Fundamental Physics with Supernovae and Superconductors

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White Dwarfs as Dark Matter Detectors

[Graham, RJ, Narayan, Rajendran, Riggins, 1805.07381]
[RJ, Narayan, Riggins, 1905.00395]

An ALP Search using Superconducting RF Cavities and a Confined Magnetic Field

[RJ, Narayan, Rajendran, Riggins, 1904.07245]

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.

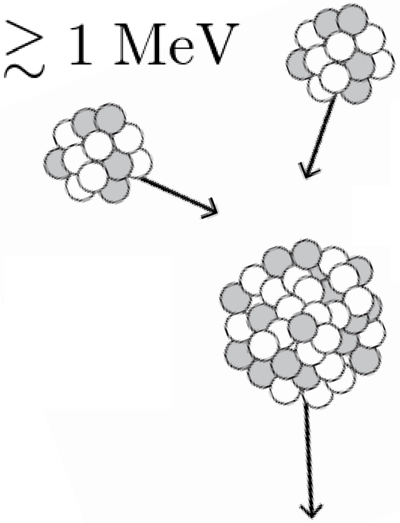
It is possible that DM is responsible for an O(1) fraction of these events.

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

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

A careful calculation (Timmes and Woosley 1992):

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

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

Trigger Energy

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

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

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

Particle Production Heating of WDs

WD medium can be heated though the thermalization of high energy SM secondaries produced by DM.

Many possible production mechanisms! This work:

Inelastic scattering with WD medium (e.g., Q-balls)

Decay or annihilation of captured DM

Hawking radiation from a BH formed from a DM core

Annihilation burst from a collapsing DM core

Particle Production Heating of WDs

WD medium can be heated though the thermalization of high energy SM secondaries produced by DM.

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

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

Particle Production Heating of WDs

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

Must compute stopping distances of SM particles in a WD

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

Stop and thermalize within a trigger size.

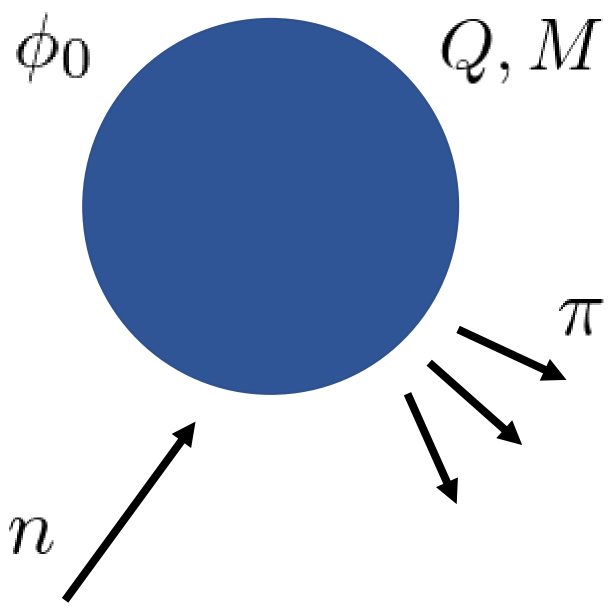
High energy electrons ($E \gtrsim 10^2 \ {\rm TeV}$) and neutrinos:

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

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

Q-ball Dark Matter

Baryonic Q-ball (B-ball)



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

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

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

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

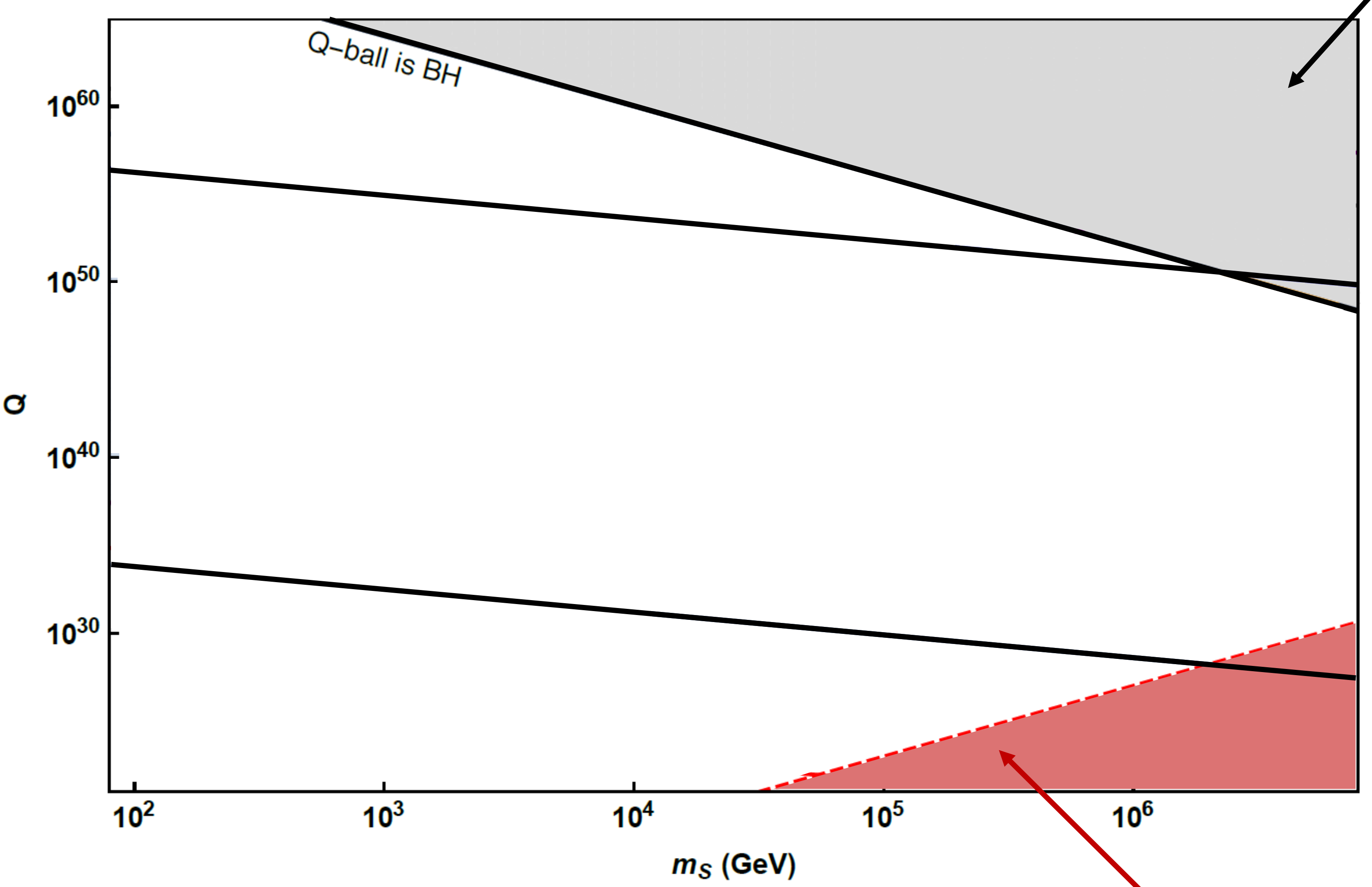
$$dM \sim \frac{M}{Q}dQ \ll m_n dQ$$

Excess energy must be emitted as pions.

Energy Deposit

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

Q-ball Dark Matter



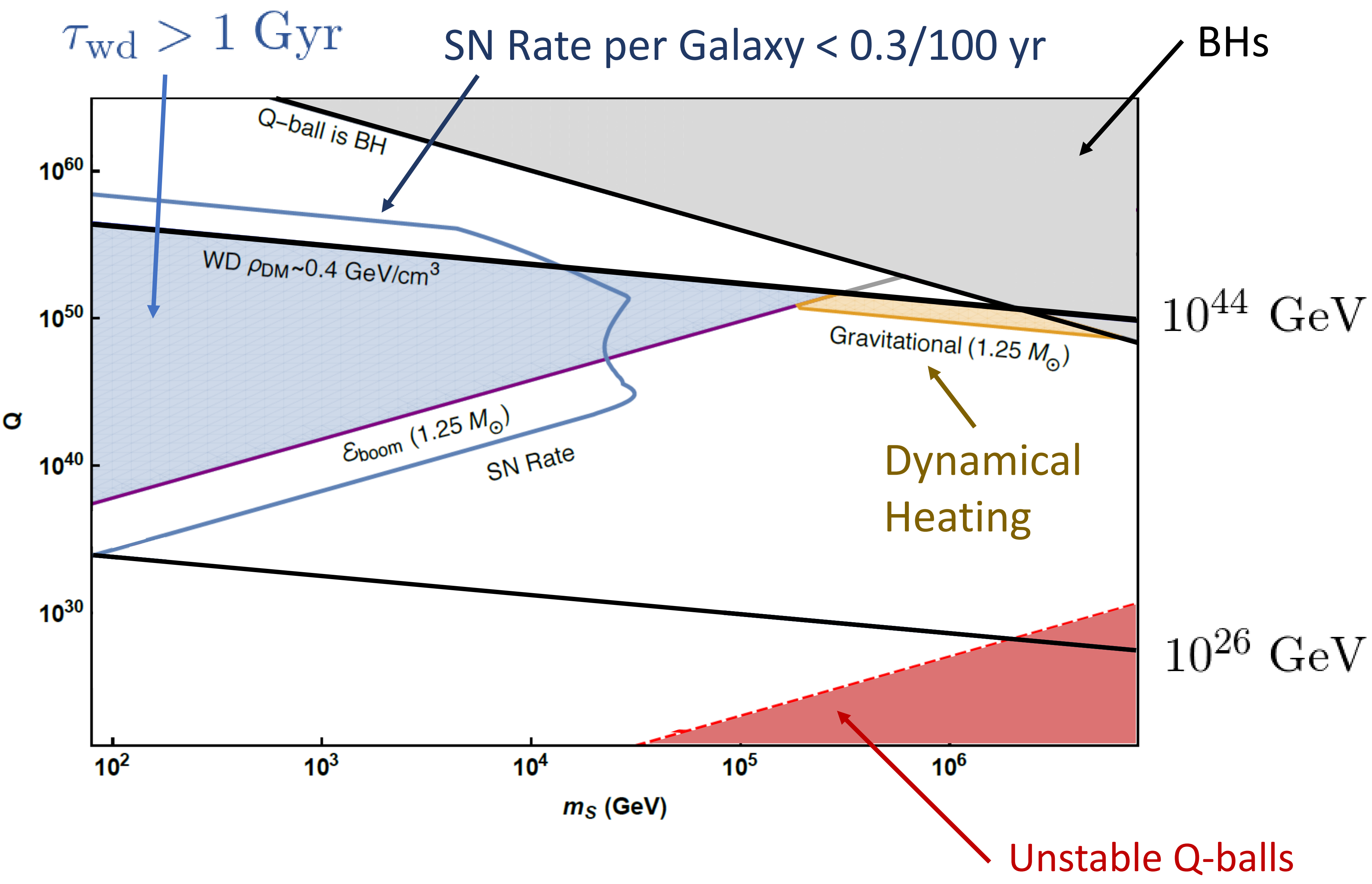
BHs

10^{44} GeV

10^{26} GeV

Unstable Q-balls

Q-ball Dark Matter



$\tau_{wd} > 1\ \mathrm{Gyr}$

SN Rate per Galaxy < 0.3/100 yr

BHs

$10^{44}\ \mathrm{GeV}$

$10^{26}\ \mathrm{GeV}$

Dynamical Heating

Unstable Q-balls

Q-ball Dark Matter

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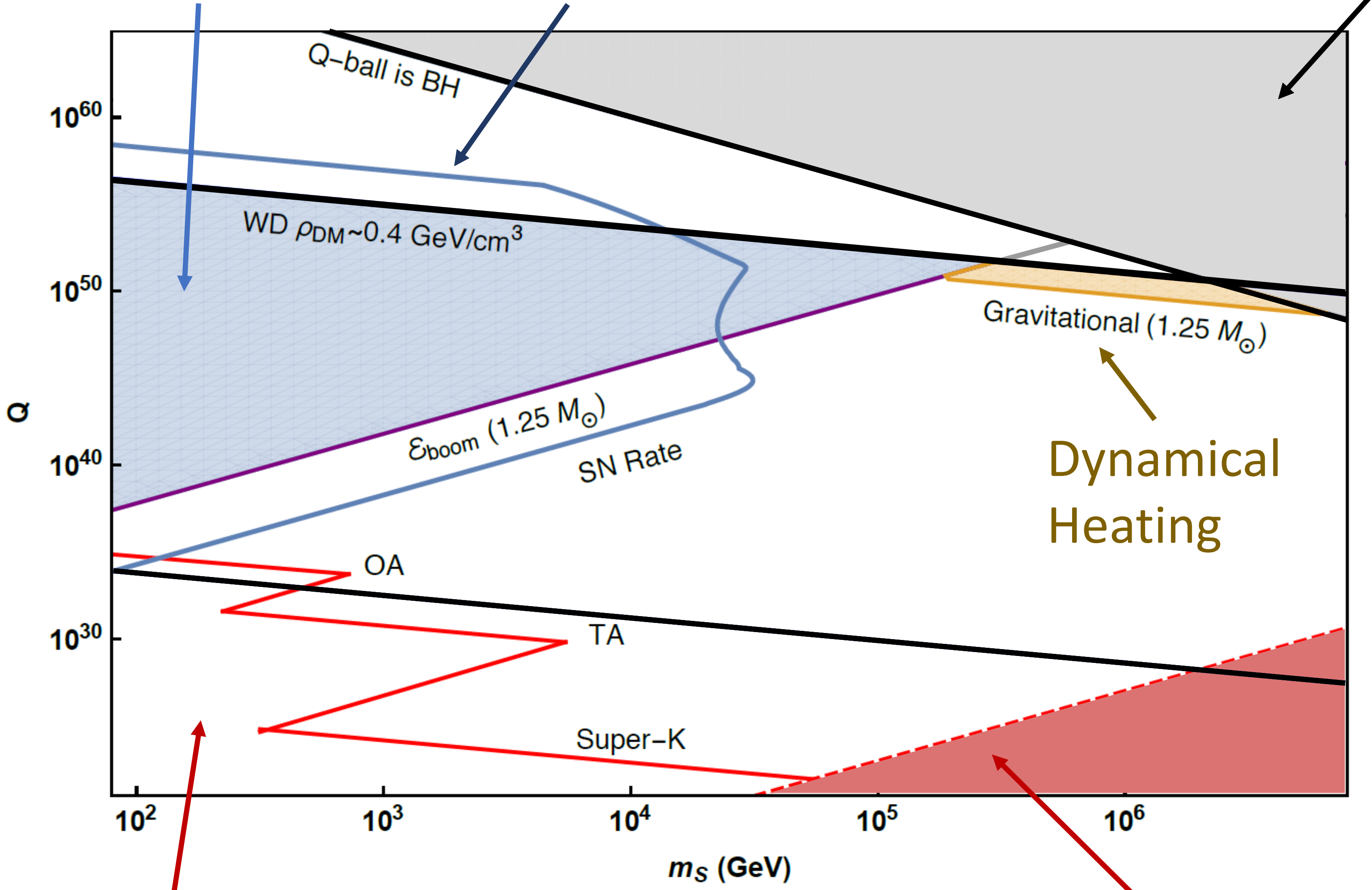
SN Rate per Galaxy < 0.3/100 yr

BHs



10^{44} GeV

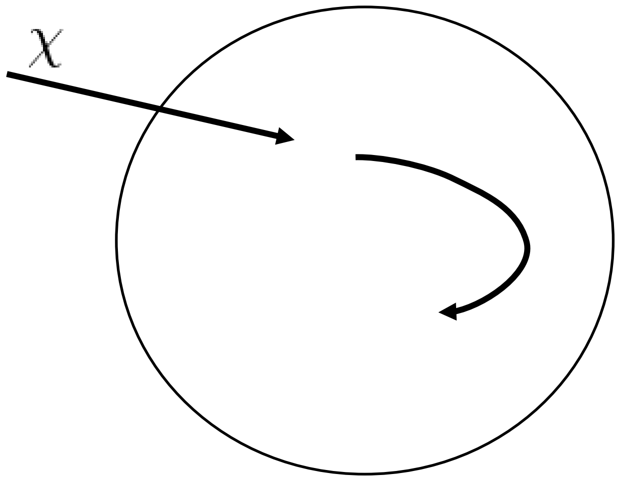
Dynamical Heating

10^{26} GeV

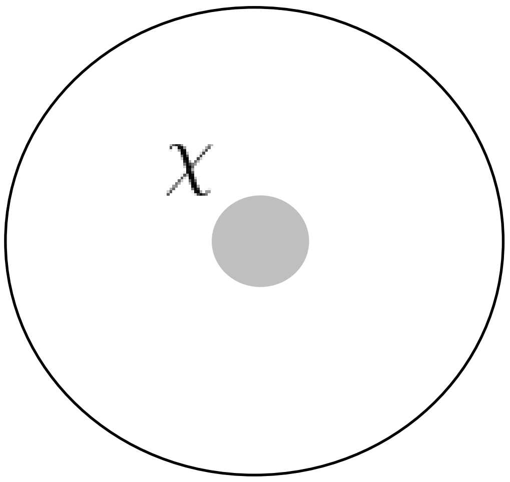
Terrestrial Searches [Kusenko et al, '98]

Unstable Q-balls

Elastic Capture of Dark Matter



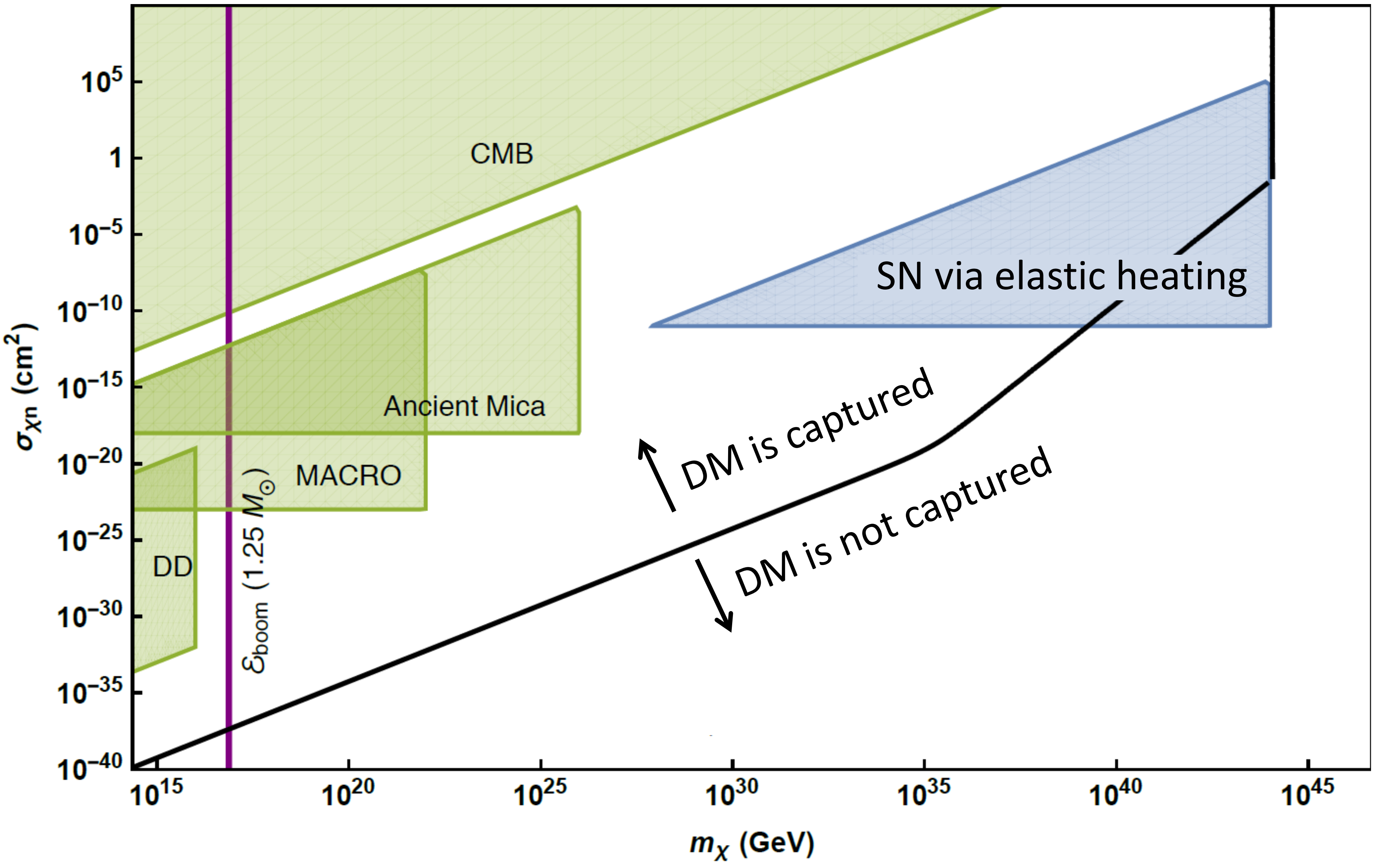
DM may lose energy via elastic scatters in the WD medium and become bound to the star.



DM thermalizes with the WD medium and forms a central core of radius r_{th}:

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

Elastic Capture of Dark Matter

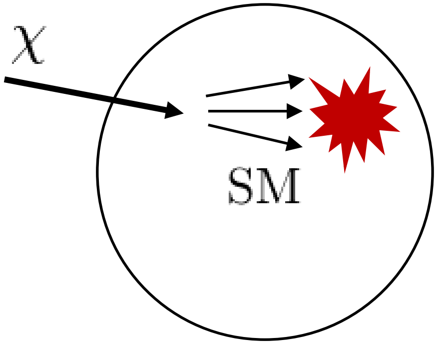


Decay and Annihilation-Induced SN

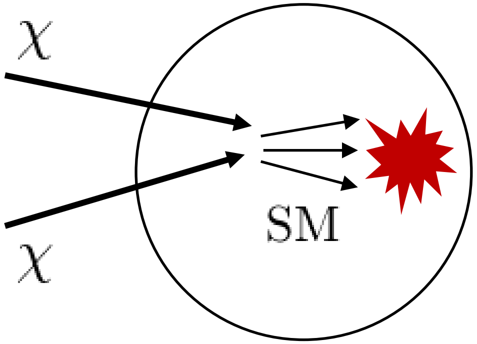
DM can locally heat a WD by decaying or annihilating into high-energy SM particles.

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

Decay



Annihilation



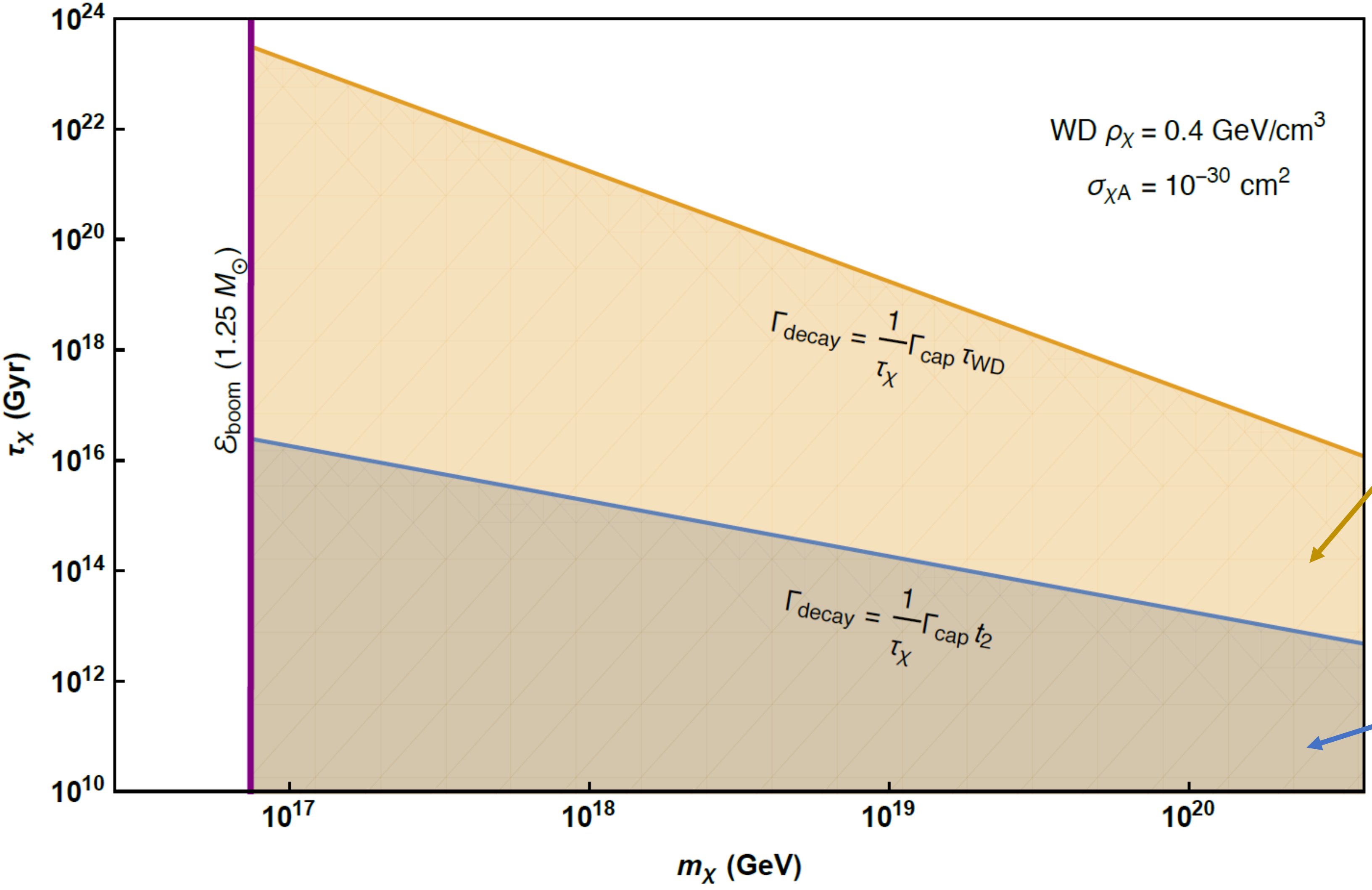
Ignition Condition: $m_\chi > \mathcal{E}_{\rm boom}$

(assuming SM product energy is O(1) photons and hadrons)

SN rate enhanced if DM is captured

Decay of Captured Dark Matter

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

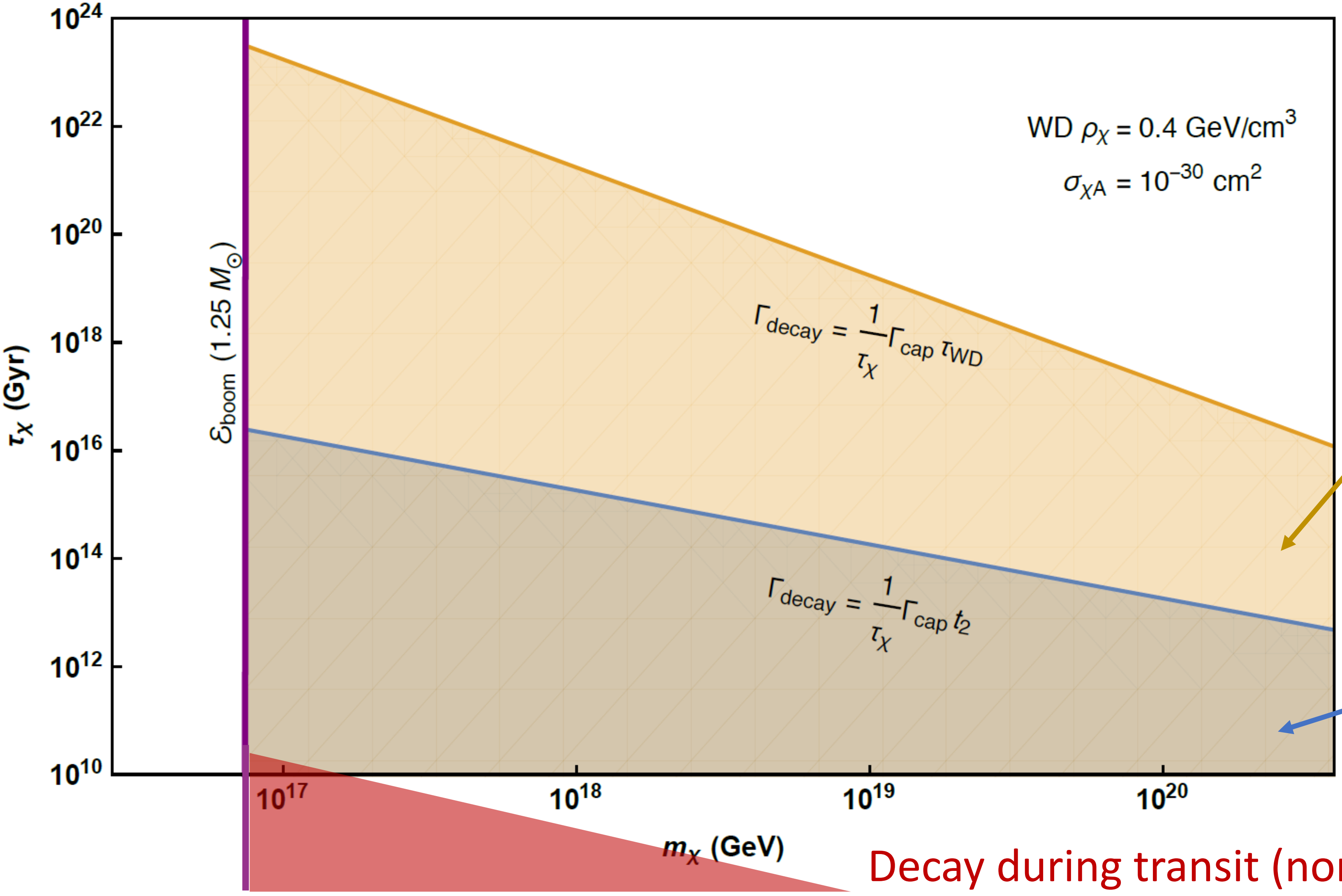


Decay in DM Core

Decay during Infall

Decay of Captured Dark Matter

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



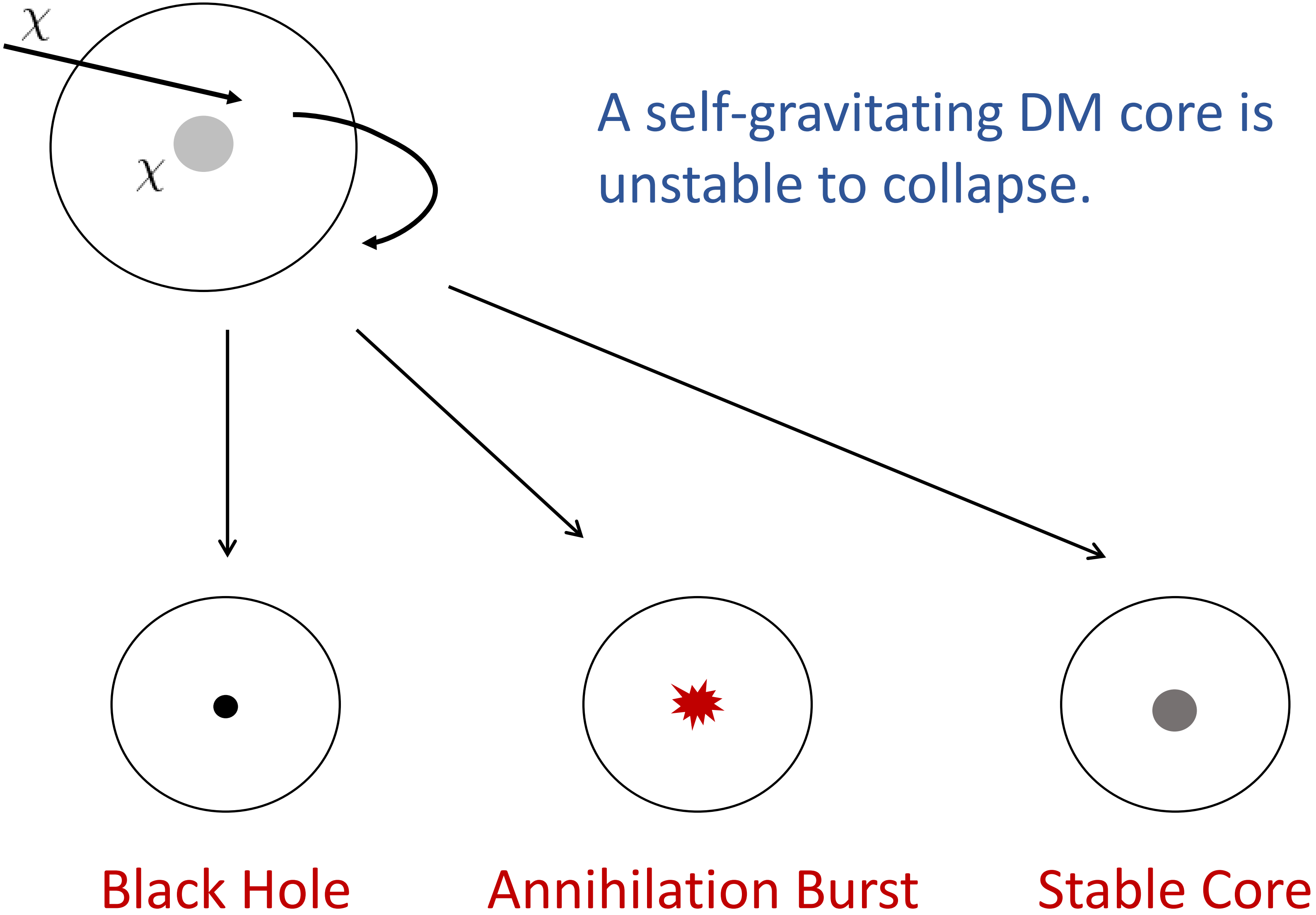
Decay in DM Core

Decay during Infall

Decay during transit (non-capture)

Collapse of a Collected DM Core

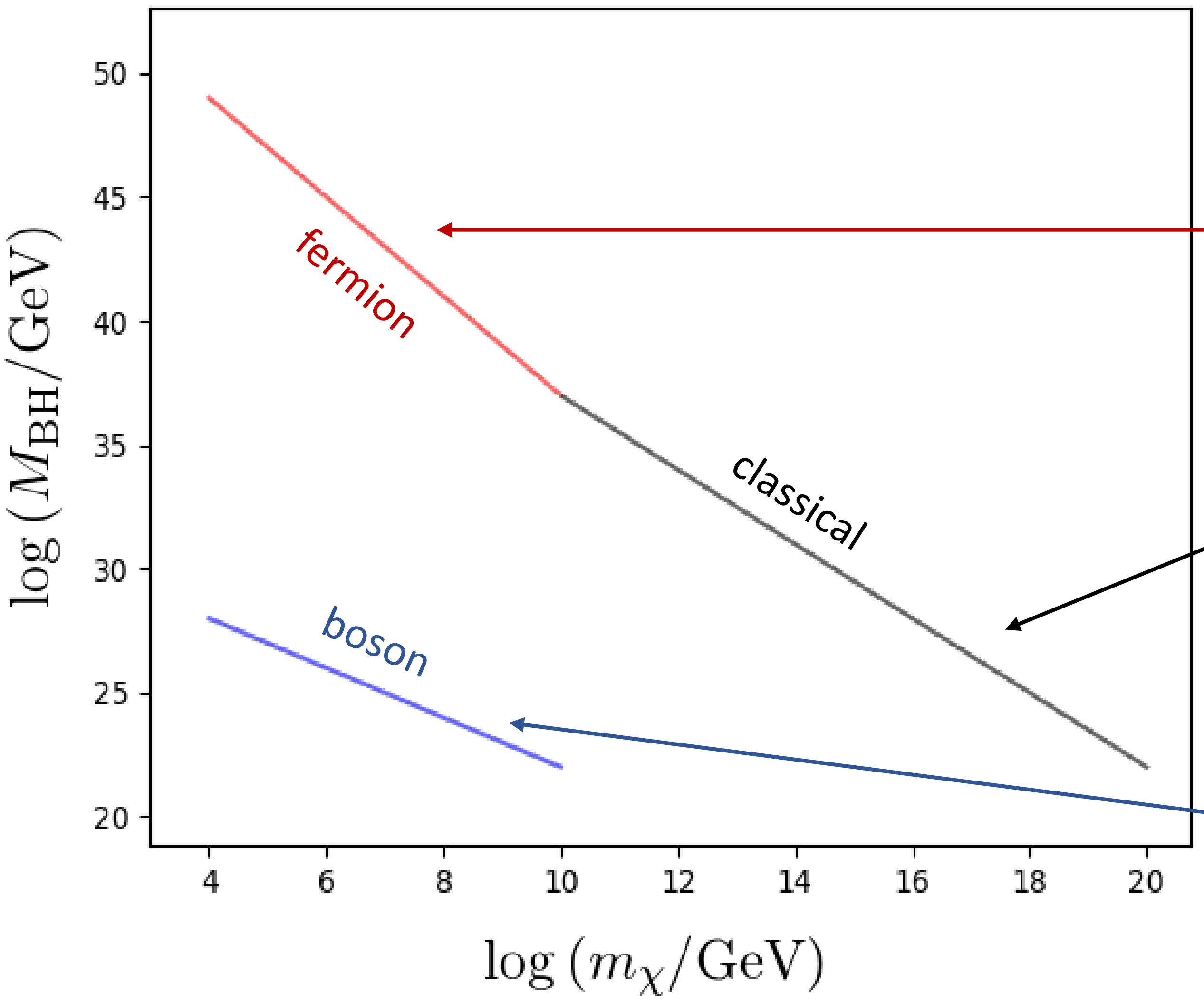
A self-gravitating DM core is unstable to collapse.



Black Holes from DM in White Dwarfs

Formation of BHs from DM cores

[Kouvaris & Tinyakov, ‘10, ‘12]



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

overcome Fermi pressure

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

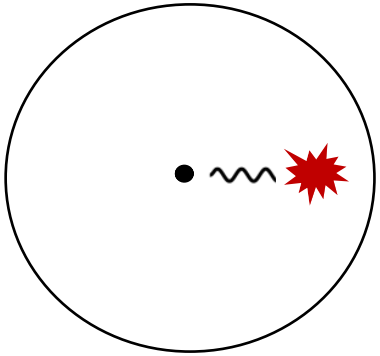
classical collapse

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

“drip” BHs via BEC

BH-induced Supernovae

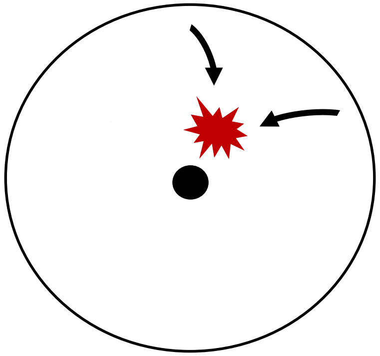
Hawking Radiation



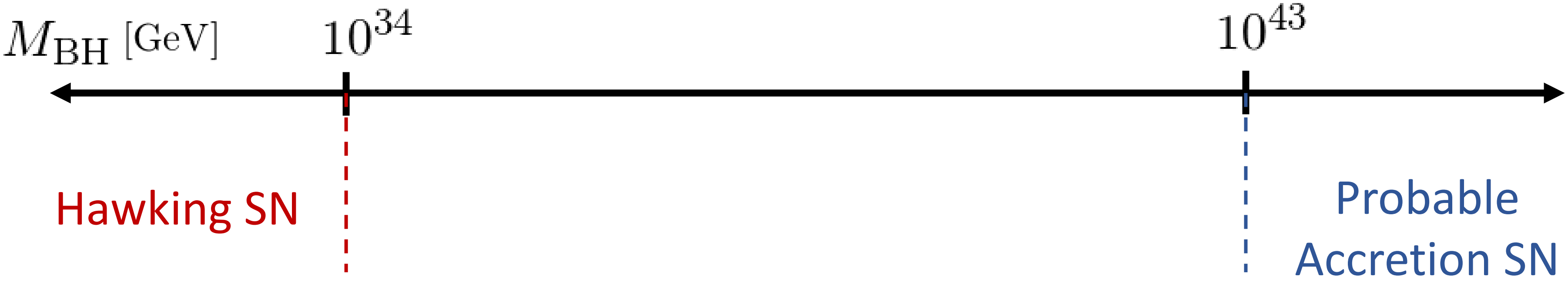
$$\dot{M}_H \tau_{\mathrm{diff}} > \mathcal{E}_{\mathrm{boom}}$$

diffusion time

Accretion Heating



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



M_{BH} [GeV]

10^{34}

10^{43}

Hawking SN

Probable Accretion SN

[RJ, Narayan, Riggins, 1905.00395]

BH-induced Supernovae

[Kouvaris & Tinyakov, ‘10]

Evaporation

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

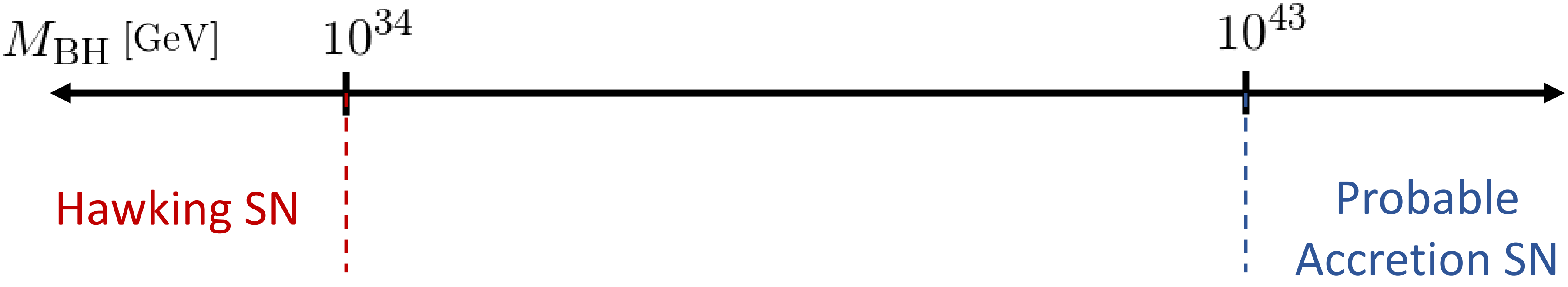
Hawking
radiation

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



$M_{\rm BH}$ [GeV]

10^{34}

10^{43}

Hawking SN

Probable
Accretion SN

[RJ, Narayan, Riggins, 1905.00395]

BH-induced Supernovae

[Kouvaris & Tinyakov, '10]

Evaporation

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

Hawking radiation

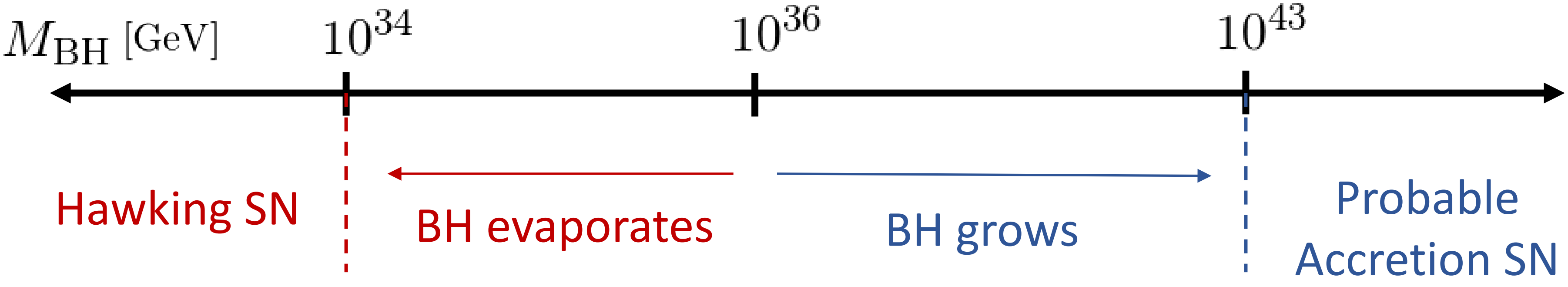
Accretion

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

Bondi accretion of stellar medium

Accretion of infalling DM

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



$M_{\rm BH}$ [GeV]

10^{34}

10^{36}

10^{43}

Hawking SN

BH evaporates

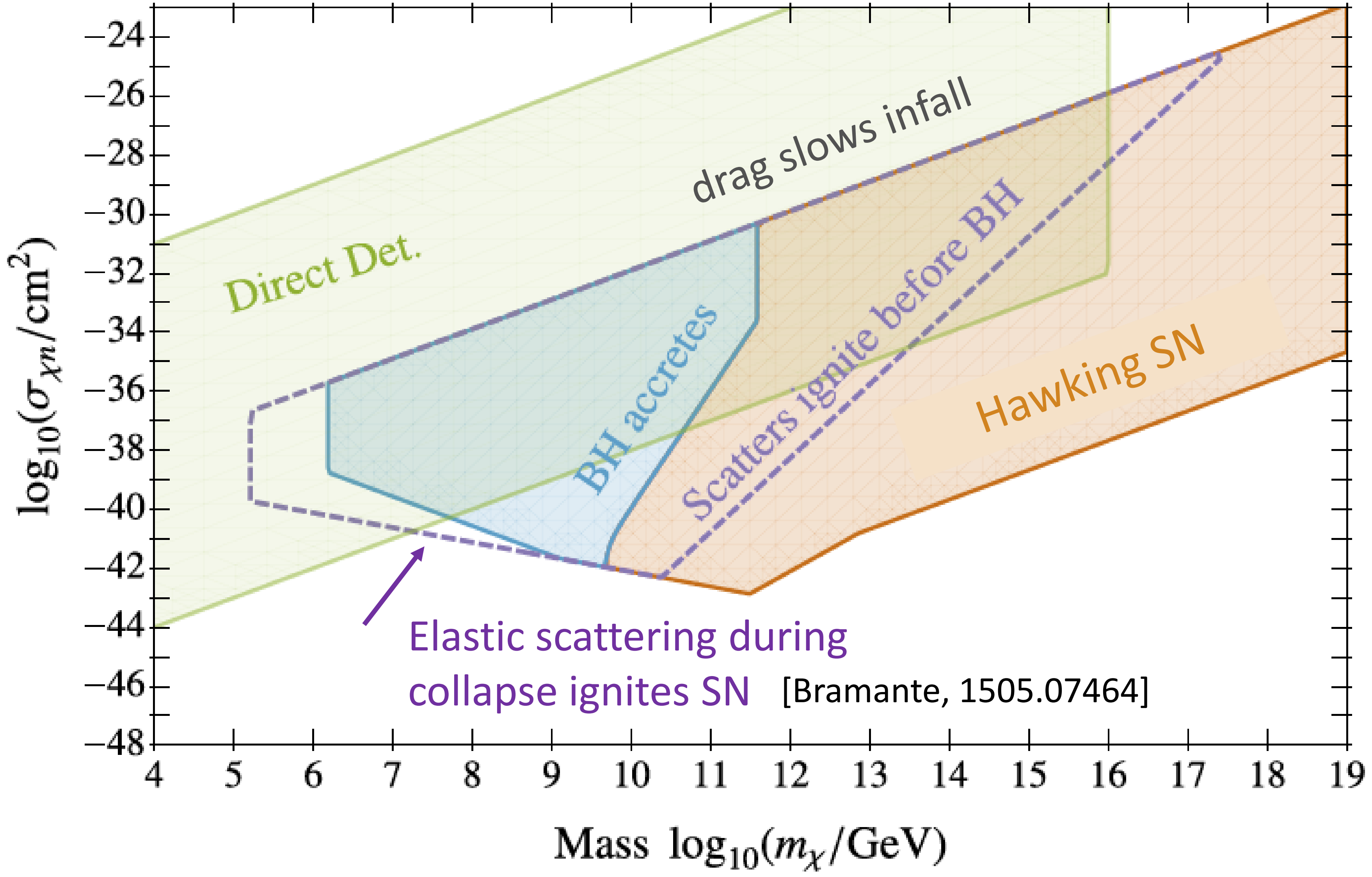
BH grows

Probable Accretion SN

[RJ, Narayan, Riggins, 1905.00395]

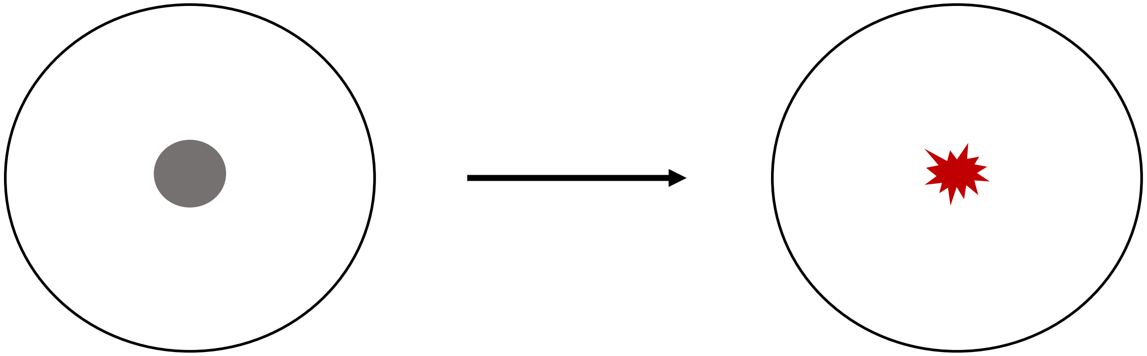
BH-induced Supernovae

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



Elastic scattering during collapse ignites SN [Bramante, 1505.07464]

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

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

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

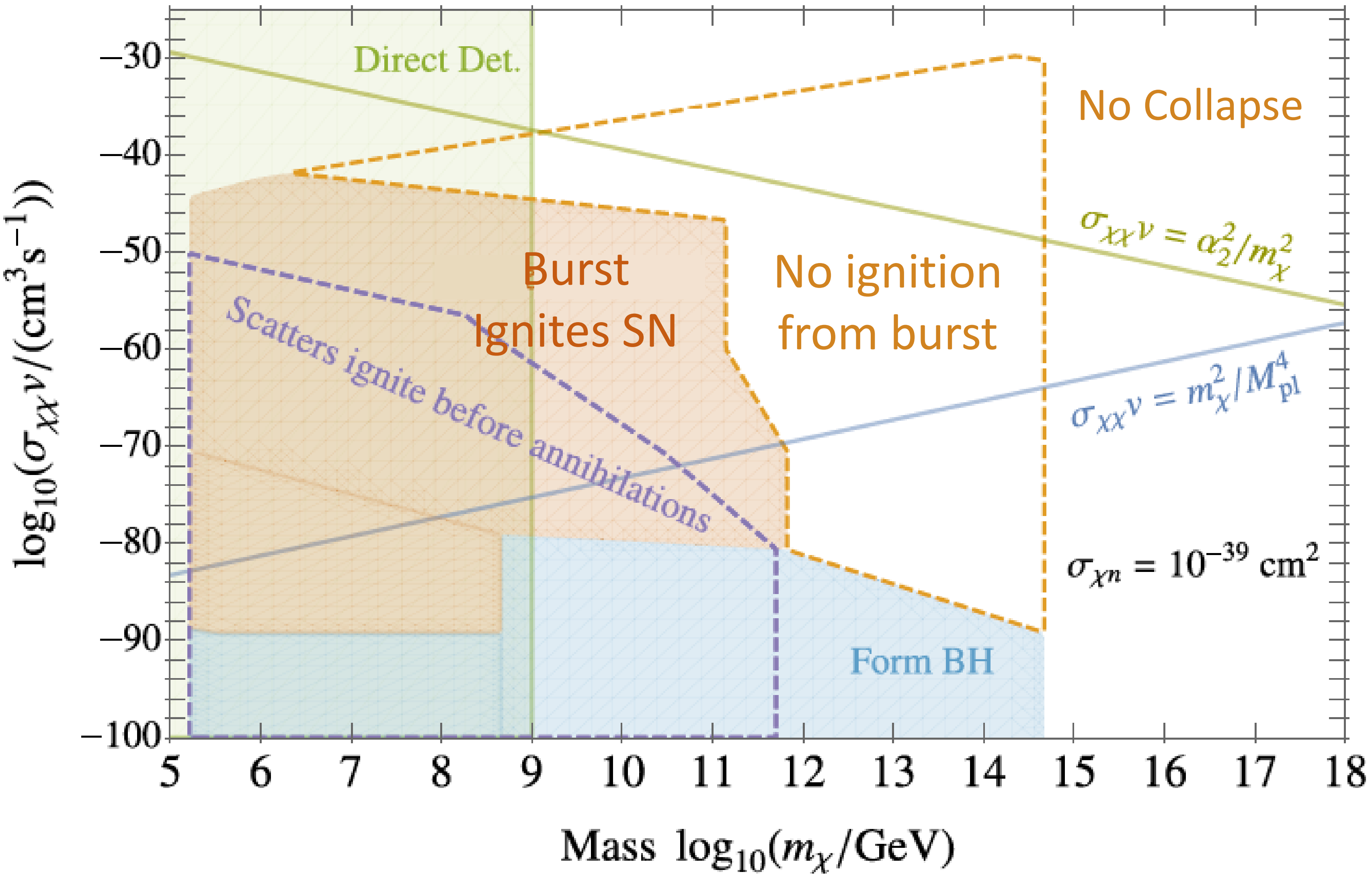
effective fusion volume

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

[RJ, Narayan, Riggins, 1905.00395]

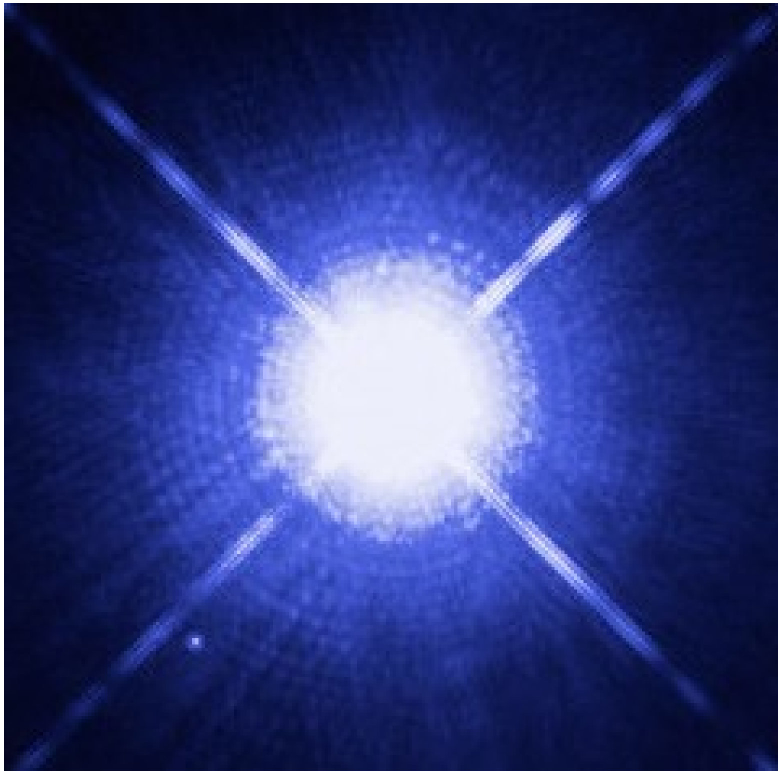
Annihilation Burst SN

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



White Dwarfs as Dark Matter Detectors

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



White Dwarfs as Dark Matter Detectors

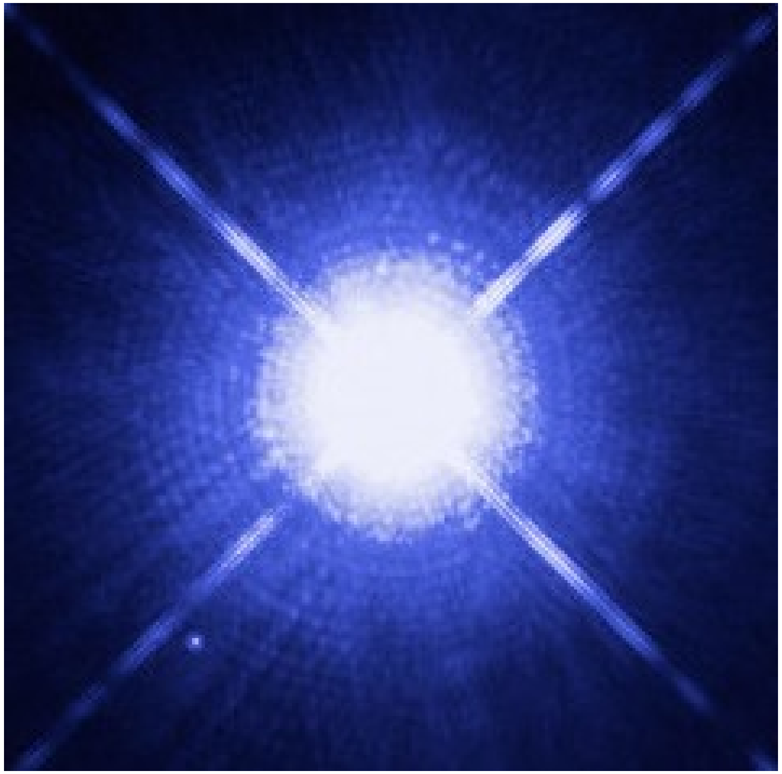
Dark matter interactions can locally heat white dwarfs, initiate runaway fusion, and cause (type Ia) supernovae.

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.

Fundamental Physics with Supernovae and Superconductors

White Dwarfs as Dark Matter Detectors

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An ALP Search using Superconducting RF Cavities and a Confined Magnetic Field

[RJ, Narayan, Rajendran, Riggins, 1904.07245]

An ALP Search using Superconducting RF Cavities and a Confined Magnetic Field

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A new light boson? Physics in the far UV can lead to light, weakly-coupled particles.

Axion-like particles (ALPs) are a generic possibility

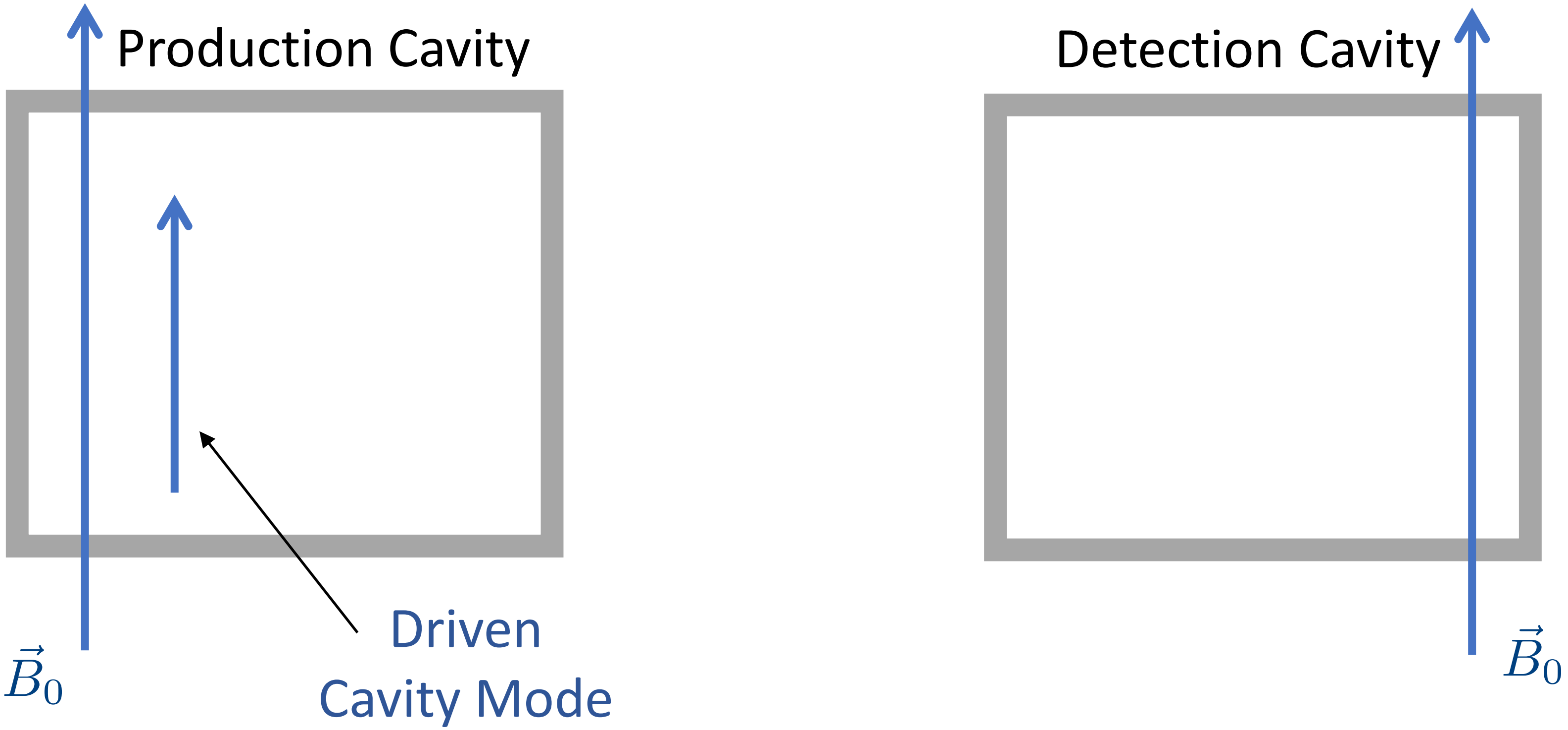
$$\mathcal{L} \supset \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}{m_a}^2 a^2 + \frac{1}{4}\underset{\nwarrow}{g}aF_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Detection Opportunity

ALP-photon mixing in a magnetic field

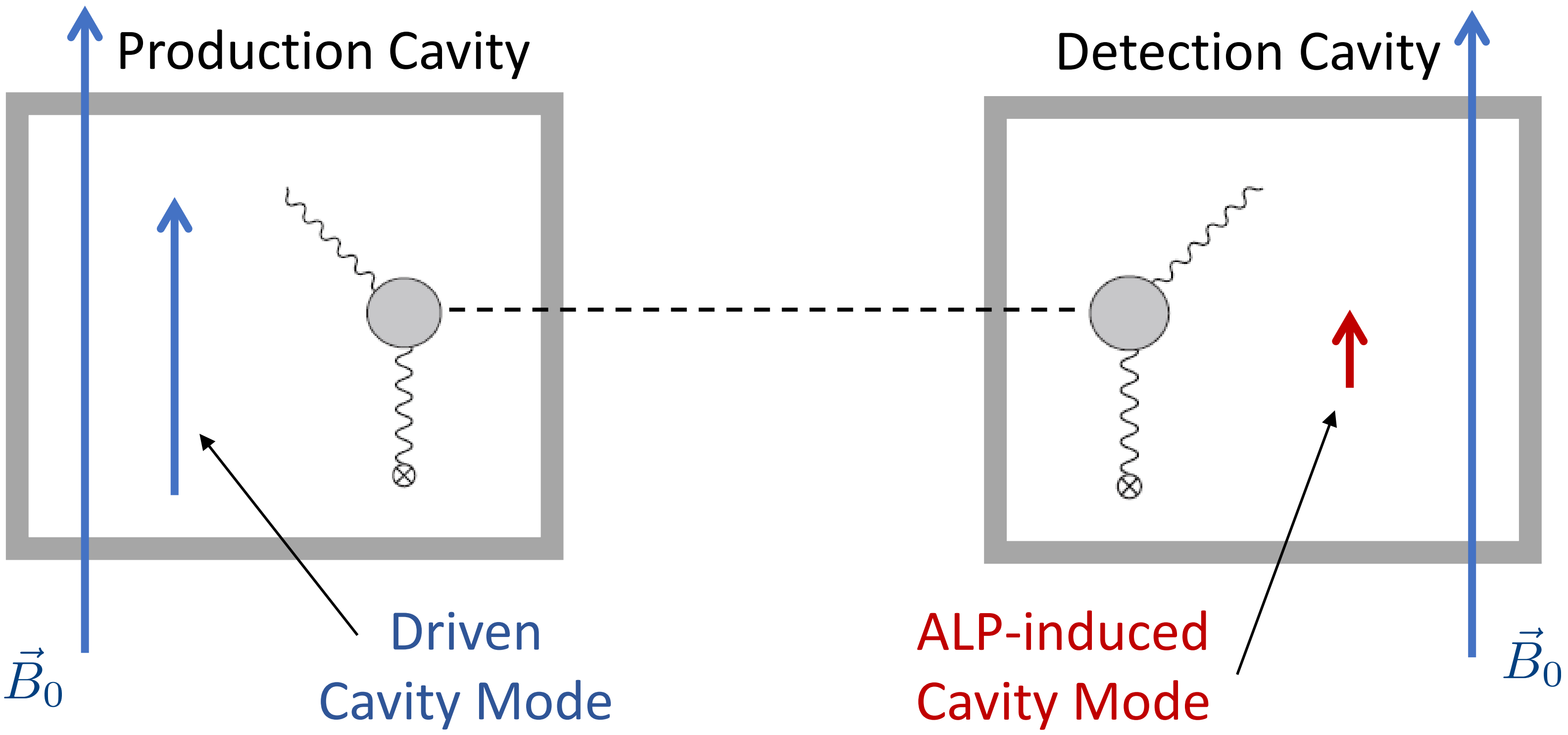
Light Shining Through Walls (LSW)

[Hoogeveen, ‘92]



Light Shining Through Walls (LSW)

[Hoogeveen, '92]



Light Shining Through Walls (LSW)

[…, Graham et al ‘16]

Optical Cavities

ω, L^{-1} are independent

ALPS $g < 5 \times 10^{-8}\ \mathrm{GeV}^{-1}$
for $m_a <$ meV

Next generation with $L \sim 100$ m
ALPS II (projected): $g < 2 \times 10^{-11}\ \mathrm{GeV}^{-1}$

RF Cavities

$\omega, L^{-1} \sim \mathcal{O}(\mathrm{GHz})$

CROWS $g < 10^{-7}\ \mathrm{GeV}^{-1}$
for $m_a <$ μeV

Next generation ???

This work: Utilize superconducting RF technology to reach $g < 7 \times 10^{-12}\ \mathrm{GeV}^{-1}$ in a next generation LSW ALP search

See [Bogorad, Hook, Kahn, Soreq, ‘19] for a different approach

LSW with SRF Cavities

$$P_{\rm signal} = P_{\rm input} \left(\frac{gB_0}{\omega}\right)^4 Q_{\rm pc} Q_{\rm dc} |G|^2$$

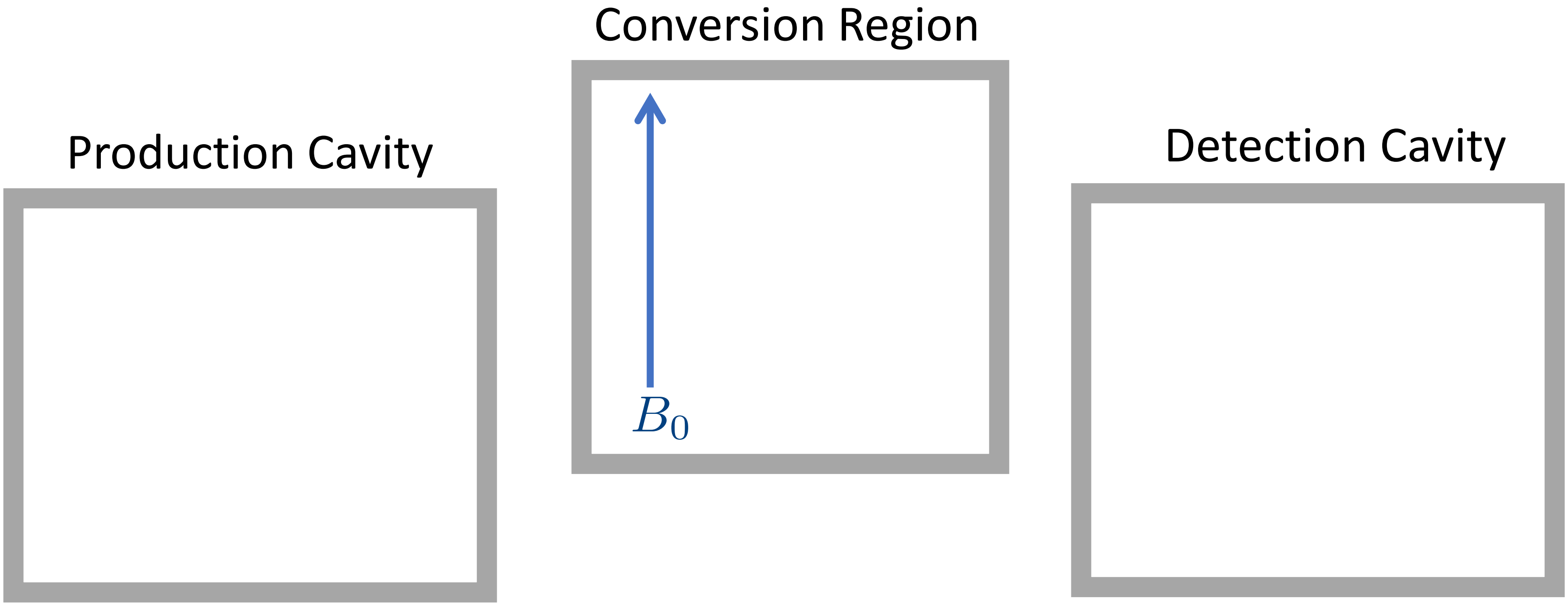
Normal Conducting RF: $Q \sim 10^5 - 10^6$

Superconducting RF: $Q \sim 10^{10} - 10^{12}$

B > O(0.2 T) critical field: flux penetration degrades SC Q

Challenge: re-design such that large B and SRF cavity can co-exist

New Design for LSW with SRF



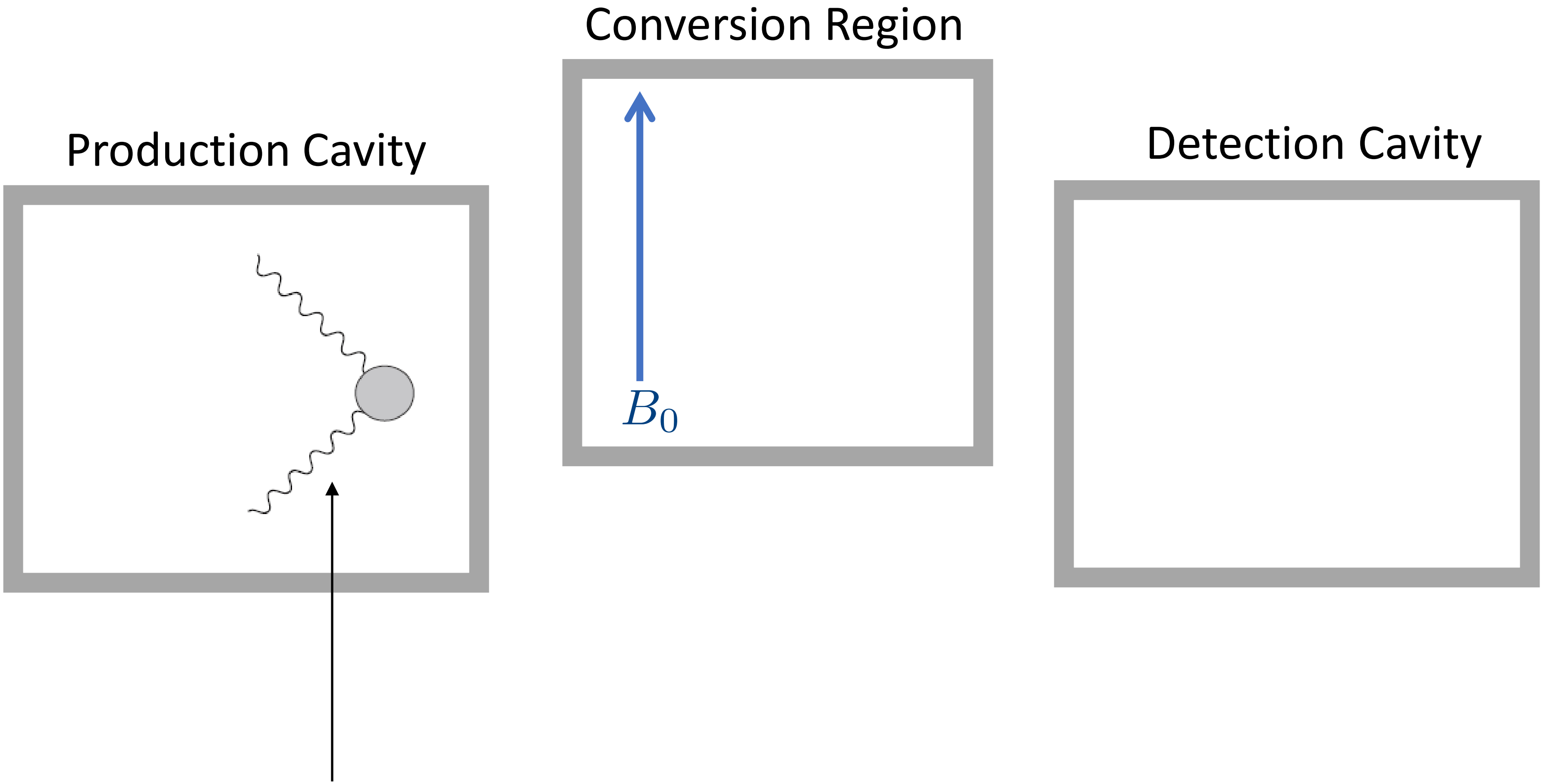
Production Cavity

Conversion Region

B_0

Detection Cavity

New Design for LSW with SRF



Conversion Region

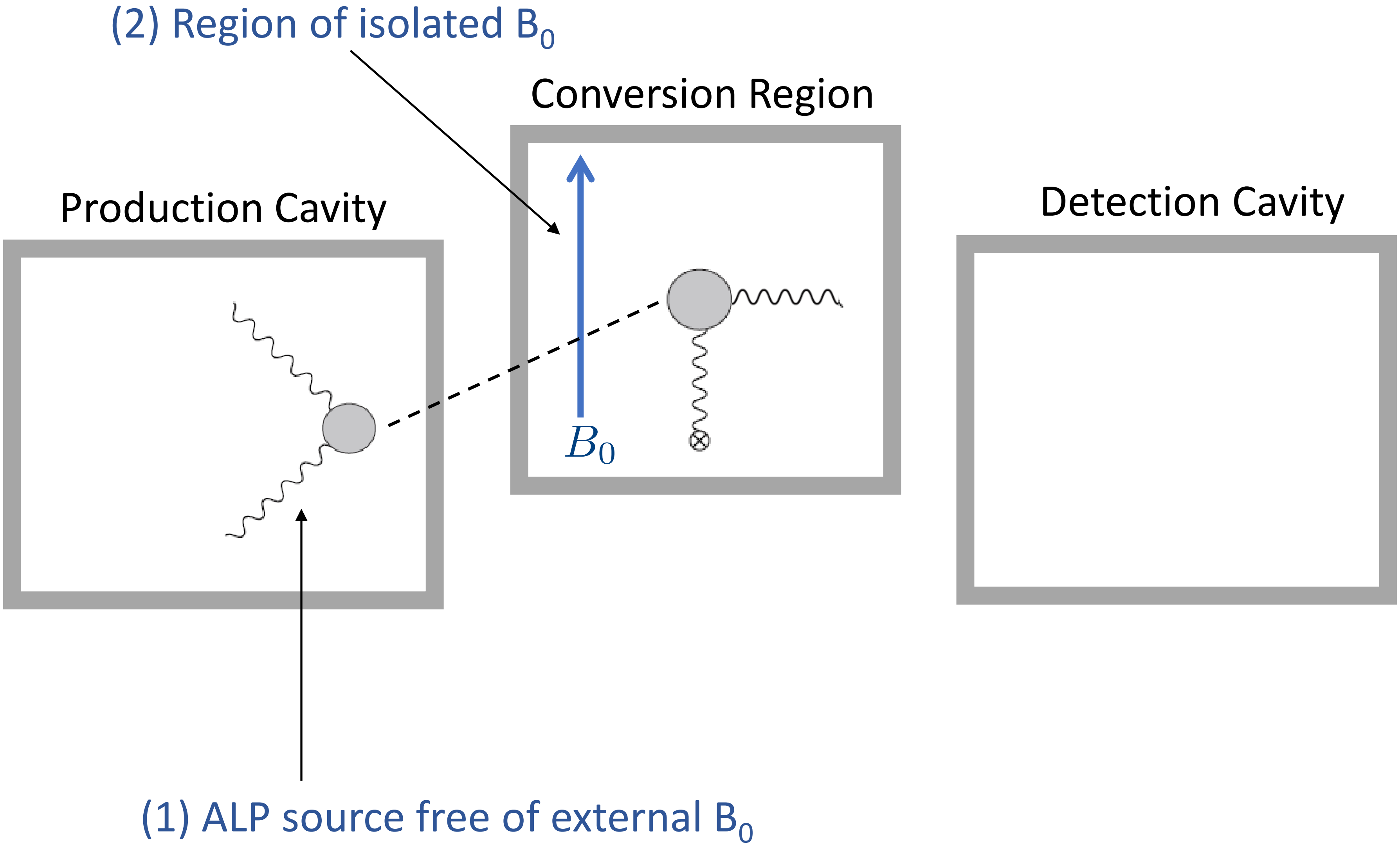
Production Cavity

Detection Cavity

B_0

(1) ALP source free of external B_0

New Design for LSW with SRF



(2) Region of isolated B_0

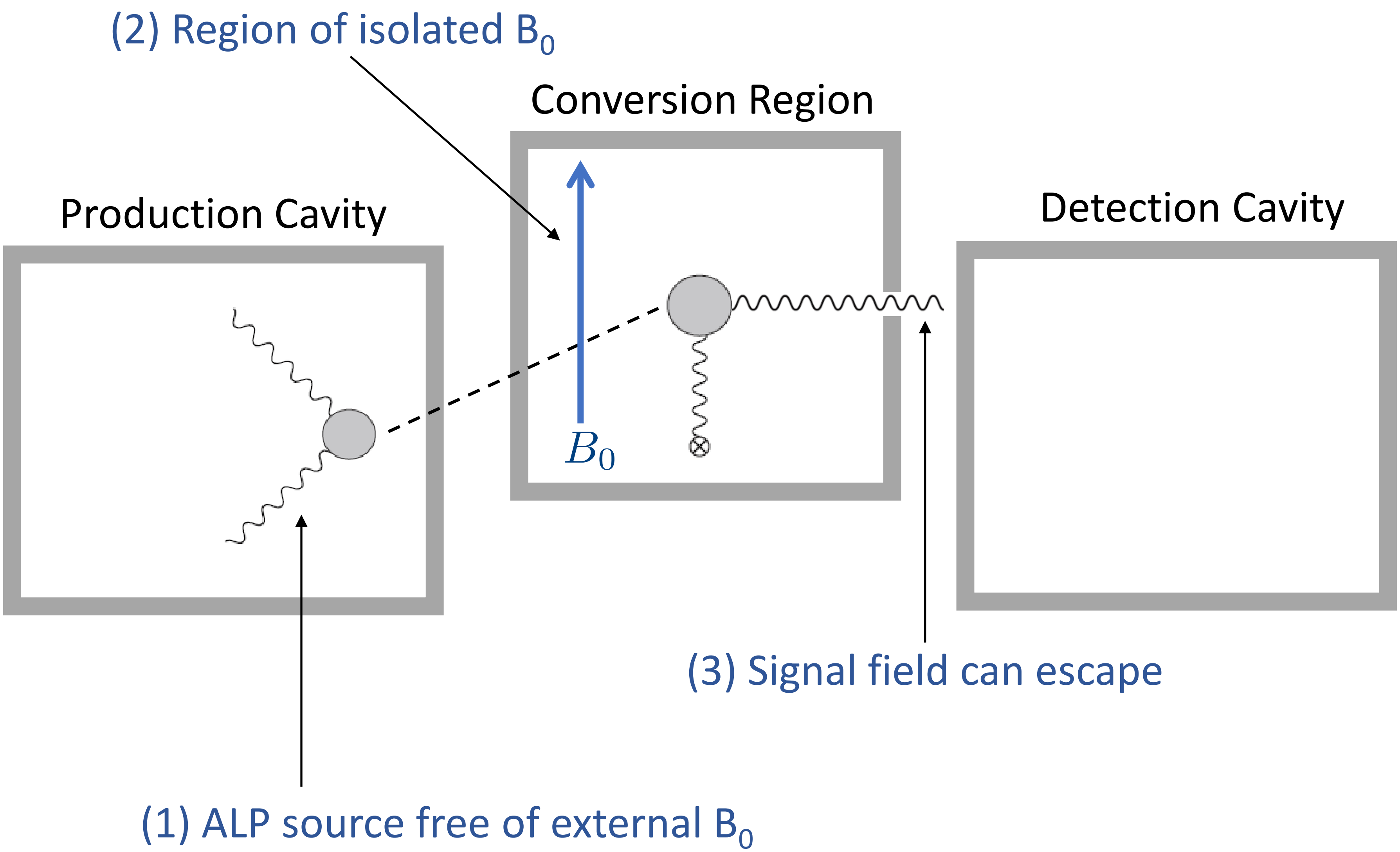
Conversion Region

Production Cavity

Detection Cavity

(1) ALP source free of external B_0

New Design for LSW with SRF

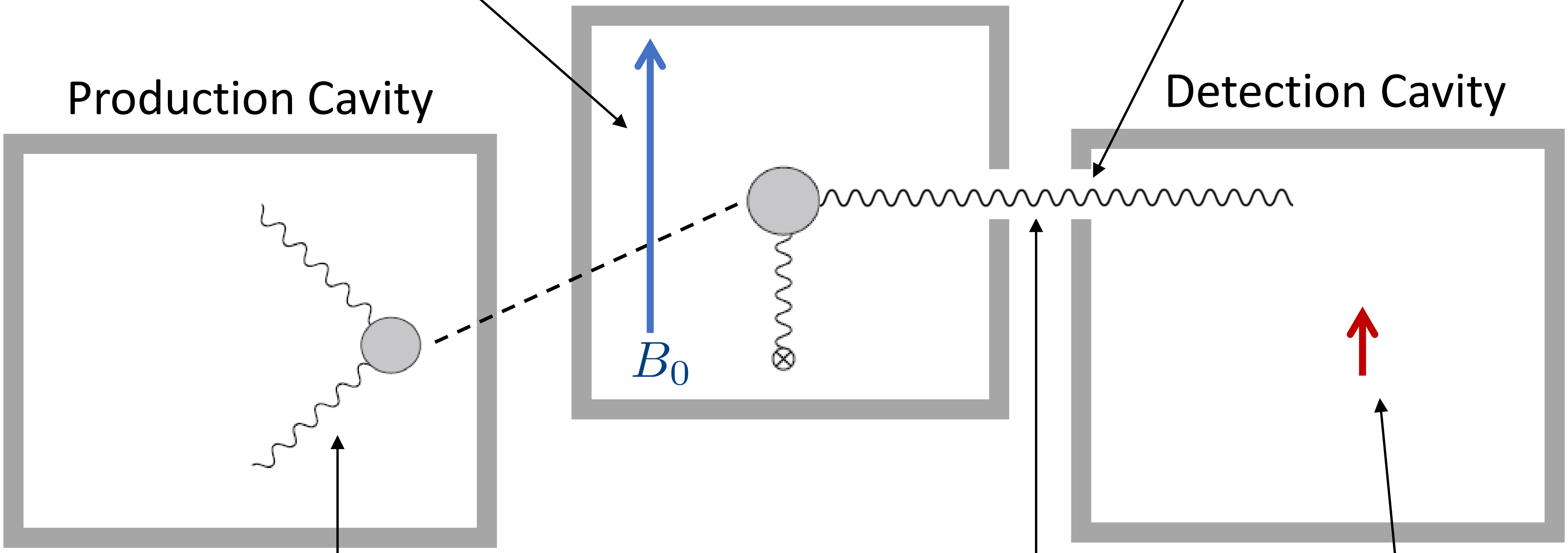


(2) Region of isolated B_0

(3) Signal field can escape

(1) ALP source free of external B_0

New Design for LSW with SRF



(2) Region of isolated B_0

(4) Coupling to detection cavity

Conversion Region

Production Cavity

Detection Cavity

(3) Signal field can escape

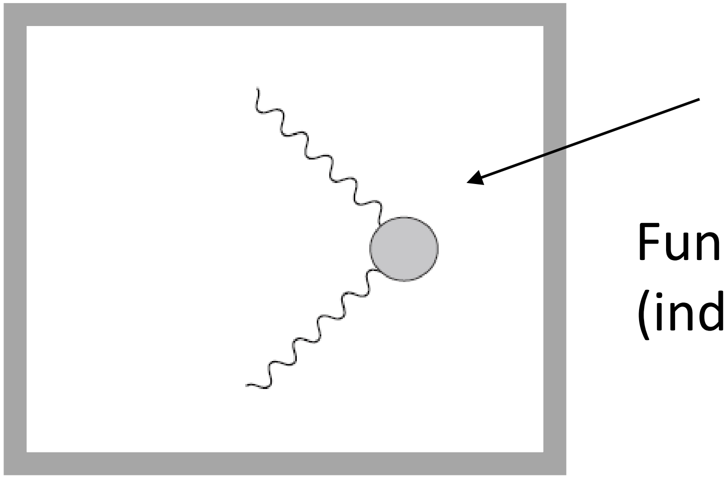
ALP-induced Cavity Mode

(1) ALP source free of external B_0

SRF Axion Source

(1) ALP source without external B_0

ALP EOM: $$(\Box + m_a^2)a(x) = -g\vec{E}\cdot\vec{B}$$



Drive cavity mode(s) such that E.B is not identically zero.

Fundamentally limited by SRF critical field (independent of Q, input power, etc.)

$$(\vec{E}\cdot\vec{B})_{\rm pc} \lesssim (0.2\ \mathrm{T})^2$$

Compare with normal conducting RF with external B_0

$$(\vec{E}\cdot\vec{B}) \sim (0.1\ \mathrm{T})^2 \left(\frac{P_{\rm input}}{100\ \mathrm{W}}\right)^{\frac{1}{2}} \left(\frac{Q_{\rm pc}}{10^5}\right)^{\frac{1}{2}} \left(\frac{B_0}{5\ \mathrm{T}}\right)$$

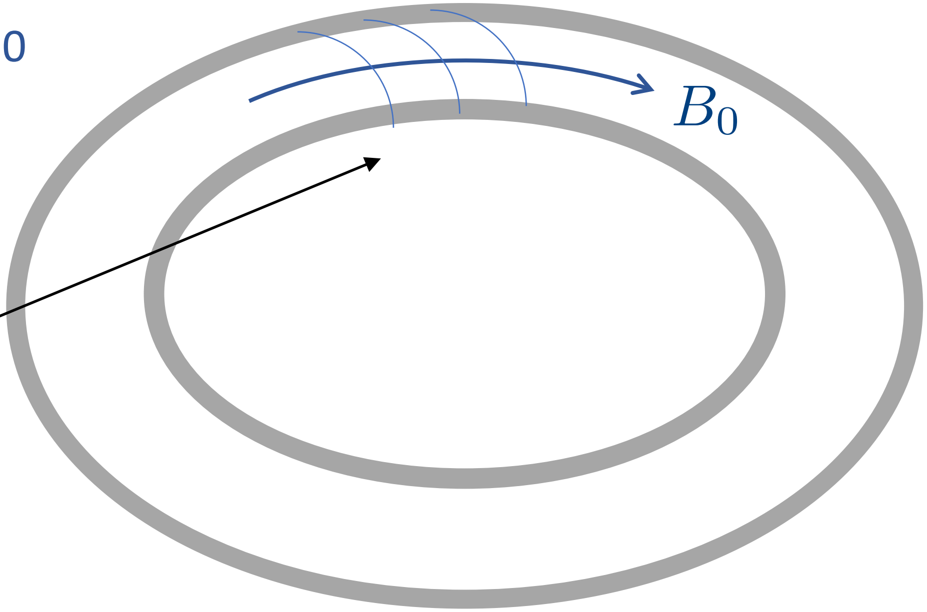
Real advantage of high-Q is on detection side!

Gapped Toroid Conversion Region

(2) Confine large static B_0

Toroidal Magnet

Generated by wrapped
DC current-carrying
superconducting wires

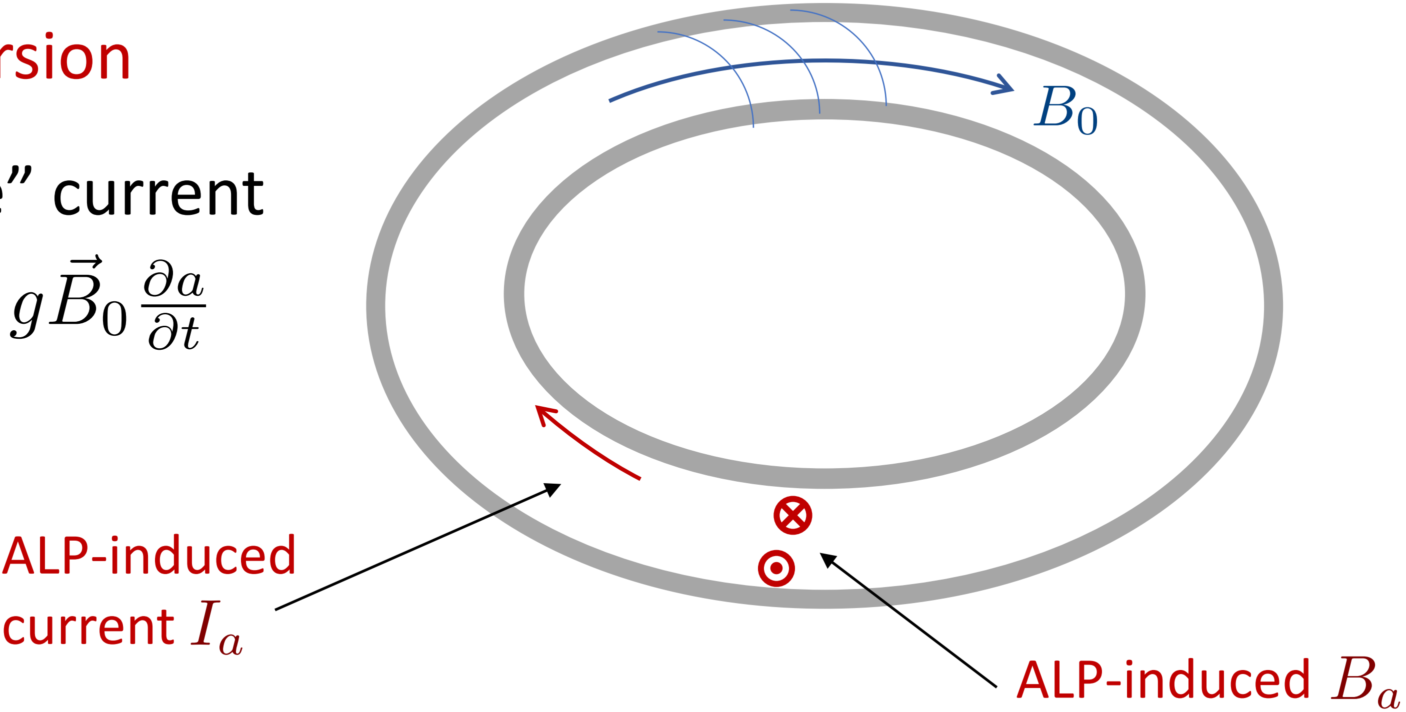


Gapped Toroid Conversion Region

ALP Conversion

"Effective" current

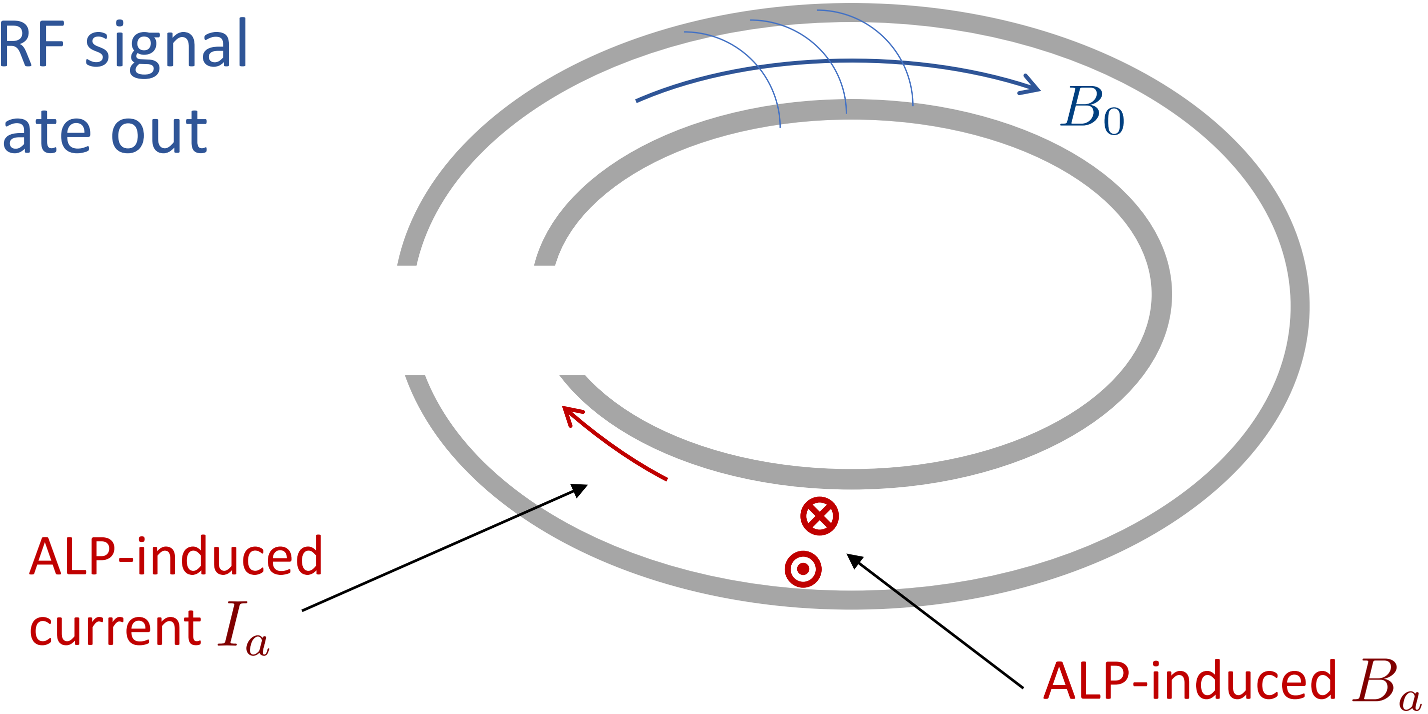
$$\vec{J}_{\rm eff} = g\vec{B}_0 \frac{\partial a}{\partial t}$$



Meissner effect: ALPs generate a super-current I_a flowing on inner surface of the toroid.

Gapped Toroid Conversion Region

(3) Allow RF signal to propagate out



B_0

ALP-induced current I_a

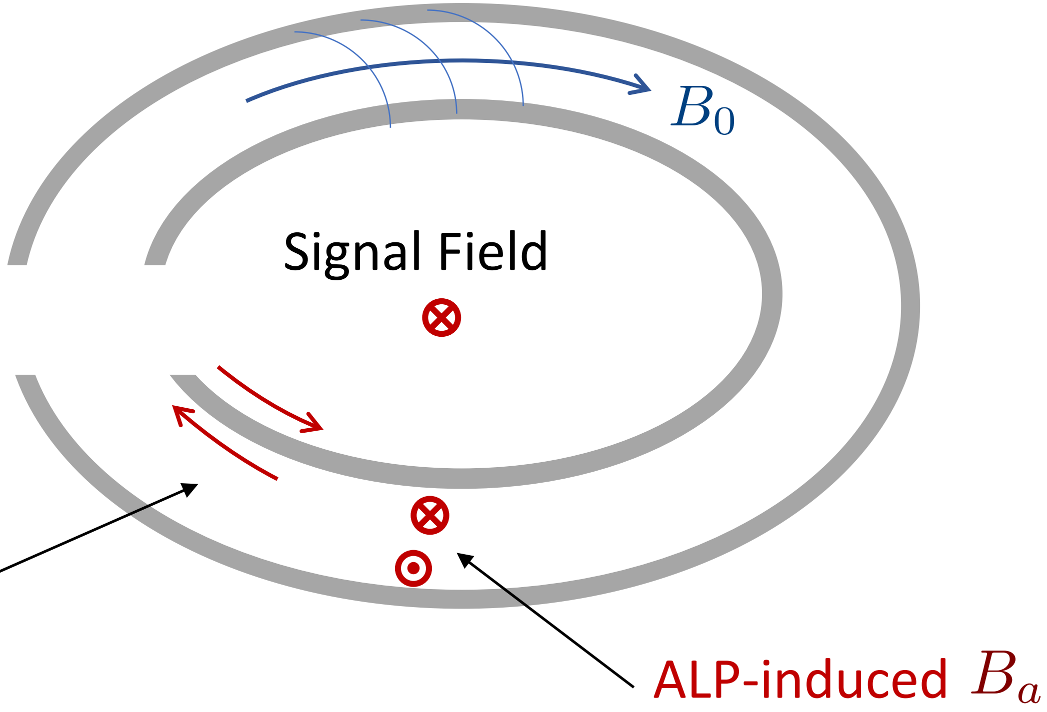
ALP-induced B_a

“Gapped” Toroid

Inspired by use in ABRACADABRA, a dark matter ALP search [Kahn, Safdi, Thaler ‘16]

Gapped Toroid Conversion Region

(3) Allow RF signal to propagate out

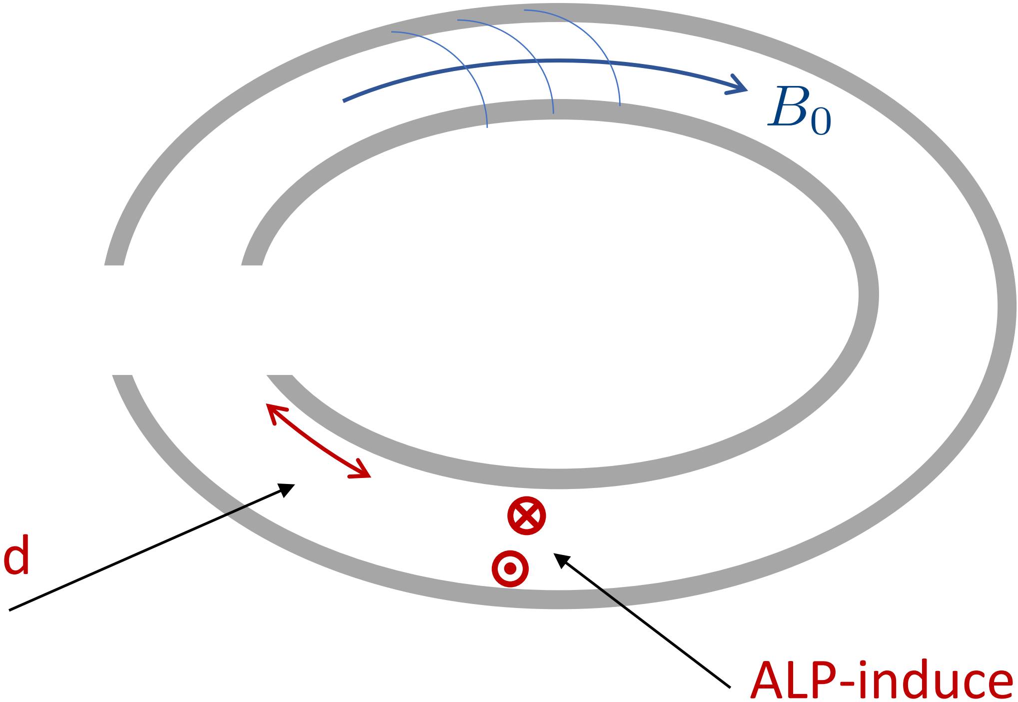


For small (quasistatic) frequencies:

I_a uniform, returns on outer surface and generates external magnetic field

Gapped Toroid Conversion Region

(3) Allow RF signal to propagate out



ALP-induced current I_a

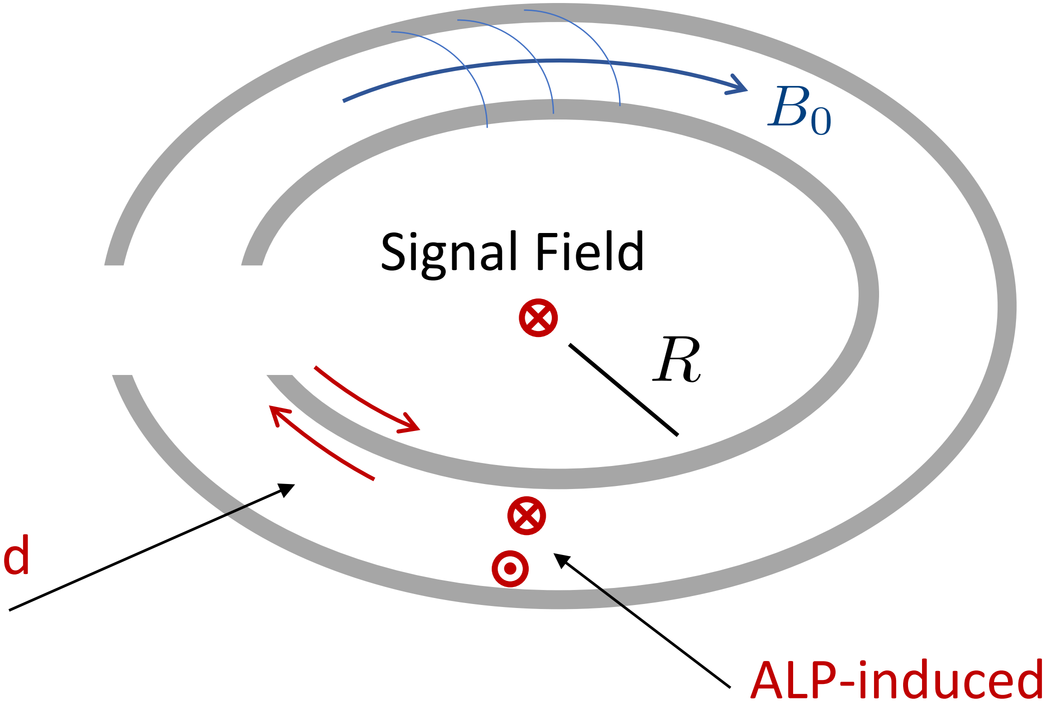
ALP-induced B_a

For large (non-quasistatic) frequencies:

I_a has spatial gradients, does not propagate to the outer surface, external magnetic field is suppressed

Gapped Toroid Conversion Region

(3) Allow RF signal to propagate out



ALP-induced current I_a

ALP-induced B_a

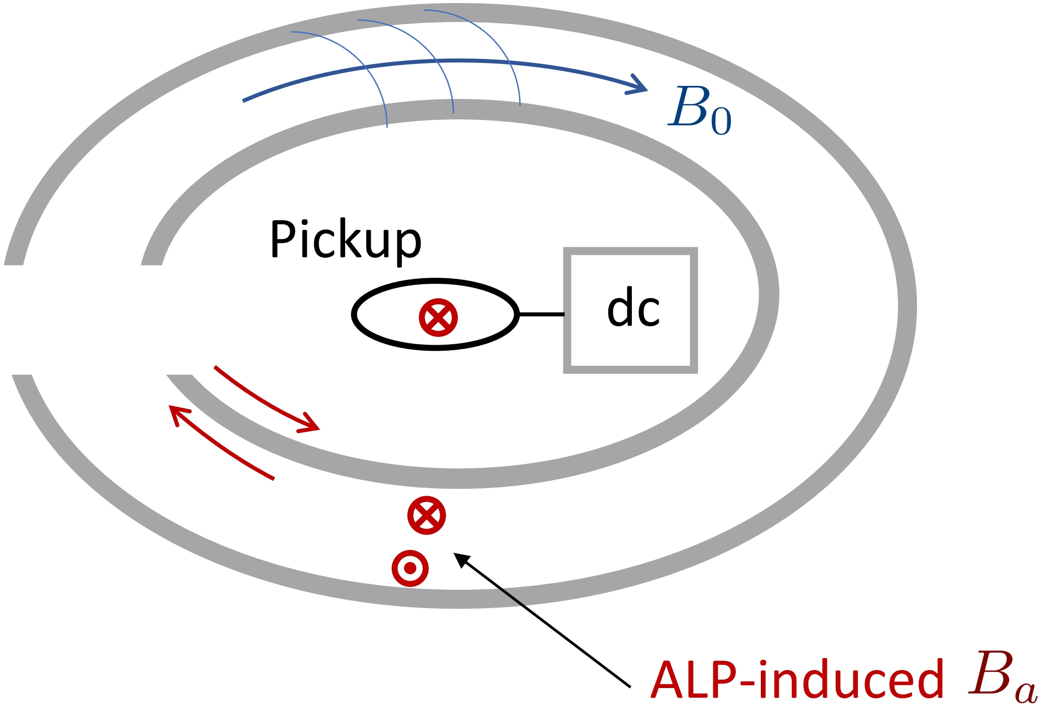
Critical scale for AC screening is set by size of toroid:

$$R \sim \omega^{-1}$$

Limits the size of the toroid to R < 10 cm

Gapped Toroid Conversion Region

(4) Couple signal to SRF detection cavity



Amplify RF signal by Q?

Toroid is not a perfect current source – there will be non-negligible back-reaction

Must account for toroid impedance

Signal Strength

Optimal Signal
$$P_{\text{signal}} \approx g^4 \frac{B_{\text{PC}}^4 B_0^2}{\omega^6} \text{ Min}\left(\frac{\omega L_t}{R_t}, Q\right)$$

Toroid Limited

Cavity Limited

Toroid Impedance

$$\frac{L_t \omega}{R_t} \approx 10^{10} \left(\frac{R}{10 \text{ cm}}\right) \left(\frac{100 \text{ n}\Omega}{R_t}\right)$$

Superconducting Toroid: $R_t \gtrsim 10^{-9} \ \Omega$

Narrowband noise

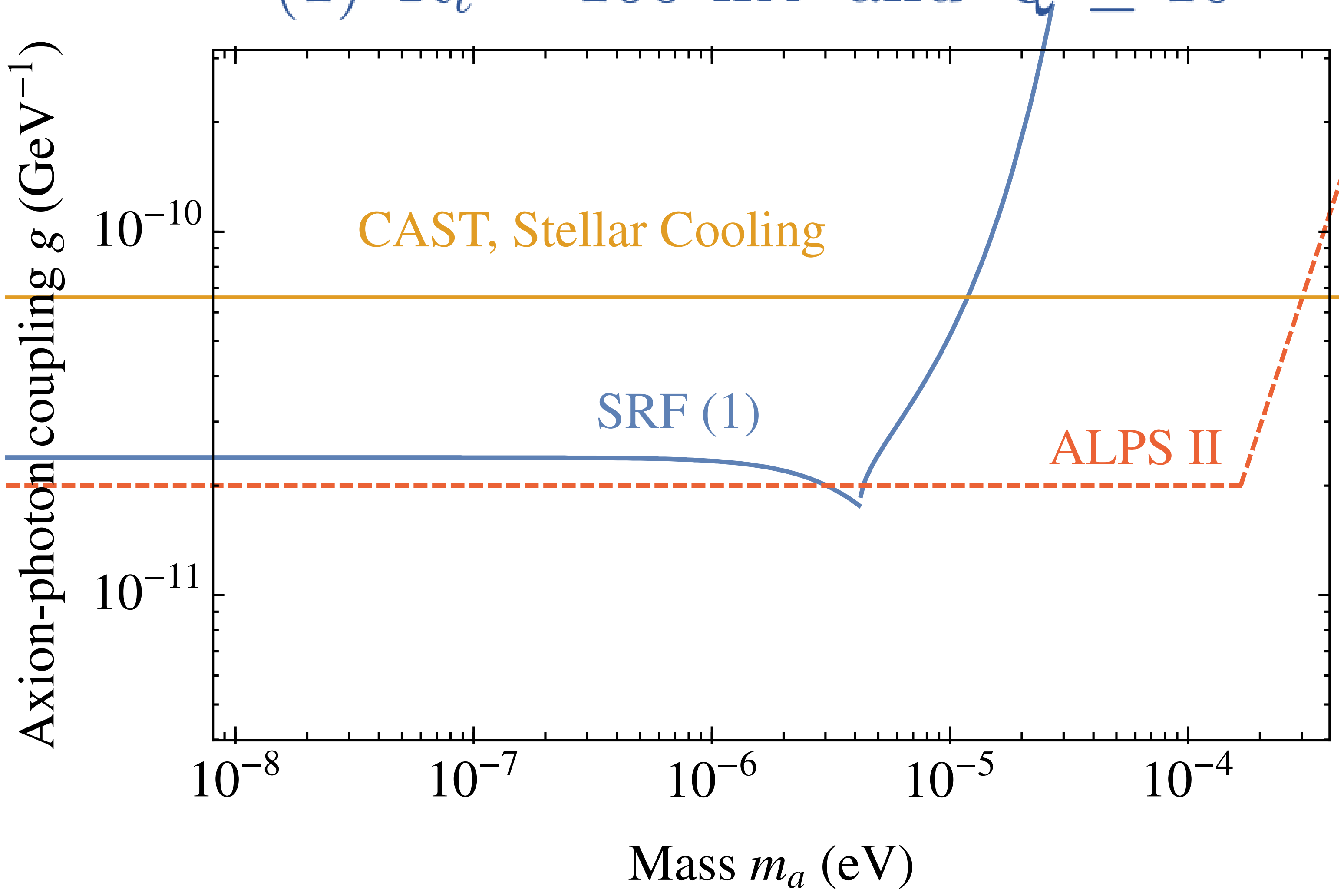
$$P_{\text{noise}} = \frac{T_{\text{sys}}}{t_{\text{int}}} \qquad T_{\text{sys}} \gtrsim \omega \sim 50 \text{ mK}$$

Quantum Limited

Projected Sensitivity

$T_{\mathrm{sys}} = 0.1\ \mathrm{K},\ t_{\mathrm{int}} = 1\ \mathrm{year},\ R = 10\ \mathrm{cm},\ \nu = 1\ \mathrm{GHz},\ B_{\mathrm{PC}} = 0.2\ \mathrm{T},\ B_0 = 5\ \mathrm{T}$

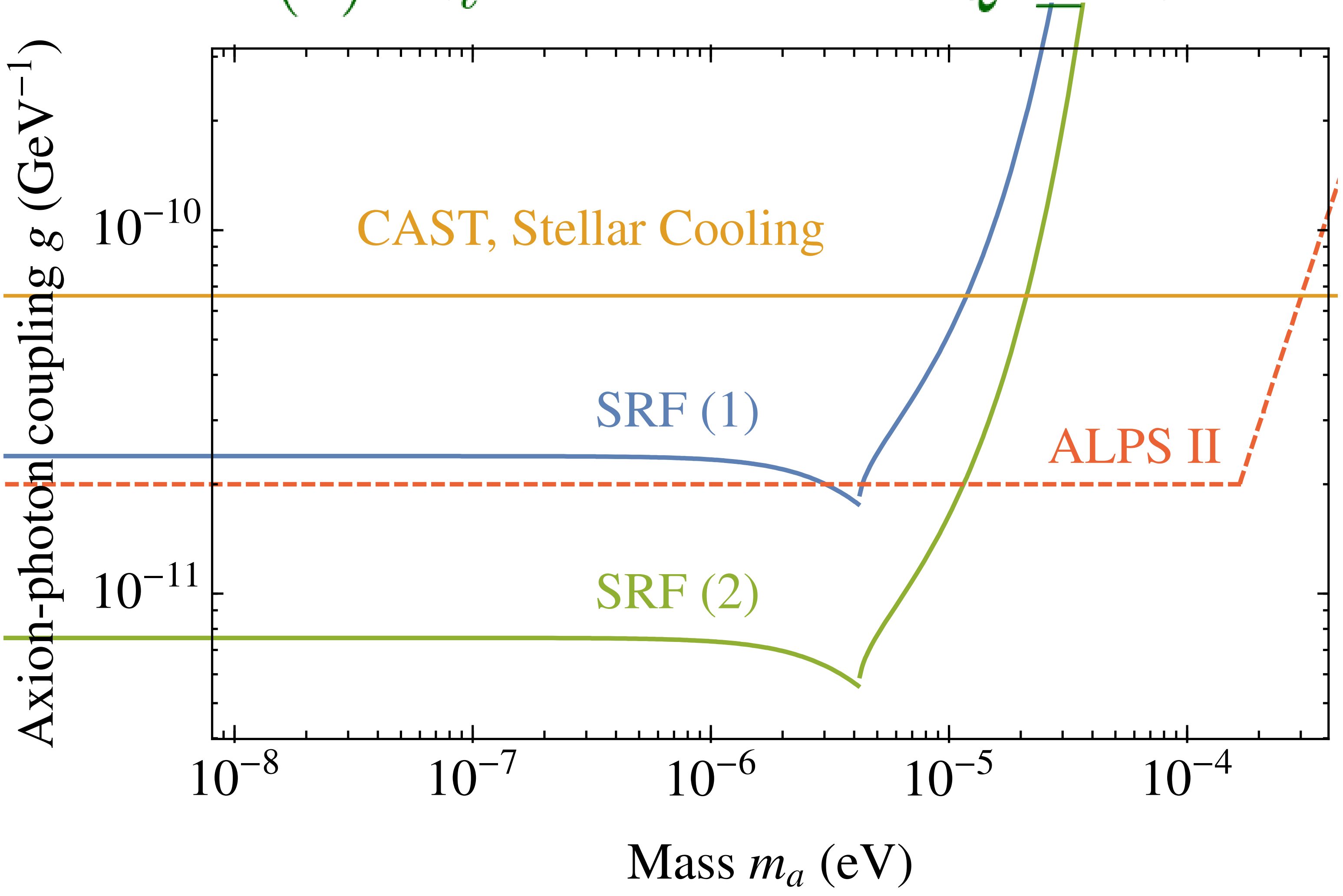
$(1)\ R_t = 100\ \mathrm{n}\Omega\ \ \mathrm{and}\ \ Q \geq 10^{10}$



Projected Sensitivity

$T_{\mathrm{sys}} = 0.1\ \mathrm{K},\ t_{\mathrm{int}} = 1\ \mathrm{year},\ R = 10\ \mathrm{cm},\ \nu = 1\ \mathrm{GHz},\ B_{\mathrm{PC}} = 0.2\ \mathrm{T},\ B_0 = 5\ \mathrm{T}$

$(1)\ \ R_t = 1\ \mathrm{n}\Omega\ \ \text{and}\ \ Q \geq 10^{12}$



An ALP Search using Superconducting RF Cavities and a Confined Magnetic Field

A new design for an LSW ALP search based on SRF cavities

Our realization uses a gapped toroid to confine the magnetic field responsible for ALP-photon conversion, protecting the SRF cavities from quenching.

Consider influence of fundamental factors such as signal back-reaction and screening on the optimal sensitivity

Comparable and complementary to future optical LSW searches and stellar constraints

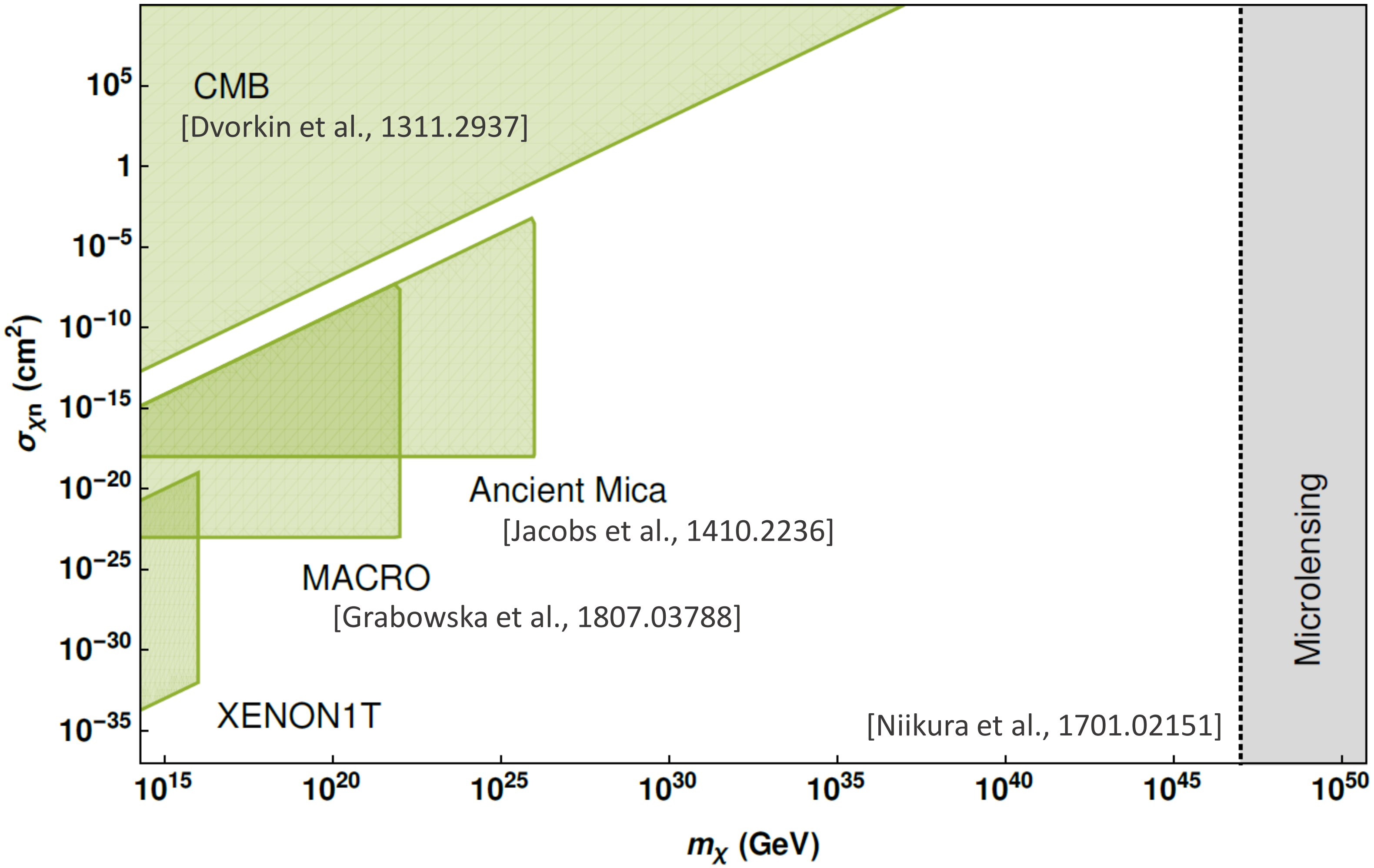
White Dwarfs as Dark Matter Detectors

Extra Slides

Ultra-heavy Dark Matter

“Exposure Limit”

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



Particle Heating of White Dwarfs

Explosion Condition

$$\boxed{L \gtrsim \lambda_T}$$

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

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

$$\begin{aligned} n_{\text{ion}} &\approx 10^{32} \text{ cm}^{-3} \quad [1.38 \text{ M}_\odot] \\ T &\approx 1 \text{ MeV} \end{aligned} \quad \Rightarrow \quad \lambda_T \sim 10^{-6} \text{ cm}$$

How to Start a Type Ia Supernova

Explosion Condition

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

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

A careful calculation (Timmes and Woosley 1992):

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

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

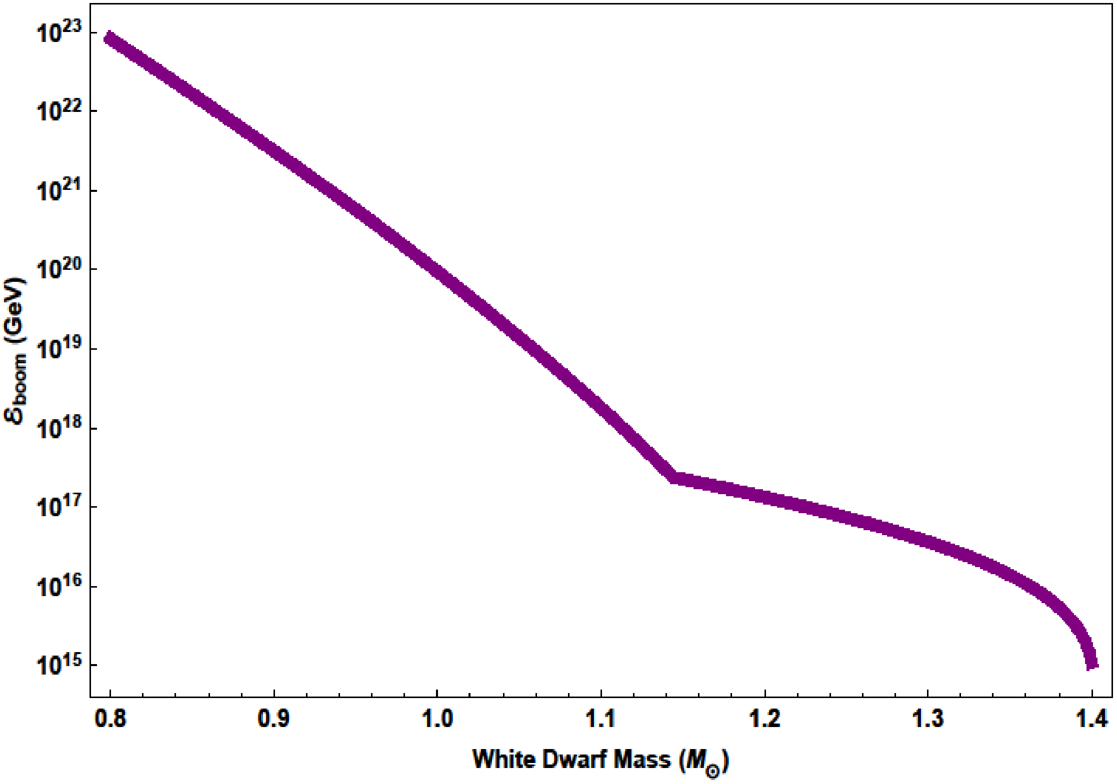
Trigger size decreases for larger stellar masses

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 $1\ \mathrm{MeV}$



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

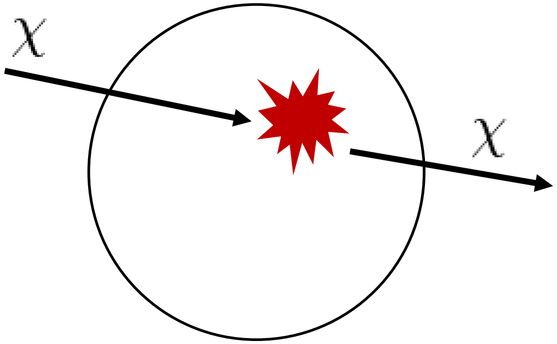
$$[1.38\ \mathrm{M}_\odot]$$

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

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

Elastic 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 $\omega \sim m_c v_{\rm esc}^2 \sim 1 - 10 \text{ MeV}$

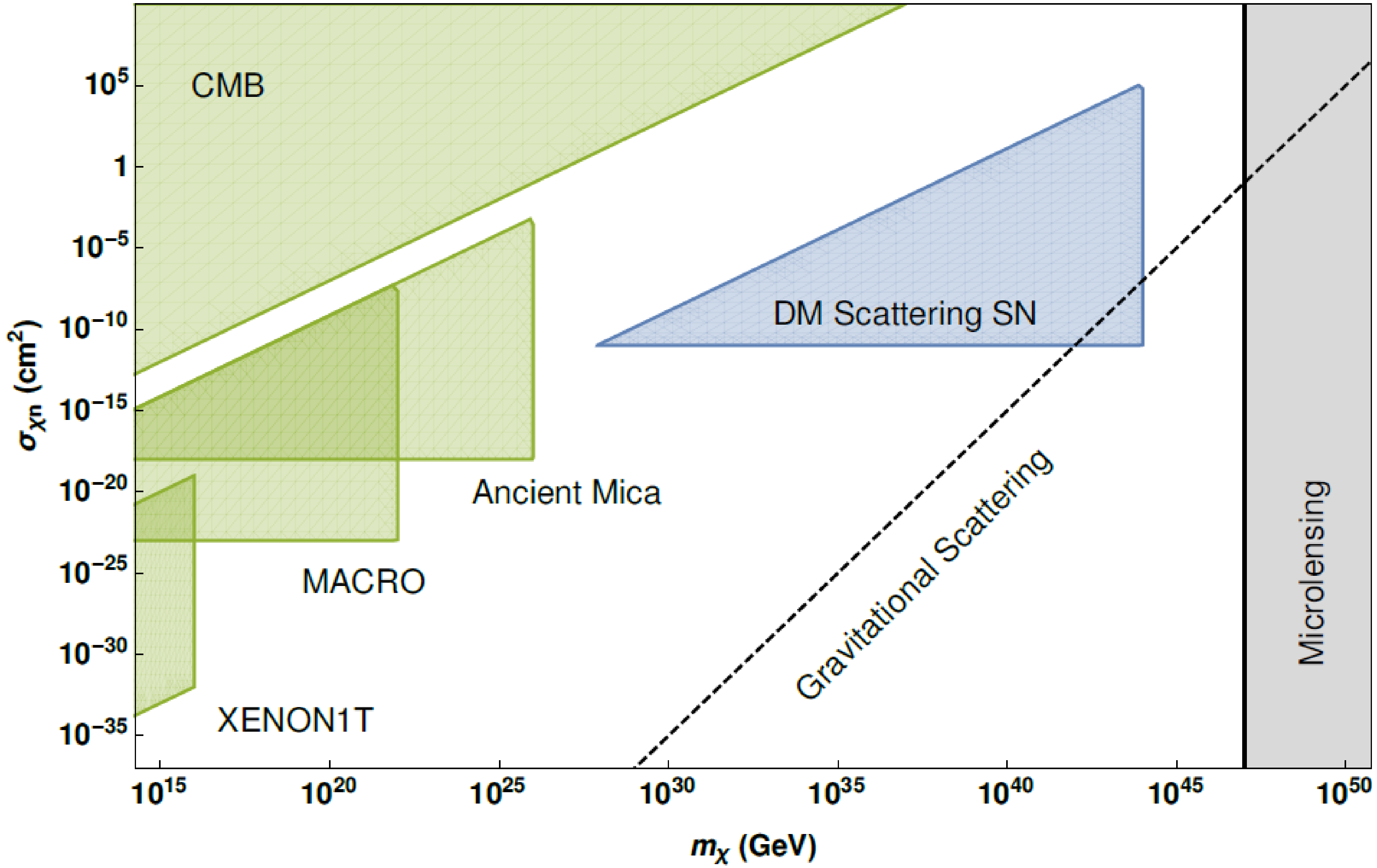
energy transfer per distance $\frac{dE}{dx} \sim n_{\rm ion}\sigma_{\chi A}\omega$

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

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

Elastic Scattering-induced SN

Demand $\tau_{\rm wd} > 1\ {\rm Gyr}$ for local WDs



Particle Production Heating of WDs

WD medium can be heated though the thermalization of high energy SM secondaries produced by DM.

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

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

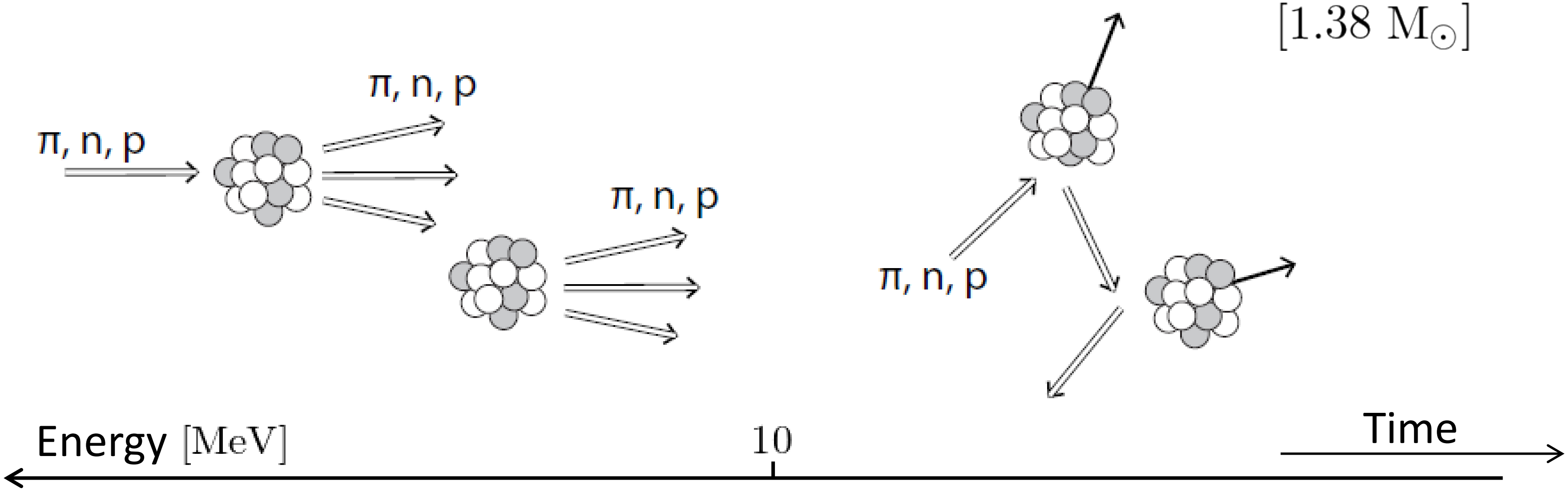
Must compute stopping distances of SM particles in a WD

Particle Stopping in White Dwarfs

Incident Hadrons

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

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



Hadronic Shower

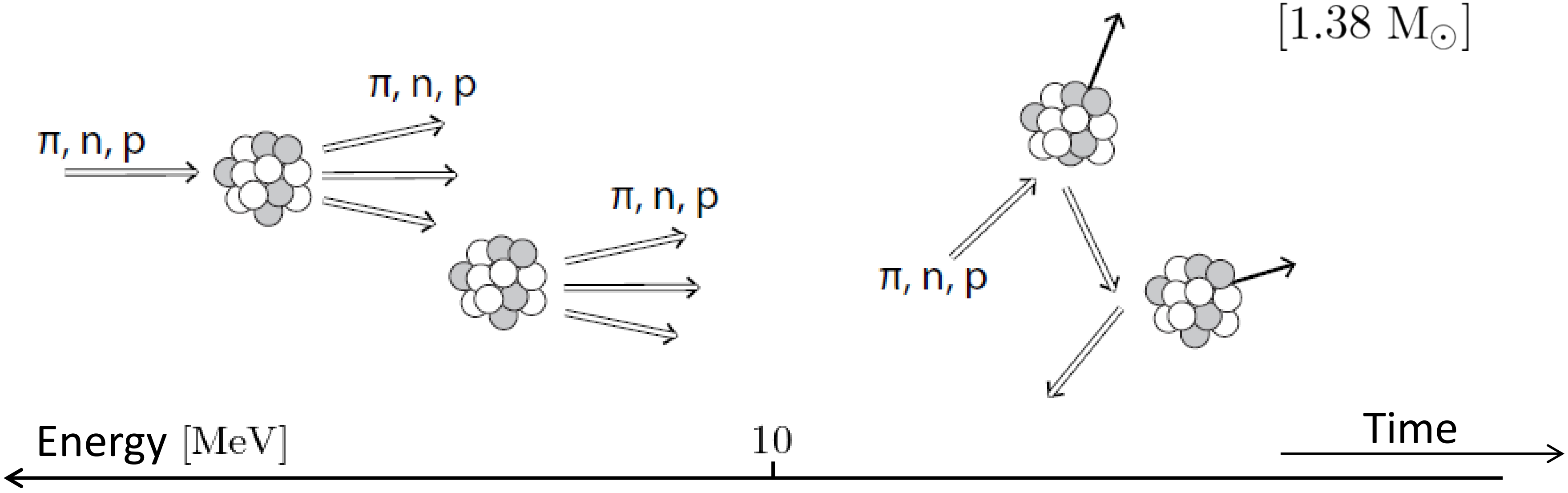
Nuclear Elastic Heating

Particle Stopping in White Dwarfs

Incident Hadrons

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

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



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

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

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

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

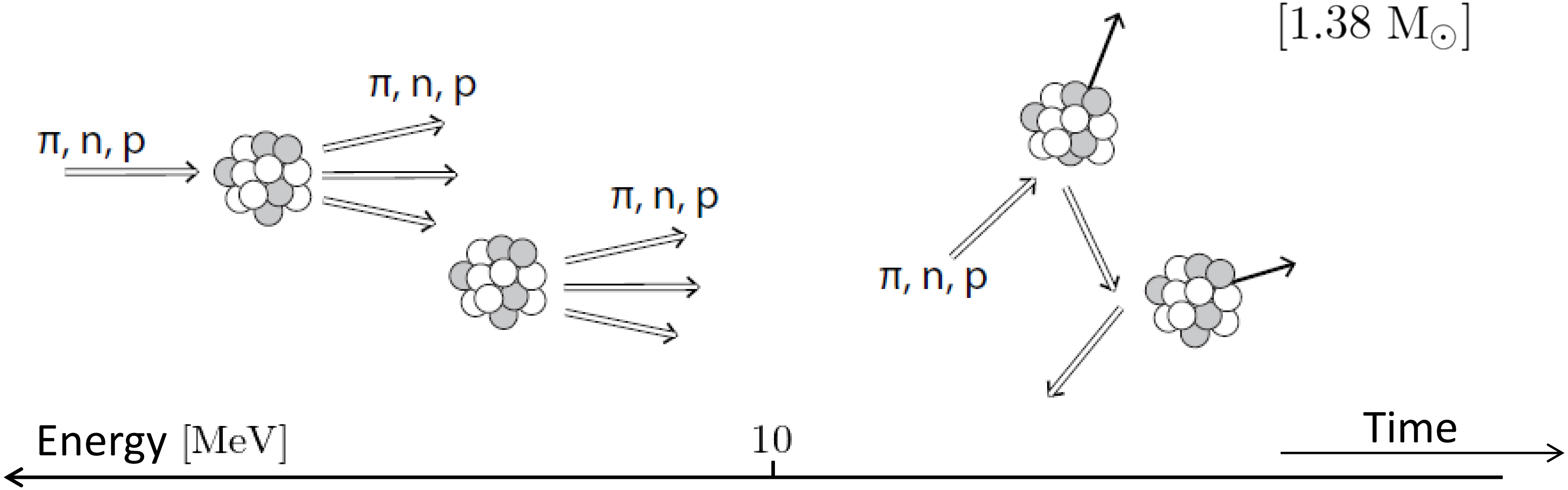
Hadrons thermalize within a trigger size.

Particle Stopping in White Dwarfs

Incident Hadrons

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

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



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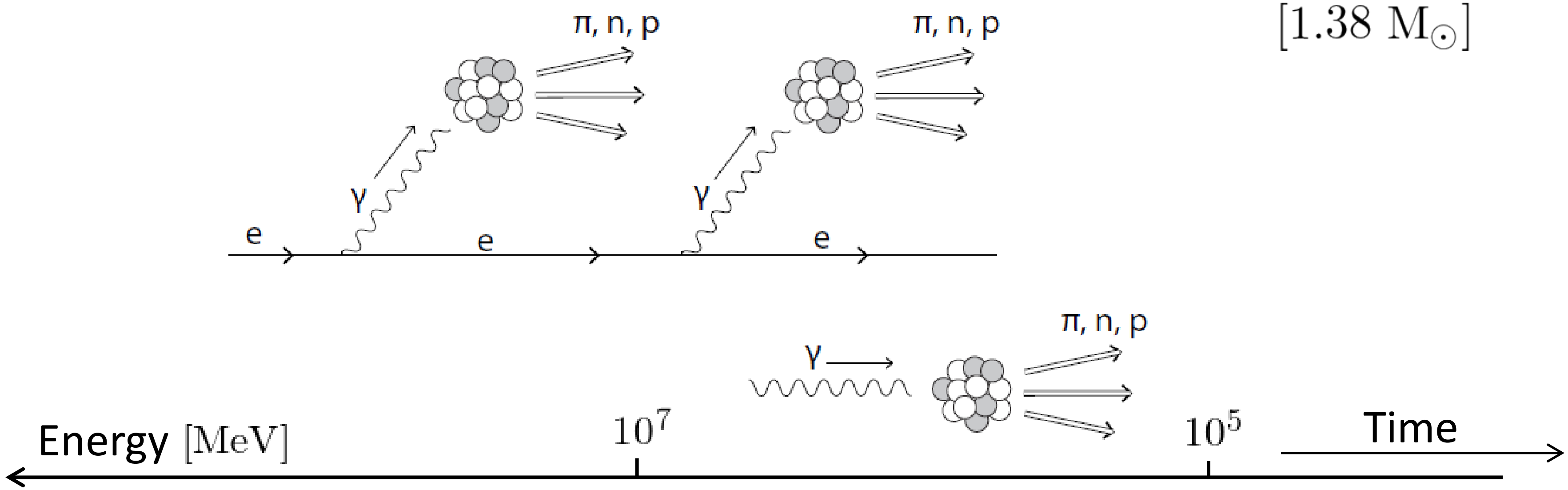
Hadrons thermalize within a trigger size.

Particle Stopping in White Dwarfs

Incident electrons and photons (high energy)

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

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



Electronuclear Shower

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

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

Photonuclear Shower

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

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

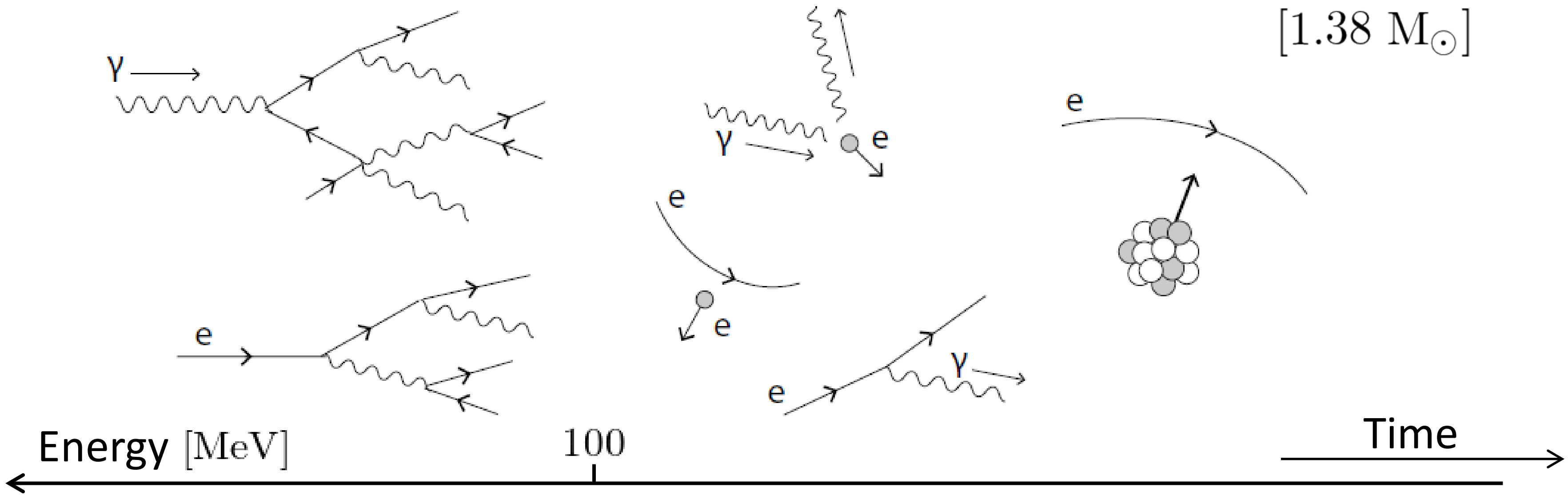
High energy e, γ thermalize between λ_T and $100\ \lambda_T$

Particle Stopping in White Dwarfs

Incident electrons and photons (low energy)

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

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



EM Showers

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

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

Electron-Ion Coulomb Scattering

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

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

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

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

Coulomb log

and a suppression factor

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

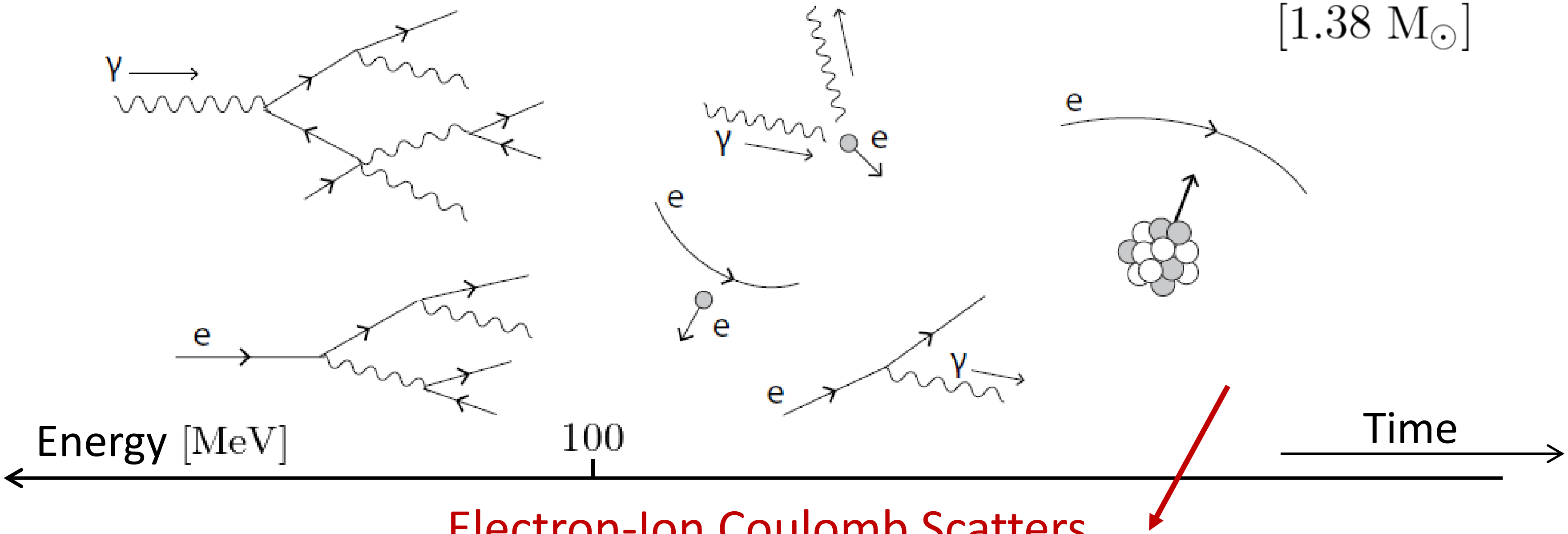
For sufficiently large incident energies, LPM will cause radiative EM showers to give way to hadronic showers as the dominant stopping mechanism for electrons and photons.

Particle Stopping in White Dwarfs

Incident electrons and photons (low energy)

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

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



Electron-Ion Coulomb Scatters

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

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

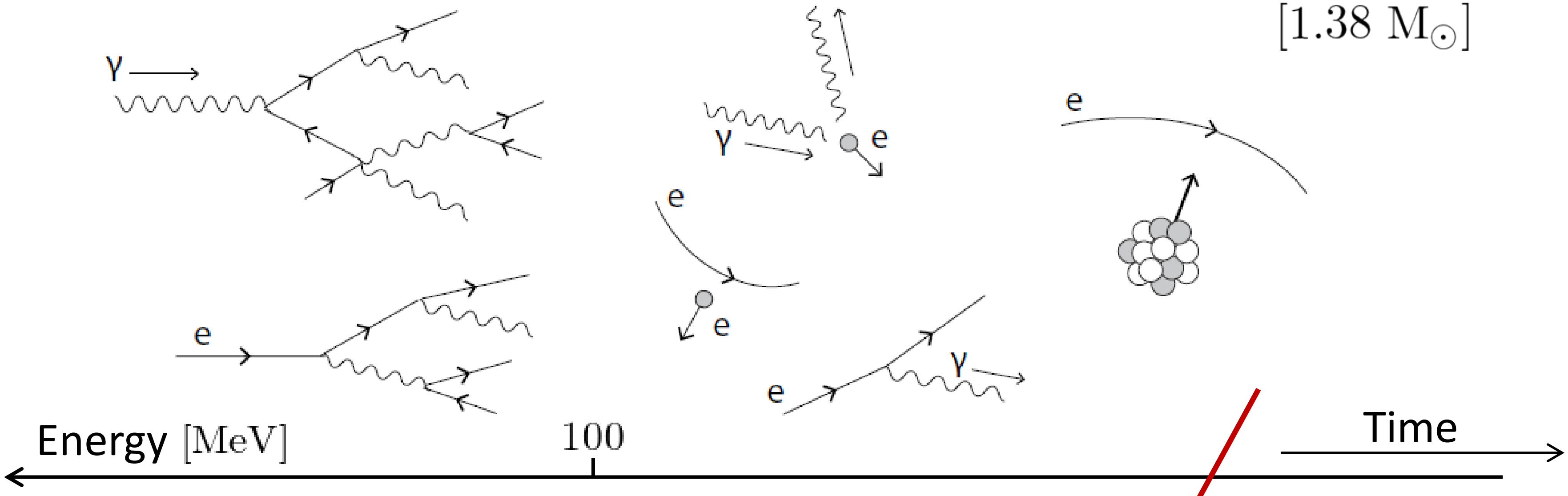
$E \gtrsim 10\ \text{MeV}$ free ion scattering

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 Phonon Production $E \lesssim 10\ {\rm MeV}$

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

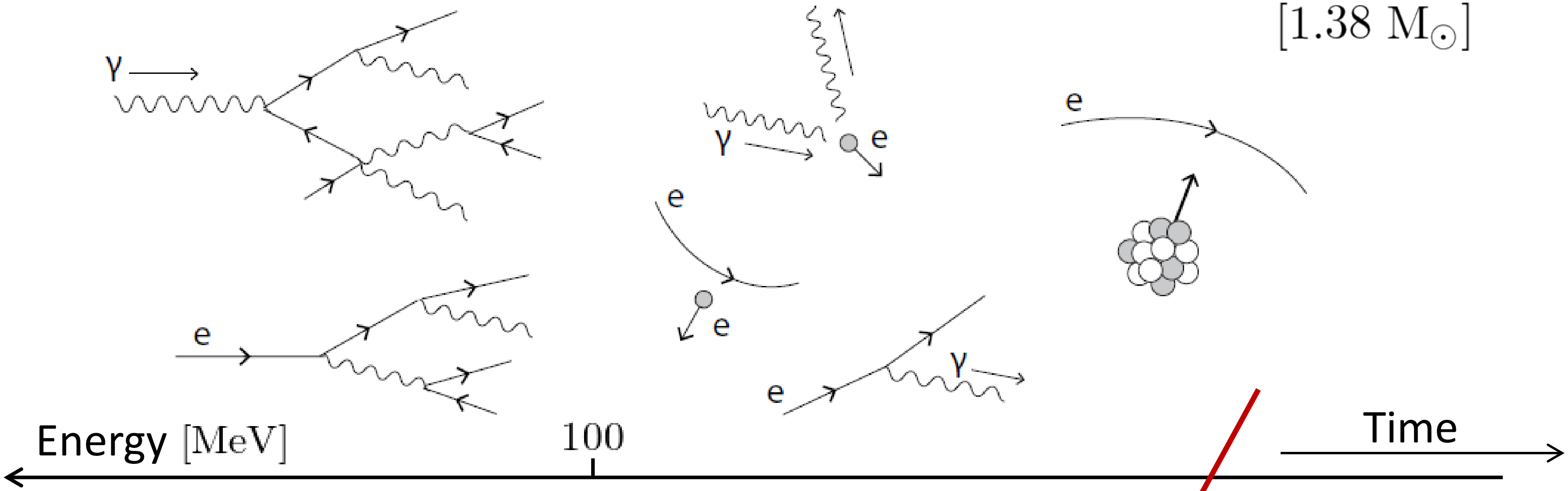
$$L_{\rm ph} \sim \left(\frac{1}{\log\Lambda}\frac{E}{\Omega_p}\right)^{1/2}\lambda_{\rm ph} \sim 10^{-6}\ {\rm cm}\left(\frac{E}{10\ {\rm MeV}}\right)^{1/2}$$

Particle Stopping in White Dwarfs

Incident electrons and photons (low energy)

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

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



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

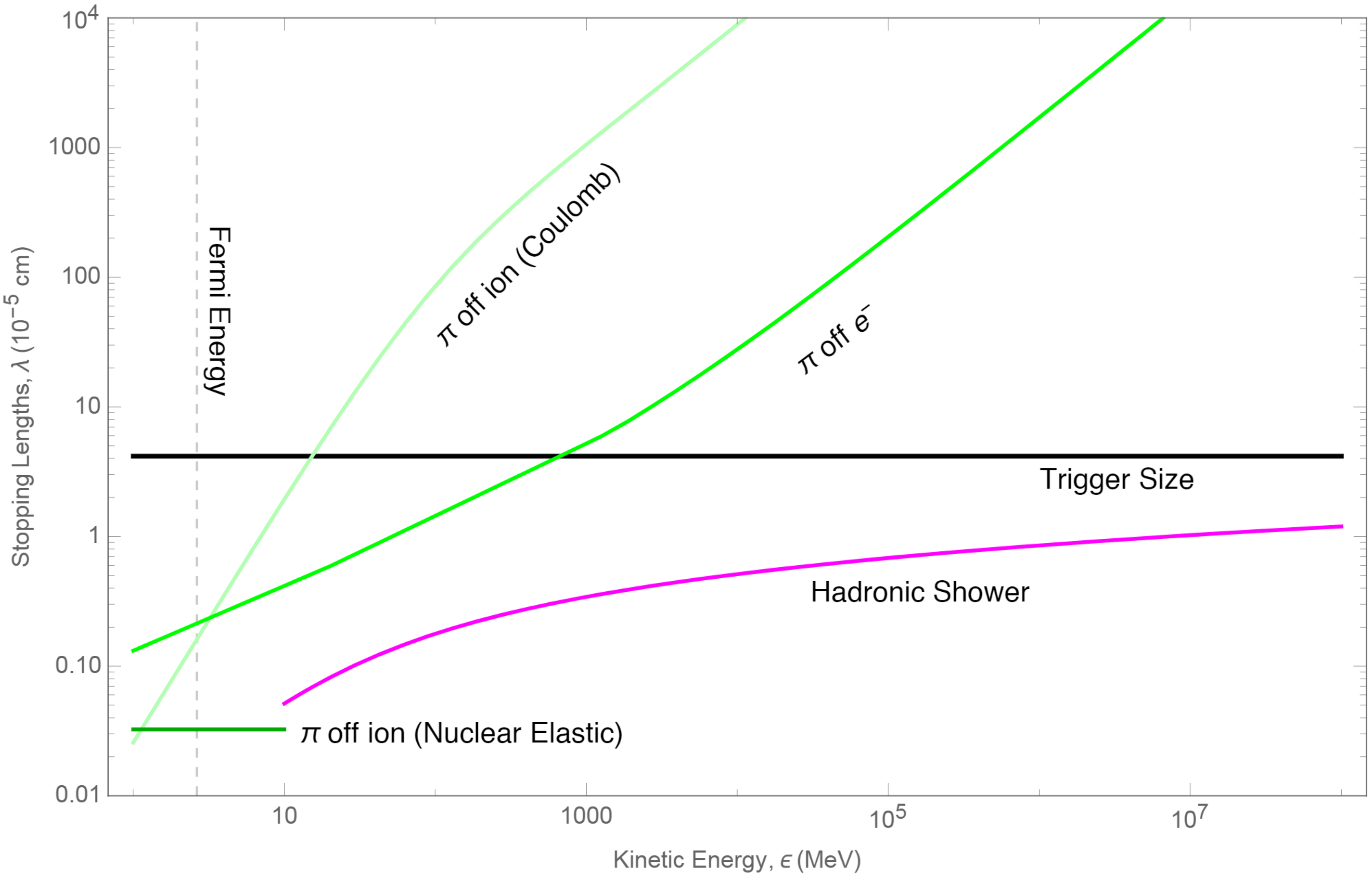
$$\lambda_{\text{free}} \sim \frac{E^2}{n_{\text{ion}}\alpha^2 Z^2} \sim 10^{-7}\left(\frac{E}{10\ \text{MeV}}\right)^2\ \text{cm}$$

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

Low energy electrons and photons stop below the trigger size.

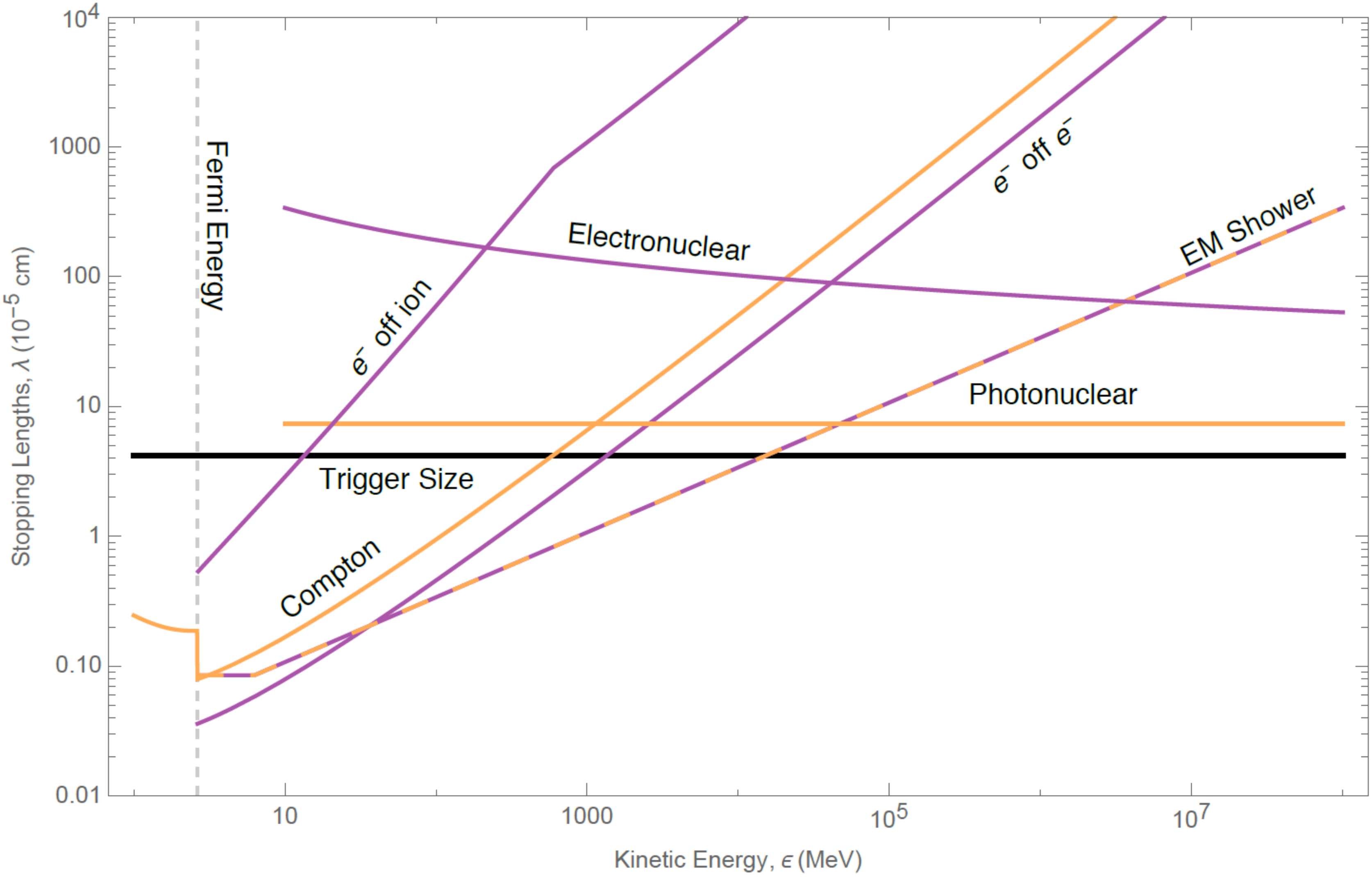
Particle Stopping in White Dwarfs

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



Particle Stopping in White Dwarfs

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



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]

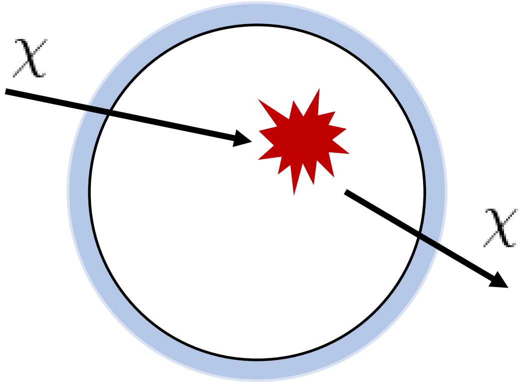
	From DM Interactions	Observed
WD Lifetime	$\tau_{\rm wd}$	$\tau_{\rm wd} > 1\ \mathrm{Gyr}$ [DeGennaro et al, '07]
SN Rate	$\Gamma_{\rm SN}^{\rm decay} \sim \int dM\ f(M)\ \tau_{\rm wd}^{-1}$	$\Gamma_{\rm sn} < 0.3\,(100\ \mathrm{yr})^{-1}$ [Van Den Berg, '91]

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]

Scattering-induced SN Constraints

Scattering



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

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

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

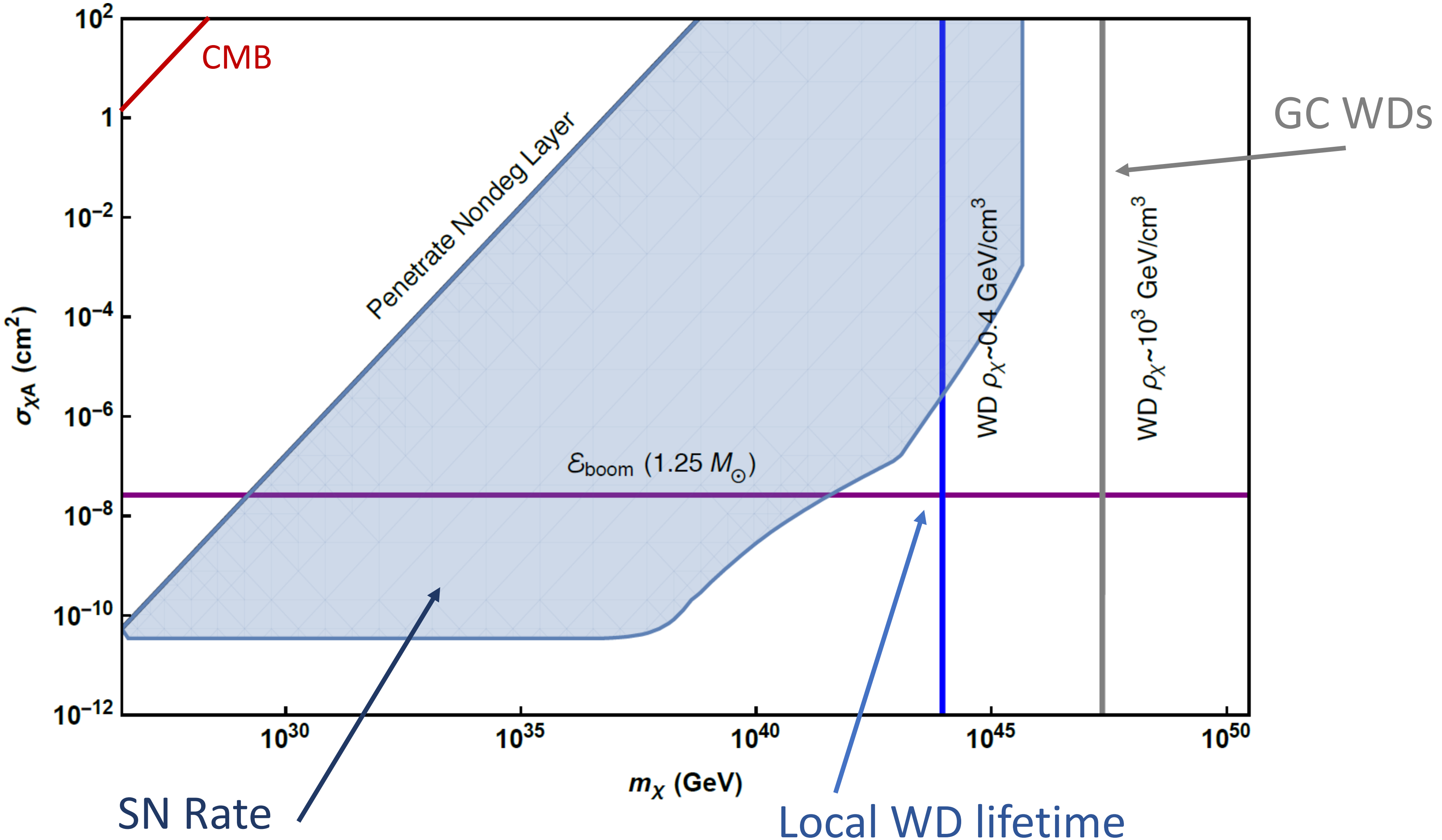
$$[\text{C} \to \text{He}]$$

$$\Longrightarrow \quad \sigma_{\chi c} > \frac{T_F}{v_{\text{esc}}^2 m_c}\lambda_T^2$$

$$\frac{\sigma_{\chi c}}{m_\chi} < \frac{1}{R_{\text{env}} n_{\text{env}} m_c}$$

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

Scattering-induced SN Constraints



GC WDs

SN Rate

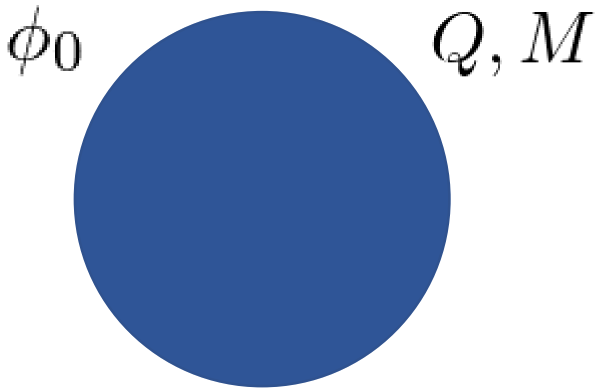
Local WD lifetime

Q-ball Dark Matter

Q-Ball

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

[Coleman, ‘85]



Stability

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

determined by $V(\phi)$

lightest particle carrying Q-charge

For nearly flat potential and large Q:

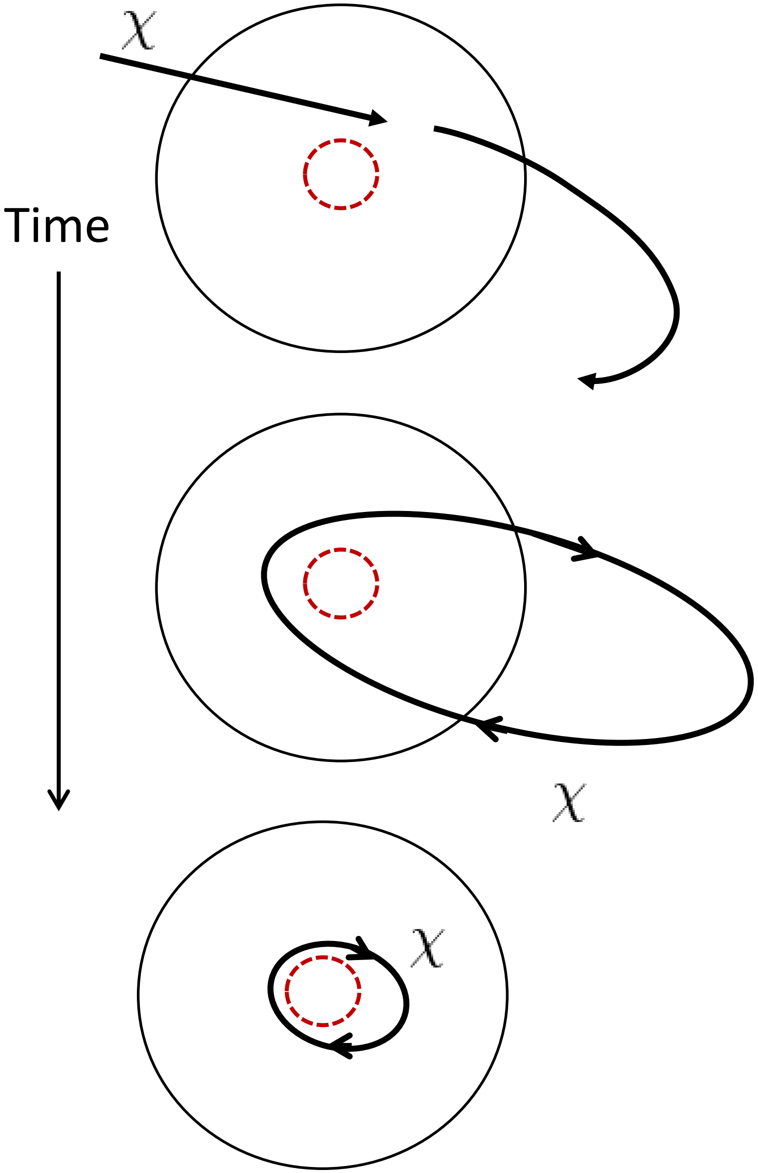
[Kusenko et al, ‘98]

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

(m_s - scalar mass)

- stable for sufficiently large Q

Elastic Capture of Dark Matter



Capture

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

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

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

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 $r_{\rm th}$

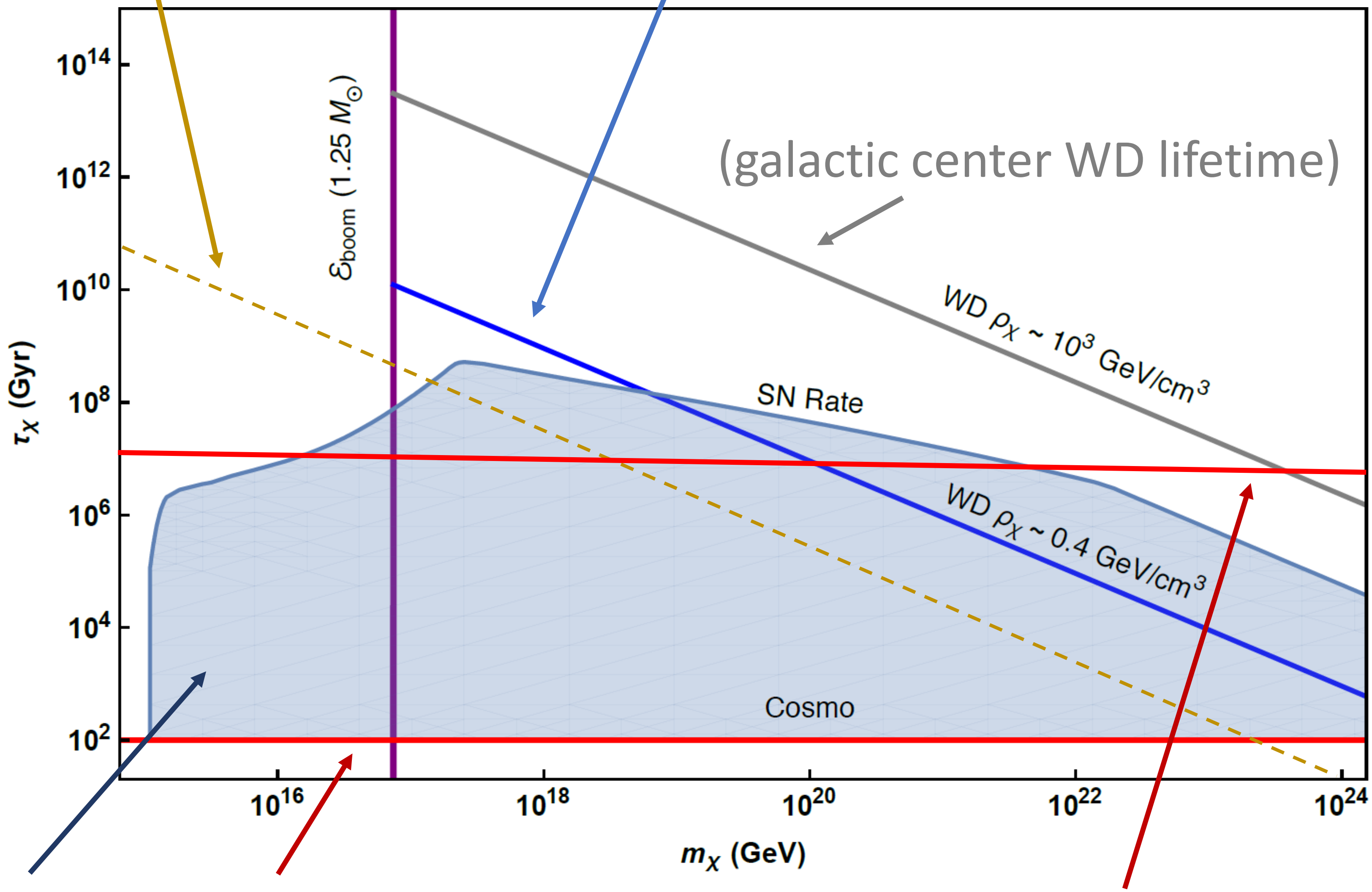
Thermal Radius $G\rho_{\rm wd} m_\chi r_{\rm th}^2 \sim T_{\rm wd}$

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

Decay-induced SN Constraints

Cosmic Ray [O(1) decay products]

Local WD lifetime



(galactic center WD lifetime)

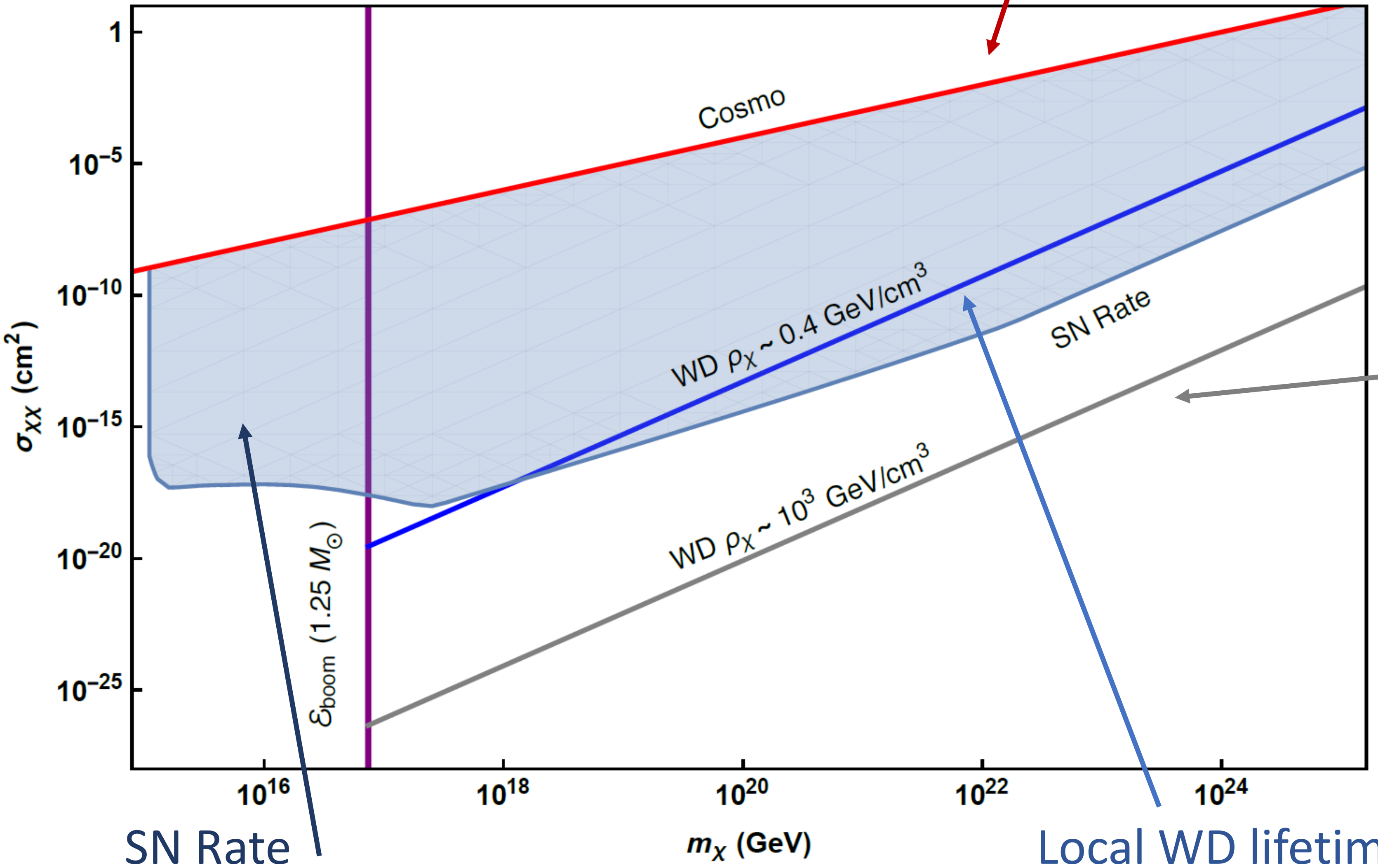
SN Rate

CMB (ISW) [Poulin et al, '16]

CMB (ionization) [Slatyer & Wu, '16]

Annihilation-induced SN Constraints

Cluster Collisions

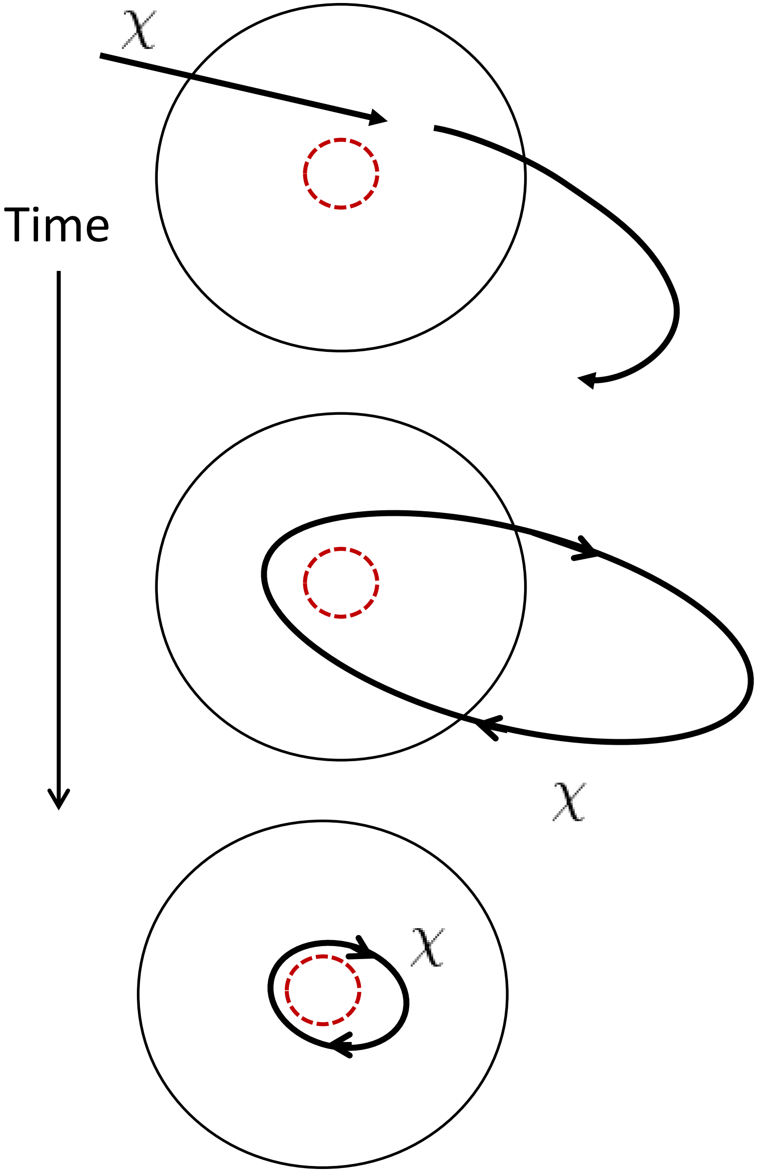


GC WDs

SN Rate

Local WD lifetime

Elastic Capture of Dark Matter



Capture

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

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

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

Stage 1 - orbital decay to stellar surface

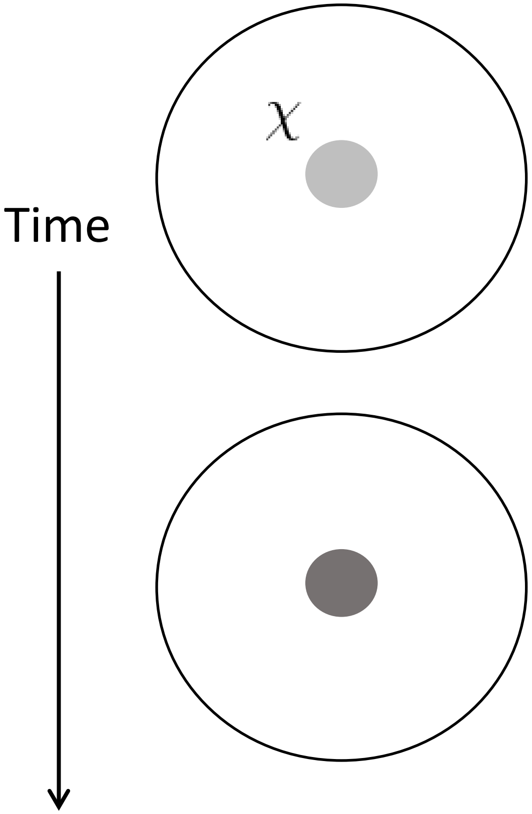
$$t_1 \sim \frac{R_{\rm wd}}{v_{\rm esc}}\left(\frac{m_\chi}{m_c N_{\rm sc}}\right)^{3/2}$$

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

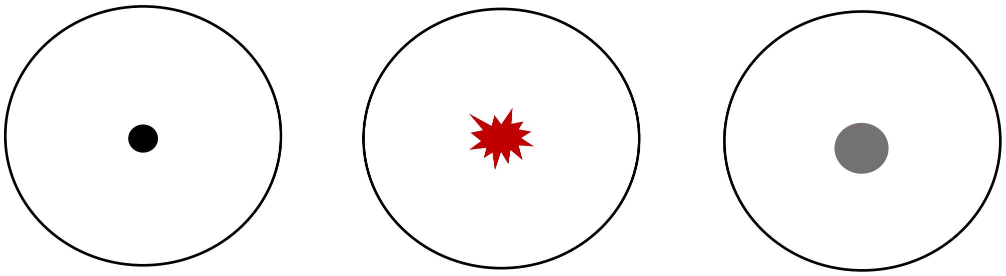
$$M_{sg} \sim \rho_{\rm wd} r_{\rm th}^3$$

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

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

Capture and Core Collapse of DM

Capture and Collection Timescales

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

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

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

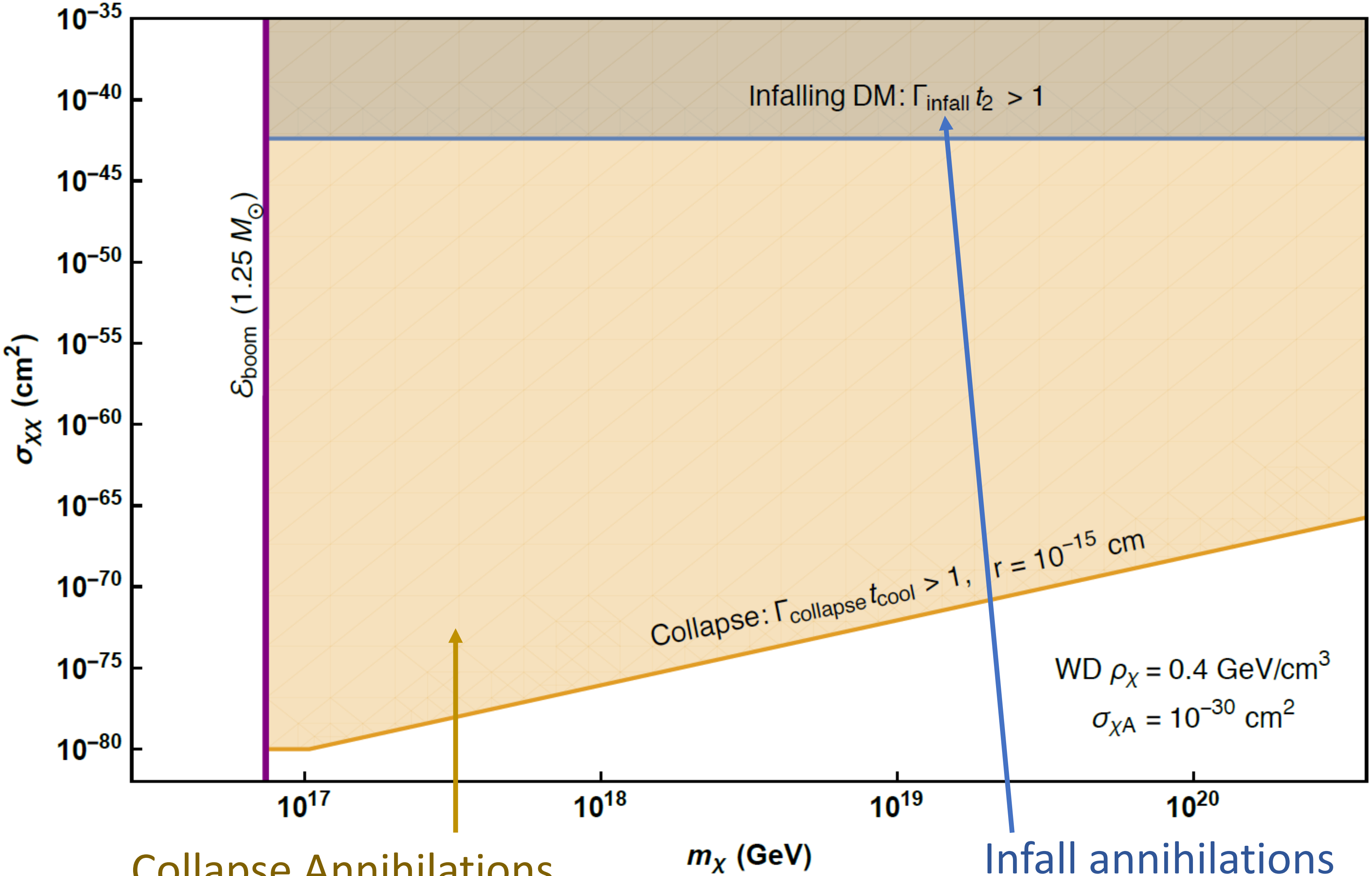
$$t_{\mathrm{collapse}} \sim t_2 \frac{v_{\mathrm{ion}}}{\mathrm{Max}[v_{\mathrm{ion}}, v_\chi]} \frac{1}{\log(m_\chi/m_{\mathrm{ion}})} < t_2$$

Core Radius

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

Annihilations of Captured DM

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

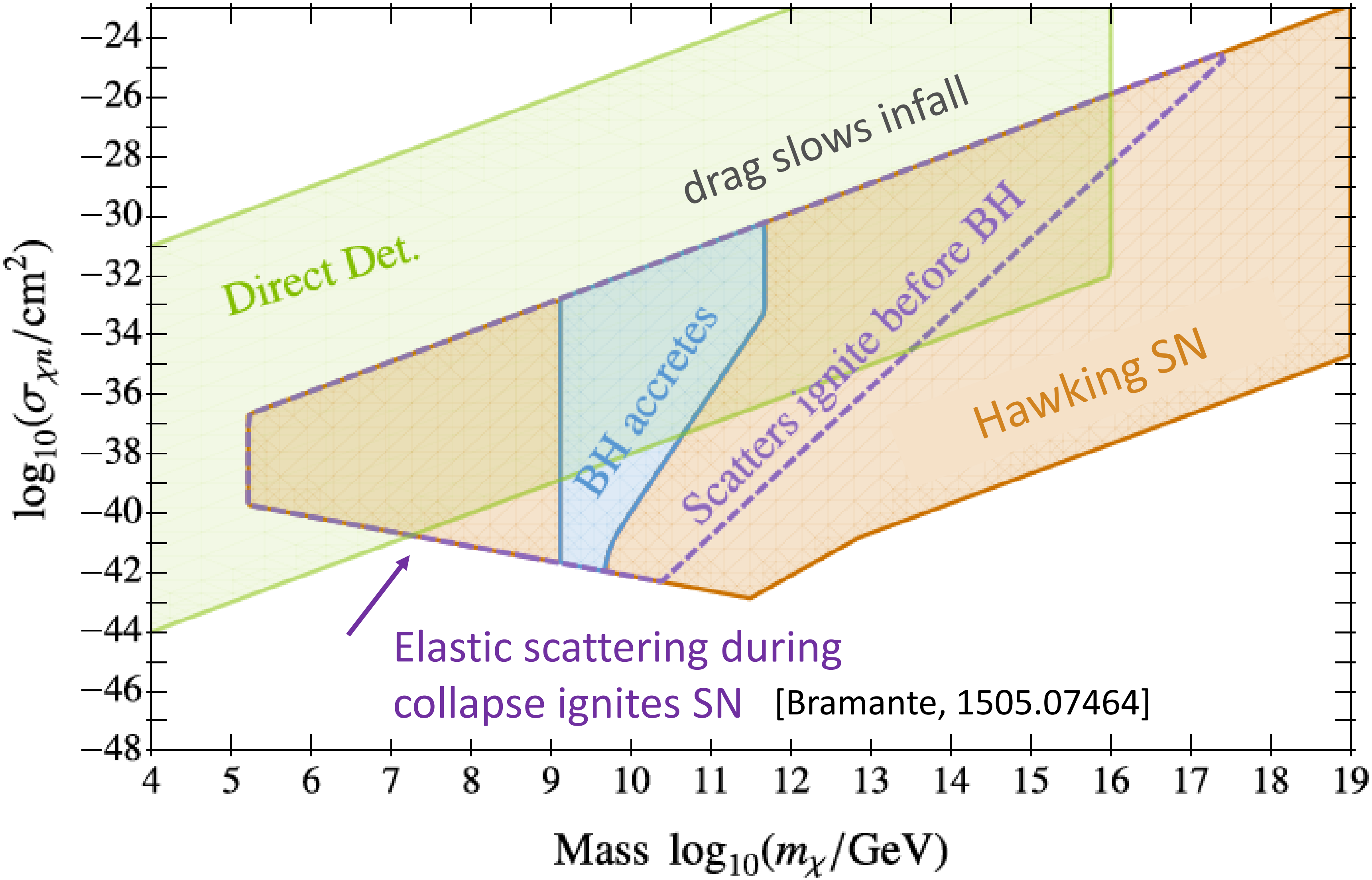


Collapse Annihilations

Infall annihilations

BH-induced Supernovae

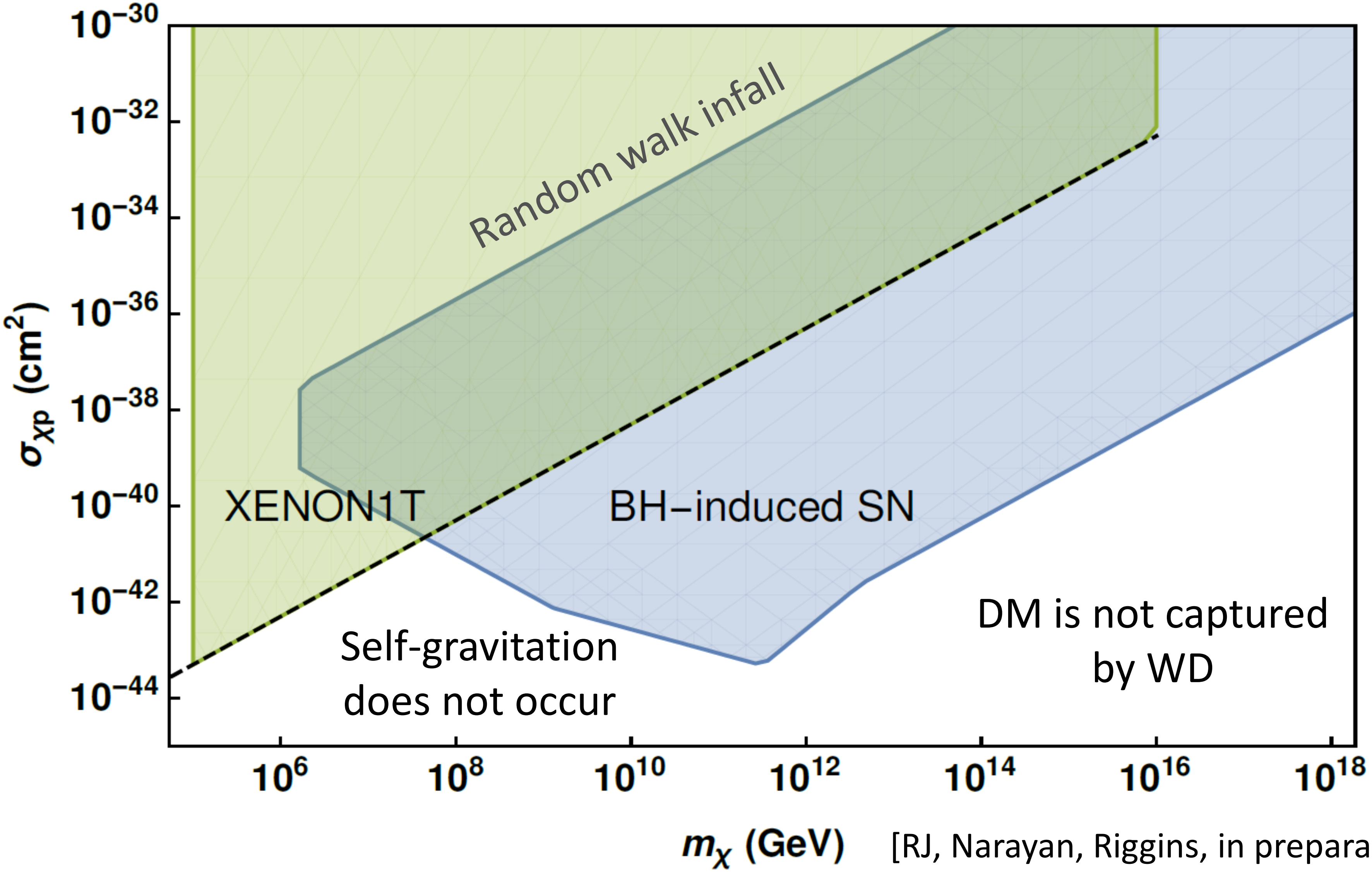
Demand $\tau_{\mathrm{wd}} > 1\ \mathrm{Gyr}$ for local WDs (Bosonic DM)



Elastic scattering during collapse ignites SN [Bramante, 1505.07464]

DM Core ⟶ BH-induced Supernovae

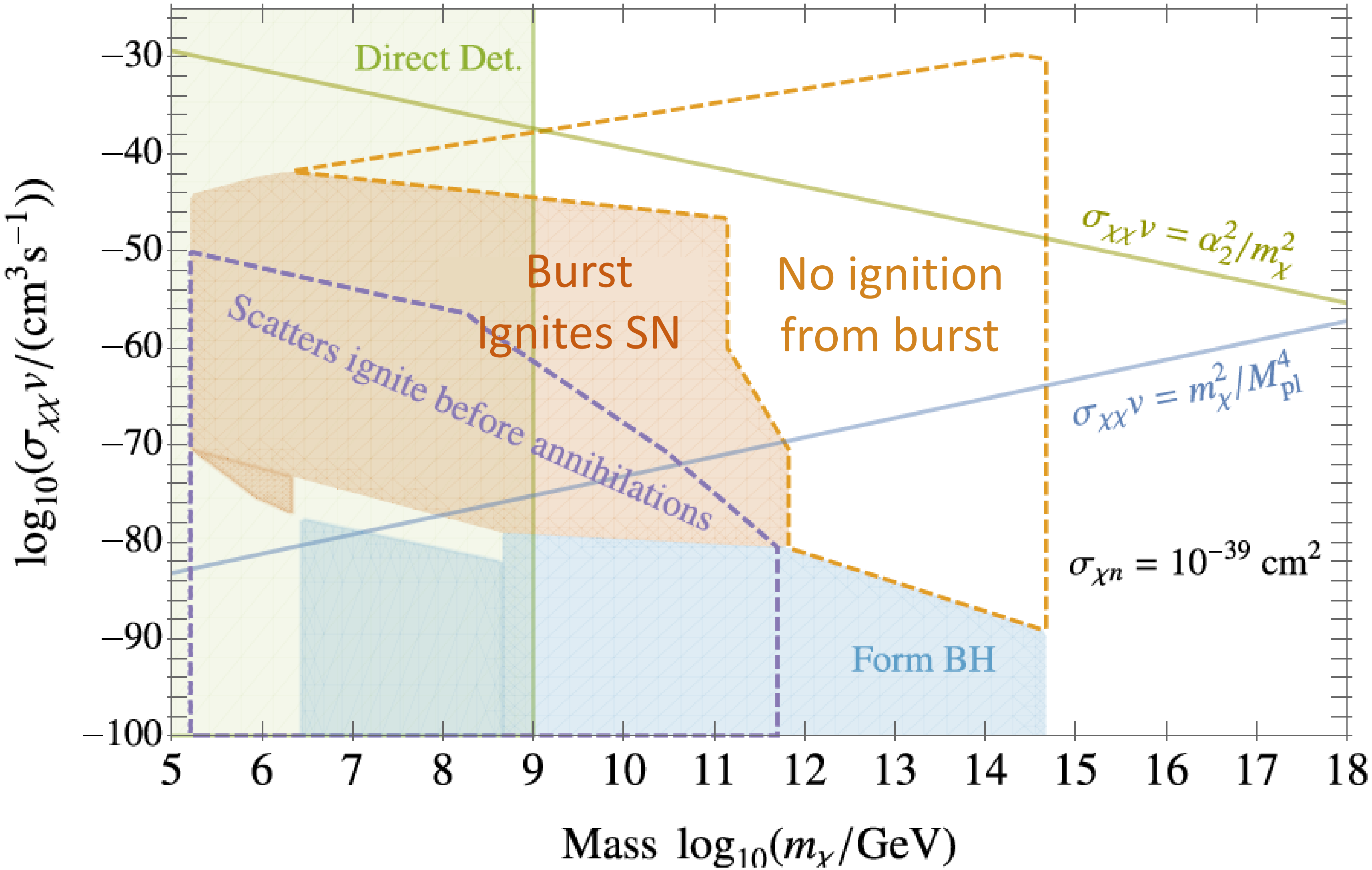
Demand $\tau_{\mathrm{wd}} > 1\ \mathrm{Gyr}$ for local WDs (Fermion DM)



[RJ, Narayan, Riggins, in preparation]

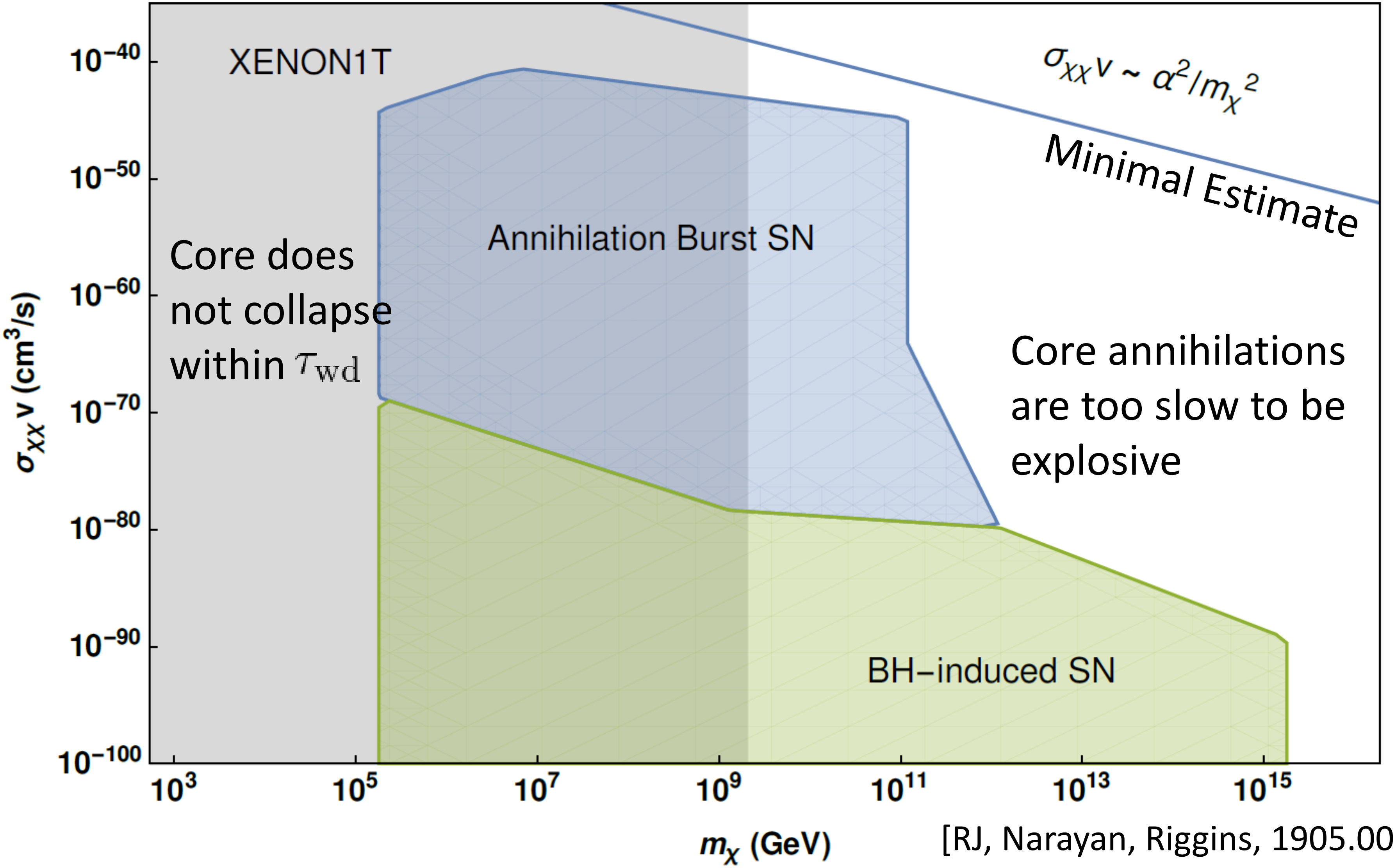
Annihilation Burst SN

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



Captured DM -> Annihilation Constraints

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



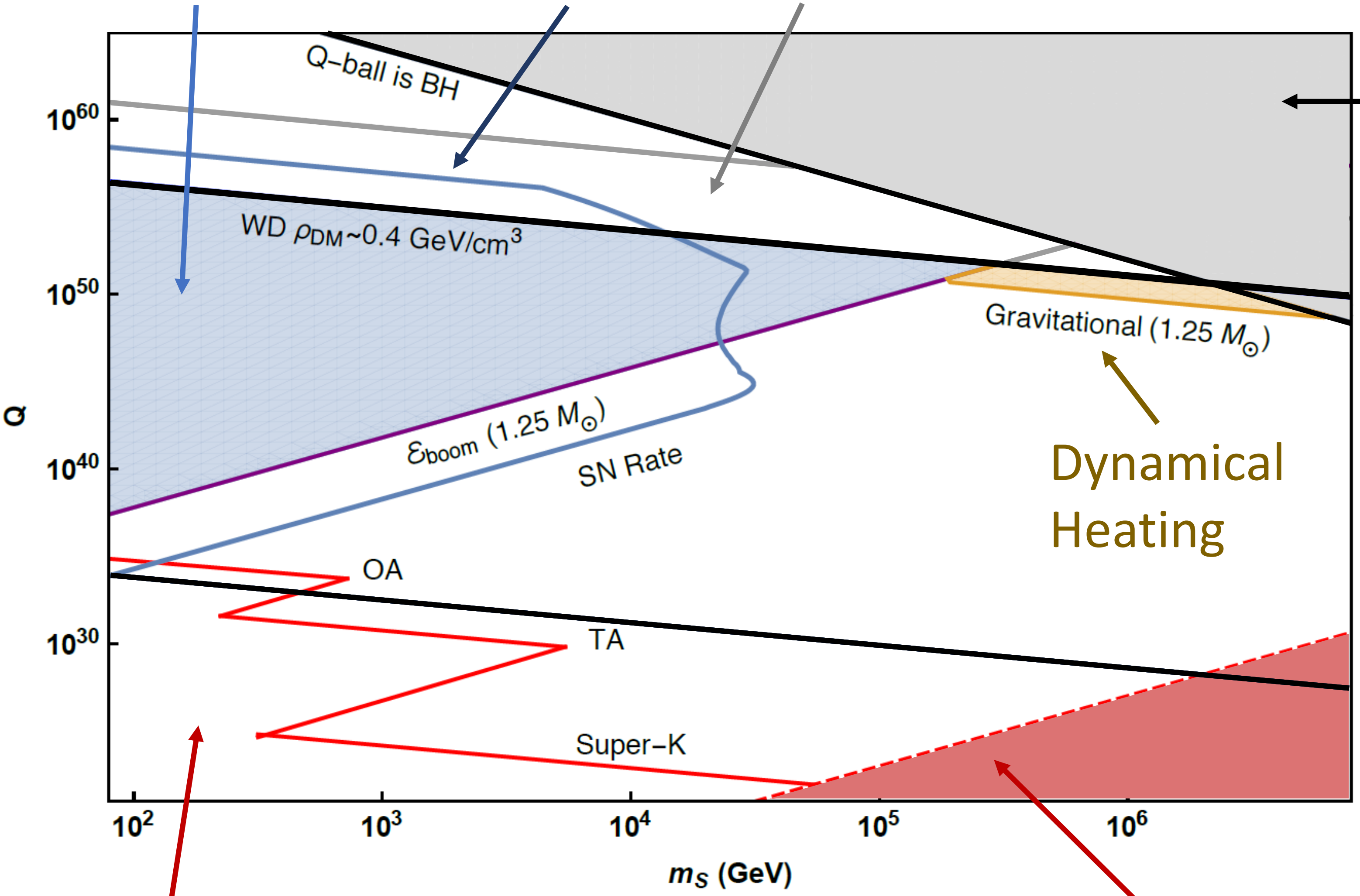
Minimal Estimate

Core does not collapse within $\tau_{\rm wd}$

Core annihilations are too slow to be explosive

[RJ, Narayan, Riggins, 1905.00395]

Q-ball Dark Matter



Local WD lifetime

SN Rate

Galactic Center WD lifetime

BHs

10^{44} GeV

10^{26} GeV

Dynamical Heating

Terrestrial Searches [Kusenko et al, ‘98]

Unstable Q-balls

An ALP Search using Superconducting RF Cavities and a Confined Magnetic Field

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Extra Slides

Axion Electrodynamics

Axion EOM: $(\Box + m_a^2)a(x) = -g\vec{E}\cdot\vec{B}$

Modifies Maxwell: $\vec{\nabla}\cdot\vec{E} = -g\vec{B}\cdot\vec{\nabla}a$

$$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} - g\left(\vec{E}\times\vec{\nabla}a - \vec{B}\frac{\partial a}{\partial t}\right)$$

Axion Electrodynamics

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Axion Production $\Longrightarrow$ $a(x) = -ge^{i\omega t}\int_{\mathrm{pc}} d^3y \;\frac{e^{ik|\vec{x}-\vec{y}|}}{4\pi|\vec{x}-\vec{y}|}(\vec{E}\cdot\vec{B})$

Axion Electrodynamics

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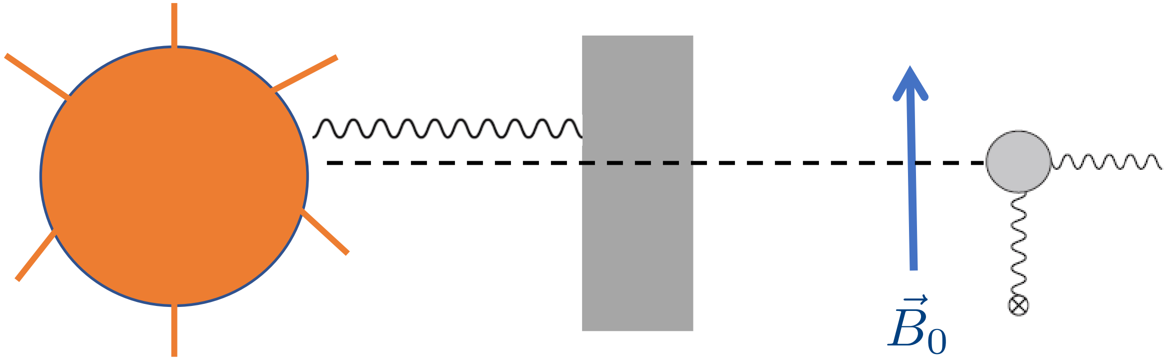
Axion Production $\Longrightarrow$ $a(x) = -ge^{i\omega t}\int_{\mathrm{pc}} d^3y\ \frac{e^{ik|\vec{x}-\vec{y}|}}{4\pi|\vec{x}-\vec{y}|}(\vec{E}\cdot\vec{B})$

Conversion in B_0 $\Longrightarrow$ "Effective" current $\vec{J}_{\mathrm{eff}} = g\vec{B}_0\frac{\partial a}{\partial t}$

Electromagnetic ALP Searches

“Sun shining through a Wall”

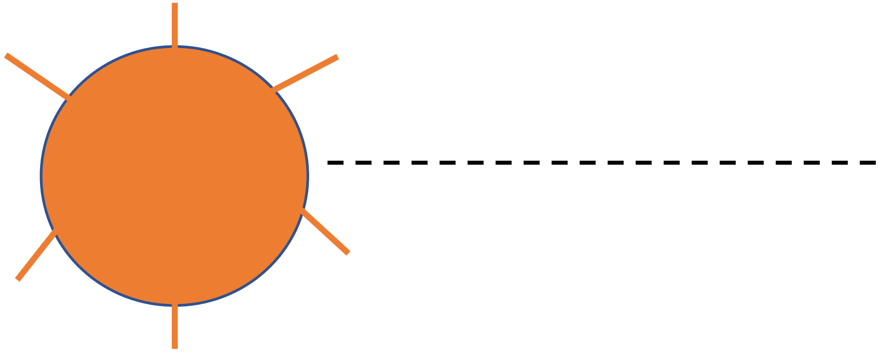
[Sikivie ‘83, …]



CAST

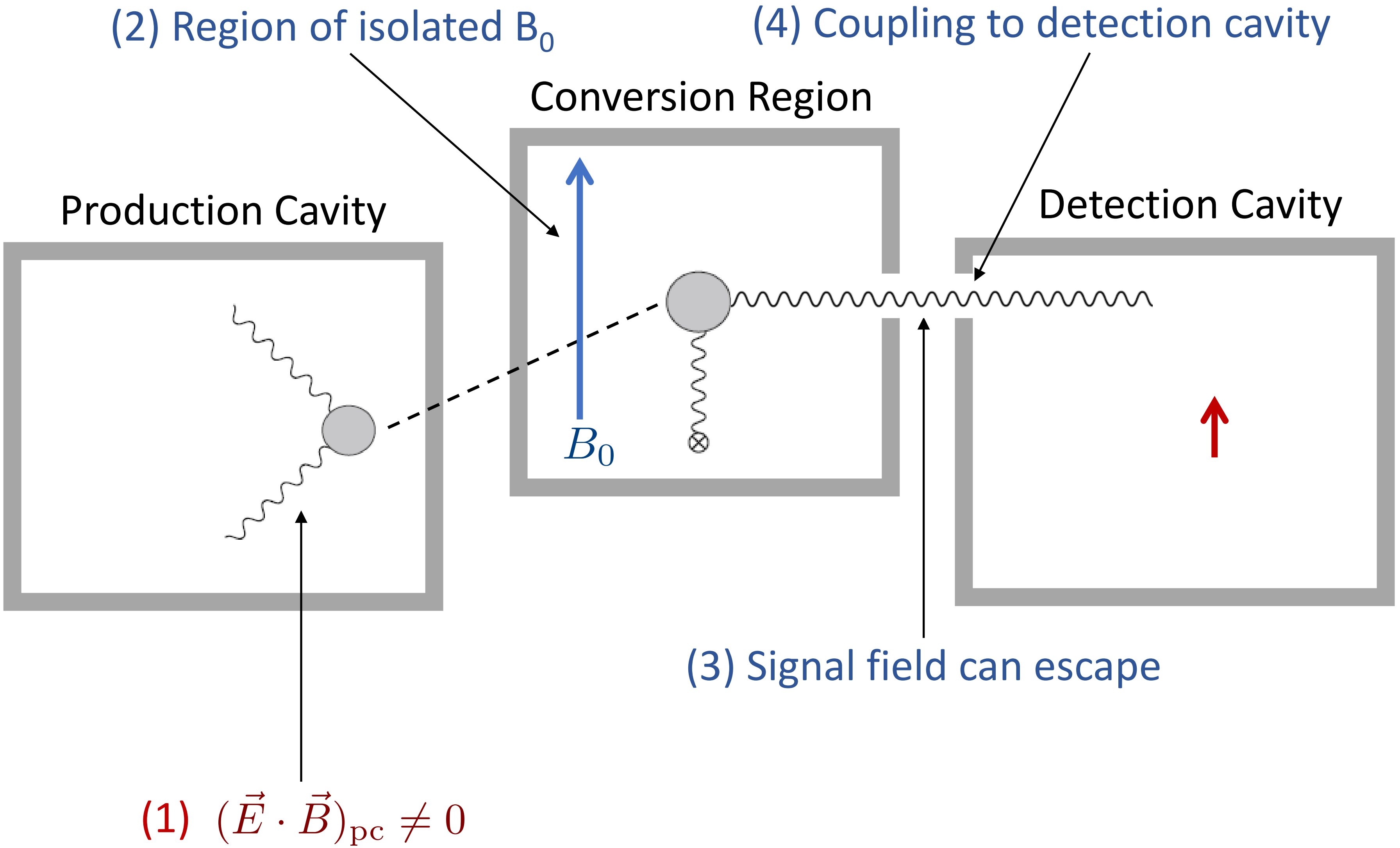
$g < 7\text{x}10^{-11}$ GeV^{-1}
for $m_a <$ eV

Stellar Cooling



$g < 7\text{x}10^{-11}$ GeV^{-1}
for $m_a <$ keV

New Design for LSW with SRF



(2) Region of isolated B_0

(4) Coupling to detection cavity

Conversion Region

Production Cavity

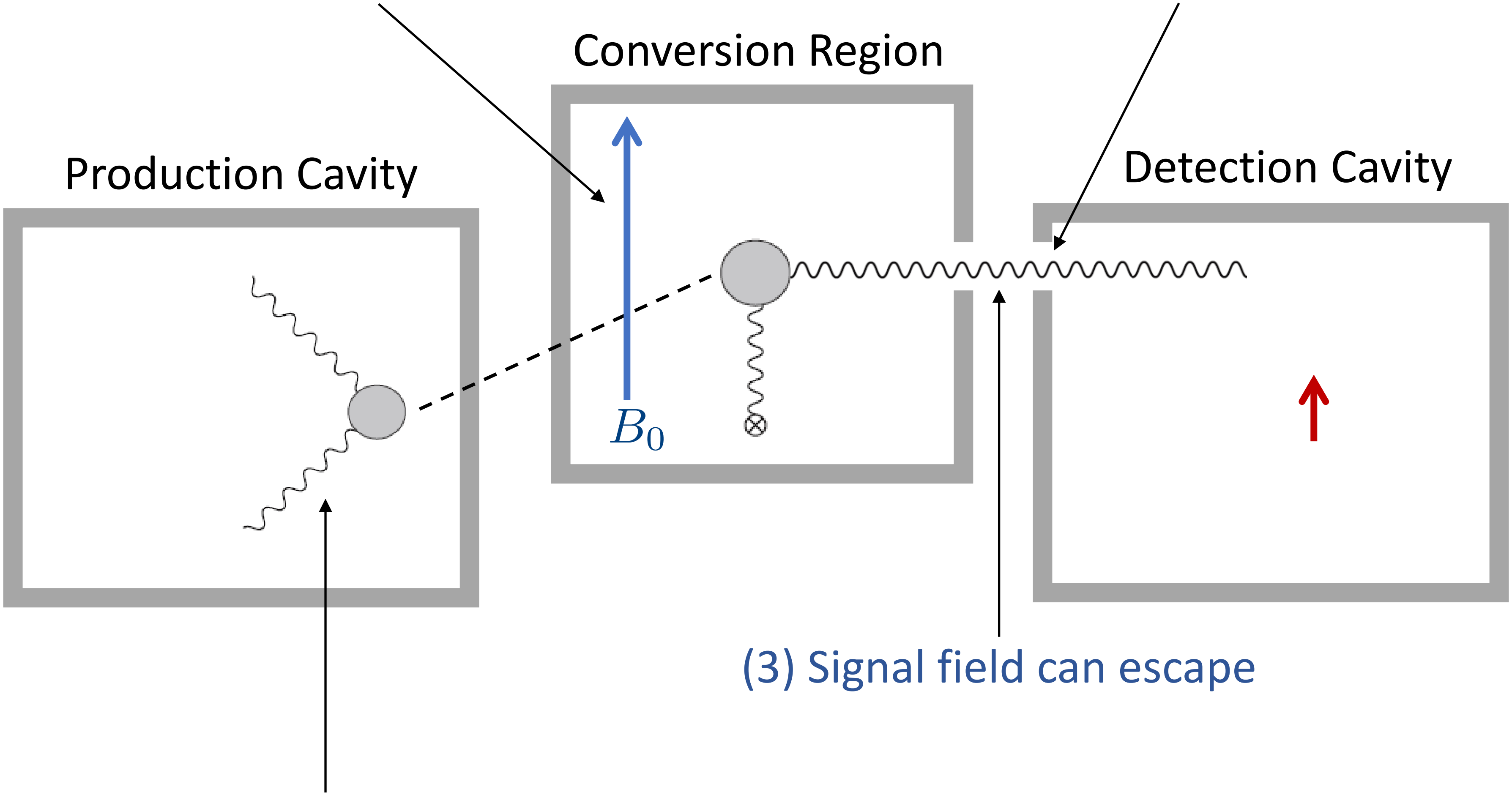
Detection Cavity

B_0

(3) Signal field can escape

(1) $(\vec{E} \cdot \vec{B})_{\mathrm{pc}} \neq 0$

New Design for LSW with SRF



(2) Toroidal Magnet

(4) Coupling to detection cavity

Conversion Region

Production Cavity

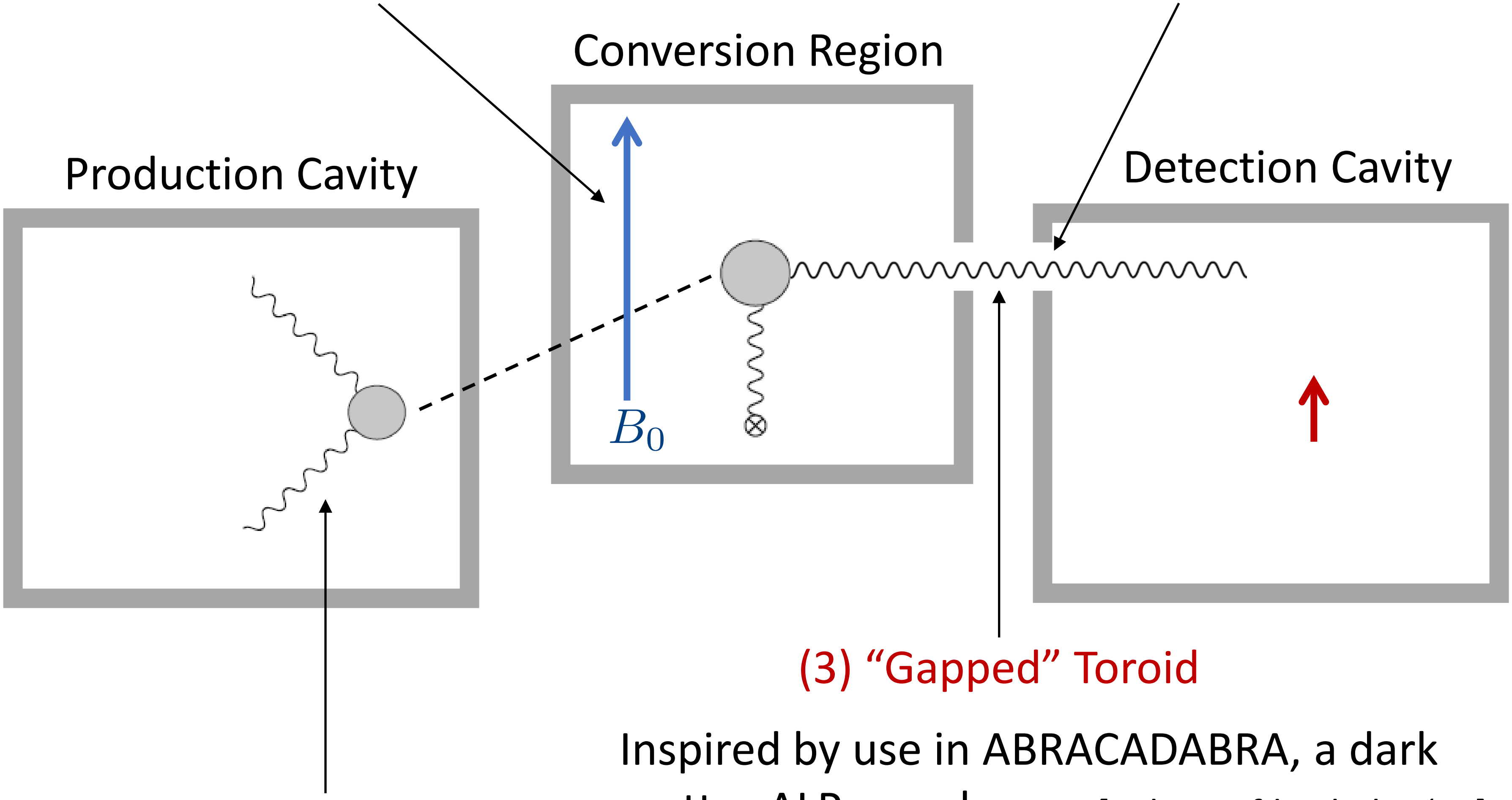
Detection Cavity

B_0

(3) Signal field can escape

(1) $(\vec{E} \cdot \vec{B})_{\mathrm{pc}} \neq 0$

New Design for LSW with SRF



(2) Toroidal Magnet

(4) Coupling to detection cavity

Conversion Region

Production Cavity

Detection Cavity

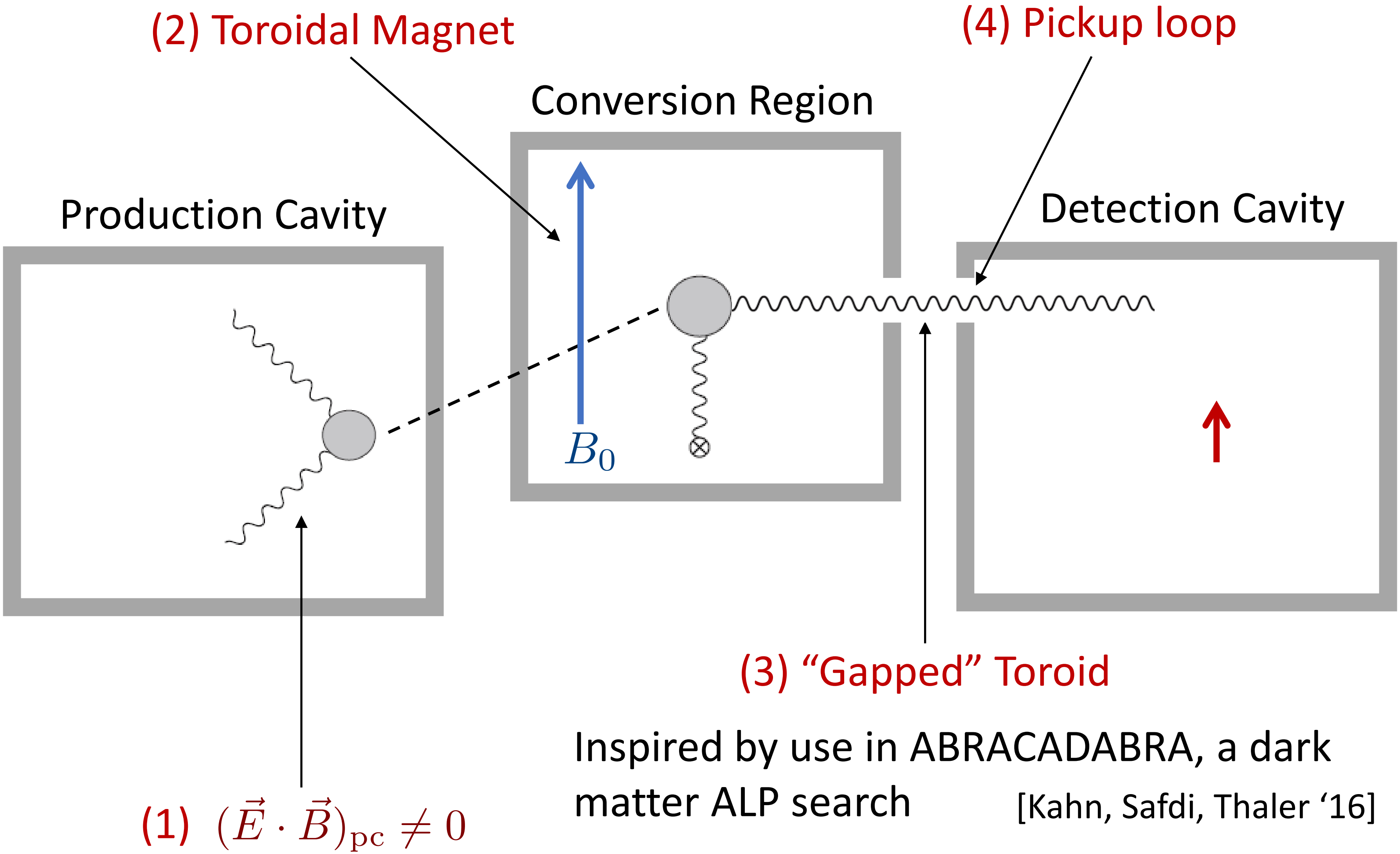
B_0

(3) “Gapped” Toroid

Inspired by use in ABRACADABRA, a dark matter ALP search [Kahn, Safdi, Thaler ‘16]

(1) $(\vec{E}\cdot\vec{B})_{\mathrm{pc}} \neq 0$

New Design for LSW with SRF



(2) Toroidal Magnet

(4) Pickup loop

Conversion Region

Production Cavity

Detection Cavity

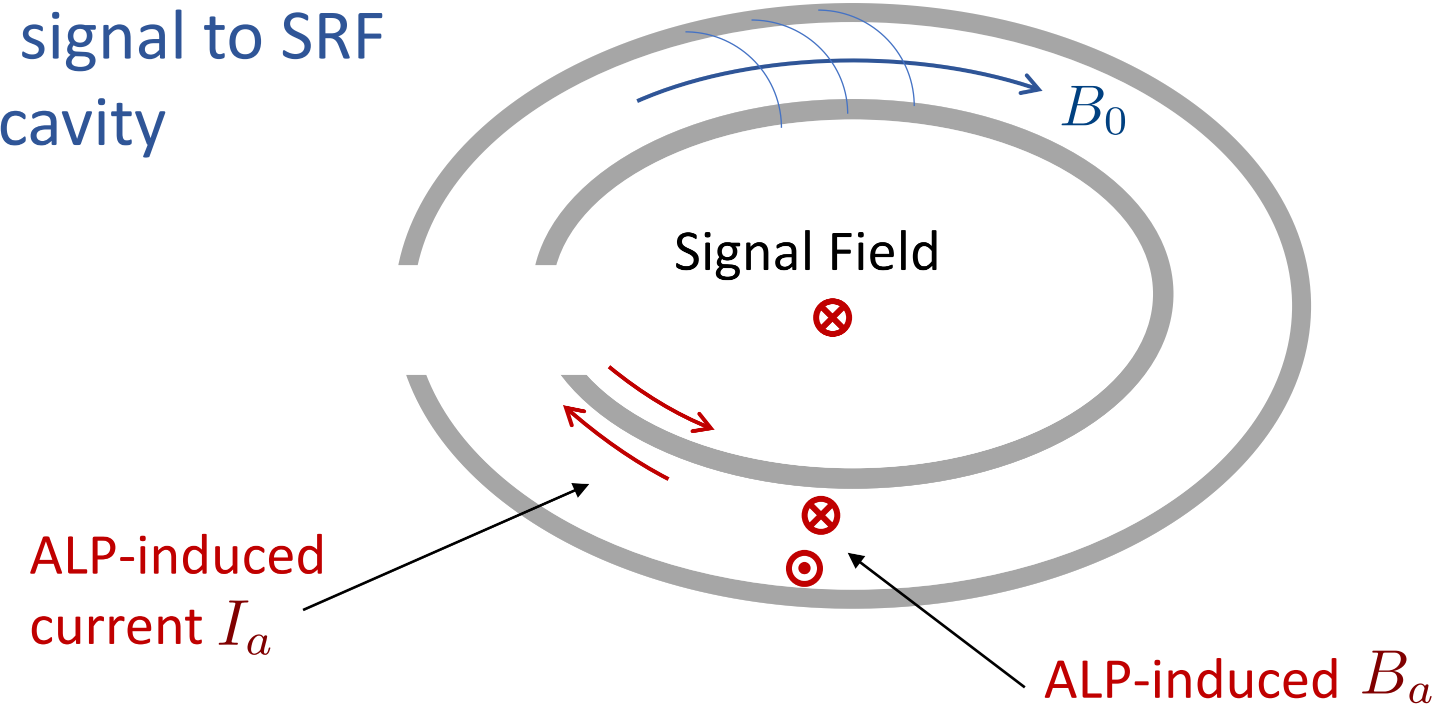
(3) “Gapped” Toroid

(1) $(\vec{E} \cdot \vec{B})_{\mathrm{pc}} \neq 0$

Inspired by use in ABRACADABRA, a dark matter ALP search [Kahn, Safdi, Thaler ‘16]

Gapped Toroid Conversion Region

(4) Couple signal to SRF detection cavity



B_0

Signal Field

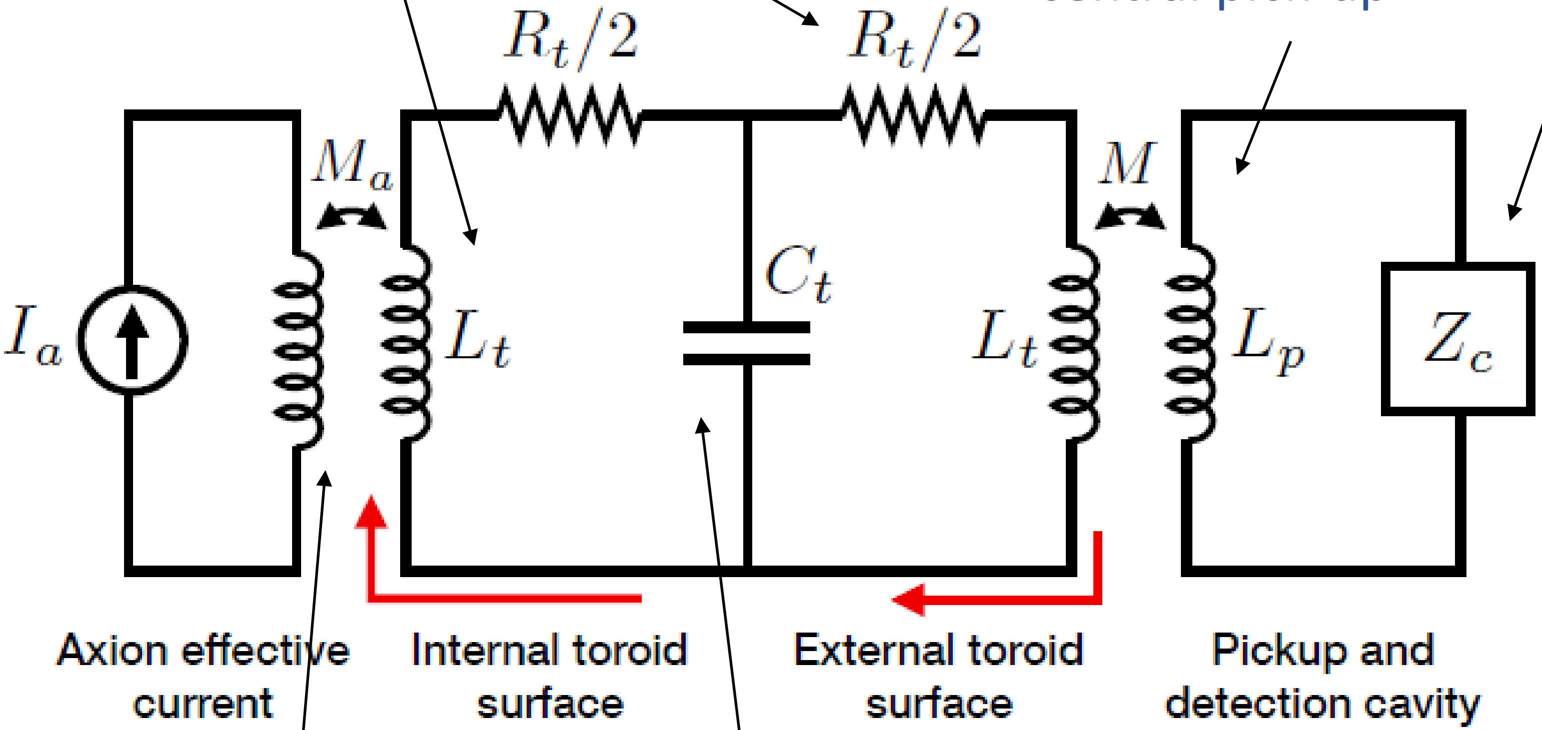
ALP-induced current I_a

ALP-induced B_a

$$I_a \approx 10^{-13}\ \mathrm{nA} \left(\frac{g\ \mathrm{GeV}}{10^{-11}}\right)^2 \left(\frac{B_{\mathrm{PC}}}{0.1\ \mathrm{T}}\right)^2 \left(\frac{B_0}{5\ \mathrm{T}}\right) \left(\frac{R}{10\ \mathrm{cm}}\right)^3$$

$$B_a \approx 10^{-26}\ \mathrm{T} \left(\frac{g\ \mathrm{GeV}}{10^{-11}}\right)^2 \left(\frac{B_{\mathrm{PC}}}{0.1\ \mathrm{T}}\right)^2 \left(\frac{B_0}{5\ \mathrm{T}}\right) \left(\frac{R}{10\ \mathrm{cm}}\right)^2$$

Effective Circuit for Toroid and DC



toroid inductance

toroid resistance

detection cavity

central pick-up

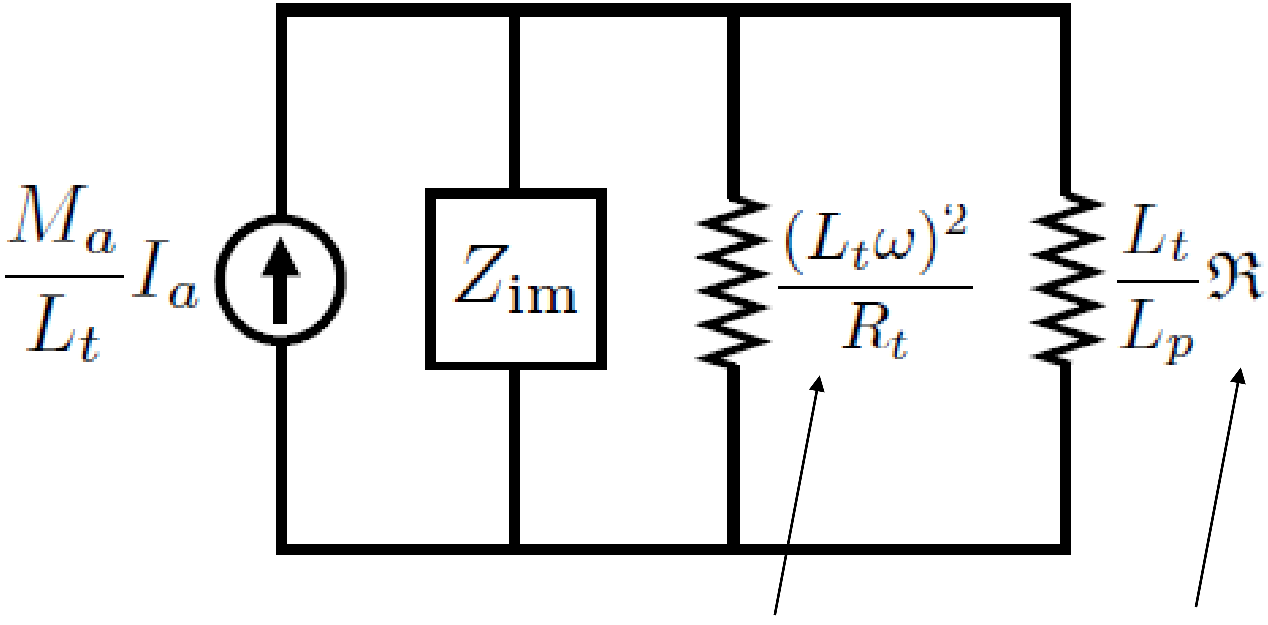
Meissner effect

toroid gap capacitance

Effective Circuit for Toroid and DC

Simplify this into:

- One imaginary impedance (determines resonance)
- Two real impedances: toroid and DC



toroid shunt resistance

DC shunt resistance

Effective Circuit for Toroid and DC

$$Z_{\mathrm{im}} \sim \left(\frac{2}{i\omega L_t} + i\omega C_t + \frac{1}{i\omega \frac{L_t}{L_p} L} + i\omega \frac{L_p}{L_t} C \right)^{-1}$$

$$\omega_{\mathrm{res}} \sim \omega_0 \sqrt{1 + 2\frac{L}{L_p}}$$

Require $L_p >> L$ to preserve GHz resonance

Prevents impedance-matching for small Q