Stellar Shocks From Dark Asteroids

Kevin Zhou

Stanford University

SLAC

arXiv: 2106.xxxxx
with Anirban Das, Sebastian Ellis, Philip Schuster

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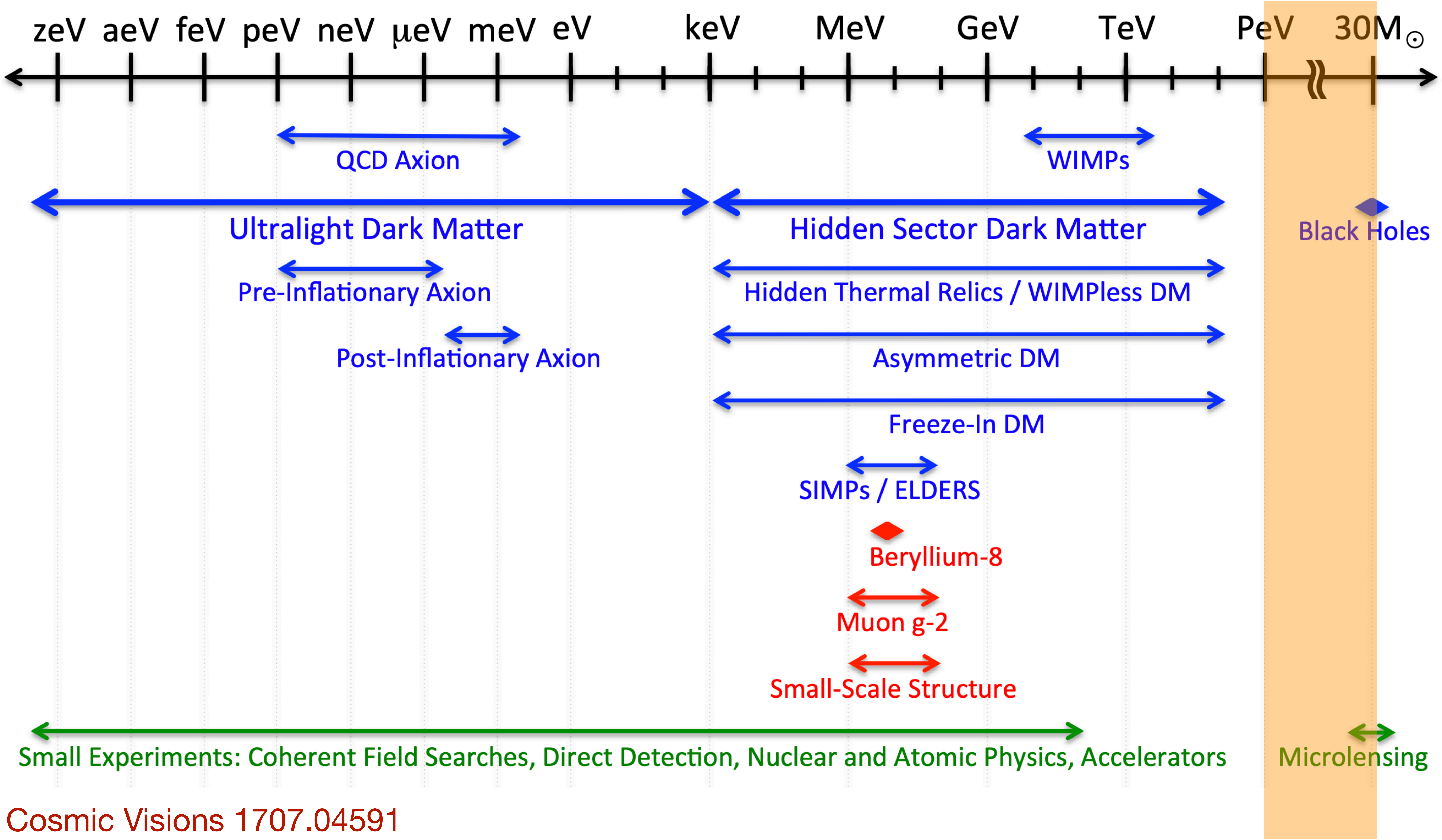
90 Orders of Magnitude



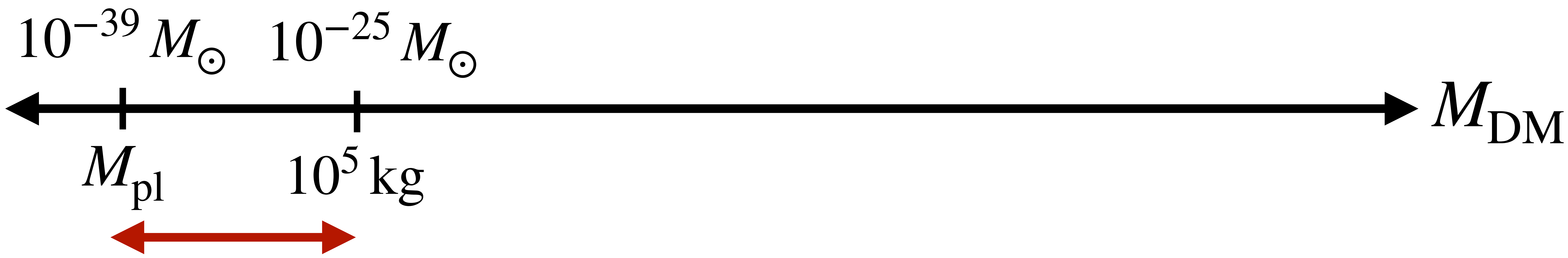
Cosmic Visions 1707.04591

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

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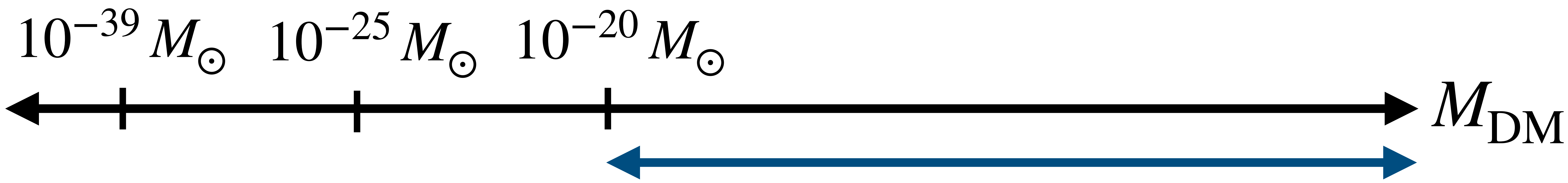

For higher masses, too rare to detect on Earth, $\Gamma \lesssim 1/(10^4\,\mathrm{yr})$

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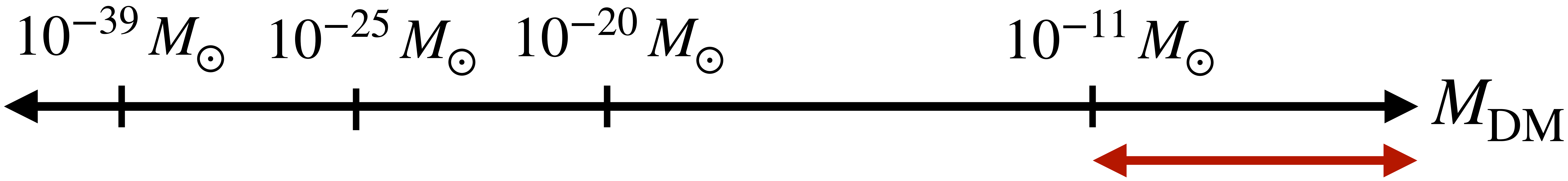

Highest masses excluded by gravitational lensing

1701.02151

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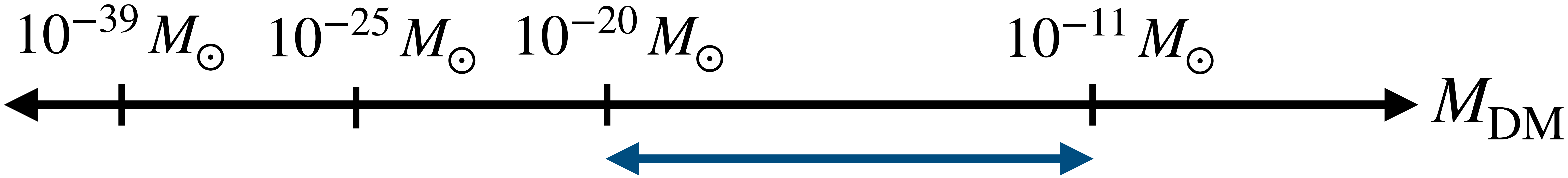
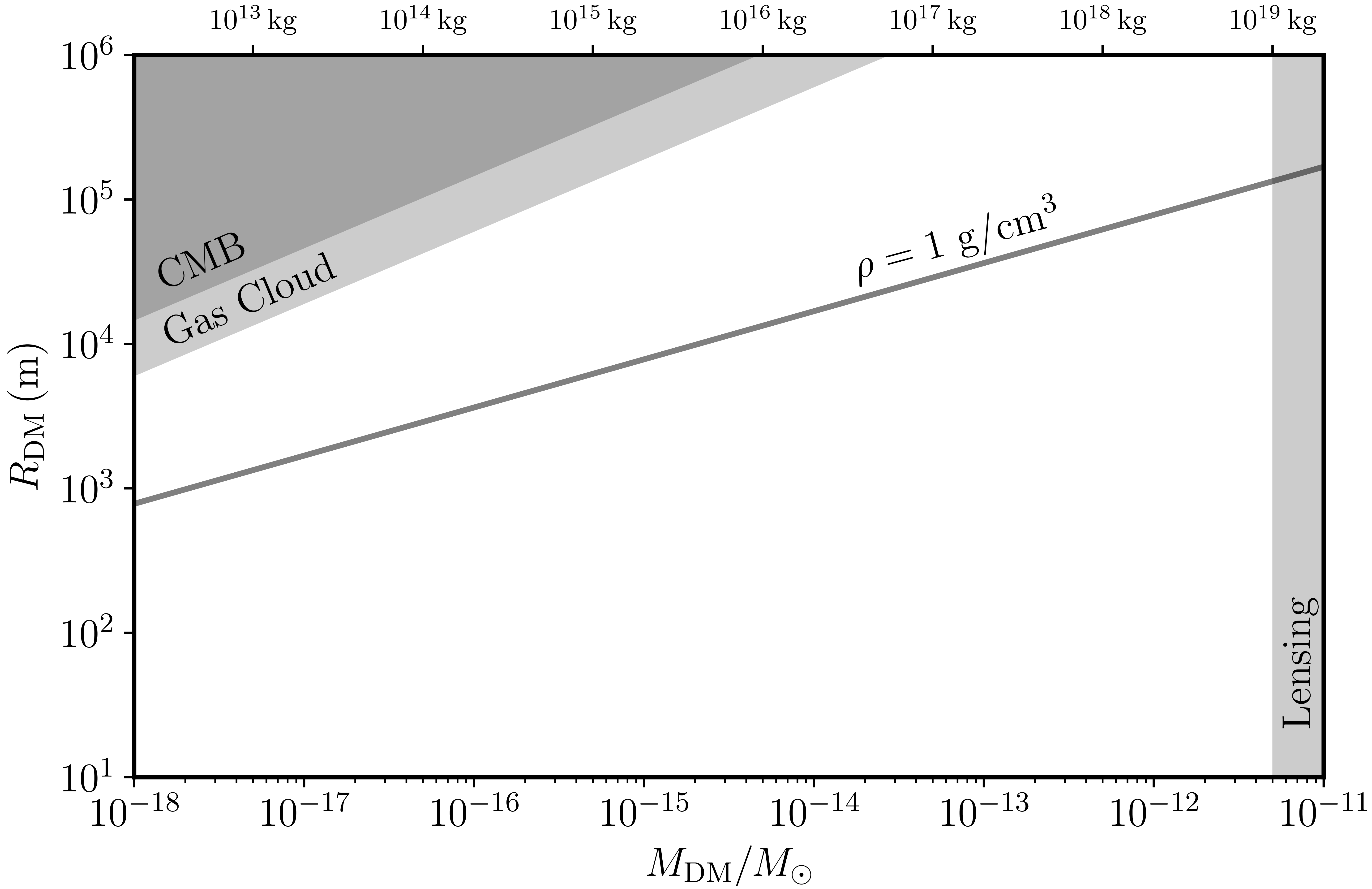
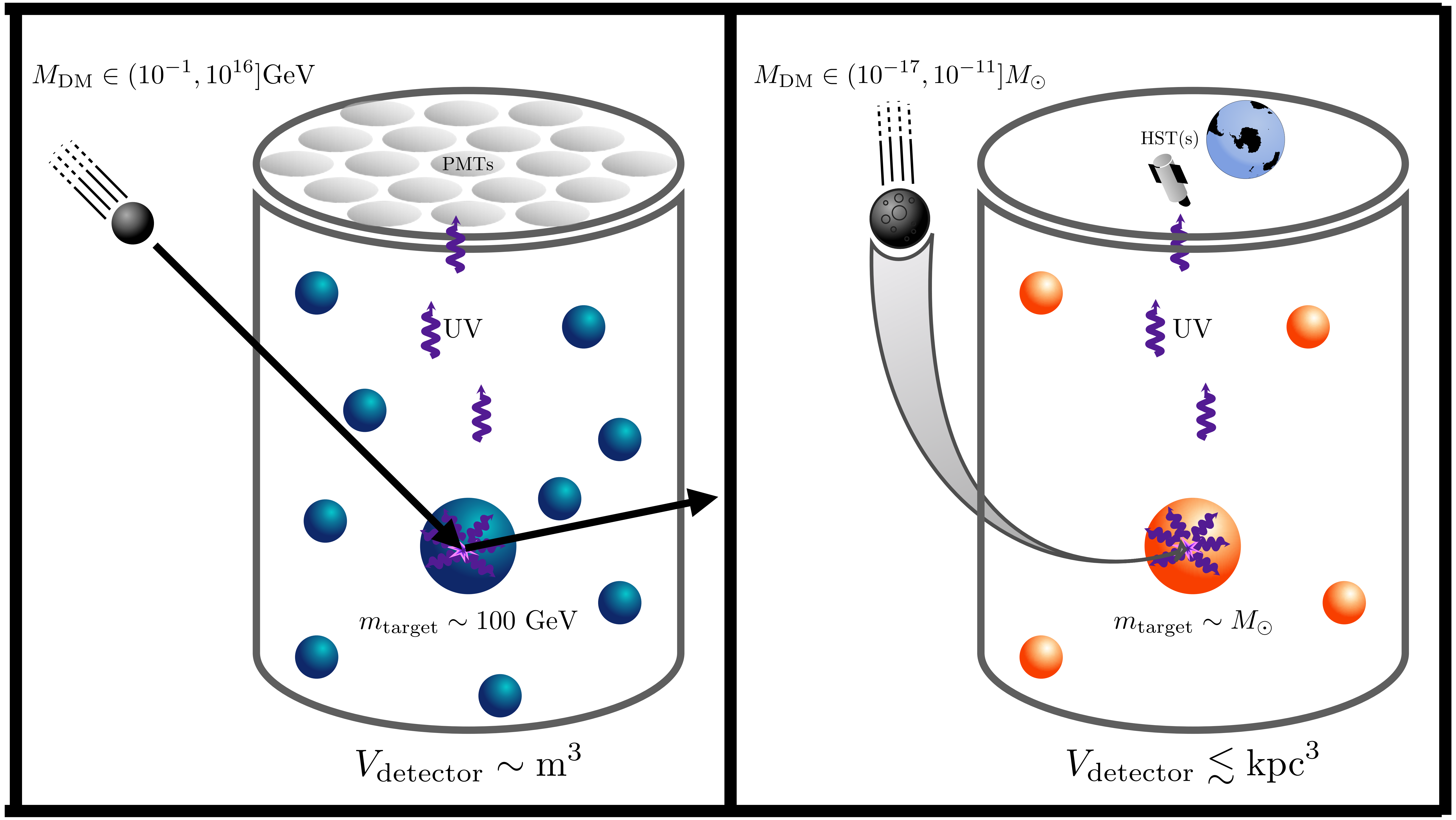


A relatively unconstrained “dark asteroid” range



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

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



Naive Estimates

Rate per star:

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

Energy dissipated in star:

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

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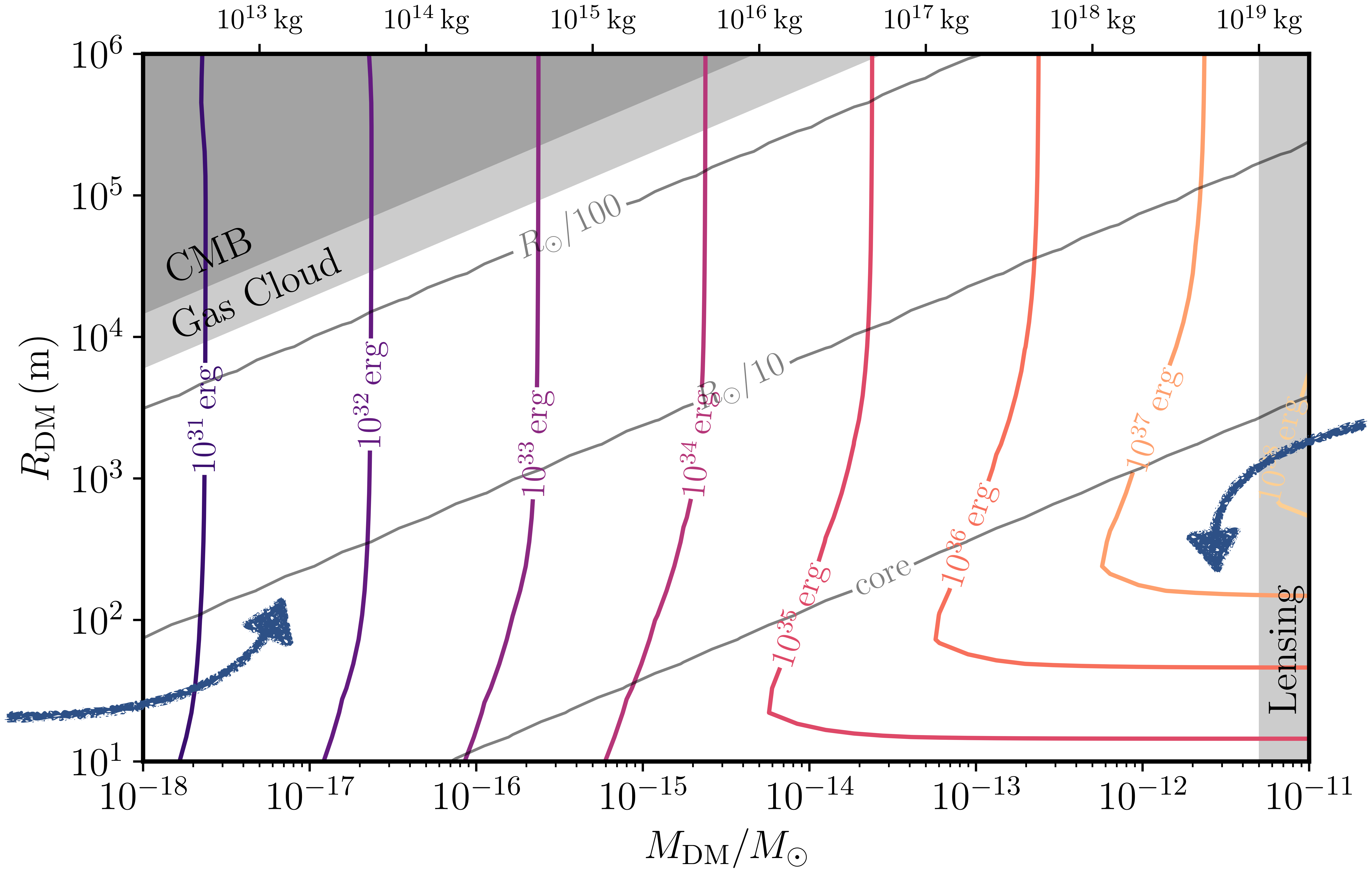
Average power ΓE_{DM} negligible, but E_{DM} high, potentially observable as strong transient



Energy **dissipated** in star

Penetration depth

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

Taking geometric cross section $\sigma = \pi R_{\mathrm{DM}}^2$, 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

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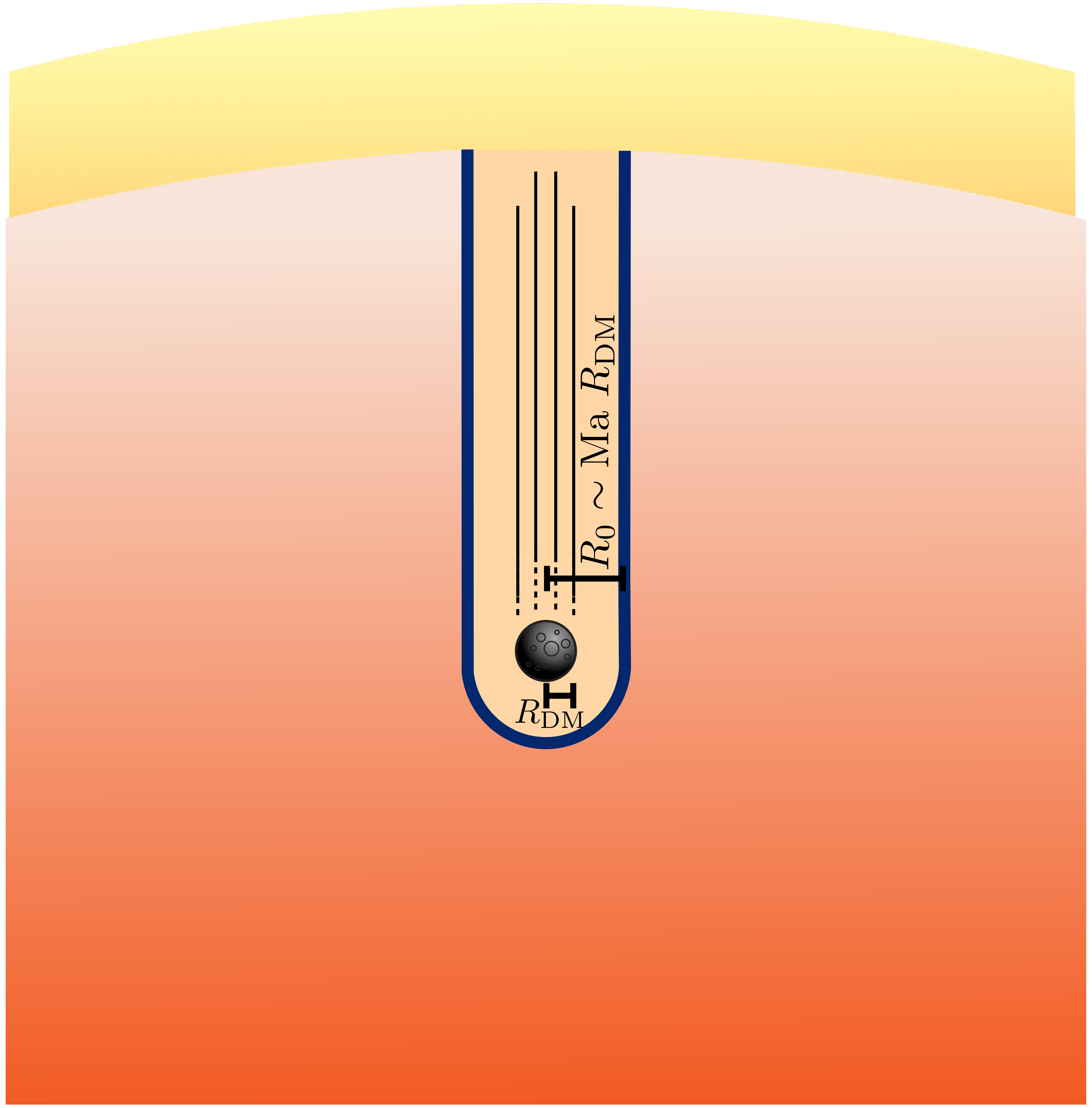
A complicated hydrodynamic problem, but solvable with controlled approximations known for decades

Whitham (1956), ReVelle (1976)

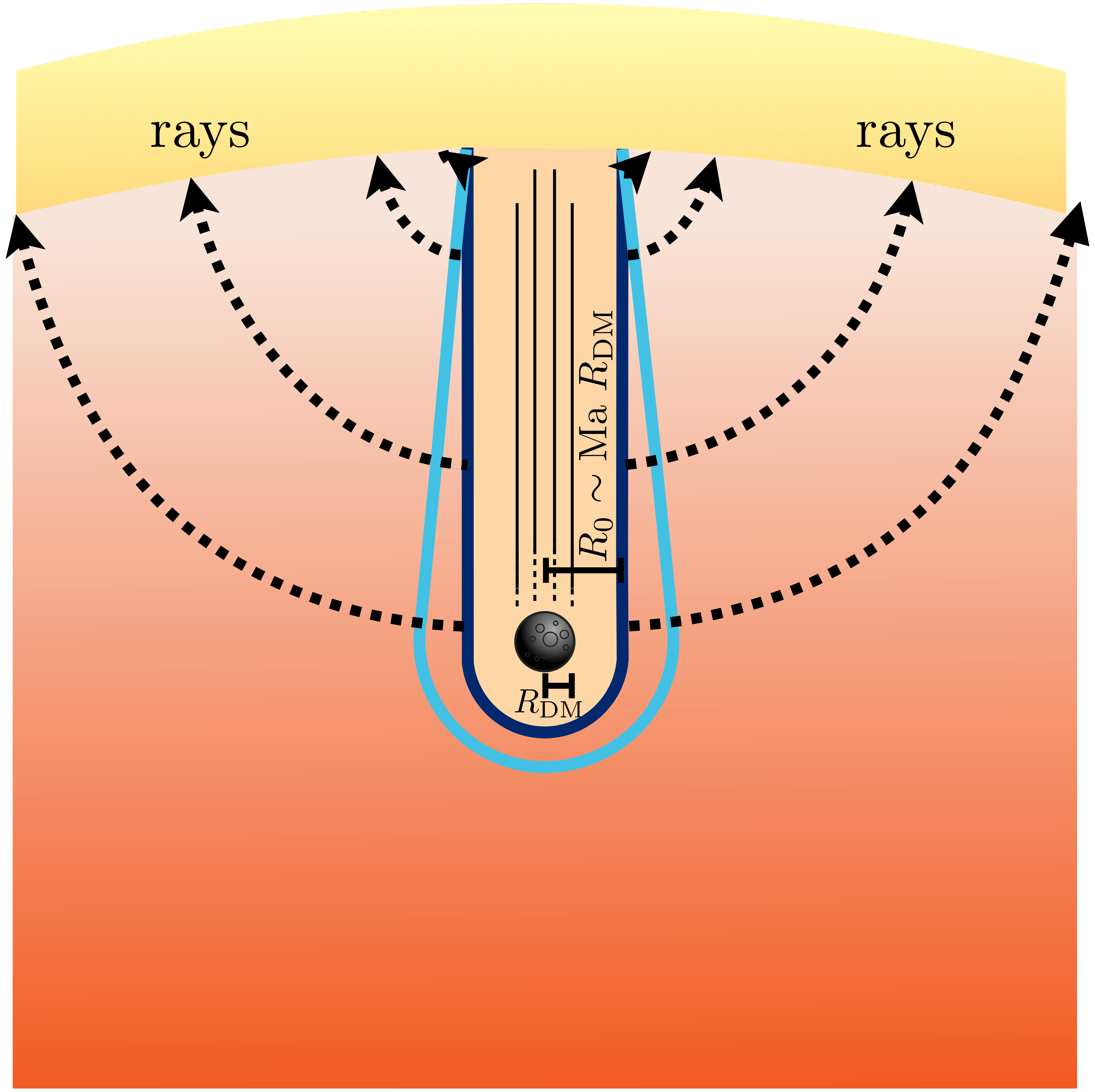
How the Energy Escapes



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

Characteristic size $R_0 \sim \mathrm{Ma}\, R_{\mathrm{DM}}$

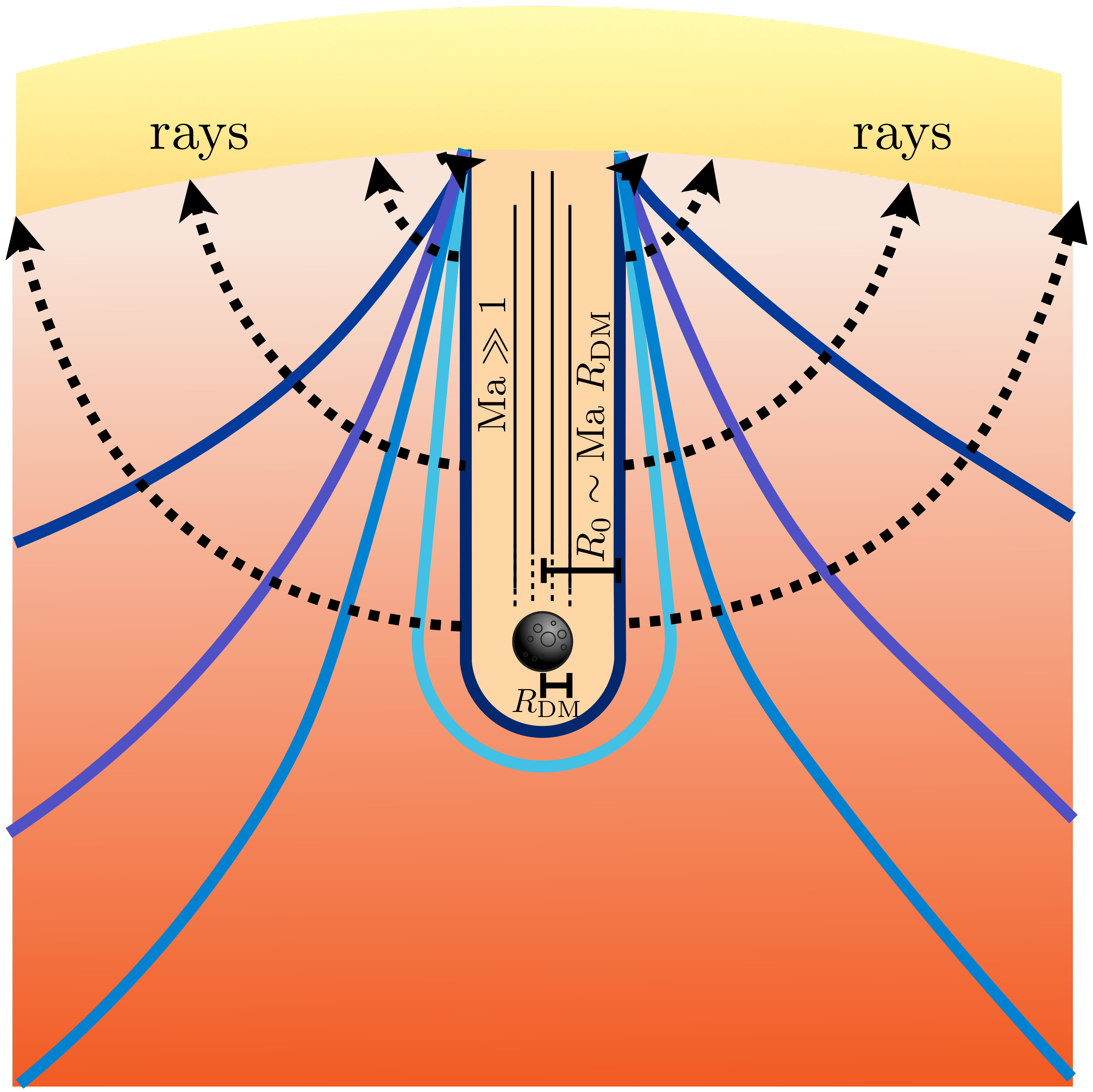
How the Energy Escapes



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

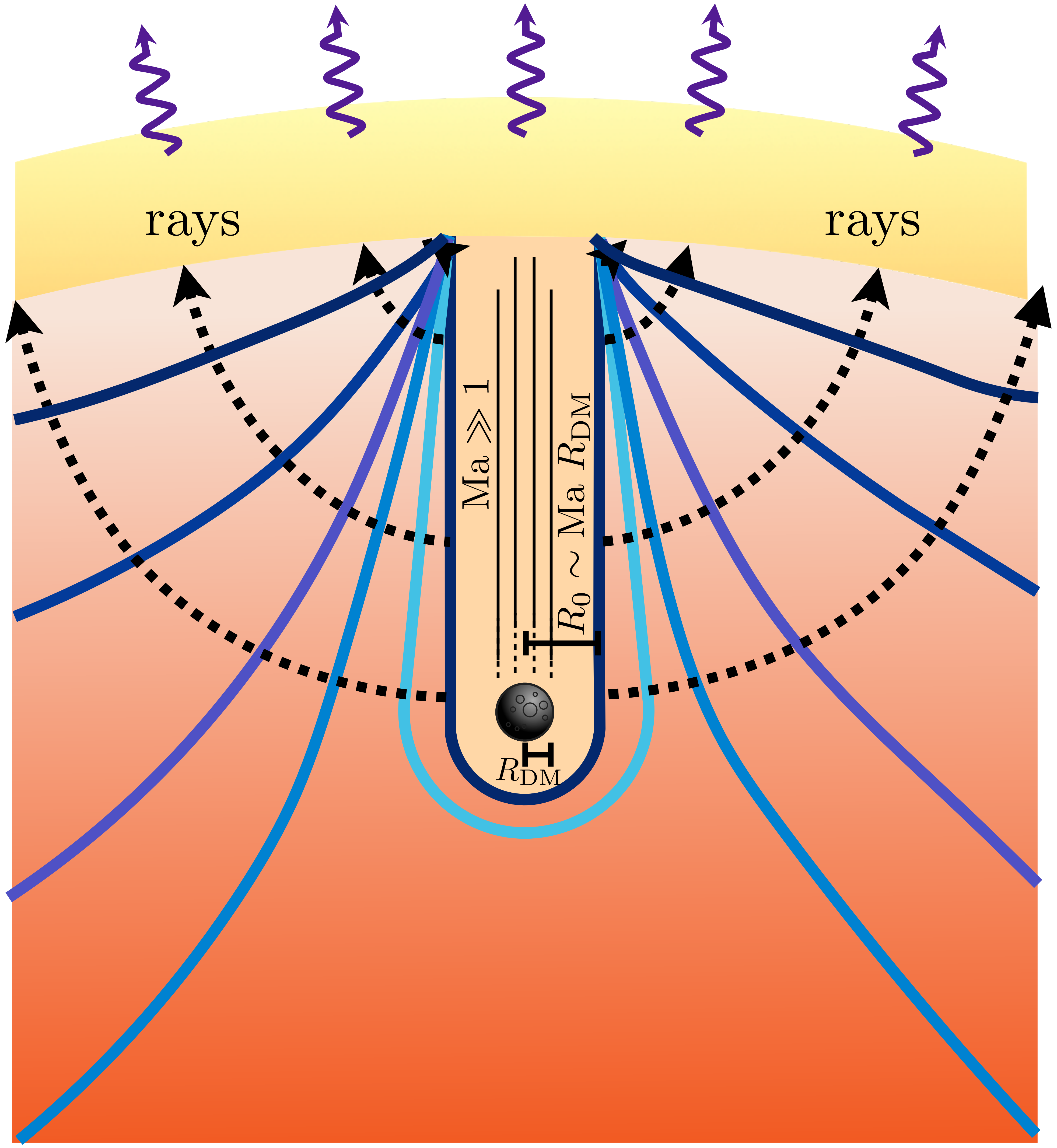
Rays refract radially outward

How the Energy Escapes

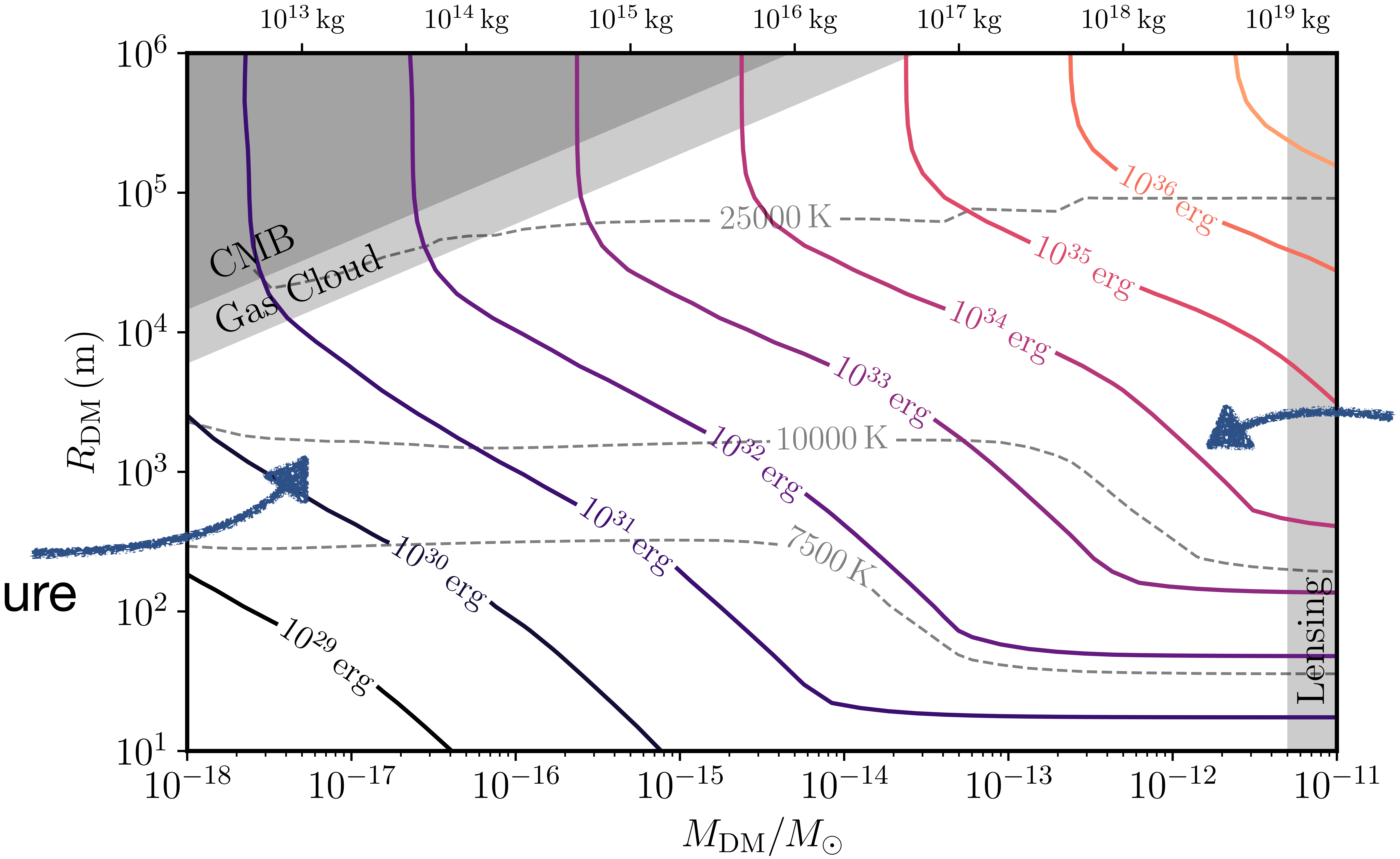


Weak shock waves lose energy, but grow in strength as they approach the stellar surface

How the Energy Escapes



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

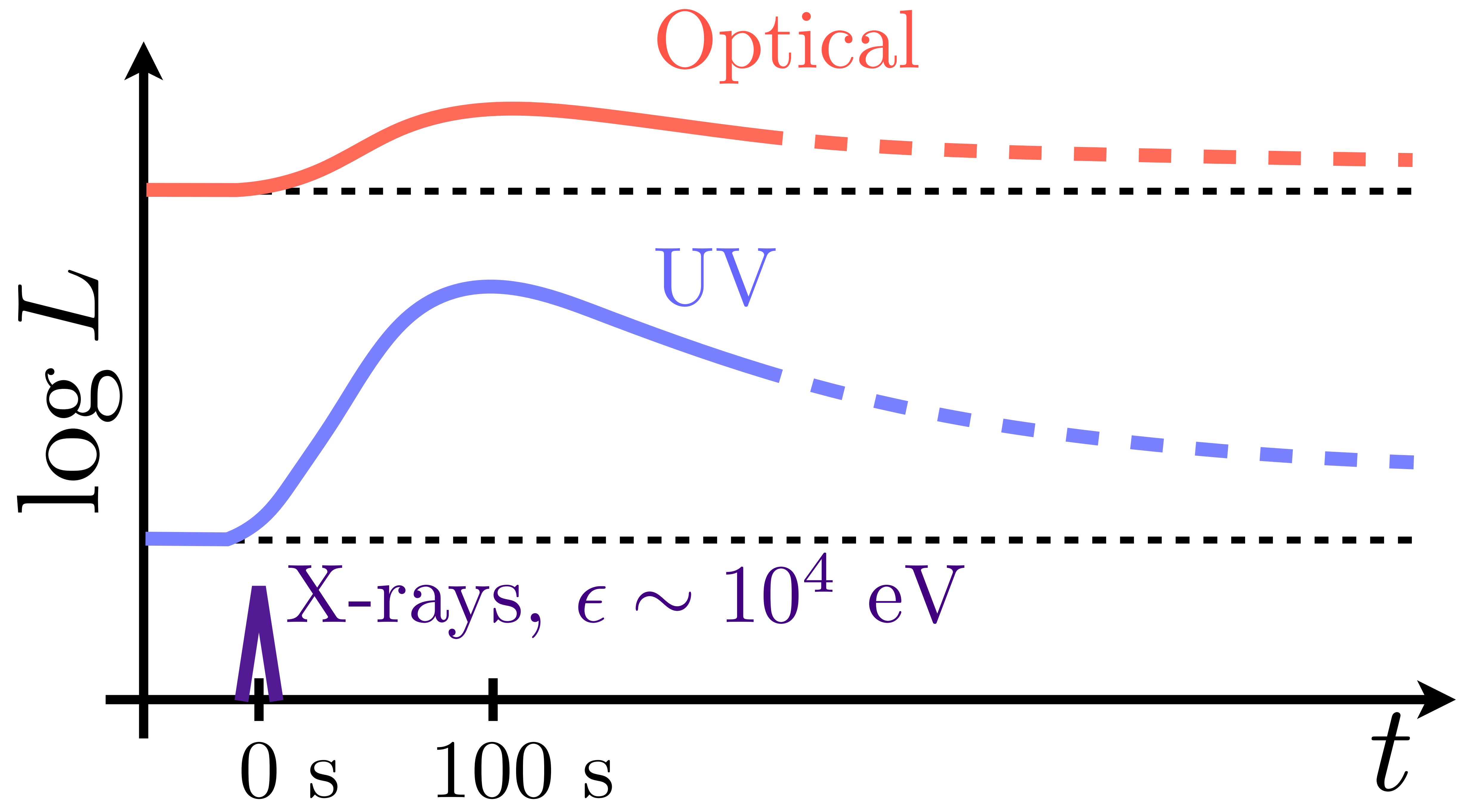


Typical shocked surface temperature

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

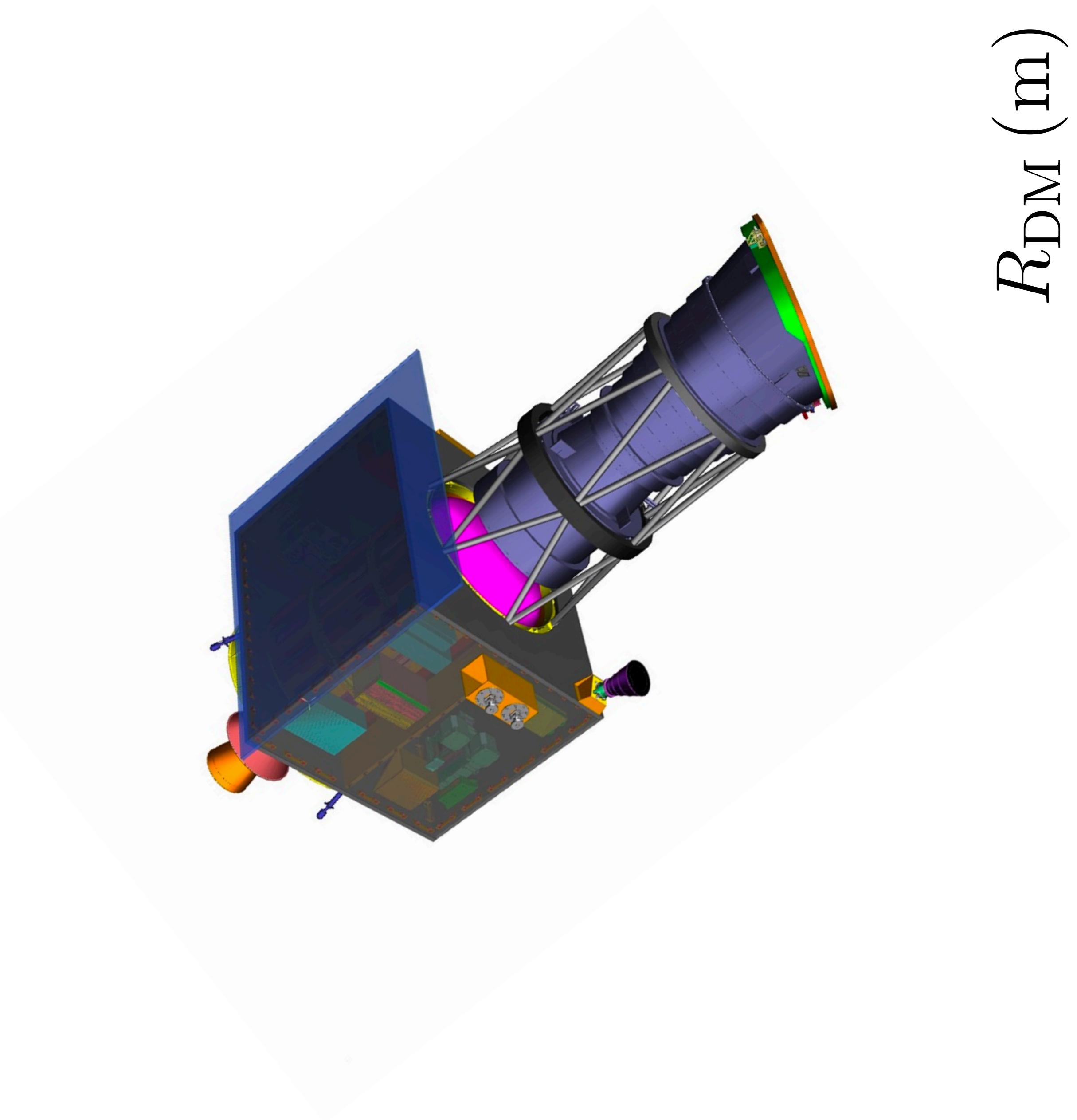
Search Strategies

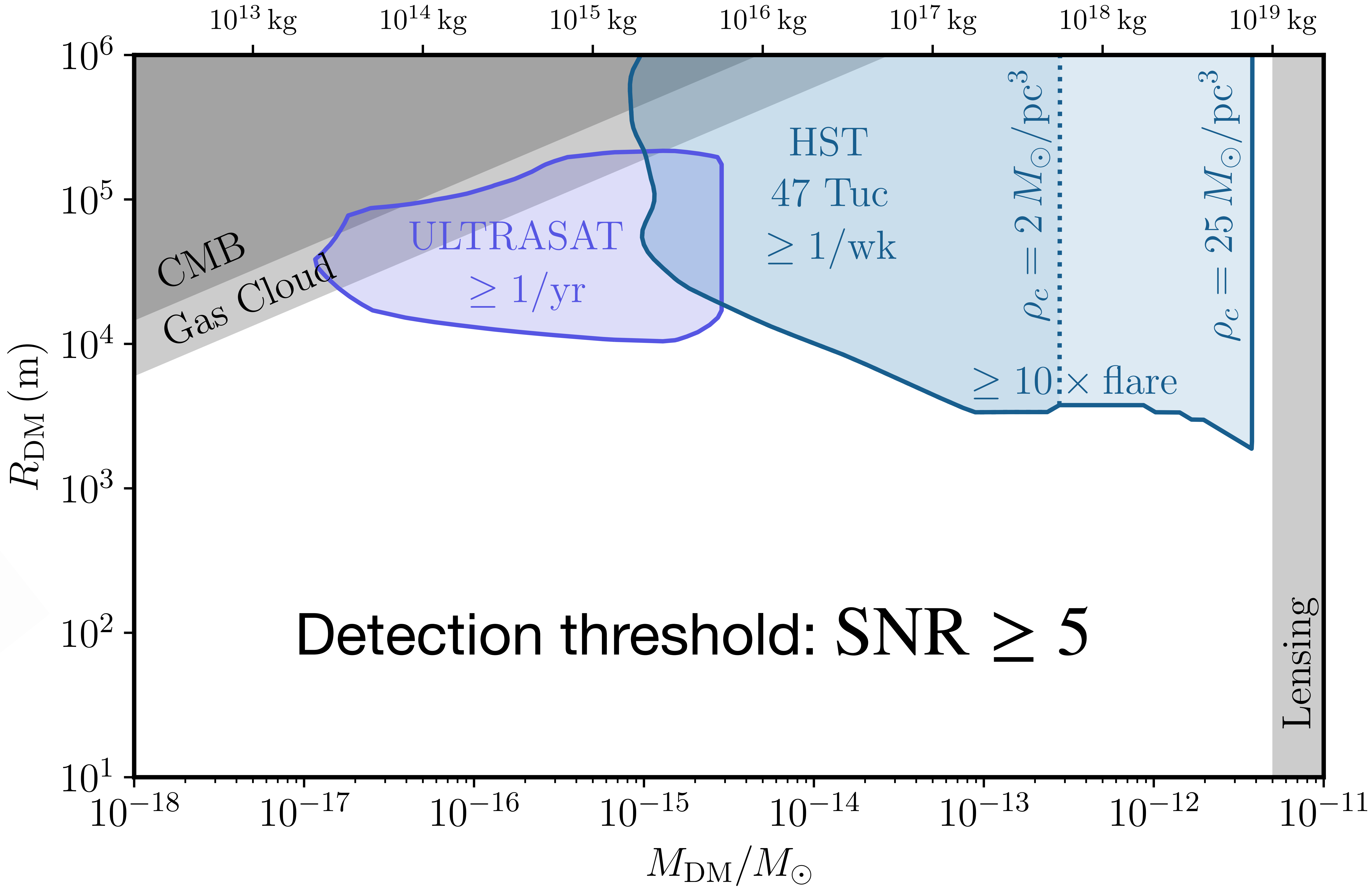
Local search

- Wide field search for transients on nearby (within $1\,\mathrm{kpc}$) 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 $\Gamma \propto \rho_{\mathrm{DM}}/v_{\mathrm{DM}}$
- Requires dedicated search with powerful UV telescope
- Multiple kpc away, so targets high M_{DM}
- Events very energetic, background negligible

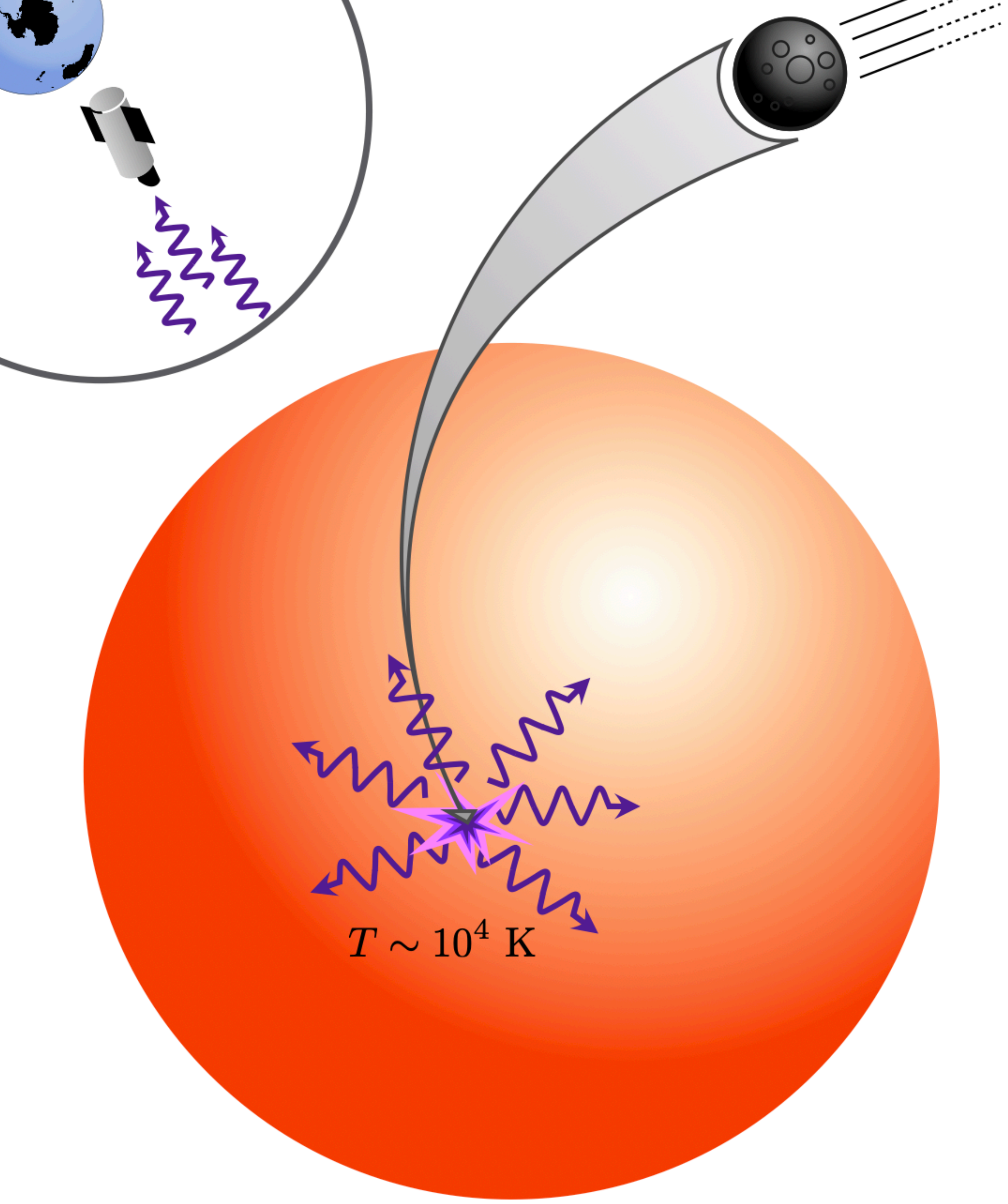




Local search: planned UV transient telescope ULTRASAT, nearby K dwarfs

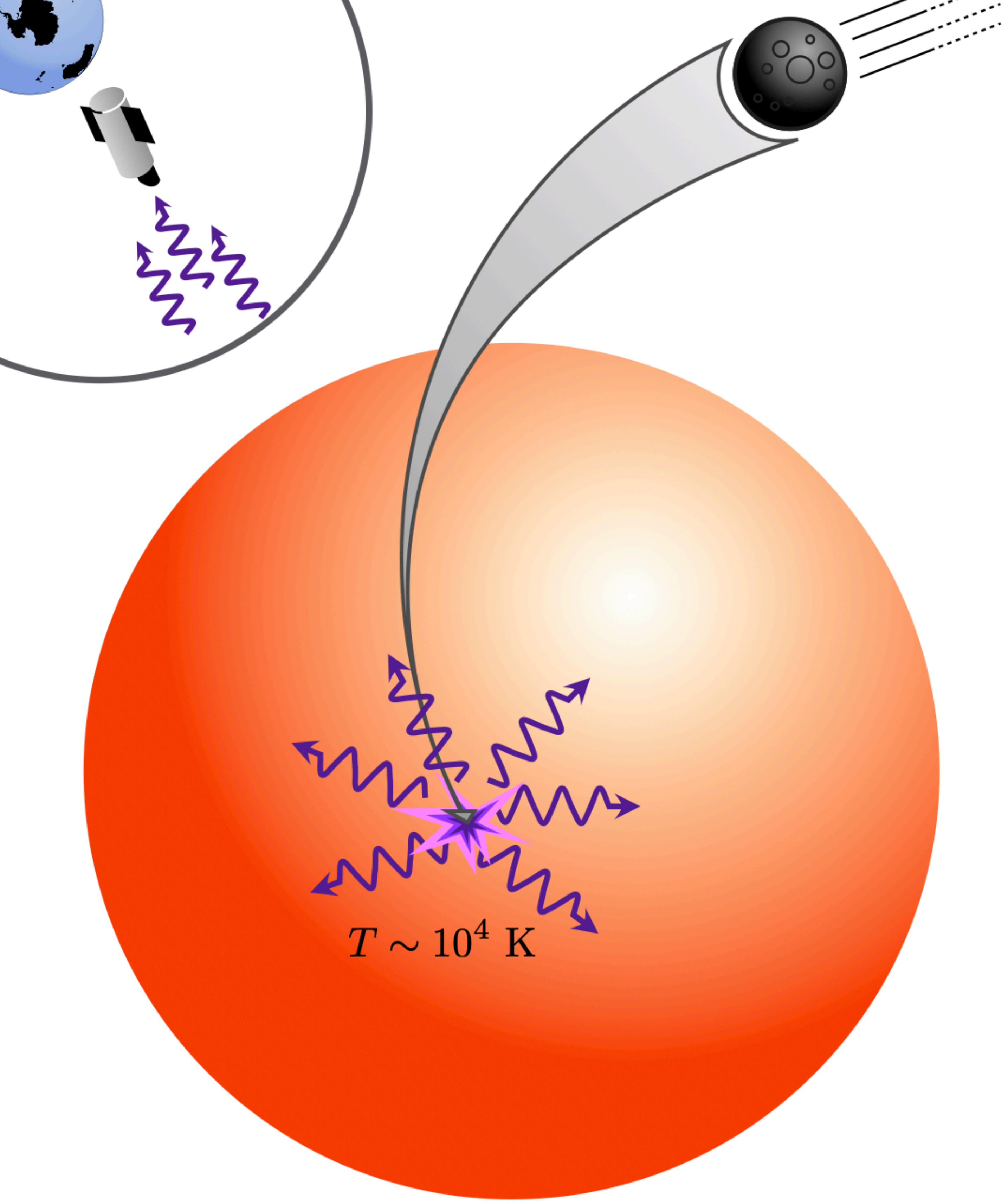
Focused search: Hubble Space Telescope, core of globular cluster 47 Tuc

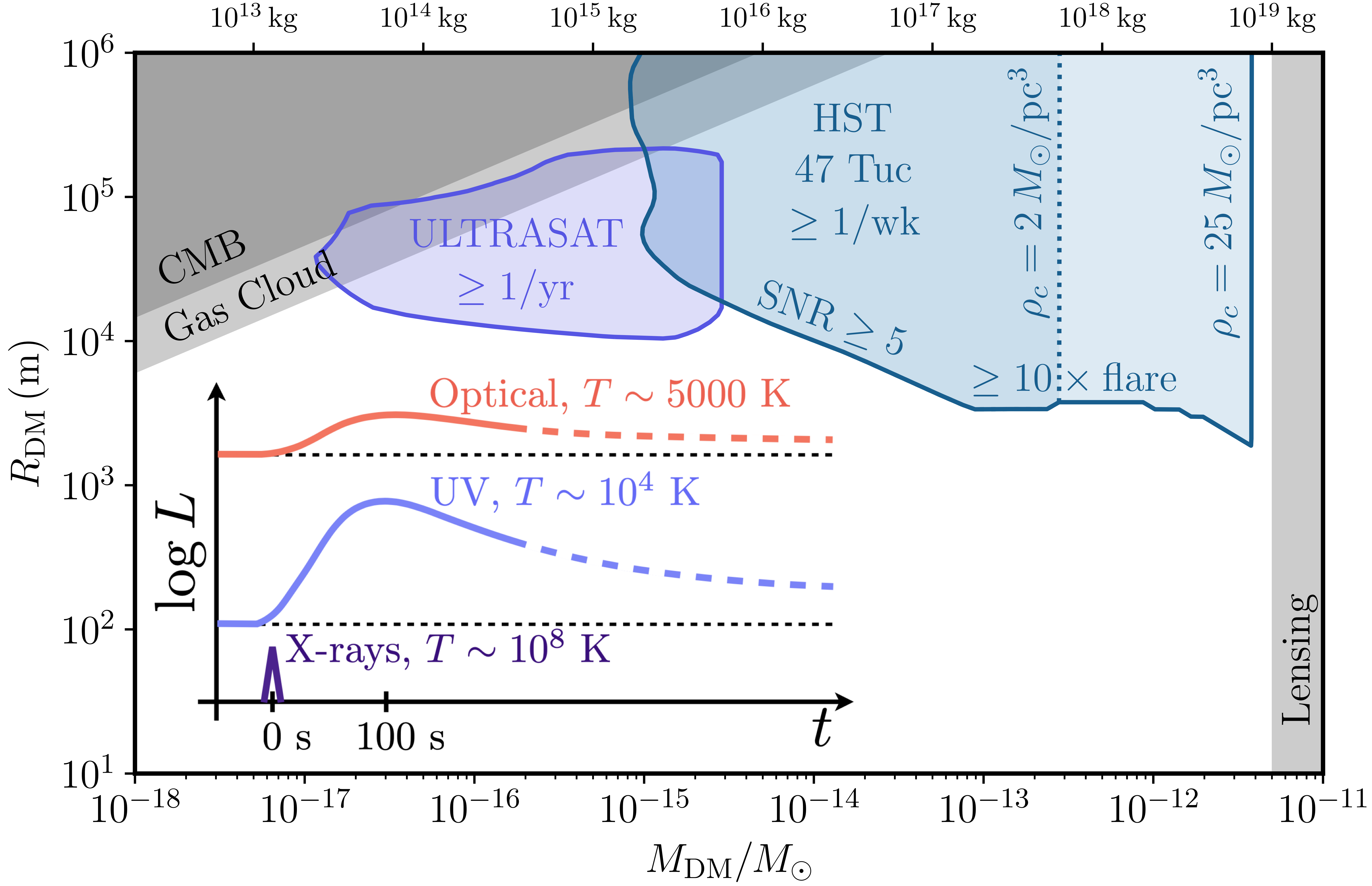
Future Directions



- 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?


$T \sim 10^4$ K


10^{13} kg
10^{14} kg
10^{15} kg
10^{16} kg
10^{17} kg
10^{18} kg
10^{19} kg
R_{DM} (m)
10^1
10^2
10^3
10^4
10^5
10^6
10^{-18}
10^{-17}
10^{-16}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
$M_{\mathrm{DM}}/M_\odot$
CMB
Gas Cloud
ULTRASAT
$\geq 1/\mathrm{yr}$
HST
47 Tuc
$\geq 1/\mathrm{wk}$
SNR ≥ 5
$\rho_c = 2\ M_\odot/\mathrm{pc}^3$
$\rho_c = 25\ M_\odot/\mathrm{pc}^3$
$\geq 10 \times$ flare
Lensing
$\log L$
Optical, $T \sim 5000$ K
UV, $T \sim 10^4$ K
X-rays, $T \sim 10^8$ K
0 s
100 s
t