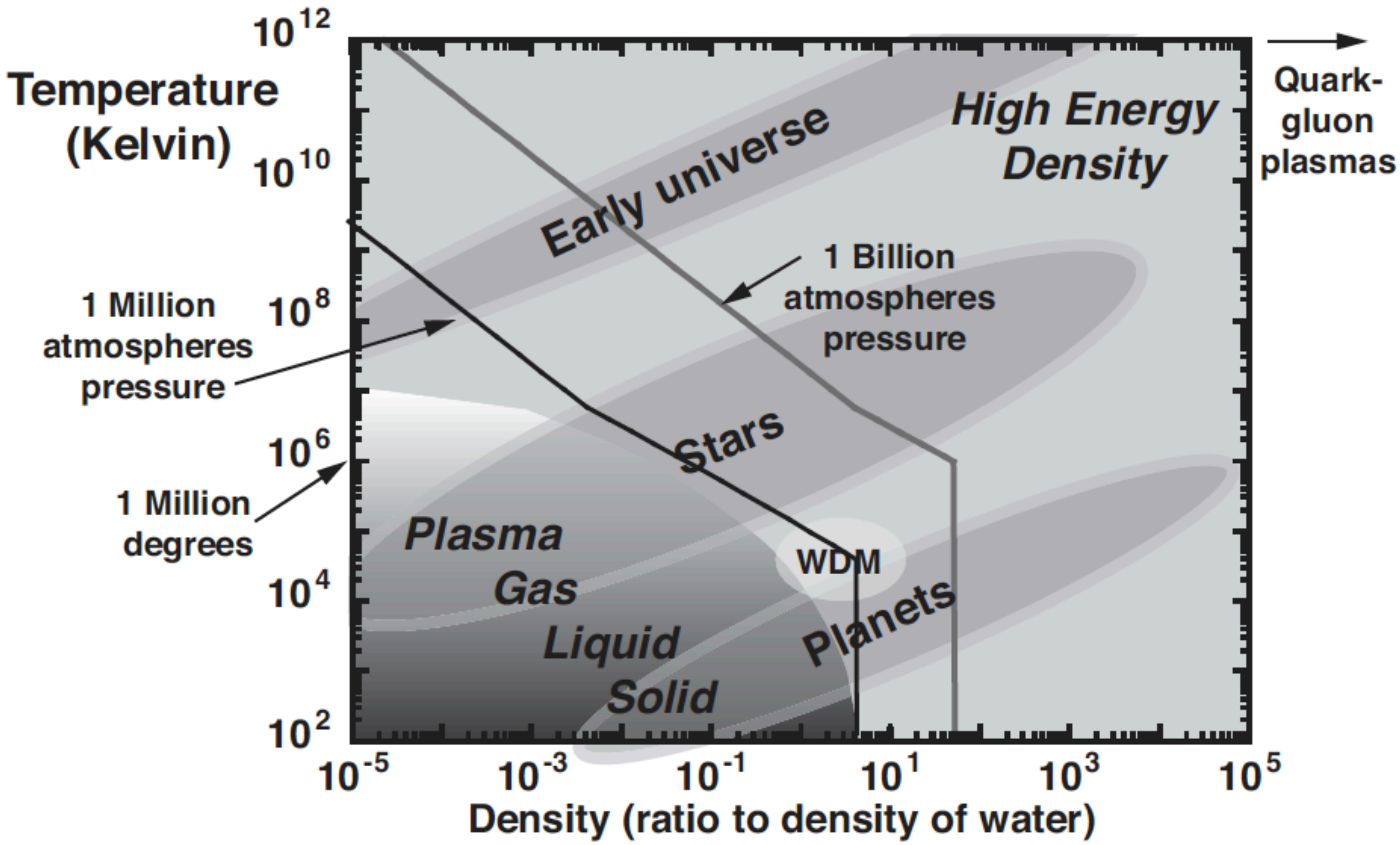


Fig. 1.1 Connection of the High-Energy Density Regime to other physical and astrophysical systems.

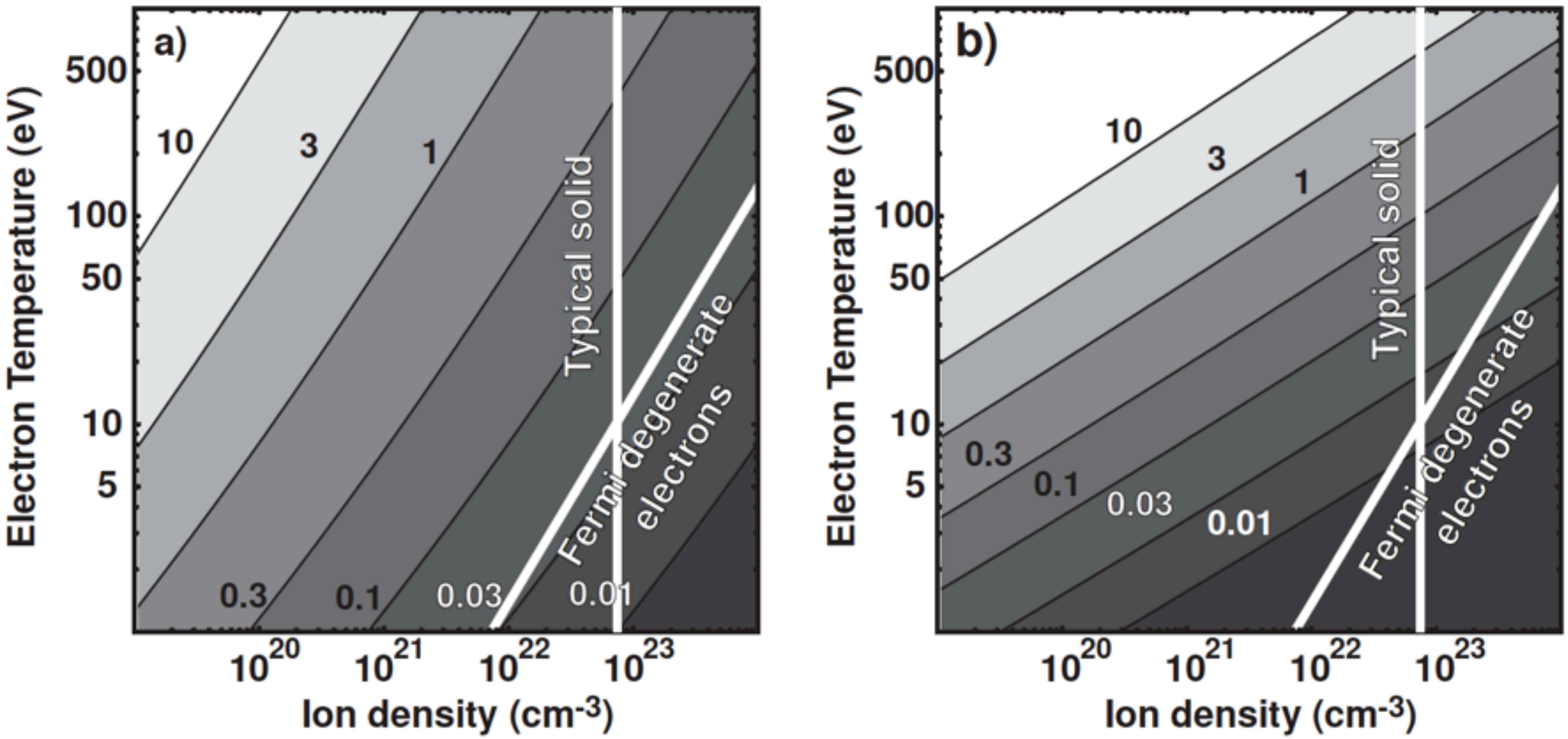


Fig. 3.4 Contours of the number of particles in a Debye sphere. The contours show 0.01, 0.03, 0.1, 0.3, 1, 3, and 10 particles, and increase to the upper left. (**a**) A high-Z plasma with $Z = 0.63\sqrt{T_{eV}}$ (see Sect. 3.4). (**b**) A low-Z plasma with $Z = 4$

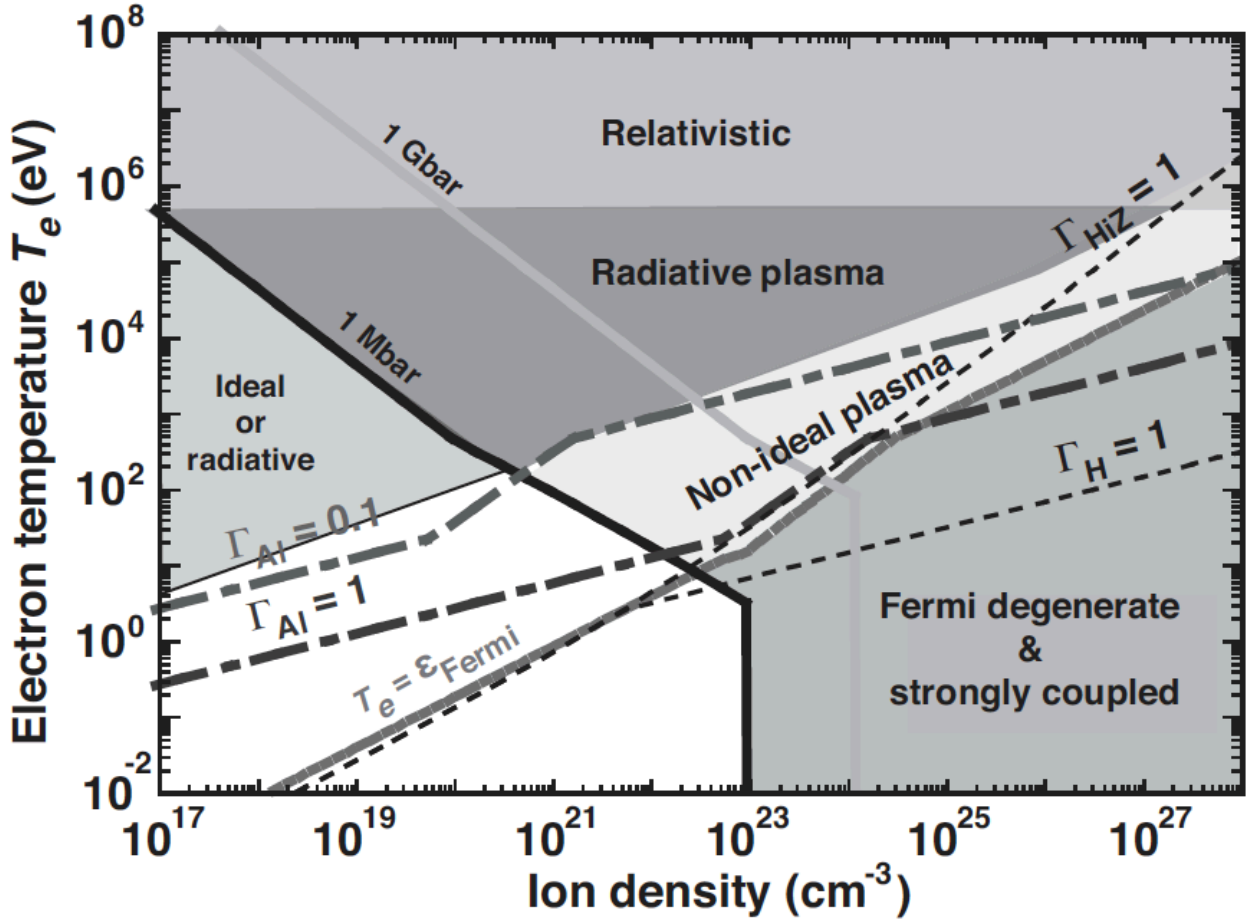


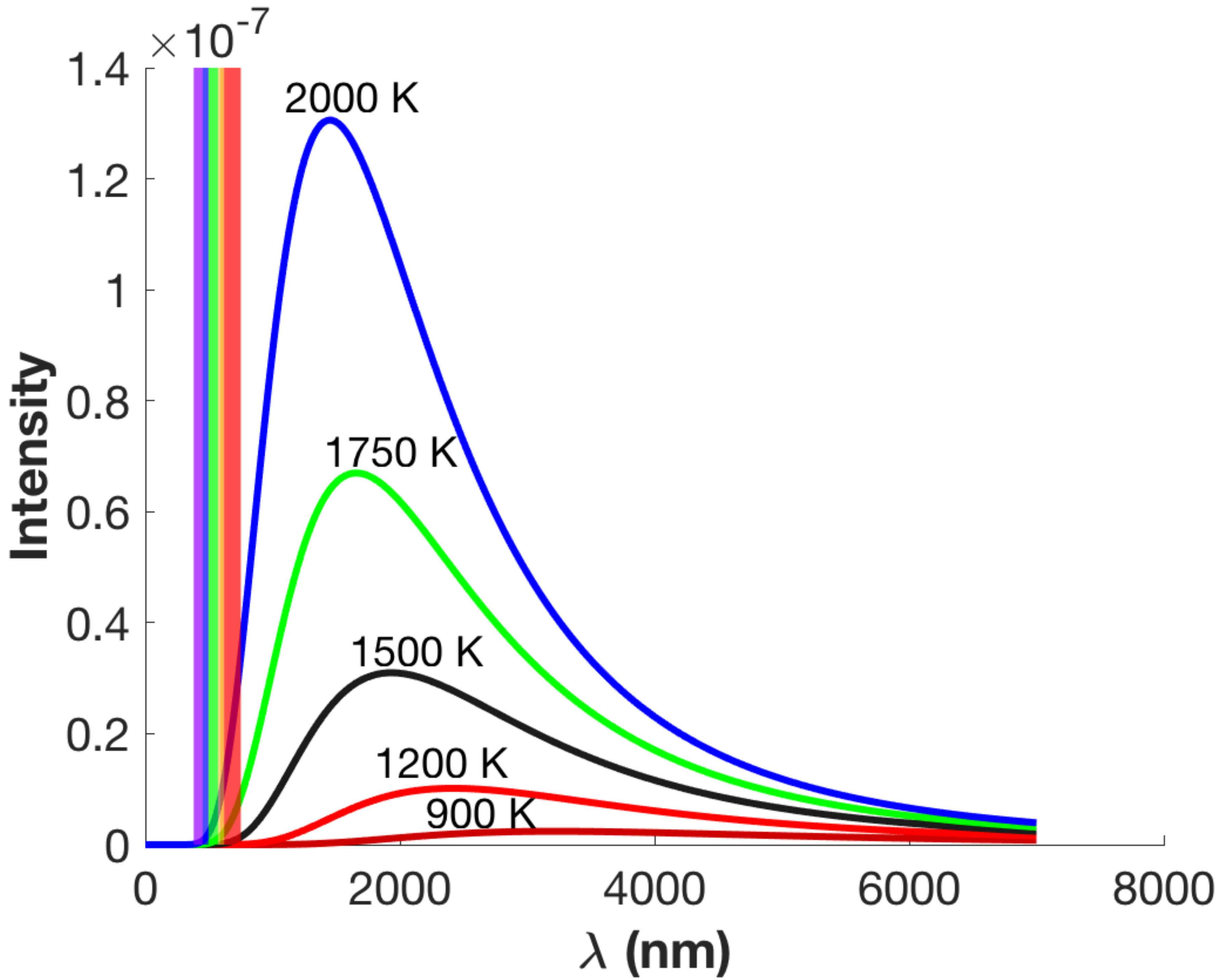
Fig. 1.2 Regimes of high-energy-density physics. The curves are primarily based on the simple models of Chap. 3, as applied to Al. Two dashed lines correspond to H or to a generic, very heavy, "Hi-Z" medium. Other aspects are discussed in the text.

Who studies HEDP and why?

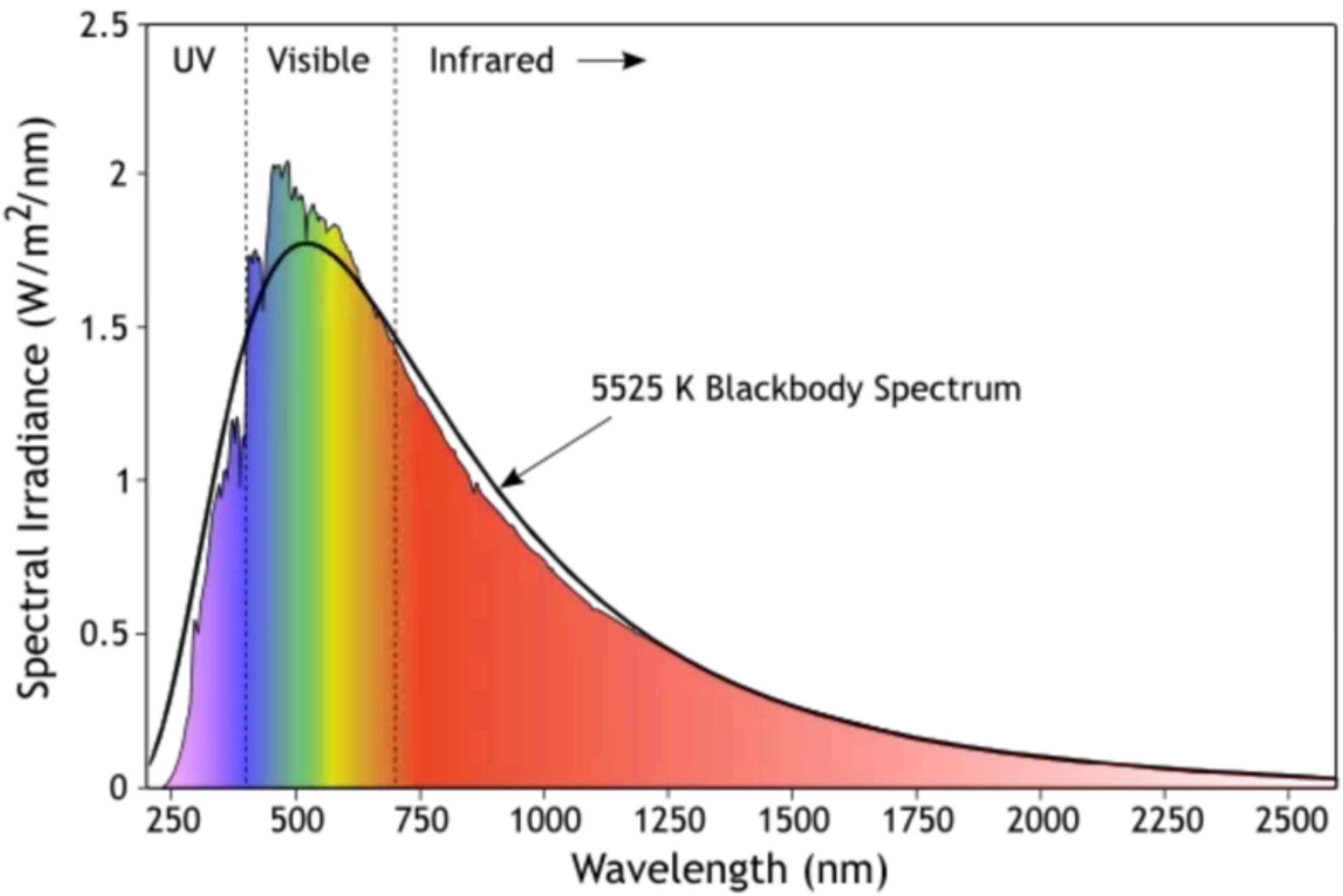
- **National Nuclear Security Association**
  - Science-based stockpile stewardship ensures a safe, secure, and effective nuclear stockpile
- **Inertial Confinement Fusion Scientists**
  - Create a nuclear fusion reaction by heating and compressing a fuel target using lasers or pulsed power device
- **Astrophysicists**
  - HEDP conditions and relevance found in SN explosions, SN remnants, accretion phenomena, reconnection, cosmic rays, and more
- **It's fun!**
  - Creating, observing, and modeling this extreme environment is challenging and rewarding

ICF
https://www.youtube.com/watch?v=yixhyPN0r3g

SPACE - Star Stuff
https://www.dailymotion.com/video/x11afti



$\times 10^{-7}$
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Intensity
2000 K
1750 K
1500 K
1200 K
900 K
0
2000
4000
6000
8000
λ (nm)



UV
Visible
Infrared
5525 K Blackbody Spectrum
Spectral Irradiance (W/m²/nm)
Wavelength (nm)
0
0.5
1
1.5
2
2.5
250
500
750
1000
1250
1500
1750
2000
2250
2500

What is HEDP and where do we find it?

Pressure above 1 Mbar = 1 million atm

Ex. 747 on hand ($P = F/A$)

In ocean $\frac{1 \text{ atm}}{10 \text{ m}}$ (1 Mbar → 10 million meters)

Mariana trench 10,000 m → 1000 atm
(HEDP 1000x greater)

Fig 1.1 ←

High pressure, highly compressible, ionized matter → free electrons → plasma

not "ideal plasma"

$\Lambda = 4\pi n_e \lambda_D^3$, $\lambda_D^2 = \frac{\epsilon_0 k T_e}{n_e q^2}$

For HEDP $n_e \gg 1$ $\Lambda = 4\pi C \frac{T_e^{3/2}}{n_e^{1/2}}$
Λ small (non ideal)

Fig 3.4 λ_D also small

HED Regimes

HED matter is typically plasma but plasma theory is not sufficient

ideal plasma → $\lambda_D \gg 1$
$\Lambda \gg 1$

Fig 1.2 solid, liquid, gas, plasma
ideal, MBar, kBar

1 eV ~ 10000 K, 10^2 eV ~ 10^6 K
10^5 eV ~ 10^9 K

WDM → Condensed Matter theory + plasma
plasma that are denser than
solids cooler than gas or plasma
- planetary core, metallic H
- white dwarf mass of sun
in volume of Earth

→ who studies HEDP? NIF movie

HEDP governing equations

- Some HEDP systems can be
described by fluid equations

$$\frac{d\rho}{dt} + \nabla \cdot \rho \bar{u} = 0$$

$$\rho \left(\frac{d\bar{u}}{dt} + \bar{u} \cdot \nabla \bar{u} \right) = - \nabla P$$

$$\frac{dP}{dt} + \bar{u} \cdot \nabla P = - \gamma P \nabla \cdot \bar{u}$$

Need EOS to close eqns
→ varies for different HED
regimes

Conservative form

$$\frac{d\rho}{dt} + \nabla \cdot \rho\bar{u} = 0$$

$$\frac{d}{dt}(\rho\bar{u}) + \nabla \cdot (\rho\bar{u}\bar{u}) = -\nabla P$$

$$\frac{d}{dt}\underbrace{\left(\rho\epsilon + \rho\frac{u^2}{2}\right)}_{\rho \to \text{energy } \cancel{\text{density}}} + \nabla \cdot \left[\rho\bar{u}\left(\epsilon + \frac{u^2}{2}\right) + P\bar{u}\right] = 0$$

$\epsilon \to$ internal energy

Integrate over a volume → change in Q is equal to the flux of Q in or out of that volume.

Flux - rate of flow through surface

What about radiation? (doesn't have to be HEDP)

$$\frac{d}{dt}\left(\cancel{\rho\frac{u^2}{2}}\ \rho\epsilon + \rho\frac{u^2}{2}\right) + \nabla \cdot \left[\rho\bar{u}\left(\epsilon + \frac{u^2}{2}\right) + P\bar{u}\right]$$

$$= -\nabla \cdot \bar{F}_R$$

$\bar{F}_R \to$ radiative flux

I_ν spectral radiation intensity

$$I_\nu = \frac{W}{sr\, m^2\, Hz} = \frac{J}{s\, sr\, m^2\, Hz}$$

~~power~~
amt ~~of energy~~ emitted

$$= \frac{ergs}{s} \frac{1}{cm^2\, sr\, Hz}$$

$Hz = \frac{1}{s}$

$\nu = \frac{c}{\lambda}$ $\quad E = h\nu$

differential elements ~~A~~, ~~t~~, Ω, ν

$\rightarrow dA, dt, d\Omega, d\nu$

$$\Delta\text{energy} = I_\nu\, dA\, dt\, d\Omega\, d\nu$$

$I_\nu(\nu, T)$ Planck showed that spectral radiance of a body @ ν and T is given by

$$I_\nu(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$ Plancks law

h = Plancks const
$= 6.6 \times 10^{-34}$ J·s
$= 4.1 \times 10^{-15}$ eV·s

$$I_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

Show Becky Plot

$$F_R = \int I_\nu(\nu,T)\, d\nu\, d\Omega$$ Radiative energy flux

Power radiated by surface through $d\Omega$ by $d\nu$

Integrate above

$$F_R = \int_0^\infty I_\nu(\nu,T)\, d\nu \int \cos\theta\, d\Omega$$

~~a~~ Lambertian → radiant intensity altered by $\cos\theta$

θ → surface → observer

$$d\Omega = \sin\theta\, d\theta\, d\phi$$

$$F_R = \int_0^\infty I_\nu(\nu,T)\, d\nu \underbrace{\int_0^{2\pi} d\phi \int_0^{\pi/2} \cos\theta \sin\theta\, d\theta}_{\pi}$$

$$= \pi \int_0^\infty I_\nu(\nu,T)\, d\nu$$

Plug in ~~??~~ Planck's Law

$$= \frac{2\pi h}{c^2} \int_0^\infty \frac{\nu^3}{e^{h\nu/kT} - 1}\, d\nu$$

sub $u = \frac{h\nu}{kT}$ $du = \frac{h}{kT}\, d\nu$

$$F_R = \frac{2\pi h}{c^2}\left(\frac{kT}{h}\right)^4 \underbrace{\int_0^\infty \frac{u^3}{e^u - 1}\,du}_{\frac{\pi^4}{15}}$$

$$F_R = \underbrace{\frac{2\pi^5 k^4}{15c^2h^3}}_{\sigma} T^4 = \sigma T^4$$ Stephens Boltzman Law

for blackbody

all frequencies

only dependent on T

Black body

- emits at every freq ν
  - ideal emitter
- Radiation is isotropic
  - independent of direction
  - diffuse emitter

If not go back to general definition

SM BB

When is radiation important?

Look at $\nabla \cdot F_R$ term in energy eqn.

When is F_R dynamically important

$\nabla \cdot F_R \to \nabla \cdot \sigma T^4$

What are the units? ~~energy density~~ ~~flux~~

U, L $\quad \frac{L}{U} \to$ time

ρ - characteristic density

$\nabla \cdot \sigma T^4$

Divergence of energy density flux

$\rho U^2 U$

normalize $\frac{\sigma T^4}{\rho U^3}$ relate KE to thermal energy

$m_i U^2 \sim k_B T$ (ignore const.)

$\sim \frac{\sigma T^4}{\rho U^2 U} = \frac{\sigma T^4}{\rho U} \approx \frac{m_p \sigma T^{\cancel{4}}}{\rho k_B \cancel{T} U} = \frac{m_p \sigma T^3}{\rho k_B U}$

plug in for ideal gas law

$\downarrow$

$\frac{1}{B_0}$

Boltzmann #

$B_0 \quad \frac{\text{fluid effects}}{\text{radiative effects}}$

B_0 small → rad. effects important

dependent on T^3

Temperature - (color temperature)

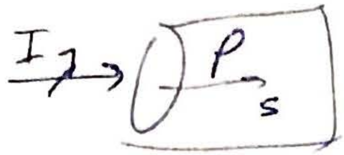
Varies w/ location - particles move
+ photons

local thermodynamic equilibrium
↳ temp. change small over
mean free path → dist. between
collisions

$l = \frac{1}{n\sigma}$ n number density $\frac{\#}{cm^3}$

σ cross section $\sigma = \pi(2a_0)^2$
for H

~~$l = \frac{1}{2\pi n a_0^2}$~~ $l = \frac{1}{\kappa_\lambda \rho}$



Radiation and Matter

Absorption → Removes photons from "beam"

Includes - scattering and absorption of photons

(1) $dI_\lambda = -\kappa_\lambda \rho I_\lambda ds$ ← decrease

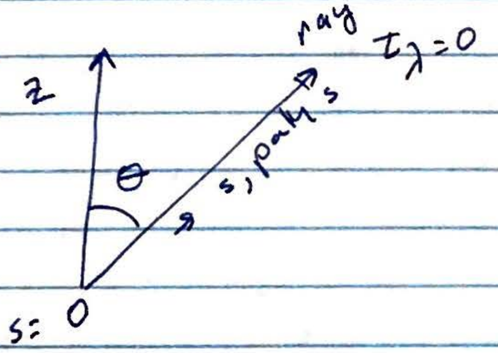
ΔI_λ, ray λ, distance traveled ds
gas density ρ

κ_λ - absorbtion coeff or opacity
↳ $\frac{cm^2}{g}$ $\quad \ell = \frac{1}{\kappa_\lambda \rho}$ mfp

---

Optical depth τ_λ

$$d\tau_\lambda = -\kappa_\lambda \rho ds \qquad \frac{cm^2}{g}\frac{g}{cm^3}\,cm \to \text{dimensionless}$$



$$\Delta \tau_\lambda = \tau_{\lambda,f} - \tau_{\lambda,0} = -\int_0^s \kappa_\lambda \rho ds$$

increasing or decreasing? decreasing
~~quality?~~ as light travels to
observer $\tau \downarrow$

$\Delta \tau_\lambda < 0$

$\tau_{\lambda,f} \to 0$

$$-\tau_\lambda = -\int_0^s \kappa_\lambda \rho \, ds$$

$$\tau_\lambda = \int_0^s \kappa_\lambda \rho \, ds = \kappa_\lambda \rho s = \frac{s}{\ell}$$

↳ relate to ~~then~~ I_λ

$$\int_0^f \frac{dI_\lambda}{I_\lambda} = -\int_0^s \kappa_\lambda \rho \, ds \quad \text{from } ①$$

$$I_\lambda = I_{\lambda,0} \, e^{-\int_0^s \kappa_\lambda \rho s}$$

$$I_\lambda = I_{\lambda 0} \, e^{-\tau_\lambda}$$ decrease by factor of e^{-1}

$\tau_\lambda = -1$ when $s = \ell$
$\tau_\lambda = -1$ when $s = -2\ell$

⋮

If $\tau_\lambda \gg 1$ optically thick
$s \gg \ell$

If $\tau_\lambda \ll 1$ optically thin
$s \ll \ell$

$\kappa_\lambda \rightarrow$ depends on λ

Earth's atm optically thin visible
thick to x-rays