Dark Matters: The Search for the Universe's Missing Mass

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UMD/NASA/GSFC

Fermi Summer School
Lewes, DE
6 June 2017

Mystery of Missing Mass

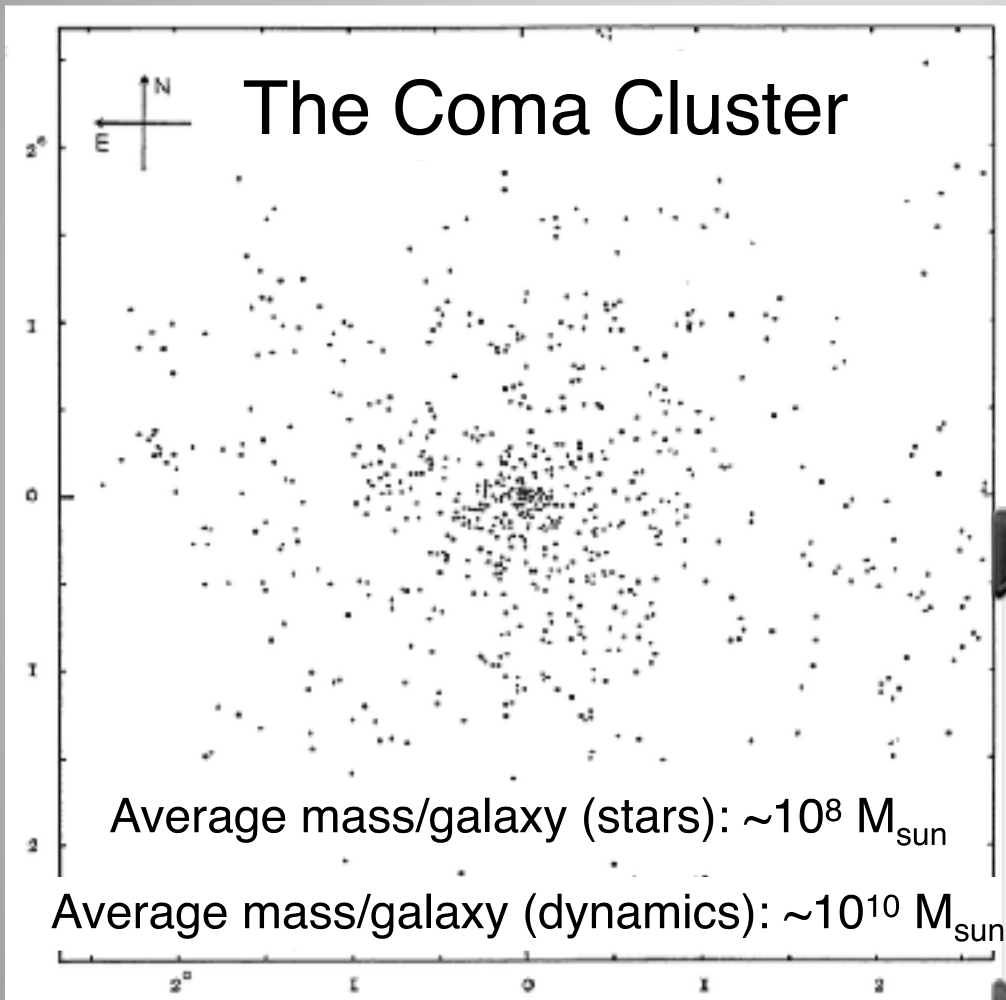


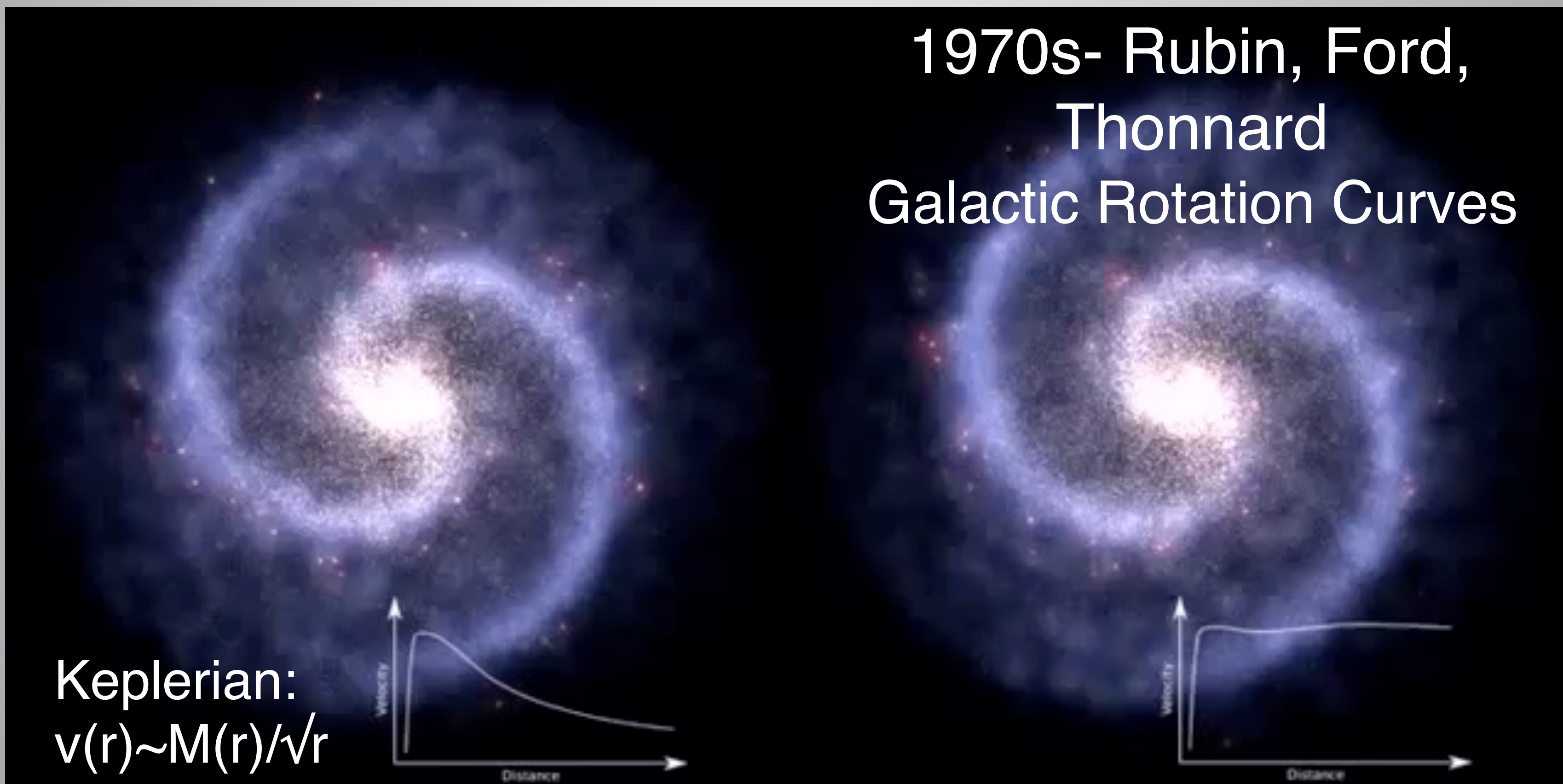
FIG. 3.—The Coma cluster of nebulae

1930s- Zwicky, others

Coma cluster of galaxies: only small % mass from luminous matter

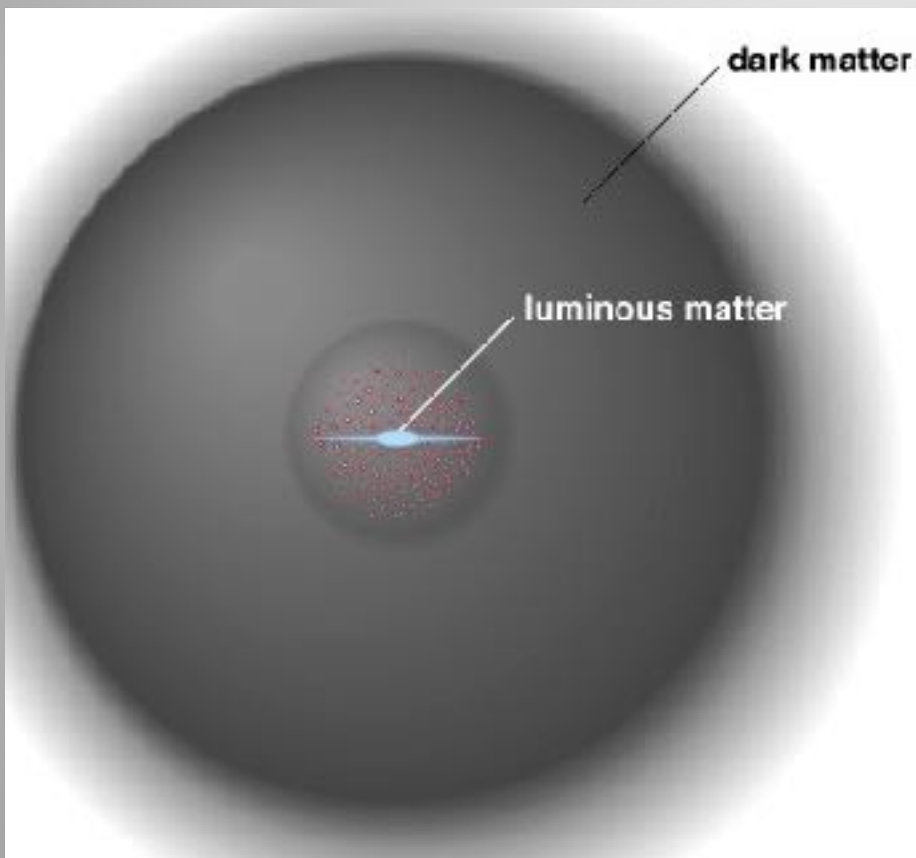
F. Zwicky, Astrophys. J. 86, 217 (1937)

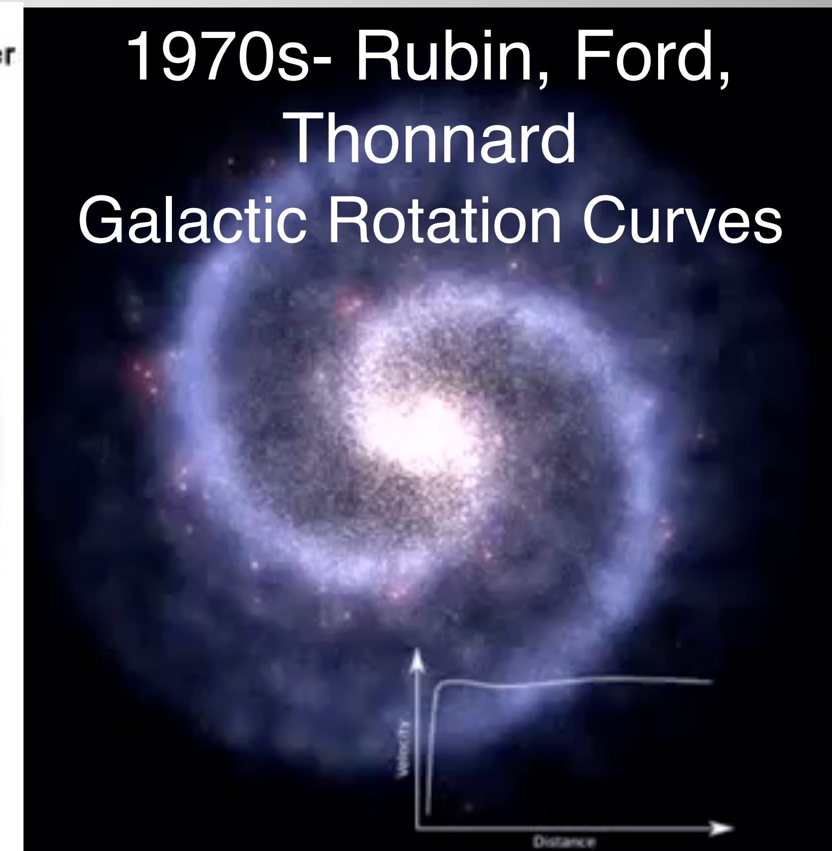
Mystery of Missing Mass



YouTube: https://www.youtube.com/watch?v=Omjx3OKAGDo
http://cse.ssl.berkeley.edu/bmendez/ay10/2002/notes/lec18.html

Mystery of Missing Mass





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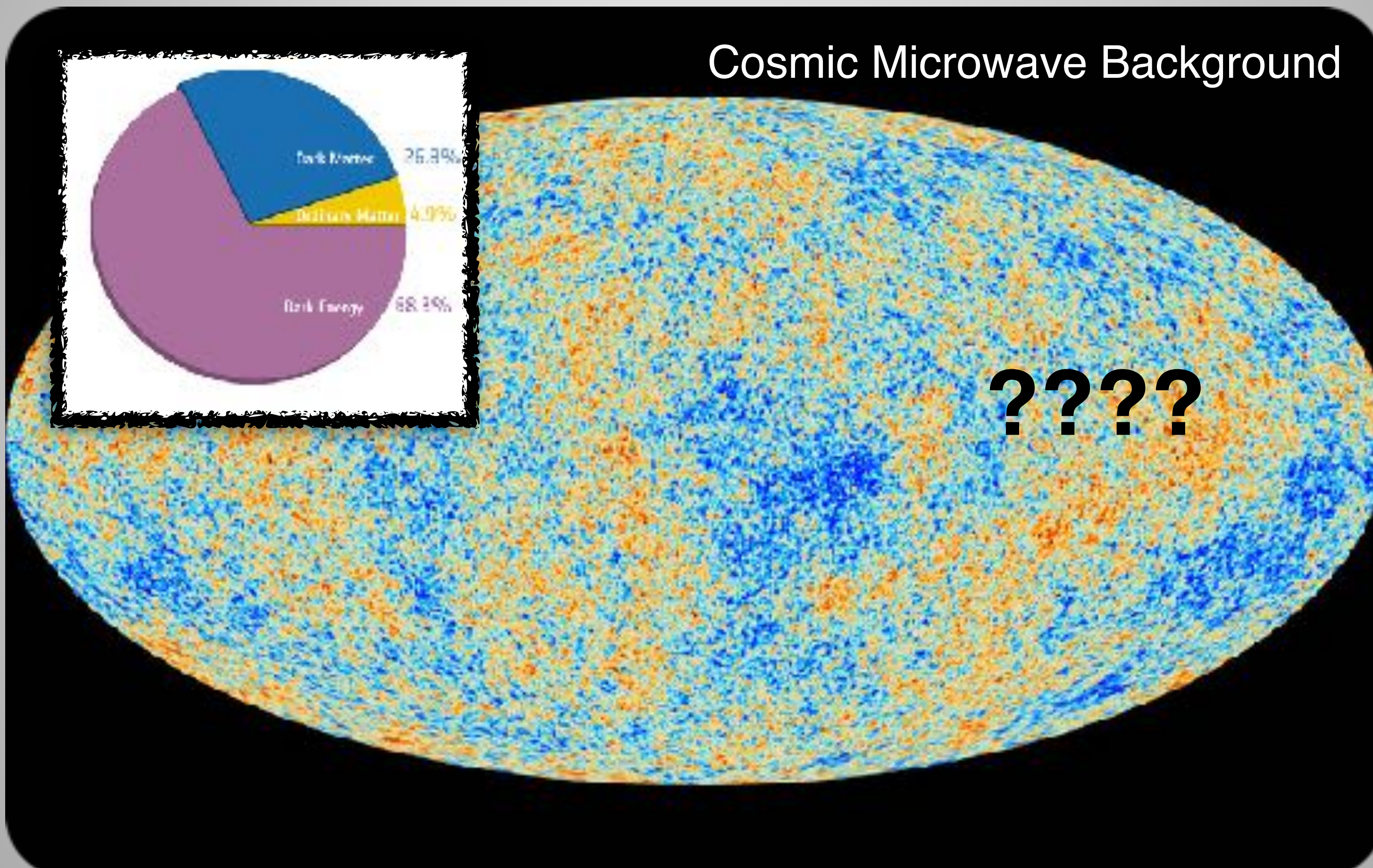
Precision Cosmology



https://lambda.gsfc.nasa.gov/toolbox/tb_camb_form.cfm

Planck Collaboration, 2013

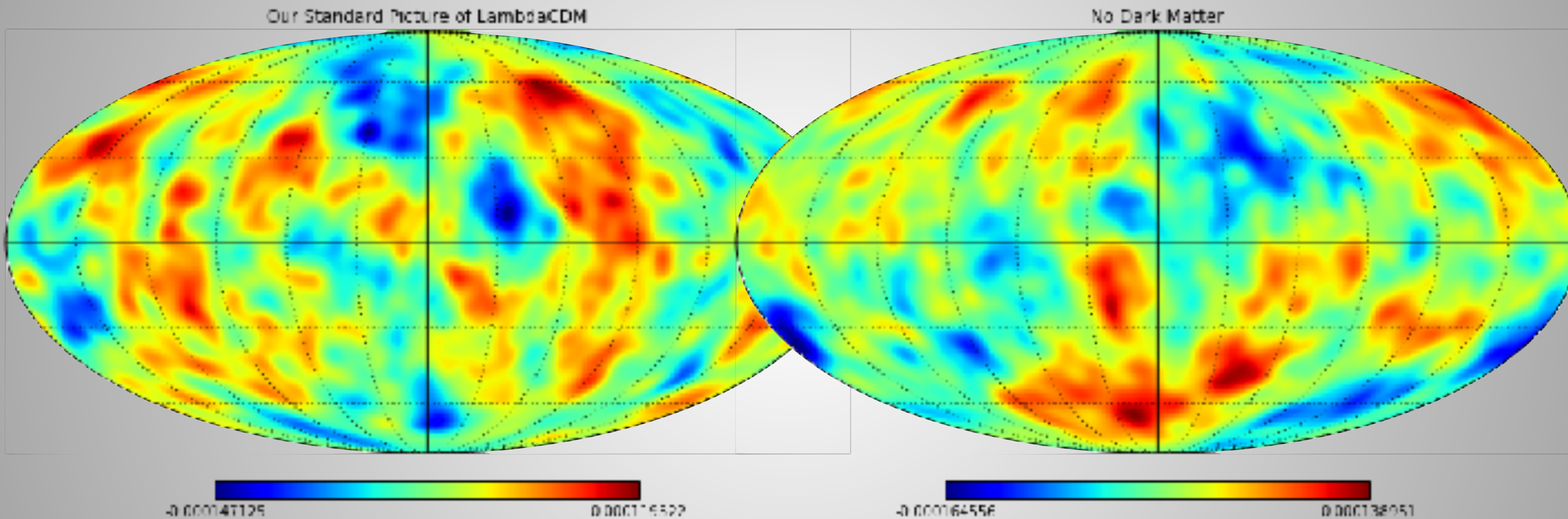
Baryonic Matter

Non-Baryonic Matter

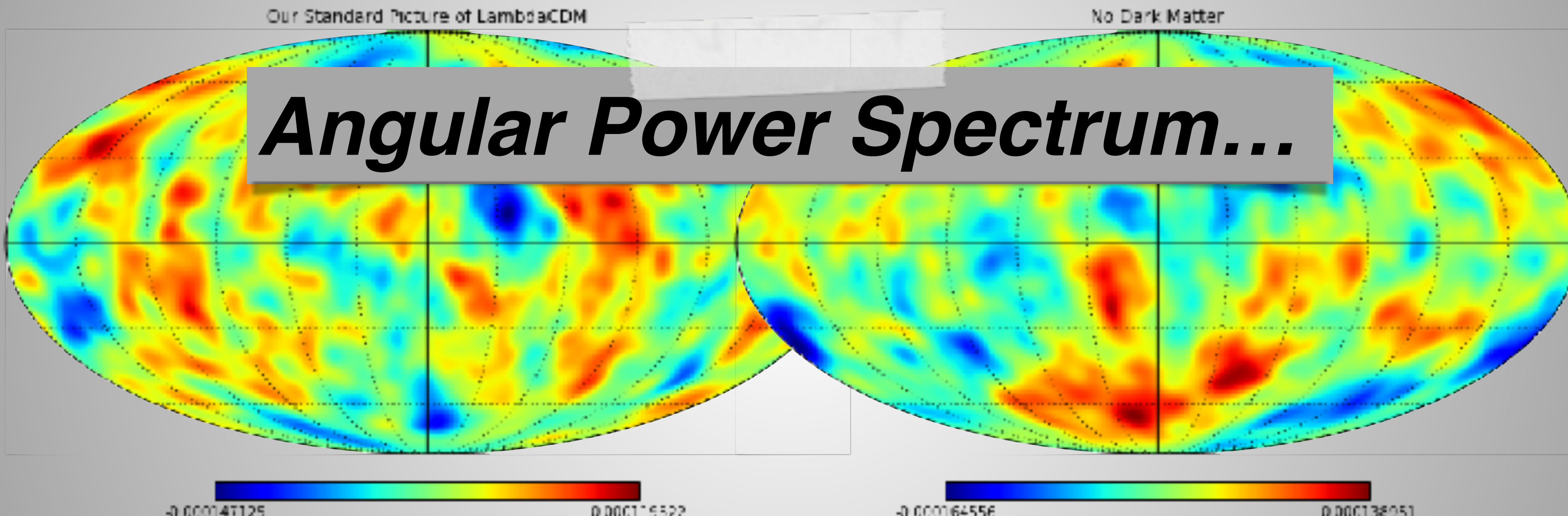
The Friedmann Equation

Planck Collaboration Cosmological parameters[12]			
	Description	Symbol	Value
Independent parameters	Physical baryon density parameter[a]	$\Omega_b h^2$	0.022 30 ±0.000 14
	Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ±0.0010
	Age of the universe	t_0	13.799 ±0.021 × 10^9 years
	Scalar spectral index	n_s	0.9667 ±0.0040
	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$ [15]
	Reionization optical depth	τ	0.066 ±0.012
Fixed parameters	Total density parameter[b]	Ω_{tot}	1
	Equation of state of dark energy	w	−1
	Sum of three neutrino masses	$\sum m_\nu$	0.06 eV/c^2[c][11]:40
	Effective number of relativistic degrees of freedom	N_{eff}	3.046[d][11]:47
	Tensor/scalar ratio	r	0
	Running of spectral index	$d\,n_s / d\ln k$	0
Calculated values	Hubble constant	H_0	67.74 ±0.46 km s^{-1} Mpc^{-1}
	Baryon density parameter[b]	Ω_b	0.0486 ±0.0010[e]
	Dark matter density parameter[b]	Ω_c	0.2589 ±0.0057[f]
	Matter density parameter[b]	Ω_m	0.3089 ±0.0062
	Dark energy density parameter[b]	Ω_Λ	0.6911 ±0.0062
	Critical density	ρ_{crit}	(8.62 ±0.12) × 10^{-27} kg/m^3[g]
	Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.8159 ±0.0086
	Redshift at decoupling	z_*	1 089.90 ±0.23
	Age at decoupling	t_*	377 700 ±3200 years[15]
	Redshift of reionization (with uniform prior)	z_{re}	$8.5^{+1.0}_{-1.1}$ [16]

How does the early universe look without DM?

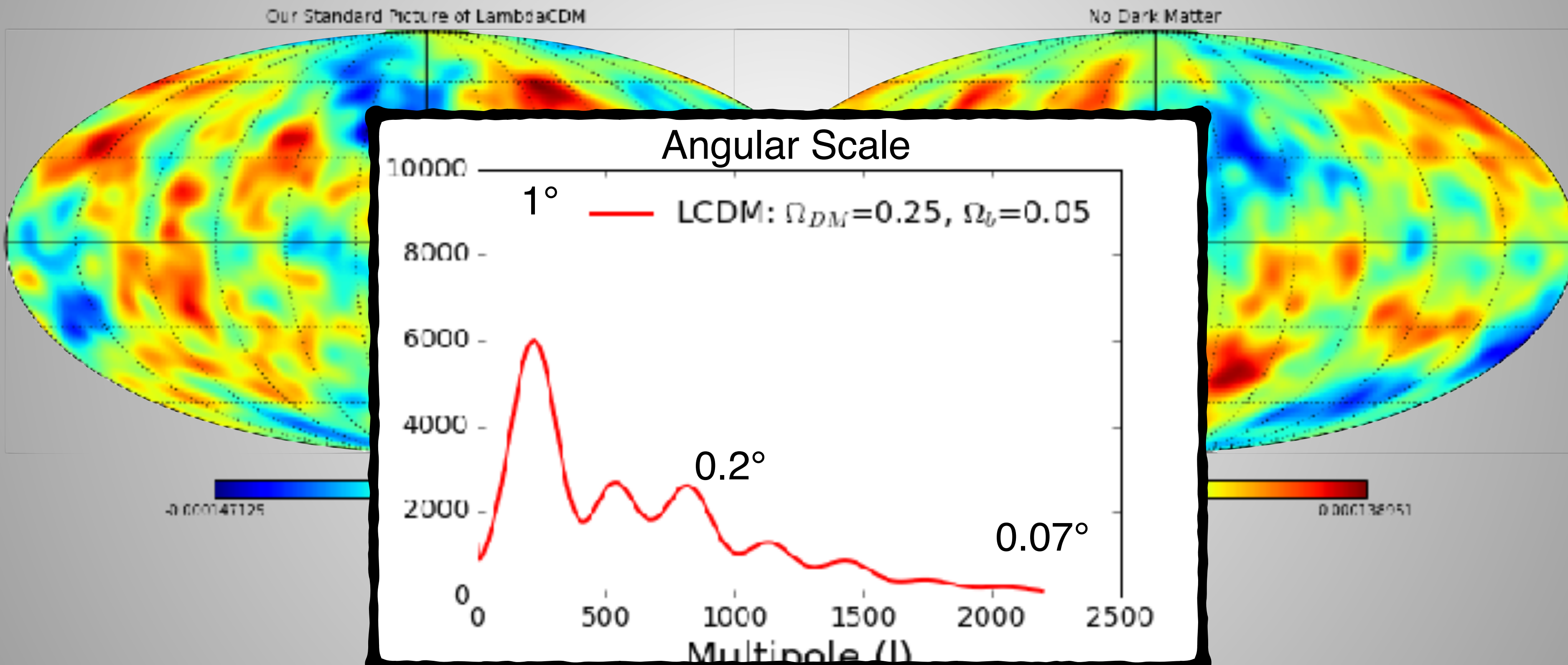


How does the early universe look without DM?



Angular Power Spectrum…

How does the early universe look without DM?



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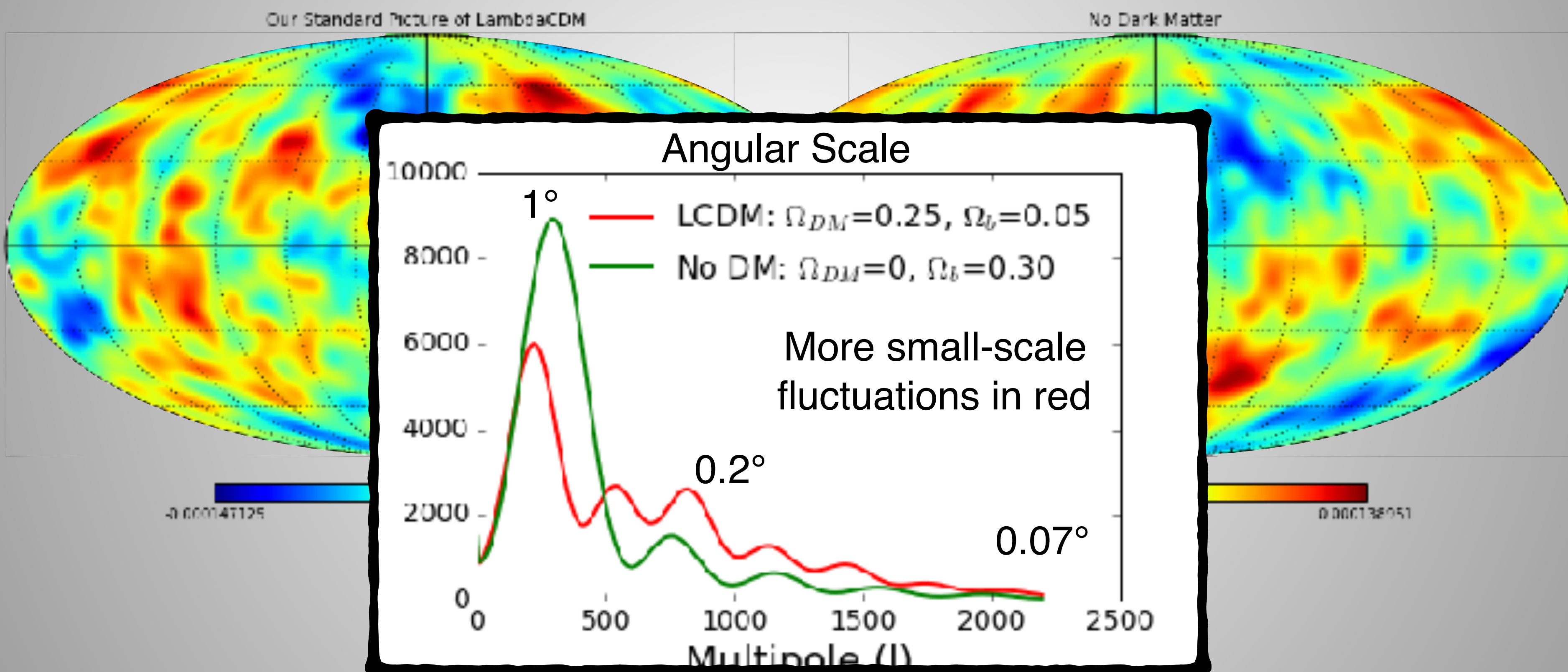

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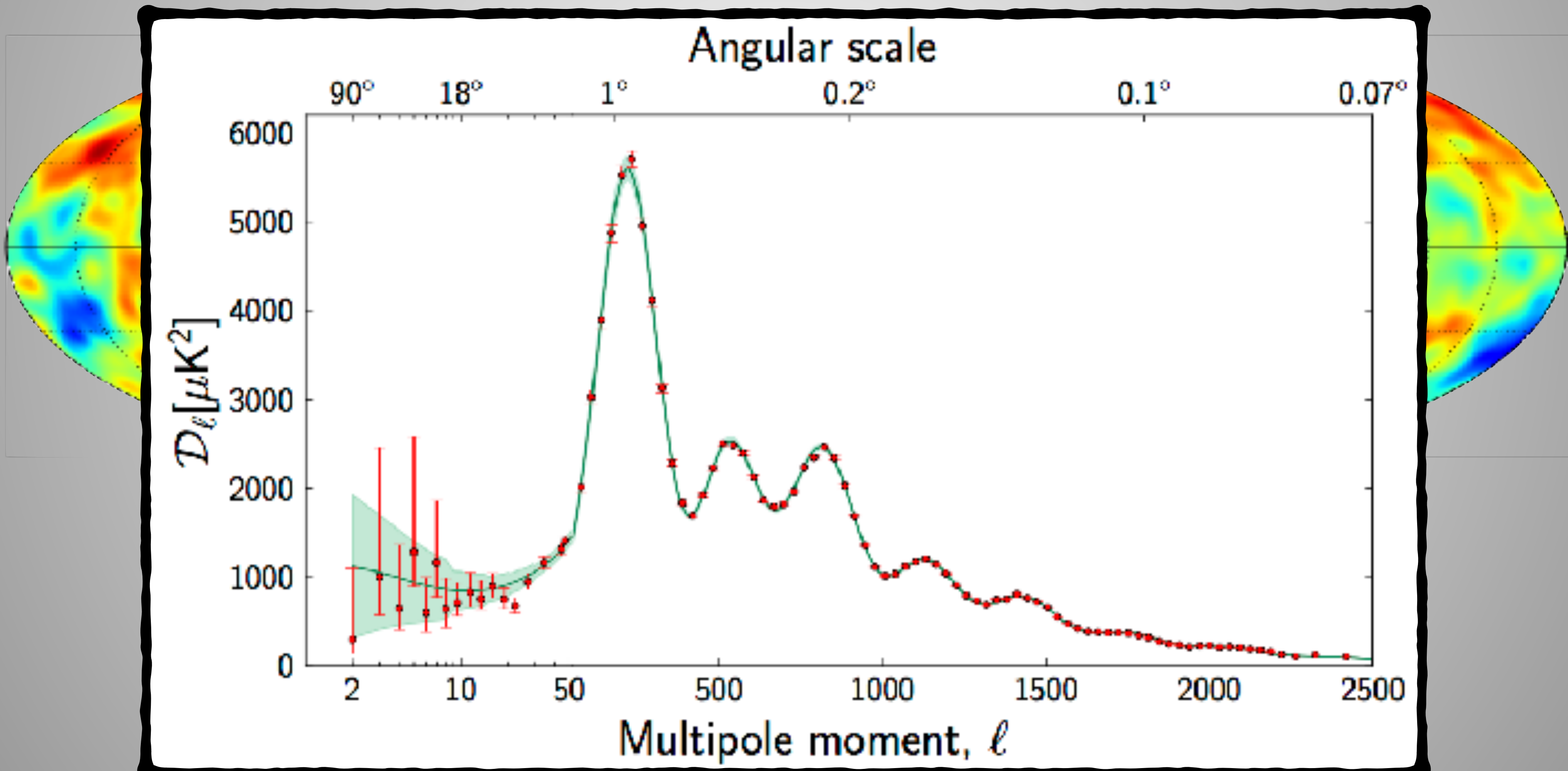
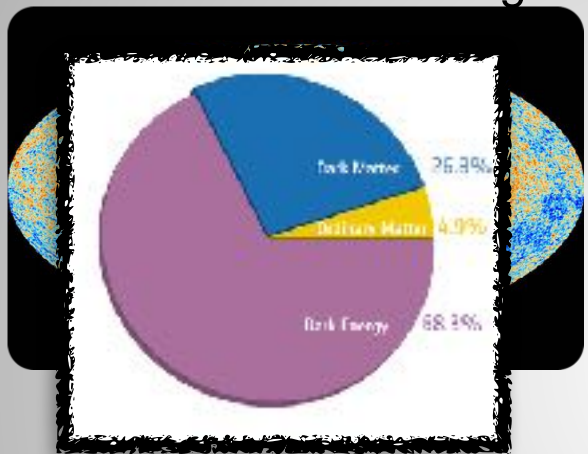


Precision Cosmology

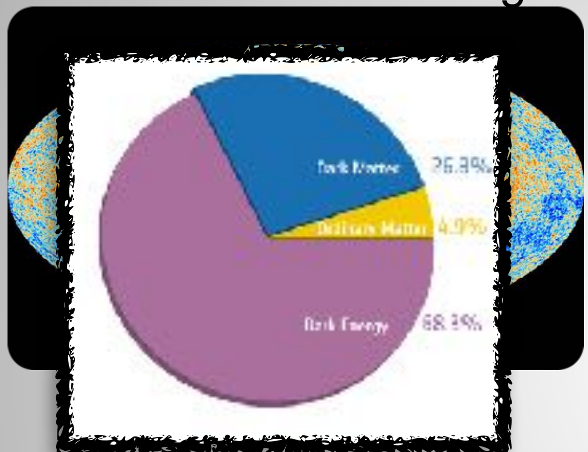
Cosmic Microwave Background



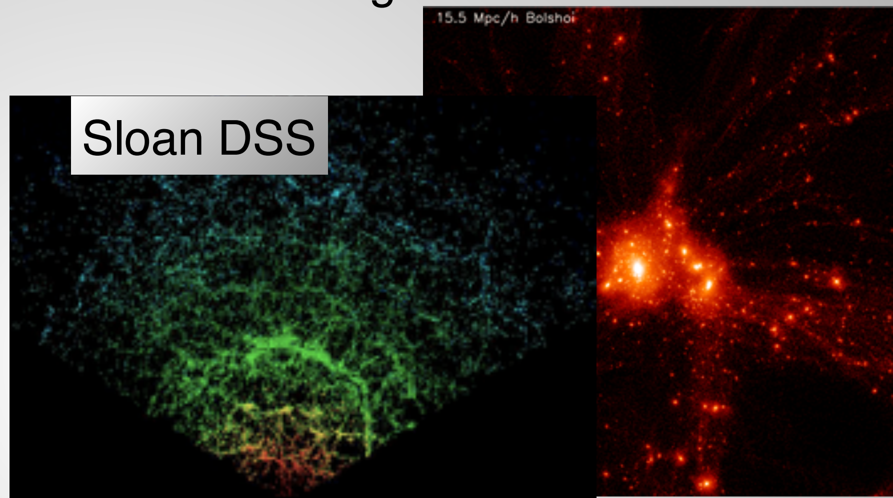
Planck Collaboration, 2013; SubbaRao et al. (2008); Bolshoi Simulation, J. Primack et al.,2011; NASA, APOD, 2006 August 24, J. A. Tyson et al., Astrophys.J.498:L107,1998

Precision Cosmology

Cosmic Microwave Background



Large Scale Structure



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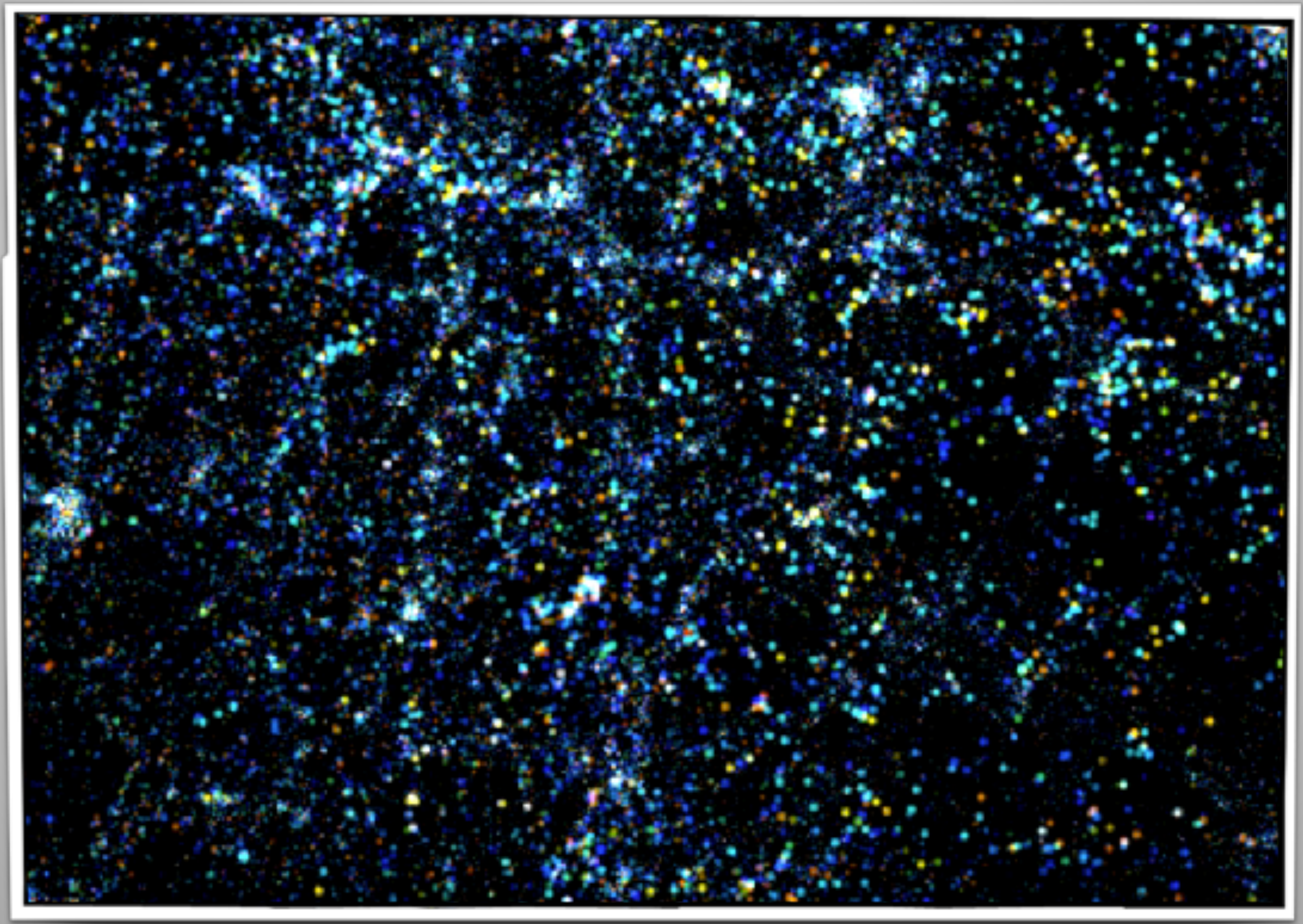
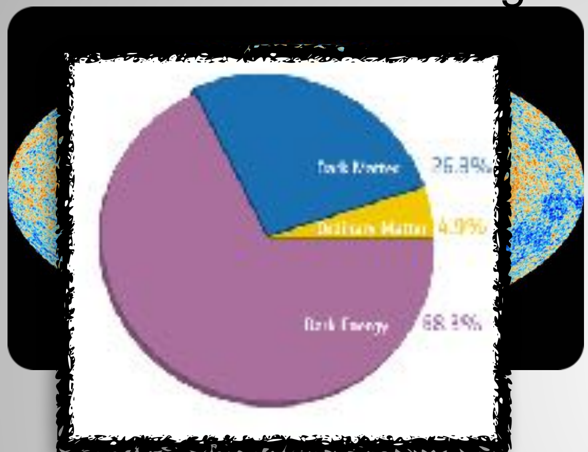
Large Scale Structure Simulation



http://risa.stanford.edu/milkyway/

Precision Cosmology

Cosmic Microwave Background



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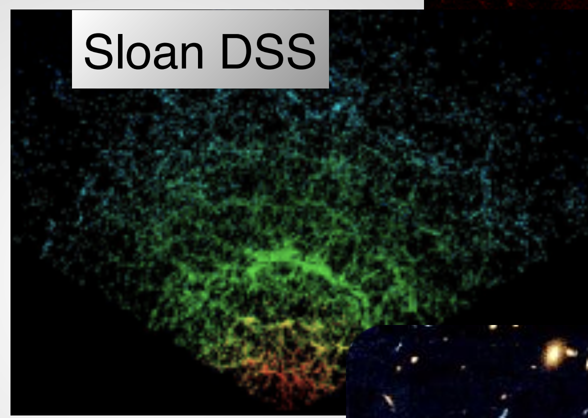
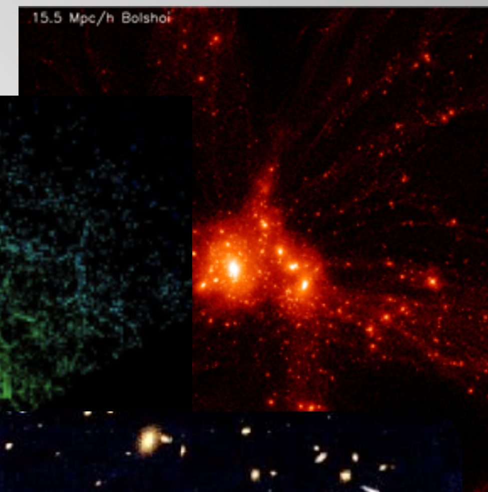




Gravitational Lensing

Planck Collaboration, 2013; SubbaRao et al. (2008); Bolshoi Simulation, J. Primack et al.,2011; NASA, APOD, 2006 August 24, J. A. Tyson et al., Astrophys.J.498:L107,1998

Precision Cosmology

Cosmic Microwave Background

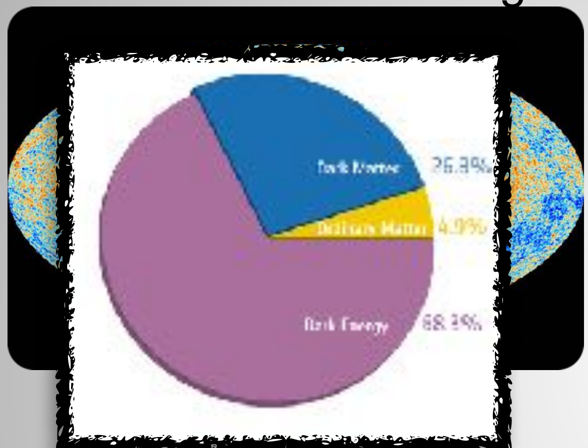
Large Scale Structure

Blue: mass from lensing

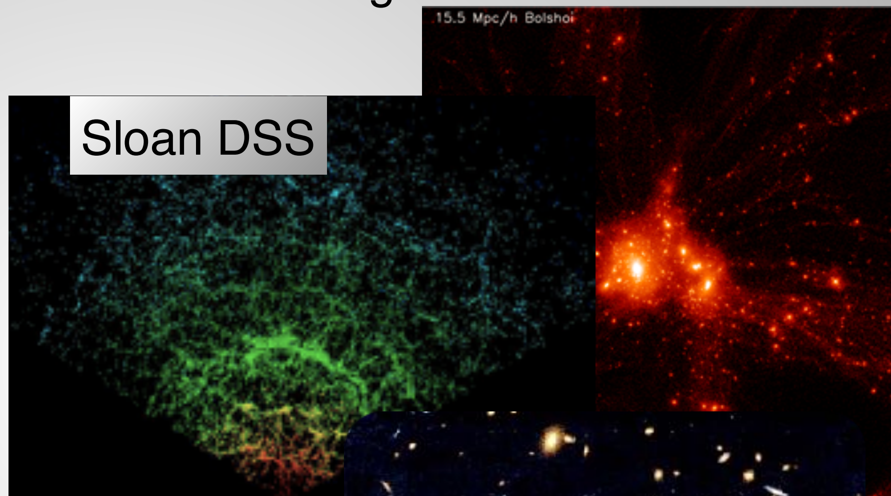
Planck Collaboration, 2013; SubbaRao et al. (2008); Bolshoi Simulation, J. Primack et al.,2011; NASA, APOD, 2006 August 24, J. A. Tyson et al., Astrophys.J.498:L107,1998

Precision Cosmology

Cosmic Microwave Background



Large Scale Structure



Lensing/
The Bullet
Cluster

Blue: mass from lensing

Gravitational
Lensing

Planck Collaboration, 2013; SubbaRao et al. (2008); Bolshoi Simulation, J. Primack et al.,2011; NASA, APOD, 2006 August 24, J. A. Tyson et al., Astrophys.J.498:L107,1998

What do we know?

mass

stable

not p/n (baryons)

constraints from CMB, N-body simulations

not hot

neutral

constraints from CMB, primordial nucleosynthesis

What do we know?

constraints from CMB, N-body simulations

Particle(s)

constraints from CMB, primordial nucleosynthesis

Potential Candidates

Potential Candidates

Weak Scale

m~ 100 GeV
100× proton

~0.5 Caffeine molecule

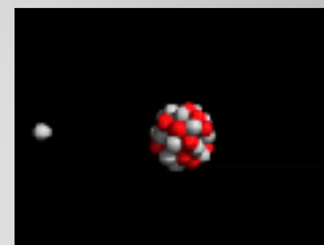
Potential Candidates

Weak Scale

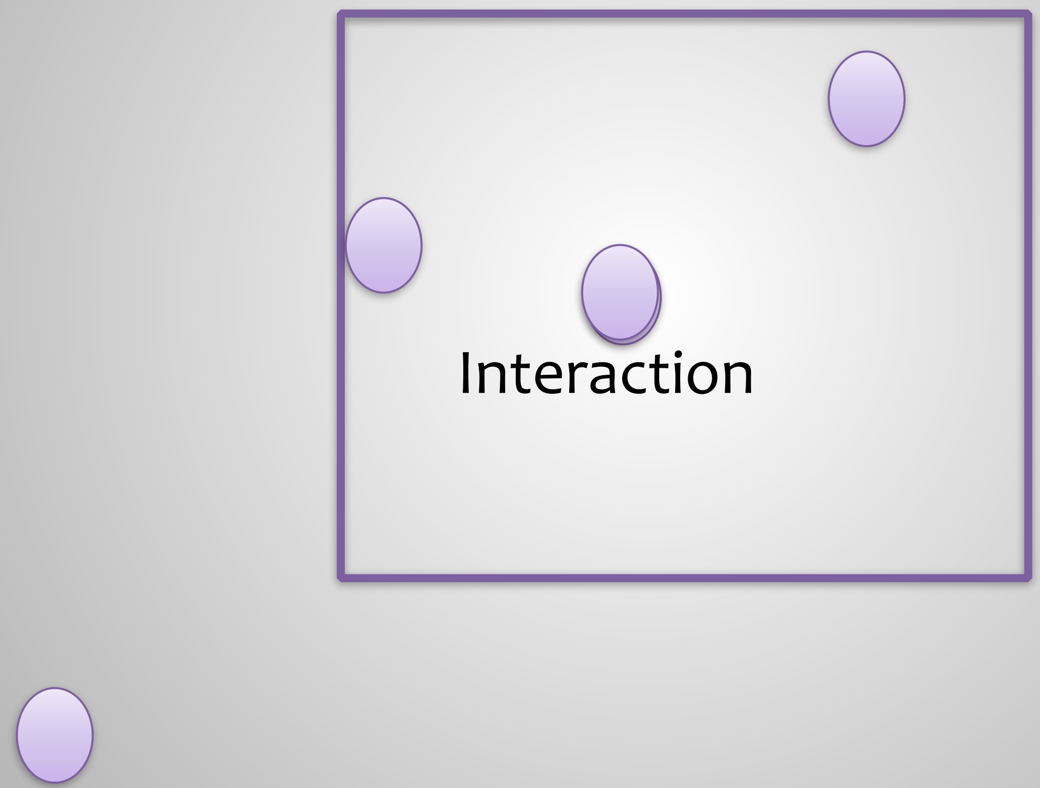
m~ 100 GeV
100× proton

~0.5 Caffeine molecule

Cross Section (σ) Cheat Sheet

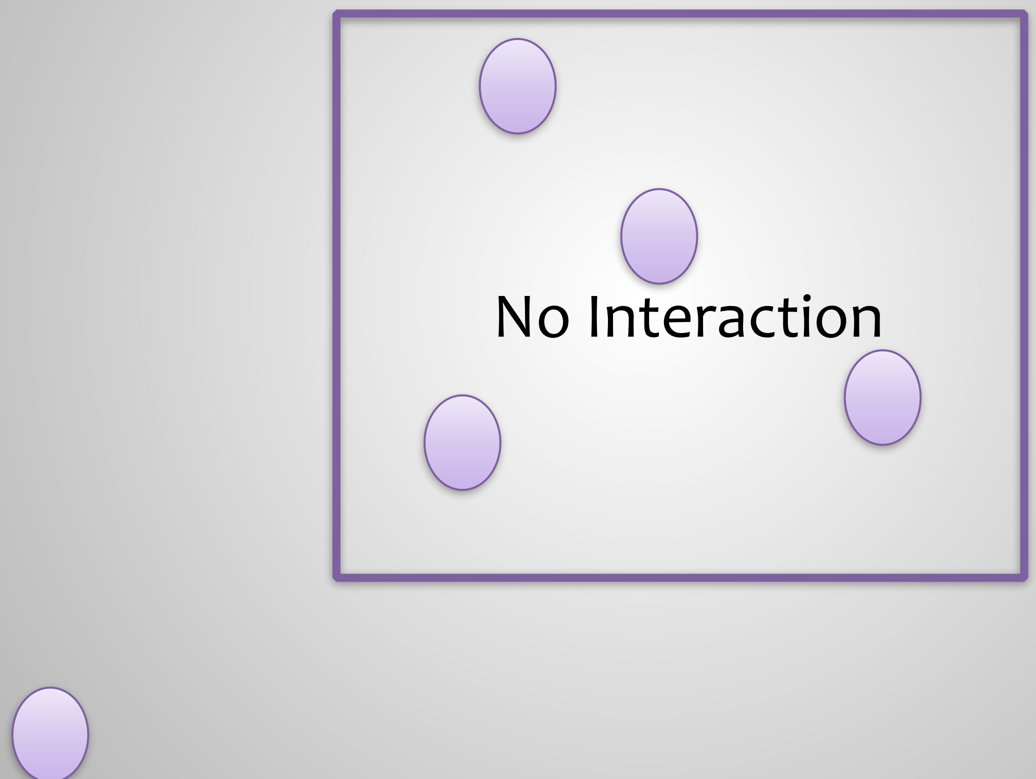
	Cross section	Force	Designation
	10^{-24} cm^2	nuclear (~10 fm)^2	
pico- 	10^{-36} cm^2	Weak	Weakly interacting
femto- 	10^{-39} cm^2	Ultra-Weak	LHC probes

Velocity (σv) Cheat Sheet



“Area of interaction” ~ σ

Velocity (σv) Cheat Sheet



"Area of interaction" ~ σ

Portrait of a Candidate

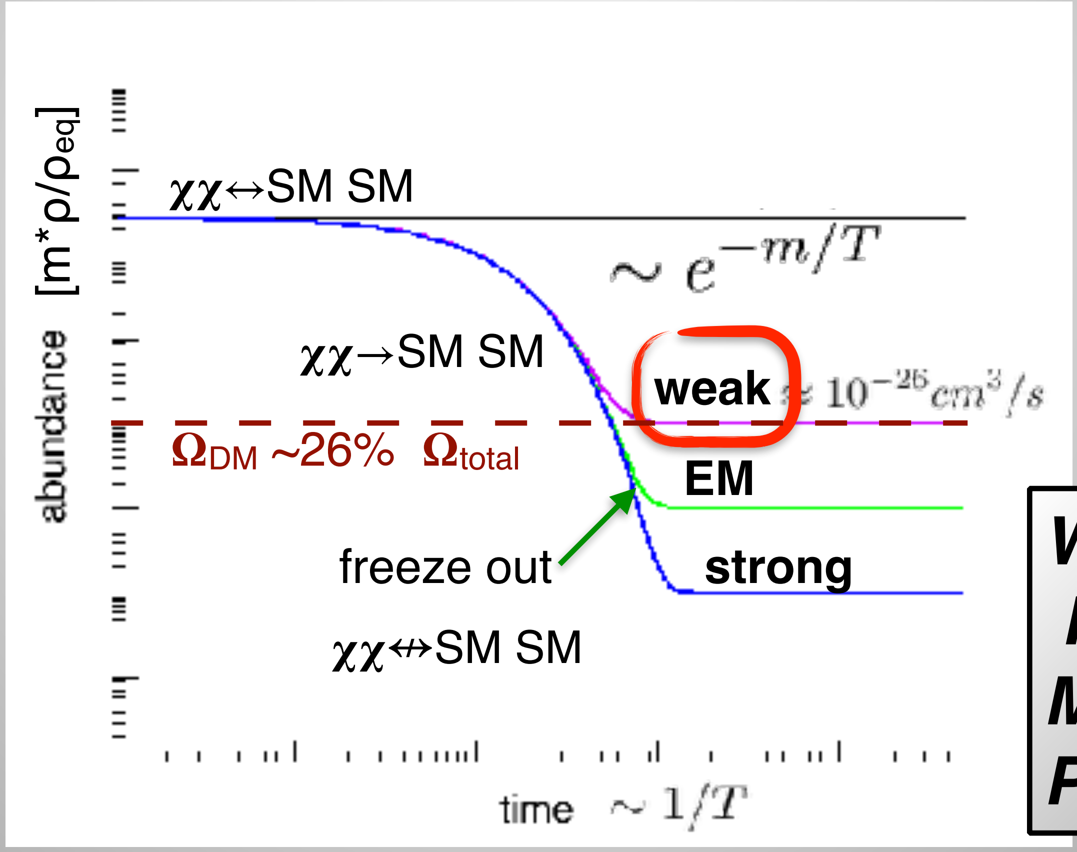
Particle Physics

DM = χ

Weak (σ): 10^{-36} cm^2

velocity (v) @
freeze out: 10^5 km/s

$\langle\sigma v\rangle \sim 10^{-26}$ cm^3/s



Abundance
$\langle\sigma v\rangle n_{eq} \sim H$
$\langle\sigma v\rangle \sim 10^{-26}$ cm^3/s

***Weakly
Interacting
Massive
Particles***

G. Steigman, et al., Phys.Rev. D86 (2012) 023506

Portrait of a Candidate

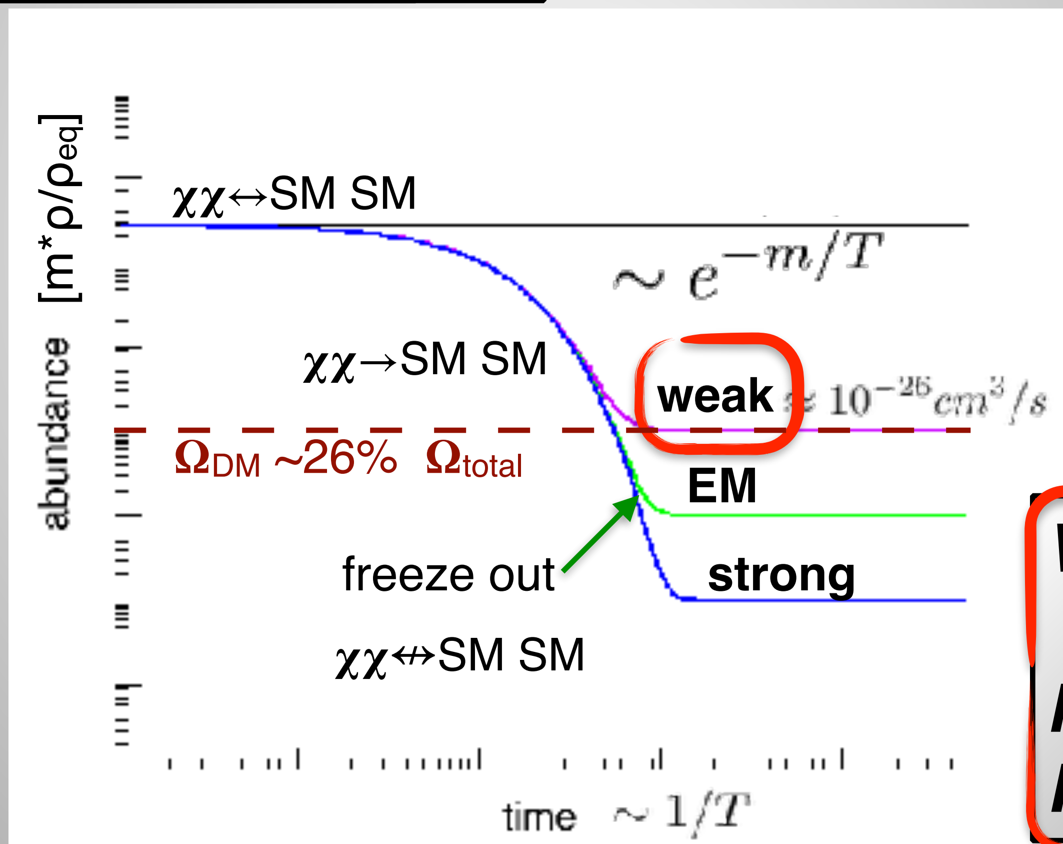
The WIMP Miracle…

DM = χ

Weak (σ): 10^{-36} cm^2

velocity (v) @ freeze out: 10^5 km/s

$\langle \sigma v \rangle \sim 10^{-26}$ cm^3/s



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Weakly Interacting Massive Particles

G. Steigman, et al., Phys.Rev. D86 (2012) 023506

Portrait of a Candidate

The WIMP Coincidence

DM = χ

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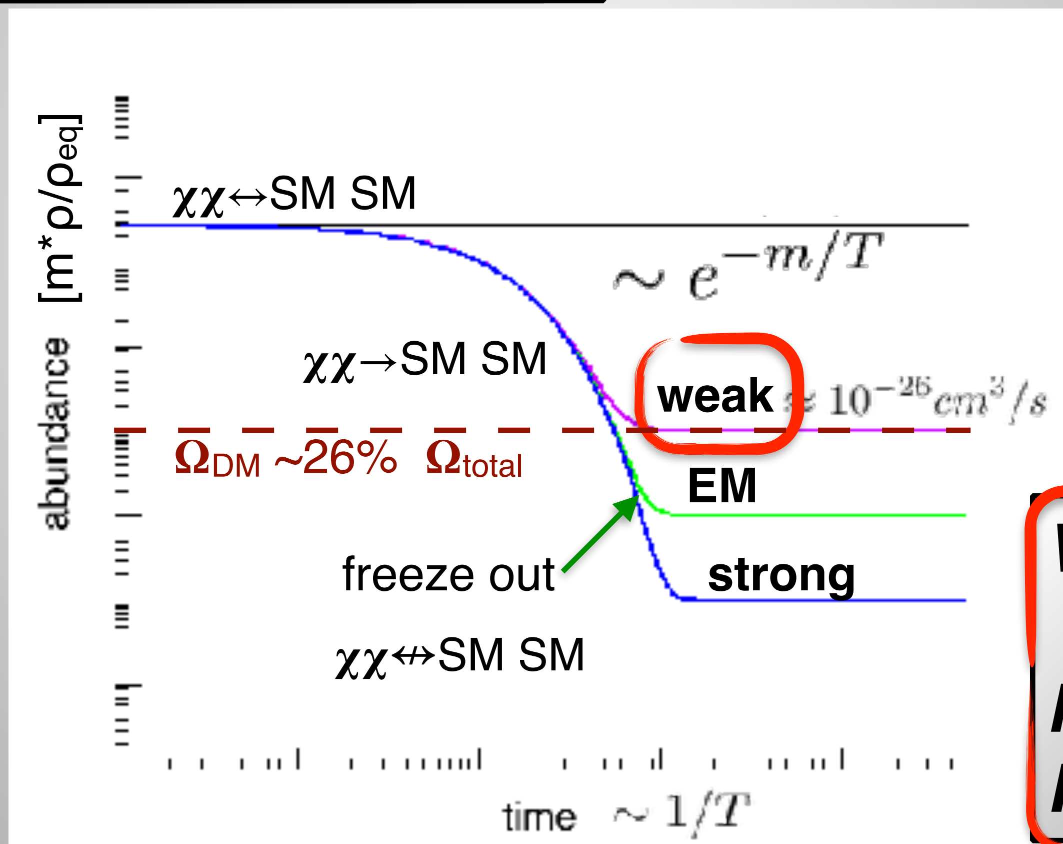

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Weakly Interacting Massive Particles

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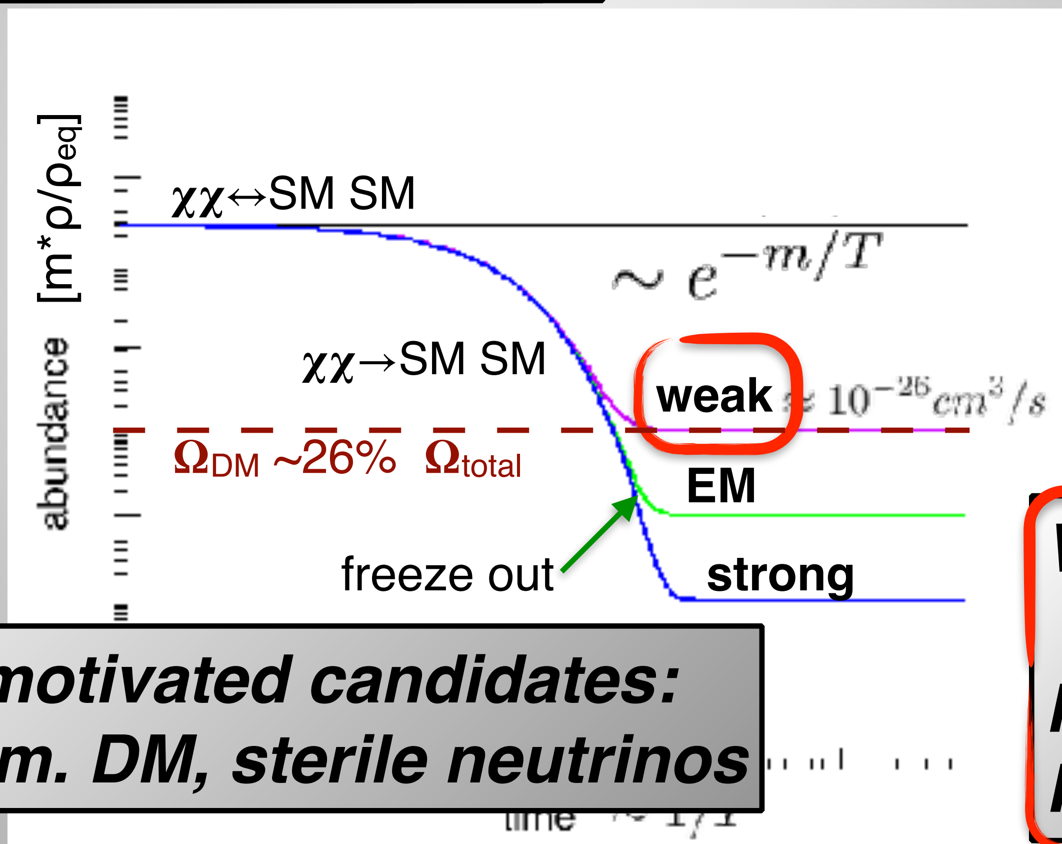


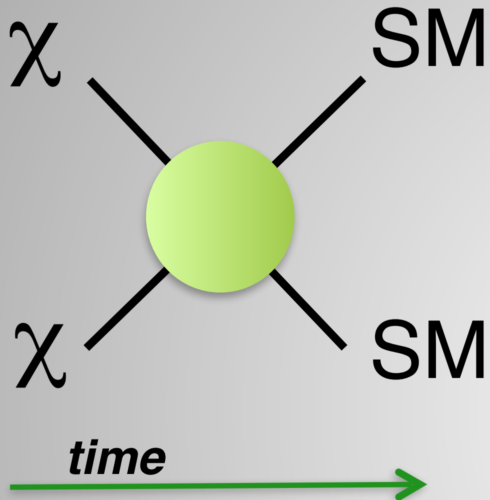
Abundance
$\langle\sigma v\rangle n_{eq} \sim H$
$\langle\sigma v\rangle \sim 10^{-26}$ cm^3/s

Other well motivated candidates: axions, asym. DM, sterile neutrinos

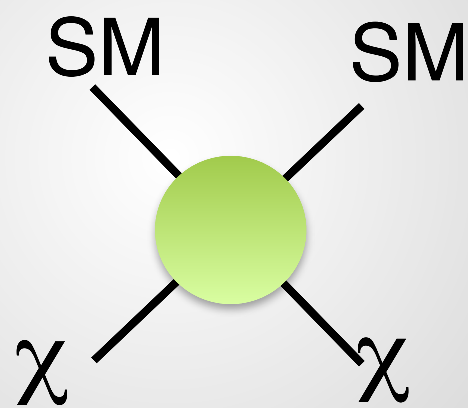
Weakly Interacting Massive Particles

G. Steigman, et al., Phys.Rev. D86 (2012) 023506

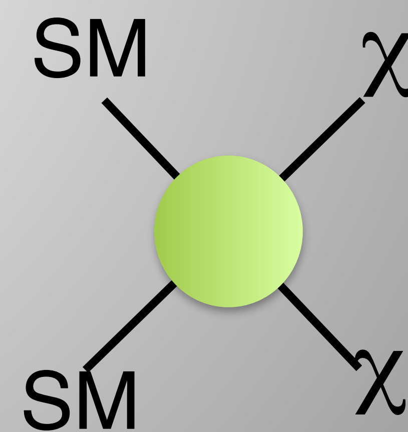
Detecting Particle Dark Matter



Indirect Detection



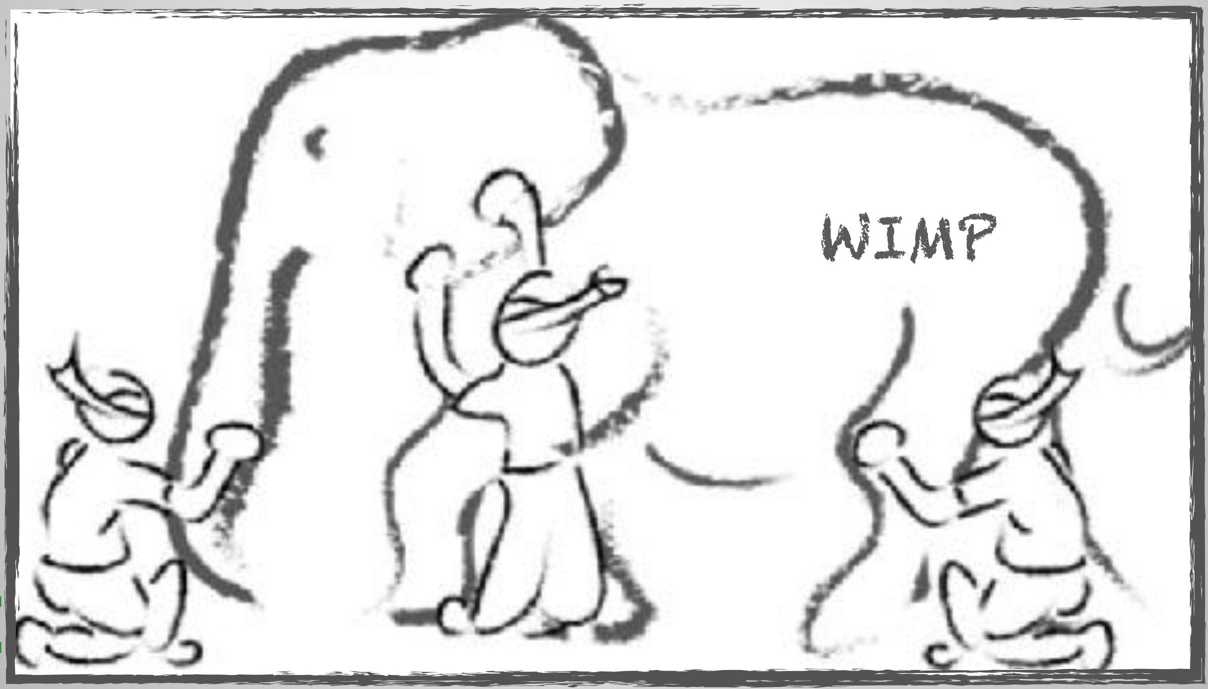
Direct Detection



Collider

Detecting the Elephant in the Room

Indirect Detection

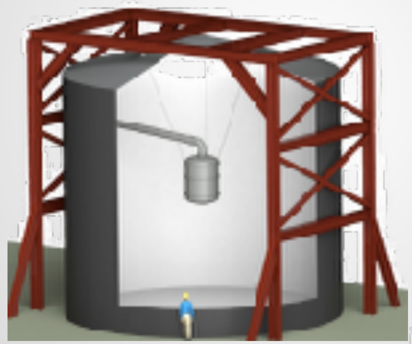


Direct Detection

Collider

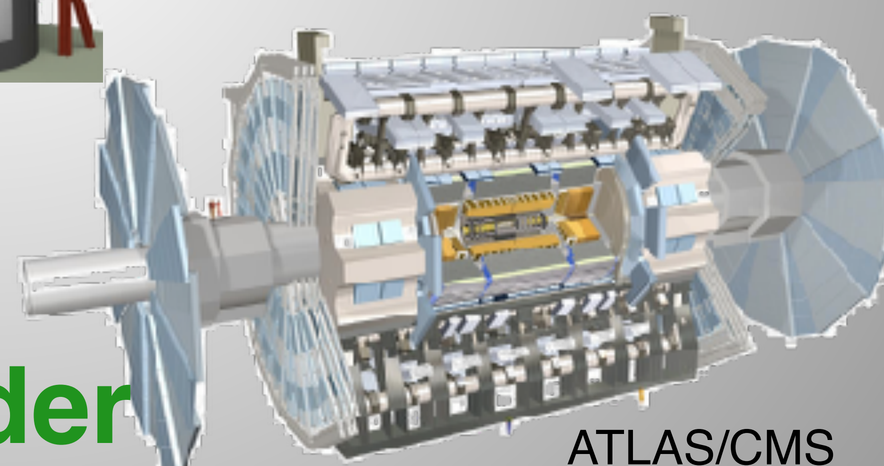
Dark Matter Searches

Indirect Detection



Direct Detection

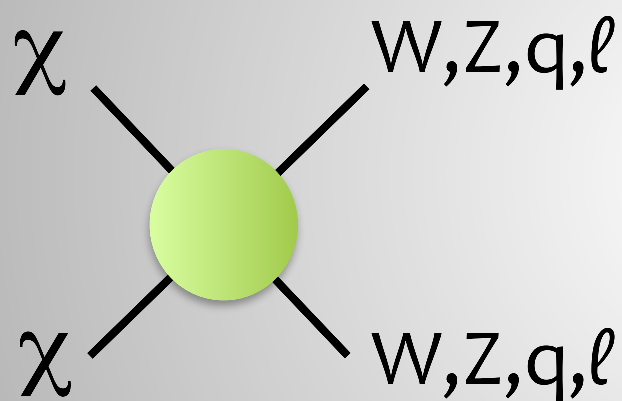
Collider



ATLAS/CMS

Indirect Searches: γ-rays

Standard
Model



$\pi^0 \rightarrow \gamma\gamma$

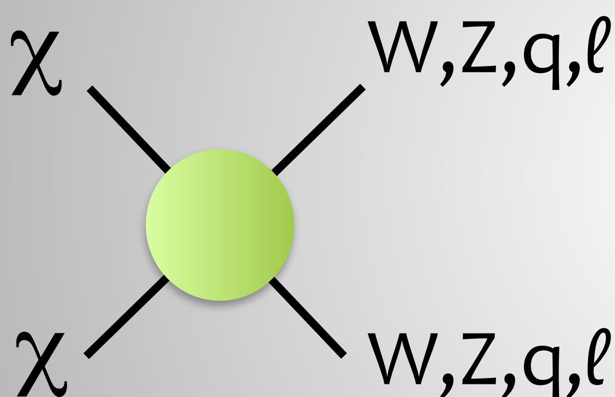
Increase in continuum flux
(overall excess)

$\pi^\pm \rightarrow \ell, \nu$

$\pi^\pm \rightarrow p^\pm$, n, anti-matter

Indirect Searches: γ-rays

Standard Model



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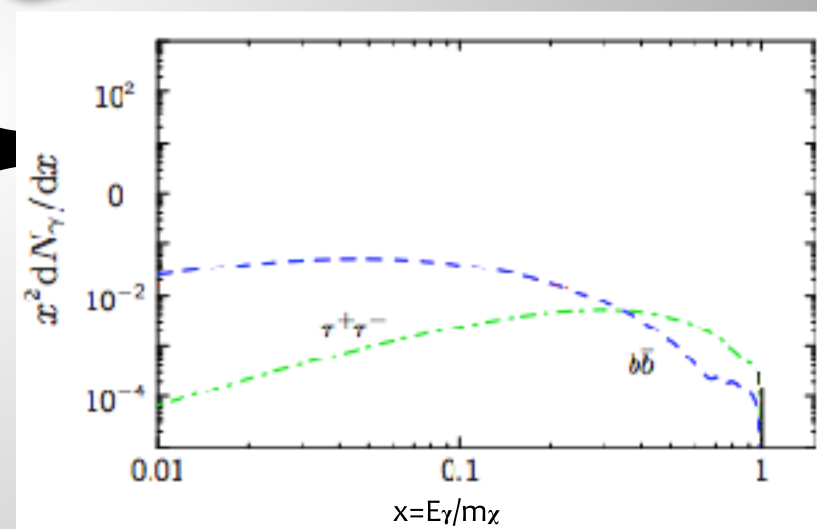
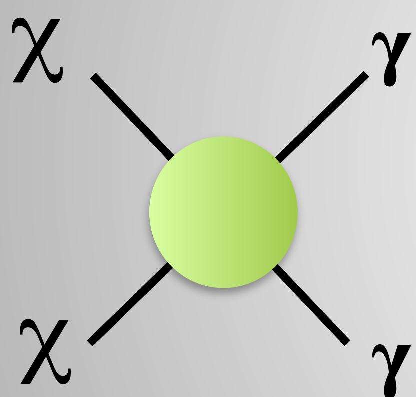
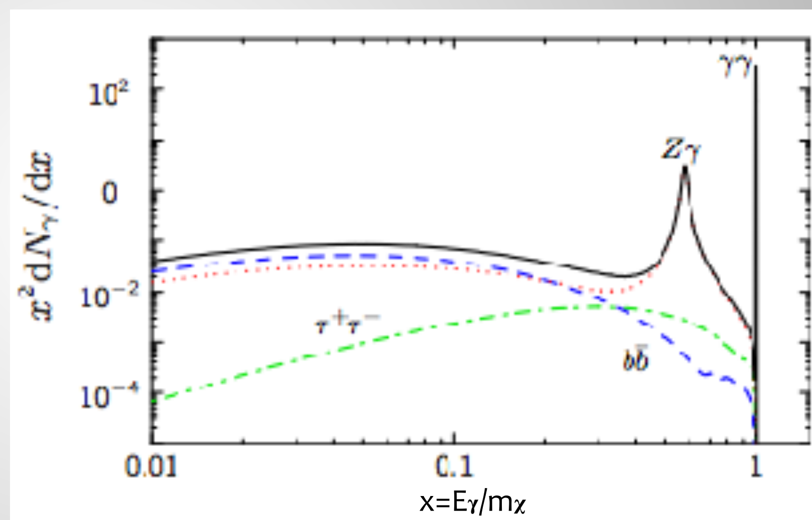


Gustafsson et al. PRL 99.041301

Indirect Searches: γ-rays

Standard
Model





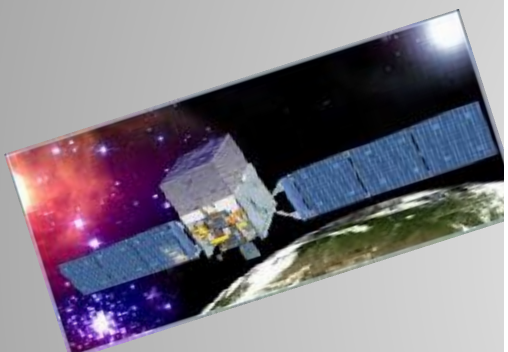
Gustafsson et al.
PRL 99.041301

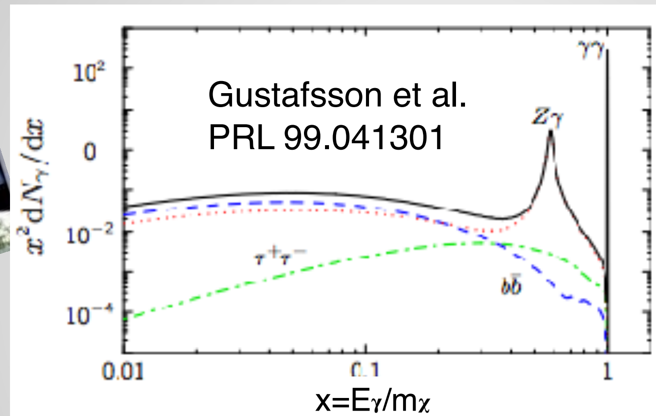
Appear as a line in the **γ**-ray spectrum

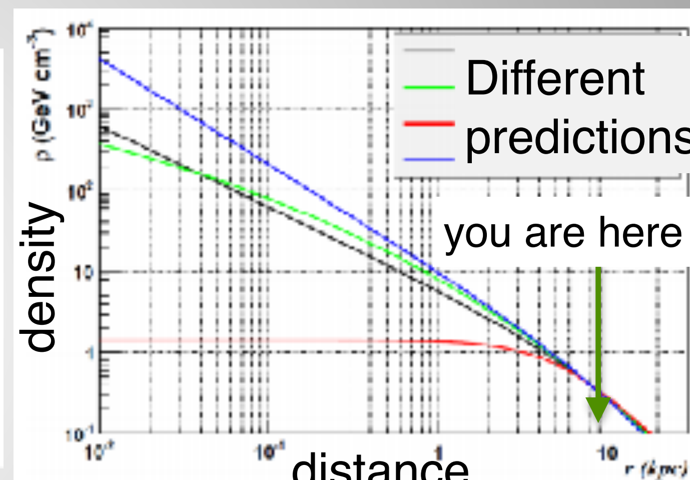
Not Astrophysical Source! Line must be Dark matter

Indirect Searches: γ-rays

Observed* = *Particle Properties* x *Astrophysics Properties







$$\Phi_\gamma(E,\psi) = \frac{1}{4\pi}\frac{\langle\sigma_\chi v\rangle}{2m_\chi^2} N_\gamma(E) \times J(\psi)$$

cross section

mass

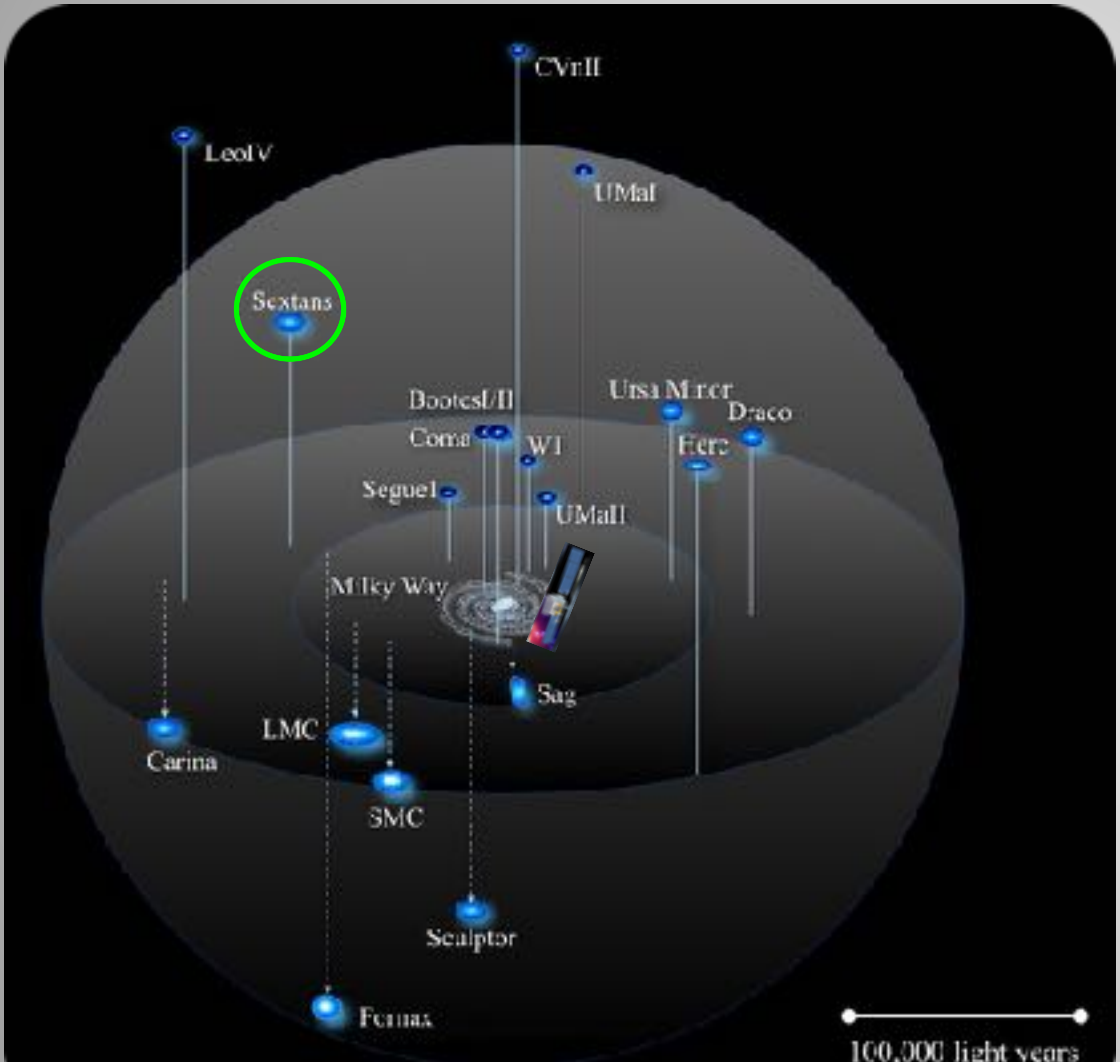
photons

J-Factor: ~ ∫ρ²

(solid angle, line of sight)

L. Bergstrom et al., Astropart.Phys.9:137-162,1998

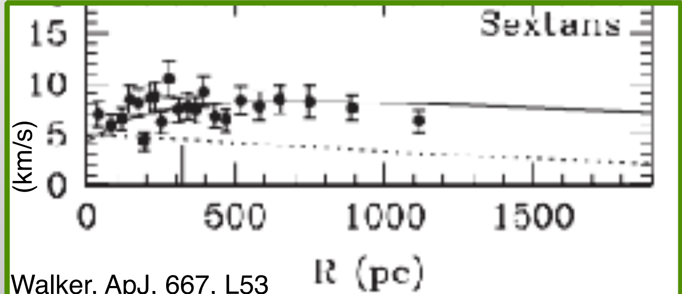
Dwarf Spheroidal Galaxies



J. Bullock, M. Geha, R. Powell

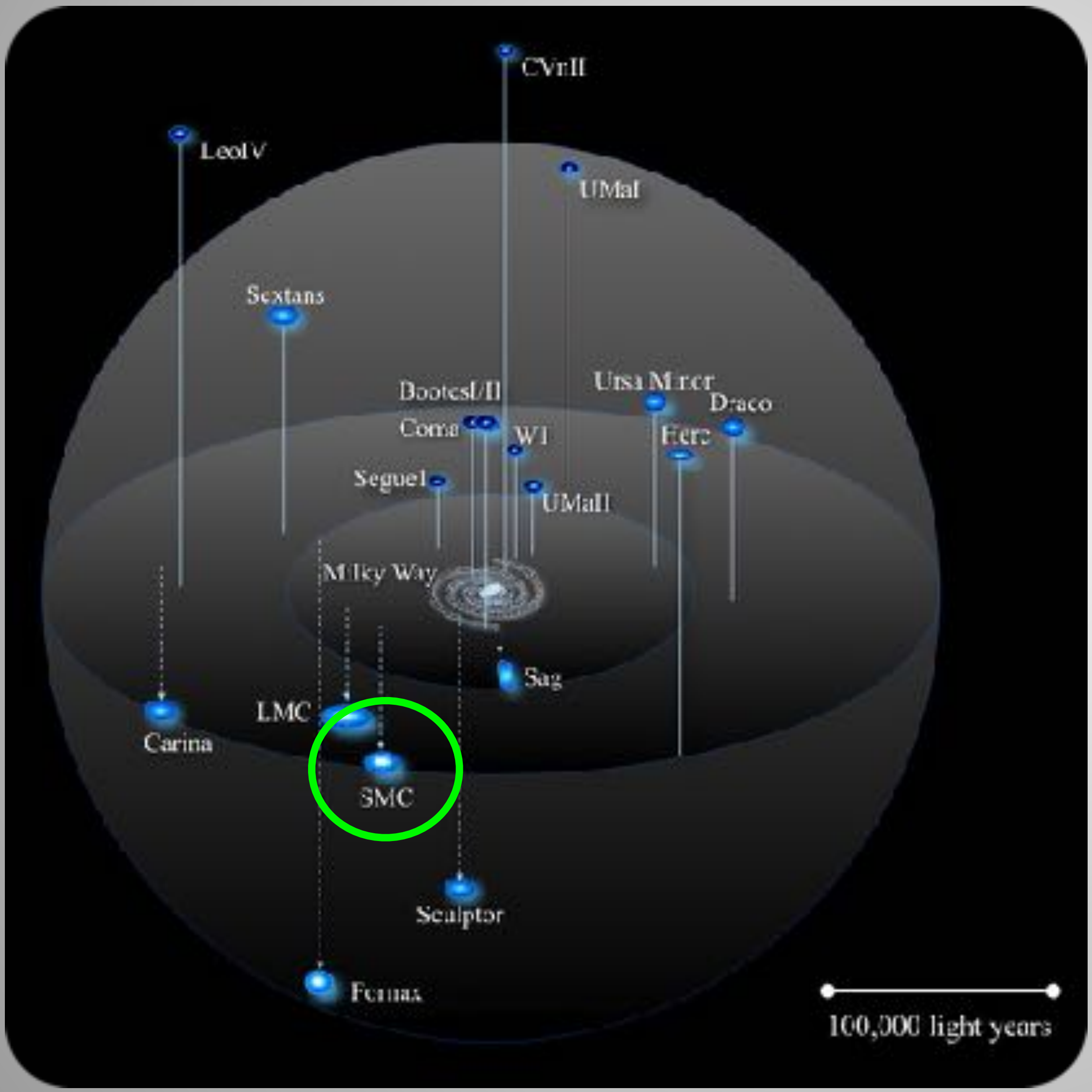
lower signal, but… lower backgrounds

High Dark Matter to Baryonic Matter Ratio

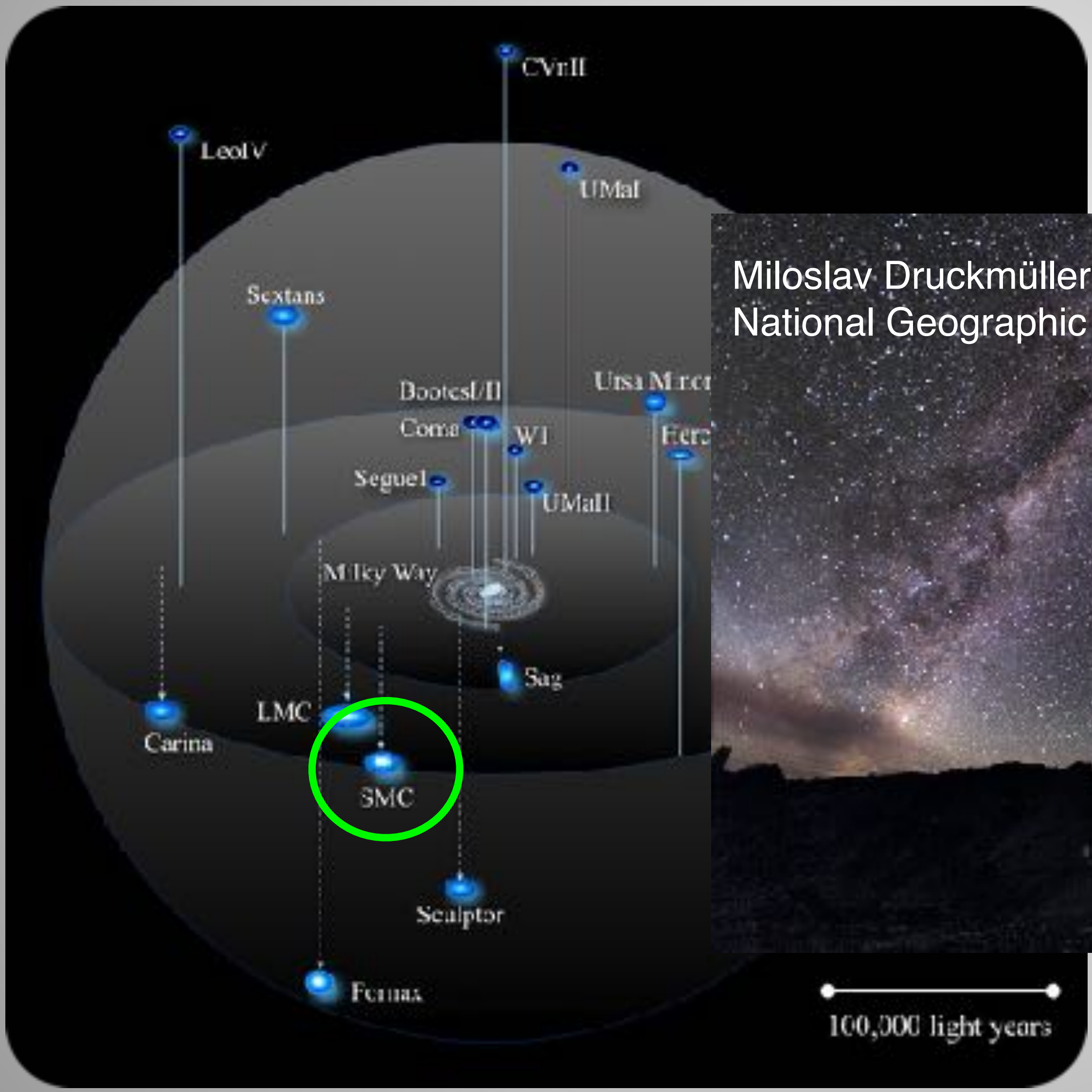


Walker, ApJ, 667, L53

Star Forming Galaxies



Star Forming Galaxies



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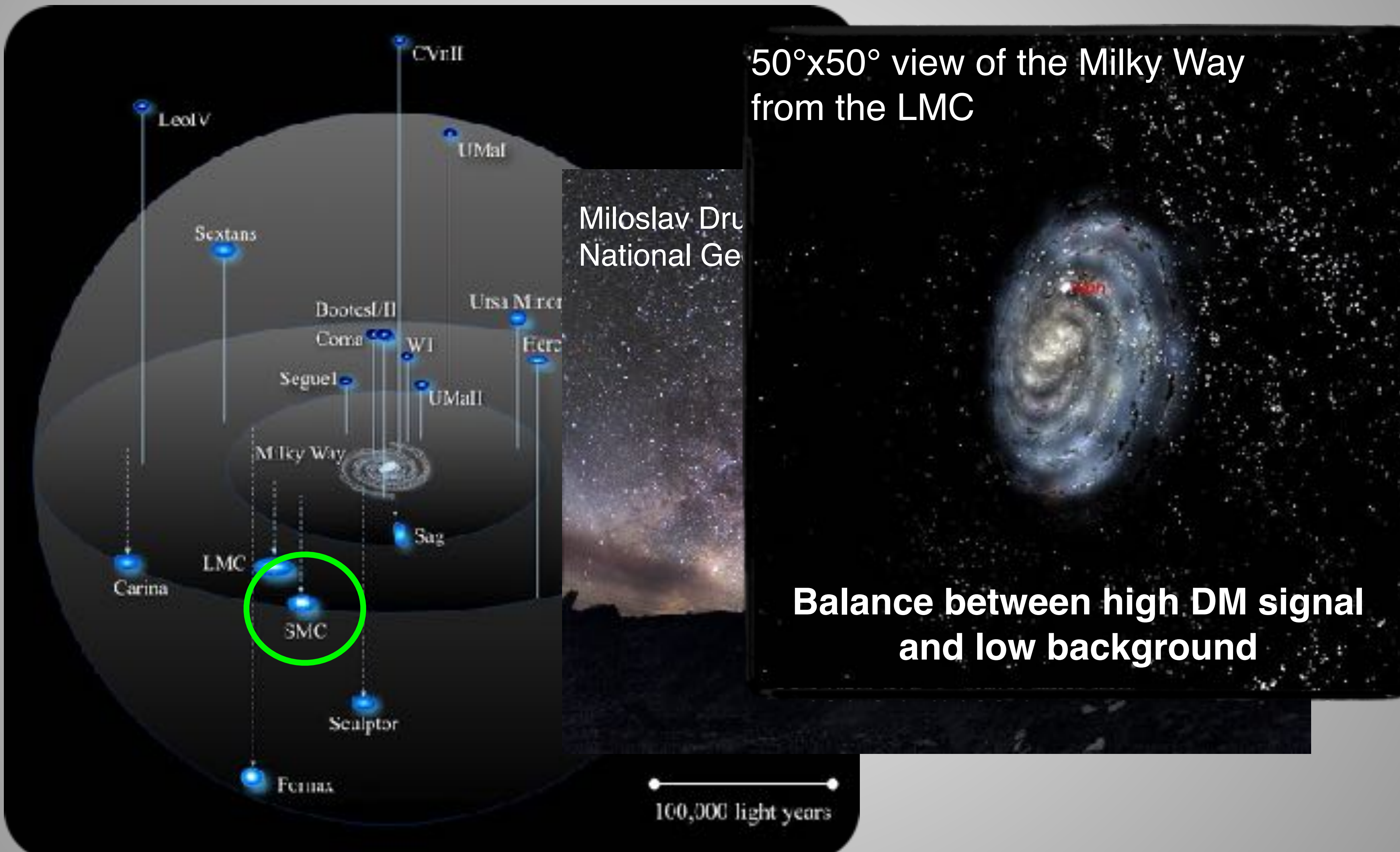

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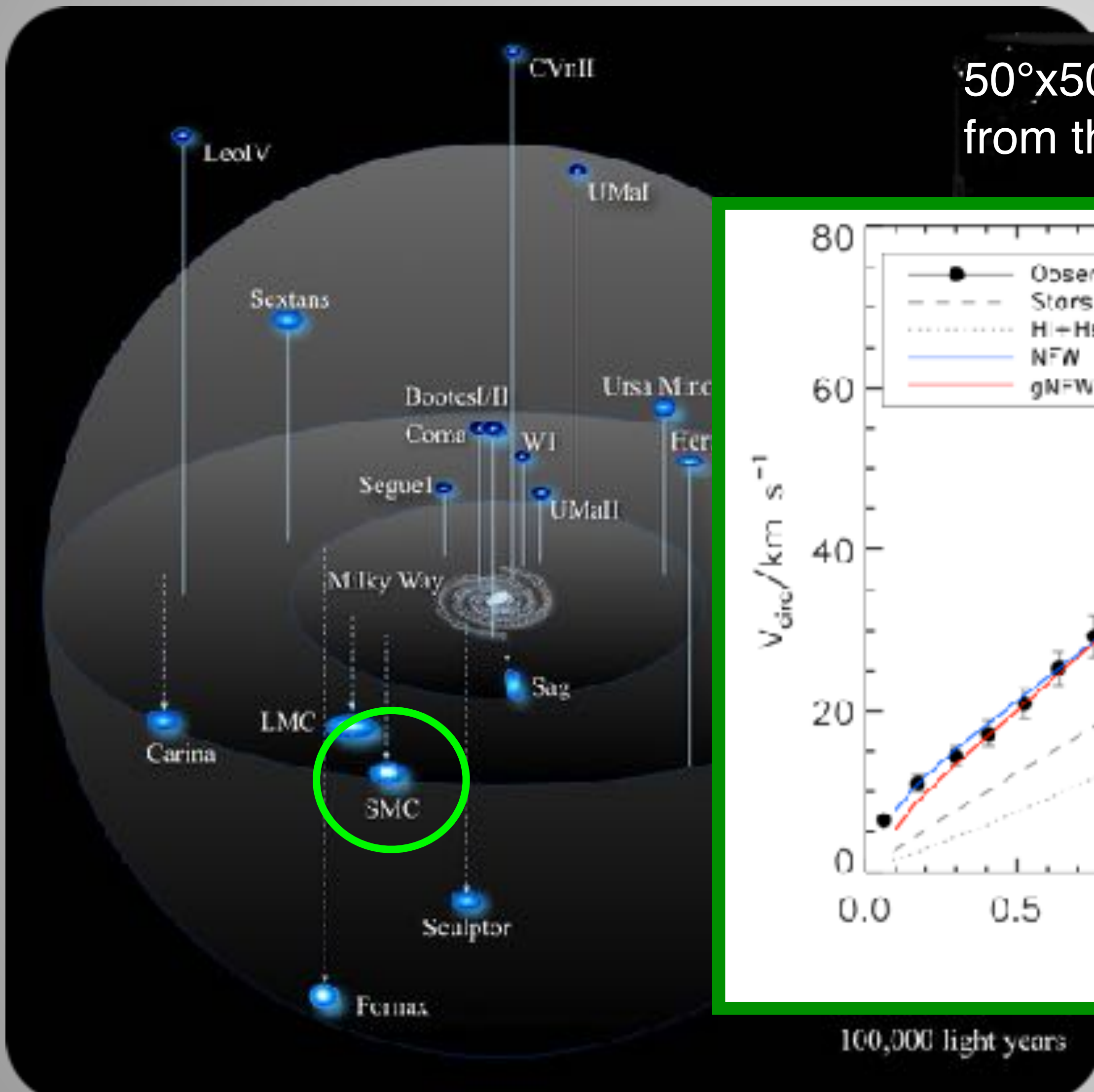
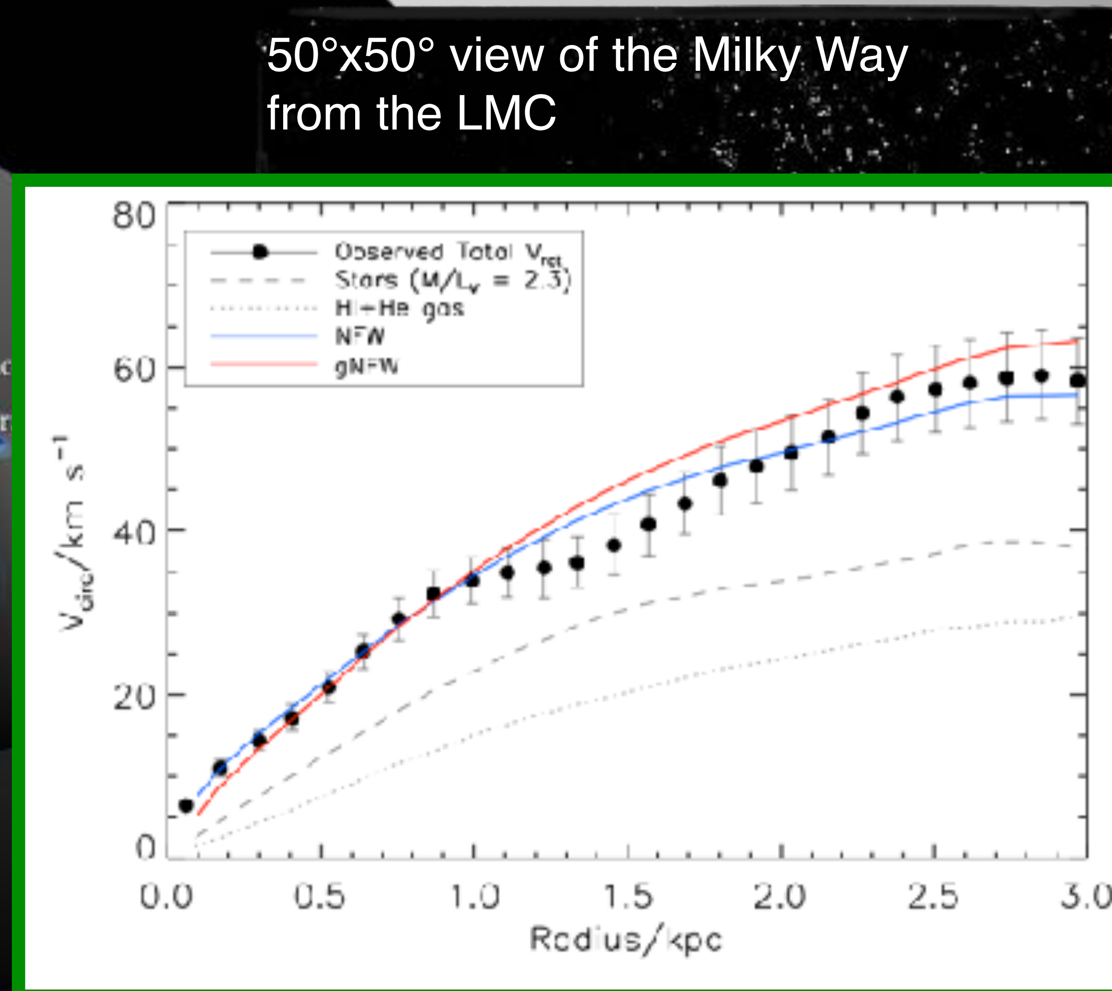
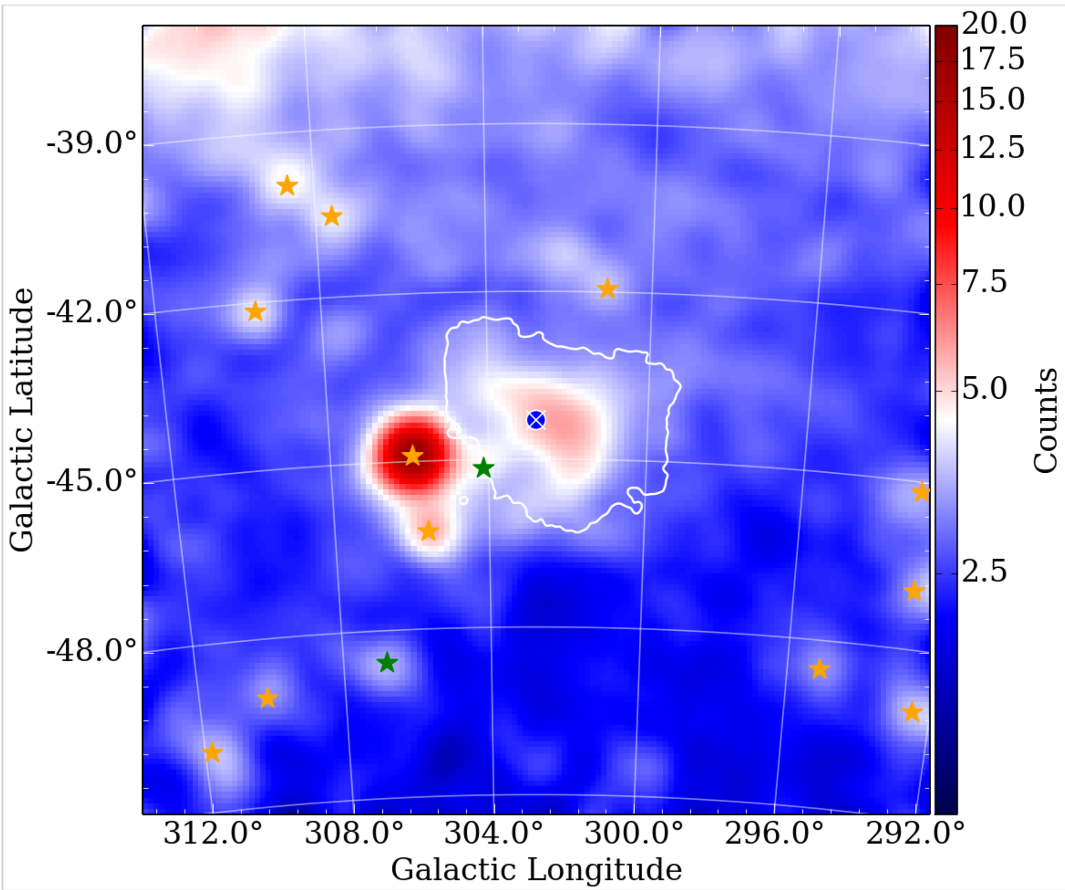




Bekki & Stanimirovic, MNRAS (2009) 395 (1)

Di Cintio et al., MINRAS (2013) 437 415

Small Magellanic Cloud

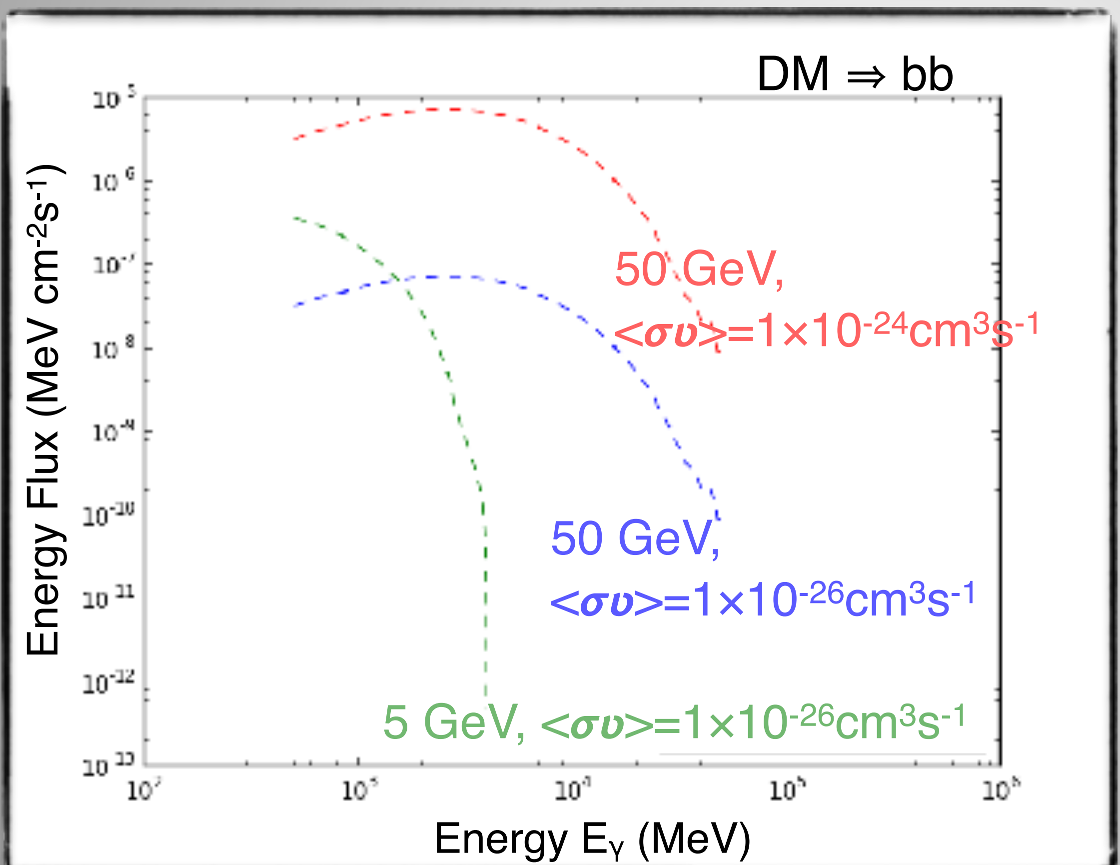


Selection	Criteria
Observation Period	2008 Aug. 4 to 2014 Aug. 5
Energy Range	0.5 to 500 GeV
Fit Region	$10^{\circ}\times10^{\circ}$ @ (ℓ,b)=(302°·80, -44°.30)

R. Caputo et al., PRD 2016

Small Magellanic Cloud

Looking for Dark Matter



R. Caputo et al., PRD 2016

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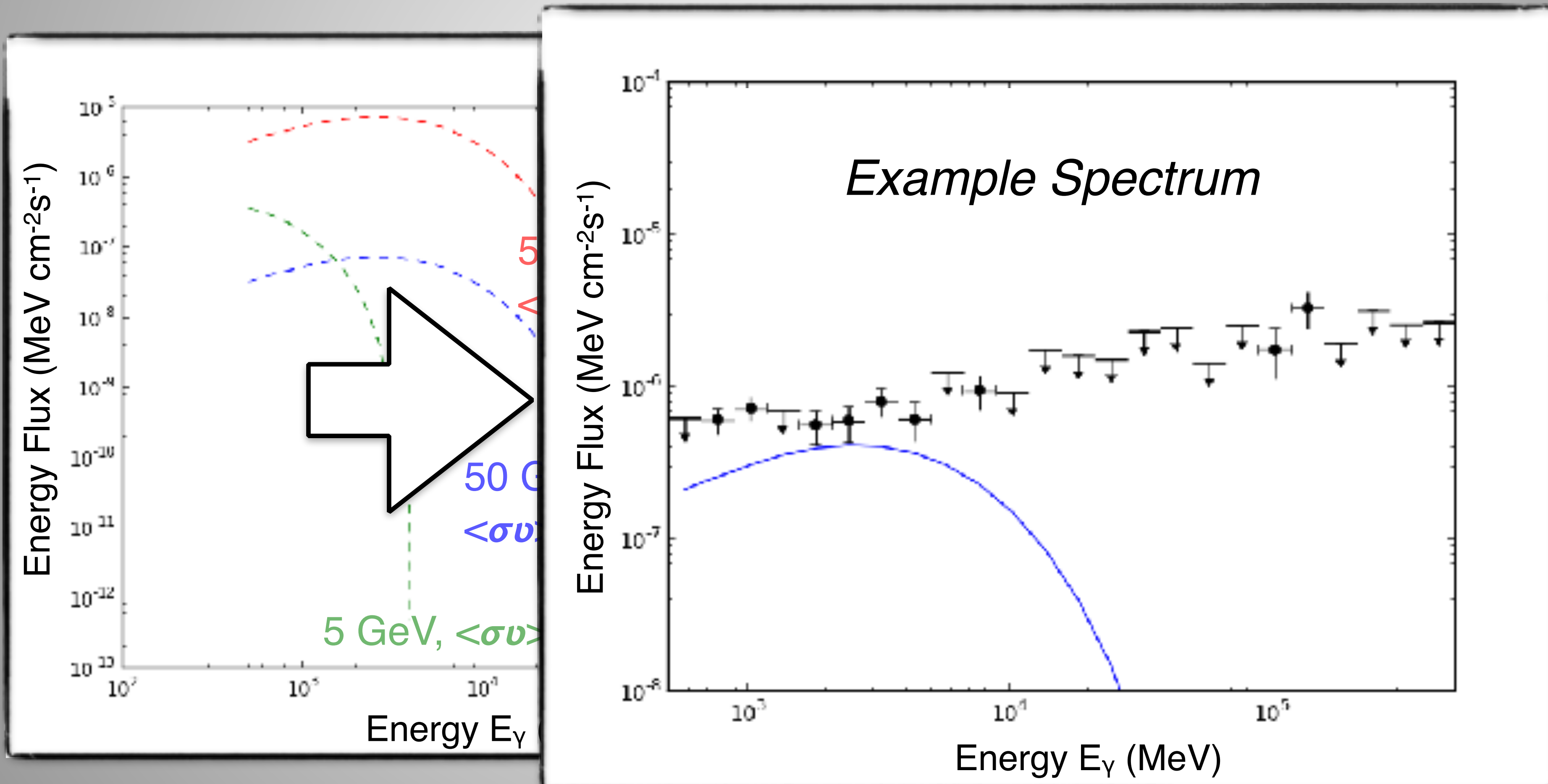
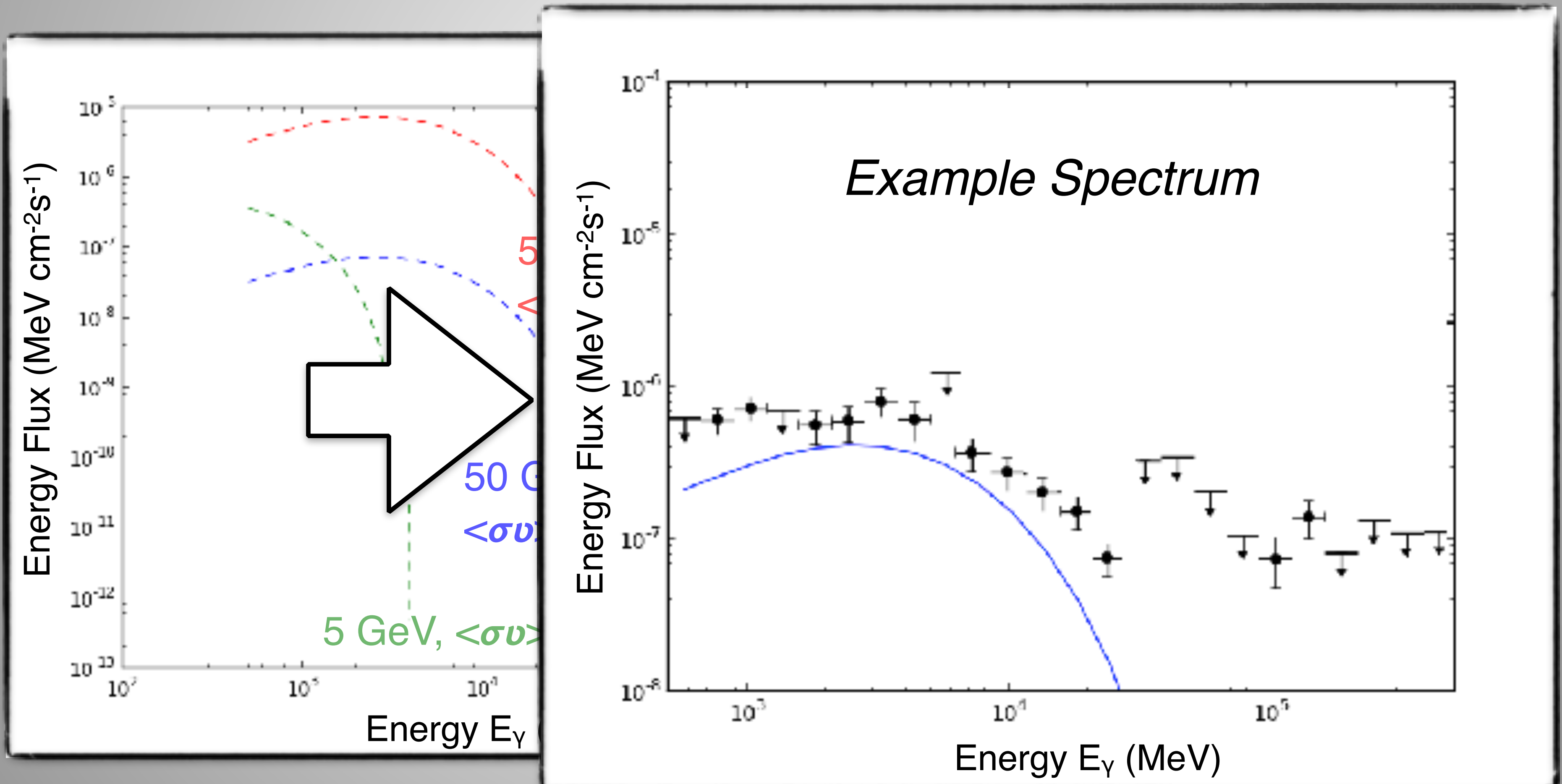


R. Caputo et al., PRD 2016

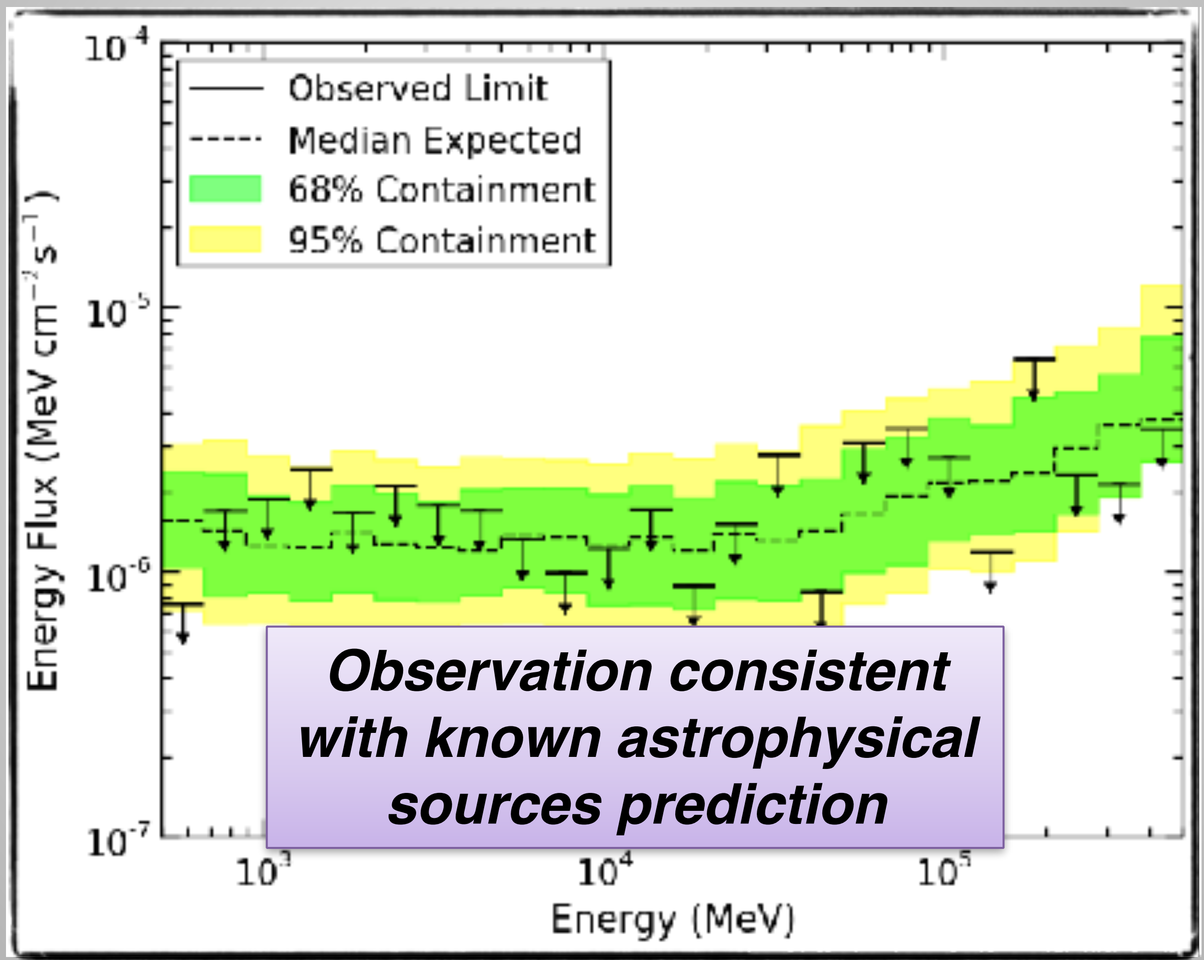
Small Magellanic Cloud

Looking for Dark Matter



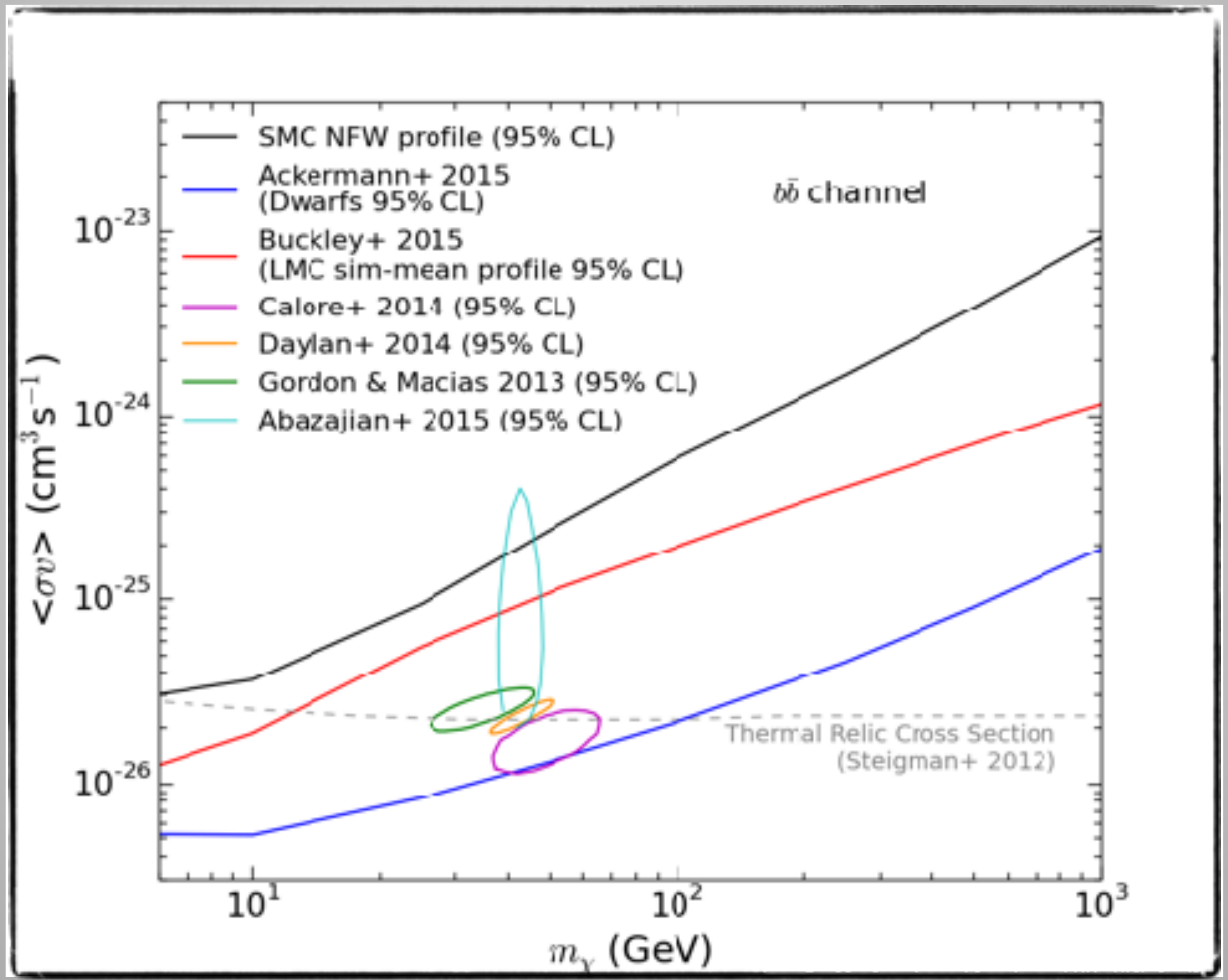
R. Caputo et al., PRD 2016

Small Magellanic Cloud



R. Caputo et al., PRD 2016

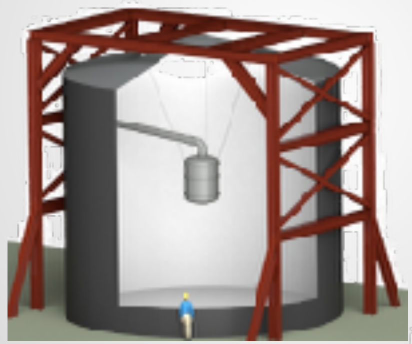
Small Magellanic Cloud



R. Caputo et al., PRD 2016

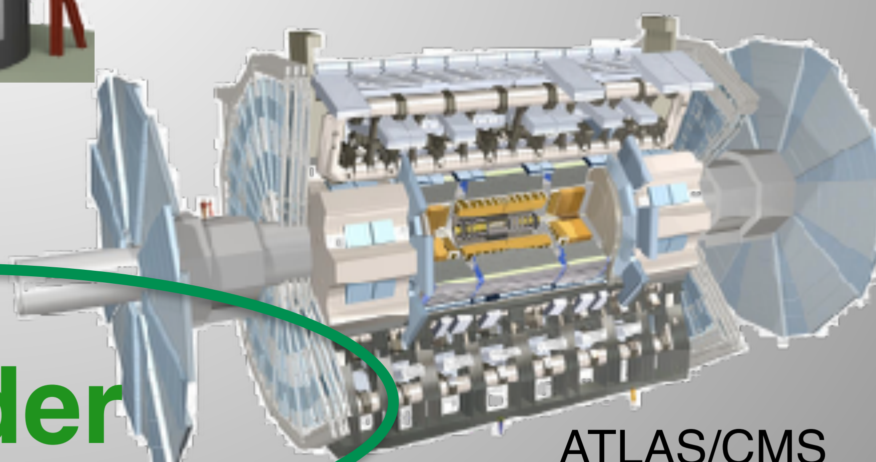
Dark Matter Searches

Indirect Detection



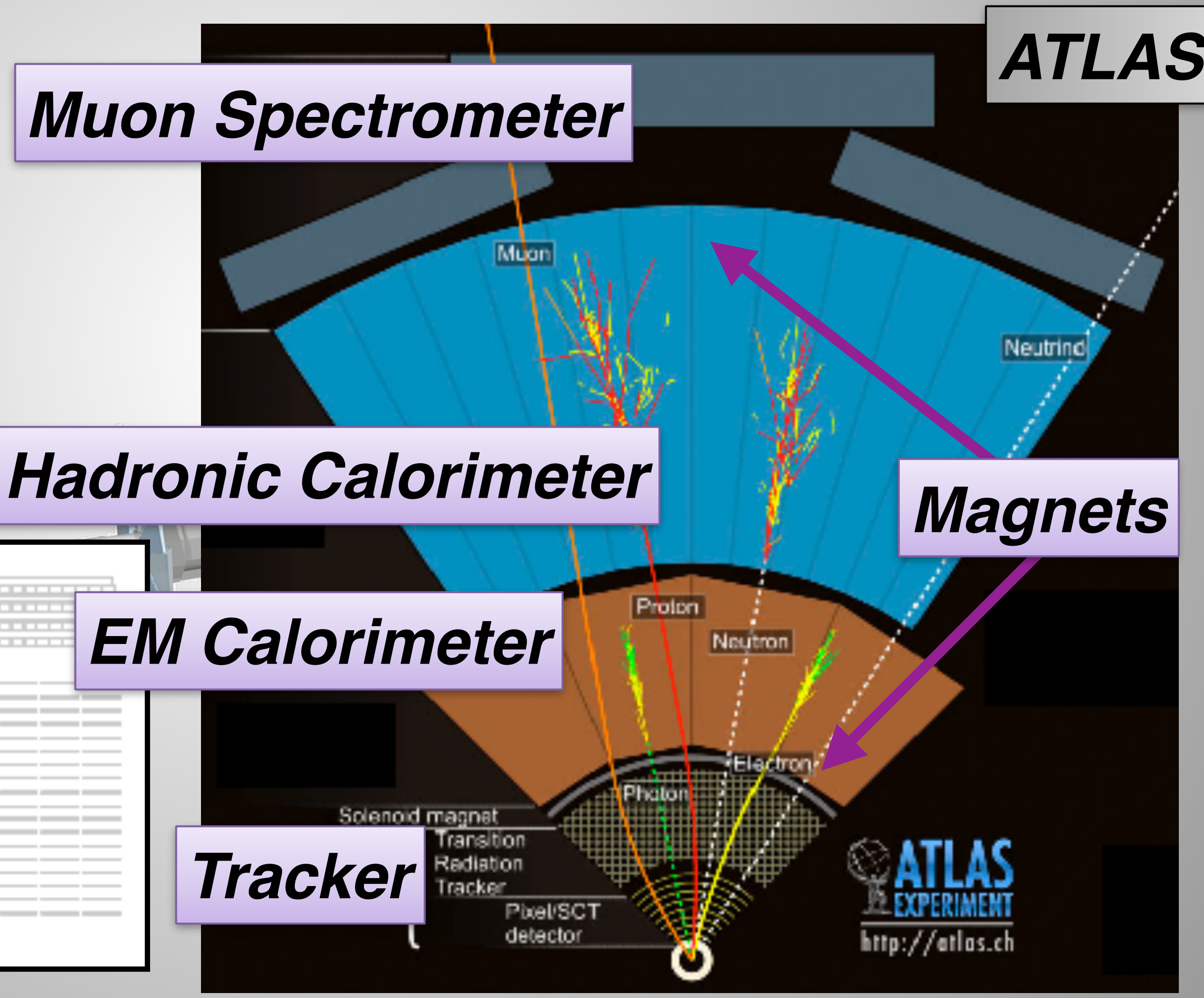
Direct Detection

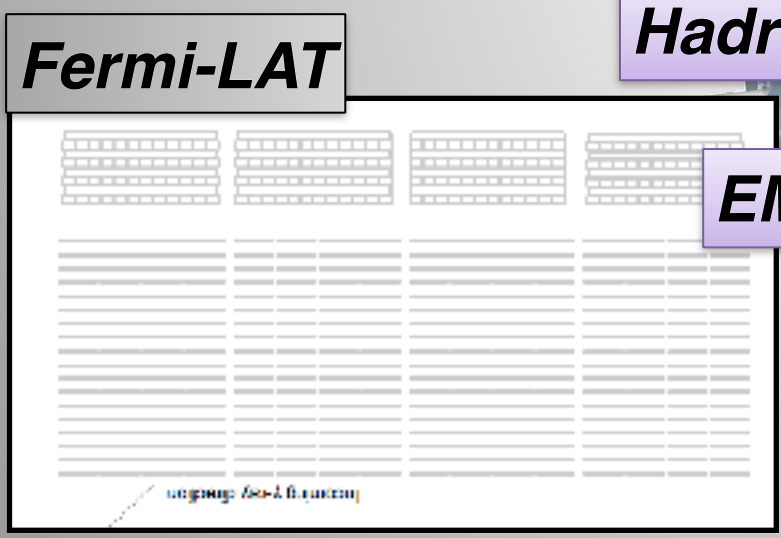
Collider



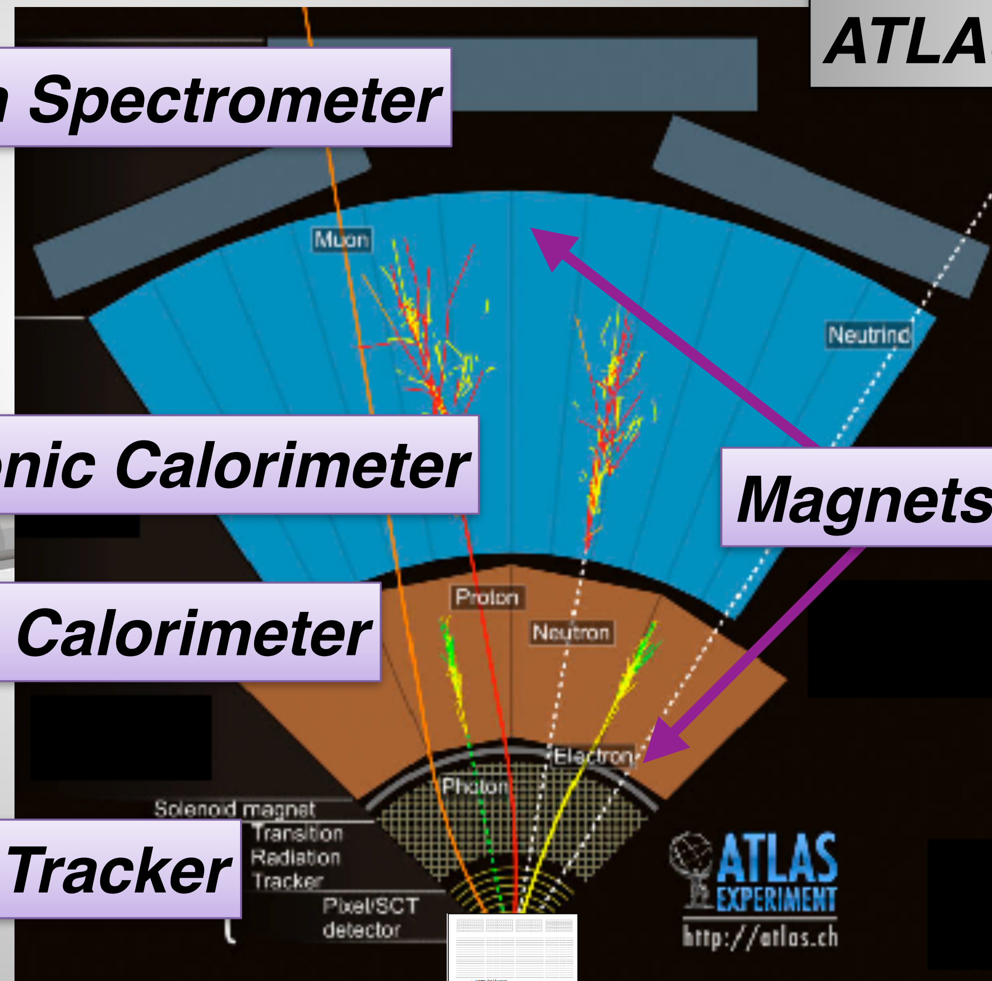
ATLAS/CMS

LHC Experiments: ATLAS/CMS



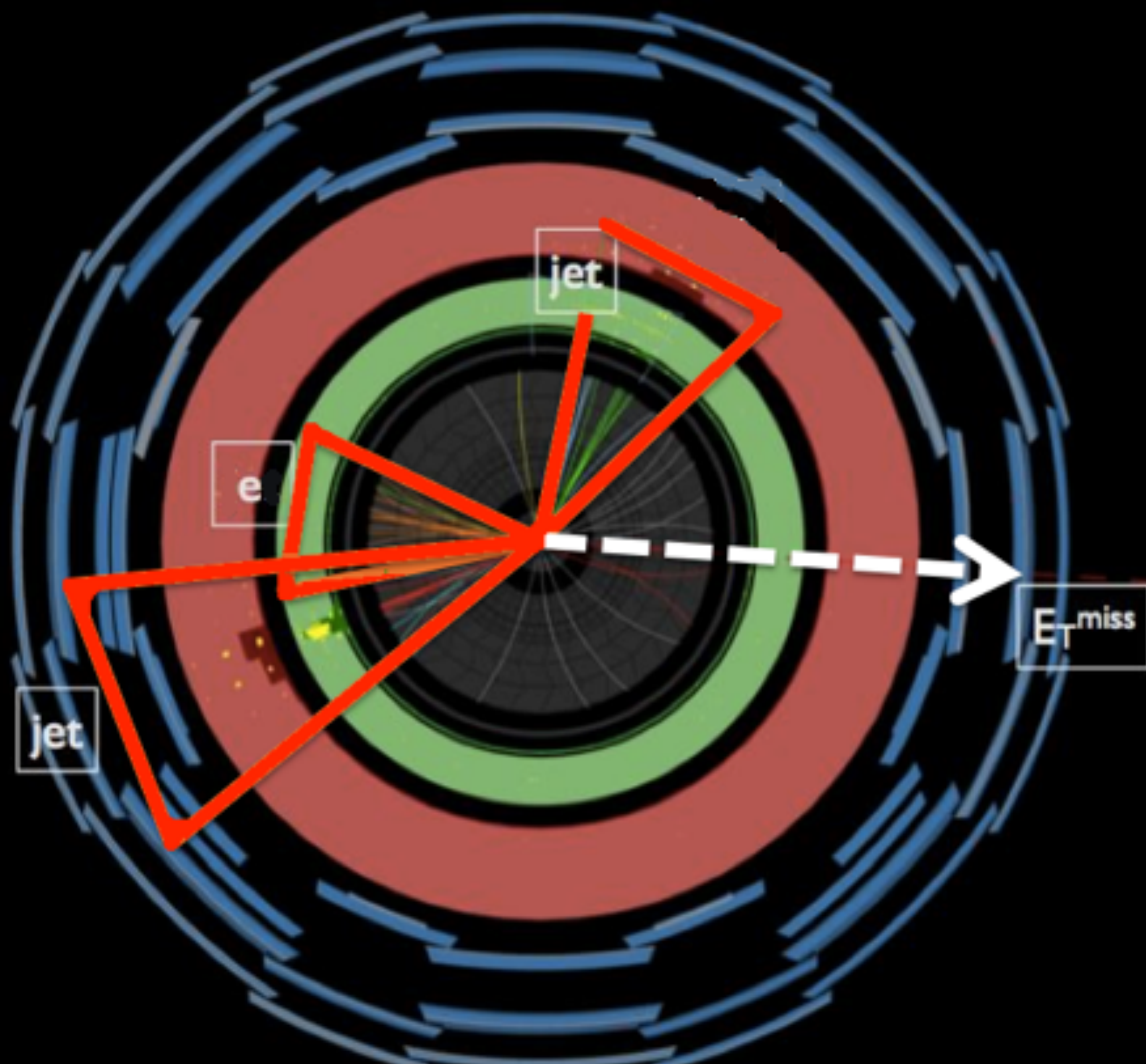


LHC Experiments: ATLAS/CMS

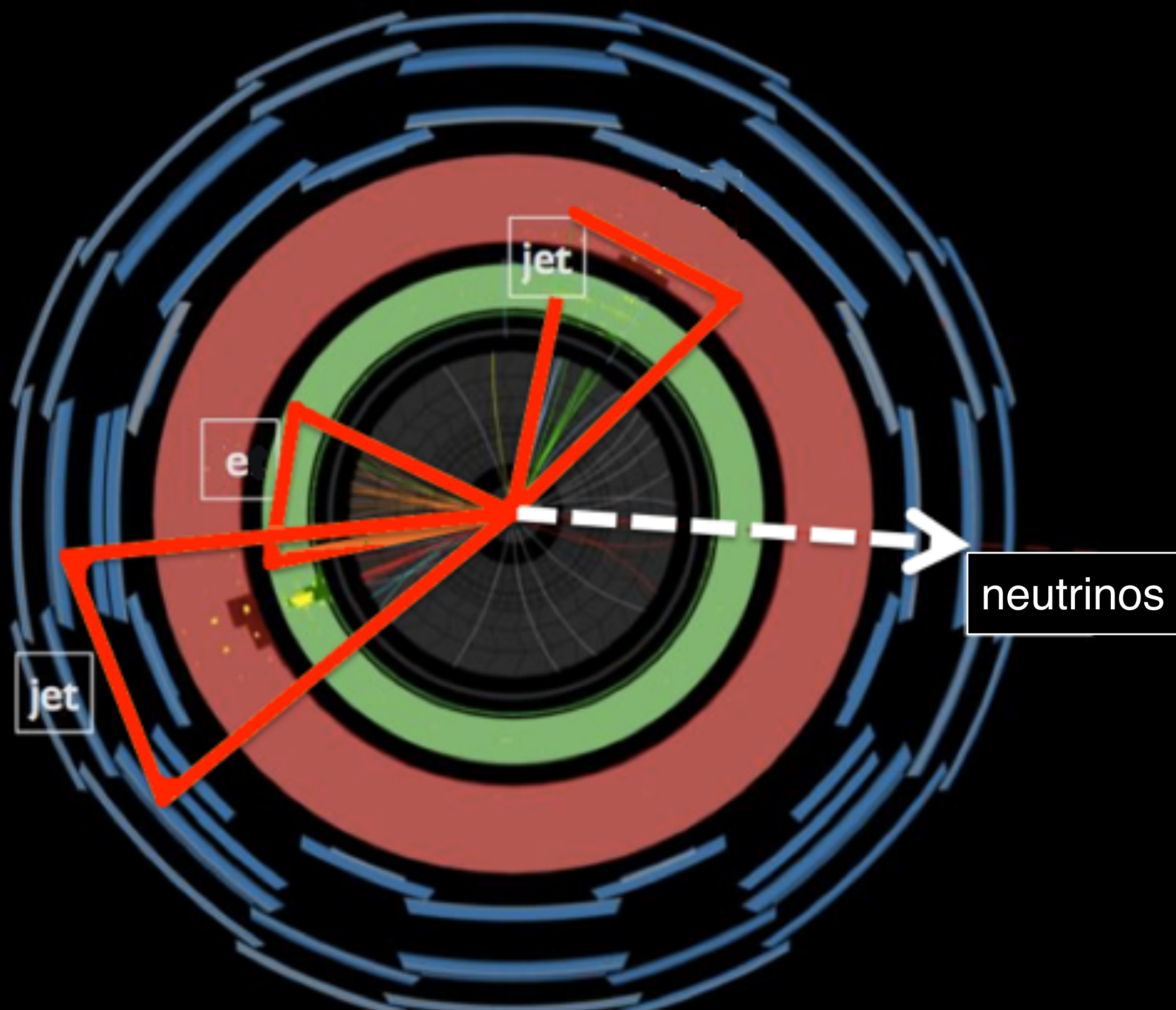


Fermi-LAT

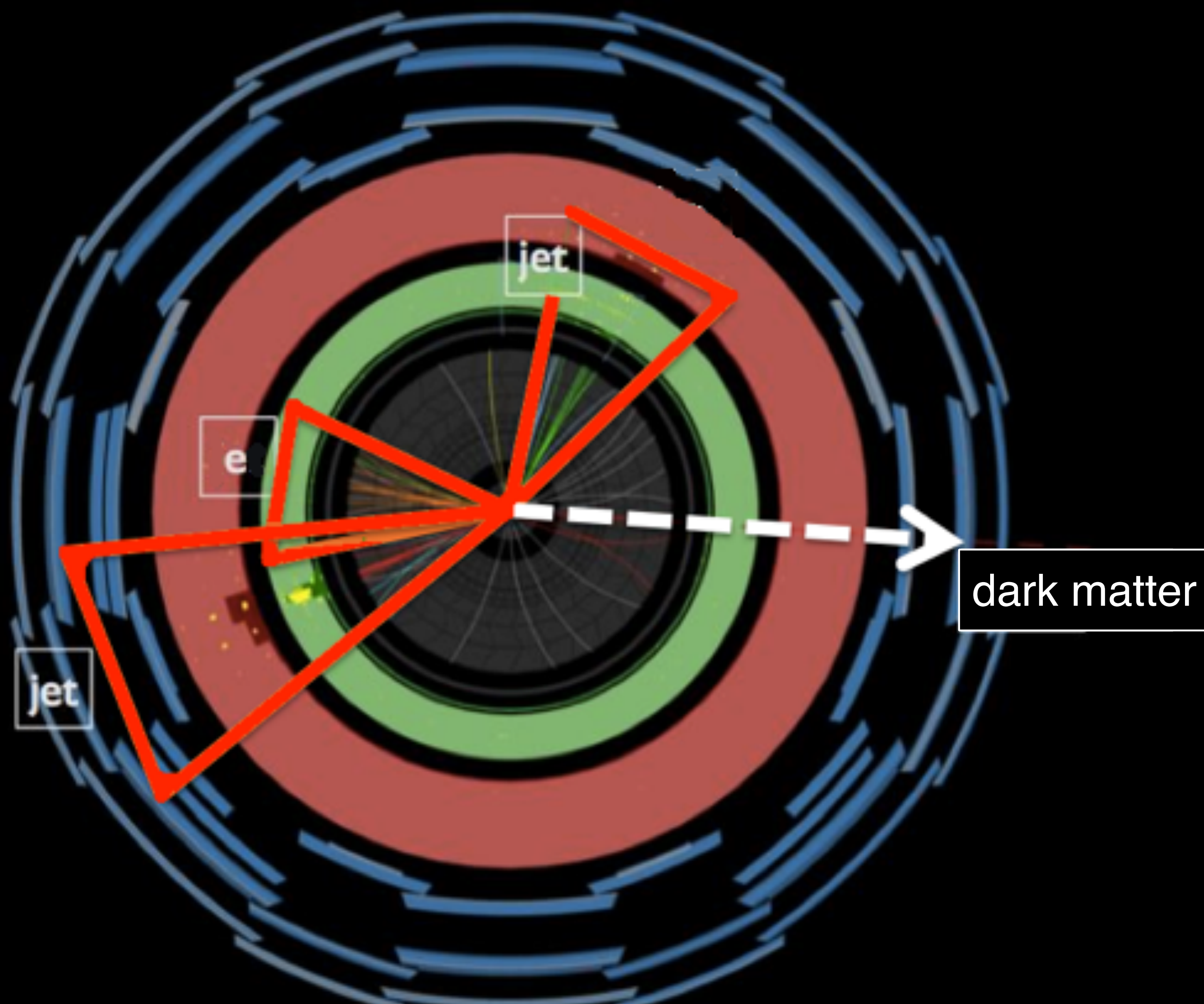
Missing Energy: *the Challenge*



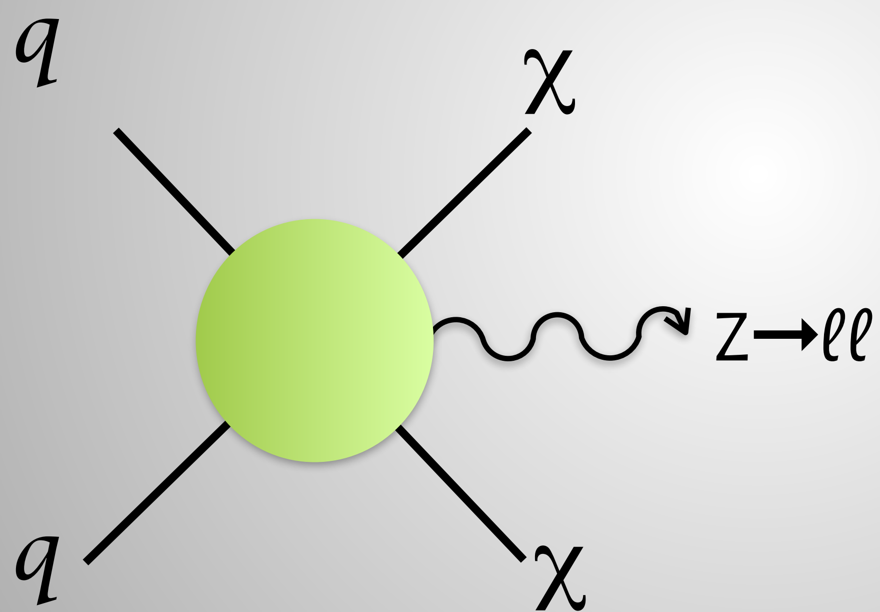
Missing Energy: *the Challenge*



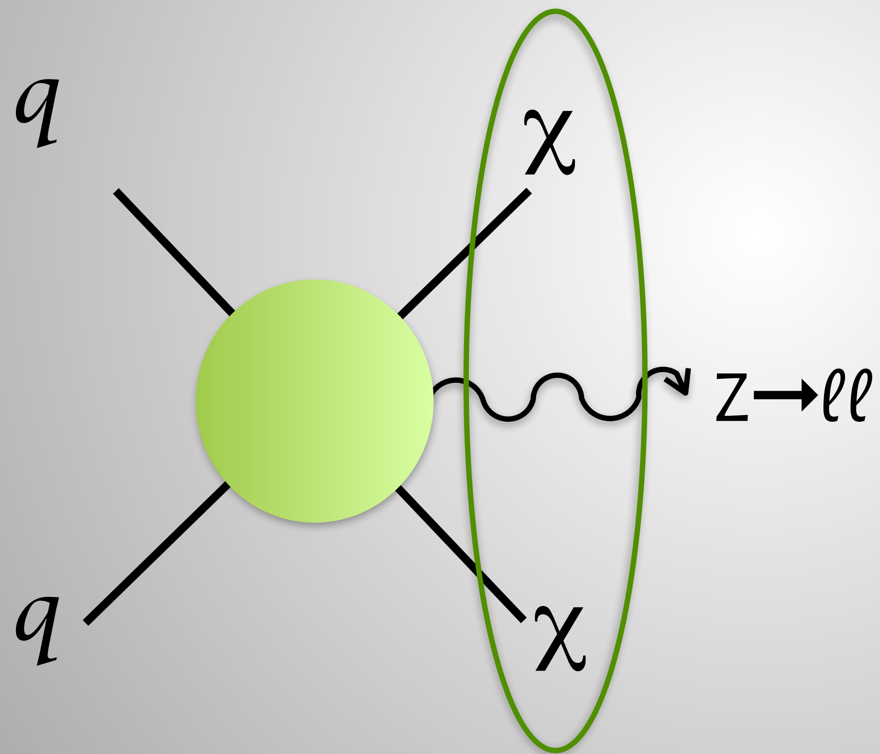
Missing Energy: *the Challenge*



Mono-Z Searches



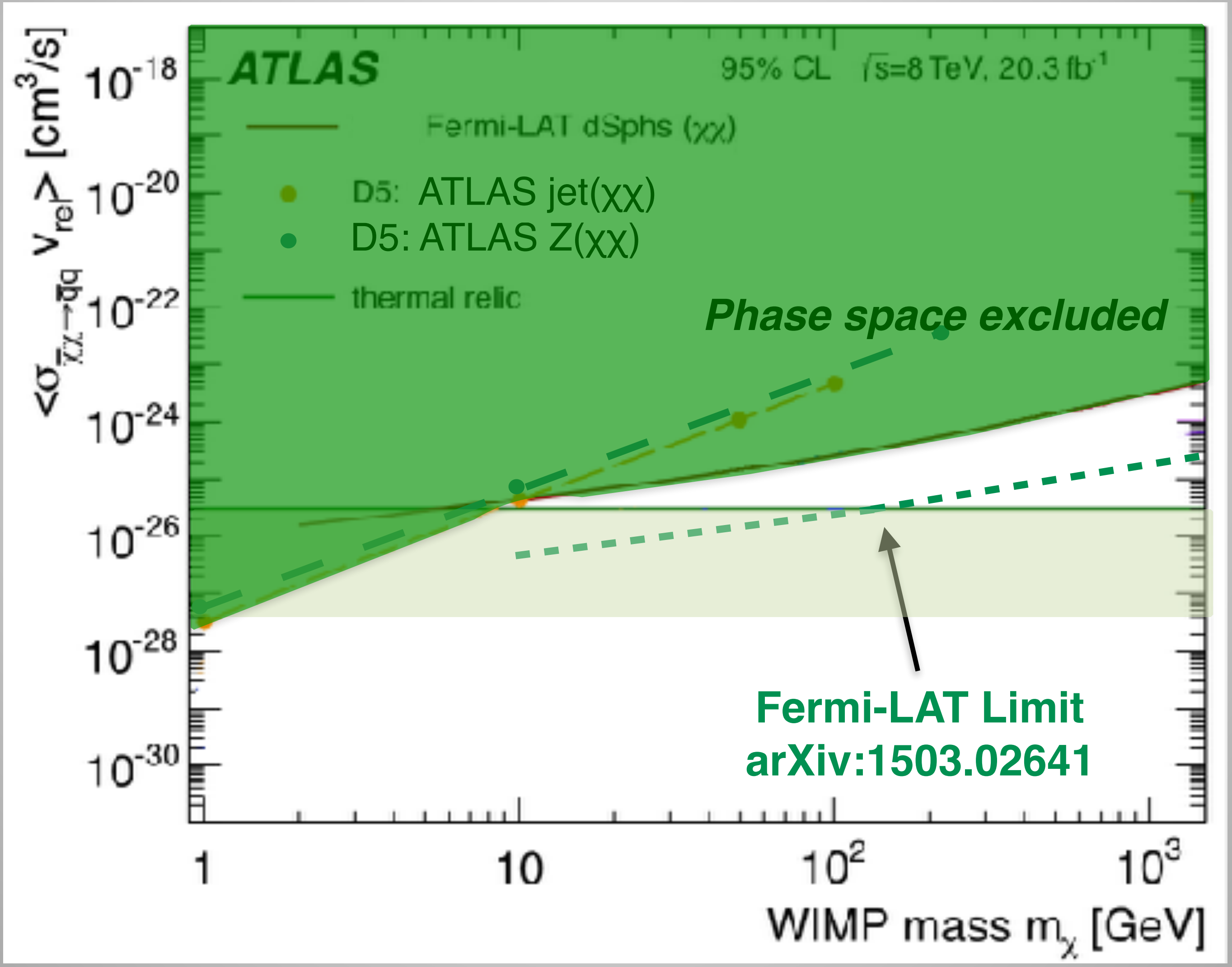
Mono-Z Searches



No explicit dependence on models (ie: Supersymmetry)

Signature:
Z produced with Missing Energy

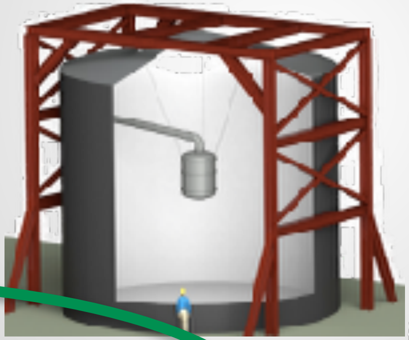
A Complementary Approach



ATLAS Collaboration, Eur. Phys. J. C, 2015

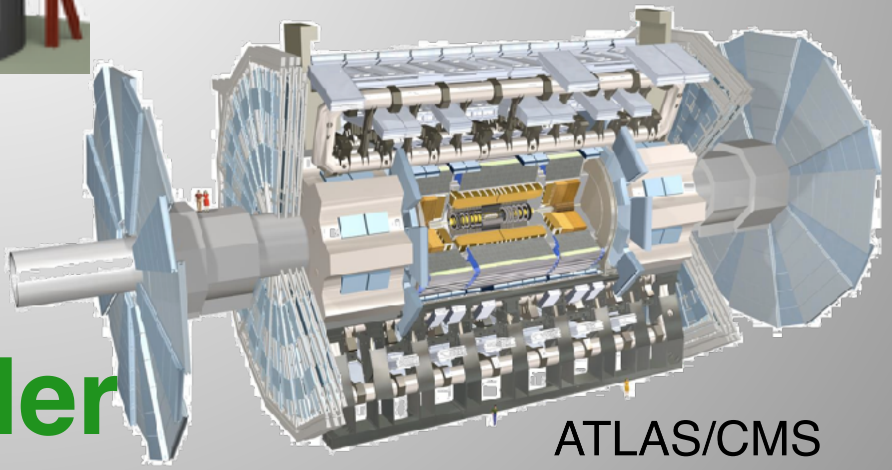
Dark Matter Searches

Indirect Detection



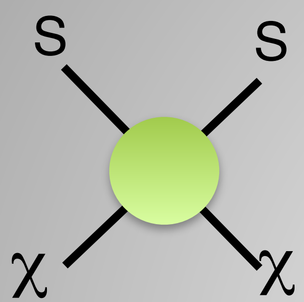
Direct Detection

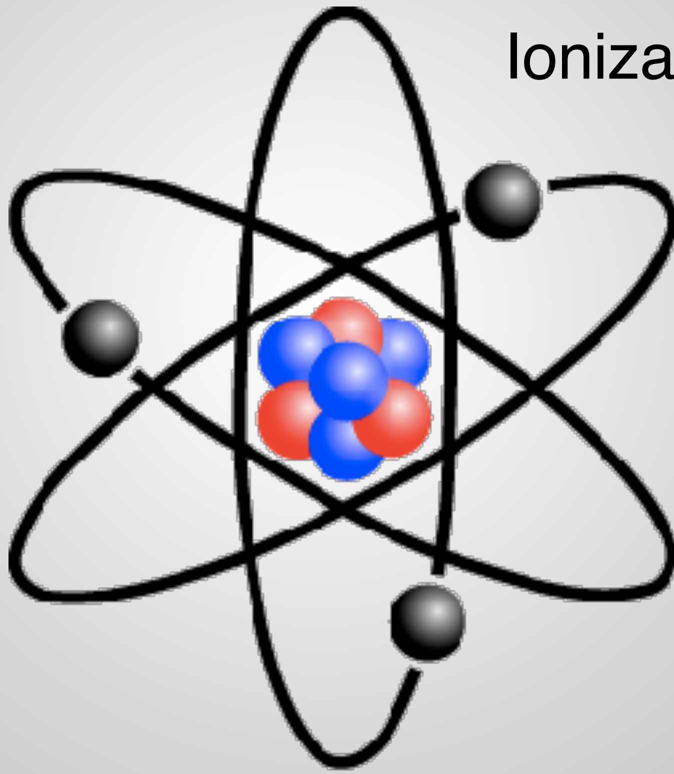
Collider



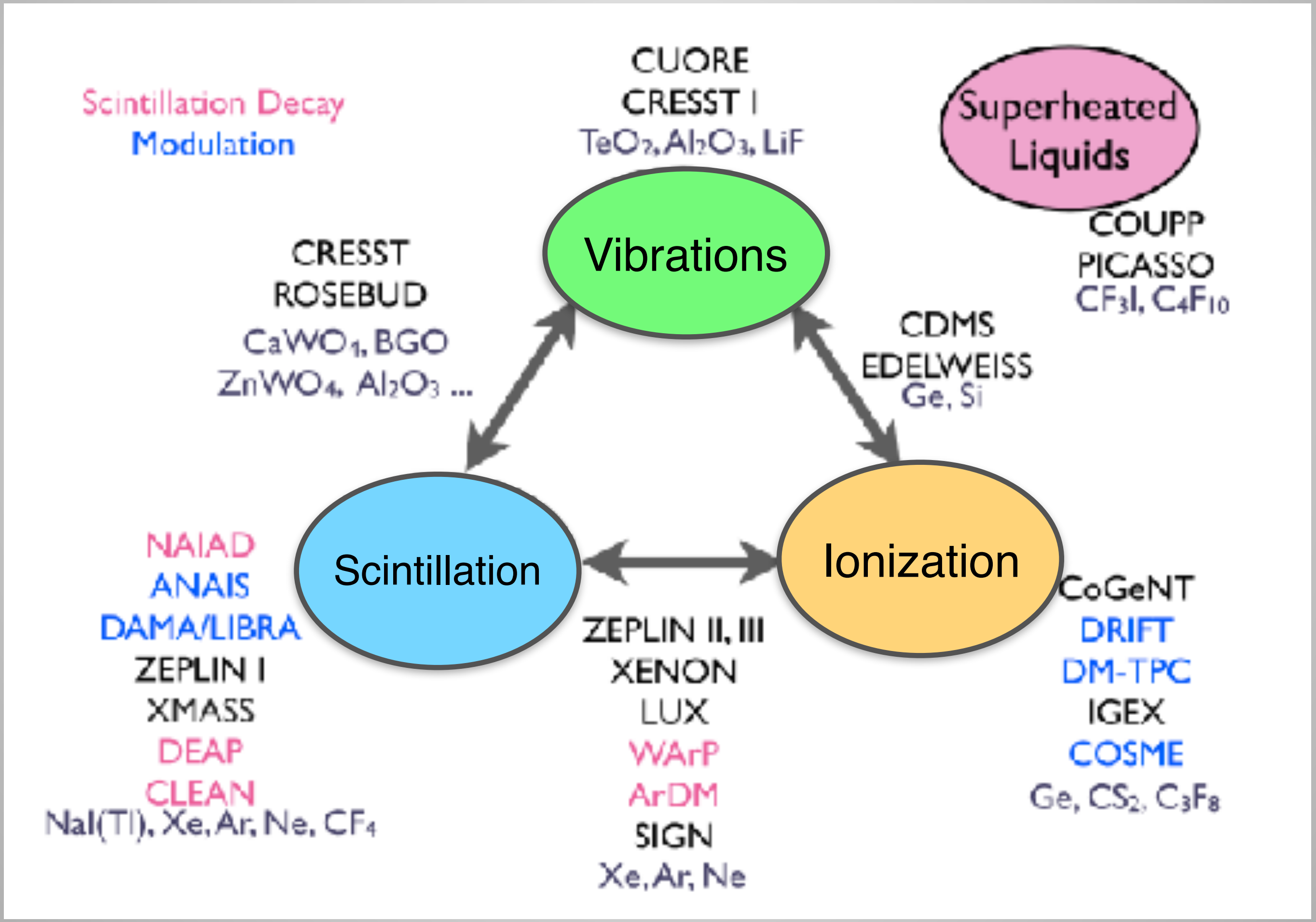
ATLAS/CMS

Direct Searches



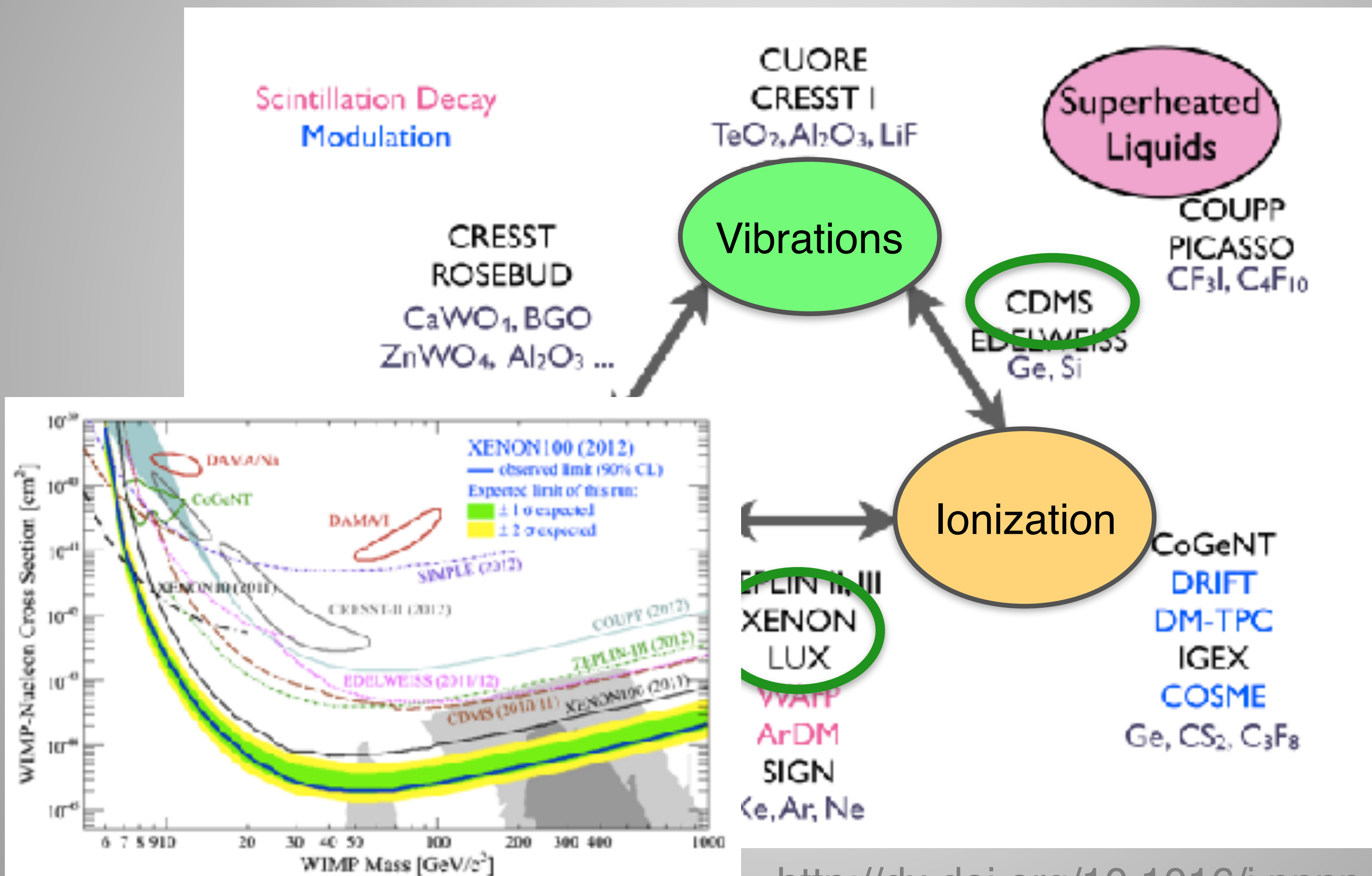


Direct Searches



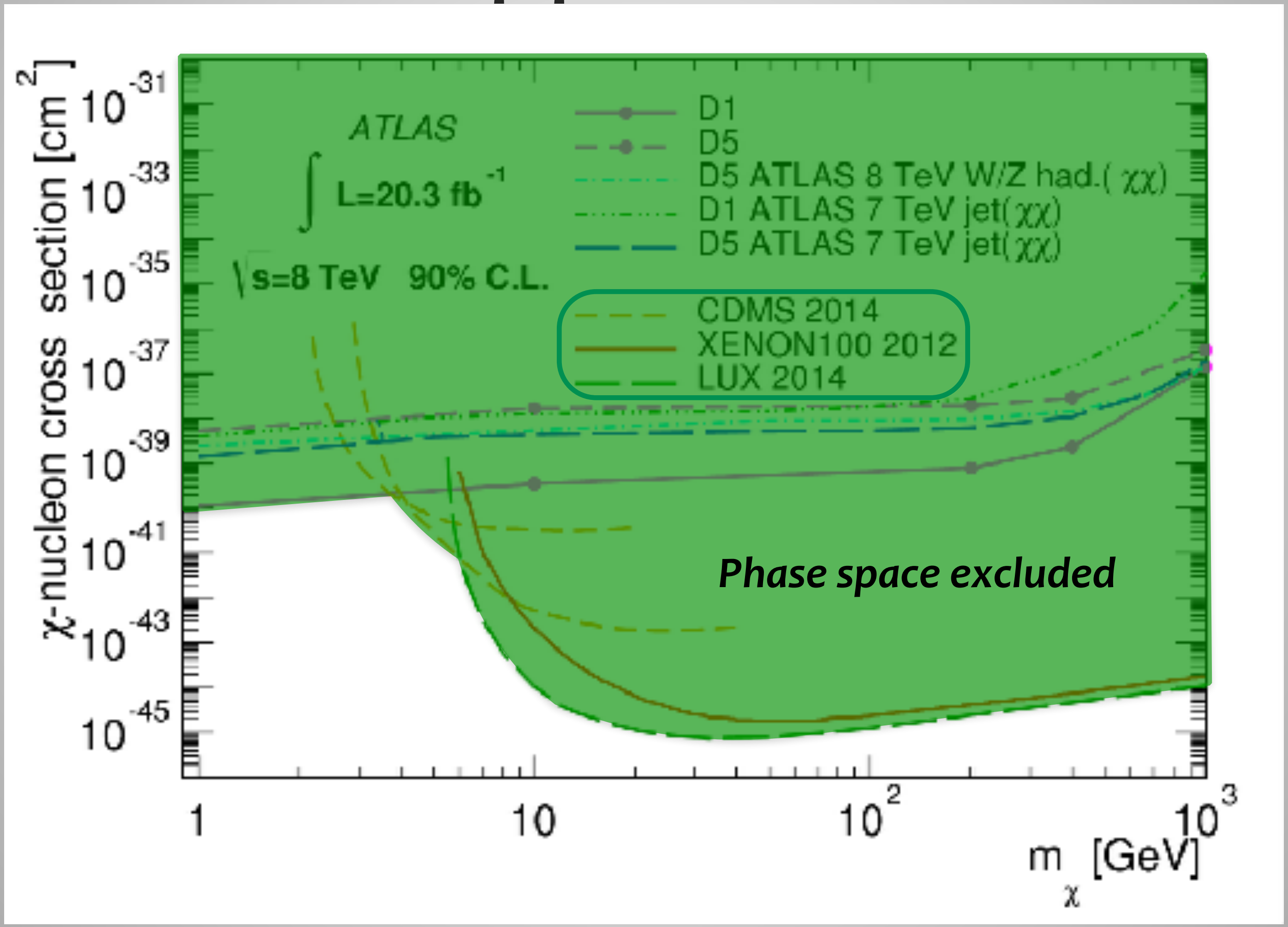
http://dx.doi.org/10.1016/j.ppnp.2011.01.003

Direct Searches



http://dx.doi.org/10.1016/j.ppnp.2011.01.003

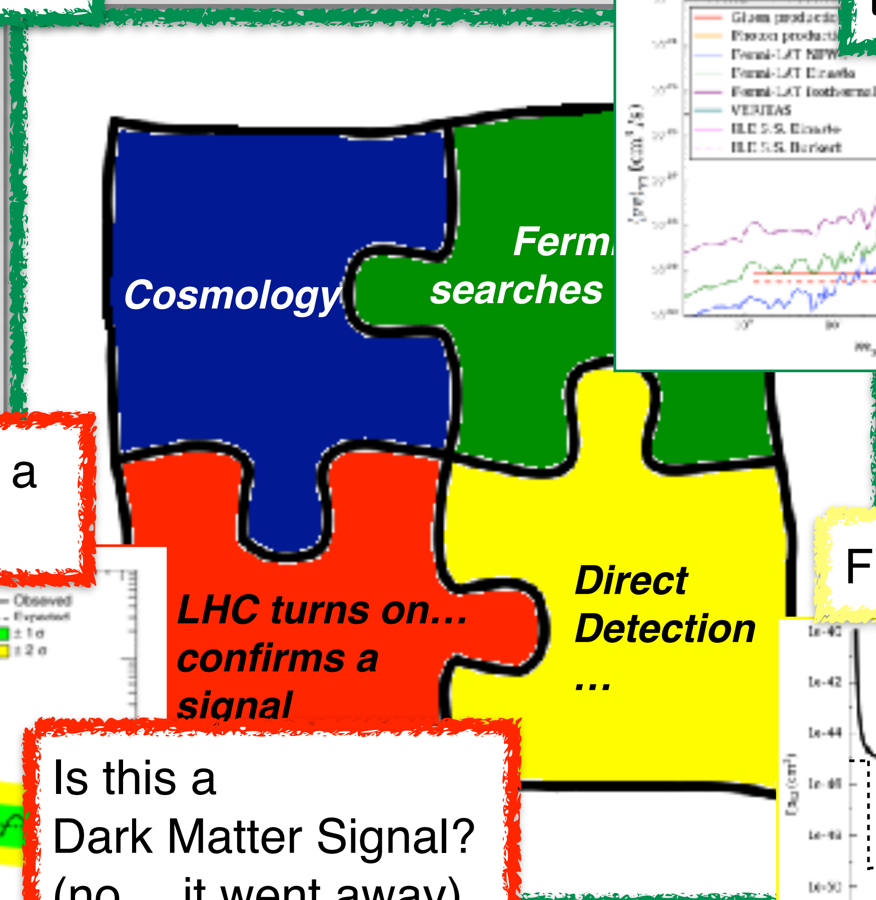
A Complementary Approach



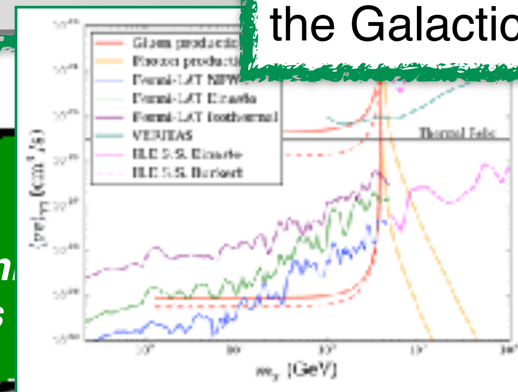
R. Caputo, ATLAS Collaboration, Phys. Rev. D. 90, 012004 (2014)

A Complementary Approach

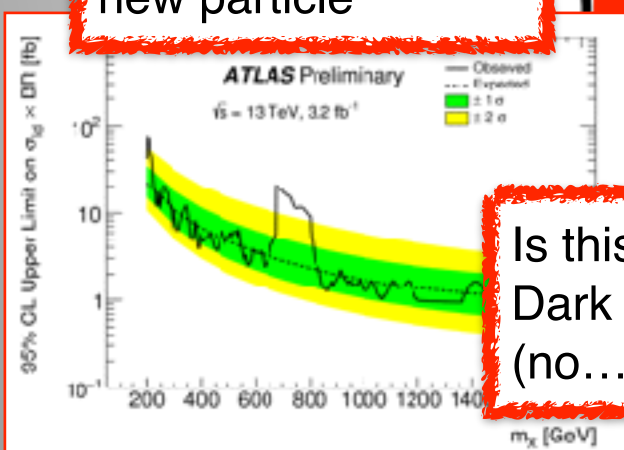
Roadmap To Discovery



A Testable signal from the Galactic Center

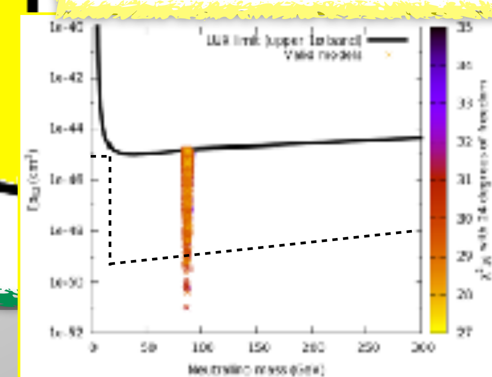


CMS/ATLAS find a new particle



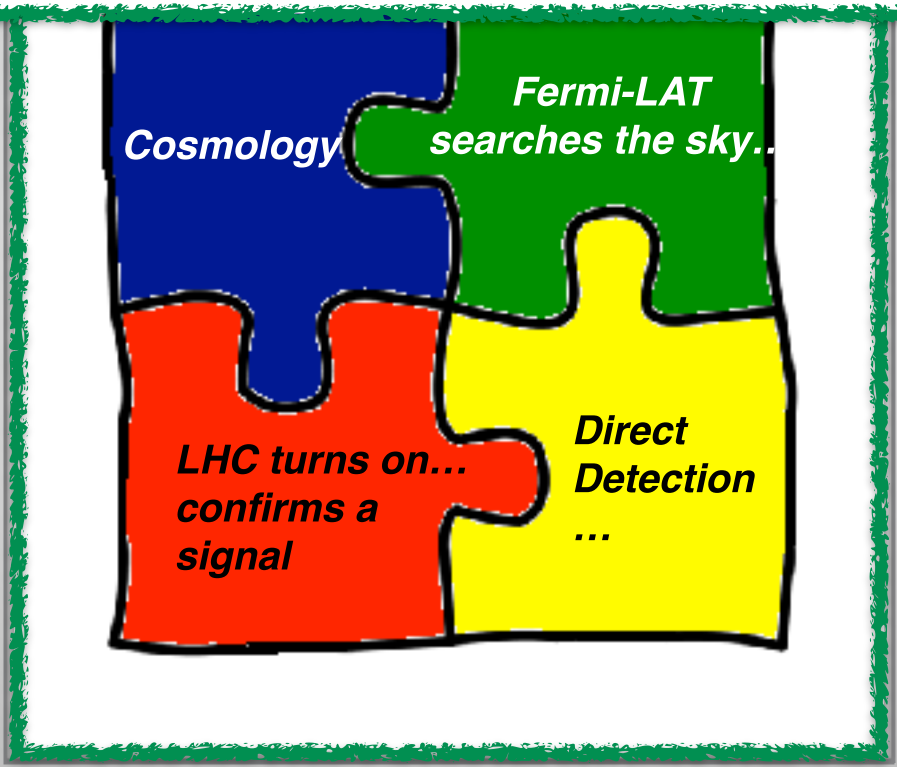
Is this a
Dark Matter Signal?
(no… it went away)

Final Confirmation…

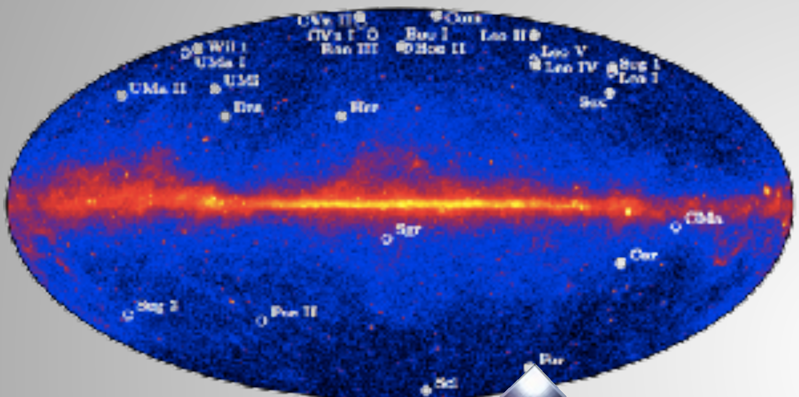


A Complementary Approach

Confirmation from different experiments is paramount to discovery



The Next Generation…



MeV mission

**33% of
Fermi Sources
are unassociated**

J. Beacom: New MeV Missions are Essential and Urgent

Fermi	DES		LSST	CTA	MeV Mission
Today		2018	2020	2023	2025

The Next Generation…

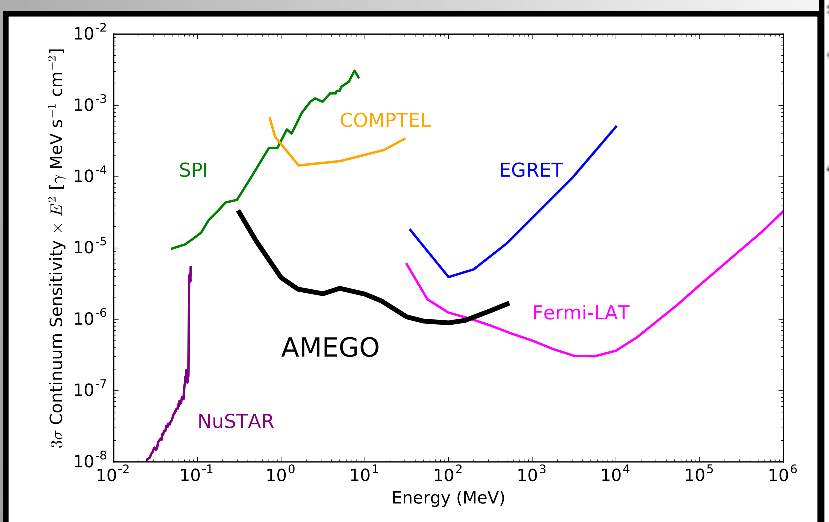
Proposed new gamma-ray missions…

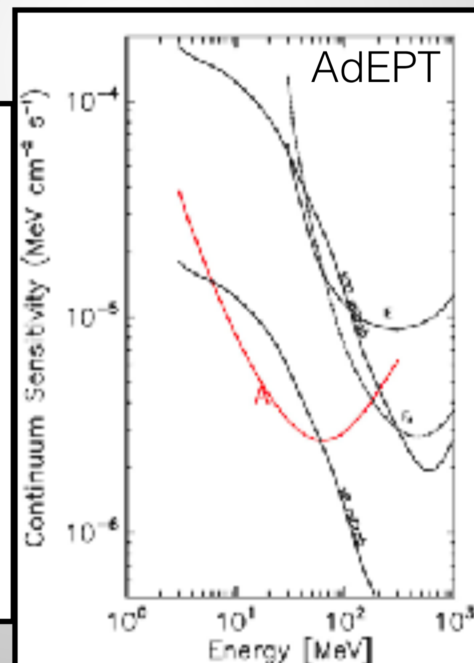
All-sky Medium Energy Gamma-ray Observatory: ***AMEGO***

enhanced ASTROGAM: ***eASTROGAM***

Advanced Energetic Pair Telescope: ***AdEPT***

- incomplete list -



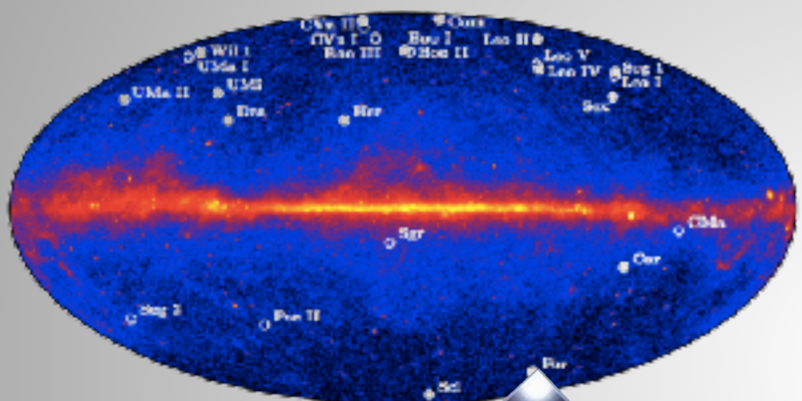


Intense Star formation at GC necessitates understanding of the MeV rage

arXiv:1206.0772

Astropart.Phys. 59 (2014) 18-28

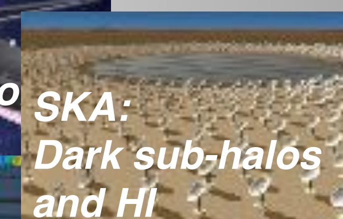
The Next Generation…



Astrophysics of Dark Matter (Special Dark)

Not to mention…

MeV mission



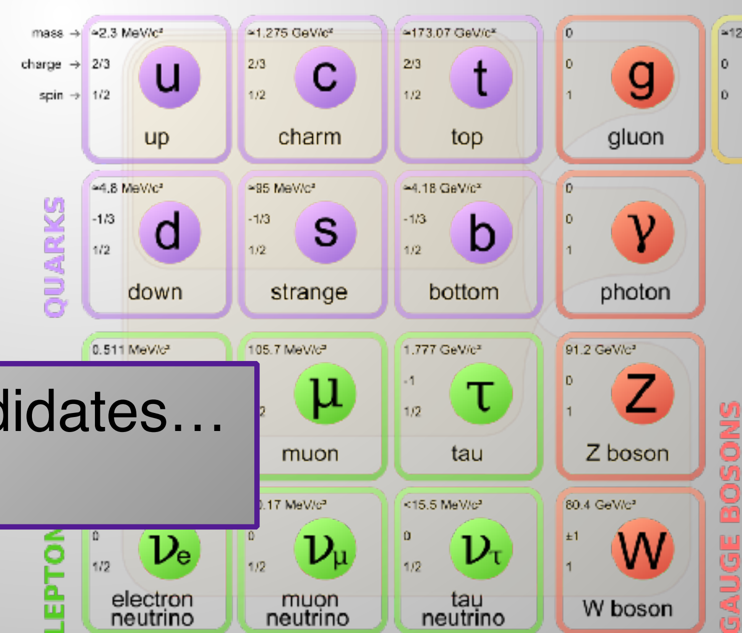
33% of Fermi Sources are unassociated

Fermi DES LSST CTA AMEGO

Today 2018 2020 2023 2025

The Future

*At least for WIMPs



Other very well motivated candidates…
Not just one particle or force

Fin

- What is Dark Matter?
- A Complementary Approach