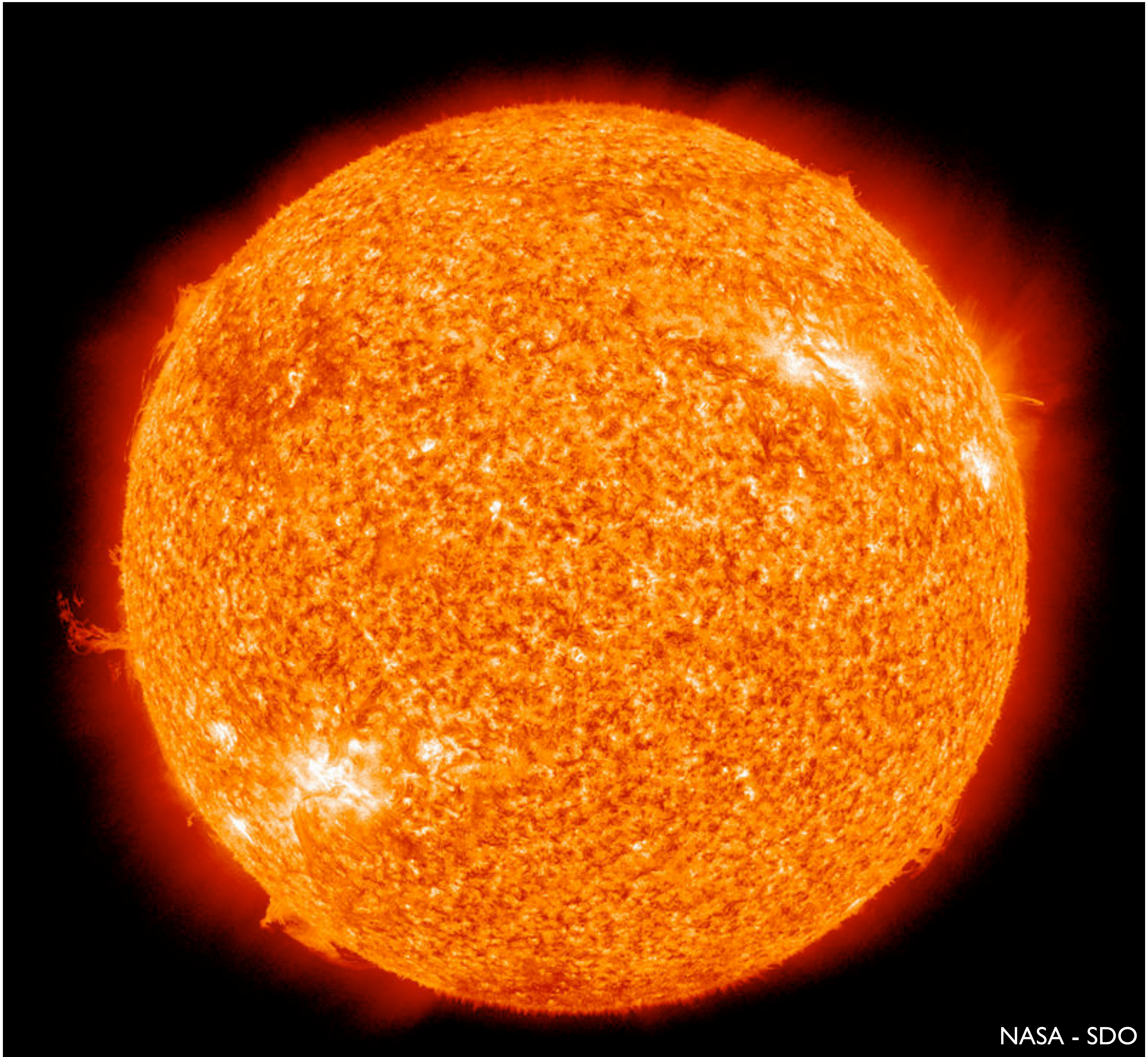
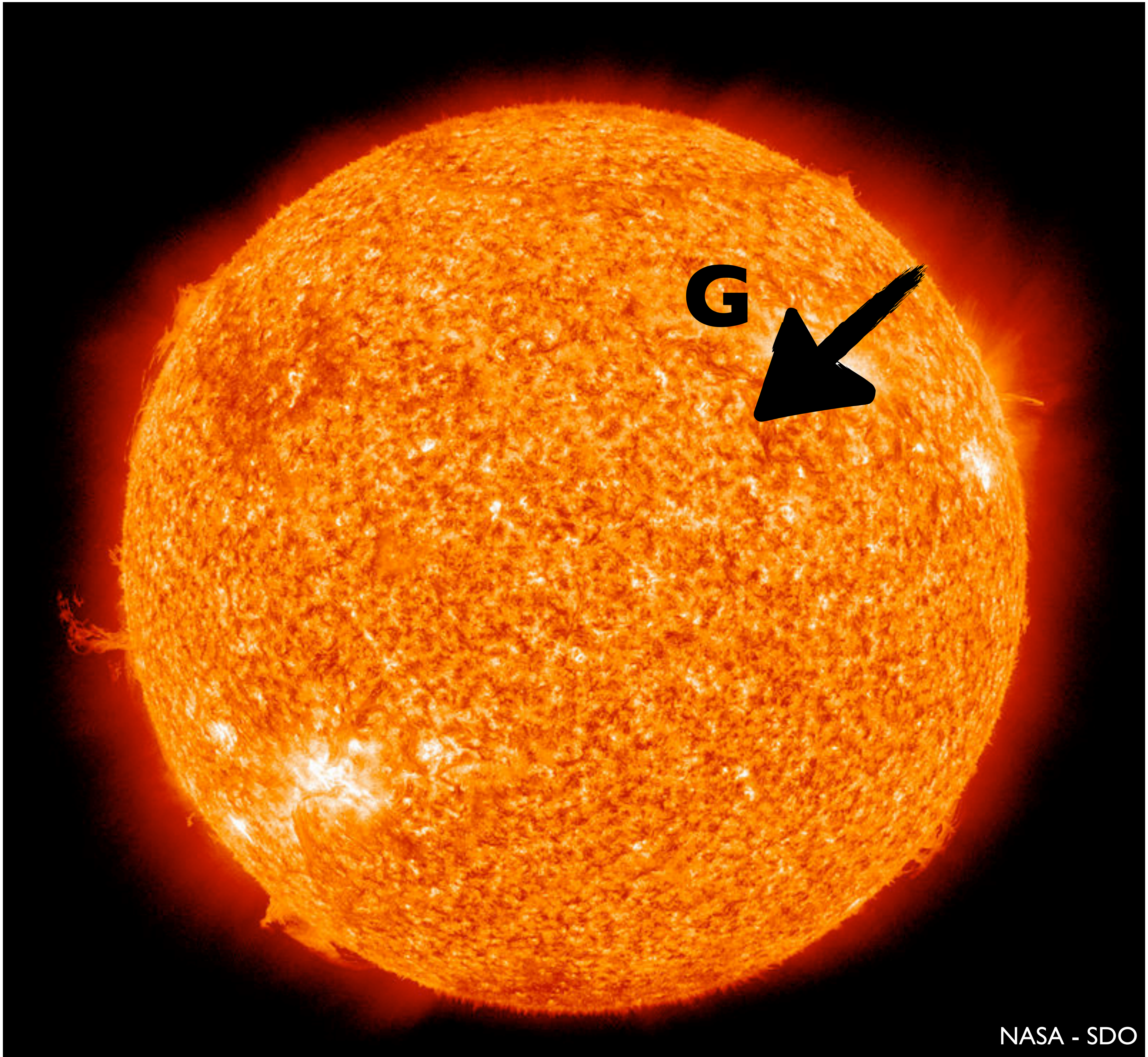
Turun yliopisto
University of Turku

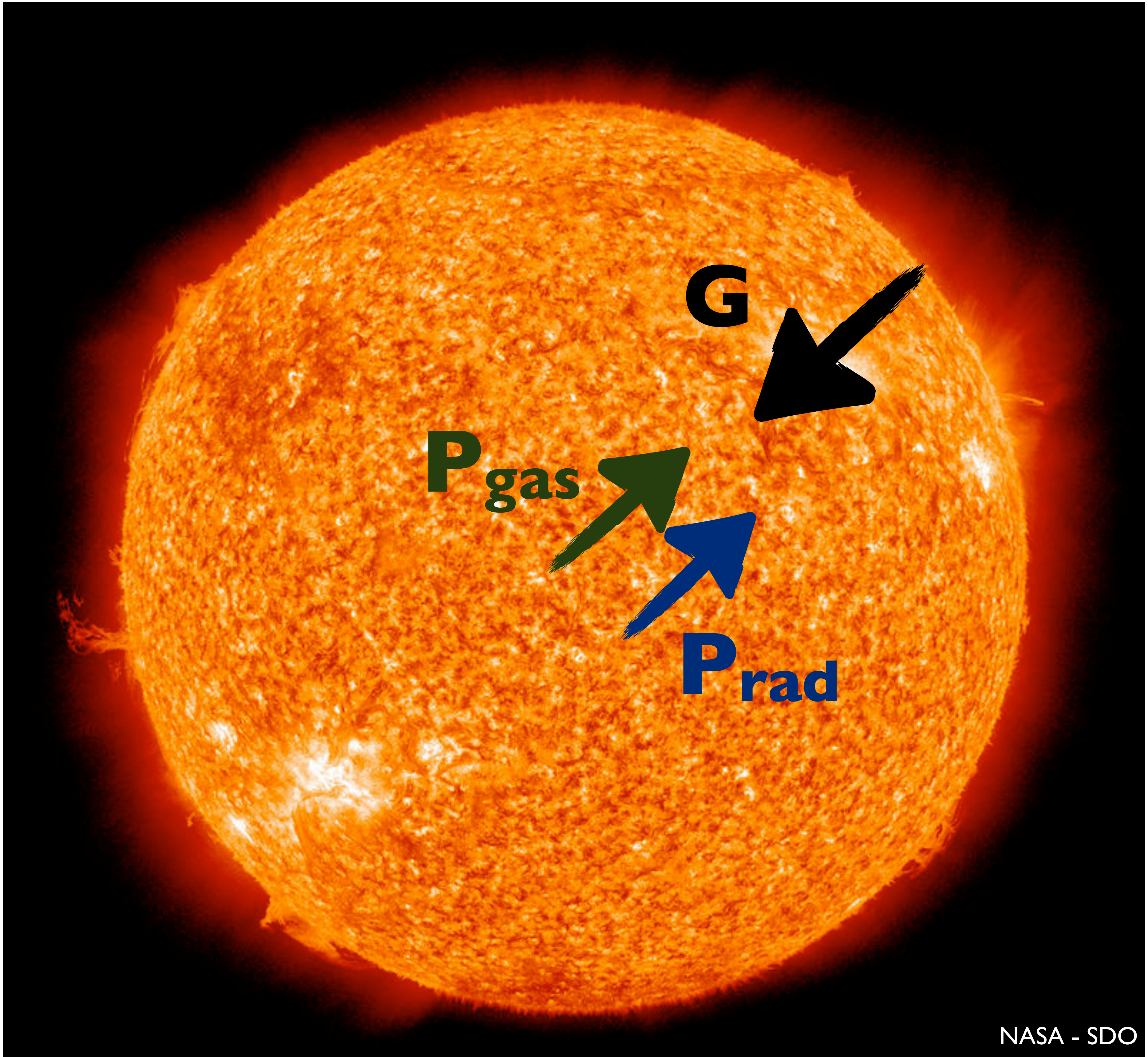
Neutron star atmospheres enriched with nuclear burning ashes

Joonas Nättilä
joonas.a.nattila@utu.fi

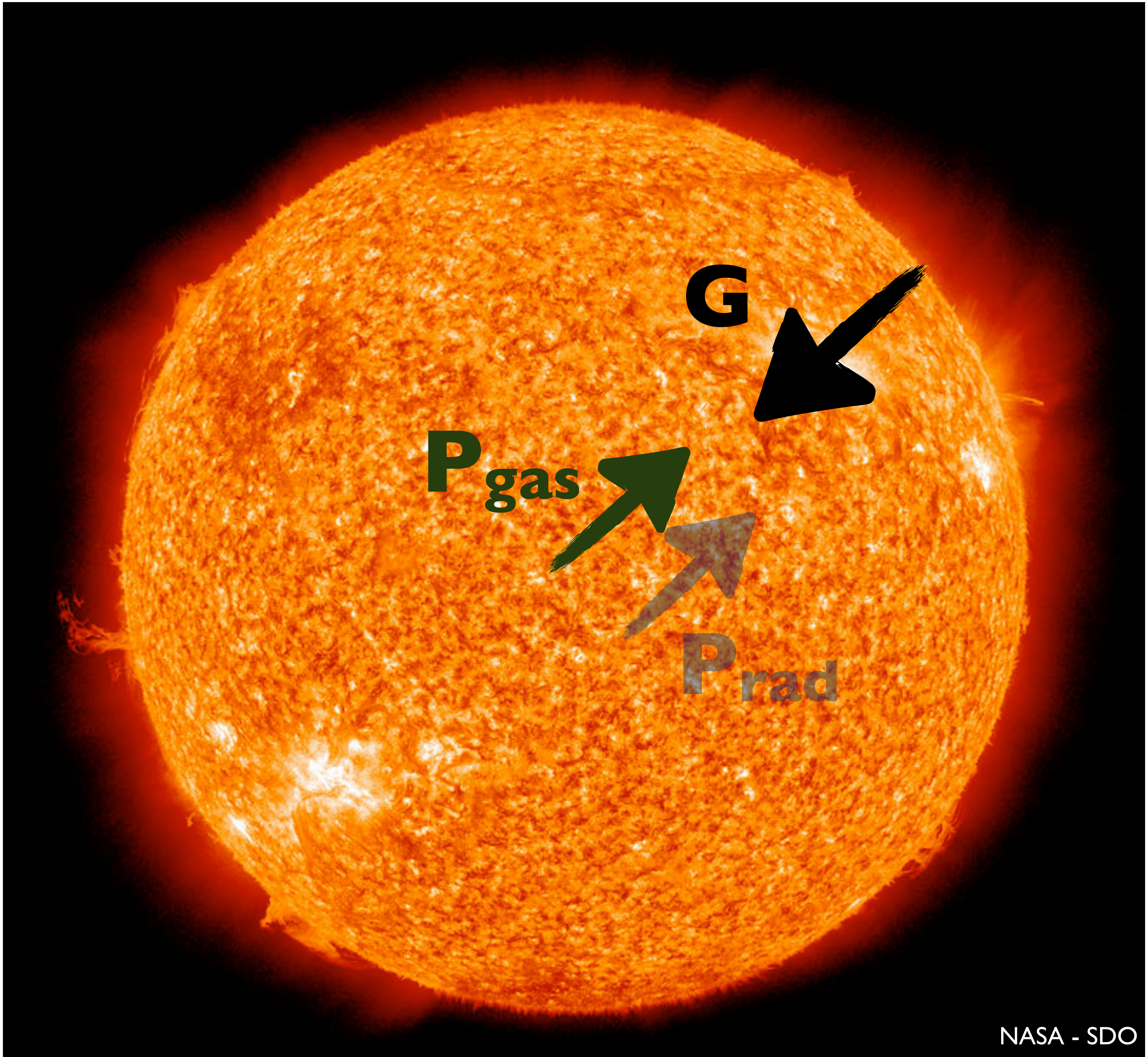
Collaborators:
Jari Kajava (ESAC)
Valery Suleimanov (Tübingen)
Juri Poutanen (Tuorla Observatory)


NASA - SDO

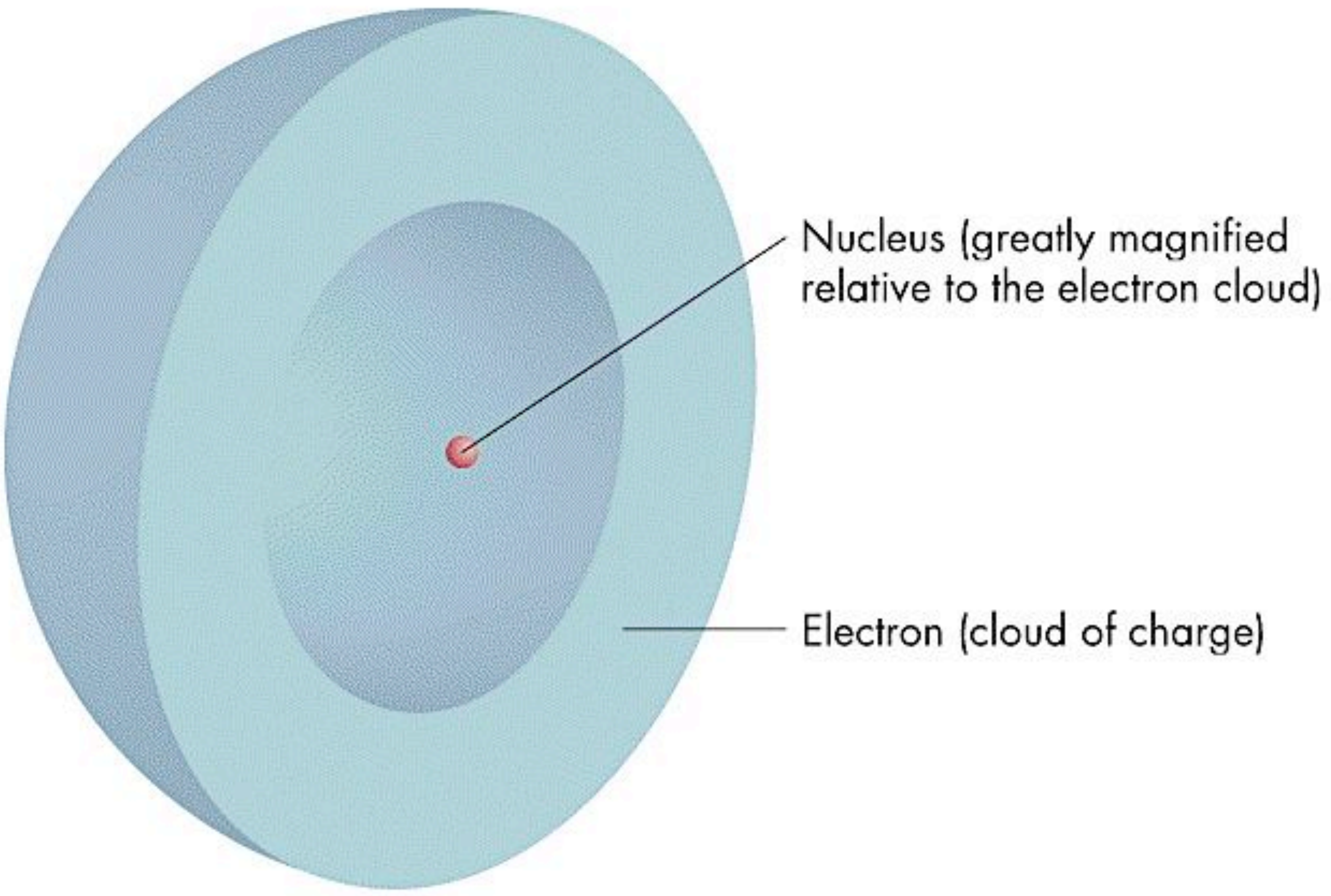

G
NASA - SDO


G
P_{gas}
P_{rad}
NASA - SDO


FUEL
½
E
F

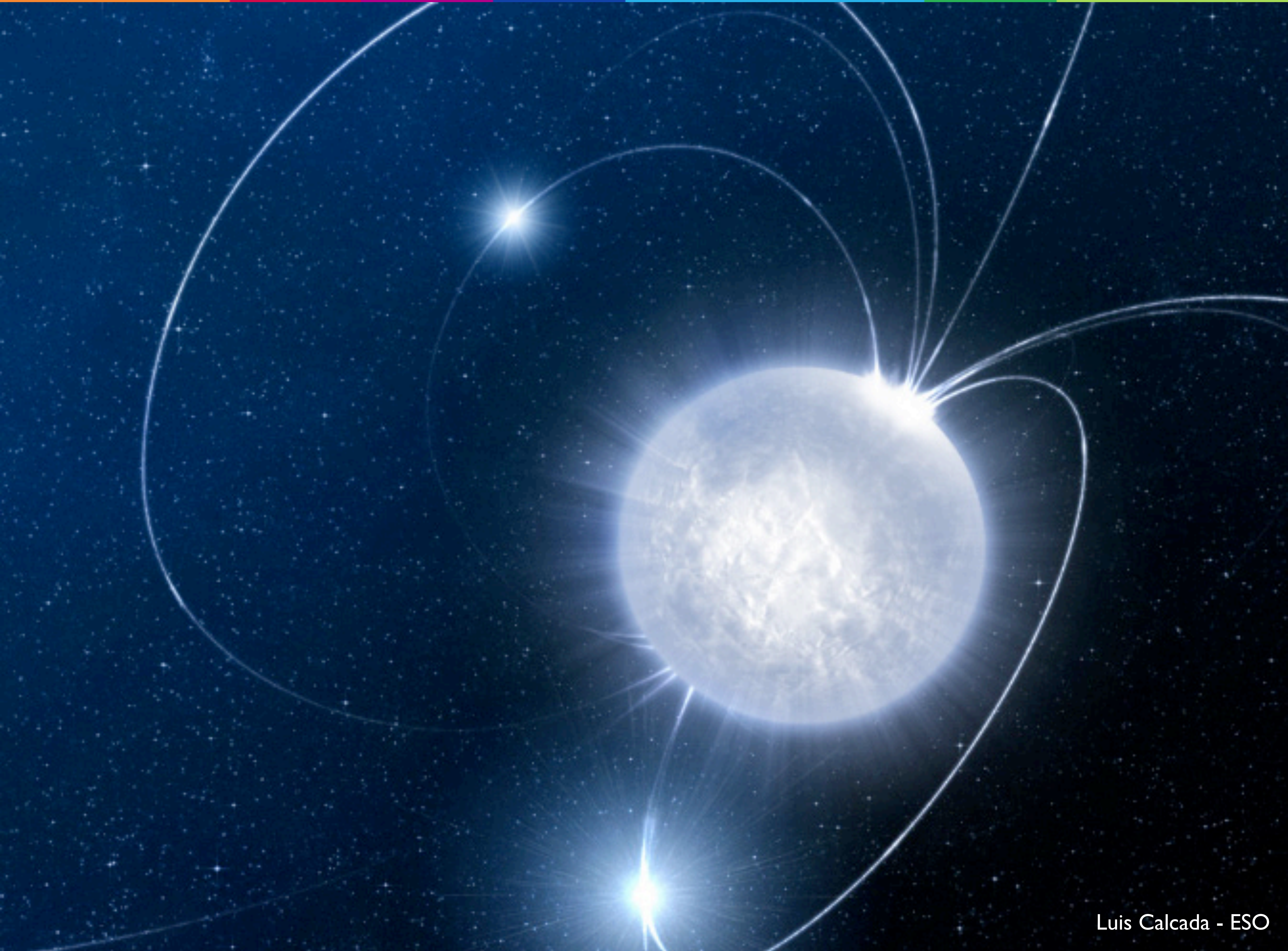

G
Pgas
Prad
NASA - SDO

From atoms to neutrons



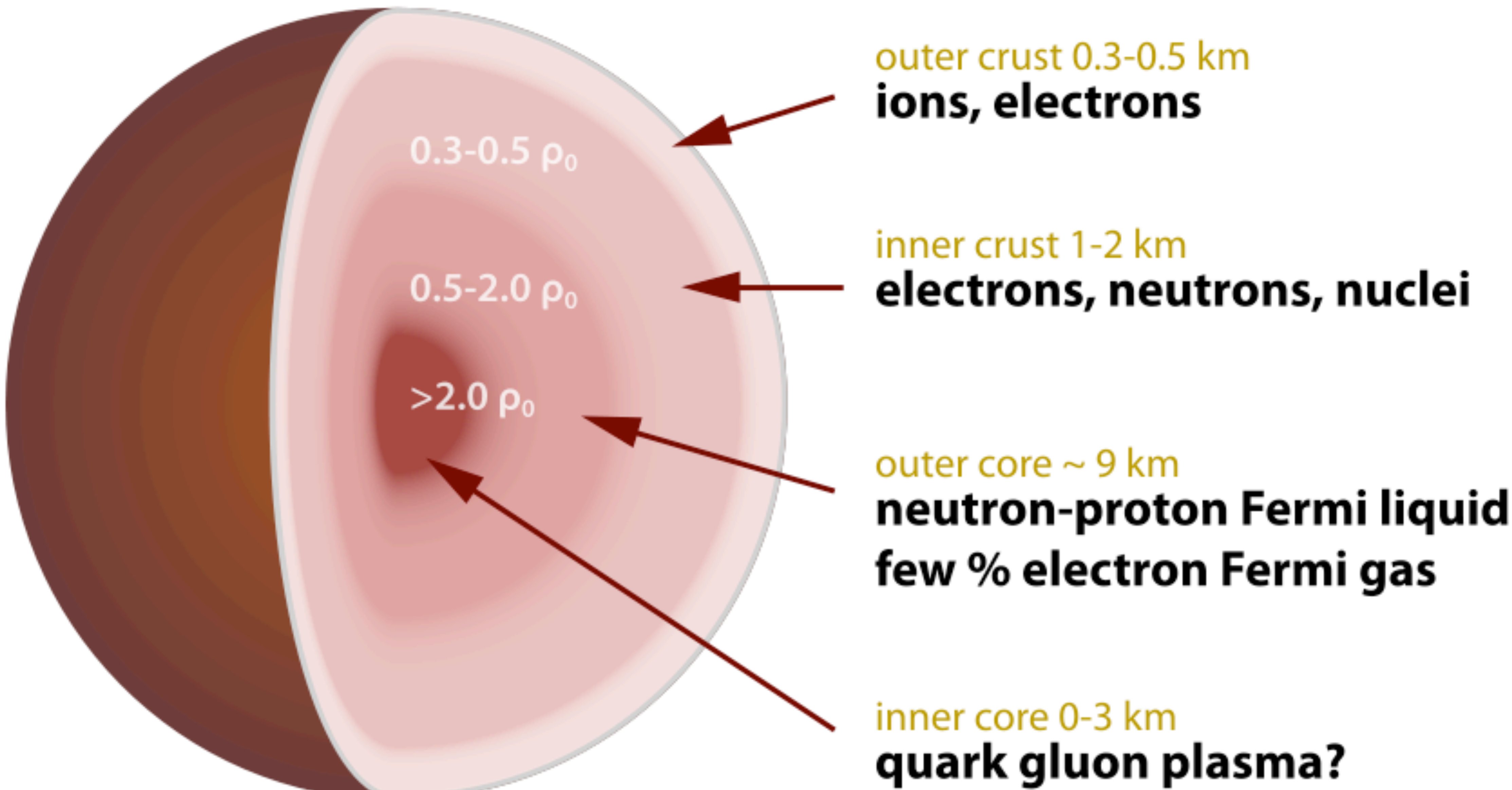
Cross section of a hydrogen atom

McGraw-Hill

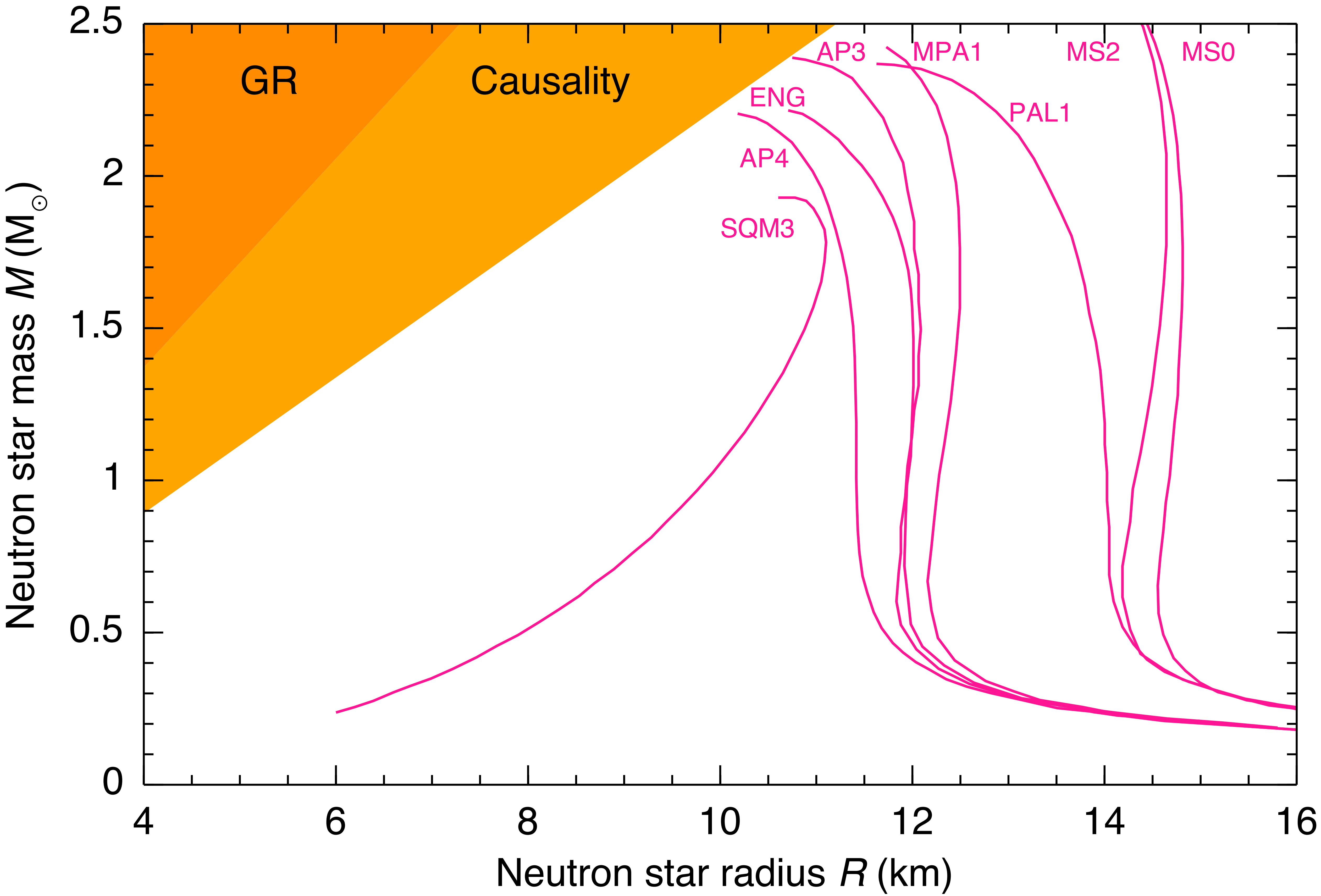

Luis Calcada - ESO


Fuencarral-El Pardo
EL PARDO
Alcobendas
Ajalvir
R-2
M-50
M-108
M-40
M-12
VALDEFUENTES
Paracuellos de Jarama
M-605
M-40
VALVERDE
Las Rozas
Aeropuerto Adolfo Suárez Madrid-Barajas
Los Berrocales del Jarama
PEÑAGRANDE
Majadahonda
A-6
ALMENARA
HORTALEZA
BARAJAS
M-30
CHAMARTÍN
ARAVACA
PIOVERA
M-14
E-90
Pozuelo
CD UNIVERSITARIA
CIUDAD LINEAL
M-50
M-503
MONCLOA - ARAVACA
GUINDALERA
ROSAS
Coslada
CASA DE CAMPO
Madrid
E-5
Boadilla del Monte
MARROQUINA
M-45
LATINA
M-30
NUMANCIA
M-40
M-50
Mejorada del Campo
M-511
R-3
ALUCHE
VICÁLVARO
PUENTE DE VALLECAS
E-90
VISTA ALEGRE
SANTA EUGENIA
M-50
CARABANCHEL
M-40
ENTREVIAS
Velilla de San Antonio
BUENAVISTA
ORCASITAS
VILLA DE VALLECAS
La Fortuna
R-5
LOS ROSALES
M-31
Alcorcón
Rivas-Vaciamadrid
VILLAVERDE
SAN ANDRÉS
BUTARQUE
M-50
Leganés
M-45
Móstoles
A-42
E-5
VACIAMADRID
M-301
R-5
Getafe
M-50

But what exactly is inside?

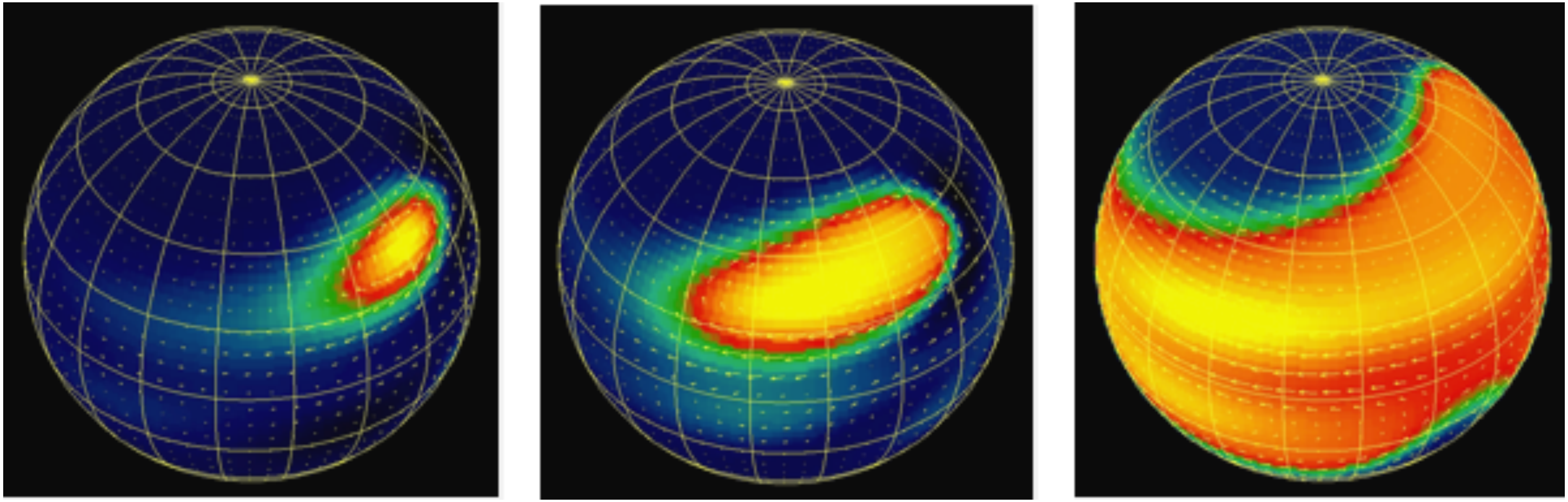


Robert Schulze


GR
Causality
AP3
MPA1
MS2
MS0
ENG
PAL1
AP4
SQM3
2.5
2
1.5
1
0.5
0
4
6
8
10
12
14
16
Neutron star mass M (M⊙)
Neutron star radius R (km)

Hot neutron stars in LMXB systems

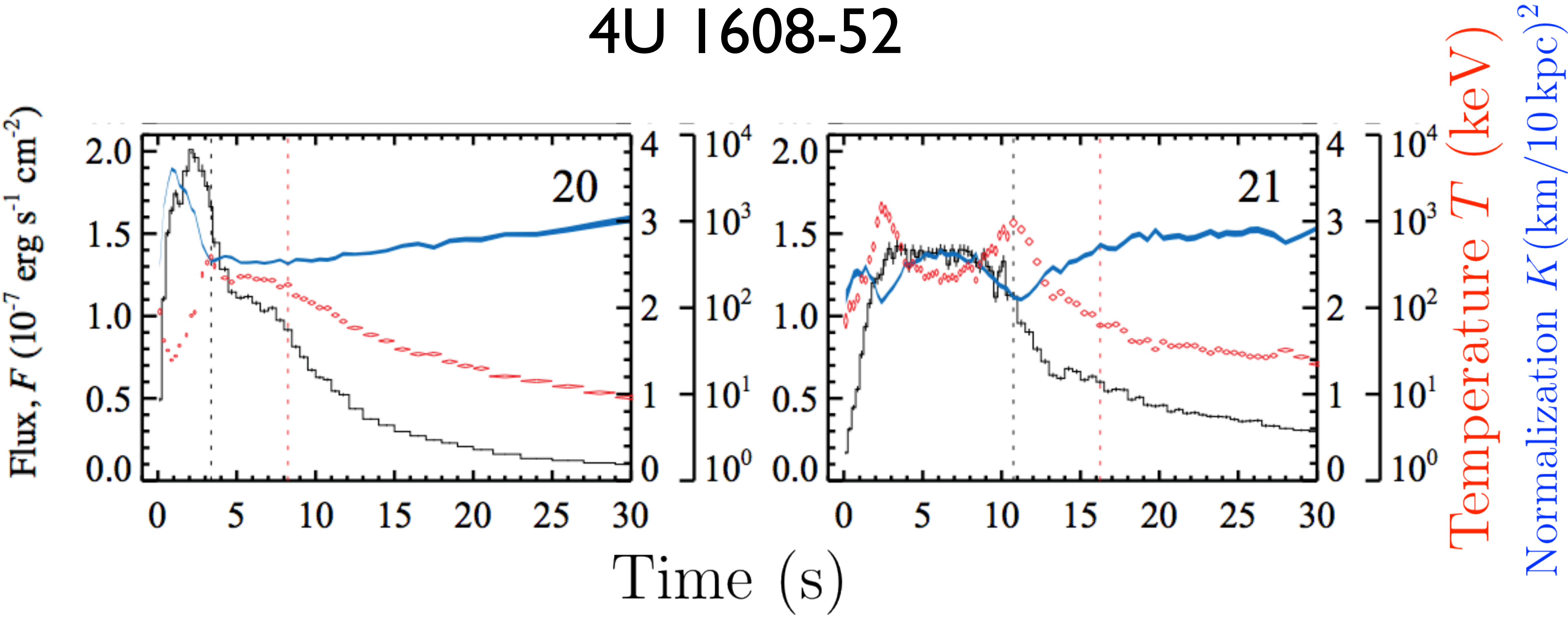
Origin of X-ray bursts



A. Spitkovsky

Photospheric Radius Expansion bursts

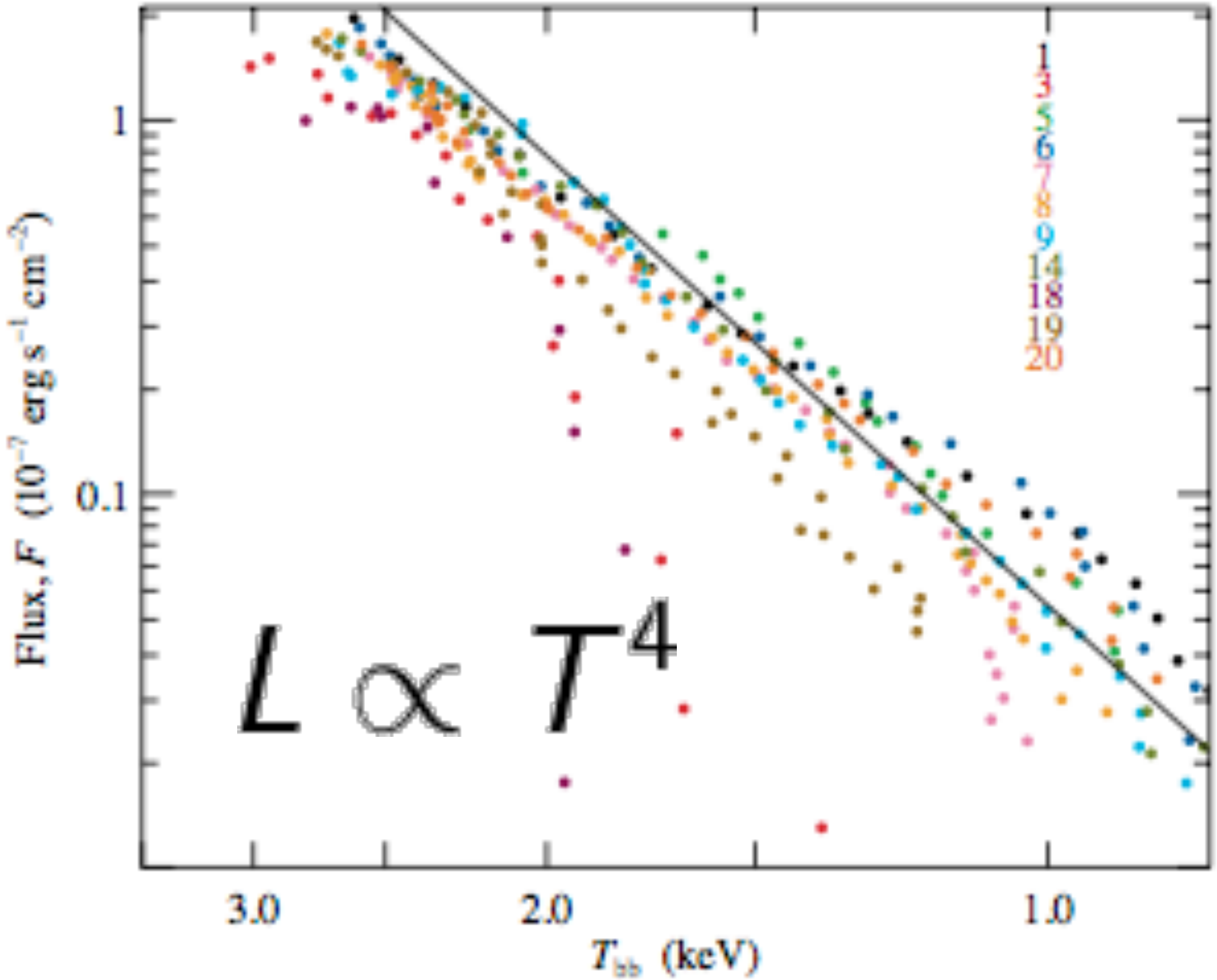
4U 1608-52



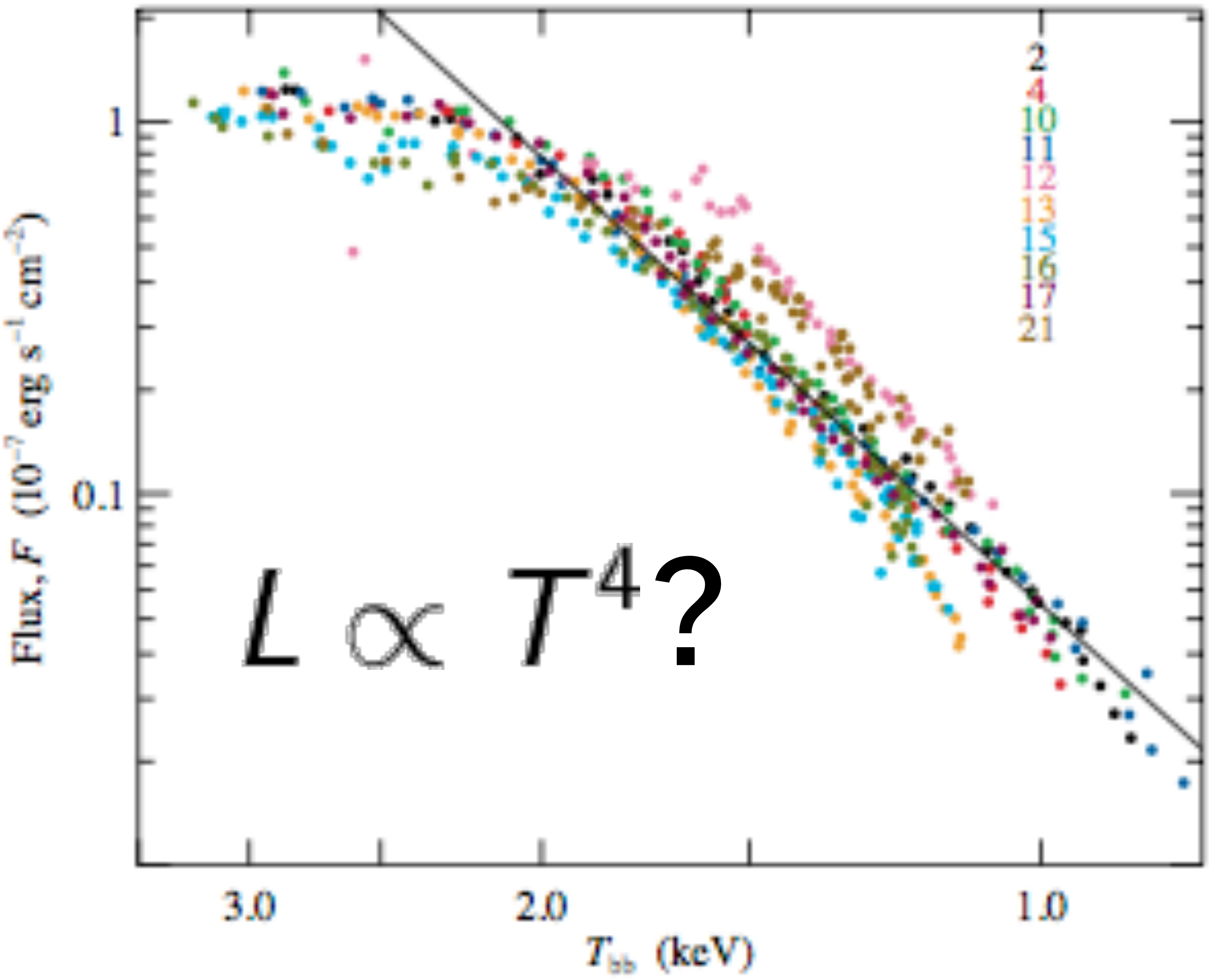
Data from RXTE/PCA instrument

Poutanen et al 2014

Soft state bursts



Hard state bursts



Which one is right?

Soft state bursts - large accretion rates?

Hard state bursts - small accretion rates?

What does the theory say?

Atmosphere models

$$\frac{dP_g}{dm} = g - g_{rad}, \qquad dm = -\rho\, ds, \qquad g = \frac{GM}{R^2}(1+z), \qquad L_{Edd} = \frac{4\pi GMc}{\kappa_e}(1+z),$$

$$\mu \frac{dI(x,\mu)}{d\tau(x,\mu)} = I(x,\mu) - S(x,\mu),$$

$$g_{rad} = \frac{dP_{rad}}{dm} = \frac{2\pi}{c}\frac{d}{dm}\int_0^\infty dx \int_{-1}^{+1} \mu^2 I(x,\mu)\, d\mu$$
$$= \frac{2\pi}{c}\int_0^\infty dx \int_{-1}^{+1} [\sigma(x,\mu)+k(x)]\,[I(x,\mu)-S(x,\mu)]\ \mu\, d\mu,$$

$$\sigma(x,\mu) = \kappa_e \frac{1}{x}\int_0^\infty x_1 dx_1 \int_{-1}^{1} d\mu_1 R(x_1,\mu_1;x,\mu)\left(1+\frac{C\,I(x_1,\mu_1)}{x_1^3}\right),$$

$$\kappa_e = \sigma_T \frac{N_e}{\rho} \approx 0.2\,(1+X)\ \mathrm{cm^2\ g^{-1}}$$

$$\int_0^\infty dx \int_{-1}^{+1} [\sigma(x,\mu)+k(x)]\,[I(x,\mu)-S(x,\mu)]\ d\mu = 0,$$

$$F^*_{Edd} = \frac{L_{Edd}}{4\pi R^2} = \frac{GMc}{R^2\kappa_e}(1+z).$$

$$S(x,\mu) = \frac{k(x)}{\sigma(x,\mu)+k(x)}B_x + \frac{\kappa_e}{\sigma(x,\mu)+k(x)}$$
$$\times\left(1+\frac{C\,I(x,\mu)}{x^3}\right)x^2 \int_0^\infty \frac{dx_1}{x_1^2}\int_{-1}^{1} d\mu_1 R(x,\mu;x_1,\mu_1) I(x_1,\mu_1),$$

$$P_g = N_{tot}\, kT,$$

Atmosphere models

$$\frac{\mathrm{d}P_{\mathrm{g}}}{\mathrm{d}m} = g - g_{\mathrm{rad}}, \qquad \mathrm{d}m = -\rho\,\mathrm{d}s,$$

Hydrostatic equilibrium

Atmosphere models

$$\frac{\mathrm{d}P_{\mathrm{g}}}{\mathrm{d}m} = g - g_{\mathrm{rad}}, \qquad \mathrm{d}m = -\rho\,\mathrm{d}s,$$

Hydrostatic equilibrium

$$\mu \frac{\mathrm{d}I(x,\mu)}{\mathrm{d}\tau(x,\mu)} = I(x,\mu) - S(x,\mu),$$

Radiative transfer

Atmosphere models

$$\frac{\mathrm{d}P_{\mathrm{g}}}{\mathrm{d}m} = g - g_{\mathrm{rad}}, \qquad \mathrm{d}m = -\rho\,\mathrm{d}s,$$

Hydrostatic equilibrium

$$\mu \frac{\mathrm{d}I(x,\mu)}{\mathrm{d}\tau(x,\mu)} = I(x,\mu) - S(x,\mu),$$

Radiative transfer

$$\sigma(x,\mu) = \kappa_{\mathrm{e}} \frac{1}{x} \int_0^\infty x_1 \mathrm{d}x_1 \int_{-1}^{1} \mathrm{d}\mu_1 R(x_1,\mu_1;x,\mu) \left(1 + \frac{C\,I(x_1,\mu_1)}{x_1^3}\right),$$

Electron opacity

Atmosphere models

$$\frac{\mathrm{d}P_\mathrm{g}}{\mathrm{d}m} = g - g_\mathrm{rad}, \qquad \mathrm{d}m = -\rho\,\mathrm{d}s,$$

Hydrostatic equilibrium

$$\mu \frac{\mathrm{d}I(x,\mu)}{\mathrm{d}\tau(x,\mu)} = I(x,\mu) - S(x,\mu),$$

Radiative transfer

$$\sigma(x,\mu) = \kappa_\mathrm{e} \frac{1}{x} \int_0^\infty x_1 \mathrm{d}x_1 \int_{-1}^{1} \mathrm{d}\mu_1 R(x_1,\mu_1; x,\mu) \left(1 + \frac{C\,I(x_1,\mu_1)}{x_1^3}\right),$$

Electron opacity

$$\int_0^\infty \mathrm{d}x \int_{-1}^{+1} [\sigma(x,\mu) + k(x)]\,[I(x,\mu) - S(x,\mu)]\ \mathrm{d}\mu = 0,$$

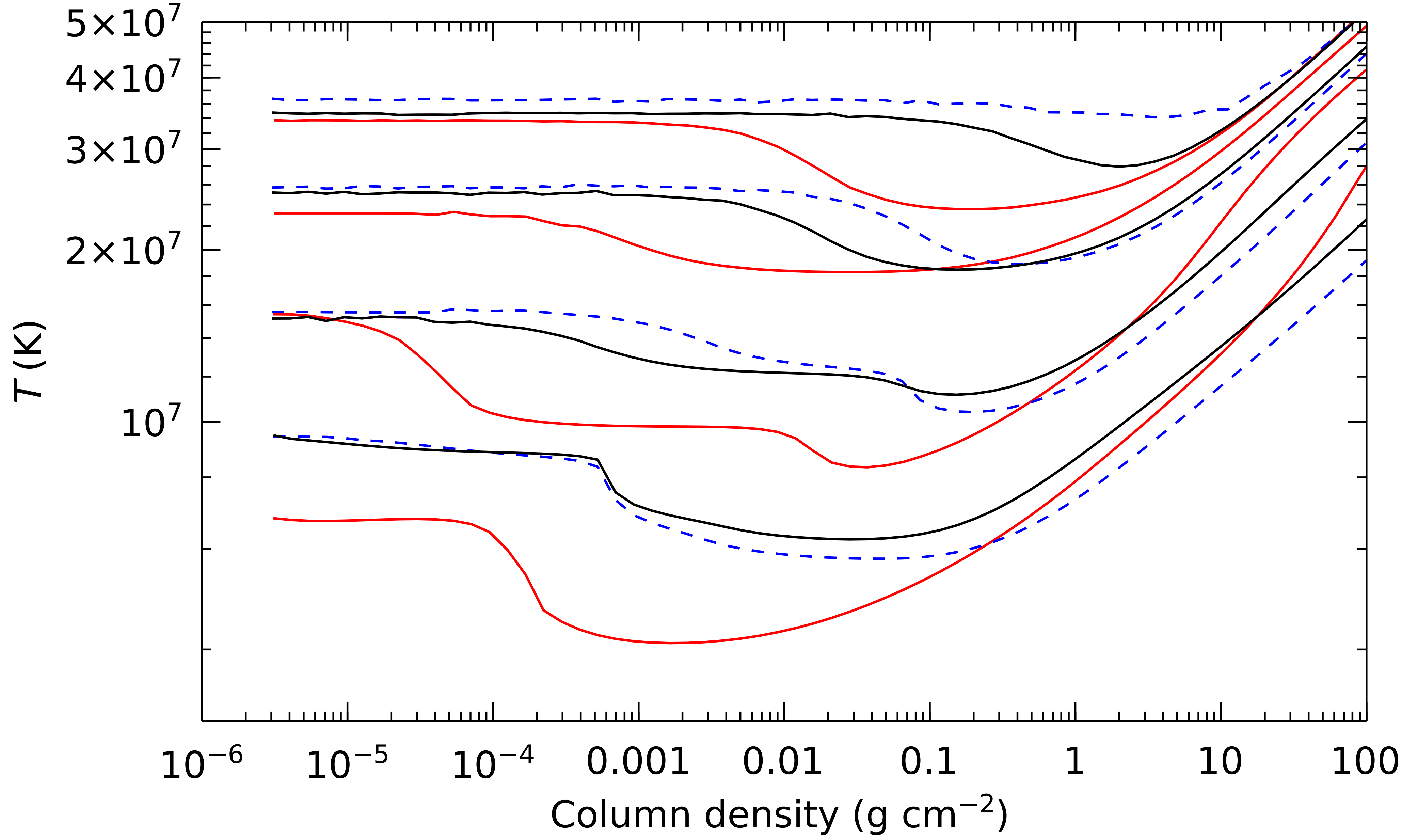
Energy balance

Atmosphere models

$\frac{\mathrm{d}P_g}{\mathrm{d}m} = g - g_{\mathrm{rad}}, \qquad \mathrm{d}m = -\rho\,\mathrm{d}s,$	Hydrostatic equilibrium
$\mu \frac{\mathrm{d}I(x,\mu)}{\mathrm{d}\tau(x,\mu)} = I(x,\mu) - S(x,\mu),$	Radiative transfer
$\sigma(x,\mu) = \kappa_e \frac{1}{x} \int_0^\infty x_1 \mathrm{d}x_1 \int_{-1}^{1} \mathrm{d}\mu_1 R(x_1,\mu_1;x,\mu) \left(1 + \frac{C\,I(x_1,\mu_1)}{x_1^3}\right),$	Electron opacity
$\int_0^\infty \mathrm{d}x \int_{-1}^{+1} [\sigma(x,\mu) + k(x)]\,[I(x,\mu) - S(x,\mu)]\ \mathrm{d}\mu = 0,$	Energy balance
$P_g = N_{\mathrm{tot}}\,kT,$	Ideal gas law

Atmosphere structure:

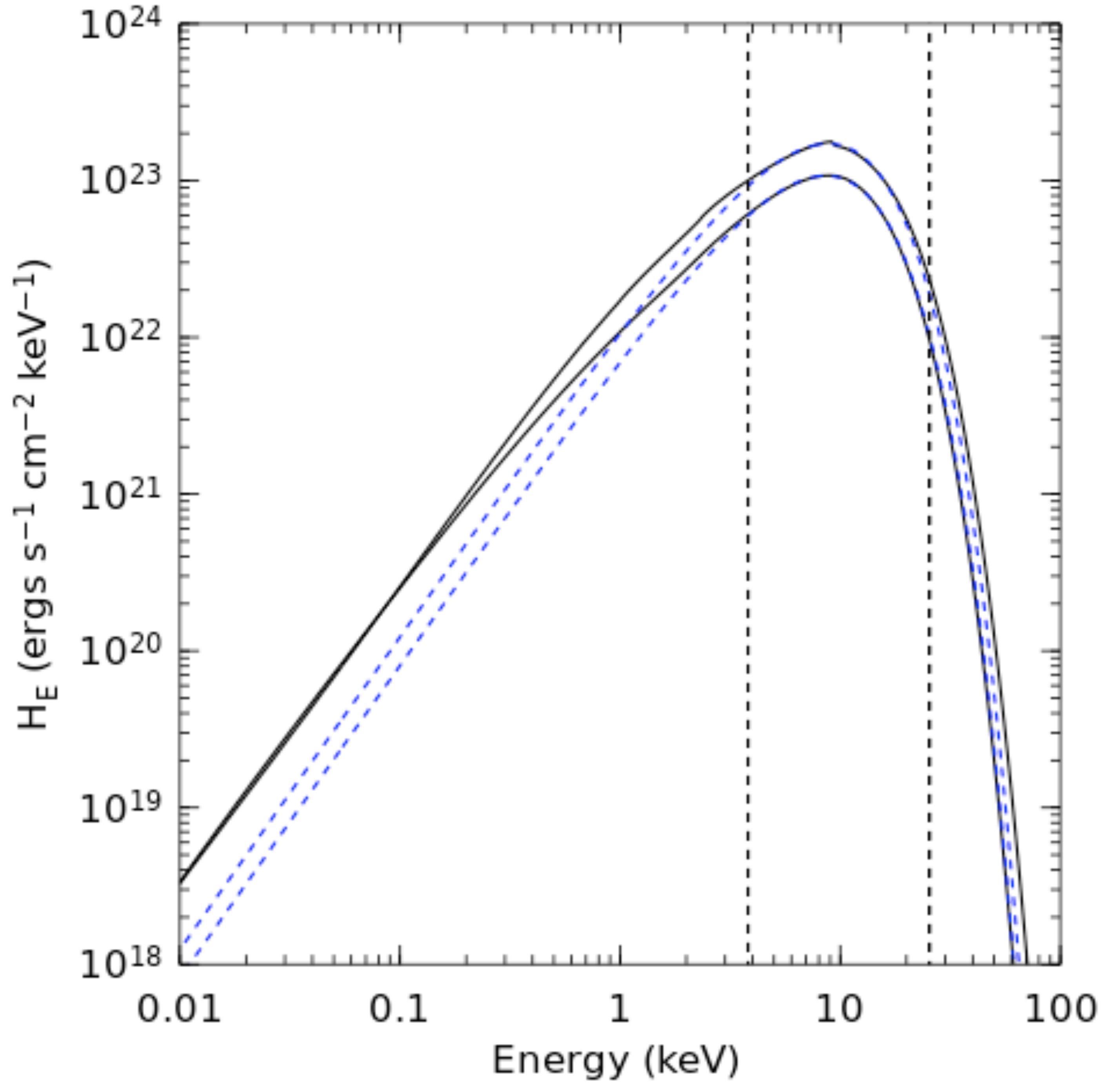
temperature profile



Emerging spectrum

Well described by diluted black body
(in range 2.5 - 25.0 keV)

$$F_{\rm E} = \frac{1}{f_{\rm c}^4} B_{\rm E}(T_{\rm c} = f_{\rm c} T_{\rm eff})$$



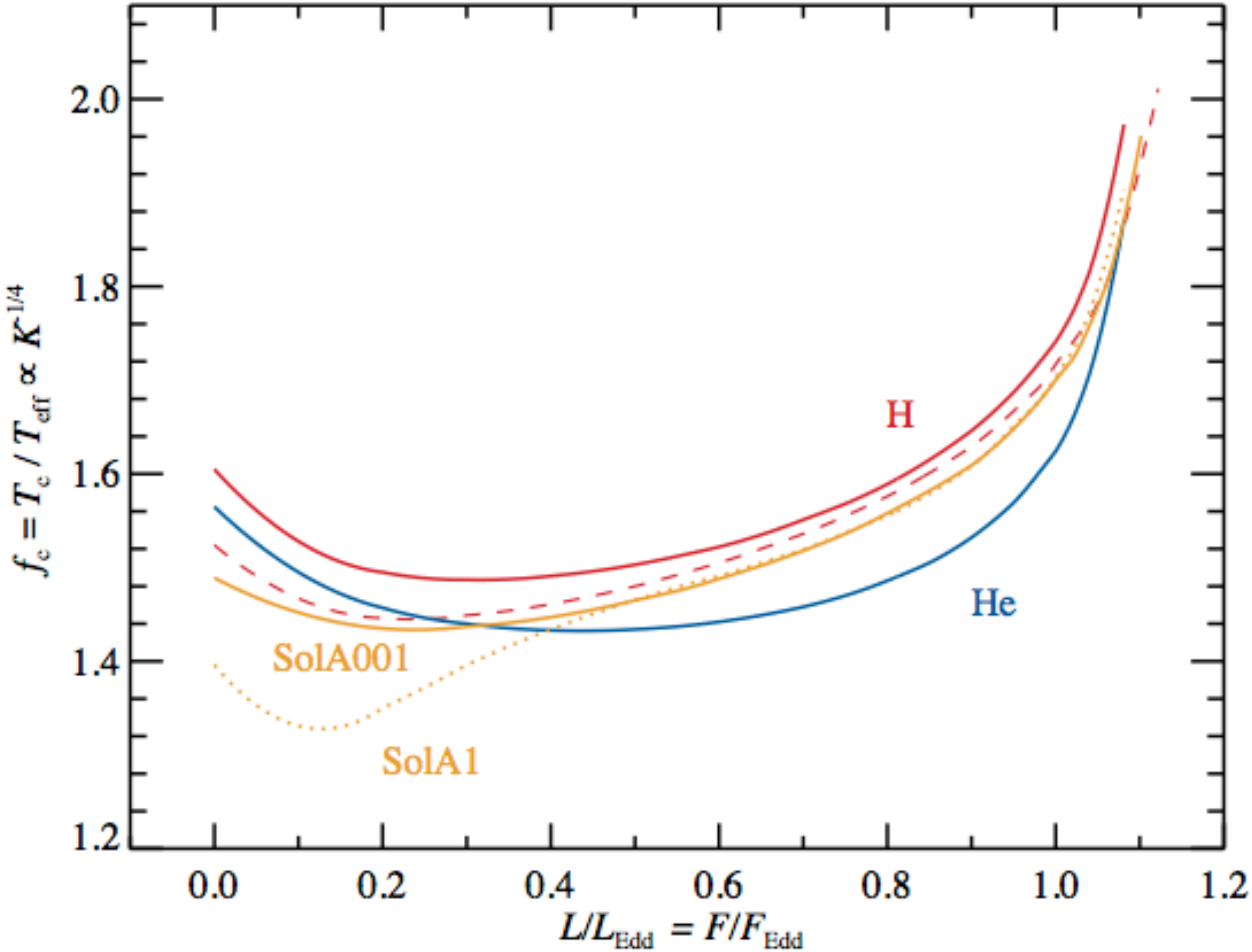
Color-correction factor f_c

Models: $$F_E = \frac{1}{f_c^4} B_E(T_c = f_c T_{eff})$$

Observations: $$F_E = K \times B_E(T)$$

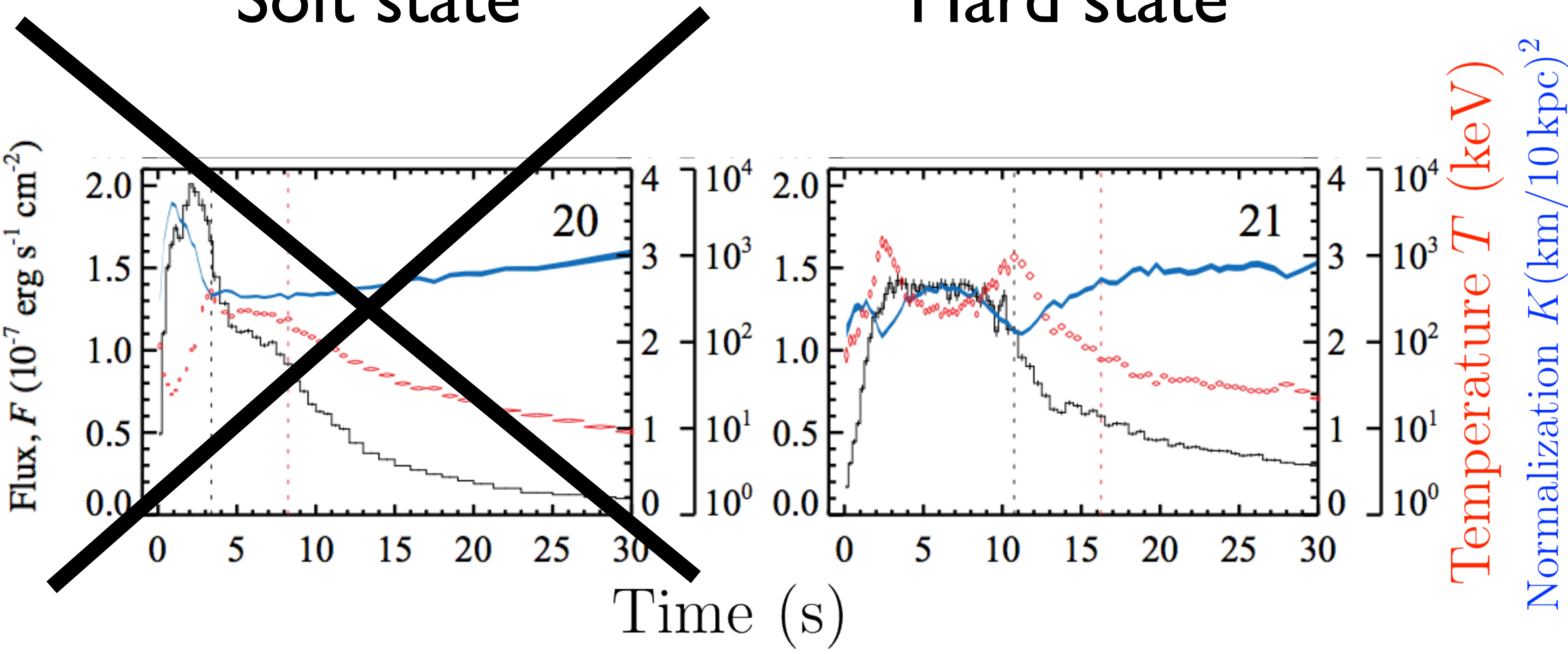
$$\Rightarrow \quad f_c \propto K^{-1/4}$$

Color-correction factor f_c



Soft state

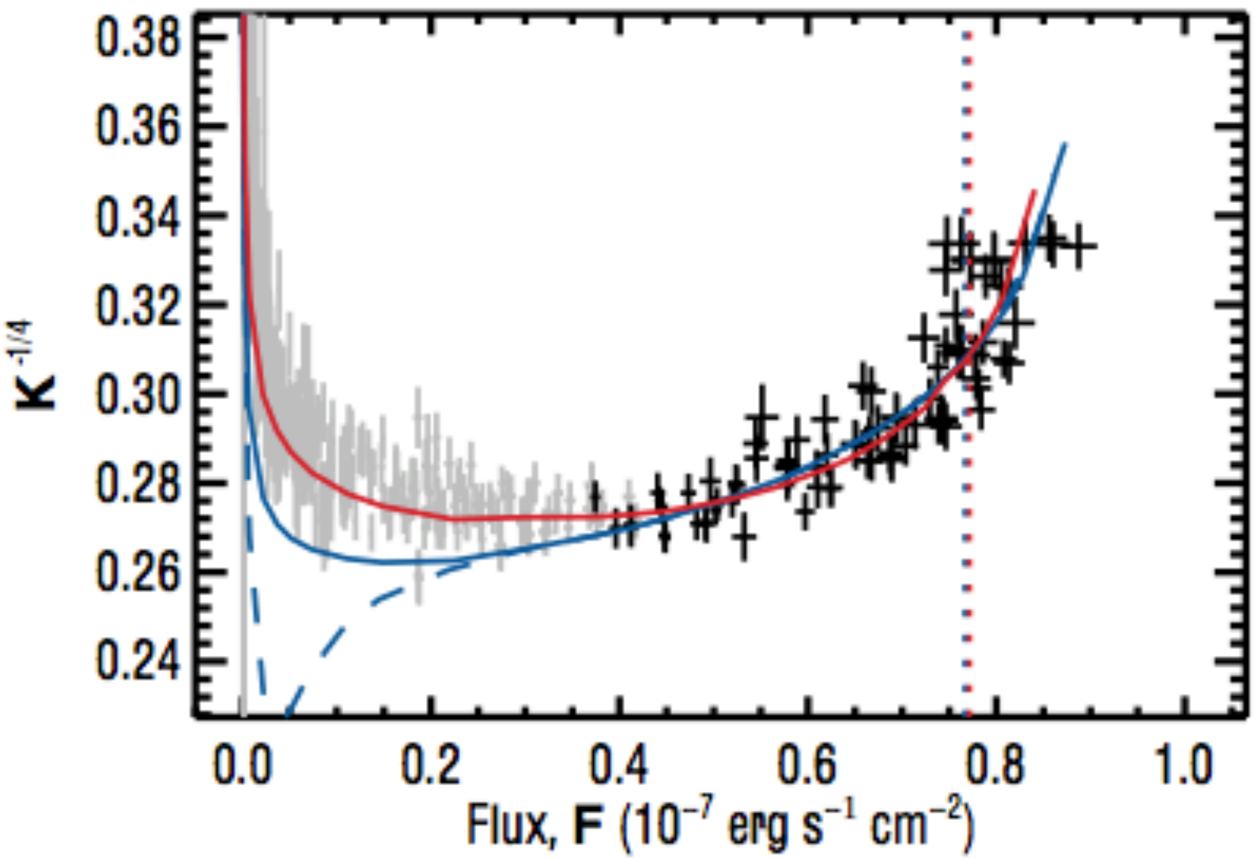
Hard state

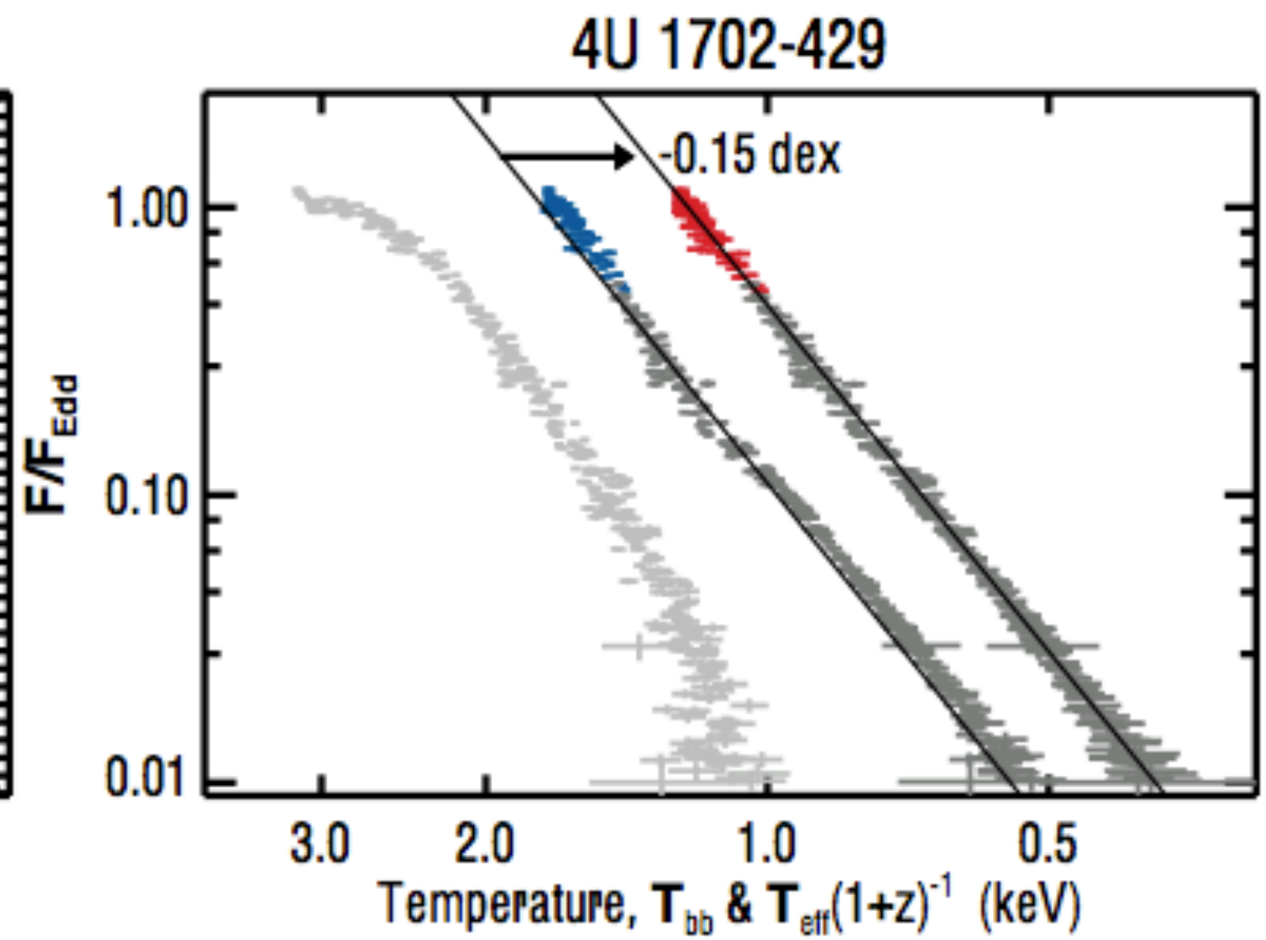


Large accretion rate

Small accretion rate

Observations with hard state bursts

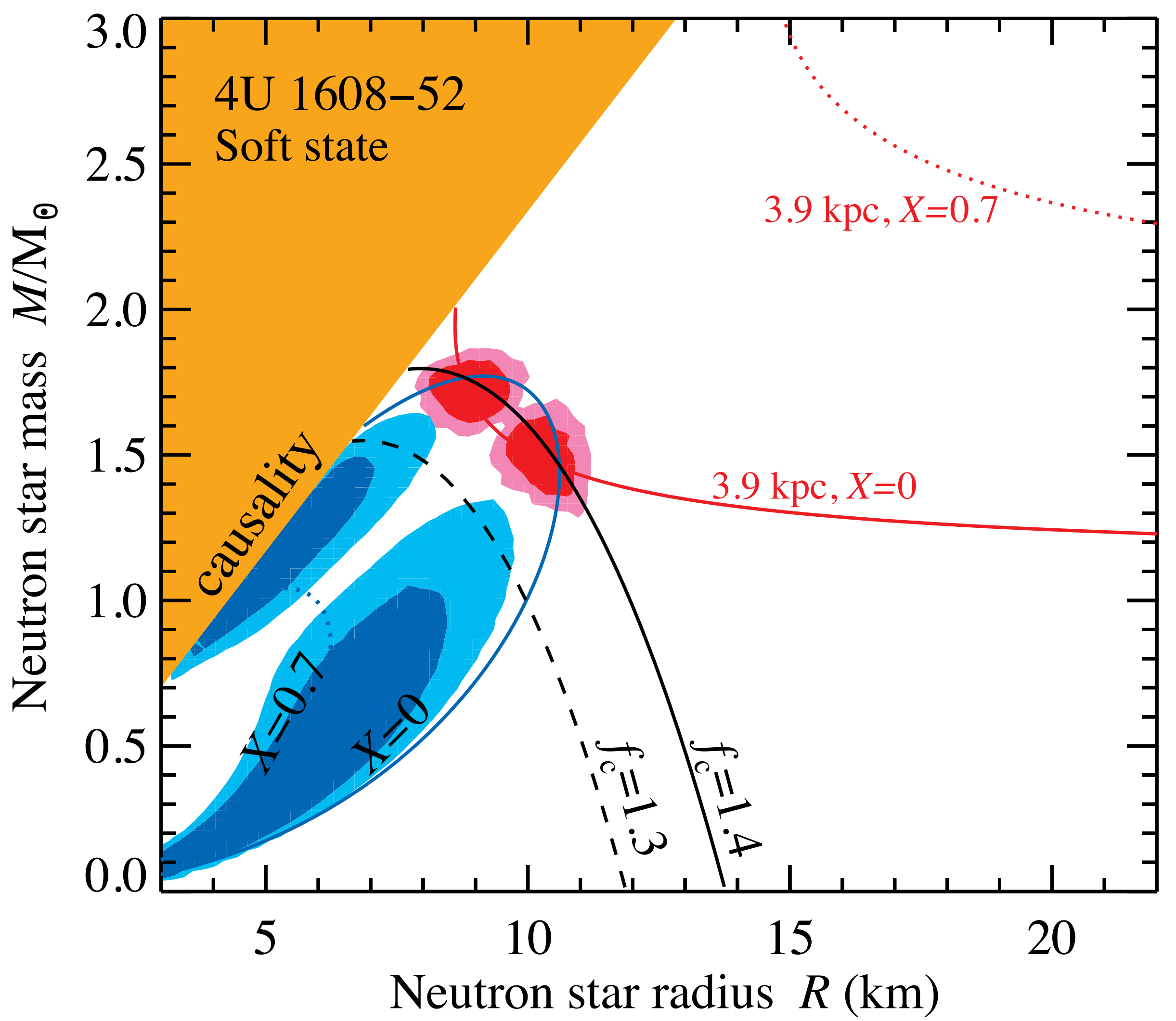




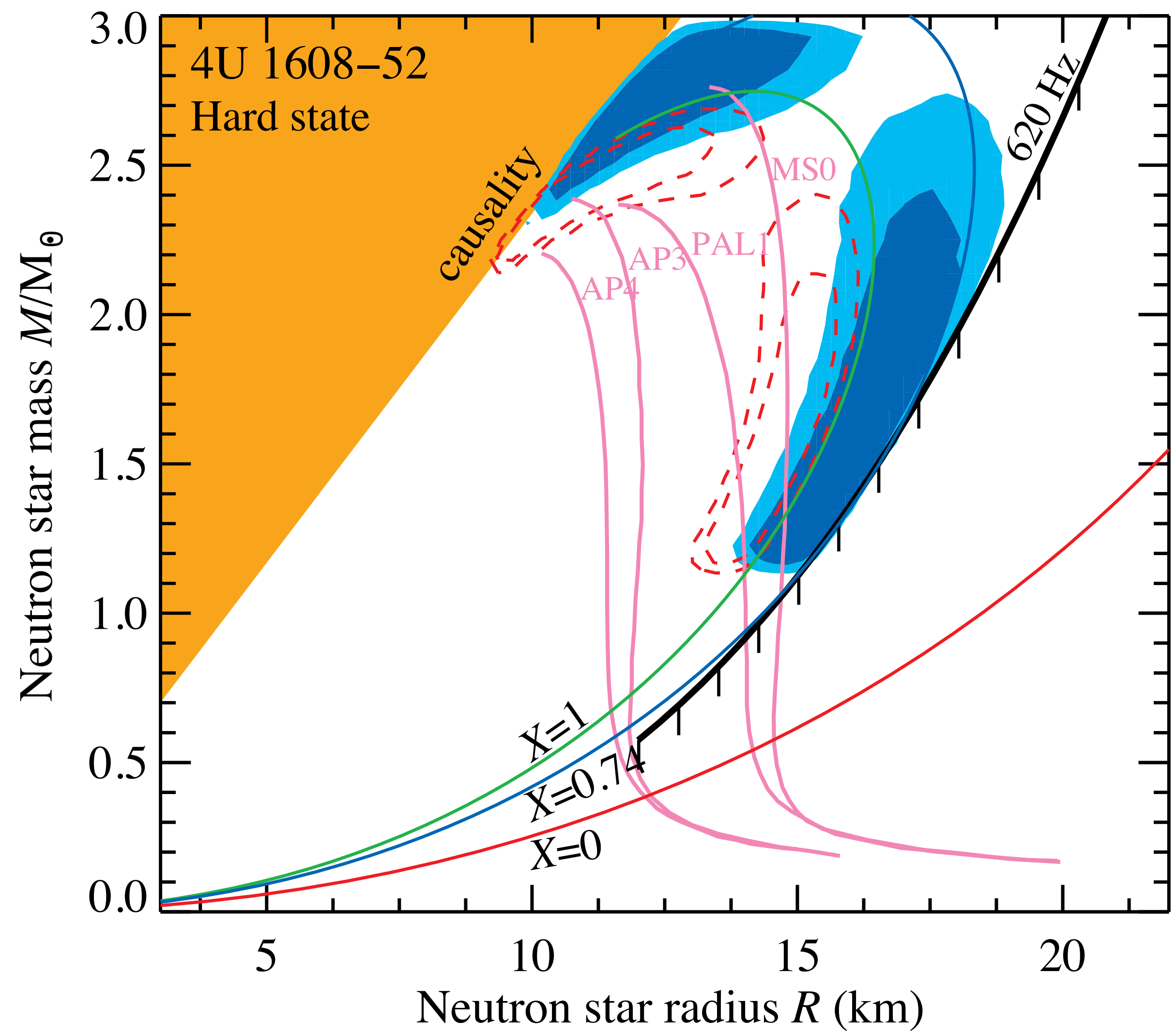
Agree! ⟶ Mass and radius

Mass & Radius

4U 1608-52

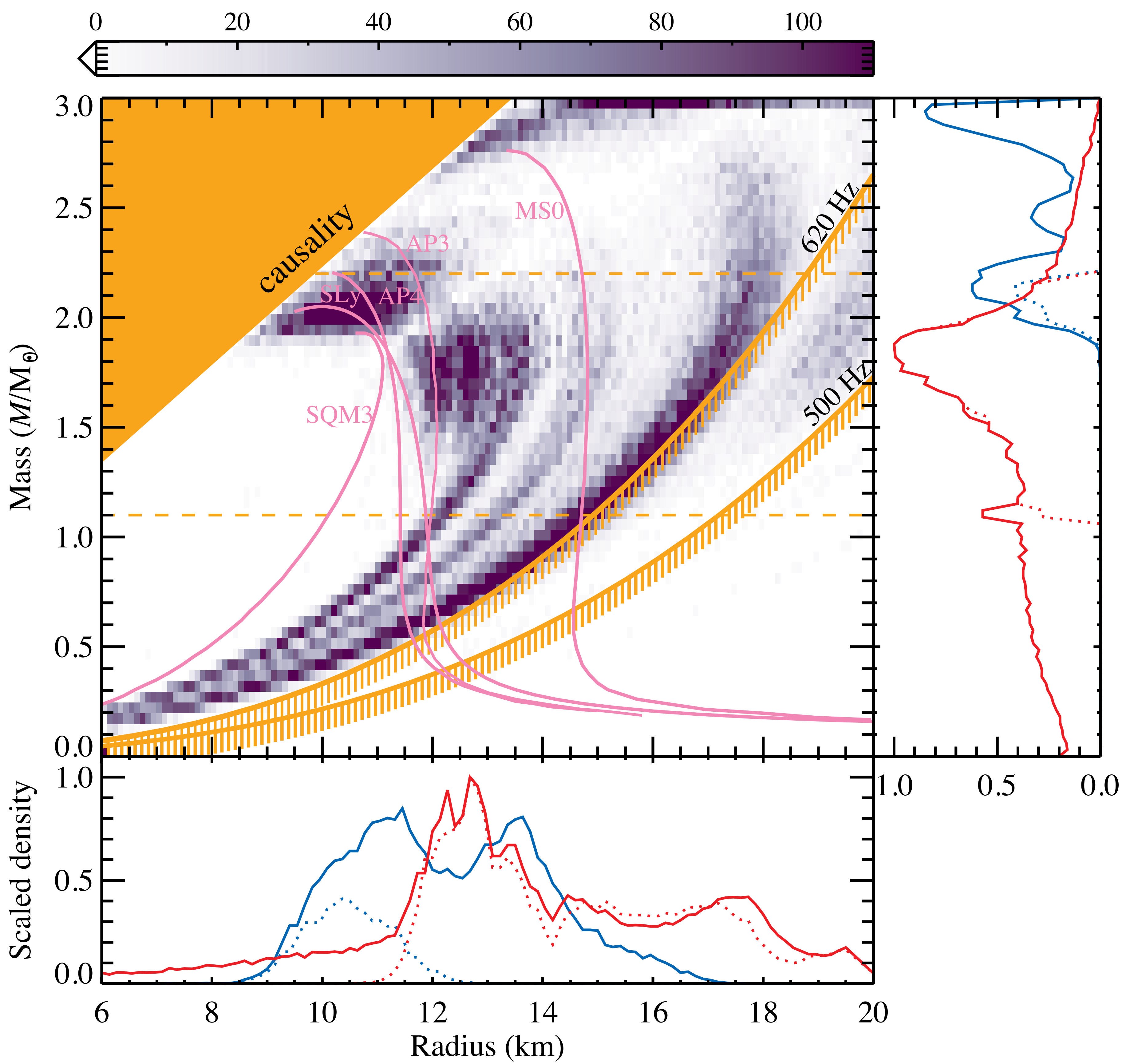


Soft state - Wrong!



Hard state

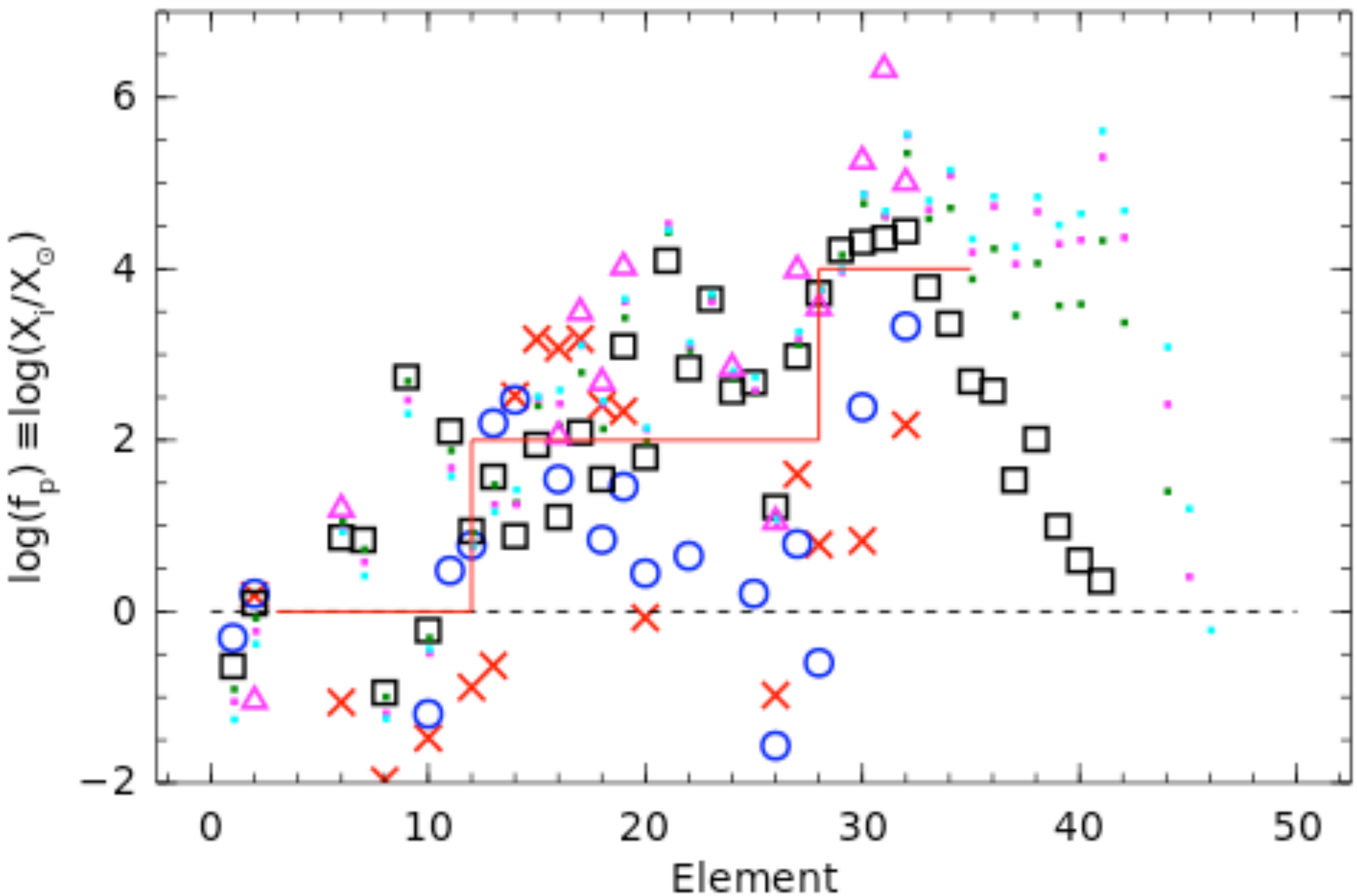
Mass & Radius



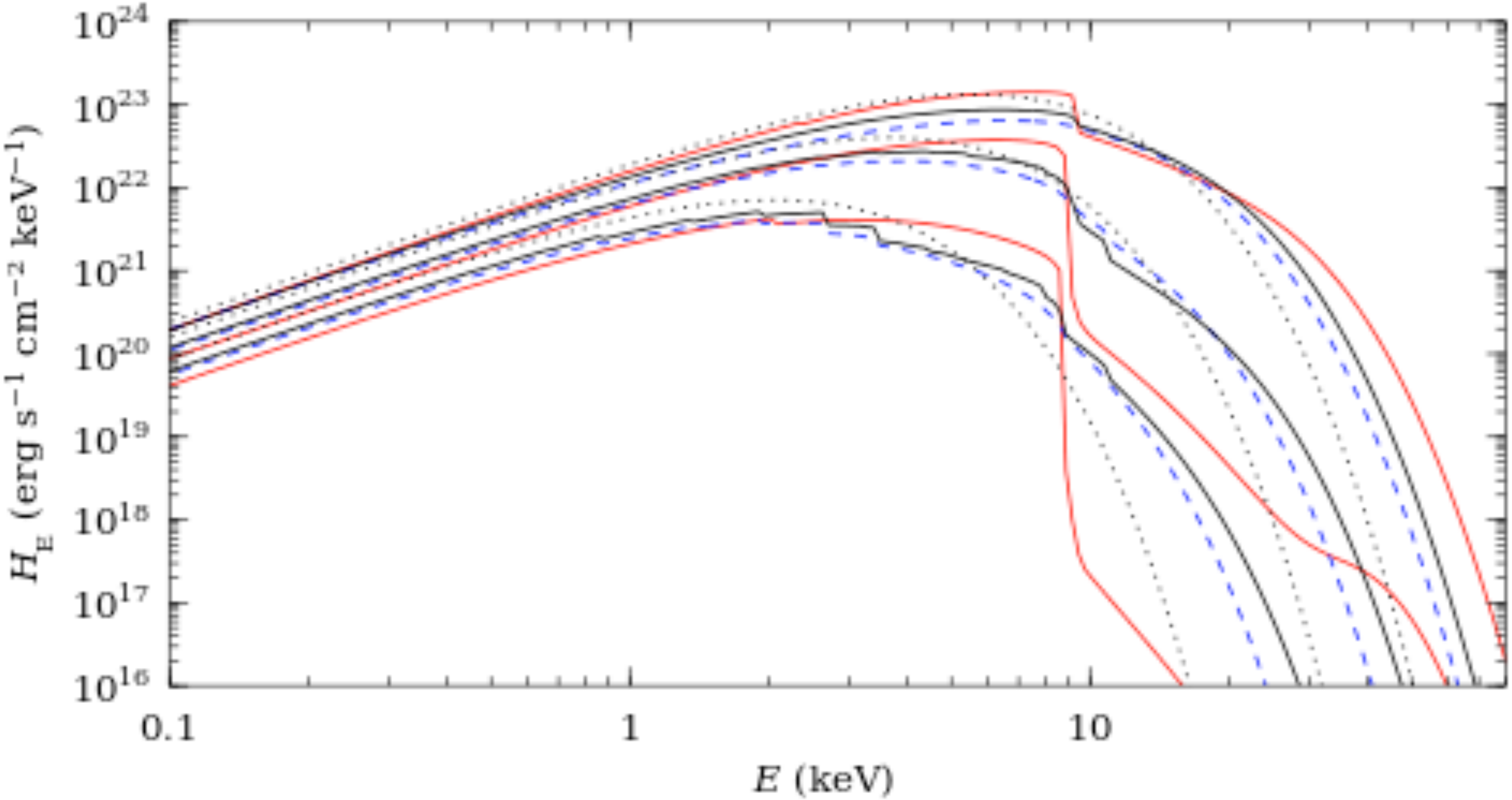
0
20
40
60
80
100
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Mass ($M/M_\odot$)
causality
MS0
AP3
SLy
AP4
SQM3
620 Hz
500 Hz
1.0
0.5
0.0
Scaled density
6
8
10
12
14
16
18
20
Radius (km)

What about metals?

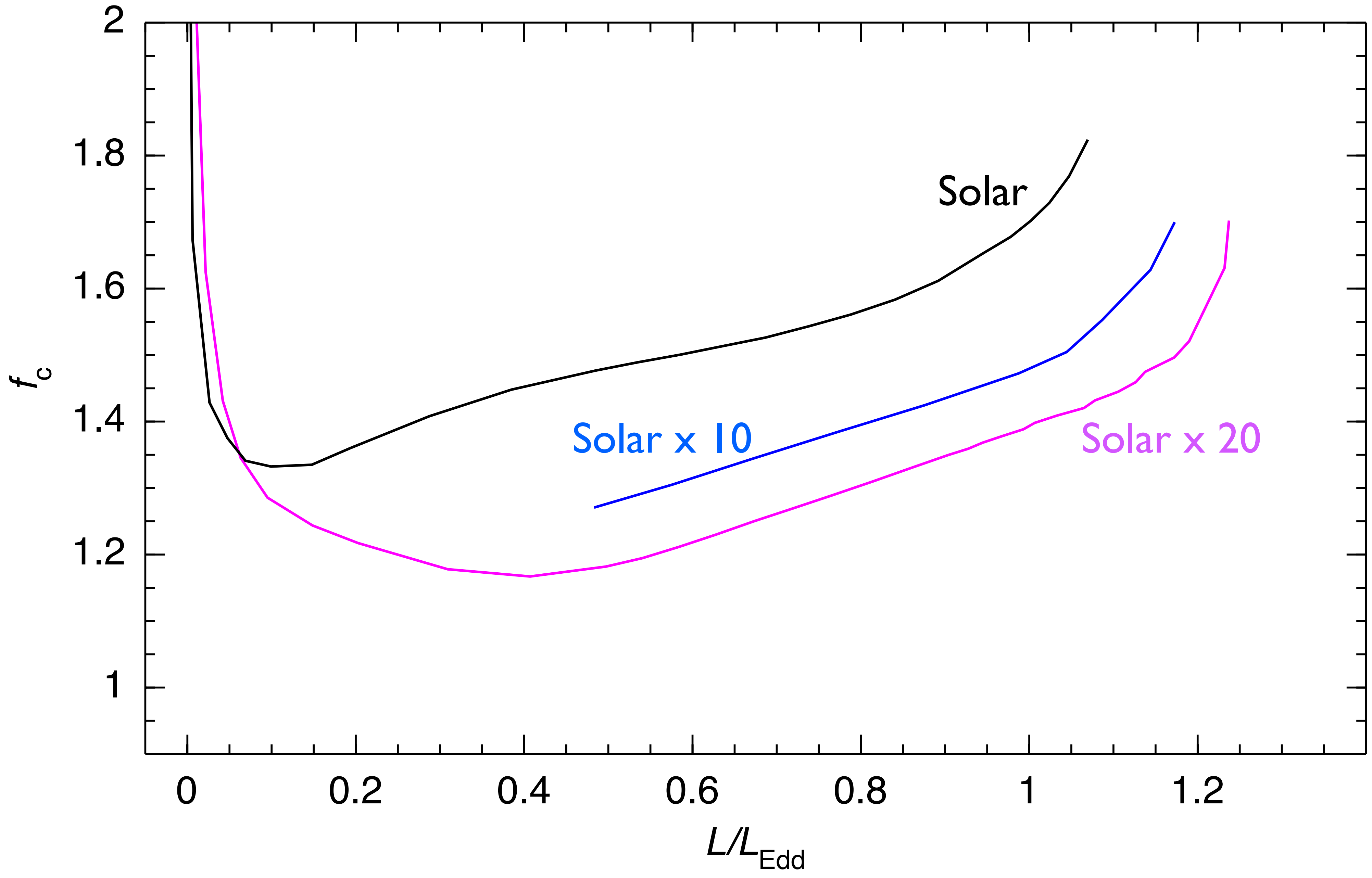
What about metals?



Metal rich atmospheres

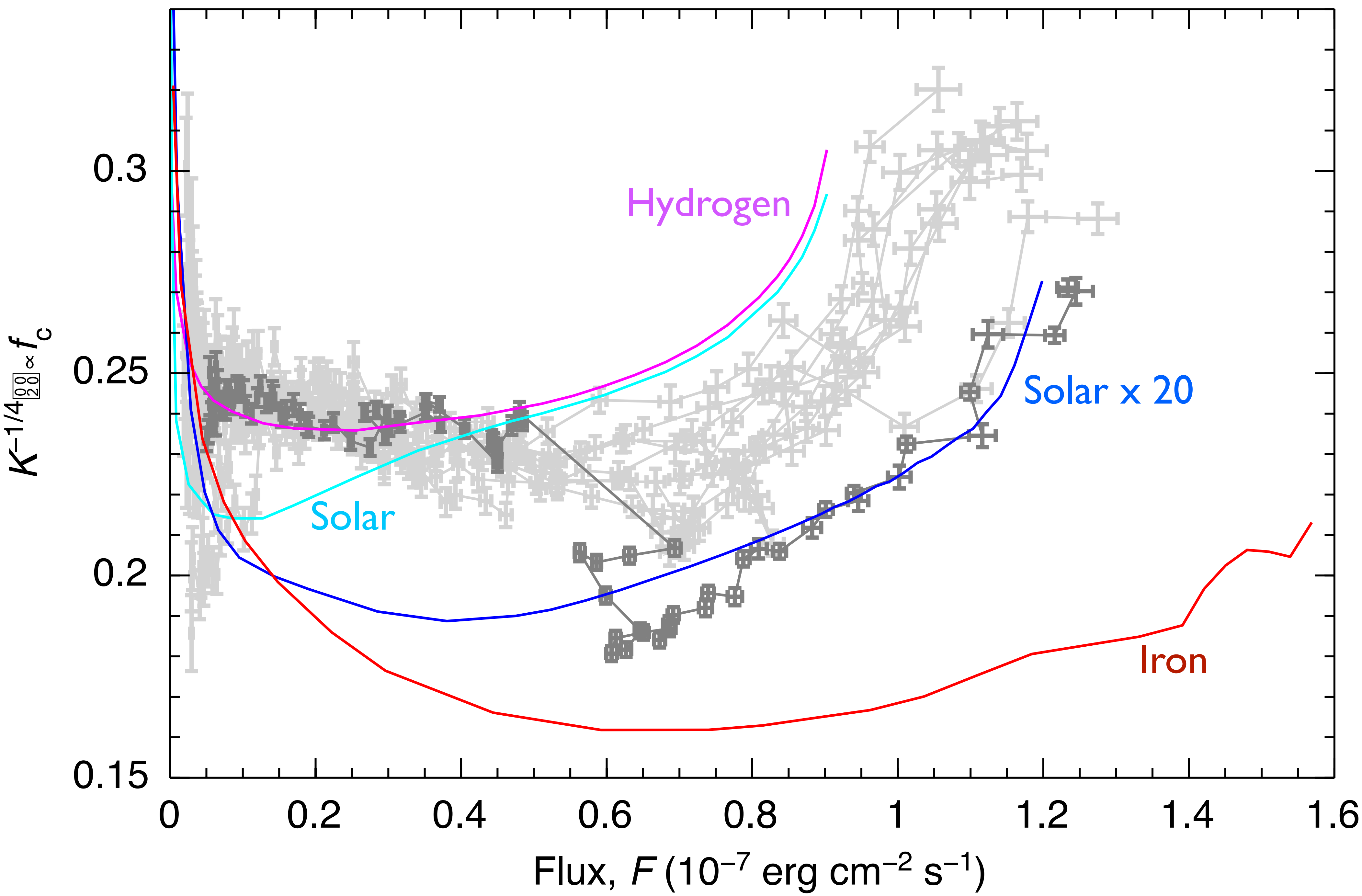


Color-correction factors f_c



Observations:

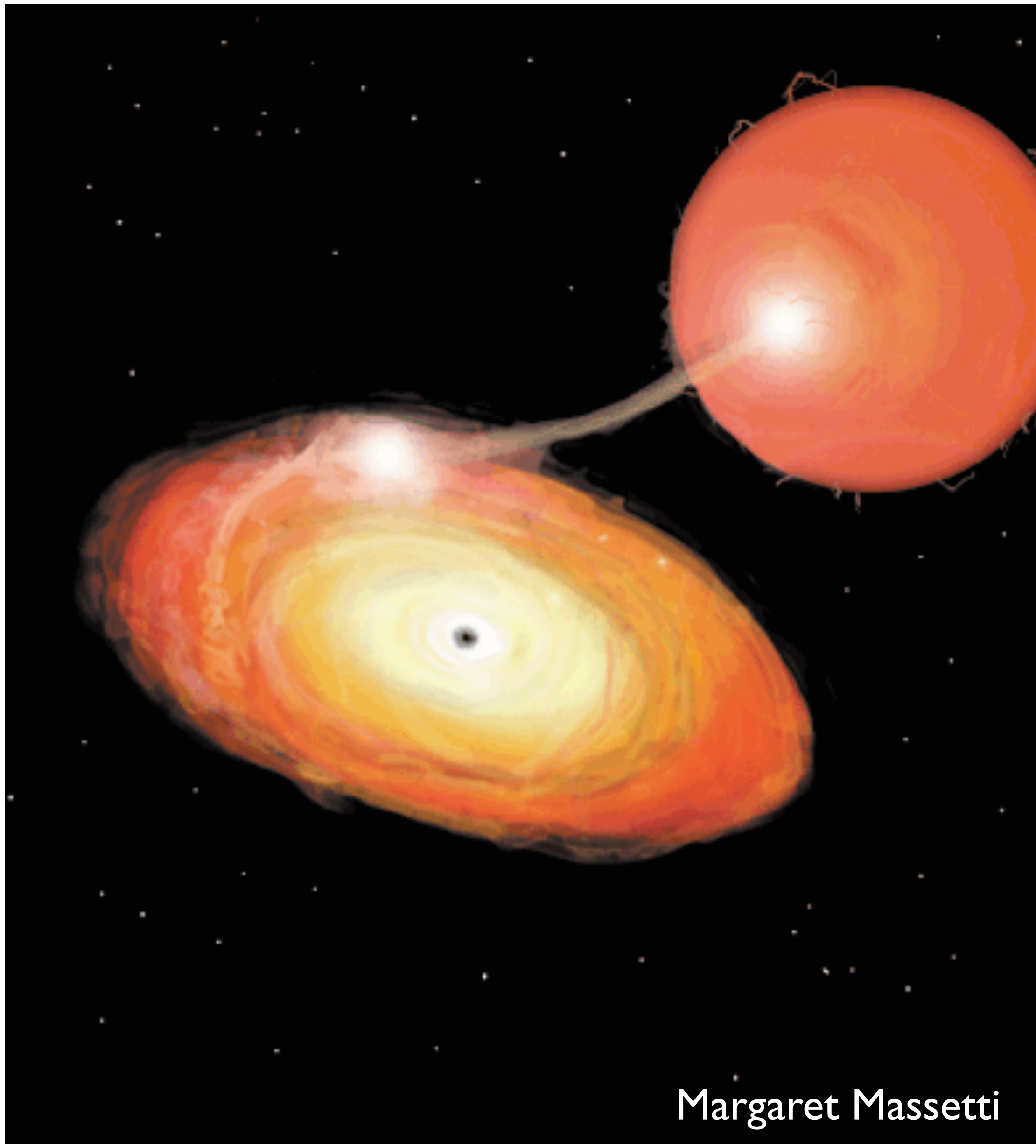
HETEJ19001-2455



Disk dynamics & pollution

Dynamic timescales of disk

New way of producing heavy metals & ejecting them into ISM



Conclusions (1/2)

- Accretion processes affect cooling
  - Hard & soft state bursts
    - Poutanen, Nättilä, Kajava, Latvala, Galloway, Kuulkers & Suleimanov 2014 MNRAS
    - Kajava, Nättilä, Latvala, Pursiainen, Poutanen, Suleimanov, Revnivtsev, Kuulkers & Galloway 2014, MNRAS
- Mass & radius estimates: 12-15 km
  - Rotational effects still missing

Conclusions (2/2)

- We have computed new metal enriched atmosphere models
    - Nättilä et al 2014, A&A, *in prep.*
- Evidence found for metals reaching photosphere
    - Best example so far: HETE J1900.1-2455
        - Nättilä et al 2015, A&A, *in prep.*
    - More examples already found in the burst database we have compiled

Thanks!