Cooking Pasta with Dark Matter

Rebecca Leane
MIT Center For Theoretical Physics

Based on 1911.06334, JCAP '20
w/ Javier Acevedo, Joe Bramante, Nirmal Raj

Pheno 2020
May 5th '20

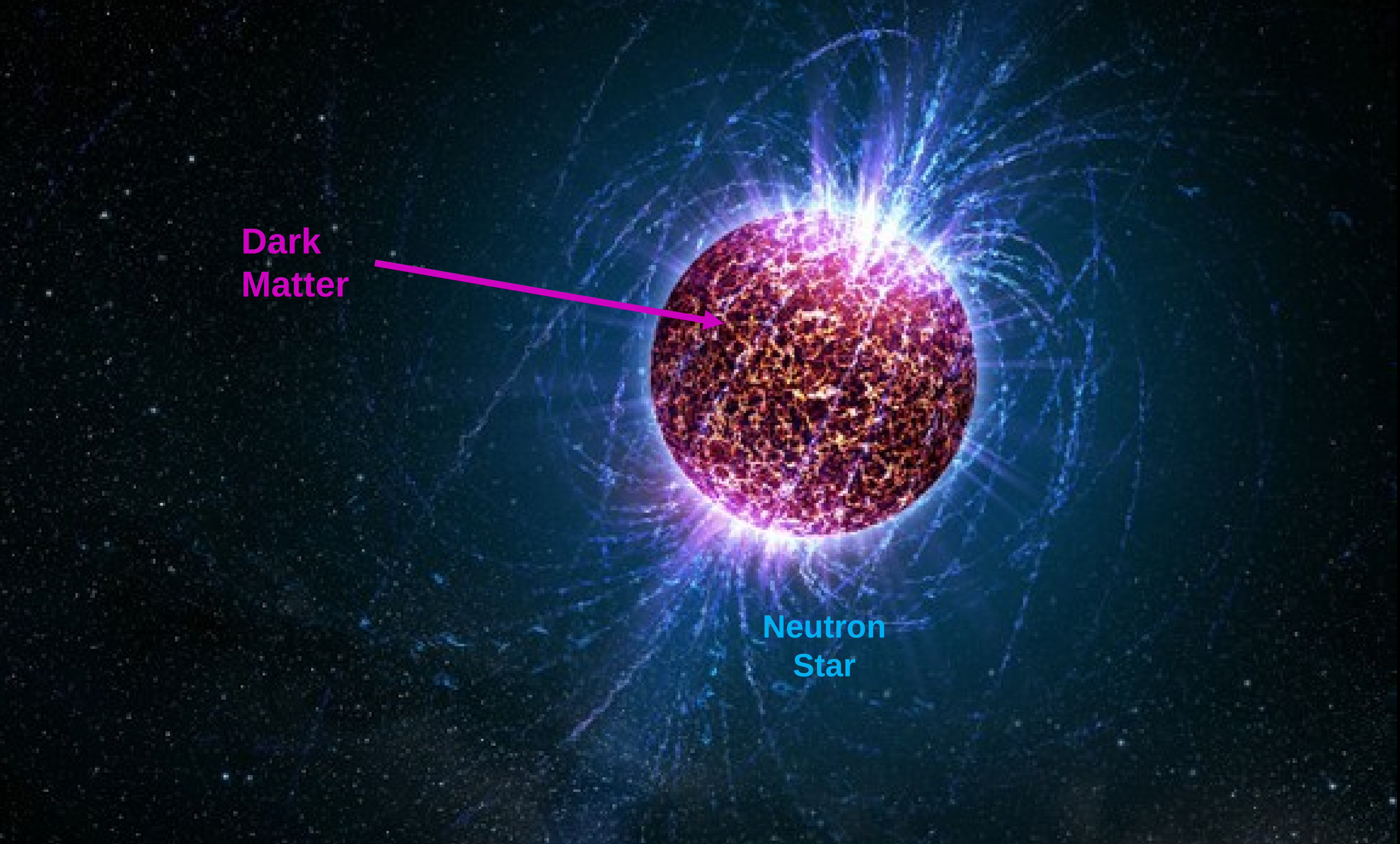
rleane at mit dot edu

Massachusetts Institute of Technology

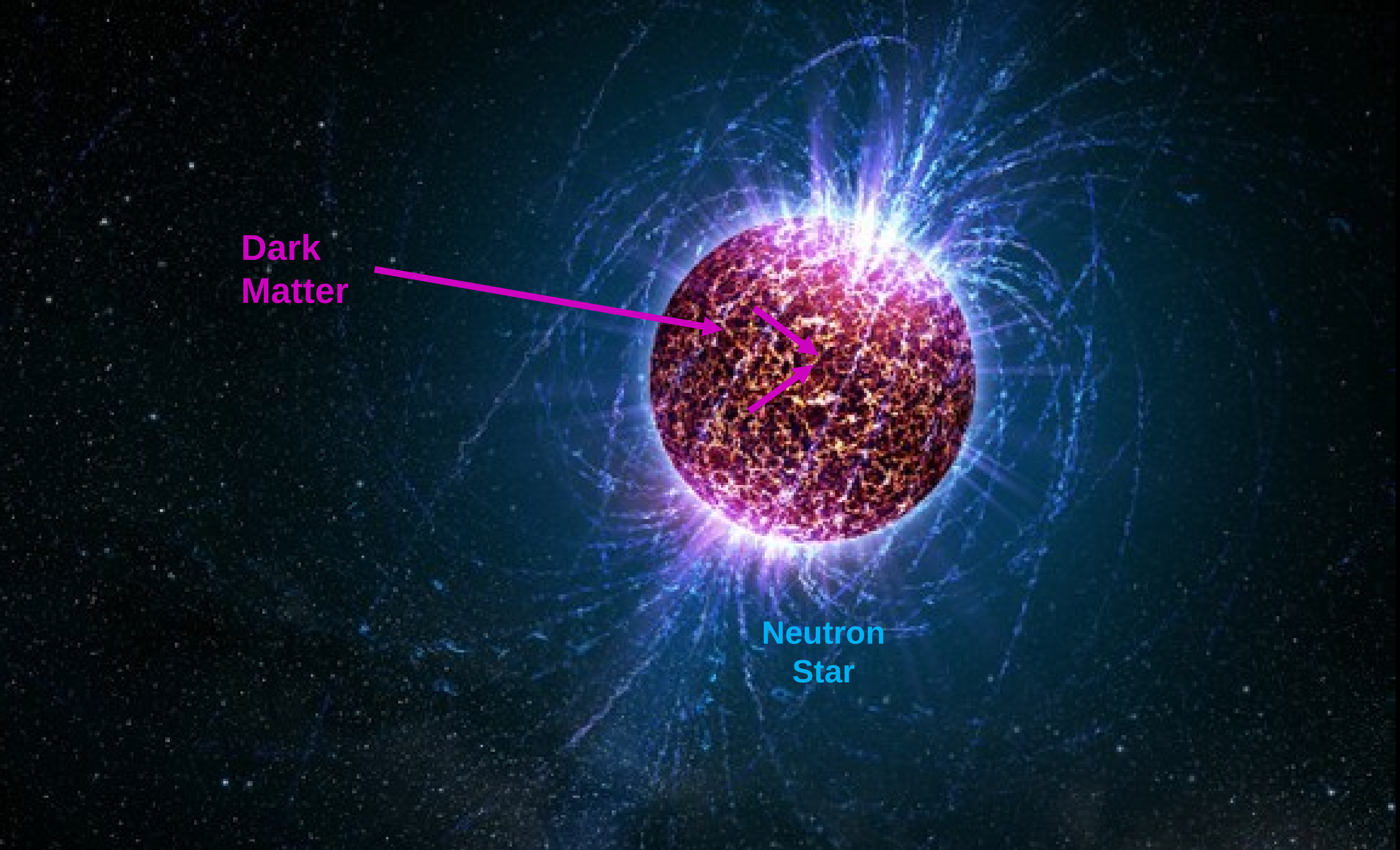
NEUTRON STARS

+ Collapsed cores of old stars
+ One of the most extreme environments in the Universe
+ Potential dark matter detectors!

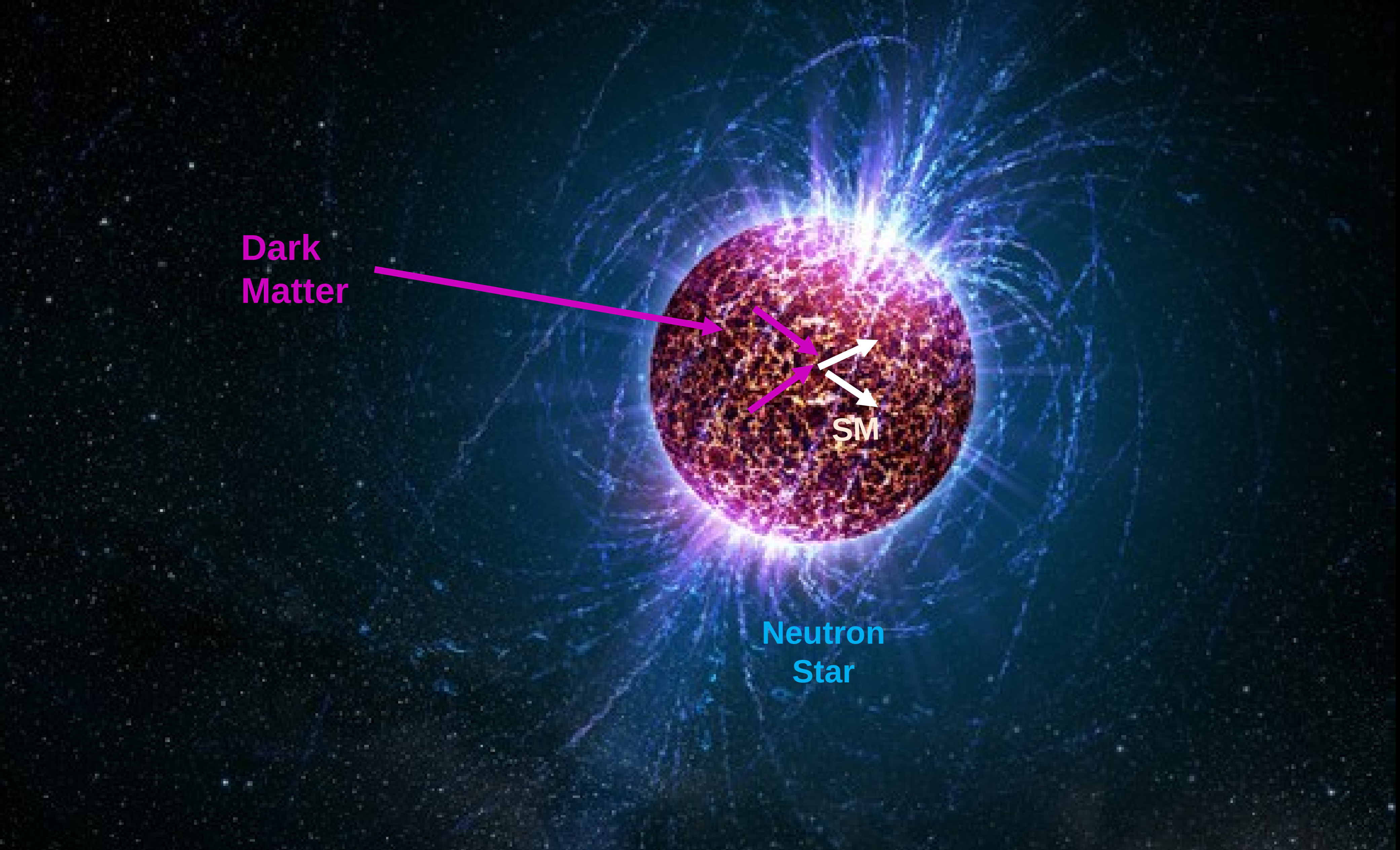
DARK MATTER IN NEUTRON STARS



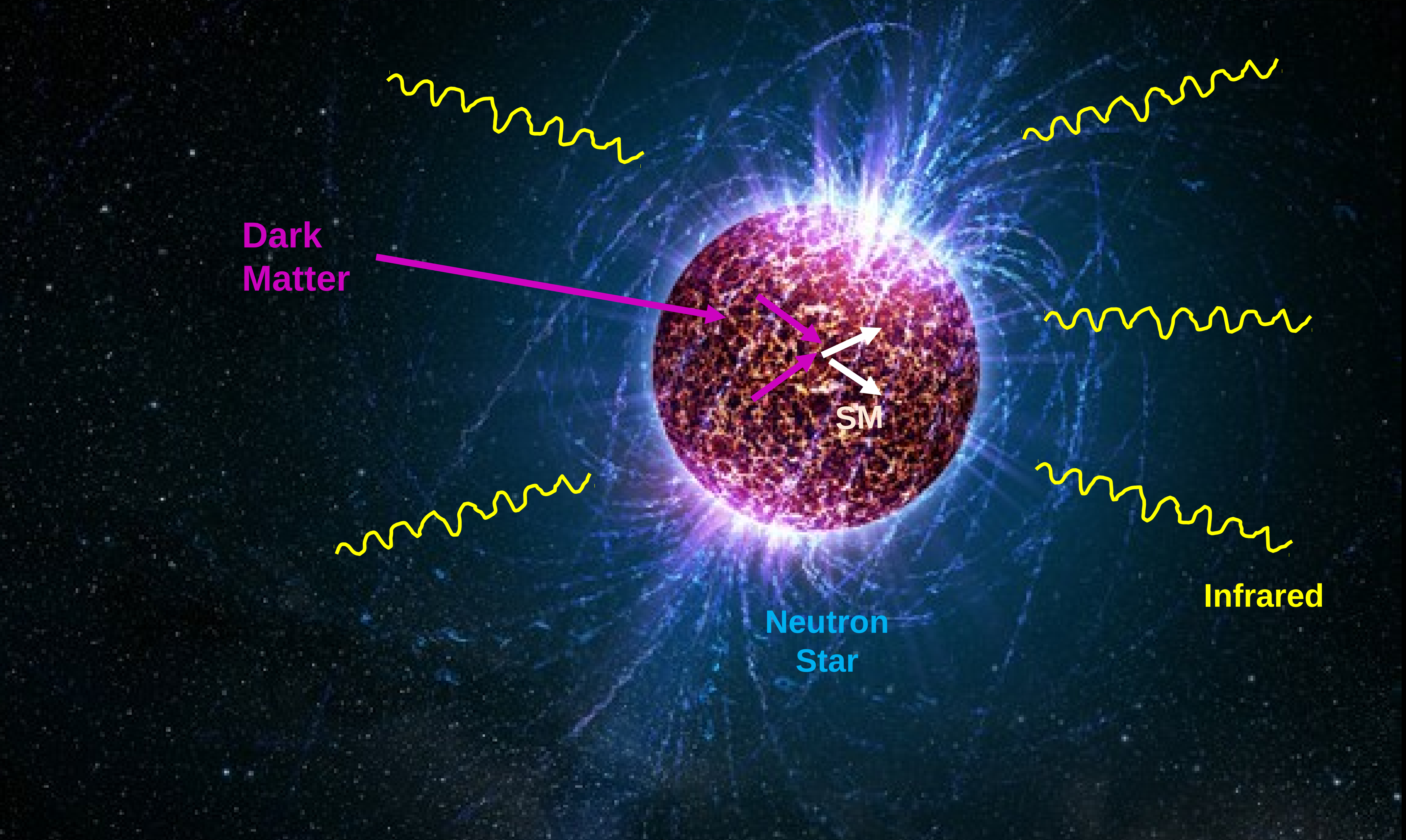
DARK MATTER IN NEUTRON STARS



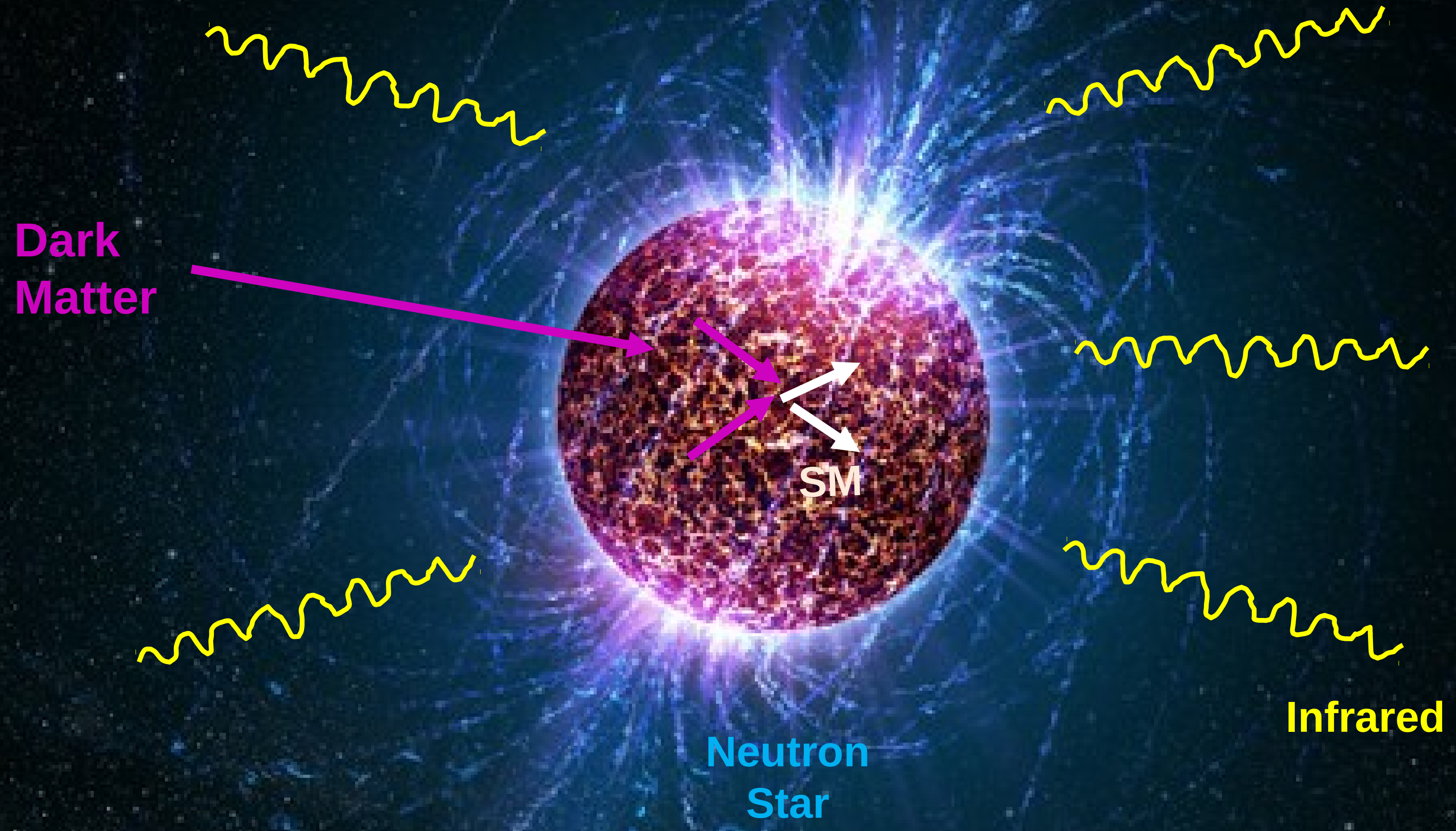
DARK MATTER IN NEUTRON STARS

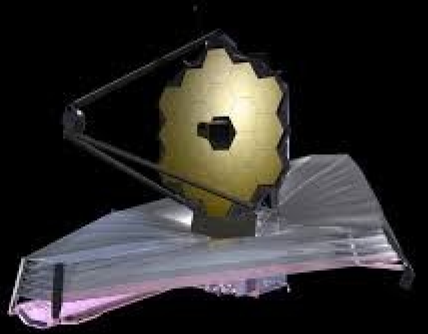


DARK MATTER IN NEUTRON STARS



DARK MATTER IN NEUTRON STARS





James Webb Telescope

Thirty Meter Telescope

Baryakhtar, Bramante, Li, Linden, Raj, PRL '17

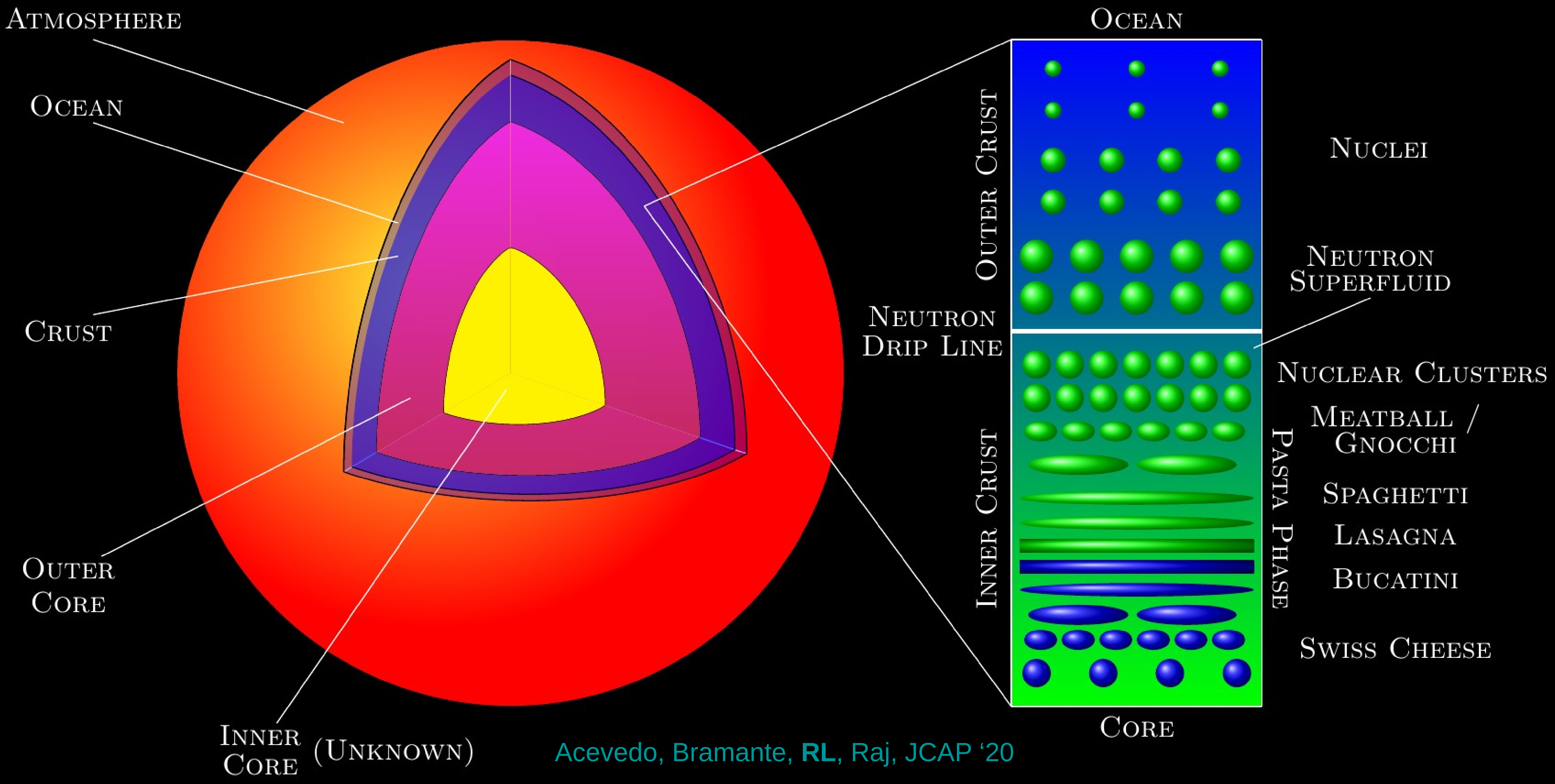
WHY NEUTRON STAR CRUSTS?

+ Previous work estimated neutron stars to be a degenerate core of neutrons
+ Core could be exotic (i.e. uds matter, meson/hyperon condensates)
  Dark matter scattering with such phases can be suppressed
+ Dark matter interactions might be density dependent
+ Further into the neutron star, less and less is understood

No imperial knowledge of NS interiors – but crust best understood!

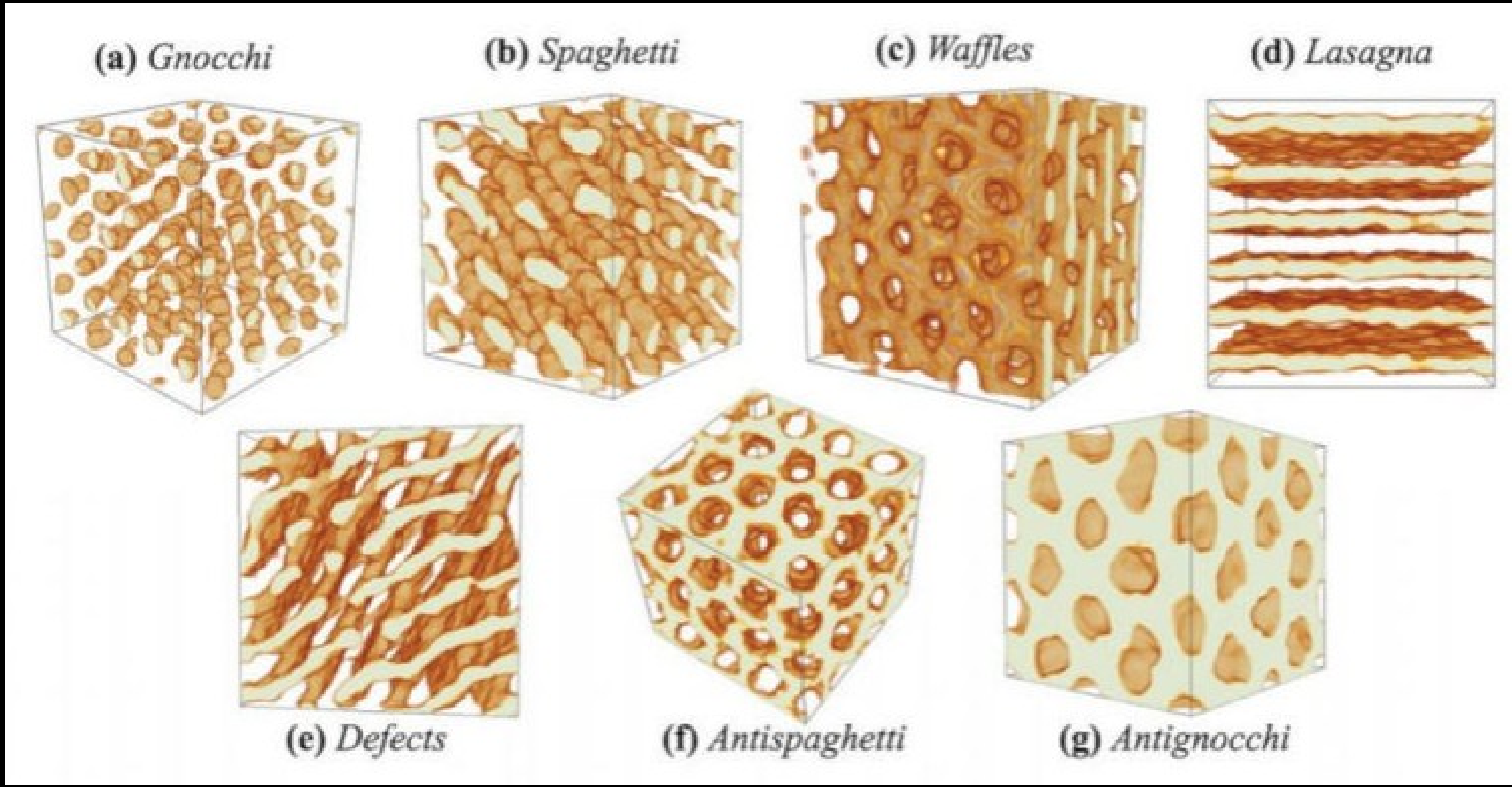
Rebecca Leane
rleane at mit dot edu

INSIDE NEUTRON STARS



Acevedo, Bramante, **RL**, Raj, JCAP ‘20

NUCLEAR PASTA



Caplan, Schneider, Horowitz '18

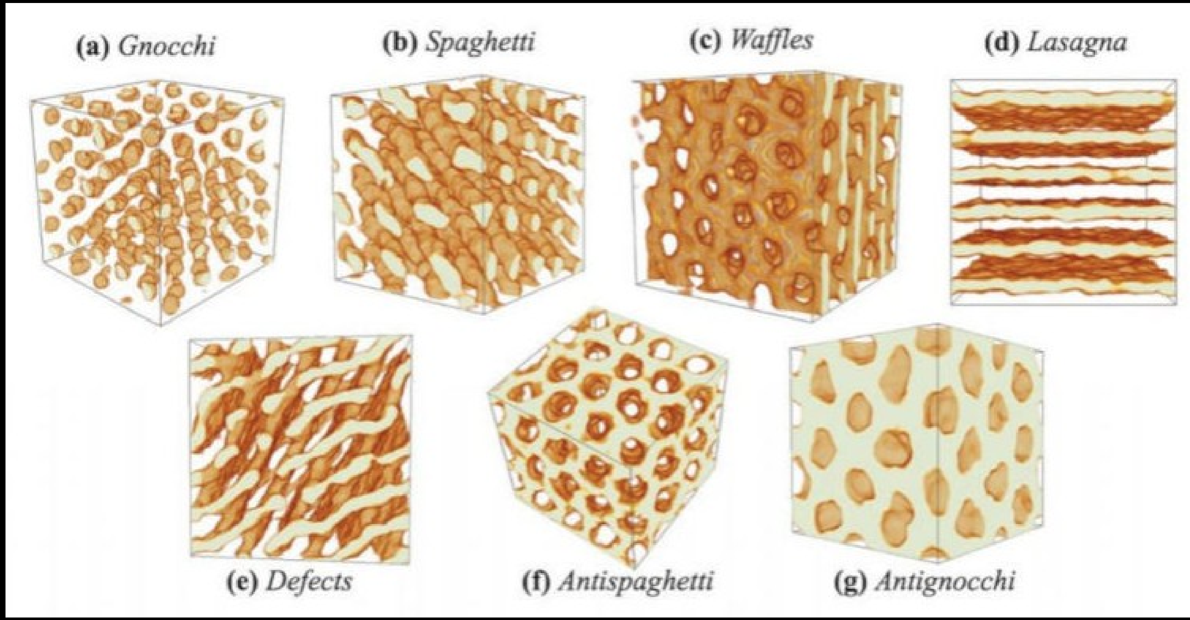
Rebecca Leane
rleane at mit dot edu

THE PASTA COMMUNITY

+ Pasta impacts properties of neutron stars and core collapse supernovae

+ Neutrino interactions: impacts neutrino opacity in supernovae

+ Electron interactions: impact shear viscosity, thermal and electrical conductivity



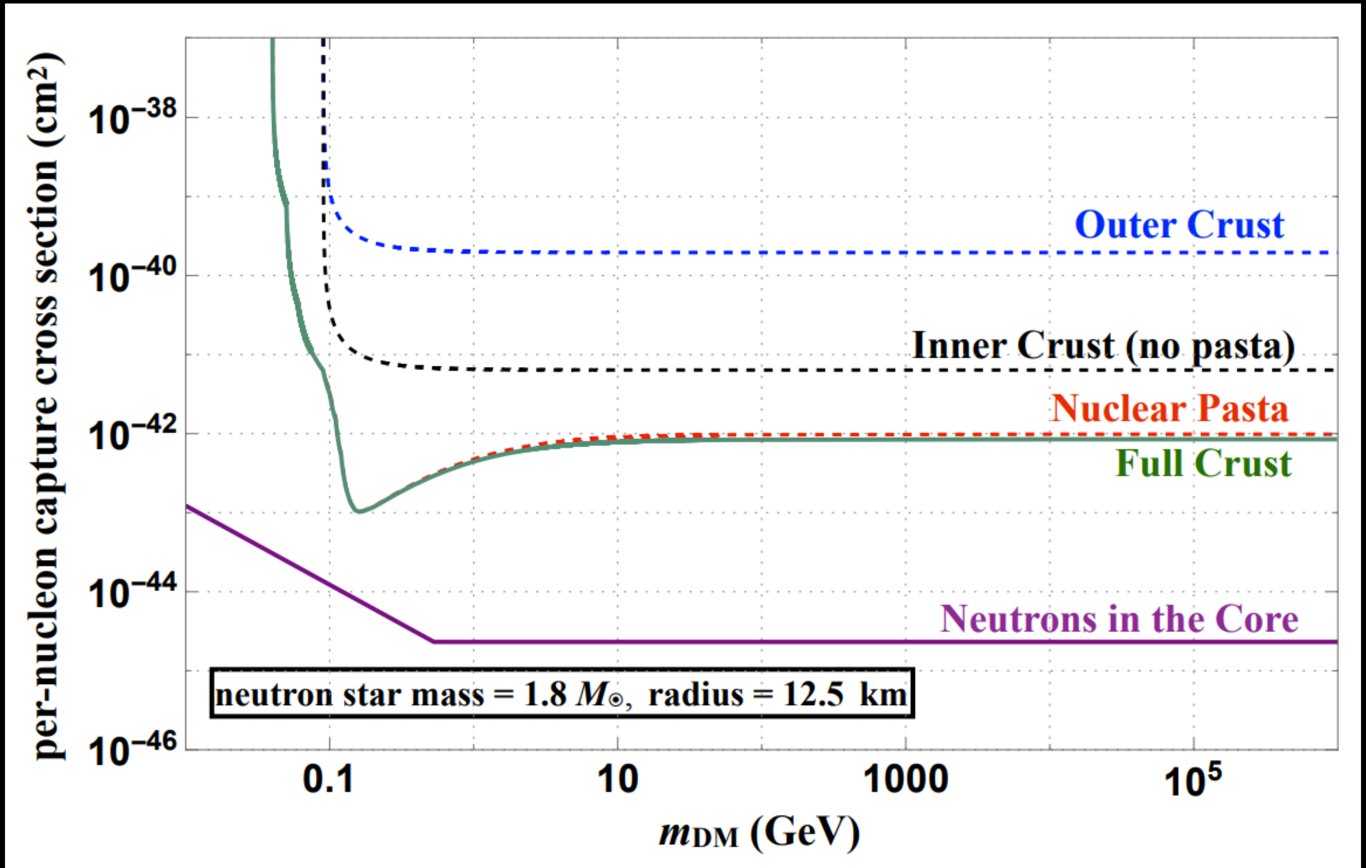
Caplan, Schneider, Horowitz ‘18

Use known response functions from simulations to calculate dark matter scattering with pasta!

Rebecca Leane
rleane at mit dot edu

DARK MATTER – NEUTRON STAR INTERACTIONS

~ 100 MeV – 1 PeV DM mass sensitivity through nucleon + pasta scattering



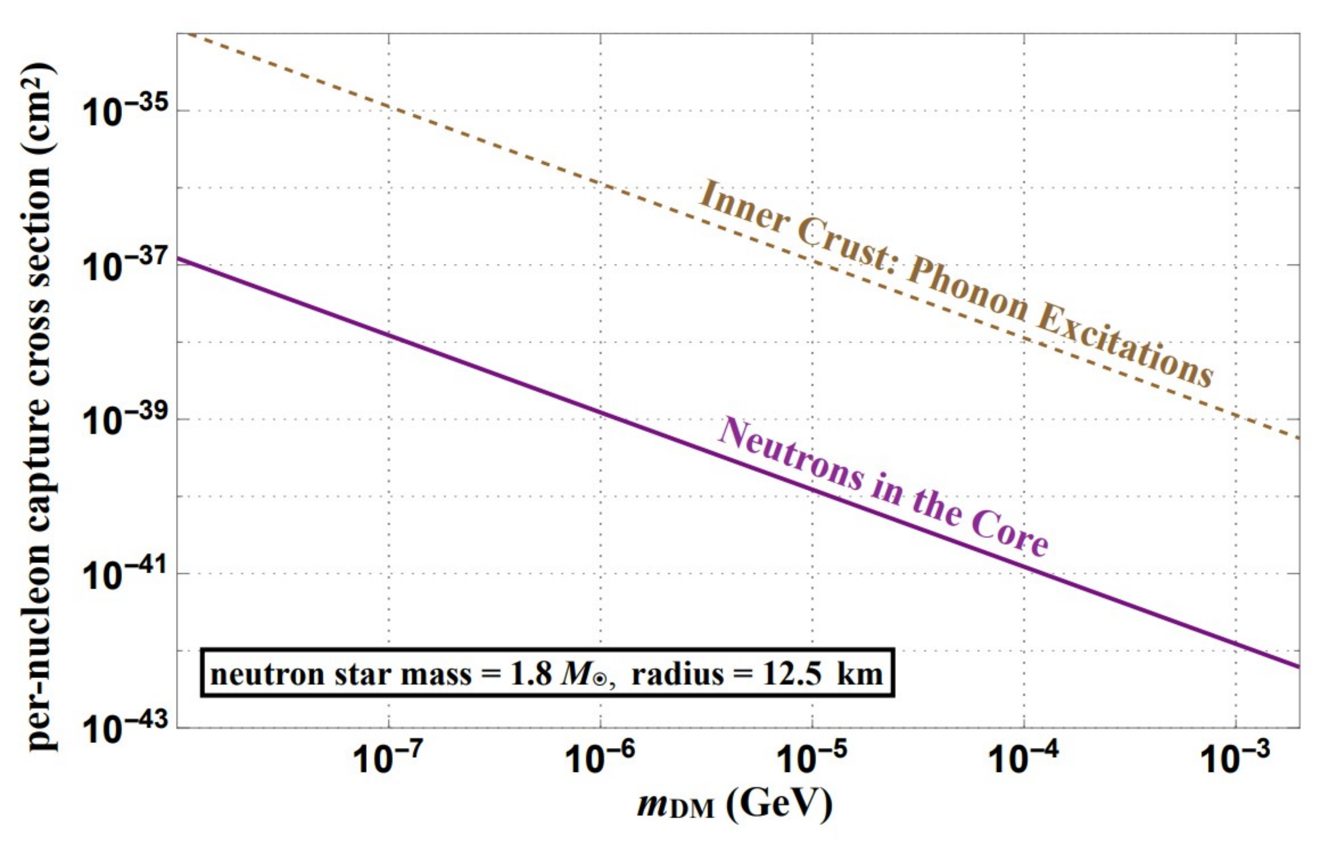
$T_\infty^{\text{crust}} = 1620$ K

Acevedo, Bramante, **RL**, Raj, JCAP '20

Rebecca Leane
rleane at mit dot edu

DARK MATTER – NEUTRON STAR INTERACTIONS

~ 10 eV – 1 MeV DM mass sensitivity through phonon excitations



$$T_\infty^{\rm crust} = 1620\ {\rm K}$$

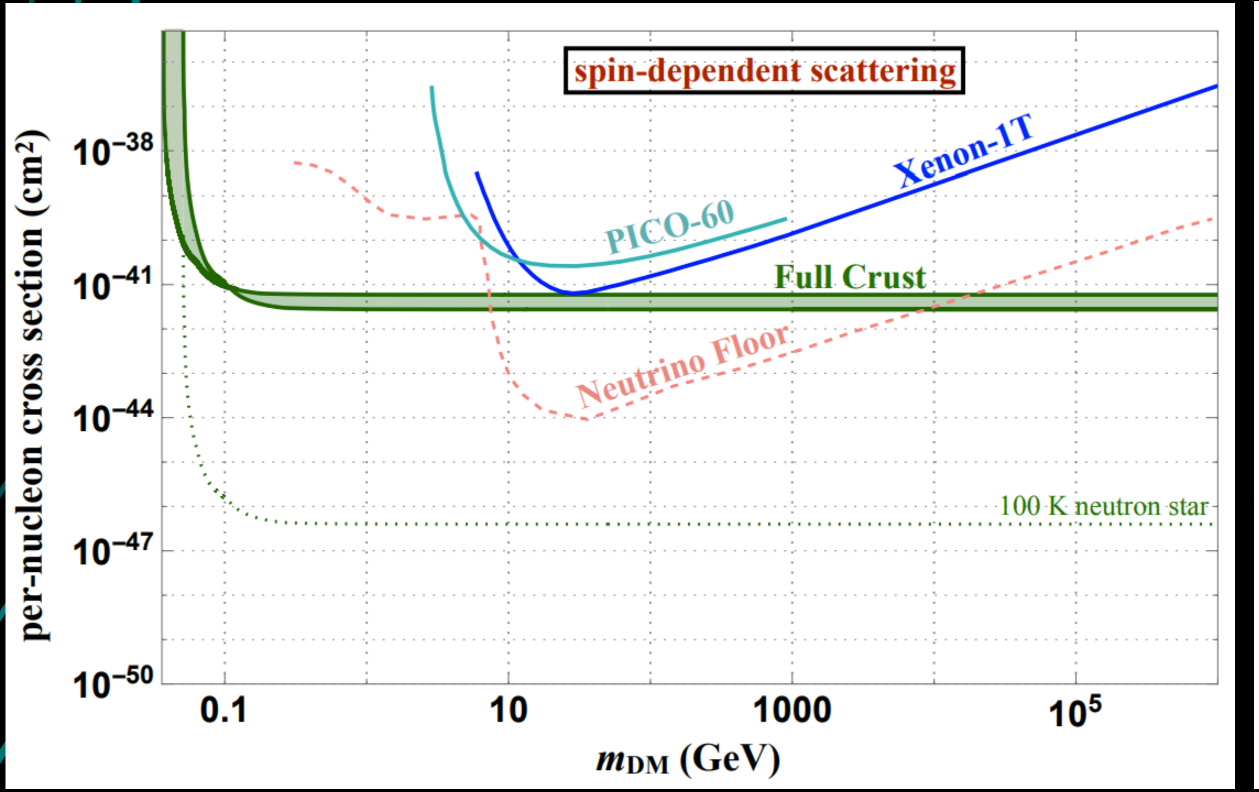
Acevedo, Bramante, **RL**, Raj, JCAP '20

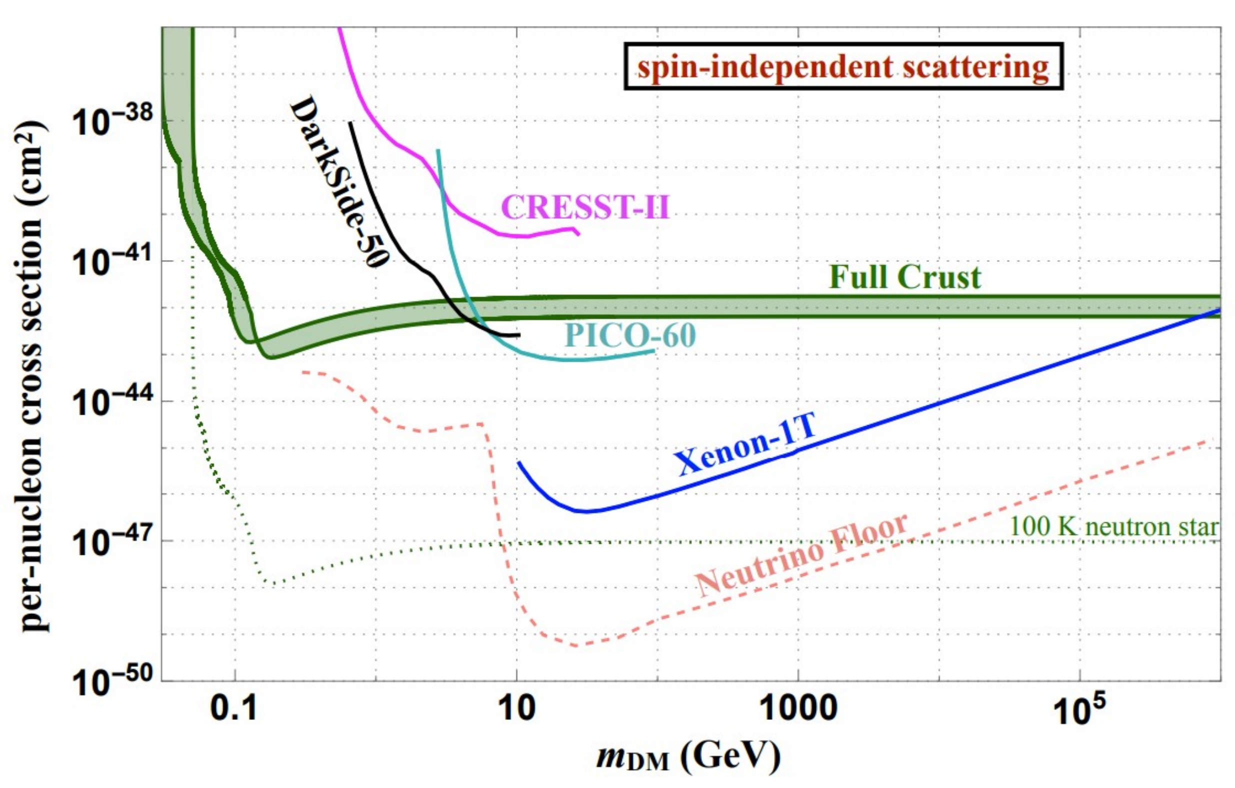
Rebecca Leane
rleane at mit dot edu

HOW DOES PASTA COMPARE WITH DIRECT DETECTION?

Rebecca Leane
rleane at mit dot edu

PASTA CAN BEAT DIRECT DETECTION

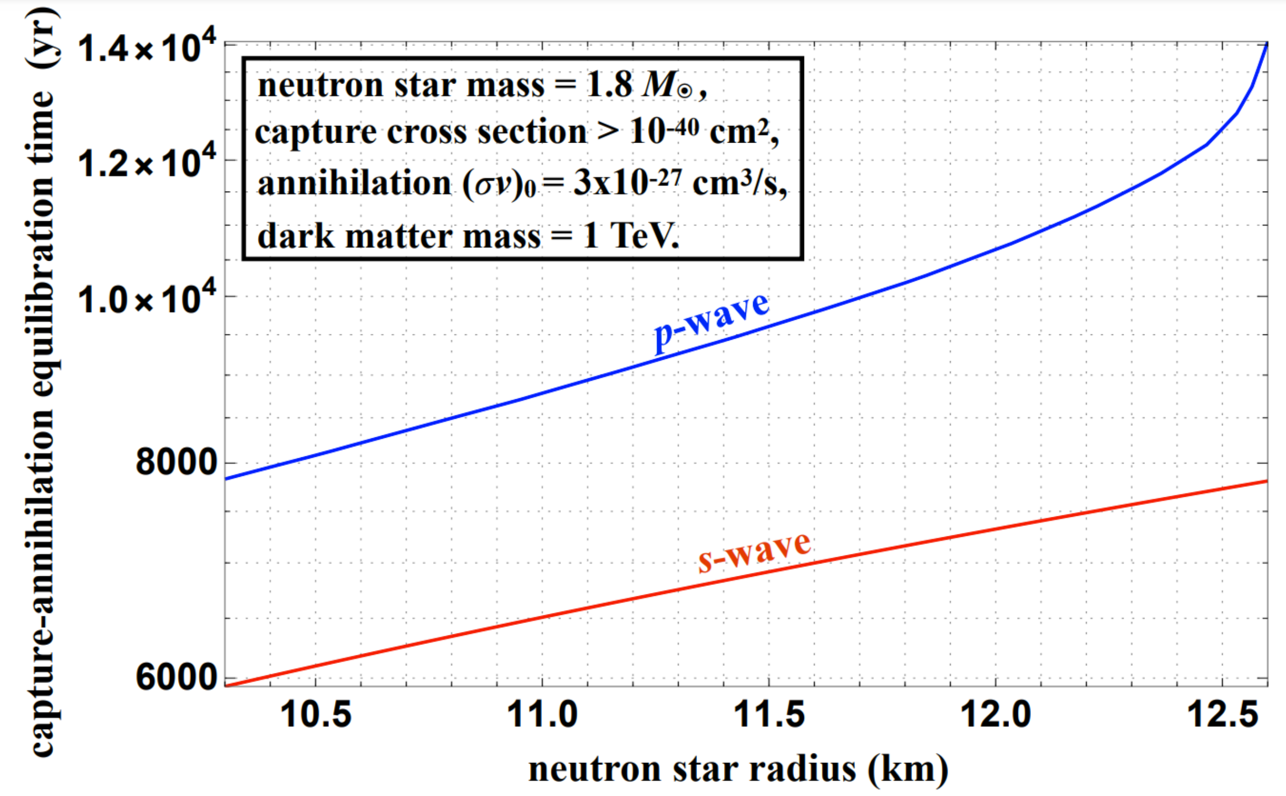




Low + high masses, velocity suppressed, spin-dependent, inelastic DM

Rebecca Leane
rleane at mit dot edu

BONUS: ANNIHILATION HEATING



+ Annihilation heating boosts temperature to ~2470K

(compared to ~1630 K kinetic heating)

→ requires less telescope time!

+ Crust-only scatters attain capture-annihilation equilibrium very fast

→ annihilation proceeds at max rate for cross sections > 10^-40 cm^2/s

Rebecca Leane
rleane at mit dot edu

CONCLUSIONS

+ Neutron stars can provide significant enhancement of DM scattering sensitivity, through kinetic and annihilation heating

+ Neutron star cores not well understood – but the crusts are!
  Calculating DM-crust scattering leads to more robust limits

+ Powerful sensitivity for DM masses ~10 eV - 1 PeV
  Can be more powerful than direct detection!
  Best sensitivity from dark matter-pasta scattering.

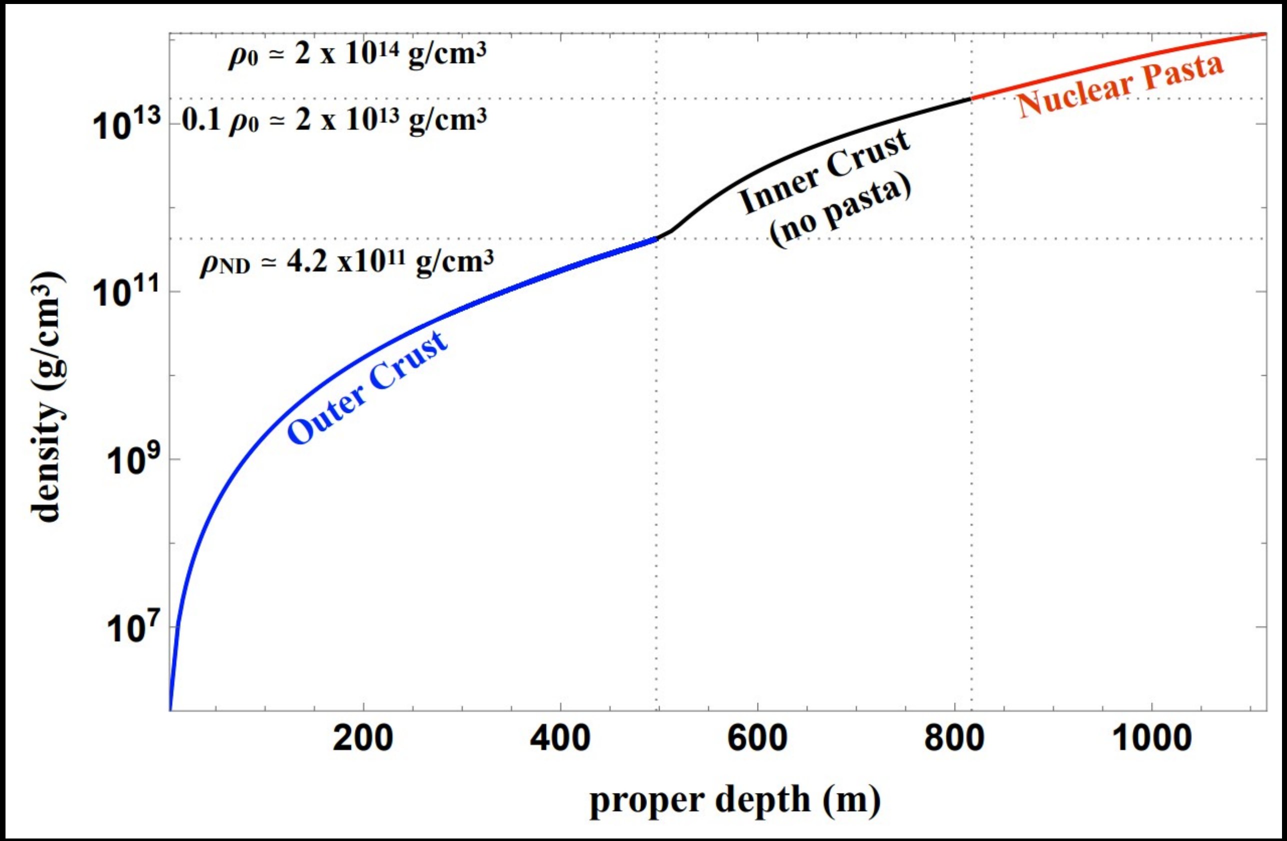
Radio and infrared telescopes coming online very soon
Signal identified potentially in a day!

Rebecca Leane
rleane at mit dot edu

EXTRA SLIDES

Massachusetts
Institute of
Technology

CRUST LAYERS AND DENSITIES



DARK MATTER - PASTA INTERACTIONS

+ Use known response functions from simulations, takes into account coherence of neutrons at different densities and temperatures

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

$$\tau_{\text{DM}} = \frac{1}{g_s}\int_{\text{crust}} n_{\text{T}}\sigma_{\text{T}\chi}\frac{1}{\rho}\frac{dP}{d\rho}d\rho$$

$$\tau_{\text{DM}} = \frac{\sigma_{\text{n}\chi}}{g_s}\int_{\text{pasta}}\langle S_{\text{pasta}}(q)\rangle_q\ \frac{n_{\text{n}}(\rho)}{\rho}\frac{dP}{d\rho}d\rho$$

DARK MATTER - PHONON INTERACTIONS

+ Single-phonon emission in the low momentum regime (w/ linear dispersion relation) is described by a static structure function, which relates per-nucleon cross section w/ phonon excitation cross section

$$S_{\mathrm{phonon}}(q) = \frac{q}{2m_{\mathrm{n}}c_{\mathrm{s}}}$$

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

Where c_s is the speed of the superfluid phonon which is ~ the neutron Fermi speed ~ 0.04c

Energy deposited > halo KE

$q * c_s > m*v_{esc}^2$

$m * v_{esc} * c_s > m*v_{esc}^2$

DARK MATTER CAPTURE

$$E_{\mathrm{DM}} = m_{\mathrm{DM}}(\gamma - 1)$$

$$\dot{M}_{\mathrm{DM}} = \rho_{\mathrm{DM}} v_{\mathrm{halo}} \times \pi b_{\mathrm{max}}^2 \times f$$

$$\tau_{\mathrm{DM}} = \int_{\mathrm{crust}} n_{\mathrm{T}} \sigma_{\mathrm{T}\chi} dz$$

$$\frac{dP}{dz} = g_s \rho$$

$$\tau_{\mathrm{DM}} = \frac{1}{g_s} \int_{\mathrm{crust}} n_{\mathrm{T}} \sigma_{\mathrm{T}\chi} \frac{1}{\rho} \frac{dP}{d\rho} d\rho$$

CRUST SCATTERING

$$\sigma_{\mathrm{T}\chi}(q) = \left(\frac{\mu_{\mathrm{T}\chi}}{\mu_{\mathrm{n}\chi}}\right)^2 A^2 F^2(q) S_{\mathrm{T}}(q) \sigma_{\mathrm{n}\chi}$$

+ F(q) (Helm form factor) captures the loss of coherence over a nucleus
  Suppresses σ for the de Broglie wavelength q^ −1 < nuclear radius

+ $S_T(q)$ (static structure function) accounts for coherence among the relative amplitudes of dark matter scattering on multiple nuclei
  Suppresses the cross section for q^ −1 > nuclear separation