Dark matter density profiles in dwarf satellites

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Based on PU & M. Valli, to appear.

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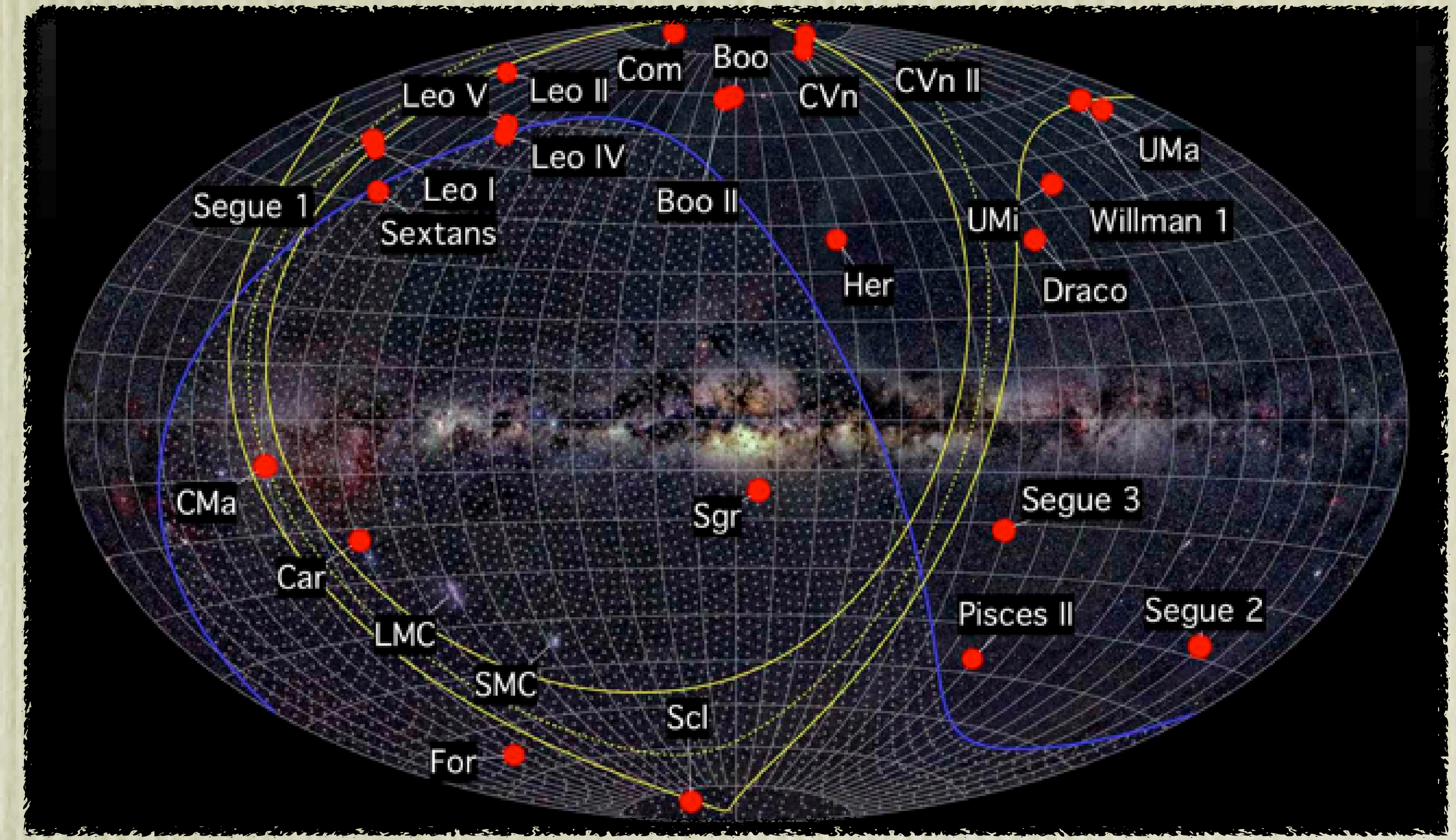
Milky Way dwarfs as Dark Matter detection Labs

Ideal targets for **detecting** a DM signal (prompt or radiative emission from DM particle pair annihilations or decays):

• objects with fairly large DM densities, located fairly close to the Sun (about 10 to 200 kpc);

• intrinsic backgrounds from "standard" astrophysical sources below detection sensitivities (?)
+ low Milky Way foregrounds (intermediate to high latitude locations).



About 35 (tentatively) identified;
8 with adequate kinematic data samples, the so-called "classical" dwarfs.

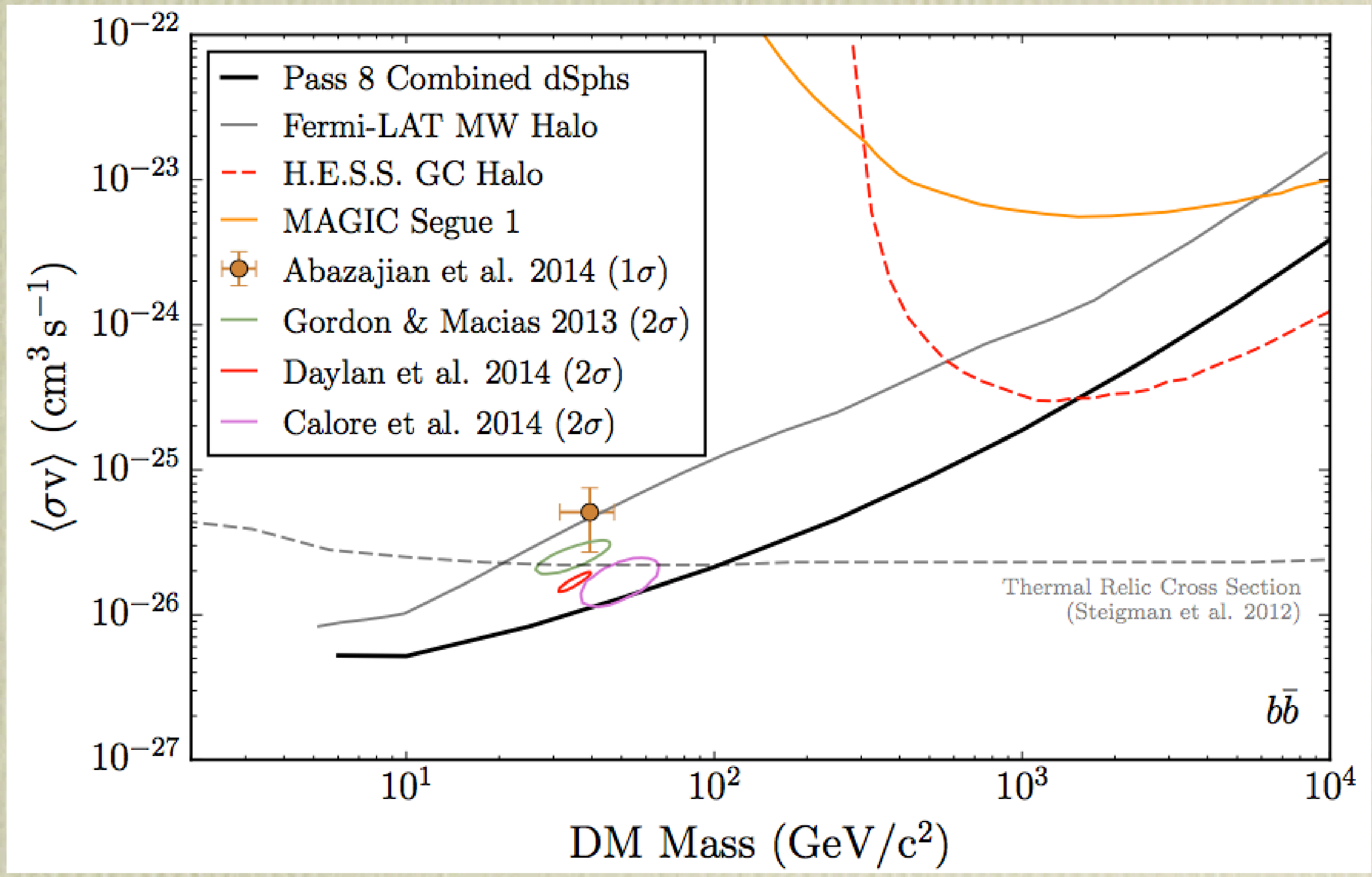
Ideal Labs also to set limits on particles physics properties?

No firmly established detection so far (tentative γ-ray signal in Reticulum 2, **Geringer-Sameth et al. 2015** + **Koushiappas talk**). Upper limits on fluxes reliably projected on **upper limits** on particle DM parameters?

For γ-rays and DM annihilations, only one "astro" factor:

$$J \equiv \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\ \rho^2_{DM}(l)$$

For the classical dwarfs 1-σ uncertainties often assumed within factors of about 1.5 ≪ the "astro" uncertainty in any other indirect detection tool!



Fermi Coll. 2015: γ-ray limits excluding WIMPs thermal cross section lighter than 100 GeV!

Mass models for dwarf galaxies

A stellar population as tracer of the gravitational potential (i.e. the DM distribution) assuming dynamical equilibrium. Velocity moments of the collision-less Boltzmann equation. Spherical symmetry for all components:

⇒ a single Jeans equation

$$\frac{d}{dr}(\nu\sigma_r^2) + \frac{2\,\beta(r)}{r}\nu\sigma_r^2 = -\nu\frac{M(r)}{r^2}$$

Usually solved for the radial pressure: $p(r) \equiv \nu(r)\sigma_r^2(r)$ in terms of the 3 unknown functions:

the star density profile	the star anisotropy profile	the DM mass profile
$\nu(r)$	$\beta(r) \equiv 1 - \dfrac{\sigma_\theta^2 + \sigma_\phi^2}{2\,\sigma_r^2}$	$M(r)$

$$-\infty \;\leq\; \beta(r) \;\leq\; 1$$

circular orbits ($-\infty$) — radial orbits (1)

isotropy: $\beta(r) = 0$

Mass models for dwarf galaxies (ii)

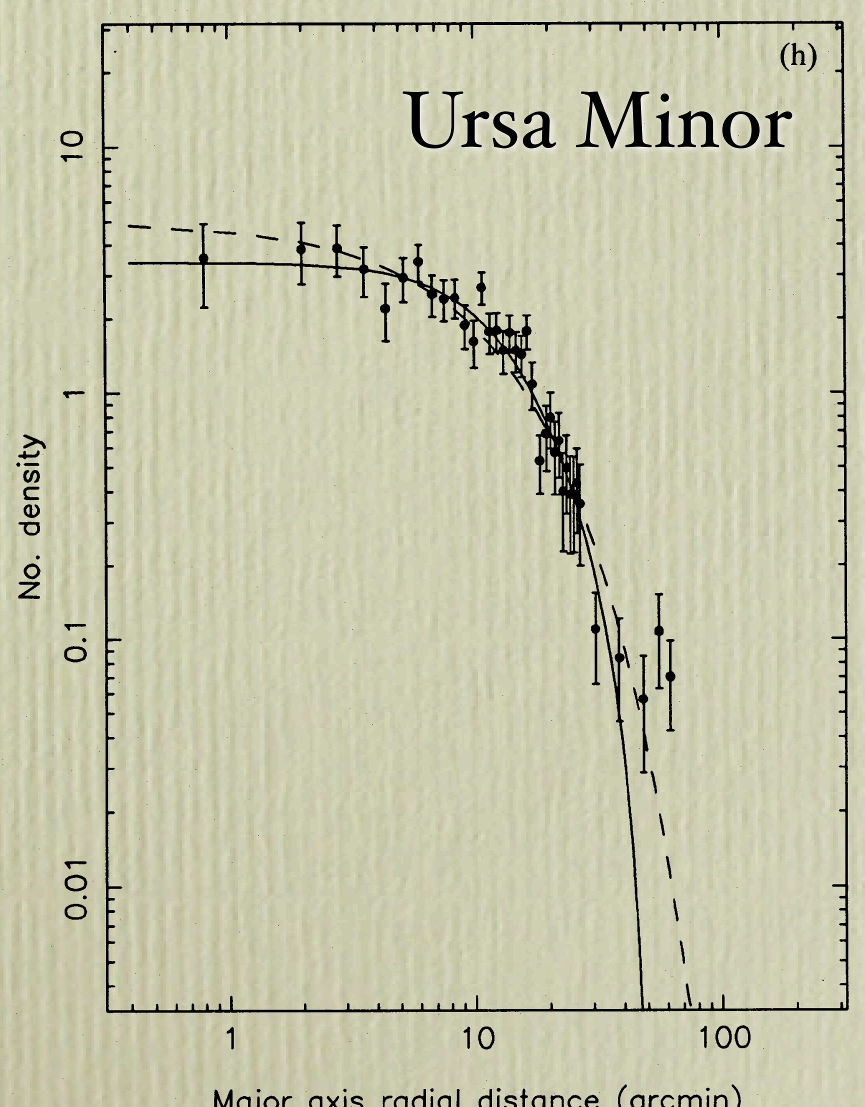
The 3 unknowns: $\nu(r)$, $\beta(r)$ and $M(r)$ can be mapped into 2 observables:

the star surface brightness

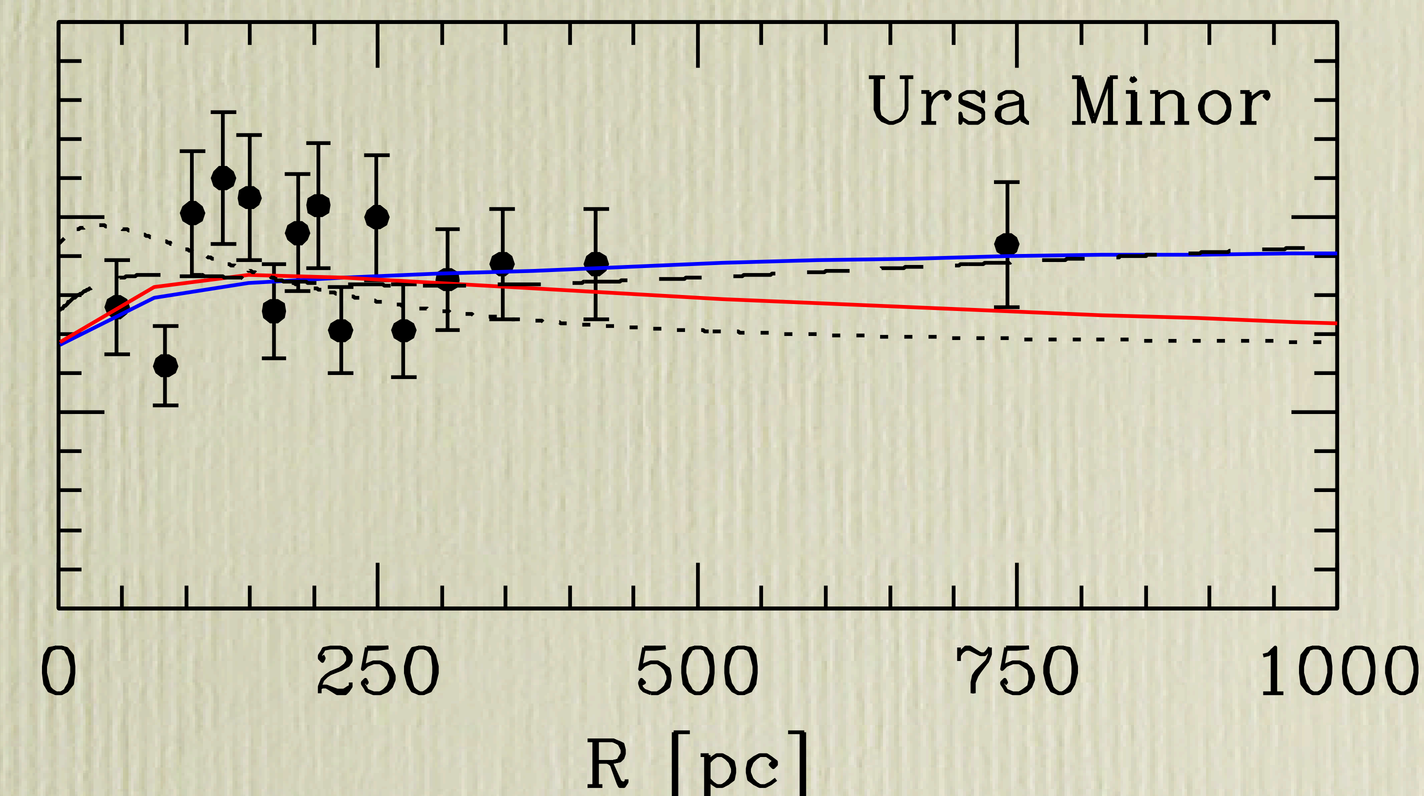
$$I(R) = 2\int_R^\infty \frac{dr\, r}{\sqrt{r^2 - R^2}}\nu(r)$$

the l.o.s. velocity dispersion

$$\sigma^2_{l.o.s.}(R) = \frac{2}{I(R)}\int_R^\infty \frac{dr\, r}{\sqrt{r^2 - R^2}}\left(1 - \beta(r)\frac{R^2}{r^2}\right)p(r)$$



Irwin + Hatzidimitriuo 1995



e.g.: **Walker et al. 2009**

Mass models for dwarf galaxies (iii)

The mapping is usually done introducing parametric forms for:

$\nu(r)$ - Plummer, King, Sersic ... profile as supported from star profiles in other observed systems;

$M(r)$ [or DM $\rho(r)$] - from N-body simulations or DM phenomenology;

$\beta(r)$ - as an arbitrary choice, since there is no real observational handle.

and performing:

- a frequentist fit of $\nu(r)$ to data on $I(R)$;

- a Markov-Chain Monte Carlo sampling of a likelihood defined from data on $\sigma^2_{l.o.s.}(R)$: posteriors on $M(r)$ [or $\rho(r)$] parameters after marginalization over $\beta(r)$ parameters [prior choice for the latter again arbitrary]. The derived posterior for J (and its small error bar) is what will enter as an input for particle physics limits.

How much should we trust this procedure?

Mass models: our approach

the star surface brightness

$$I(R) = 2\int_R^\infty \frac{dr\, r}{\sqrt{r^2 - R^2}}\nu(r)$$

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are in a form which resembles the Abel integral transform for the pair $f \leftrightarrow \widehat{f}$:

$$f(x) = \mathbf{A}[\widehat{f}(y)] = \int_x^\infty \frac{dy}{\sqrt{y - x}}\,\widehat{f}(y) \quad \longleftrightarrow \quad \widehat{f}(y) = \mathbf{A}^{-1}[f(x)] = -\frac{1}{\pi}\int_y^\infty \frac{dx}{\sqrt{x - y}}\,\frac{df}{dx}$$

Actually $I(R^2) \leftrightarrow \widehat{I}(r^2) = \nu(r)$. Analogously you can invert also the projected dynamical pressure $P(R^2) \equiv I(R)\,\sigma^2_{l.o.s.}(R)$ and find:

$$M(r) = \frac{r^2}{G_N\,\widehat{I}(r)}\left\{-\frac{d\widehat{P}}{dr}[1 - a_\beta(r)] + \frac{a_\beta(r)}{r}\cdot b_\beta(r)\left[\widehat{P}(r) + \int_r^\infty d\tilde{r}\frac{a_\beta(\tilde{r})}{\tilde{r}}\mathcal{H}_\beta(r,\tilde{r})\,\widehat{P}(\tilde{r})\right]\right\}$$

having defined: $a_\beta(r) \equiv -\frac{\beta}{1-\beta}$ $\qquad b_\beta(r) = 3 - a_\beta(r) - \frac{d\log a_\beta}{d\log r}$

$$\mathcal{H}_\beta(r,\tilde{r}) \equiv \exp\left(\int_r^{\tilde{r}} dr'\,\frac{a_\beta(r')}{r'}\right)$$

see also: **Wolf et al. 2010** + **Mamon & Boué 2009**.

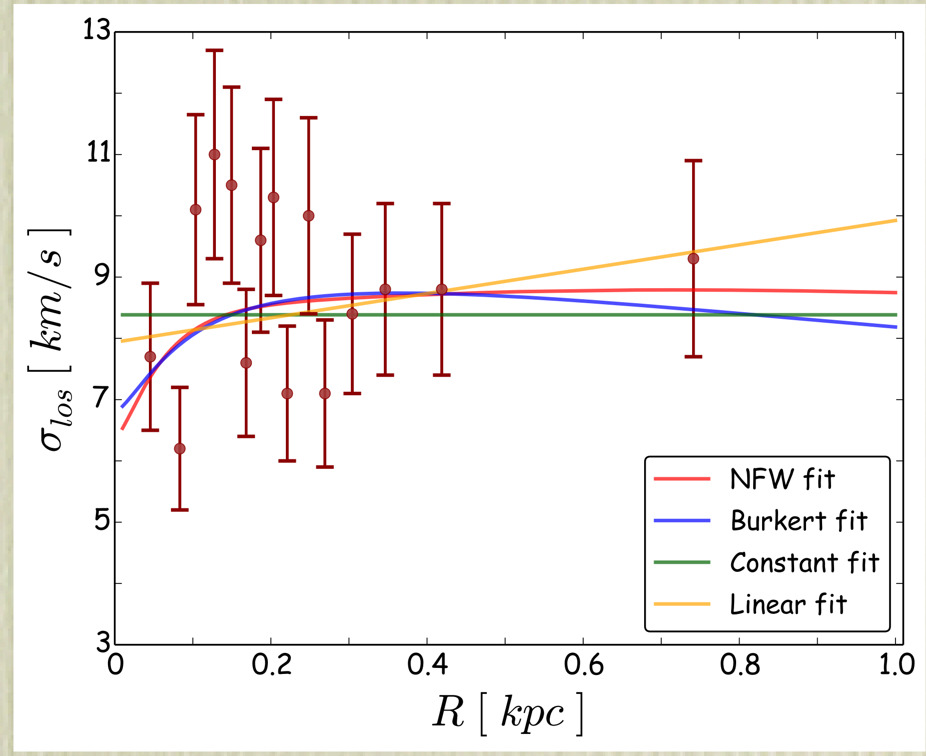
Mass models: our approach (ii)

Now: model $I(R)$ and $\sigma_{l.o.s.}(R)$ with a direct parametric fit on data for these observables. E.g.: assume for the surface brightness a Plummer model:

$$I(R) = \frac{L_0}{\pi R_{1/2}^2} \frac{1}{(1 + R^2/R_{1/2}^2)^2}$$

and fit the half-light radius $R_{1/2}$, i.e. in Ursa Minor: $R_{1/2} \simeq 0.3 \text{ kpc}$.

For the line-of-sight projected velocity dispersion in general data are less constraining and one can consider different possibilities, e.g.:

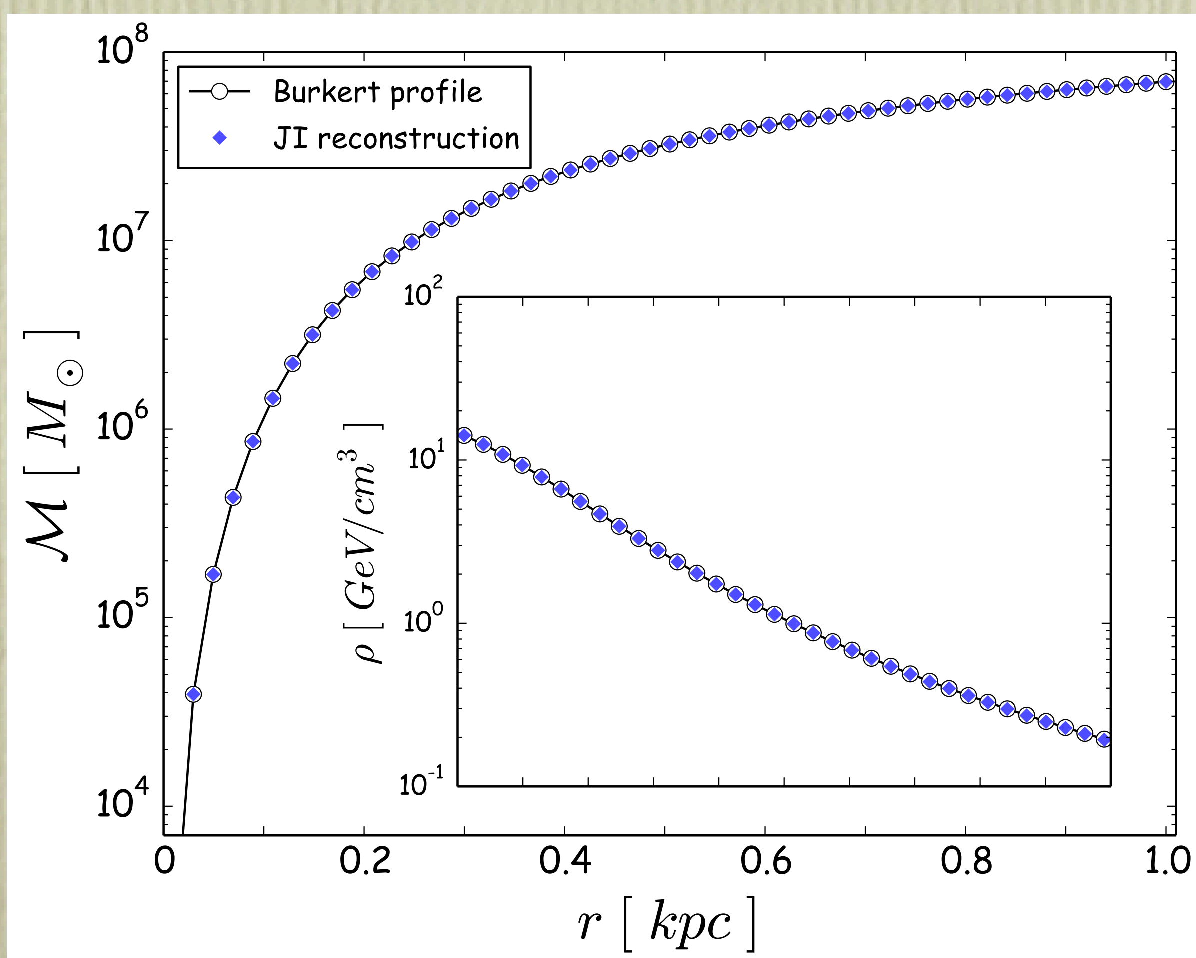


The Abel transforms $\widehat{P}(r)$ and $\widehat{I}(r)$ are computed numerically, and then one can perform a direct projection of what you do (not) know about $\beta(r)$ into a prediction for $M(r)$, $\rho(r)$ and J , and hence have a more direct assessment of uncertainties in the predictions for dark matter signals.

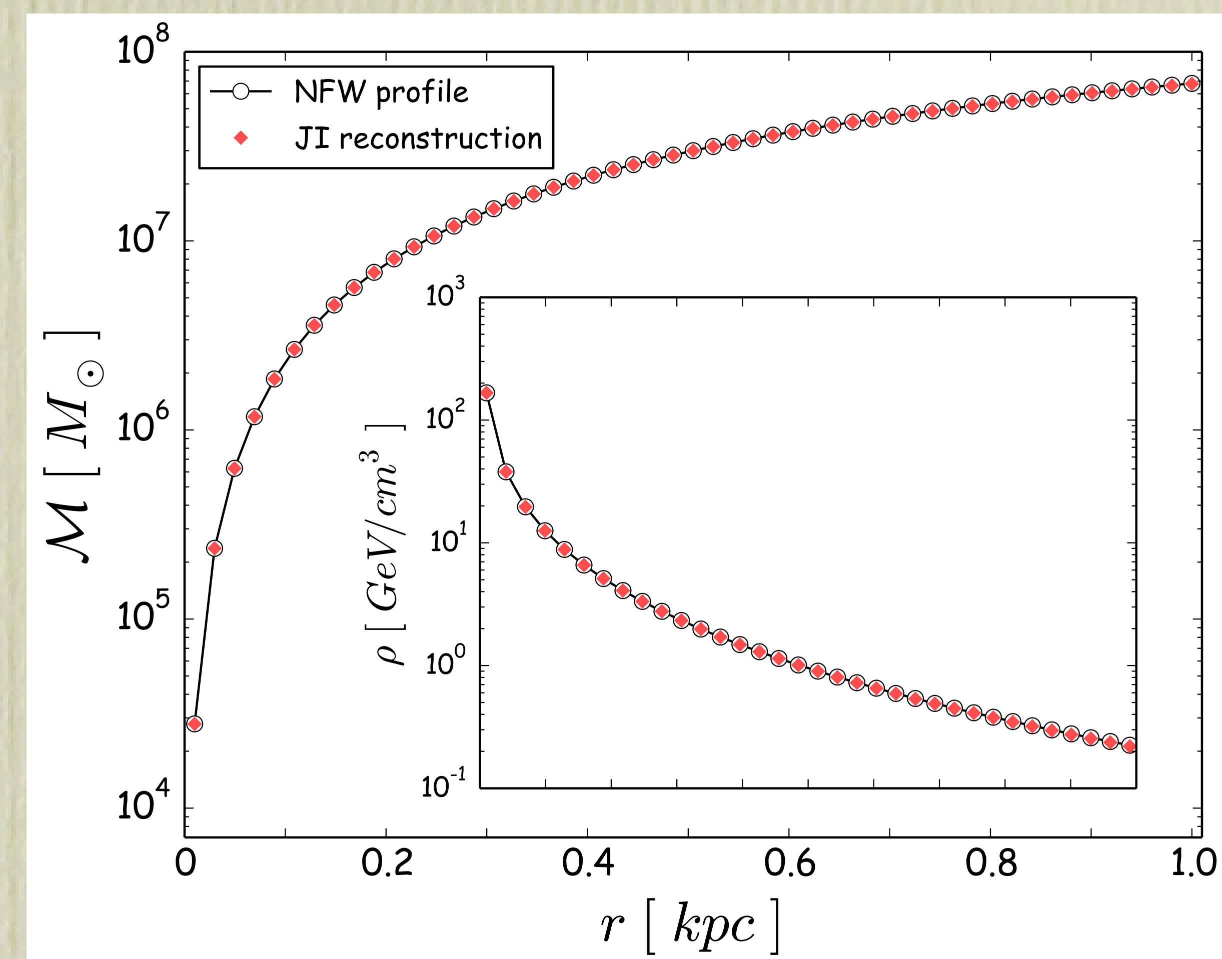
We have a numerical tool that works:

Sample check: assume given $M(r)$ [or $\rho(r)$] and $\beta(r)$, compute for these the projected dynamical pressure $P(r)$, Abel transform the latter into $\widehat{P}(r)$ and use this to retrieve $M(r)$ [or $\rho(r)$].

The check shown here is on the best fit of Ursa Minor $\sigma_{l.o.s.}(R)$:



Burkert profile



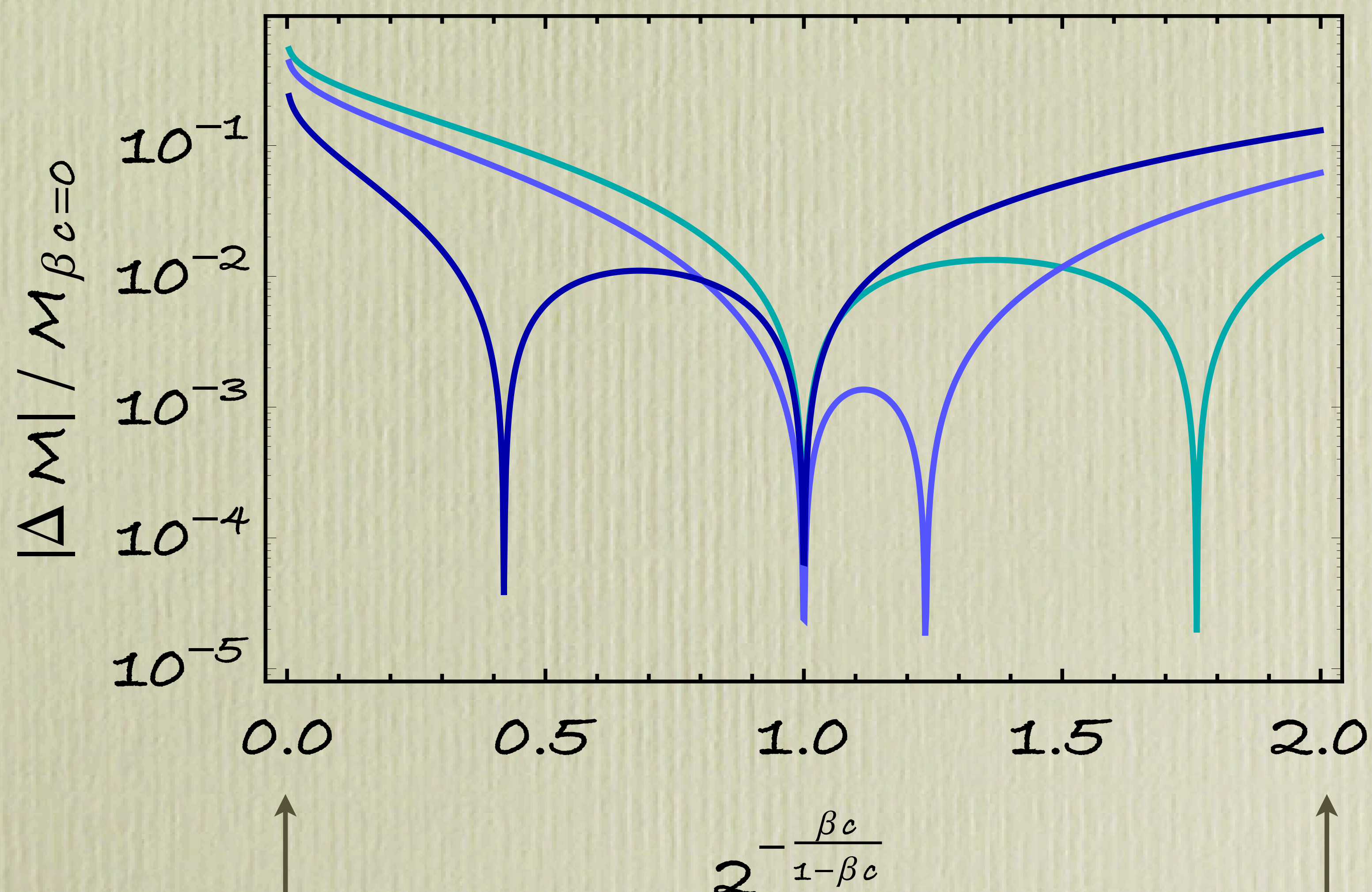
NFW profile

Direct check on the existence of a mass estimators:

It has been claimed, first from MCMC scans (**Strigari et al. 2008**) and then with closer look to features in the Jeans eq. solution (**Wolf et al. 2010**) that there is a radius $r_\star$ such that $M(r_\star)$ is nearly independent on choice of $\beta(r)$ ($r_\star \simeq 1.23\, R_{1/2}$ for a Plummer surface brightness).

Assuming, e.g., a flat velocity dispersion $\sigma_{l.o.s.}(R) = \text{const.}$ as well as a constant $\beta(r) = \beta_c$, from the mass inversion formula we find:

Mass differences compared to the isotropic case



results at fixed radius:

t = 1.32

t = 1.44

t = 1.69

with:

$t \equiv r^2 / R_{1/2}^2$

radial orbits

isotropy

circular orbits

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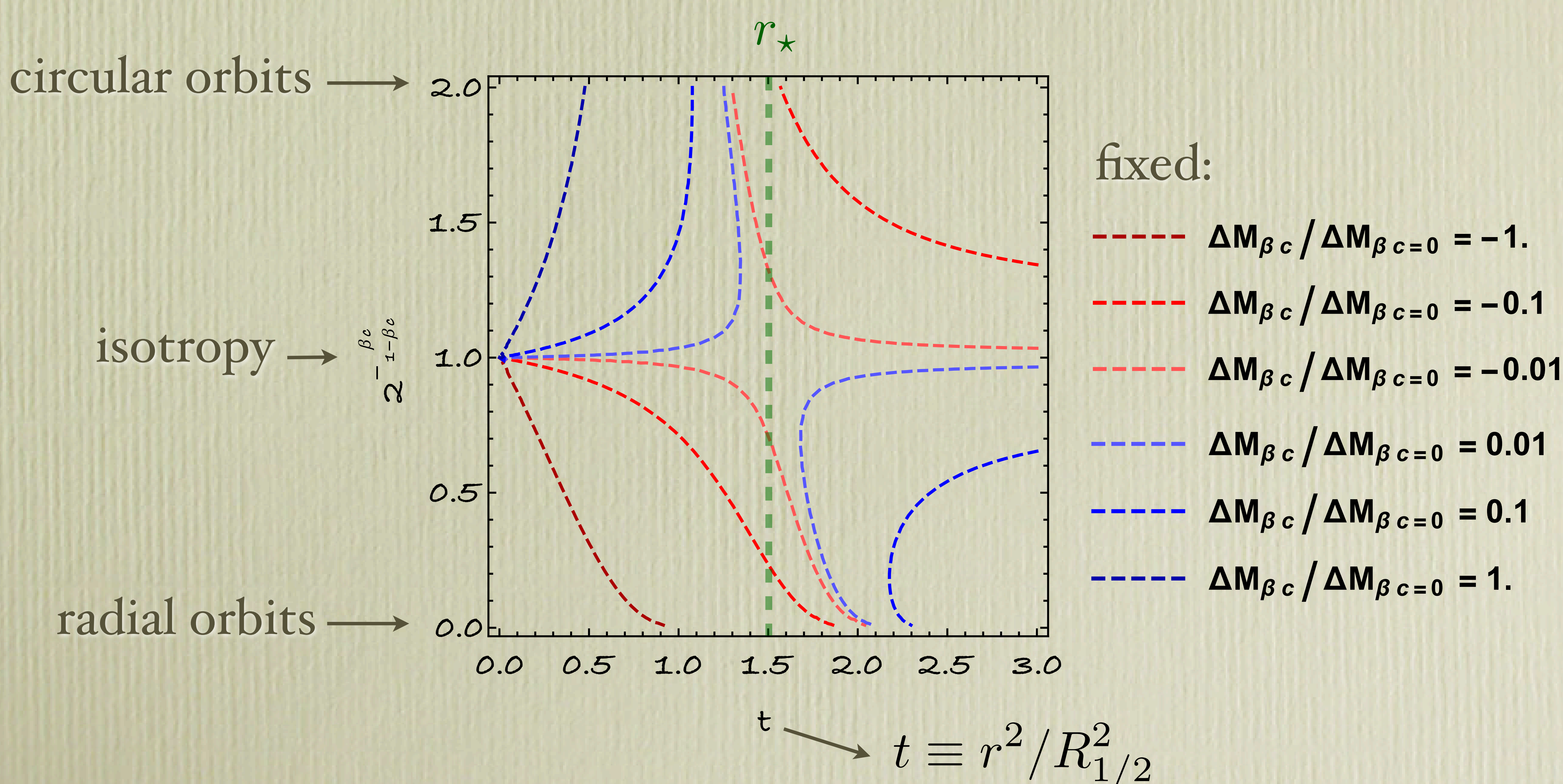
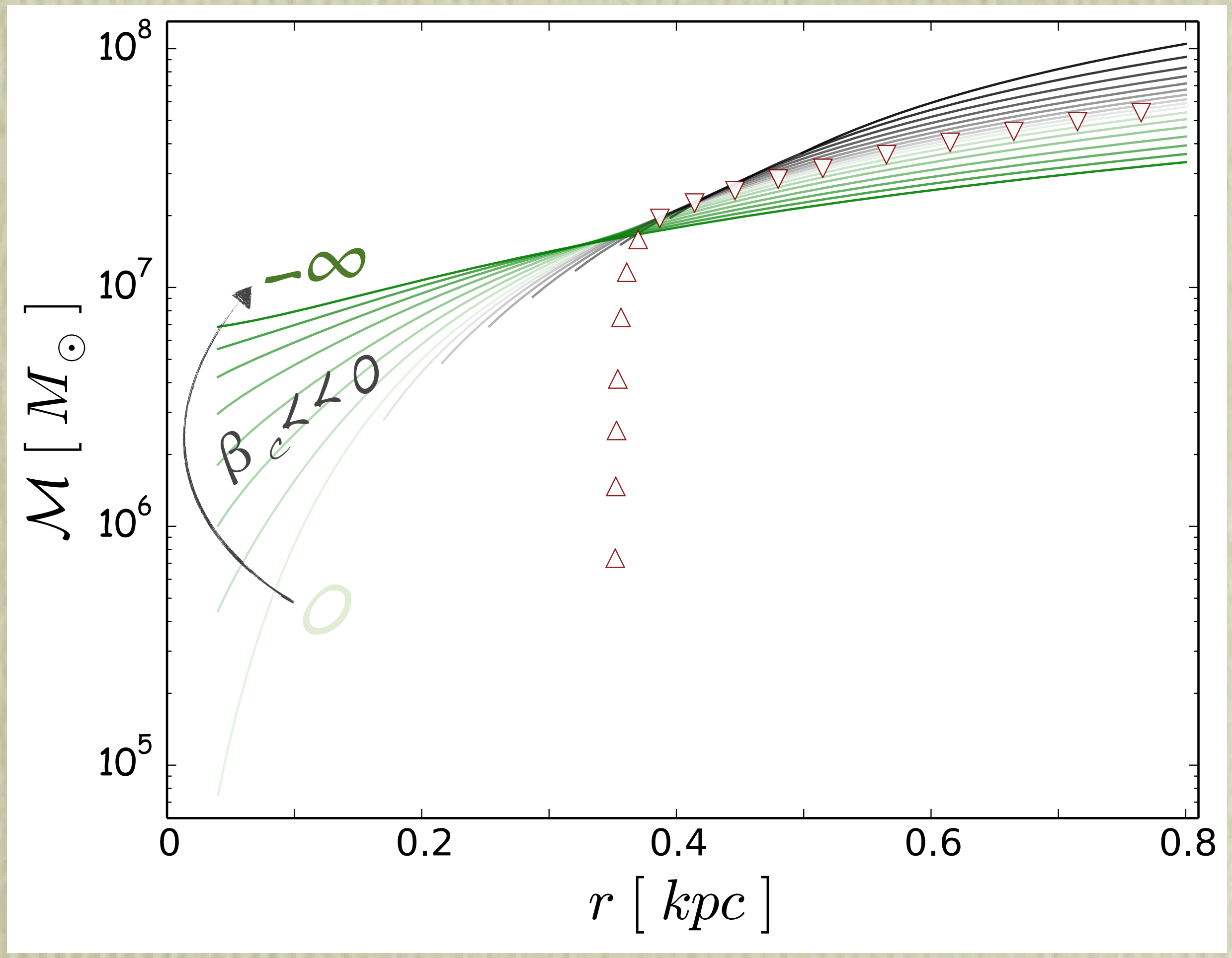
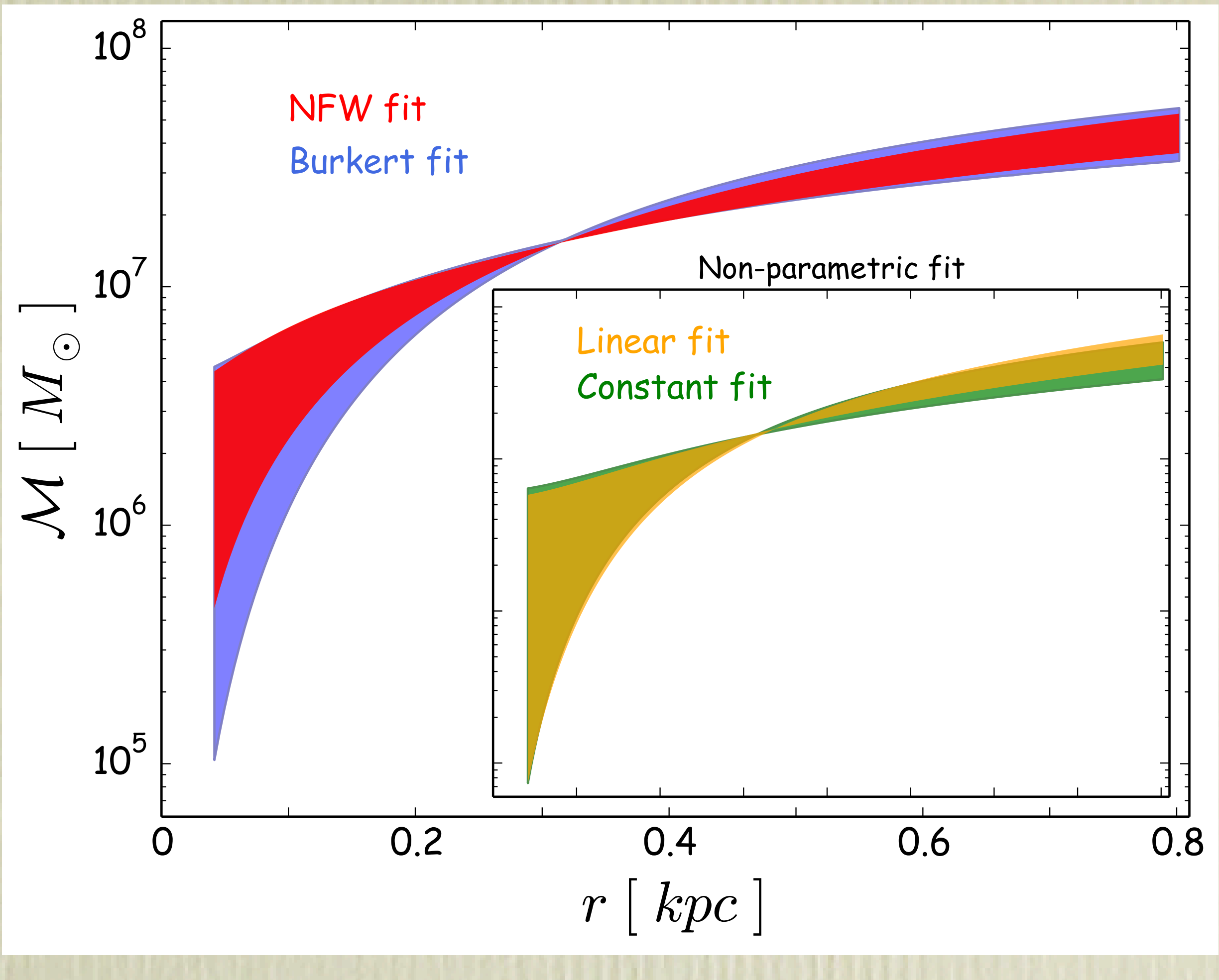


Mass profiles in Ursa Minor as a function of constant β:

In practice, agnostic mass reconstruction with our inversion formula not always give physical results. In a concrete example we need to restrain (a posteriori) to cases in which we get $M(r) > 0$, $dM/dr > 0$ and $d\rho/dr \leq 0$:



Burkert profile: imposing radial orbits gives unphysical results at low radii



Span of results for 4 different possible fits of the line-of-sight projected velocity dispersion

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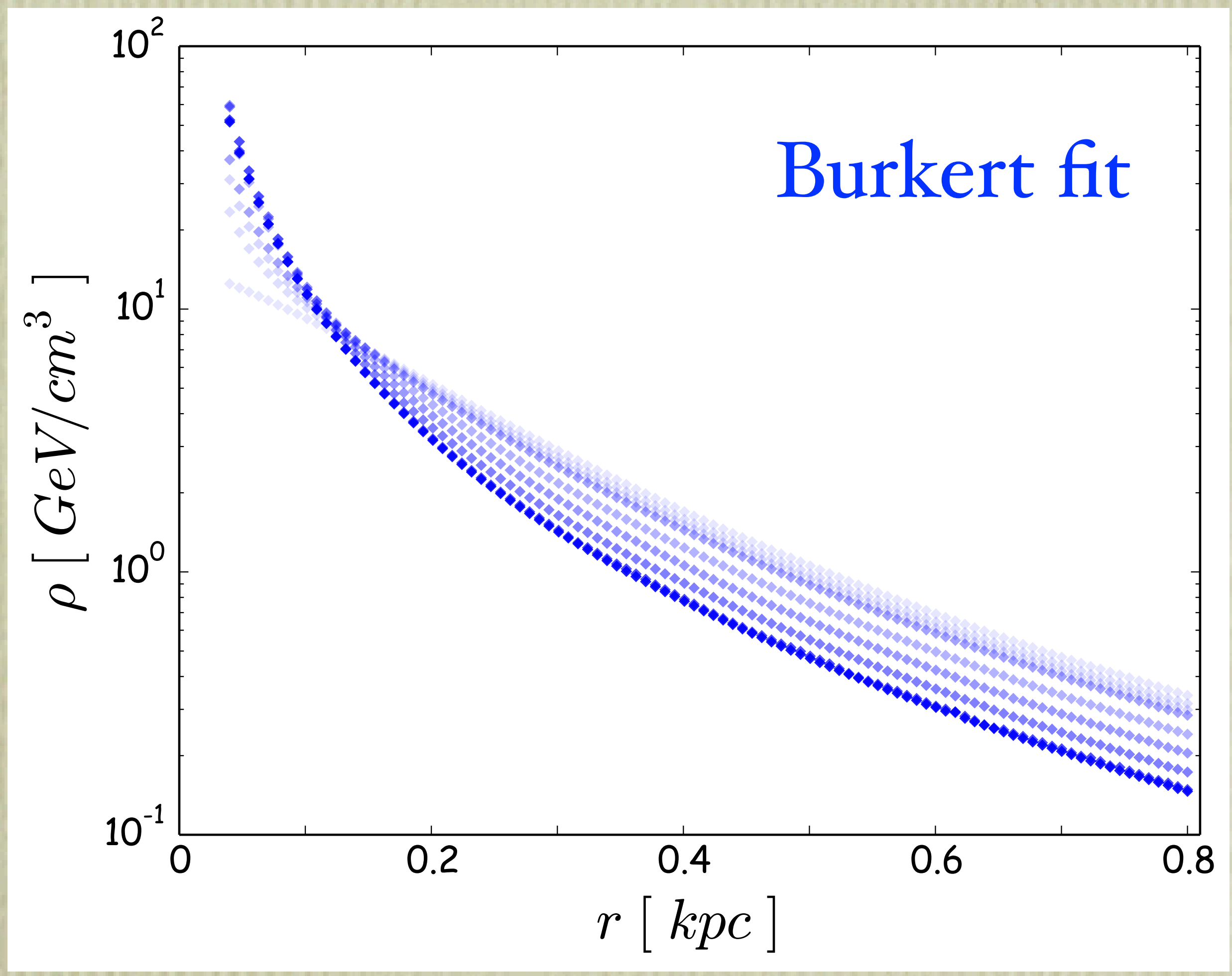
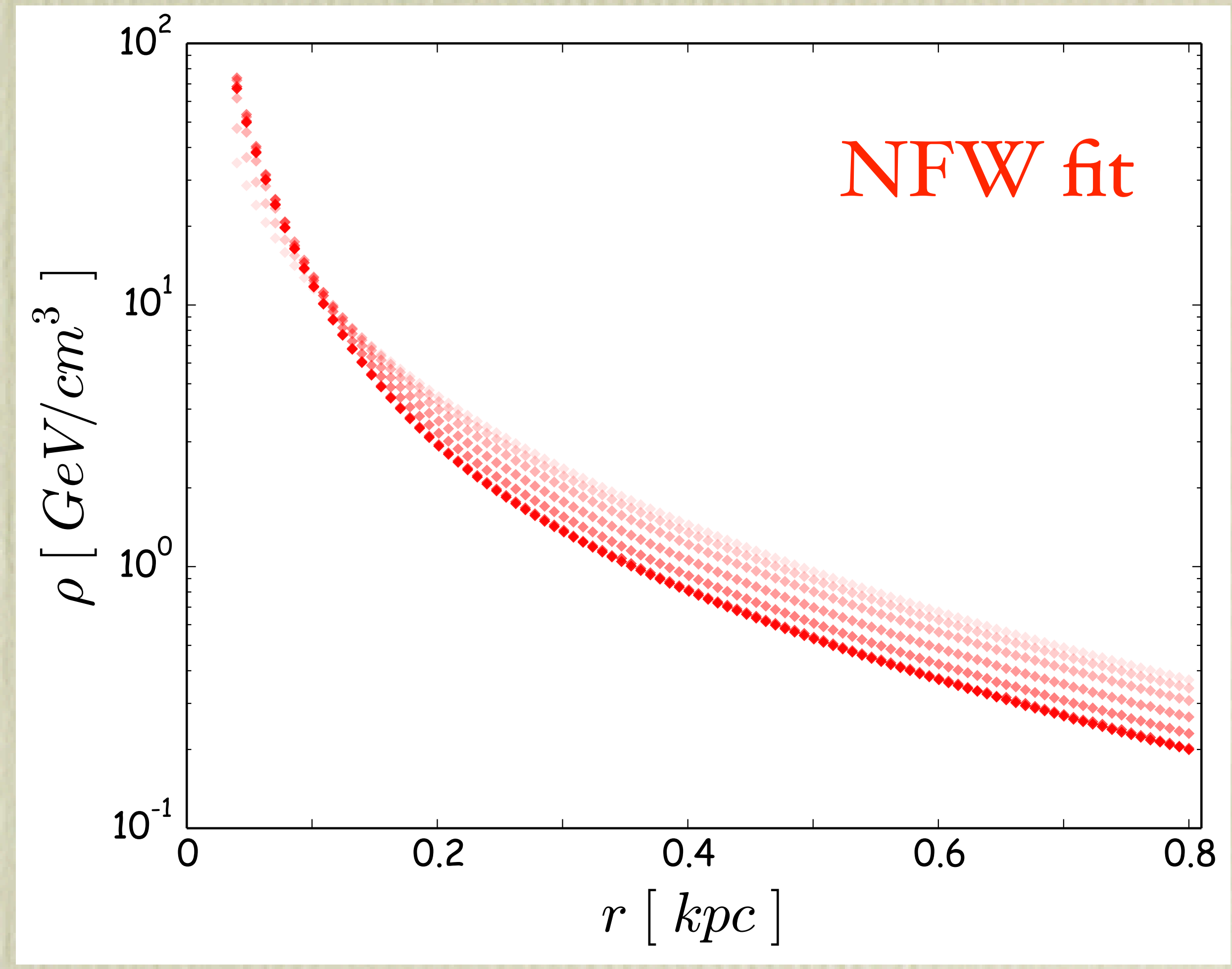




Sample limits:

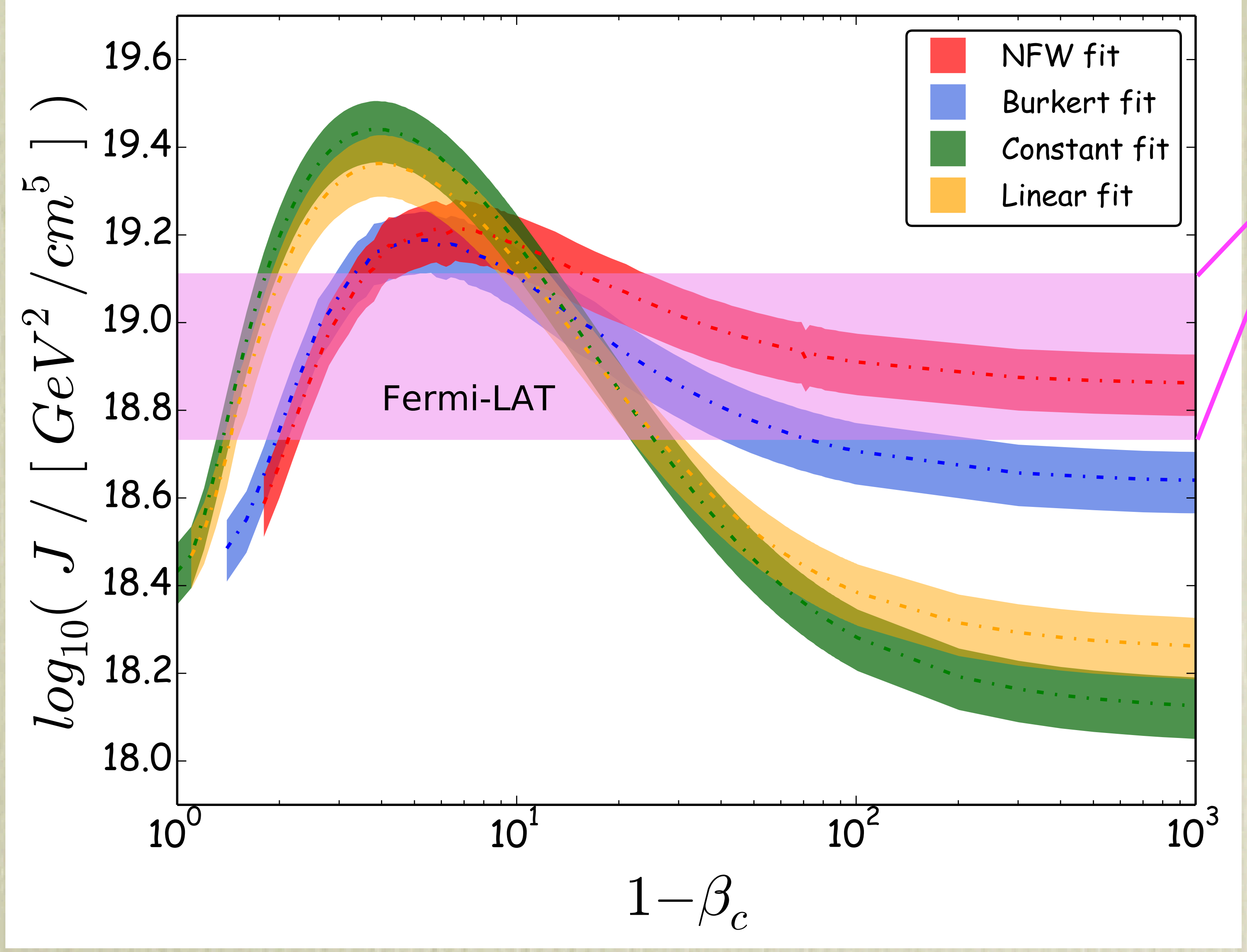
- for $\sigma_{l.o.s.}(R) = \text{const.}$, Plummer $I(R)$ + $\beta(r) = 0$ $\Rightarrow$ $\rho(r) \overset{r \to 0}{\simeq} \text{const}$
- for $\sigma_{l.o.s.}(R) = \text{const.}$, Plummer $I(R)$ + $\beta(r) = -\infty$ $\Rightarrow$ $\rho(r) \overset{r \to 0}{\propto} r^{-2}$ + black hole

J-factors in Ursa Minor as a function of constant β:

In line-of-sight integrals: $J \equiv \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\ \rho^2_{DM}(l)$

we conservative set $\rho(r)$ to a constant at radii smaller than the radius at which $\sigma_{l.o.s.}(R)$ can be measured (smallest radius in our data binning):

Span of predictions for the 4 sample fits of $\sigma_{l.o.s.}(R)$



1-σ band for Ursa Minor in **Fermi Coll. 2015** apparently not fully catching the β uncertainty

Conclusions:

We have presented a method to map solutions of the Jeans equation for dynamical-equilibrium spherically-symmetric systems onto observables for dwarf galaxies which keeps track of the indetermination related to the anisotropy of the dynamical tracer population.

We have checked the claim of existence of a mass estimator for dwarf galaxies, finding that indeed, despite some caveats, it cannot be grossly violated.

On the other hand, we have found that the approach to derive J-factor uncertainties by marginalizing over a predefined parametric forms for the functions entering in the Jeans equation, does not fully account for the uncertainties related the anisotropy of the dynamical tracer population.