The Dark Matter distribution of the Milky Way
(its uncertainties and consequences on the determination of new physics)
An empirical approach

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DSU 2019, July 17
Buenos Aires
**A story of LCDM the single halo**

A “universal” DM profile?

Navarro-Frenk-White (not in scale!)

\[
\rho(R) \propto \frac{R_s}{R} \left(1 + \frac{R}{R_s}\right)^{-2}
\]
A story of LCDM
the dark matter distribution

A “dynamical” DM profile

$\rho_{DM}(R) \propto \rho_0 \left( \frac{R}{R_s} \right)^{-\gamma} \left( 1 + \frac{R}{R_s} \right)^{-3+\gamma}$

See talks by
J. Navarro
S. White
A story of LCDM
the small scale problems

Cusp vs core

Missing satellite

Too big to fail

...and more:

See talk by J. Navarro
And now for something completely different: the Milky Way

The road to Zeus’ home on Olympus
The sacred path of Iberian pilgrims
An average-sized $10^{12}$ Msun spiral,
but the truth is…
The Milky Way:
una mirada desde el Sur

...Ya nunca alumbraré con las estrellas nuestra marcha sin querellas por las noches de Pompeya...

e.g. [H. Manzil], and many others...
What is the **actual** distribution of DM in the Milky Way?

And most notably in the proximity of the Sun?

Some additional hints on why you would care, later on.

Bear with me (but you should know, really)…
Empirical determination of local DM density

Determinations of local DM density are consistent, but noisy

[Graph showing data points and error bars for various years.]
Local determination of $\rho_0$

Vertical motion of stars in local region $O(100pc)$ provides total Grav Pot
Subtracting visible (stellar) contribution
Obtain (or not) DM without assumption on its presence
Inferring the DM density structure

Fitting a pre-assigned shape on top of luminous

\[ \rho_{DM}(R) \propto \rho_0 \left( \frac{R}{R_s} \right)^{-\gamma} \left( 1 + \frac{R}{R_s} \right)^{-3+\gamma} \]

Einasto

\[ \rho_{DM}(R) \propto \rho_0 \exp \left[ -\frac{2}{\gamma} \left( \left( \frac{R}{R_s} \right)^{\gamma} - 1 \right) \right] \]

[many authors, e.g. Iocco et al. 2011]
Dark Matter in the Milky Way:
a purely observational approach

Fabio Iocco

and continued with: María Benito, Ekaterina Karukes (2016-2019)
The case of the Milky Way: ingredients

- The observed rotation curve
- The “expected” rotation curve
- Some “grano salis”
- Working hypothesis (later on)
The Milky Way: observed rotation curve

II. tracers

Doppler shift
1. gas (21cm, Hα, CO)
2. stars (H, He, O, ...)
3. masers (H₂O, CH₃OH, ...)

distance
1. terminal velocities (gas)
2. photo-spectroscopy (stars)
3. parallax (masers)
The Milky Way: observed rotation curve

III. curve

Data compilation by [Sofue et al, ‘08]
# The Milky Way:
observed rotation curve

II'. data again (a new compilation)

<table>
<thead>
<tr>
<th>Object type</th>
<th>$R$ [kpc]</th>
<th>quadrants</th>
<th># objects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HI terminal velocities</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fich+ '89</td>
<td>2.1 – 8.0</td>
<td>1,4</td>
<td>149</td>
</tr>
<tr>
<td>Malhotra '95</td>
<td>2.1 – 7.5</td>
<td>1,4</td>
<td>110</td>
</tr>
<tr>
<td>McClure-Griffiths &amp; Dickey '07</td>
<td>2.8 – 7.6</td>
<td>4</td>
<td>701</td>
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<tr>
<td><strong>HI thickness method</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Honma &amp; Sofue '97</td>
<td>6.8 – 20.2</td>
<td>–</td>
<td>13</td>
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<tr>
<td><strong>CO terminal velocities</strong></td>
<td></td>
<td></td>
<td></td>
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<td>Burton &amp; Gordon '78</td>
<td>1.4 – 7.9</td>
<td>1</td>
<td>284</td>
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<tr>
<td>Clemens '85</td>
<td>1.9 – 8.0</td>
<td>1</td>
<td>143</td>
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<tr>
<td>Knapp+ '85</td>
<td>0.6 – 7.8</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>Luna+ '06</td>
<td>2.0 – 8.0</td>
<td>4</td>
<td>272</td>
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<td><strong>HII regions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blitz '79</td>
<td>8.7 – 11.0</td>
<td>2,3</td>
<td>3</td>
</tr>
<tr>
<td>Fich+ '89</td>
<td>9.4 – 12.5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Turbide &amp; Moffat '93</td>
<td>11.8 – 14.7</td>
<td>3</td>
<td>5</td>
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<tr>
<td>Brand &amp; Blitz '03</td>
<td>5.2 – 16.5</td>
<td>1,2,3,4</td>
<td>148</td>
</tr>
<tr>
<td>Hou+ '09</td>
<td>3.5 – 15.5</td>
<td>1,2,3,4</td>
<td>274</td>
</tr>
<tr>
<td><strong>giant molecular clouds</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Hou+ '09</td>
<td>6.0 – 13.7</td>
<td>1,2,3,4</td>
<td>30</td>
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<td><strong>open clusters</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Frinchaboy &amp; Majewski '08</td>
<td>4.6 – 10.7</td>
<td>1,2,3,4</td>
<td>60</td>
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<tr>
<td><strong>planetary nebulae</strong></td>
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<tr>
<td>Durand+ '98</td>
<td>3.6 – 12.6</td>
<td>1,2,3,4</td>
<td>79</td>
</tr>
<tr>
<td><strong>classical cepheids</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pont+ '94</td>
<td>5.1 – 14.4</td>
<td>1,2,3,4</td>
<td>245</td>
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<tr>
<td>Pont+ '97</td>
<td>10.2 – 18.5</td>
<td>2,3,4</td>
<td>32</td>
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<tr>
<td><strong>carbon stars</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demers &amp; Battinelli '07</td>
<td>9.3 – 22.2</td>
<td>1,2,3</td>
<td>55</td>
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<tr>
<td>Battinelli+ '13</td>
<td>12.1 – 24.8</td>
<td>1,2</td>
<td>35</td>
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<tr>
<td><strong>masers</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reid+ '14</td>
<td>4.0 – 15.6</td>
<td>1,2,3,4</td>
<td>80</td>
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<tr>
<td>Honma+ '12</td>
<td>7.7 – 9.9</td>
<td>1,2,3,4</td>
<td>11</td>
</tr>
<tr>
<td>Stepanishchev &amp; Bobylev '11</td>
<td>8.3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Xu+ '13</td>
<td>7.9</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Bobylev &amp; Bajkova '13</td>
<td>4.7 – 9.4</td>
<td>1,2,4</td>
<td>7</td>
</tr>
</tbody>
</table>

The Milky Way Rotation Curve

as observed

[Iocco, Pato, Bertone, Nature Physics 2015]

All tracers, optimized for precision between R=3-20 kpc
The Milky Way: “expected” rotation curve from visible (baryon) component

\[ \Phi_{\text{baryon}} = \Phi_{\text{bulge}} + \Phi_{\text{disk}} + \Phi_{\text{gas}} \]

\[ \rho_i(x, y, z) \rightarrow \phi_i(r, \theta, \varphi) \rightarrow v_{c,i}^2(R) = \sum_{\varphi} R \frac{d\phi_i}{dr}(R, \pi/2, \varphi) \]

Constructing the curve expected from observed mass profiles
The Milky Way:
expected rotation curve
1. the baryonic components

Milky Way
edge-on

dark halo

bulge/bar

bulge
tilted bar
disk
thin+thick
gas
$\text{H}_2, \text{HI}, \text{HII}$

not to scale!

Courtesy of Miguel Pato
The luminous Milky Way: observations of morphology

2. BARYONS: STELLAR BULGE

\[ \rho_{\text{bulge}} = \rho_0 f(x, y, z) \]

**morphology** \( f(x, y, z) \)

<table>
<thead>
<tr>
<th>Model</th>
<th>Function</th>
<th>Parameters</th>
<th>Inclination</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanek+ '97 (E2)</td>
<td>( e^{-r} )</td>
<td>0.9:0.4:0.3</td>
<td>24º</td>
<td>optical</td>
</tr>
<tr>
<td>Stanek+ '97 (G2)</td>
<td>( e^{-r_s^2/2} )</td>
<td>1.2:0.6:0.4</td>
<td>25º</td>
<td>optical</td>
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<tr>
<td>Zhao '96</td>
<td>( e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a} )</td>
<td>1.5:0.6:0.4</td>
<td>20º</td>
<td>infrared</td>
</tr>
<tr>
<td>Bissantz &amp; Gerhard '02</td>
<td>( e^{-r_s^2/(1+r)^{1.8}} )</td>
<td>2.8:0.9:1.1</td>
<td>20º</td>
<td>infrared</td>
</tr>
<tr>
<td>Lopez-Corredoira+ '07</td>
<td>Ferrer potential</td>
<td>7.8:1.2:0.2</td>
<td>43º</td>
<td>infrared/optical</td>
</tr>
<tr>
<td>Vanhollebecke+ '09</td>
<td>( e^{-r_s^2/(1+r)^{1.8}} )</td>
<td>2.6:1.8:0.8</td>
<td>15º</td>
<td>infrared/optical</td>
</tr>
<tr>
<td>Robin+ '12</td>
<td>( \text{sech}^2(-r_s) + e^{-r_s} )</td>
<td>1.5:0.5:0.4</td>
<td>13º</td>
<td>infrared</td>
</tr>
</tbody>
</table>

**normalisation** \( \rho_0 \)

microlensing optical depth: \( \langle \tau \rangle = 2.17^{+0.47}_{-0.38} \times 10^{-6}, (\ell, b) = (1.50\degree, -2.68\degree) \)  
(MACHO '05)
The luminous Milky Way: observations of morphology

## 2. BARYONS: STELLAR DISK

\[ \rho_{\text{disk}} = \rho_0 f(x, y, z) \]

### morphology \( f(x, y, z) \)

<table>
<thead>
<tr>
<th>Source</th>
<th>Formula</th>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Han &amp; Gould ’03</td>
<td>( e^{-R \text{sech}^2(z)} )</td>
<td>2.8:0.27</td>
<td>thin optical</td>
</tr>
<tr>
<td></td>
<td>( e^{-R-</td>
<td>z</td>
<td>} )</td>
</tr>
<tr>
<td>Calchi-Novati &amp; Mancini ’11</td>
<td>( e^{-R-</td>
<td>z</td>
<td>} )</td>
</tr>
<tr>
<td></td>
<td>( e^{-R-</td>
<td>z</td>
<td>} )</td>
</tr>
<tr>
<td>deJong+ ’10</td>
<td>( e^{-R-</td>
<td>z</td>
<td>} )</td>
</tr>
<tr>
<td></td>
<td>( e^{-R-</td>
<td>z</td>
<td>} )</td>
</tr>
<tr>
<td></td>
<td>( (R^2 + z^2)^{-2.75/2} )</td>
<td>1.0:0.88</td>
<td>halo</td>
</tr>
<tr>
<td>Jurić+ ’08</td>
<td>( e^{-R-</td>
<td>z</td>
<td>} )</td>
</tr>
<tr>
<td></td>
<td>( e^{-R-</td>
<td>z</td>
<td>} )</td>
</tr>
<tr>
<td></td>
<td>( (R^2 + z^2)^{-2.77/2} )</td>
<td>1.0:0.64</td>
<td>halo</td>
</tr>
<tr>
<td>Bovy &amp; Rix ’13</td>
<td>( e^{-R-</td>
<td>z</td>
<td>} )</td>
</tr>
</tbody>
</table>

### normalisation \( \rho_0 \)

Local surface density: \( \Sigma_* = 38 \pm 4 \text{M}_\odot/\text{pc}^2 \) [Bovy & Rix ’13]
The luminous Milky Way: observations of morphology

2. BARYONS: GAS

\[ n_{H} = 2n_{H_{2}} + n_{HI} + n_{HII} \]

**morphology**

<table>
<thead>
<tr>
<th>Author</th>
<th>Distance</th>
<th>Gas Characteristics</th>
<th>Molecular Gas</th>
<th>Neutral Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrière '12</td>
<td>( r &lt; 0.01 \text{ kpc} )</td>
<td>( M_{gas} \sim 7 \times 10^{5} \text{ M}_{\odot} )</td>
<td>CO, 21cm, H( \alpha ), ...</td>
<td></td>
</tr>
<tr>
<td>Ferrière+ '07</td>
<td>( r = 0.01 - 2 \text{ kpc} )</td>
<td>CMZ, holed disk</td>
<td>H(_2)</td>
<td>CO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CMZ, holed disk</td>
<td>H I</td>
<td>21cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>warm, hot, very hot</td>
<td>H II</td>
<td>disp. meas.</td>
</tr>
<tr>
<td>Ferrière '98</td>
<td>( r = 3 - 20 \text{ kpc} )</td>
<td>molecular ring</td>
<td>H(_2)</td>
<td>CO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cold, warm</td>
<td>H I</td>
<td>21cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>warm, hot</td>
<td>H II</td>
<td>disp. meas., H( \alpha )</td>
</tr>
<tr>
<td>Moskalenko+ '02</td>
<td>( r = 3 - 20 \text{ kpc} )</td>
<td>molecular ring</td>
<td>H(_2)</td>
<td>CO</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H I</td>
<td>21cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H II</td>
<td>disp. meas.</td>
</tr>
</tbody>
</table>

**uncertainties**

CO-to-H\(_2\) factor: \( X_{CO} = 0.25 - 1.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s} \) for \( r < 2 \text{ kpc} \)

\[ X_{CO} = 0.50 - 3.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s} \] for \( r > 2 \text{ kpc} \)

[FERRIÈRE+ '07, ACKERMANN '12]
The luminous Milky Way: expected rotation curve

\[ \phi_i(r, \theta, \varphi) = -4\pi G \sum_{l,m} \frac{Y_{lm}(\theta, \varphi)}{2l + 1} \left[ \frac{1}{r^{l+1}} \int_0^r \rho_{i,lm}(a) a^{l+2} da + r^l \int_r^\infty \rho_{i,lm}(a) a^{1-l} da \right] \]

full 3d morphology
integrating observed profiles

\[ \rho_i(x, y, z) \rightarrow \phi_i(r, \theta, \varphi) \rightarrow v_{c,i}(R) = \sum_\varphi R \frac{d\phi_i}{dr}(R, \pi/2, \varphi) \]

[Iocco, Pato, Bertone, Nature Physics 2015]
The Milky Way: testing expectations (with no additional assumptions)

[Iocco, Pato, Bertone, Nature Physics 2015]
Systematic uncertainties
(luminous component)

- Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017
- Iocco, Pato, Bertone, Nature Physics 2015
Extracting the DM density structure

\[ \rho_{DM}(R) \propto \rho_0 \left( \frac{R}{R_s} \right)^{-\gamma} \left( 1 + \frac{R}{R_s} \right)^{-3+\gamma} \]

gen. NFW, \( r_s = 20 \text{ kpc} \)

[Pato, Iocco, Bertone, 2015]
What to do of our measurement?
(Our instrument is very precise. Is it accurate?)

Test the system with known conditions (mock data)

Remarkable accuracy on local DM density

full Bayesian framework, test of data consistency, more to in the paper when what telling you here
The Milky Way:
observed rotation curve
Neglecting some quite remarkable uncertainties (for now)

observing tracers from our own position,
transforming into GC-centric reference frame

\[ v_{\text{LSR}}^{\text{l.o.s.}} = \left( \frac{v_c(R')}{{R'}/R_0} - v_0 \right) \cos b \sin \ell \]
How to reconstruct DM density profile in Galactic Bulge region?

Most of the galaxy’s light comes from stars and gas in the galactic disk and central bulge ...

\( (x, y, z) = (\pm 2.2, \pm 1.4, \pm 1.2) \text{ kpc} \)

\[ M_{total} = (1.85 \pm 0.05) \times 10^{10} \, M_\odot \]


\[ M_i^* = \int_{box} \rho_i^*(x, y, z) \, dV \]

Stellar mass

Iocco & MB
Methodology

Allowed DM mass

\[ M_{total} - M_* = M_{DM}^i \]
\[ \sigma_{M_{DM}} = \sqrt{\sigma_{M_{total}}^2 + \sigma_{M_*}^2} \]

\[ M_{total} = (1.85 \pm 0.05) \times 10^{10} M_\odot \]

\[ M_* = (1.1 - 1.7) \times 10^{10} M_\odot \]
\[ M_{DM} = (0.1 - 0.7) \times 10^{10} M_\odot \]

DM mass corresponds to 7-37%

\[ \rho_{DM}(r) = \rho_0 \left( \frac{R_0}{r} \right)^\gamma \left( \frac{R_s + R_0}{R_s + r} \right)^{3-\gamma} \]

gNFW density profile

Study parameter space that gives a mass in excess or defect with respect to the allowed DM mass.
Galactic Bulge Region - Results: varying bulge morphology

\[ R_s = 20 \text{kpc} \]
\[ R_0 = 8 \text{kpc} \]

Same disc, varying bulge

\[ \gamma \]

[\(\rho_0\) [GeV cm\(^{-3}\)]

[Iocco & Benito, 2017]
arXiv:1611.09861
Direct and indirect searches of WIMP DM complementary to colliders

Direct detection:
DM scattering against nuclei, recoil

Indirect detection:
Annihilation in astrophysical envir.
Observation of SM products of annihilation.

Production at LHC
Indirect Detection: principles and dependencies

\[ \chi + \chi \rightarrow q\bar{q}, W^+W^-, \ldots \rightarrow \gamma, \bar{p}, \bar{D}, e^+ \& \nu' s \]

\[ F_i \propto \frac{1}{4\pi d^2} B_i \frac{\langle \sigma v \rangle}{m_\chi} \int \rho^2(r) dV \]
Direct Detection: principles and dependencies (to go...)

\[ \frac{dR}{dE} \propto \frac{1}{\mu^2} \frac{\sigma_{\chi}}{m_\chi} \rho_0 \eta(v, t) \]

See talk by A. Ibarra
Extracting the DM density structure

\[ \rho_{DM}(R) \propto \rho_0 \left( \frac{R}{R_s} \right)^{-\gamma} \left( 1 + \frac{R}{R_s} \right)^{-3+\gamma} \]

gen. NFW, \( r_s = 20 \) kpc

[Pato, Iocco, Bertone, 2015]
But do Galactic uncertainties affect PP, for real?

\[ J_{\text{annih}} \propto \int_{\text{los}} \rho^2(r) dV \]

It is well known that uncertainties affect inDirect (some more, some less) and its interpretation.

[Calore et al., 2015]

It is well known that uncertainties affect Direct Detection

Current LUX limits, but varying astrophysical uncertainties

The effect of astrophysical uncertainties on the determination of new physics

Uncertainties accounted for:

Calore analysis:
observed GC signal
(only stat. on gamma flux)

This analysis:
observed GC signal
+ DM density profile
(Gal. Param. + Morphologies + stat)

Ready-to-use likelihood publicly available @
https://github.com/mariabenitocst/UncertaintiesDMinTheMW

[Benito, Cuoco, Iocco, JCAP
arXiv:1901.02460]
Let’s quantify this effect in a specific case: Singlet Scalar DM

\[ V = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \mu_S^2 S^2 + \lambda_S S^4 + \lambda_{HS} |H|^2 S^2 \]

\[ \nu_H = 246 \text{ GeV} \quad \langle S \rangle = 0 \]

\[ m_S^2 = 2 \mu_S^2 + \lambda_{HS} \nu_H^2 \]

“WIMP phenomenology” entirely dictated by the Higgs coupling and physical DM mass.

[Mc Donald, 1994] [Burgess, Pospelov, Velthuis, 2001]
Singlet Scalar DM
Constraints and interplay of experiments

Relic density

Direct detection

Combined

[Duerr et al., 2015]
Singlet Scalar DM
Constraints and interplay of experiments

\[ V = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \mu_S^2 S^2 + \lambda_S S^4 + \lambda_{HS} |H|^2 S^2 \]
Let’s look at the effect of astrophysics uncertainties: Direct Detection

[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]
Let’s look at the effect of astrophysics uncertainties: Direct Detection

[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]
Let’s look at the effect of astrophysics uncertainties: Indirect Detection

[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]
• Determining the local DM density from actual data is possible.

• RC method is accurate and precise, in spite of large range of observational systematic and statistical uncertainties.

• Slope (i.e. full profile of MW) is not very accurate, and quite depending from several systematics.

• Astrophysical uncertainties are actually affecting determination of PP, in virtuous interplay with collider physics, direct and indirect probes.

• Providing a ready-to-use likelihood for PP use, including astrophysical uncertainties on DM distribution.
South American Dark Matter workshop
December 2-4, 2020

Third in a successful series (2017, 2018)
www.ictp-saifr.org/DMw2018

Invited speakers have included (e.g.):

Graciela Gelmini
Christopher McCabe
Cecilia Scannapieco
Tomer Volansky

São Paulo
Brazil
(not Rio de Janeiro!)