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Warming Nuclear Pasta with Dark Matter

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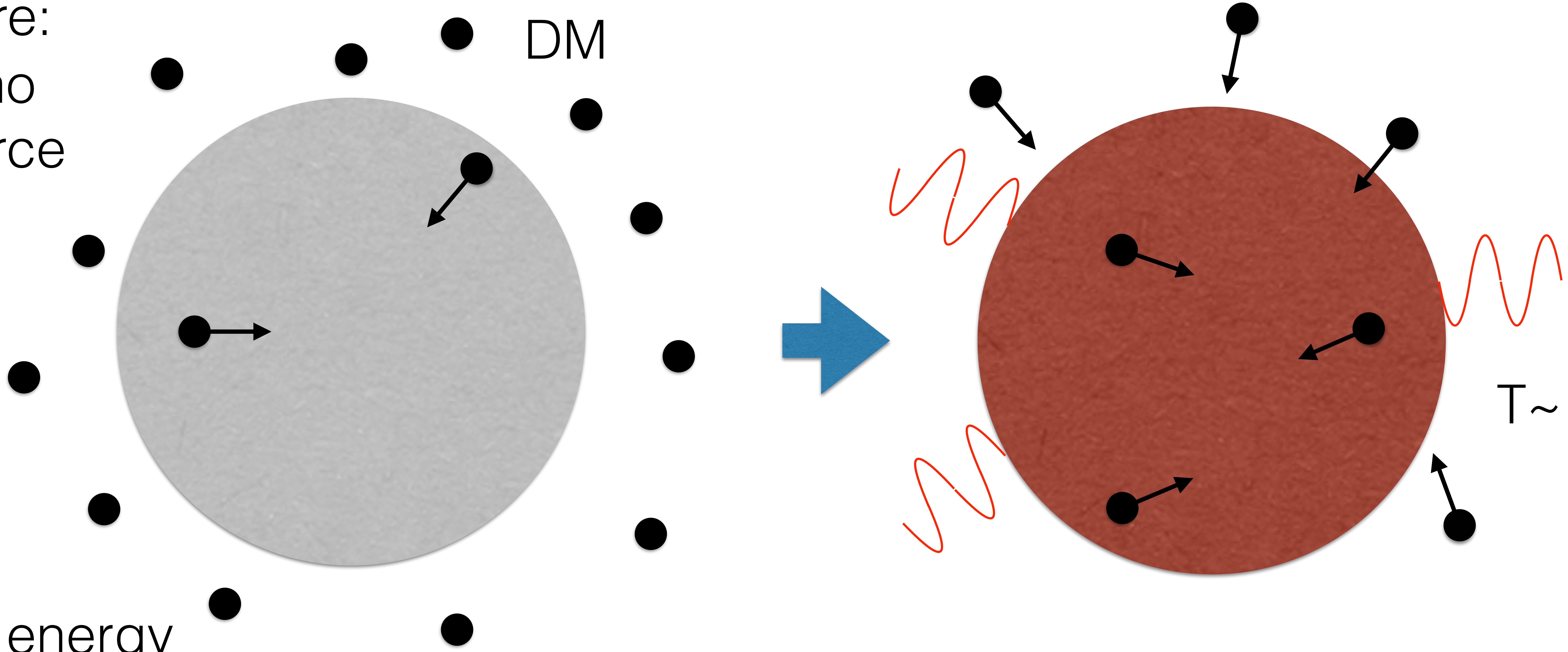
Neutron Stars as thermal DM detectors

Basic picture:
~Gyr NS, no
heating source

T~100 K



T~1700 K

DM kinetic energy

$$E_{DM} = m_{DM}(\gamma - 1) \sim \mathcal{O}(m_{DM})$$

$$\gamma = \sqrt{1 - v_{esc}^2} \simeq 1.35$$

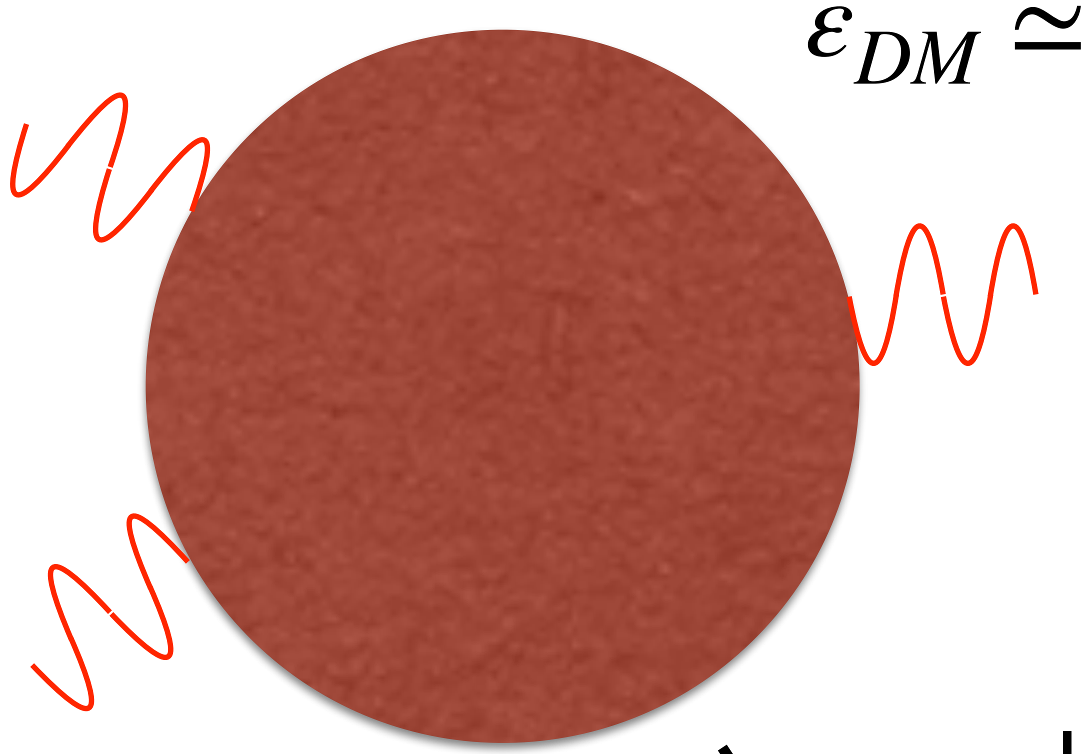
DM flux through NS

$$\dot{m}_{DM} \simeq \rho_{DM} v_{DM} \times 4\pi b_{max}^2$$

1704.01577

$$\dot{\varepsilon}_{DM} \simeq \dot{m}_{DM}(\gamma - 1) \times \min\left(1, \frac{\sigma_{n\chi}}{\sigma_{min}}\right)$$

accounts for
fraction captured



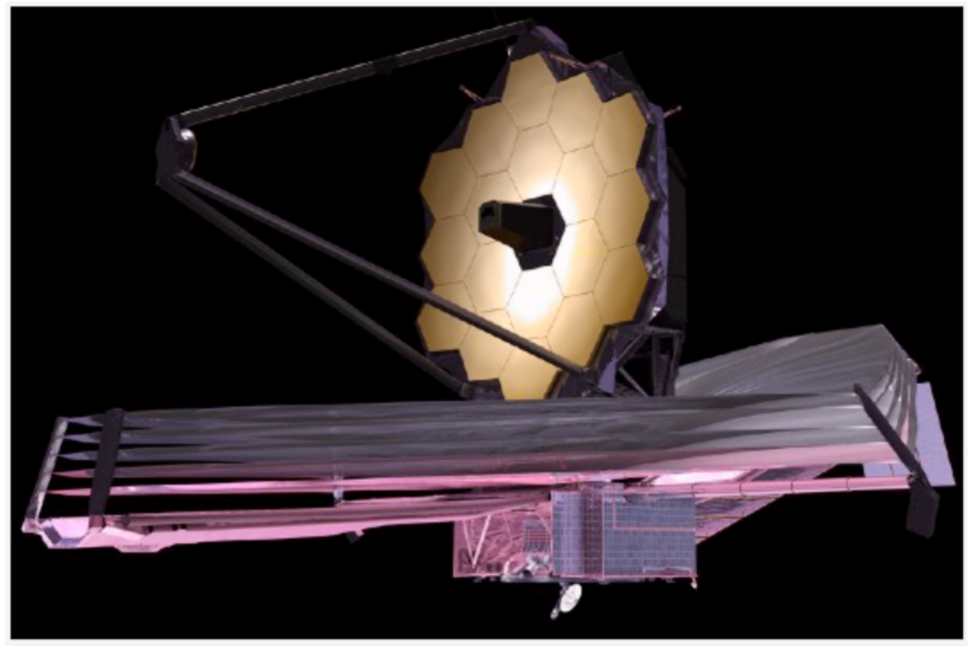
NS < 50 pc

luminosity:

$$L = 4\pi R_*^2 \sigma T_{eff}^4$$

$$T_{eff} = \gamma T_\infty$$

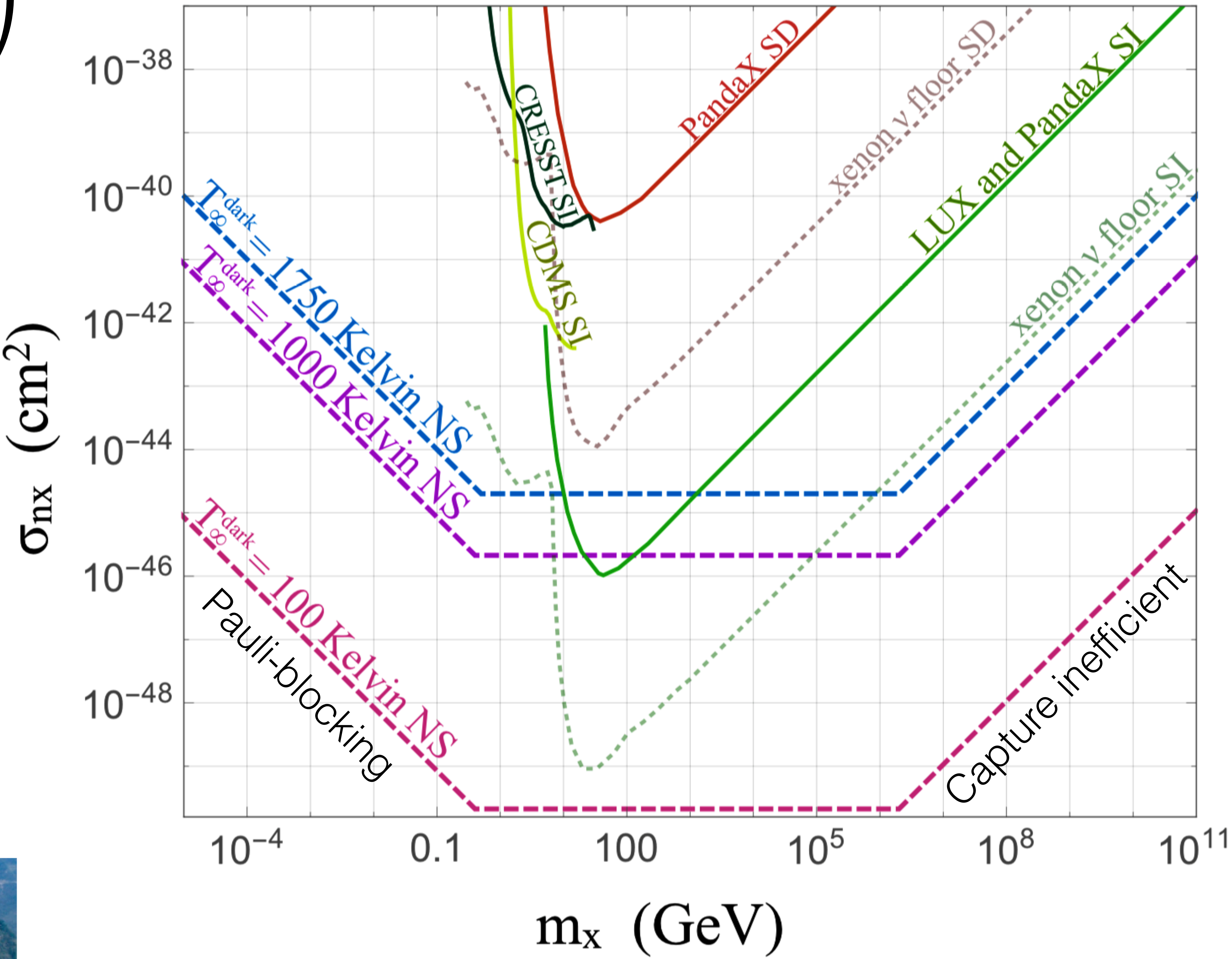
thermal
signature



JWST

radio pulses

FAST

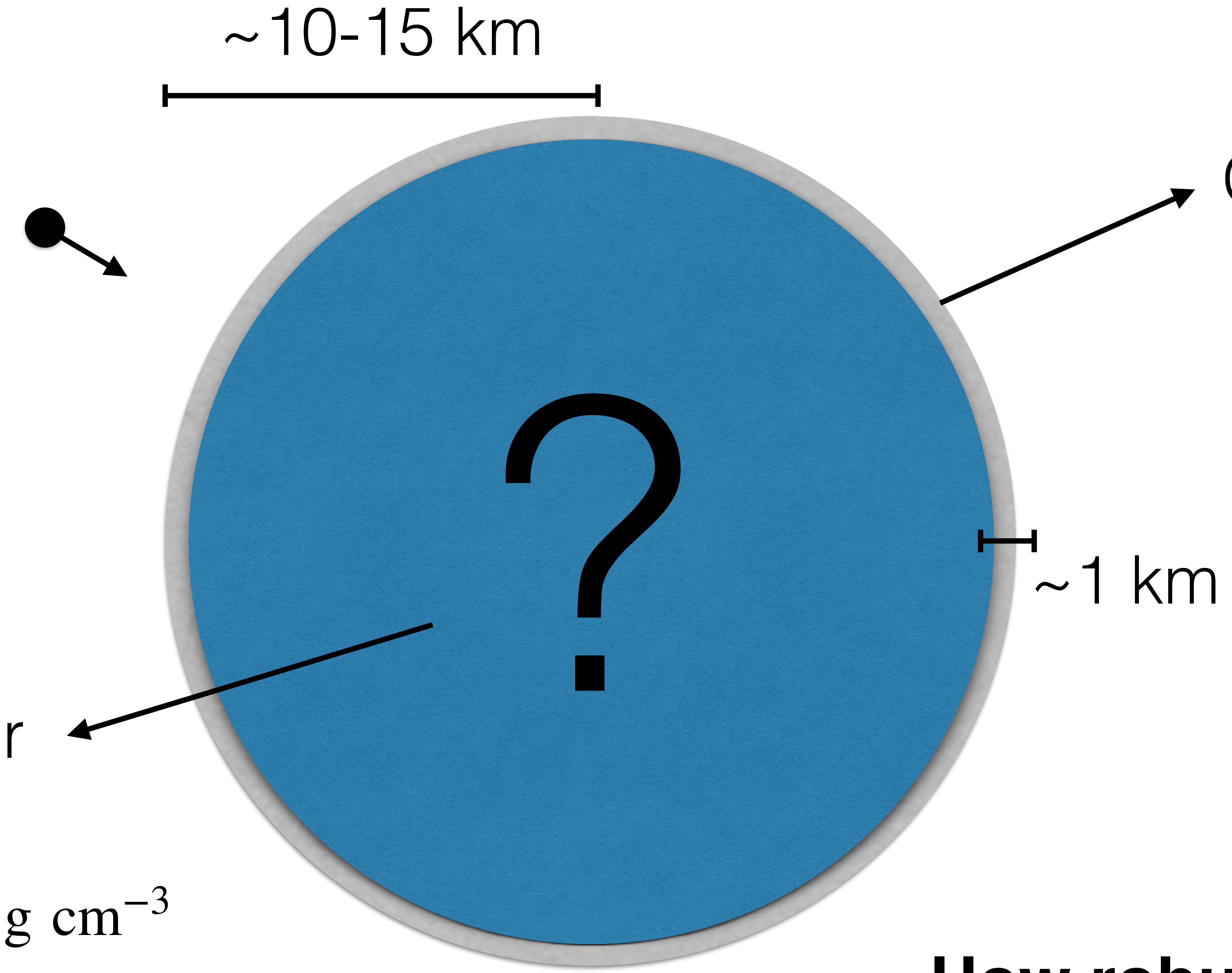


temperature observed constrains
cross-section

$$T_\infty \simeq 100 - 1700 \text{ K}$$

1911.06334

However, uncertainty in core composition remains:



outer+inner+pasta phases

$10^6 \text{ g cm}^{-3} \lesssim \rho \lesssim 3 \times 10^{14} \text{ g cm}^{-3}$

Outer/Inner core:

$\rho \gtrsim 3 \times 10^{14} \text{ g cm}^{-3}$

Quark matter, CFL phases

Meson, hyperon condensates

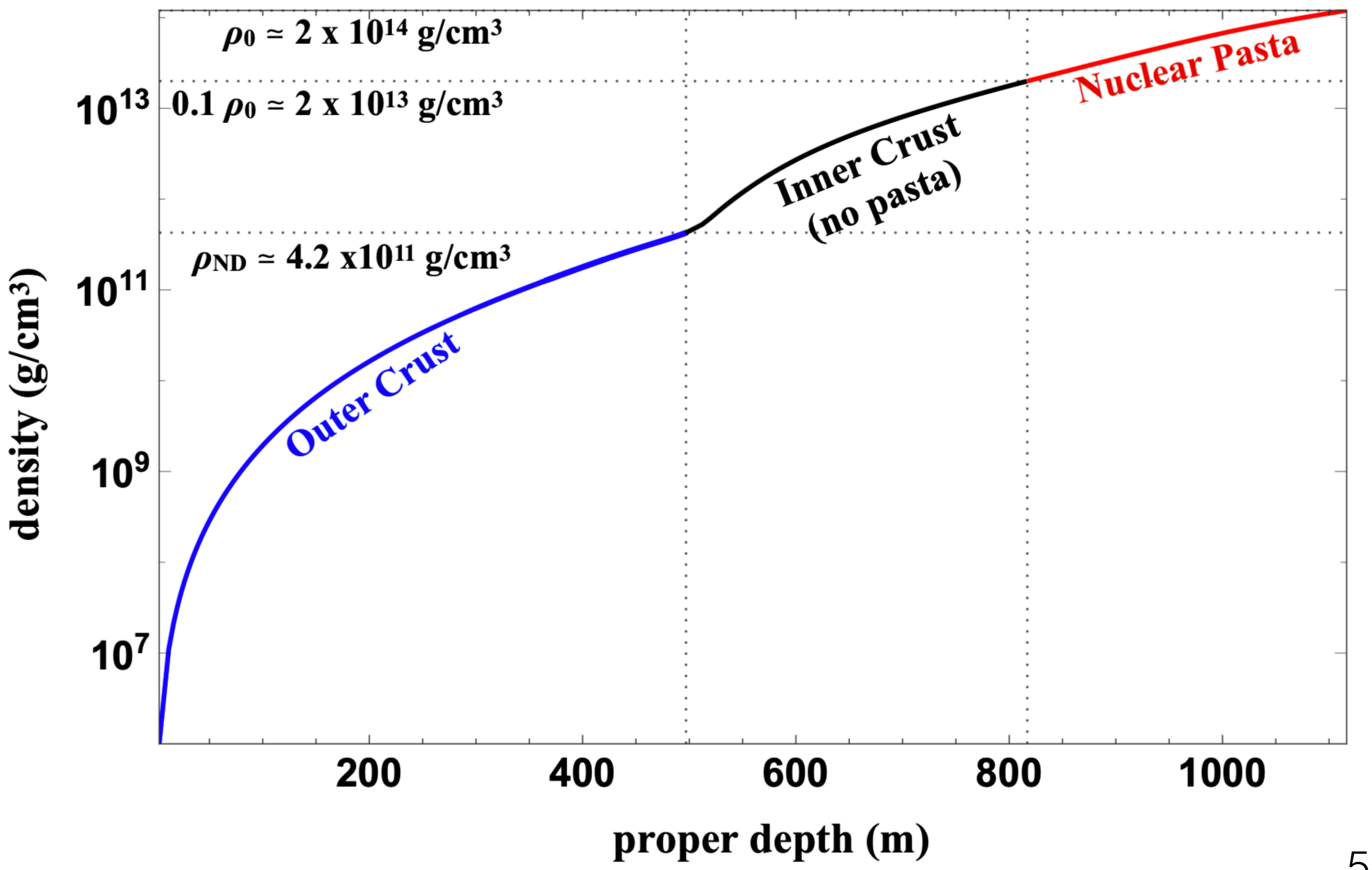
How robust are the constraints derived based on DM kinetic heating?

DM scattering in the crust

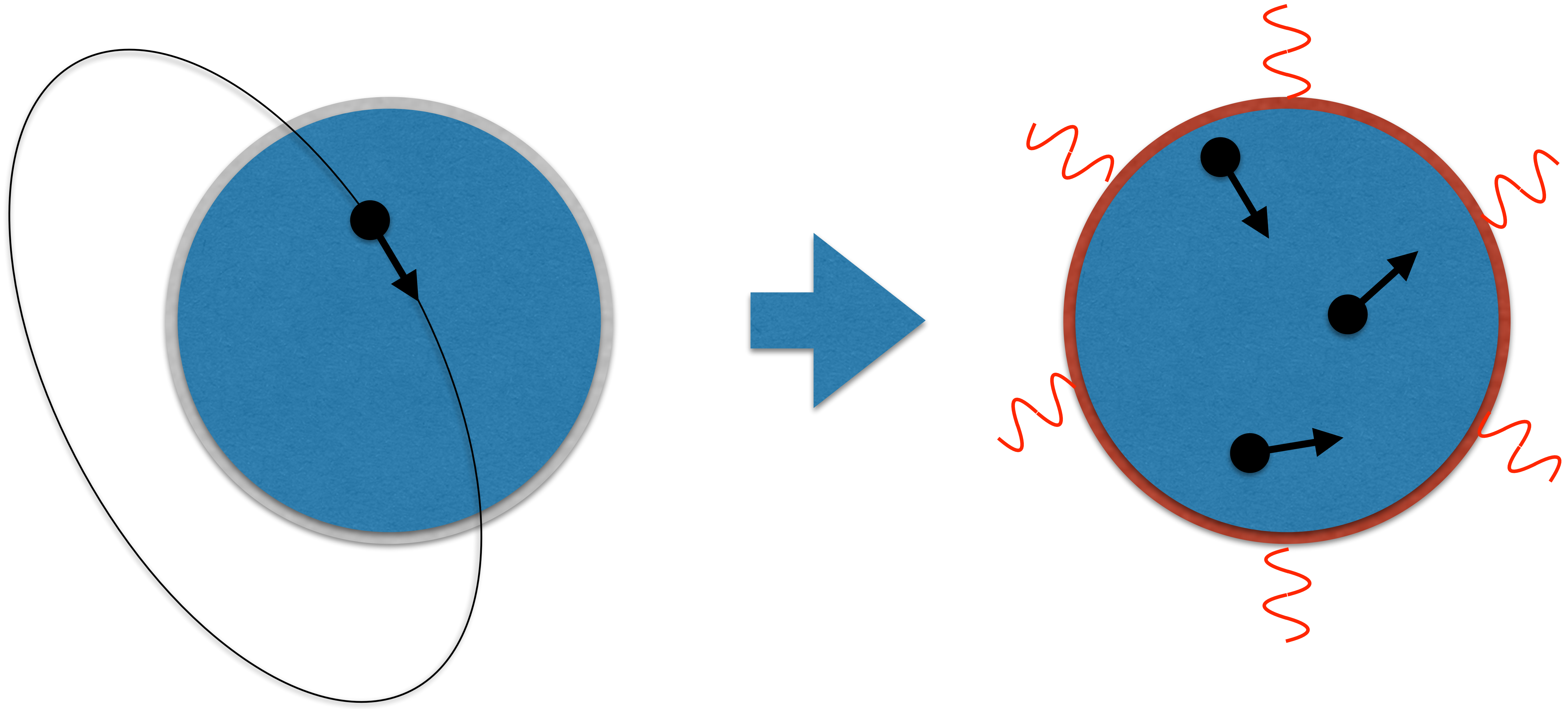
Crust is robustly understood unlike core:

"BsK21" EoS

- Multiple phases the DM can scatter against
- Highest sensitivity attained for 'nuclear pasta' phase
- Crust accounts <10 % NS mass, thickness -> overall sensitivity decreases



Some quantities of interest:



Optical depth: $\tau_{DM} = \int_{crust} n_T \sigma_{T\chi} dz$

$$\simeq \frac{1}{g_s} \int_{crust} n_T \sigma_{T\chi} \frac{dP}{d\rho} \frac{d\rho}{\rho}$$

where

$z = \gamma(R_* - r)$

surface gravity

equation of state

Average energy transfer per scatter: $\Delta E_{ave} = \frac{m_n m_{DM}^2 \gamma^2 v_{esc}^2}{m_{DM}^2 + m_n^2 + 2\gamma m_{DM} m_n}$ $(m_n \simeq \text{GeV})$

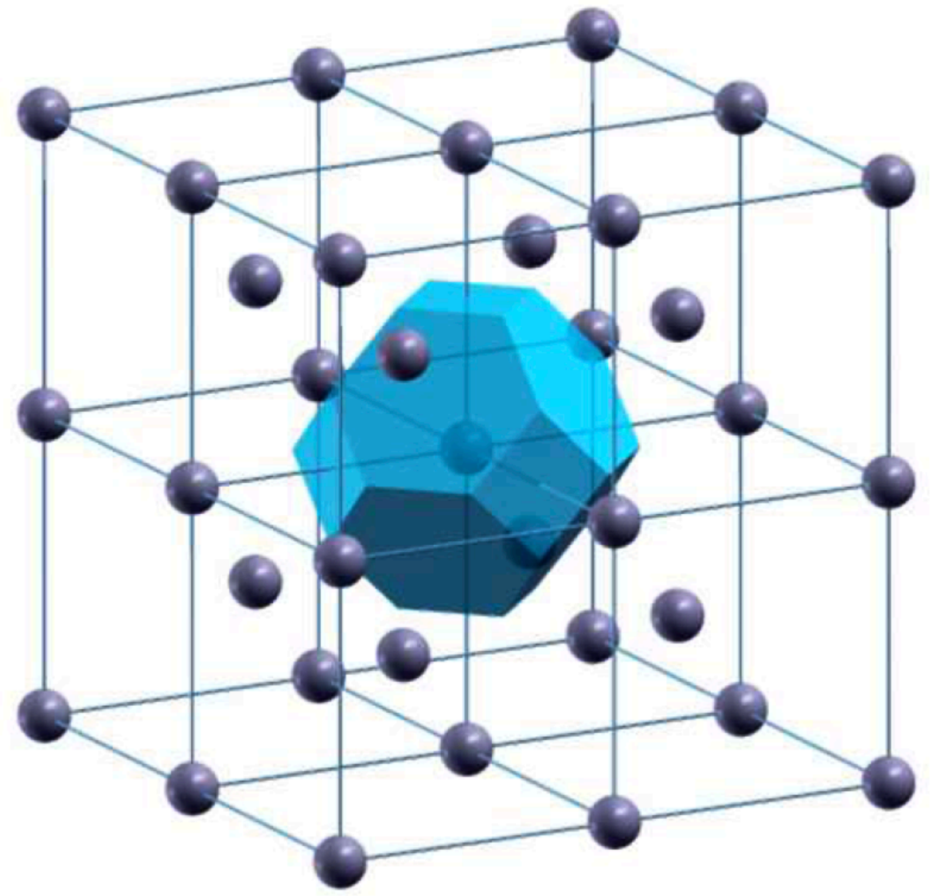
$\boxed{\text{MeV} \lesssim m_{DM} \lesssim \text{PeV}}$ ⟶ single scatter captures DM

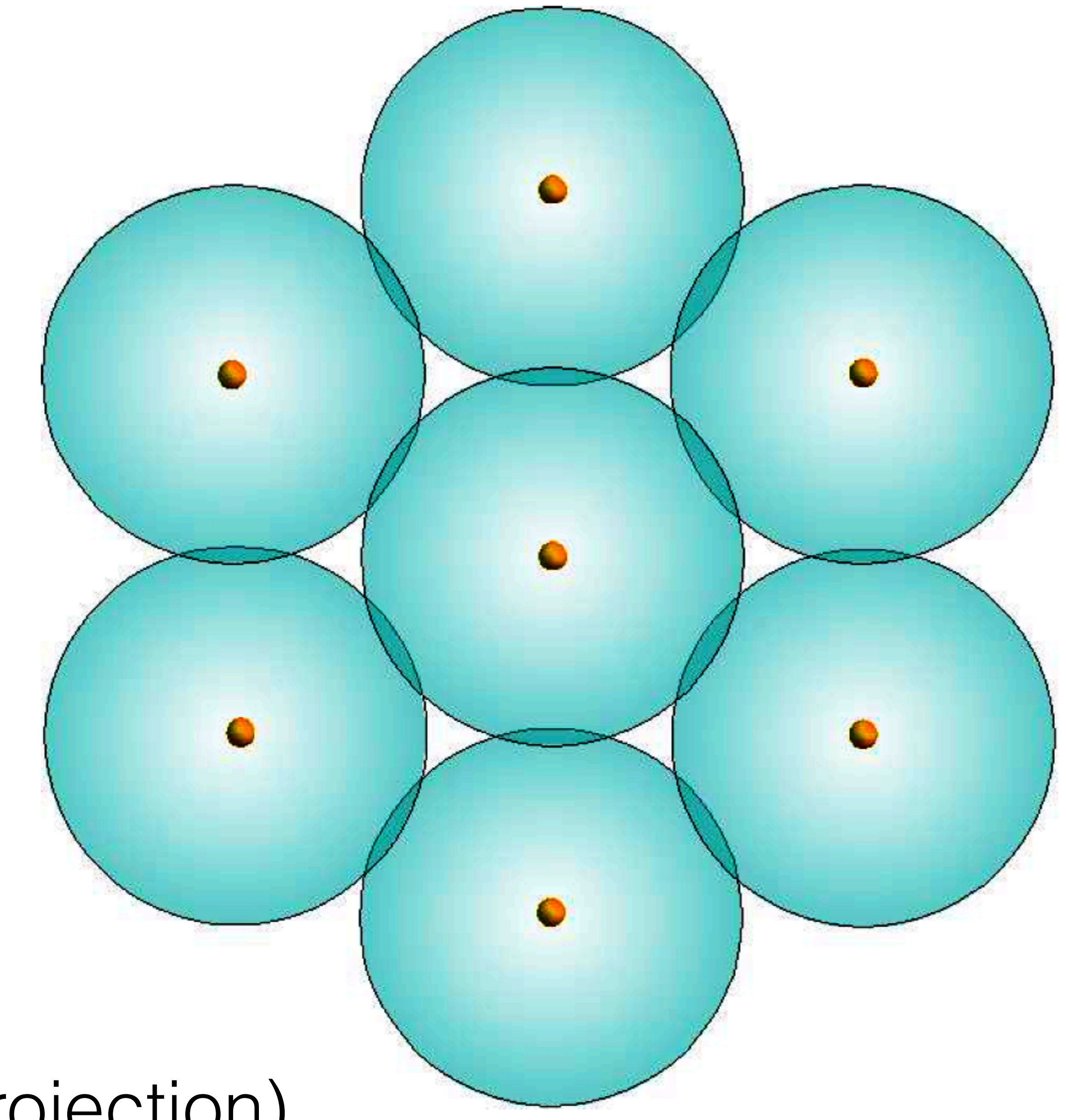
Energy deposited: $\Delta E = (m_{DM} + m_{DM} v_{halo}^2/2) - \gamma^{-1} m_{DM}$

Maximal heating rate: $T_\infty^{crust} \simeq 1600 \text{ K}$ (~all DM flux captured)

1) DM scattering in outer crust

nuclei in BCC lattice
+ ~free relativistic e- gas





(2D projection)

DM-nucleus scattering: $\langle q \rangle \sim \min\left(m_T, m_{DM}\right) \gamma v_{esc}$

$$\sigma_{T\chi} = \left(\frac{\mu_{T\chi}}{\mu_{n\chi}}\right)^2 A^2 \underbrace{F^2(q)}_{\text{suppresses at large } q} \underbrace{S_T(q)}_{\text{suppresses at low } q} \sigma_{n\chi}$$

consider DM-nucleon scattering: $\tau_{DM}^{outer} = \frac{\sigma_{n\chi}}{g_s} \int_{outer} n_n \frac{dP}{d\rho} \frac{d\rho}{\rho}$

kinematics impose: $\Delta E \gtrsim E_{bind} \sim 10$ MeV

'3 layer' model

layer	elements	mass number A	density (g/cm^3)	electron chemical potential (MeV)
1	Fe, Ni	56	$[10^6, 2 \times 10^9]$	[0.5, 5]
2	Ni, Kr, Zn, Ge	82	$[2 \times 10^9, 7 \times 10^{10}]$	[5, 17]
3	Mo, Zr, Kr, Se	118	$[7 \times 10^{10}, 3 \times 10^{11}]$	[17, 26]

2) DM scattering in inner crust:

same argument as before,
add optical depth:

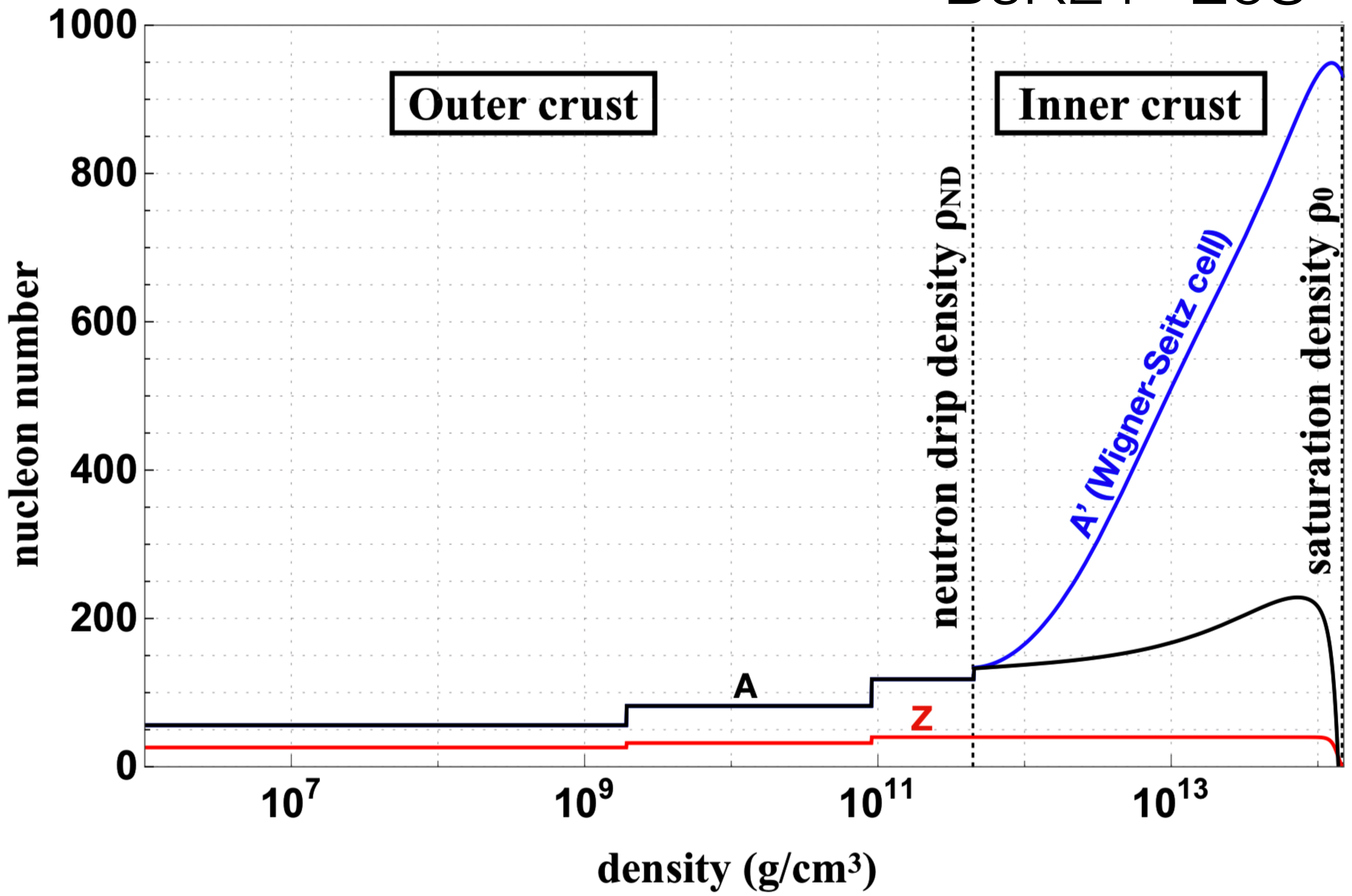
$$\tau_{DM}^{inner} = \frac{\sigma_{n\chi}}{g_s} \int_{outer} n_n^{(bound)} \frac{dP}{d\rho} \frac{d\rho}{\rho}$$

accounts for most nucleons being free

can also consider lighter DM exciting collective neutron modes, see 1911.06334

nucleon 'clusters' in BCC lattice
+~free relativistic e⁻ gas + neutron superfluid

"BsK21" EoS

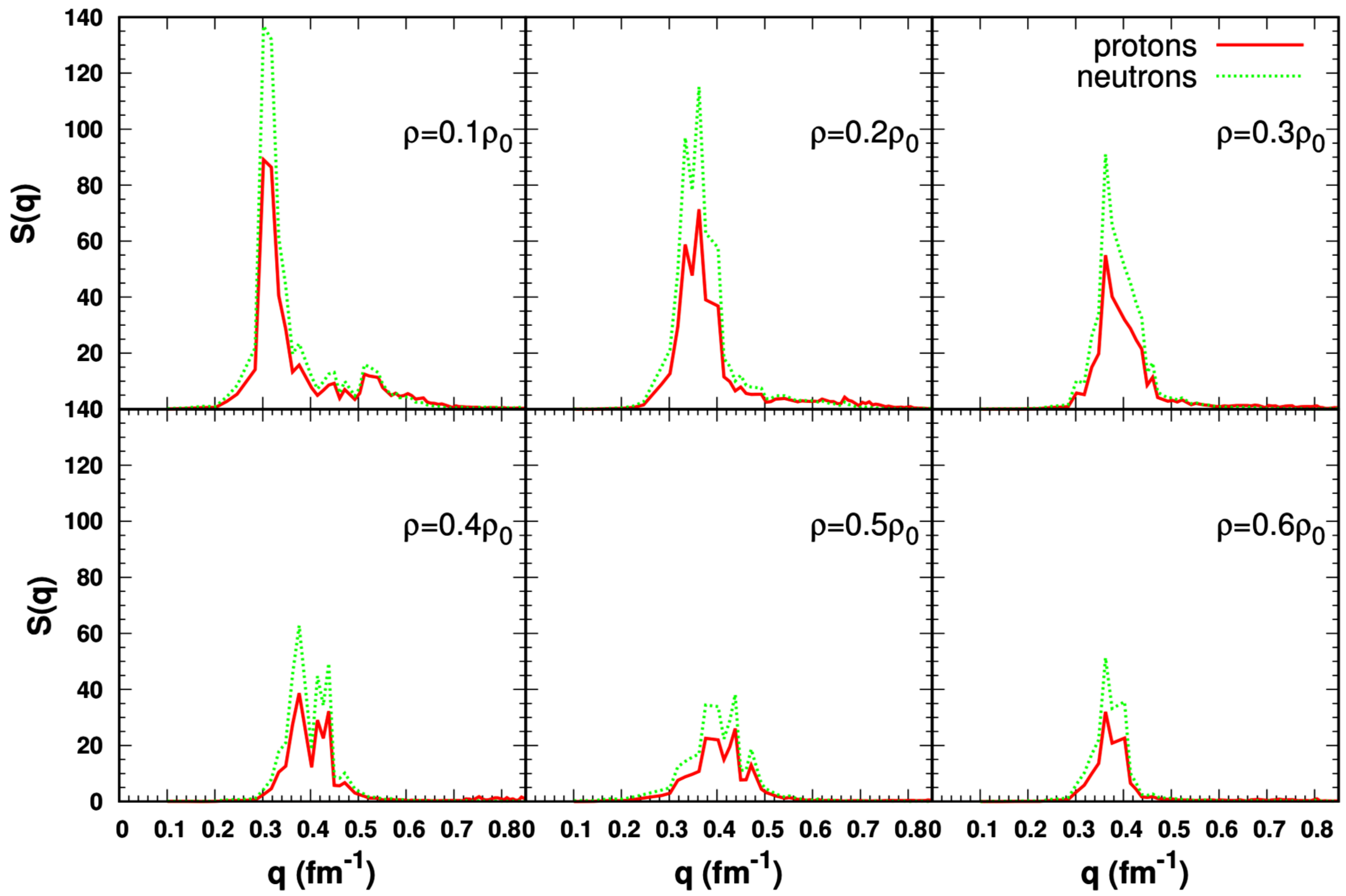


3) DM scattering in pasta phases:

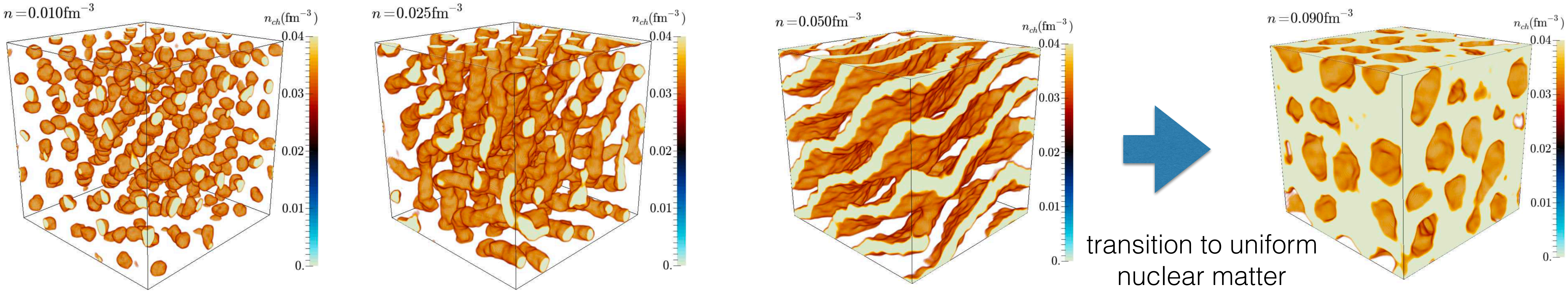
$$\sigma_{pasta} = S_{pasta}(q)\ \sigma_{n\chi}$$

$$\langle S_{pasta}(q)\rangle \simeq \frac{1}{q_{max}} \int_0^{q_{max}} S_{pasta}(q)\ dq$$

$$\tau_{DM}^{pasta} = \frac{\sigma_{n\chi}}{g_s} \int_{pasta} \langle S_{pasta}(q)\rangle\ n_n \frac{dP}{d\rho}\frac{d\rho}{\rho}$$



gnocchi | spaghetti | lasagna | ‘anti-gnocchi’



transition to uniform nuclear matter

Comparison with DD experiments

1) Spin-independent

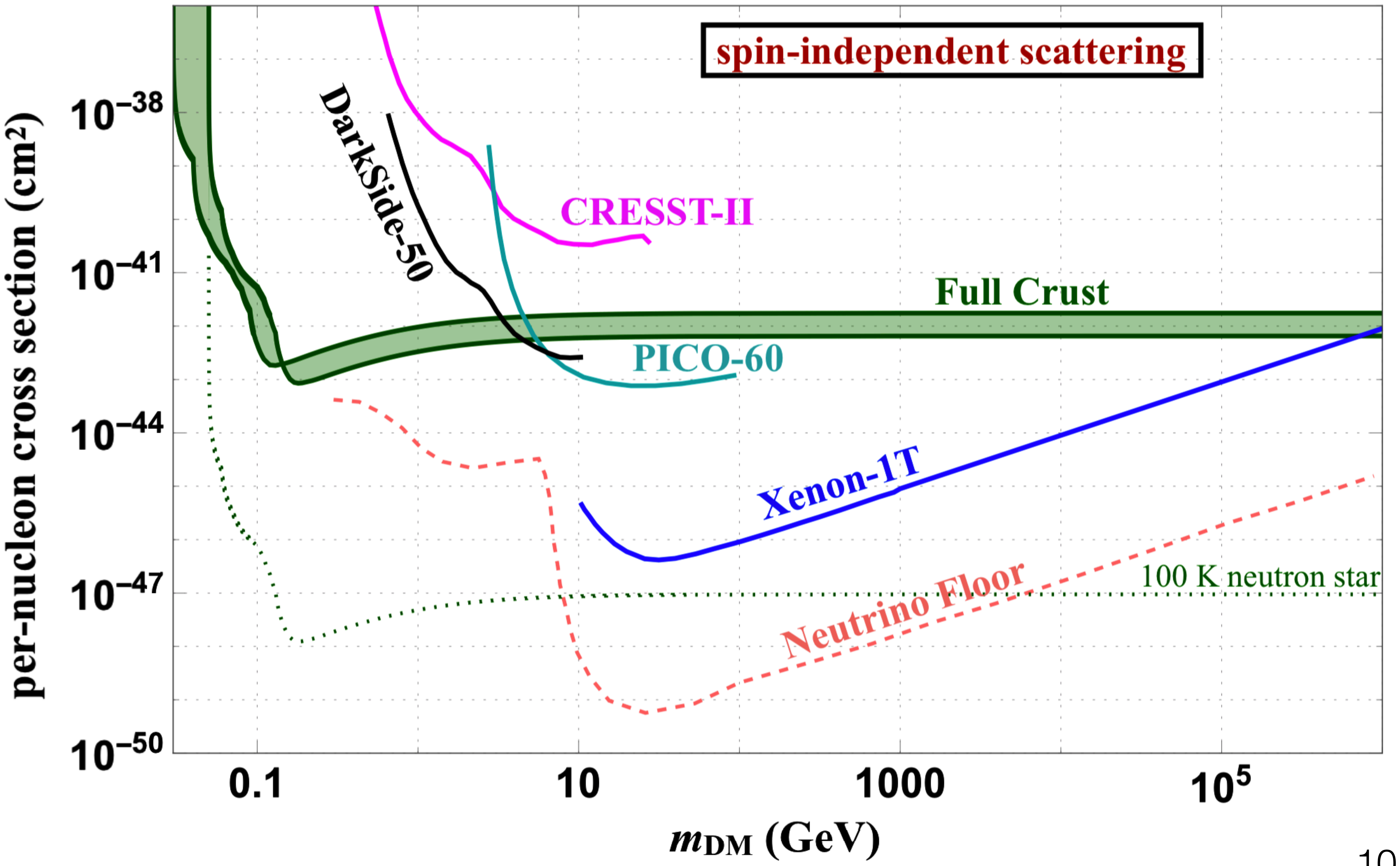
$$\tau_{DM}^{crust} = \tau_{DM}^{outer} + \tau_{DM}^{inner} + \tau_{DM}^{pasta}$$

band illustrates crust capture reach:

$$[2.3M_\odot,\ 11.5\ \text{km},\ 716\ \text{Hz},\ \text{BsK21}]$$

$$\downarrow$$

$$[1.4M_\odot,\ 11.75\ \text{km},\ 0\ \text{Hz},\ \text{BsK20}]$$



2) Spin-dependent

rescale by:

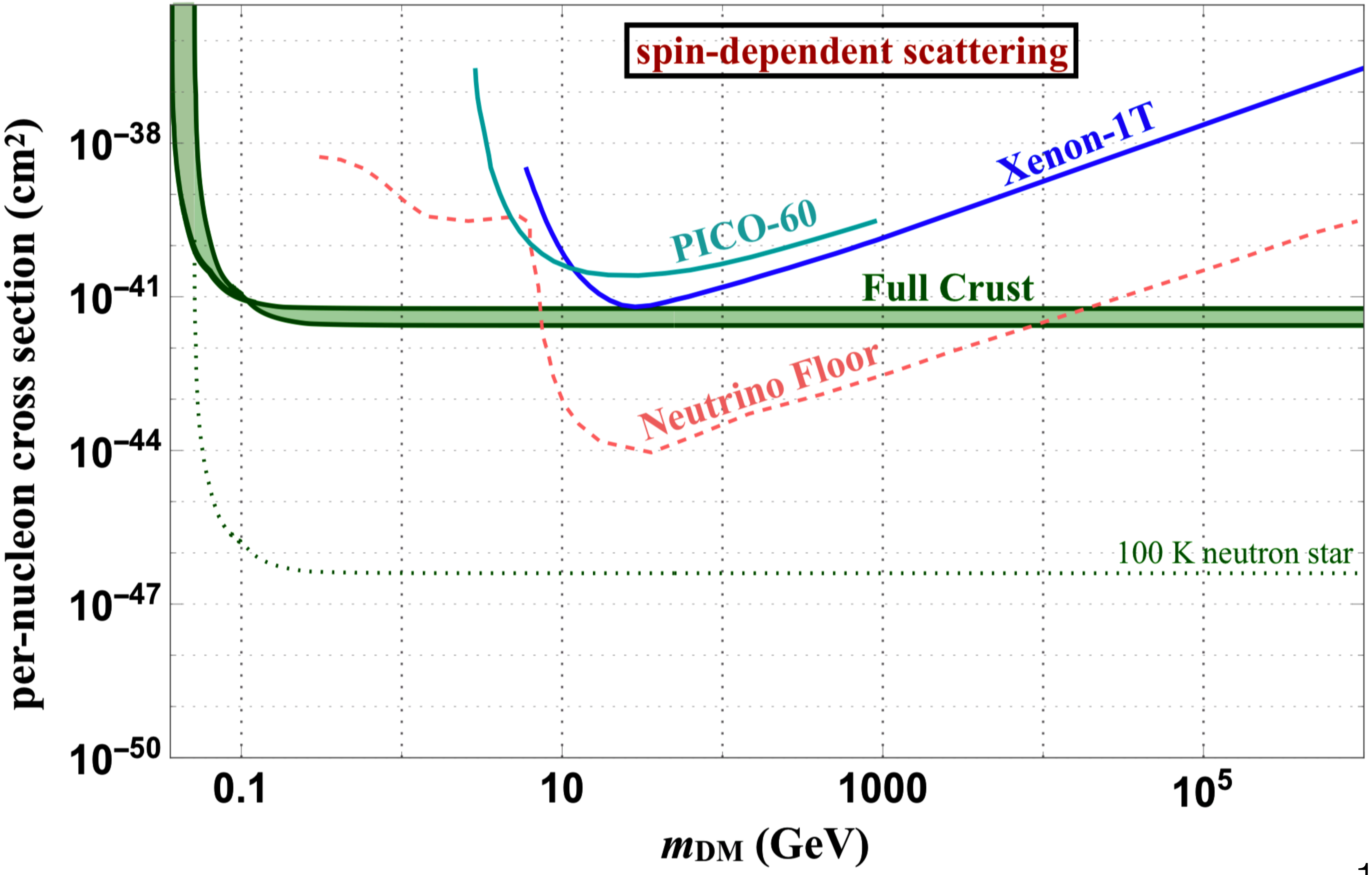
$$\propto \left[\frac{4}{3}\frac{J_n}{J_n+1}(\langle S_p\rangle + \langle S_n\rangle)^2\right]^{-1}$$

$$J_n = 1/2$$
$$\langle S_n\rangle = 1/2$$
$$\langle S_p\rangle = 0$$

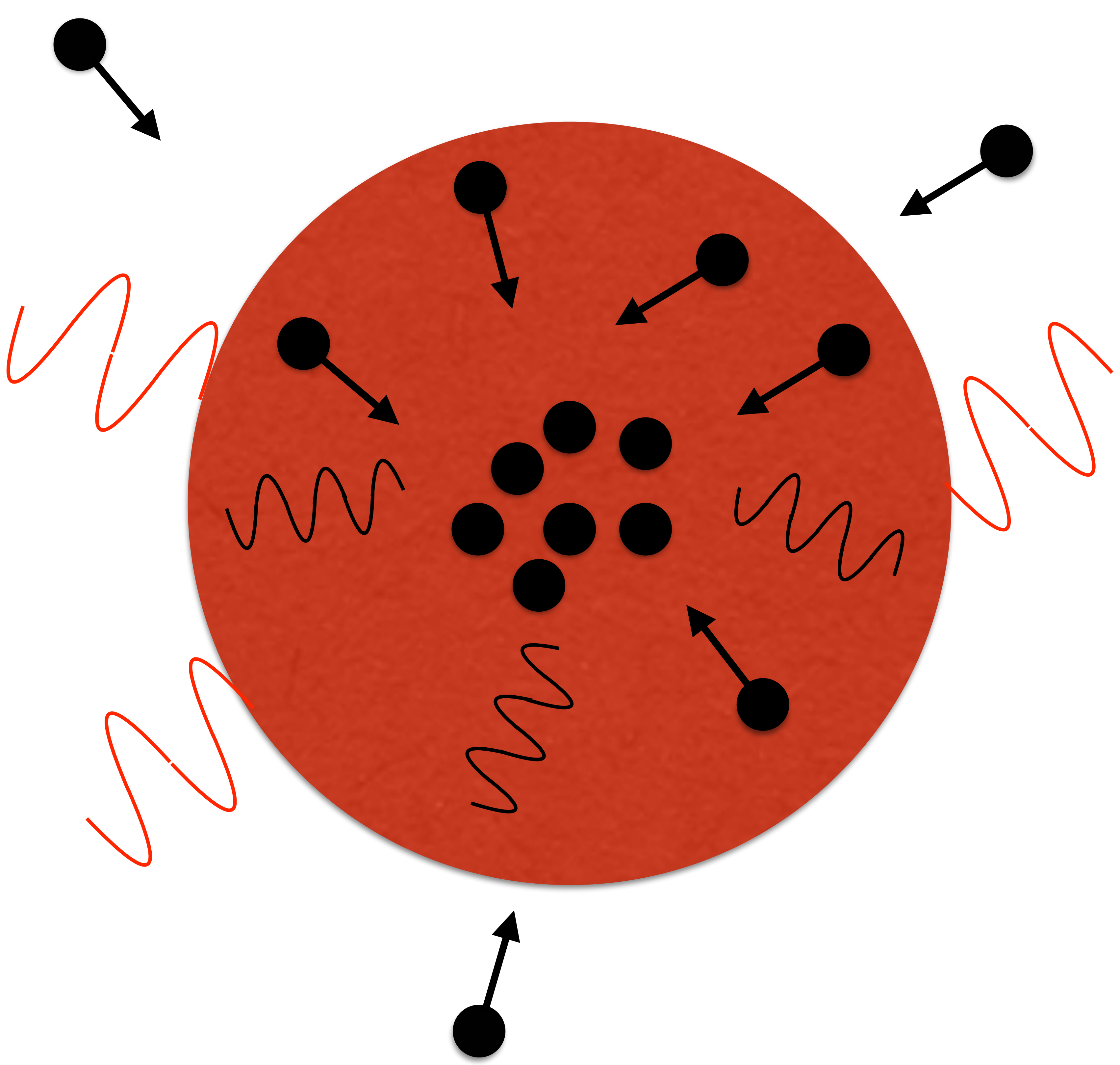
impose:

$$S_{pasta}(q) \leqslant 1$$

no enhancement



DM annihilation



SM annihilation products further heat NS:

$$\dot{m}_{DM} + \dot{E}_{ann} \propto C_{DM} m_{DM} \gamma \longrightarrow T_\infty^{crust} \simeq 2470\ \mathrm{K}$$

$$\frac{dN}{dt} \simeq C_{DM} - \frac{\sigma_{ann}}{V} N^2 \longrightarrow N(t) \sim \tanh\left(\frac{t}{\tau_{eq}}\right)$$

$$\tau_{eq} = \sqrt{\frac{V}{C_{DM}\langle \sigma_{ann} v \rangle}} \lesssim \mathcal{O}(10^4\ \mathrm{yrs})$$

remarkable sensitivity to inelastic DM models (e.g. higgsinos), see 1911.06334

Conclusions

→ NS crusts alone guarantee substantial sensitivity to both SI and SD interactions in searches for dark kinetic heating.

→ Crust-only interactions imply DM will thermalize with the NS, capture-annihilation equilibrium is attained in short timescales.

→ Results independent of the uncertain physics of the core.

Thank you for
your attention!