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# Nuclear Fusion inside Dark Matter

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**2012.10998**

# Composite DM

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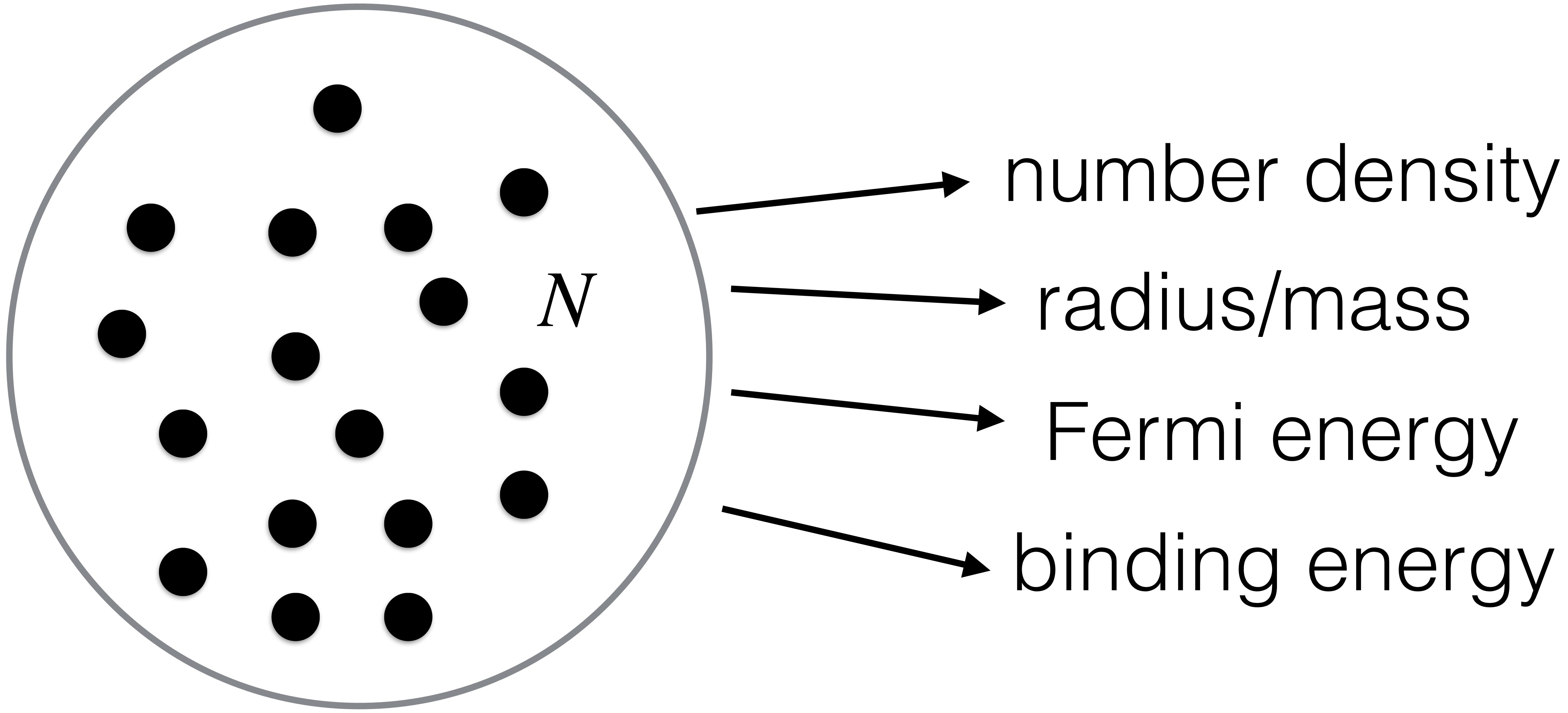
1407.4121

Consider simple model for asymmetric DM where

$$\mathscr{L}_0 = \frac{1}{2}\partial^2\phi + \frac{1}{2}m_\phi^2\phi^2 + \bar{X}\left(i\gamma^\mu\partial_\mu - m_X\right)X + g_\phi\bar{X}\phi X$$

Scalar field provides attractive force for stable bound states:



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Large N-limit: $\phi(x) \to \langle\phi\rangle$ RMFT $\longrightarrow$ valid when: $R_X \gg m_\phi^{-1}$

Field value determined from energy density minimum:

$$\varepsilon \simeq \frac{1}{2}m_\phi^2\langle\phi\rangle^2 + \frac{1}{\pi}\int_0^{p_F} dp\ p^2\left(p^2 + \big(\underbrace{m_X - g_X\langle\phi\rangle}_{\text{effective mass } m_*}\big)^2\right)^{1/2}$$

$$\mu = \left(p_F^2 + m_*^2\right)^{1/2} = \frac{\varepsilon}{n_X}$$

$$n_X = \frac{p_F^3}{3\pi^2}$$

Simple scaling relations are recovered when $m_X \gg m_\phi$

binding field: $\langle\phi\rangle \simeq \dfrac{m_X}{g_\phi}$ $(m_* \simeq 0)$ chem. potential: $\mu \simeq p_F = \bar{m}_X$

$$\boxed{\bar{m}_X \simeq (3\pi m_X^2 m_\phi^2/\alpha_\phi)^{1/4}}$$

comp. mass: $M_X \simeq N\bar{m}_X$ comp. radius: $R_X \simeq \left(\dfrac{9\pi N}{4\bar{m}_X^3}\right)^{\frac{1}{3}}$

# Cosmological formation

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1411.3739

$\bar{X}X$ annihilation $\longrightarrow$ $^2X$ formation $\longrightarrow$ $^NX$ formation $\longrightarrow$ $X$ depletion

$X$ overabundance

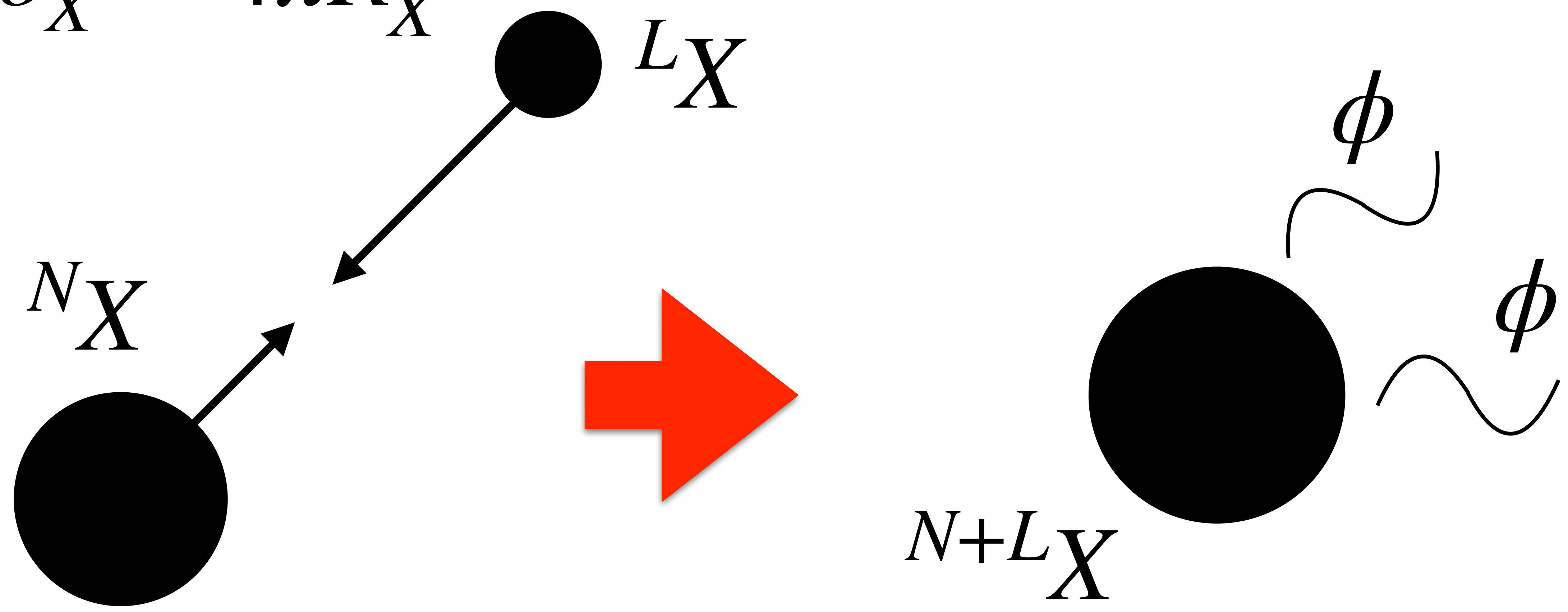
$T_{ca} \sim m_X/10$

e.g. phase transitions
metastable field decay

$$\Omega_X^{dep} = \Omega_{DM}\zeta$$

fusion in strong binding limit:

$$\sigma_X \simeq 4\pi R_X^2$$



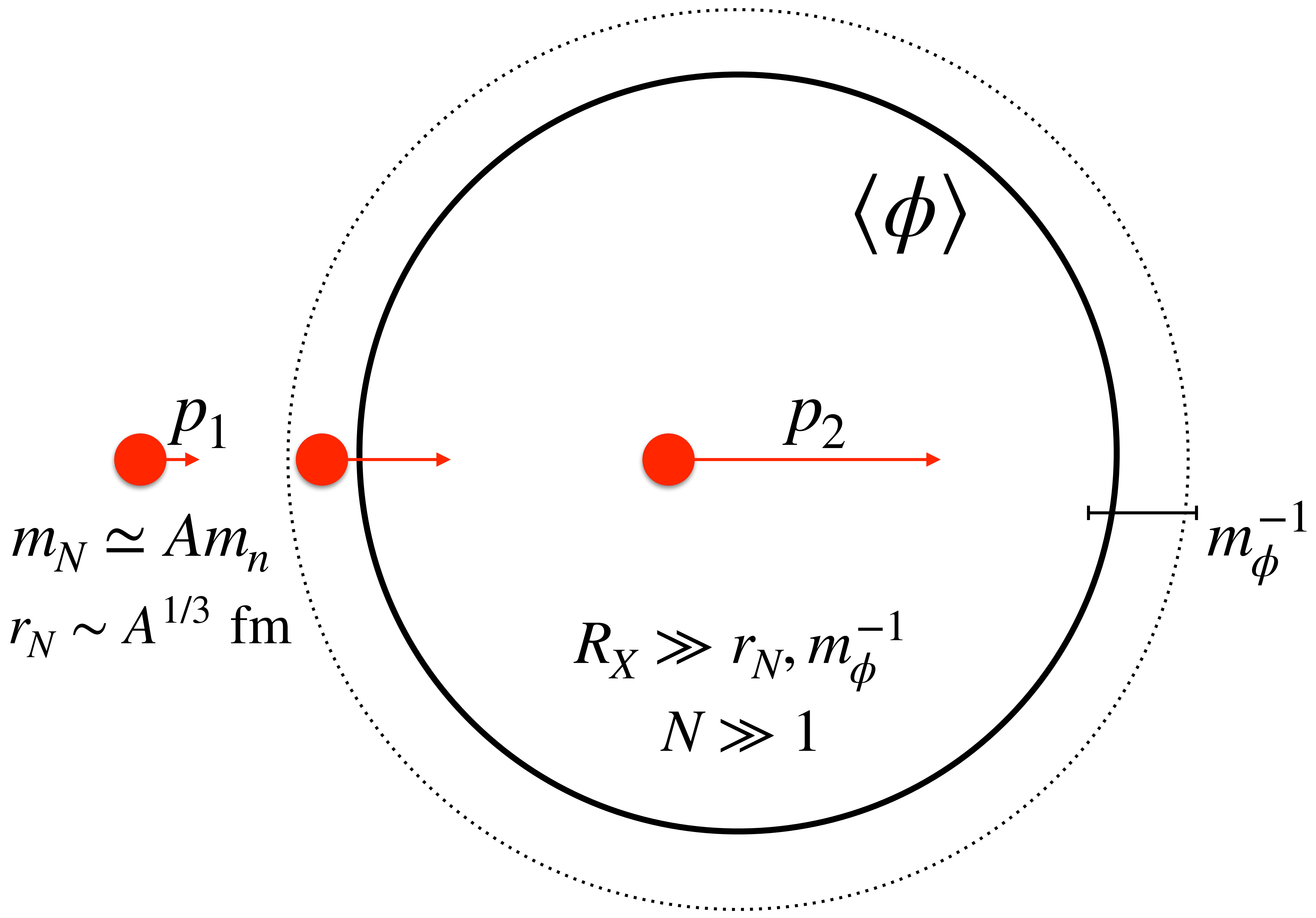

Depending on parameters:

$$10^{14}\ \text{GeV} \lesssim M_X \lesssim 10^{42}\ \text{GeV}$$

$$10^{-3}\ \text{nm} \lesssim R_X \lesssim 10^{2}\ \mu\text{m}$$

# Nuclear coupling

Consider an interaction term with SM nucleons: $\mathscr{L} = \mathscr{L}_0 + g_n \bar{n} \phi n$




boundary conditions impose:

$$\phi(r > R_X) = \langle \phi \rangle e^{-m_\phi (r - R_X)} \left( \frac{R_X}{r} \right)$$

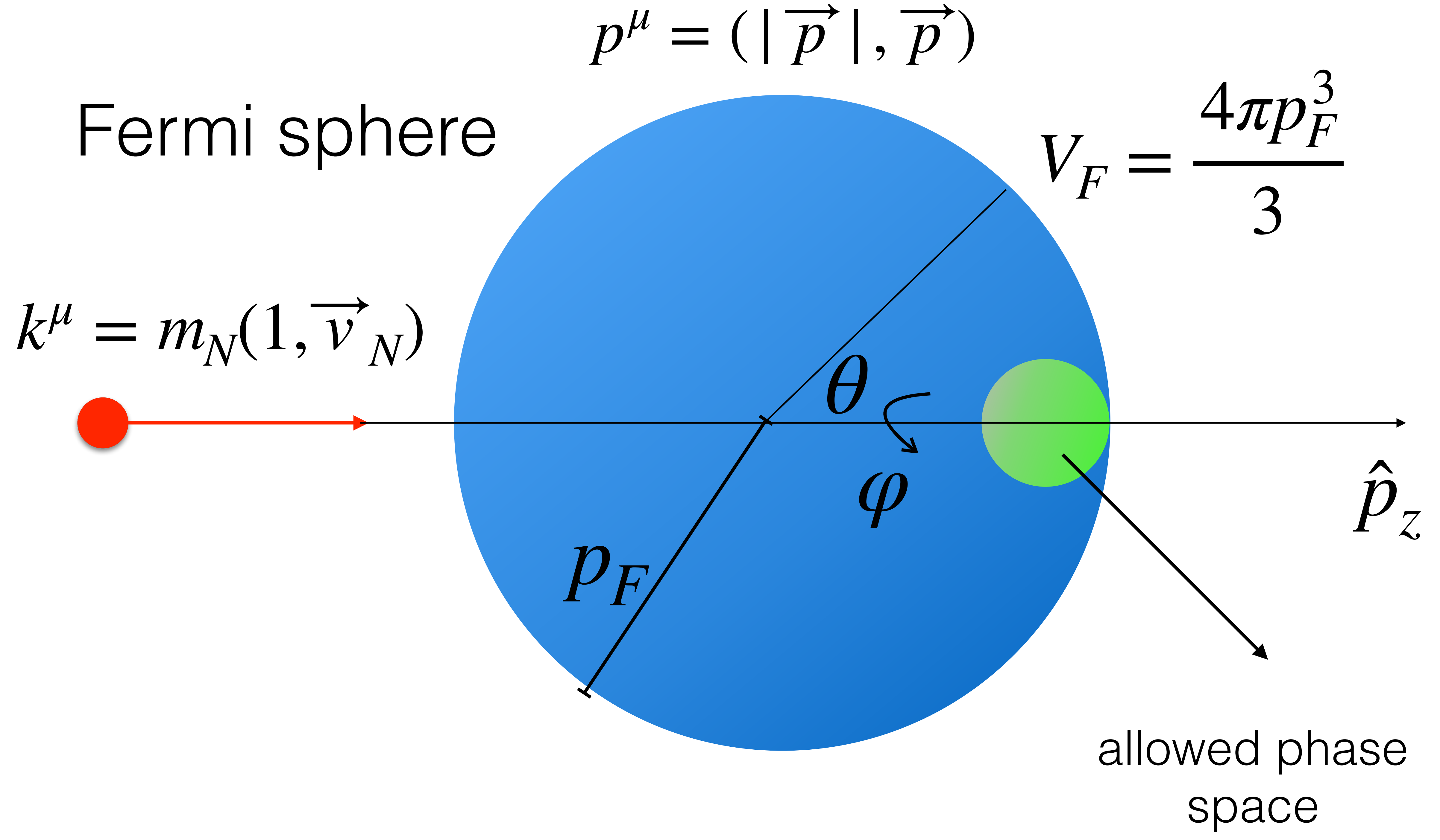
$$\langle \phi \rangle \simeq \frac{m_X}{g_\phi}$$

$$p_1^2 + m_N^2 = p_2^2 + (m_N - A g_n \langle \phi \rangle)^2$$

$$A g_n \langle \phi \rangle \ll m_N \longrightarrow A g_n \langle \phi \rangle \equiv V_n = \frac{p_2^2 - p_1^2}{2 m_N}$$

# N-X scattering

DM constituents are ultra-relativistic and degenerate:




Scattering rate:

$$\Gamma_{NX} = n_X \underbrace{\int_0^{p_F} \frac{dp\, p^2}{V_F} \int d\varphi\, d(\cos\theta)}_{\substack{\text{integrate over target phase space} \\ \text{(composite rest frame)}}} \underbrace{\int d\alpha\, d(\cos\psi) \left(\frac{d\sigma}{d\Omega}\right)_{(CM)}}_{\substack{\text{relativistic kinematics} \\ \text{(centre-of-momentum frame)}}} \overbrace{\tilde{v}}^{\text{Moller velocity}} \underbrace{\Theta(\Delta E + p - p_F)}_{\text{Pauli-blocking}}$$

Energy loss rate: $\dot{E}_{NX} \simeq \Gamma_{NX} \times \Delta E_{max} \simeq A^2 g_n^2 g_\phi^2 \left(\frac{m_N^5}{p_F^4}\right)(m_N + 2p_F) v_N^8$

$v_N \lesssim 10^{-2}$

$g_n \lesssim 10^{-10}$

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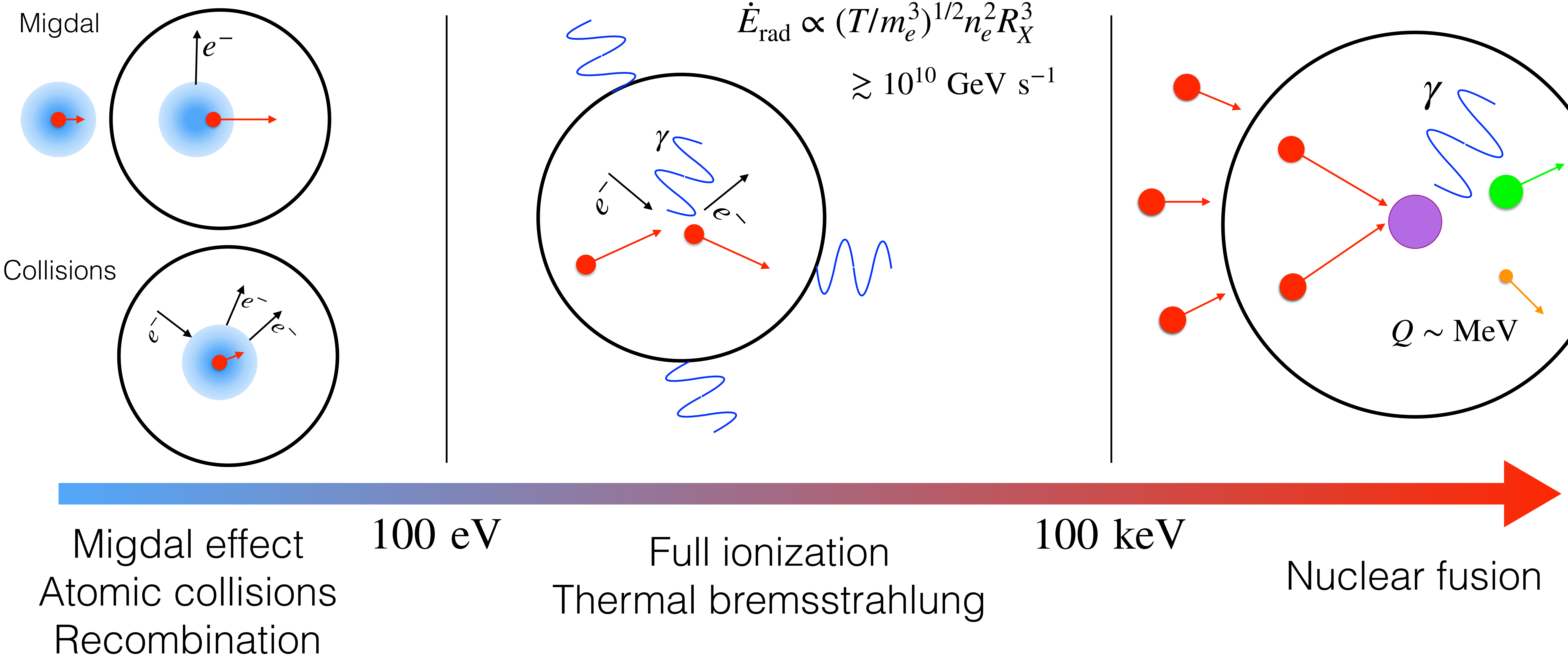
$\langle \phi \rangle \propto m_X \sim \mathrm{MeV} - \mathrm{EeV} \longrightarrow$ substantial acceleration even if $g_n \ll 1$




$T \propto g_n m_X$

# Detection

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1) Massive/strongly-coupled:

$$10^{21}\ \mathrm{GeV} \lesssim M_X \lesssim 10^{25}\ \mathrm{GeV} \qquad \mathrm{nm} \lesssim R_X \lesssim \mu\mathrm{m}$$

Thresholds:

SNO+: ~1 MeV per 100 ns

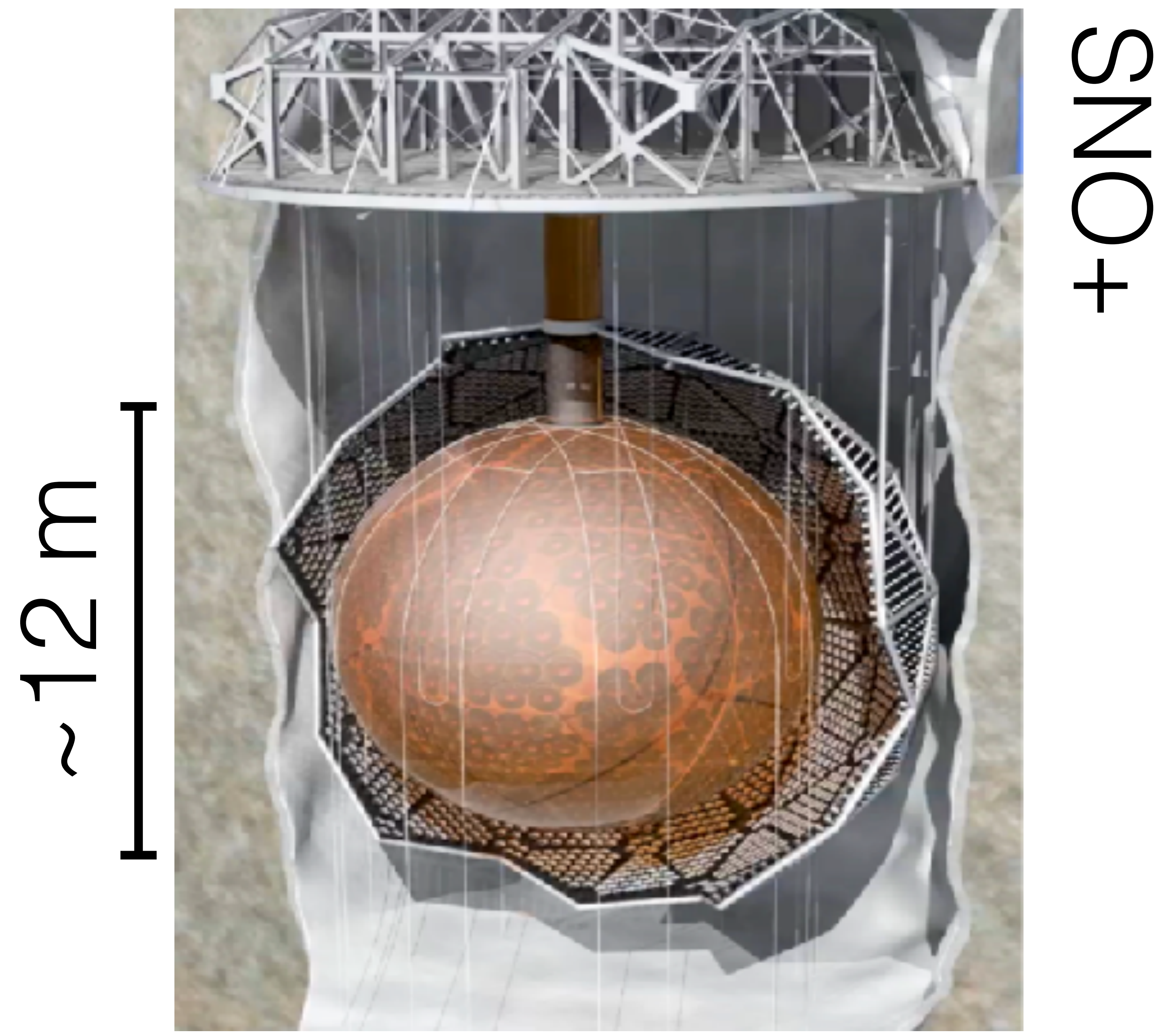
IceCube: ~10 TeV per 100 ns

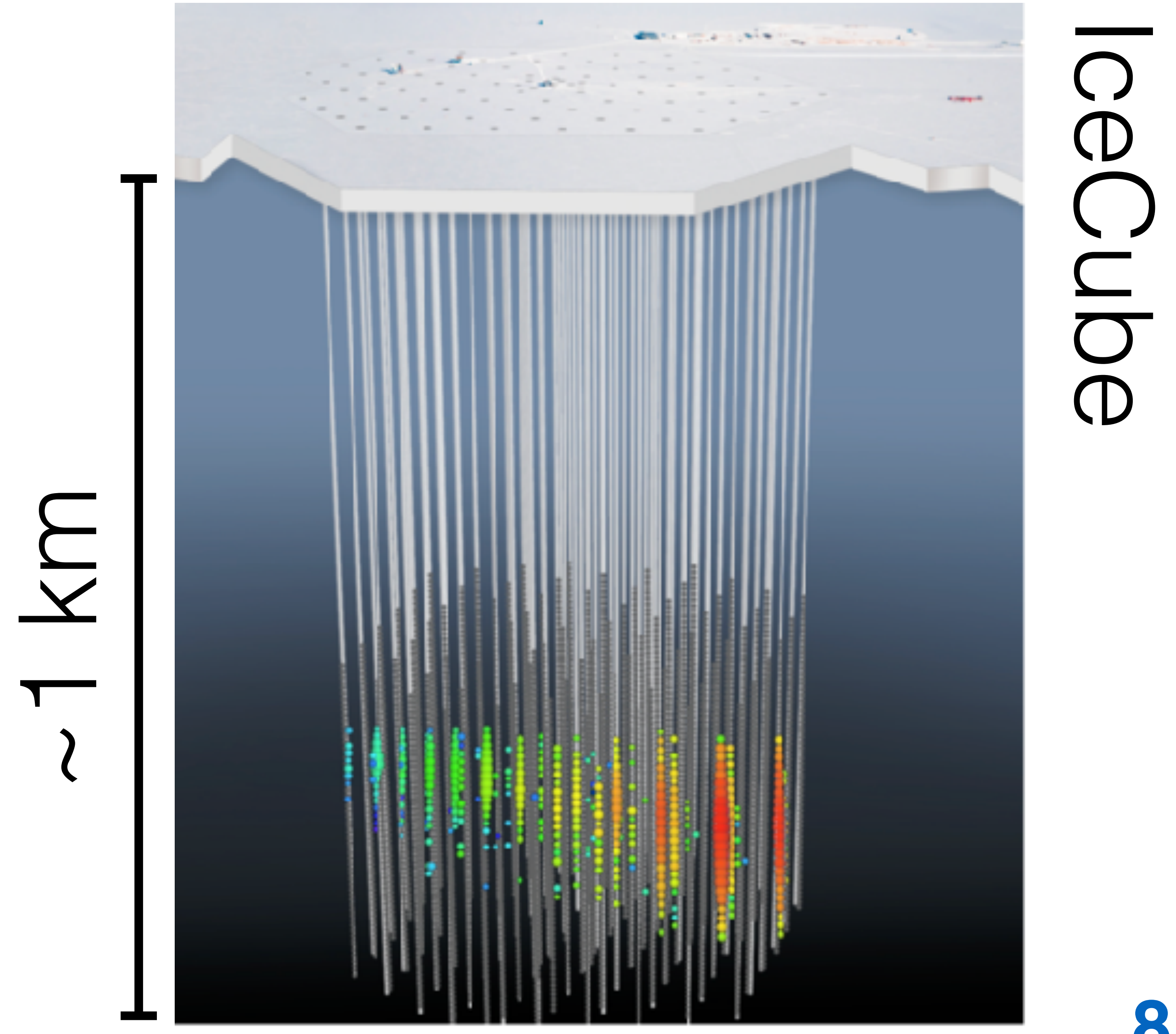
(~100 PeV in single crossing)

Composites radiate continuously along path:

$$\dot{E}_{SNO+} \simeq 10^4\ \mathrm{GeV\ s^{-1}} \qquad \dot{E}_{IC} \simeq 10^{11}\ \mathrm{GeV\ s^{-1}}$$

$$M_X^{max} \simeq 10^{22}\ \mathrm{GeV} \qquad M_X^{max} \simeq 3 \times 10^{25}\ \mathrm{GeV}$$



# Parameter space for detection:

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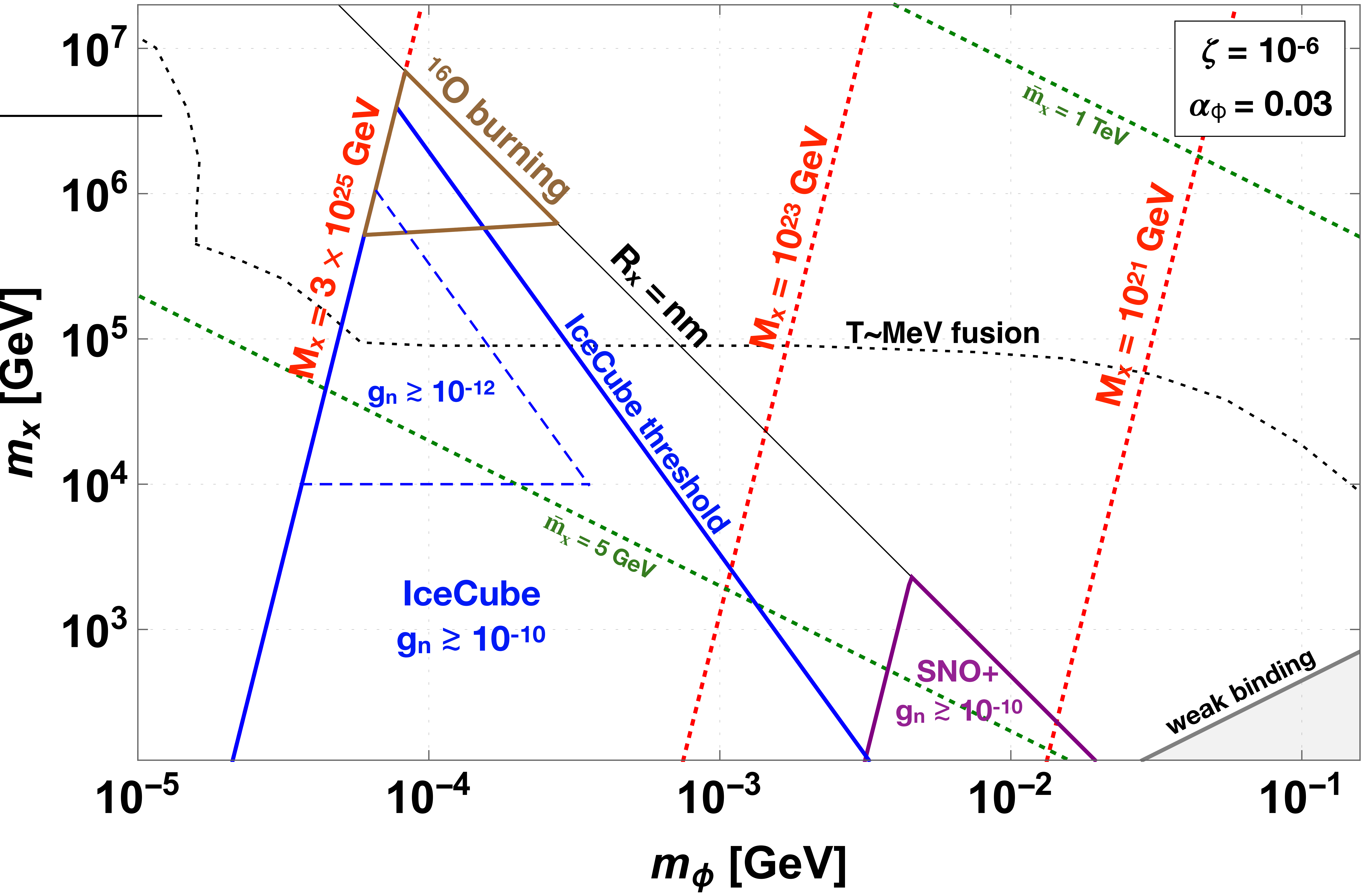
increasing radius/mass

stellar cooling constraints $g_n \lesssim 10^{-10}$




increasing temperature (fixed coupling)
increasing composite binding energy

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A, B & G, 21XX.XXXXX

# 2) Lighter/weakly-coupled:

$$10^{12}\ \mathrm{GeV} \lesssim M_X \lesssim 10^{18}\ \mathrm{GeV} \qquad 10^{-4}\ \mathrm{nm} \lesssim R_X \lesssim \mu\mathrm{m}$$

LNE experiments → large mass numbers

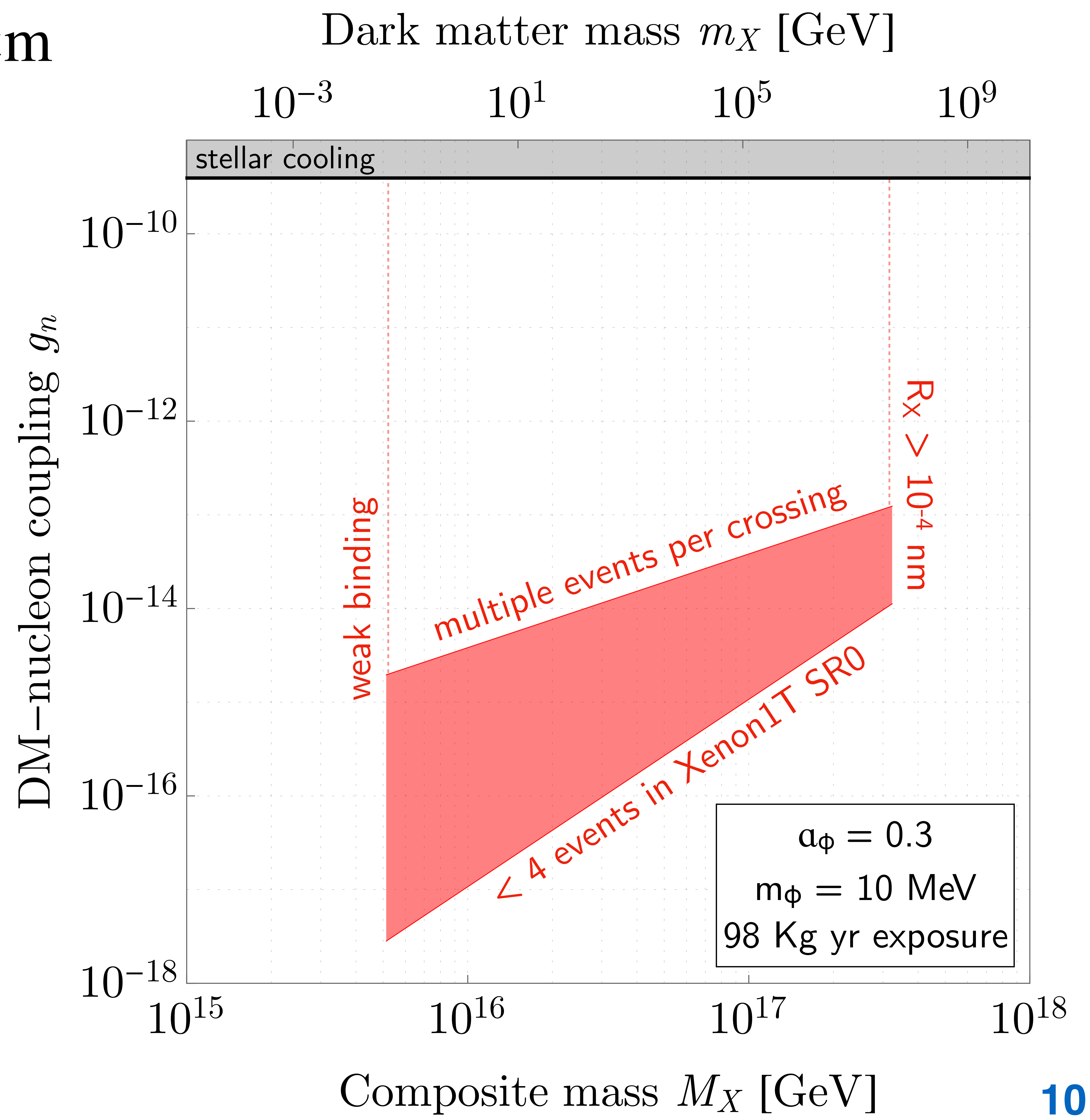
LNE experiments → low e- background

Differential event rate:

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_N M_\chi} \int_{v > v_\chi^{(min)}} \frac{d\sigma}{dE_R}\, v\, f(v)\, dv$$

$\frac{d\sigma}{dE_R} \sim 4\pi R_X^2\, \delta(E_R - E_R^0)$

$$\frac{dR_{ion}}{dE_R dE_e} = \frac{dR}{dE_R} \times \left( \frac{1}{2\pi} \sum_{n,l} \frac{dp_q}{dE_e}(n, l \to E_e) \right)$$



# Type-Ia supernovae

Energy dissipated in the composite transit via conduction:

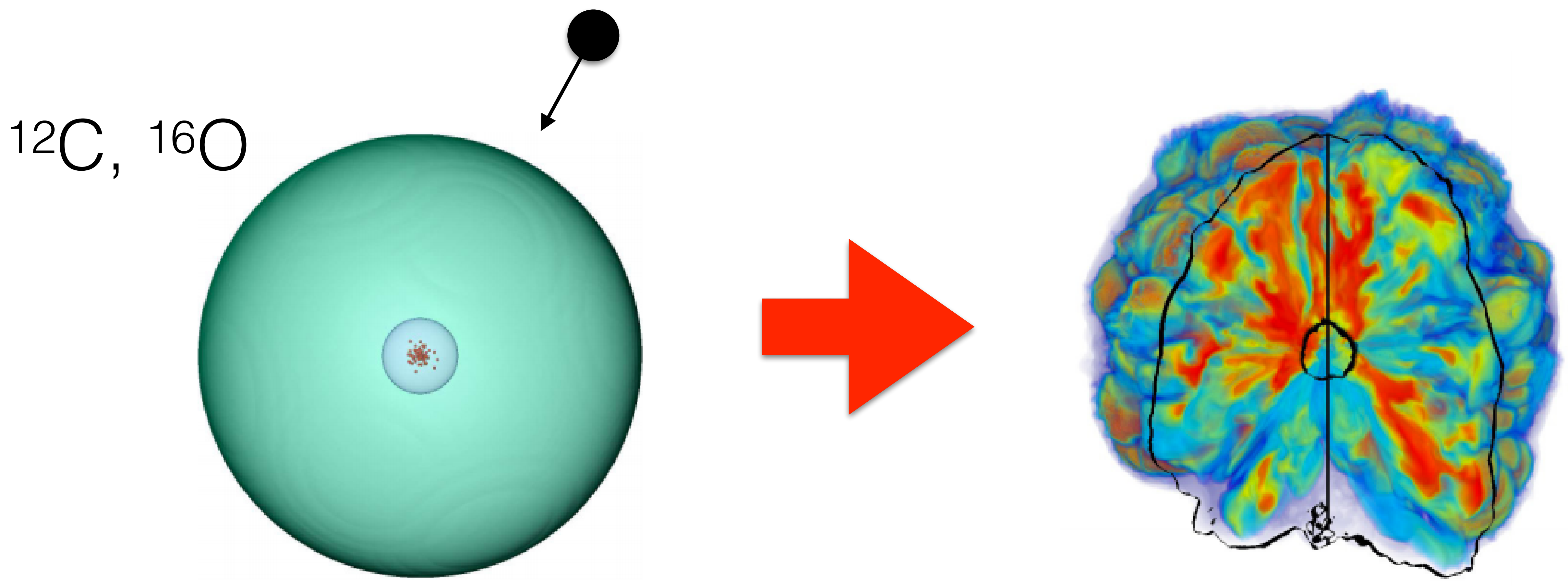
$$\dot{Q}_{cond} = \frac{4\pi^2 T^4 R_X}{15\kappa_c \rho_*} \simeq 10^{27}\ \mathrm{GeV\ s^{-1}} \left(\frac{R_X}{\mu\mathrm{m}}\right)$$

Composite kinetic energy:

$$\frac{1}{2} M_X v_{\rm esc}^2 \simeq 10^{28}\ \mathrm{GeV} \left(\frac{M_X}{10^{32}\ \mathrm{GeV}}\right) \left(\frac{v_{\rm esc}}{3\times 10^{-2}}\right)^2$$

$$\Delta t_{cross} \simeq 1\ \mathrm{s}$$

Thermonuclear explosions of WDs:




localized heat deposition leads to runaway fusion:

1) nuclear energy prod. > diffusion

2) critical temp. ~ $10^{10}$ K ~ MeV

Carbon burning rate:

$$^{12}\mathrm{C} + ^{12}\mathrm{C} \to ^{24}\mathrm{Mg}^* \quad \Bigg| \quad R_{th}\Big|_{\mathrm{T=MeV}} \simeq 10^{42}\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1} \left(\frac{\rho_*}{10^9\ \mathrm{g\ cm}^{-3}}\right)^2 \quad \Bigg| \quad \bar{Q} \sim 3\ \mathrm{MeV}$$

Nuclear energy release: $\dot{Q}_{fus} \simeq \bar{Q} R_{th} \left(\frac{4\pi R_X^3}{3}\right) \simeq 10^{28}\ \mathrm{GeV\ s}^{-1} \left(\frac{R_X}{\mu\mathrm{m}}\right)^3$

Ignition requires: $\dot{Q}_{\mathrm{fus}} \gtrsim \dot{Q}_{\mathrm{cond}}$ $\to$ $\boxed{R_X \gtrsim \mu\mathrm{m}}$, $\boxed{M_X \gtrsim 10^{32}\ \mathrm{GeV}}$

WD survival in turn implies constraints:

$$g_n \lesssim 10^{-12} \left(\frac{10^7\ \mathrm{GeV}}{m_X}\right)$$

(~MeV temp. not reached)

$$10^{32}\ \mathrm{GeV} \lesssim M_X \lesssim 10^{42}\ \mathrm{GeV}$$

(~1 encounter/Gyr)

# Conclusions

Composite states with a binding field coupled to nuclei presents new interesting phenomenology:

→ Radiation and fusion observable at large neutrino observatories, ionization events at DM detection experiments.

→ On the astrophysical side: white dwarf explosions, could also look for stellar/planetary capture and heating, alterations to isotope abundances.

→ Model can be extended to include other fields and interactions.

Thank you for
your attention!

# Backup slide

Cosmological synthesis:

$$N_c \simeq \left(\frac{2n_X v_X \sigma_X}{3H}\right)^{6/5} \simeq 10^{27}\left(\frac{g_{ca}}{10^2}\right)^{\frac{3}{5}}\left(\frac{T_{ca}}{10^5\ \mathrm{GeV}}\right)^{\frac{9}{5}}\left(\frac{\bar{m}_X}{5\ \mathrm{GeV}}\right)^{\frac{21}{5}}\left(\frac{\zeta}{10^{-6}}\right)^{\frac{6}{5}}$$

Radiative WD losses: $\dot{Q}_{rad} = \dfrac{4\pi R_X^2}{\kappa_r \rho_*}\nabla(\sigma T^4) \simeq 10^{22}\ \mathrm{GeV\ s^{-1}}\left(\dfrac{R_X}{\mu\mathrm{m}}\right)^2\left(\dfrac{m_\phi}{\mathrm{keV}}\right)$

Acceleration/Migdal: $\tau_{\mathrm{accel}} \simeq \dfrac{1}{m_\phi}\left(\dfrac{1}{v_X^2 + v_N^2}\right) \simeq 10^{-19}\ \mathrm{s}\left(\dfrac{\mathrm{MeV}}{m_\phi}\right)\left(\dfrac{10^{-3}}{v_X}\right)^2$

$$v_\chi^{(min)} \simeq \frac{1}{m_\phi \tau_{e^-}} \simeq 10^{-5}\left(\frac{\mathrm{MeV}}{m_\phi}\right) \qquad \tau_{e^-} \sim (10\ \mathrm{eV})^{-1}$$