Detecting Composite Dark Matter with Bremsstrahlung and the Migdal Effect

BNL High Energy Theory Seminar

Javier Acevedo

Dec. 2nd 2021

based on:

JA, Bramante & Goodman

2108.10889

2012.10998

17jfa1@queensu.ca

Queen's University

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

Outline

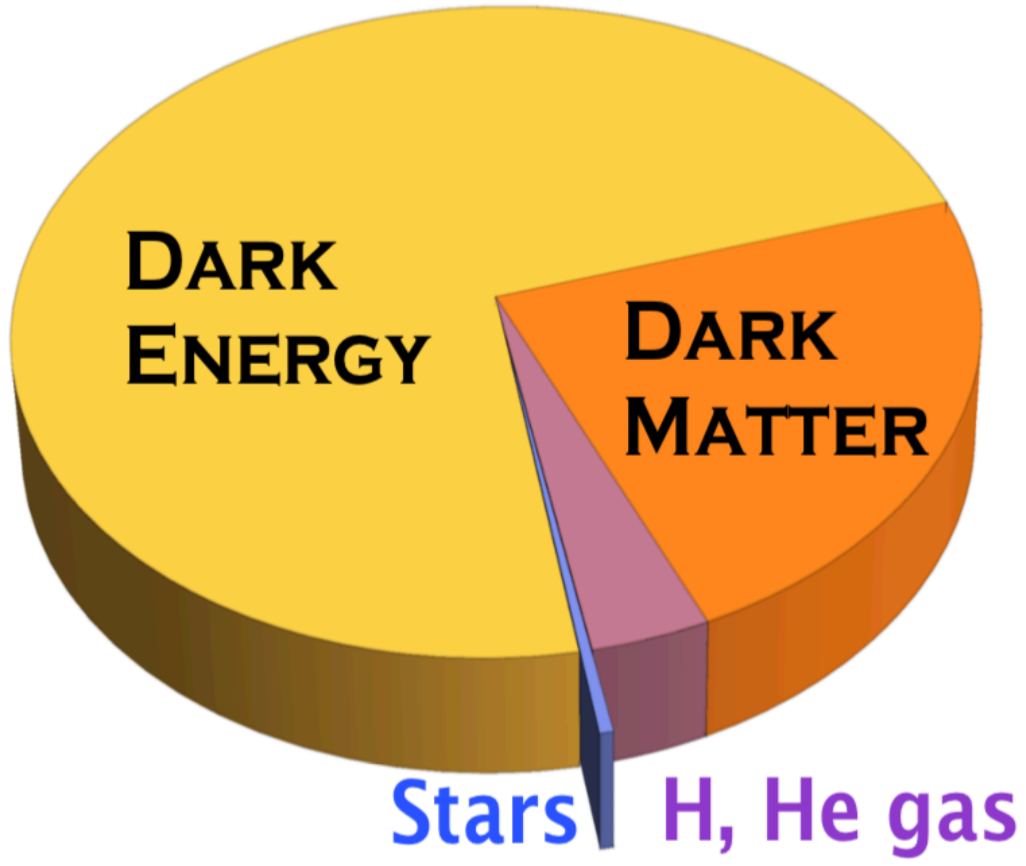
I. Composite Dark Matter

II. Direct Detection Signals

III. Astrophysical Signatures

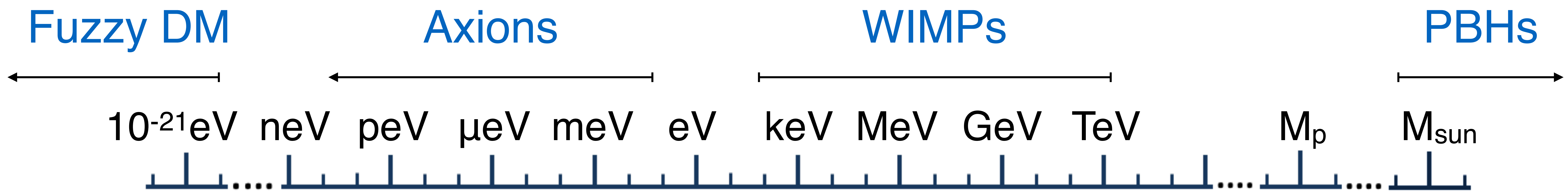
I. Composite Dark Matter

Dark Matter

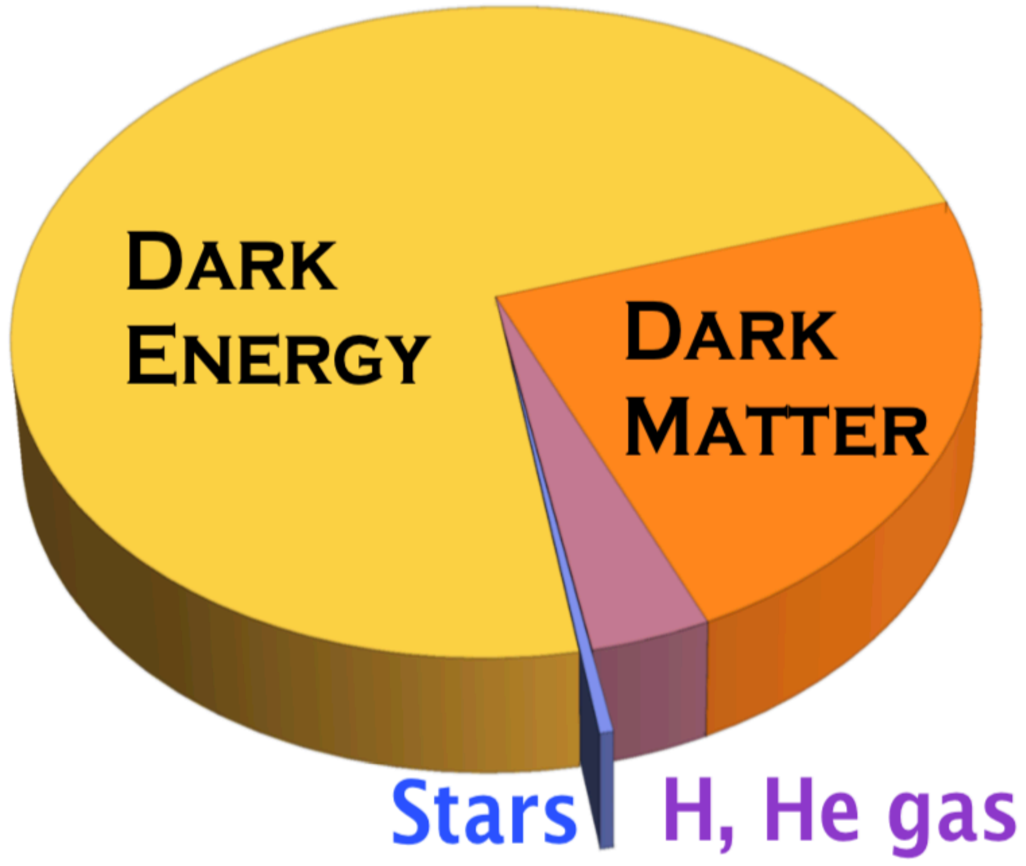


~ 26% energy content, but only gravitational interactions known

Mass range is extremely broad:



Dark Matter



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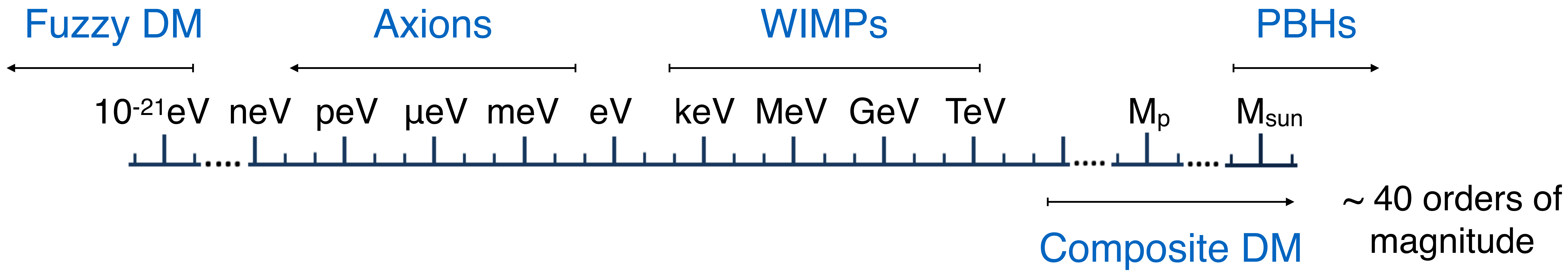
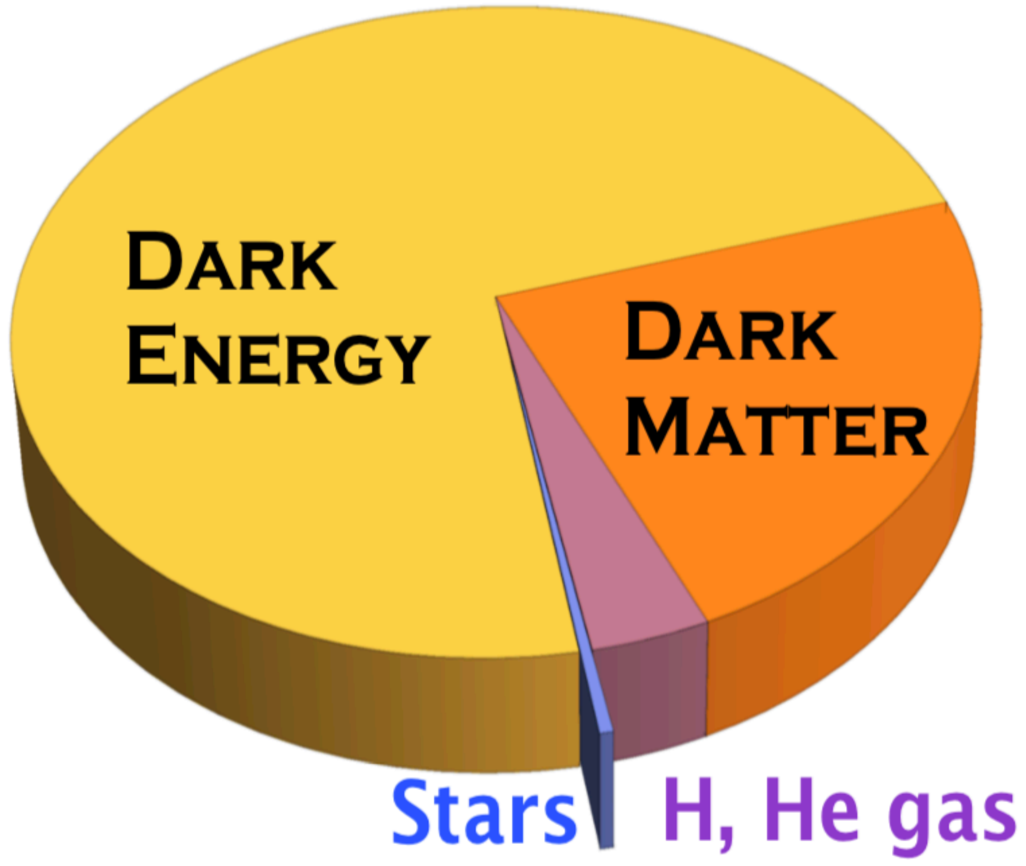


Dark Matter



~ 26% energy content, but only gravitational interactions known

Mass range is extremely broad:

Fuzzy DM   Axions   WIMPs   PBHs

10^{-21}eV neV peV μeV meV eV keV MeV GeV TeV M_p M_{sun}

~ 40 orders of magnitude

Composite DM

few events at DM exp.

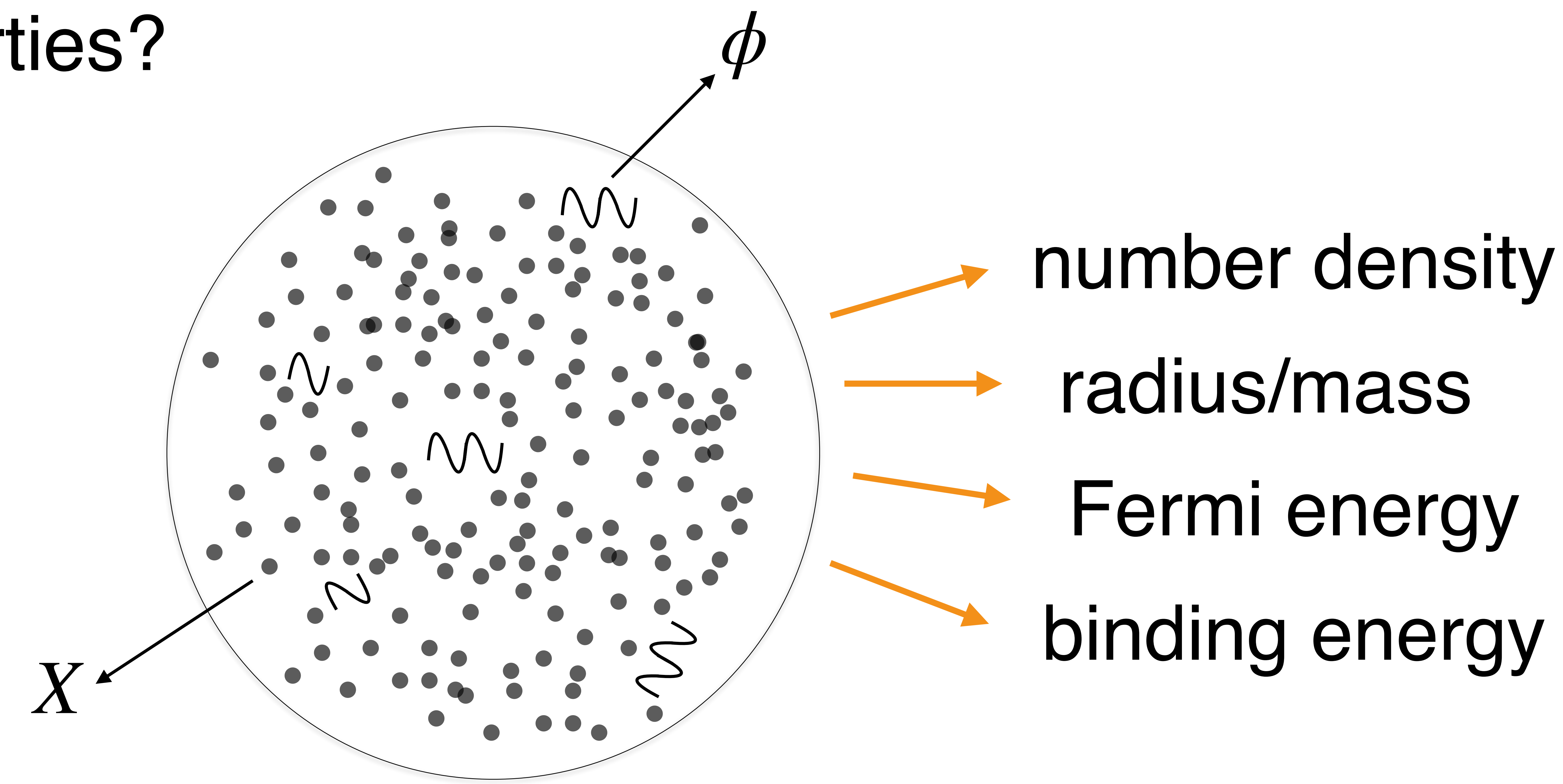
need large couplings to SM for detection?

Asymmetric DM model:

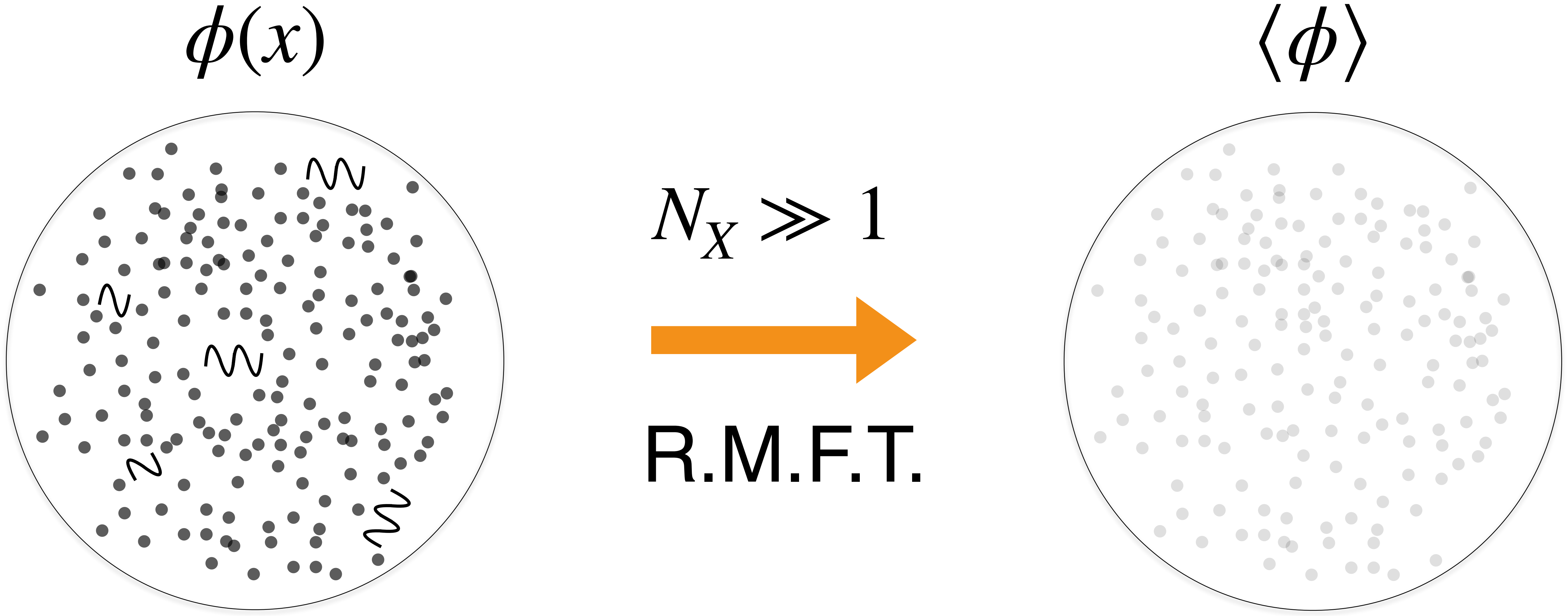
$$\mathscr{L}_{\rm DM} = \frac{1}{2}\partial^2\phi + \frac{1}{2}m_\phi^2\phi^2 + \bar{X}\left(i\gamma^\mu\partial_\mu - m_X\right)X + g_X\bar{X}\phi X$$

Can DM bound states form in the early universe?

If so, what are their properties?



Wise & Zhang, 1407.4121
Gresham et. al., 1707.02313



$m_* \equiv m_X - g_X\langle\phi\rangle$ effective mass

composite equations

$$\mu = \left(p_F^2 + m_*^2\right)^{1/2}$$ chemical potential

$$\varepsilon \simeq \frac{1}{2}m_\phi^2\langle\phi\rangle^2 + \frac{1}{\pi}\int_0^{p_F} dp\ p^2\left(p^2 + m_*^2\right)^{1/2}$$ energy density

$$p = -\left(\frac{dE}{dV}\right)_N = \frac{\mu - \varepsilon}{V}$$ pressure

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

$$\frac{m_*}{m_X} \sim \frac{m_\phi}{m_X}$$ effective mass

$$\frac{p_F}{m_X} \simeq \frac{\mu}{m_X} \sim \left(\frac{m_\phi}{m_X}\right)^{1/2}$$ Fermi momentum/energy

$\Rightarrow$

$m_* \ll m_X \rightarrow \boxed{\langle\phi\rangle \simeq \frac{m_X}{g_X}}$

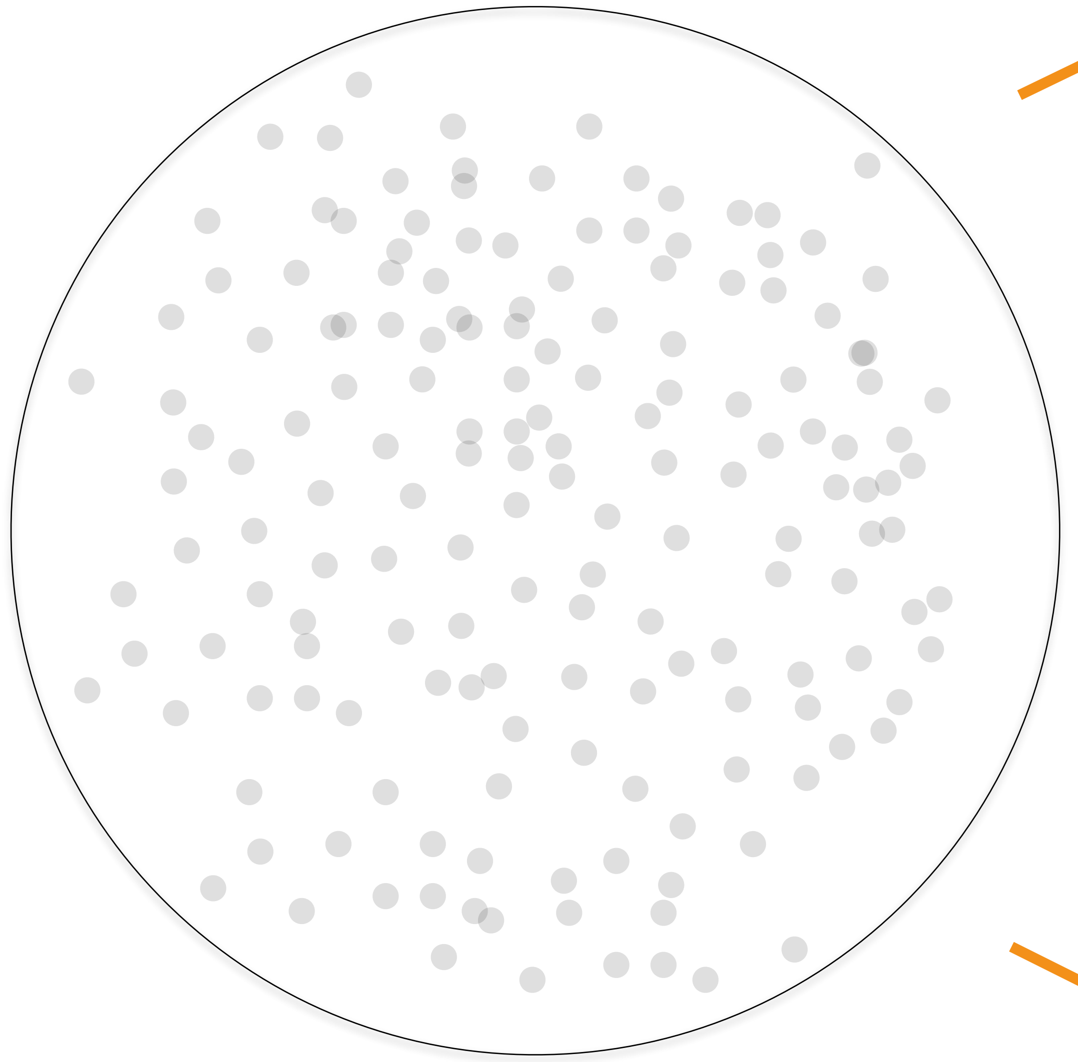
$m_* \ll p_F \sim \mu \rightarrow$ relativistic constituents

Composite properties:

given $\bar{m}_X, N_X$

$$\boxed{\mu \equiv \bar{m}_X \sim m_X^{1/2} m_\phi^{1/2}}$$

$\langle \phi \rangle \propto m_X$



$$n_X = \frac{\bar{m}_X^3}{3\pi^2}$$ number density

$$M_X = N_X \bar{m}_X$$ mass

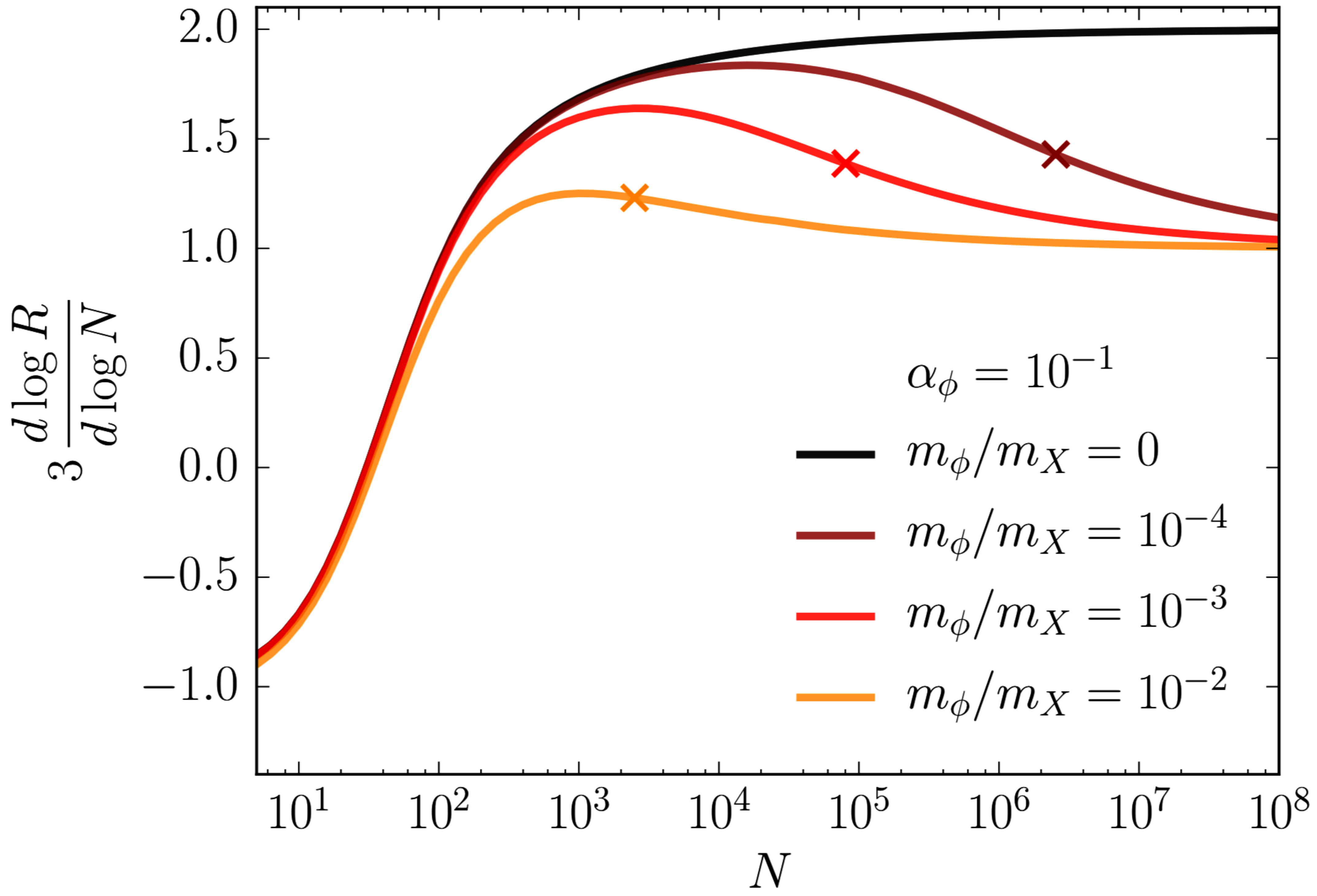
$$R_X = \left(\frac{9\pi N_X}{4\bar{m}_X^3} \right)^{1/3}$$ radius

$$BE(N_X) \simeq N_X \left(m_X - \bar{m}_X \right)$$ binding energy

Gresham et. al., 1707.02313

How good is this mean-field approximation?

Numerical studies indicate transition when $R_X \gtrsim m_\phi^{-1}$

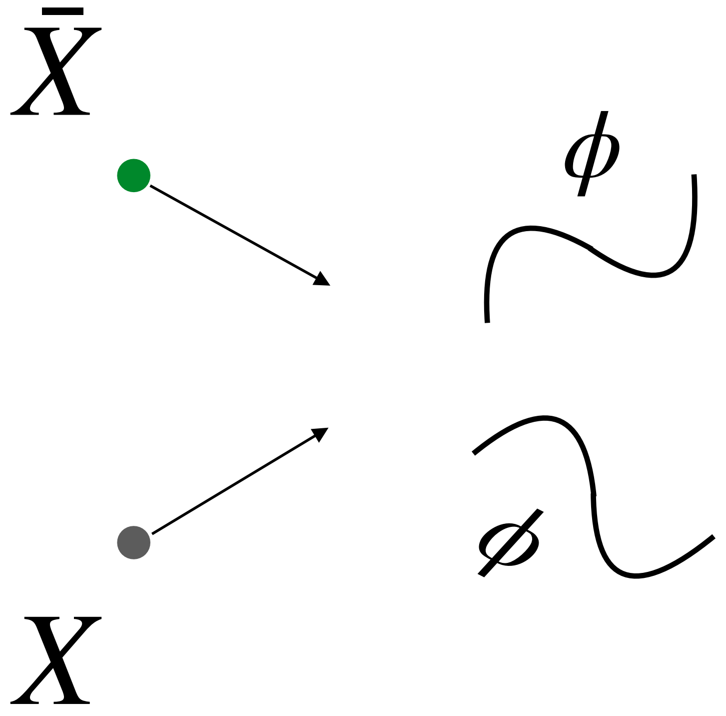


$R_X \sim m_\phi^{-1}$ $\longrightarrow$ $$N_X \simeq \left(\frac{\bar{m}_X}{m_\phi}\right)^3 \simeq 10^{10} \left(\frac{\alpha_X}{0.3}\right)^{-\frac{3}{4}} \left(\frac{m_X}{\mathrm{TeV}}\right)^{\frac{3}{2}} \left(\frac{m_\phi}{\mathrm{MeV}}\right)^{-2}$$

saturation number

Cosmological Synthesis

Gresham et. al., 1707.02316
Bramante & Unwin, 1701.05859
JA, Bramante & Goodman, 2012.10998



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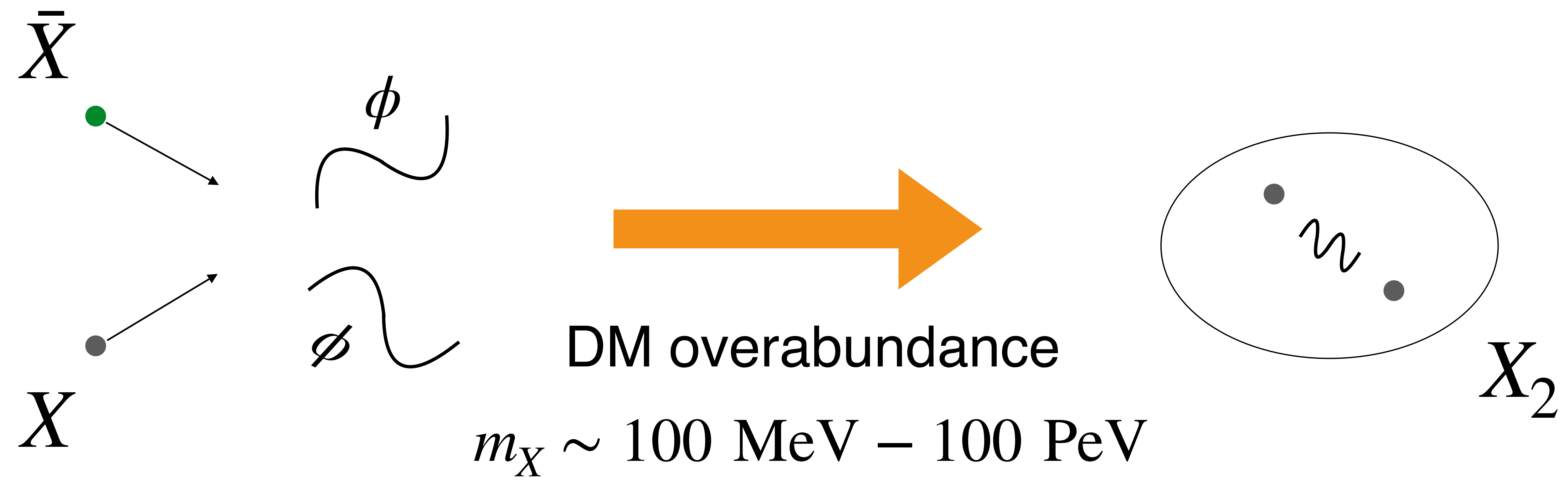

DM overabundance

$m_X \sim 100$ MeV – 100 PeV

$m_\phi \sim 1$ eV – 100 MeV

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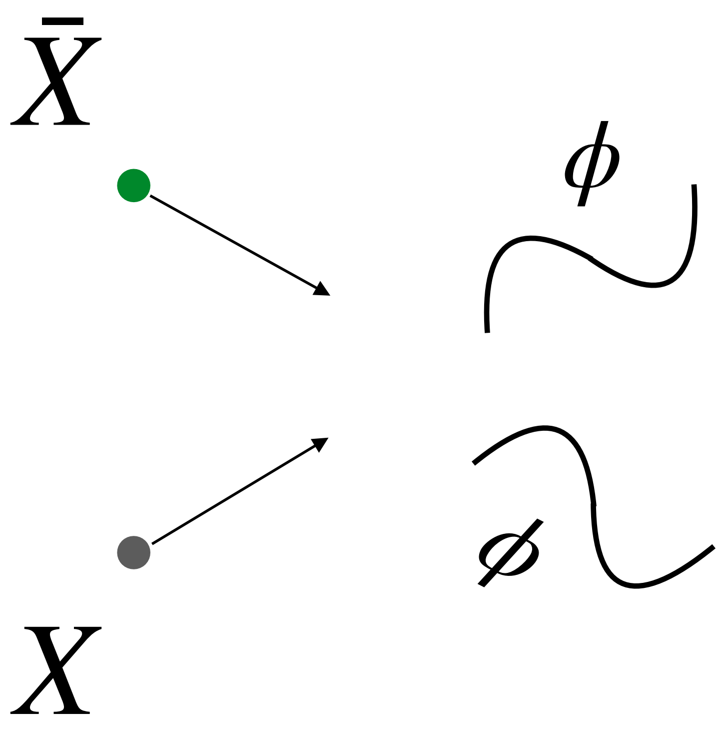

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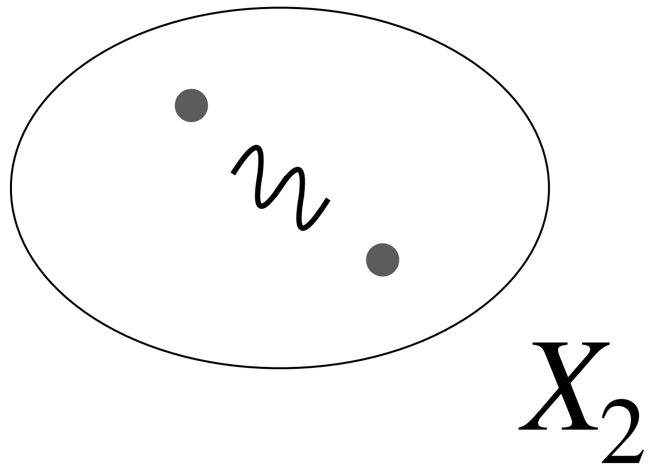

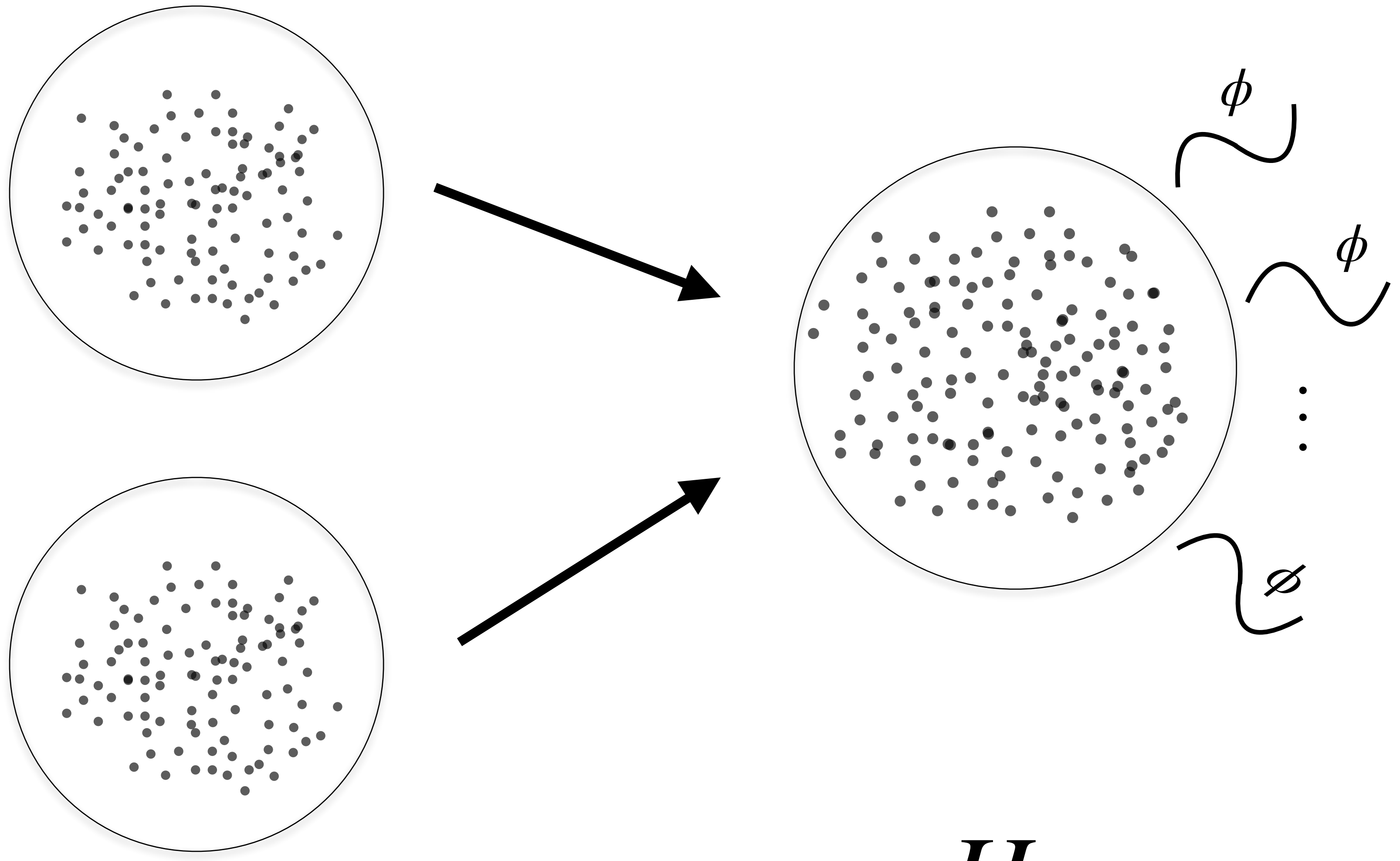

$n_X \sigma_{XX} v_X \sim H$

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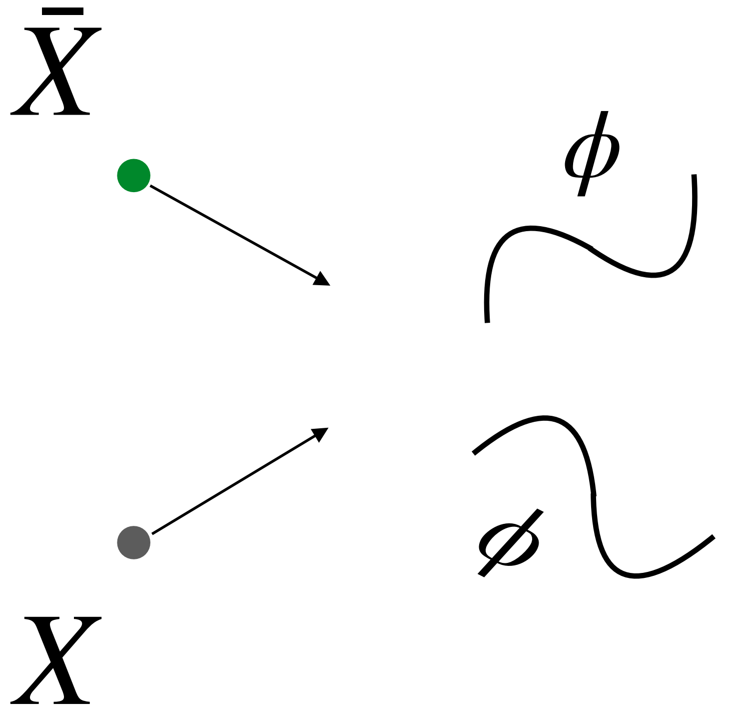

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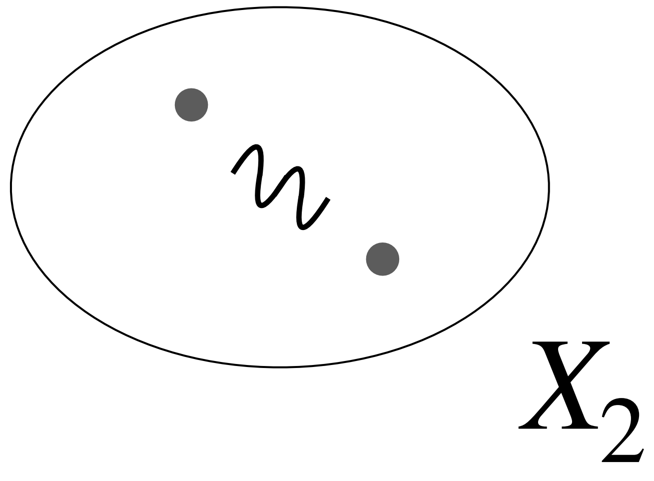
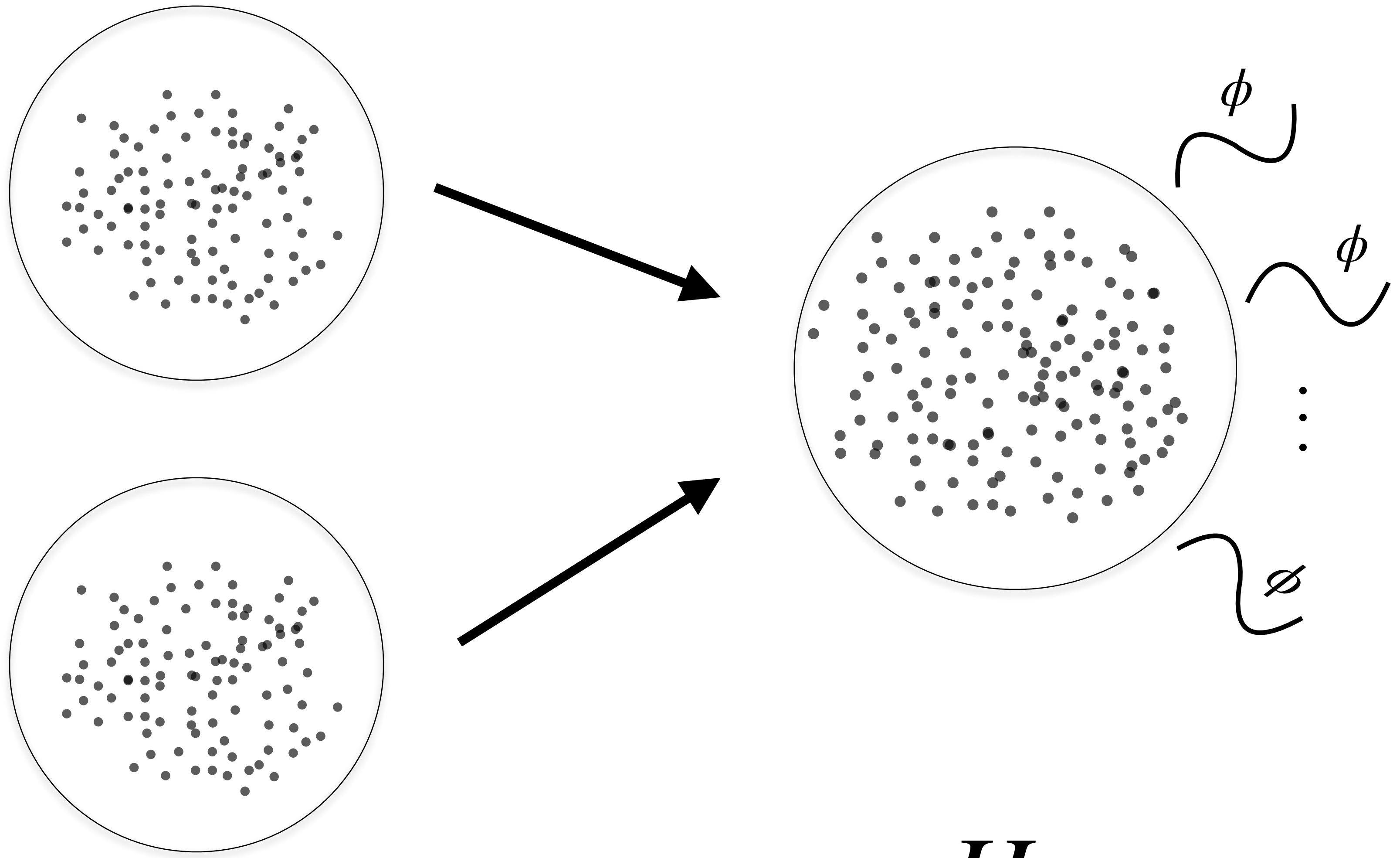




$n_X \sigma_{XX} v_X \sim H$

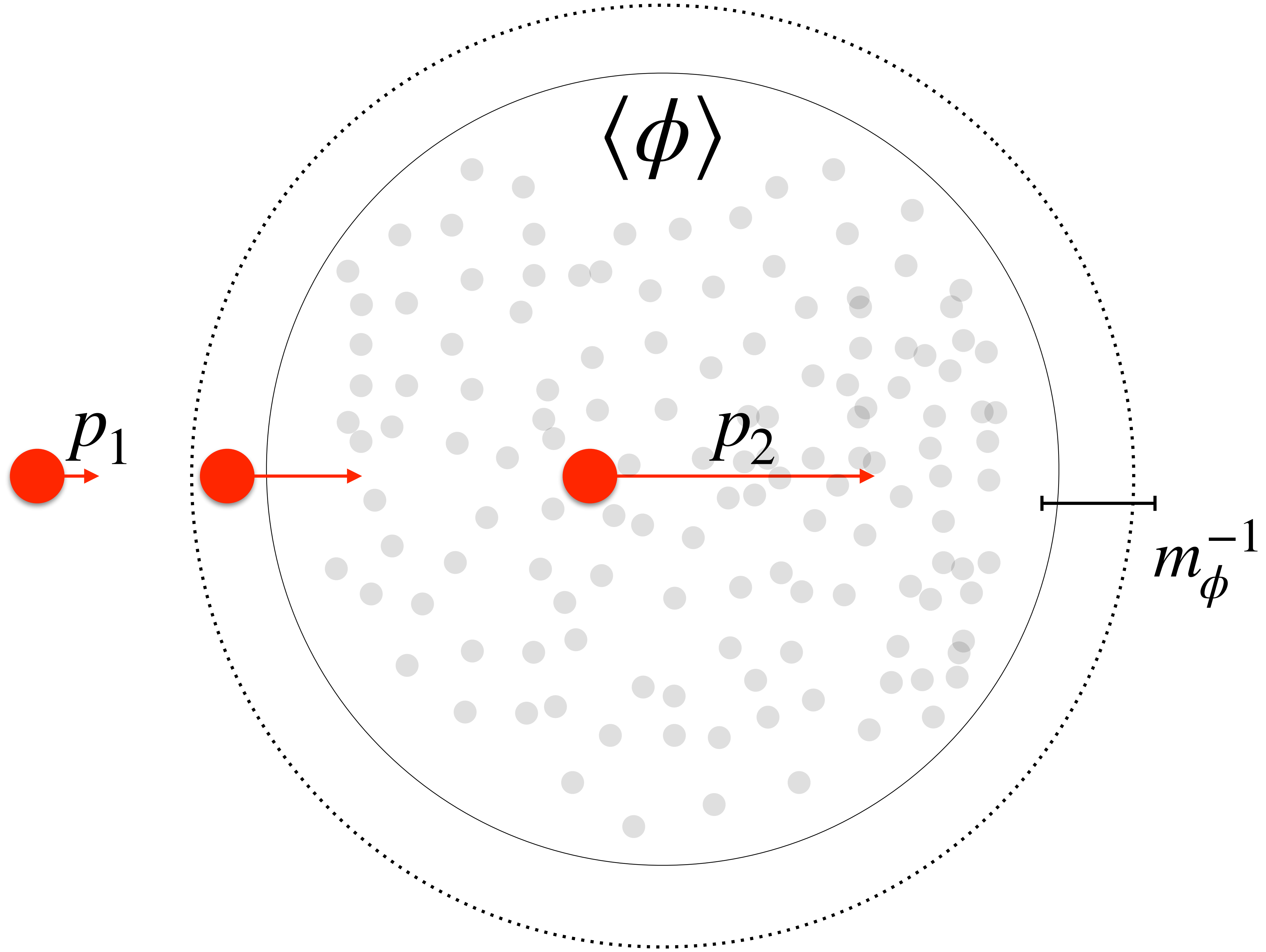
+ subsequent dilution by a factor ζ

When assembly is complete:

$$\boxed{\begin{array}{c} 10^{10}\ \text{GeV} \lesssim M_X \lesssim 10^{45}\ \text{GeV} \\ 100\ \text{fm} \lesssim R_X \lesssim 10\ \mu\text{m} \end{array}}$$

Nuclear Coupling

Add attractive Yukawa interaction: $\mathscr{L} = \mathscr{L}_{\mathrm{DM}} + g_n \bar{n} \phi n$



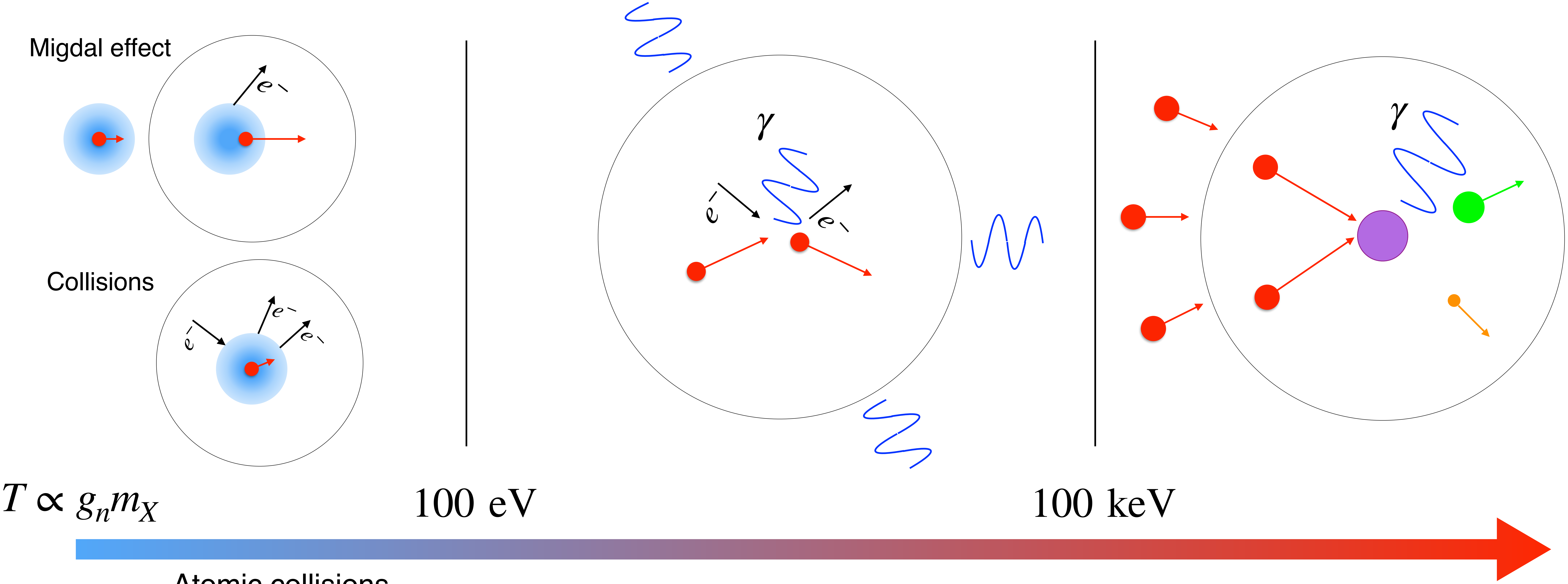
$$p_1^2 + m_N^2 = p_2^2 + (m_N - A g_n \langle \phi \rangle)^2$$

NR limit

$$\boxed{\frac{p_2^2 - p_1^2}{2m_N} \simeq A g_n \langle \phi \rangle \propto g_n m_X}$$

JA, Bramante & Goodman, 2012.10998

Pheno summary:



Atomic collisions
Migdal effect
Recombination
Line emission

Full ionization
Thermal bremsstrahlung

Nuclear fusion

JA, Bramante & Goodman, 2108.10889
Joglekar et. al., 2004.09539

Nucleus-DM Scattering

How much energy nuclei lose as they scatter against DM constituents?

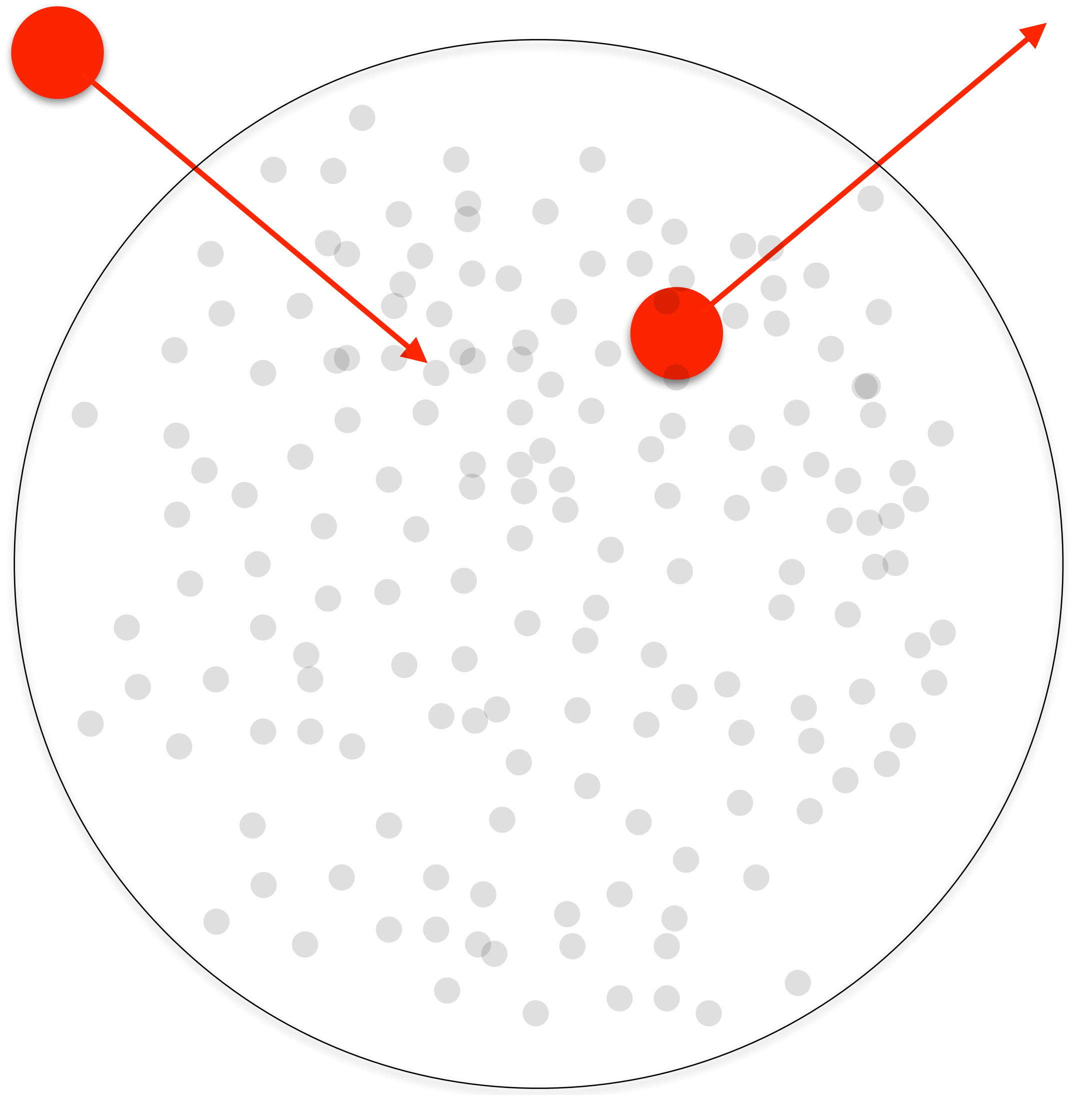
(not much!)

Some considerations:

- Coupling is very constrained: $g_n \lesssim 10^{-10}$

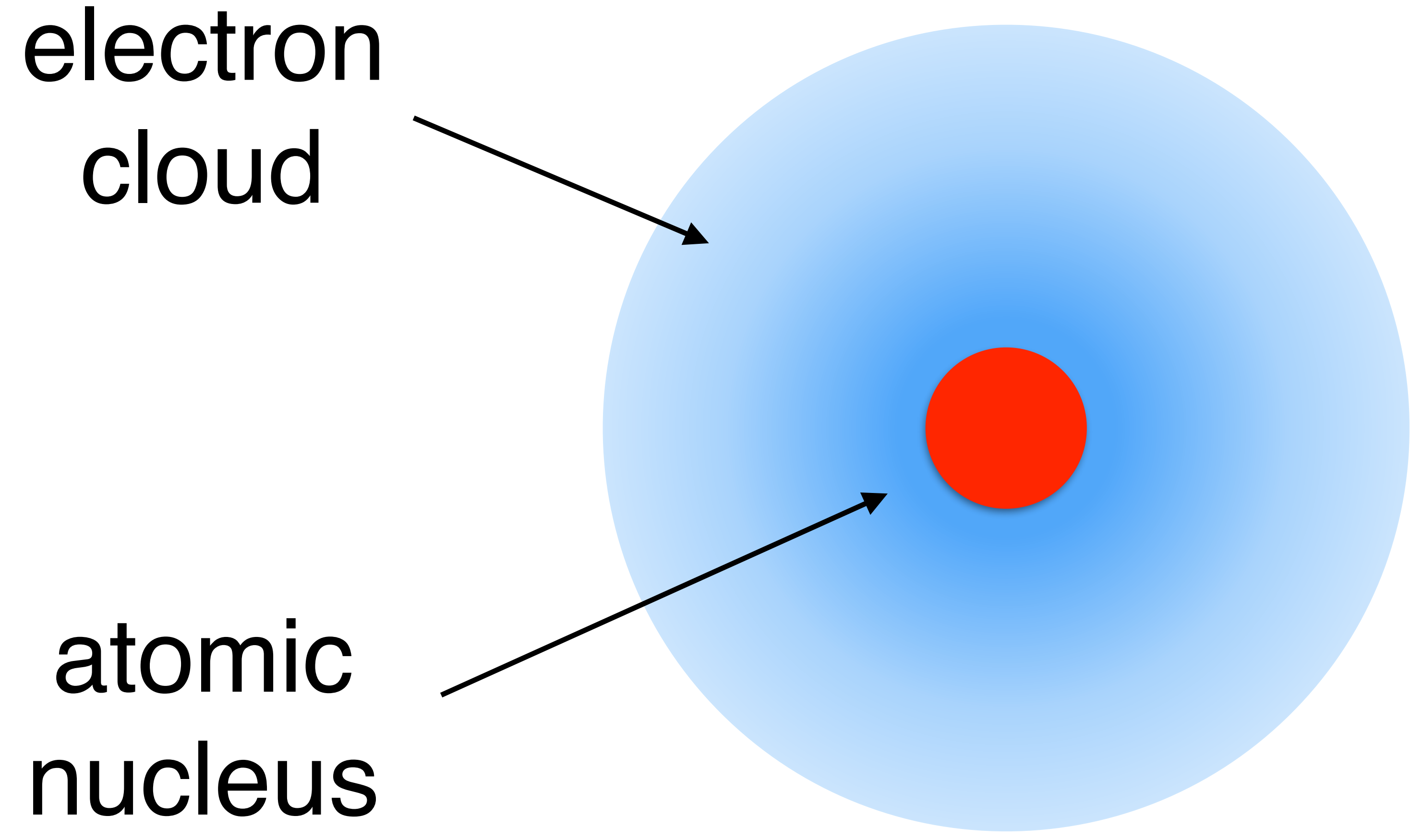
- Nuclei at most transfer: $\Delta E \sim \frac{1}{2} m_N v_N^2 \longrightarrow \frac{\Delta E}{p_F} \ll 10^{-4}$

- Proper calculation yields: $\Gamma_{NX \to NX^*} \sim g_n^5 \sim \mathcal{O}\left(10^{-50}\right)$



II. Direct Detection Signatures

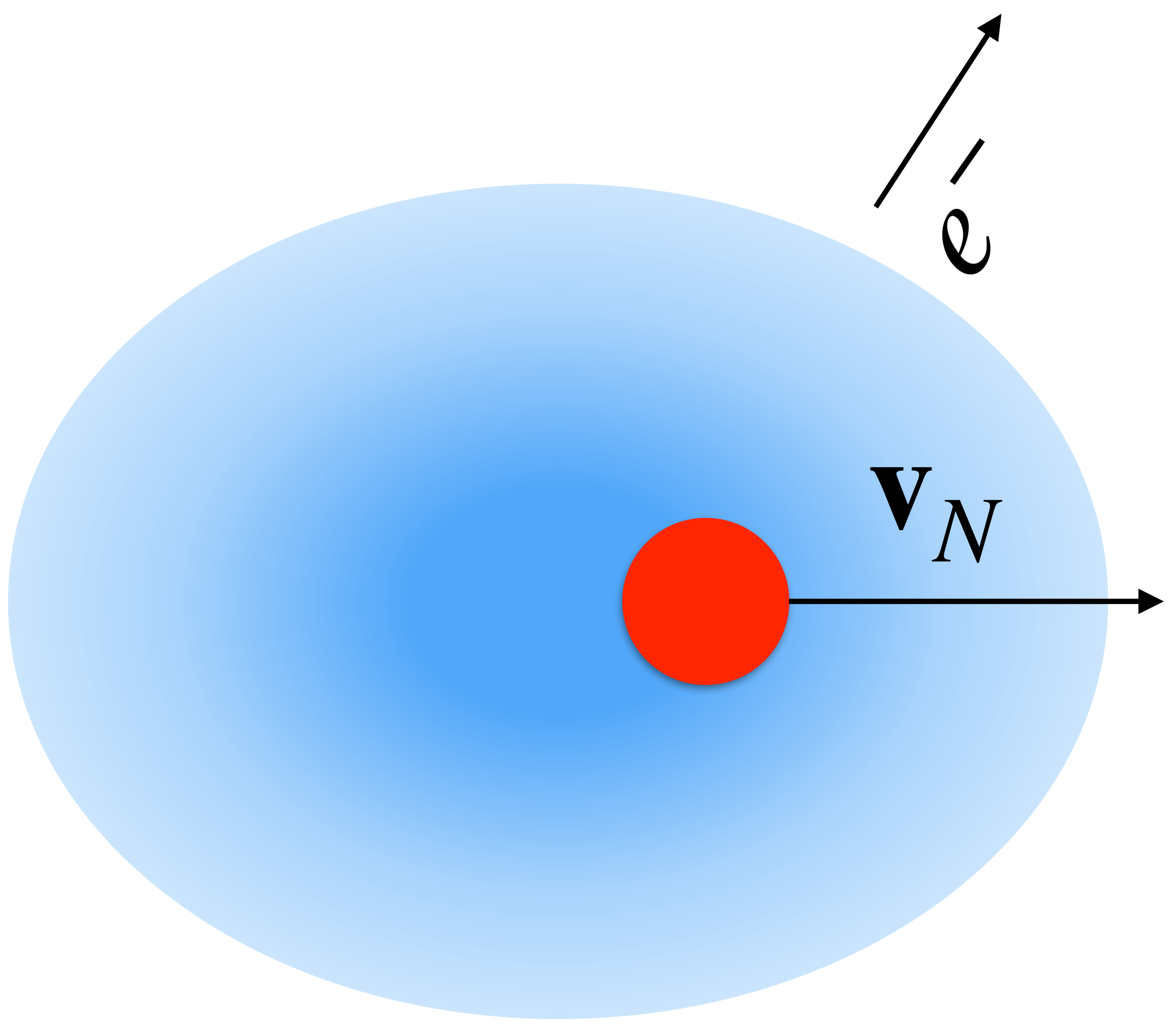
Migdal Effect at Xenon-1T



sudden nuclear recoil

e.g. $\alpha, \beta^{\pm}$ decay

DM scattering?



$$|\psi_0\rangle$$

$$\langle\psi_k|\psi_0\rangle = 0$$

$$|\psi\rangle \simeq e^{\left(-im_e \sum_j \mathbf{v_N}\cdot\hat{\mathbf{x}}_j\right)}|\psi_0\rangle$$

$$\langle\psi_k|\psi\rangle \neq 0$$

How sudden? $\longrightarrow$ $\Delta t_{\text{recoil}} \ll 10^{-17}\ \text{s}$ Migdal approximation

(e.g. Xe, Ar)

Ionization prob:

initial level

Xe ($q_e = m_e \times 10^{-3}$)

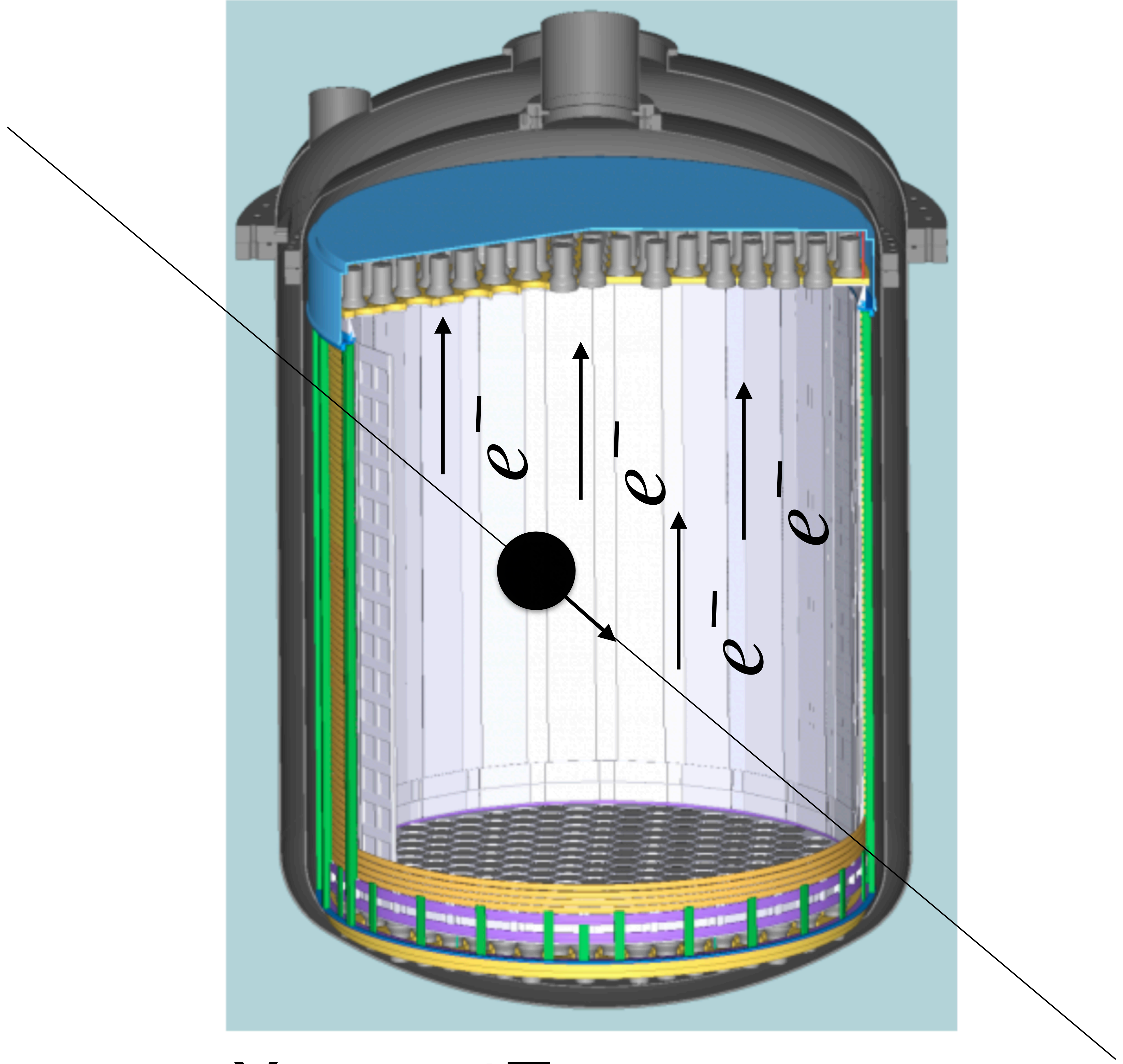
(n,ℓ)	$\mathcal{P}_{\to 4f}$	$\mathcal{P}_{\to 5d}$	$\mathcal{P}_{\to 6s}$	$\mathcal{P}_{\to 6p}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
1s	–	–	–	7.3×10^{-10}	3.5×10^{4}	4.9×10^{-6}
2s	–	–	–	1.8×10^{-8}	5.4×10^{3}	3.0×10^{-5}
2p	–	3.0×10^{-8}	6.5×10^{-9}	–	4.9×10^{3}	1.3×10^{-4}
3s	–	–	–	2.7×10^{-7}	1.1×10^{3}	1.1×10^{-4}
3p	–	3.4×10^{-7}	4.0×10^{-7}	–	9.3×10^{2}	6.0×10^{-4}
3d	2.3×10^{-9}	–	–	4.3×10^{-7}	6.6×10^{2}	3.6×10^{-3}
4s	–	–	–	3.1×10^{-6}	2.0×10^{2}	3.6×10^{-4}
4p	–	4.1×10^{-8}	3.0×10^{-5}	–	1.4×10^{2}	1.5×10^{-3}
4d	7.0×10^{-7}	–	–	1.5×10^{-4}	6.1×10	3.6×10^{-2}
5s	–	–	–	1.2×10^{-4}	2.1×10	4.7×10^{-4}
5p	–	3.6×10^{-2}	2.1×10^{-2}	–	9.8	7.8×10^{-2}

(n,ℓ)	$4f$	$5d$	$6s$	$6p$
$E_{n\ell}$[eV]	0.85	1.6	3.3	2.2

Ibe et. al., 1707.07258

Ionization prob:

initial level



Xenon-1T

Xe ($q_e = m_e \times 10^{-3}$)

(n, ℓ)	$\mathcal{P}_{\to 4f}$	$\mathcal{P}_{\to 5d}$	$\mathcal{P}_{\to 6s}$	$\mathcal{P}_{\to 6p}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
1s	–	–	–	7.3×10^{-10}	3.5×10^{4}	4.9×10^{-6}
2s	–	–	–	1.8×10^{-8}	5.4×10^{3}	3.0×10^{-5}
2p	–	3.0×10^{-8}	6.5×10^{-9}	–	4.9×10^{3}	1.3×10^{-4}
3s	–	–	–	2.7×10^{-7}	1.1×10^{3}	1.1×10^{-4}
3p	–	3.4×10^{-7}	4.0×10^{-7}	–	9.3×10^{2}	6.0×10^{-4}
3d	2.3×10^{-9}	–	–	4.3×10^{-7}	6.6×10^{2}	3.6×10^{-3}
4s	–	–	–	3.1×10^{-6}	2.0×10^{2}	3.6×10^{-4}
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5s	–	–	–	1.2×10^{-4}	2.1×10	4.7×10^{-4}
5p	–	3.6×10^{-2}	2.1×10^{-2}	–	9.8	7.8×10^{-2}

(n, ℓ)	$4f$	$5d$	$6s$	$6p$
$E_{n\ell}$[eV]	0.85	1.6	3.3	2.2

JA, Bramante & Goodman, 2108.10889

Expected number of events:

$$\frac{dR}{dE_R} = \frac{\rho_X}{m_N M_X} \int_{v > v_X^{(min)}} \frac{d\sigma}{dE_R} \, v \, f(v) \, dv$$

$\longrightarrow$ ionization prob.

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

Integrate over recoil/electronic energies:

$$R_{ion} = \left(\frac{4\pi R_X^2 n_X}{m_N} \right) \times \left(\int_{v > v^{(\mathrm{min})}} dv \; v \; g(v) \right) \times \left(\frac{1}{2\pi} \sum_{n,l} \int dE_e \; \varepsilon(E_{em}) \frac{dp_q}{dE_e}(n, l \to E_e) \right)$$

event rate

$$E_{em} = E_{nl} + E_e \sim \mathcal{O}\left(\mathrm{keV}\right)$$

total e.m. energy

JA, Bramante & Goodman, 2108.10889

Xenon-1t's 1st DM search exposure:

$$\boxed{N_{ion} \simeq (98 \text{ kg yr})\, R_{ion} \simeq 10 \left(\frac{m_X}{\text{TeV}}\right)^{-\frac{2}{5}} \left(\frac{m_\phi}{\text{MeV}}\right)^{-\frac{4}{5}} \left(\frac{g_n}{10^{-17}}\right) \left(\frac{\alpha_X}{0.3}\right)^{-\frac{1}{10}}}$$

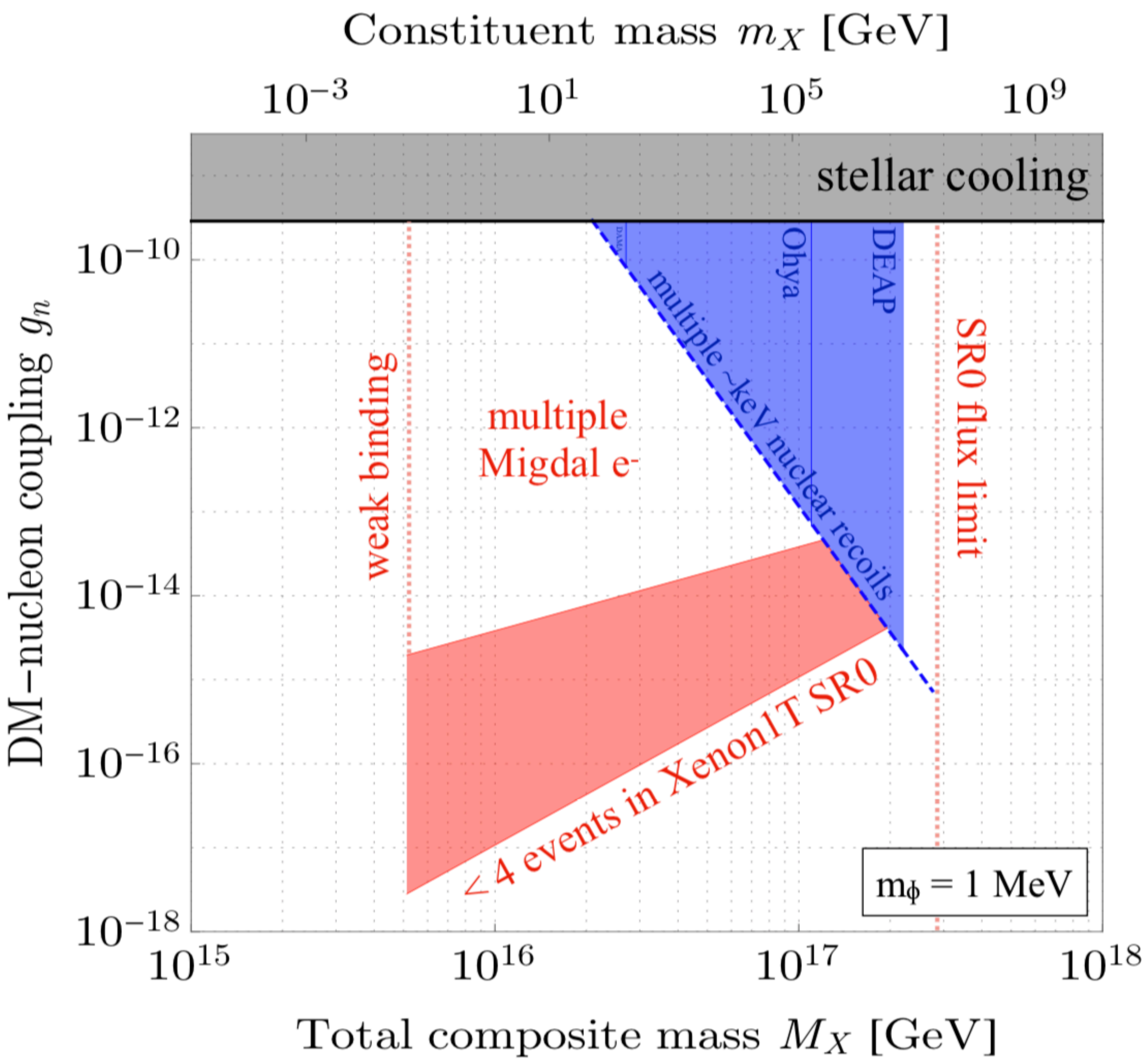
Can also compute # ionization events during single transit:

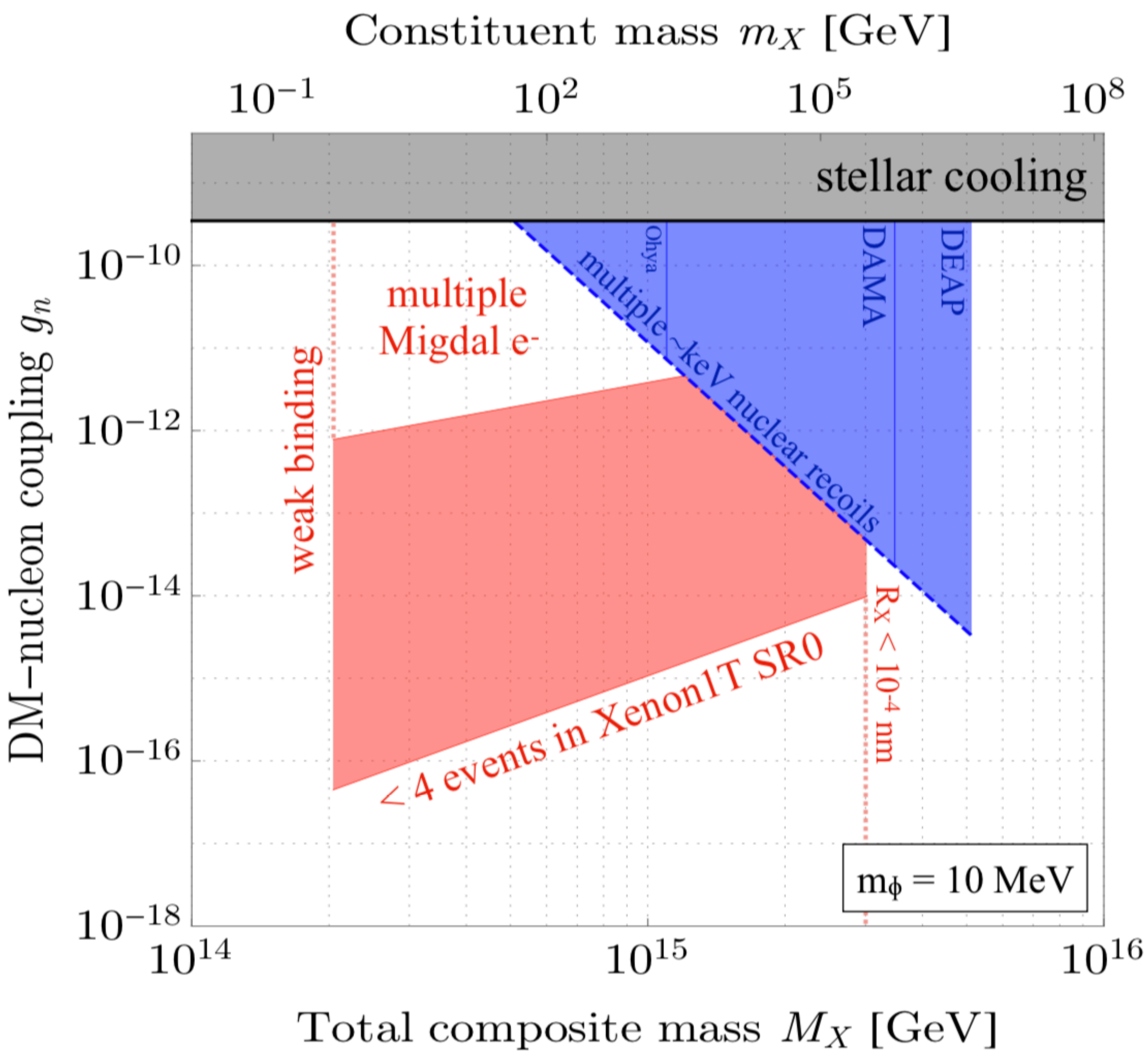
$$N_{transit} \simeq (2\pi R_X^2 n_N L_{det}) \times \left(\frac{1}{2\pi} \sum_{n,l} \int dE_e \ \varepsilon(E_{em}) \frac{dp_q}{dE_e}(n, l \to E_e) \right)$$

$$\boxed{N_{transit} \simeq 10^7 \left(\frac{R_X}{\text{nm}}\right)^2 \left(\frac{m_X}{\text{TeV}}\right) \left(\frac{g_n}{10^{-17}}\right) \left(\frac{\alpha_X}{0.3}\right)^{-\frac{1}{2}}}$$

JA, Bramante & Goodman, 2108.10889

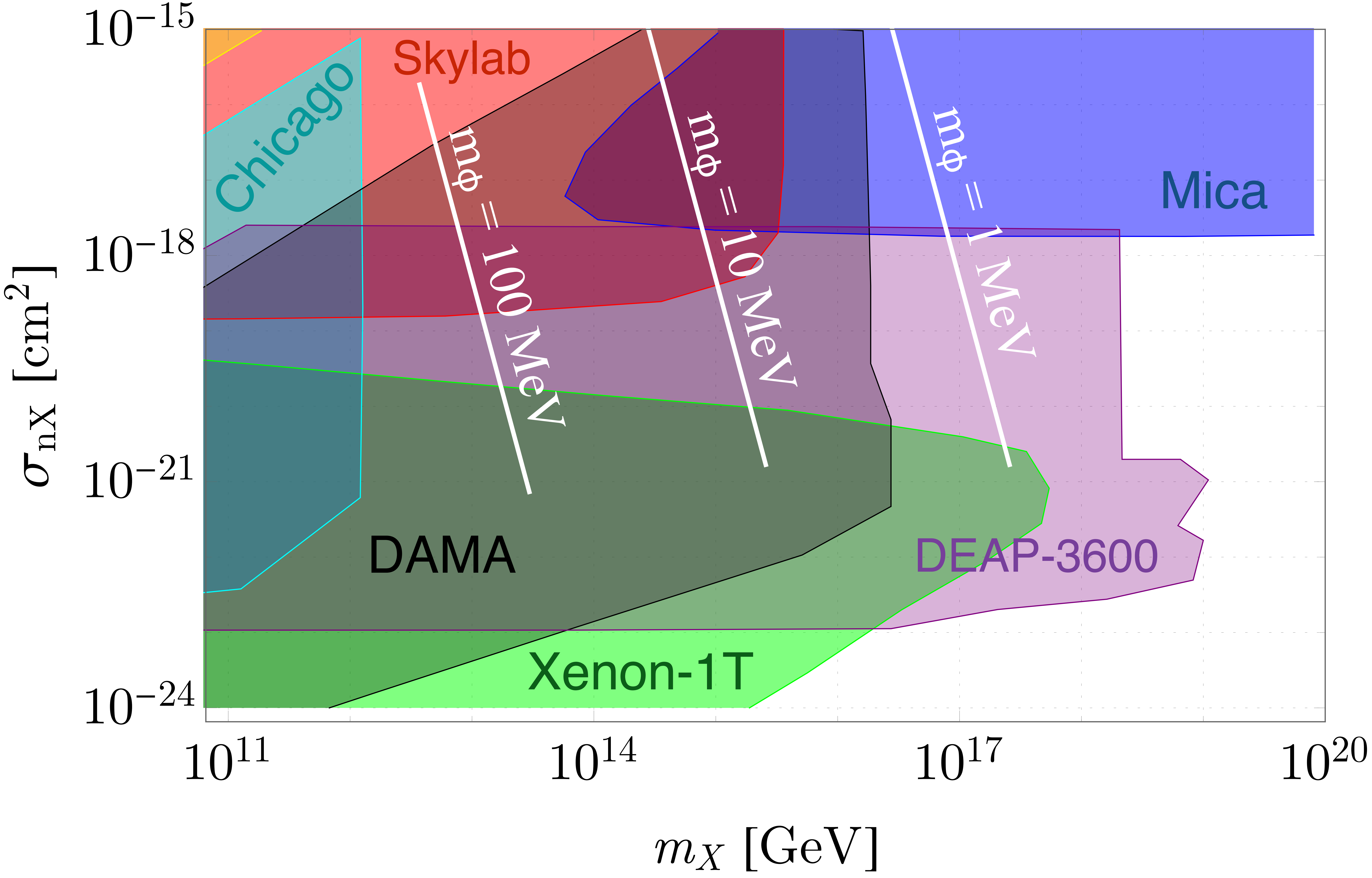
Constraints obtained at $\alpha_X = 0.3$





Landscape of experimental bounds:

Bhoonah et. al., 2012.13406
JA, Bramante & Goodman, 2105.06473
Adhikari et. al., DEAP collaboration, 2108.09405



Large Composite Detection

Bramante et. al., 1812.09325
JA, Bramante & Goodman, 2012.10998

In most of parameter space, composites have masses $M_X \gtrsim M_P$

DD experiments require ~1 event per year:

$$\frac{\rho_X v_X A_{\rm det} t_{\rm exp}}{M_X^{max}} \sim 1 \quad \xrightarrow[\boxed{\begin{array}{c} A_{\rm det} \simeq 10^3 \text{ cm}^2 \\ t_{\rm exp} \sim 10 \text{ yrs} \end{array}}]{\begin{array}{c} \rho_X \simeq 0.3 \text{ GeV cm}^{-3} \\ v_X \simeq 220 \text{ km s}^{-1} \end{array}} \quad M_X^{max} \simeq 10^{18} \text{ GeV}$$

e.g. Xenon-1T, DEAP, LZ

Need $A_{det} \gg 10^3 \text{ cm}^2$ $\longrightarrow$ IceCube, SNO+

Where in parameter space may these experiments have sensitivity?

- Maximum composite mass:

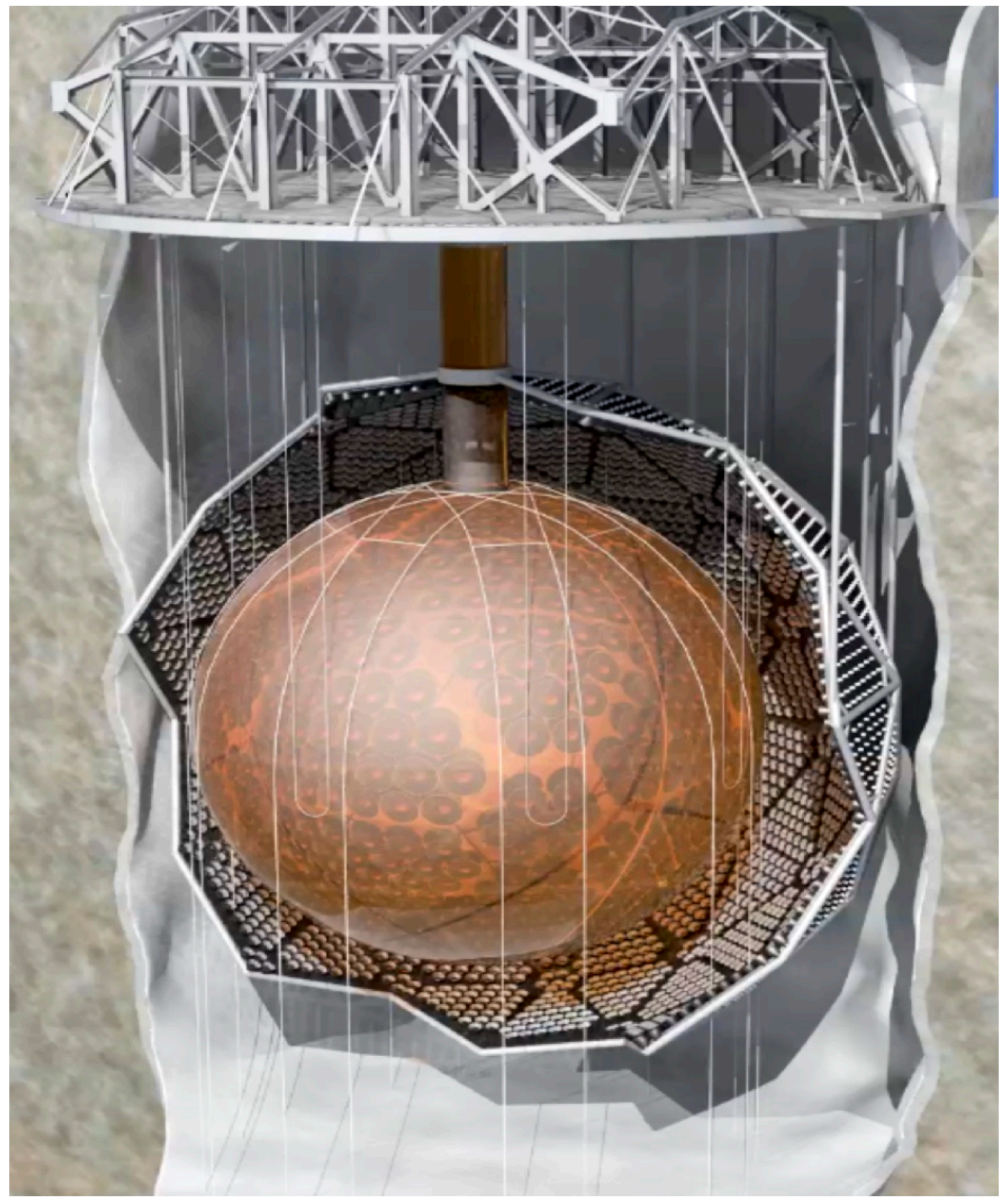
SNO+: $M_X^{max} \simeq 10^{22}$ GeV

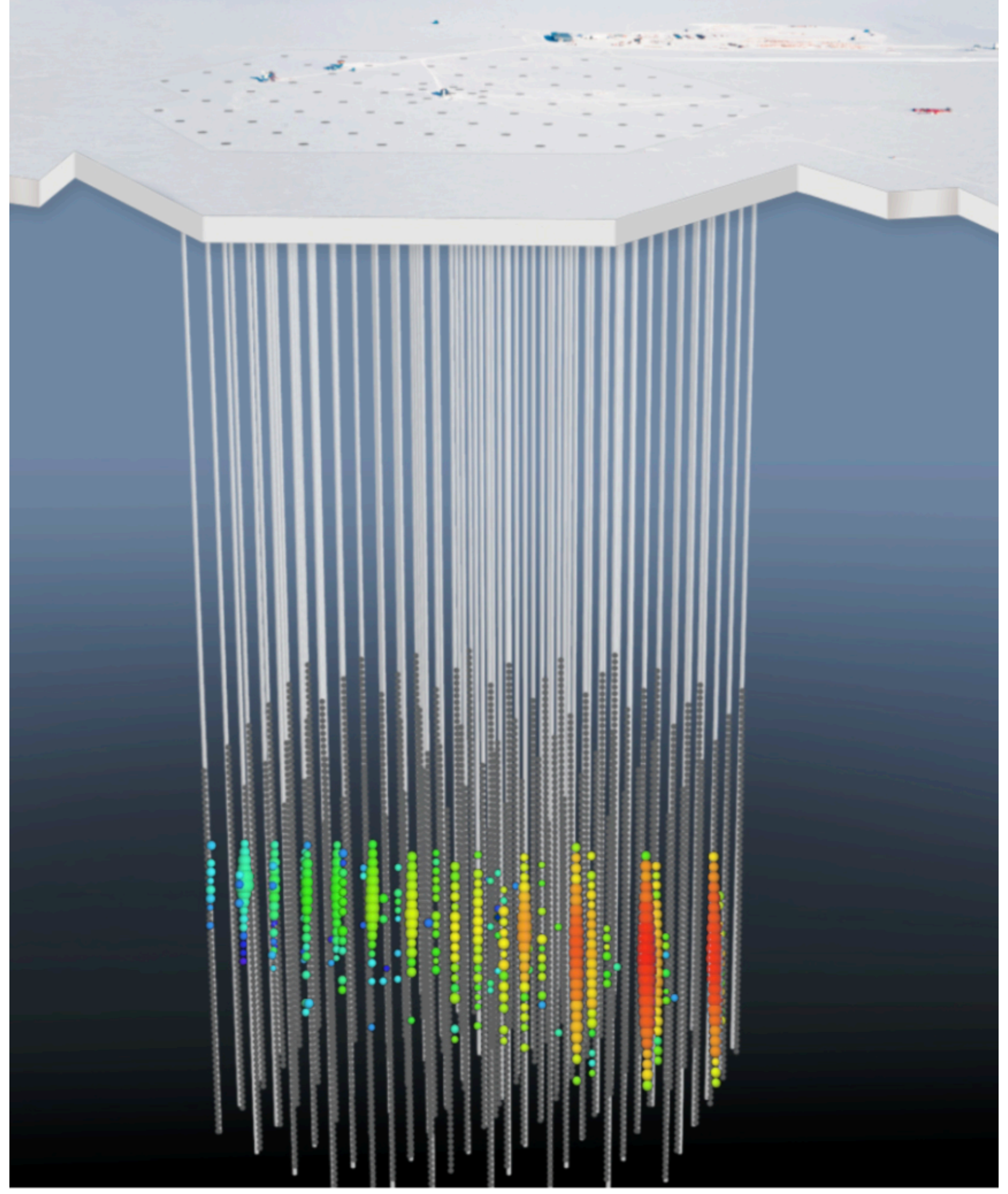
IceCube: $M_X^{max} \simeq 3 \times 10^{25}$ GeV

- Triggering detectors:

SNO+: ~1 MeV per 100 ns $\longrightarrow$ $\dot{E} \simeq 10^4 \text{ GeV s}^{-1}$

IceCube: ~10 TeV per 100 ns $\longrightarrow$ $\dot{E} \simeq 10^{11} \text{ GeV s}^{-1}$



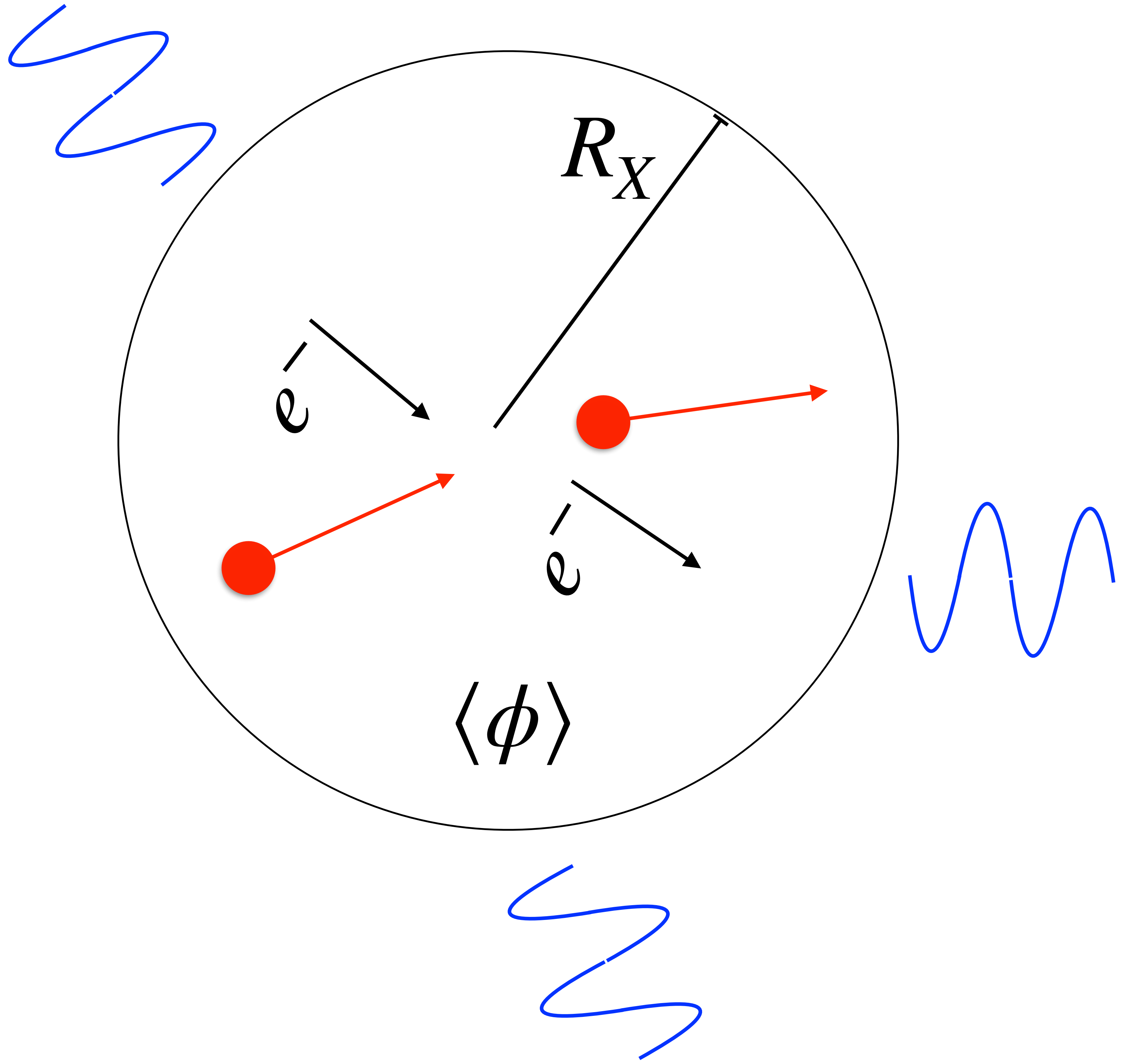


JA, Bramante & Goodman, 2012.10998

1) Thermal bremsstrahlung

Low-Z atoms are fully ionized at $T \gtrsim 100$ eV

γ mean free path: $(n_e \sigma_T)^{-1} \simeq 5$ cm $\gg R_X$ → photons stream out w/out scattering



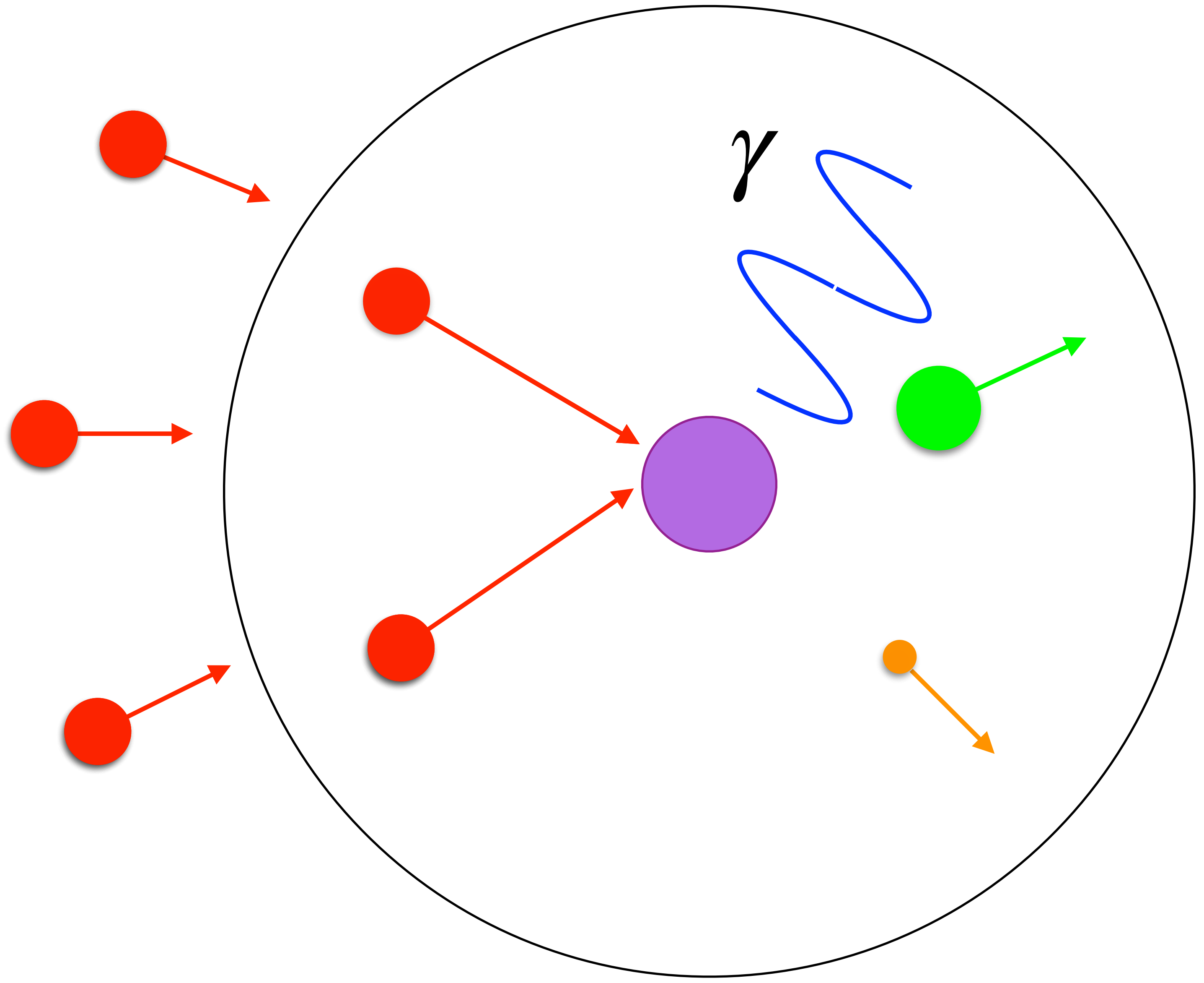
$$\dot{E}_{brem} \sim \left(\frac{e^6 n_e^2}{m_e^2}\right) \int e^{-\frac{\hbar\omega}{T}} \, d\omega dV \simeq$$

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

integrated bremsstrahlung rate

JA, Bramante & Goodman, 2012.10998

2) Thermonuclear fusion



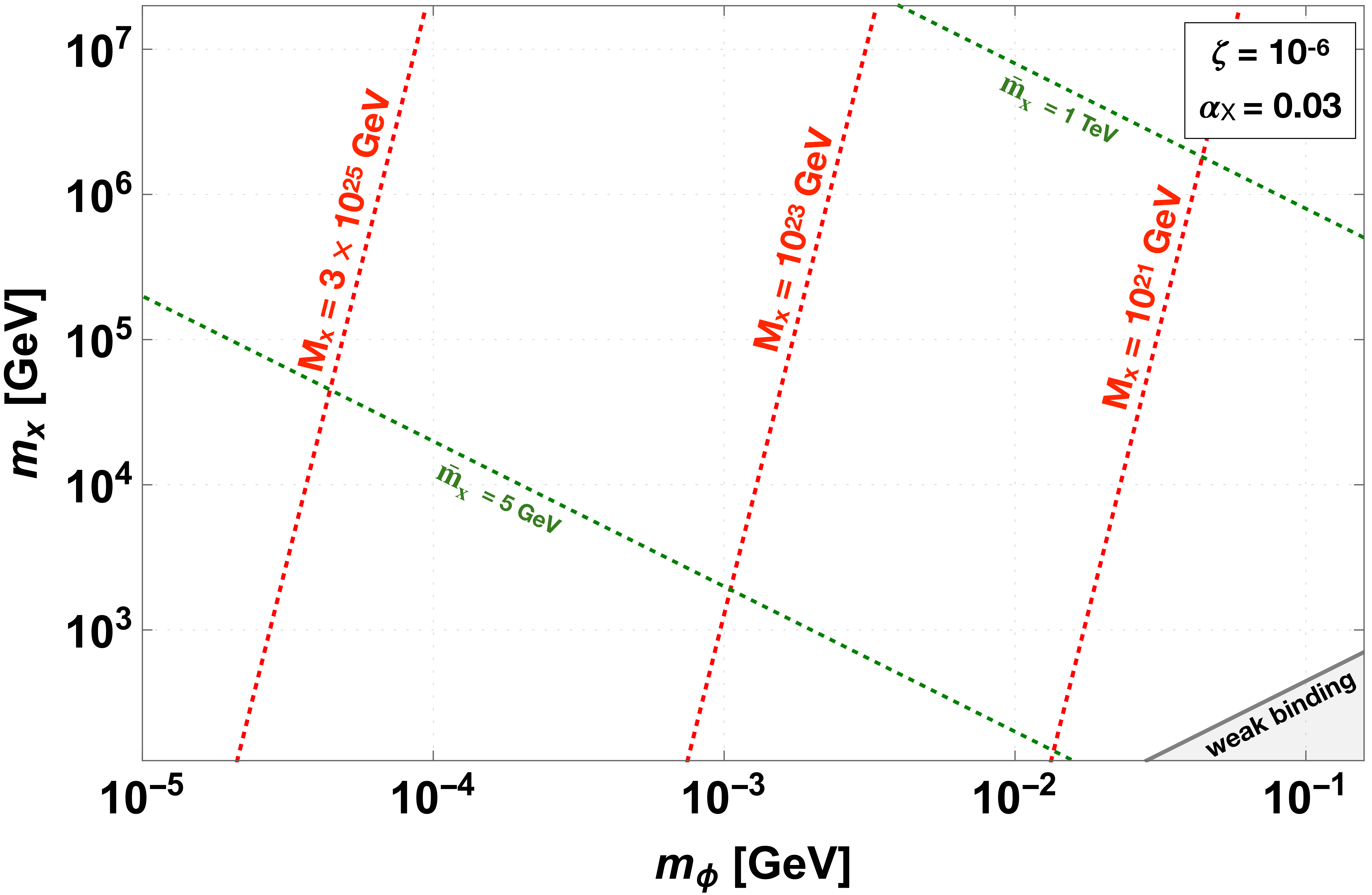
$$\left[\begin{array}{lll} {}^{12}\mathrm{C} + {}^{12}\mathrm{C} \to {}^{24}\mathrm{Mg}^* & \bar{Q}_{CC} \simeq 3.16 \text{ MeV} & \text{SNO+} \\ {}^{16}\mathrm{O} + {}^{16}\mathrm{O} \to {}^{32}\mathrm{S}^* & \bar{Q}_{OO} \simeq 13.09 \text{ MeV} & \text{IceCube} \end{array}\right.$$

At least ~1 reaction per composite crossing: $\dfrac{\dot{R}_{th}(T) R_X^3 L_{det}}{v_X} \sim 1$

JA, Bramante & Goodman, 2012.10998

Parameter space for detection:

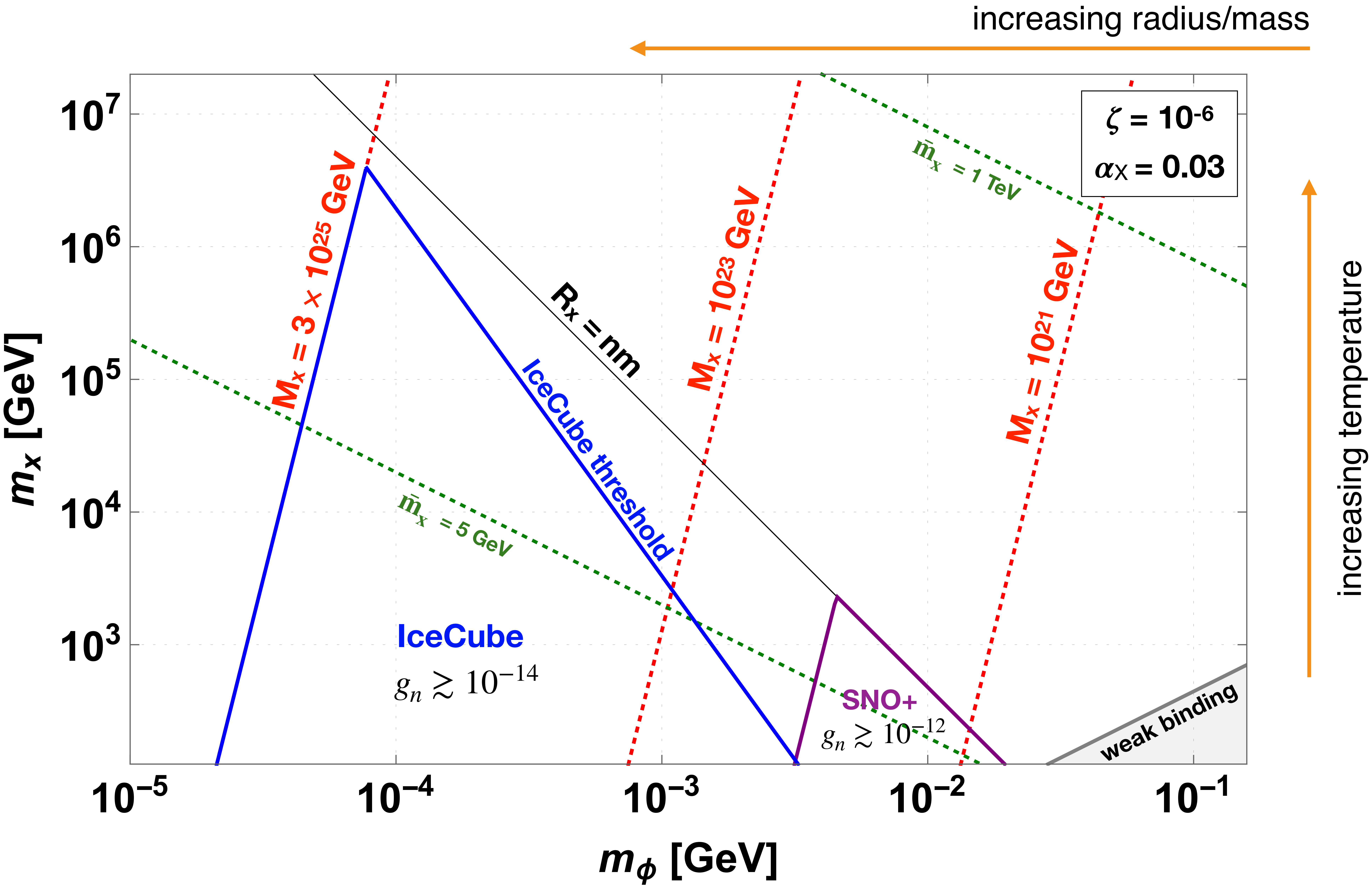
increasing radius/mass



increasing temperature

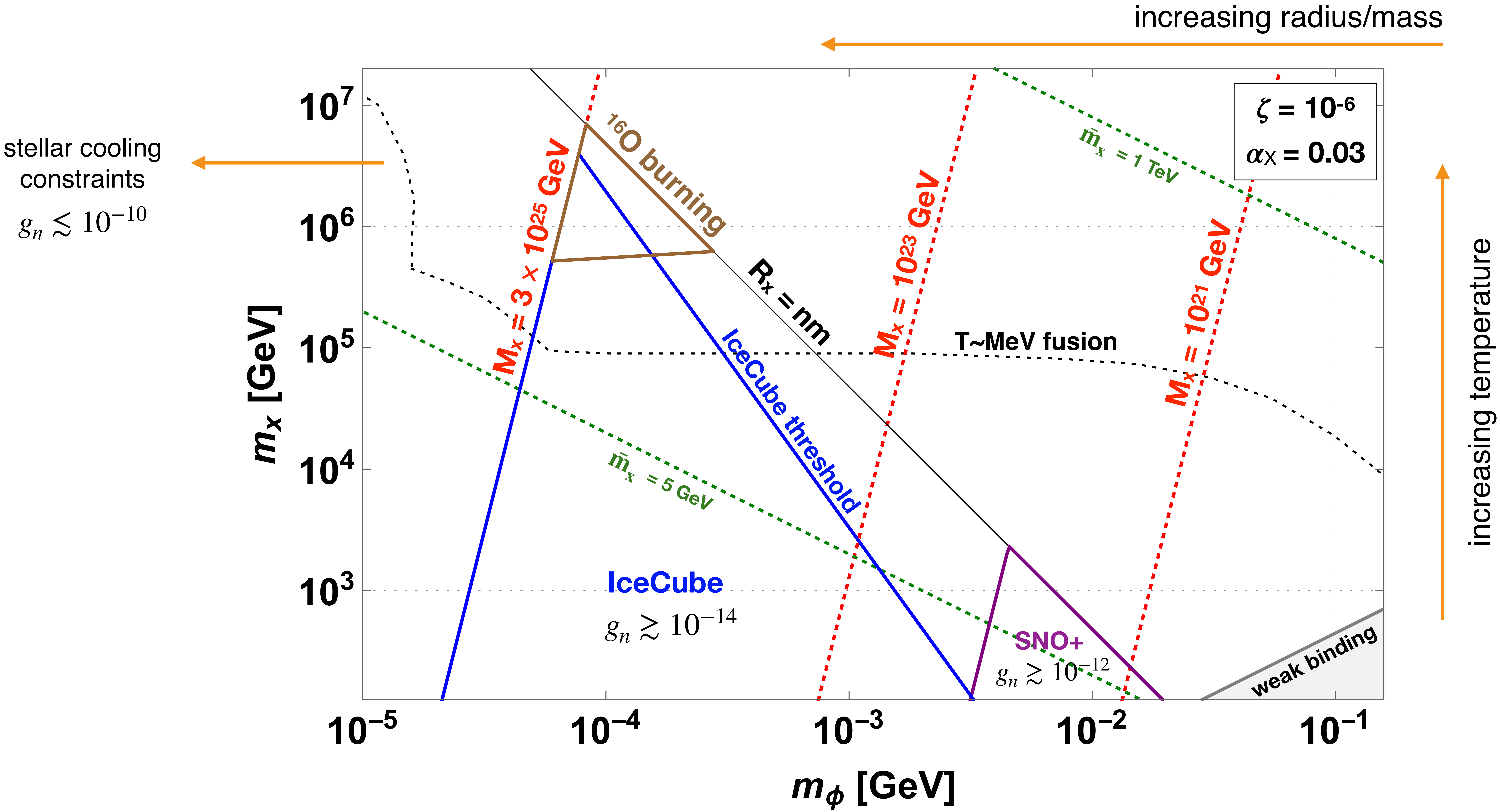
JA, Bramante & Goodman, 2012.10998

Parameter space for detection:



JA, Bramante & Goodman, 2012.10998

Parameter space for detection:



In summary:

Composite Detection

"Light", very-weakly coupled

Heavy, weakly coupled

Large DD experiments

Neutrino observatories

Migdal effect probes

$$g_n \sim 10^{-17}$$

$$10^{11}\ \text{GeV} \lesssim M_X \lesssim 10^{17}\ \text{GeV}$$

Bremsstrahlung, fusion probes

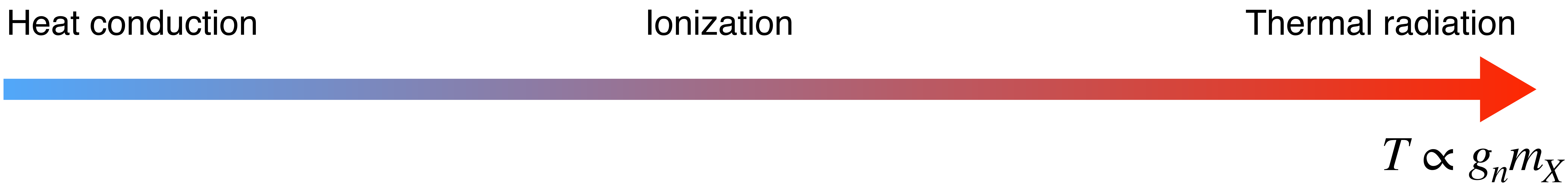
$$g_n \sim 10^{-14}$$

$$10^{20}\ \text{GeV} \lesssim M_X \lesssim 10^{25}\ \text{GeV}$$

III. Astrophysical Signatures

Astrophysical Capture

Composites are efficiently stopped via dissipation processes:



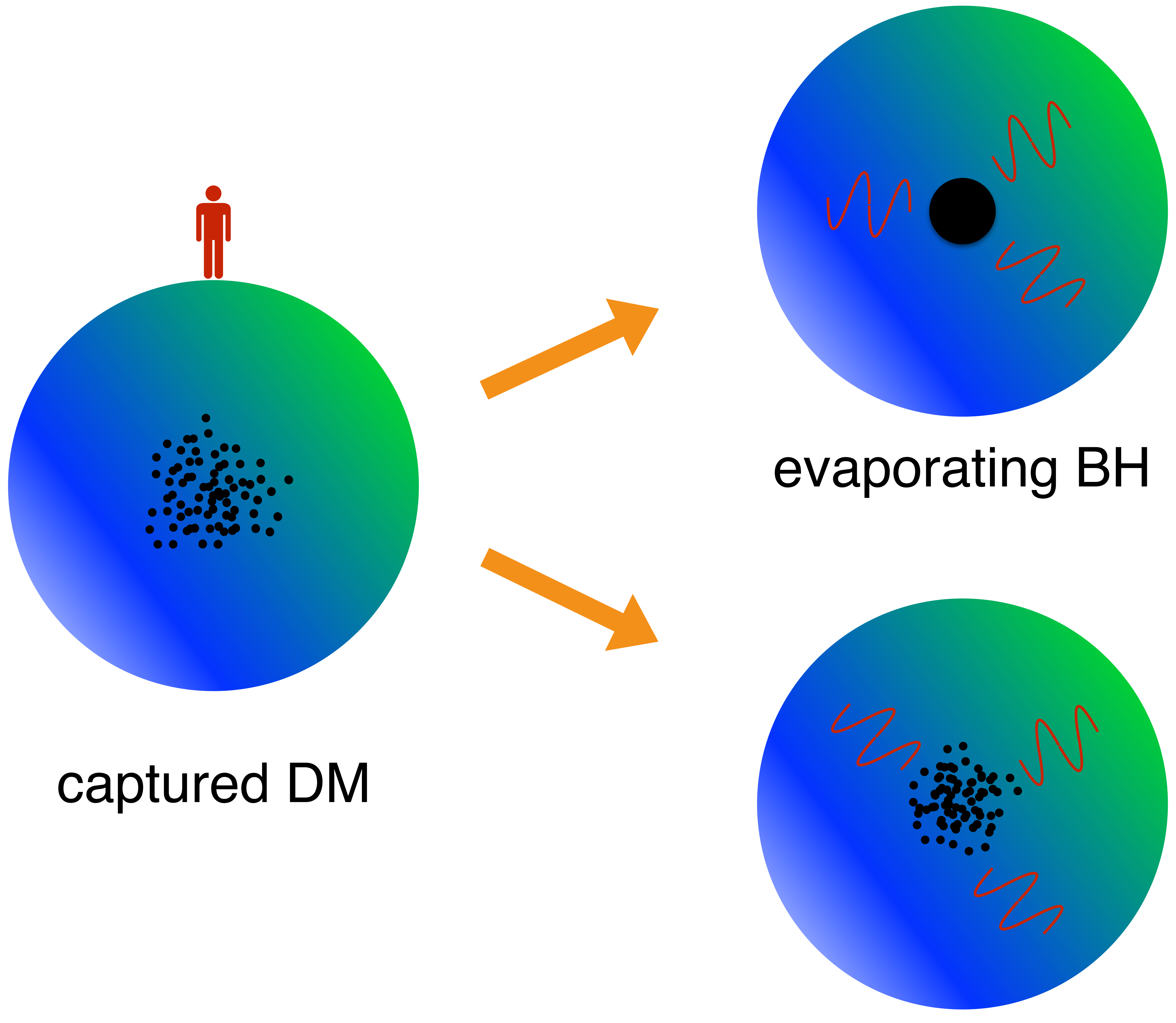
e.g. with thermal bremsstrahlung:

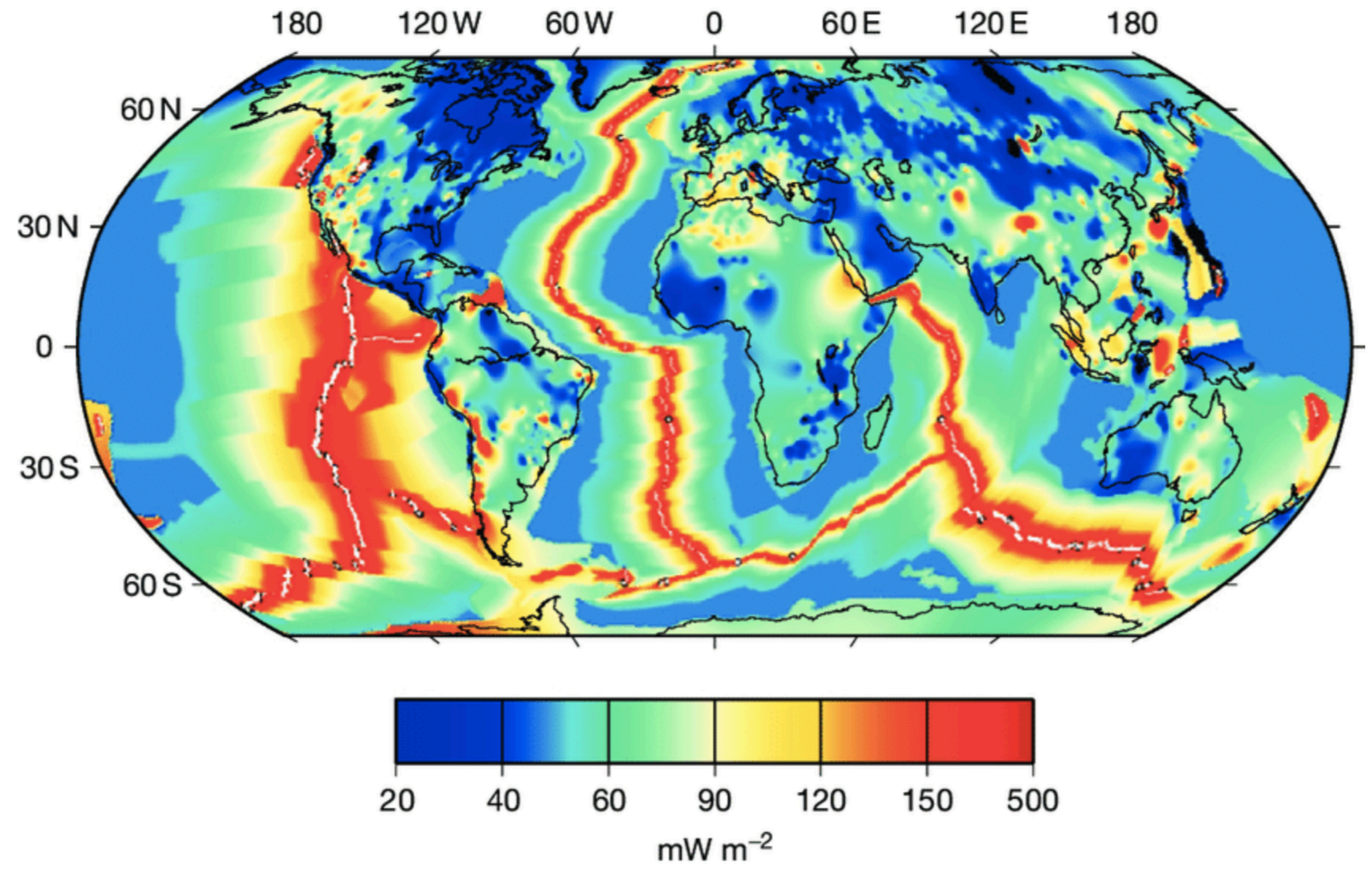
$$L_{stop} \simeq 10^{-2}\ \text{km} \left(\frac{m_X}{\text{TeV}}\right)^{\frac{3}{2}} \left(\frac{m_\phi}{\text{keV}}\right)^{2} \left(\frac{g_n}{10^{-10}}\right)^{-\frac{1}{2}} \qquad \text{at}\ \ \rho \sim 1\ \text{g cm}^{-3}$$

What are the signatures of composites accumulating in stellar objects?

JA, Bramante, Goodman, Kopp & Opferkuch, 2012.09176
Bramante et. al., 1909.11683
Mack et. al., 0705.4298

One possibility: Earth heating!



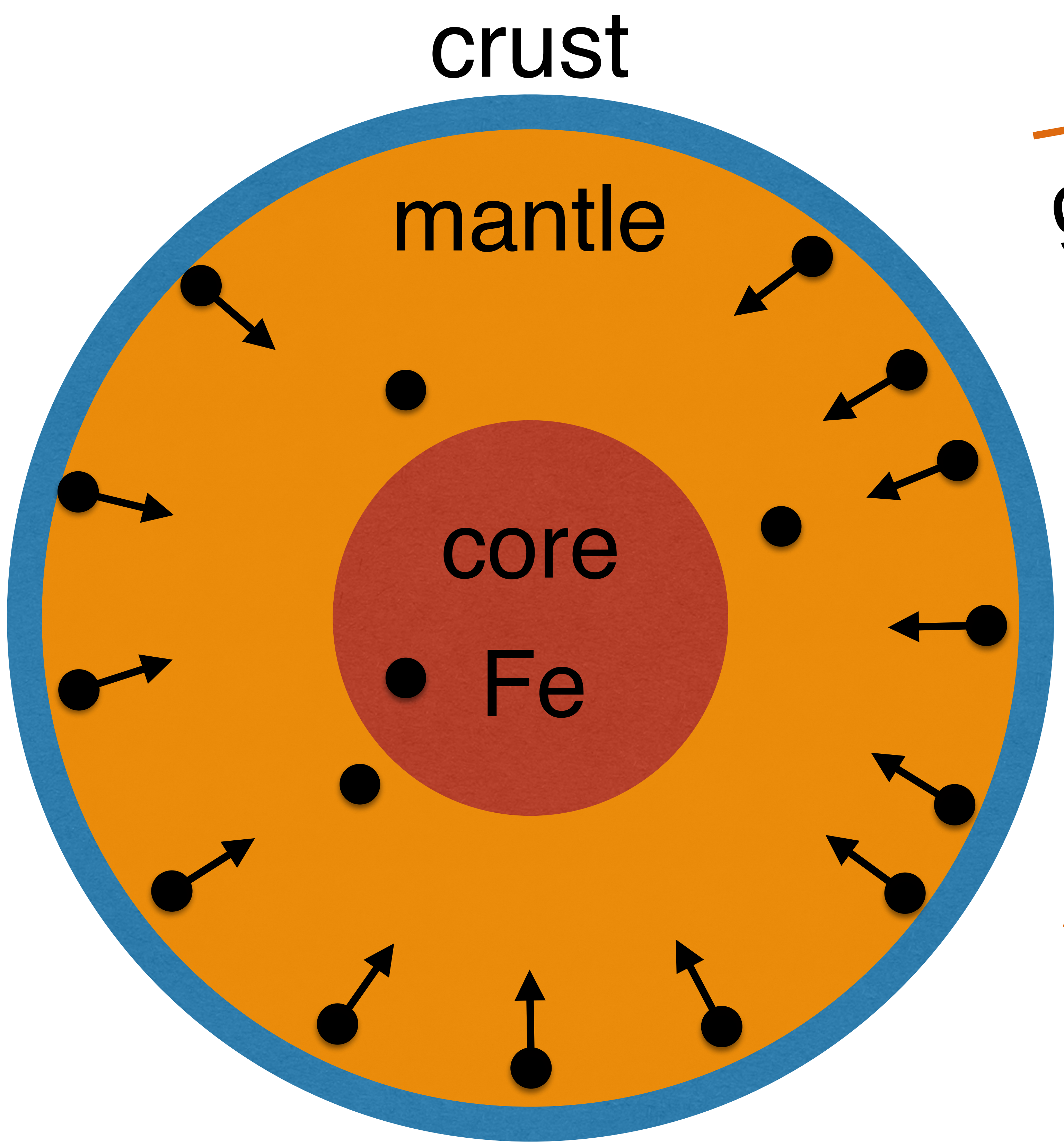


$$\dot{Q}_{\oplus} \sim 44 \text{ TW}$$

rule out parameter space where:

$$\dot{Q}_{DM}(\sigma_{NX}, \ldots) \gtrsim \dot{Q}_{\oplus}$$

Different heating processes:



grav. collapse

$$M_{crit} \sim \frac{M_{pl}^3}{\bar{m}_X^2} \gtrsim 10^{55}\ \mathrm{GeV}$$

but capture rate is $\dot{M}_X \simeq 10^{25}\ \mathrm{GeV\ s^{-1}}$

fusion

$$\dot{E} \sim \bar{Q}\dot{R}_{th}R_X^3 \longrightarrow \dot{Q}_{fus} \lesssim \dot{Q}_{\oplus}$$

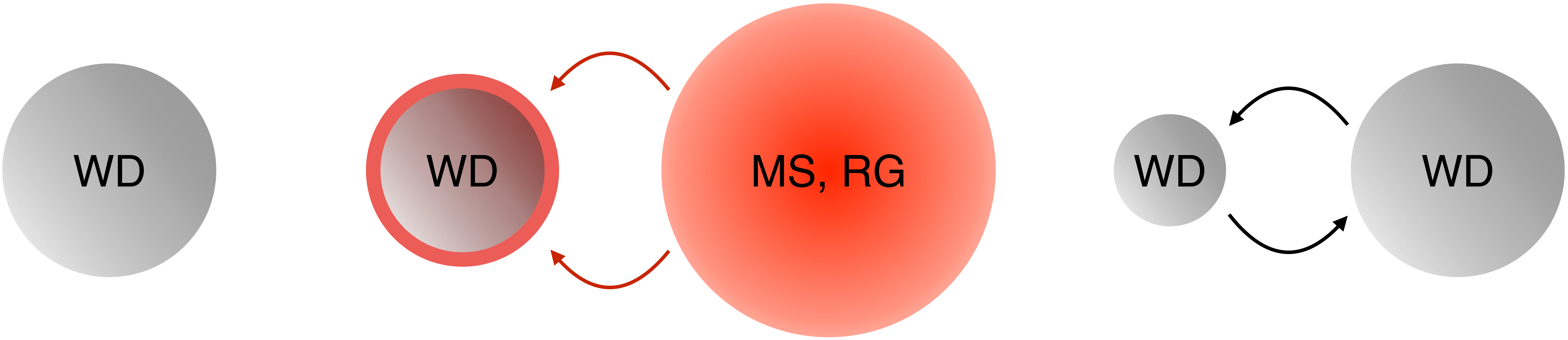
compression

$$\Delta E \sim n_N R_X^3 \langle \phi \rangle \sim \mathrm{MeV}\ \bar{m}_X^{-4}$$

$\dot{Q}_{comp} \gtrsim \dot{Q}_{\oplus}$ for $\bar{m}_X \lesssim \mathrm{GeV}$

Type-Ia Supernovae

- Thermonuclear explosions of white dwarfs
- Standard candles
- Exact trigger channel/s still debated:



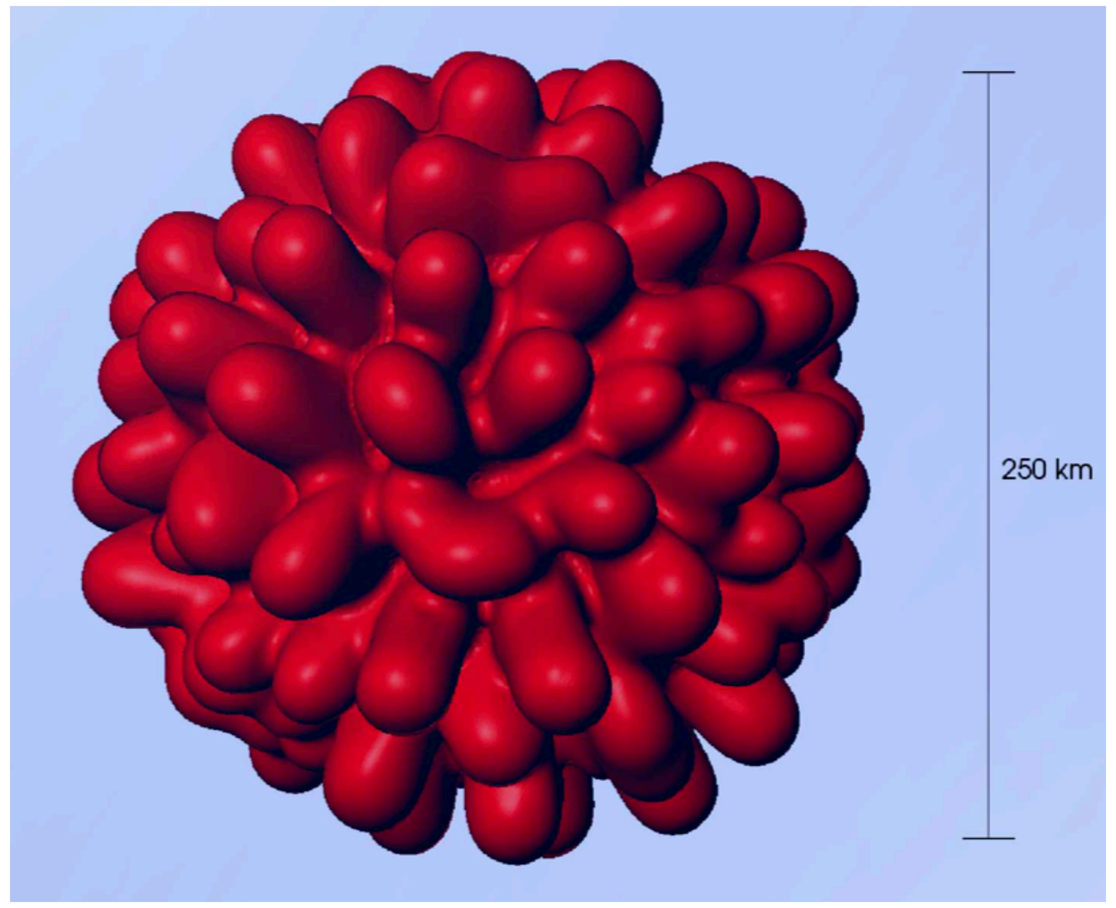
single WD

single degenerate

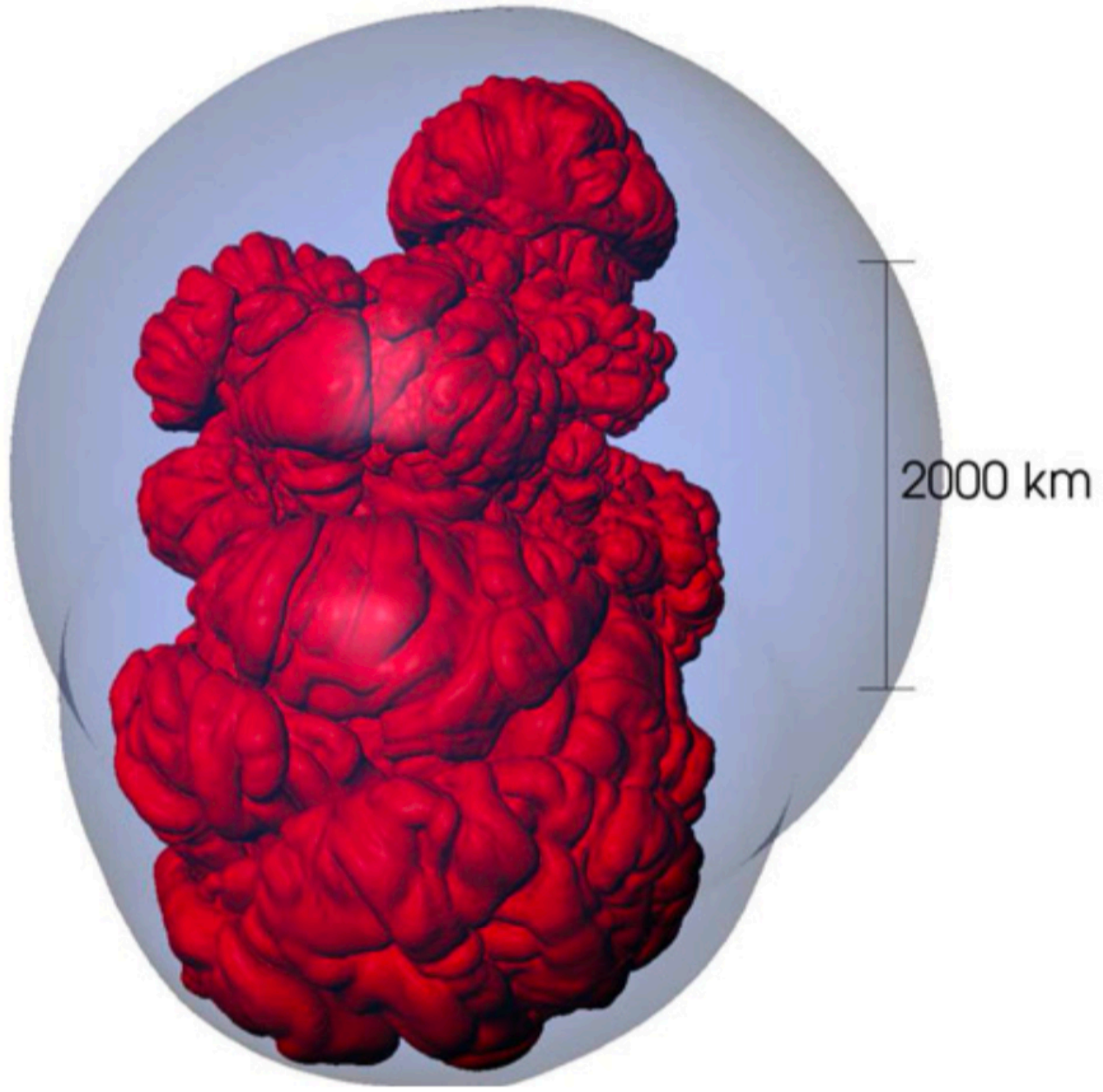
double degenerate

Timmes & Woosley, ApJ 396 (1992)
Niemeyer & Woosley, ApJ 475 (1997)
Woosley et. al., 1305.2433

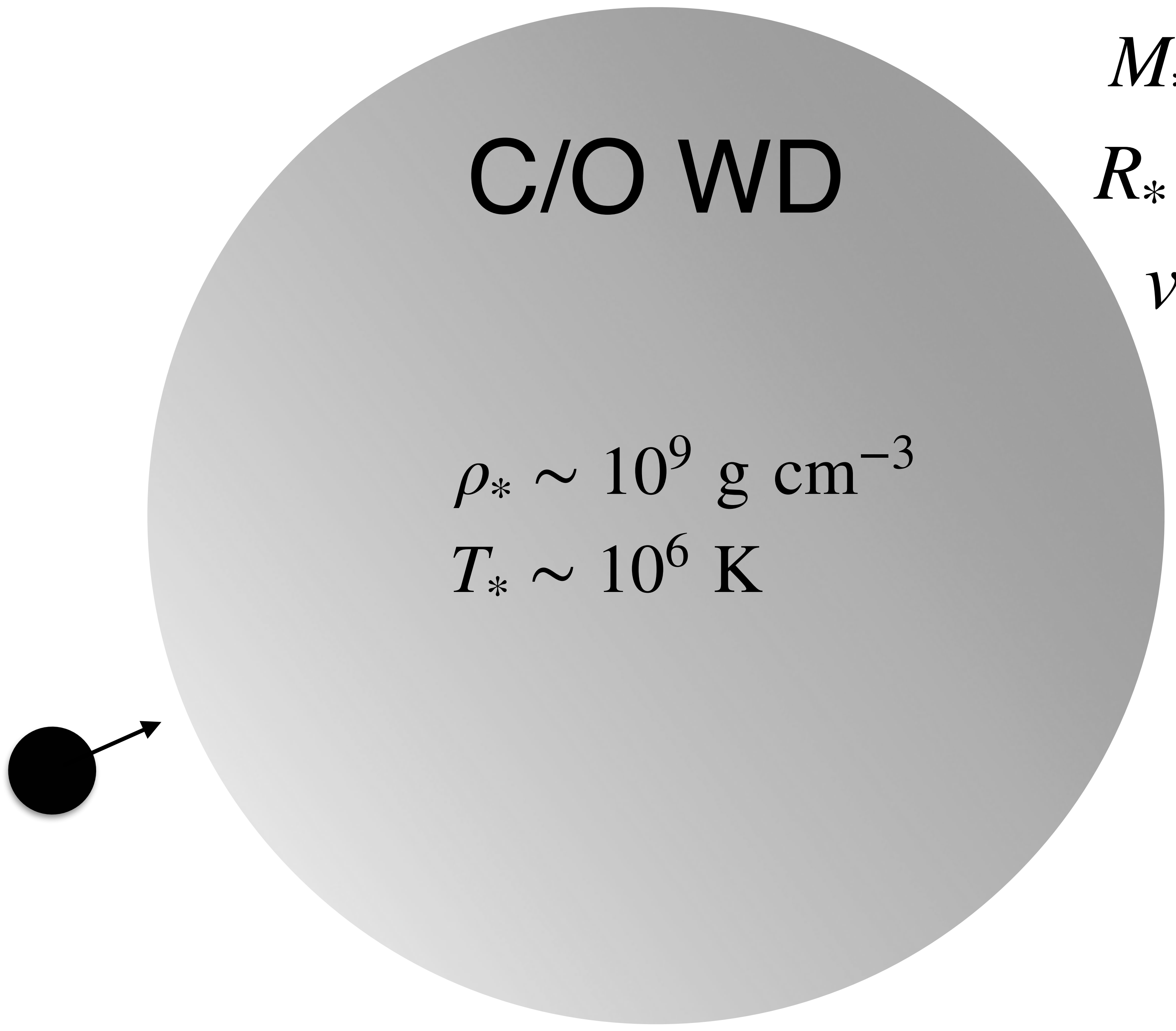
Ignition requires localized heat deposition at WD core:



nuclear flame expands



Composites may cause single WDs to explode upon transit:

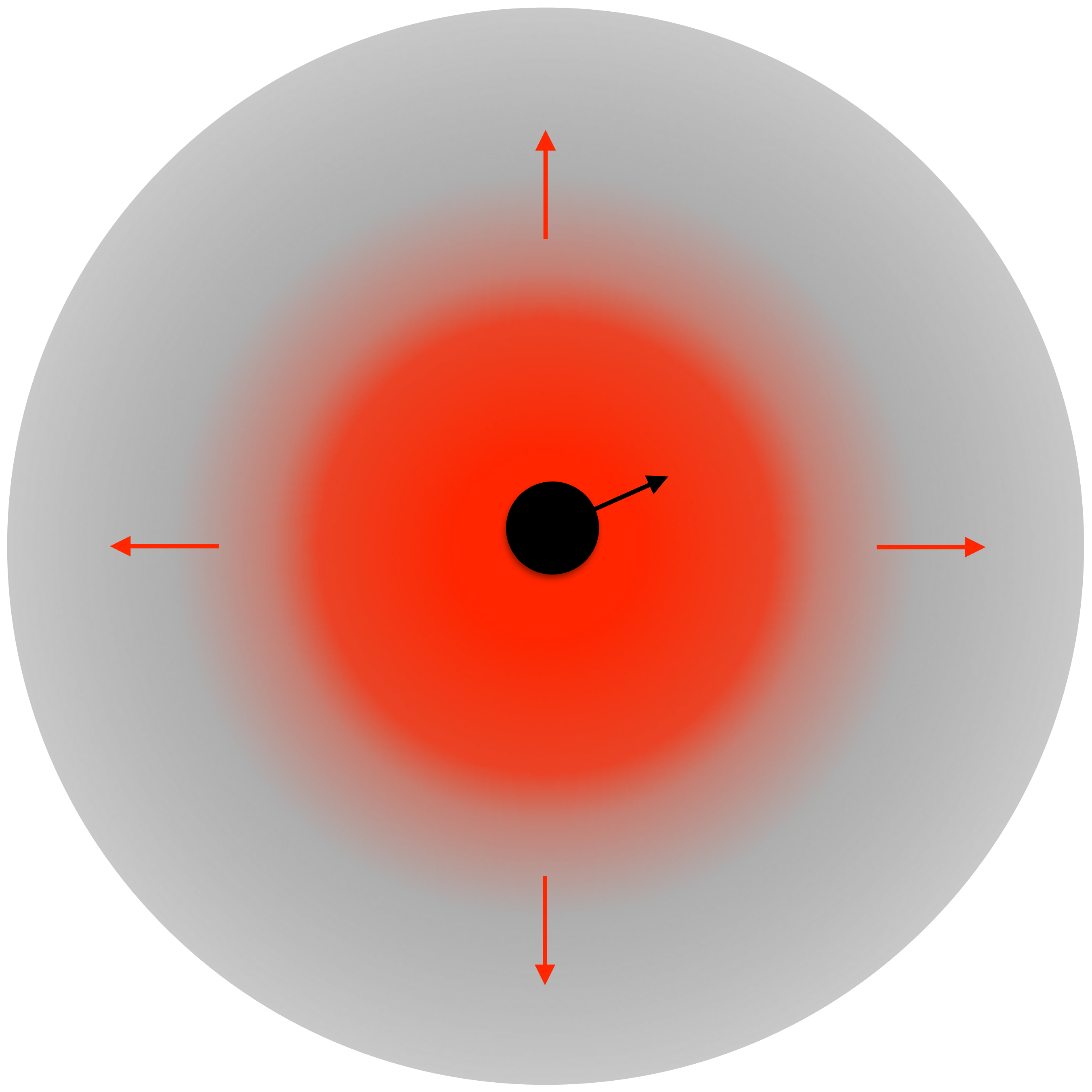


$M_* \sim 1.3 M_\odot$

$R_* \sim 3000$ km

$v_{esc} \sim 10^{-2}$

composite reaches centre



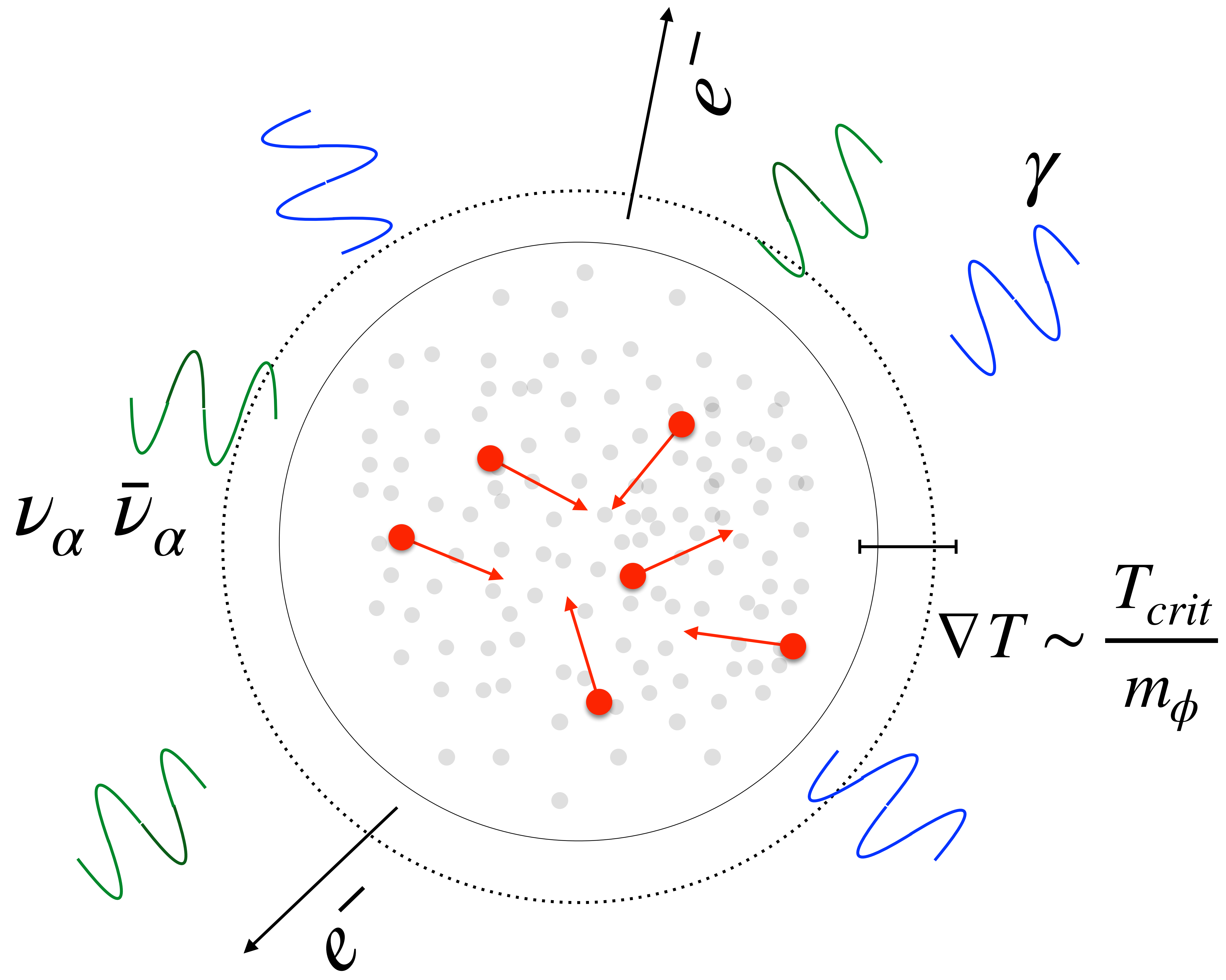
Ignition requires:

heating rate > heat dissipation (I)

$$T_{\rm crit} \sim 10^{10}\ {\rm K} \sim {\rm MeV} \qquad \text{(II)}$$

WD dissipation processes:

Dicus, PRD 6 941 (1972)
Schinder et. al., ApJ 313:531-542 (1986)
Potekhin et. al., astro-ph/9903127



1) Electron conduction

$$\dot{Q}_{\rm cond} \simeq 10^{27}\ {\rm GeV\ s^{-1}} \left(\frac{\rho_*}{10^9\ {\rm g\ cm^{-3}}}\right)^{\frac{4}{15}} \left(\frac{R_X}{\mu{\rm m}}\right)$$

2) Photon emission

$$\dot{Q}_{\rm rad} \simeq 10^{24}\ {\rm GeV\ s^{-1}} \left(\frac{m_\phi}{\rm keV}\right) \left(\frac{R_X}{\mu{\rm m}}\right)^2$$

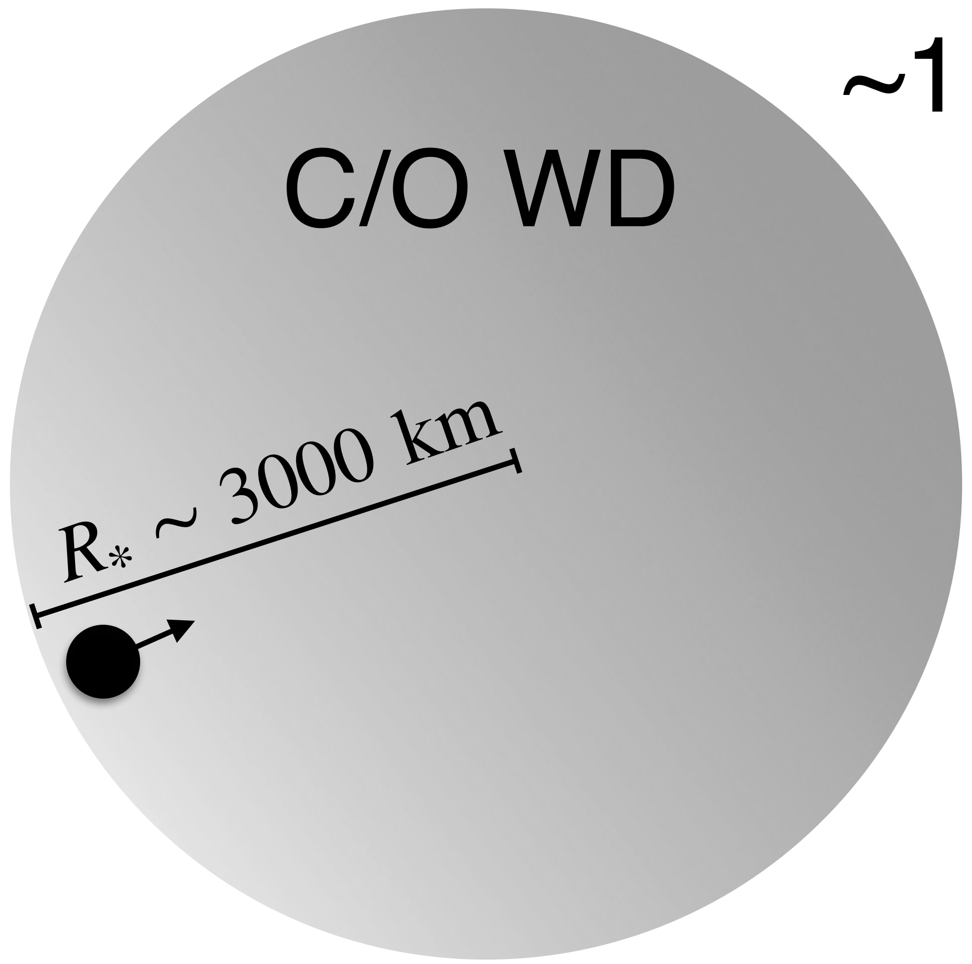
3) Neutrino emission

$$\dot{Q}_{\nu\bar{\nu}} \simeq 10^{18}\ {\rm GeV\ s^{-1}} \left(\frac{R_X}{\mu{\rm m}}\right)^3$$

How **heavy** must composites be to **reach** the core?

$$v_{esc} = \sqrt{\frac{2GM_*}{R_*}} \sim 0.05 \longrightarrow E_i \simeq 10^{27}\ \text{GeV}\ \left(\frac{M_X}{10^{30}\ \text{GeV}}\right)$$

~1 s crossing time



$$\frac{E_i}{\max(\dot{Q}_{\text{cond}}, \dot{Q}_{\text{rad}}, \dot{Q}_{\nu\bar{\nu}})} \gtrsim 1\ \text{s} \longrightarrow \boxed{M_X \gtrsim 10^{30}\ \text{GeV}}$$

How **large** must composites be to **ignite** the core?

nuclear energy rate > heat dissipation

JA, Bramante & Goodman, 2108.10889

Need to account for relevant reactions:

3 main reactions

$$\left[\begin{array}{lll} {}^{12}\mathrm{C} + {}^{12}\mathrm{C} \to {}^{24}\mathrm{Mg}^* & \bar{Q}_{CC} \simeq 3.16 \text{ MeV} & \dot{R}_{CC} \simeq 10^{43} \text{ cm}^{-3} \text{ s}^{-1} \\ {}^{12}\mathrm{C} + {}^{16}\mathrm{O} \to {}^{28}\mathrm{Si}^* & \bar{Q}_{CO} \simeq 6.51 \text{ MeV} & \dot{R}_{CO} \simeq 10^{42} \text{ cm}^{-3} \text{ s}^{-1} \\ {}^{16}\mathrm{O} + {}^{16}\mathrm{O} \to {}^{32}\mathrm{S}^* & \bar{Q}_{OO} \simeq 13.09 \text{ MeV} & \dot{R}_{OO} \simeq 10^{40} \text{ cm}^{-3} \text{ s}^{-1} \end{array}\right.$$

$$\boxed{\dot{Q}_{\rm fus} \simeq 10^{32} \text{ GeV s}^{-1} \left(\frac{R_X}{\mu\text{m}}\right)^3}$$

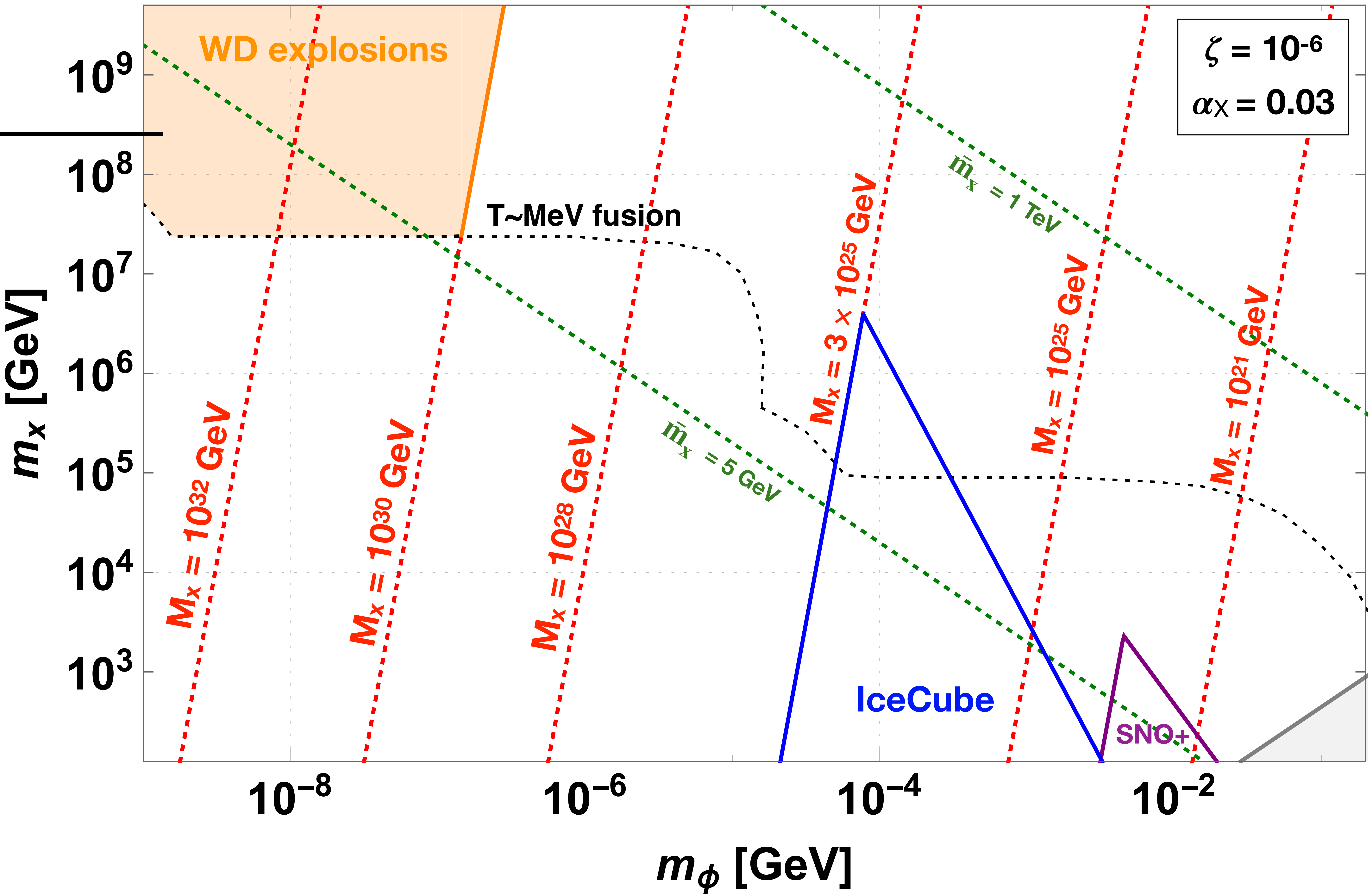
50/50 C/O mix

require $R_X \gtrsim 10^{-2}\ \mu\text{m}$ to ignite core

JA, Bramante & Goodman, 2108.10889
2012.10998

Set bounds based on WD survival:

$$A g_n \langle \phi \rangle \lesssim \mathrm{MeV}$$



In summary:

Composite Signatures

Planets

Compact stars

MS, RG stars

Excess heat,
isotope abundances

Type-Ia SN, stability,
cooling timescale

Fusion rate,
metallicity

future work

Concluding Remarks

- Composite dark matter with weak couplings to the SM could be detected through energetic signatures at various experiments.

- Astrophysical implications include substantial capture and heating of stellar objects, even leading to the ignition of Type-Ia supernovae.

- Various fermionic and bosonic composite dark matter models may present similar phenomenology.

Detecting Composite Dark Matter with Bremsstrahlung and the Migdal Effect

Javier Acevedo

17jfa1@queensu.ca

Thank you for your attention!

Backup slide: Composite Equations I

Scalar only:

i) $$\frac{\partial \varepsilon}{\partial \langle \phi \rangle} = 0 \longrightarrow 3C_\phi^2 \left(\frac{m_*}{m_X}\right) \int_0^{\frac{p_F}{m_X}} \frac{x^2 dx}{\sqrt{x^2 + \left(m_*/m_X\right)^2}} = 1 - \frac{m_*}{m_X}$$

ii) $$p = 0 \longrightarrow \int_0^{\frac{p_F}{m_X}} \frac{x^4 dx}{\sqrt{x^4 + \left(m_*/m_X\right)^2}} = \frac{1}{2C_\phi^2} \left(1 - \frac{m_*}{m_X}\right)^2$$

iii) $$C_\phi^2 = \frac{4\alpha_\phi}{3\pi} \frac{m_X^2}{m_\phi^2}$$

Backup slide: Composite Equations II

Add vector field:

i) $$\frac{\partial \varepsilon}{\partial \langle \phi \rangle} = 0 \longrightarrow 3C_\phi^2 \left(\frac{m_*}{m_X}\right) \int_0^{\frac{p_F}{m_X}} \frac{x^2 dx}{\sqrt{x^2 + \left(m_*/m_X\right)^2}} = 1 - \frac{m_*}{m_X}$$

ii) $$p = 0 \longrightarrow \int_0^{\frac{p_F}{m_X}} \frac{x^4 dx}{\sqrt{x^4 + \left(m_*/m_X\right)^2}} = \frac{1}{2C_\phi^2}\left(1 - \frac{m_*}{m_X}\right)^2 - \frac{C_V^2}{2}\left(\frac{p_F}{m_X}\right)^6$$

iii) $$C_\phi^2 = \frac{4\alpha_\phi}{3\pi}\frac{m_X^2}{m_\phi^2} \qquad C_V^2 = \frac{4\alpha_V}{3\pi}\frac{m_X^2}{m_V^2}$$

Backup slide: Composite Equations III

Add $V(\phi) \sim \lambda\phi^4$ potential:

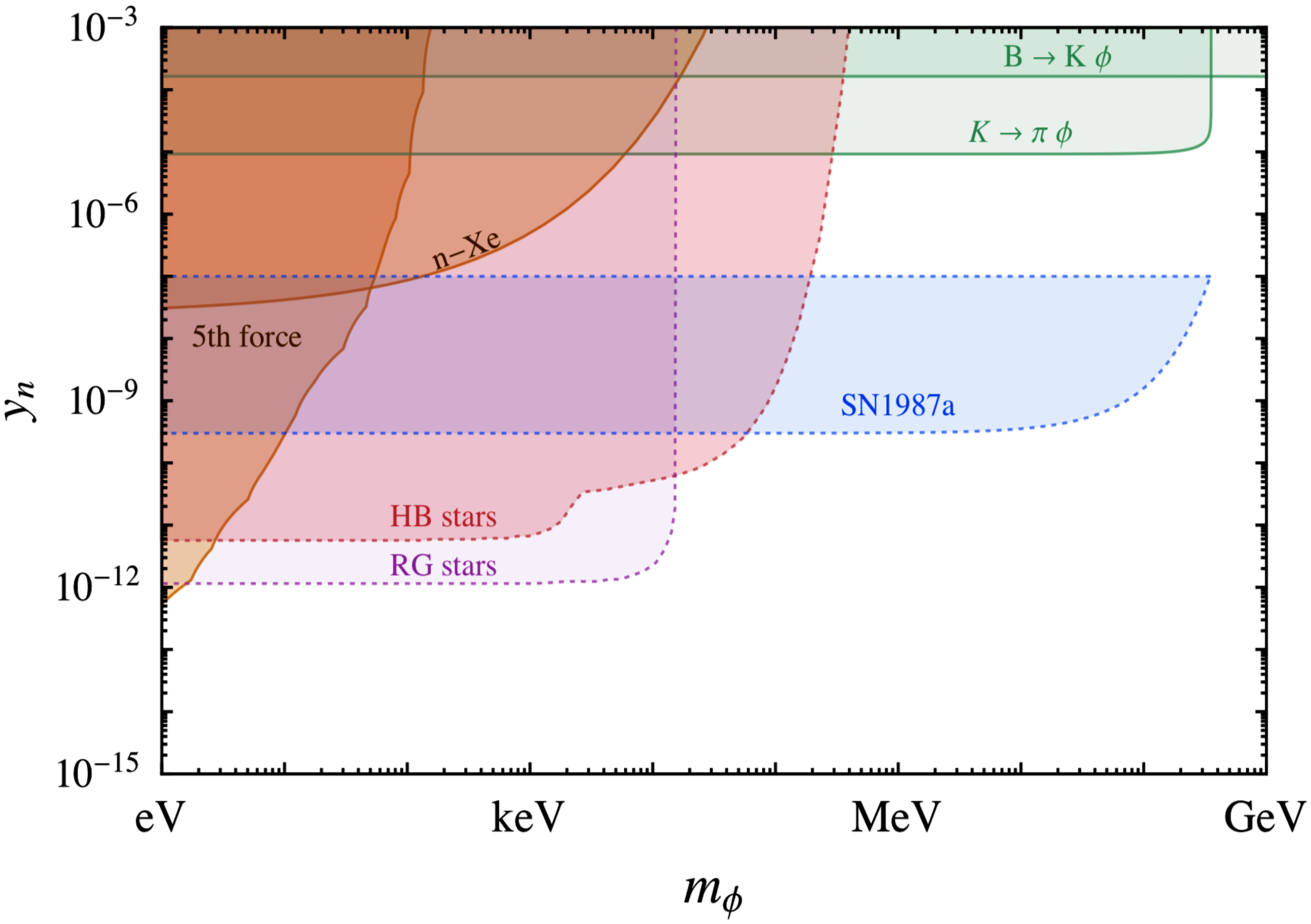
i) $$\frac{\partial\varepsilon}{\partial\langle\phi\rangle} = 0 \longrightarrow 3C_\phi^2\left(\frac{m_*}{m_X}\right)\int_0^{\frac{p_F}{m_X}}\frac{x^2dx}{\sqrt{x^2+\left(m_*/m_X\right)^2}} = 1-\frac{m_*}{m_X}+C_\phi^2\lambda\left(1-\frac{m_*}{m_X}\right)^3$$

ii) $$p = 0 \longrightarrow \int_0^{\frac{p_F}{m_X}}\frac{x^4dx}{\sqrt{x^4+\left(m_*/m_X\right)^2}} = \frac{1}{2C_\phi^2}\left(1-\frac{m_*}{m_X}\right)^2+\frac{\lambda}{4}\left(1-\frac{m_*}{m_X}\right)^4$$

iii) $$C_\phi^2 = \frac{4\alpha_\phi}{3\pi}\frac{m_X^2}{m_\phi^2}$$

Hardy et. al., 1611.05852
Knapen et. al.,1709.07882

Backup slide: Stellar Cooling Bounds on g_n



limits energy to:

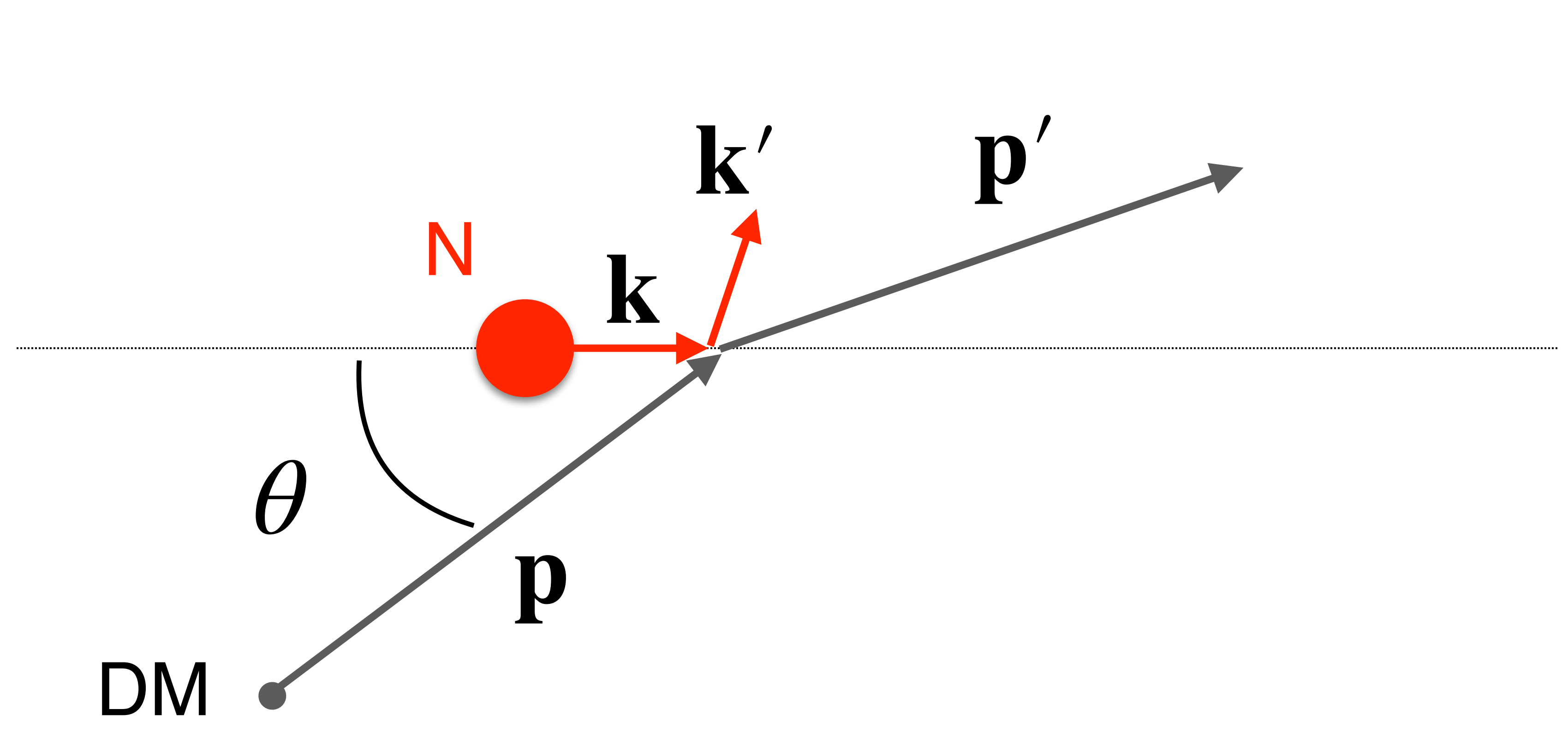
$$\Delta E \simeq A g_n \left(\frac{m_X}{g_\phi}\right)$$

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

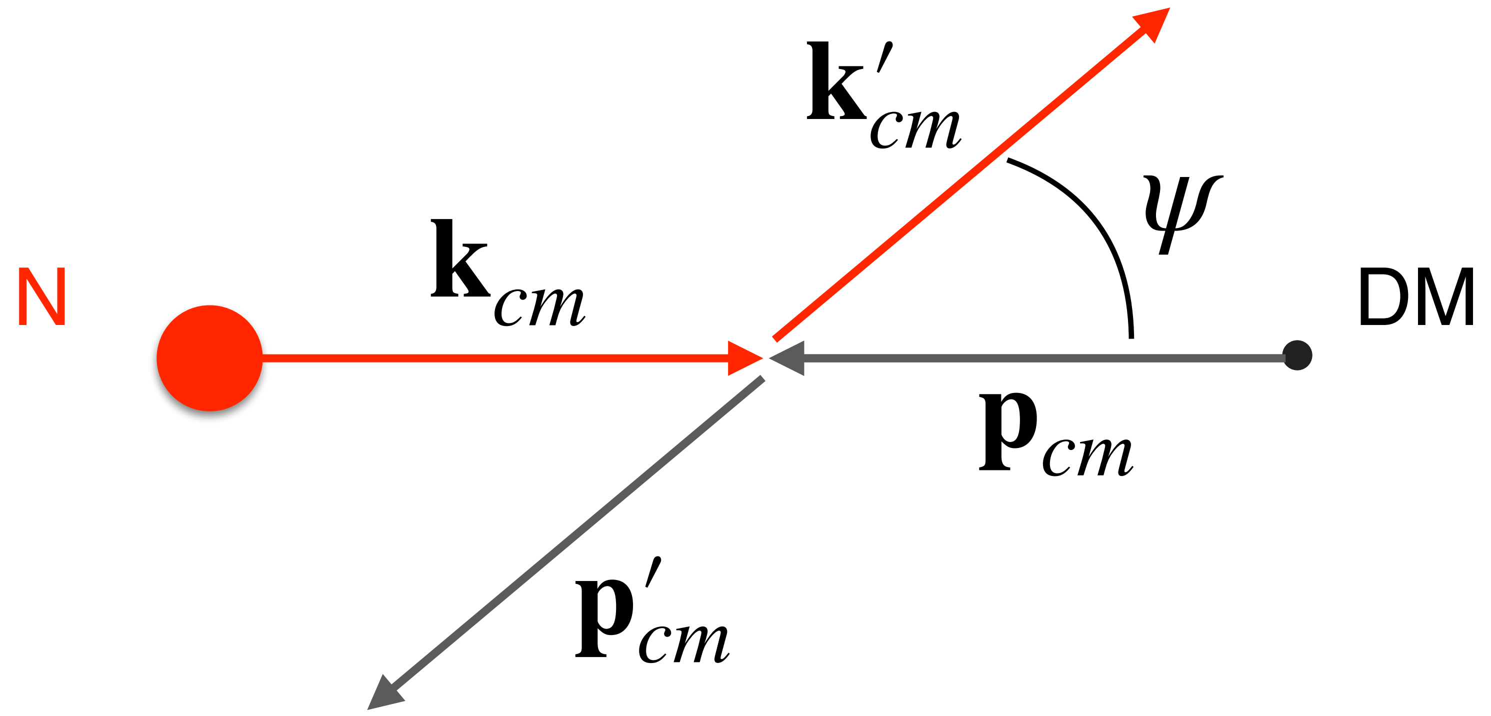
Joglekar et. al., 1911.13293
2004.09539

Backup slide: DM-Nucleus Scattering I

Composite frame:



CM frame:



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

Backup slide: DM-Nucleus Scattering II

$$\tilde{v} \simeq 1 - v_N \cos\theta$$ Moller velocity

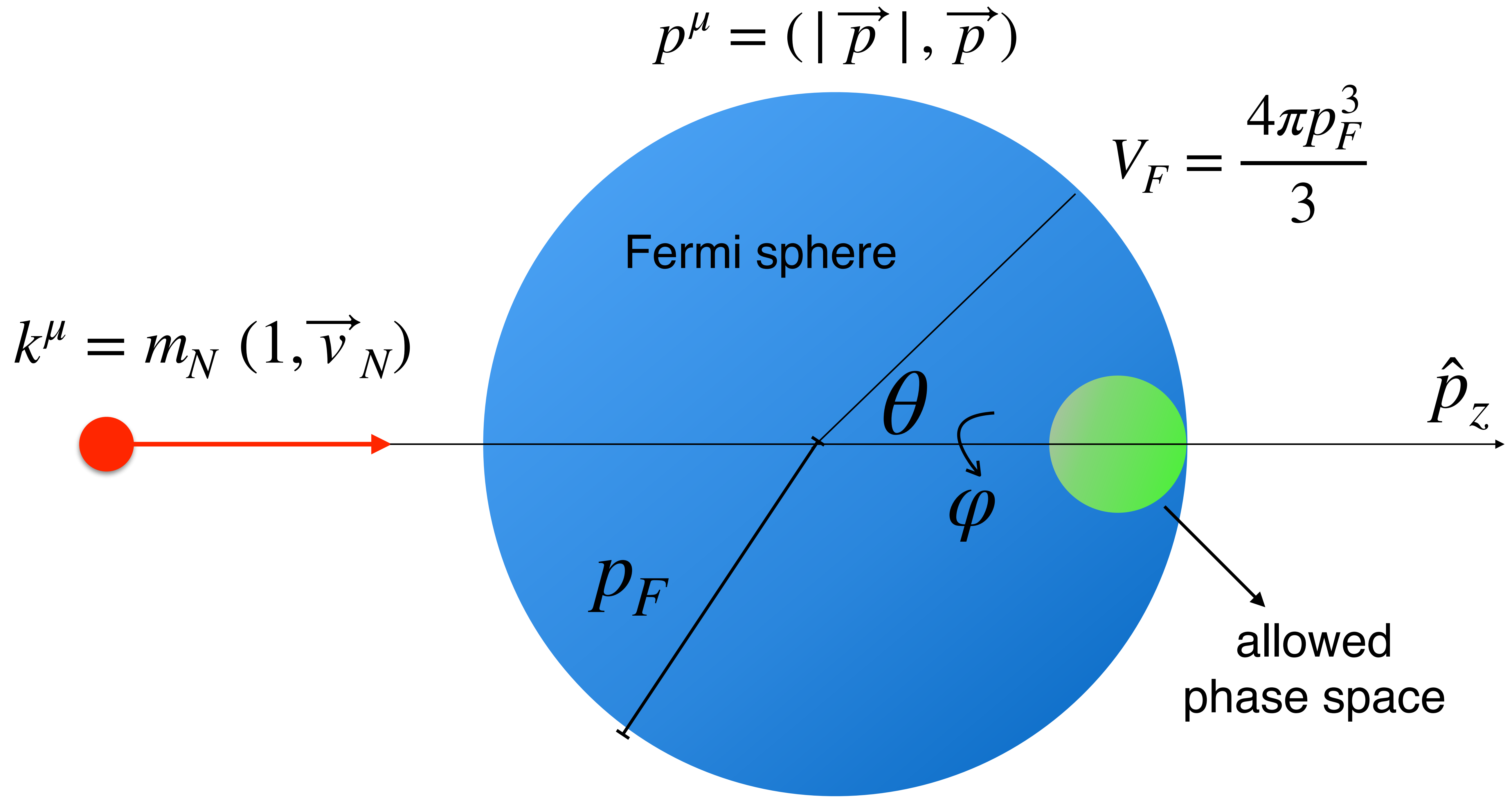
$$E_{cm}^2 \simeq m_N^2 + 2 m_N p (1 - v_N \cos\theta)$$ CM energy

$$\Delta E_{max} \simeq \frac{1}{2} m_N v_N^2 \sin^2\theta$$ Max energy transfer

$$k_{cm}^2 \simeq \frac{m_N p^2}{m_N + 2p} - \frac{2 m_N p^2 (m_N + p) v_N \cos\theta}{(m_N + 2p)^2}$$ CM momentum

$$\beta \simeq \frac{p}{m_N + p} + \frac{m_N v_N \cos\theta}{m_N + p}$$ Boost parameter

$$\psi_{max} \simeq \frac{\left(m_N (m_N + 2p)\right)^{1/2} v_N \cos\alpha}{p}$$ Max scattering angle



$$\boxed{\Gamma_{NX} \sim \frac{A^2 g_n^2 g_X^2 m_N^4 (m_N + 2p_F) v_N^6}{p_F^4}}$$

scattering rate

Backup slide: Coherent Composite-Nucleus Scattering

$$\left(\frac{d\sigma}{dq}\right)_{XN\to XN} = A^2 N_X^2 f^2(\Lambda)\bar{\sigma}_0 \left(\frac{q}{2m_N^2 v_X^2}\right) |F_X(qR_X)|^2 \, |F_a(qr_N)|^2$$

diff. cross section

$$F_X(qR_X) = \frac{3j_1(qR_X)}{qR_X}$$

composite substructure

$$\bar{\sigma}_0 = \frac{g_n^2 g_X^2 m_N^2}{4\pi\tilde{m}_\phi^4}$$

ref. cross section

$$F_a(qr_N) = \frac{3j_1(qr_N)}{qr_N} e^{-q^2 r_N^2}$$

nuclear substructure

$$f(\Lambda) = \min\left[1, \left(\frac{\Lambda}{R_X}\right)^3\right]$$

scatterer wavefunction overlap

Backup slide: Collective Excitations - Surface Modes

$$\left(\frac{d\sigma}{dq}\right)_{0\to 1_l} \simeq A^2 N_X^2 f^2(\Lambda)\bar{\sigma}_0 \left(\frac{q}{2m_N^2 v_X^2}\right) |F_{\rm surf}^{(l)}(qR_X)|^2$$

diff. cross section

$$F_{\rm surf}^{(l)}(qR_X) = \epsilon_l \; (2l+1)^{1/2} j_l(qR_X)$$

surface mode form factor

$$\epsilon_l \propto m_X^{-1/4} \bar{m}_X^{-3/2} R_X^{-7/4} \simeq 10^{-14} \left(\frac{m_X}{\rm TeV}\right)^{-\frac{1}{4}} \left(\frac{\bar{m}_X}{5 \text{ GeV}}\right)^{-\frac{3}{2}} \left(\frac{R_X}{\rm nm}\right)^{-\frac{7}{4}}$$

mode amplitude

$$\bar{\sigma}_0 = \frac{g_n^2 g_X^2 m_N^2}{4\pi \tilde{m}_\phi^4}$$

reference cross section

$$f(\Lambda) = \min\left[1, \left(\frac{\Lambda}{R_X}\right)^3\right]$$

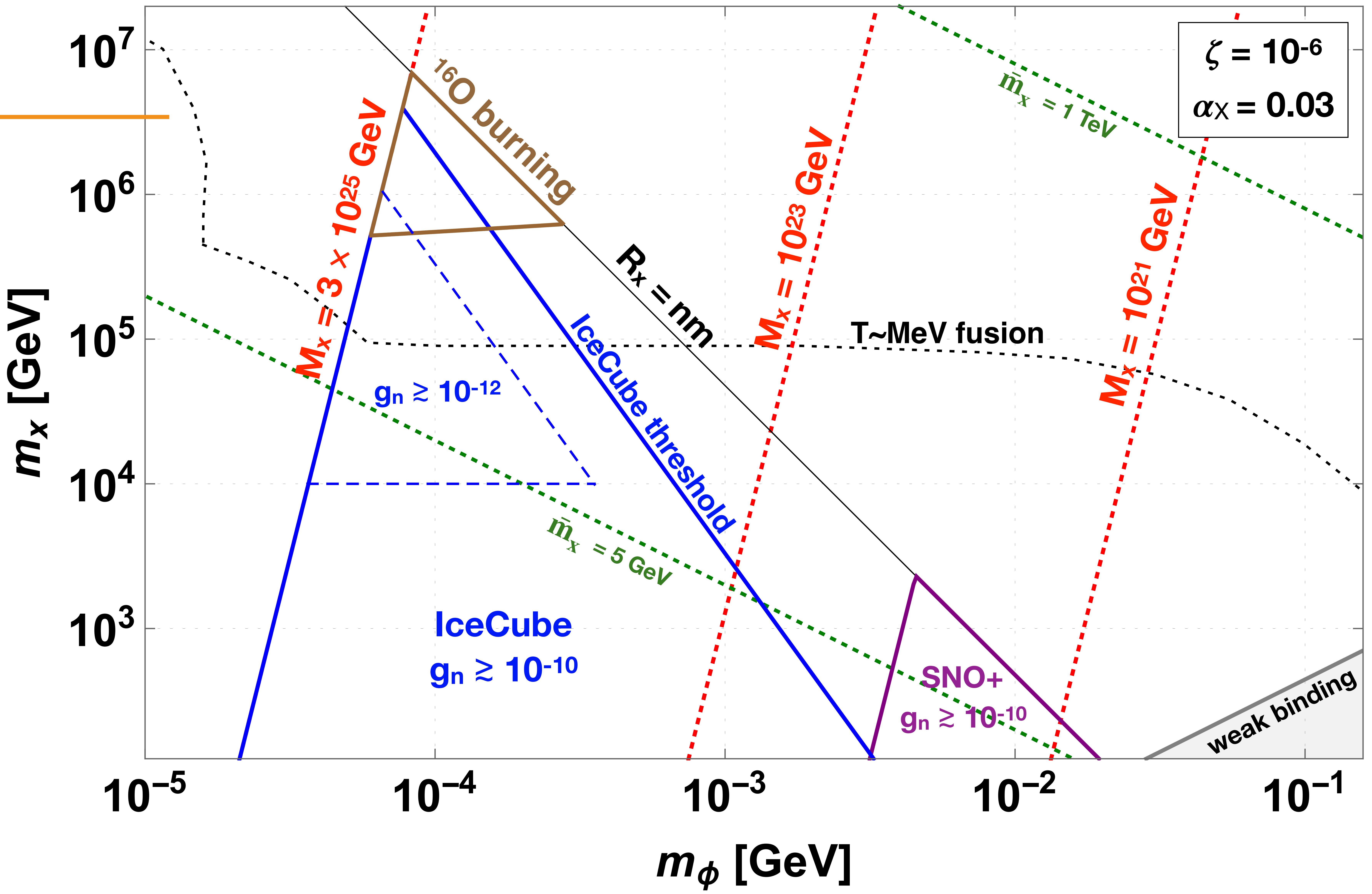
scatterer wavefunction overlap

Backup slide: DD at Neutrino Obs.

increasing radius/mass

stellar cooling constraints

$g_n \lesssim 10^{-10}$



increasing temperature

Backup slide: DM Velocity Distribution

$$f_*(\mathbf{v}) = \frac{(v^2 - v_e^2)^{3/2}}{N_*} \exp\left(- \frac{\tilde{v}^2}{v_0^2} \right) \Theta(v - v_e)\, \Theta(v_{eg} - \tilde{v})$$

$$\tilde{v}^2 \equiv v^2 - v_e^2 + v_{rf}^2 + 2 v_{rf} \sqrt{v^2 - v_e^2}\, \cos\phi$$

$$\left[\begin{array}{l} v_{\rm rf} = |\mathbf{v}_{\rm rf}| = 230\,\mathrm{km/s} \\ v_e \approx 11.2\,\mathrm{km/s} \\ v_{eg} = 528\,\mathrm{km/s} \end{array} \right.$$

JA, Bramante, Goodman, Kopp & Opferkuch, 2012.09176

Backup slide: WD Dissipation Processes I

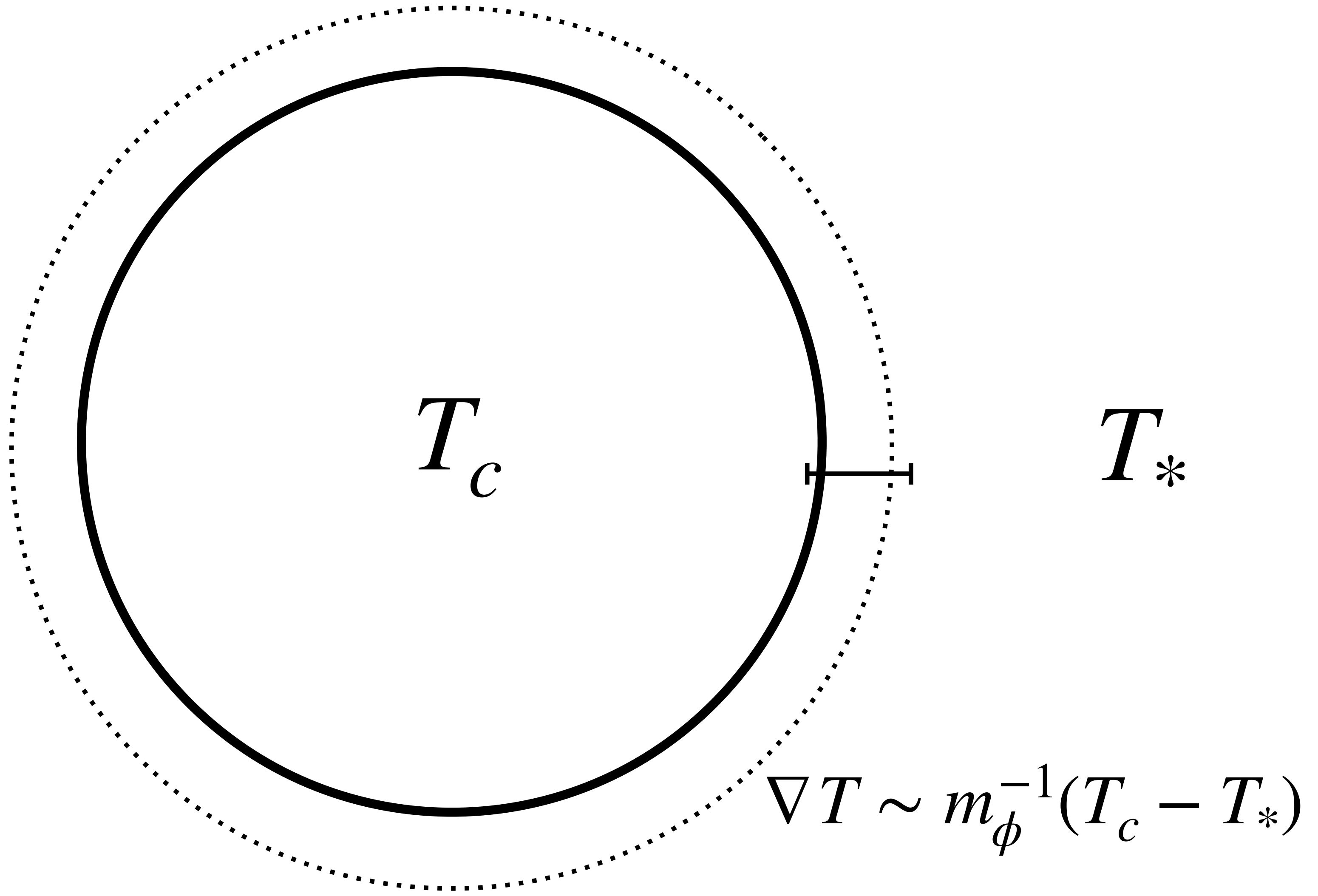
1) Electron conduction

$$\dot{Q}_{\rm cond} = \frac{4\pi^2 R_X T_c^3 (T_c - T_*)}{15\kappa_c \rho_*} \simeq 10^{27}\ \mathrm{GeV\ s^{-1}} \left(\frac{\rho_*}{10^9\ \mathrm{g\ cm^{-3}}}\right)^{\frac{4}{15}} \left(\frac{R_X}{\mu\mathrm{m}}\right)$$

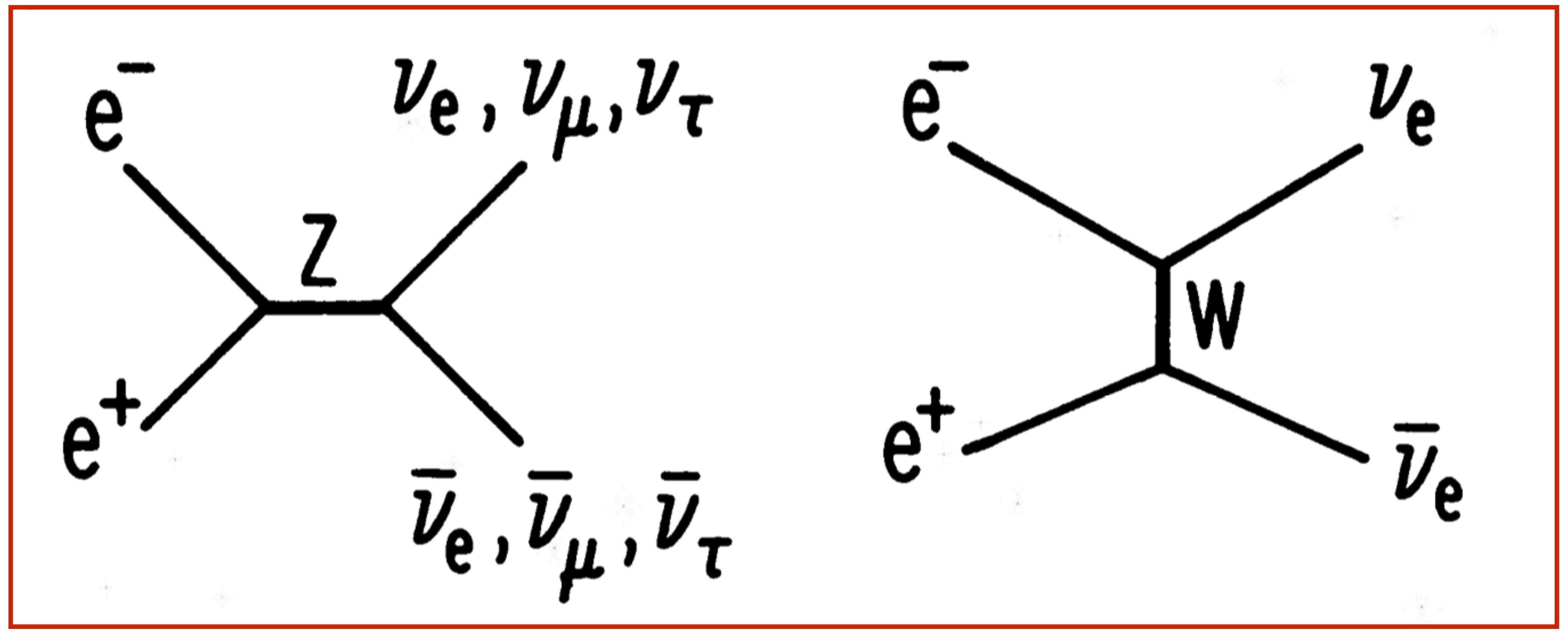
2) Photon emission

High stellar opacity → blackbody spectrum

$$\dot{Q}_{\rm rad} = \frac{4\pi R_X^2 \sigma_{\rm SB} \nabla T^4}{\kappa_r \rho_*} \simeq 10^{24}\ \mathrm{GeV\ s^{-1}} \left(\frac{m_\phi}{\mathrm{keV}}\right) \left(\frac{R_X}{\mu\mathrm{m}}\right)^2$$



Backup slide: WD Dissipation Processes II

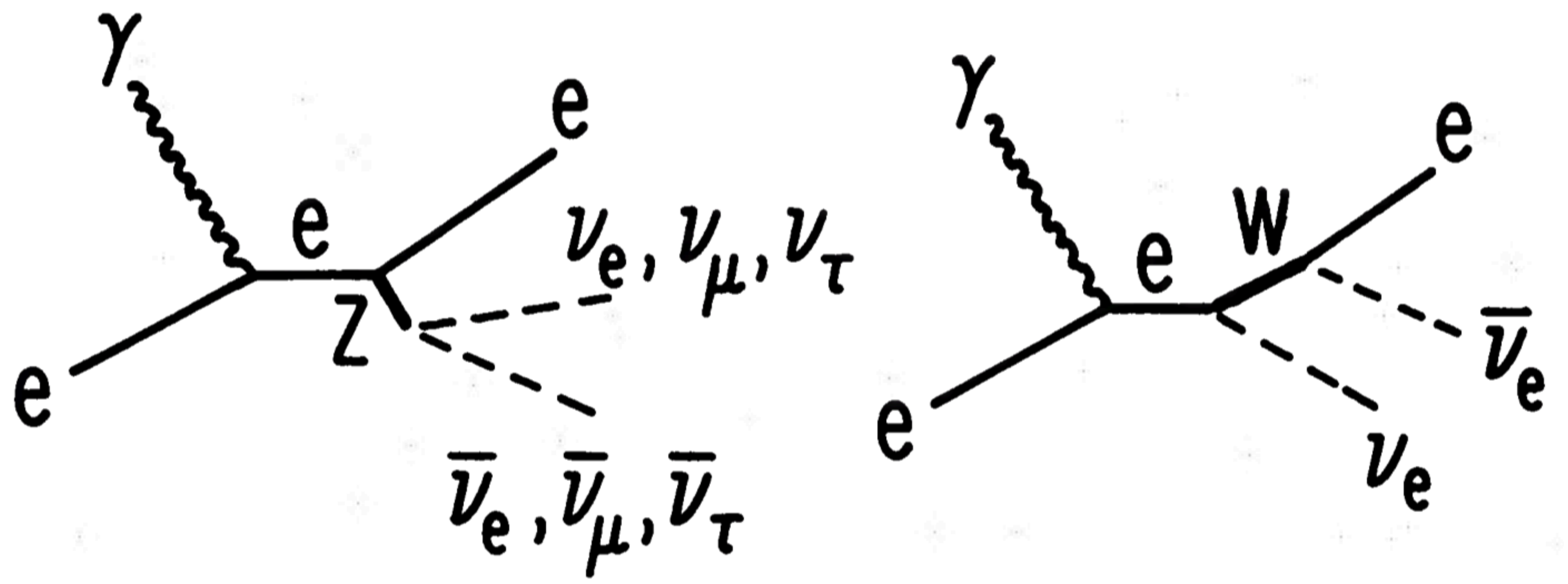


e^+e^- annihilation

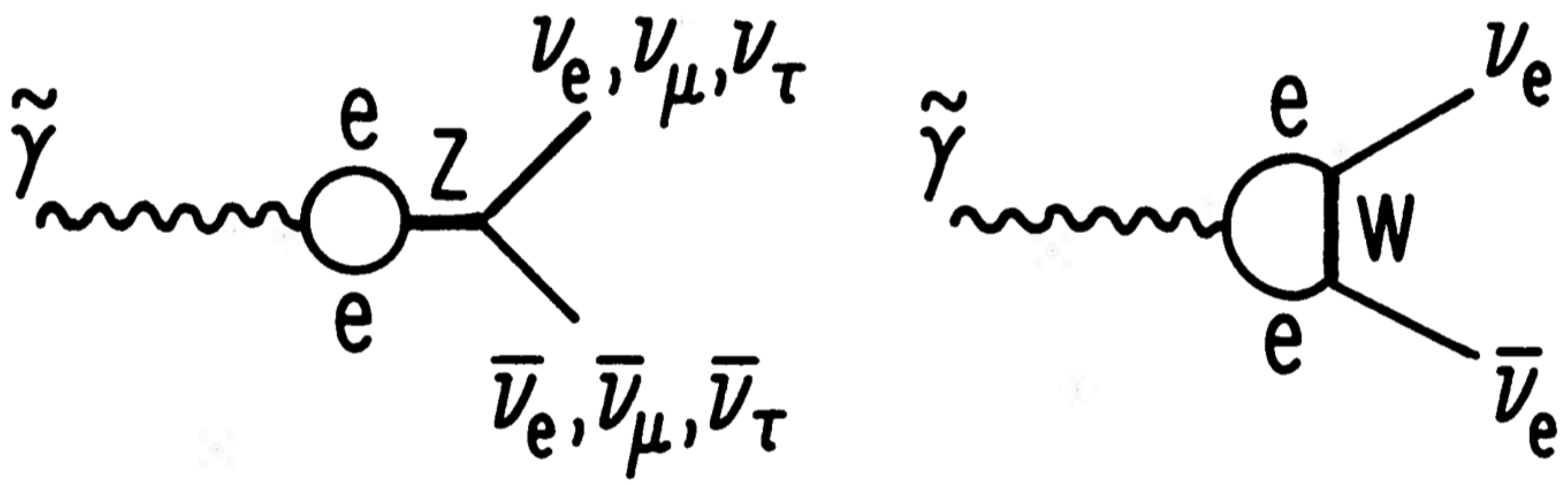
Sum over all neutrino processes:

$$\dot{Q}_{\nu\bar{\nu}} \simeq 10^{18}\ \mathrm{GeV\ s^{-1}} \left(\frac{R_X}{\mu\mathrm{m}}\right)^3$$

Subdominant processes:

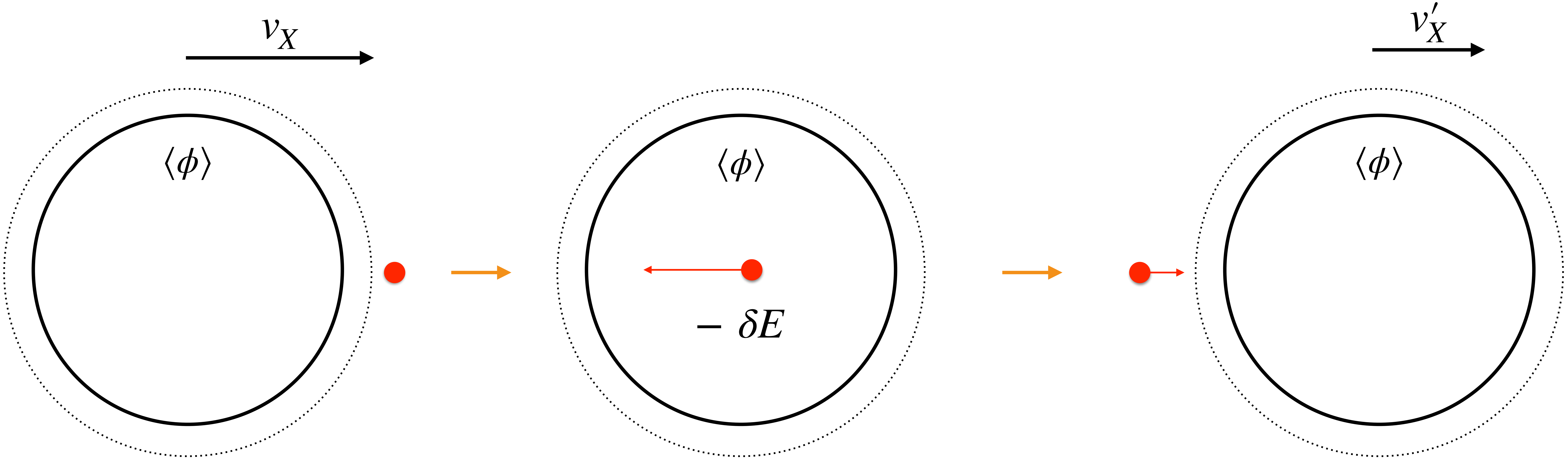


photoproduction



plasmon decay

Backup slide: Composite Stopping



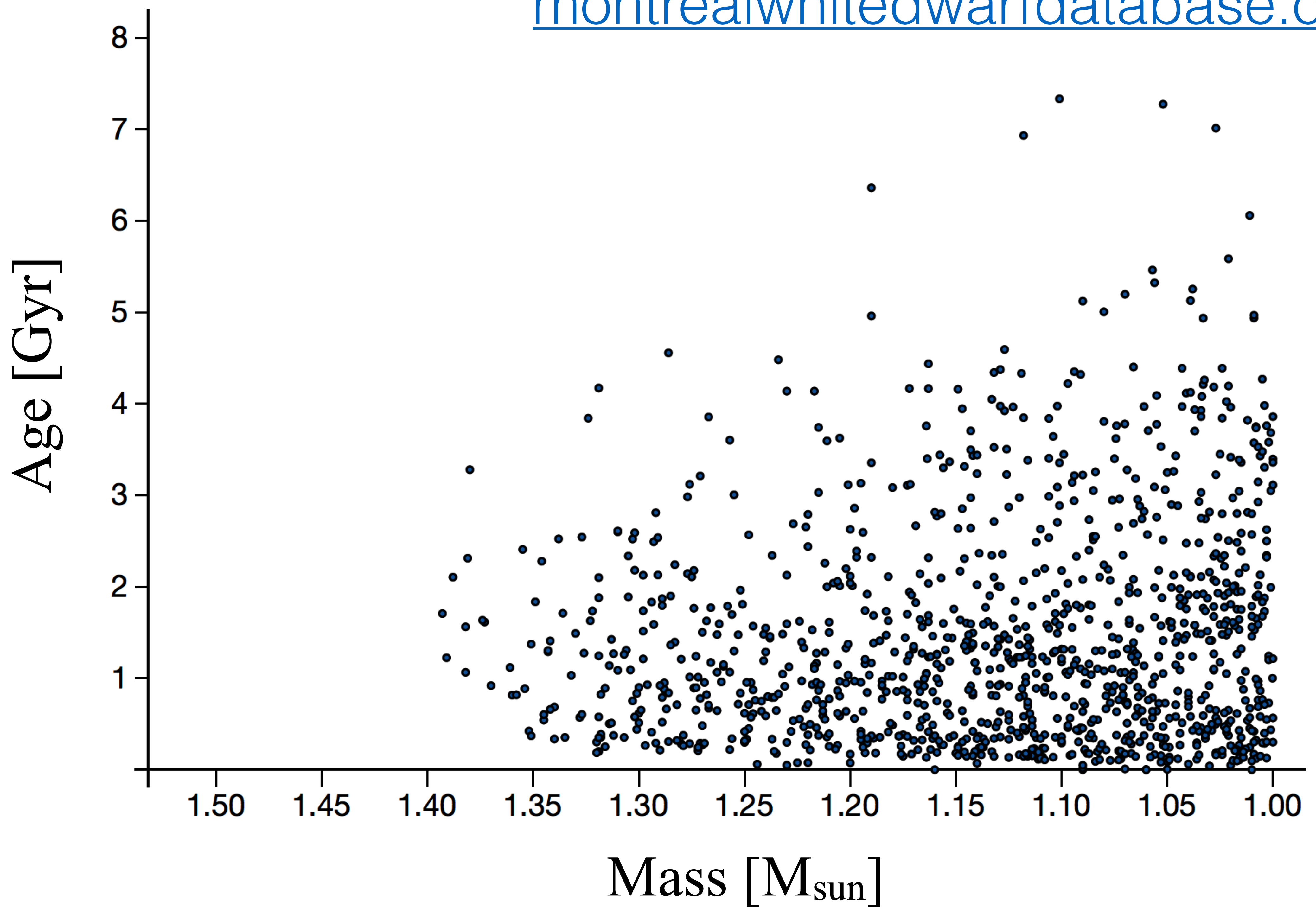
nucleus interacts with composite

nucleus loses energy

$$\frac{1}{2}M_X\left(v'_X - v_X\right) \simeq \delta E$$

Backup slide: WD Sample

montrealwhitedwarfdatabase.org



~1200 WDs → ~ O(1) fraction are C/O

90% at < 1000 pc

> Gyr cooling ages

~1 encounter if $(\rho_X \sim 0.3 \text{ GeV cm}^{-3})$

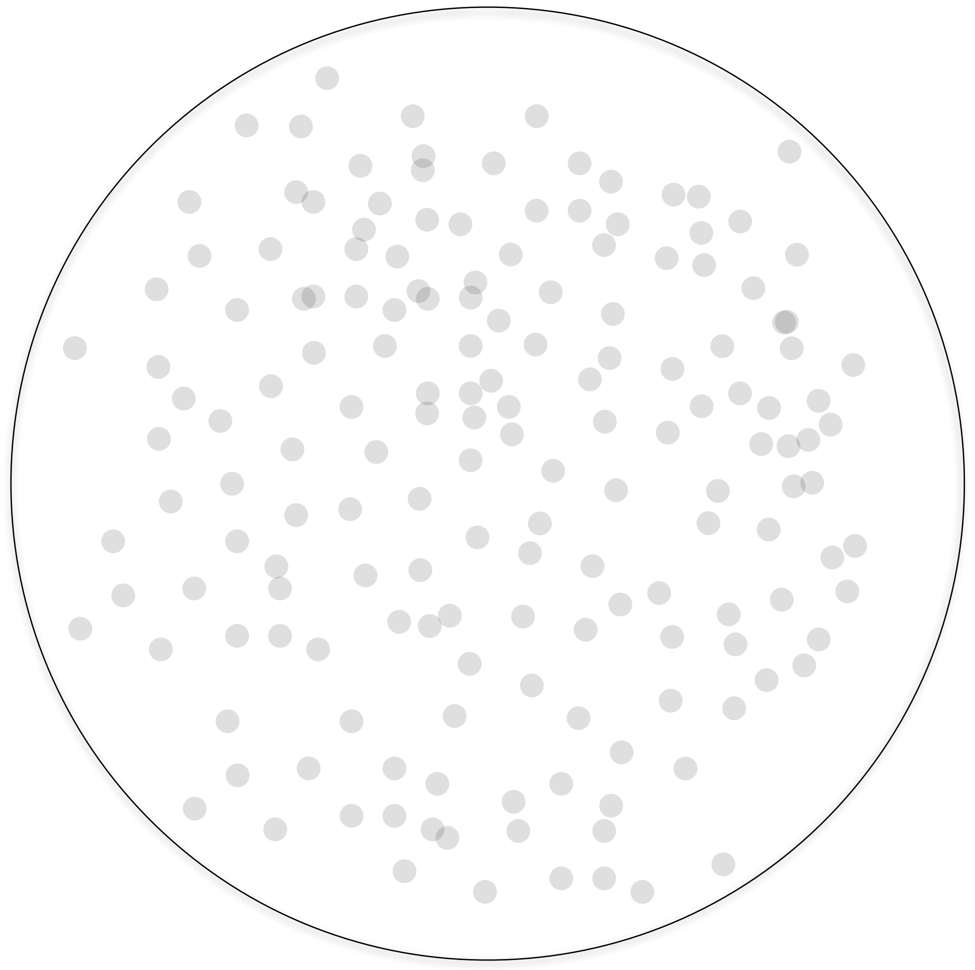
$M_X \lesssim 10^{42}$ GeV

Gresham et. al., 1707.02313

Backup slide: Extended Composite Model

$$\mathscr{L}_{\mathrm{DM}} = \frac{1}{2}\partial^2\phi + \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}m_V V^2 - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \bar{X}\left(i\gamma^\mu\partial_\mu - g_V V^\mu\partial_\mu - m_X\right)X + g_\phi\bar{X}\phi X$$

Repeat mean-field approach:



$$\langle\phi\rangle \neq 0$$

$$\langle V^0\rangle \neq 0$$

$$\boxed{\langle V^0\rangle \sim \left(\frac{m_\phi}{m_V}\right)^3 \frac{m_X^3}{m_V^2}}$$