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Phys. Rev. D75, 083526 (2007)

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Astronomy Journal Club 05/11/07

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# Outline:

- Motivation: Observing Dark Matter Decay
- Dwarf Galaxy Kinematics
- Data
- Flux Predictions: Take 1
- Substructure!
- Flux Predictions: Take 2
- Caveat Emptor



-35

At a resolution of  $10^{-35}$  meters, isolated clumps of neutralinos pop out of the vacuum to debate the existence of cosmologists

# Neutralino dark matter:

- SUSY solves hierarchy / gauge unification problems
- SUSY doubles SM particle number: Free dark matter!
- Neutralinos:  $\tilde{\chi}_1^0 = N_{01}\tilde{B} + N_{02}\tilde{W}^3 + N_{03}\tilde{H}_1^0 + N_{04}\tilde{H}_2^0$
- Cold WIMPs can be all the dark matter:

$$\Omega_\chi = \frac{5.5 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \times \text{Function of slowly varying logarithms}$$

# Detecting $\chi$ annihilation in the $\gamma$ -ray spectrum:

- $\gamma$  flux from  $\chi\chi \rightarrow \dots$

$$\frac{dN_\gamma}{dAdt} = \frac{1}{4\pi} \mathcal{P}[\langle\sigma v\rangle, M_\chi, dN_\gamma/dE] \mathcal{L}(\rho_s, r_s, \mathcal{D}).$$

- Geometry and density profile:

$$\mathcal{L} = \int_0^{\Delta\Omega} \left\{ \int_{\text{LOS}} \rho^2[r(\theta, \mathcal{D}, s)] ds \right\} d\Omega$$

- DM physics:

$$\mathcal{P} = \int_{E_{\text{th}}}^{M_\chi} \sum_i \frac{dN_{\gamma,i}}{dE} \frac{\langle\sigma v\rangle_i}{M_\chi^2} dE.$$

# Decay channels

- Line Emission:

$$\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \rightarrow \gamma\gamma$$

$$\text{Non-relativistic } \chi \rightarrow E_\gamma = M_\chi$$

$$\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \rightarrow \gamma Z$$

$$\text{Non-relativistic } \chi \rightarrow E_\gamma = M_\chi - \frac{m_Z^2}{4M_\chi}$$

$\langle\sigma v\rangle$  depends on supersymmetric parameters, but optimistically,  
 $\langle\sigma v\rangle \simeq 10^{-28} \text{ cm}^3\text{s}^{-1}$

- Continuum Emission:

$$\chi\chi \rightarrow q\bar{q} \text{ or } ZZ \text{ or } WW \rightarrow \text{hadronic shower including } \pi^0 \rightarrow \gamma\gamma$$

$\langle\sigma v\rangle$  depends on supersymmetric parameters, but optimistically,  
 $\langle\sigma v\rangle \simeq 5 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$

$$\frac{dN, \gamma}{dE} = \alpha_1 \frac{E}{M_\chi} \left( \frac{E}{M_\chi} \right)^{-3/2} \exp \left[ -\alpha_2 \frac{E}{M_\chi} \right]$$

# Dwarf spheroidal galaxies (dSphs) in the Milky Way halo:

- Dwarf spheroidals:
  - 18 and counting
  - ~kpc sized
  - Old stellar populations
  - Gas poor
  - Metal poor
  - Missing satellites problem
  - DM Dominated!  $M/L \sim 1000$ ,  
 $M : 10^8 \rightarrow 10^9 M_{\odot}$

TABLE I. Properties of the dSphs used in this study. The adopted distance to each galaxy is shown in the second column. For reference, the third and fourth columns list the luminosity and central velocity dispersion for each dwarf. The fifth and sixth columns give the King core and tidal radii as determined from Refs. [61–66]. The last column shows a derived result: the range of halo  $V_{\max}$  values that simultaneously matches the observed velocity dispersion profiles and the CDM theoretical normalization priors (see Fig. 2).

dSph	$\mathcal{D}$ [kpc] from [20]	$L_V$ ( $10^6 L_{\odot}$ ) from [20]	$\sigma_0$ [km s $^{-1}$ ]	$r_c$ [kpc]	$r_t$ [kpc]	$V_{\max}$ [km s $^{-1}$ ]
Ursa Minor	66	0.29	$15 \pm 4$	0.30	1.50	15–40
Draco	80	0.26	$5.5 \pm 1.2$	0.18	0.93	15–35
Sculptor	79	2.2	$8.5 \pm 1.0$	0.28	1.63	11–19
Fornax	138	15.5	$11.1 \pm 2.5$	0.39	2.71	19–36
Carina	101	0.43	$6.8 \pm 1.0$	0.25	0.86	10–15
Sextans	86	0.50	$5.8 \pm 1.3$	0.40	4.0	6–10

**Carina, Ursa Minor, Draco, Sculptor:** Majewski, Munoz, Palma, et al.

*Photometry:* Mosaic WFIcam at CTIO, Mayall 4m at KPNO, MiniMO on WIYN at KPNO, Las Campanas Swope 1m

*Spectroscopy:* MIKE on Magellan at LC, Keck HIRES, WYFFOS on Herschel at La Palma, CTIO 4m Hydra spectrograph.

BHB, Old RG used to select candidates

Bootstrap methods used to determine membership with spectra in hand

**Sextans, Fornax:** Walker et al.

*Photometry:* Archival, 40 inch at Las Campanas

*Spectroscopy:* MIKE on Magellan Clayat LC, Keck HIRES, WYFFOS on Herschel at La Palma, BHB, Old RG used to select candidates

Bootstrap methods used to determine membership with spectra in hand

# Getting at the dark matter content of dSphs: Kinematic constraints

- Equilibrium stellar systems obey Jeans equation:

$$r \frac{d(\rho_{\star} \sigma_r^2)}{dr} = -\rho_{\star}(r) V_c^2(r) - 2\beta(r) \rho_{\star} \sigma_r^2.$$

- Stellar profile reasonably fit by tidally truncated King profile:

$$I(R) = k \left[ \left( 1 + \frac{R^2}{r_c^2} \right)^{-1/2} - \left( 1 + \frac{r_t^2}{r_c^2} \right)^{-1/2} \right]^2$$

- System seen in projection:

$$\sigma_{\text{Los}}^2(R) = \frac{2}{I(R)} \int_R^{\infty} \left( 1 - \beta \frac{R^2}{r^2} \right) \frac{\rho_{\star} \sigma_r^2 r}{\sqrt{r^2 - R^2}} dr$$

- Low M/L: stellar contribution to total mass ignored.



# Dark matter halos in a CDM universe:

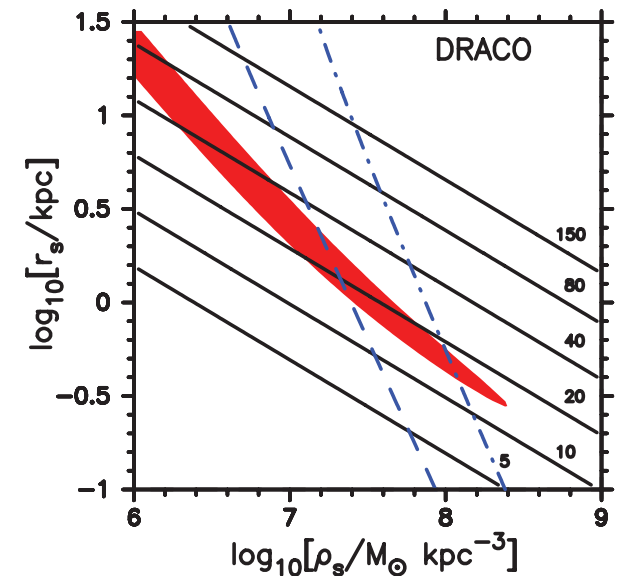
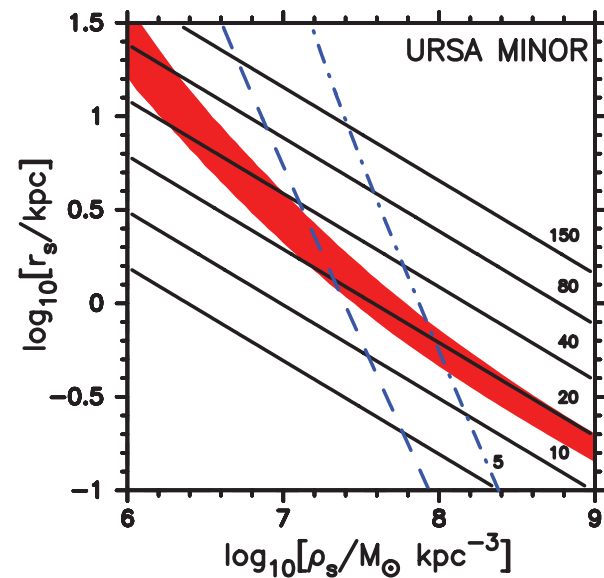
- N-Body simulations indicate DM has a nearly universal density profile (NFW 1997):

$$\rho(\tilde{r}) = \frac{\rho_s}{\tilde{r}^\gamma (1 + \tilde{r})^{\delta-\gamma}}; \quad \tilde{r} = r/r_s \quad \delta \simeq 3$$
$$c = \frac{r_v}{r_s} \quad \rho_s \equiv \rho_{crit} \Omega_m \Delta_v \frac{c^3}{3 [\ln(1+c) - c/(1+c)]} \quad \Delta_v \simeq 177$$
$$0.7 \leq \gamma \leq 1.2$$

- Appears to hold true in dissipationless mergers, high resolution re-simulations
- Controversy over inner slope
- Concentration-Mass relationship reflects CM halo formation history

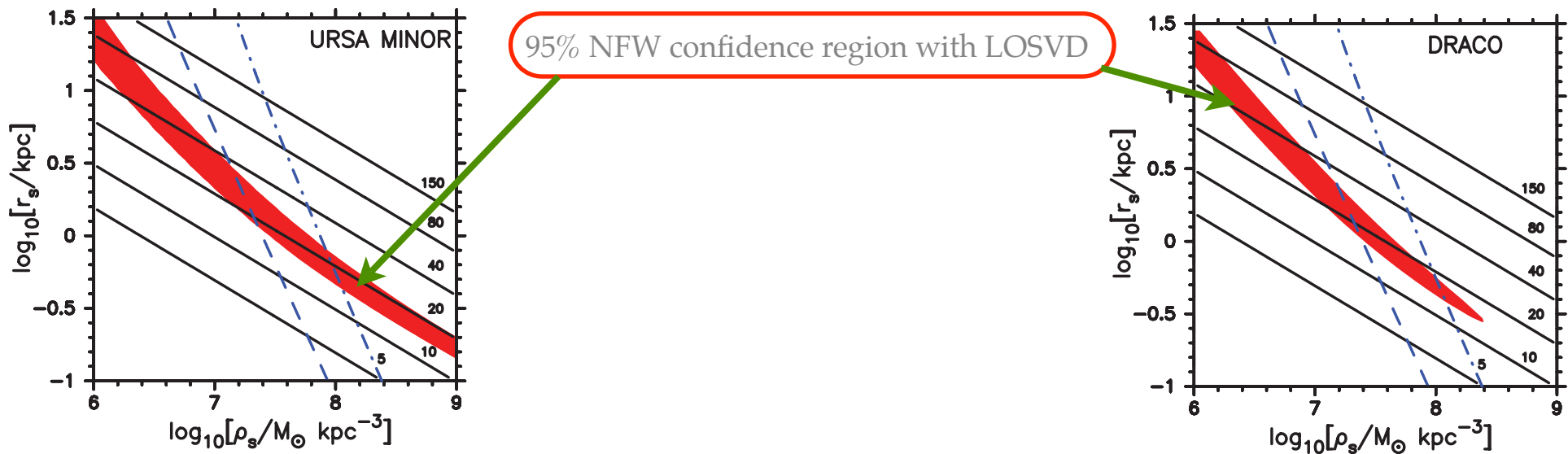
$$c \simeq 33 \left( \frac{M}{10^8 M_\odot} \right)^{-0.06} \quad M \leq 10^8 M_\odot$$

# Summary of kinematic constraints:



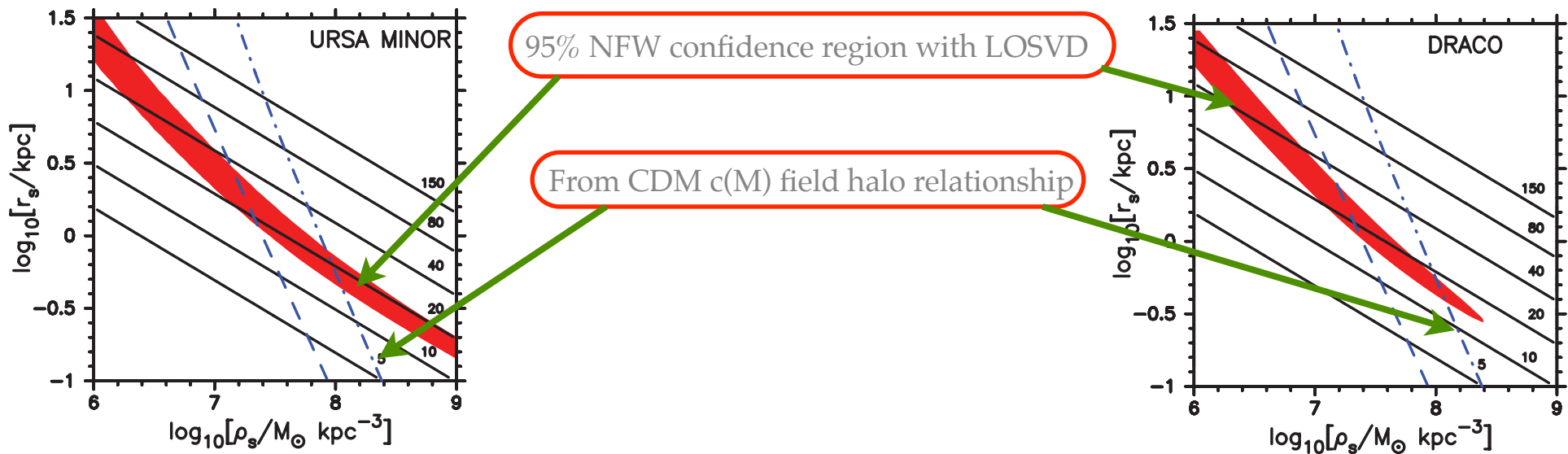
- Marginalize over  $\beta$ , find  $\rho_s, r_s$  consistent with observed  $\sigma_{\text{LOS}}(R)$ : Define 95% Confidence Region
- UMi/Draco are clearly most promising candidates for detection
- CDM field halo expectations
- Tidal stripping causes modified concentration/mass relation: Authors use fits to Bullock et al (2001)

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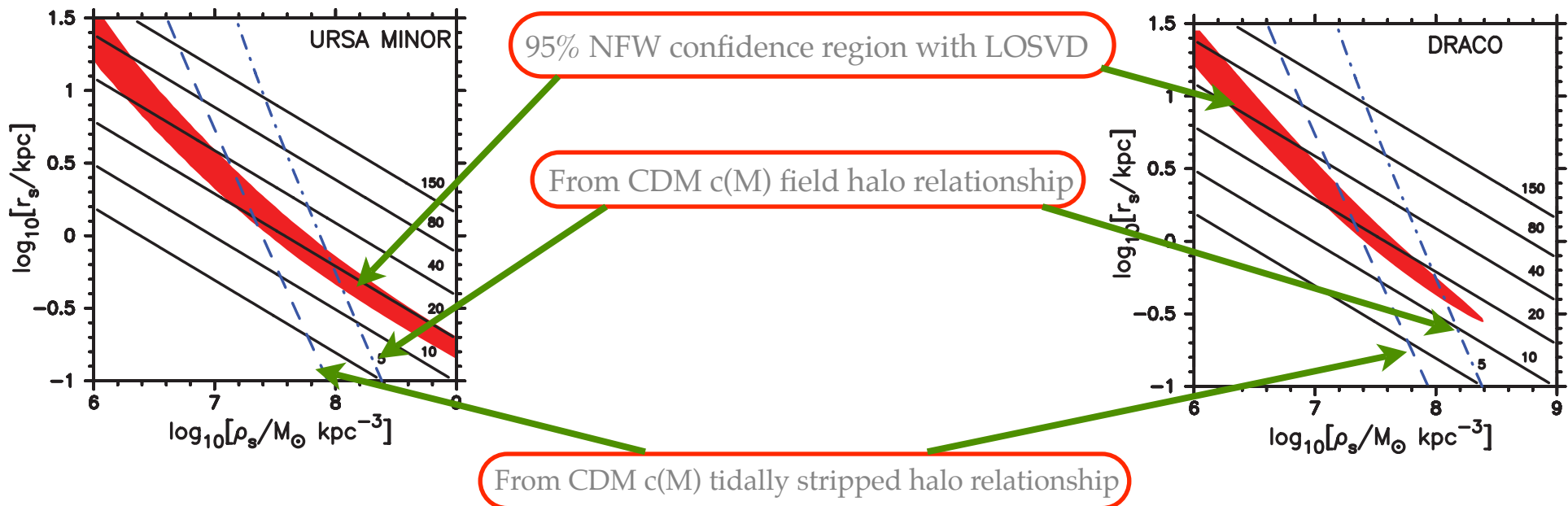
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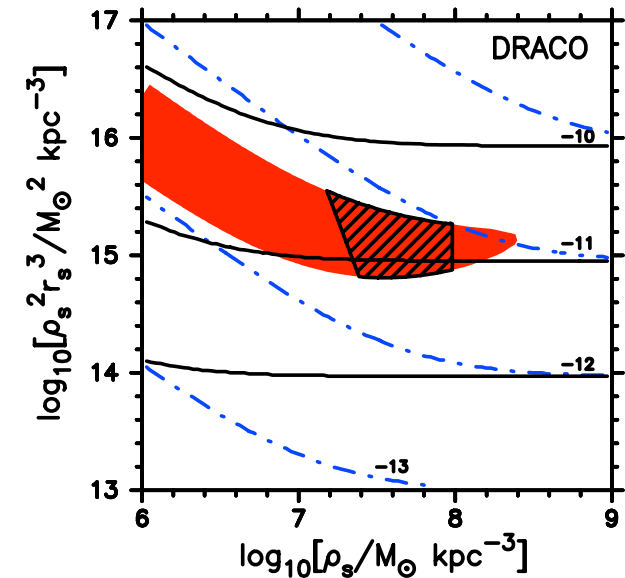
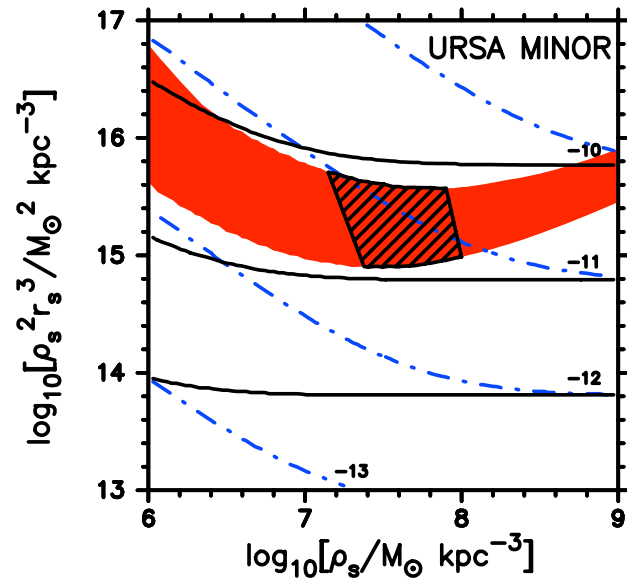
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# What to expect from a smooth NFW halo:

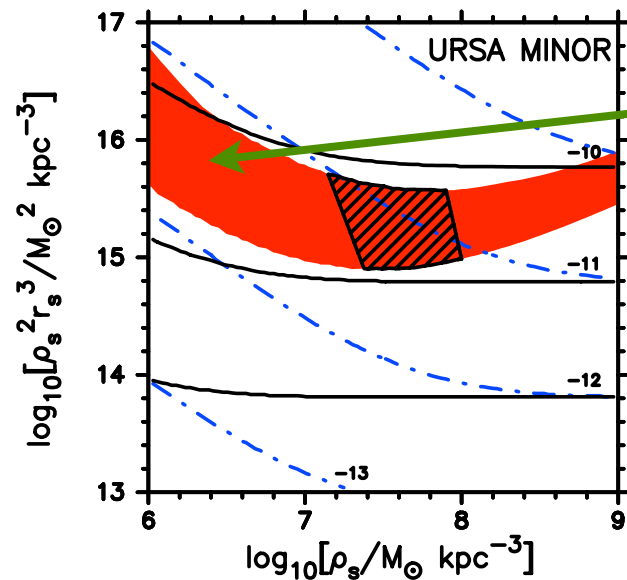


- For NFW halo,  $\rho_s^2 r_s^3$  sets expected signal:

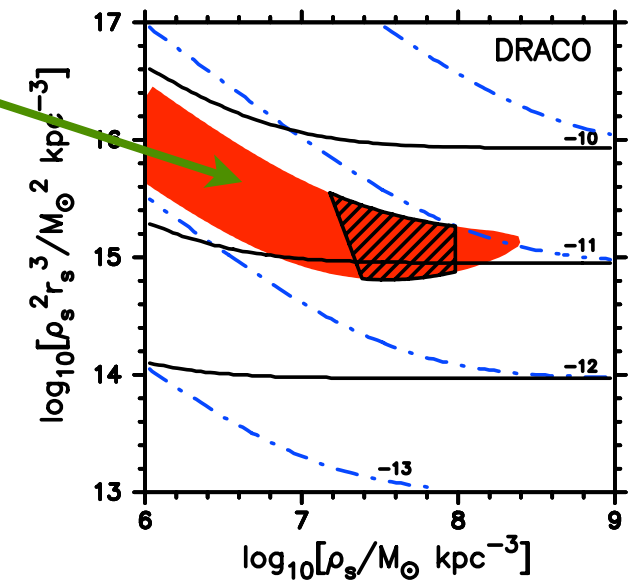
$$\mathcal{L}(\rho_s, r_s) = \frac{4\pi}{3} \rho_s^2 r_s^3 \left\{ 1 - \frac{1}{[1 + \tilde{r}_{\max}(\Delta\Omega, \mathcal{D})]^3} \right\}.$$

- UMi/Draco have highest M/L of MW dSph: Unshocking conclusions

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Kinematic constraints

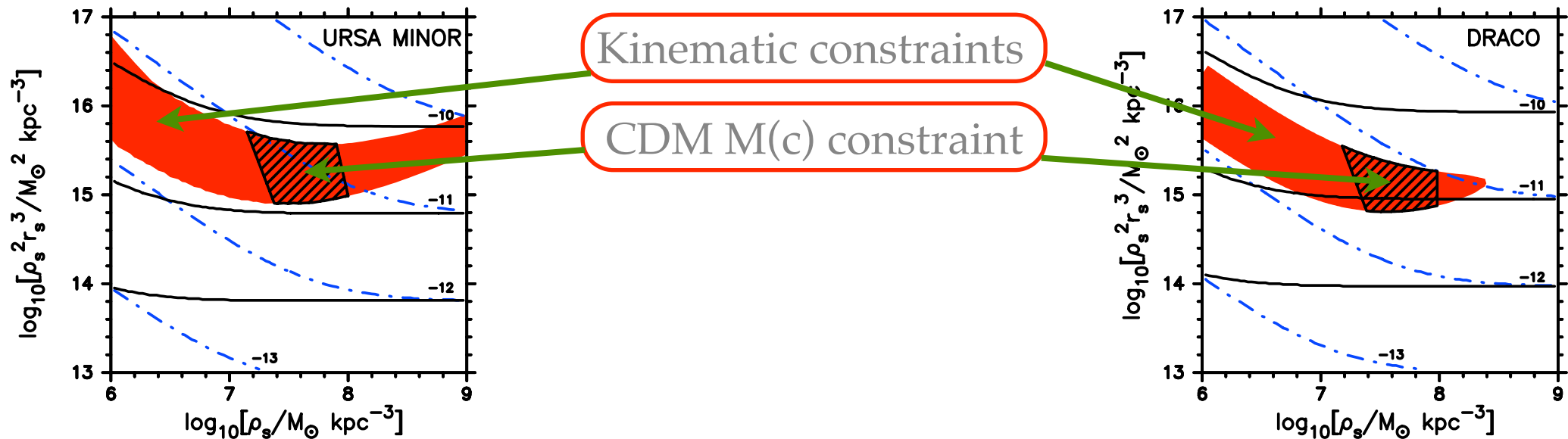


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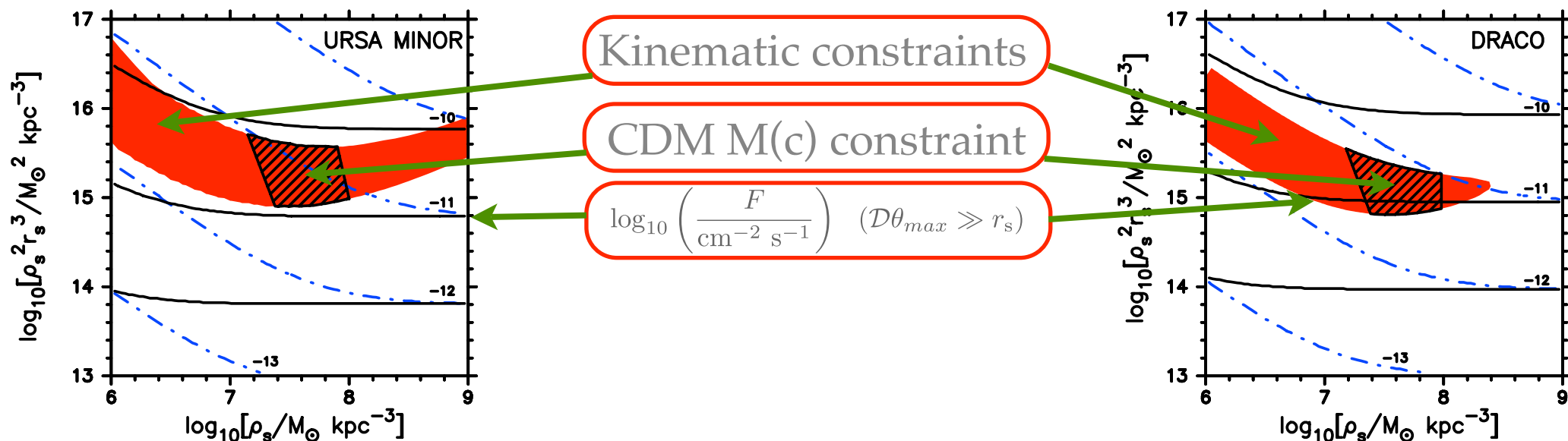
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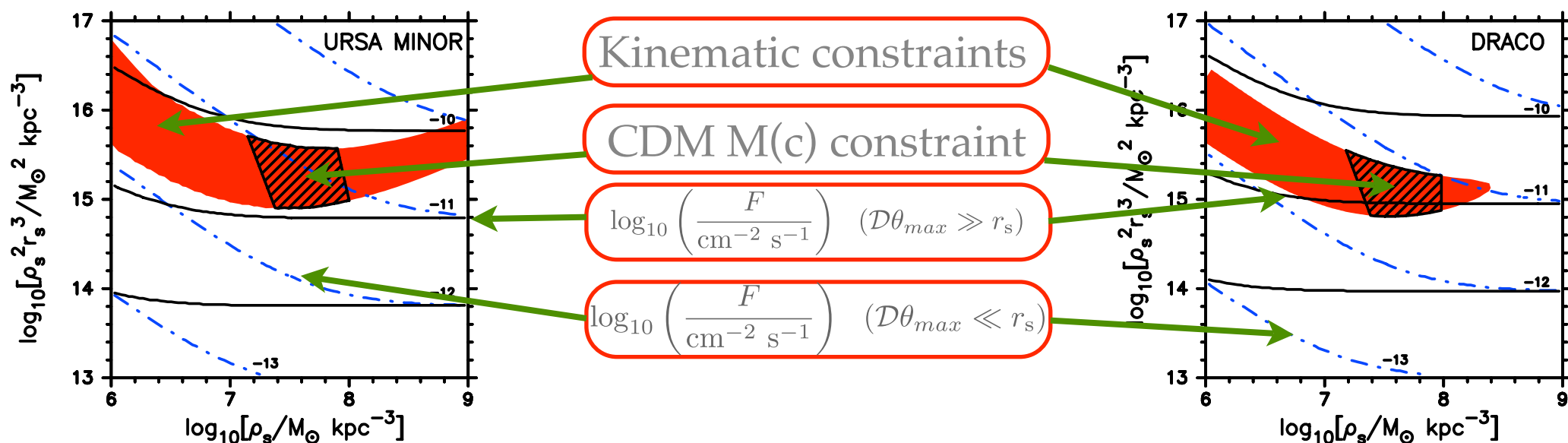


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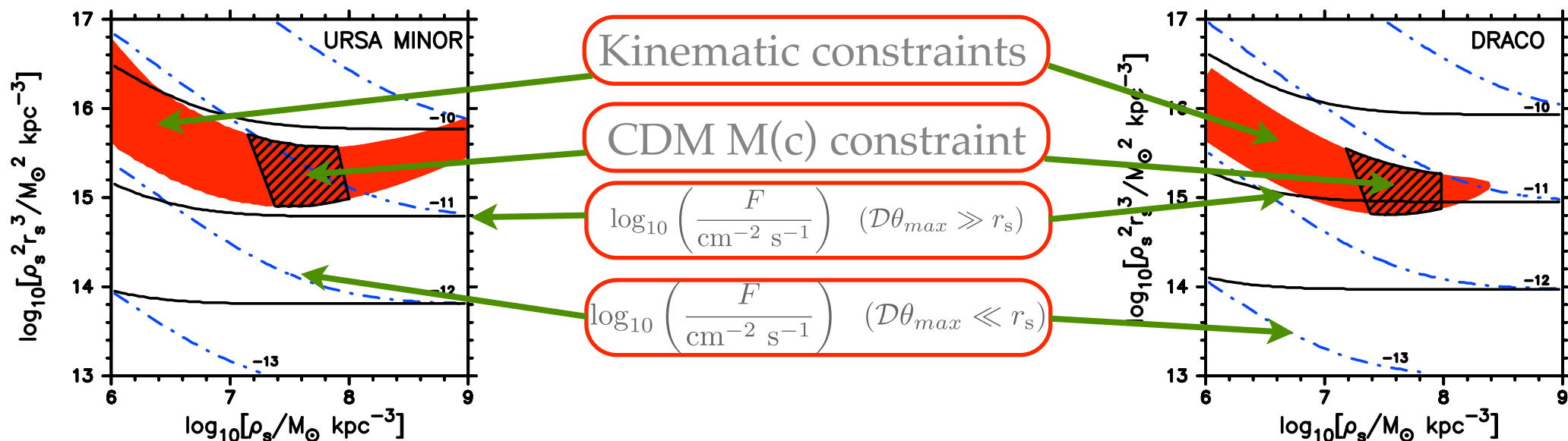


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$$\begin{aligned} \gamma = 1.2 &\hookrightarrow \mathcal{L} \rightarrow 5\mathcal{L} \\ \gamma = 0.7 &\hookrightarrow \mathcal{L} \rightarrow \mathcal{L}/7 \end{aligned}$$

- UMi/Draco have highest M/L of MW dSph: Unshocking conclusions

# What to expect from a smooth NFW halo:

- Not much! Even for optimistic SUSY parameters, signal is near BG: Would like a sub-structure boost of  $\sim 100$
- Spectrum
- Backgrounds:
  - $\gamma$ -ray blazars (extragalactic)
  - CR interacting with ISM (galactic)
  - Unresolved SGR?

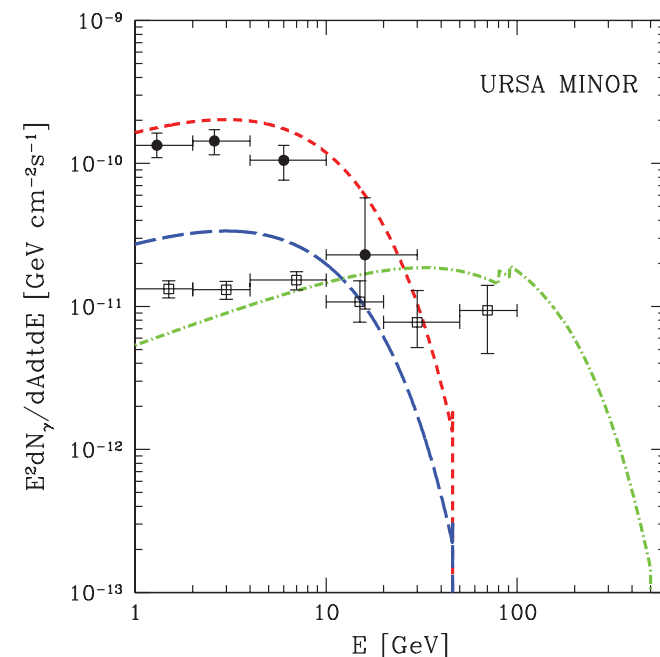


FIG. 4 (color online). Examples of the flux spectrum of Ursa Minor for three cases where the quantities  $(\log_{10}\rho_s, \log_{10}r_s, M_\chi)$  take the values of  $(7.4, 0.033, 46)$  depicted with the long-dashed line,  $(7.9, -0.067, 46)$  shown as a short-dashed line, and  $(7.9, -0.067, 500)$  shown as the dot-dashed line. The value of  $\mathcal{L}$  that corresponds to these 3 cases is  $[2.08 \times 10^{14}, 1.25 \times 10^{15}, 1.25 \times 10^{15}]$   $\text{GeV cm}^{-2} \text{s}^{-1}$ , respectively. The units for  $\rho_s$  are  $M_\odot \text{kpc}^{-3}$ , while  $r_s$  is in kpc and  $M_\chi$  in GeV. No enhancement of flux from substructure is included; substructure could increase the flux by up to a factor of 100, increasing the prospects for detection. The calculated flux is integrated over an angular region of radius 0.1 degrees centered on the dSph, and the value of  $\mathcal{P} = \mathcal{P}_{\text{SUSY}} \approx 10^{-28} \text{ cm}^3 \text{s}^{-1} \text{GeV}^{-2}$ , which corresponds to the most optimistic scenario for supersymmetric dark matter (see Sec. II). Open squares show the amplitude of the  $\gamma$ -ray extragalactic emission [75], while filled circles correspond to the galactic emission of  $\gamma$ -rays at high galactic latitudes [76].

# CDM on small scales:

- CDM is hierarchical- structure on arbitrarily small length scales: Mergers should preserve some as substructure (Simulations: Zentner et al., Reed et al.)

- Early times, DM kinetically coupled to radiation (LZ 2005, GH 2005):

$$M < M_{\text{cut}} \equiv 10^{-4} \left( \frac{T_d}{10\text{MeV}} \right)^{-3} M_{\odot}$$

- Affect on halo  $N(M)$  determined by PS formalism or N-body simulations

# CDM on small scales:

- Raging controversy on halo-cutoff (tidal stripping?) :  
Diemand, Moore, Stadel vs Zhao, Taylor, Silk, Hooper (2005)  
Affect of disk, bulge? Berezinsky 2005

- Argument is over cutoff in subhalo mass function:

$$\frac{dN}{d \ln m} (m|M) = \theta (m - m_0) \left( \frac{M}{m} \right)^\alpha A$$

- Simulations and EPS merger tree arguments imply  
 $1 \leq \alpha \leq 2$
- Our authors use  $m_0 \simeq 10^{-5} M$

# The 'Boost' factor from sub-halos:

- Boost Factor:

$$\mathcal{L}(M) = [1 + B(M, m_0)] \tilde{\mathcal{L}}(M).$$

- Consistency demands

$$B(M) = \frac{1}{\tilde{\mathcal{L}}(M)} \int_{m_0}^M \frac{dN}{dm} [1 + B(m)] \tilde{\mathcal{L}}(m) dm$$

- Tidal stripping ignored:

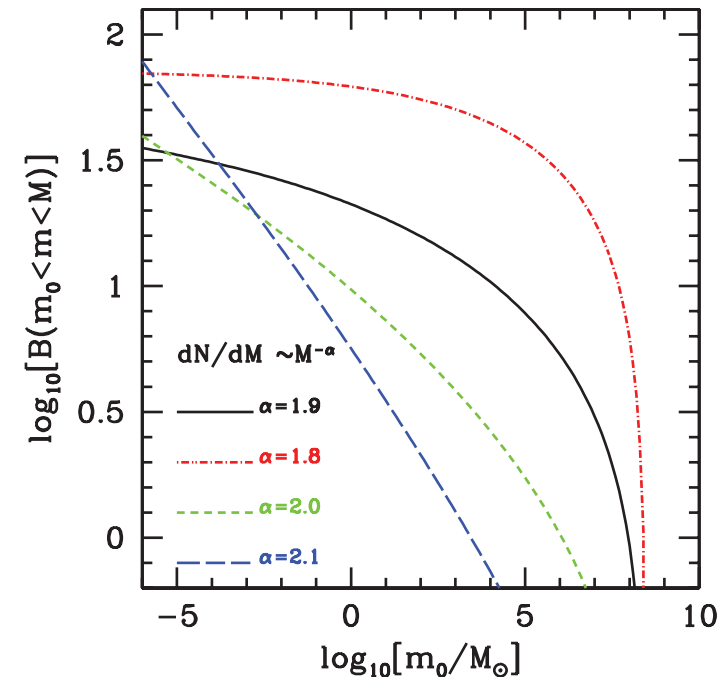
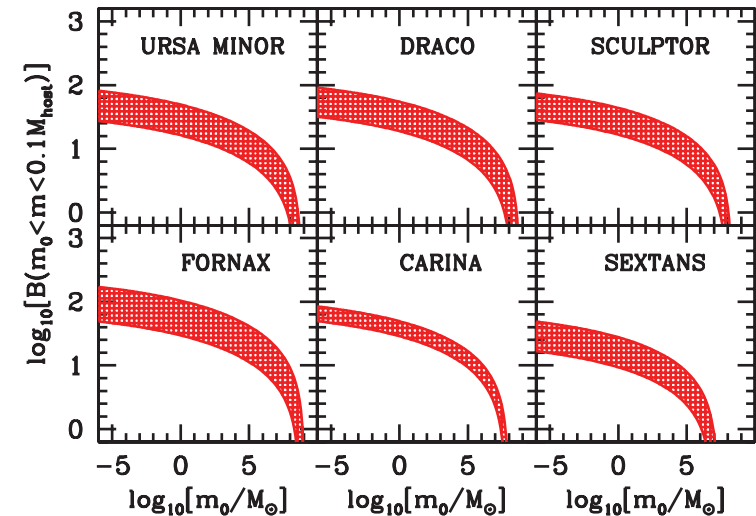
$$\mathcal{L}_s(m) = \mathcal{L}_f(m)$$

- Bound derived:

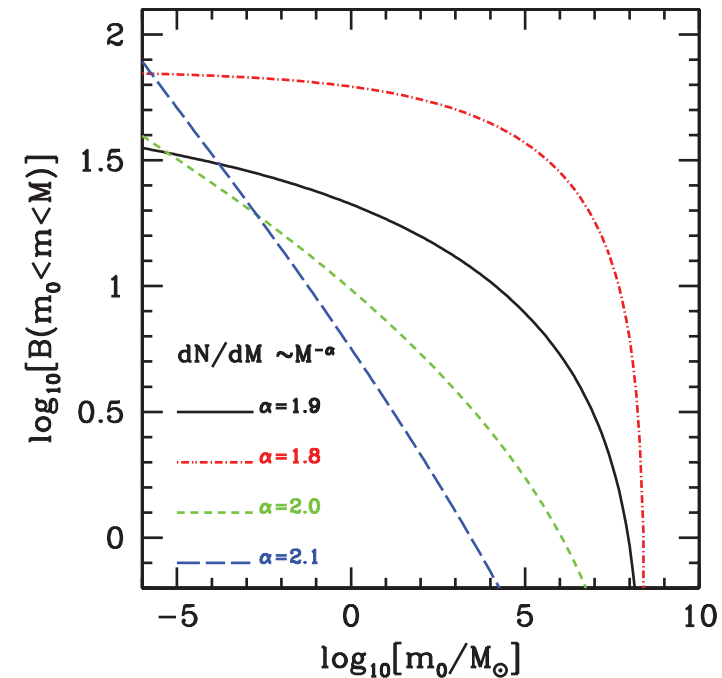
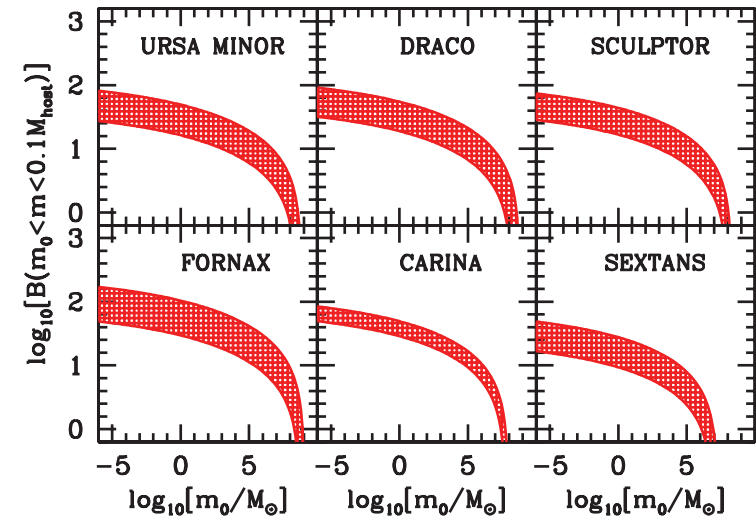
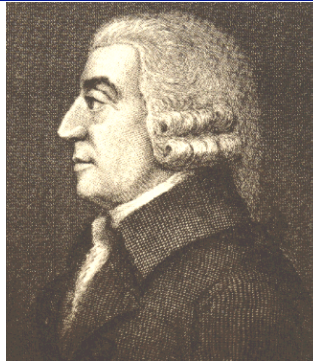
$$B(M) < A \frac{(M/m_0)^{\alpha - \gamma' + A} - 1}{\alpha - \gamma' + A}$$

$$\gamma' \equiv d \ln(\tilde{\mathcal{L}}) / d \ln(M)$$

- Boost: strong function of cutoff/  
slope of subhalo mass function



# The 'Boost' factor from sub-halos:





# Caveats / Conclusions:

- Cross-sections are optimistic
- Substructure controversy must be carefully dealt with
- Tidal stripping should be included in substructure estimates
- LHC+followup would be spectacular

# GLAST (Gamma Ray Large Area Telescope): 4/15

- Sensitivity is factor  $\sim 50$  better than EGRET
- Threshold energy of 20 MeV (up to 300 GeV)
- Tracker, calorimeters, anti-coincidence shields
- $\gamma$  are detected by conversion to  $e^+e^-$

- People try!
- Poor understanding of bulge/halo / disk decomposition
- Poor constraints to MW halo profile
- BH at GC--  $10^6 M_{\odot}$ : spike, mergers, heating
- dSph are thought to be DM-dominated