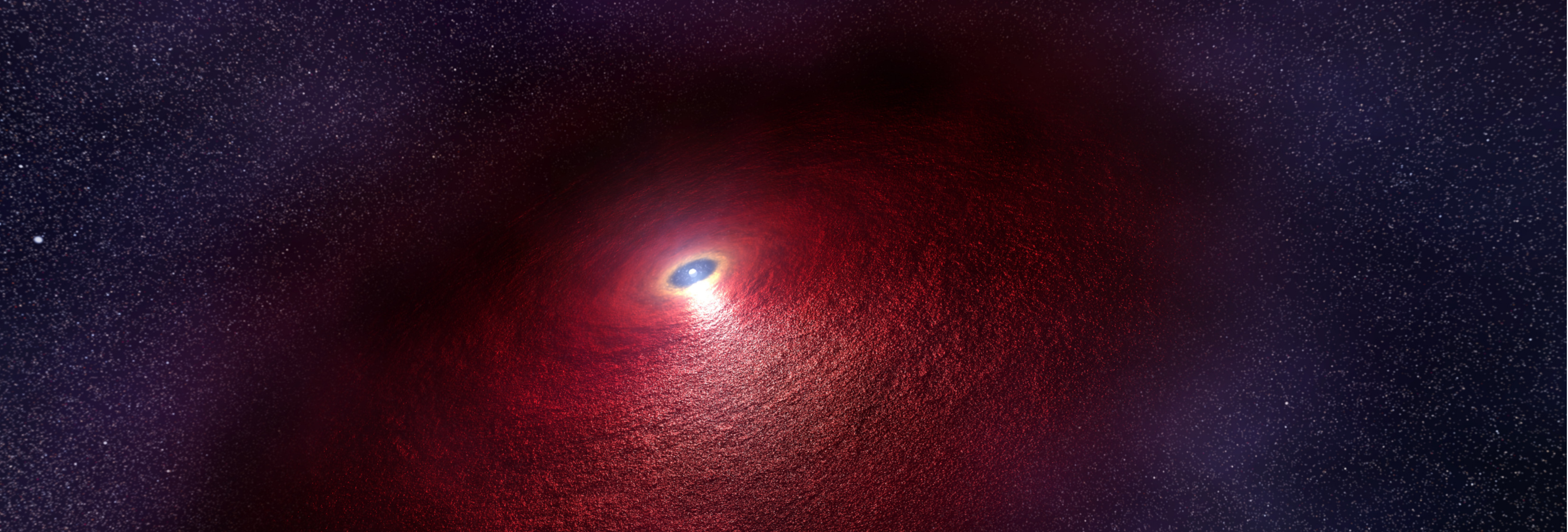


Disks around neutron stars

Bettina Posselt
University of Oxford, UK
Pennsylvania State University, USA

There are different possible disks around neutron stars

Remnants of progenitor disks – very unlikely due to supernova explosion

Supernova fallback disks
general prediction of supernova models, but very few detected candidates

Accretion disks in binary systems*
well-known and studied, e.g. in X-ray binaries

Disks from evaporated binaries*, planets, or asteroids
The 3 planets around PSR 1257+12 are explained by formation in such a disk

* 90% of the known pulsars are isolated

Disks around neutron stars are interesting for many reasons.

Study of **accretion processes** and **disk/wind interactions**.

Supernova fallback disks can probe models of **supernova explosions**.

Interaction with a the torque of a disk modifies the **evolution** of isolated neutron stars and could explain

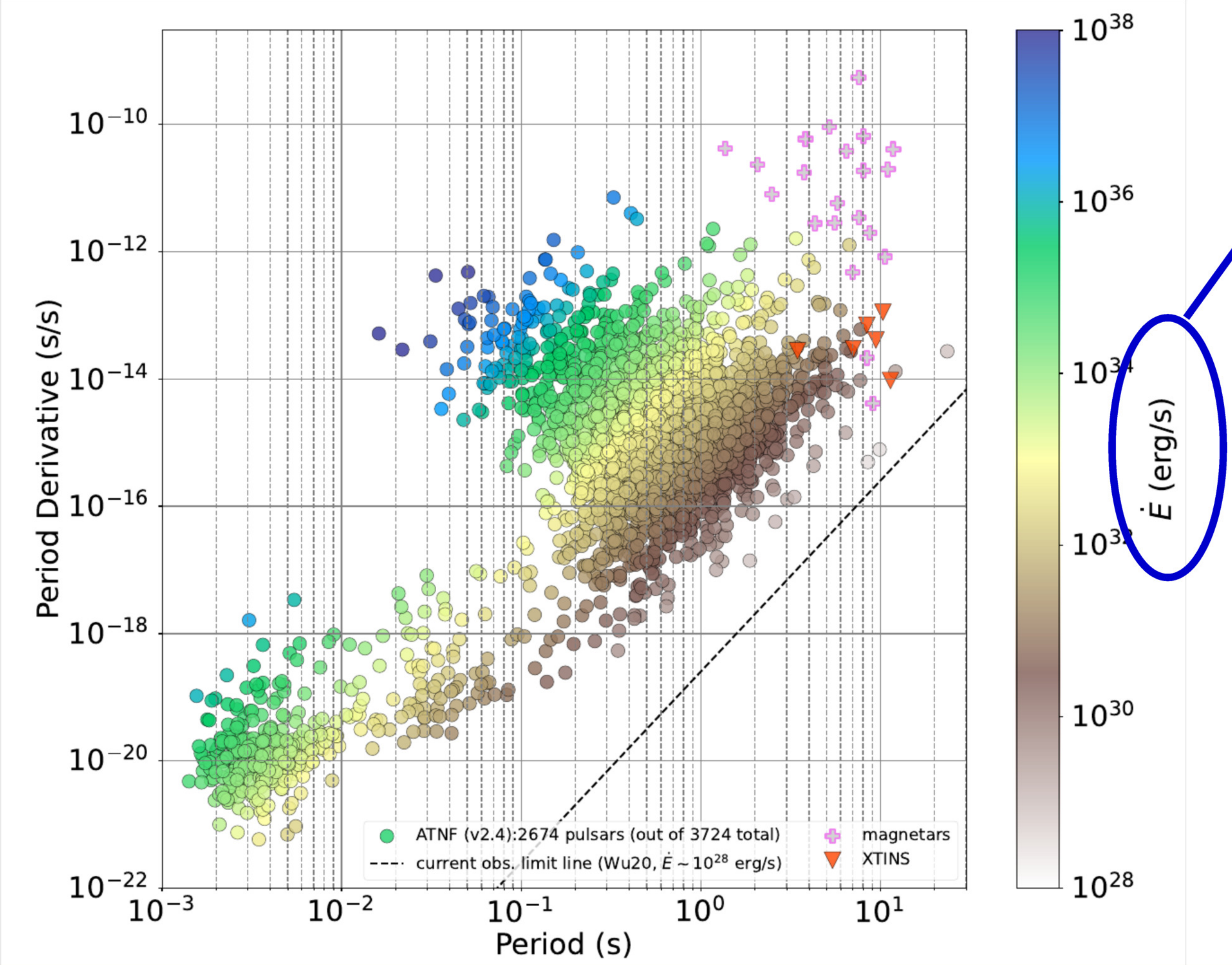
- the **"too-many"-neutron-stars problem**
- the recent discoveries of **ultra slowly rotating pulsars**

Investigations of **extreme conditions** for

- disk composition & survival
- planet formation

Bettina Posselt (U.Oxford)

The energy resources of neutron stars

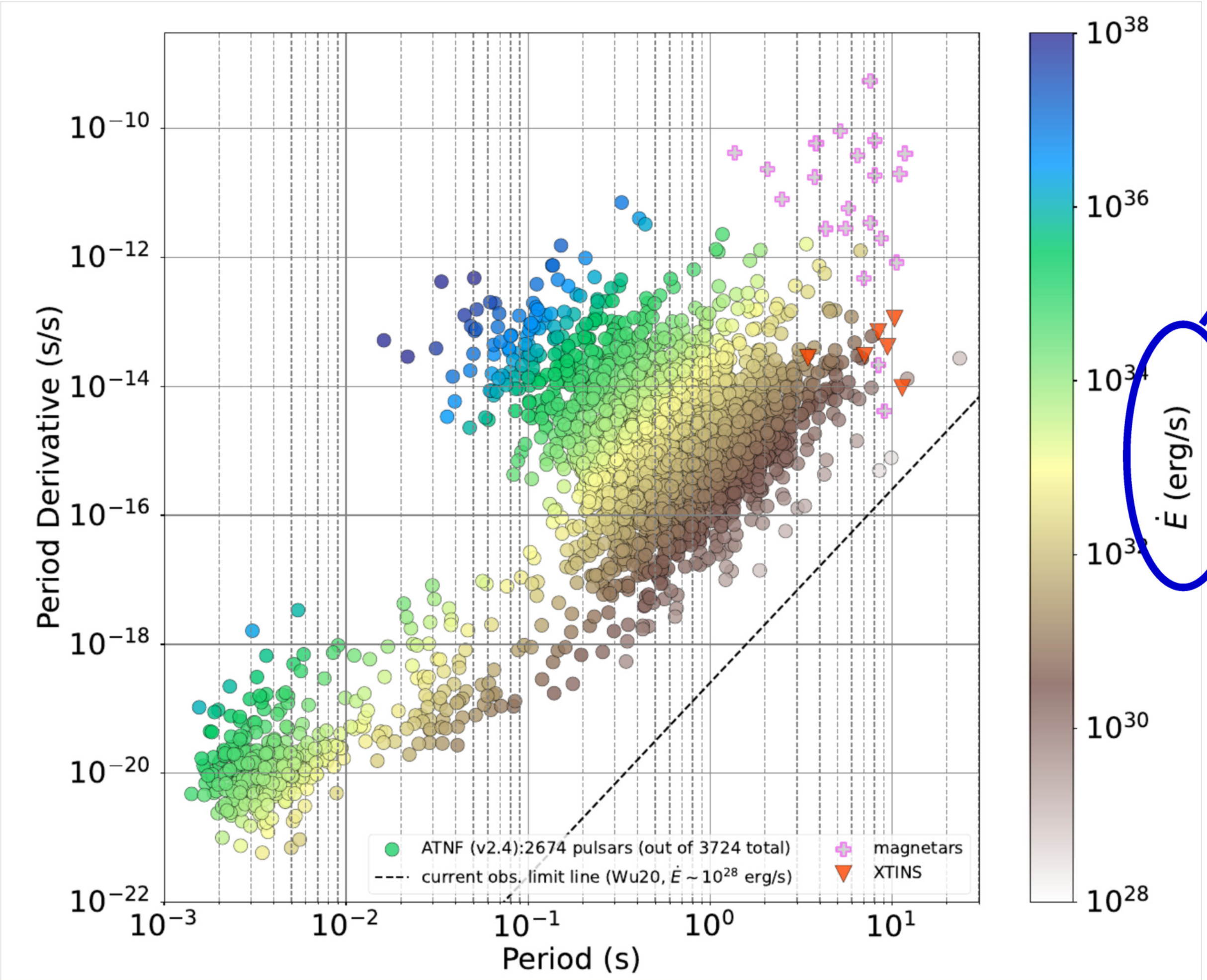


the spin-down power

$$\mathrm{d}E_{\mathrm{rot}}/\mathrm{d}t = -4\pi^2 I \dot{P} P^{-3}$$

commonly assumed:
~½ go into the pulsar wind

The energy resources of neutron stars



the spin-down power

$$\mathrm{d}E_{\mathrm{rot}}/\mathrm{d}t = -4\pi^2 I \dot{P} P^{-3}$$

commonly assumed:
~½ go into the pulsar wind

cooling of the interior

decay of the strong ($\sim 10^{12}$ G) magnetic fields

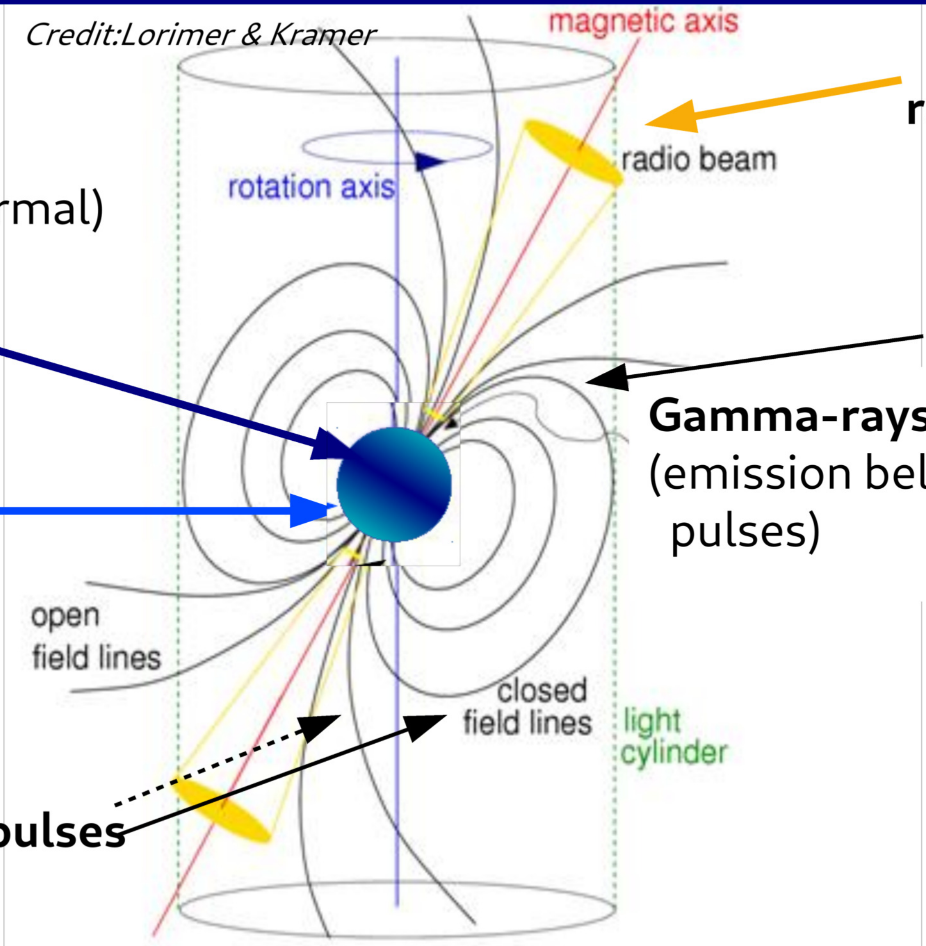
perhaps accretion energy in binary systems

An isolated neutron star can emit (and pulse!) at all λ.

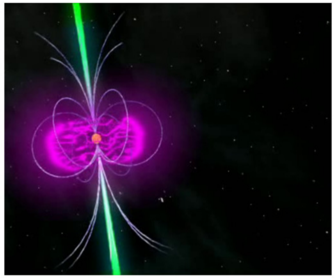
UV - Optical
(thermal & non-thermal)

(thermal)
soft X-rays pulses

soft & hard X-rays pulses



(coherent)
radio pulses



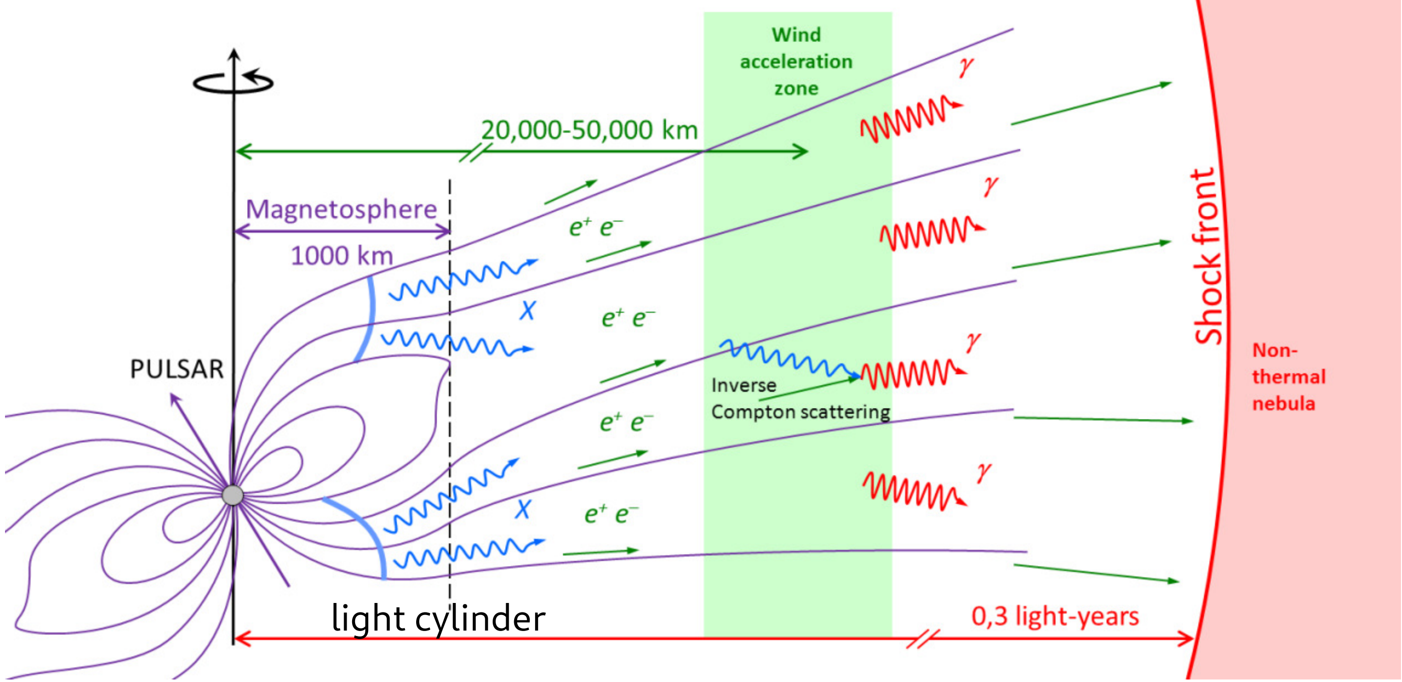
Gamma-rays
(emission belt,
pulses)

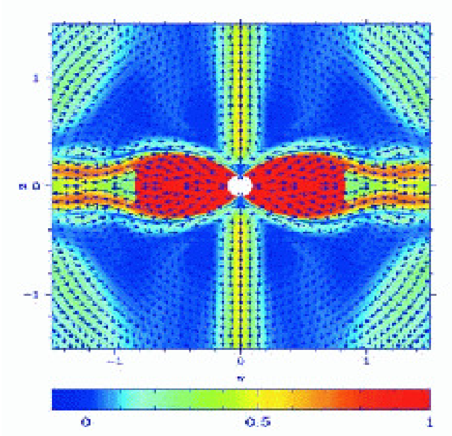
In addition:
- Pulsar Wind Nebulae
- supernova remnants
- TeV ``bubbles"

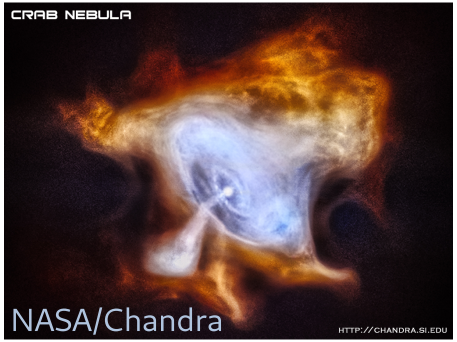
Soft X-rays: : 0.1 keV bis 1 keV   Hard X-rays : > 1keV   (1 eV = 1.602 10^{-19} J)

Many pulsars produce powerful anisotropic winds.

© MIPK/based on Aharonian et al. 2012



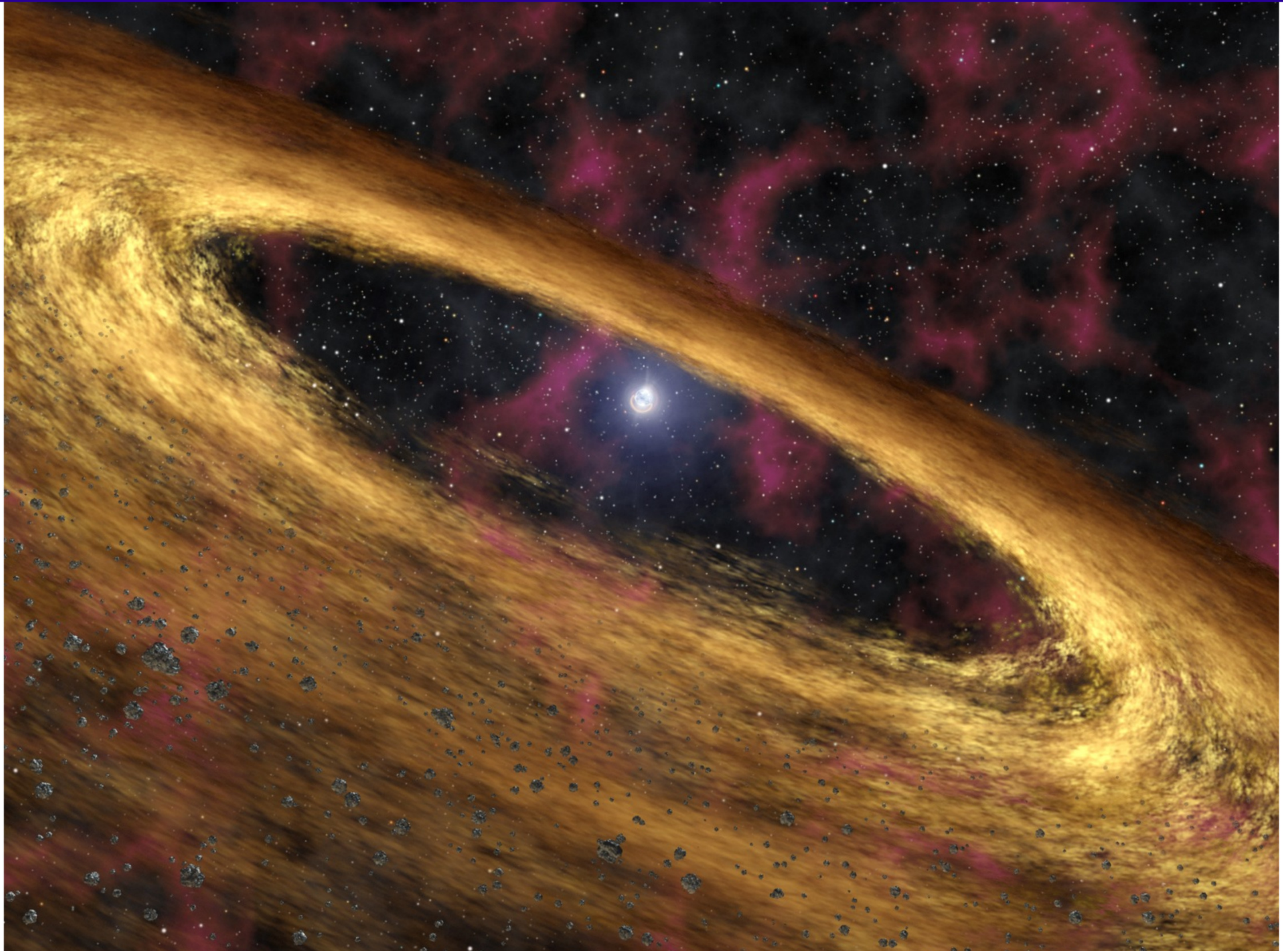




jet and torus
structures: ~1-2 lyr

About half of the pulsar's emitted energy is transformed into
a fast (relativistic, i.e. with velocity close to the speed of light) wind

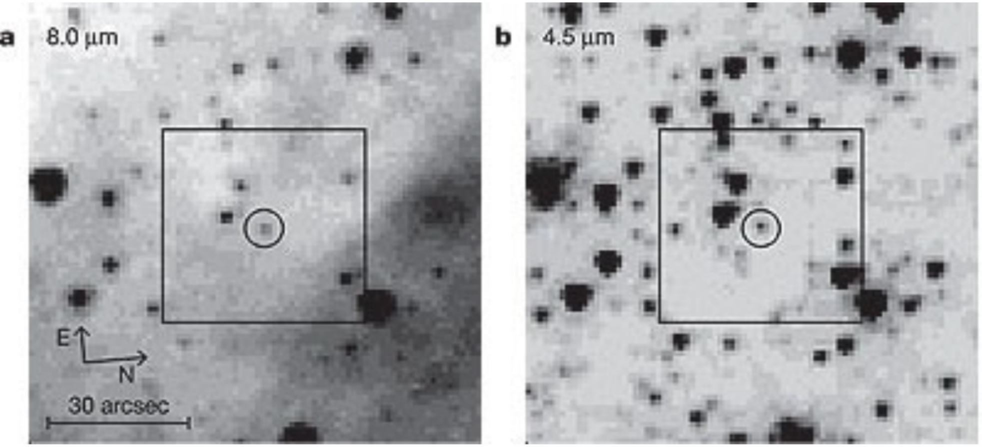
A disk around the magnetar 4U0142+61 ?



Credit: NASA/JPL-Caltech/R. Hurt (SSC)

The disk candidate around the magnetar 4U0142+61

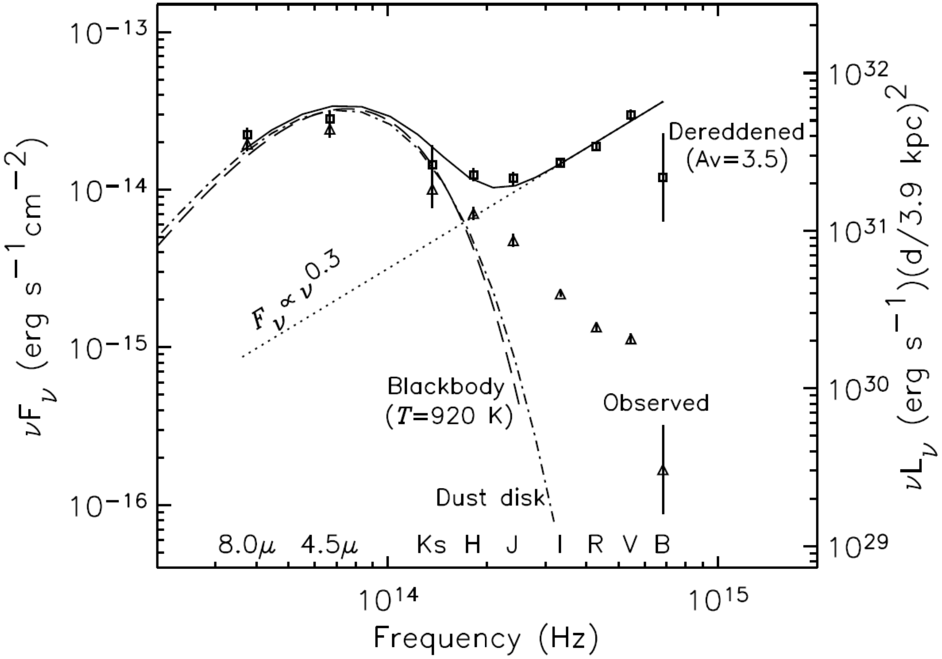
Wang et al. 2006



Nature, Vol. 440, 772–775 (6 April 2006)

A debris disk around an isolated young neutron star

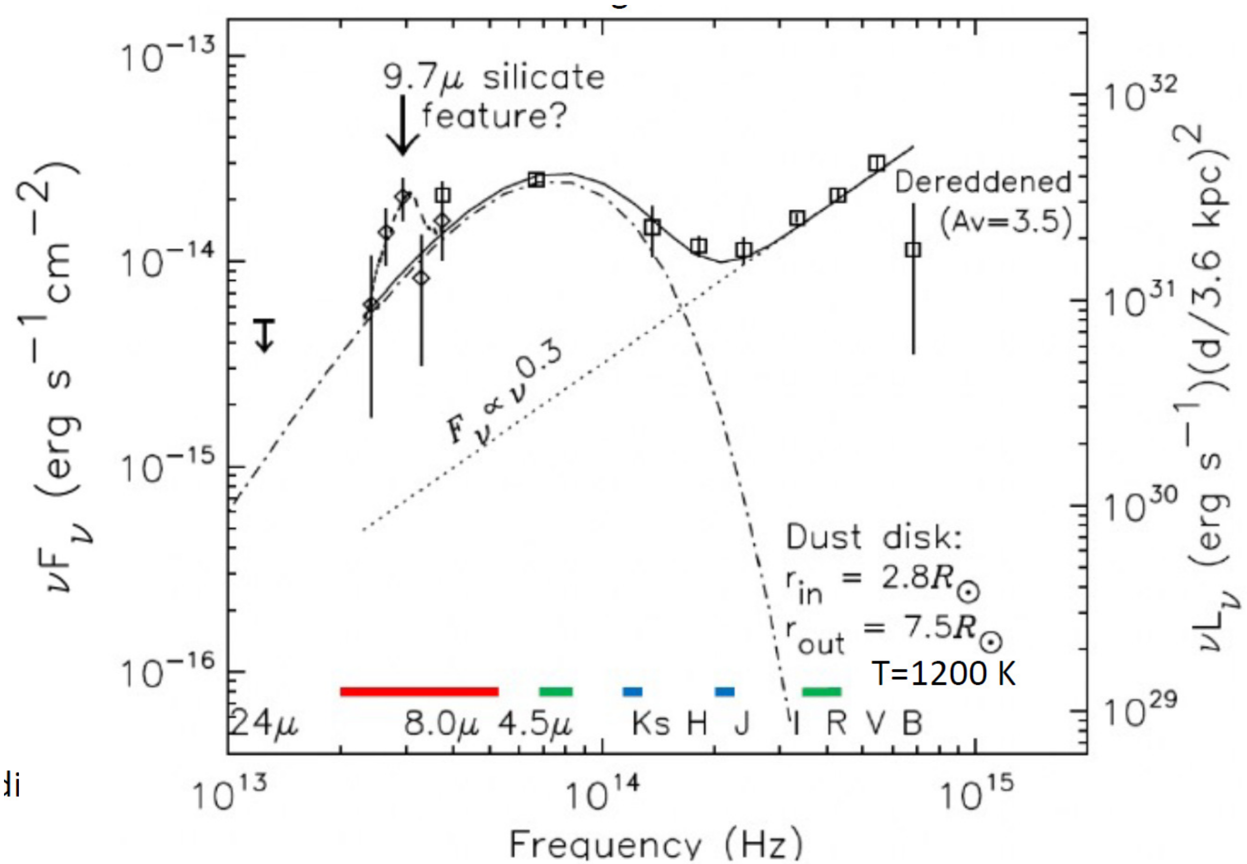
Zhongxiang Wang, Deepto Chakrabarty, & David L. Kaplan



The data can be fit with (different) disk models: a gaseous supernova fallback disk (viscous dissipation & irradiated; Ertan et al. 2007)

More Spitzer data and observation windows of our new JWST data

Wang et al. 2008



MIRI:
LRS spectrum
Done: 20. September 2022

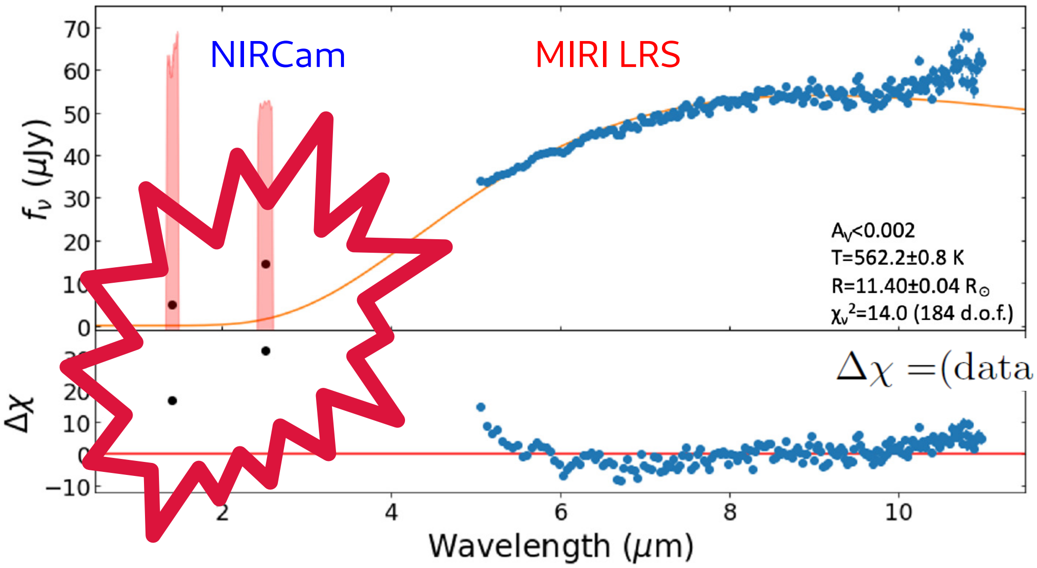
NIRCam:
F250M and F140M images
Done: 21 September 2022

published: Hare et al. 2024 (ApJ; arXiv 2405.03947)

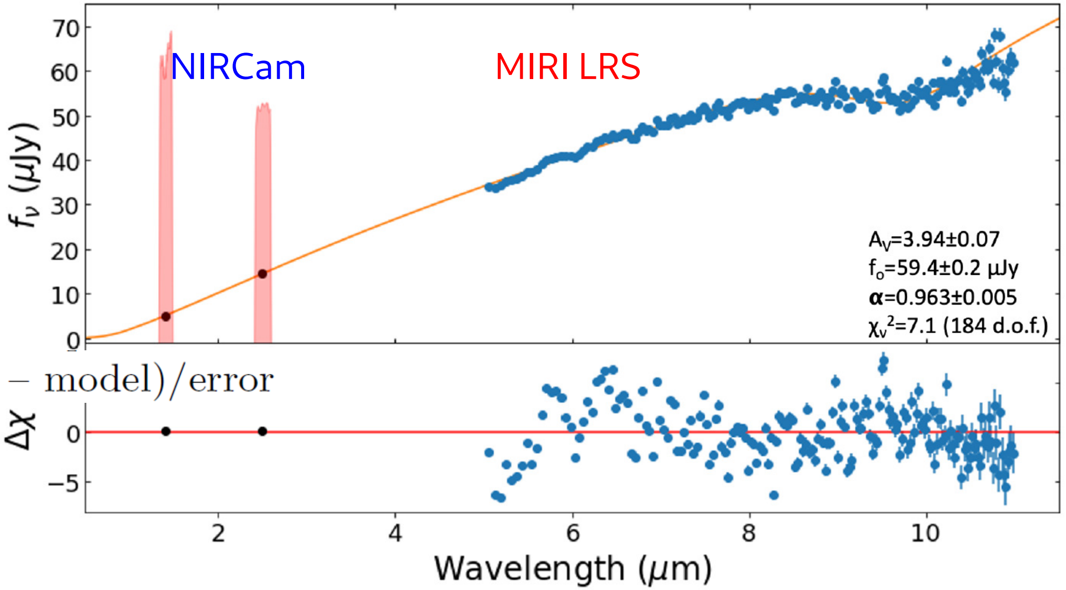
NIRCam:
F410M and F070W timing
technical issues,
recently re-observed

A blackbody model cannot explain the MIRI+NIRCam data

Model: absorbed blackbody spectrum



Model: absorbed power law



$$\Delta\chi = (\text{data} - \text{model})/\text{error}$$

$$f_\nu = f_0(\lambda/\lambda_0)^\alpha 10^{-0.4A_\lambda}$$

$\alpha = 0.963 \pm 0.005$ $A_V = 3.94 \pm 0.07$

$f_0 = 59.4 \pm 0.2\ \mu\text{Jy}$ at $\lambda_0 = 8\ \mu\text{m}$

No silicate feature either!

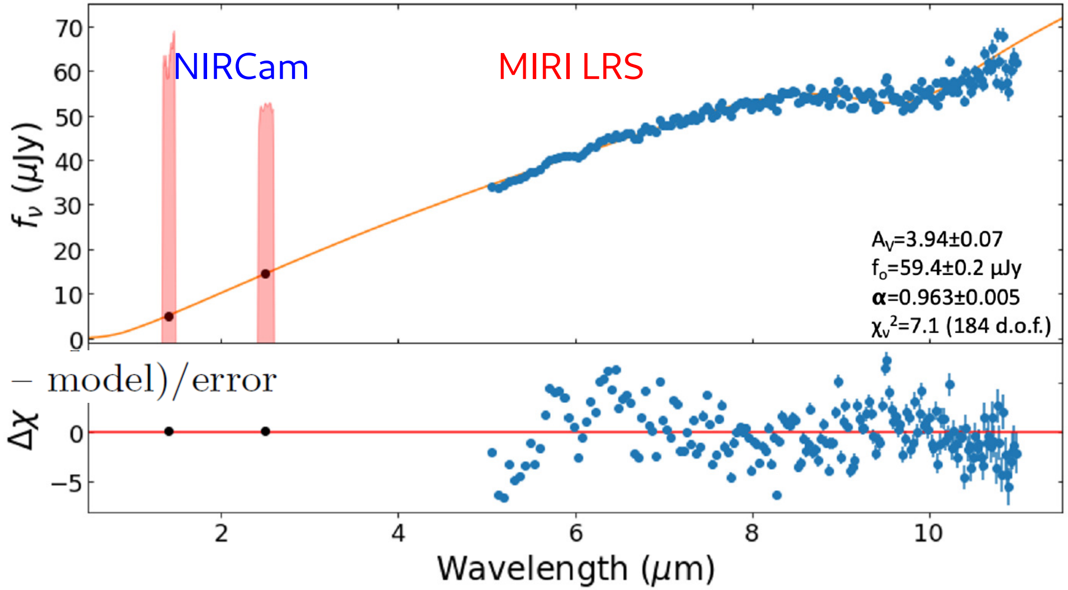
Hare et al. 2024 (ApJ; arXiv 2405.03947)

A blackbody model cannot explain the MIRI+NIRCam data

The power law emission could be produced by the magnetosphere!

no disk?

Model: absorbed power law



$$f_\nu = f_0(\lambda/\lambda_0)^\alpha 10^{-0.4A_\lambda}$$

$$\alpha = 0.963 \pm 0.005 \qquad A_V = 3.94 \pm 0.07$$

$$f_0 = 59.4 \pm 0.2\ \mu\text{Jy at } \lambda_0 = 8\ \mu\text{m}$$

Hare et al. 2024 (ApJ; arXiv 2405.03947)

But the power law slope does not exclude all disk models.

Approximation of a multi-temperature blackbody (BB) flat disk (optically thick):

$$f_\nu = \frac{2\pi \cos i}{d^2} \frac{2h\nu^3}{c^2} \int_{r_{\rm in}}^{r_{\rm out}} \frac{r\,dr}{\exp[h\nu/kT(r)] - 1}$$

Assuming radial dependence of the local effective temperature:

$$T(r) = T_{\rm in}(r/r_{\rm in})^{-\beta} = T_{\rm out}(r/r_{\rm out})^{-\beta}$$

$$f_\nu \propto \nu^{3-2/\beta} \quad \text{at} \quad (2/\beta - 1)kT_{\rm out} \ll h\nu \ll kT_{\rm in}$$

$$\alpha = 2/\beta - 3$$

$$\boxed{\beta = 2/(\alpha + 3) = 0.505 \text{ for } \alpha = 0.96}$$

if $r_{\rm out}/r_{\rm in} \gg (2/\beta - 1)^{1/\beta}$

Our JWST data power law result:

$$f_\nu = f_0(\lambda/\lambda_0)^\alpha 10^{-0.4A_\lambda}$$

$$\alpha = 0.963 \pm 0.005$$

Likely more complicated: not BB emission, flared disk, optical thick and optical thin regions
Problem (?): Spitzer MIPS data/limit cannot be fit with this simple model

The radial power law temperature model seems to be consistent with the previous fallback disk model by Ertan et al. 2007

Ertan et al. 2007

TABLE 1

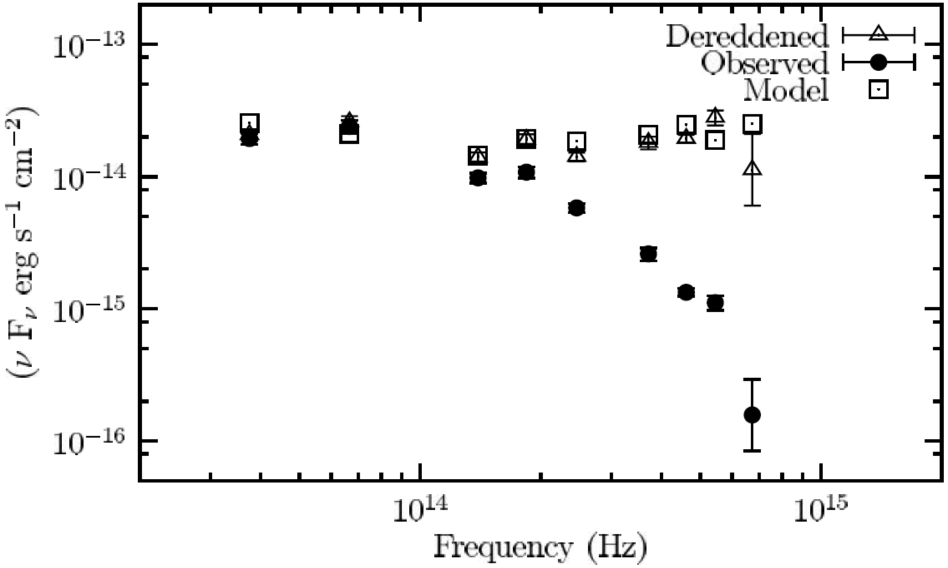
MODEL TEMPERATURES AND RADII CORRESPONDING TO DIFFERENT OPTICAL AND INFRARED BANDS

Band	T_{BB} (K)	R (cm)	D/F_{irr}
B	6516	7.0×10^{9}	0.45
V	5263	1.0×10^{10}	0.3
R	4454	1.4×10^{10}	0.30
I	3585	2.2×10^{10}	0.14
J	2377	4.8×10^{10}	0.07
H	1779	7.9×10^{10}	0.04
K_s	1324	1.4×10^{11}	0.02
4.5 μm	644	5.9×10^{11}	0.005
8 μm	362	1.9×10^{12}	0.002

NOTE.—The rightmost column shows the ratio of viscous dissipation rate to irradiation flux.

$$T(r) \propto r^{-0.51}$$

$$\alpha = 0.92$$

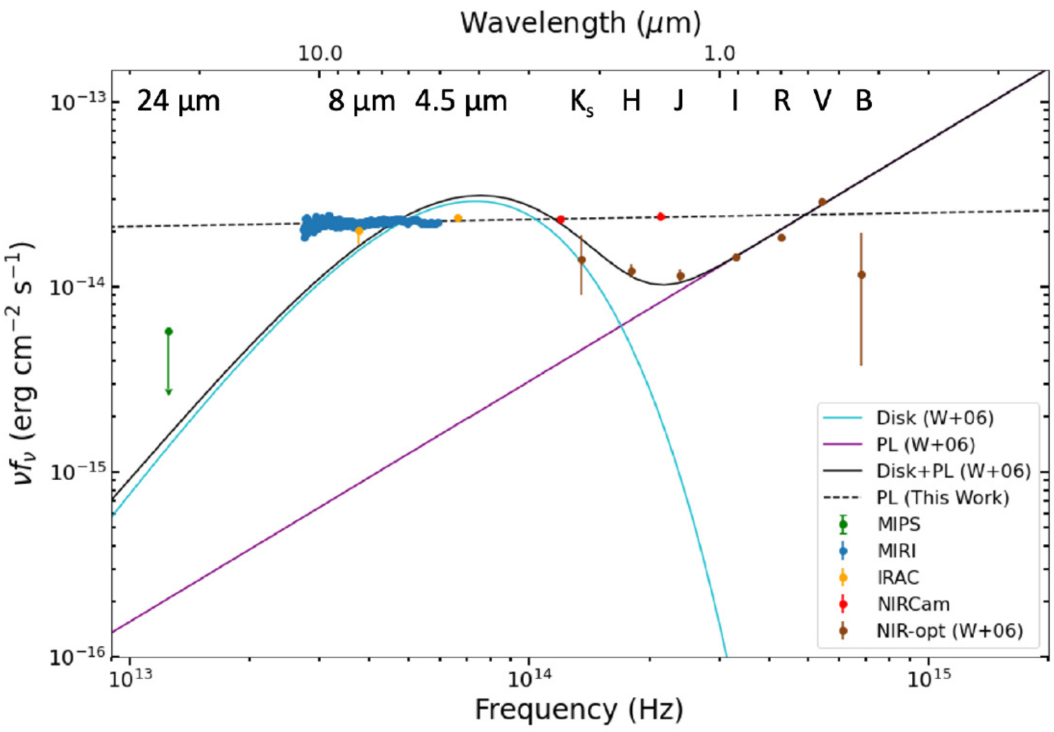


This is very close to

$$\beta = 2/(\alpha + 3) = 0.505 \text{ for } \alpha = 0.96$$

Conclusion – many exciting things to discuss:

Hare et al. 2024



Can models of irradiated dusty disks
or debris disks produce such a spectrum?

Suggested models to try?

How typical are "no spectral features" in disks?
Can we exclude some gas/dust compositions ?

regarding variability:
How quick is the process
X-ray irradiation → IR re-emission ?

Could one have "pulsing" disk emission
(e.g., in a warped disk) ?