Dynamics of solar system bound WIMPs

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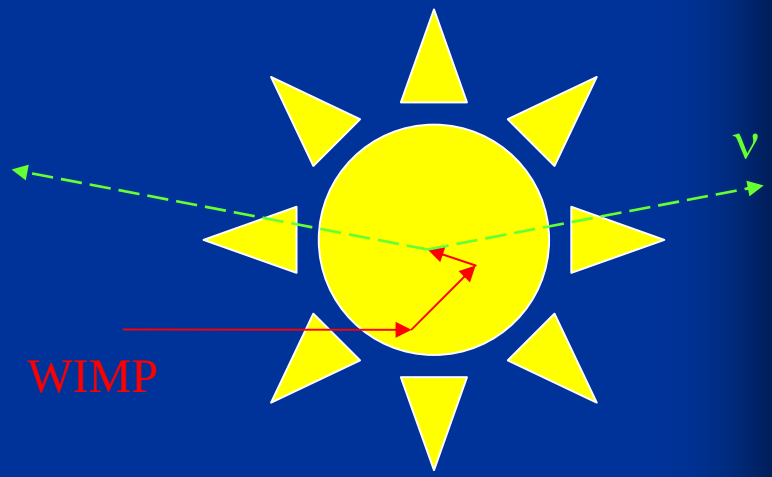
Overview

- Indirect detection of WIMPs from neutrinos

  Silk & Srednicki (1984)
  Silk, Olive & Srednicki (1985)
  Freese (1986)



- Gravitational capture

some stuff happens

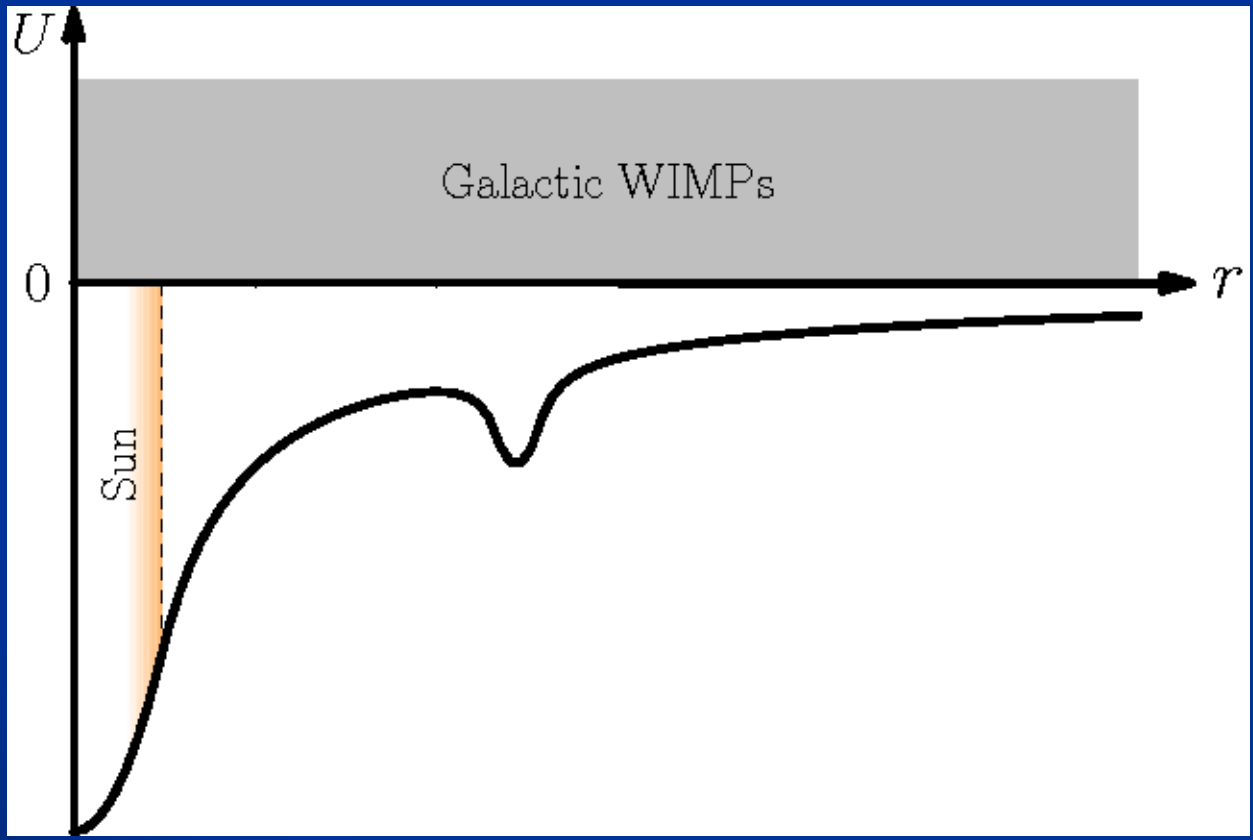
→ Annihilation

  - Neutrino-induced muons
  - Sun: WIMP-proton cross-section
  - Baksan, Super-K, ANTARES, AMANDA, IceCube, etc.

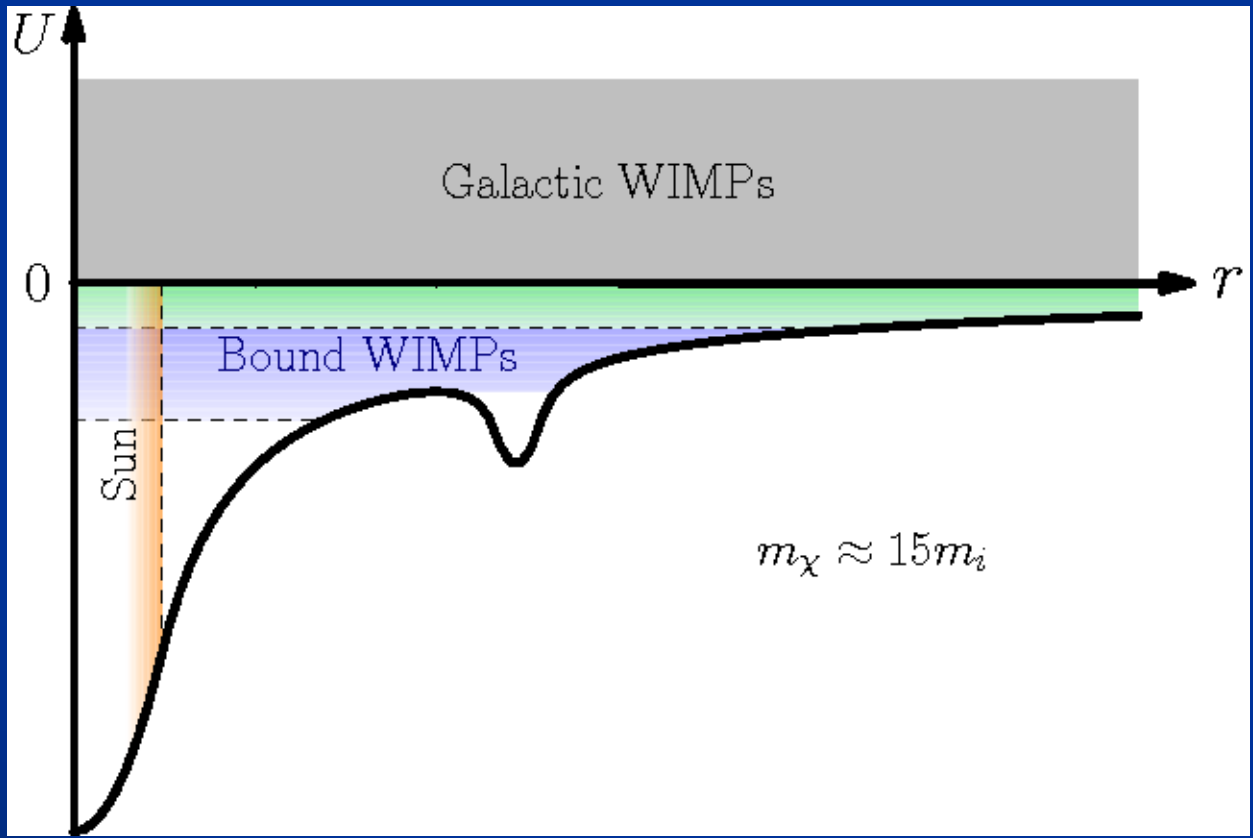
Outline

- Initial capture
- Subsequent scatters (infall)
- Gravitational scatter from planets
- Gravitational perturbations
- Non- Sun crossing, bound WIMP populations

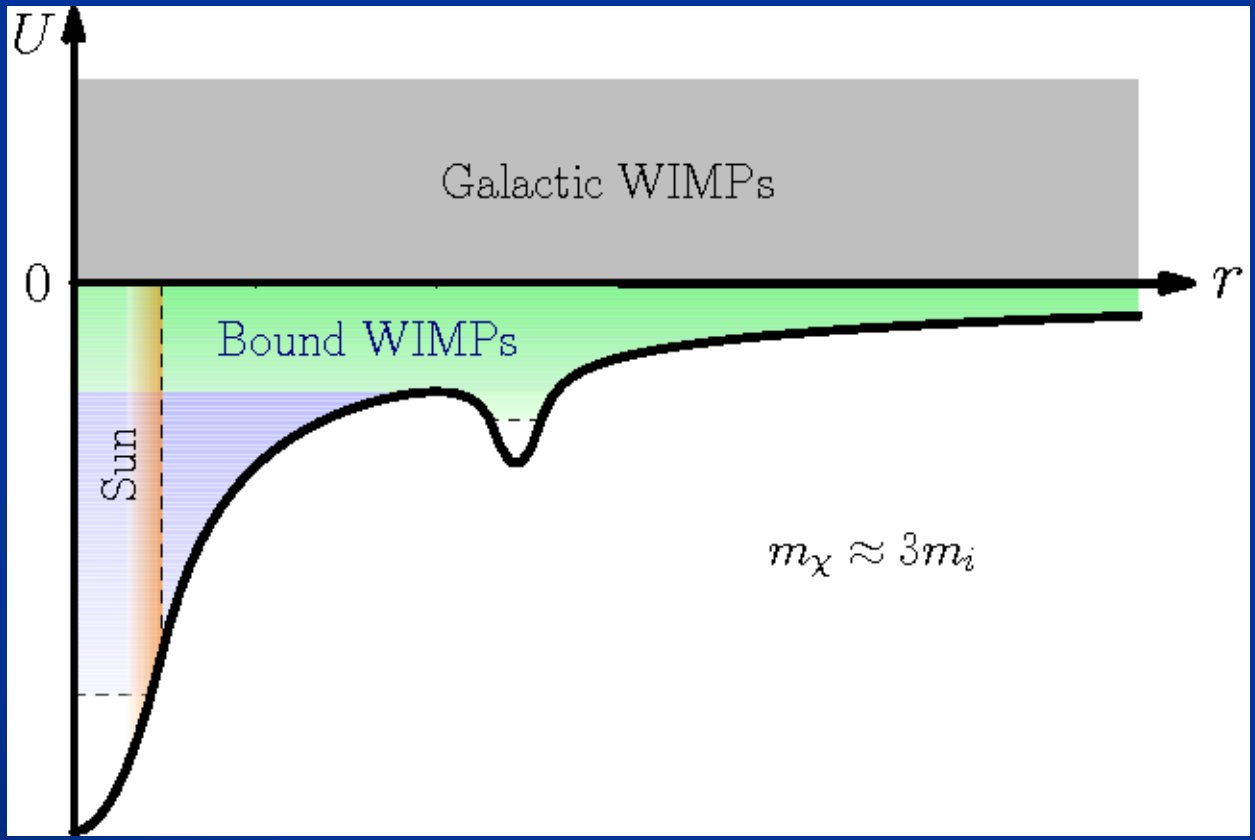
Solar Potential



Initial Scatter: Heavy WIMP



Initial Scatter: Light WIMP



Solar Elements

Element	Mass Abundance	Capture (SI) $(m_\chi = 1000\,\mathrm{GeV})$
Hydrogen	71.3%	
Helium	27.3	
Carbon	0.245	
Nitrogen	0.0788	
Oxygen	0.652	
Neon	0.124	
Magnesium	0.073	
Silicon	0.081	
Sulfur	0.041	
Iron	0.140	

Solar Elements

Element	Mass Abundance	Capture (SI) $(m_\chi = 1000\,\mathrm{GeV})$
Hydrogen	71.3%	0.096%
Helium	27.3	8.84
Carbon	0.245	4.85
Nitrogen	0.0788	2.58
Oxygen	0.652	31.8
Neon	0.124	10.9
Magnesium	0.073	8.94
Silicon	0.081	11.6
Sulfur	0.041	6.17
Iron	0.140	14.2

$$\times\left(1+\frac{\sigma_{\mathrm{SD,p}}}{\sigma_{\mathrm{SI,p}}}\right)$$

Solar Elements

- Scattering cross-section:

$$\sigma_i \approx A^2 \sigma_{SI,N} \qquad (m_\chi \sim m_i)$$

$$\sigma_i \approx A^4 \sigma_{SI,N} \qquad (m_\chi >> m_i) \qquad \text{e.g.} \quad \sigma_{\mathrm{Fe}} \sim 10^7 \sigma_{SI,p}$$

- Energy loss (ξ is specific energy):

$$\left|\Delta\xi\right| \sim \beta_{i,+} \equiv \frac{4 m_\chi m_i}{(m_\chi + m_i)^2} \sim \frac{4 m_i}{m_\chi} \text{ for } m_\chi >> m_i$$

- Heavy elements important

MSSM

- Spin-dependent WIMP-nucleon cross-section typically *O*(100-500) larger than spin-independent cross-section

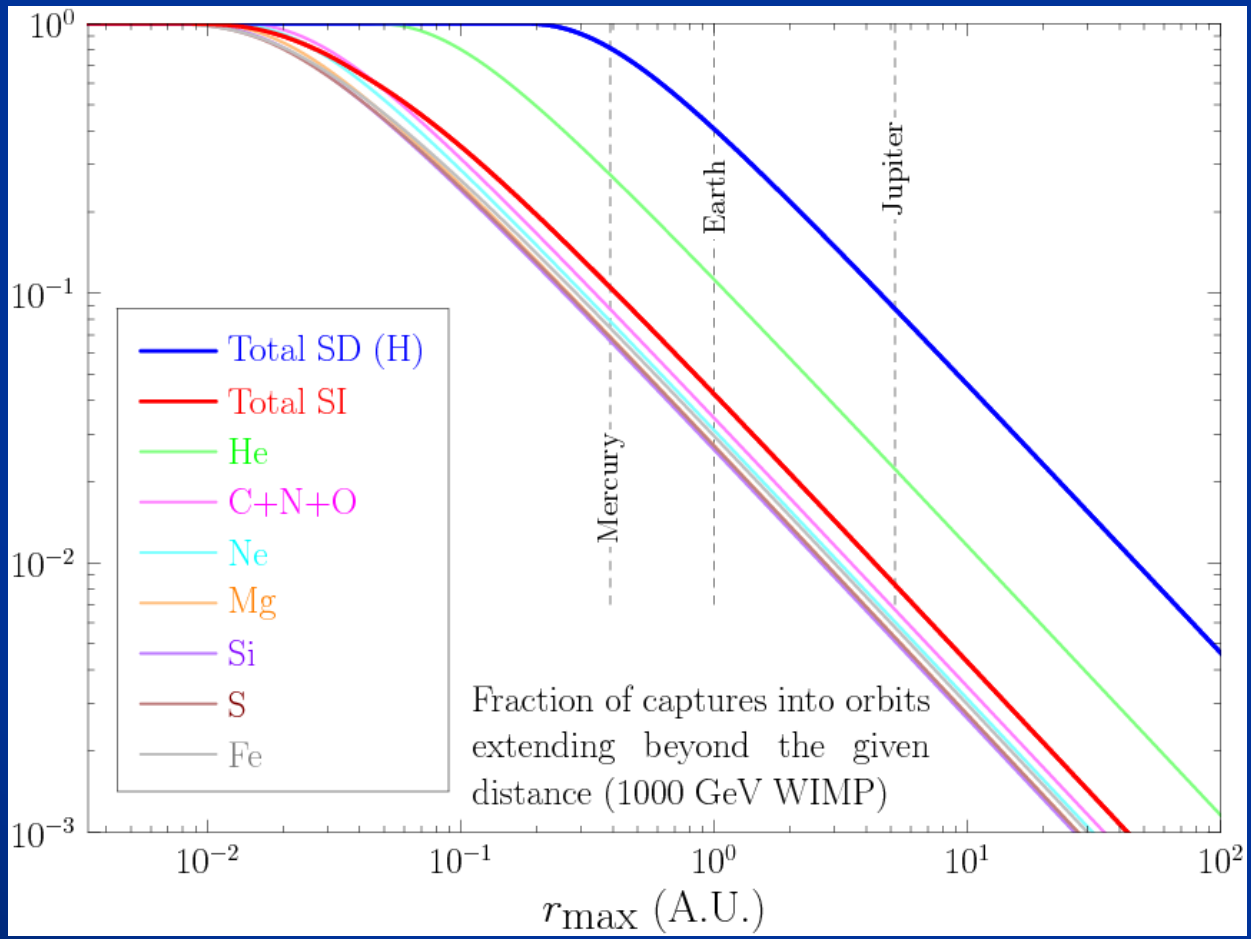
- Fiducial value:

$$\sigma_{SD,p} = 250\ \sigma_{SI,N}$$

Hydrogen/SD still only accounts for 20% of captures

Initial Orbits

$$m_\chi = 1000\,\mathrm{GeV}$$



Infall

- Annihilations occur in thermalized population of WIMPs at center of Sun

- “Thermal” capture rate:
  rate at which WIMPs come to thermal equilibrium in the Sun

  $\neq$ gravitational capture rate!

- WIMPs must infall from initial capture orbit

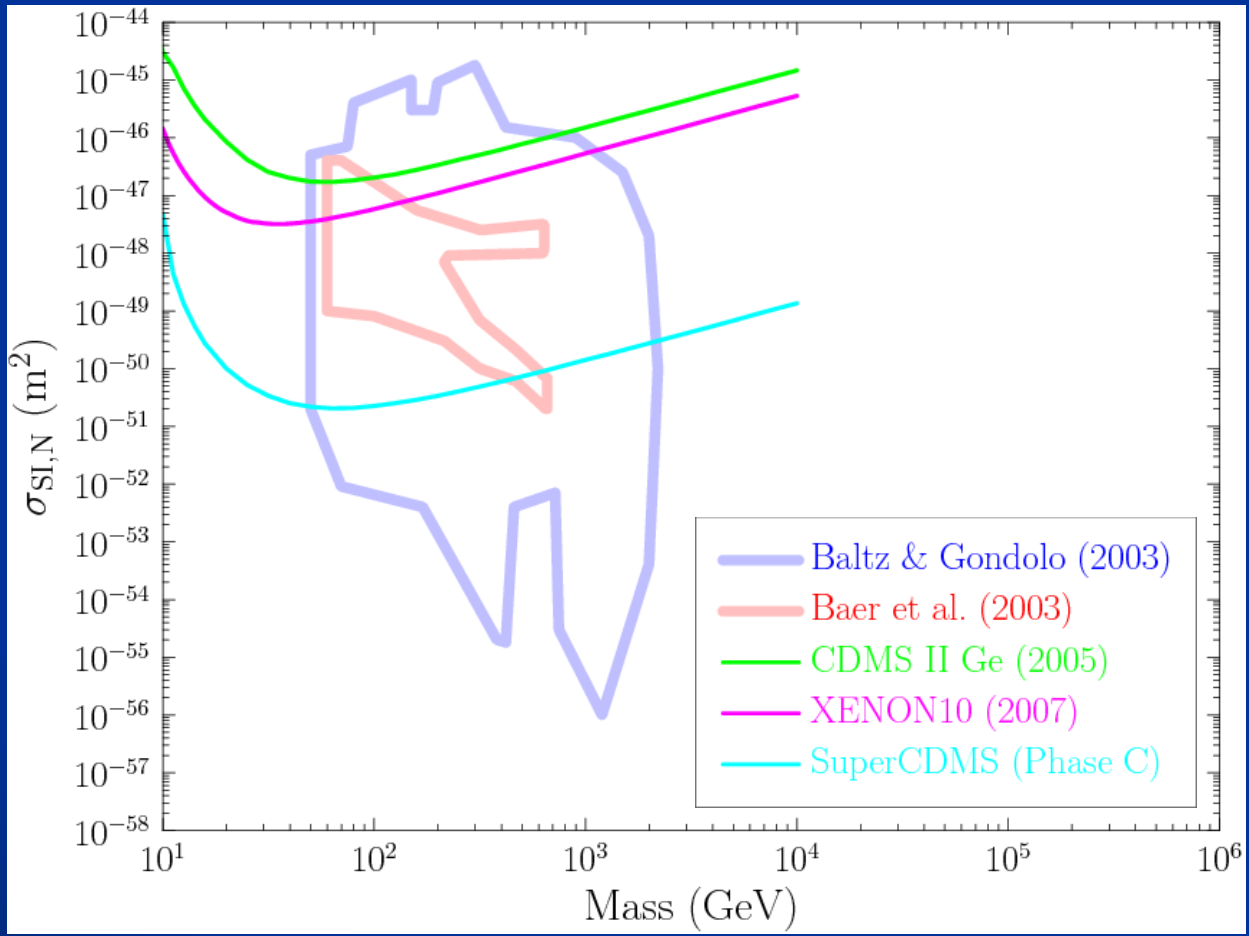
Infall

- How long does infall process take?
- Typical opacity of Sun (scatters per orbit):

$$N_{SI} \sim O(100)\left(\frac{\sigma_{SI,N}}{1\,\text{pbn}}\right) \qquad N_{SD} \sim O(1)\left(\frac{\sigma_{SD,p}}{1\,\text{pbn}}\right)$$

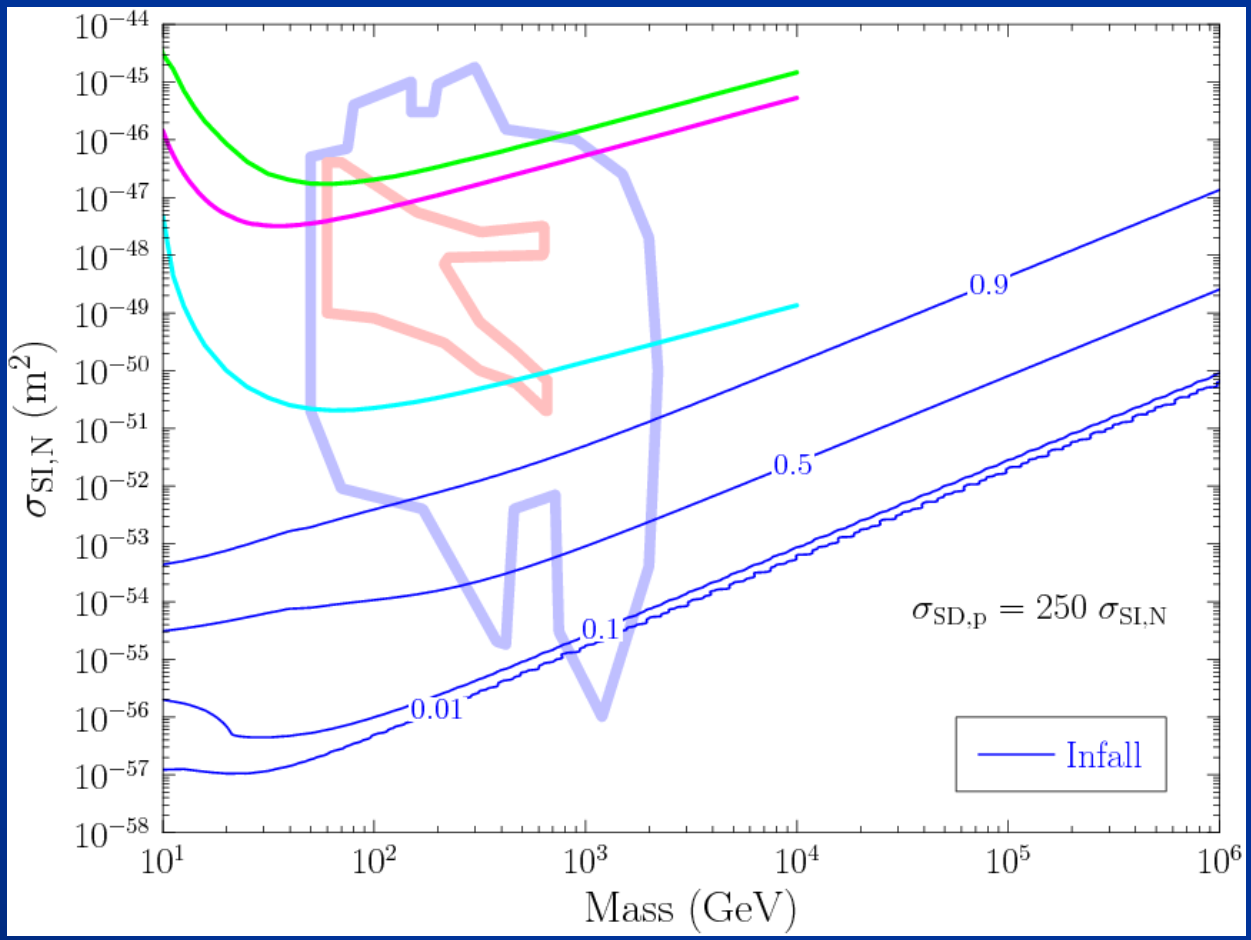
- For 10^{-10} pbn SI cross-section on Earth crossing orbit, second scatter takes ~ 100 million years
- Heavy WIMPs require more scatters to lose energy

Infall


10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-51}
10^{-52}
10^{-53}
10^{-54}
10^{-55}
10^{-56}
10^{-57}
10^{-58}
$\sigma_{SI,N}$ (m^2)
10^1
10^2
10^3
10^4
10^5
10^6
Mass (GeV)
Baltz & Gondolo (2003)
Baer et al. (2003)
CDMS II Ge (2005)
XENON10 (2007)
SuperCDMS (Phase C)

Infall

$$\sigma_{SD,p} = 250\,\sigma_{SI,N}$$



ratio of thermal capture to gravitational capture
(contours at 0.9, 0.5, 0.1, 0.01)

Infall (SD population)

Initial orbits from SD interactions:

Smaller energy loss (hydrogen recoil)

$\Downarrow$

Larger orbital distances

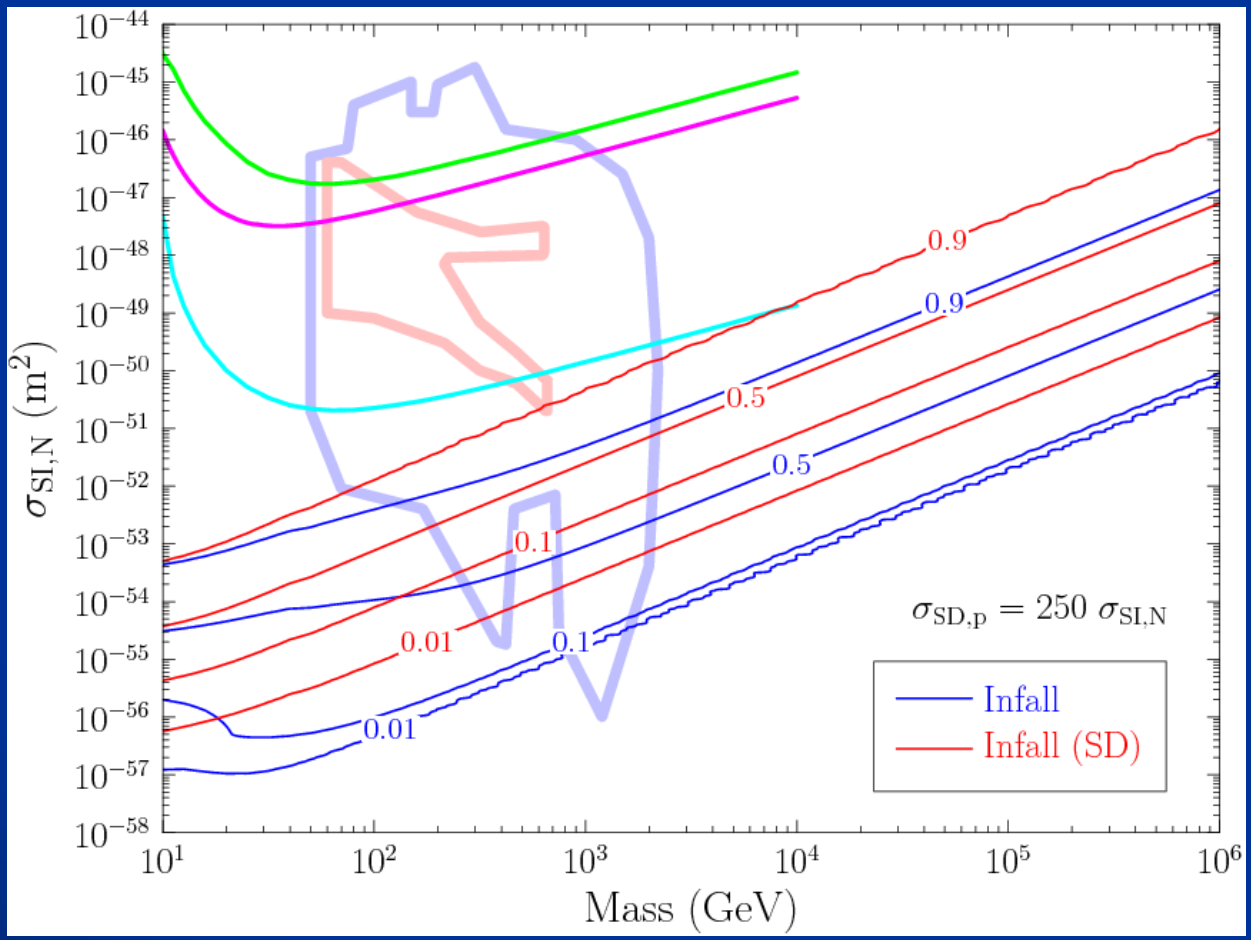
$\Downarrow$

Longer orbital times

$\Rightarrow$ Thermal capture of this population suppressed relative to SI-scatter initial orbit population

Infall (SD population)

$$\sigma_{SD,p} = 250\,\sigma_{SI,N}$$

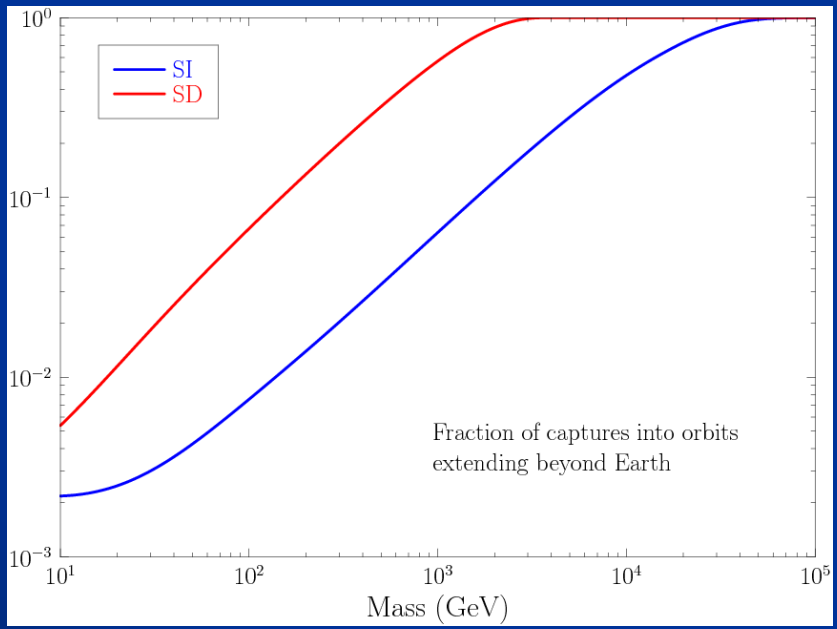


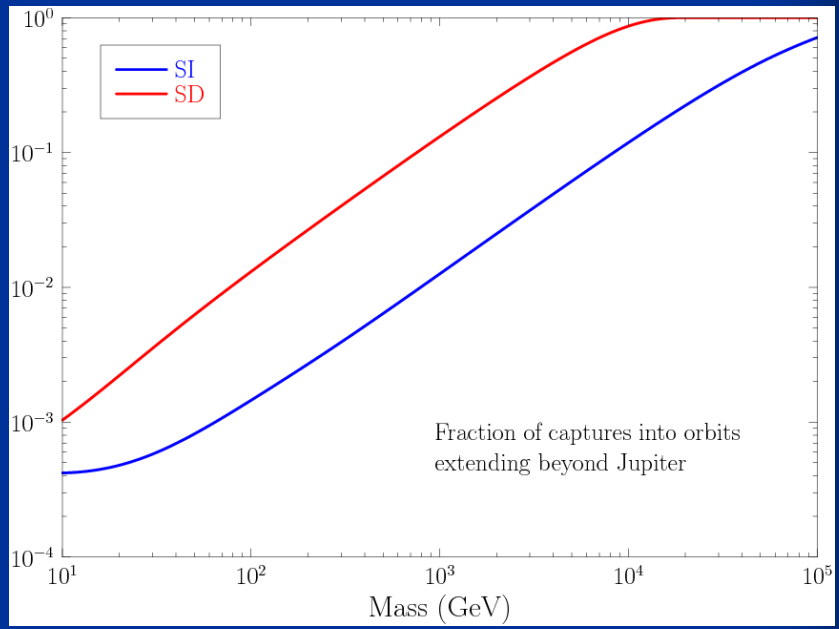
ratio of thermal capture to gravitational capture
(contours at 0.9, 0.5, 0.1, 0.01)

Infall

- Infall effects important for: $\sigma_{SI,N} < 10^{-14}\ \text{pbn} \left(\frac{m_\chi}{\text{GeV}} \right)^{7/5}$
- MSSM mostly unaffected
  - Some suppression of SD capture population
- SI scattering dominant contribution to infall rate.
  SD only case?
- Radial orbits: minimum velocity w.r.t. Earth is 30 km/s
  (Earth capture only in resonance)
- WIMPzillas, SIMPzillas, etc.
  - High masses: thermal capture & neutrino emission may be suppressed

Initial Orbits





Fraction of captures into orbits extending beyond Earth (left) and Jupiter (right)

Are orbital dynamics important?

Planets: Gravitational Interactions

- Can gravitational interactions with planets put WIMPs in non- Sun crossing orbits?

  $\Rightarrow$ No thermal capture

- Gravitational scattering
  - Strong:
    single scatter takes WIMP from radial orbit to
    non- Sun crossing orbit
  - Weak:
    smaller scatters (several required) [not significant?]

- Perturbations

Gravitational Scattering

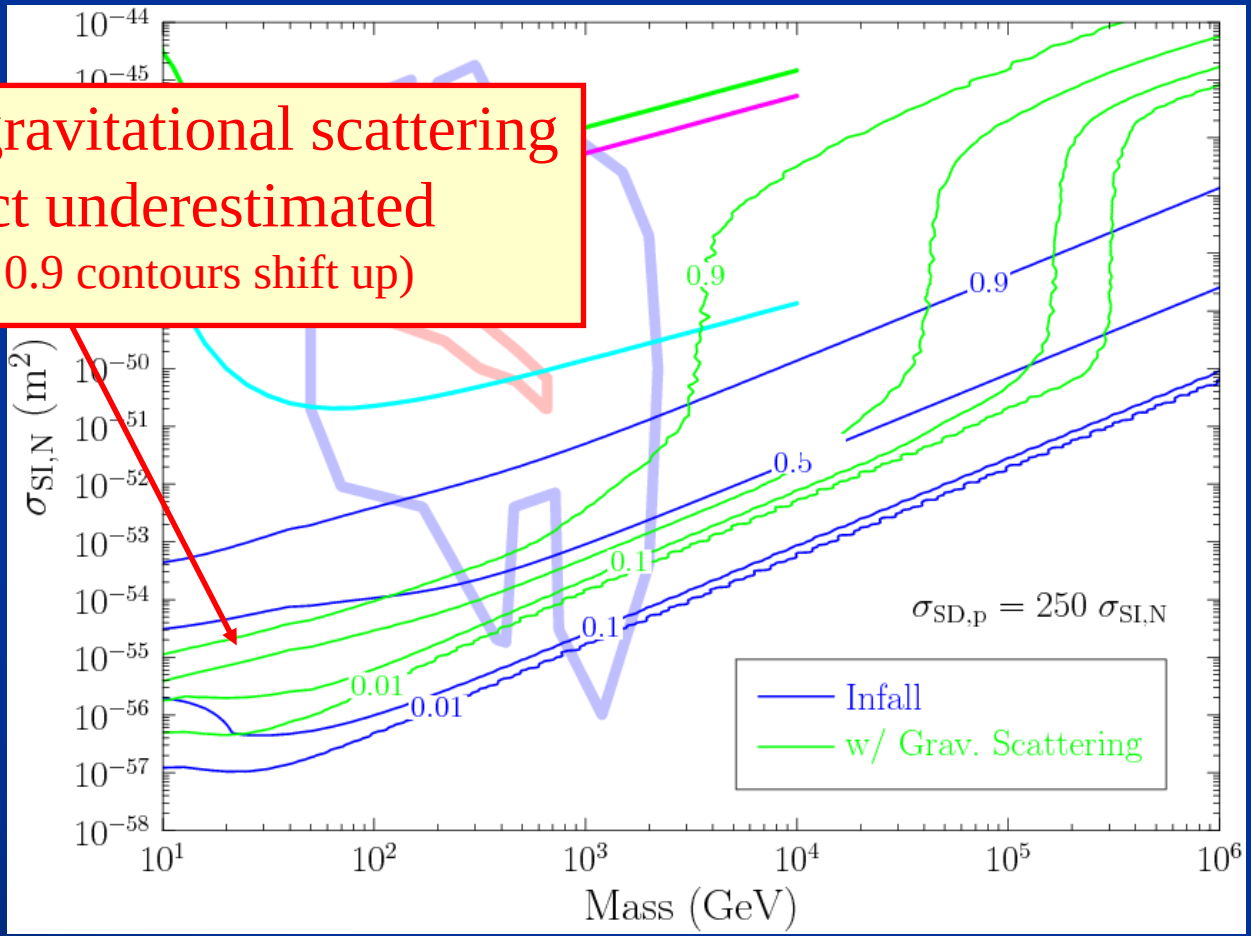
- Requires WIMP orbit to extend beyond planet's orbit

- Time scales $\tau \sim T_p \left(\frac{R_{\text{Sun}}}{r_p} \right) \left(\frac{M_p}{M_{\text{Sun}}} \right)^{-2}$
  - Mercury ~ 40 billion years
  - Earth ~ 100 million years
  - Jupiter ~ 50,000 years

Gravitational Scattering

$\sigma_{SD,p} = 250\,\sigma_{SI,N}$

Caveat: gravitational scattering effect underestimated
(0.5, 0.9 contours shift up)



ratio of thermal capture to gravitational capture
(contours at 0.9, 0.5, 0.1, 0.01)

Gravitational Scattering

- Spin-dependent population? *IN PROGRESS*
- Significant effect for:

$$m_\chi > 1000\,\mathrm{GeV} \quad (10^4 - 10^5\ \mathrm{GeV\ for\ SI})$$

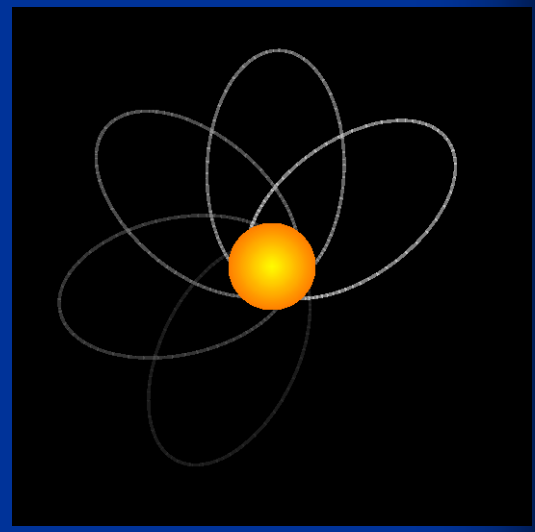
- MSSM mostly unaffected
  - Affected at small cross-sections or large masses
  - Some suppression of SD capture population
- SI scattering dominant contribution to infall rate. SD only case?
- WIMPzillas, SIMPzillas, etc.
  - High masses: thermal capture & neutrino emission may be suppressed

Gravitational Perturbations

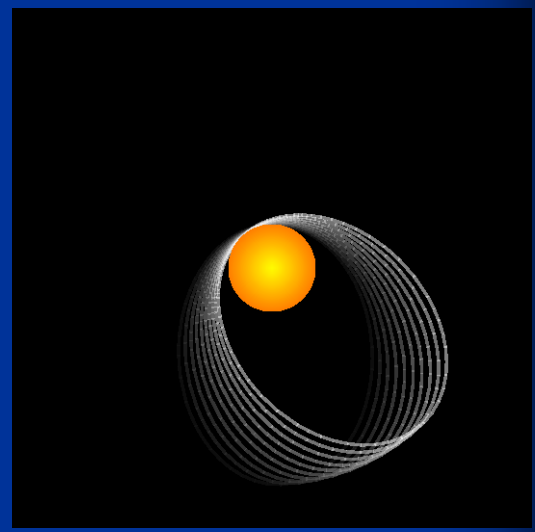
- Will perturbations drive WIMPs outside of Sun-crossing orbits?
- Effective inside planet orbits?
- Difficulties….

Gravitational Perturbations

- Inside Sun: non-Keplerian potential
  - Angular momentum vector fixed
  - Major axis lags each orbit
    (less than 2π covered per radial oscillation)



- Shallow (“grazing”) orbits
  - Pass through Sun only near surface
  - Damour & Krauss (1999)
  - Small perturbation to Keplerian orbits



Gravitational Perturbations

- Determining perturbations:
  - Non- Keplerian potential / boundary
  - High ellipticity ($e \approx 1$)
  - High accuracy over long time scales:
    - $> 10^4$ - 10^9 orbits
    - $r_{min} << r_{max}$
  - WIMP population ($\times N$)

Bound Populations of WIMPs

- Trapped during solar system formation

  Steigman et al. (1978); Griest (1988)

  - Significant only for fast collapse

- Gravitational scattering/diffusion (three body interaction)

  Gould, Frieman & Freese (1989); Gould (1991)

  - Capture unbound WIMPs $\Leftrightarrow$ Eject bound WIMPs
  - Earth & Venus: some phase space filled
  - Jupiter: fast diffusion

- Sun-grazing orbit scatters

  Damour & Krauss (1999)

  - Grazing orbits: small probability of additional scatter
  - Orbits perturbed to non- Sun crossing orbits
  - Models leading to significant population mainly excluded

Infall: Bound Populations of WIMPs

- Infall: WIMPs that have become bound via scattering off a nucleus in the Sun, but have not undergone enough additional scatters to fall in
  - Reaches σ_0-independent equilibrium density (<< ρ_{halo})
- Infall + gravitational scattering:
  - Scattered population subject to evaporation (via additional scattering)
  - Jupiter
    - scattering ~ 50,000 years
    - evaporation ~ 5 million years
  - Density still << ρ_{halo} ?
- Infall + gravitational scattering + perturbations:
  - Perturbed populations may be entirely inside planetary orbit $\Rightarrow$ no evaporation
  - m_χ = 1000 GeV: ~ 3% of captures between $a_{\text{Jupiter}}/2$ and a_{Jupiter}
  - Density?

Infall: Bound Populations of WIMPs

- For MSSM, majority of gravitationally scattered infall WIMPs will have initially been captured via a SD interaction in the Sun
  - For m_χ = 1000 GeV, $\sigma_{SD,p} = 250\ \sigma_{SI,N}$:
    ~ 75% local density of population from SD scatter
  - Hydrogen (SD) scatters: higher energy orbits, remain longer
  - Population proportional to SD cross-section, but can be detected through SI interactions

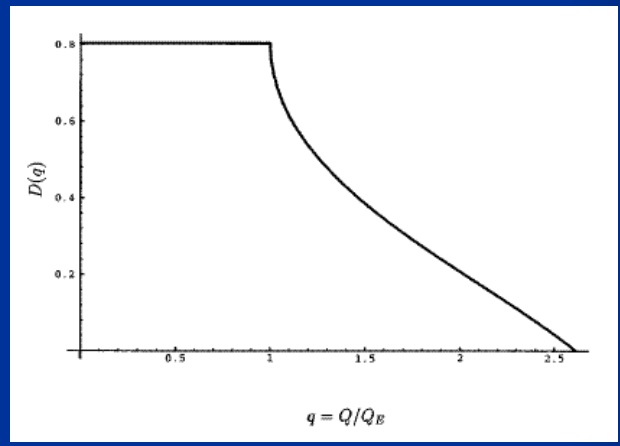
Detection: Bound Populations of WIMPs

- Capture by Earth:
  - Diffusion cannot populate low relative velocity phase space
  - Infall population has radial orbit: minimum relative velocity is v_{Earth}
  - Requires resonance for capture

- Direct detection:

  Damour & Krauss (1999), Collar (1999)
  - Bound WIMPs must have relative speed < 72 km/s
  - Requires low energy thresholds (~ 1 keV)

    e.g. Barbeau, Collar & Tench (2007)
  - Boost in event rate at low energy



Damour & Krauss (99)

Conclusions

- Dynamics of gravitationally captured WIMPs may reduce thermal capture and indirect detection signal from Sun
- MSSM mostly unaffected
  - SD induced captures?
  - Gravitational perturbations?
- Additional (SD based) bound population. Detectable?