White Dwarfs as Dark Matter Detectors

Ryan Janish

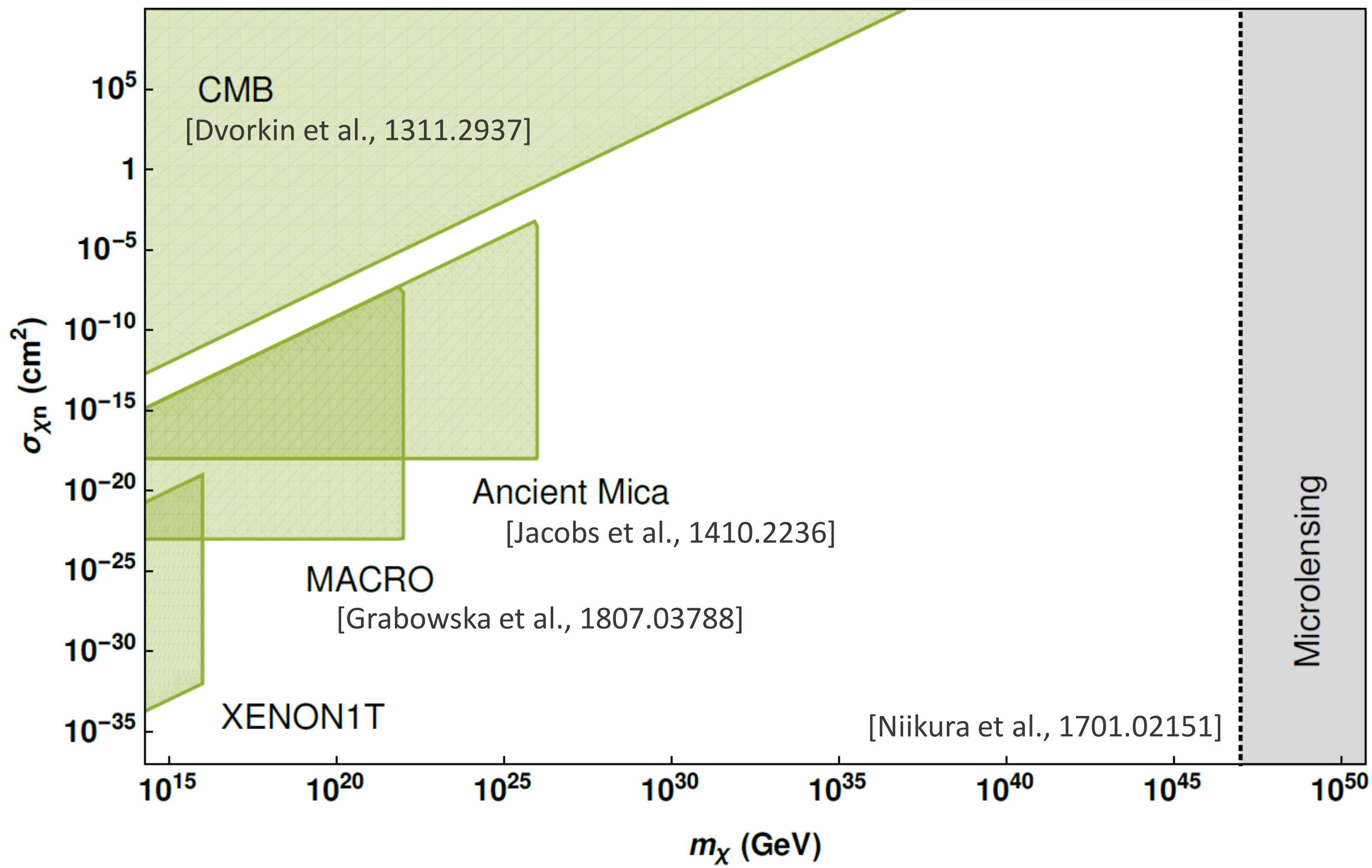
(UC Berkeley)

[Graham, RJ, Narayan, Rajendran, Riggins, 1805.07381]
[RJ, Narayan, Riggins, *in preparation*]

Ultra-heavy Dark Matter

“Exposure Limit”

$$\text{local flux of dark matter} \approx \frac{1}{\mathrm{m}^2\ \mathrm{year}} \left(\frac{10^{18}\ \mathrm{GeV}}{m_\chi} \right)$$



White Dwarfs as Dark Matter Detectors

WD + DM → SN

Dark matter can locally heat white dwarfs, initiate runaway fusion, and cause supernovae. [Graham et al, '15]

WD Lifetime $\sim \mathrm{Gyr}$

Collecting area

$$\sim \left(10^4\ \mathrm{km}\right)^2 \cdot N_{\mathrm{WD}}$$

White Dwarfs as Dark Matter Detectors

This work: constrain a variety of DM-SM interactions and DM masses due to existence of WDs and the observed SN rate.

Puzzles remain in observations of Type Ia and other WD transients.

It is possible that DM is responsible for an O(1) fraction of these events.

White Dwarfs as Dark Matter Detectors

How to Start Type Ia Supernovae

- SN energy threshold $\mathcal{E}_{\rm boom}$

SN via DM-SM Scattering

- Elastic
- Inelastic (E.g., Q-balls)

SN via DM-DM Annihilation and Decay

- Thermalization of SM Particles
- Elastic Capture of DM in WD

SN via Collapsing DM Cores

- Formation and Evolution of DM Cores
- BH-induced SN
- Annihilation Burst SN

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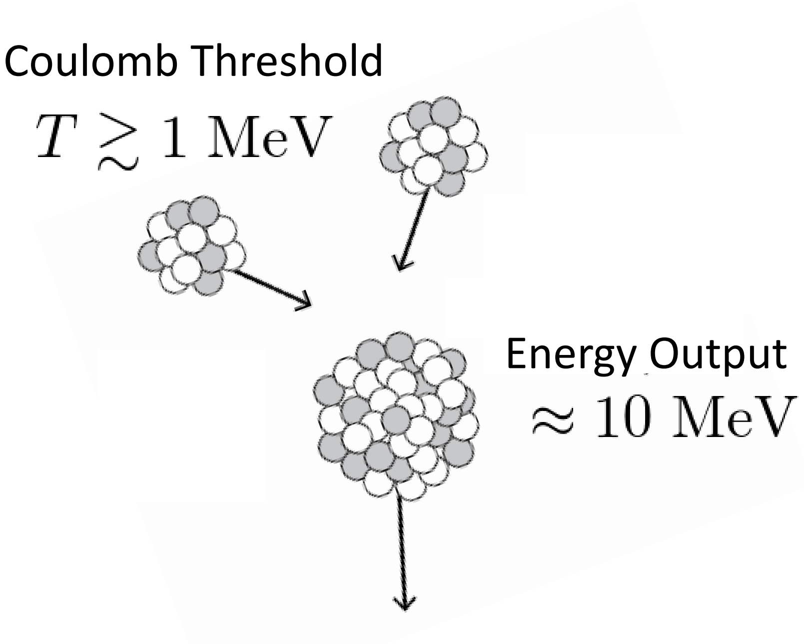
How to Start a Type Ia Supernova

Carbon Fusion



Detonation/Deflagration

Fusion heats stellar medium faster than it can cool.

Degenerate medium – negligible PdV cooling.

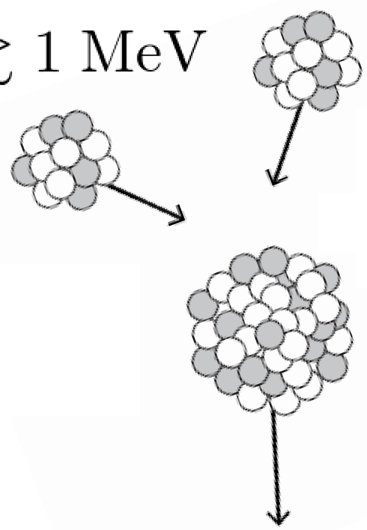
Thermal diffusion slows with distance: $\tau_{\mathrm{cool}} \propto L^2$

How to Start a Type Ia Supernova

Carbon Fusion

Coulomb Threshold

$T \gtrsim 1\ \mathrm{MeV}$



Energy Output

$\approx 10\ \mathrm{MeV}$

Detonation/Deflagration

Fusion heats stellar medium faster than it can cool.

Degenerate medium – negligible PdV cooling.

Thermal diffusion slows with distance: $\tau_{\mathrm{cool}} \propto L^2$

Trigger Size

timescale for (degenerate) electron or photon diffusion $\sim$ timescale for carbon-carbon fusion

How to Start a Type Ia Supernova

Ignition Condition

$$L \gtrsim \lambda_T \qquad T \gtrsim 1\ \mathrm{MeV}$$

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A careful calculation (Timmes and Woosley 1992):

$$\lambda_T \approx 10^{-5}\ \mathrm{cm} \qquad n_{\mathrm{ion}} \approx 10^{32}\ \mathrm{cm}^{-3}\ \ [1.38\ \mathrm{M}_\odot]$$

$$\lambda_T \approx 2 \cdot 10^{-3}\ \mathrm{cm} \qquad n_{\mathrm{ion}} \approx 10^{30}\ \mathrm{cm}^{-3}\ \ [0.85\ \mathrm{M}_\odot]$$

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Trigger Energy

Energy required to heat a volume λ_T^3 to a temperature of $1\ \mathrm{MeV}$

$$\mathcal{E}_{\mathrm{boom}} \approx 10^{16}\ \mathrm{GeV} \qquad [1.38\ \mathrm{M}_\odot]$$

$$\mathcal{E}_{\mathrm{boom}} \approx 10^{22}\ \mathrm{GeV} \qquad [0.85\ \mathrm{M}_\odot]$$

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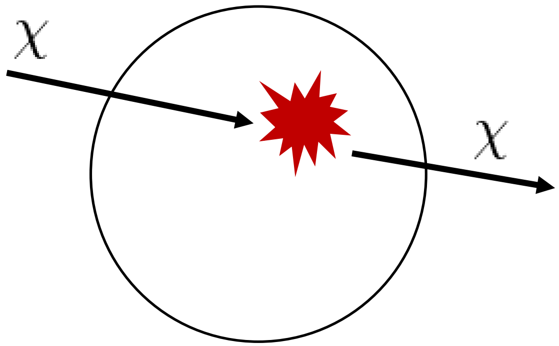
Scattering-induced SN

DM can locally heat a WD though elastic scattering of DM and carbon ions. [Graham, RJ, Narayan, Rajendran, Riggins, 1805.07381]



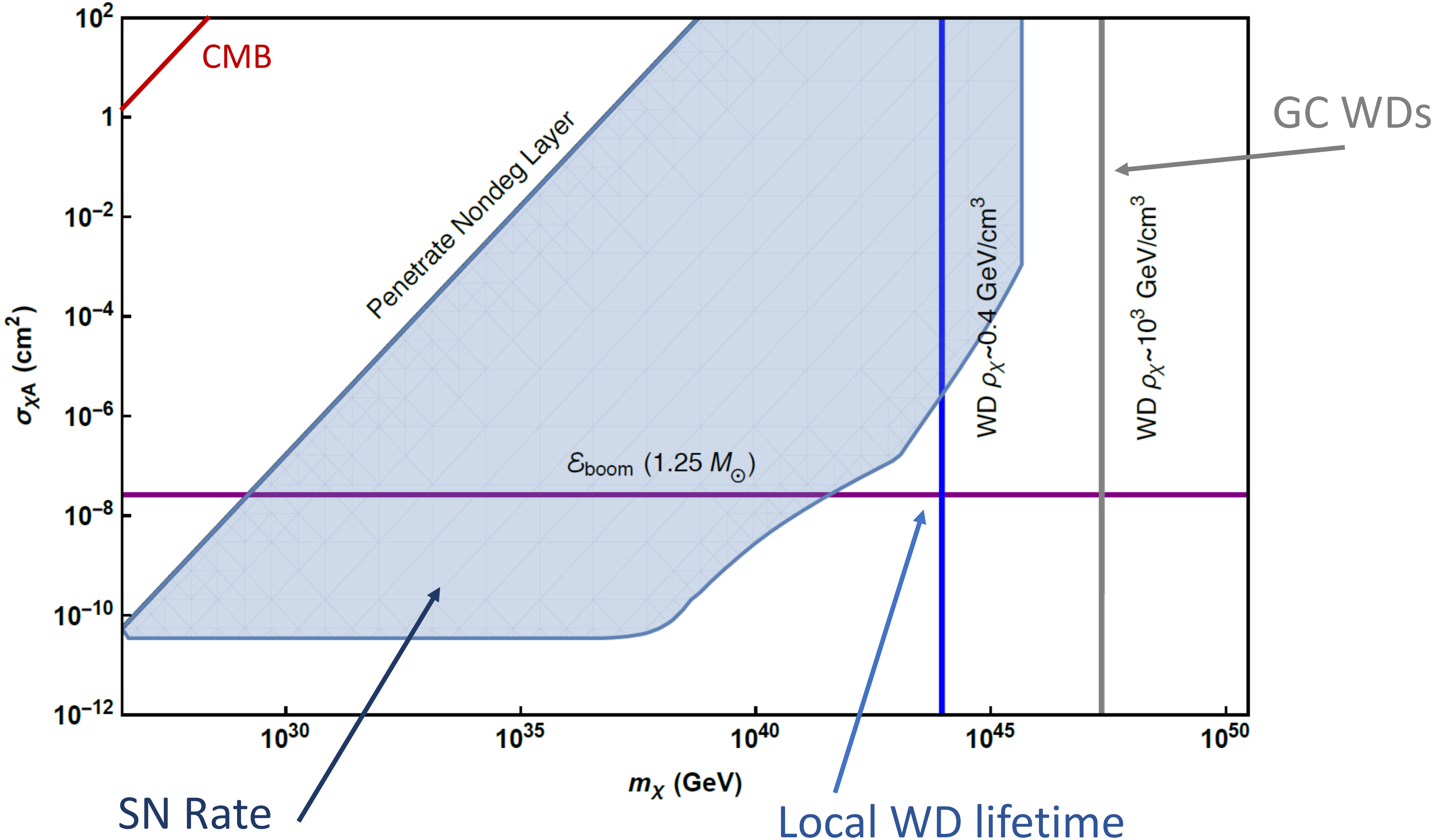
energy transfer per scatter $\omega \sim m_c v_{\rm esc}^2 \sim 1 - 10 \text{ MeV}$

energy transfer per distance $\frac{dE}{dx} \sim n_{\rm ion} \sigma_{\chi A} \omega$

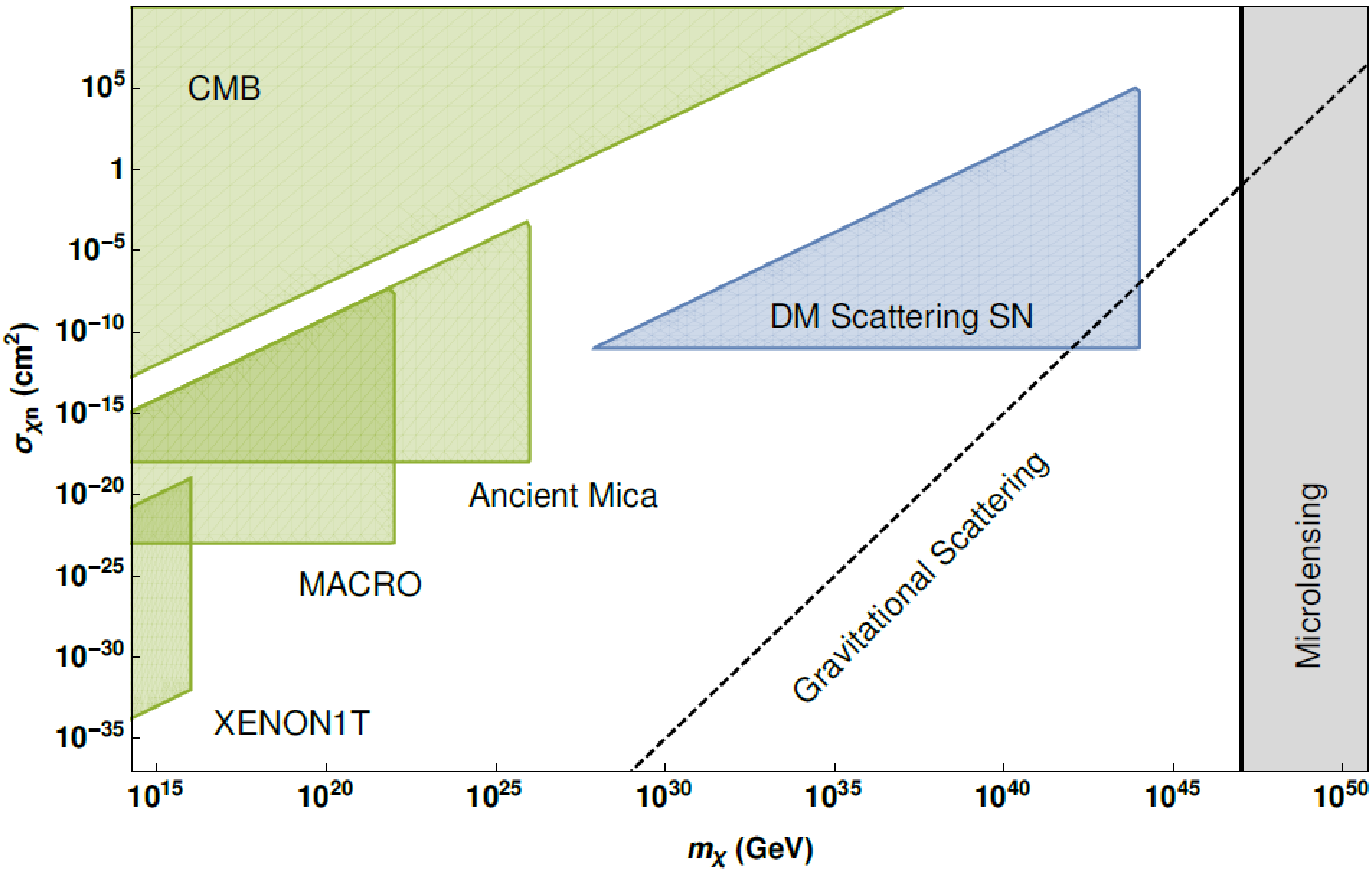
Ignition Condition: $$\frac{dE}{dx} \lambda_T > \mathcal{E}_{\rm boom}$$

Overburden (non-degenerate envelope): $$\left(\frac{dE}{dx}\right)_{\rm env} R_{\rm env} \lesssim m_\chi v_{\rm esc}^2$$

Scattering-induced SN Constraints



Scattering-induced SN Constraints

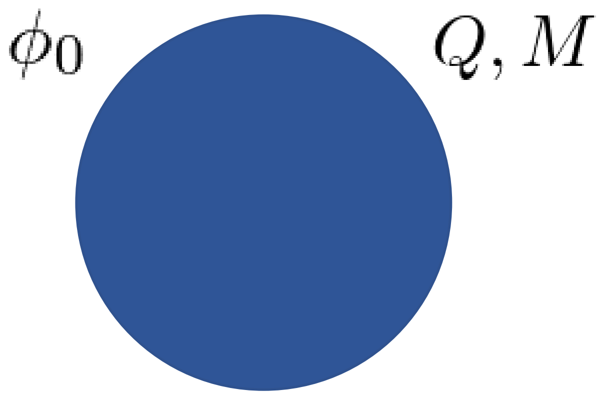


Q-ball Dark Matter

Q-Ball

- Scalar condensate stabilized by a conserved charge
- Allowed if $V(\phi)$ is sufficiently flat

[Coleman, ‘85]



Stability

$$\frac{M}{Q} < m$$

$\frac{M}{Q}$ → determined by $V(\phi)$

m → lightest particle carrying Q-charge

For nearly flat potential and large Q:

[Kusenko et al, ‘98]

$$R \sim \frac{1}{m_s} Q^{1/4} \qquad M \sim m_s Q^{3/4}$$

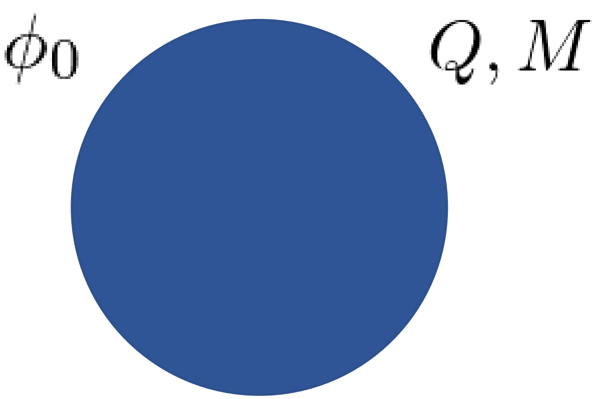
(m_s - scalar mass)

- stable for sufficiently large Q

Q-ball Dark Matter

Baryonic Q-ball (B-ball)

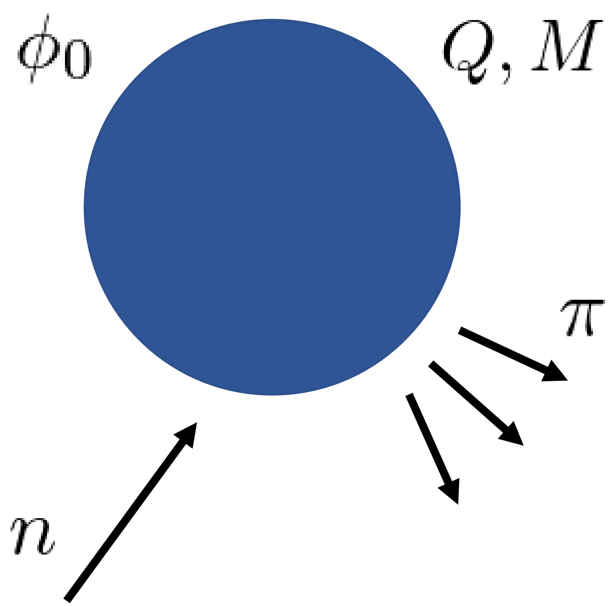
Supersymmetric theories generically allow B-balls composed of a squark condensate.



Stability $$Q > 10^{20}\left(\frac{m_s}{100\ \mathrm{TeV}}\right)^4$$

Q-ball Dark Matter

Baryonic Q-ball (B-ball)



Supersymmetric theories generically allow B-balls composed of a squark condensate.

Stability $Q > 10^{20}\left(\frac{m_s}{100\ \mathrm{TeV}}\right)^4$

B-ball – Nucleon Interaction [Kusenko et al, '98]

Q-ball can absorb baryon number, but only a small fraction of the nucleon's energy:

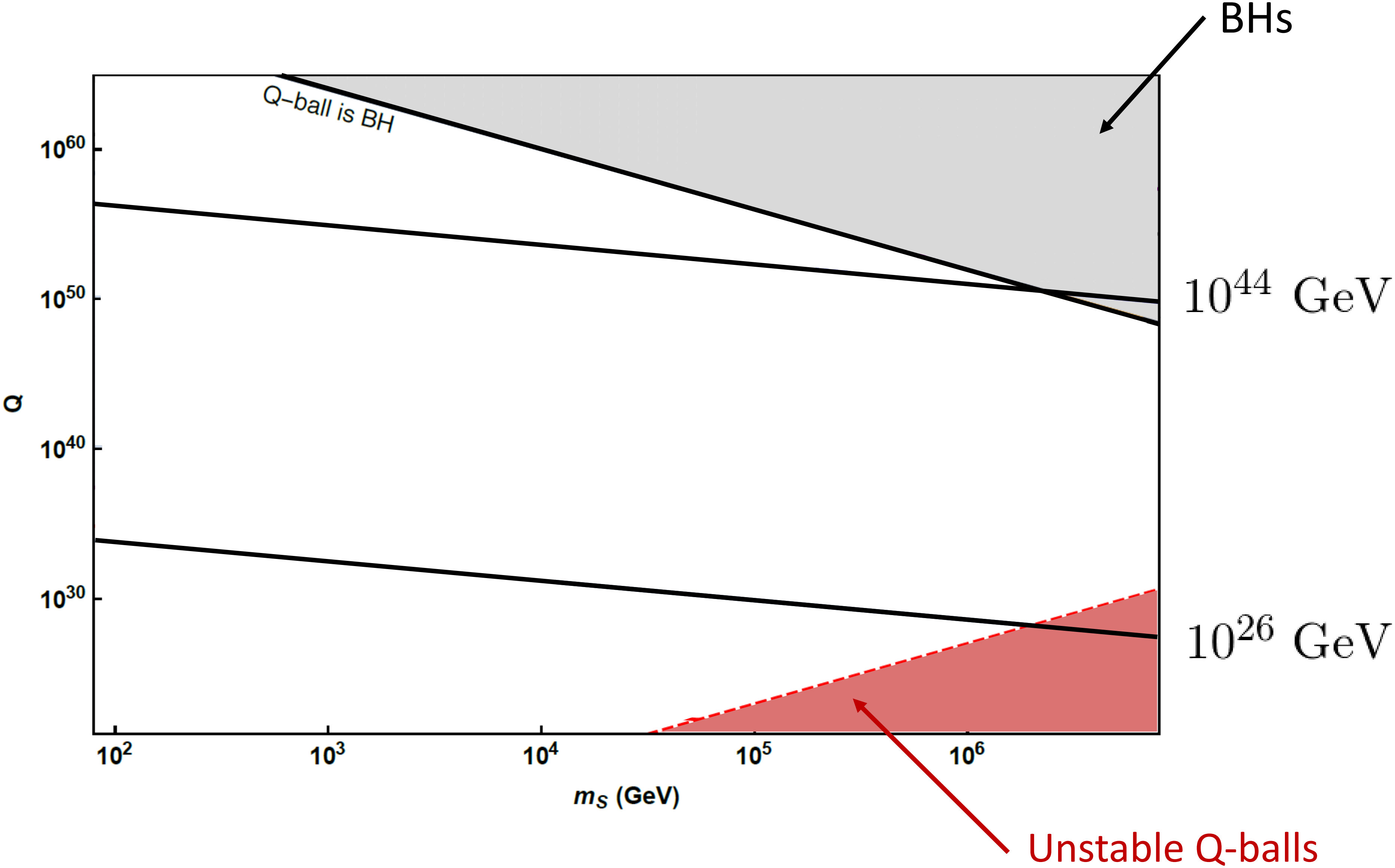
$$dM \sim \frac{M}{Q} dQ \ll m_n dQ$$

Excess energy must be emitted as pions.

Energy Deposit

$$\frac{dE}{dx} \sim n_{\mathrm{ion}} R_Q^2 m_c$$

Q-ball Dark Matter



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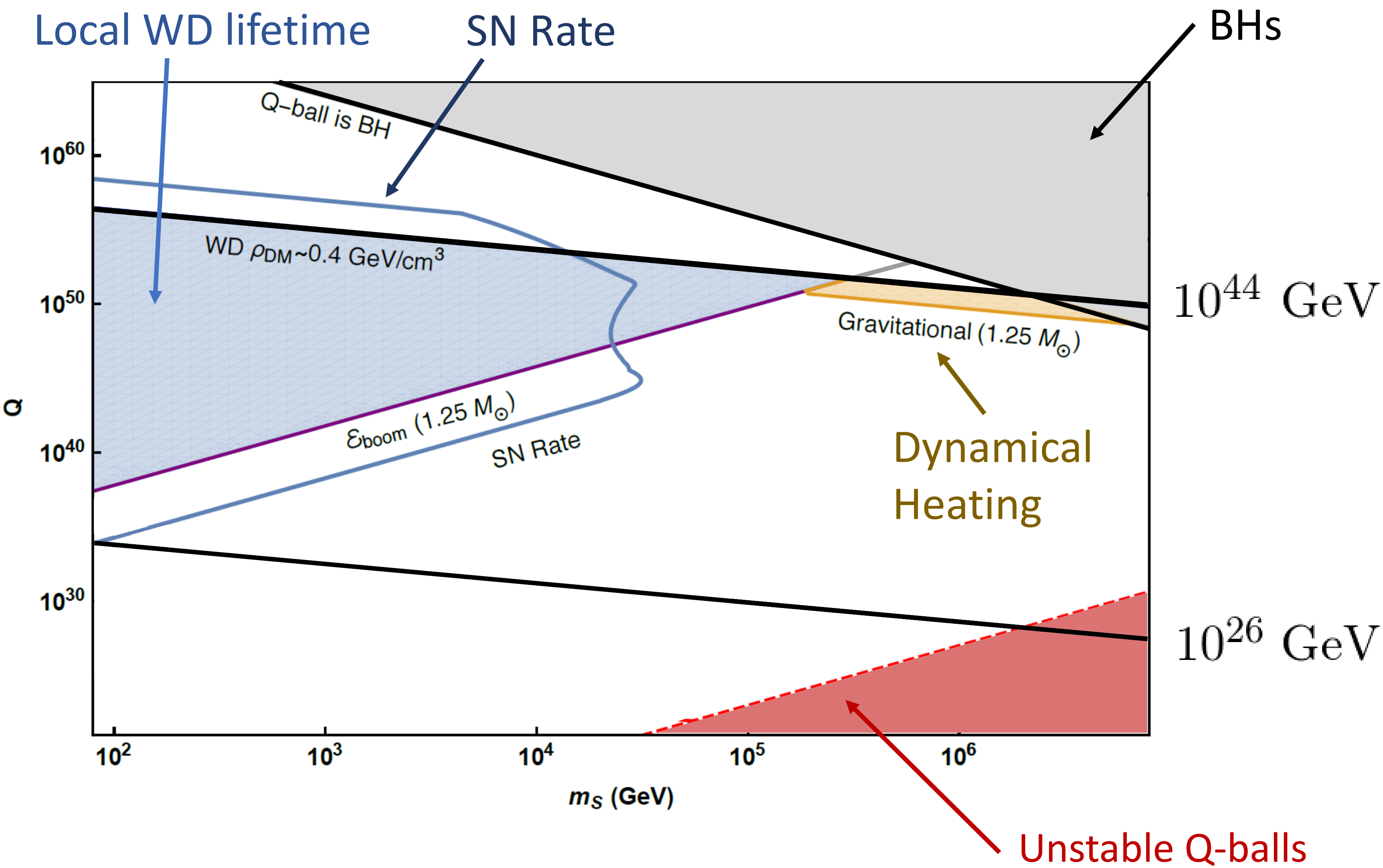

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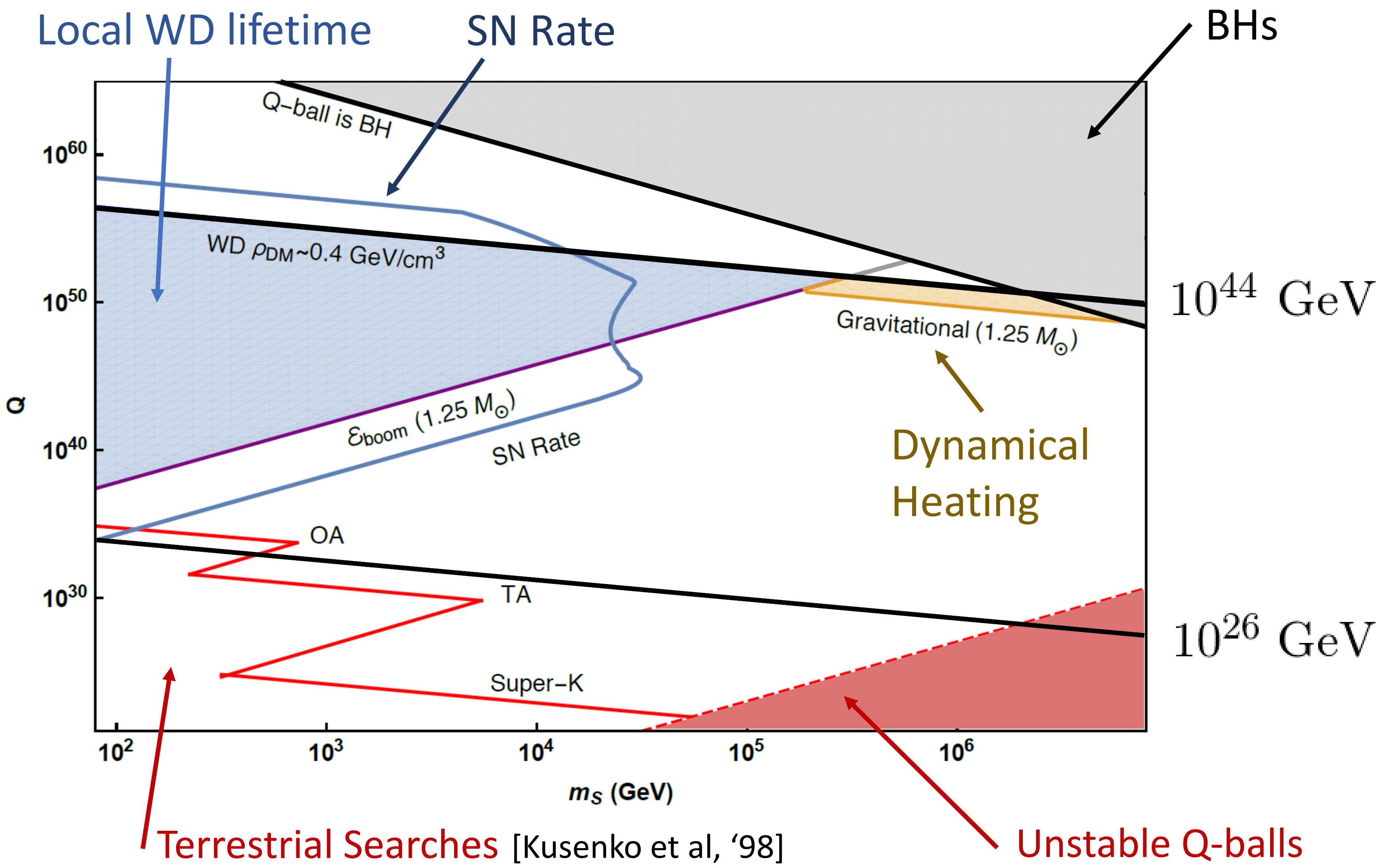

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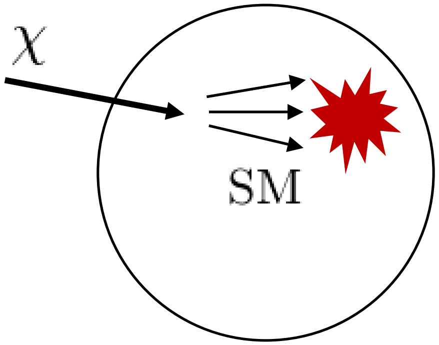
Decay and Annihilation-Induced SN

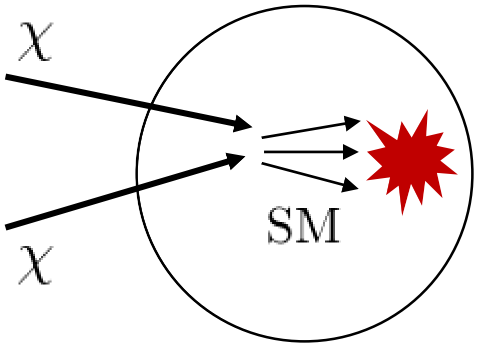
DM can locally heat a WD by decaying or annihilating into high-energy SM particles.

[Graham, RJ, Narayan, Rajendran, Riggins, 1805.07381]

Decay



Annihilation



Supernova occurs if SM secondaries satisfy ignition condition.

Particle Heating of White Dwarfs

We must verify that runaway fusion occurs due to thermalization of SM secondaries.

If the SM products thermalize over a large distance $L > \lambda_T$, then the required ignition energy is parametrically larger than $\mathcal{E}_{\text{boom}}$

$$\text{SN Threshold Energy} \sim \mathcal{E}_{\text{boom}} \cdot \text{Min}\left[1, \frac{L}{\lambda_T}\right]^3$$

Must compute stopping distances of SM particles in a WD

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SN Threshold Energy $\sim \mathcal{E}_{\text{boom}} \cdot \text{Min}\left[1, \frac{L}{\lambda_T}\right]^3$

Must compute stopping distances of SM particles in a WD

Photons, hadrons, low energy electrons ($E \lesssim 10^2 \text{ TeV}$)

Stop and thermalize within a trigger size.

High energy electrons ($E \gtrsim 10^2 \text{ TeV}$) and neutrinos:

Stop over a distance $> \lambda_T$, and then thermalize within a trigger size.

[Graham, RJ, Narayan, Rajendran, Riggins, 1805.07381]

Decay and Annihilation-Induced SN

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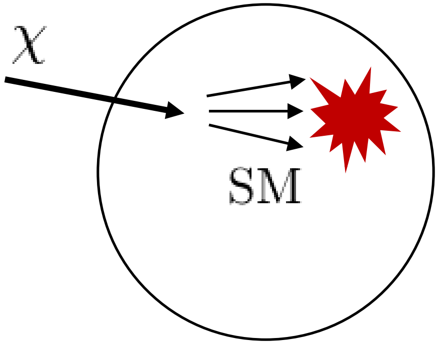
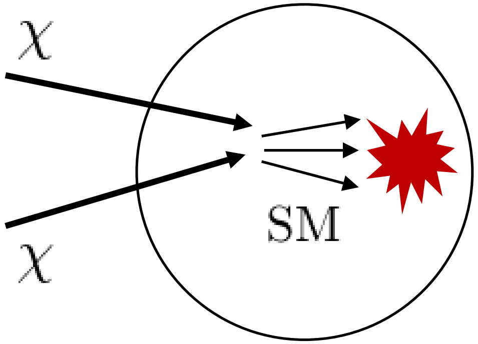


Annihilation

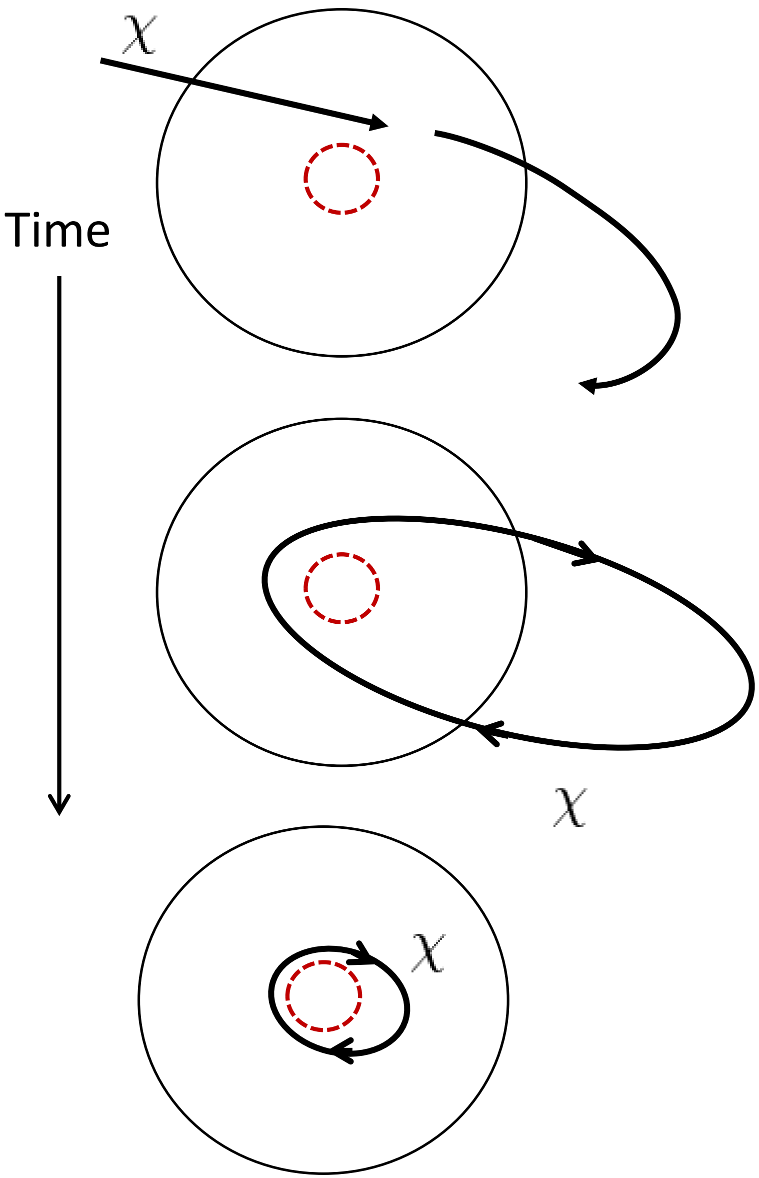


Ignition Condition: $m_\chi > \mathcal{E}_{\text{boom}}$

(assuming SM products are primarily photons and hadrons)

SN rate enhanced if DM is captured

Elastic Capture of Dark Matter



Capture

$$N_{\text{sc}} \sim n_{\text{ion}} \sigma_{\chi c} R_{\text{wd}}$$

$$N_{\text{cap}}(v_\chi) \sim \frac{m_\chi v_\chi^2}{m_c v_{\text{esc}}^2}$$

$$\Gamma_{\text{cap}} \sim \Gamma_{\text{transit}} \; \text{Min}\left[\frac{N_{\text{sc}}}{N_{\text{cap}}(v_{\text{halo}})}, 1\right]$$

Stage 1 - orbital decay to stellar surface

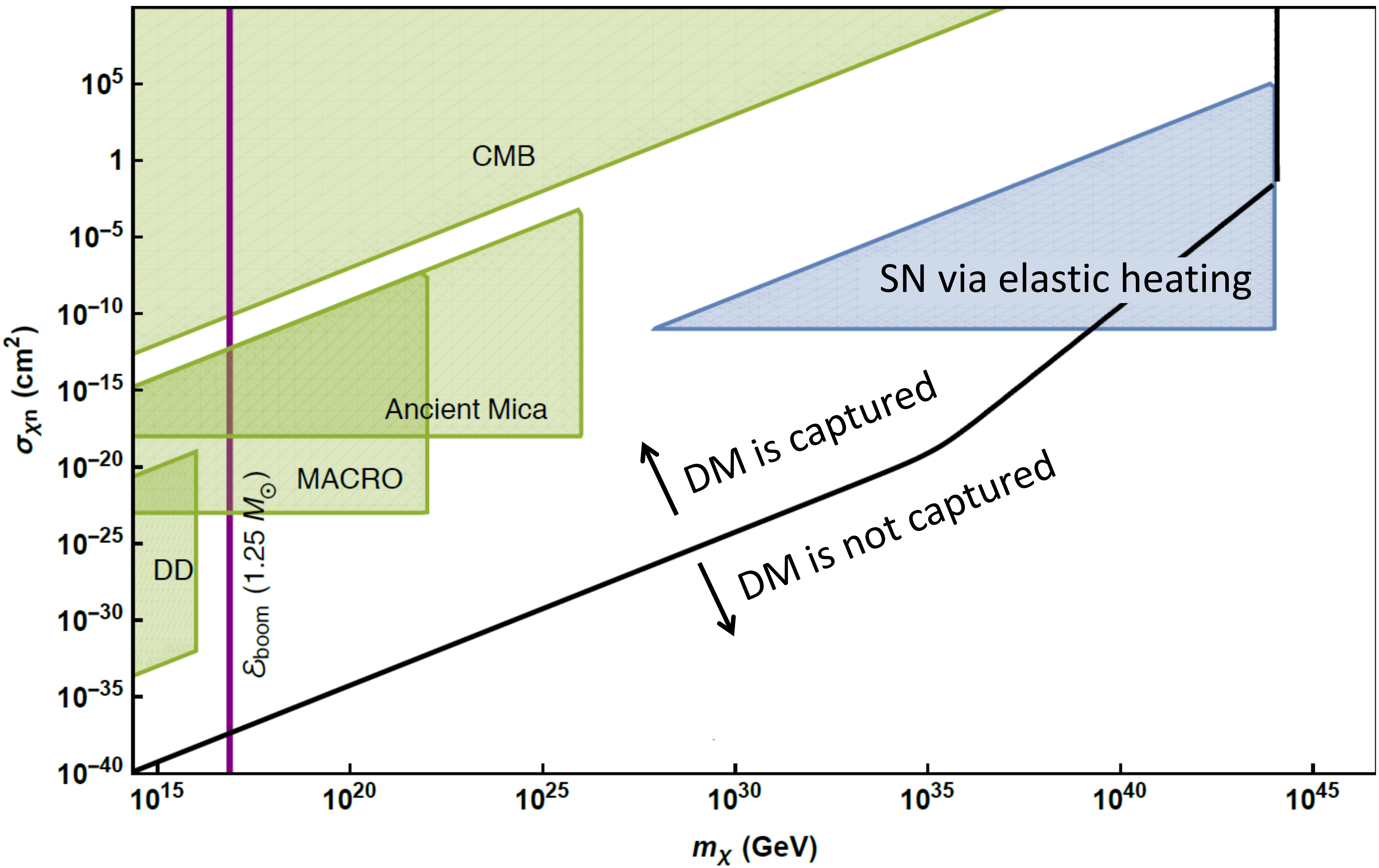
$$t_1 \sim \frac{R_{\text{wd}}}{v_{\text{esc}}} \left(\frac{m_\chi}{m_c N_{\text{sc}}}\right)^{3/2}$$

Stage 2 - orbital decay from surface to r_{th}

Thermal Radius $G \rho_{\text{wd}} m_\chi r_{\text{th}}^2 \sim T_{\text{wd}}$

$$t_2 \sim \frac{m_\chi}{\sigma_{\chi c} \rho_{\text{wd}} v_{\text{ion}}} \log\left(\frac{m_\chi}{m_c}\right)$$

Elastic Capture of Dark Matter



Decay of Captured Dark Matter

Demand $\tau_{\rm wd} > 1\ {\rm Gyr}$ for local WDs (with $\sigma_{\chi c} = 10^{-30}\ {\rm cm}^2$)

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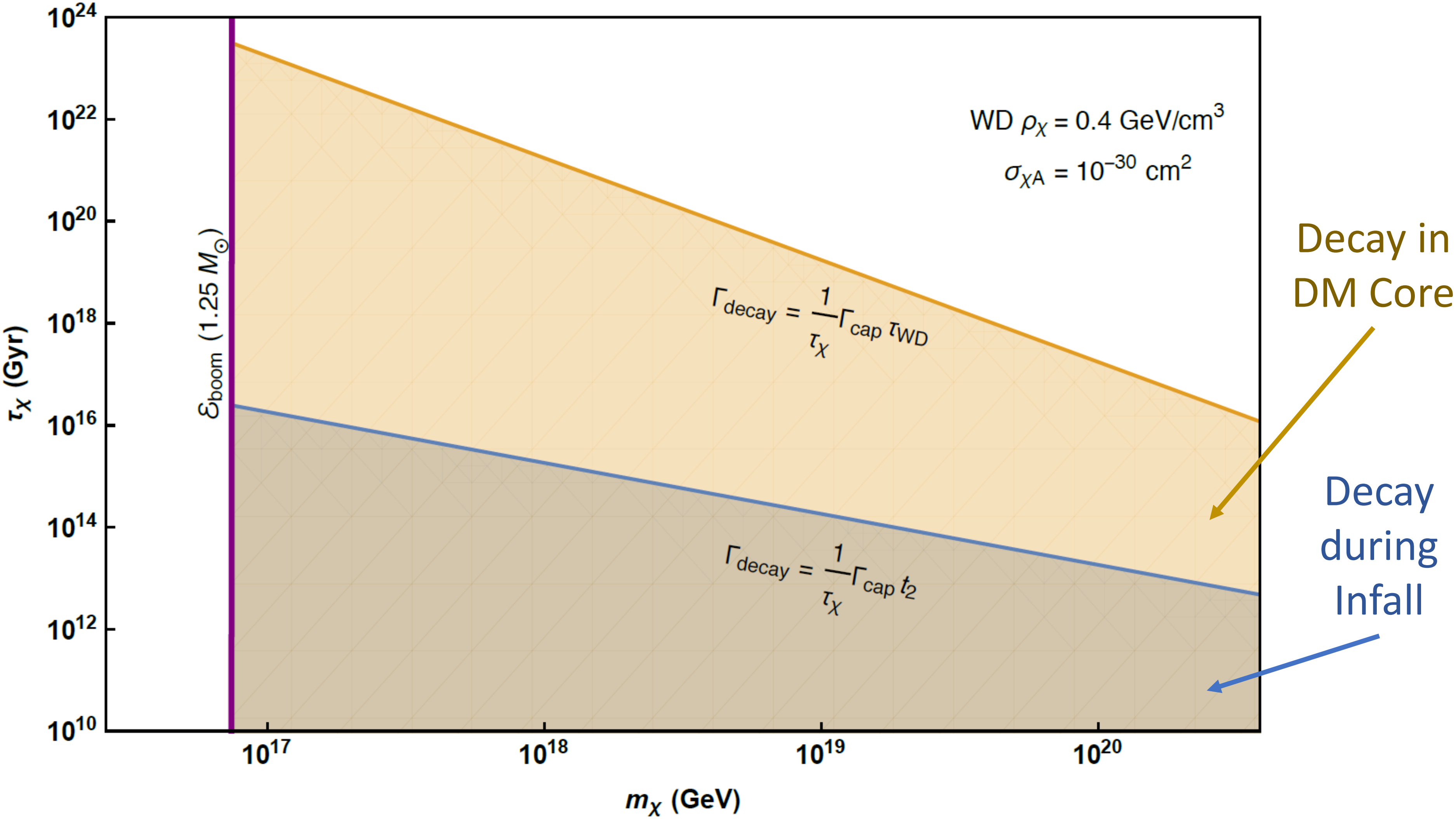

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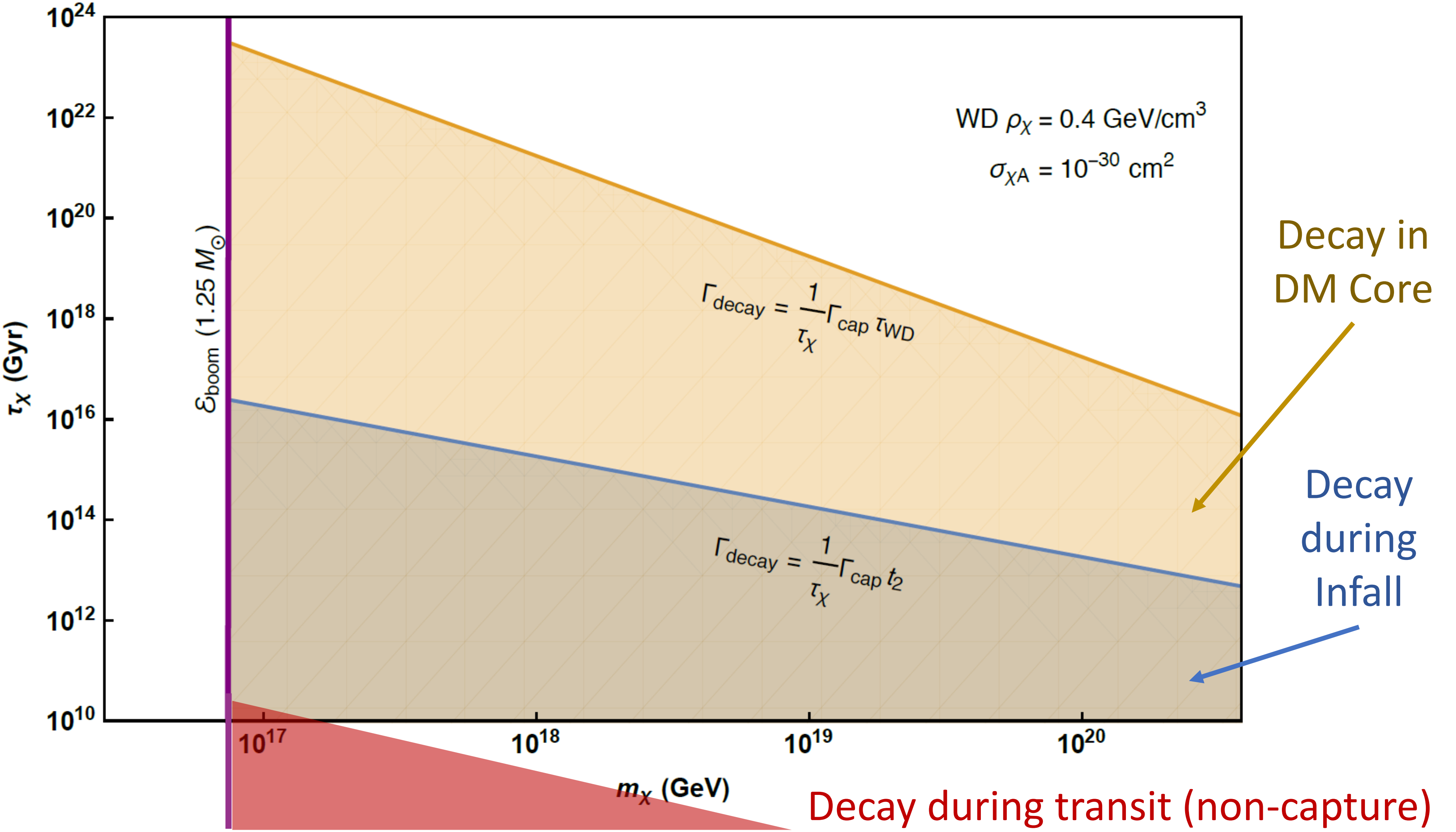

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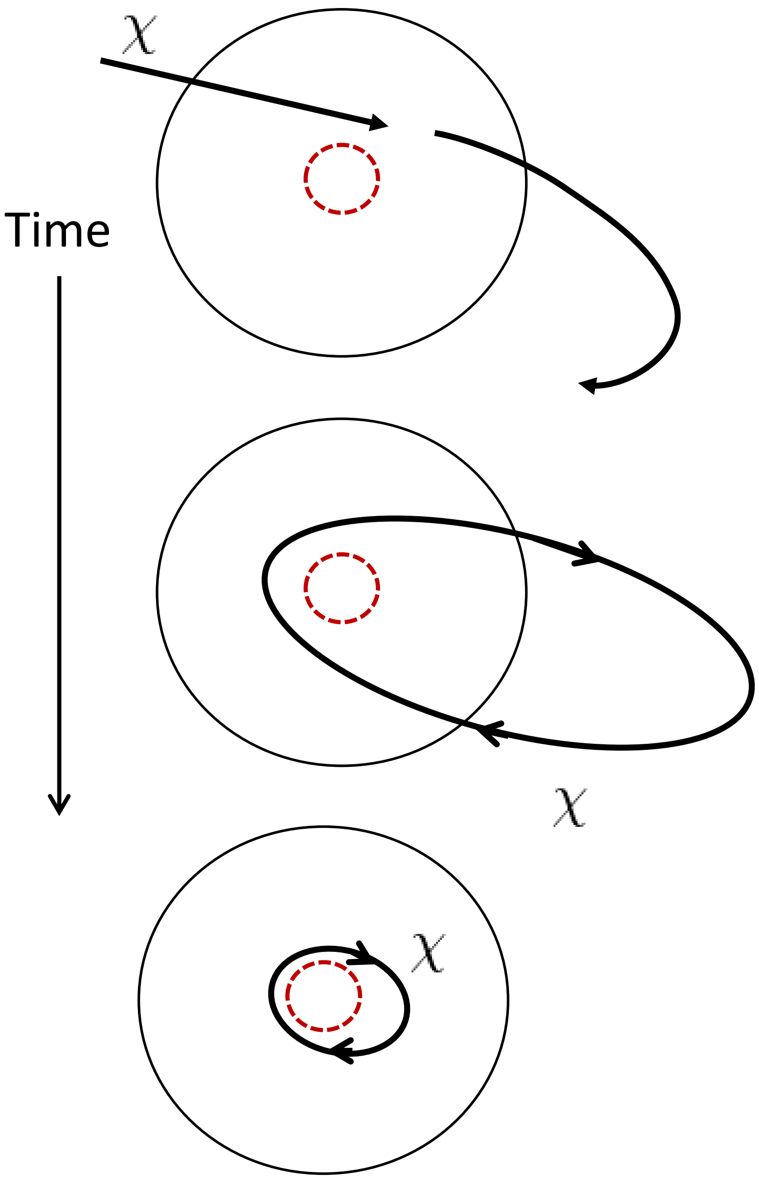


Capture

$$N_{\rm sc} \sim n_{\rm ion}\sigma_{\chi c} R_{\rm wd}$$

$$N_{\rm cap}(v_\chi) \sim \frac{m_\chi v_\chi^2}{m_c v_{\rm esc}^2}$$

$$\Gamma_{\rm cap} \sim \Gamma_{\rm transit}\ {\rm Min}\left[\frac{N_{\rm sc}}{N_{\rm cap}(v_{\rm halo})}, 1\right]$$

Stage 1 - orbital decay to stellar surface

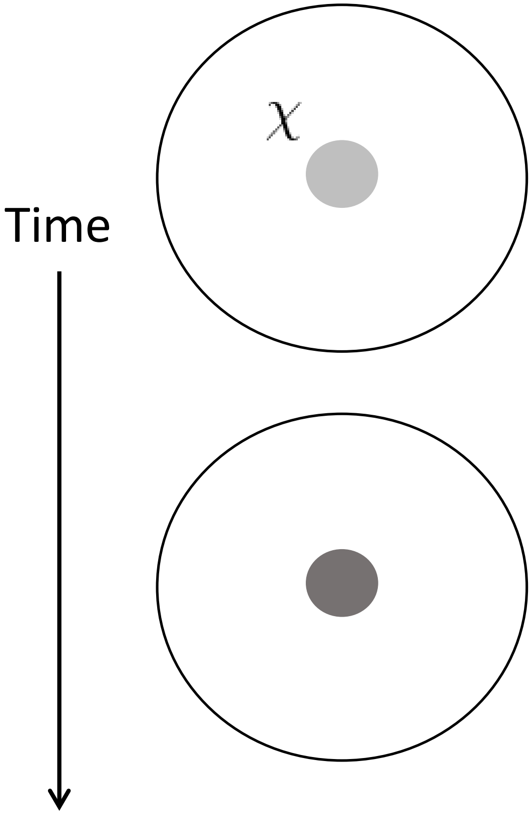
$$t_1 \sim \frac{R_{\rm wd}}{v_{\rm esc}}\left(\frac{m_\chi}{m_c N_{\rm sc}}\right)^{3/2}$$

Stage 2 - orbital decay from surface to $r_{\rm th}$

Thermal Radius $G\rho_{\rm wd} m_\chi r_{\rm th}^2 \sim T_{\rm wd}$

$$t_2 \sim \frac{m_\chi}{\sigma_{\chi c}\rho_{\rm wd} v_{\rm ion}} \log\left(\frac{m_\chi}{m_c}\right)$$

Evolution of Dark Matter Core



Collection

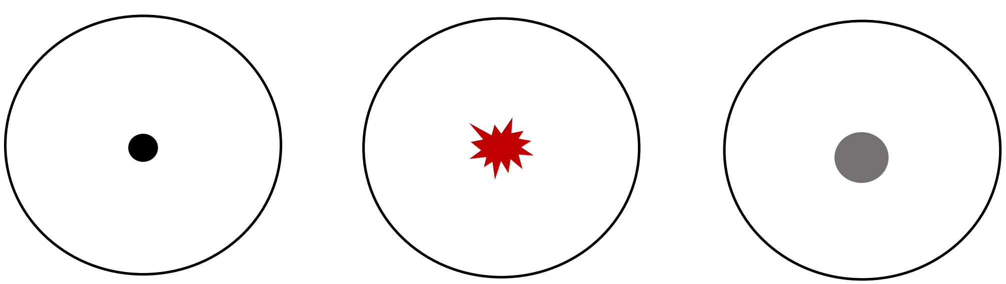
$$M_{sg} \sim \rho_{\rm wd} r_{\rm th}^3$$

$$t_{\rm collect} \sim \frac{M_{sg}}{m_\chi \Gamma_{\rm cap}}$$

Gravitational Collapse

$$t_{\rm cool} \sim \frac{m_\chi}{\sigma_{\chi c}\rho_{\rm wd}} \frac{1}{{\rm Max}[v_{\rm ion}, v_\chi]}$$

$$v_\chi \sim \left(\frac{G M_{\rm sg}}{r}\right)^{1/2}$$

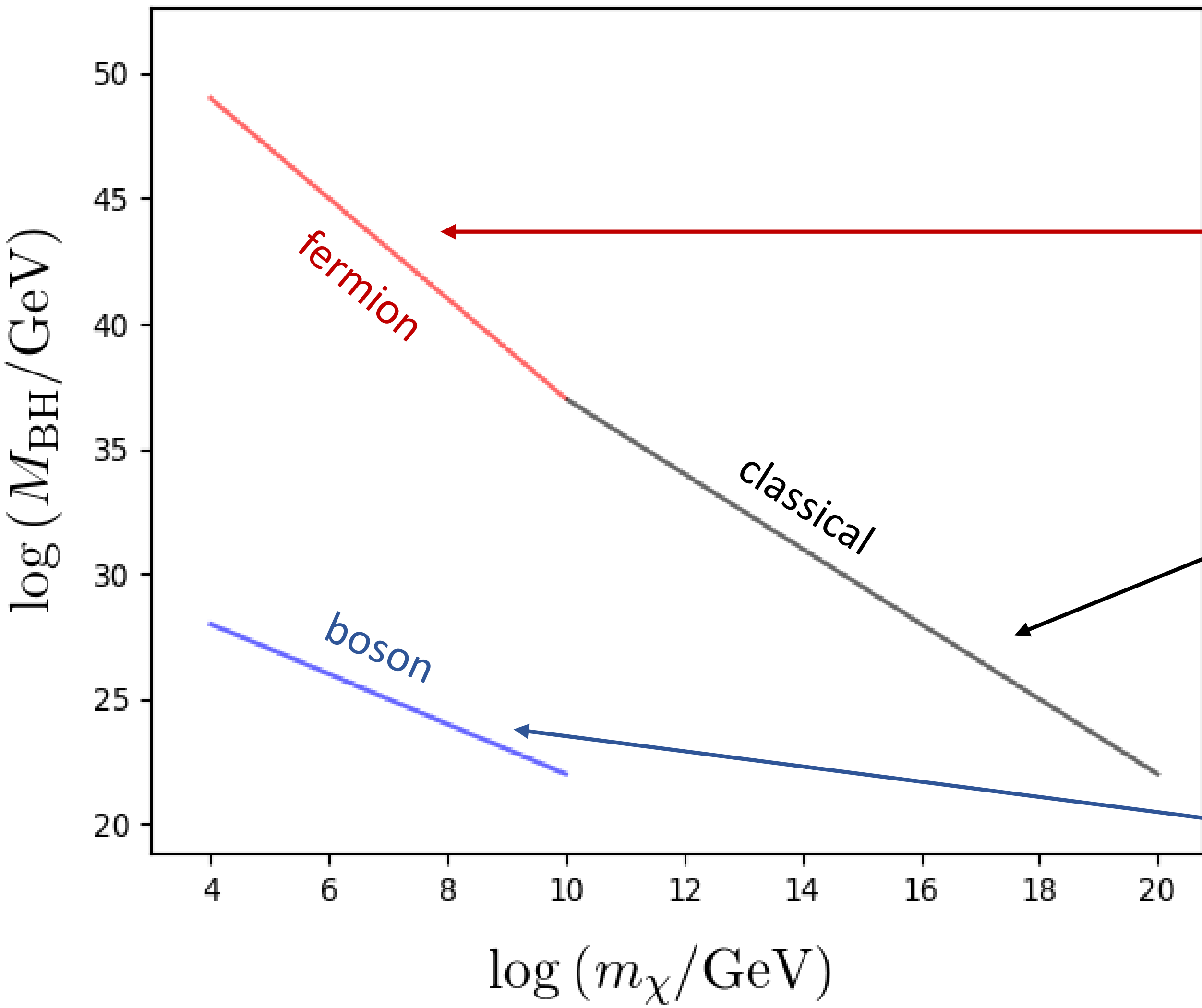


Black Hole, Annihilation, or Stable Core

Dark Matter Black Holes in White Dwarfs

Formation of BHs from DM cores

[Kouvaris & Tinyakov, ‘10, ‘12]



$M_{\rm BH} = M_{\rm Ch,\ Fermi}$

overcome Fermi pressure

$M_{\rm BH} = M_{\rm sg}$

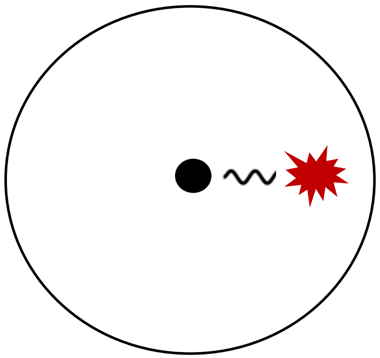
classical collapse

$M_{\rm BH} = M_{\rm Ch,\ Bose}$

“drip” BHs via BEC

BH-induced Supernovae

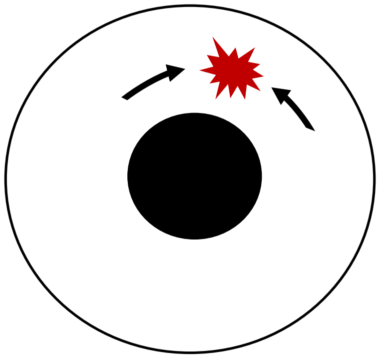
Hawking Radiation



$$\dot{M}_H \tau_{\rm diff} > \mathcal{E}_{\rm boom}$$

diffusion time

Dynamical Heating (gravitational acceleration)



$$\frac{G M_{\rm BH} m_\chi}{\lambda_T} > 1~{\rm MeV}$$

$M_{\rm BH}$ [GeV] 10^{34} 10^{43}

Hawking SN | Dynamical SN

[RJ, Narayan, Riggins, in preparation]

BH-induced Supernovae

Evolution of BHs in White Dwarfs

[Kouvaris & Tinyakov, ‘10]

Evaporation

$$\dot{M} \sim 10^{-4} \left(\frac{1}{GM} \right)^2$$

Hawking radiation

Accretion

$$\dot{M} \sim \frac{\rho_{\rm wd}}{c_s^2} (GM)^2 + m_\chi \Gamma_{\rm cap}$$

Bondi accretion of stellar medium

Accretion of infalling DM

[RJ, Narayan, Riggins, in preparation]

BH-induced Supernovae

Evolution of BHs in White Dwarfs

[Kouvaris & Tinyakov, '10]

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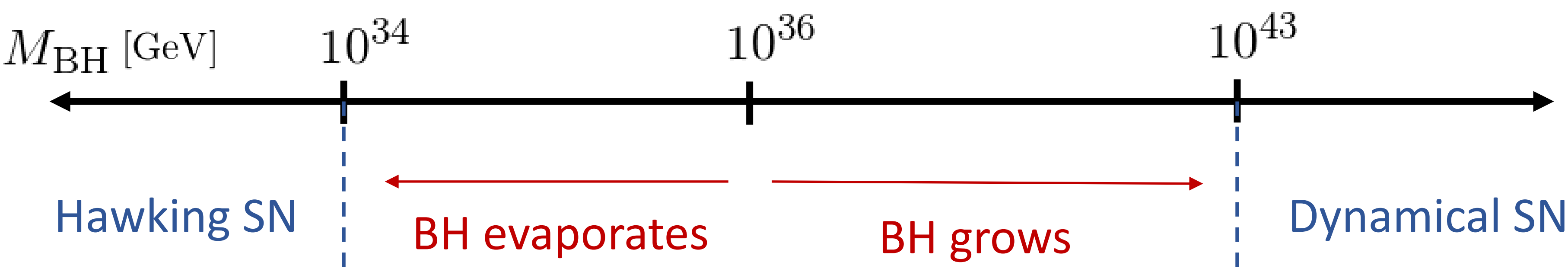
$$\dot{M} \sim \frac{\rho_{\rm wd}}{c_s^2} (GM)^2 + m_\chi \Gamma_{\rm cap}$$

Bondi accretion of stellar medium

Accretion of infalling DM

$$\Longrightarrow \quad M_{\rm crit} \sim 10^{36}\ {\rm GeV}$$

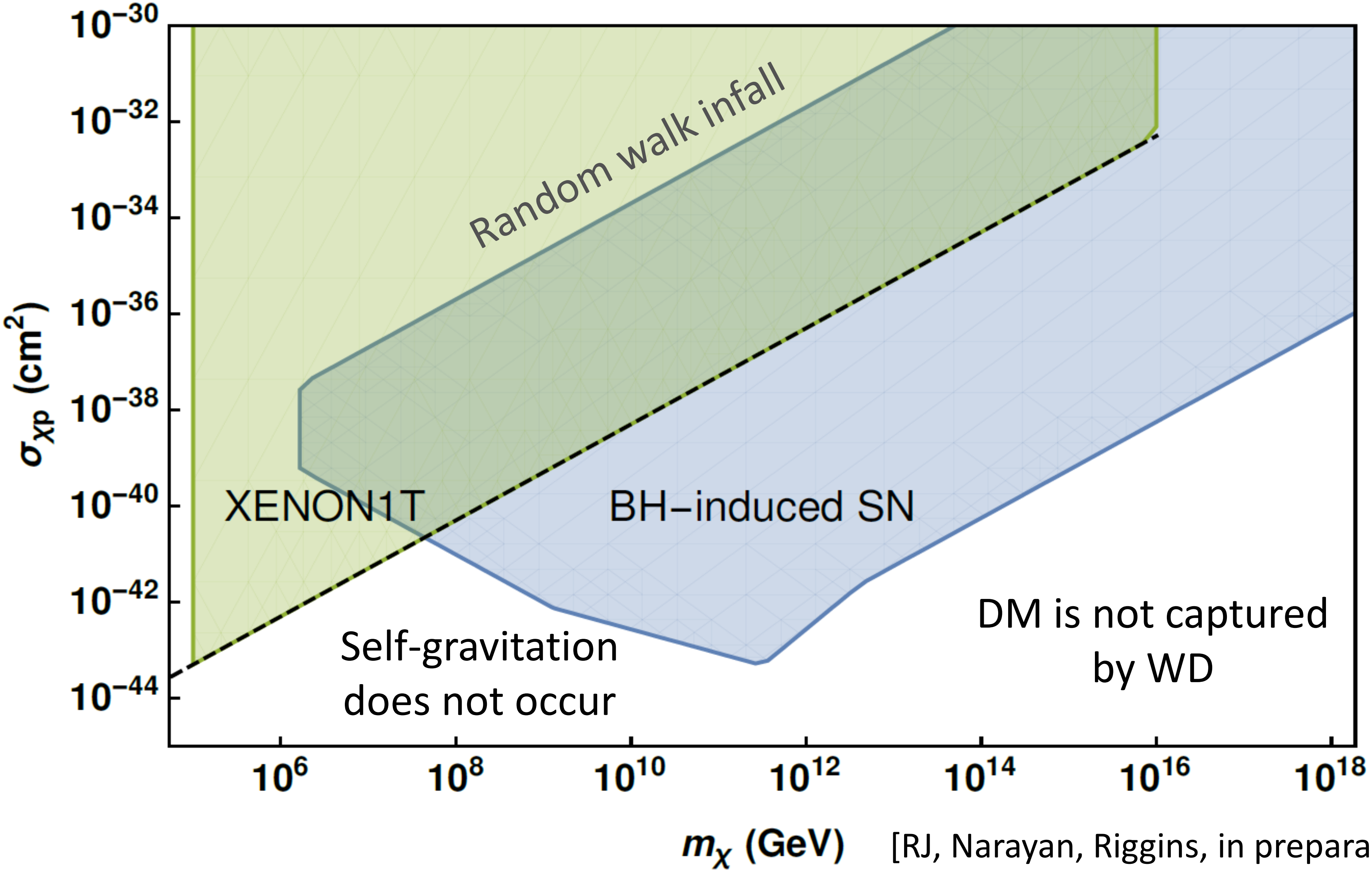


All BHs that form in a WD will lead to SN.

[RJ, Narayan, Riggins, in preparation]

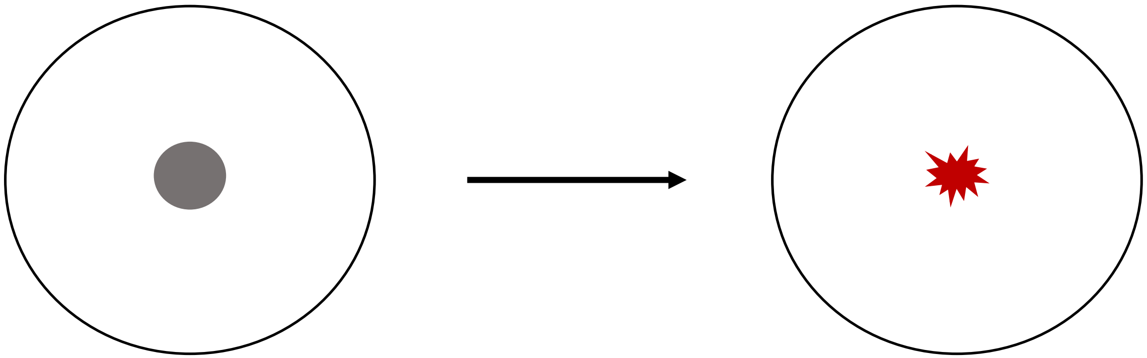
DM Core ⟶ BH-induced Supernovae

Demand $\tau_{\rm wd} > 1\ {\rm Gyr}$ for local WDs (Fermion DM)



[RJ, Narayan, Riggins, in preparation]

Gravitational Collapse with Annihilations



DM core "bursts" into SM particles at a radius $r_{\chi\chi}$, at which the annihilation rate exceeds the collapse timescale

$$\Gamma_{\chi\chi} t_{\text{collapse}} \gtrsim 1$$

$$\text{Effective Energy Deposit} \sim m_\chi \left(\frac{M_{\text{sg}}}{m_\chi r_{\chi\chi}^3} \right) \Gamma_{\chi\chi} \cdot \text{Min}\left[r_{\chi\chi}, \lambda_T \right]^3 \cdot \tau_{\text{diff}}$$

annihilation rate per volume

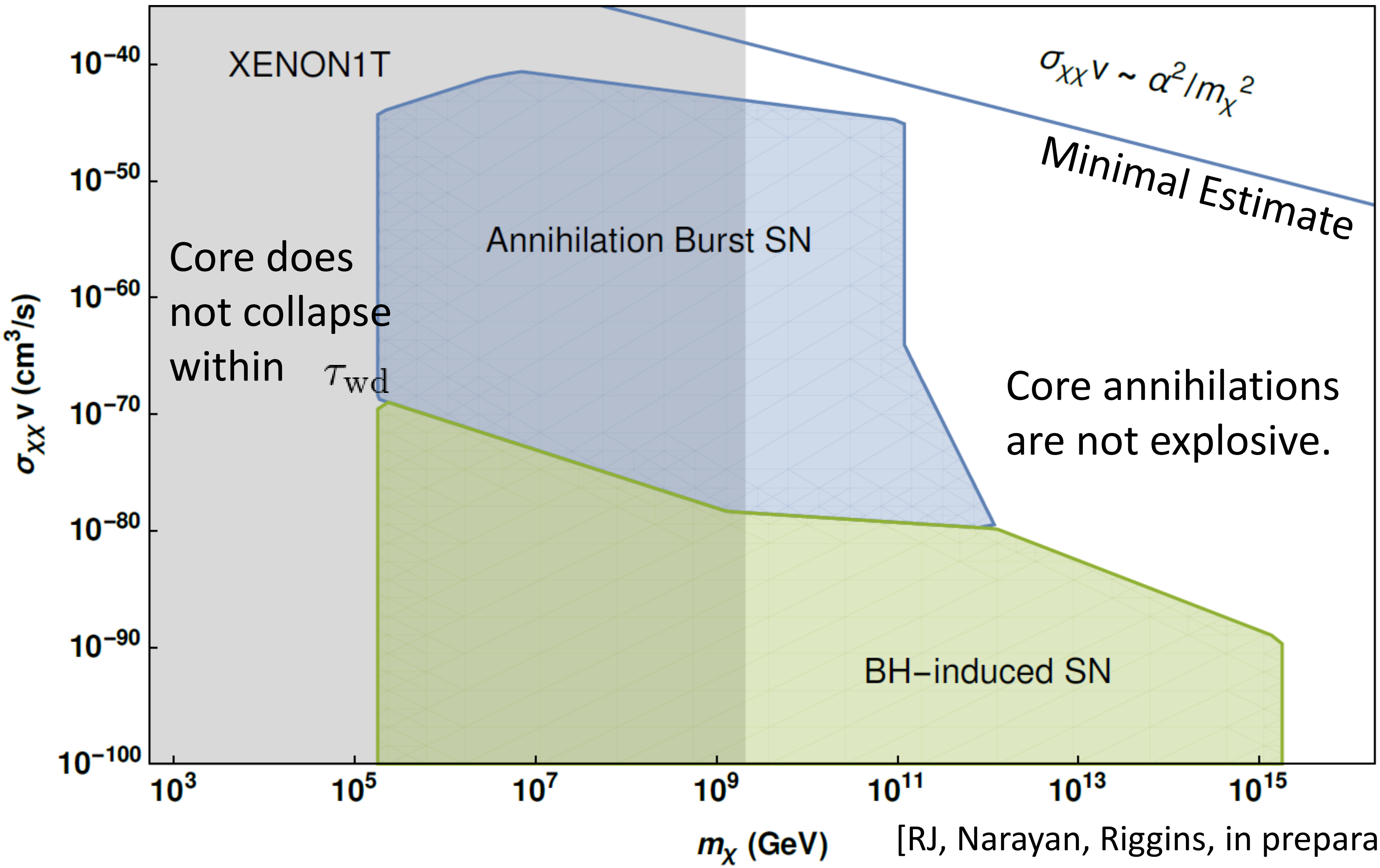
effective fusion volume

Effective energy deposit Increases for decreasing $\sigma_{\chi\chi}$

[RJ, Narayan, Riggins, in preparation]

Captured DM -> Annihilation Constraints

Demand $\tau_{\rm wd} > 1\ {\rm Gyr}$ for local WDs (with $\sigma_{\chi c} = 10^{-36}\ {\rm cm}^2$)



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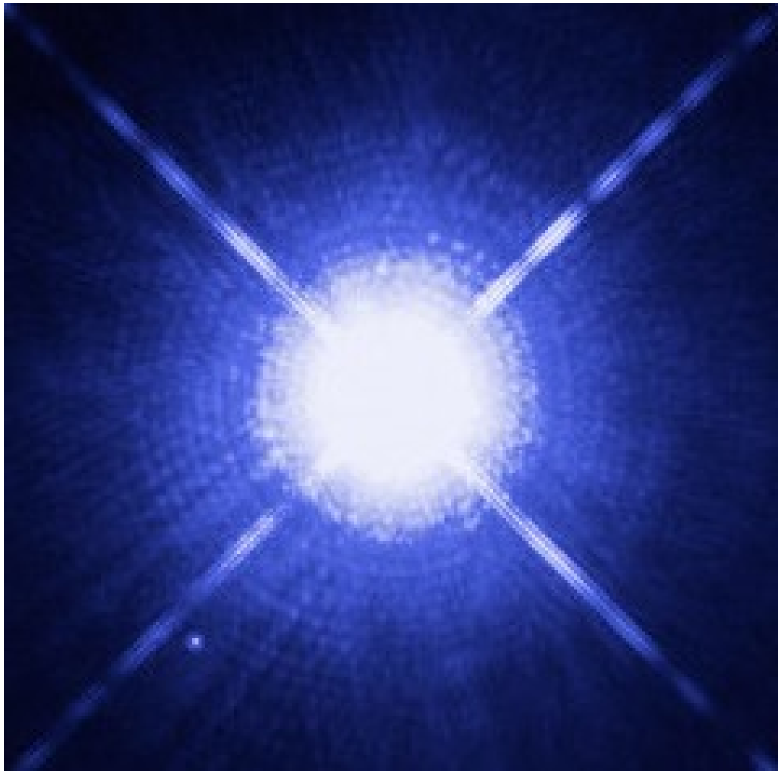
Dark matter interactions can locally heat white dwarfs, initiate runaway fusion, and cause (type Ia) supernovae.



White Dwarfs as Dark Matter Detectors

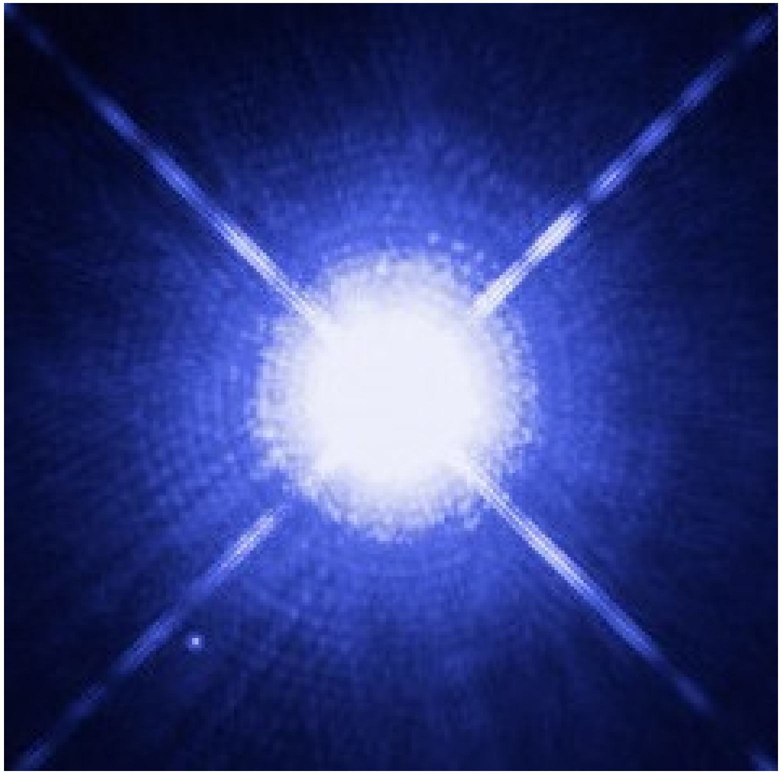
Dark matter interactions can locally heat white dwarfs, initiate runaway fusion, and cause (type Ia) supernovae.

New Type Ia SN mechanisms:

- SM particles heat WD by scattering
- BHs in a WD will heat via Hawking radiation or gravitational acceleration.

Constrain DM that produces SM particles or leads to BH formation:

- Probes terrestrially inaccessible DM
- Severe constraints for captured DM
- New constraints via BH formation and annihilation bursts



Puzzles remain in Type Ia observations. It is possible that DM is responsible for an O(1) fraction of observed WD transients.

White Dwarfs as Dark Matter Detectors

Extra Slides

Particle Heating of White Dwarfs

Explosion Condition

$$L \gtrsim \lambda_T$$

$$T \gtrsim 1 \text{ MeV}$$

Degenerate Electron Diffusion

$$\tau_{\text{cool}} \sim \frac{\alpha^2 m_e^2}{T} \cdot L^2$$

Carbon-Carbon Fusion

$$\tau_{\text{heat}} \sim \frac{(m_c T)^{1/2}}{n_{\text{ion}} \sigma_{cc} Q}$$

Q - energy released per reaction

$$n_{\text{ion}} \approx 10^{32} \text{ cm}^{-3} \;\; [1.38 \text{ M}_\odot]$$

$$T \approx 1 \text{ MeV}$$

$$\Rightarrow \;\; \lambda_T \sim 10^{-6} \text{ cm}$$

How to Start a Type Ia Supernova

Explosion Condition

$$L \gtrsim \lambda_T \qquad T \gtrsim 1 \text{ MeV}$$

timescale for (degenerate) electron or photon diffusion $\sim$ timescale for carbon-carbon fusion $\Longrightarrow$ λ_T

A careful calculation (Timmes and Woosley 1992):

$$\lambda_T \approx 10^{-5} \text{ cm} \qquad n_{\text{ion}} \approx 10^{32} \text{ cm}^{-3} \quad [1.38 \text{ M}_\odot]$$

$$\lambda_T \approx 2 \cdot 10^{-3} \text{ cm} \qquad n_{\text{ion}} \approx 10^{30} \text{ cm}^{-3} \quad [0.85 \text{ M}_\odot]$$

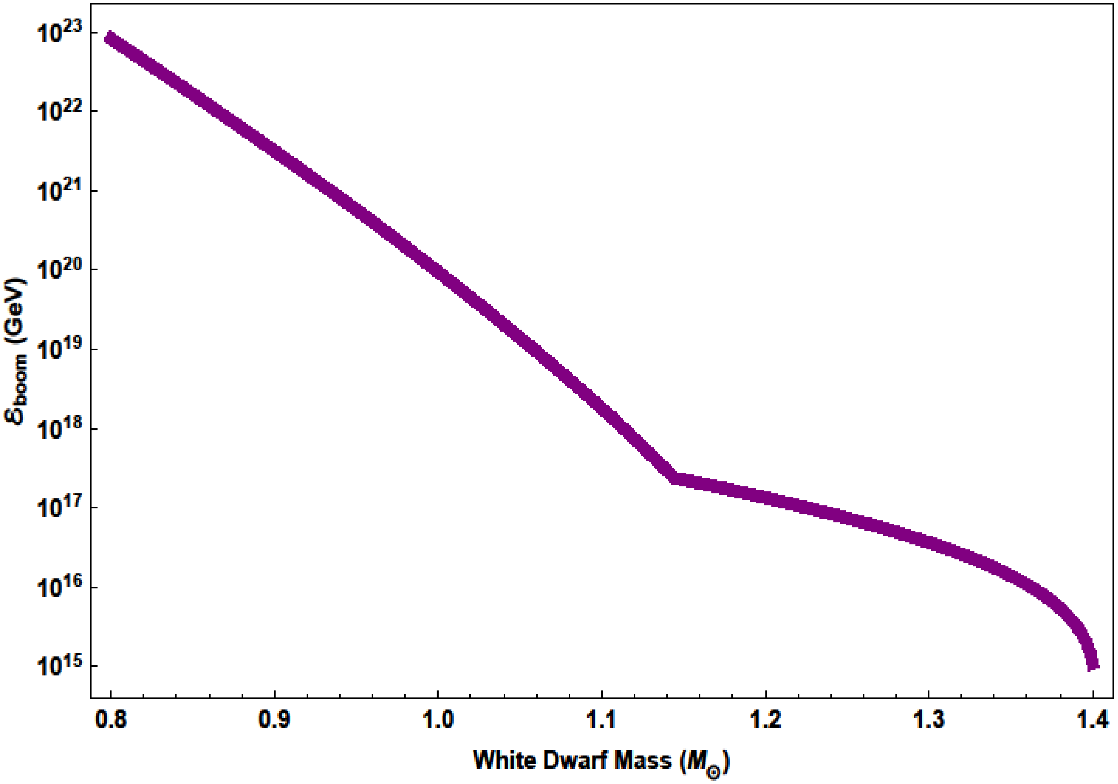
Trigger size decreases for larger stellar masses

How to Start a Type Ia Supernova

Explosion Condition $L \gtrsim \lambda_T$ $T \gtrsim 1\ \mathrm{MeV}$

Trigger Energy $\mathcal{E}_{\mathrm{boom}}$

Energy required to heat a volume λ_T^3 to a temperature of $1\ \mathrm{MeV}$



$\mathcal{E}_{\mathrm{boom}} \approx 10^{16}\ \mathrm{GeV}$

$[1.38\ \mathrm{M}_\odot]$

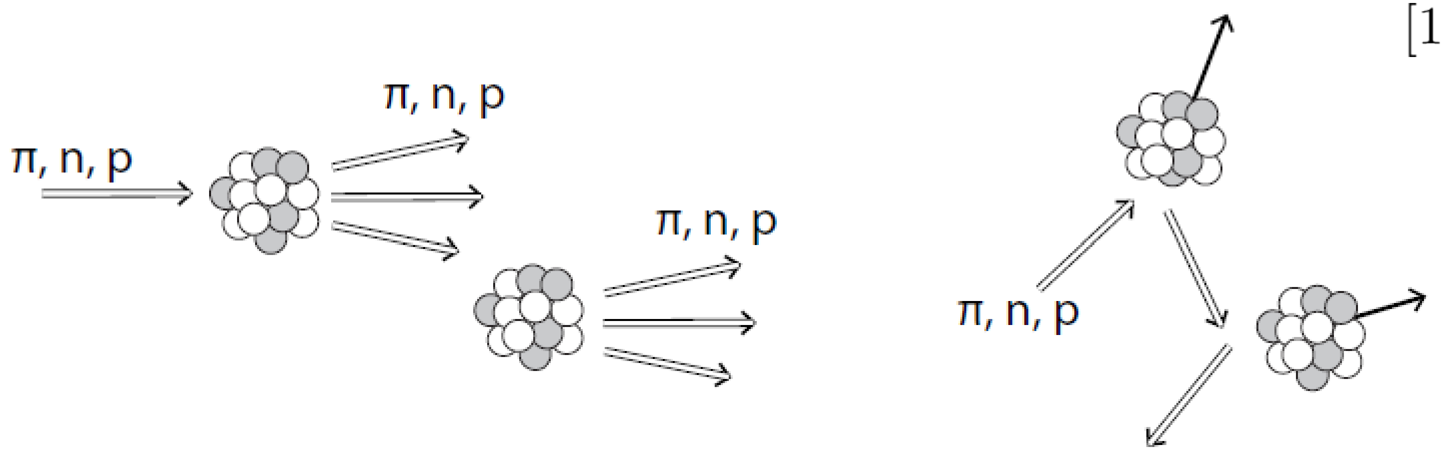
$\mathcal{E}_{\mathrm{boom}} \approx 10^{22}\ \mathrm{GeV}$

$[0.85\ \mathrm{M}_\odot]$

Particle Stopping in White Dwarfs

Incident Hadrons

$n_{\rm ion} \sim 10^{32}\ {\rm cm}^{-3}$
$[1.38\ {\rm M}_\odot]$



Energy $[\rm MeV]$ — 10 — Time

Hadronic Shower

$$\sigma_{\rm inel} \sim 0.1\ {\rm bn}$$

$$\lambda \sim 10^{-7}\ {\rm cm}$$

$$L \sim \lambda\ \log\left(\frac{E}{10\ {\rm MeV}}\right)$$

Nuclear Elastic Heating

$$\sigma_{\rm el} \sim 1\ {\rm bn}$$

$$\lambda \sim 10^{-8}\ {\rm cm}$$

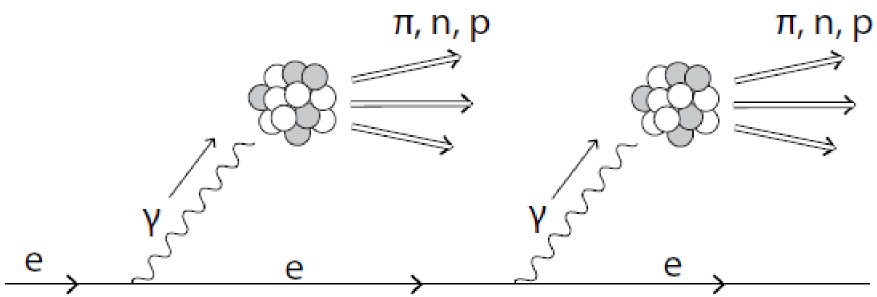
$$L \sim \left(\frac{m_c}{m_n}\right)^{1/2} \lambda$$

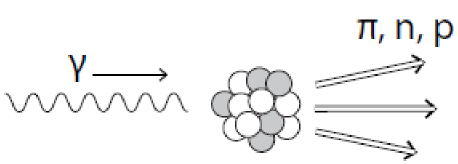
Hadrons thermalize within a trigger size.

Particle Stopping in White Dwarfs

Incident electrons and photons (high energy) $n_{\text{ion}} \sim 10^{32}\ \text{cm}^{-3}$

$[1.38\ \text{M}_\odot]$





Energy $[\text{MeV}]$ 10^7 10^5 Time

Electronuclear Shower

$$\frac{d\sigma_{eA}}{dk} \sim \frac{\alpha^2}{k}\sigma_{\text{inel}}$$

$$L \sim 10^{-4}\ \text{cm} \cdot \log\left(\frac{E}{10^7\ \text{MeV}}\right)$$

Photonuclear Shower

$$\sigma_{\gamma A} \sim \alpha\ \sigma_{\text{inel}}$$

$$L \sim 10^{-5}\ \text{cm}$$

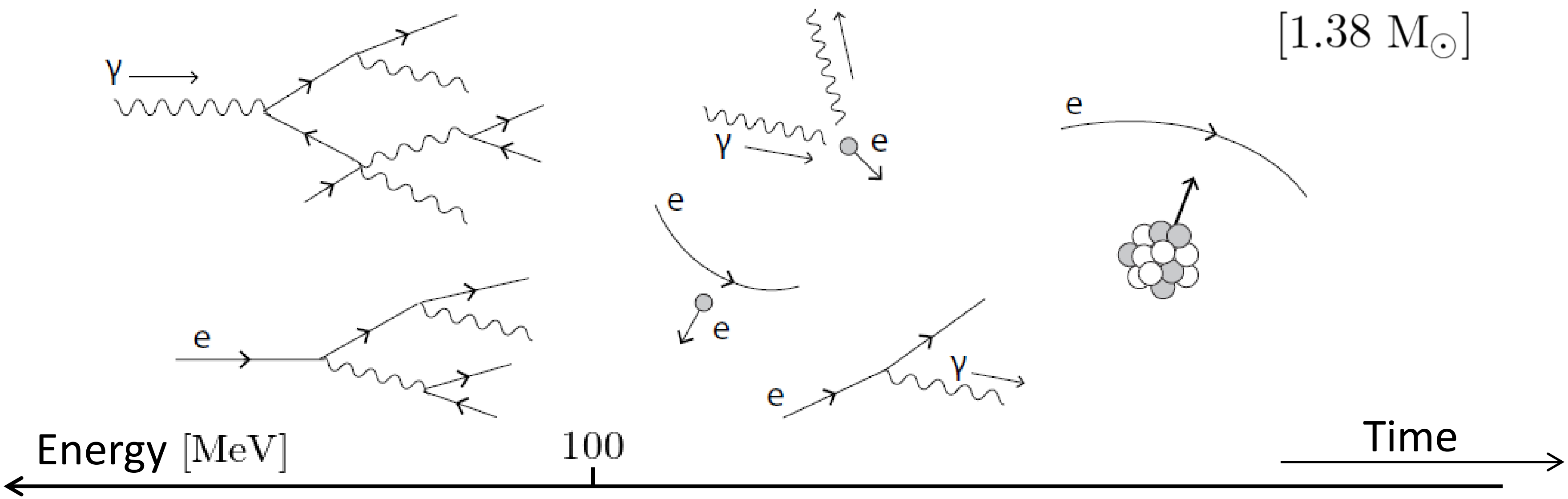
High energy e, γ thermalize between λ_T and $100\ \lambda_T$

Particle Stopping in White Dwarfs

Incident electrons and photons (low energy)

$n_{\rm ion} \sim 10^{32}\ {\rm cm}^{-3}$

$[1.38\ {\rm M}_\odot]$



EM Showers

$$L \sim 10^{-6}\ {\rm cm} \left(\frac{E}{1\ {\rm MeV}}\right)^{1/2}$$

LPM suppression: decoherence due to multiple ion interactions [Klein, '99]

Electron-Ion Coulomb Scattering

$$\lambda \sim \frac{E^2}{n_{\rm ion}\alpha^2 Z^2} \sim 10^{-9}{\rm cm} \left(\frac{E}{1\ {\rm MeV}}\right)^2$$

$$L \sim \left(\frac{1}{\log \Lambda}\frac{m_c}{E}\right)^{1/2} \lambda$$

Low-energy electrons and photons thermalize within a trigger size.

Landau-Pomeranchuk-Midgal Effect

For large target densities and high incident energy, bremsstrahlung radiation is suppressed due to multiple-scattering interactions.

Semi-classical calculations (Klein 1999) including multiple-scattering find a scale

$$E_{\mathrm{LPM}} \sim \frac{m^4}{n_{\mathrm{ion}} Z^2 \alpha^2 \log \Lambda}$$

→ Coulomb log

and a suppression factor

$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{\mathrm{single}} \cdot \left(\frac{E_{\mathrm{LPM}}}{E}\right)^{1/2}$$

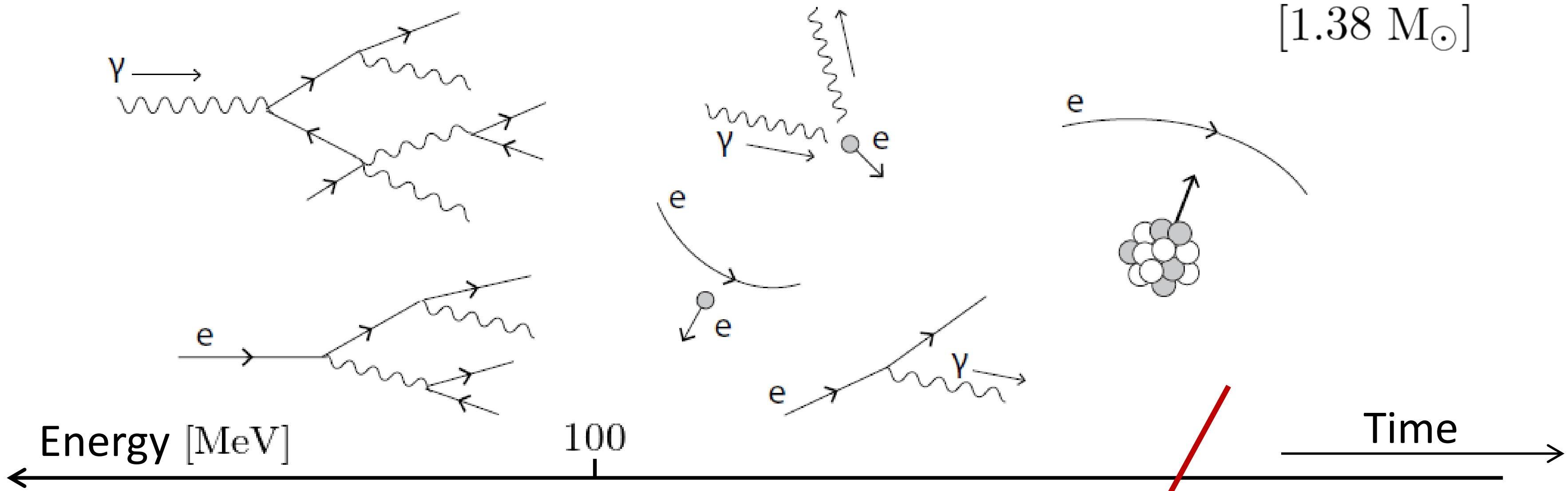
For sufficiently large incident energies, LPM will cause radiative EM showers to give way to hadronic showers as the dominant stopping mechanism for electrons and photons.

Particle Stopping in White Dwarfs

Incident electrons and photons (low energy)

$n_{\rm ion} \sim 10^{32}\ {\rm cm}^{-3}$

$[1.38\ {\rm M}_\odot]$



Electron-Ion Coulomb Scatters

$$E \sim 10\ {\rm MeV} \Rightarrow \frac{E^2}{2M_c} \sim \Omega_p$$

$E \lesssim 10\ {\rm MeV}$ phonon production

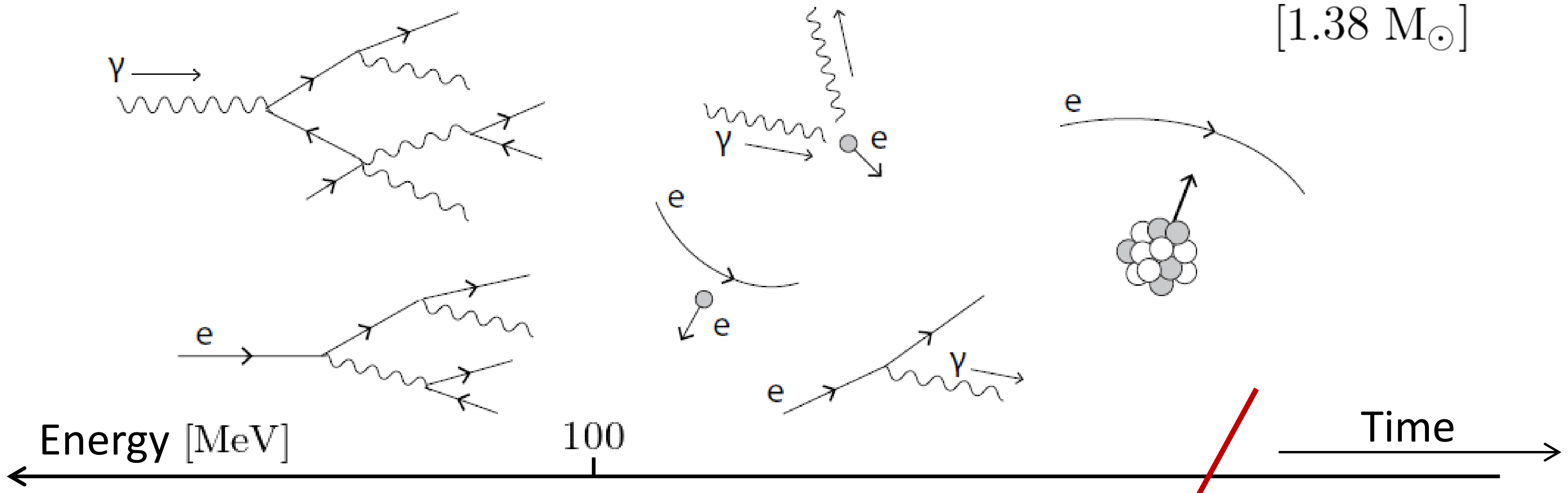
$E \gtrsim 10\ {\rm MeV}$ free ion scattering

Particle Stopping in White Dwarfs

Incident electrons and photons (low energy)

$n_{\mathrm{ion}} \sim 10^{32}\ \mathrm{cm}^{-3}$

$[1.38\ \mathrm{M}_\odot]$



Electron-Ion Phonon Production $E \lesssim 10\ \mathrm{MeV}$

$$\lambda_{\mathrm{ph}} \sim \frac{M_c \Omega_p}{n_{\mathrm{ion}} \alpha^2 Z^2} \sim 10^{-7}\ \mathrm{cm}$$

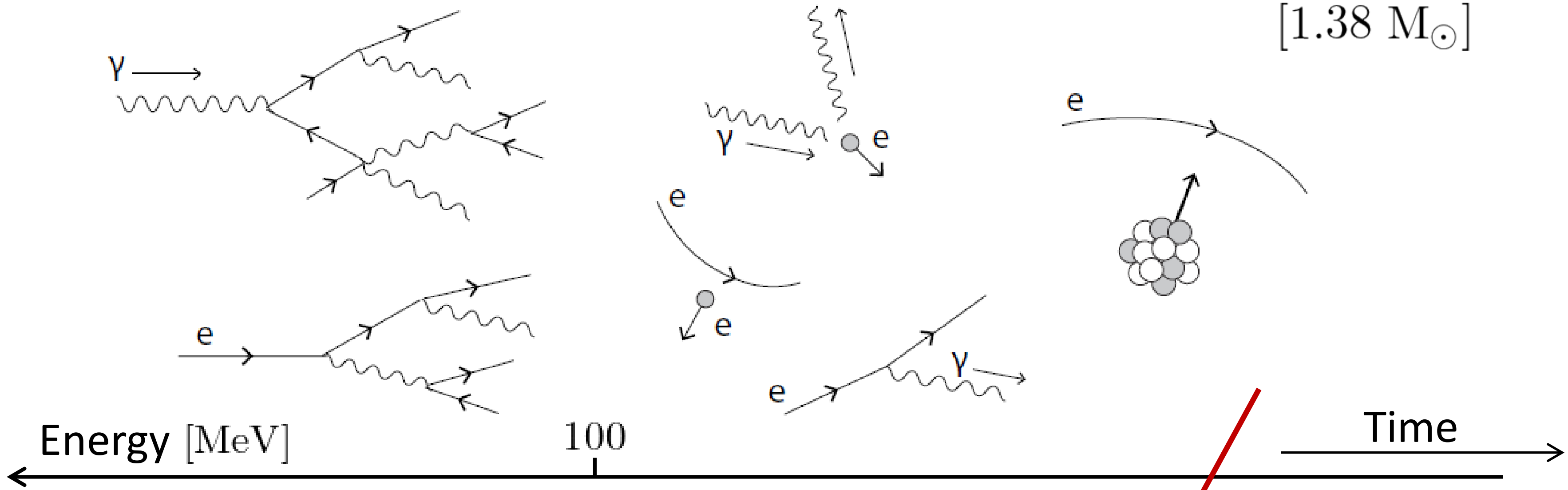
$$L_{\mathrm{ph}} \sim \left(\frac{1}{\log \Lambda} \frac{E}{\Omega_p}\right)^{1/2} \lambda_{\mathrm{ph}} \sim 10^{-6}\ \mathrm{cm} \left(\frac{E}{10\ \mathrm{MeV}}\right)^{1/2}$$

Particle Stopping in White Dwarfs

Incident electrons and photons (low energy)

$n_{\rm ion} \sim 10^{32}\ {\rm cm}^{-3}$

$[1.38\ {\rm M}_\odot]$



Electron-Ion Free Coulomb $E \gtrsim 10\ {\rm MeV}$

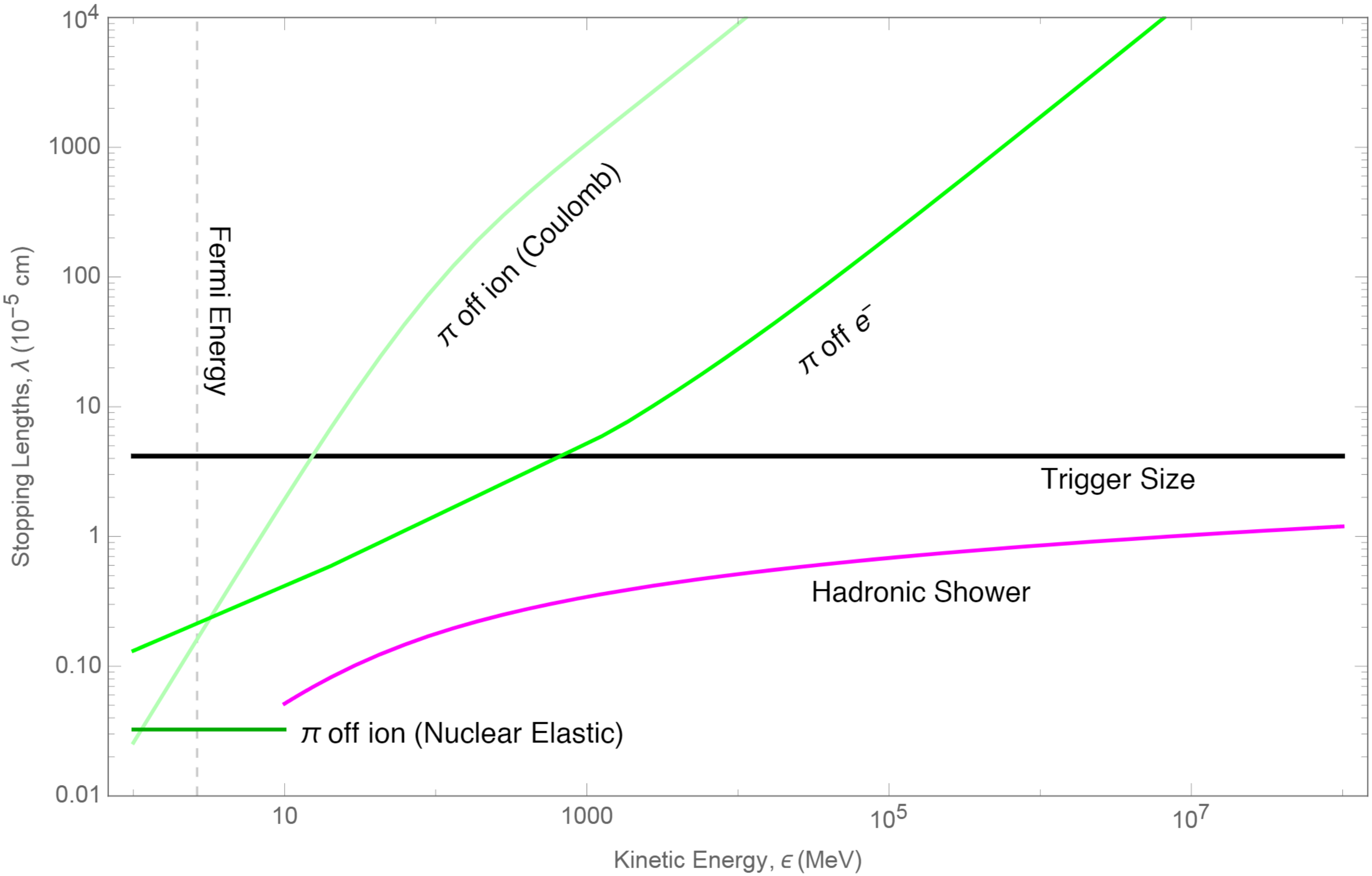
$$\lambda_{\rm free} \sim \frac{E^2}{n_{\rm ion}\alpha^2 Z^2} \sim 10^{-7} \left(\frac{E}{10\ {\rm MeV}}\right)^2\ {\rm cm}$$

$$L_{\rm free} \sim \left(\frac{1}{\log\Lambda}\frac{M_c}{E}\right)^{1/2} \lambda_{\rm free} \sim 10^{-6}\ {\rm cm} \left(\frac{E}{10\ {\rm MeV}}\right)^{3/2}$$

Low energy electrons and photons stop below the trigger size.

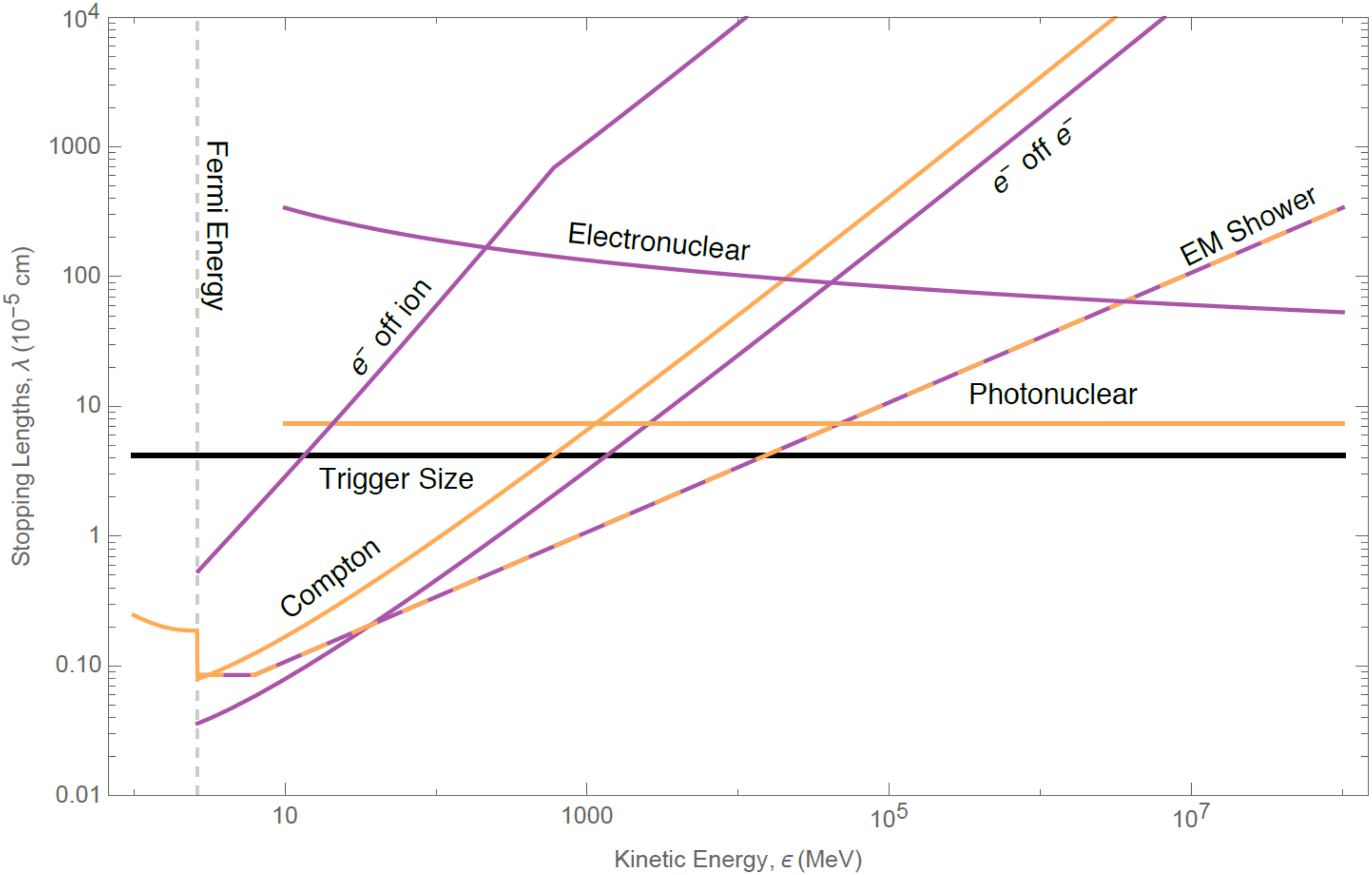
Particle Stopping in White Dwarfs

Incident Hadrons $n_{\rm ion} \sim 10^{32}\ {\rm cm}^{-3}$ $[1.38\ {\rm M}_\odot]$



Particle Stopping in White Dwarfs

Incident Electrons and Photons $n_{\rm ion} \sim 10^{32}\ {\rm cm}^{-3}$ $[1.38\ {\rm M}_\odot]$



Constraints on DM-induced SN

Explosion Condition: SM Energy Deposit $\gtrsim \mathcal{E}_{\rm boom}$ [Graham et al, '15]

Heaviest stars give the best constraint:

RX J0648.04418 (and 16 others) $M \approx 1.25 \mathrm{M}_\odot$ [Kleinman et al, '13]

	From DM Interactions	Observed
WD Lifetime	$\tau_{\rm wd}$	$\tau_{\rm wd} > 1~\mathrm{Gyr}$ [DeGennaro et al, '07]
SN Rate	$\Gamma^{\rm decay}_{\rm SN} \sim \int dM~f(M)~\tau^{-1}_{\rm wd}$	$\Gamma_{\rm sn} < 0.3\,(100~\mathrm{yr})^{-1}$ [Van Den Berg, '91]

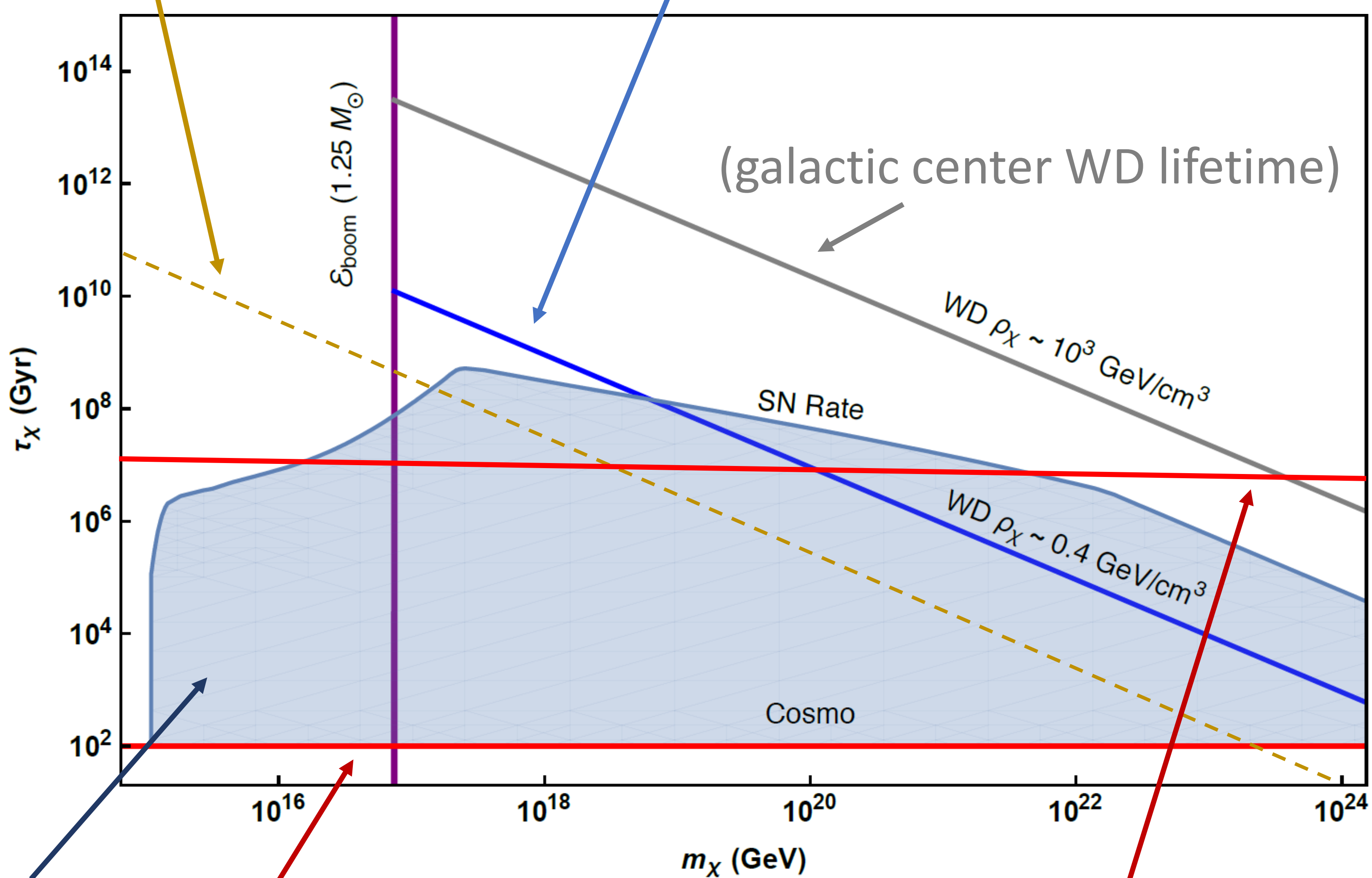
Integrate over all WDs that can be ignited, and which produce visible SN.

$M > 0.85~\mathrm{M}_\odot$ required to yield a visible amount of ^{56}Ni [Sim et al, '10]

Decay-induced SN Constraints

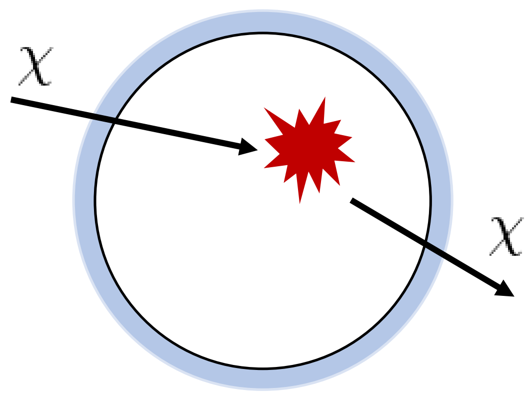
Cosmic Ray [O(1) decay products]

Local WD lifetime



SN Rate   CMB (ISW) [Poulin et al, '16]   CMB (ionization) [Slatyer & Wu, '16]

Scattering-induced SN Constraints



Explosion Condition

$$\left(\frac{dE}{dx}\right)_{\text{interior}} \lambda_t \gtrsim \mathcal{E}_{\text{boom}}$$

$$\left(\frac{dE}{dx}\right)_{\text{env}} R_{\text{env}} \lesssim m_\chi v_{\text{esc}}^2$$

WD Lifetime $\tau_{\text{wd}}^{-1} \sim \Gamma_{\text{transit}}$

Elastic Scattering

$$\left(\frac{dE}{dx}\right)_{\text{interior}} \sim n_{\text{ion}} \sigma_{\chi c} \cdot m_c v_{\text{esc}}^2$$

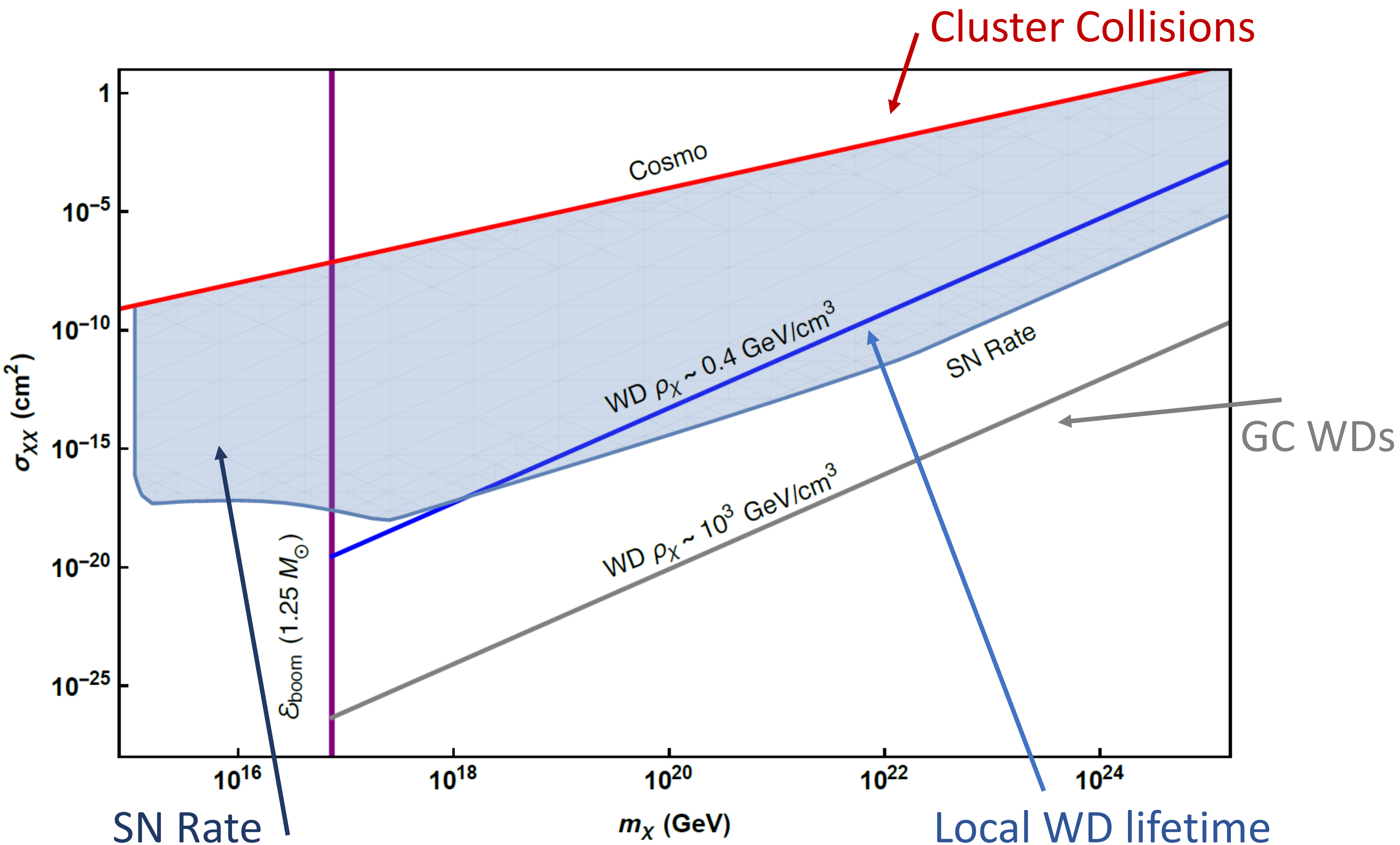
$$\left(\frac{dE}{dx}\right)_{\text{env}} \sim n_{\text{env}} \sigma_{\chi c} \cdot m_c v_{\text{esc}}^2$$

$$[\text{C} \to \text{He}]$$

$$\Longrightarrow \quad \sigma_{\chi c} > \frac{T_F}{v_{\text{esc}}^2 m_c} \lambda_T^2 \qquad \frac{\sigma_{\chi c}}{m_\chi} < \frac{1}{R_{\text{env}} n_{\text{env}} m_c}$$

$$\frac{R_{\text{env}}}{R_{\text{wd}}} \sim 10^{-2} \qquad \frac{n_{\text{env}}}{n_{\text{ion}}} \sim 10^{-3}$$

Annihilation-induced SN Constraints



Elastic Capture of Dark Matter

Capture and Collection Timescales

$$t_1 \sim 100 \text{ yr} \left(\frac{m_\chi}{10^{10} \text{ GeV}}\right)^{3/2} \left(\frac{10^{-36} \text{ cm}^{-2}}{\sigma_{\chi c}}\right)^{3/2}$$

$$t_2 \sim 100 \text{ yr} \left(\frac{m_\chi}{10^{10} \text{ GeV}}\right) \left(\frac{10^{-36} \text{ cm}^{-2}}{\sigma_{\chi c}}\right)$$

$$t_{\text{sg}} \sim 10^7 \text{ yr} \left(\frac{m_\chi}{10^{10} \text{ GeV}}\right)^{1/2} \left(\frac{10^{-36} \text{ cm}^{-2}}{\sigma_{\chi c}}\right)$$

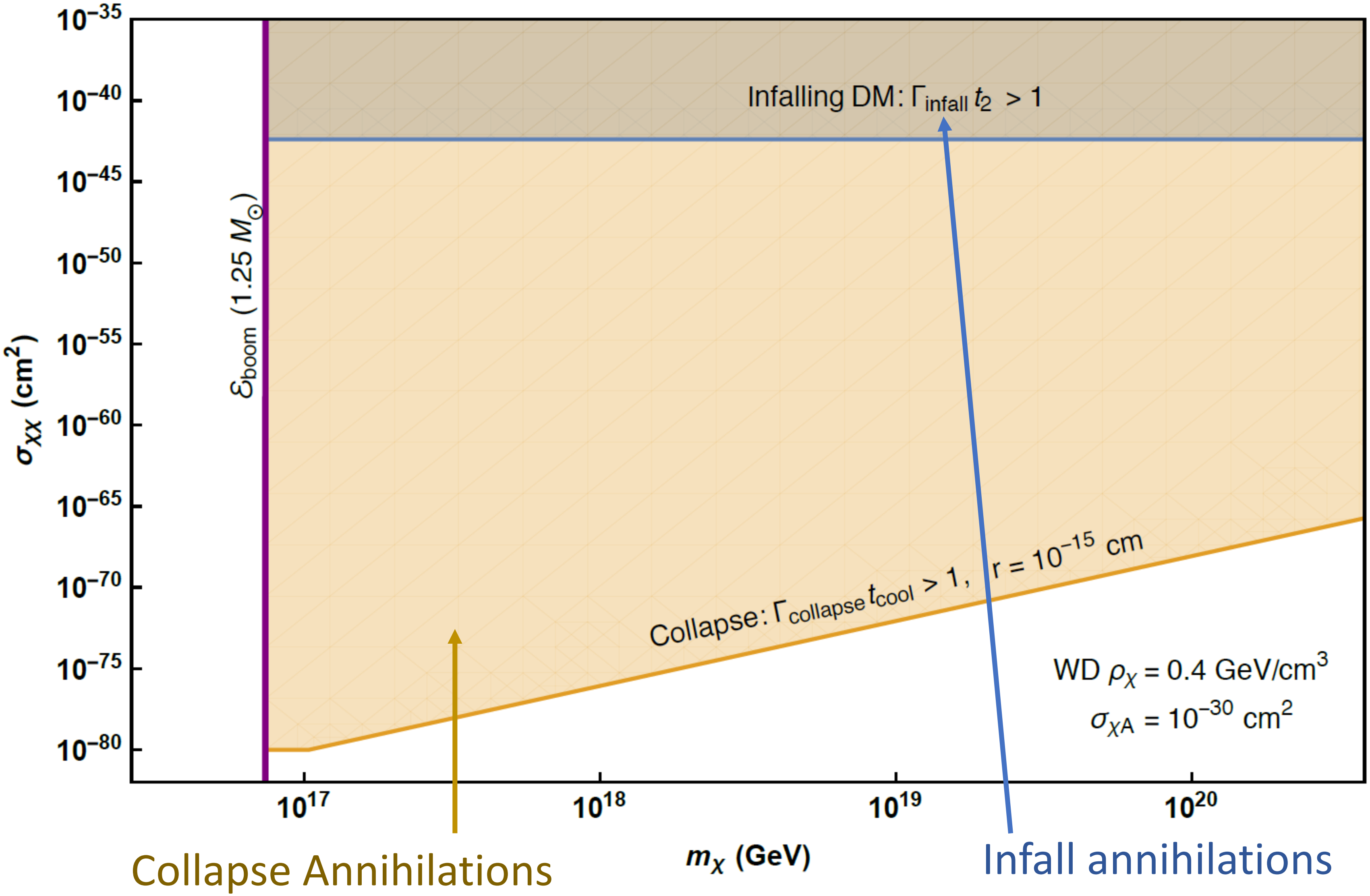
$$t_{\text{collapse}} \sim t_2 \frac{v_{\text{ion}}}{\text{Max}[v_{\text{ion}}, v_\chi]} \frac{1}{\log(m_\chi / m_{\text{ion}})} < t_2$$

Core Radius

$$r_{\text{th}} \sim 100 \text{ cm} \left(\frac{10^{10} \text{ GeV}}{m_\chi}\right)^{1/2}$$

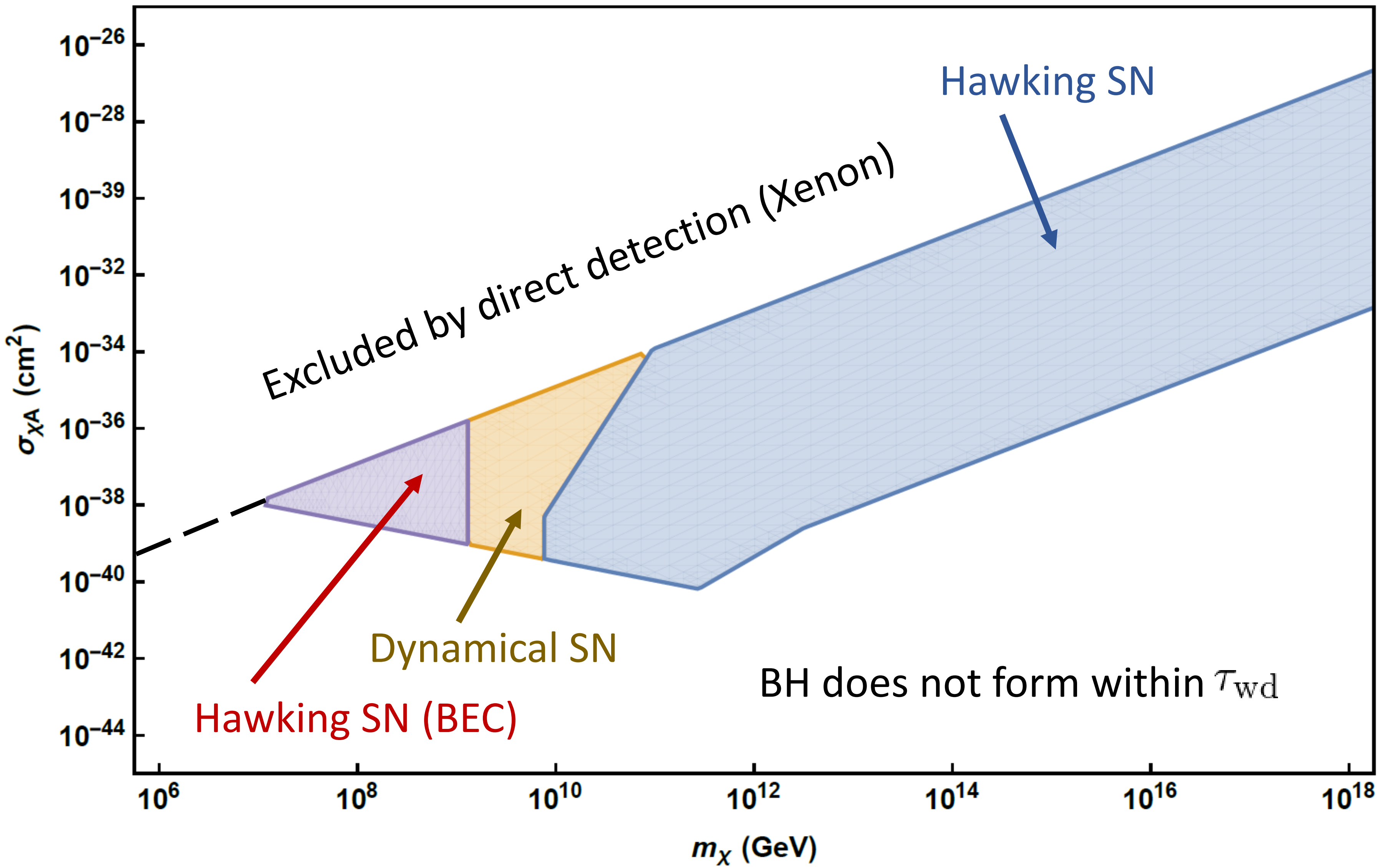
Annihilations of Captured DM

Demand $\tau_{\rm wd} > 1\ {\rm Gyr}$ for local WDs (with $\sigma_{\chi c} = 10^{-30}\ {\rm cm}^2$)



BH-induced Supernovae Constraints

Demand $\tau_{\mathrm{wd}} > 1\ \mathrm{Gyr}$ for local WDs (Boson DM)



Q-ball Dark Matter