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Nuclear Fusion inside Dark Matter

Dark Matter as a Portal to New Physics

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Acevedo, Bramante & Goodman, 2012.10998
Acevedo, Bramante & Goodman, in preparation

apctp
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Outline

1. Composite DM
2. Composite-nucleus interactions
3. Direct detection signals
4. Astrophysical effects
5. Conclusions

Composite DM

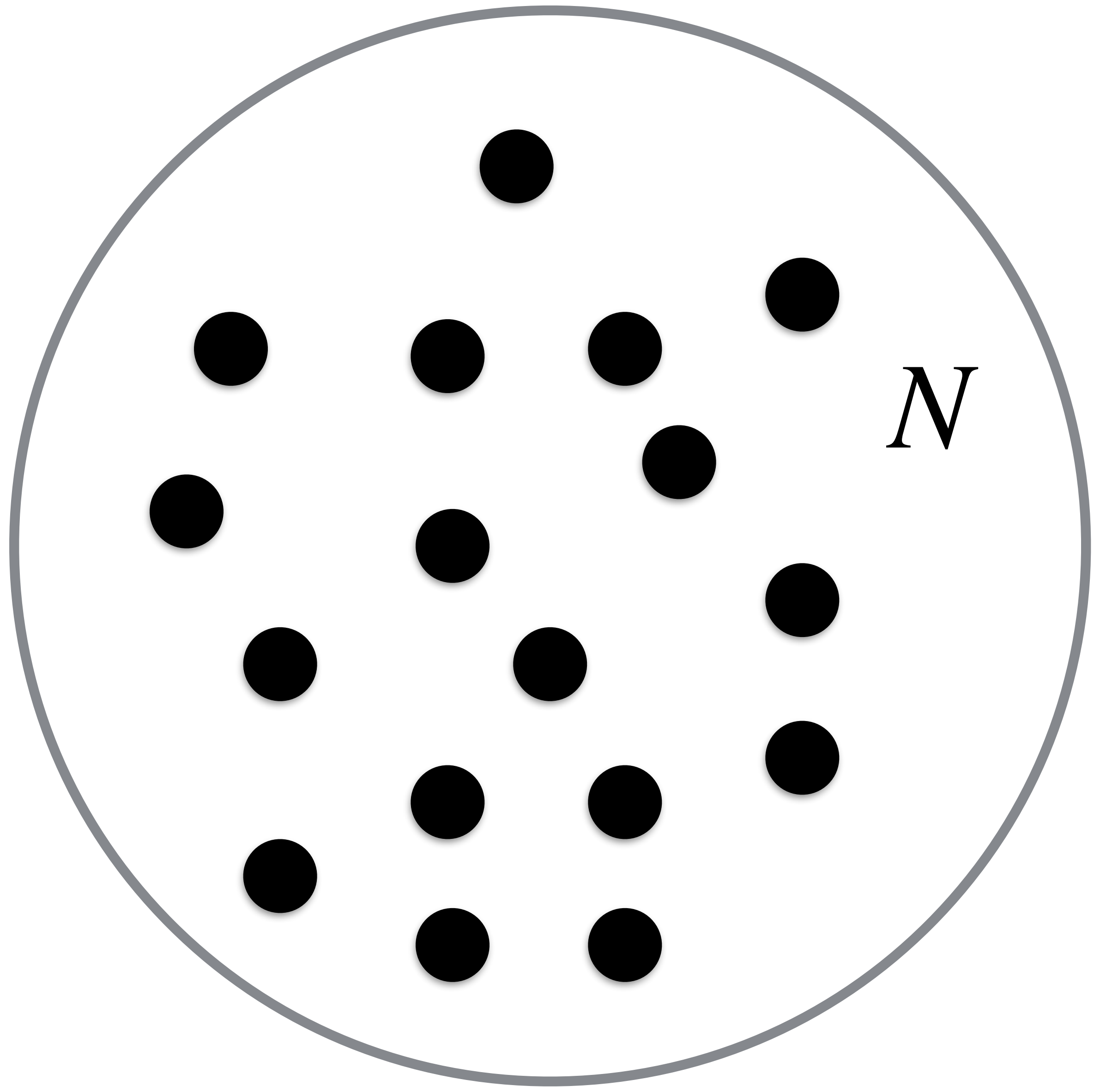
1707.02313
1407.4121

Consider simple model for asymmetric DM where

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

Dirac fermion+real scalar

Scalar field provides attractive force
for stable bound states:



$$M_X = N\bar{m}_X$$

$$BE_N = N(m_X - \bar{m}_X)$$

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Properties of ground state?

- number density n_X
- radius R_X
- Fermi energy/momentum ϵ_F, p_F
- binding energy $m_X - \bar{m}_X$

Consider large-N limit: $N \gg 1$ ⟶ $\phi(x)$ spatially-varying classical field

field equations:

$$\left(i\gamma^\mu \partial_\mu - (m_X - g_X \phi(x))\right) X(x) = 0$$

$$\left(\nabla^2 - m_\phi^2 - g_\phi \langle \bar{X} X \rangle\right) \phi(x) = 0$$

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Thomas-Fermi approximation: $p_F^3(x) \sim n_X(x) \quad \left(p_F(r > R_X) \equiv 0 \right)$

particle number: $N \sim \int dr\, r^2\, p_F^3$

chemical potential: $\mu = \sqrt{p_F(x)^2 + \underbrace{\left(m_X - g_\phi \phi(x)\right)}_{= m_*(x)}{}^2} \longrightarrow$ implies $p_F = p_F(\phi)$

$= m_*(x)$ effective mass

Solve field equation:
+boundary conditions

$$\nabla^2\phi - m_\phi^2\phi = \frac{1}{\pi}\int_0^{p_F(\phi)} dp\, \frac{p^2\, m_*(\phi)^2}{\sqrt{p^2 + m_*(\phi)^2}}$$

Composite total energy:

$$E\left(p_F(x), \phi(x)\right) = \int dr\, 4\pi r^2 \left[\frac{1}{2}\left(\nabla\phi\right)^2 + \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{\pi}\int_0^{p_F} dp\, p^2\sqrt{p^2 + m_*^2}\right]$$

⟶ minimization yields radius R_X and binding energy $m_X - \bar{m}_X$

Analytic results recovered when: $p_F(x) \to p_F \quad \phi(x) \to \langle\phi\rangle$ — relativistic mean-field theory

Introduce $C_\phi^2 = 4\alpha_\phi m_X^2/3\pi m_\phi^2$ with $\alpha_\phi = g_\phi^2/4\pi$

Fermi-momentum:

$$\frac{p_F}{m_X} = \left(\frac{2}{C_\phi^2}\right)^{\frac{1}{4}} \left(1 - \frac{1}{3}\left(\frac{2}{C_\phi^2}\right)^{\frac{1}{2}}\right)^{\frac{1}{2}}$$

effective-mass:

$$\frac{m_*}{m_X} \simeq \frac{1}{3}\left(\frac{2}{C_\phi^2}\right)^{\frac{1}{2}}$$

$C_\phi^2 \gg 1$ ⇒ $m_* \ll p_F \ll m_X$

$\longrightarrow \langle\phi\rangle \simeq \dfrac{m_X}{g_\phi}$

$\longrightarrow p_F \simeq \bar{m}_X$

Composite state basic properties are therefore:

mass:	radius:	number-density:
$M_X = N\bar{m}_X$	$R_X = \left(\dfrac{9\pi N}{4\bar{m}_X^3}\right)^{\frac{1}{3}}$	$n_X = \dfrac{\bar{m}_X^3}{3\pi^2}$

Cosmological formation

1707.02316
1701.05859
1411.3739

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

X overabundance

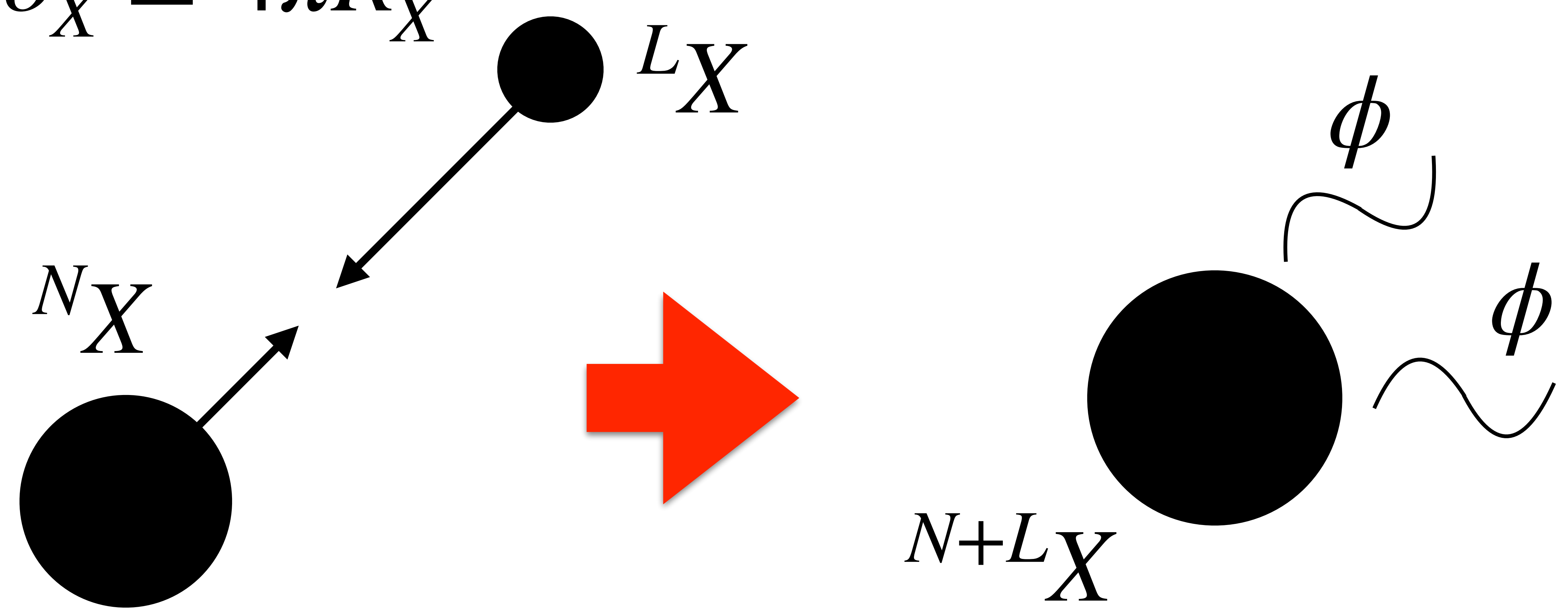
$T_{ca} \sim m_X/10$

e.g. phase transitions
metastable field decay
additional inflation

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

fusion in strong binding limit:

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



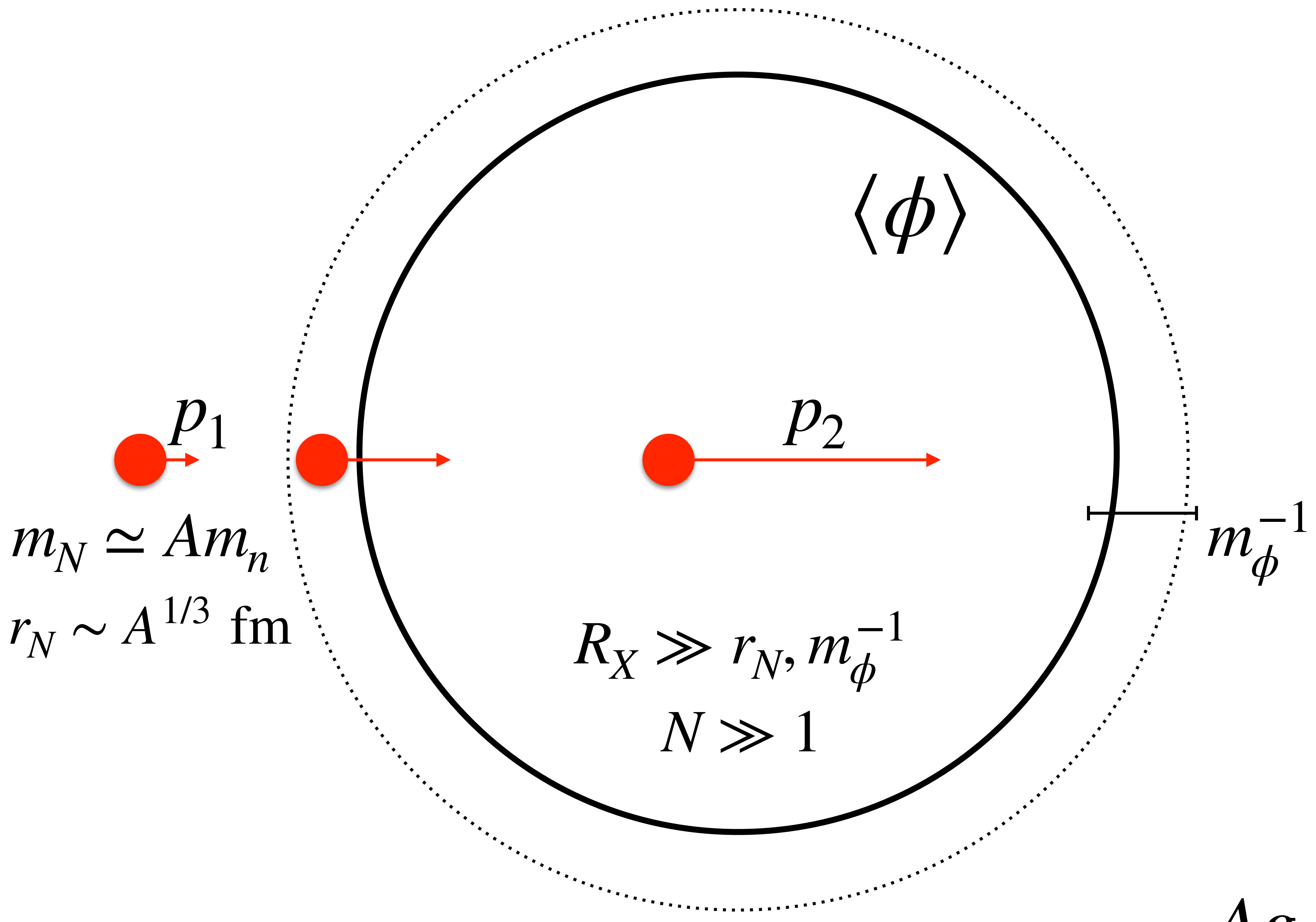
large composites can be formed by this process:

$$N_c \simeq \left(\frac{2 n_X v_X \sigma_X}{3H}\right)^{6/5} \simeq$$

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

Nuclear coupling

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



boundary conditions impose:

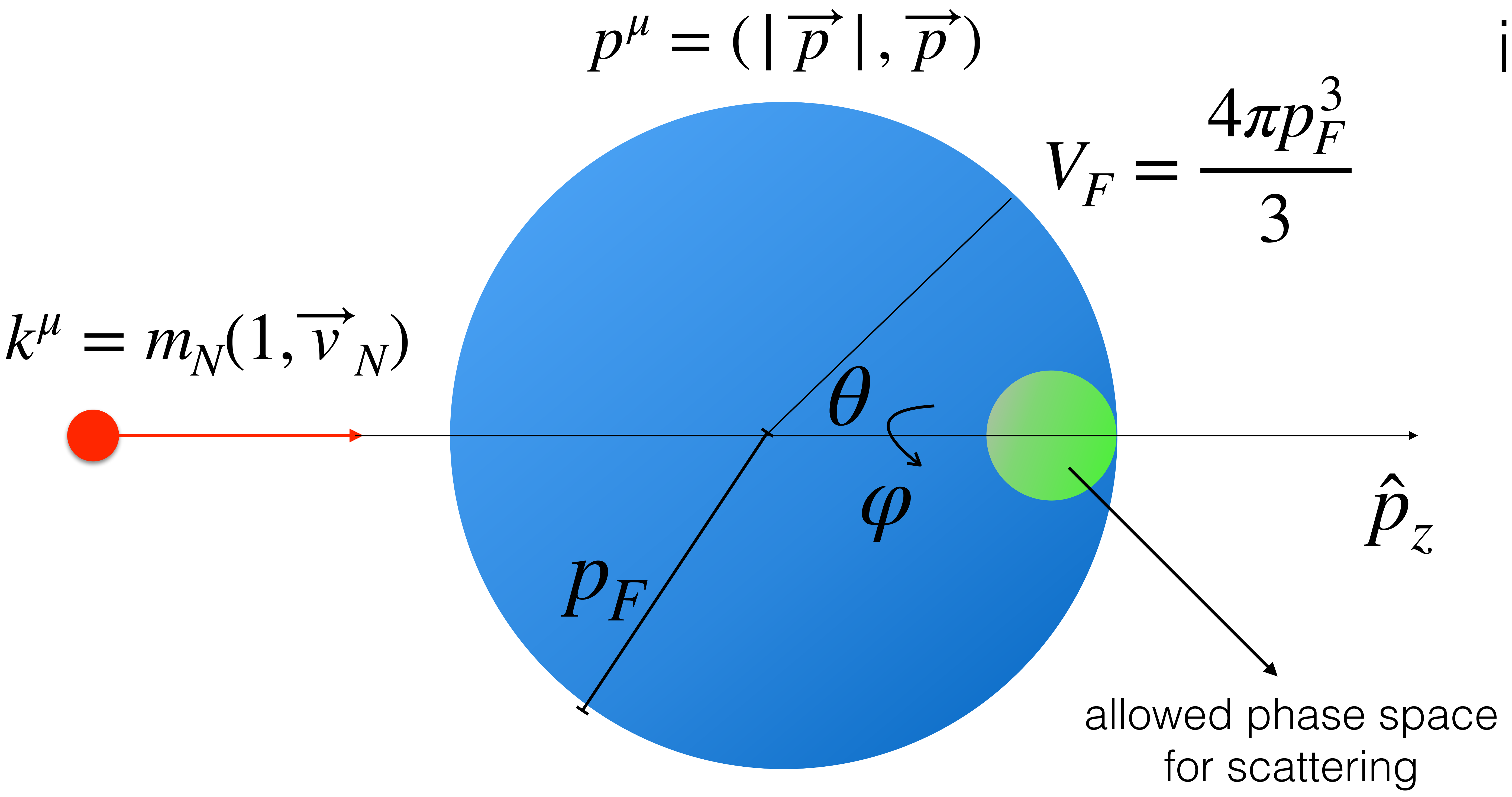
$$\phi(r) = \begin{cases} \langle\phi\rangle e^{-m_\phi(r-R_X)} \left(\frac{R_X}{r}\right) & r \geq R_X \\ \langle\phi\rangle \simeq \frac{m_X}{g_\phi} & r < R_X \end{cases}$$

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

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

N-X scattering

DM constituents are ultra-relativistic and degenerate:



Fermi sphere

in saturation limit: $\langle \phi \rangle \simeq \frac{m_X}{g_X}$

$$\mu = \epsilon_F = \sqrt{p_F^2 + \underbrace{(m_X - g_X\langle\phi\rangle)^2}_{= m_*^2}}$$

$$n_X = \frac{p_F^3}{3\pi^2} \sim \bar{m}_X^3$$

$$m^* \ll \bar{m}_X \simeq \epsilon_F, p_F \gtrsim \mathcal{O}(\mathrm{GeV})$$

naive scaling

$\Gamma_{NX} \sim n_X \sigma_{NX} v_{NX}$ wrong

Scattering rate of nuclei:

$$\Gamma_{NX} = 2\pi n_X \int_0^{p_F} \frac{dp\, p^2}{V_F} \int d(\cos\theta) \int d\alpha \int d(\cos\psi) \left(\frac{d\sigma}{d\Omega}\right)_{(CM)} \tilde{v}\ \Theta(\Delta E + p - p_F)$$

differential cross-section

Pauli-blocking

integrate over target phase space
(composite rest frame)

relativistic kinematics
(centre-of-momentum frame)

Energy loss rate: $\dot{E}_{NX} \simeq \Gamma_{NX} \times \Delta E_{max}$

Consider 2 limits:

$\dot{E}_{NX} \simeq A^2 g_n^2 g_\phi^2 \bar{m}_X^2 v_X^2\ ,\ \bar{m}_X \ll m_N$ 'heavy probe'

$\dot{E}_{NX} \simeq A^2 g_n^2 g_\phi^2 m_N^5 \bar{m}_X^{-3} v_X^8\ ,\ \bar{m}_X \gg m_N$ 'light probe'

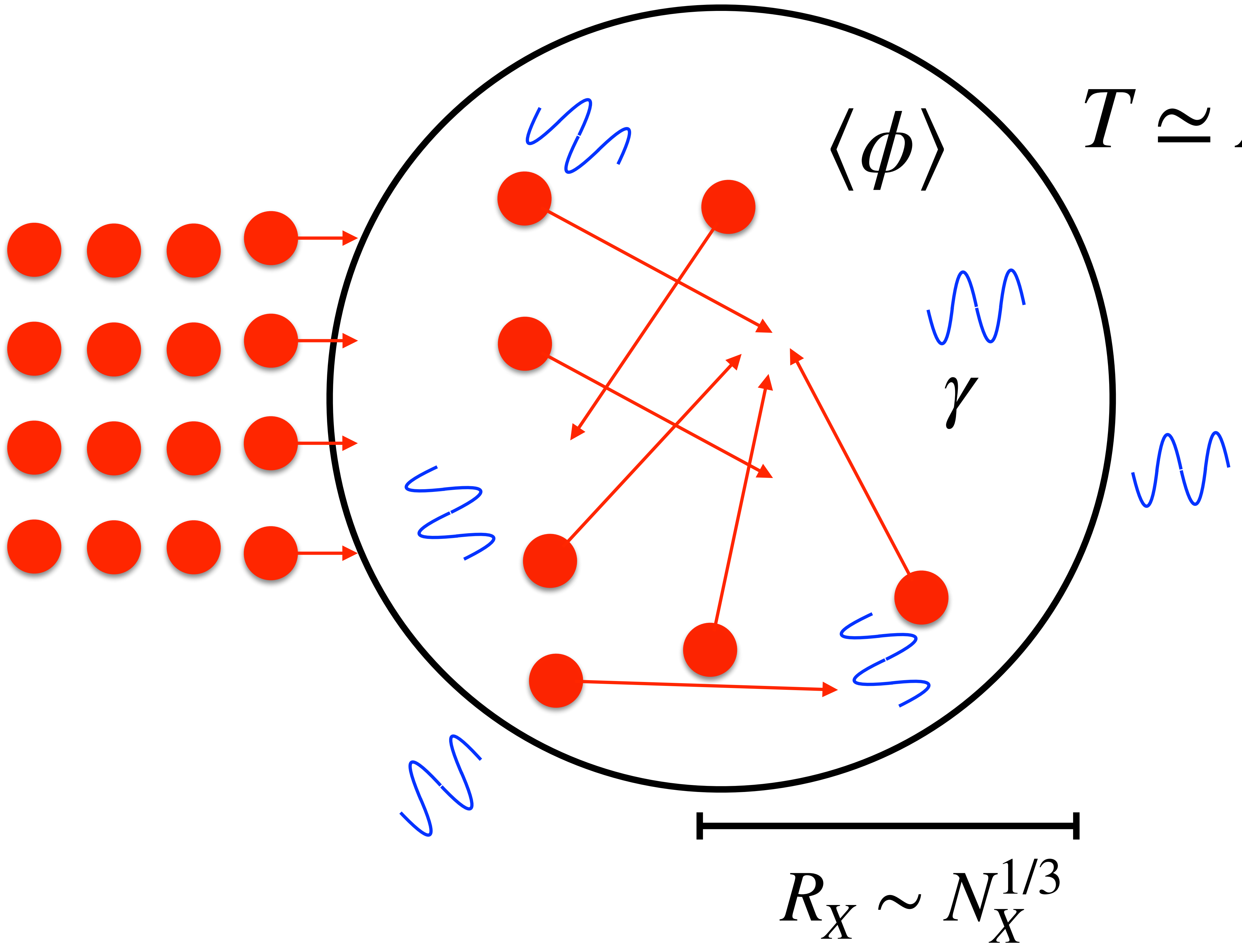
2004.09539

1911.13293

$g_n \lesssim 10^{-10}$ → nuclei barely scatter with DM constituents

Considering:

$\langle\phi\rangle \propto m_X \sim \mathrm{TeV} - \mathrm{EeV}$ ⟶ acceleration is substantial even for $g_n \ll 1$



$T \simeq A g_n \langle\phi\rangle$

Ionization (Migdal, collisions)

Thermal bremsstrahlung

Thermonuclear fusion

↓ temperature/energy

Potential signatures of this effect?

⟶ Direct detection

⟶ Type Ia supernovae

⟶ Earth heating (in progress)

2012.10998

Direct detection signatures

bremsstrahlung + fusion requires $R_X \gtrsim 10^{-7}$ cm $\longrightarrow$ $M_X \gtrsim 10^{21}$ GeV

$$N_c = \left(\frac{2n_X\sigma_X v_X}{3H}\right)^{6/5} \quad R_X = \left(\frac{9\pi N_c}{4\bar{m}_X{}^3}\right)^{\frac{1}{3}}$$

~1 detectable DM event per year requires: $\dfrac{\rho_X v_X A_{det} t_{exp}}{M_X} \simeq 1$

$$M_X^{max} \simeq \rho_X v_X A_{det} t_{exp} \longrightarrow M_X^{max} \simeq 10^{18} \text{ GeV}$$

$\rho_X \simeq 0.3$ GeV cm^{-3}

$v_X \simeq 220$ km s^{-1}

$t_{exp} \sim 10$ yrs

e.g. Xenon
Lux
PandaX

Need $A_{det} \gtrsim 10^6$ cm^2 $\longrightarrow$ neutrino obs., e.g. IceCube, SNO+

1812.09325

Where in parameter space may these experiments have sensitivity?

→ Energetics

→ Existing bounds on coupling

To trigger detectors:

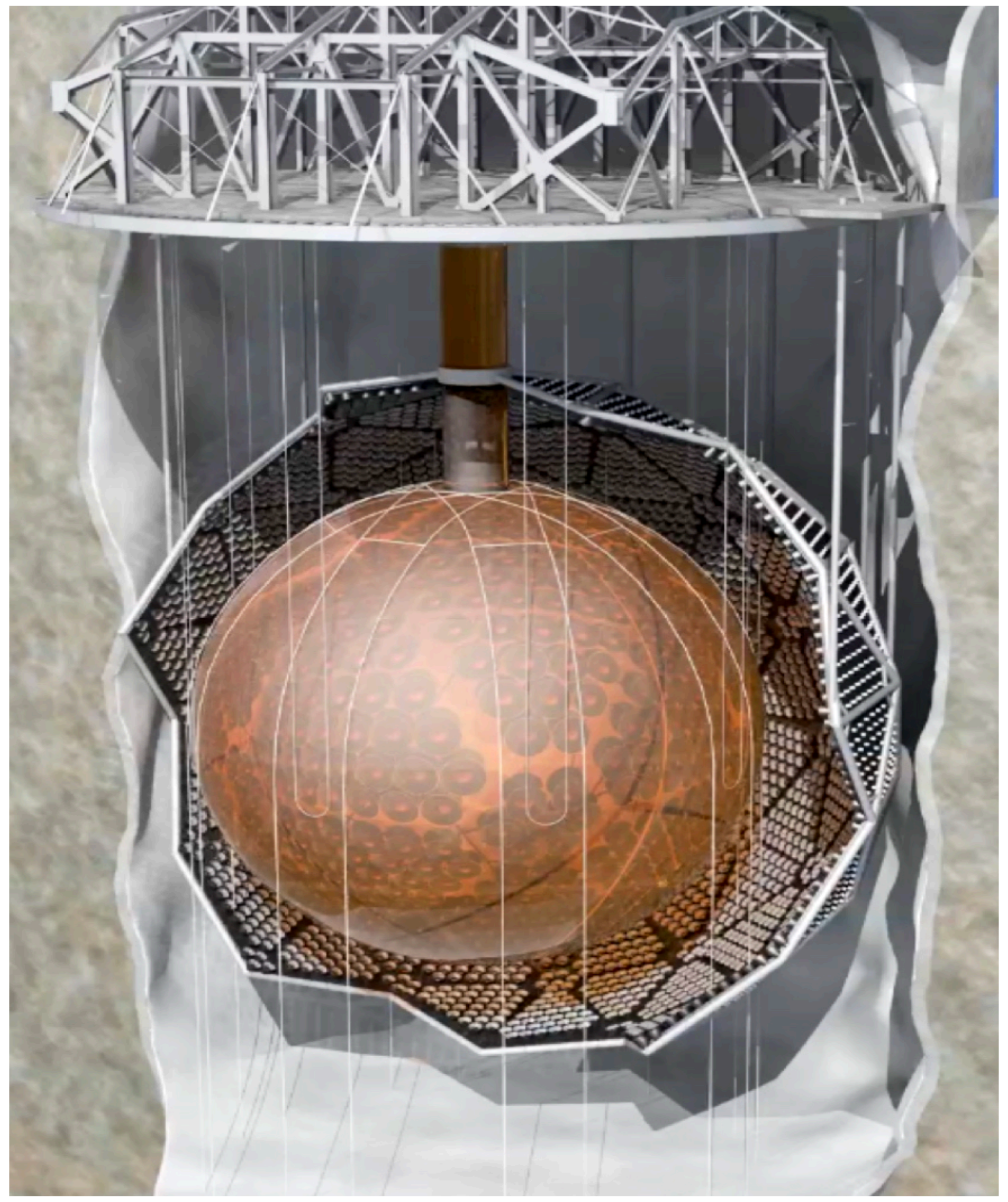
SNO+: ~1 MeV per 100 ns

IceCube: ~10 TeV per 100 ns (~100 PeV in single crossing)

Composites radiate continuously along path:

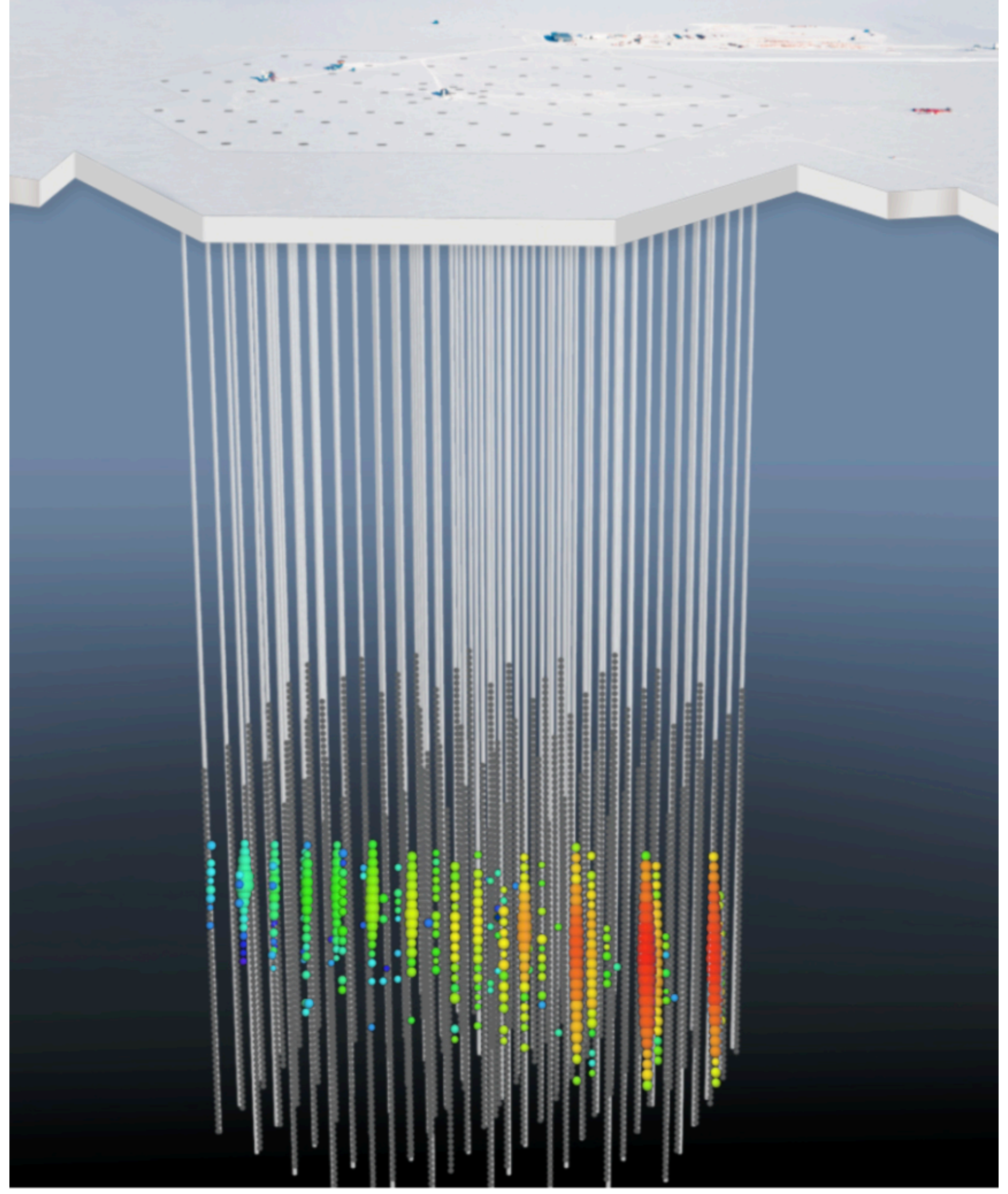
$$\dot{E}_{SNO+} \simeq 10^4 \text{ GeV s}^{-1} \qquad \dot{E}_{IC} \simeq 10^{11} \text{ GeV s}^{-1}$$

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



~12 m

SNO+



~1 km

IceCube

1611.05852

1709.07882

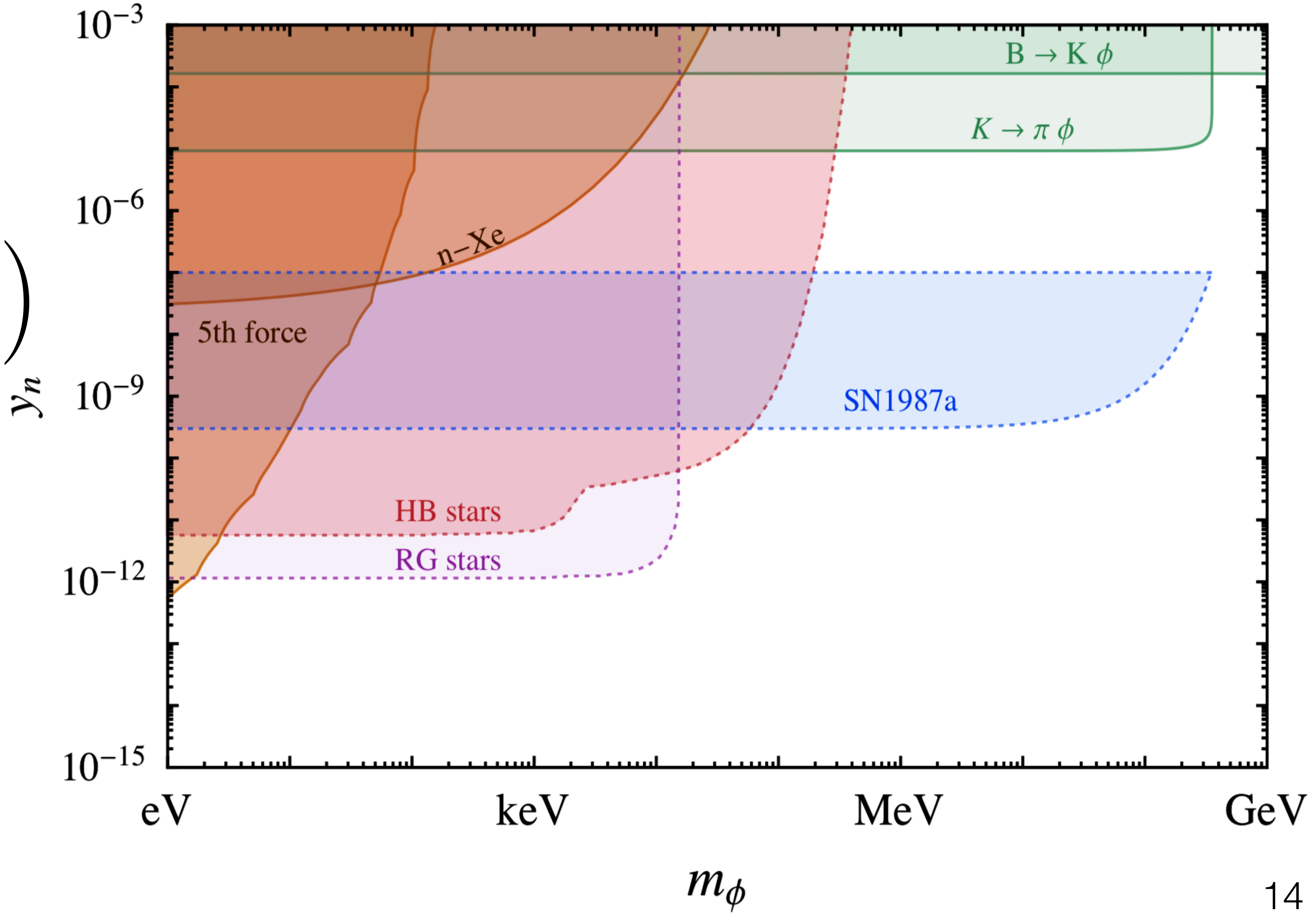
Stellar cooling bounds on coupling limit the kinetic energy:

$$\Delta E \simeq A g_n \left(\frac{m_X}{g_\phi}\right)$$

$$\lesssim \text{keV} \left(\frac{g_n}{10^{-10}}\right)\left(\frac{m_X}{\text{TeV}}\right)\left(\frac{1}{g_\phi}\right)\left(\frac{A}{10}\right)$$

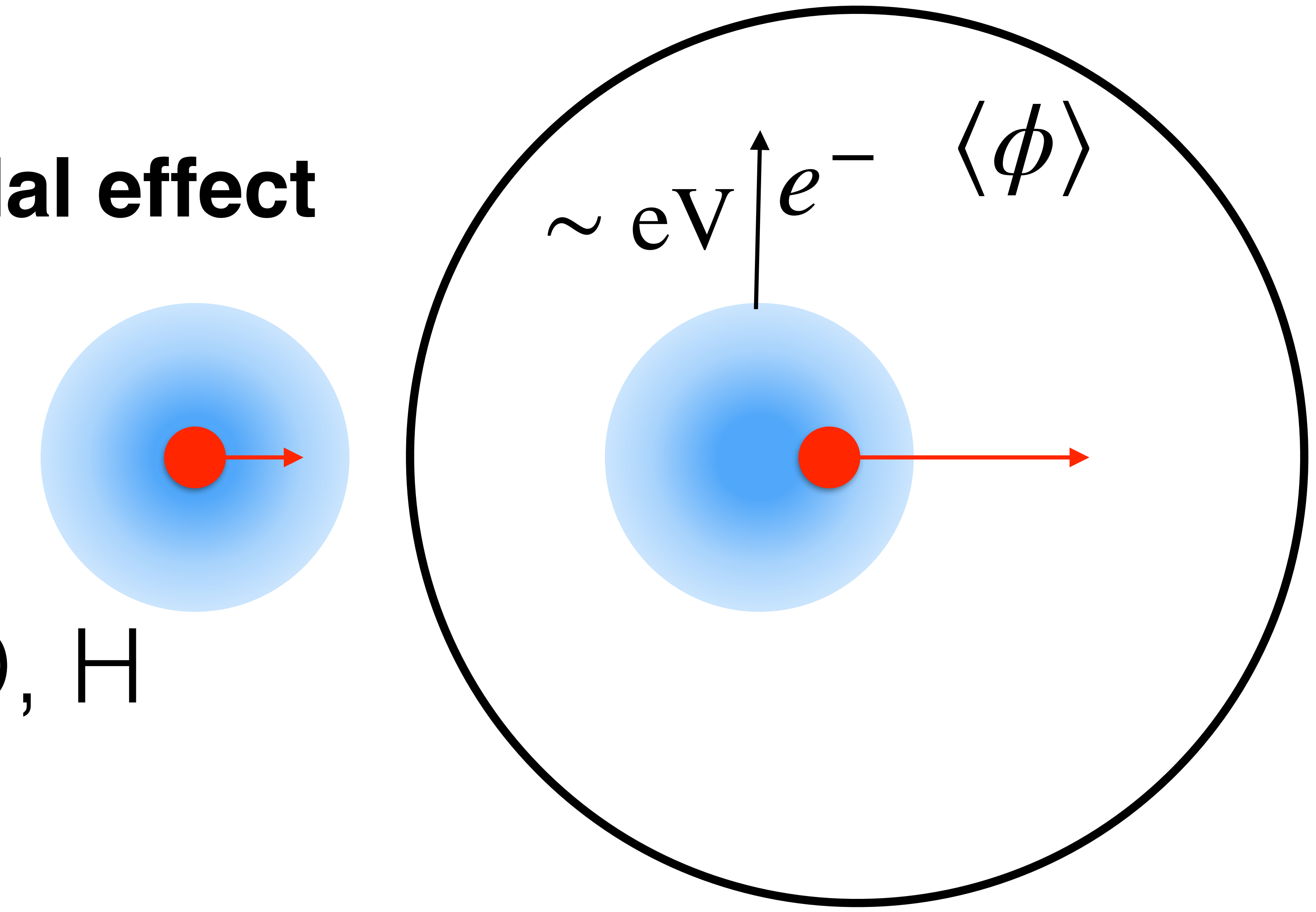
for ϕ masses < eV

5th force searches further constrain coupling



1) Ionization $R_X m_\phi \gg 1$

Migdal effect



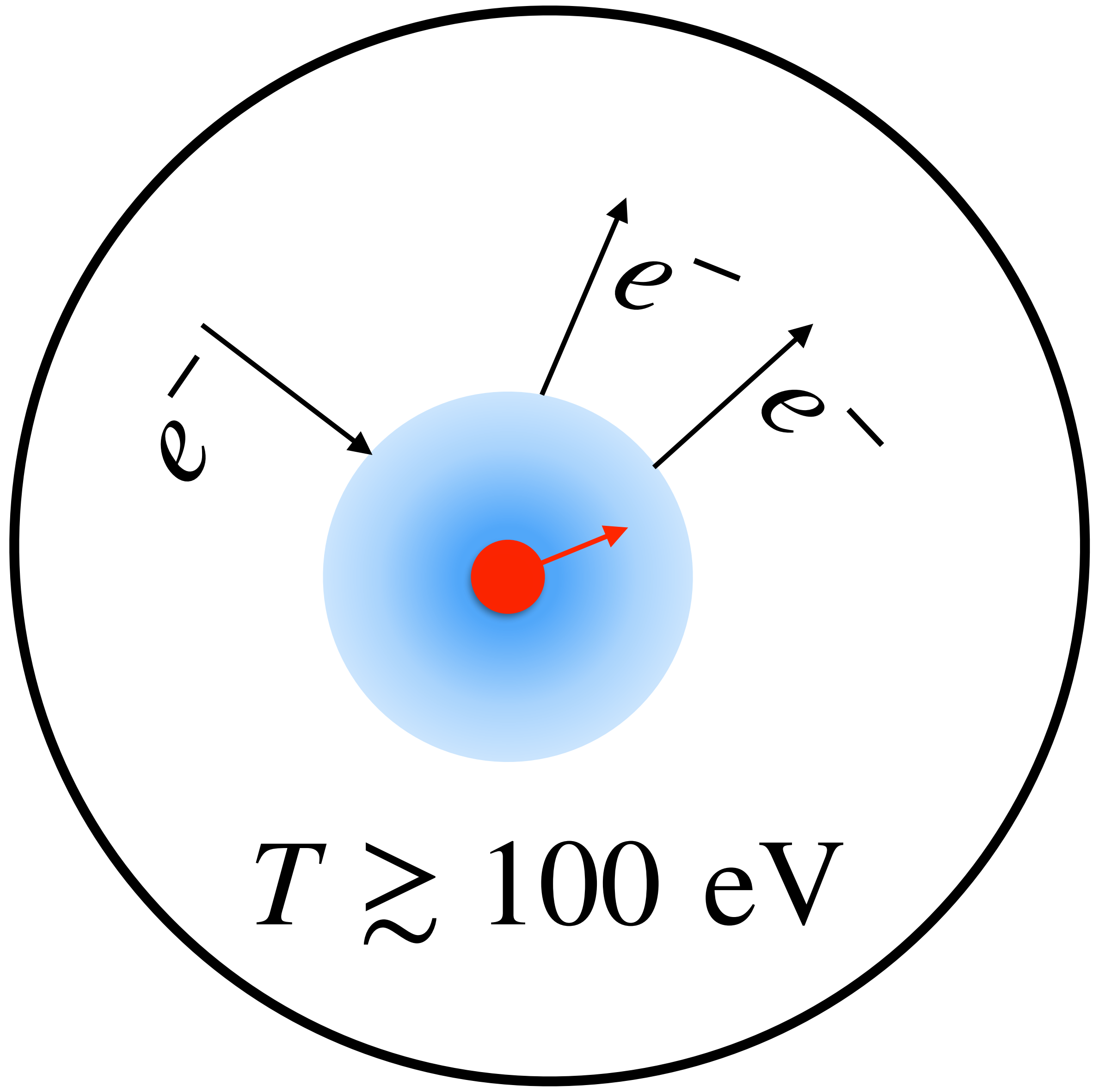
C, O, H

acceleration timescale:

$$\tau_{accel} \simeq (m_\phi v_X)^{-1} \left(1 + \frac{2V_n}{m_N v_X^2} \right)^{-\frac{1}{2}} \lesssim 10^{-18}\ \mathrm{s} \left(\frac{10\ \mathrm{keV}}{m_\phi} \right)$$

electrons are unbound w/ prob $f_e \gtrsim 10^{-2}$

Collisional ionization



ionization from e- impacts:

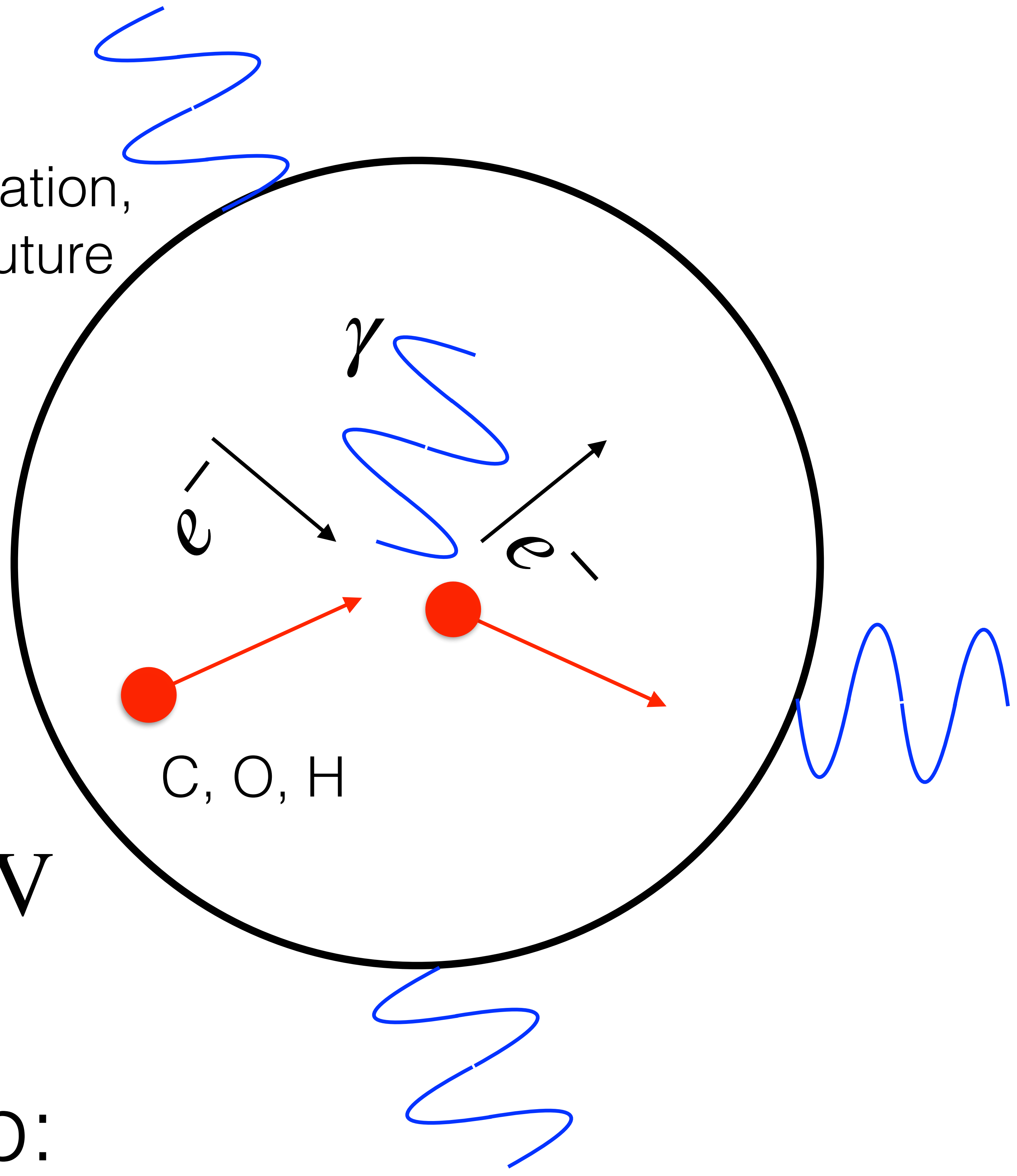
$$\left(f_e n_e v_N \sigma_i \right)^{-1} \lesssim 10^{-15}\ \mathrm{s}$$

$n_e \sim 10^{23}\ \mathrm{cm}^{-3}$

$\sigma_i \gtrsim 10^{-17}\ \mathrm{cm}^2$

$T \gtrsim 100\ \mathrm{eV}$ completely ionized matter

2) Bremmsstrahlung



$T \gtrsim 100 \text{ eV}$

photon mfp:

$$(n_e \sigma_T)^{-1} \simeq 5 \text{ cm} \gg R_X$$

$$\sigma_T \simeq 10^{-24} \text{ cm}^2$$

specific emissivity:

$$j_\omega = \frac{16\pi e^6 n_e^2}{3\sqrt{3} m_e^2} \exp\left(-\frac{\omega}{T}\right), \quad n_e \sim 10^{23} \text{ cm}^{-3}$$

radiated energy rate:

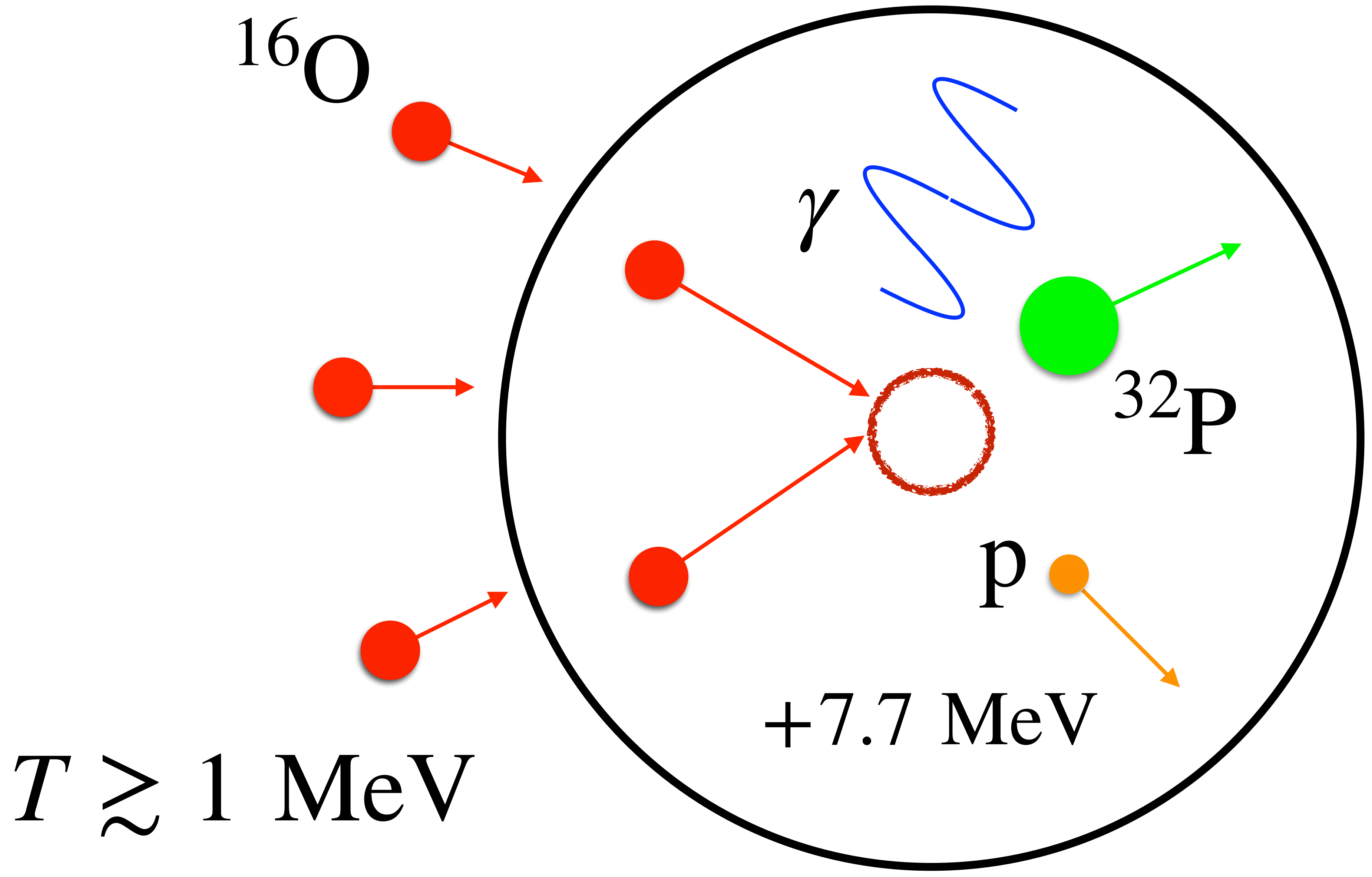
$$\dot{E}_{brem} = \int j_\omega(T) \, d\omega dV \simeq$$

$$\simeq 10^{10} \text{ GeV s}^{-1} \left(\frac{m_X}{\text{TeV}}\right)^{\frac{3}{2}} \left(\frac{R_X}{\text{nm}}\right)^3 \left(\frac{g_\phi}{1}\right)^{-\frac{1}{2}} \left(\frac{g_n}{10^{-10}}\right)^{\frac{1}{2}}$$

can also compute stopping length:

$$L_{stop} \simeq 2 \text{ km} \left(\frac{m_X}{\text{TeV}}\right)^{\frac{3}{2}} \left(\frac{m_\phi}{10 \text{ keV}}\right)^2 \left(\frac{g_n}{10^{-10}}\right)^{-\frac{1}{2}} \left(\frac{g_\phi}{1}\right)^{-\frac{3}{2}} \left(\frac{v_X}{200 \text{ km s}^{-1}}\right)^3$$

3) Fusion



reaction rate per unit volume:

$$R_{th}(T \simeq \text{MeV}) \sim 10^{24}\ \text{cm}^{-3}\ \text{s}^{-1} \left(\frac{\rho}{1\ \text{g cm}^{-3}} \right)^2$$

Caughlan & Fowler, 1988

average energy release: $\bar{Q} \sim 10$ MeV

more complete reaction network left for future work

(e.g. disintegration/recapture)

rare to occur while in detection volume:

SNO+ too small $\longrightarrow$ $M_X \lesssim 10^{22}$ GeV

IceCube requires $T \gtrsim 5$ MeV $\longrightarrow$ ~1 reaction per crossing

Parameter space of potential detectability:

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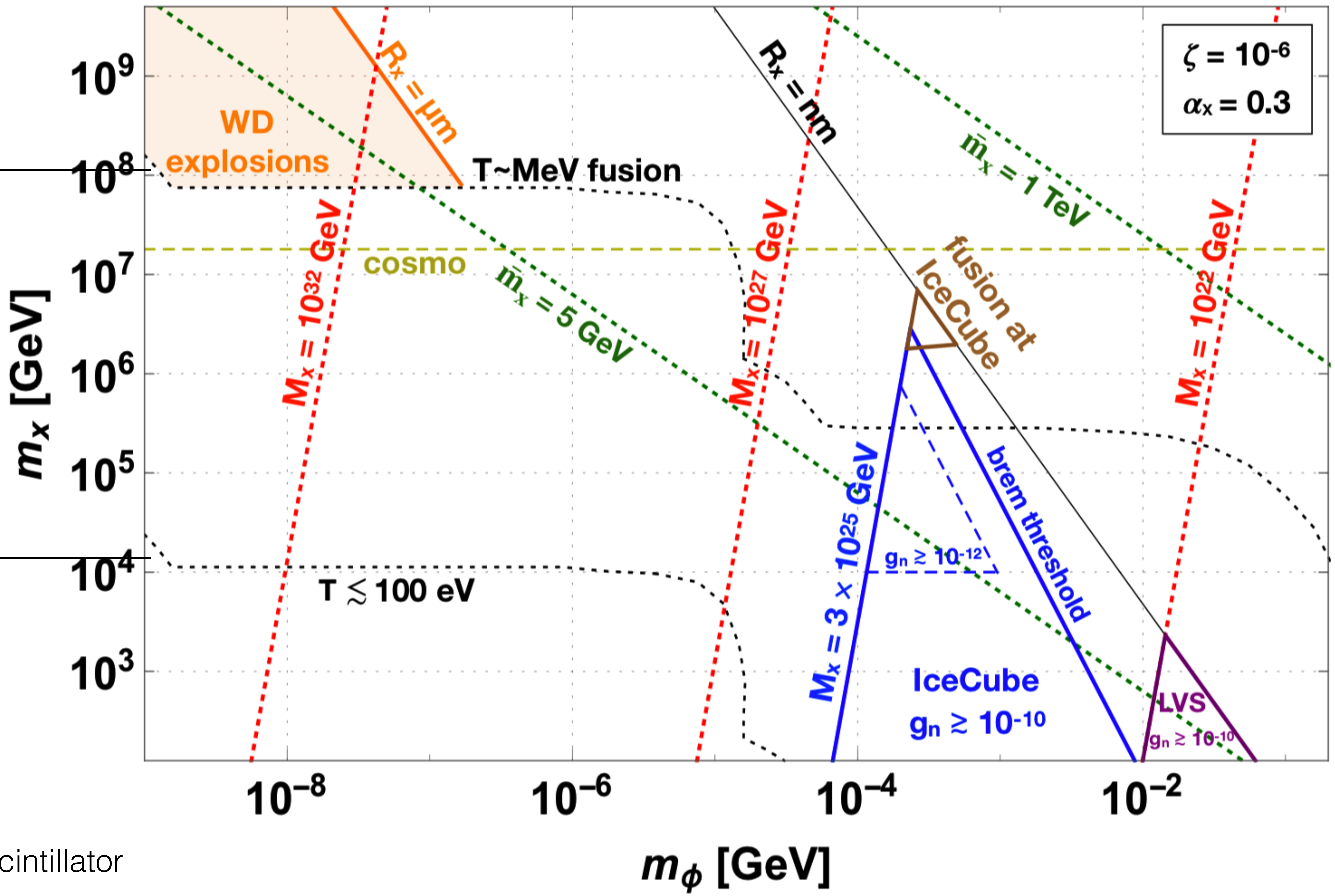
increasing radius/mass

stellar cooling constraints

stellar cooling constraints



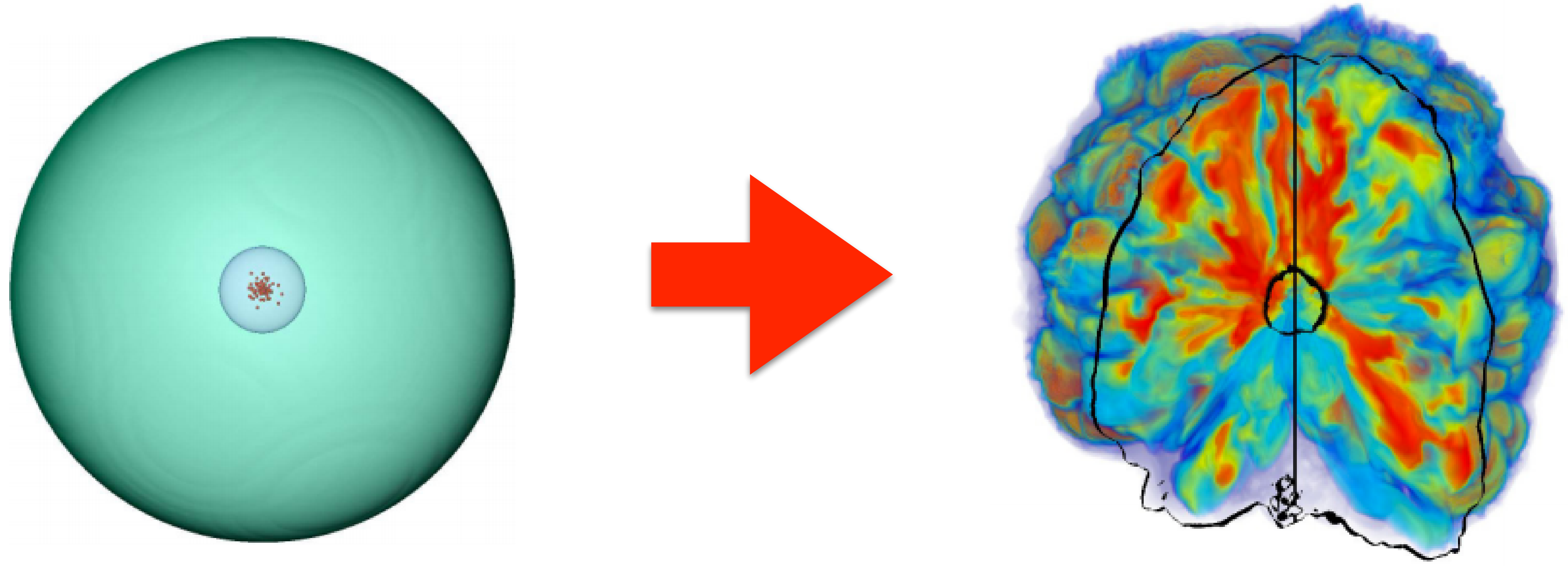
increasing temperature (fixed coupling)

increasing composite binding energy

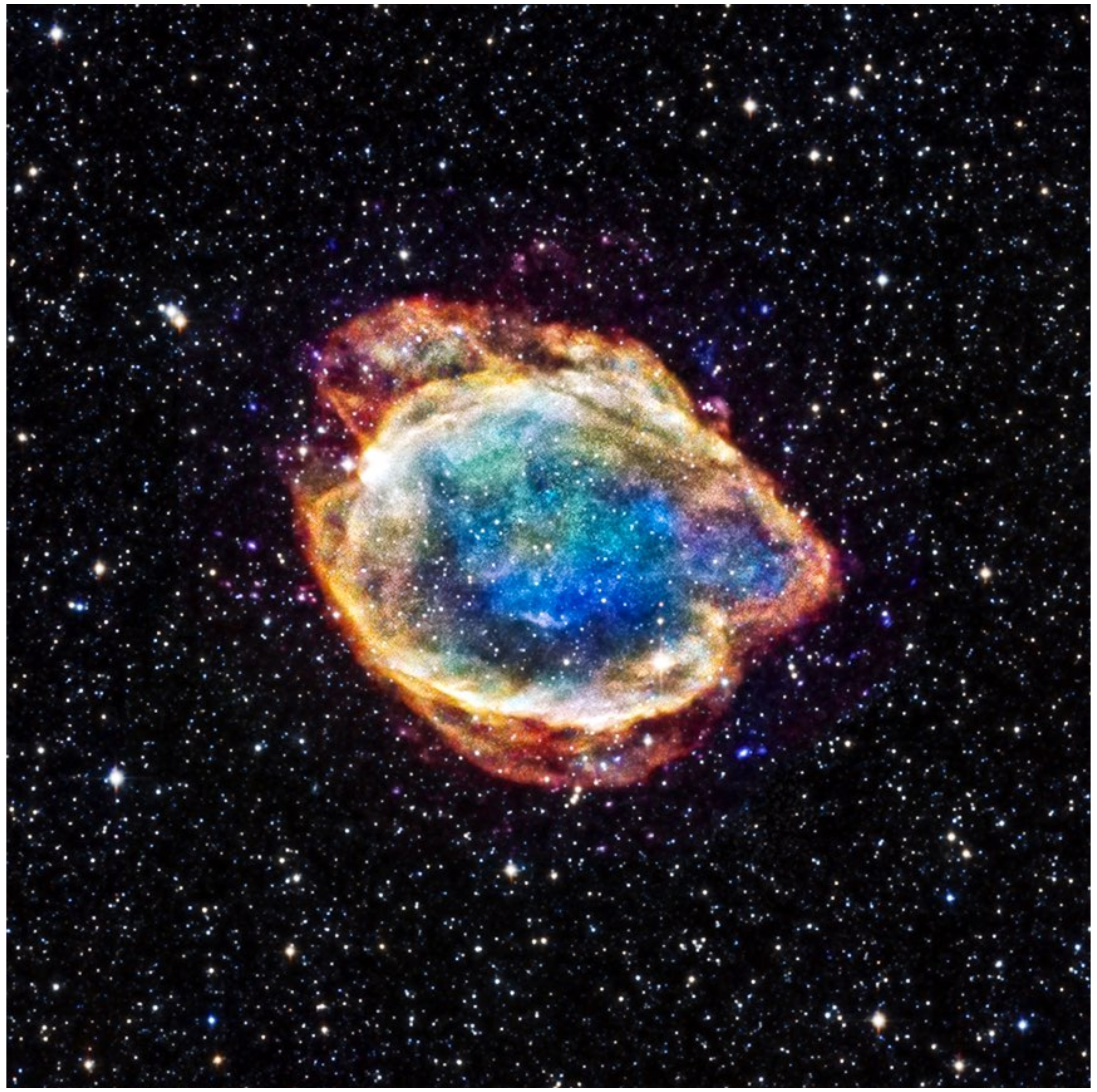
LVS = large volume scintillator

Type Ia supernovae

Thermonuclear explosions of WDs



localized heat deposition leads to runaway fusion

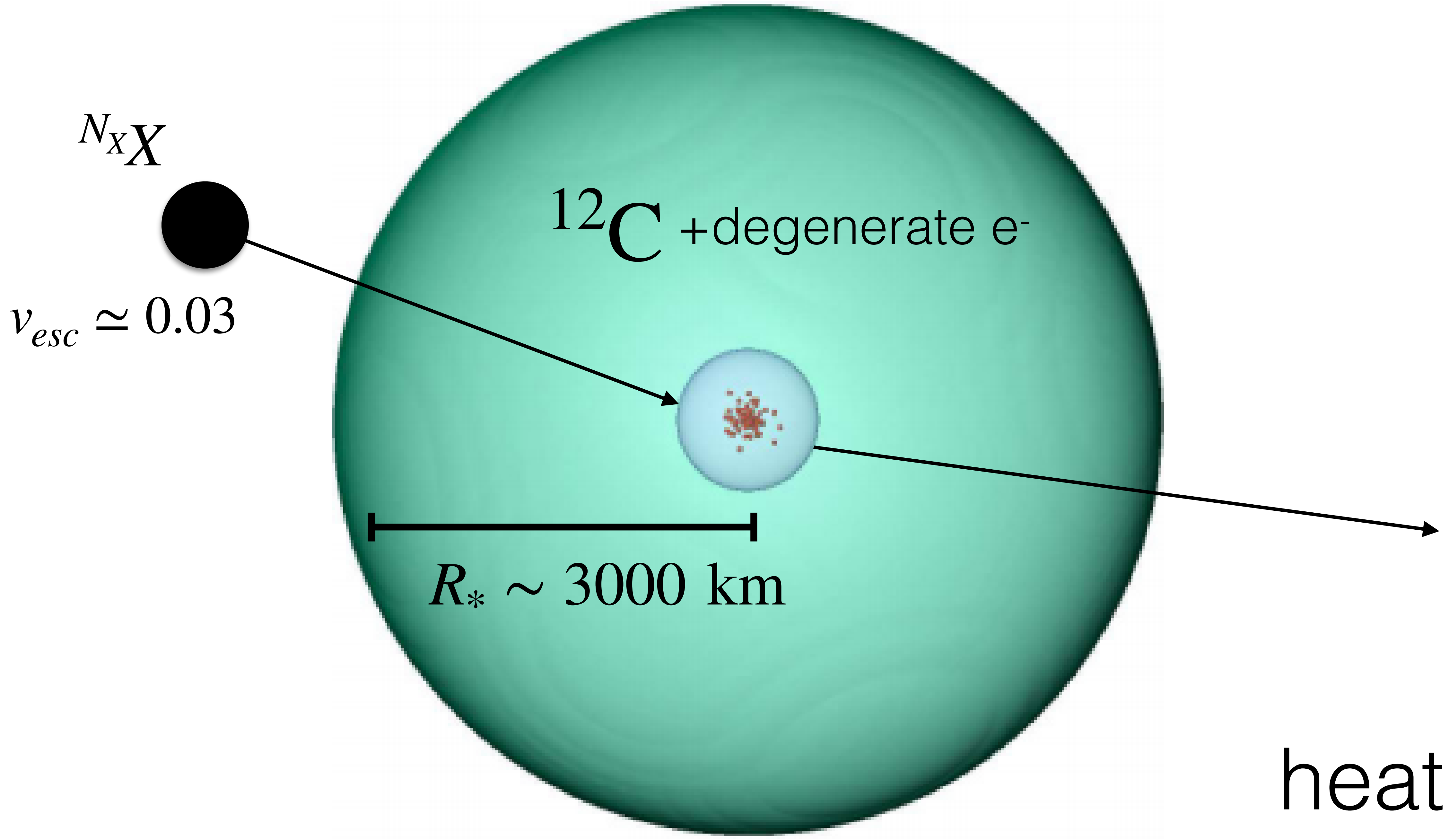


G299.2-2.9, Chandra X-ray telescope

- Accretion/double detonation, WD mergers
- Dark matter accumulation
- PBH transit

0506.386
1505.07464
1904.11993

Consider large composite state crossing WD:



ignition requires

$T_{crit} \simeq 10^{10}$ K $\sim$ MeV

$\rho_* \simeq 10^9$ g cm^{-3}

heating rate > heat diffusion

'trigger mass'

relevant reactions:

$^{12}\mathrm{C}(^{12}\mathrm{C}, \alpha)^{20}\mathrm{Ne} + 4.6\ \mathrm{MeV}$

$^{12}\mathrm{C}(^{12}\mathrm{C}, \mathrm{p})^{23}\mathrm{Na} + 2.2\ \mathrm{MeV}$

$^{12}\mathrm{C}(^{12}\mathrm{C}, \mathrm{n})^{23}\mathrm{Mg} - 2.6\ \mathrm{MeV}$

yield:

0.53/0.40/0.07

$\bar{Q} \sim 3$ MeV

rate: $R_{th}(T = \mathrm{MeV}) \simeq 10^{42}\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1} \left(\frac{\rho_*}{10^9\ \mathrm{g\ cm}^{-3}}\right)^2$

2012.10998

Must also consider energy dissipation:

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

e^- conduction

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

radiation

Composite kinetic energy: $$\frac{1}{2} M_X v_{esc}^2 \gtrsim 10^{28}\ \mathrm{GeV} \left(\frac{M_X}{10^{32}\ \mathrm{GeV}}\right)$$

heavy composites not significantly stopped

$$v_{esc} \simeq 0.03$$
$$R_* \simeq 3000\ \mathrm{km} \longrightarrow \Delta t_{cross} \simeq 1\ \mathrm{s}$$

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

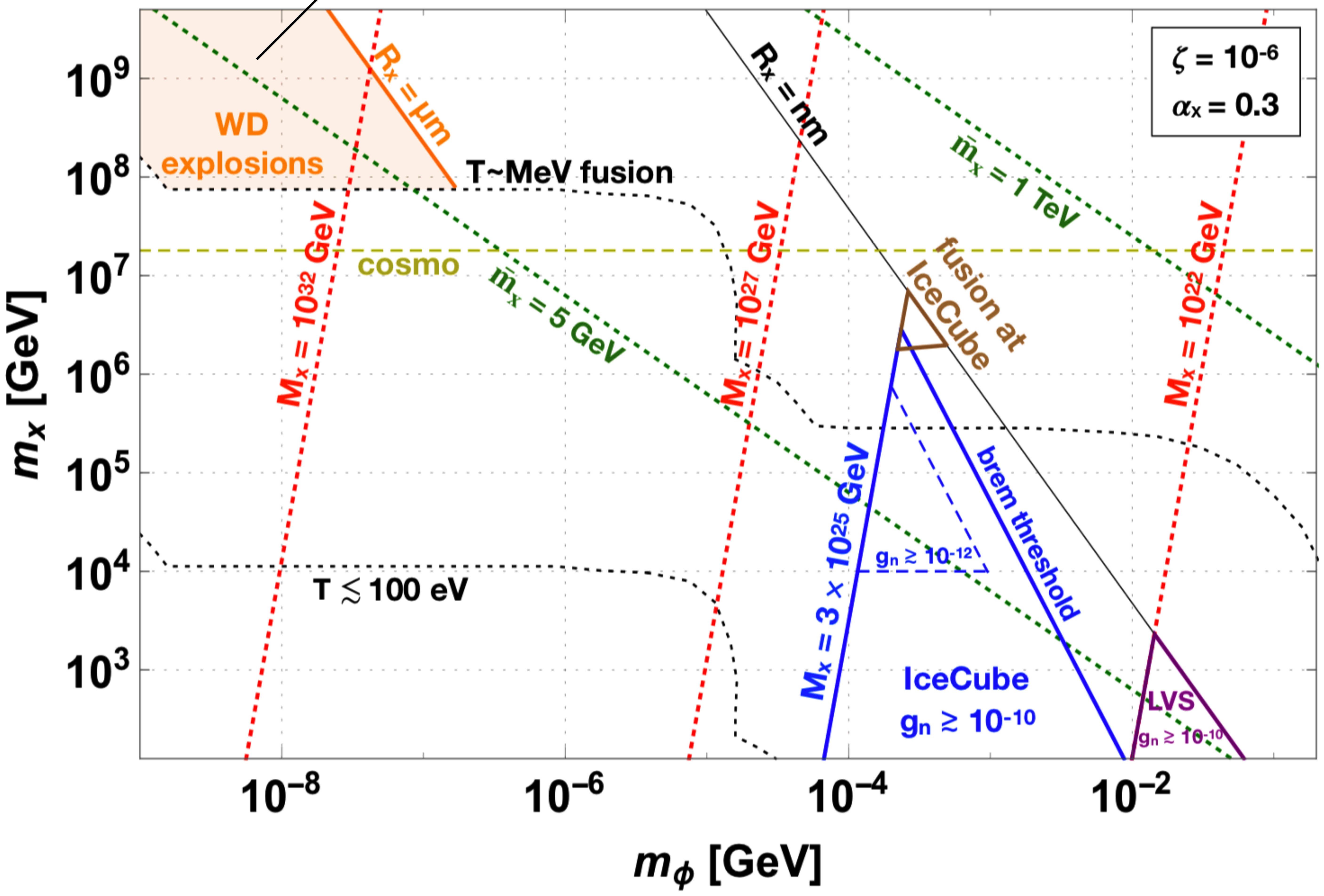
~μm sized composites can ignite core

Trigger mass lines up with ignition simulation results

WD survival on ~Gyr scales imply bounds on coupling, for masses

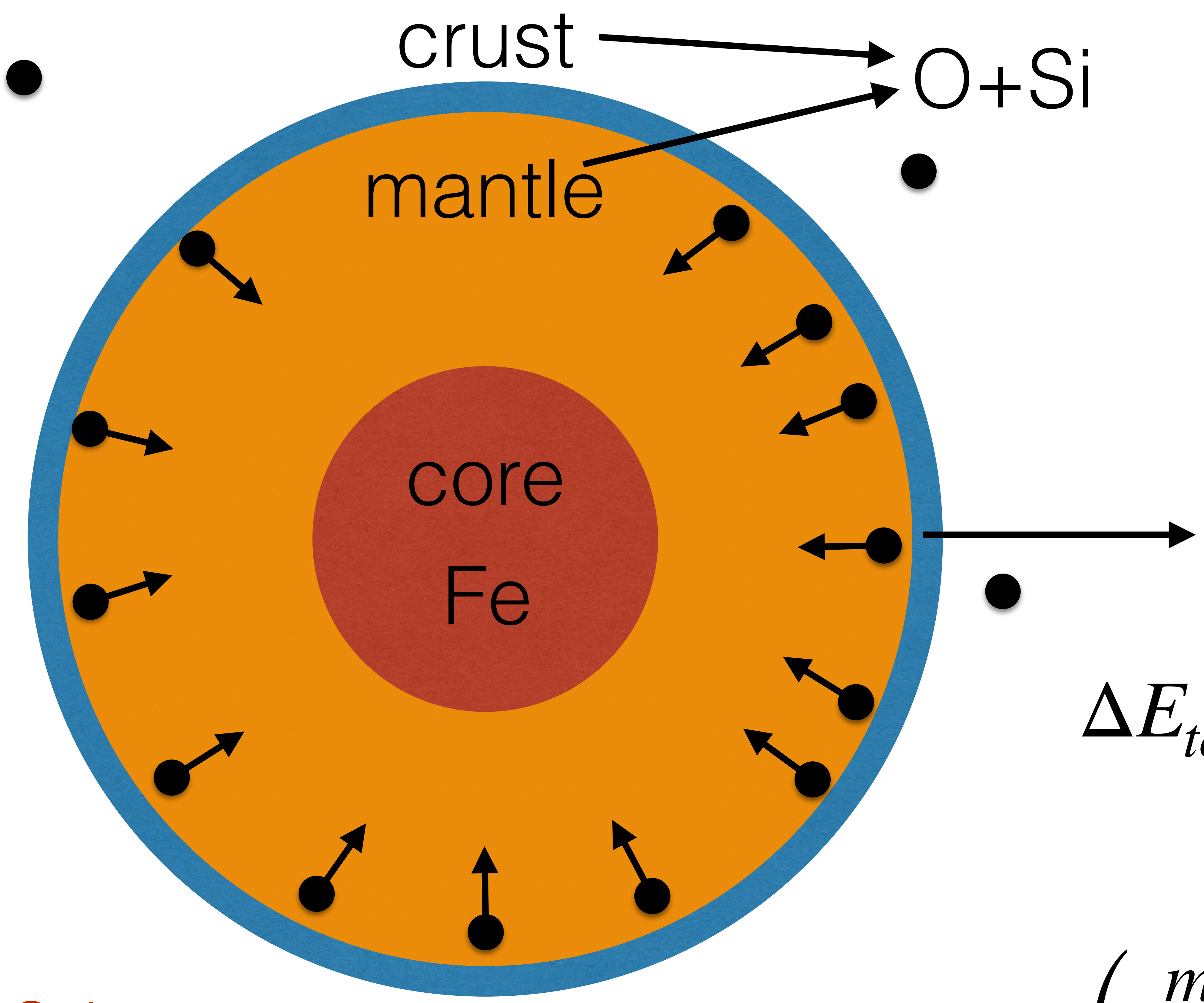
$$M_X \lesssim 10^{42}\ \text{GeV}$$

$$g_n \lesssim 10^{-12}\left(\frac{10^8}{m_X}\right)$$



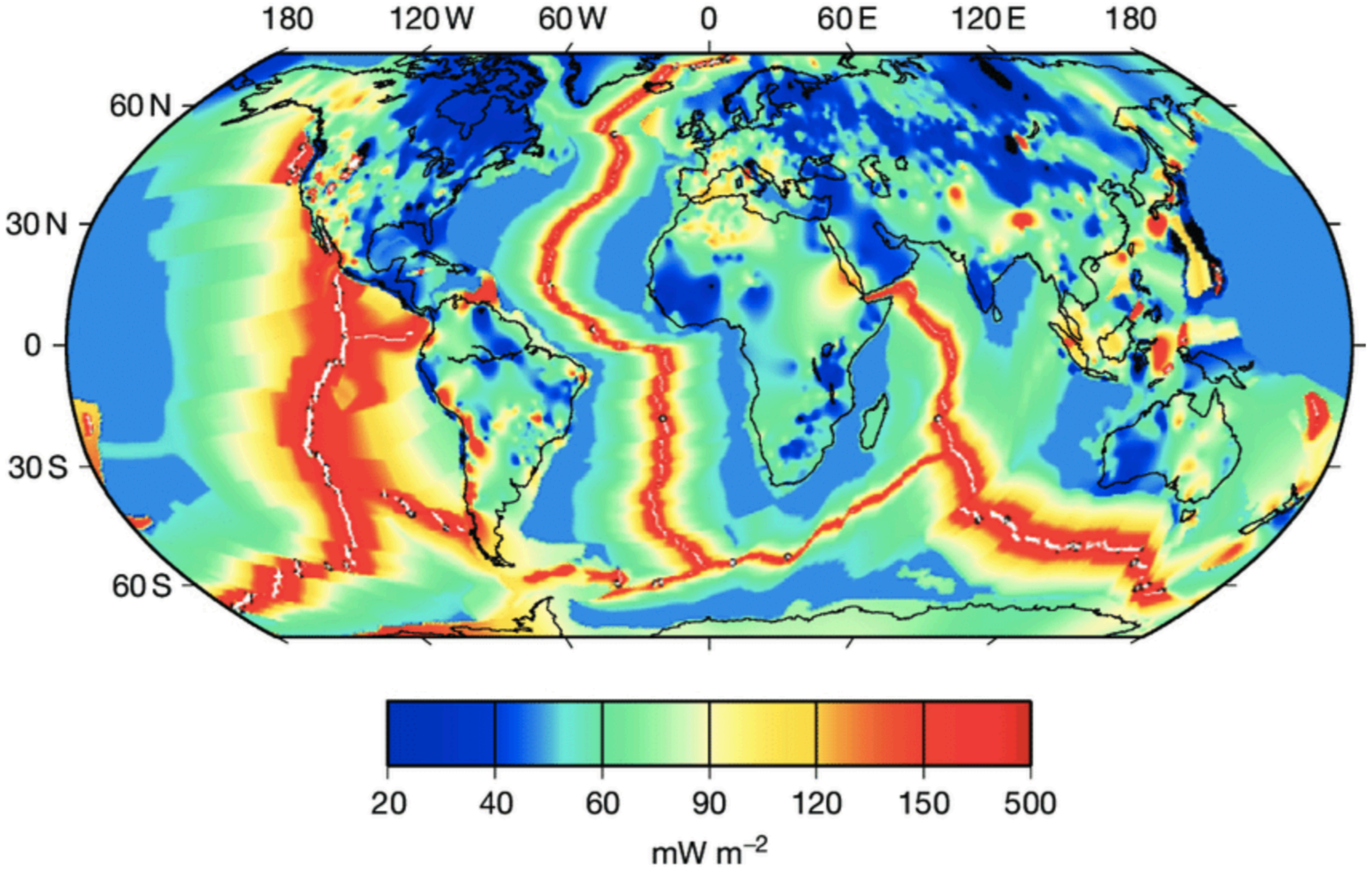
Earth heating

Composite capture, reactions in the mantle:



$$\dot{E} \sim R_X^3 R_{th} \bar{Q}$$

$$\Delta E_{tot} = N_{tot}(t) \times \dot{E} \times \Delta t_{cross}$$



total heat flux
~44 TW

$$L_{stop} \simeq 2\ \mathrm{km} \left(\frac{m_X}{\mathrm{TeV}}\right)^{\frac{3}{2}} \left(\frac{m_\phi}{10\ \mathrm{keV}}\right)^{2} \left(\frac{g_n}{10^{-10}}\right)^{-\frac{1}{2}} \left(\frac{g_X}{1}\right)^{-\frac{3}{2}} \left(\frac{v_X}{200\ \mathrm{km\ s^{-1}}}\right)^{3}$$

A,B&G, in prep.
2012.09176
1909.11683

Conclusions

Large composite states whereby nuclei are coupled to the binding field presents interesting phenomenology:

→ Radiation and fusion potentially observable at large neutrino observatories.

→ Can catalyze thermonuclear runaway in WDs, leading to Type Ia SNe.

→ Earth's heat flux may be used to set bounds on the coupling.

More to be done

→ Inclusion of vector field that couples to nuclei:

$$\mu \to g_V V_0 + \sqrt{k_F^2 + (m_X - g_\phi \phi)^2} \qquad V_0 \equiv \langle V^\mu \rangle \delta_{\mu 0}$$

→ Migdal effect and searches for weakly-coupled composites.

→ Implications for BBN abundances and other cosmological observables.

→ Stellar and planetary capture and heating.

→ Look into other composite DM models.

Thank you for
your attention!