

Stellar Shocks From Dark Asteroids

Kevin Zhou



Stanford
University

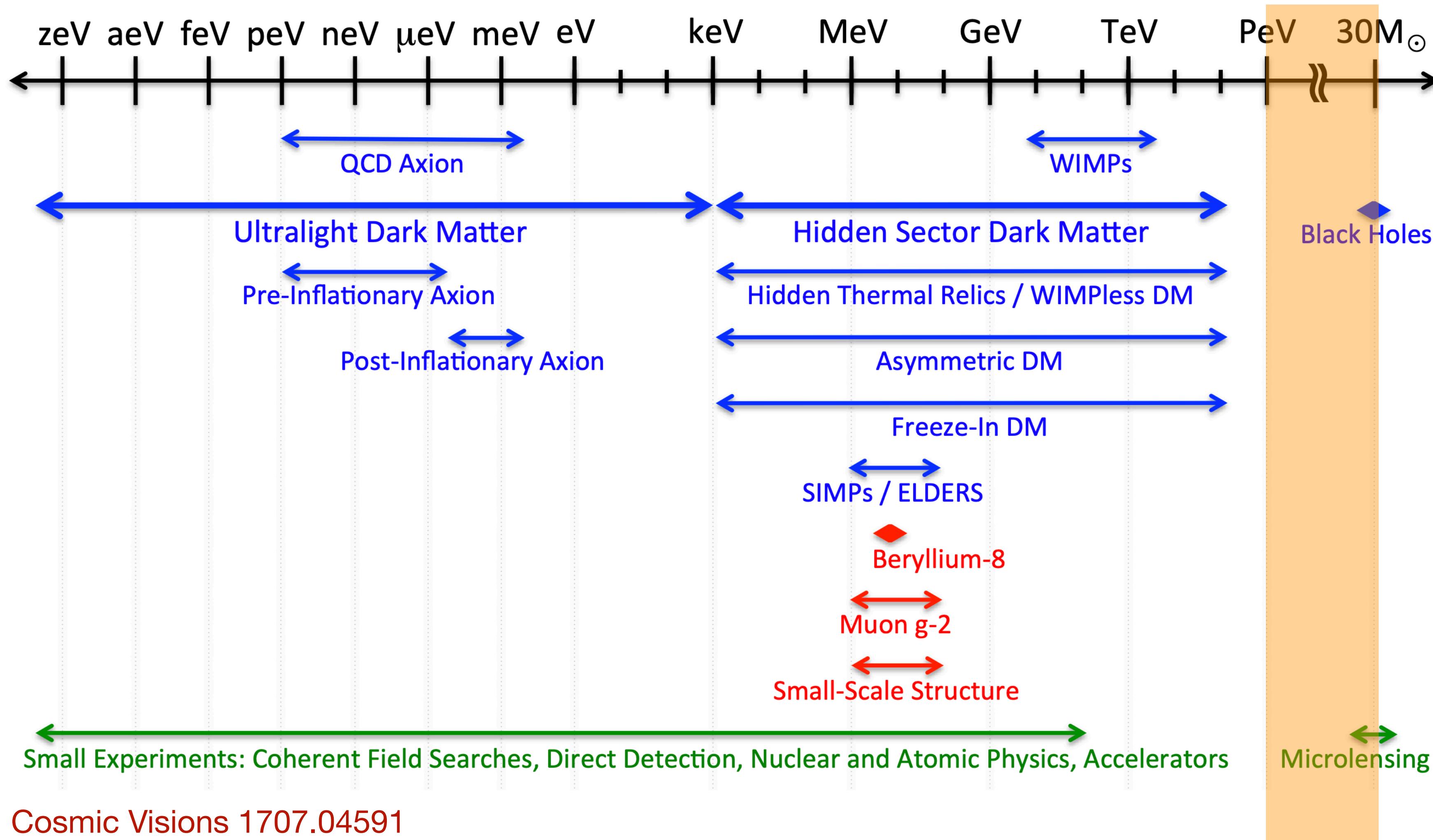


arXiv: 2106.xxxxx

with Anirban Das, Sebastian Ellis, Philip Schuster

PHENO Symposium – May 24, 2020

90 Orders of Magnitude

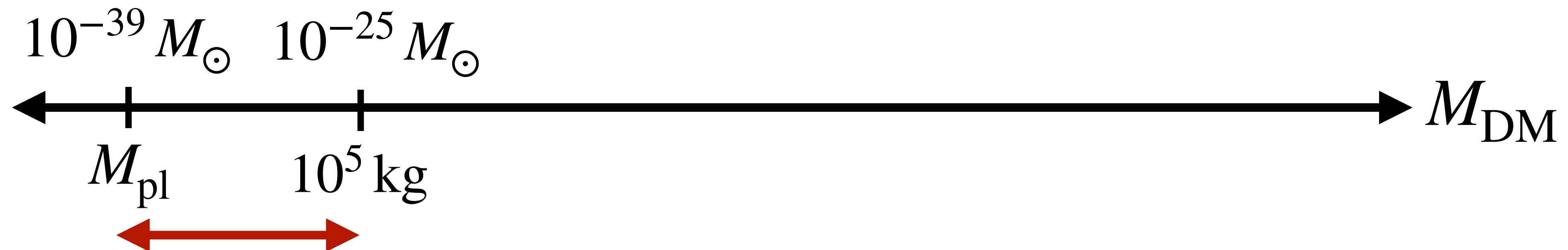


Macroscopic Dark Matter

- Wide mass range available
- Forms in a variety of models
 - Direct fusion in asymmetric DM, dark nucleosynthesis
[1411.3739](#), [1707.02316](#)
 - Collapse and cooling by dark $U(1)$
[1707.03829](#), [1812.07000](#)
 - Phase transitions forming “nuggets” or solitons
[1810.04360](#), [2105.02840](#)

Macroscopic DM Searches

Strong DM-SM interactions allowed, but still hard to detect because of rarity



“Low” masses probed by terrestrial searches:

WIMP/neutrino detectors
1803.08044, 1812.09325

Ancient mica
2105.06473

Etched plastic
2012.13406

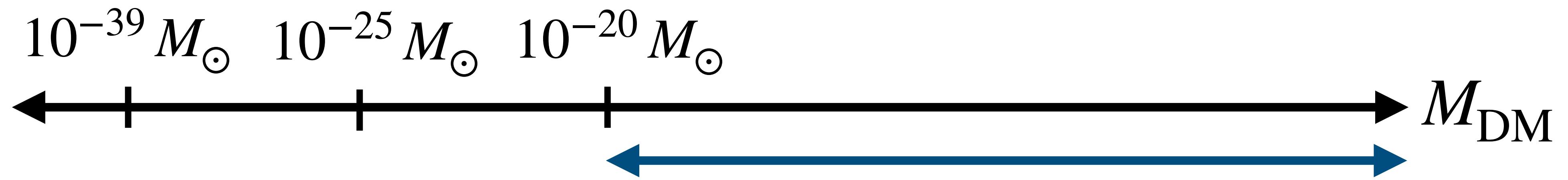
Gravitational wave detectors
1807.03788

Meteors and cosmic rays
2008.01285

Seismic waves
1610.09680

Macroscopic DM Searches

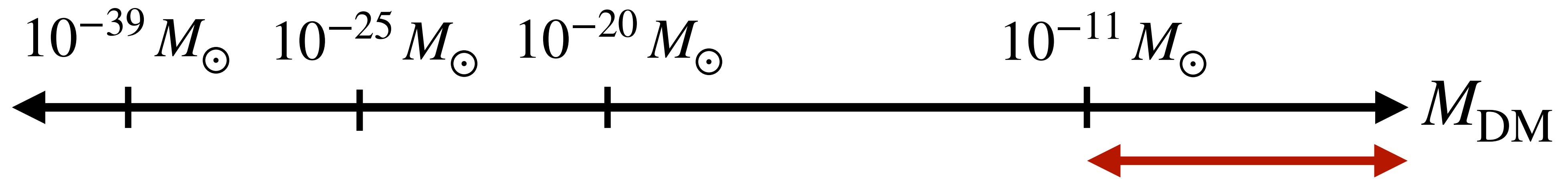
Strong DM-SM interactions allowed, but still hard to detect because of rarity



For higher masses, too rare to detect on Earth, $\Gamma \lesssim 1/(10^4 \text{ yr})$

Macroscopic DM Searches

Strong DM-SM interactions allowed, but still hard to detect because of rarity

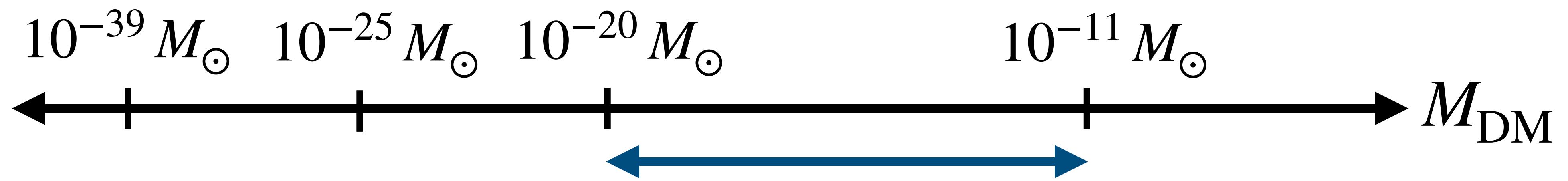


Highest masses excluded by gravitational lensing

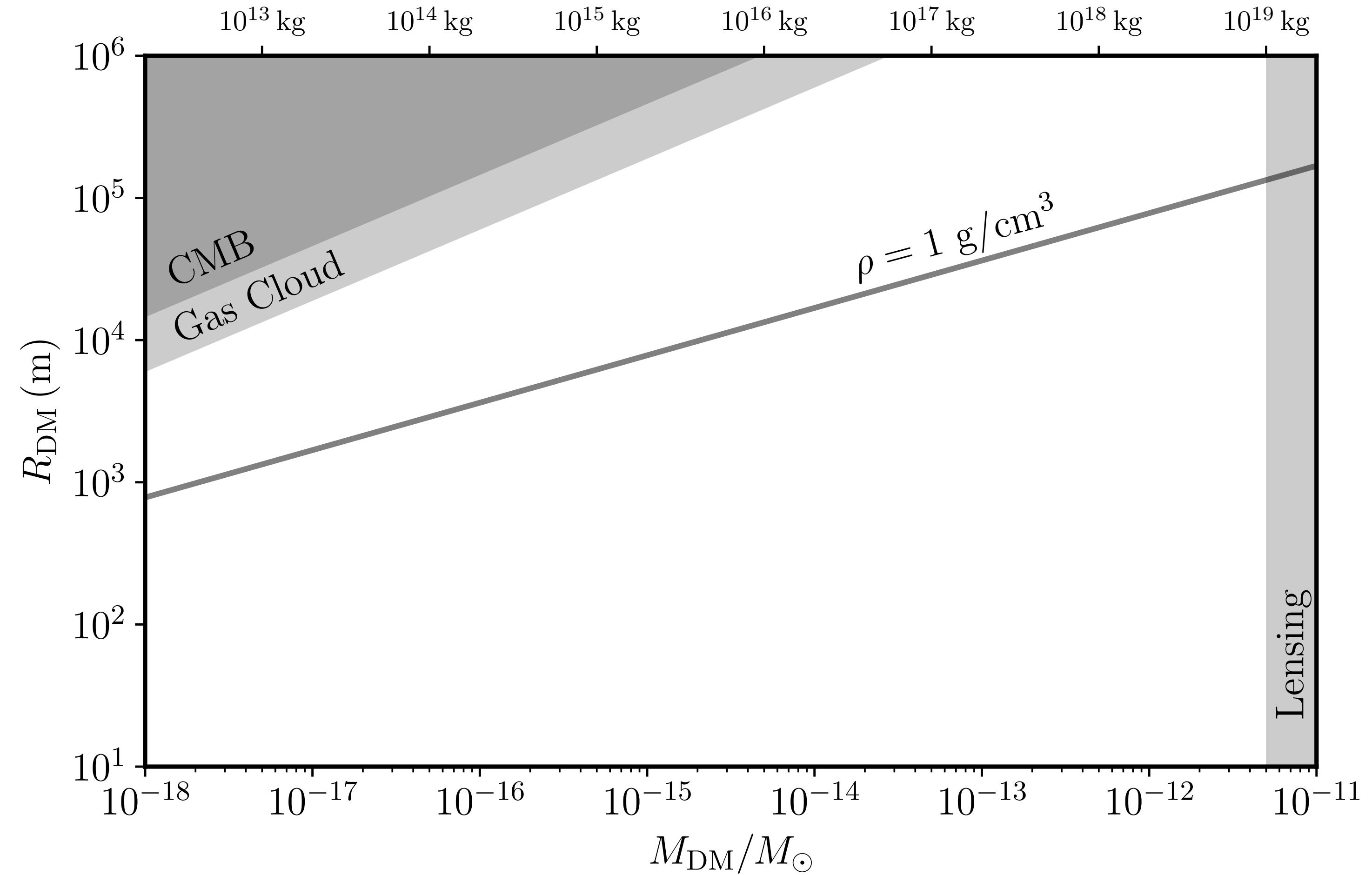
1701.02151

Macroscopic DM Searches

Strong DM-SM interactions allowed, but still hard to detect because of rarity

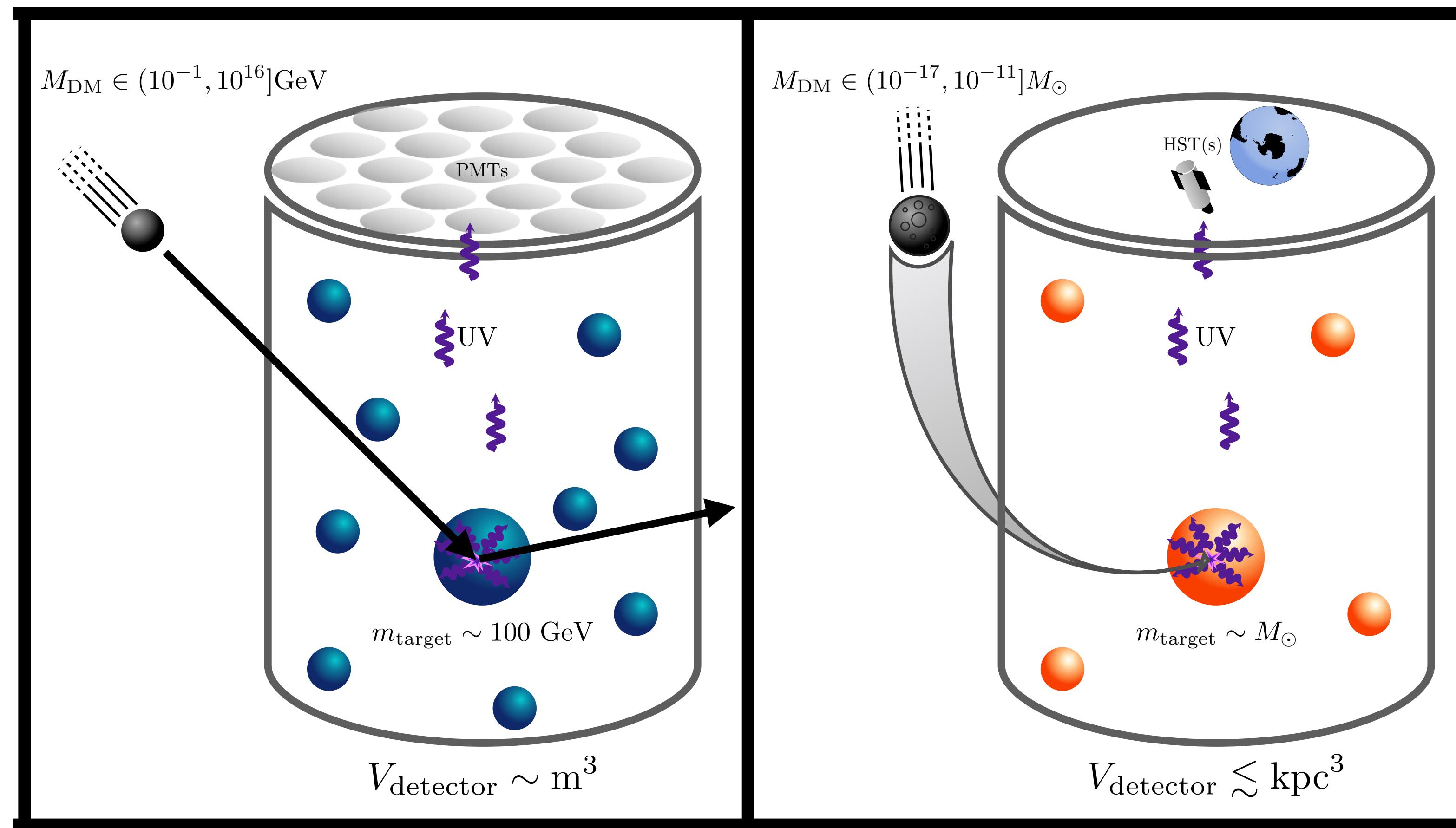


A relatively unconstrained “dark asteroid” range



Few existing constraints, near atomic density and higher, even for geometric cross section $\sigma = \pi R_{\text{DM}}^2$

Probe by looking for stellar impacts: a dark matter direct detection experiment on astronomical scales!



Naive Estimates

Rate per star:

$$\Gamma \sim \frac{\rho_{\text{DM}} v_{\text{DM}}}{M_{\text{DM}}} \pi R_{\star}^2 \left(1 + \frac{v_{\text{esc}}^2}{v_{\text{DM}}^2} \right) \sim \frac{1}{10^4 \text{ yr}} \frac{10^{-15} M_{\odot}}{M_{\text{DM}}}$$

Energy dissipated in star:

$$E_{\text{DM}} \sim \frac{1}{2} M_{\text{DM}} v_{\text{esc}}^2 \sim 10^{34} \text{ erg} \frac{M_{\text{DM}}}{10^{-15} M_{\odot}}$$

Naive Estimates

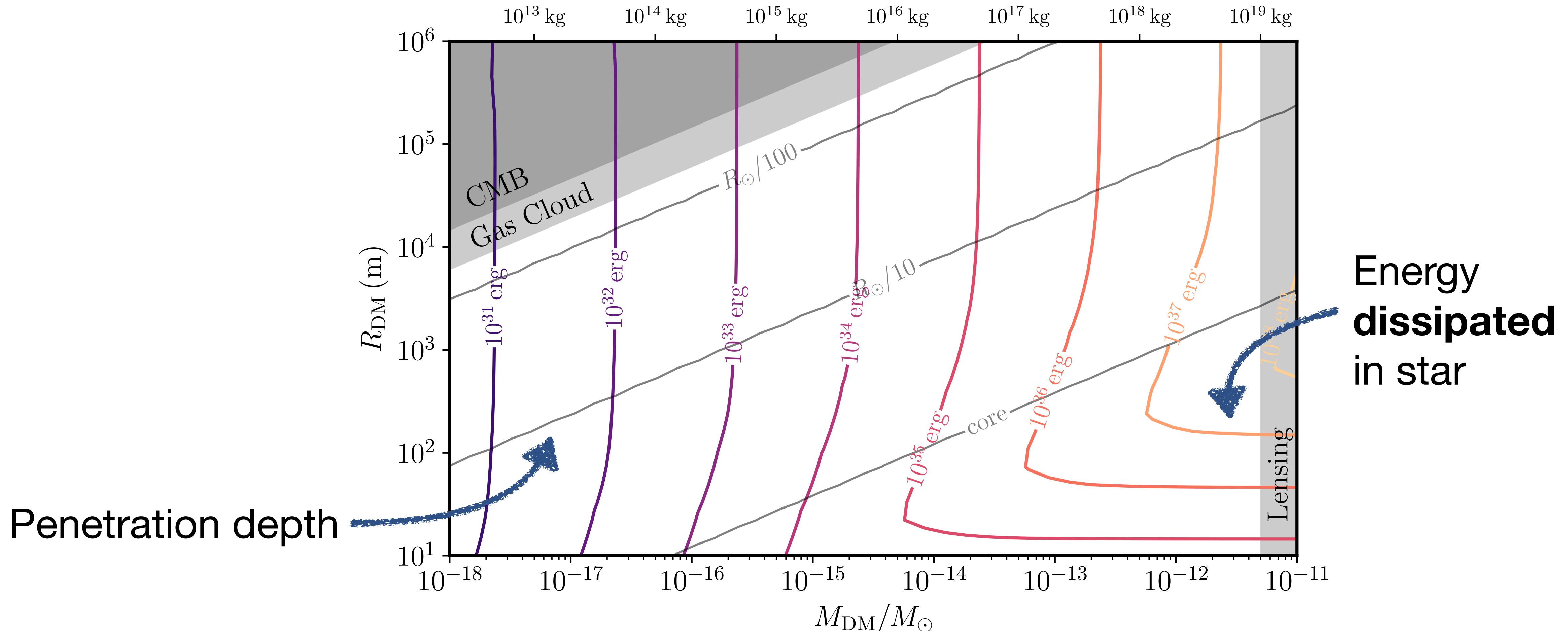
Rate per star:

$$\Gamma \sim \frac{\rho_{\text{DM}} v_{\text{DM}}}{M_{\text{DM}}} \pi R_{\star}^2 \left(1 + \frac{v_{\text{esc}}^2}{v_{\text{DM}}^2} \right) \sim \frac{1}{10^4 \text{ yr}} \frac{10^{-15} M_{\odot}}{M_{\text{DM}}}$$

Energy dissipated in star:

$$E_{\text{DM}} \sim \frac{1}{2} M_{\text{DM}} v_{\text{esc}}^2 \sim 10^{34} \text{ erg} \frac{M_{\text{DM}}}{10^{-15} M_{\odot}}$$

Average power ΓE_{DM}
negligible, but E_{DM} high,
potentially observable as
strong transient



Dark asteroid experiences gravitational force $M_{\text{DM}}g$ and drag $F_d \sim \rho\sigma v^2$

Taking geometric cross section $\sigma = \pi R_{\text{DM}}^2$, but qualitatively similar for lower σ

How the Energy Escapes

Naively, energy deposited even at depth $R_\star/10$ takes **very** long time to get out

How the Energy Escapes

Naively, energy deposited even at depth $R_\star/10$ takes **very** long time to get out

But dark asteroid is traveling supersonically, at $\text{Ma} = v_{\text{esc}}/c_s \sim 100$, so energy dissipated forms shock waves, which efficiently propagate to surface!

How the Energy Escapes

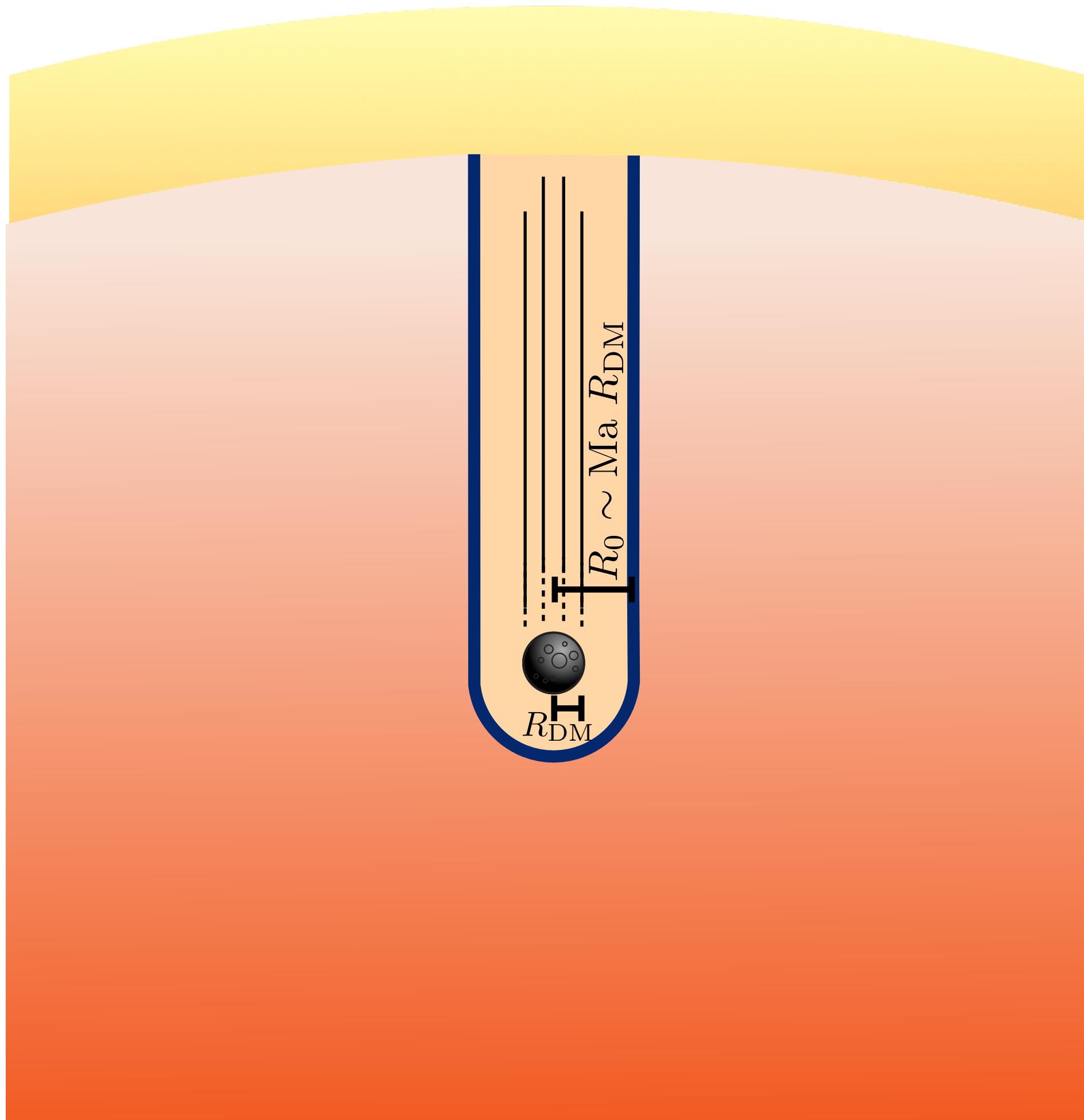
Naively, energy deposited even at depth $R_\star/10$ takes **very** long time to get out

But dark asteroid is traveling supersonically, at $\text{Ma} = v_{\text{esc}}/c_s \sim 100$, so energy dissipated forms shock waves, which efficiently propagate to surface!

A complicated hydrodynamic problem, but solvable with controlled approximations known for decades

Whitham (1956), ReVelle (1976)

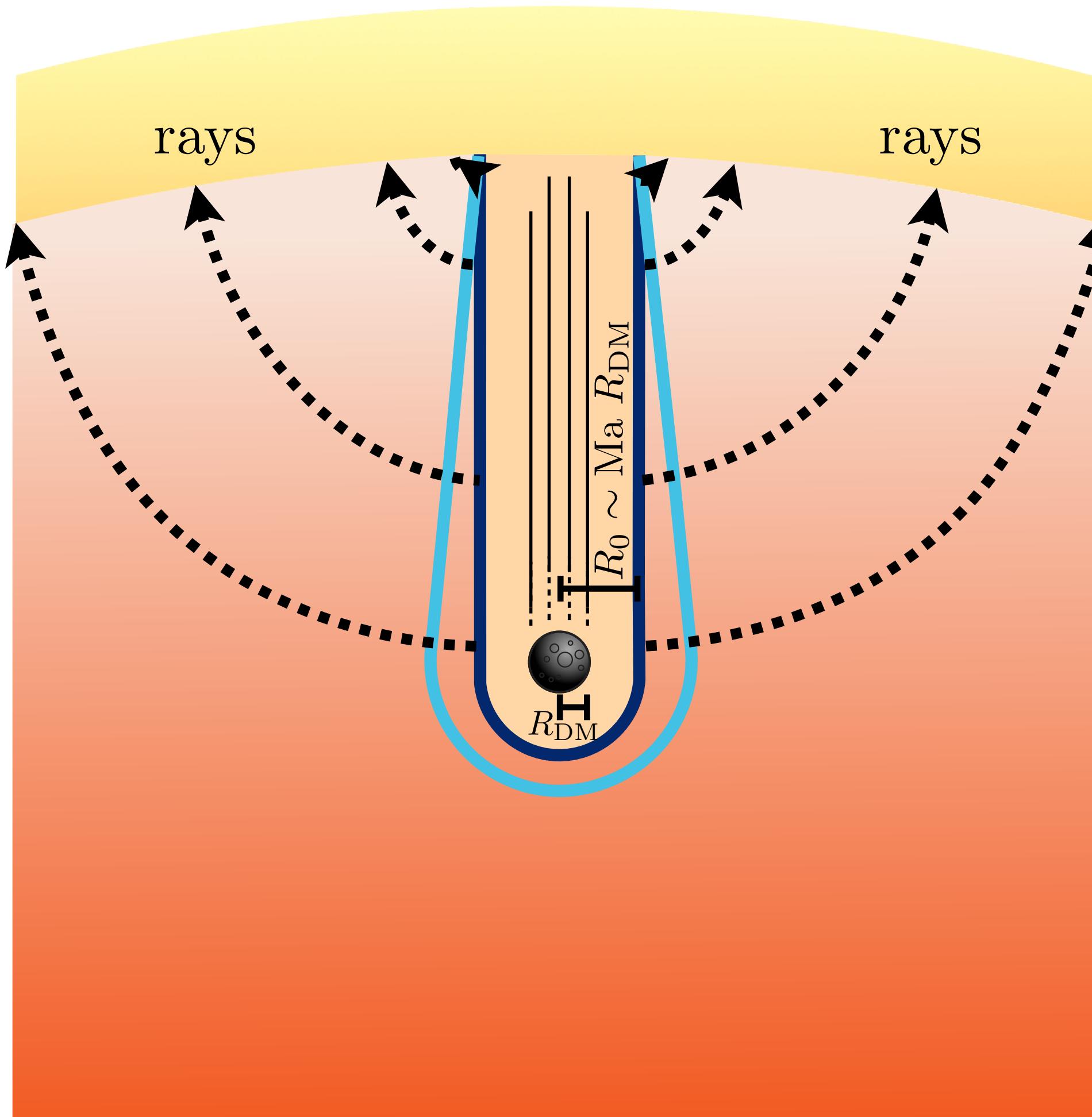
How the Energy Escapes



Near the dark asteroid: since $\text{Ma} \gg 1$, can approximate with known cylindrical blast wave

Characteristic size $R_0 \sim \text{Ma } R_{\text{DM}}$

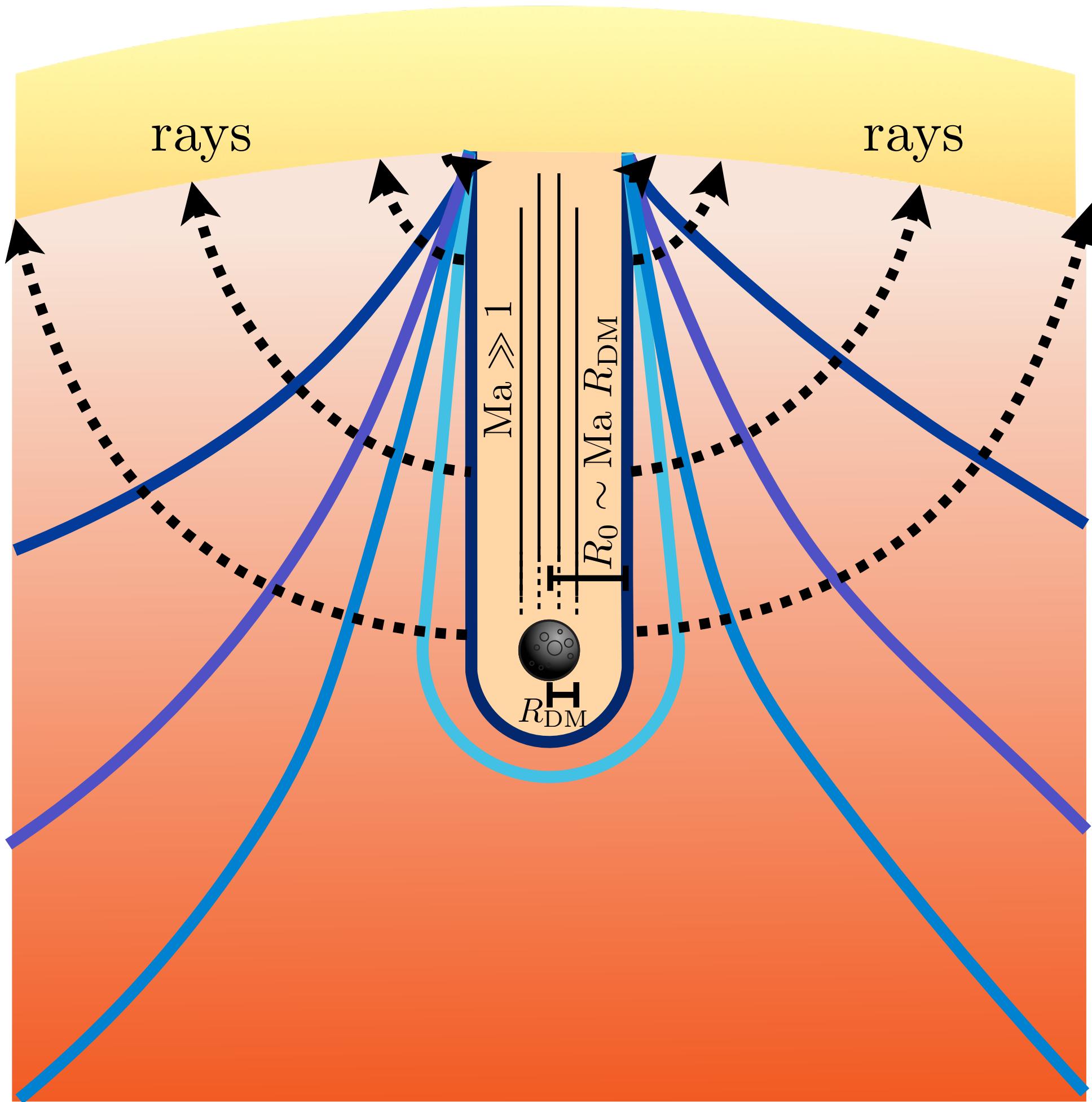
How the Energy Escapes



Beyond R_0 , match onto a weak shock solution — essentially an acoustic wave with additional dissipation

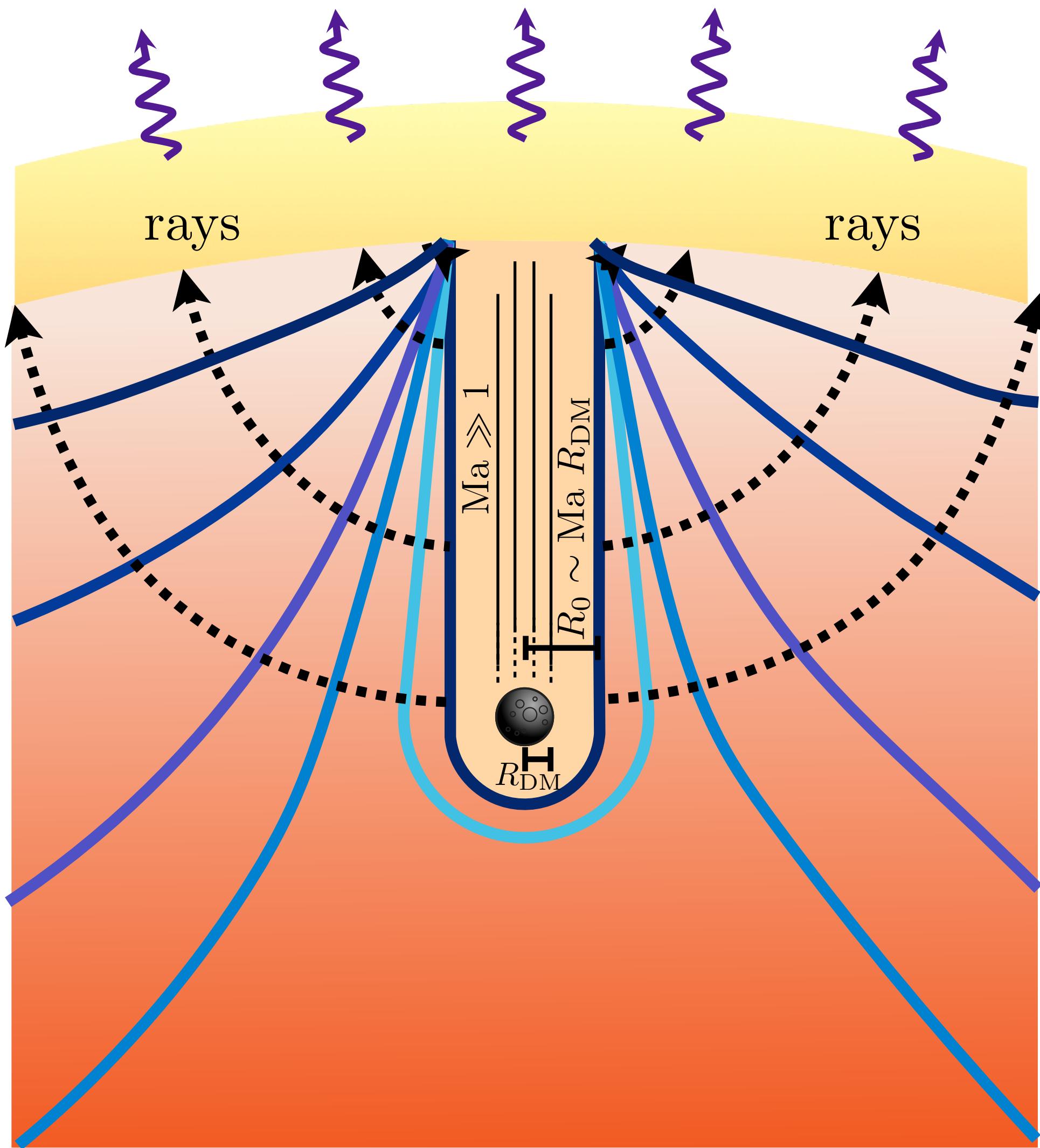
Rays refract radially outward

How the Energy Escapes



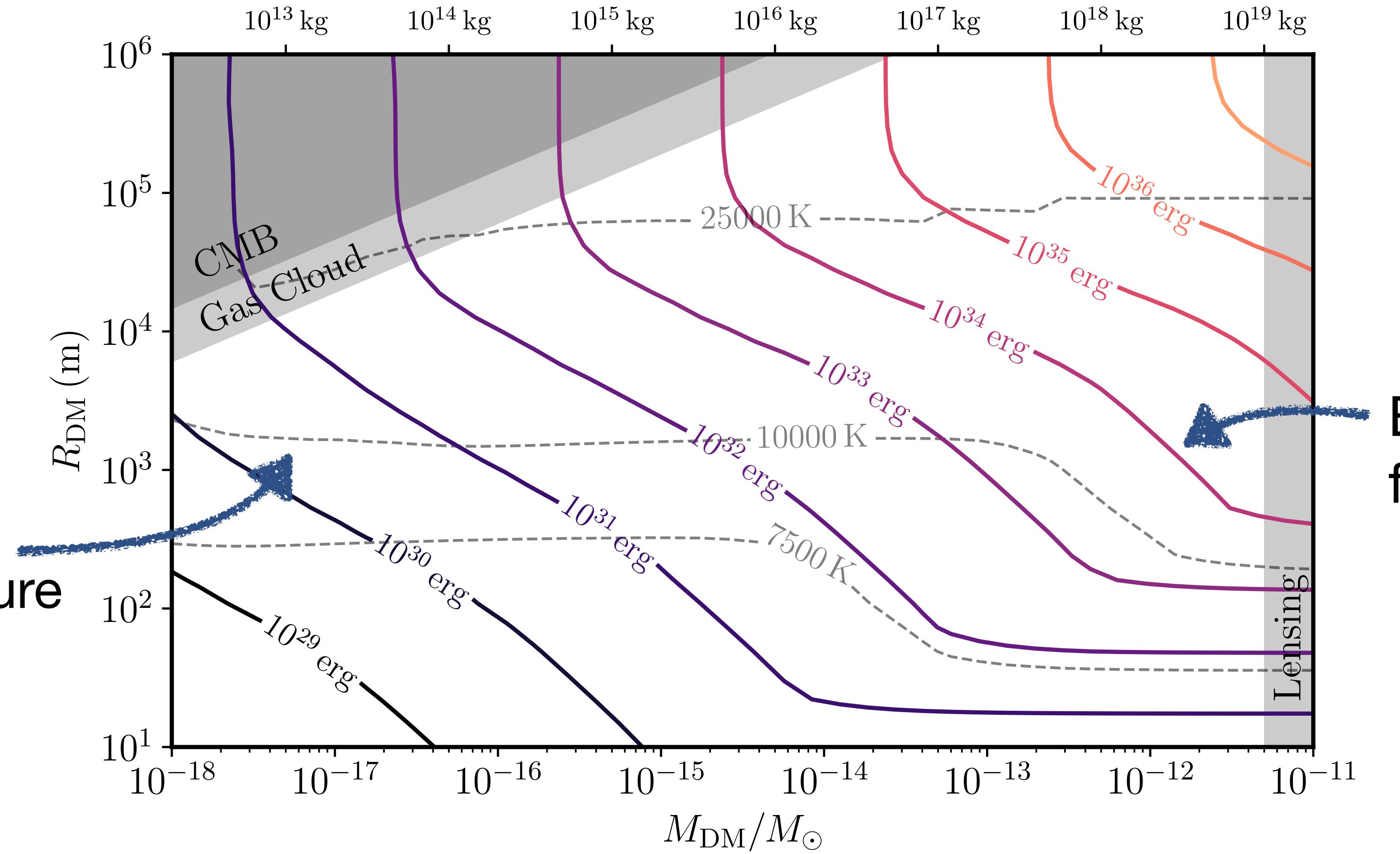
Weak shock waves lose energy,
but grow in strength as they
approach the stellar surface

How the Energy Escapes



Shock waves grow strong very close to the photosphere, heating a patch of the surface

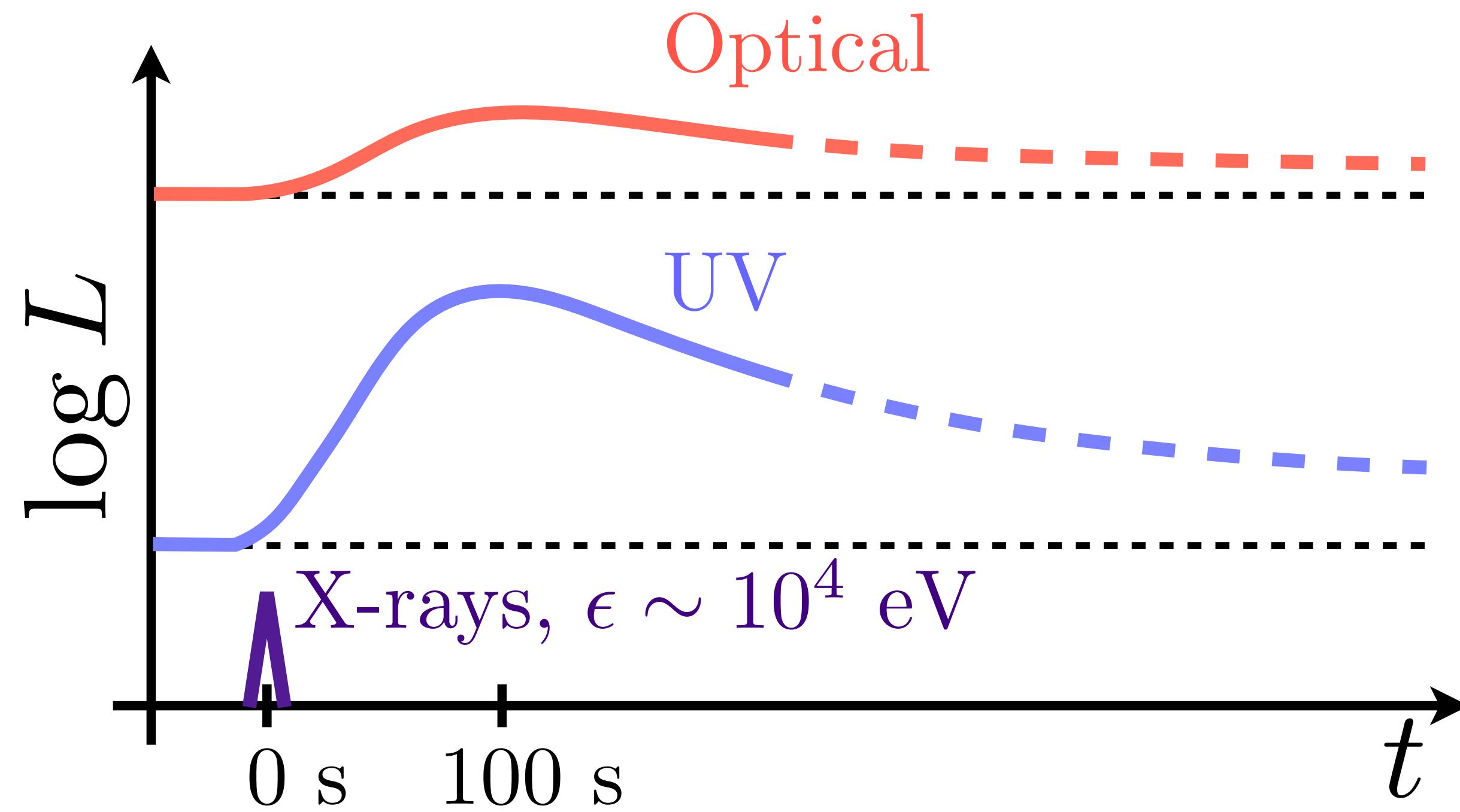
Typical shocked
surface temperature



Energy **released**
from star surface

Point of shock calculation: typical final temperature is UV; energy released is suppressed by shock dissipation as R_{DM} decreases, but still sizable

Detecting the Signal



Main signature: thermal UV transient spread over ~hundreds of seconds

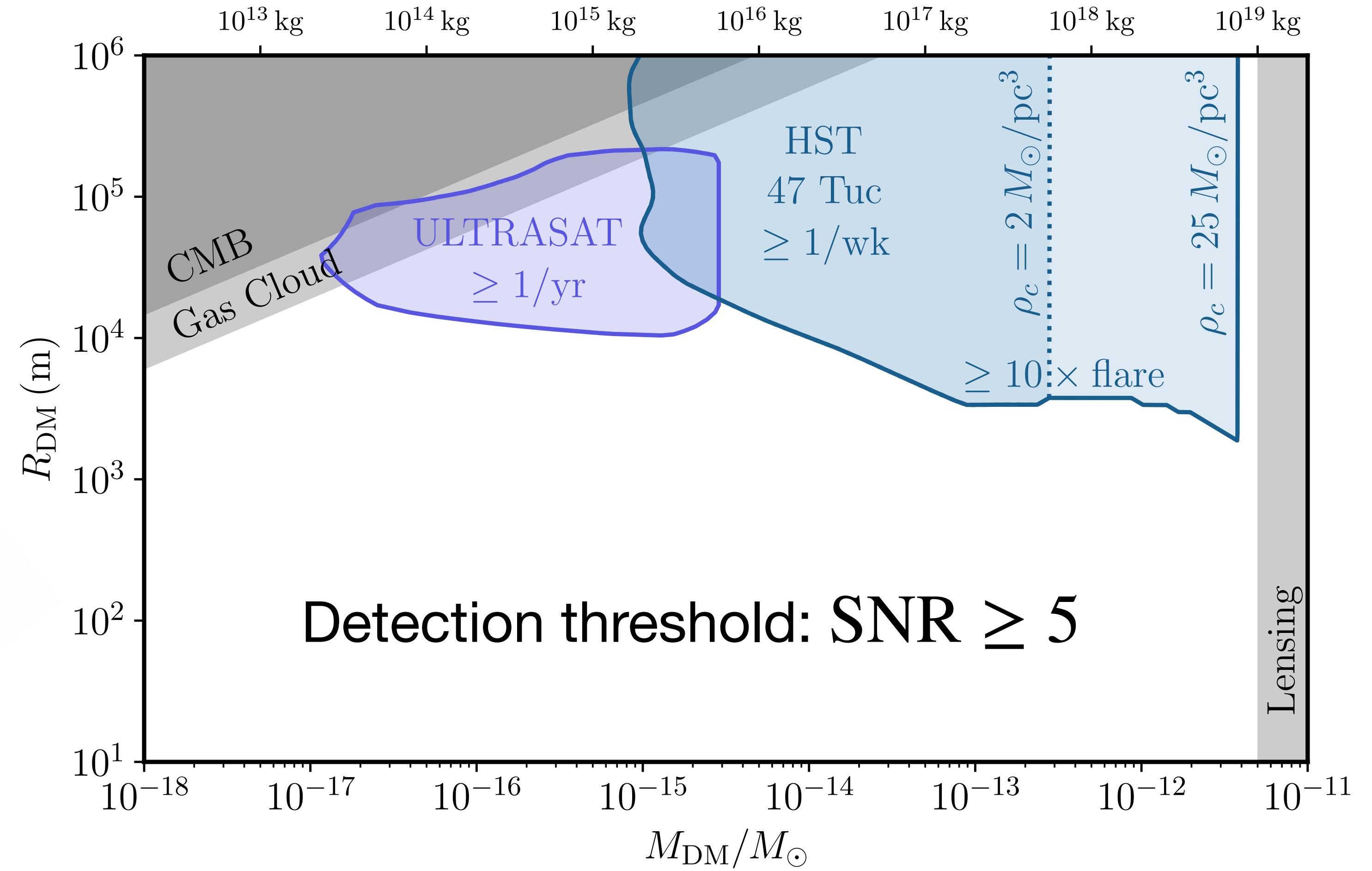
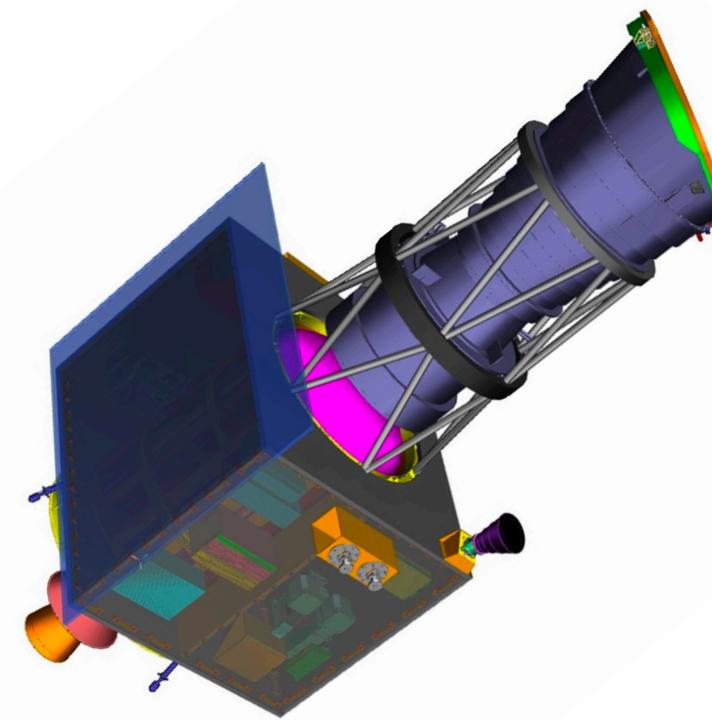
Search Strategies

Local search

- Wide field search for transients on nearby (within 1 kpc) stars
- Does not require dedicated survey
- Rate low, so targets low M_{DM}
- Stellar superflare background could be high

Focused search

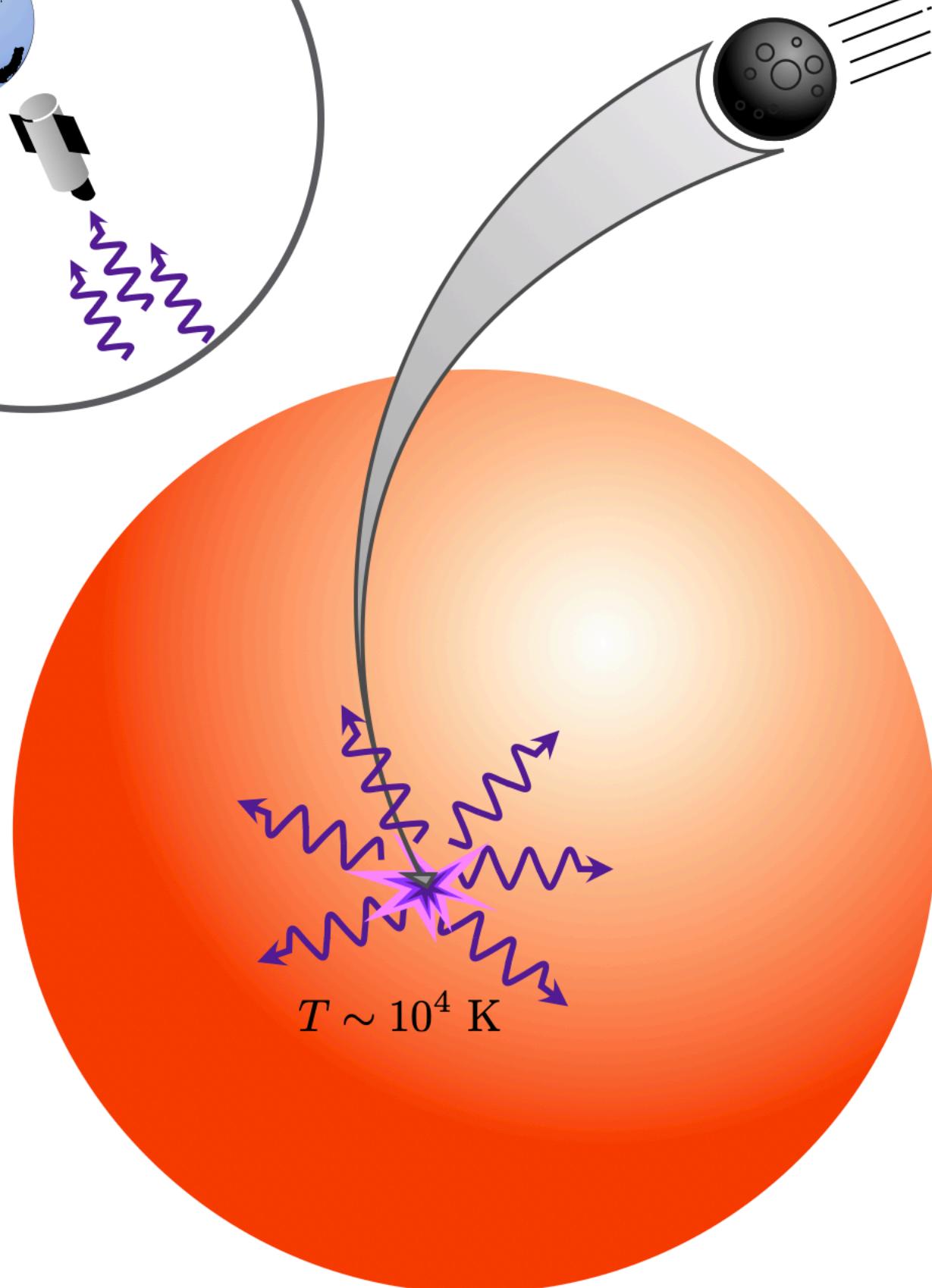
- Point to region with high $\Gamma \propto \rho_{\text{DM}}/v_{\text{DM}}$
- Requires dedicated search with powerful UV telescope
- Multiple kpc away, so targets high M_{DM}
- Events very energetic, background negligible



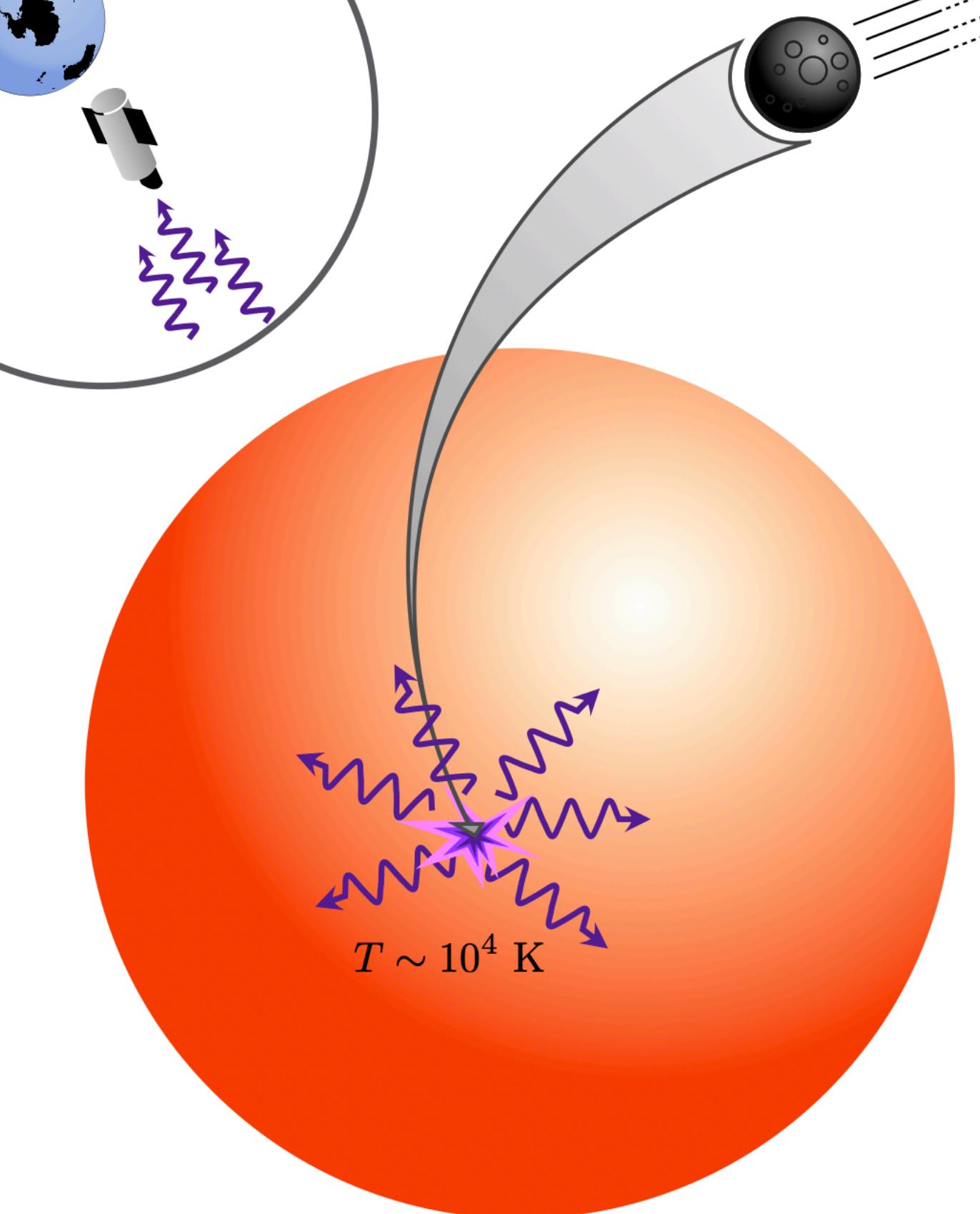
Local search: planned UV transient telescope **ULTRASAT**, nearby K dwarfs

Focused search: Hubble Space Telescope, core of globular cluster 47 Tuc

Future Directions



- Other star types (brown dwarf) and telescopes (LSST)?
- Constraints with archival data?
- Other focused searches (galactic center, Milky Way satellites, other globular clusters)?
- Hydrodynamic simulation of shock propagation and subsequent cooling?



Questions?

