Los Alamos
NATIONAL LABORATORY

# White Dwarf Matter

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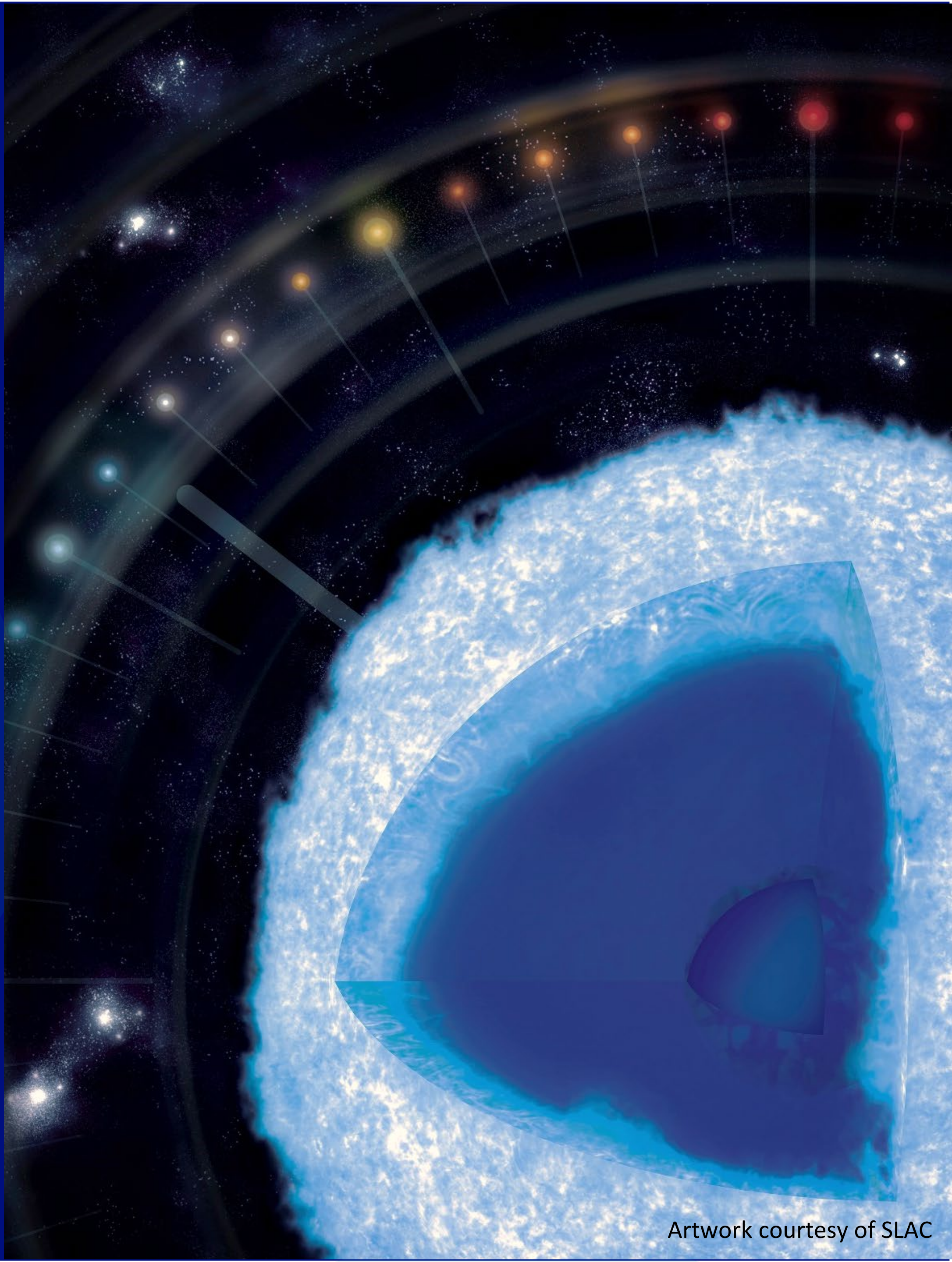
High Energy Density Science Center seminar, LLNL
21 September 2023

LA-UR-23-30516



Artwork courtesy of SLAC

# Outline

## White dwarf stars

- Origin and nature
- Astrophysical significance
- Physical conditions

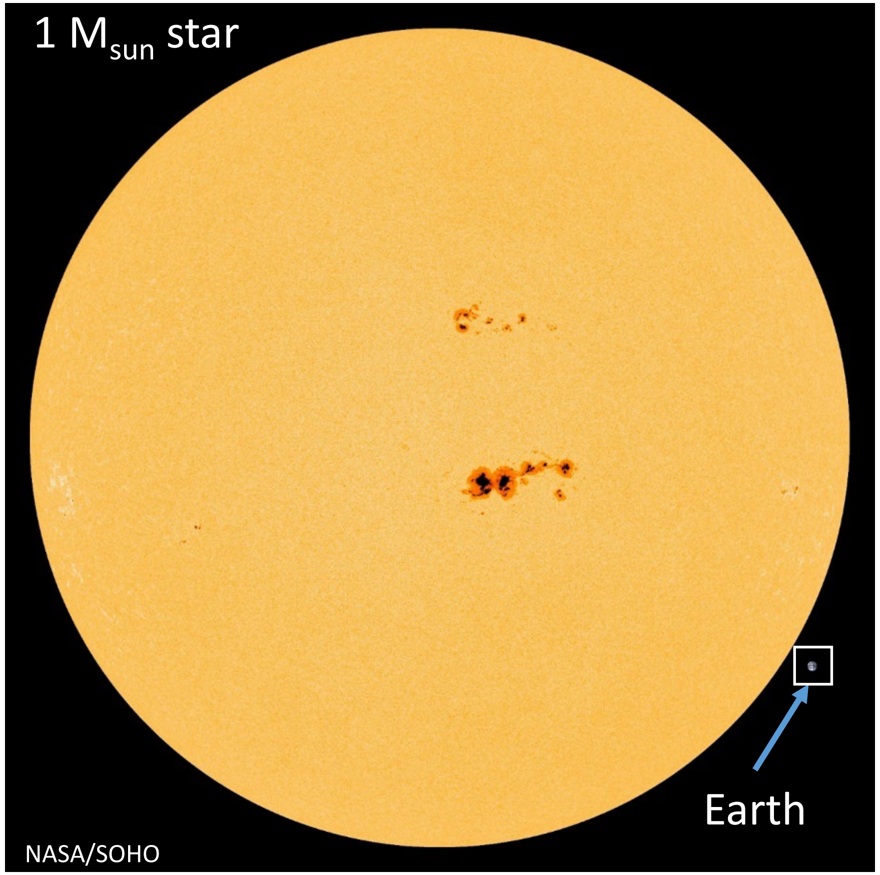
## Four problems related to WDM

- Electron thermal conductivity
- Inter-diffusion of mid-Z elements in dense He plasma
- Ionization and opacity of He
- EOS of partially ionized carbon

## An invitation

# What is a white dwarf?

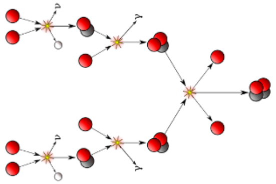
- End state of the evolution of 1 – 8$M_{sun}$ stars



H/He star

**Nuclear fusion**

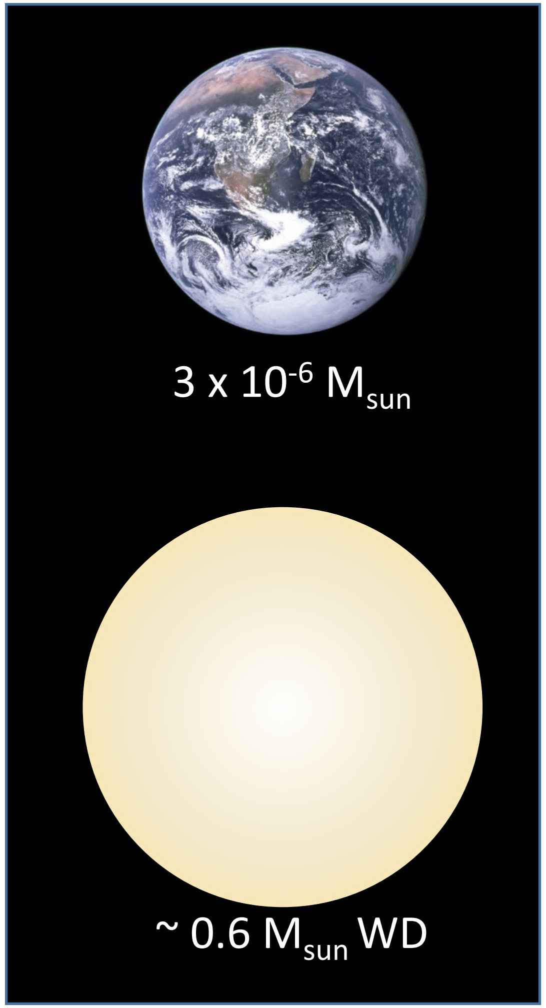
H → He → C/O



**11 Gyr of evolution**

**Mass loss**

H/He envelope is lost



A cooling C/O star

# A mature field of stellar astrophysics

- **White dwarfs are common**

  ~250 000 known

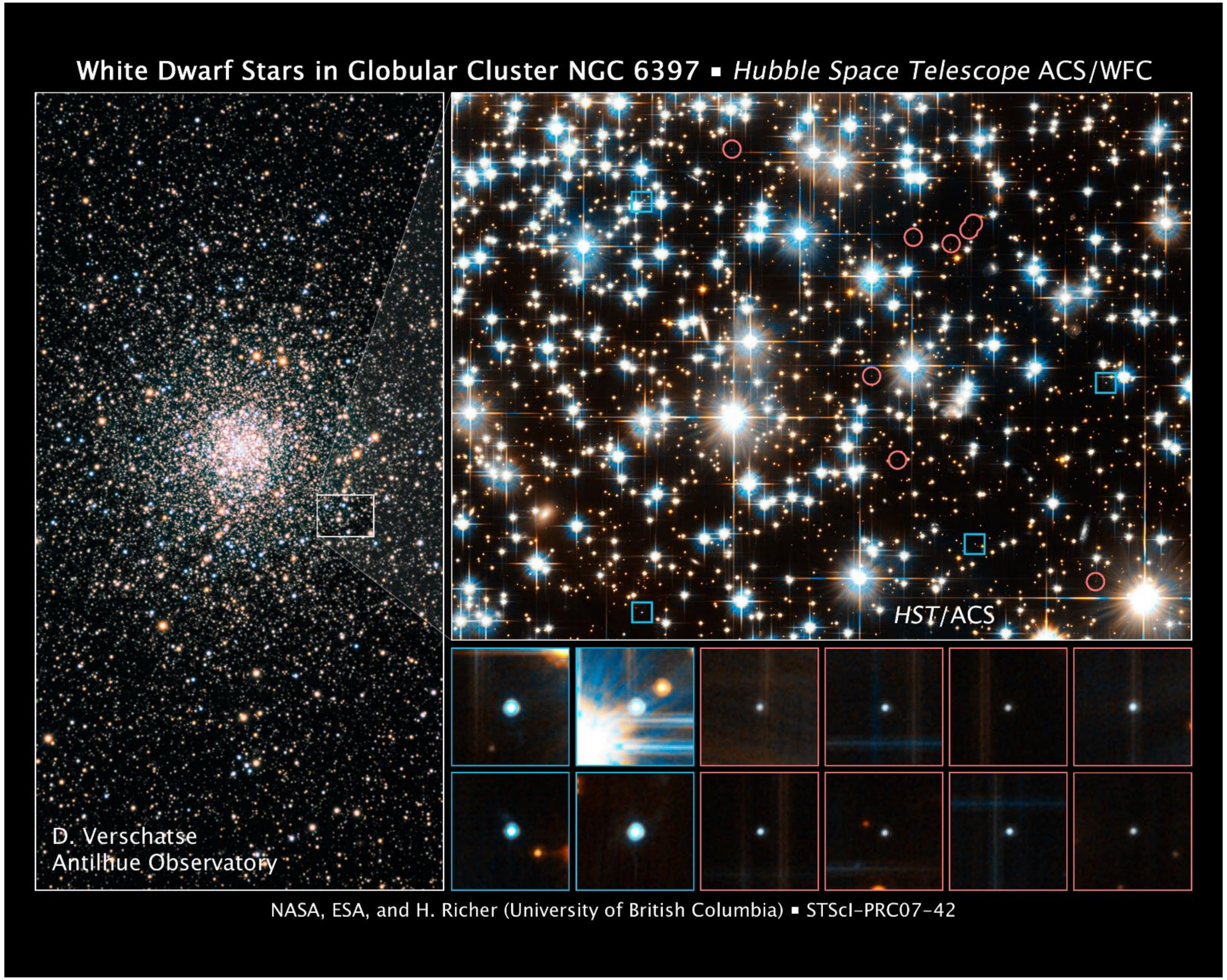
  ~18 000 well-studied

- **High quality data available**

  (spectra, luminosity and color distributions, space motion, distances)

- **Observations**

  Effectively constrain models of WDM



White Dwarf Stars in Globular Cluster NGC 6397 ▪ *Hubble Space Telescope* ACS/WFC

NASA, ESA, and H. Richer (University of British Columbia) ▪ STScI-PRC07-42

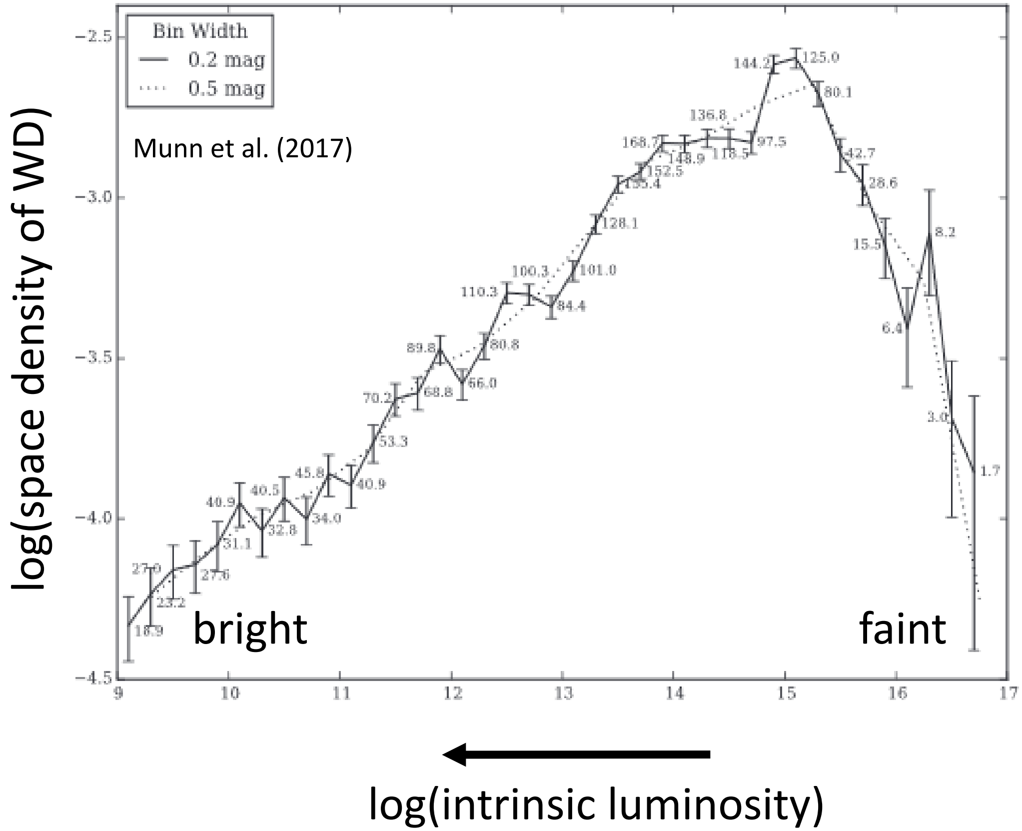
# Astrophysical significance of white dwarfs

- **White dwarf cosmochronology**

  Age of stellar populations

  History of star formation in the Milky Way

Luminosity function of thin disk white dwarfs



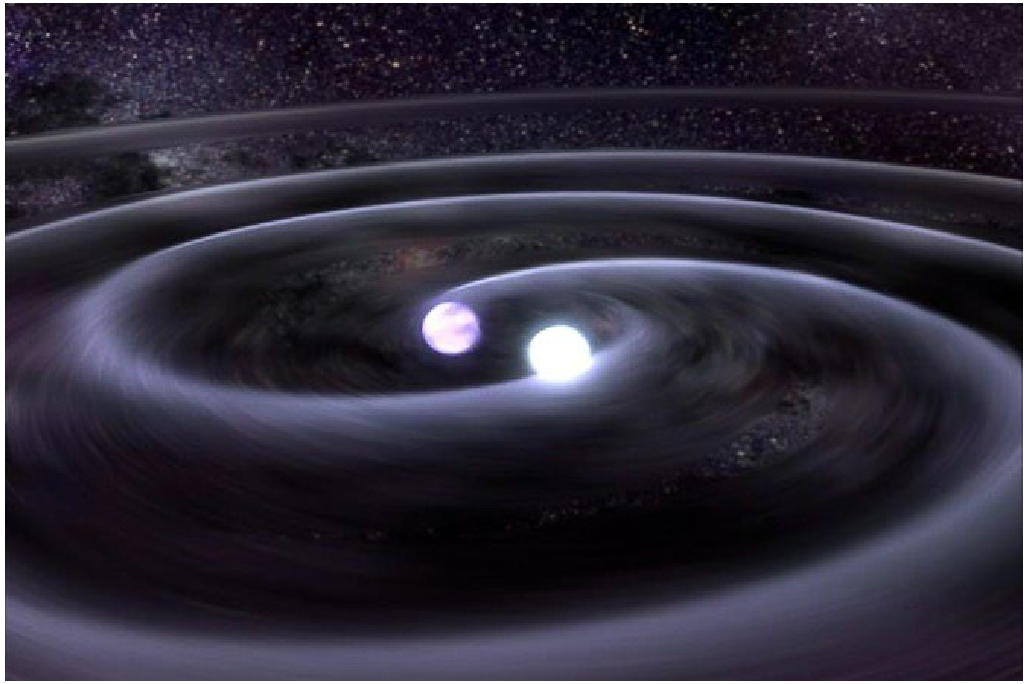
Munn et al. (2017)

# Astrophysical significance of white dwarfs

- **White dwarf cosmochronology**

- **Type Ia supernovae / WD mergers**

  Low mass mergers don’t explode: hot DQ

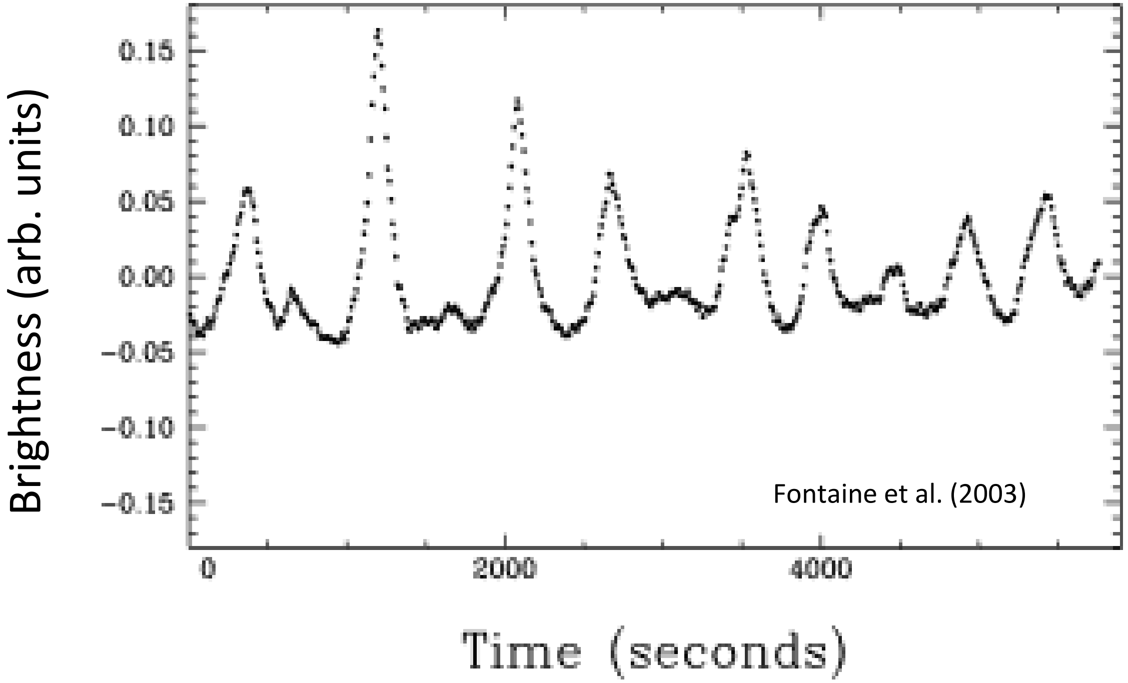


# Astrophysical significance of white dwarfs

- **White dwarf cosmochronology**

- **Type Ia supernovae / WD mergers**

- **Pulsating white dwarfs**
  Probe interior structure with asteroseismology

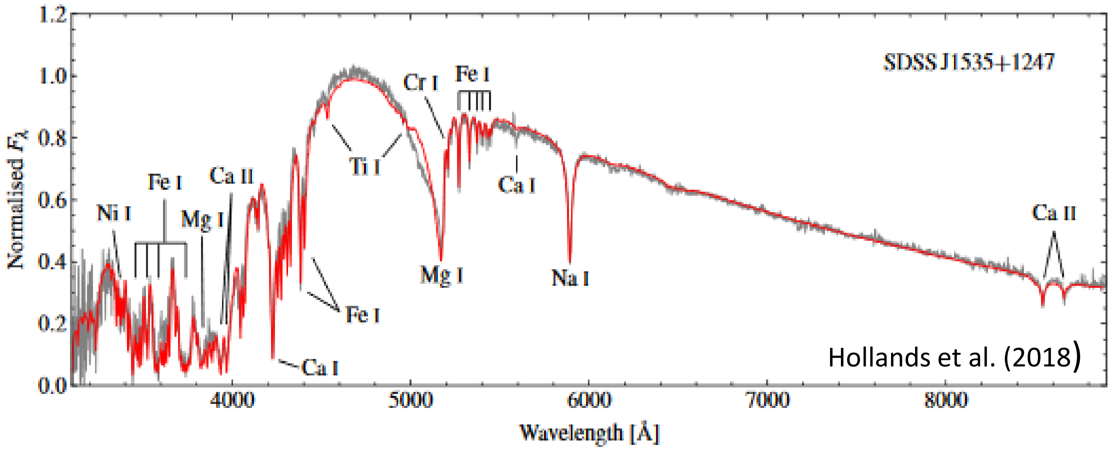


Fontaine et al. (2003)

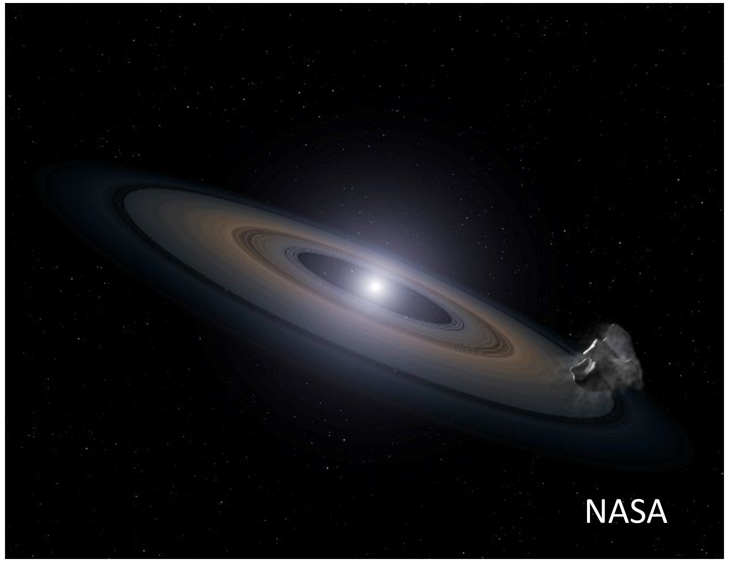
# Astrophysical significance of white dwarfs

- **White dwarf cosmochronology**
- **Type Ia supernovae / WD mergers**
- **Pulsating white dwarfs**
- **Composition of very old exoplanetary systems**

  Elemental composition of infalling solid material



Hollands et al. (2018)



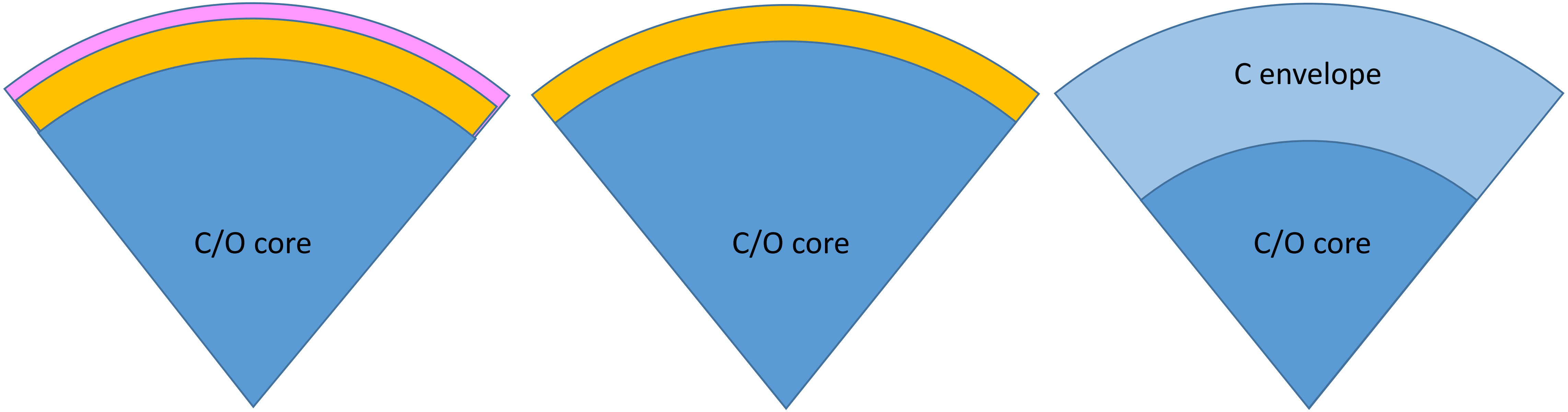
NASA

# Astrophysical significance of white dwarfs

- **White dwarf cosmochronology**
- **Type Ia supernovae / WD mergers**
- **Pulsating white dwarfs**
- **Composition of very old exoplanetary systems**
- **These applications depends on the reliability of WD models!**

  (EOS, opacity, transport coefficients)

# Three main types of white dwarfs



“H-rich” WD

“He-rich” WD

Carbon WD

C/O core: $0.6M_{sun}$

He layer: $10^{-2}M_{*}$

H layer: $10^{-4}M_{*}$

We are primarily concerned in the physics of C/O mixtures, H, He and traces of heavier elements

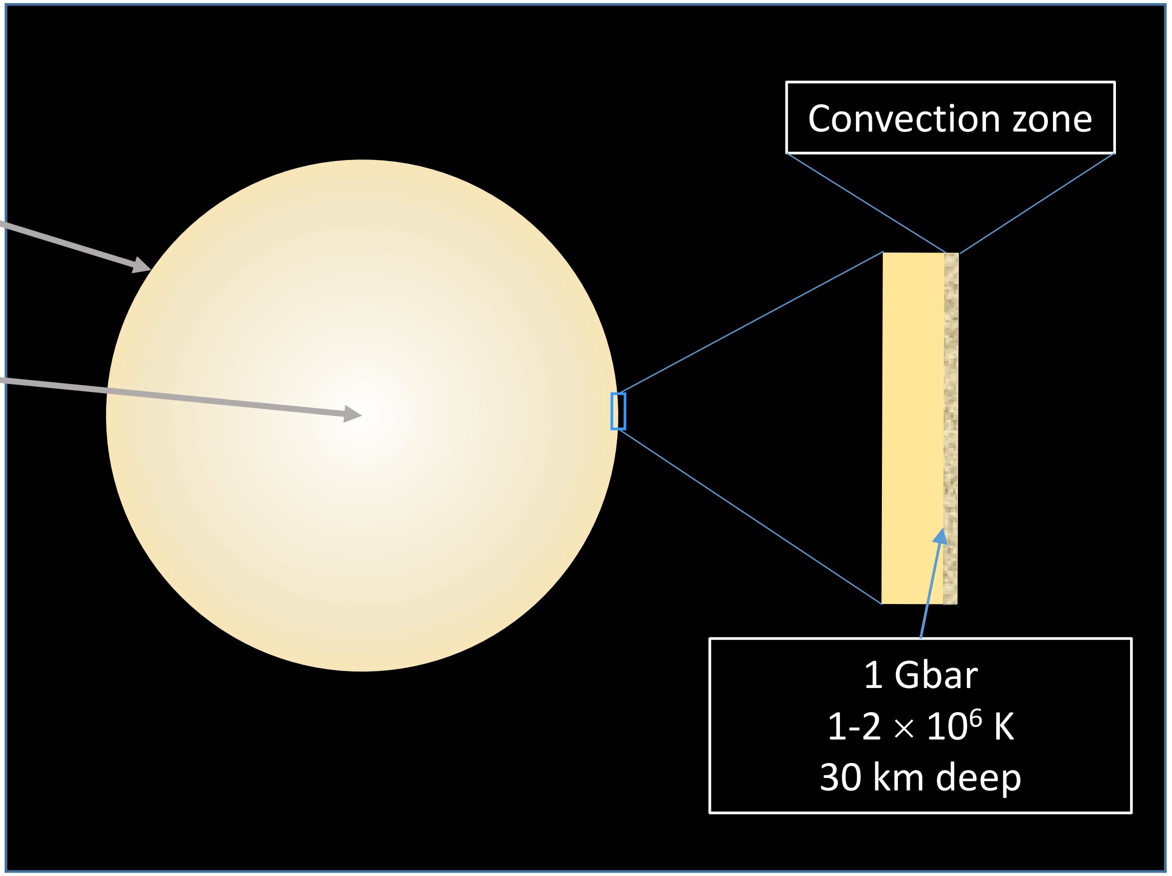
# Physical conditions in white dwarfs

## Physical conditions

- Photosphere ("surface"): "normal conditions"
  $T \sim 0.5 - 10$ eV $\rho \sim 10^{-4} - 0.1$ g/cm$^3$
- Center (C/O core): "extreme conditions"
  $T_c \sim 10^2 - 10^3$ eV $\rho_c \sim 10^6$ g/cm$^3$
  $P_c \sim 10^{13}$ Mbar
  Fully ionized, strongly degenerate plasma

## Zone of partial ionization (WDM)

Rapid variations in EOS and opacity
Trigger convection near surface
Affect mixing, cooling rate, and drive pulsations
**Where the EOS and opacity are most uncertain!**



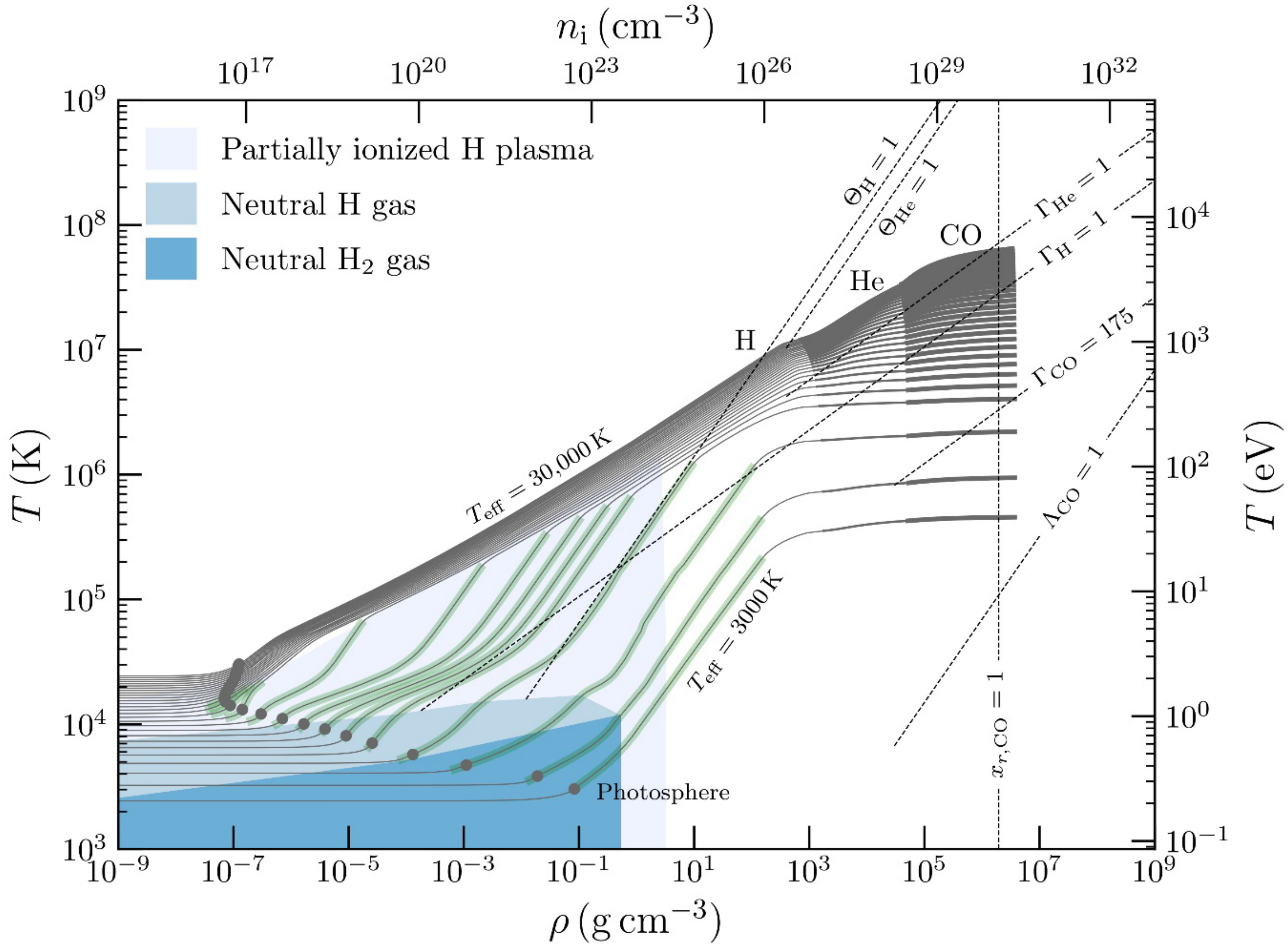
Convection zone

1 Gbar
1-2 × $10^6$ K
30 km deep

# Physical conditions in “H-rich” white dwarfs of $0.6M_{sun}$

## Physical regimes

- Electron degeneracy
  $$\theta = k_B T / \epsilon_F$$
- Ion Coulomb coupling
  $$\Gamma = \frac{Z^2 e^2}{a k_B T}$$
- Relativistic electrons
  $$x_r = p_F / m_e c$$
- Ion quantum effects
  $$\Lambda = \lambda_{th} / a$$
- Partial ionization

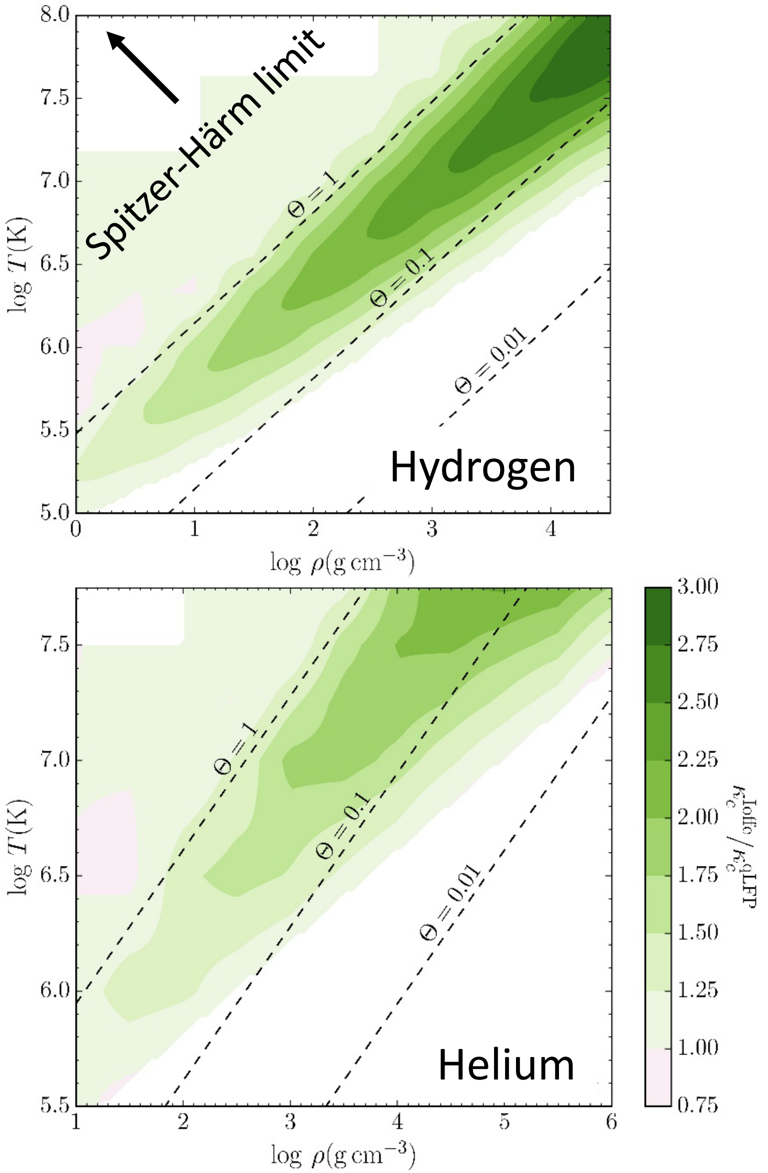


# Electron thermal conductivity of H and He for θ=0.1 – 1

## Application: Ages of white dwarfs

### Thermal conductivity controls the flow of energy from the degenerate core to the surface

- Well understood in highly degenerate regime (θ<<1, Γ>>1) and in Spitzer-Härm regime (θ>>1, Γ<<1) (Cassisi et al. 2007)
- Shaffer et al. (2020): Extend Spitzer-Härm to smaller θ and larger Γ with Chapman-Enskog solution of transport equation using
  - quantum Landau-Fokker-Plank collision operator (Daligault 2018)
  - potential of mean force from an average atom model
- Results in higher thermal conductivity
- Shortens the cooling time by ~1Gyr for H-rich, ~1/3 Gyr for He-rich. A big effect!



# Electron thermal conductivity of H and He for $\theta$=0.1 – 1

## Application: Ages of white dwarfs

- Cassisi et al. (2021)

  Criticize the validity of qLFP model for $\theta < 1$

  Uncertainty in electron thermal conductivities for $0.1 < \theta < 1$ can affect age from 0 to 1Gyr!

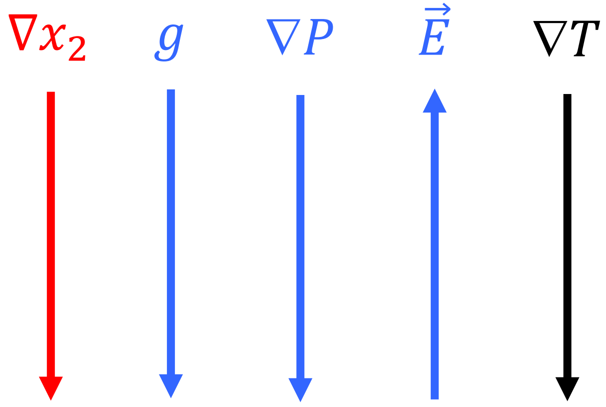
### What is needed?

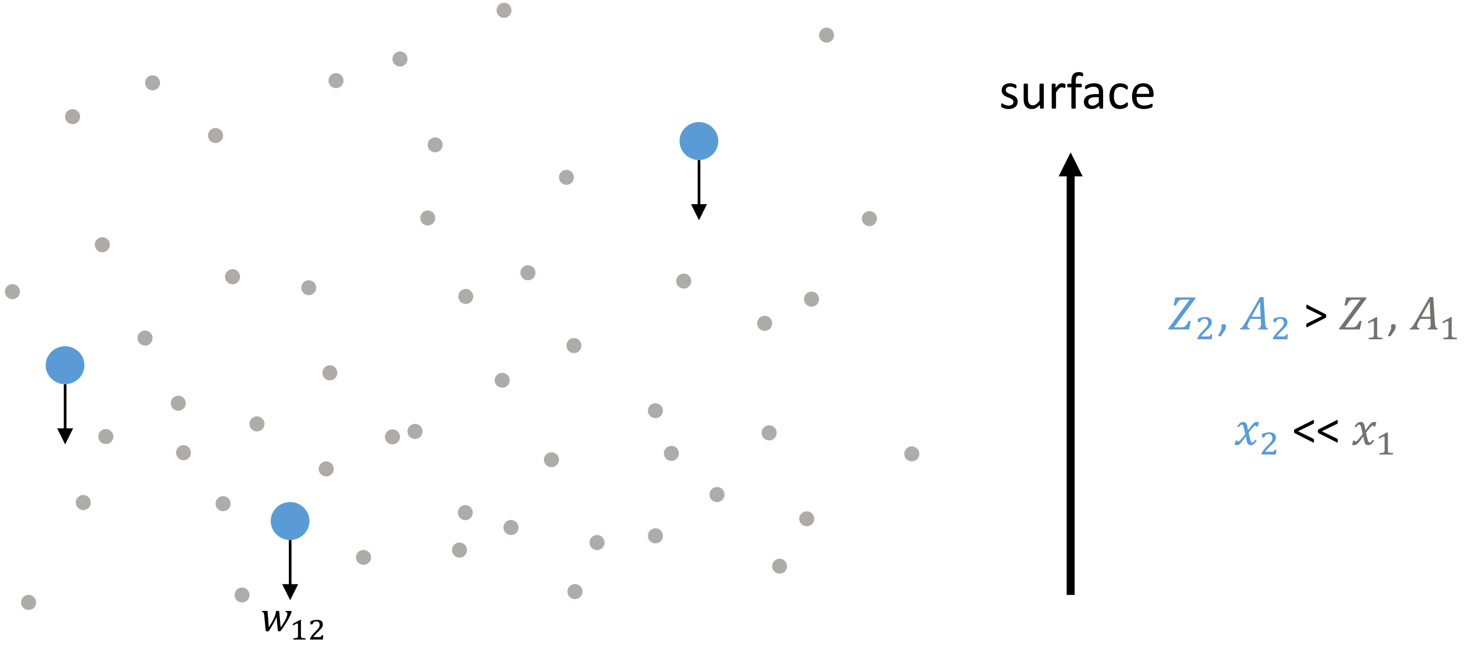
- Better theory of electron thermal conductivity of H and He for $\theta \sim 0.1 - 1$

# Interdiffusion coefficients

## Application: Composition of exoplanetary systems

Gradients in a star





**Relative diffusion velocity:**

$$w_{12} = \boxed{\boldsymbol{D}_{\mathbf{12}}}(1+\gamma)\left[-\frac{\mathbf{d}\ln \boldsymbol{x}_2}{\mathbf{d}r} + \left(\frac{A_1\boldsymbol{Z}_2 - A_2\boldsymbol{Z}_1}{\boldsymbol{Z}_1 + \gamma \boldsymbol{Z}_2}\right)\frac{m_0\boldsymbol{g}}{k_B T} + \left(\frac{\boldsymbol{Z}_2 - \boldsymbol{Z}_1}{\boldsymbol{Z}_1 + \gamma \boldsymbol{Z}_2}\right)\frac{\mathbf{d}\boldsymbol{P}_i}{\mathbf{d}r} + \boxed{\alpha_T}\frac{\mathbf{d}\ln T}{\mathbf{d}r}\right]$$

$$\gamma = \frac{x_2}{x_1}$$

chemical diffusion

barodiffusion

thermal diffusion

# Interdiffusion coefficients

## Application: Composition of exoplanetary systems

- White dwarf models require the coefficients of inter-diffusion $D_{12}$ and of thermal diffusion $\alpha_T$
- Typically consider a trace of a mid-Z element (C, Na, Ca, Mg, Si, Fe…) in bath of fully ionized He
- Conditions of interest: T ~ 10 – 300eV $\rho \sim 1 - 3000 \mathrm{g/cm}^3$
- Mid-Z element is typically partially ionized: What is $Z_2$ (or the ion-ion interaction potential)?

$$w_{12} = \boxed{\boldsymbol{D_{12}}}(1+\gamma)\left[-\frac{\mathbf{d}\ln \boldsymbol{x}_2}{\mathbf{d}r} + \left(\frac{A_1\boldsymbol{Z}_2 - A_2\boldsymbol{Z}_1}{\boldsymbol{Z}_1 + \gamma \boldsymbol{Z}_2}\right)\frac{m_0\boldsymbol{g}}{k_BT} + \left(\frac{\boldsymbol{Z}_2 - \boldsymbol{Z}_1}{\boldsymbol{Z}_1 + \gamma \boldsymbol{Z}_2}\right)\frac{\mathbf{d}\boldsymbol{P}_i}{\mathbf{d}r} + \boxed{\alpha_T}\frac{\mathbf{d}\ln T}{\mathbf{d}r}\right]$$

chemical diffusion

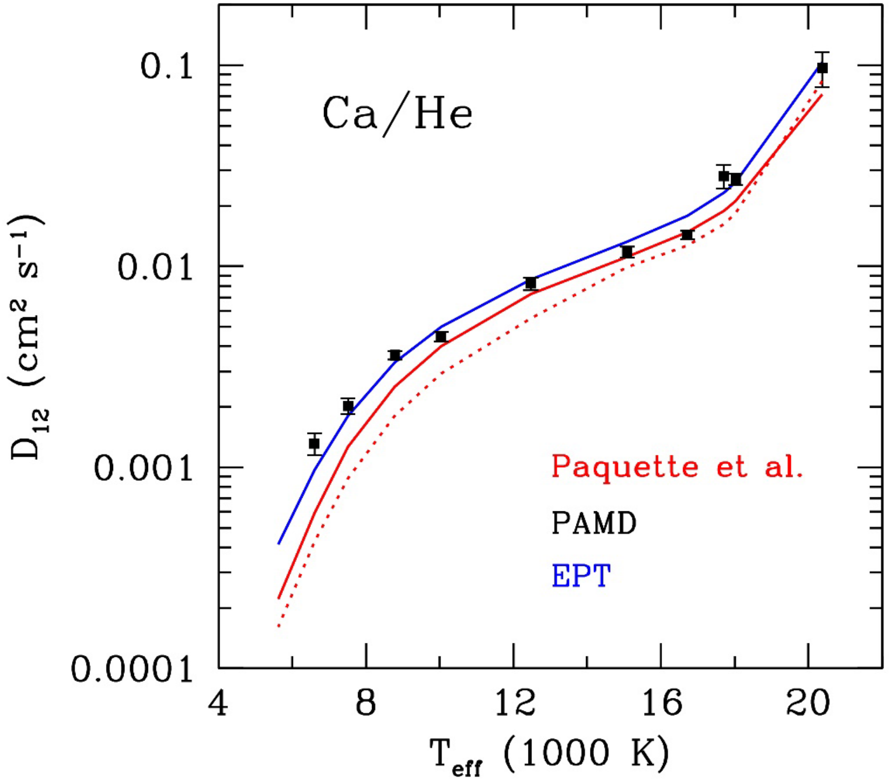
barodiffusion

thermal diffusion

# Interdiffusion coefficients

## Application: Composition of exoplanetary systems

- Current $D_{12}$ and $\alpha_T$ are from Paquette et al. (1986)!



### What is needed?

- New, more advanced models and tables of diffusion coefficients
- Benchmark ab initio simulations to validate simpler models of $D_{12}$ and $\alpha_T$
- Experiments to measure an effective $Z_2$ or $D_{12}$ or $\alpha_T$ to constrain models

# Ionization and opacity of He

## Applications: Atmospheres, ages of He-rich white dwarfs

### He opacities in cool white dwarf atmospheres

- Dominated by continuum absorption

  1) He + e free-free   2) $He_2^+$ bound-free

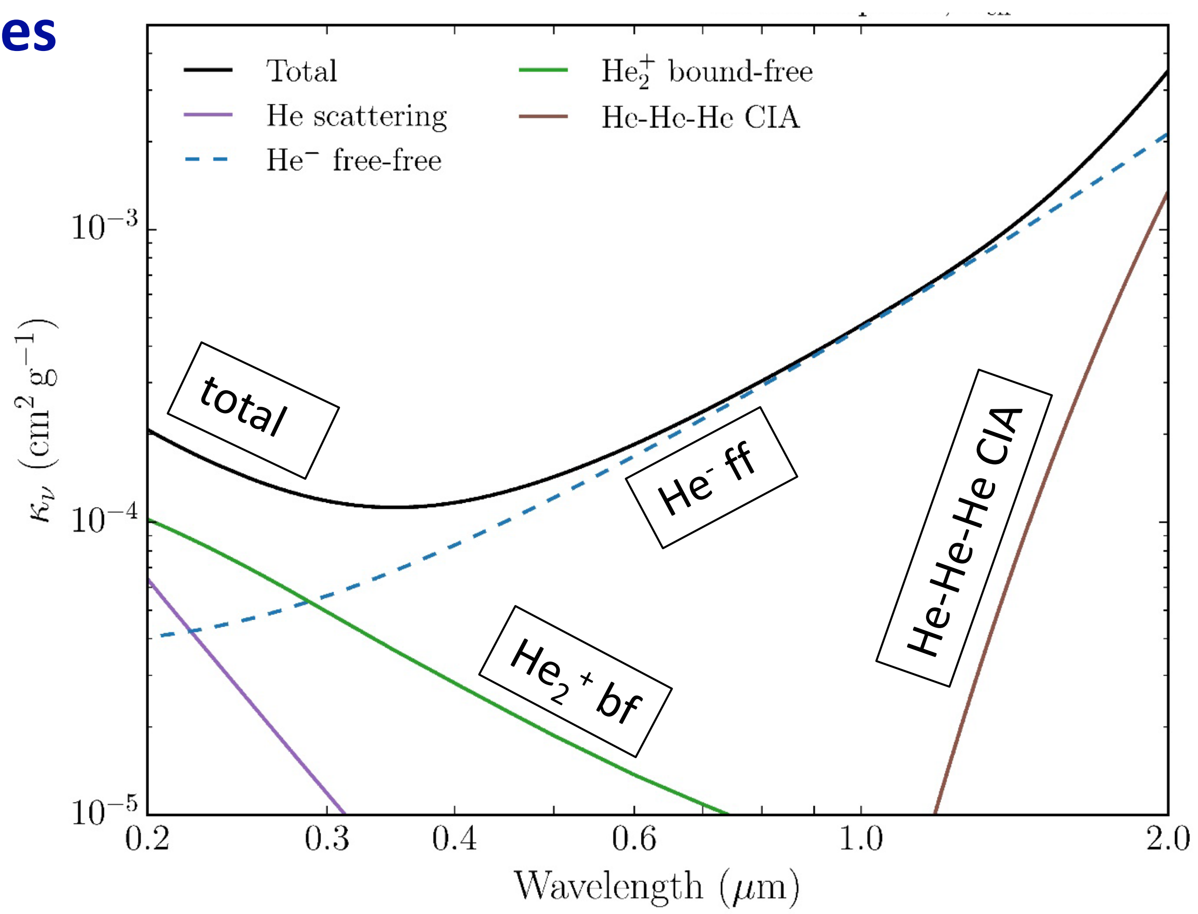
  3) He + He + He Collision-induced absorption

- Depends sensitively on the very low degree of ionization of He ($n_e/n_{He} \sim 10^{-10} - 10^{-6}$)

- T ~ 0.5eV  $\rho \sim 0.5 g/cm^3$

  Non-ideal effects, weak pressure ionization

  Very hard to model!



# Ionization and opacity of He

## Applications: Atmospheres, ages of He-rich white dwarfs

### He opacities in cool white dwarfs

- Experiment: heated DAC (McWilliams et al. 2015)

  P=22 and 52GPa  T=3200 – 16000K
- Insulator-poor conductor transition at ~10000K
- Band gap ~ 11eV  vs T < 1eV in atmosphere!
- Kowalski et al. (2007) combined

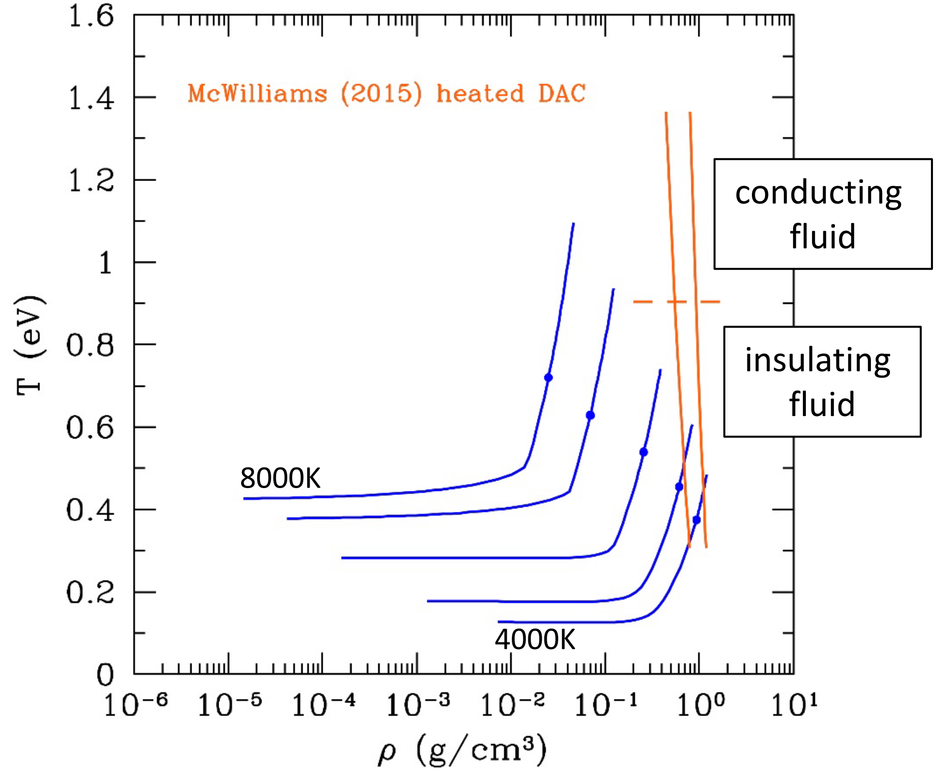
  Chemical model of ionization

  Ab initio simulations

    band gap closure vs (T,ρ)

    e – He interactions

  Limited validation!



# Ionization and opacity of He

## Applications: Atmospheres, ages of He-rich white dwarfs

### What is needed

- Better models and more extensive experiments to answer:

  1) What is $n_e/n_{He}$ ?

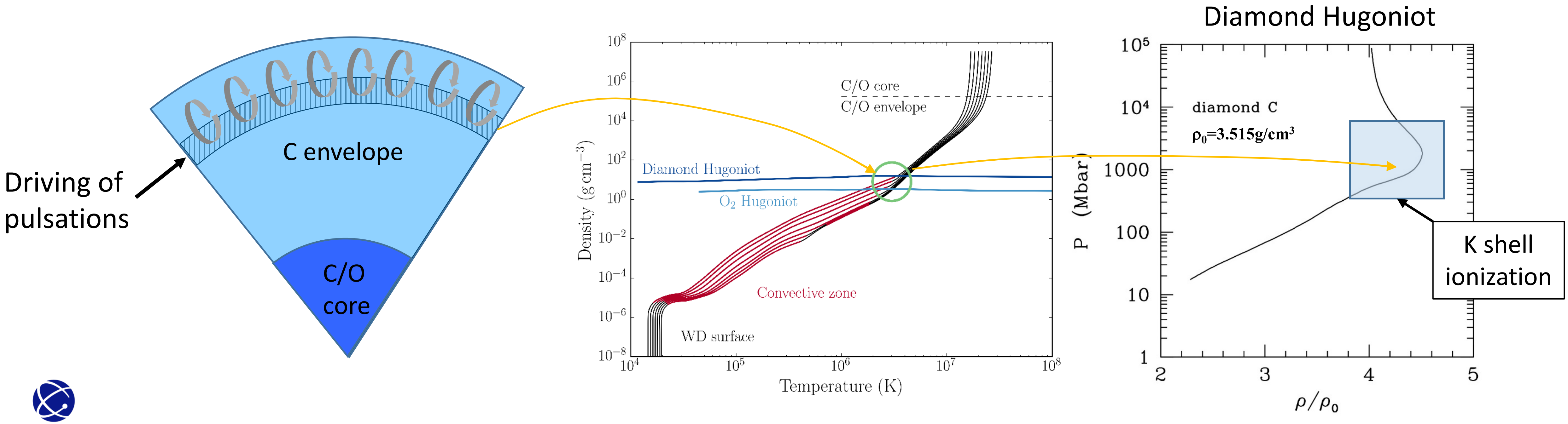
  2) How are the absorption cross-sections affected by density?

# EOS of partially ionized carbon

## Applications: WD+WD mergers and their pulsations

### Pulsations of “carbon” white dwarfs

- Driven at the bottom of the superficial convective layer
- Convection caused primarily by the physics of partial ionization (EOS, opacities)
- EOS tables untested in this regime
- It is now possible to reach those conditions experimentally for carbon!

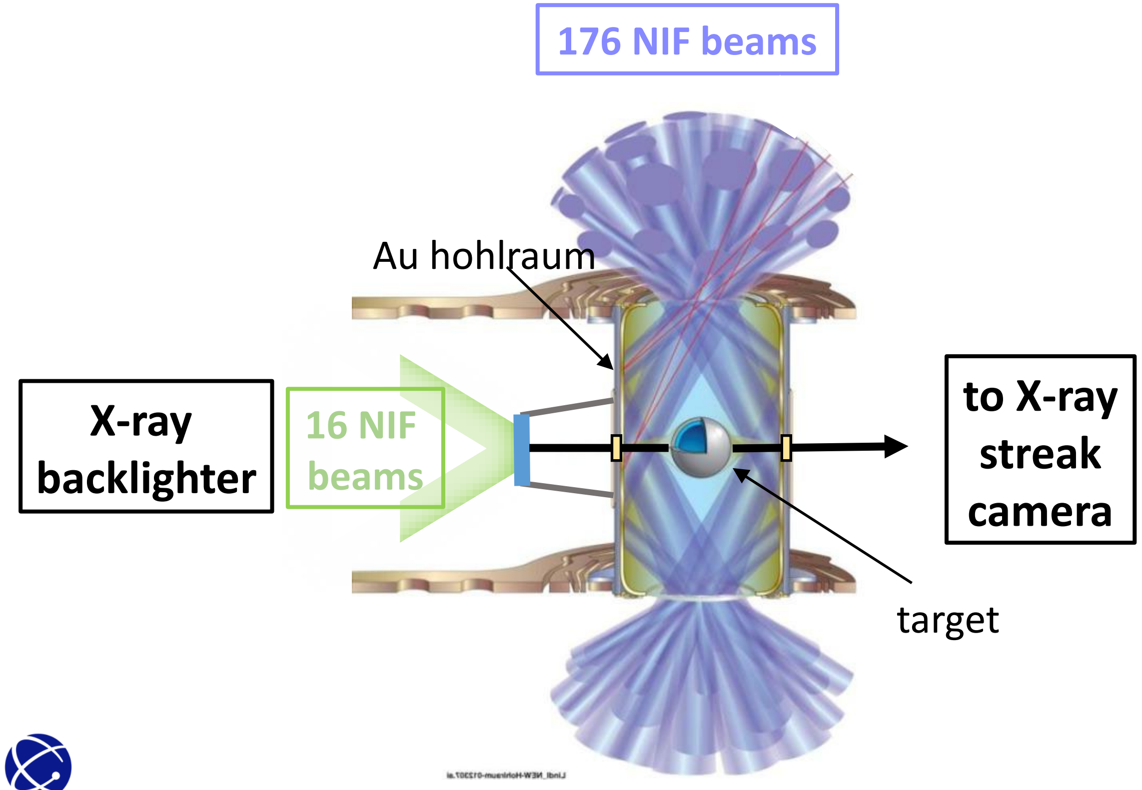


# EOS of partially ionized carbon

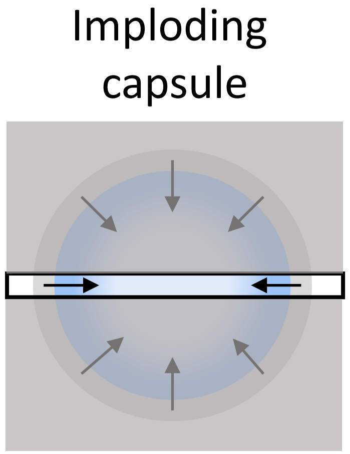
## Applications: WD+WD mergers and their pulsations

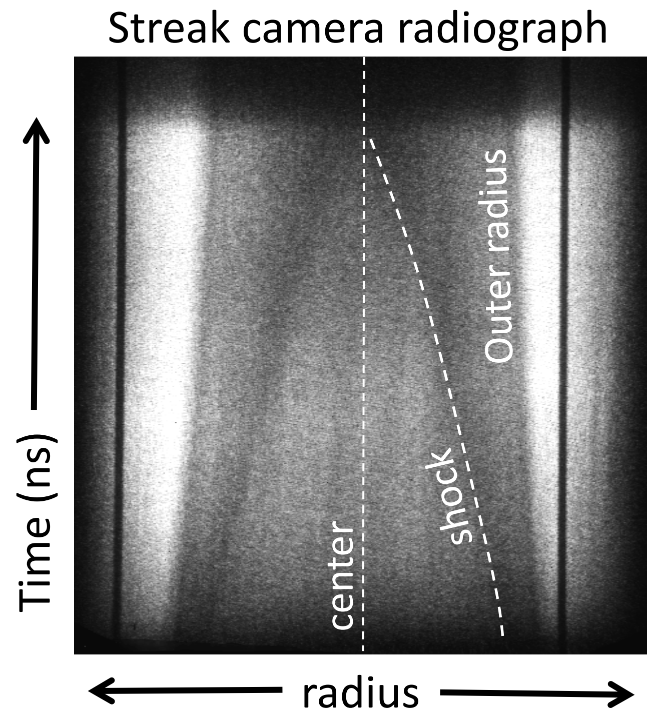
### Experimental test of EOS models with the Gbar platform at NIF (Jenei et al.)

- Spherical target inside hohlraum. Converging spherical shock wave
- Radiograph: continuous record of $U_s$ and $\Delta\rho$ at shock front: Hugoniot states



Kritcher et al. (2020)

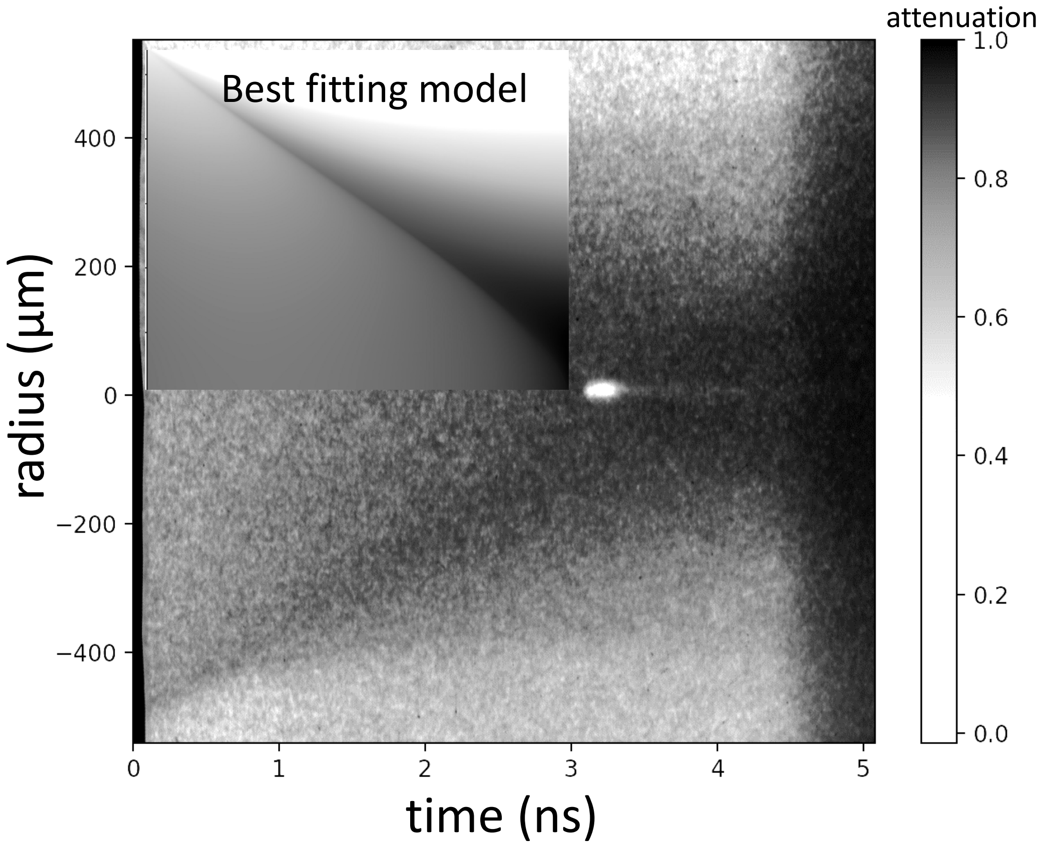


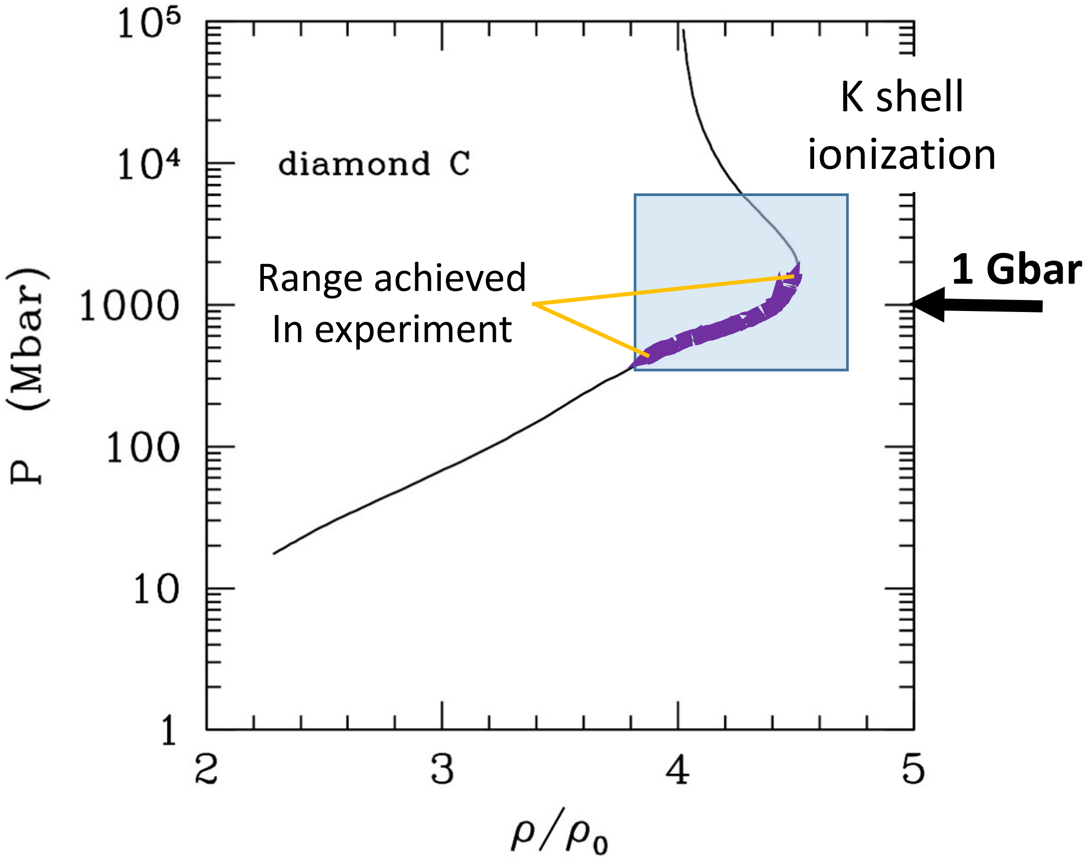


# 3 Diamond shots so far

## Preliminary analysis (D. Swift)

- Data spans 0.3 – 1.6Gbar
- Previous diamond Hugoniot data ≤ 0.8Gbar





# Many other problems of interest

- Combined Zeeman-Stark line broadening models and experiments
- Ionization and opacity of He ($\rho \sim 0.1$–$1$ g/cm$^3$ T~0.1–1eV)
- Dissociation equilibrium of diatomic molecules ($H_2$, $C_2$, $He_2^+$, $HeH^+$)
- EOS in partial ionization/WDM regime for C (and He and O)
- Line broadening of strong optical transition of mid-Z elements
- Broadening of optical lines of He by collisions with He atoms
- Modeling and measurements of the distortion of $C_2$ molecular Swan bands in dense He and strong magnetic fields
- Crystallization dynamics and lattice structure in crystallized white dwarfs for mixtures, including impurities
- Robust calculations of high-Z (uranium) impurity fractionation in crystallizing white dwarfs
- Inter-diffusion coefficients: benchmark ab initio simulations and experiments
- Electron thermal conductivity of H and He in the $\theta \sim 0.1 - 1$ regime
- Experimental measurements of the absorption coefficient of dense, heated He
- Experimental validation of the latest Stark line shapes of H and He
- Spectral line formation in an inhomogeneous convective medium
- Experimental measurements of the $H_2$-He collision-induced absorption
- 3D hydrodynamics simulations of convective overshoot and thermohaline instabilities
- Magnetic effects on convection, envelope structure, vertical diffusion, horizontal spreading of accreted material

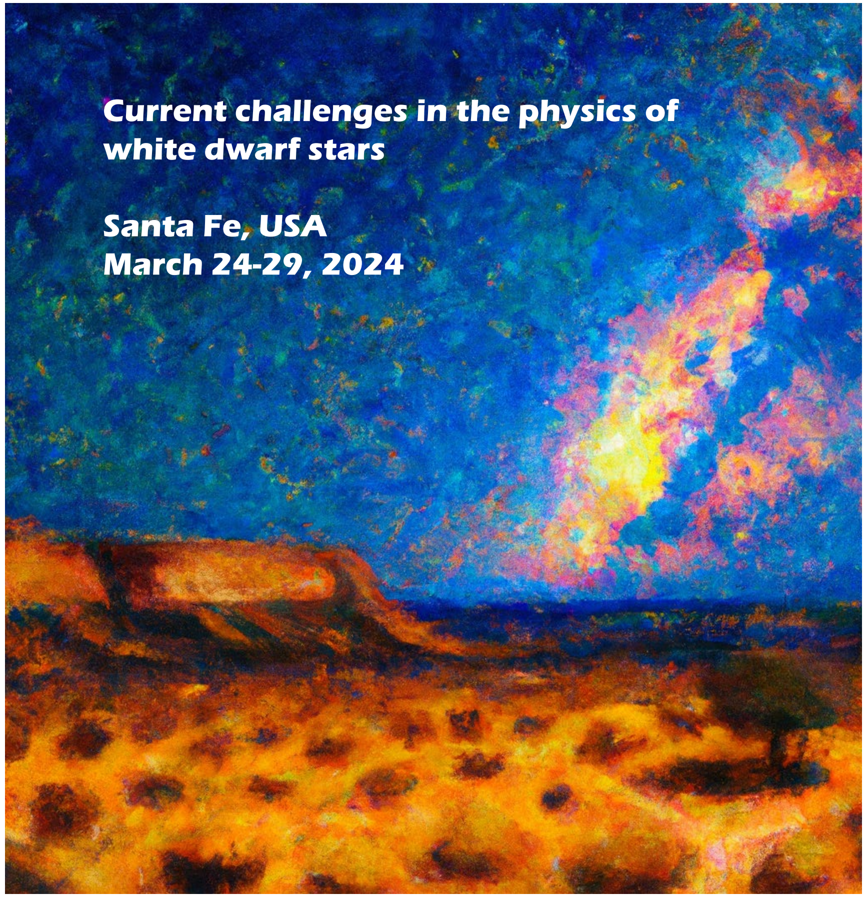
# Current challenges in the physics of white dwarf stars

A review (2022)

PHYSICS REPORTS

CURRENT CHALLENGES IN THE PHYSICS OF WHITE DWARF STARS

A workshop (2024)



Current challenges in the physics of white dwarf stars

Santa Fe, USA
March 24-29, 2024

Saumon, Blouin, Tremblay, Physics Reports 988, 1-64 (2022)