Title: Getting the most out of dark matter observations and experiments

Date: May 03, 2010 02:00 PM

URL: http://pirsa.org/10050007

Abstract: Dark matter, constituting a fifth of the mass-energy in the Universe today, is one of the major "known unknowns" in physics. A number of different experimental and observational techniques exist to try to identify dark matter. However, these techniques are not only sensitive to the "physics" of dark matter (mass, cross sections, and the theory in which the dark matter particles live) but to the "astrophysics" of dark matter as well, namely the phase-space density of dark matter throughout the Milky Way and other galaxies and its evolution through cosmic time.
In order to accurately map signals in experiments or observations to the particle-physics properties of dark matter, we need to understand the astrophysics of dark matter. In this talk, I will demonstrate how to get robust constraints on the particle-physics properties of dark matter either by careful modeling the astrophysics properties of dark matter or by elevating the astrophysics properties of dark matter as something to be extracted from future data sets alongside particle-physics parameters, and which approach (modeling vs. empirical) is more useful for given problems.
As an example, I will show which aspects of the local dark-matter phase-space density can be understood through modeling and which aspects may be possible to infer empirically, and what the implications are for determining the particle-physics of dark matter from direct and indirect detection.

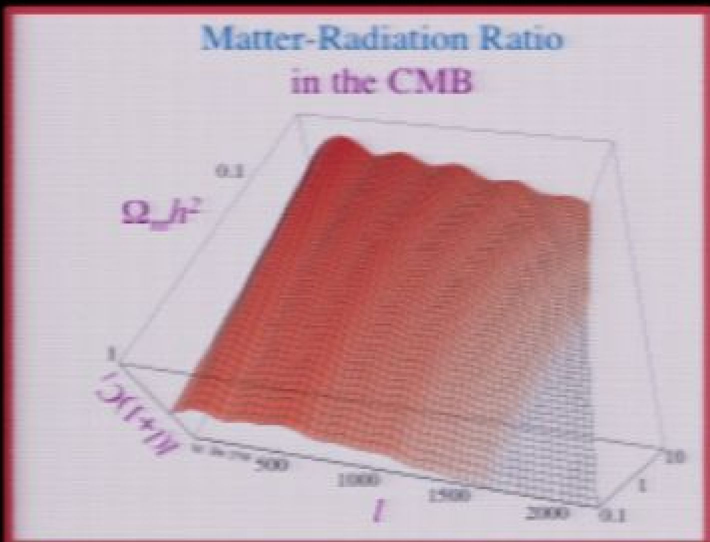
Getting the most out of dark matter observations and experiments

Annika Peter

Caltech

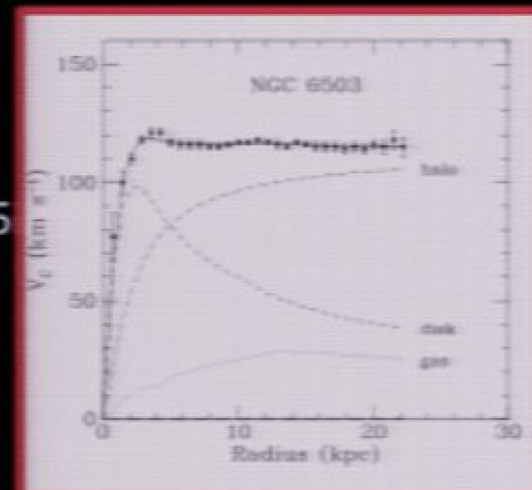
5/3/2010

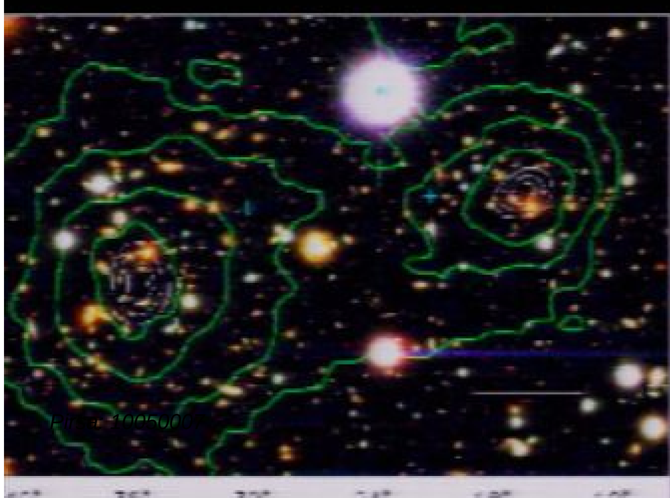
Lines of Evidence for Dark Matter



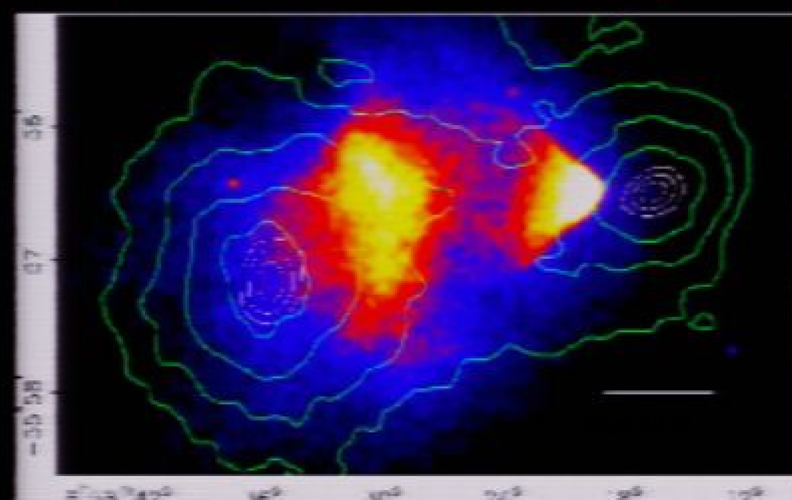
Wayne Hu's website

From Bertone et al. 2005
With data from
Begeman et al. 1991





Bullet Cluster
Clowe et al.
2006

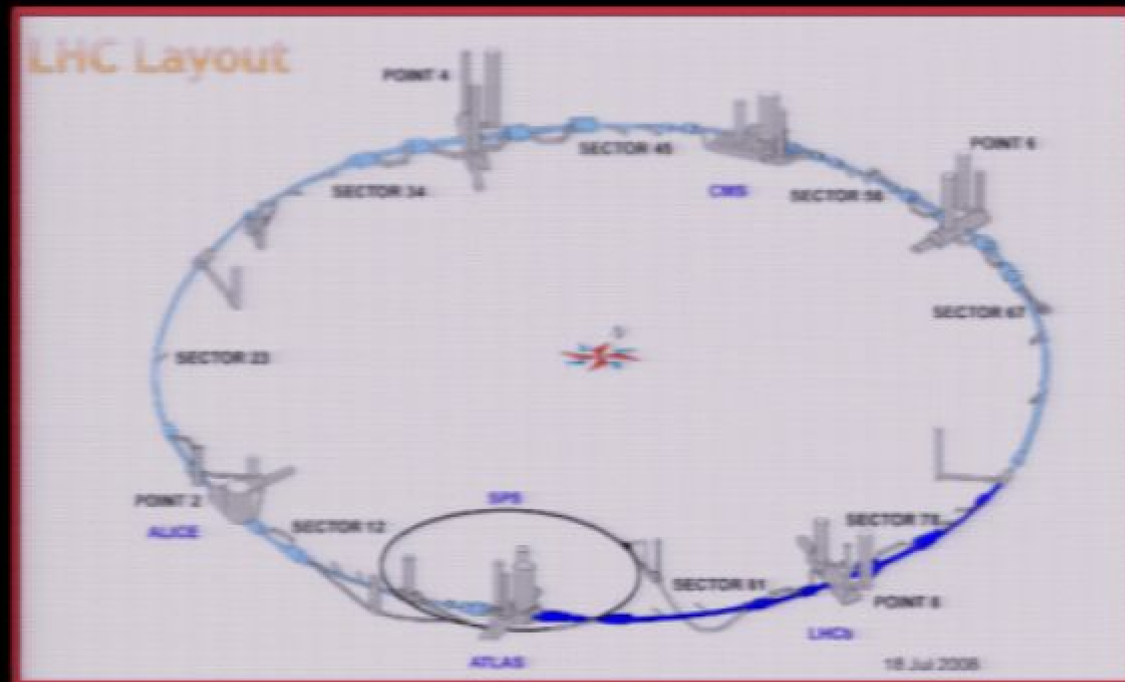


What is Dark Matter?

- Astrophysical (not favored)
- Particle physics:
  - WIMPs (weakly interacting massive particles): neutralinos, Kaluza-Klein photons
  - SuperWIMPs: gravitinos
  - Sterile neutrinos
  - Axions
  - Hidden sector particles
  - Self-interacting dark matter
  - …

How to Nail Down Dark Matter

- Make it (e.g. in a collider)



From E. Prebys, Aspen 2010

- Direct detection
- Indirect detection via annihilation/interaction/ decay products
- “Gravitational probes”

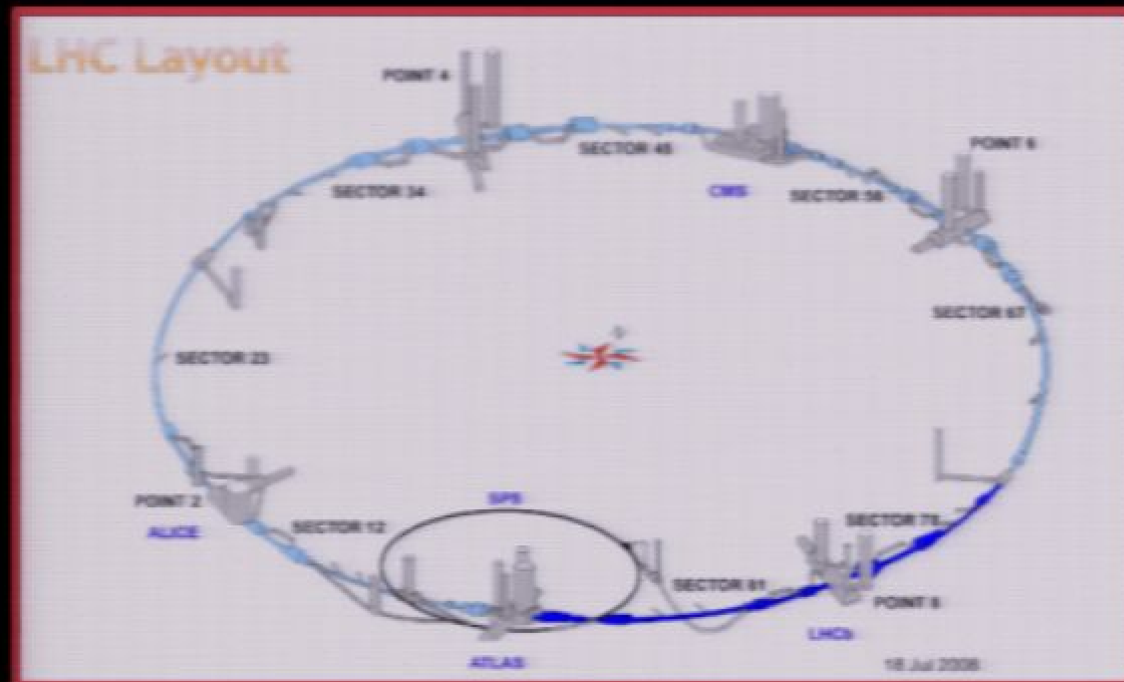
What is Dark Matter?

- Astrophysical (not favored)
- Particle physics:
  - WIMPs (weakly interacting massive particles): neutralinos, Kaluza-Klein photons
  - SuperWIMPs: gravitinos
  - Sterile neutrinos
  - Axions
  - Hidden sector particles
  - Self-interacting dark matter
  - ...

How to Nail Down Dark Matter

- Make it (e.g. in a collider)

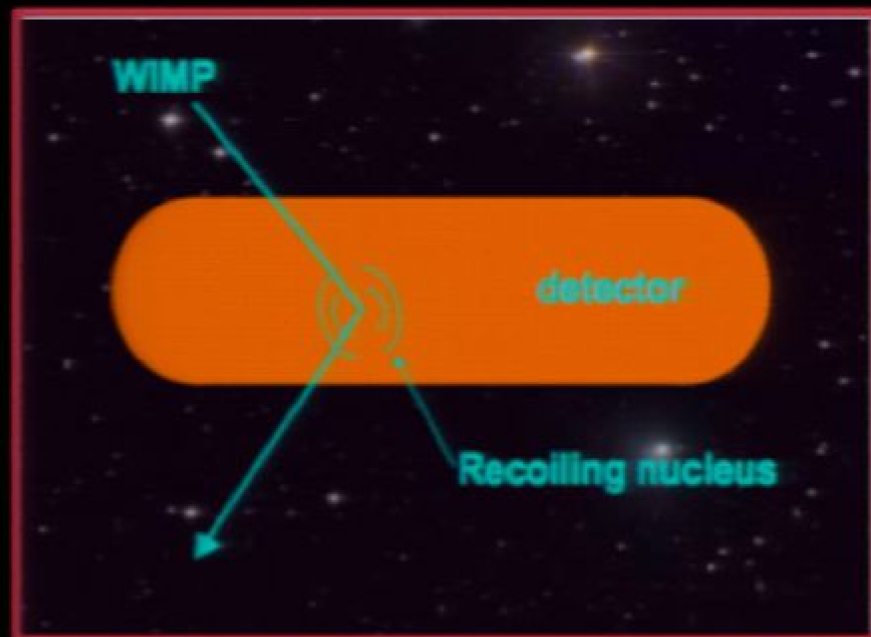
  From E. Prebys, Aspen 2010



- Direct detection
- Indirect detection via annihilation/interaction/decay products
- “Gravitational probes”

How to Nail Down Dark Matter

- Make it (e.g., collider)
- Direct detection

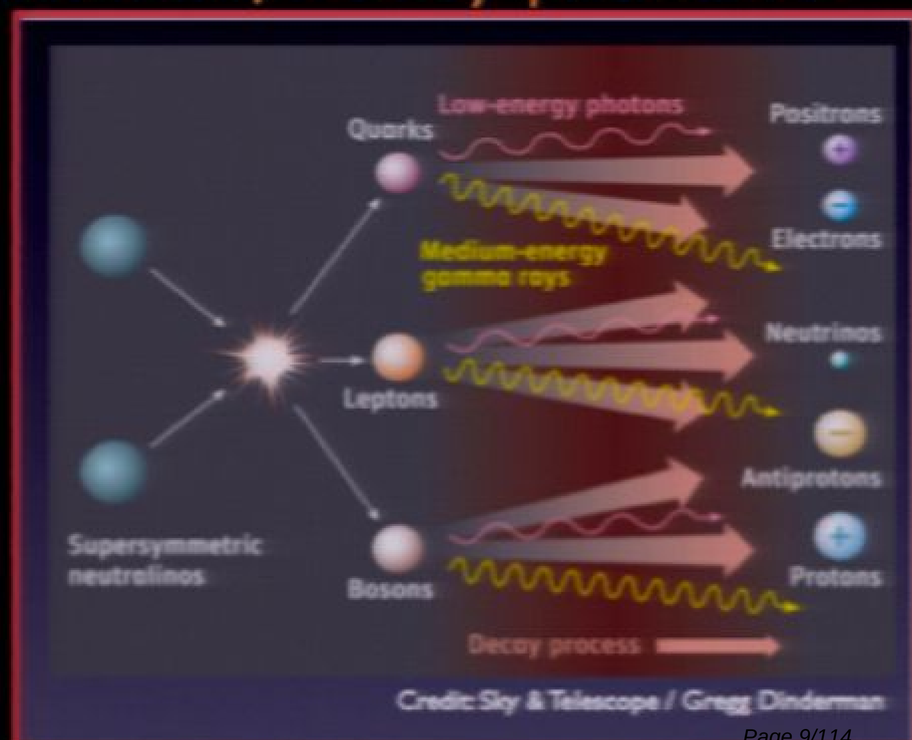


From D. Bauer, TeVPA 2005

- Indirect detection via annihilation/interaction/ decay products
- "Gravitational probes"

How to Nail Down Dark Matter

- Make it (e.g., collider)
- Direct detection
- Indirect detection via annihilation/decay products



- "Gravitational probes"

How to Nail Down Dark Matter

- Make it (e.g., collider)
- Direct detection
- Indirect detection via annihilation/interaction/ decay products
- "Gravitational probes"
  - Lensing
  - Dwarf galaxy satellite kinematics
  - Rotation curves

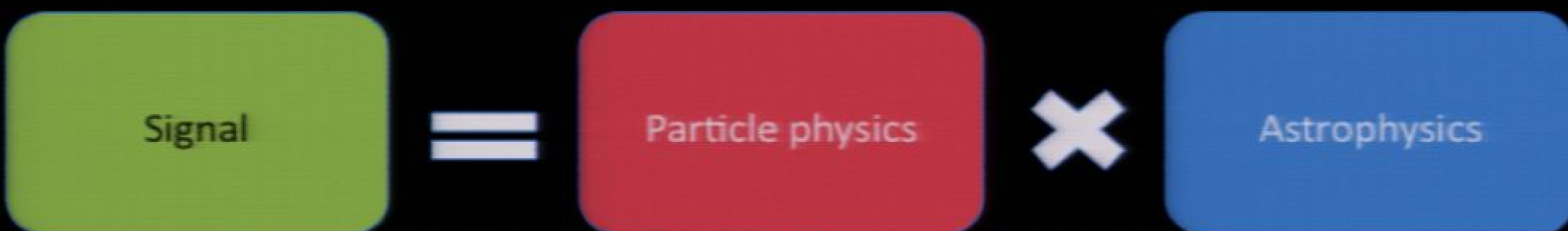
How to Nail Down Dark Matter

- Make it (e.g., collider)
- Direct detection
- Indirect detection via annihilation/interaction/ decay products
- "Gravitational probes"

These probes depend on "astrophysical" dark matter!

Pseudo-formula for the identification of dark matter:

- We have:



- We want:

Pseudo-formula for the identification of dark matter:

- We have:

Signal = Particle physics × Astrophysics

To understand the particle physics of dark matter, we must understand the ASTROPHYSICS of dark matter!

Particle physics = Signal × Astrophysics

However, this is easier said than done...

- Example:
  - Constraints on the WIMP annihilation cross section from annihilation of dark matter throughout the lifetime of the Universe from measurements of the diffuse isotropic gamma-ray background with Fermi (1002.4415)

$$\frac{\phi_\gamma}{E_0} \equiv \frac{dN_\gamma}{dA\, d\Omega dt_0 dE_0} = \frac{1}{4\pi}\int dr\, R_0 e^{-\tau(z,E_0)} \int dM \frac{dn}{dM}(M,z) \frac{dN_\gamma}{dE}(E_0(1+z),M,z)$$

Ullio et al. 2002

$$\sim \langle \sigma v \rangle \int \rho^2(r) dV \sum_i B_i \frac{dN_i}{dE}$$

Astrophysical Uncertainties

- Dark-matter macrostructures:
  - Dark matter-only simulations show definite predictions for ρ(r)
  - No consensus on what happens to ρ(r) when baryons are added—see papers by Romano-Diaz, Gnedin, Abadi, Blumenethal, Scannapieco, Governato, for a diversity of views. What drives changes?
  - Additional macroscopic structures ("dark disk"; Read et al. 2009, Purcell et al. 2009)?

However, this is easier said than done...

- Example:
  - Constraints on the WIMP annihilation cross section from annihilation of dark matter throughout the lifetime of the Universe from measurements of the diffuse isotropic gamma-ray background with Fermi (1002.4415)

$$\frac{\phi_\gamma}{E_0} \equiv \frac{dN_\gamma}{dA\, d\Omega dt_0 dE_0} = \frac{1}{4\pi}\int dr\, R_0 e^{-\tau(z,E_0)} \int dM \frac{dn}{dM}(M,z) \frac{dN_\gamma}{dE}(E_0(1+z),M,z)$$

Ullio et al. 2002

$$\sim \langle \sigma v \rangle \int \rho^2(r) dV \sum_i B_i \frac{dN_i}{dE}$$

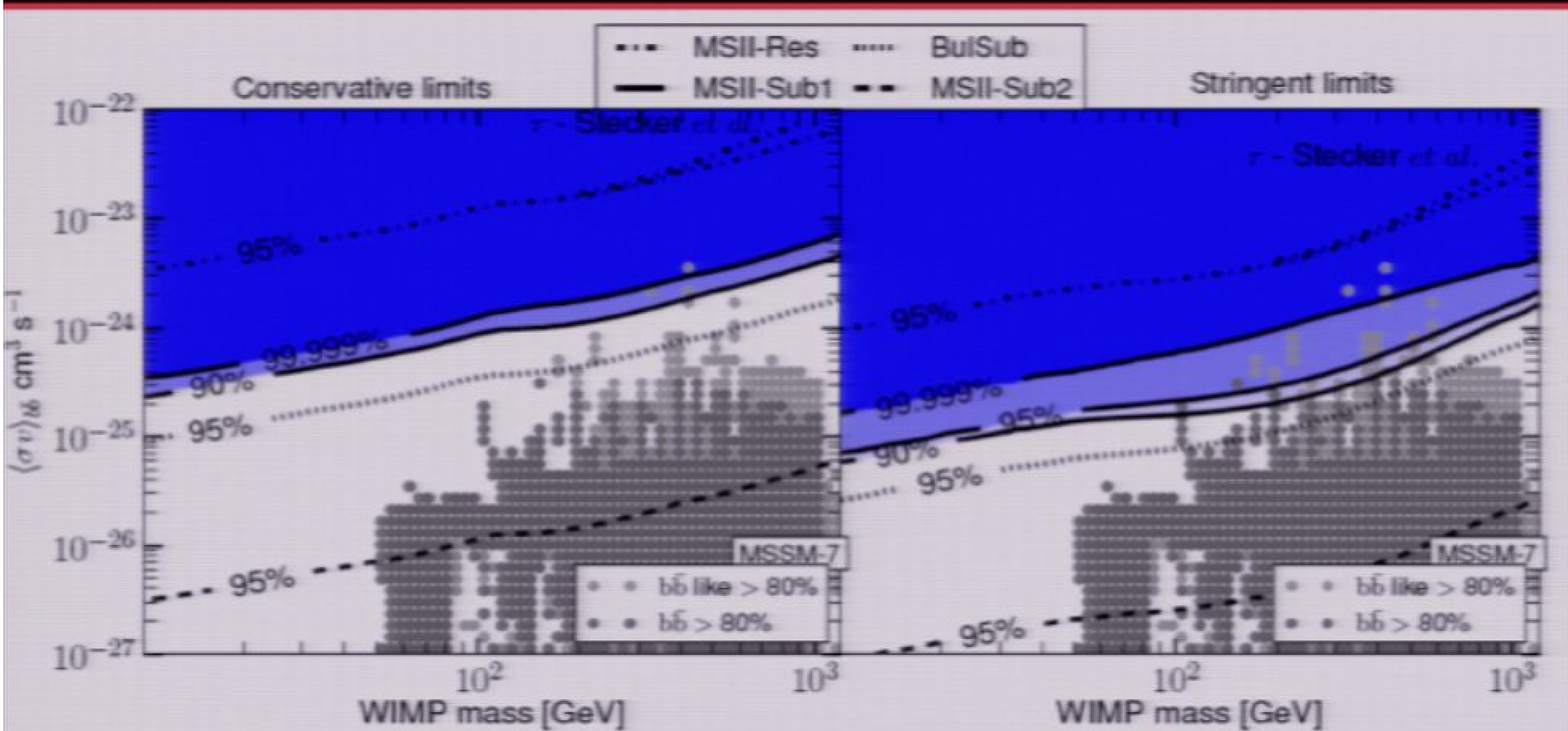
Astrophysical Uncertainties

- Dark-matter macrostructures:
  - Dark matter-only simulations show definite predictions for ρ(r)
  - No consensus on what happens to ρ(r) when baryons are added—see papers by Romano-Diaz, Gnedin, Abadi, Blumenethal, Scannapieco, Governato, for a diversity of views. What drives changes?
  - Additional macroscopic structures ("dark disk"; Read et al. 2009, Purcell et al. 2009)?

Astrophysical Uncertainties

- Substructure
  - How much is there? Down to what scales? (Quite complicated even for vanilla WIMPs due to hierarchical structure formation, small-scale interactions with baryons.)
  - Tidal debris: stream density on mpc scales? How long do the structures survive before being phase-mixed?

Limits for annihilation to b-bbar



Fermi Collaboration, 1002.4415

What do we do now?

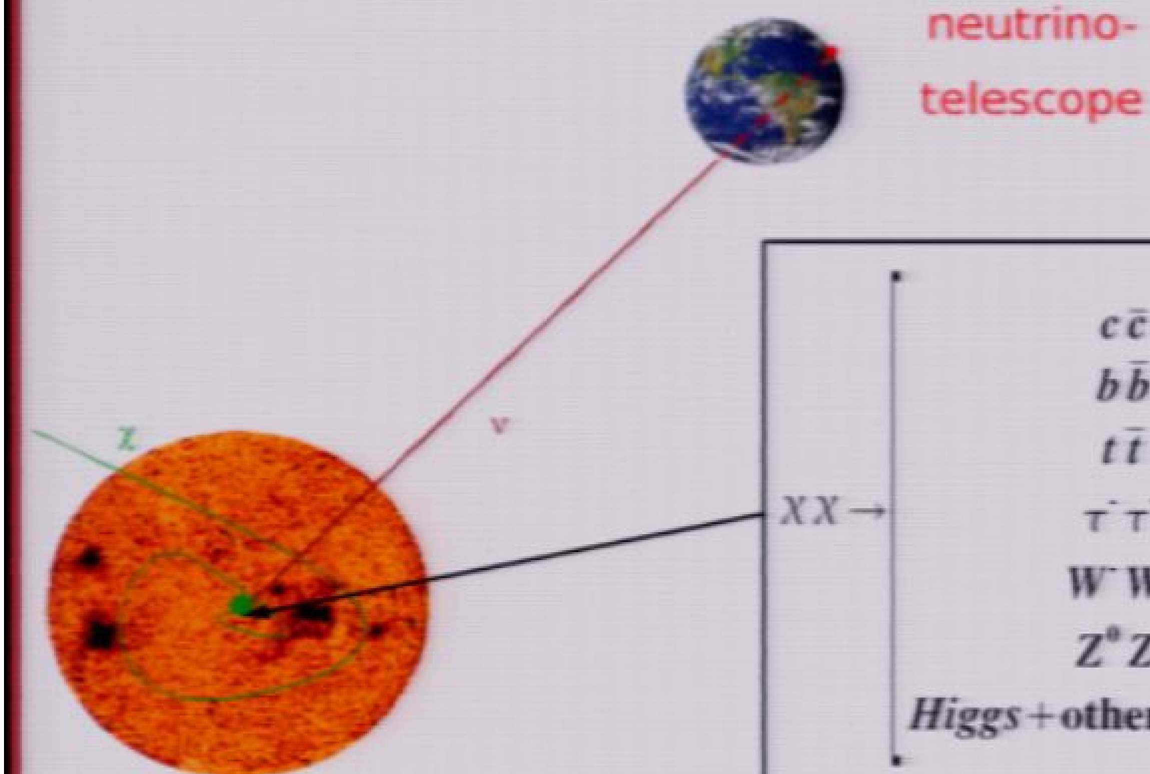
Two Approaches

- There are essentially two approaches to understanding these astrophysical uncertainties:
  1. Better modeling.
  2. Treat the astrophysical uncertainties on par with the particle-physics uncertainties, try to extract both from data (approach inspired by cosmological data analysis).
- The trick is figuring out which techniques are most useful for a given problem.

Example: Solar System dark matter

- Modeling:
  - thermalization of WIMP dark matter in the Sun
- Data mining:
  - Determining the local phase space density of dark matter as well as its mass, interaction cross sections using capture/annihilation in the Sun and Earth, direct detection experiments.

Capture/annihilation of WIMPs in the Sun



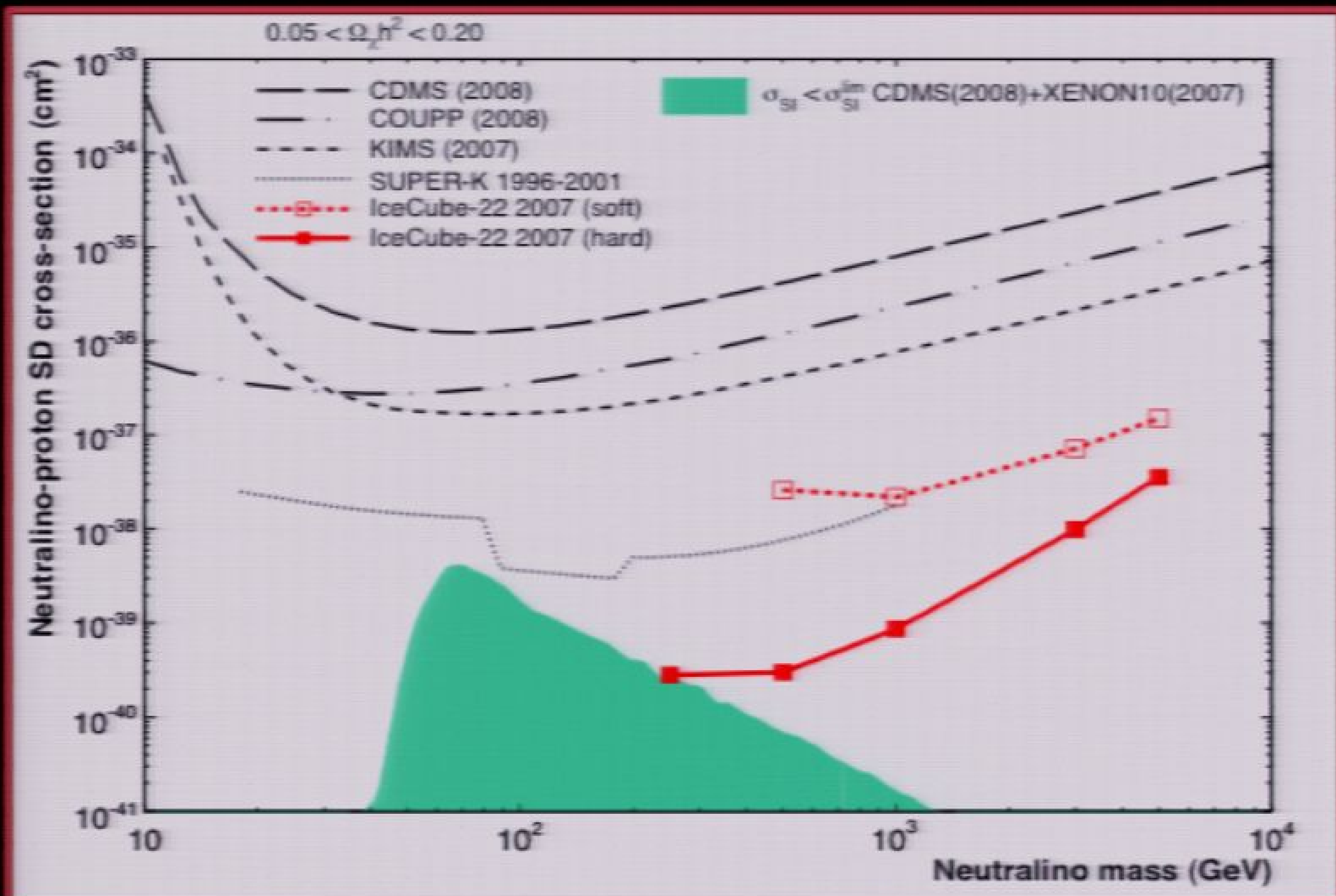
$$XX \rightarrow \begin{bmatrix} c\bar{c} \\ b\bar{b} \\ t\bar{t} \\ \tau^-\tau^+ \\ W^-W^+ \\ Z^0Z^0 \\ Higgs + \text{other particles} \end{bmatrix} \rightarrow \nu + \bar{\nu} + \text{other particles}$$

from Antares website

ν's in the Sun

- Standard Thermalization Model (Griest and Seckel, Gould):
  - WIMPs that scatter onto bound orbits are almost instantaneously thermalized.
  - Once thermalized to this dense core, they annihilate. Typically, Γ = C/2 (unless the elastic scattering cross section is quite small), where C is the capture rate of WIMPs in the Sun.
  - We can see the neutrinos from these annihilations in terrestrial neutrino telescopes (Super-K, AMANDA, IceCube, Antares).
  - Currently the most sensitive probe of σ_p^{SD} (Desai et al. 2004, Abbasi et al. 2009).

ν's from the Sun in IceCube



Abbasi et al. 2009

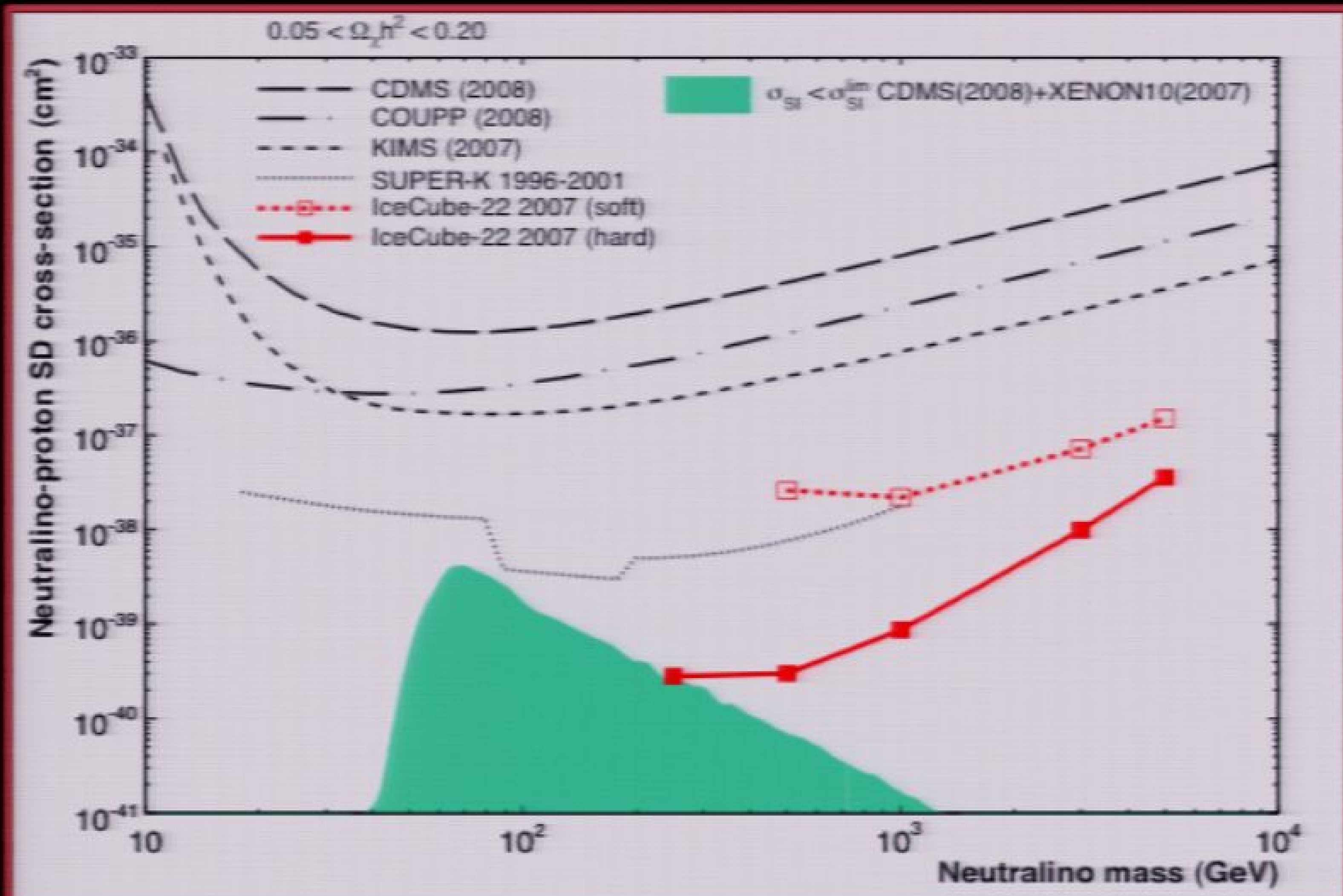
Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_{\chi}/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

ν's from the Sun in IceCube



Abbasi et al. 2009

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as t $\sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_{\chi}/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_\chi/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Changes to the standard thermalization model

- Even if the Sun were an isolated body, typically many scatters are required to thermalize the WIMPs in the Sun, and the time between scatters scales as $t \sim P_{\chi}/\tau$.
- Gravitational perturbations from planets can alter the time between scatters, or can eject WIMPs from the Solar System.
- Thus, to understand how the standard model is modified, you need to know the lifetime distribution as a function of WIMP mass/cross section.

Simulations $\rightarrow$ Lifetime Distributions

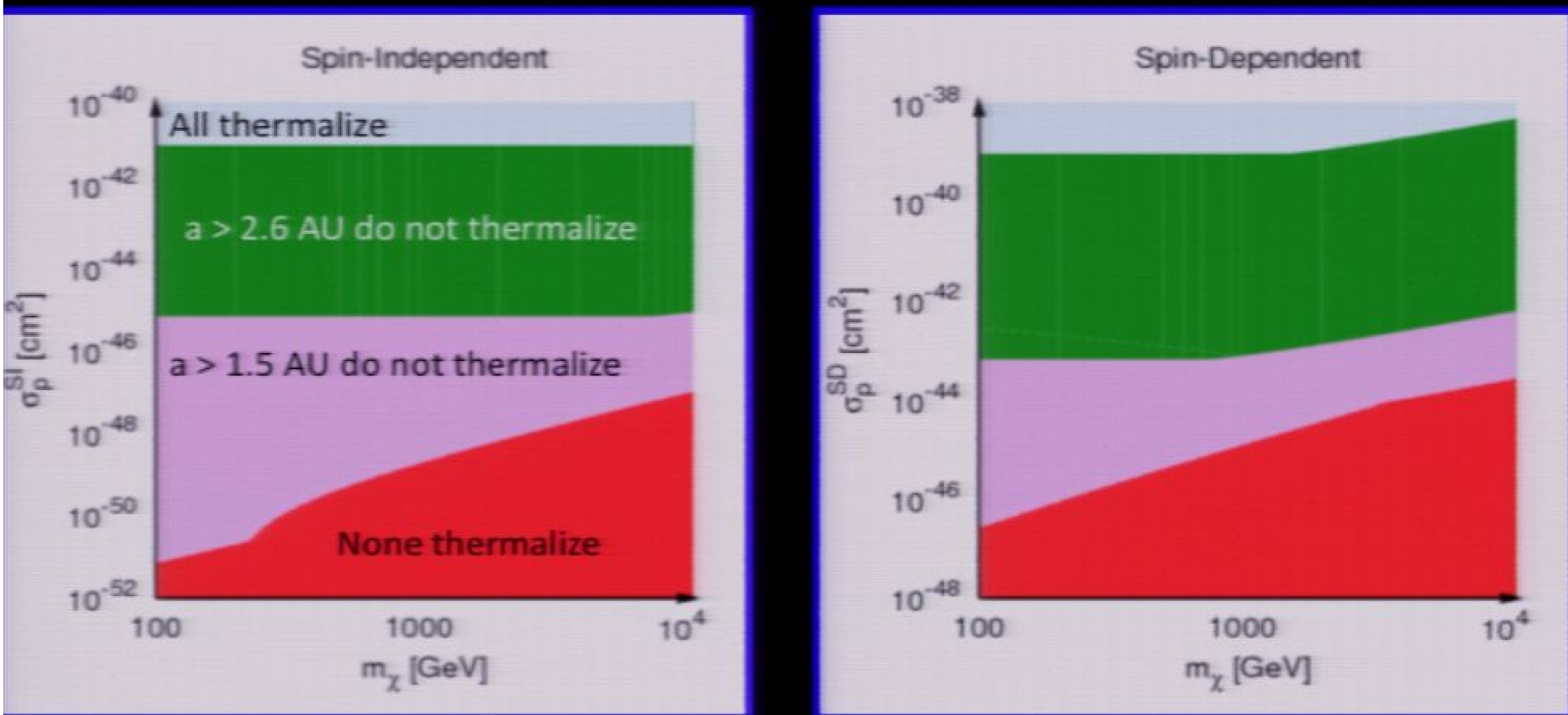
(AHGP, Phys. Rev. D 79, 103531 + 103532)

- 1.5 million orbits
- Integration is terminated if:
  - The particle rescatters onto an ``uninteresting'' orbit.
  - The particle is ejected.
  - $t > t_{\odot}$
- Realistic solar model: BS(OP), and Monte Carlo treatment of scattering in the Sun.
- Simplified solar system consisting of Jupiter and the Sun only to more easily understand the results.
- See papers for details on integration method.

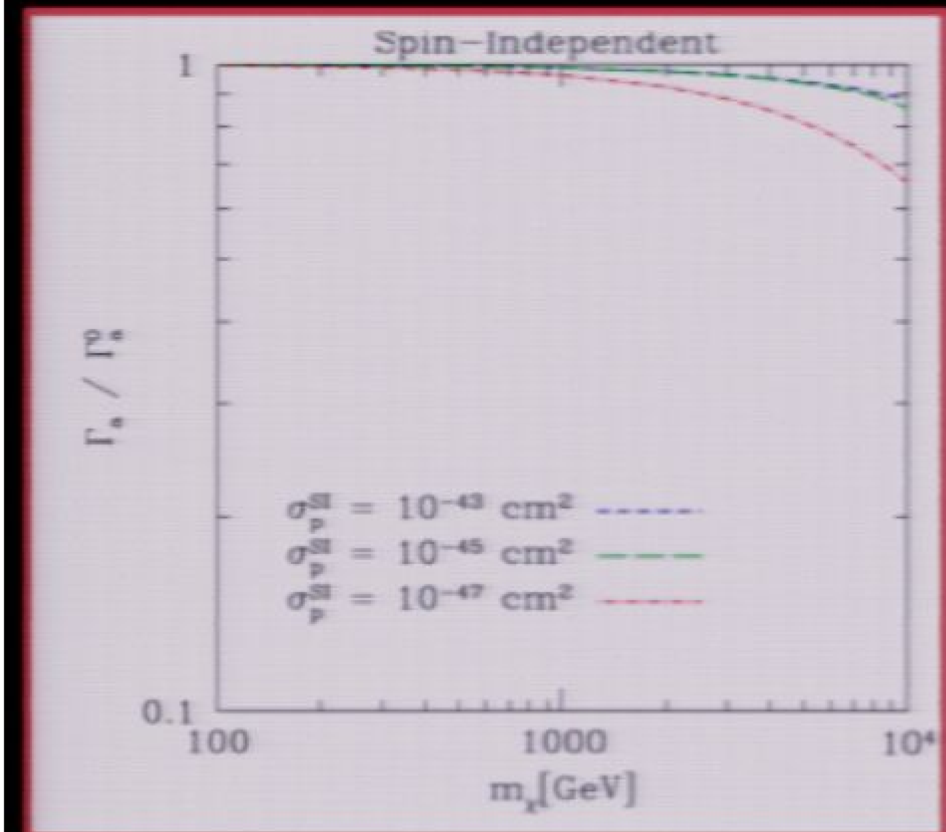
Lifetimes

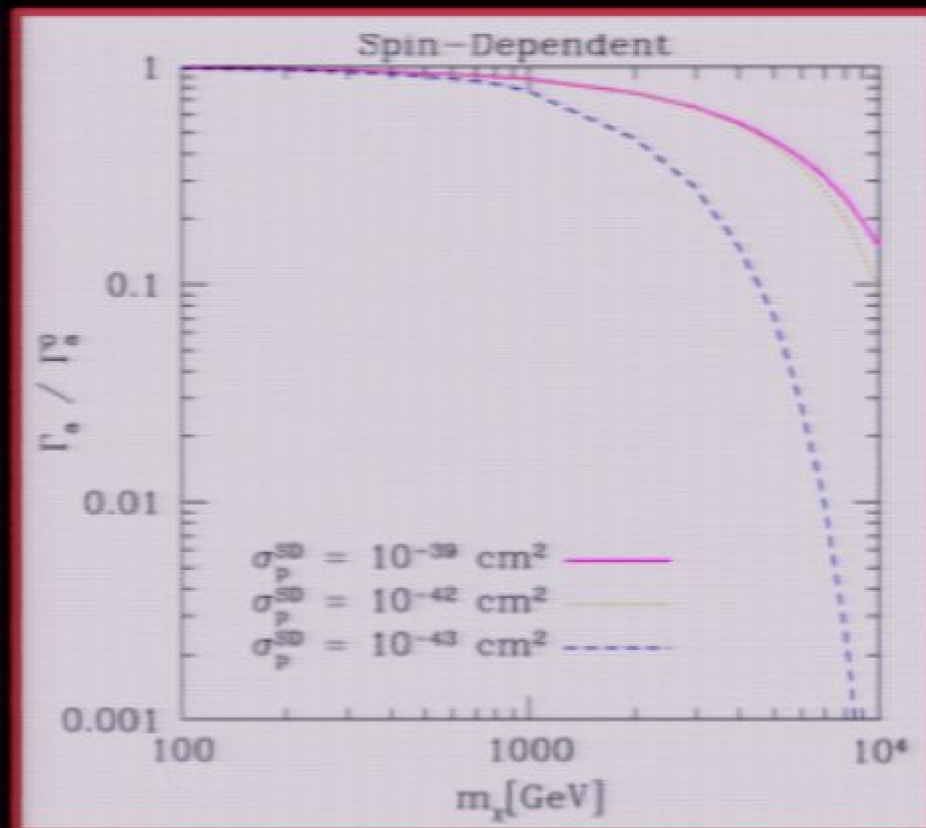
- Three types of behaviors:
  - a < 1.5 AU: the typical time between scatters goes as $t \sim P_\chi/\tau$
  - 1.5 AU < a < 2.6 AU (half Jupiter's semi-major axis): the time between scatters goes as $t \sim 300\ P_\chi/\tau$ (due to interactions between the Kozai and mean-motion resonances)
  - a > 2.6 AU (Jupiter-crossing): ejected on timescales of ~ Myr unless the timescale for rescattering in the Sun is shorter than the angular momentum diffusion timescale.
- The distribution of initial a is skewed higher for higher WIMP masses.
- It takes more scatters to thermalize a heavier WIMP.

t_{life} vs. $t_{\odot}$

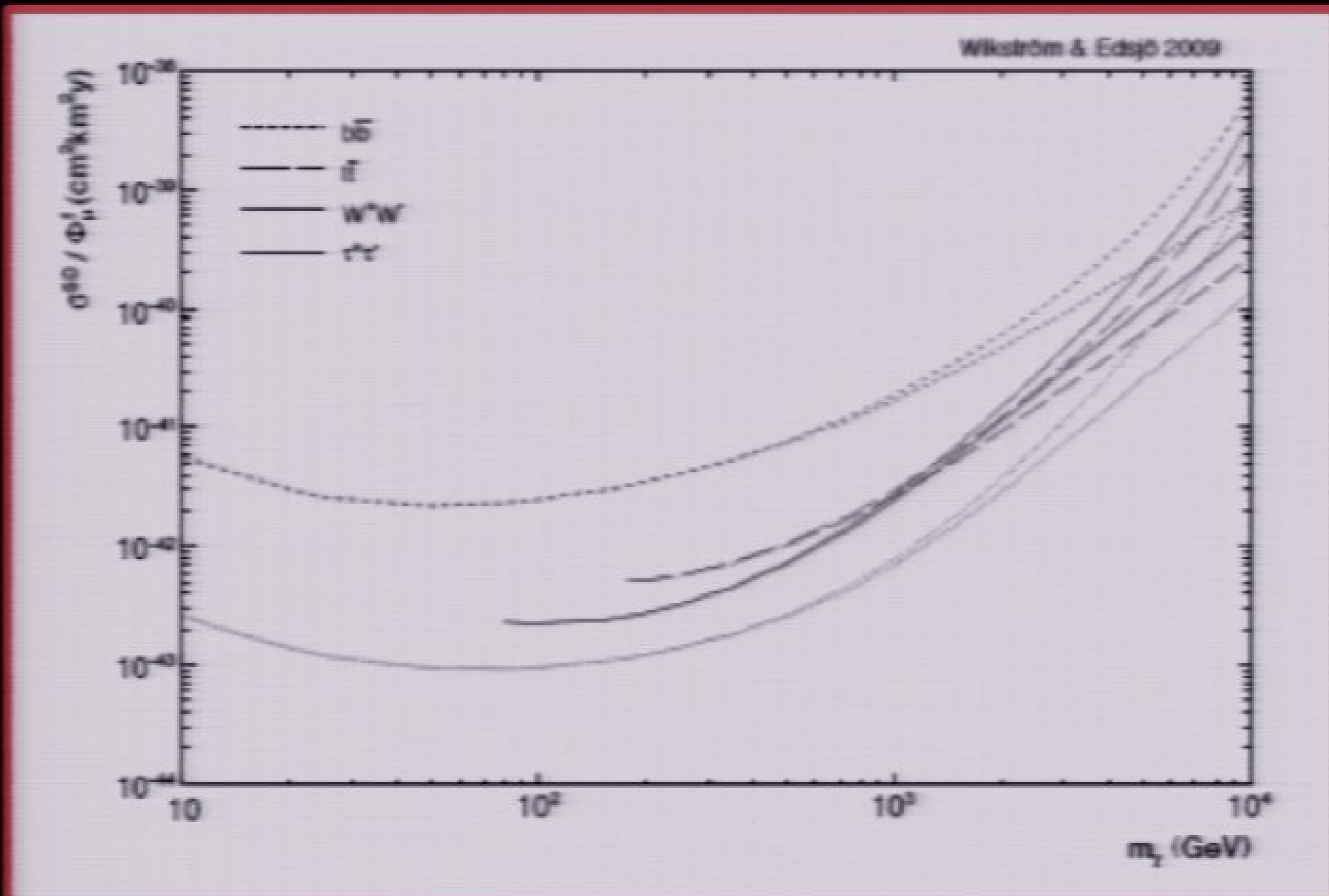


Suppression of the Annihilation Rate
(Standard Halo Model)



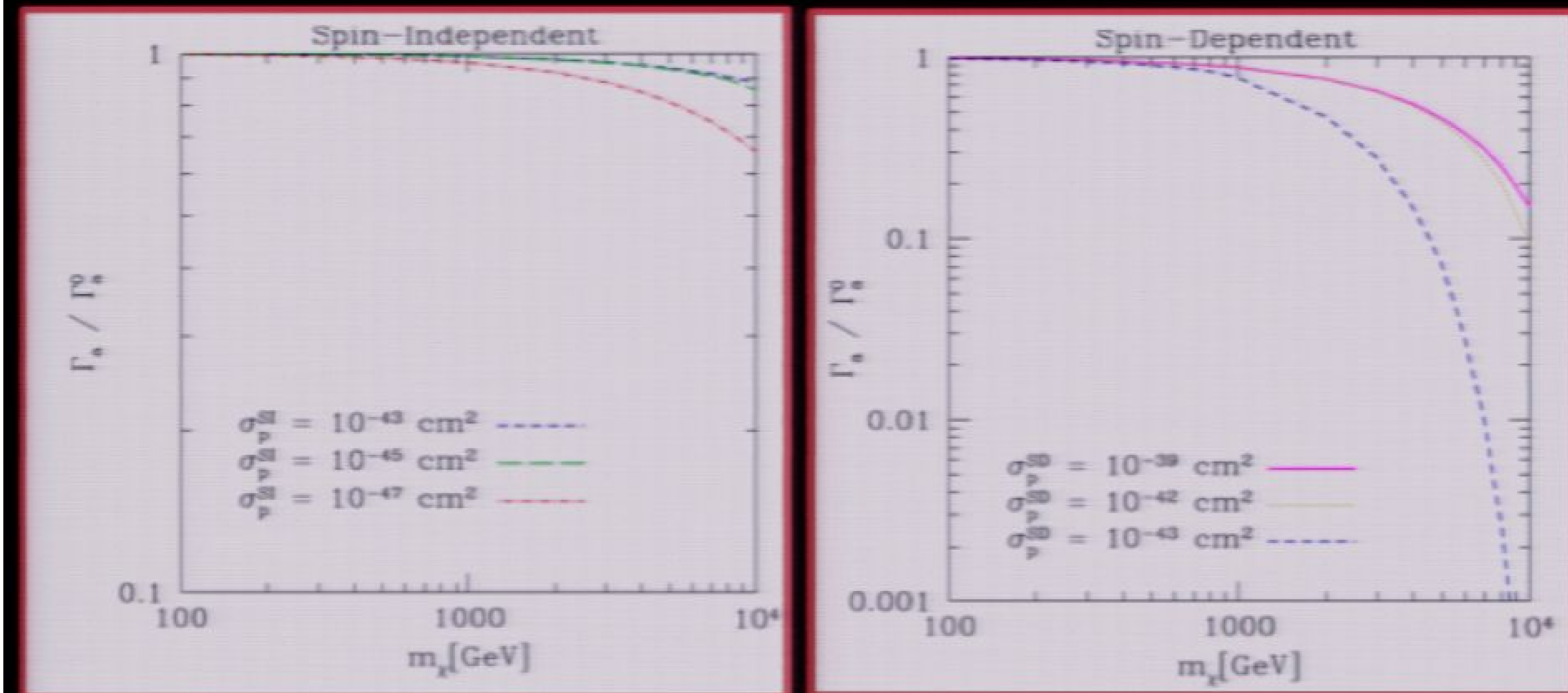


Implications for IceCube

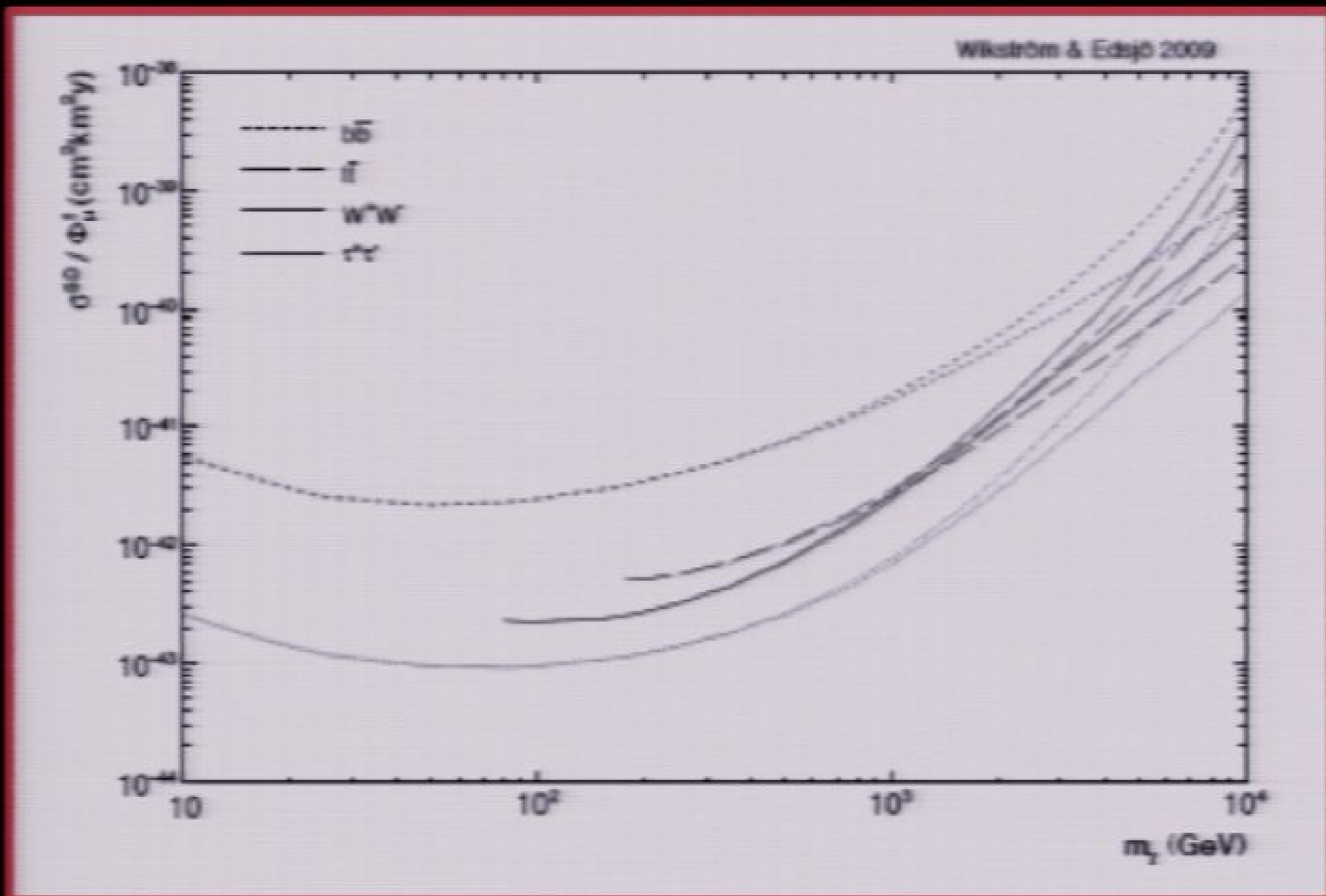


Suppression of the Annihilation Rate

(Standard Halo Model)



Implications for IceCube



Summary so far

- The WIMP annihilation rate in the Sun is suppressed by gravitational interactions between WIMPs and planets.
  - The effect increases for increasing WIMP mass.
- With simulations, can get accurate mappings between the neutrino signal and particle-physics parameters.
- Current work: add in inner planets and check the thermalization times as a function of WIMP mass, cross sections, and the Galactic WIMP phase space density.

Summary so far

- The WIMP annihilation rate in the Sun is suppressed by gravitational interactions between WIMPs and planets.
  - The effect increases for increasing WIMP mass.
- With simulations, can get accurate mappings between the neutrino signal and particle-physics parameters.
- Current work: add in inner planets and check the thermalization times as a function of WIMP mass, cross sections, and the Galactic WIMP phase space density.

Summary so far

- The WIMP annihilation rate in the Sun is suppressed by gravitational interactions between WIMPs and planets.
  - The effect increases for increasing WIMP mass.
- With simulations, can get accurate mappings between the neutrino signal and particle-physics parameters.
- Current work: add in inner planets and check the thermalization times as a function of WIMP mass, cross sections, and the Galactic WIMP phase space density.

Summary so far

- The WIMP annihilation rate in the Sun is suppressed by gravitational interactions between WIMPs and planets.
  - The effect increases for increasing WIMP mass.
- With simulations, can get accurate mappings between the neutrino signal and particle-physics parameters.
- Current work: add in inner planets and check the thermalization times as a function of WIMP mass, cross sections, and the Galactic WIMP phase space density.

Summary so far

- The WIMP annihilation rate in the Sun is suppressed by gravitational interactions between WIMPs and planets.
  - The effect increases for increasing WIMP mass.
- With simulations, can get accurate mappings between the neutrino signal and particle-physics parameters.
- Current work: add in inner planets and check the thermalization times as a function of WIMP mass, cross sections, and the Galactic WIMP phase space density.

Summary so far

- The WIMP annihilation rate in the Sun is suppressed by gravitational interactions between WIMPs and planets.
  - The effect increases for increasing WIMP mass.
- With simulations, can get accurate mappings between the neutrino signal and particle-physics parameters.
- Current work: add in inner planets and check the thermalization times as a function of WIMP mass, cross sections, and the Galactic WIMP phase space density.

Example: Solar System dark matter

- Modeling:
  - thermalization of WIMP dark matter in the Sun
- Data mining:
  - Determining the local phase space density of dark matter f(r,v) as well as its mass, interaction cross sections using capture/annihilation in the Sun and Earth, direct detection experiments.

Other Solar System probes of dark matter

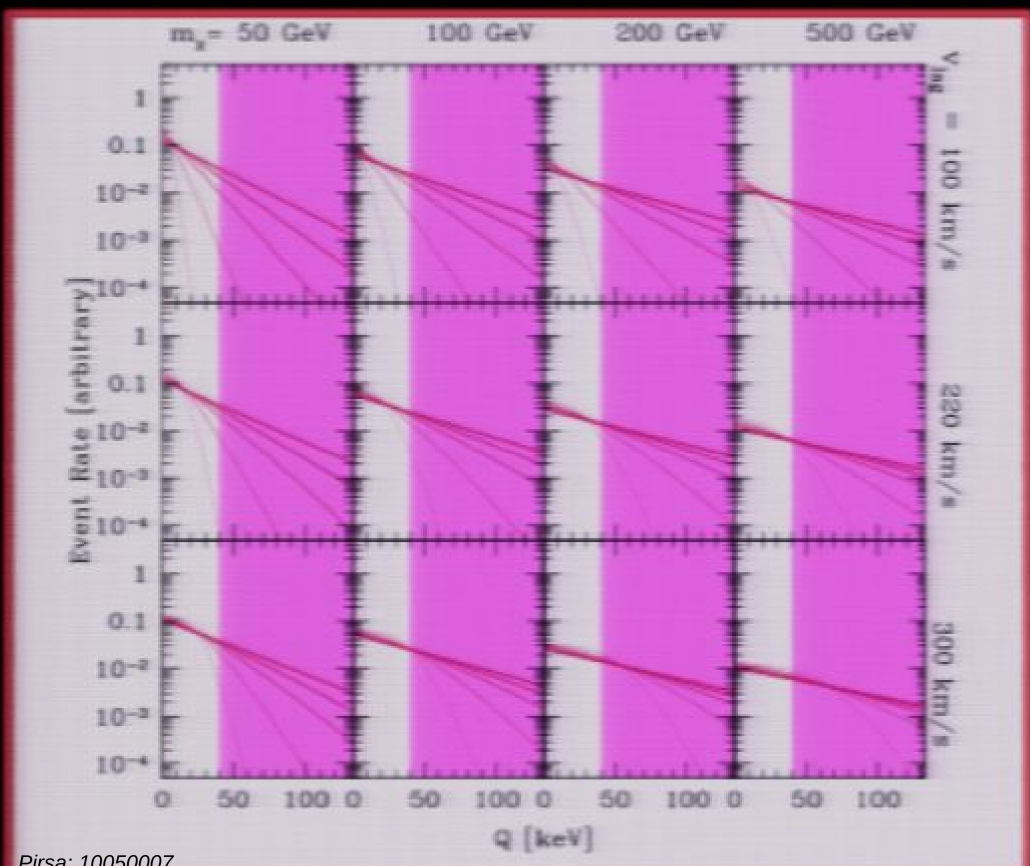
- Direct detection

$$\frac{dR}{dQ} \propto \int_{v_{cut}}^{v_{esc}} d^3v f(r,v) v \frac{d\sigma}{dQ}, v_{cut} = \sqrt{\frac{m_A Q}{2\mu^2}}$$

Direct Detection

(Goodman & Witten; Wasserman)

Recoil spectrum depends on the WIMP mass, cross sections, local phase space density, target nucleus.



Some experiments will have directional sensitivity, too, and not just indirectly via annual modulation.

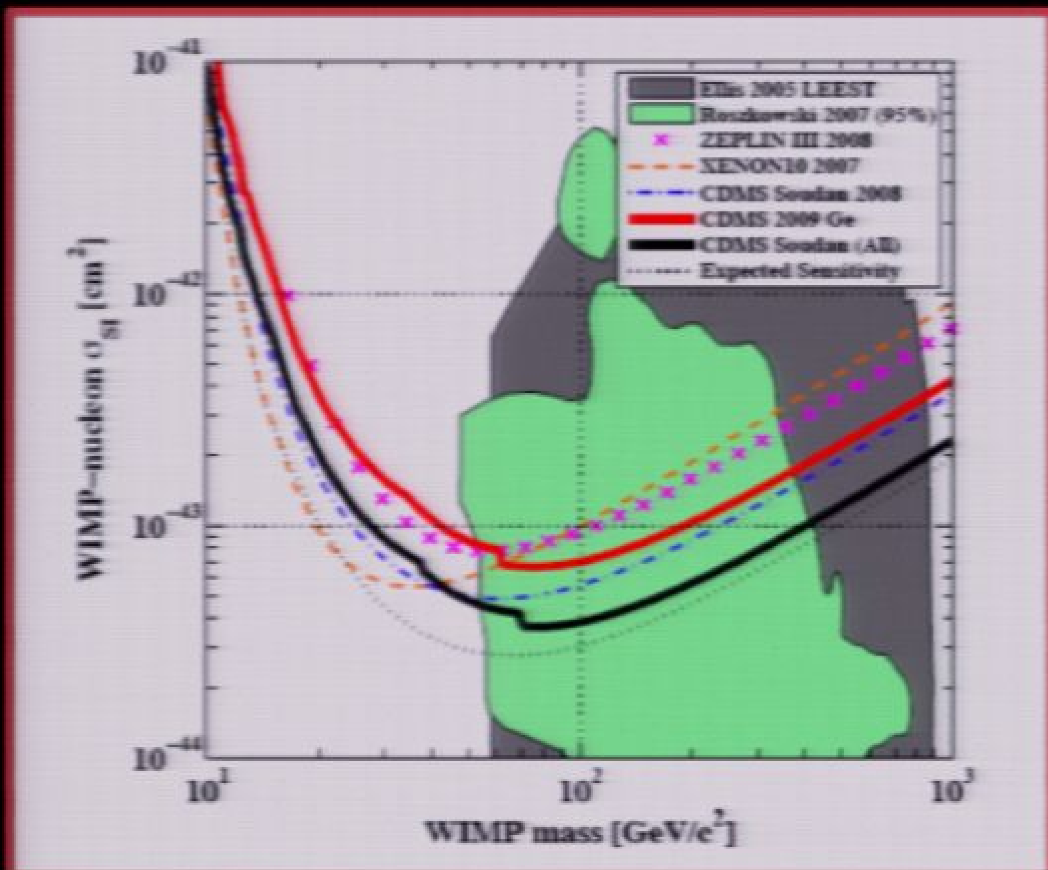
Other Solar System probes of dark matter

- Direct detection
- Neutrino capture/annihilation in the Earth

Goal:

- Determine WIMP properties from these experiments. We can only do this if we can deal with f(r,v), the local WIMP phase space density.

What does a plot like this:



CDMS Collaboration,
0912.3592

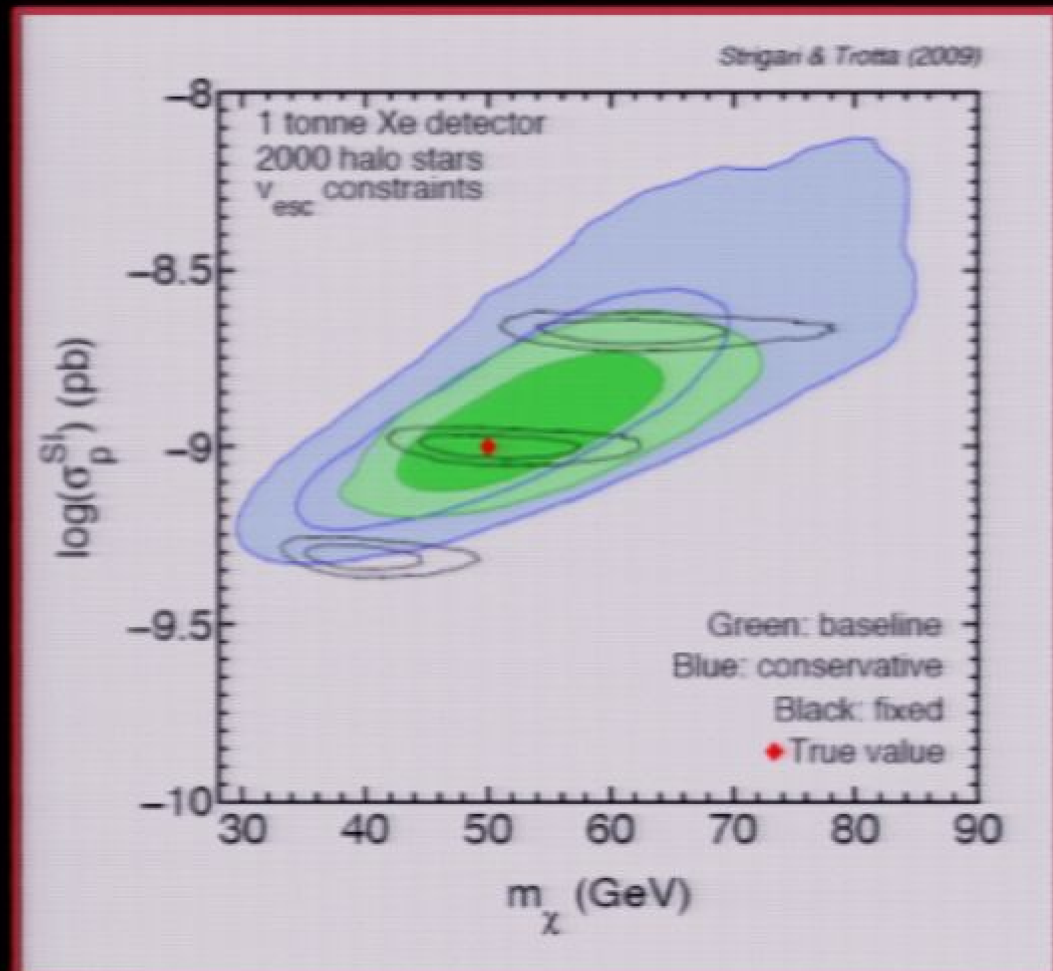
- actually mean?

Usual assumption: local f(r,v)

- $f(r, v) = \rho_\chi g(v)$.
- Usual smooth halo assumptions:
  - $\rho \sim r^{-2}$ and a completely phase-mixed, static system. Assuming an isotropic velocity ellipsoid and spherical symmetry, $\sigma = v_\odot/\sqrt{2}$.
- What happens when one relaxes assumptions about the Galactic dark matter?

Strigari & Trotta 2009

- 1 ton Xe experiment along with hypothetical kinematics of 2000 halo stars (to constrain the halo).
- Spherical symmetry.
- Baseline: Fix stellar disk and bulge, fix inner and outer slopes of the dark matter density profile, marginalize over dark matter halo parameters (scale density, scale radius, constant velocity anisotropy).
- Conservative: Marginalize over other halo parameters and the disk parameters, too. Keep bulge fixed.



Additional Complications

- Macroscopic:
  - Even if the dark matter density profile is well constrained from stellar kinematics, the velocity distribution is NOT.
  - Dark disk

The Halo is Not Alone:
The Dark Disk

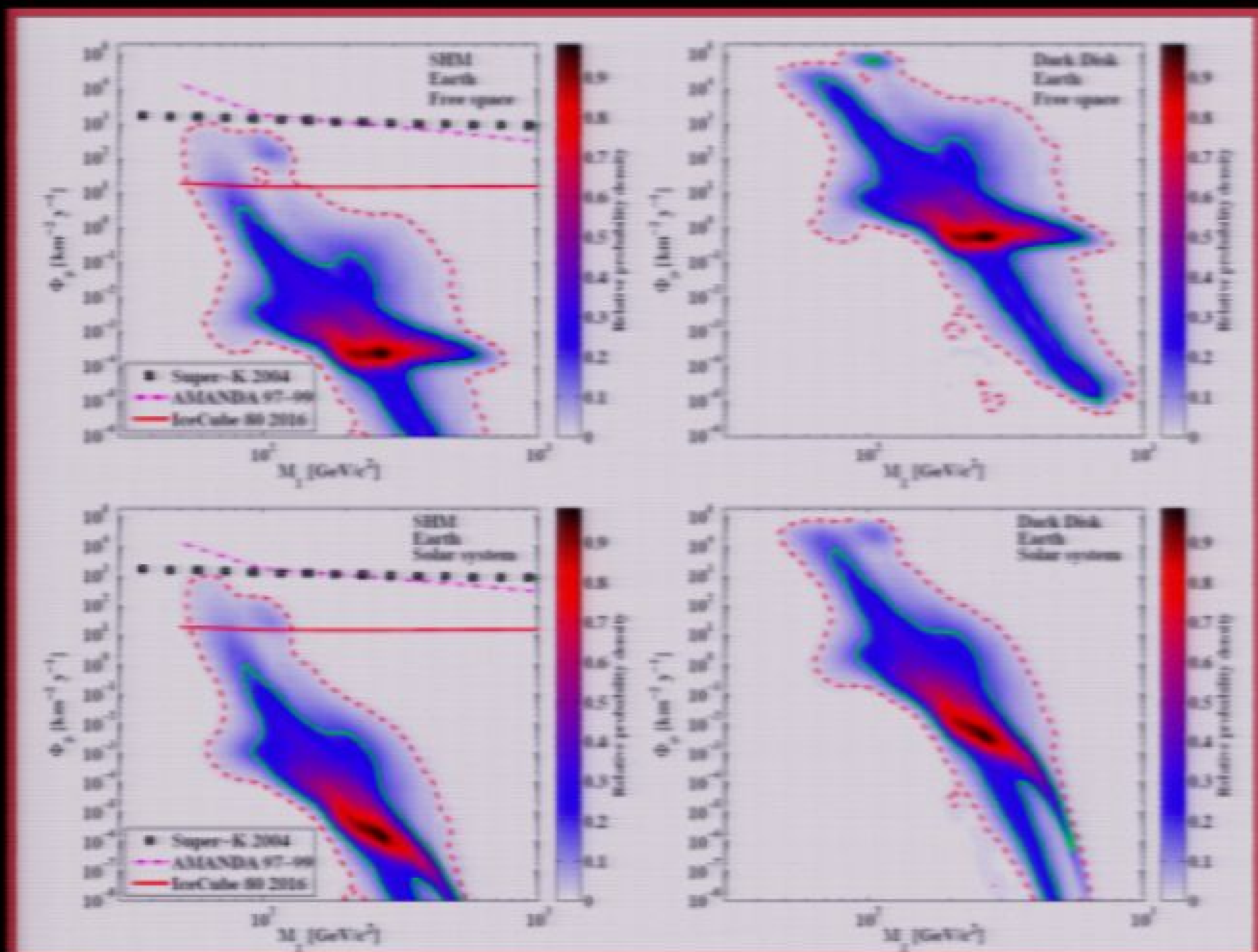
- Simulations that include baryons show that the stellar disk drags satellites into the disk plane, where they dissolve.
- This yields a DARK DISK with properties similar to the stellar disk generated by these satellites.
- The dark disk properties are extremely sensitive to the merger history of the Galaxy.
- Typically, speeds wrt to the solar system are MUCH smaller-- much easier to capture.

(Read et al. 2008, 2009; Purcell et al. 2009)

The Dark Disk & ν's in the Earth

(Bruch, AHGP et al., Phys. Lett. B 674, 250 (2009))

ν-induced μ flux



Free space phase density

Phase space density from my simulations

halo WIMP mass disk

Additional Complications

- Macroscopic:
  - What is the halo f(r, v) in simulations with baryons?
  - Dark disk
- Microscopic:
  - Are we passing through clumps?
  - Tidal streams: What is the local stream density on mpc scales? How long till streams phase mix?

How to Deal with f(r, v)

- Imagine a world in which WIMPs have been detected (definitively) in at least one direct detection experiment.
- My approach: estimate how well one can extract the WIMP mass and elastic scattering cross sections as well as f(r, v) using two ideas inspired by cosmology:
  - minimal theoretical priors on the phase space density.
  - combining data sets.
- NB: Direct detection experiments and neutrino telescopes are the ONLY ways to learn about the dark matter velocity distribution.

Additional Complications

- Macroscopic:
  - What is the halo f(r, v) in simulations with baryons?
  - Dark disk
- Microscopic:
  - Are we passing through clumps?
  - Tidal streams: What is the local stream density on mpc scales? How long till streams phase mix?

How to Deal with f(r, v)

- Imagine a world in which WIMPs have been detected (definitively) in at least one direct detection experiment.
- My approach: estimate how well one can extract the WIMP mass and elastic scattering cross sections as well as f(r, v) using two ideas inspired by cosmology:
  - minimal theoretical priors on the phase space density.
  - combining data sets.
- NB: Direct detection experiments and neutrino telescopes are the ONLY ways to learn about the dark matter velocity distribution.

Test of Principle

(Peter 2010, Phys. Rev. D 81, 087301)

- Use large, directionally-insensitive, energy-sensitive, "background-free" direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution (theoretical prior for first pass) with 1-d dispersion v_{rms}, isotropic velocities, and lagging the Earth by v_{lag}. No restriction on the velocity parameters, though.

Test of Principle

(Peter 2010, Phys. Rev. D 81, 087301)

- Use large, directionally-insensitive, energy-sensitive, "background-free" direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution (theoretical prior for first pass) with 1-d dispersion v_{rms}, isotropic velocities, and lagging the Earth by v_{lag}. No restriction on the velocity parameters, though.

Test of Principle

(Peter 2010, Phys. Rev. D 81, 087301)

- Use large, directionally-insensitive, energy-sensitive, "background-free" direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution (theoretical prior for first pass) with 1-d dispersion v_{rms}, isotropic velocities, and lagging the Earth by v_{lag}. No restriction on the velocity parameters, though.

Test of Principle

(Peter 2010, Phys. Rev. D 81, 087301)

- Use large, directionally-insensitive, energy-sensitive, "background-free" direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution (theoretical prior for first pass) with 1-d dispersion v_{rms}, isotropic velocities, and lagging the Earth by v_{lag}. No restriction on the velocity parameters, though.

Test of Principle

(Peter 2010, Phys. Rev. D 81, 087301)

- Use large, directionally-insensitive, energy-sensitive, "background-free" direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution (theoretical prior for first pass) with 1-d dispersion v_{rms}, isotropic velocities, and lagging the Earth by v_{lag}. No restriction on the velocity parameters, though.

Test of Principle

(Peter 2010, Phys. Rev. D 81, 087301)

- Use large, directionally-insensitive, energy-sensitive, "background-free" direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution (theoretical prior for first pass) with 1-d dispersion v_{rms}, isotropic velocities, and lagging the Earth by v_{lag}. No restriction on the velocity parameters, though.

Test of Principle

(Peter 2010, Phys. Rev. D 81, 087301)

- Use large, directionally-insensitive, energy-sensitive, "background-free" direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution (theoretical prior for first pass) with 1-d dispersion v_{rms}, isotropic velocities, and lagging the Earth by v_{lag}. No restriction on the velocity parameters, though.

Test of Principle

(Peter 2010, Phys. Rev. D 81, 087301)

- Use large, directionally-insensitive, energy-sensitive, "background-free" direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution (theoretical prior for first pass) with 1-d dispersion v_{rms}, isotropic velocities, and lagging the Earth by v_{lag}. No restriction on the velocity parameters, though.

Test of Principle

(Peter 2010, Phys. Rev. D 81, 087301)

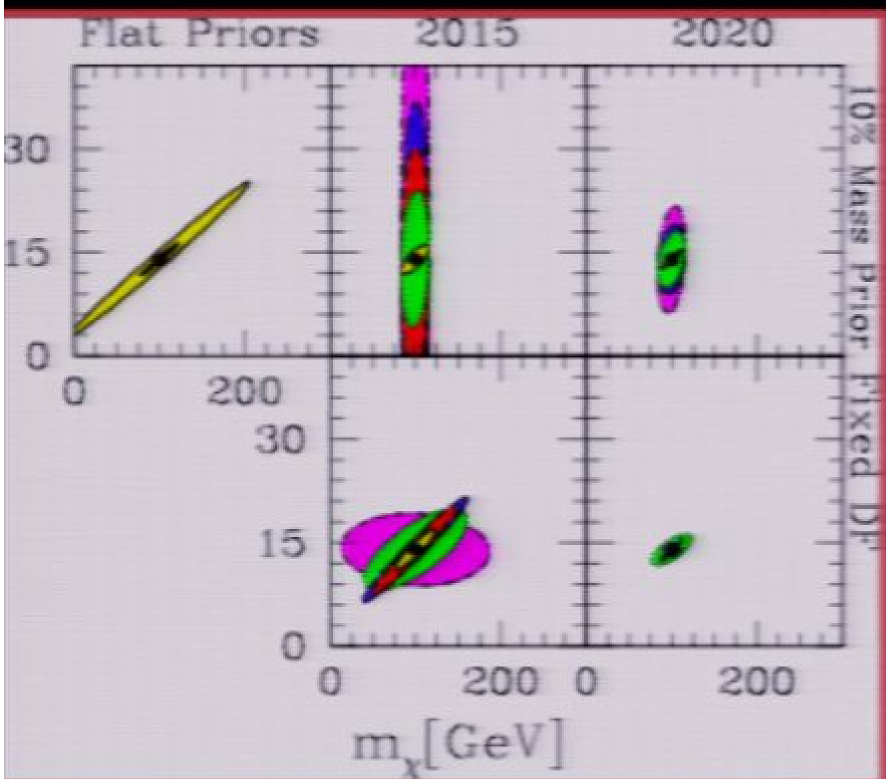
- Use large, directionally-insensitive, energy-sensitive, "background-free" direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution (theoretical prior for first pass) with 1-d dispersion v_{rms}, isotropic velocities, and lagging the Earth by v_{lag}. No restriction on the velocity parameters, though.

Standard Halo Model & Particle Physics

m_χ = 100 GeV, $\sigma_p^{SI} = 10^{-44}$ cm^2

ρ_χ=0.3 GeV cm^{-3}, v_{lag} = 220 km/s, v_{rms} = 155 km/s

$A \sim \sigma_p^{SI} \rho_\chi$



2015-era experiments : WArP, SuperCDMS, LUX, XENON1T

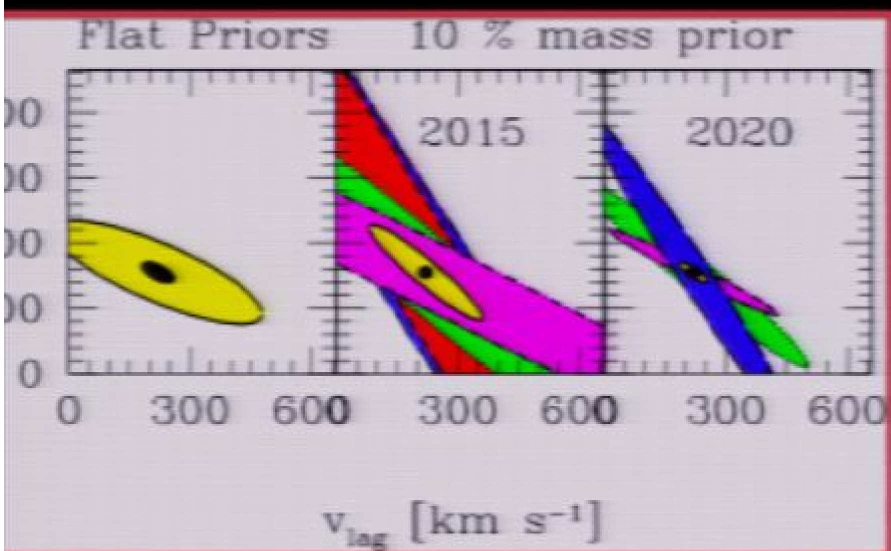
2020-era experiments : 10 ton liquid argon, 20 ton xenon, 1 ton germanium

Standard Halo Model & Particle Physics

m_χ = 100 GeV, $\sigma_p^{SI} = 10^{-44}$ cm^2

ρ_χ=0.3 GeV cm^{-3}, v_{lag} = 220 km/s, v_{rms} = 155 km/s

$A \sim \sigma_p^{SI} \rho_\chi$



2015-era experiments :WArP, SuperCDMS, LUX, XENON1T

2020-era experiments :10 ton liquid argon, 20 ton xenon, 1 ton germanium

Current Work

- Local velocity distribution (w/Vera Glusevic, Caltech):
  1. Fold in backgrounds.
  2. Improve analysis techniques (currently experimenting with MCMCs).
  3. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  4. Fold in annual modulation and other types of direct detection experiments, especially directionally-sensitive experiments.
  5. Try to reconstruct the velocity information non-parametrically (Drees & Shan 2007 have some ideas on this, but I have an idea that I think may be easier to understand, easier to implement, and potentially far more powerful—but this is still in the "idea stage").

Current Work

- Local velocity distribution (w/Vera Glusevic, Caltech):
  1. Fold in backgrounds.
  2. Improve analysis techniques (currently experimenting with MCMCs).
  3. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  4. Fold in annual modulation and other types of direct detection experiments, especially directionally-sensitive experiments.
  5. Try to reconstruct the velocity information non-parametrically (Drees & Shan 2007 have some ideas on this, but I have an idea that I think may be easier to understand, easier to implement, and potentially far more powerful—but this is still in the "idea stage").

Current Work

- Local velocity distribution (w/Vera Glusevic, Caltech):
  1. Fold in backgrounds.
  2. Improve analysis techniques (currently experimenting with MCMCs).
  3. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  4. Fold in annual modulation and other types of direct detection experiments, especially directionally-sensitive experiments.
  5. Try to reconstruct the velocity information non-parametrically (Drees & Shan 2007 have some ideas on this, but I have an idea that I think may be easier to understand, easier to implement, and potentially far more powerful—but this is still in the "idea stage").

Current Work

- Local velocity distribution (w/Vera Glusevic, Caltech):
  1. Fold in backgrounds.
  2. Improve analysis techniques (currently experimenting with MCMCs).
  3. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  4. Fold in annual modulation and other types of direct detection experiments, especially directionally-sensitive experiments.
  5. Try to reconstruct the velocity information non-parametrically (Drees & Shan 2007 have some ideas on this, but I have an idea that I think may be easier to understand, easier to implement, and potentially far more powerful—but this is still in the "idea stage").

Current Work

- Local velocity distribution (w/Vera Glusevic, Caltech):
  1. Fold in backgrounds.
  2. Improve analysis techniques (currently experimenting with MCMCs).
  3. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  4. Fold in annual modulation and other types of direct detection experiments, especially directionally-sensitive experiments.
  5. Try to reconstruct the velocity information non-parametrically (Drees & Shan 2007 have some ideas on this, but I have an idea that I think may be easier to understand, easier to implement, and potentially far more powerful—but this is still in the "idea stage").

Current Work

- Local velocity distribution (w/Vera Glusevic, Caltech):
  1. Fold in backgrounds.
  2. Improve analysis techniques (currently experimenting with MCMCs).
  3. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  4. Fold in annual modulation and other types of direct detection experiments, especially directionally-sensitive experiments.
  5. Try to reconstruct the velocity information non-parametrically (Drees & Shan 2007 have some ideas on this, but I have an idea that I think may be easier to understand, easier to implement, and potentially far more powerful—but this is still in the "idea stage").

Current Work

- Local velocity distribution (w/Vera Glusevic, Caltech):
  1. Fold in backgrounds.
  2. Improve analysis techniques (currently experimenting with MCMCs).
  3. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  4. Fold in annual modulation and other types of direct detection experiments, especially directionally-sensitive experiments.
  5. Try to reconstruct the velocity information non-parametrically (Drees & Shan 2007 have some ideas on this, but I have an idea that I think may be easier to understand, easier to implement, and potentially far more powerful—but this is still in the "idea stage").

Current Work

- Local velocity distribution (w/Vera Glusevic, Caltech):
  1. Fold in backgrounds.
  2. Improve analysis techniques (currently experimenting with MCMCs).
  3. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  4. Fold in annual modulation and other types of direct detection experiments, especially directionally-sensitive experiments.
  5. Try to reconstruct the velocity information non-parametrically (Drees & Shan 2007 have some ideas on this, but I have an idea that I think may be easier to understand, easier to implement, and potentially far more powerful—but this is still in the "idea stage").

Current Work

- Local velocity distribution (w/Vera Glusevic, Caltech):
  1. Fold in backgrounds.
  2. Improve analysis techniques (currently experimenting with MCMCs).
  3. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  4. Fold in annual modulation and other types of direct detection experiments, especially directionally-sensitive experiments.
  5. Try to reconstruct the velocity information non-parametrically (Drees & Shan 2007 have some ideas on this, but I have an idea that I think may be easier to understand, easier to implement, and potentially far more powerful—but this is still in the "idea stage").

Comment on Modeling/Data Mining

- Model those things that CAN, even if imperfectly:
  - WIMP orbits in the Solar System: this can be modeled to high accuracy.
  - Less accurate but still important: put baryons in N-body sims—even if we don't know the physics exactly, can discover things like the dark disk.
- Things that will almost certainly come from data, not modeling:
  - Dark-matter density in specific halos or ensembles.
  - Microstructure in general (including the local DF).
- The challenge: figure out which approach is more appropriate for given problems, and figure out how to best parameterize problems for the data-mining approach.

Comment on Modeling/Data Mining

- Model those things that CAN, even if imperfectly:
  - WIMP orbits in the Solar System: this can be modeled to high accuracy.
  - Less accurate but still important: put baryons in N-body sims—even if we don't know the physics exactly, can discover things like the dark disk.
- Things that will almost certainly come from data, not modeling:
  - Dark-matter density in specific halos or ensembles.
  - Microstructure in general (including the local DF).
- The challenge: figure out which approach is more appropriate for given problems, and figure out how to best parameterize problems for the data-mining approach.

Comment on Modeling/Data Mining

- Model those things that CAN, even if imperfectly:
  - WIMP orbits in the Solar System: this can be modeled to high accuracy.
  - Less accurate but still important: put baryons in N-body sims—even if we don't know the physics exactly, can discover things like the dark disk.
- Things that will almost certainly come from data, not modeling:
  - Dark-matter density in specific halos or ensembles.
  - Microstructure in general (including the local DF).
- The challenge: figure out which approach is more appropriate for given problems, and figure out how to best parameterize problems for the data-mining approach.

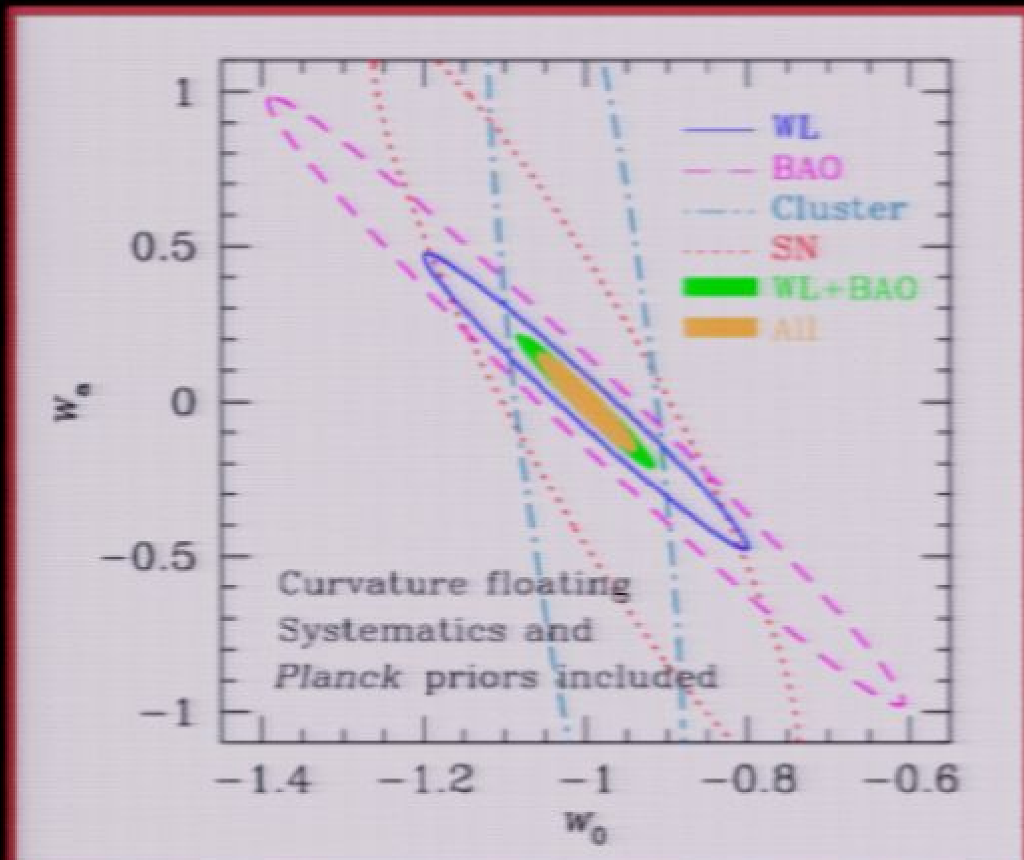
Comment on Modeling/Data Mining

- Model those things that CAN, even if imperfectly:
  - WIMP orbits in the Solar System: this can be modeled to high accuracy.
  - Less accurate but still important: put baryons in N-body sims—even if we don't know the physics exactly, can discover things like the dark disk.
- Things that will almost certainly come from data, not modeling:
  - Dark-matter density in specific halos or ensembles.
  - Microstructure in general (including the local DF).
- The challenge: figure out which approach is more appropriate for given problems, and figure out how to best parameterize problems for the data-mining approach.

Comment on Modeling/Data Mining

- Model those things that CAN, even if imperfectly:
  - WIMP orbits in the Solar System: this can be modeled to high accuracy.
  - Less accurate but still important: put baryons in N-body sims—even if we don't know the physics exactly, can discover things like the dark disk.
- Things that will almost certainly come from data, not modeling:
  - Dark-matter density in specific halos or ensembles.
  - Microstructure in general (including the local DF).
- The challenge: figure out which approach is more appropriate for given problems, and figure out how to best parameterize problems for the data-mining approach.

Data-mining goal: Something like dark-energy search but for dark matter!



LSST Science Book

- Need to figure out a phenomenological description of both the particle-physics and astrophysics of dark matter

Data Mining: Identifying Complementary Data Sets

γ-rays from dwarf galaxies or diffuse isotropic background:

- $\langle\sigma v\rangle$ or decay time degenerate w/ρ (both smooth part and "substructure factor")
- M_χ, BF from shape of the spectrum

Colliders:

- M_χ, σ's with some uncertainty

Microlensing in strong-lens systems (e.g., OMEGA)

- Subhalo mass function—could tell you about the "substructure" part of ρ or any cut-off in the matter power spectrum

Conclusion

- There are significant dark matter astrophysical uncertainties.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples
- Future:
  - First step: more local f(r, v) data analysis.
  - Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting, and think hard about which things can be modeled.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples
- Future:
  - First step: more local f(r, v) data analysis.
  - Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting, and think hard about which things can be modeled.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples
- Future:
  - First step: more local f(r, v) data analysis.
  - Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting, and think hard about which things can be modeled.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples
- Future:
  - First step: more local f(r, v) data analysis.
  - Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting, and think hard about which things can be modeled.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples
- Future:
  - First step: more local f(r, v) data analysis.
  - Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting, and think hard about which things can be modeled.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples
- Future:
  - First step: more local f(r, v) data analysis.
  - Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting, and think hard about which things can be modeled.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples
- Future:
  - First step: more local f(r, v) data analysis.
  - Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting, and think hard about which things can be modeled.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples
- Future:
  - First step: more local f(r, v) data analysis.
  - Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting, and think hard about which things can be modeled.

Conclusion

- There are significant dark matter astrophysical uncertainties.
- These may be teased out in two ways:
  - Better modeling: even if baryonic physics is wrong, at least it is better than nothing. Case in point: dark disk.
  - Treating the astrophysical uncertainties on par with particle physics uncertainties, and try to get them both out of the data.
- Solar System examples
- Future:
  - First step: more local f(r, v) data analysis.
  - Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting, and think hard about which things can be modeled.