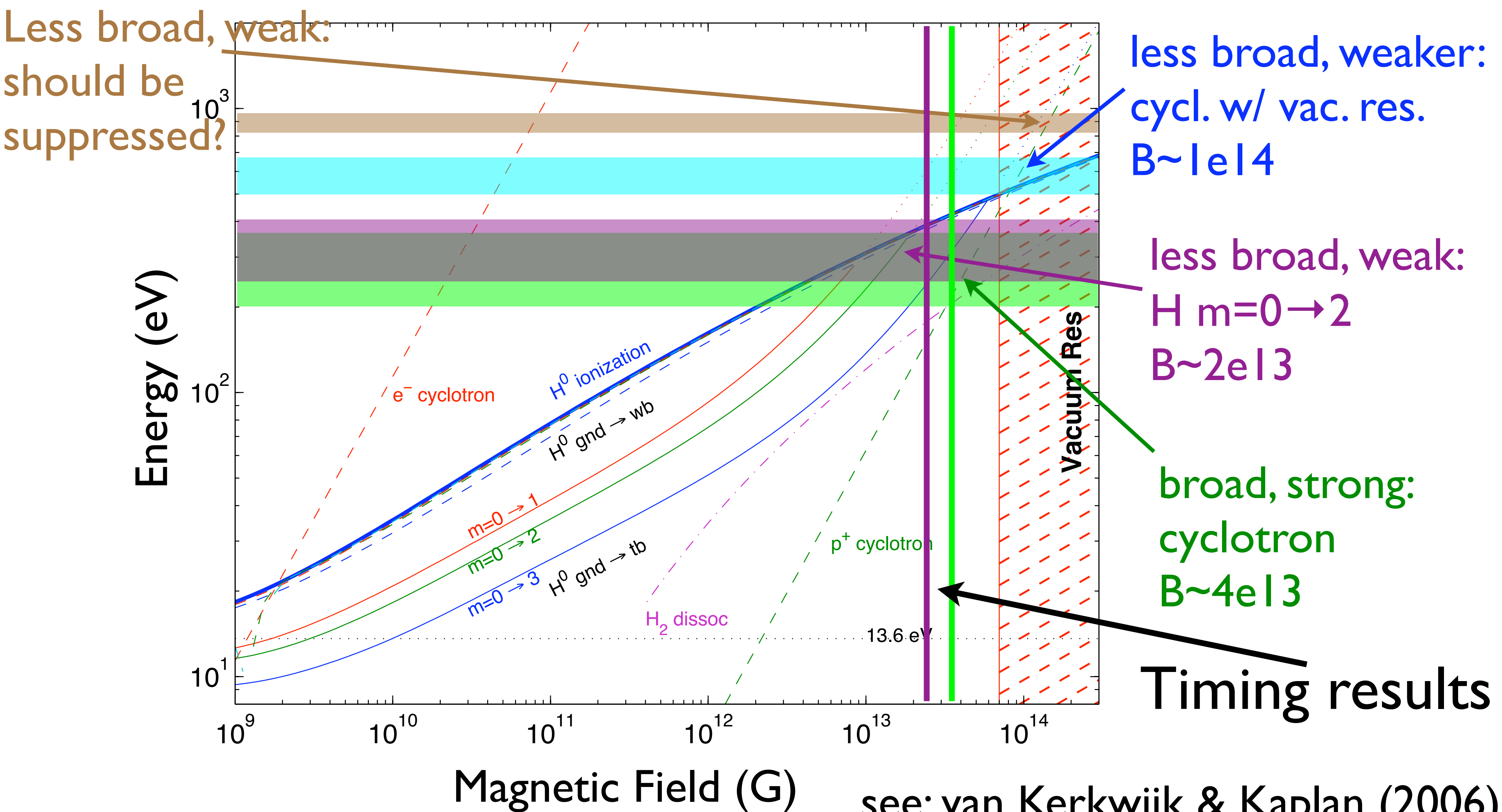

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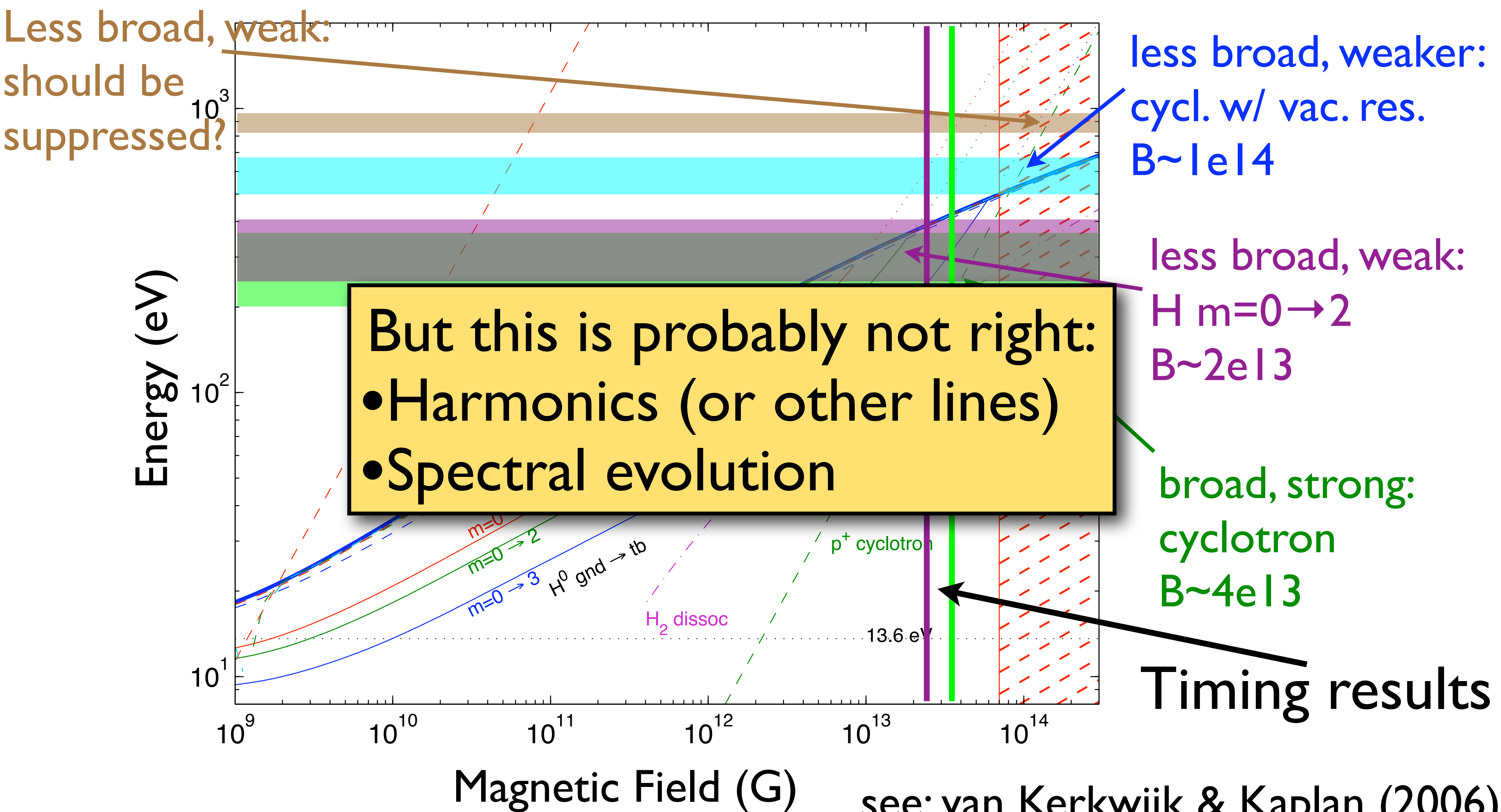

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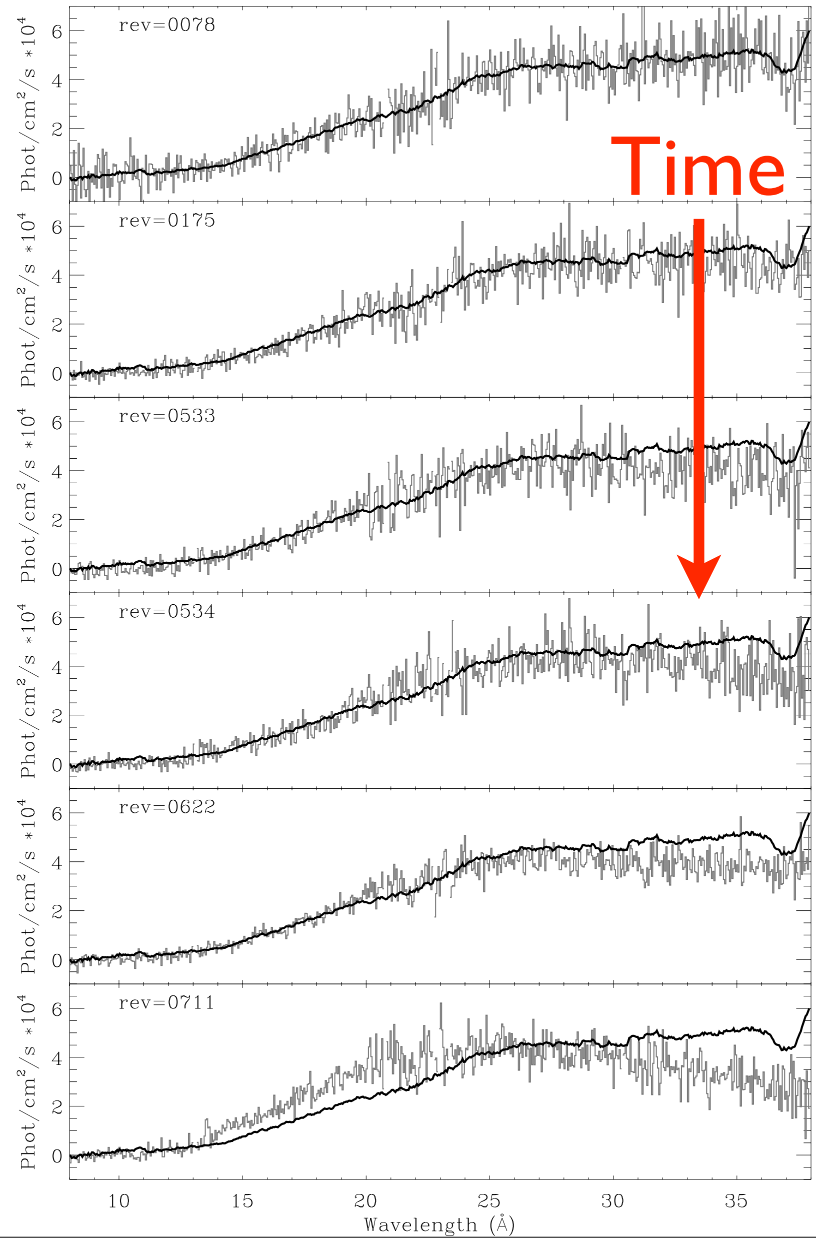
RX J0720: Variability

- Spectrum changed over ~months



de Vries et al. (2004); Vink et al. (2004)

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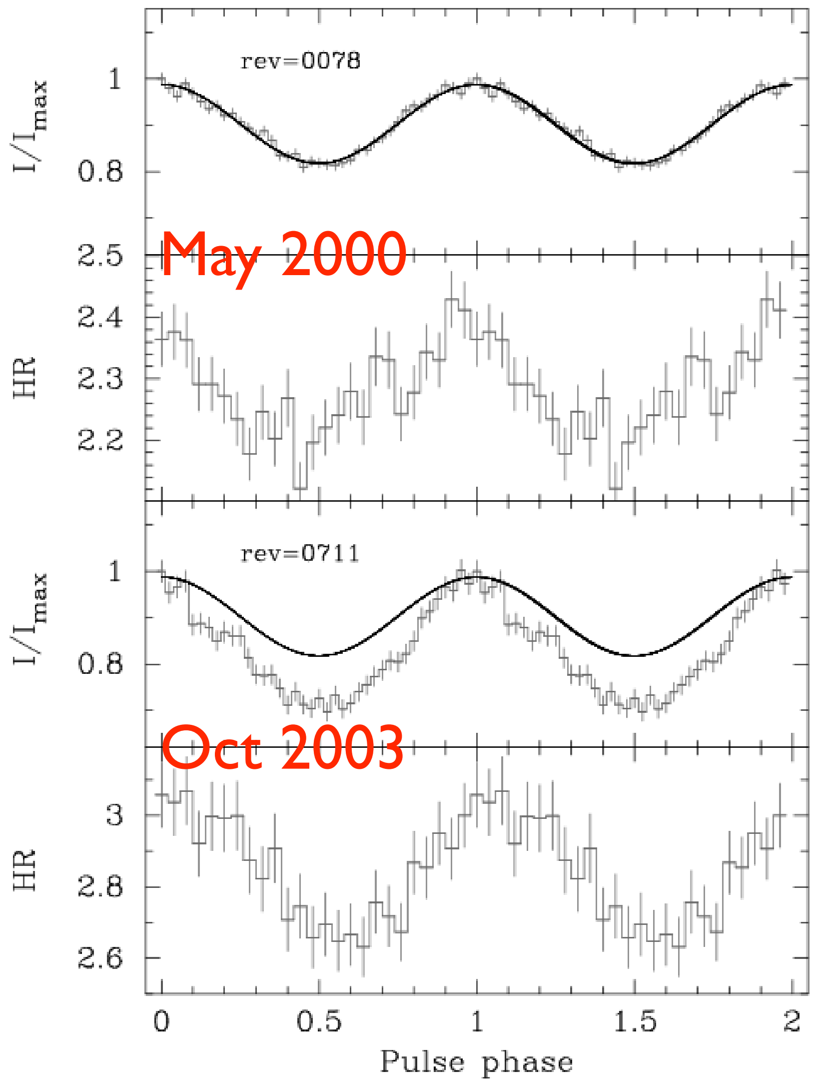

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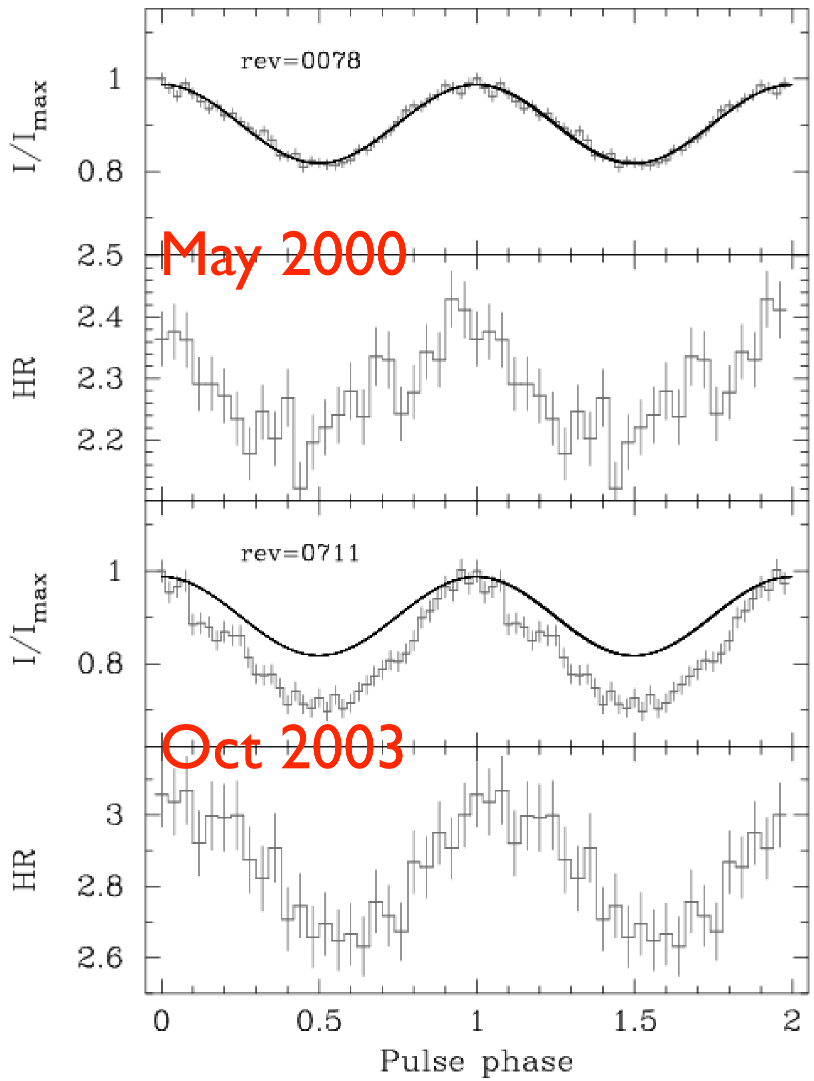

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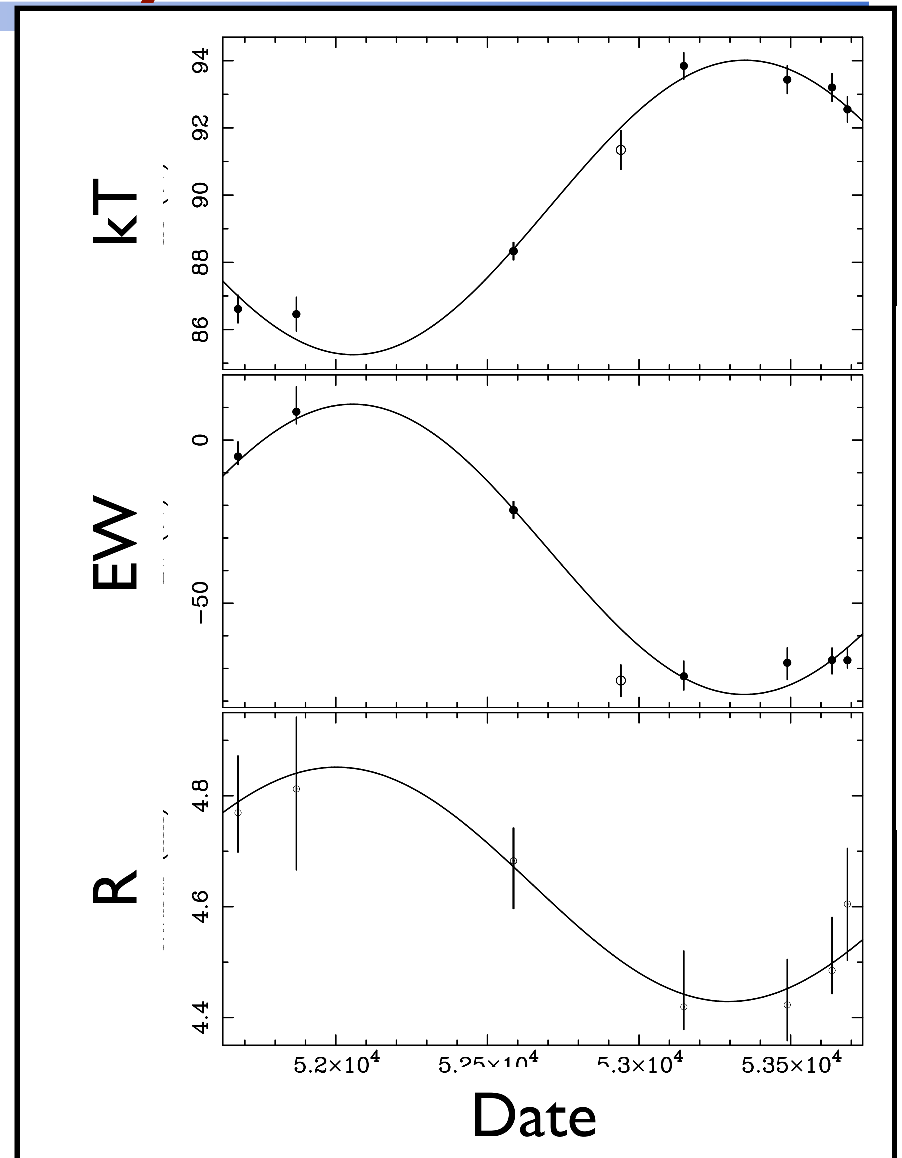

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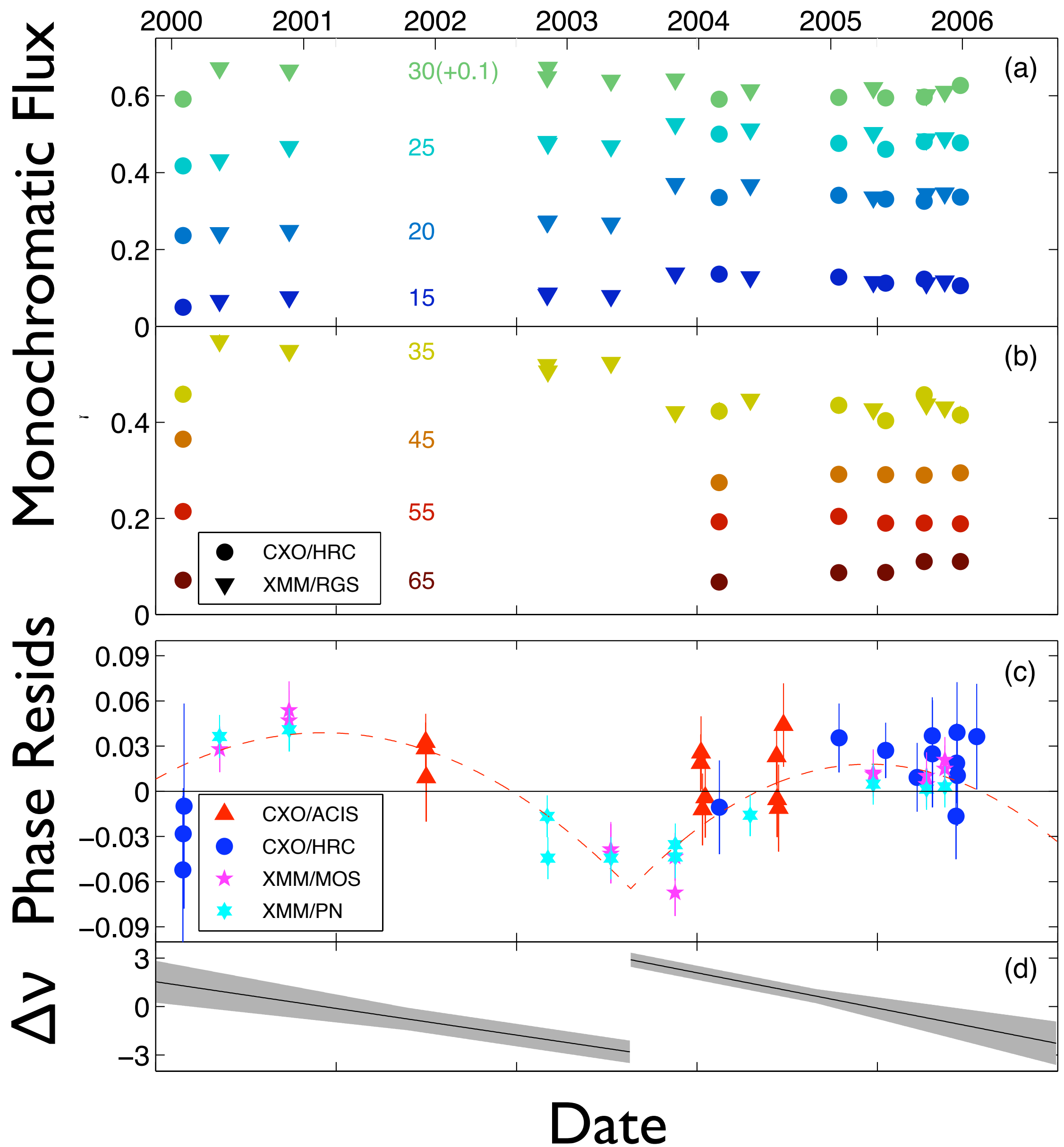
Spectrum Coupled to Timing?



van Kerkwijk et al. '07

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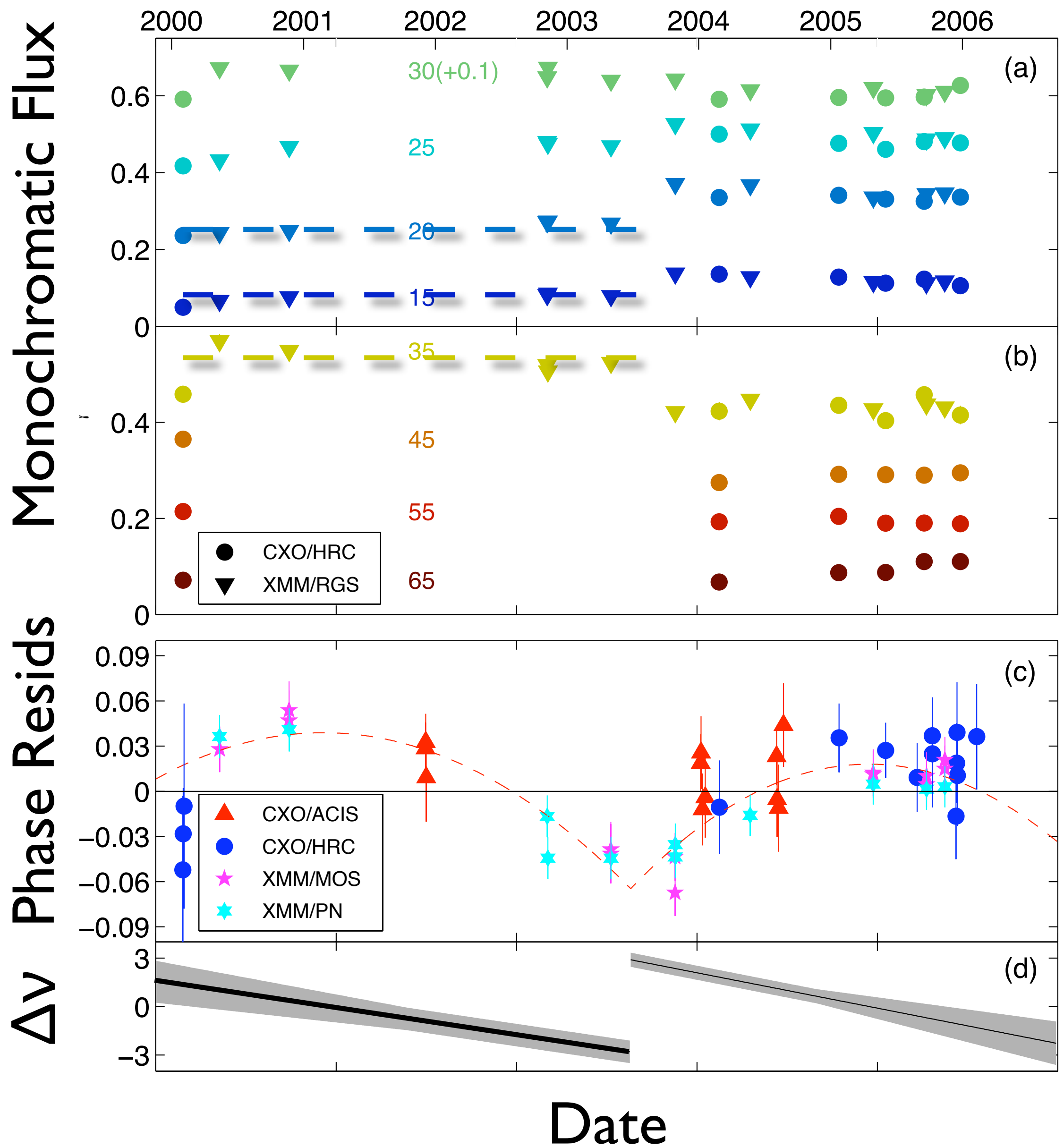

van Kerkwijk et al. '07

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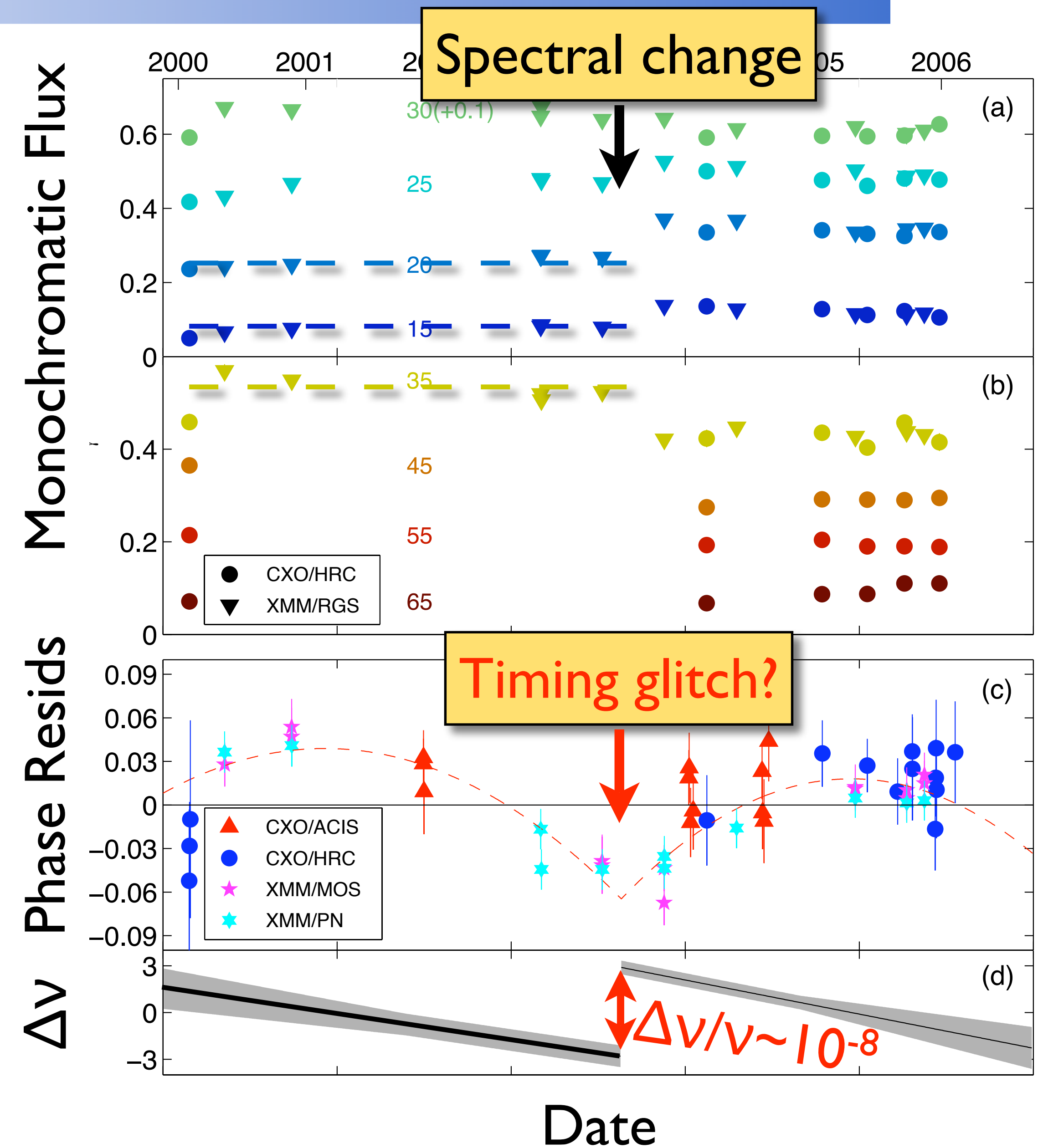
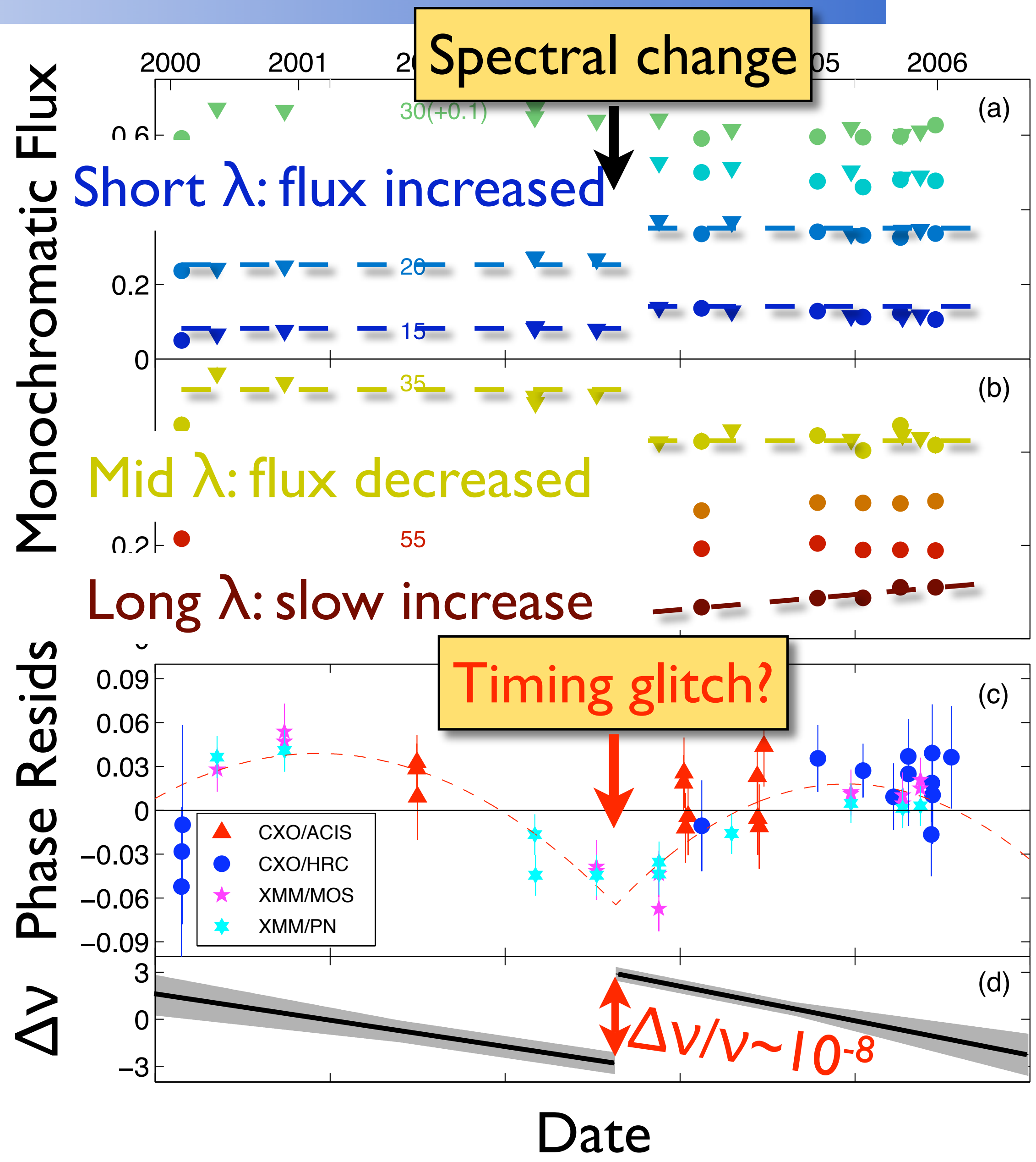


van Kerkwijk et al. '07

Spectrum Coupled to Timing?

- Change in surface composition?
- Still working on nature of change:
  - Glitch related to coupling of superfluid core to crust via *B*?
  - Change in *B* topology?
  - Accretion of debris/ dust?



van Kerkwijk et al. '07

Conclusions

- Too early to get real physics out
- Bring together:
  - Timing
  - X-ray spectroscopy
  - Optical photometry
  - Astrometry
- But are learning:
  - Atmospheres
  - NS population: how do these objects fit?
- Comparisons are vital

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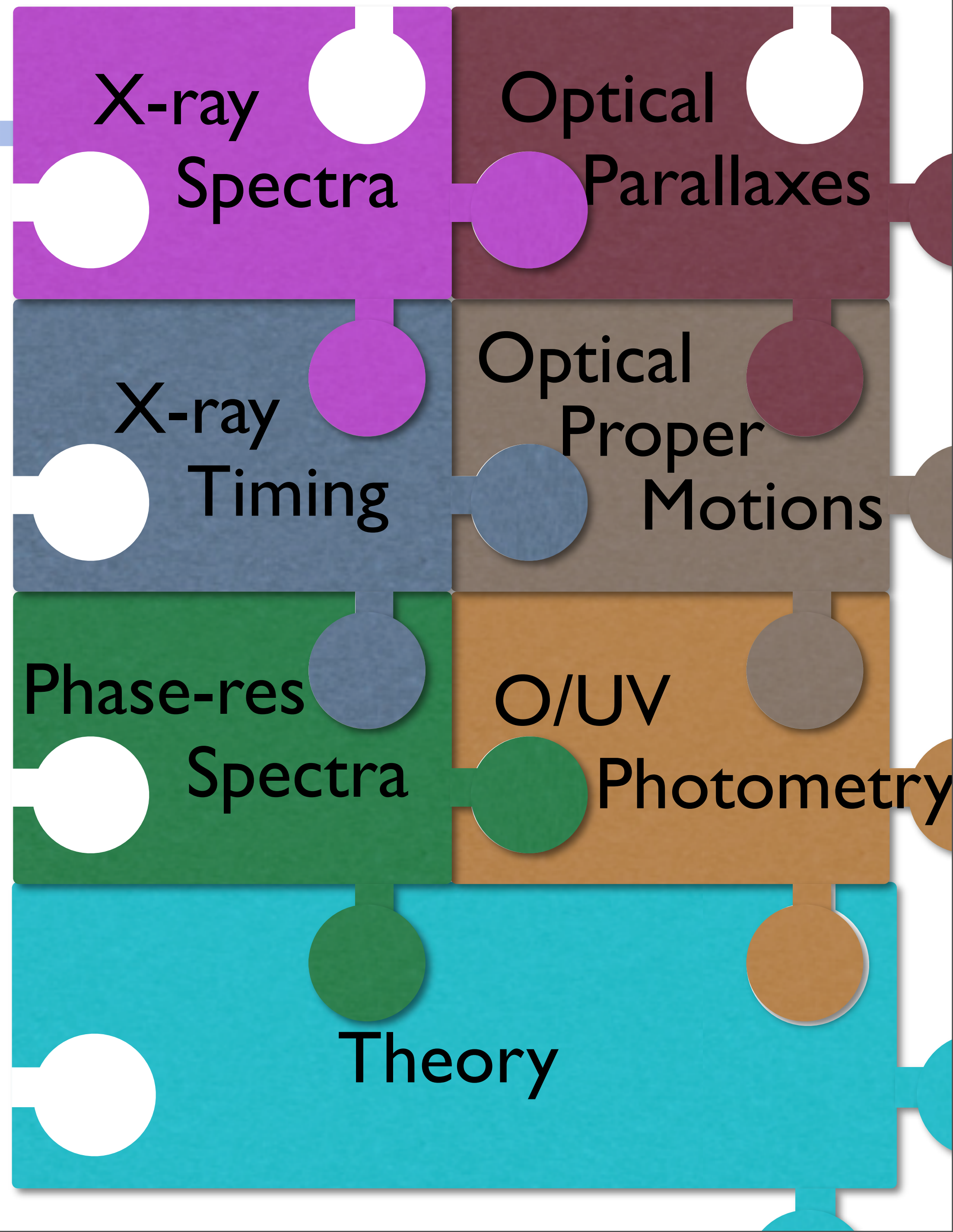

Future Efforts

- Astrometry → distance(s) and ages
- X-ray timing → magnetic fields
  - Working on timing noise
- X-ray spectra → try to understand surface
  - Phase resolved? Multiple absorption lines?
- Optical/UV spectra → characterize emission
  - Non-thermal emission?
- Find more source → improve statistics (see recent results by Rutledge et al.)