Theory Colloquium, TIFR

9 October 2012

The Hunt for Dark Matter

Basudeb Dasgupta

The Ohio State University

Three Key Questions

Why do we need Dark Matter?

Gravitational effects at all scales

What sets its abundance?

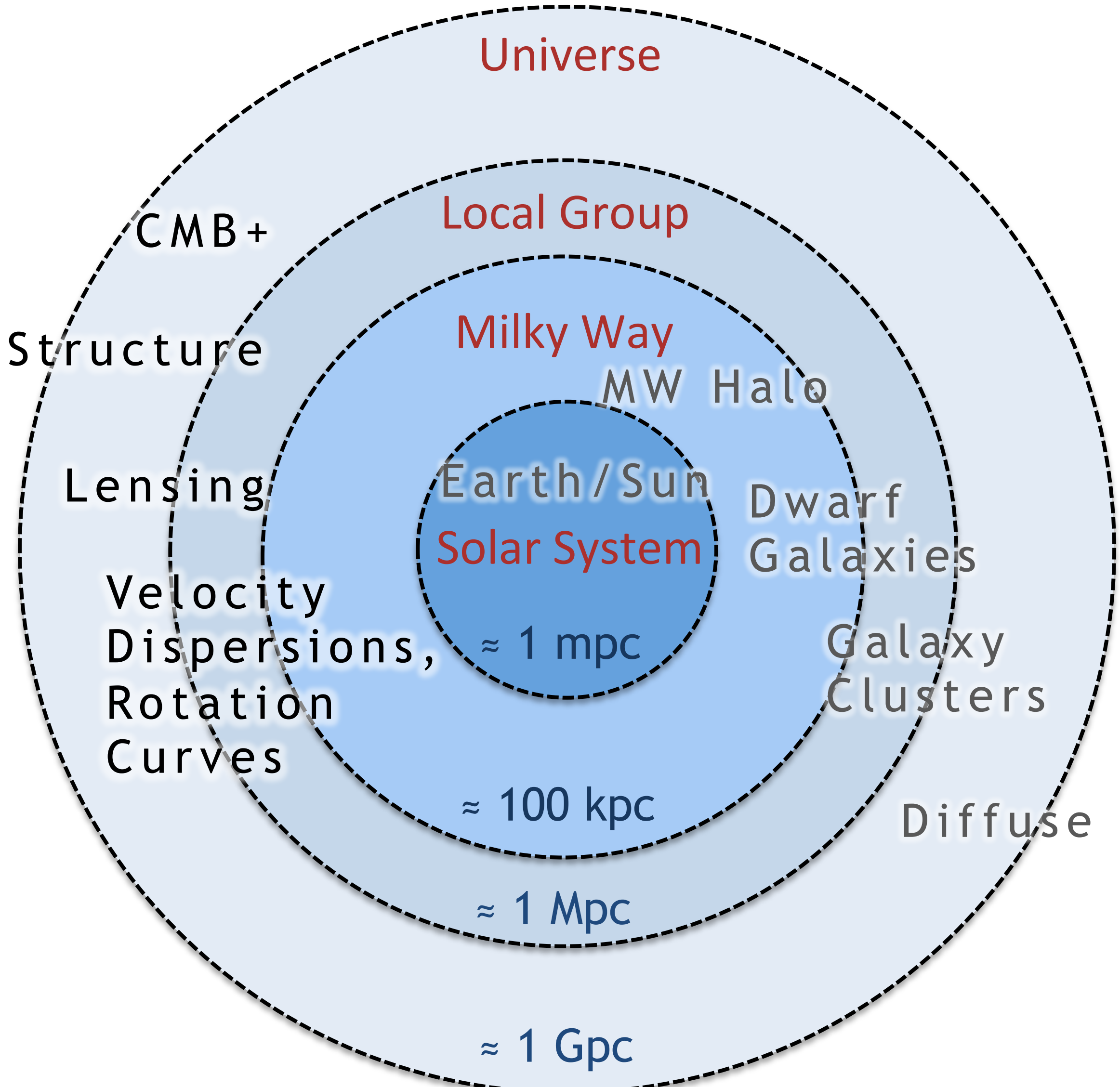
Thermal Relic/Asymmetry/...

How are we probing it?

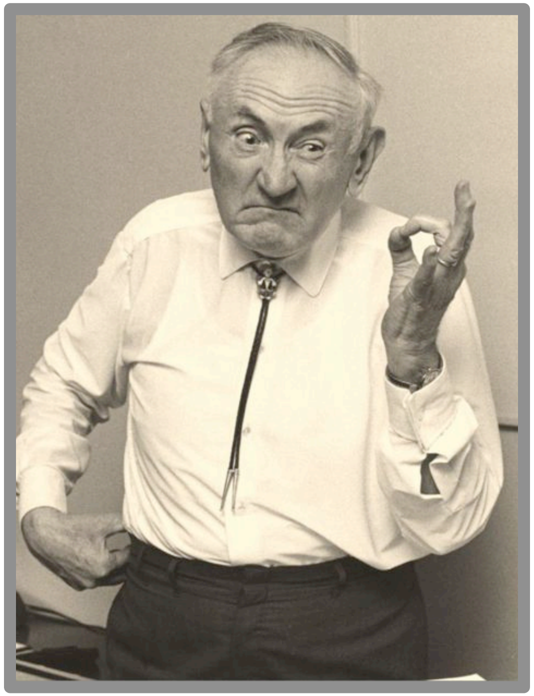
Direct, Indirect, ...

Evidence for DM

Dark Matter at All Scales



Velocity Dispersion



Fritz Zwicky, 1930s

$$\langle K.E. \rangle = -\frac{1}{2} P.E.$$

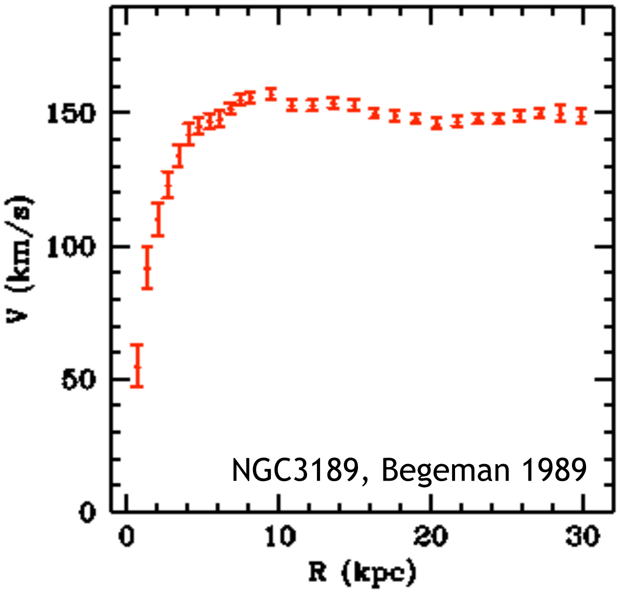
$$\frac{1}{2} m \langle v^2 \rangle = \frac{-GMm}{2R}$$

$$M = \frac{R \langle v^2 \rangle}{2G}$$

400 x mass seen in Coma cluster!

Rotation Curves

Vera Rubin, 1960s-70s



$$\frac{mv(r)^2}{r} = \frac{GM(r)m}{r^2}$$

$$M(r) \propto rv(r)^2$$

Invisible Mass well “beyond” the galaxy

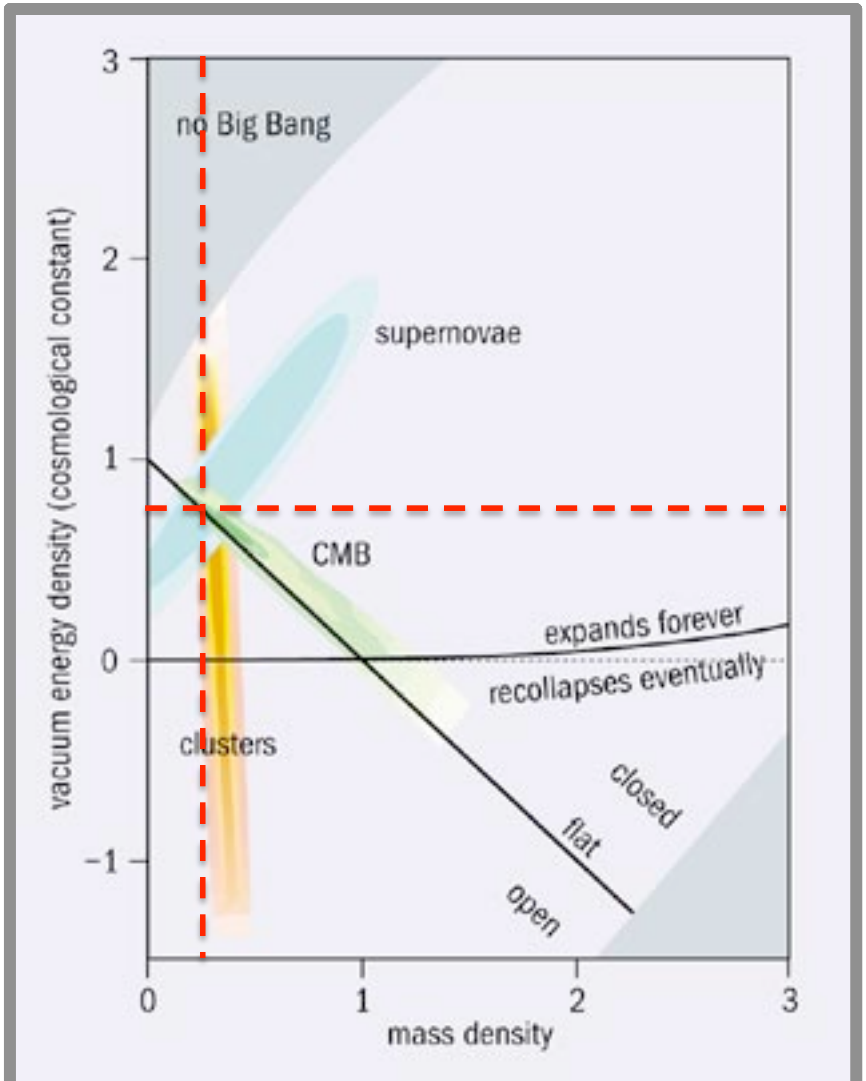
Gravitational Lensing

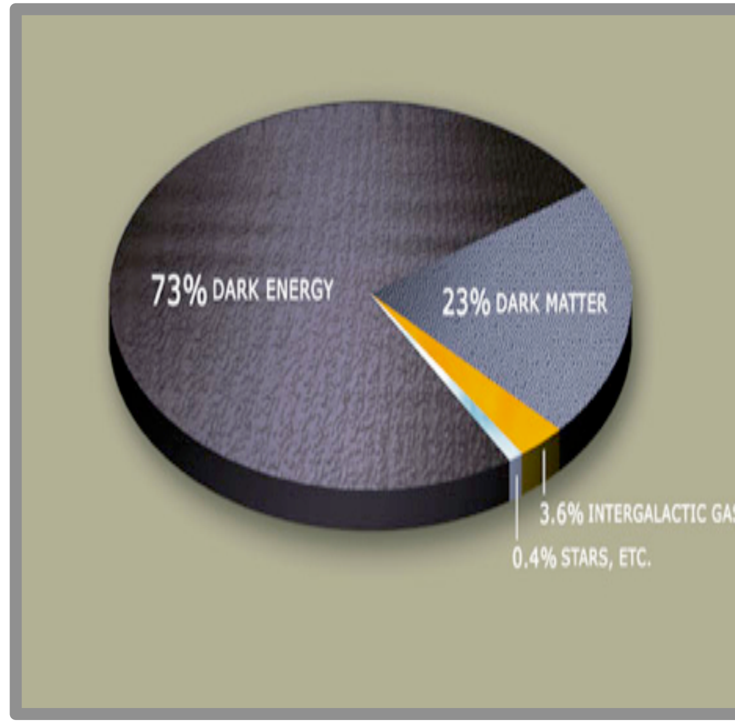
1E 0657-56 (Bullet Cluster), APOD

Clowe et al (2006)

Dark Matter Exists and is Weakly Interacting

Cosmic Abundance of DM





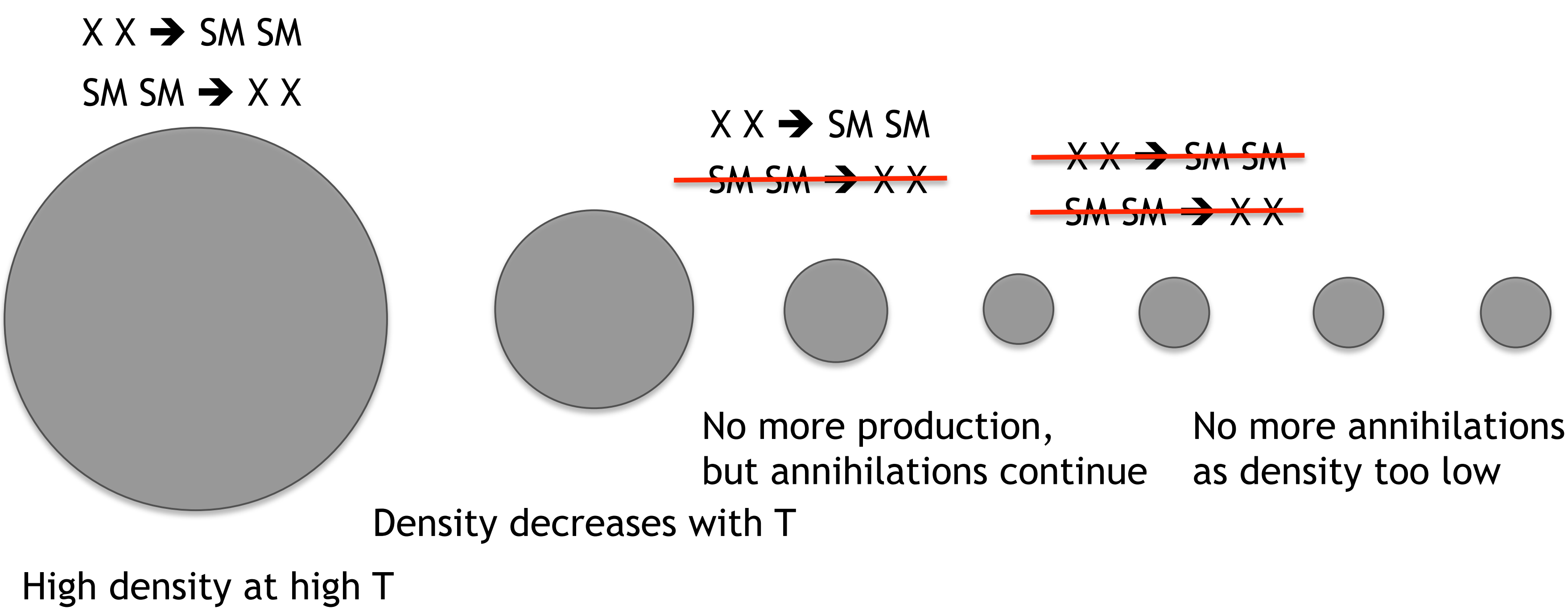
$\Omega_{CDM}h^2 \approx 0.11$

$\Omega_{CDM}/\Omega_B \approx 5$

Abundance of DM

Thermal Relic

As the Universe expands and cools …
the DM density decreases …



and eventually freezes out.

Freeze-out

$$n_{\rm eq}^{\rm ER} = 3\zeta(3) g_\chi T^3/(4\pi^2)$$

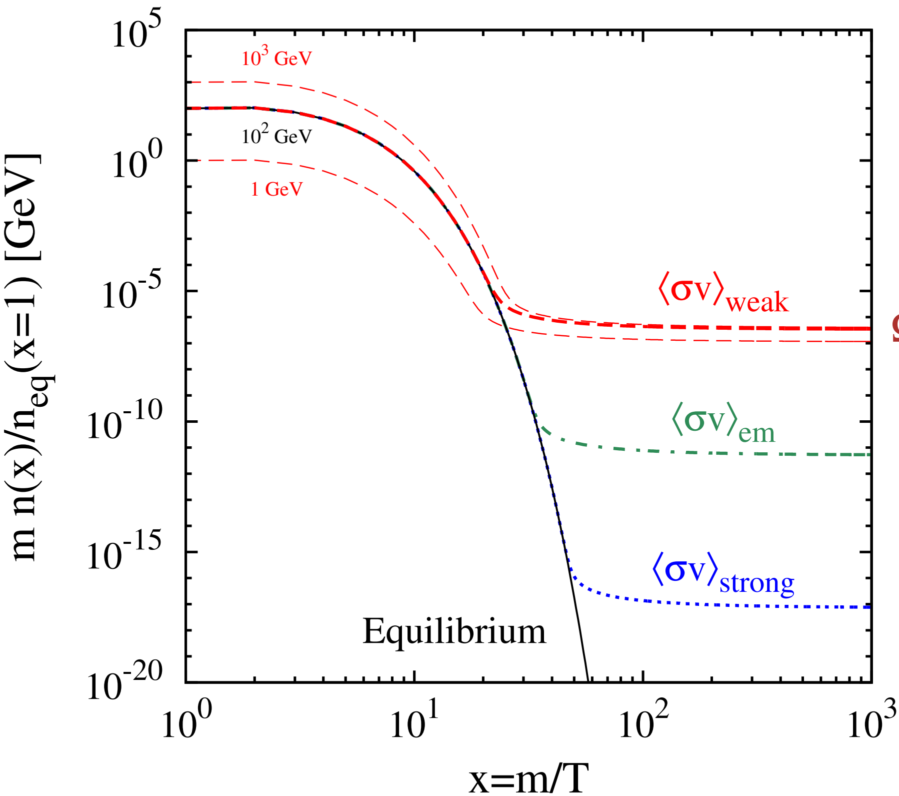
$$n_{\rm eq}^{\rm NR} = g_\chi (mT/(2\pi))^{3/2} {\rm exp}(-m/T)$$

$$\frac{d(na^3)}{a^3 dt} = \langle\sigma v\rangle \left(n_{\rm eq}^2 - n^2\right)$$

Two "Tricks":

1. Time to Temperature
2. x^2 – y^2 = (x+y)(x-y)

Freeze-out and WIMP Miracle



$\Omega_{CDM}h^2 \approx 0.11$

$$10^{26}\langle\sigma v\rangle = 0.902\left(\frac{0.11}{\Omega h^2}\right)\left(\frac{x_*}{g_*^{1/2}}\right)$$

Weak Cross Sections lead to Correct Relic Density

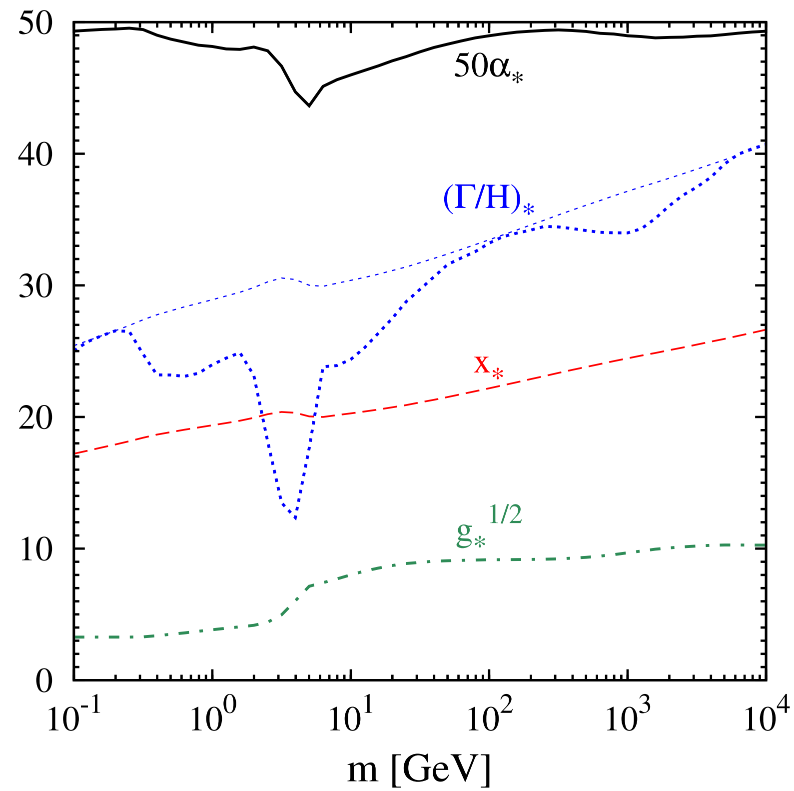
Zeldovich (1965), Chiu (1966), Lee and Weinberg (1977), Hut (1977), Wolfram (1979), Steigman (1979)

Precision Calculation

$$10^{26}\langle\sigma v\rangle = 0.902\left(\frac{0.11}{\Omega h^2}\right)\left(\frac{x_*}{g_*^{1/2}}\right)\left(\frac{(\Gamma/H)_*}{1+\alpha_*(\Gamma/H)_*}\right)$$

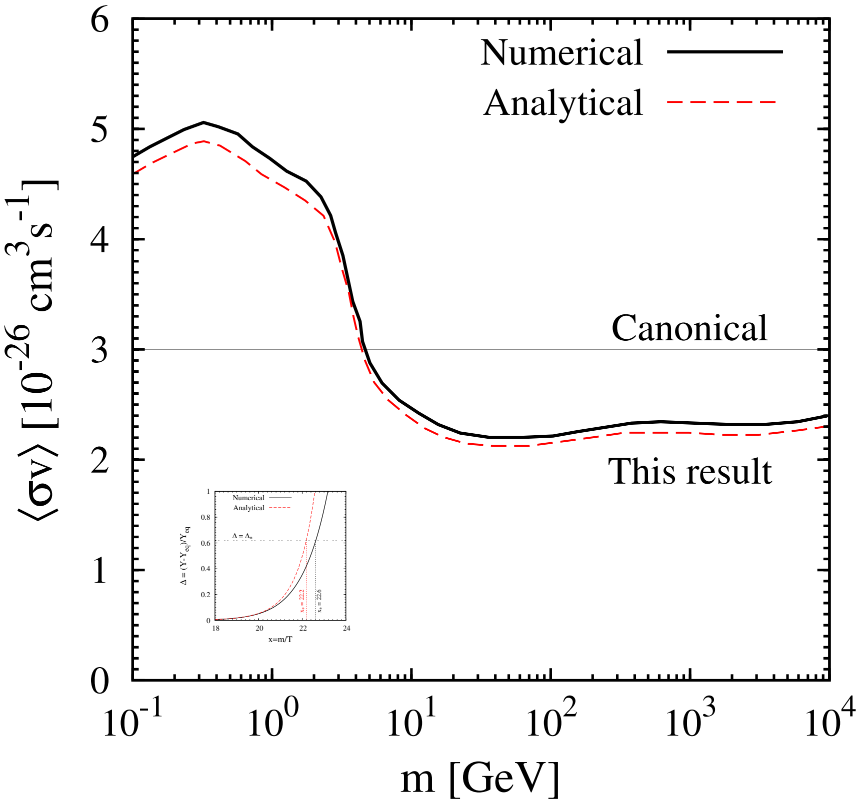
$$\alpha_* \equiv \int_{T_f}^{T_*}\frac{dT}{T_*}\sqrt{\frac{g}{g_*}}\left[1+\frac{1}{3}\frac{d(\ln g)}{d(\ln T)}\right].$$

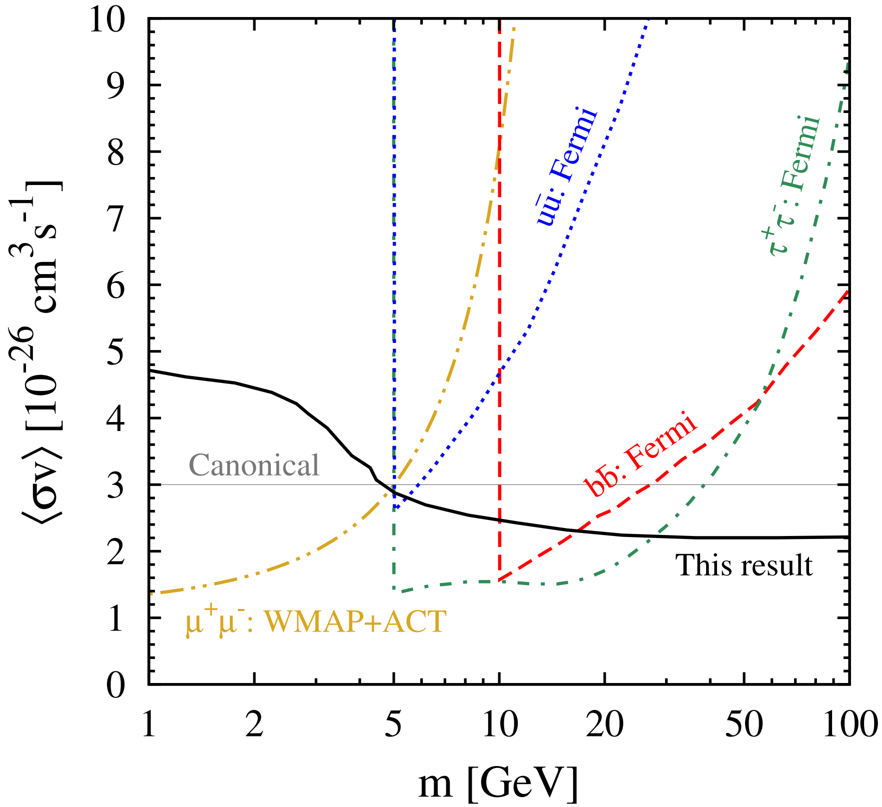
Effect of
Time-varying d.o.f



Steigman, Dasgupta, Beacom (2012)

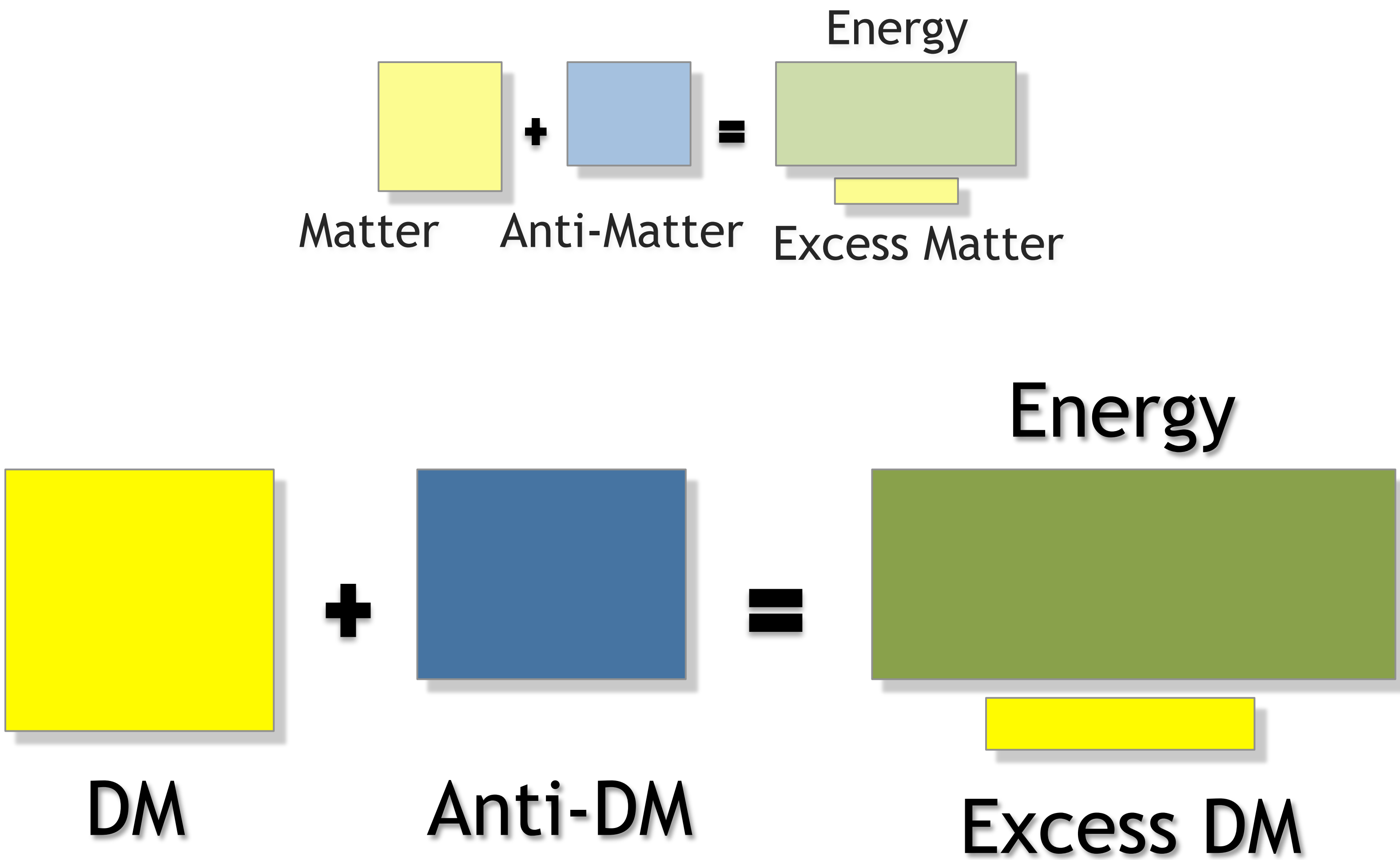
Precision WIMP Miracle





Steigman, Dasgupta, Beacom (2012)

Asymmetric Dark Matter



Basics of Asymmetric DM

1. DM with a Global Quantum Number
2. Explain $N_{Baryon} \approx N_{DM}$
3. Predict $M_X \approx 5$ GeV

Nussinov 1985; Barr, Chivukula and Farhi 1990; Kaplan 1992; Kuzmin 1997; Kusenko 1999; Kitano and Low 2004, 05; Hooper, March-Russell and West 2004; Farrar and Zaharijas 2004, 05; Agashe and Servant 2004; Cosme, Lopez-Honorez and Tytgat 2005; Suematsu 2005; Banks, Echols and Jones 2006; Page 2007; Nardi, Sannino and Strumia 2009; Kaplan, Luty, Zurek 2009; Kribs, Roy, Terning, Zurek 2010; Cohen, Phalen, Pierce, Zurek 2010; Frandsen, Sarkar 2010; An, Chen, Mohapatra, Zhang 2010; Davoudiasl, Morrissey, Sigurdson, Tulin 2010; Shelton, Zurek 2010; Haba, Matsumoto 2010; Buckley, Randall 2010; Chun 2010; Gu, Lindner, Sarkar, Zhang 2010; Blennow, Dasgupta, Fernandez-Martinez, Rius 2010; McDonald 2010; Hall, March-Russell, West 2010; Dutta, Kumar 2010; Falkowski, Ruderman, Volansky 2011; Heckmann, Rey 2011; Graesser, Shoemaker, Vechhi 2011; Frandsen, Sarkar, Schmidt-Hoberg 2011; … + few dozen more

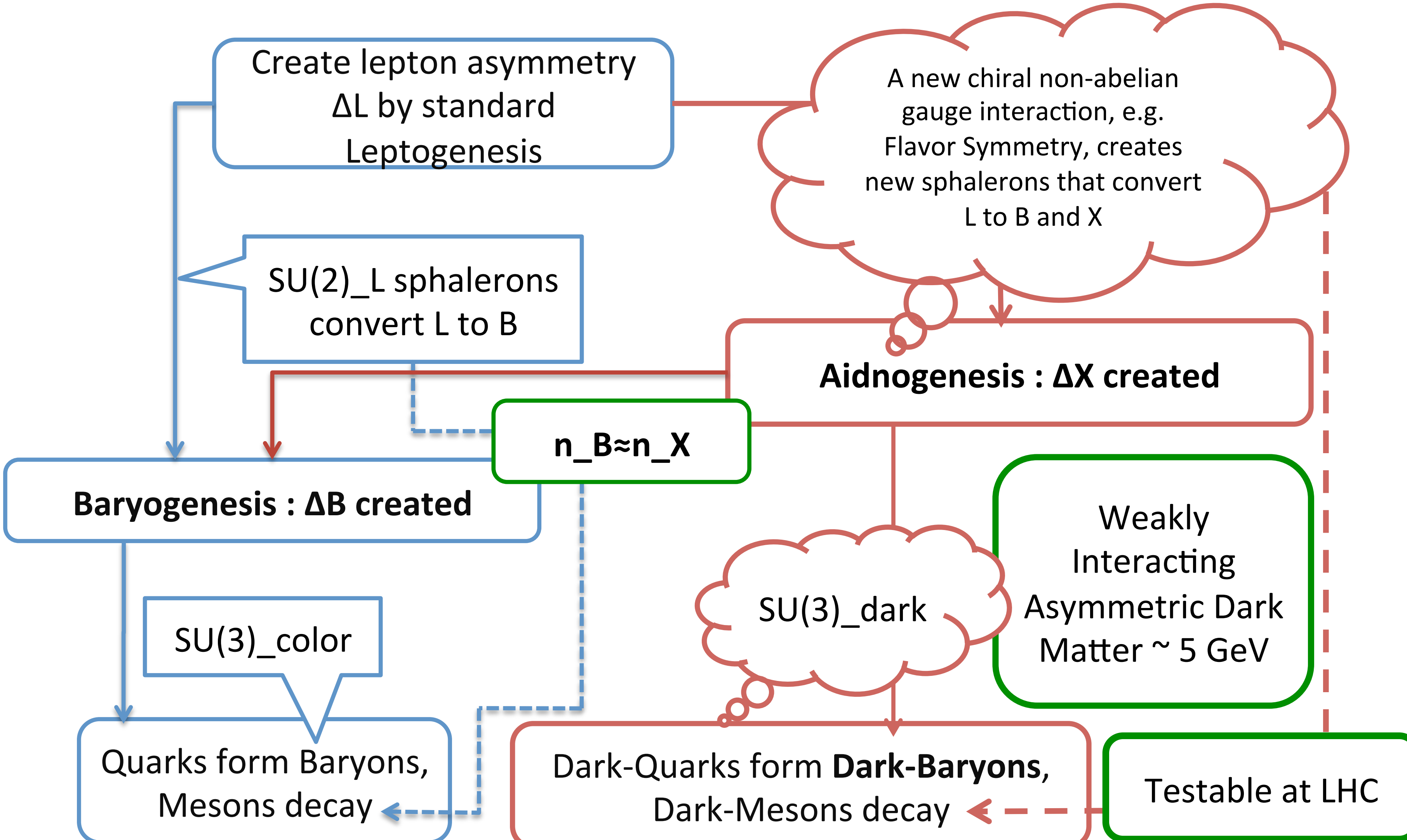
Aidnogenesis

αιδνος (aidnos) = dark

DM asymmetry created via
new sphalerons which partially transfer
lepton asymmetry created by leptogenesis

Blennow, Dasgupta, Fernandez-Martinez, Rius (2010)

Aidnogenesis at a glance



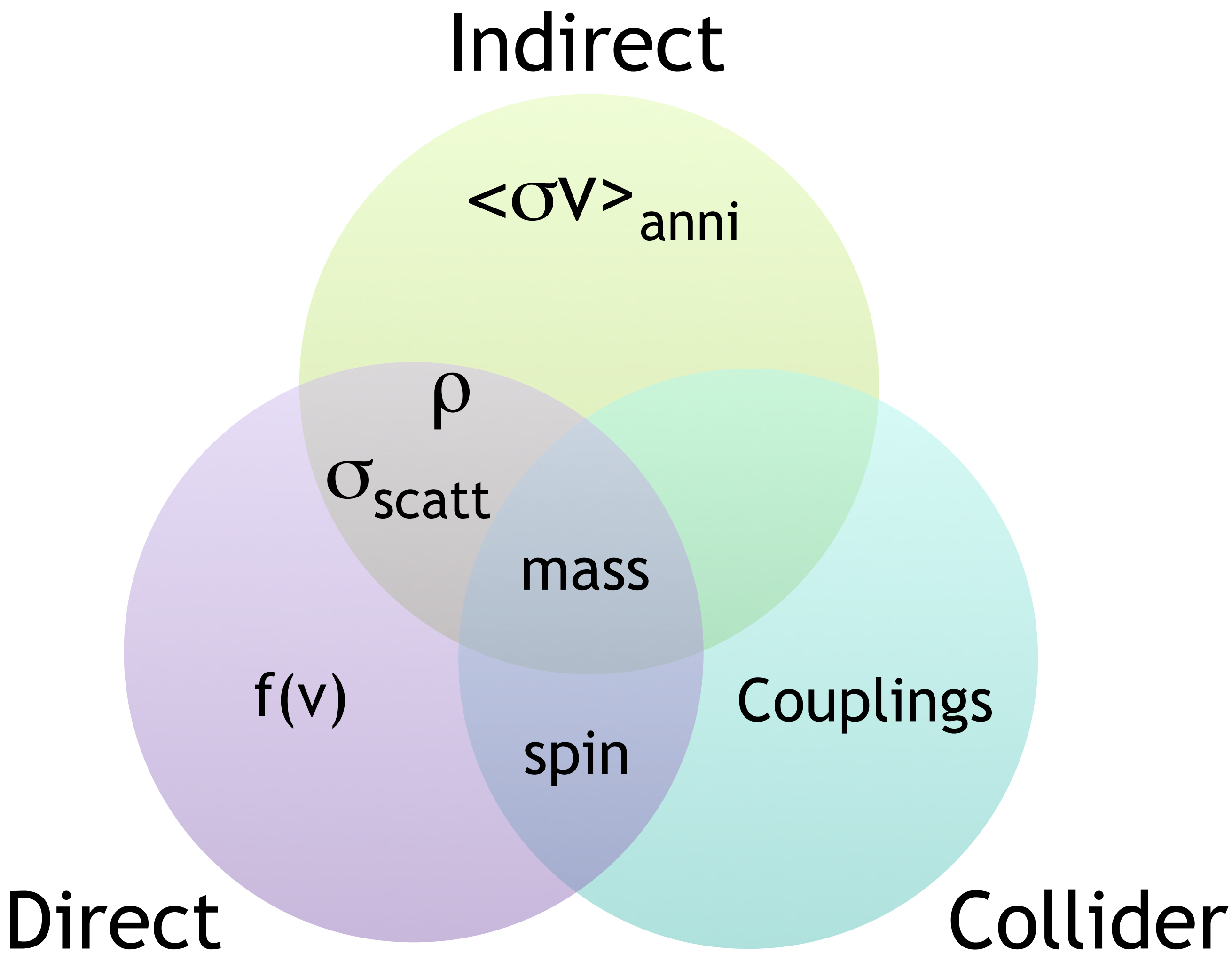
A specific model

- Extend each SM generation with a N_R and X_R
- Connect the right fermions with a $SU(2)_H$
- Give $SU(3)_{DC}$ to X_R
- No triangle anomalies or Witten anomaly
- ΔL=ΔB and ΔL=ΔB/2=ΔX
- ΔX/ΔB = -11/14, M_X=5.94±0.42 GeV

Field	Y	L	H	C	DC
$L_{L\alpha}$ $(\nu_{\alpha L}, \ell_{\alpha L})$	$-1/2$	$\mathbf{2}$	1	1	1
L_H (e_R, μ_R)	-1	1	$\mathbf{2}$	1	1
τ_R	-1	1	1	1	1
$\nu_{\alpha R}$	0	1	1	1	1
$Q_{\alpha L}$ $(u_{\alpha L}, d_{\alpha L})$	$1/6$	$\mathbf{2}$	1	$\mathbf{3}$	1
Q_H^u (u_R, c_R)	$2/3$	1	$\mathbf{2}$	$\mathbf{3}$	1
Q_H^d (d_R, s_R)	$-1/3$	1	$\mathbf{2}$	$\mathbf{3}$	1
t_R	$2/3$	1	1	$\mathbf{3}$	1
b_R	$-1/3$	1	1	$\mathbf{3}$	1
X_H (x_R^1, x_R^2)	0	1	$\mathbf{2}$	1	$\mathbf{3}$
x_R^3, x_L^α	0	1	1	1	$\mathbf{3}$

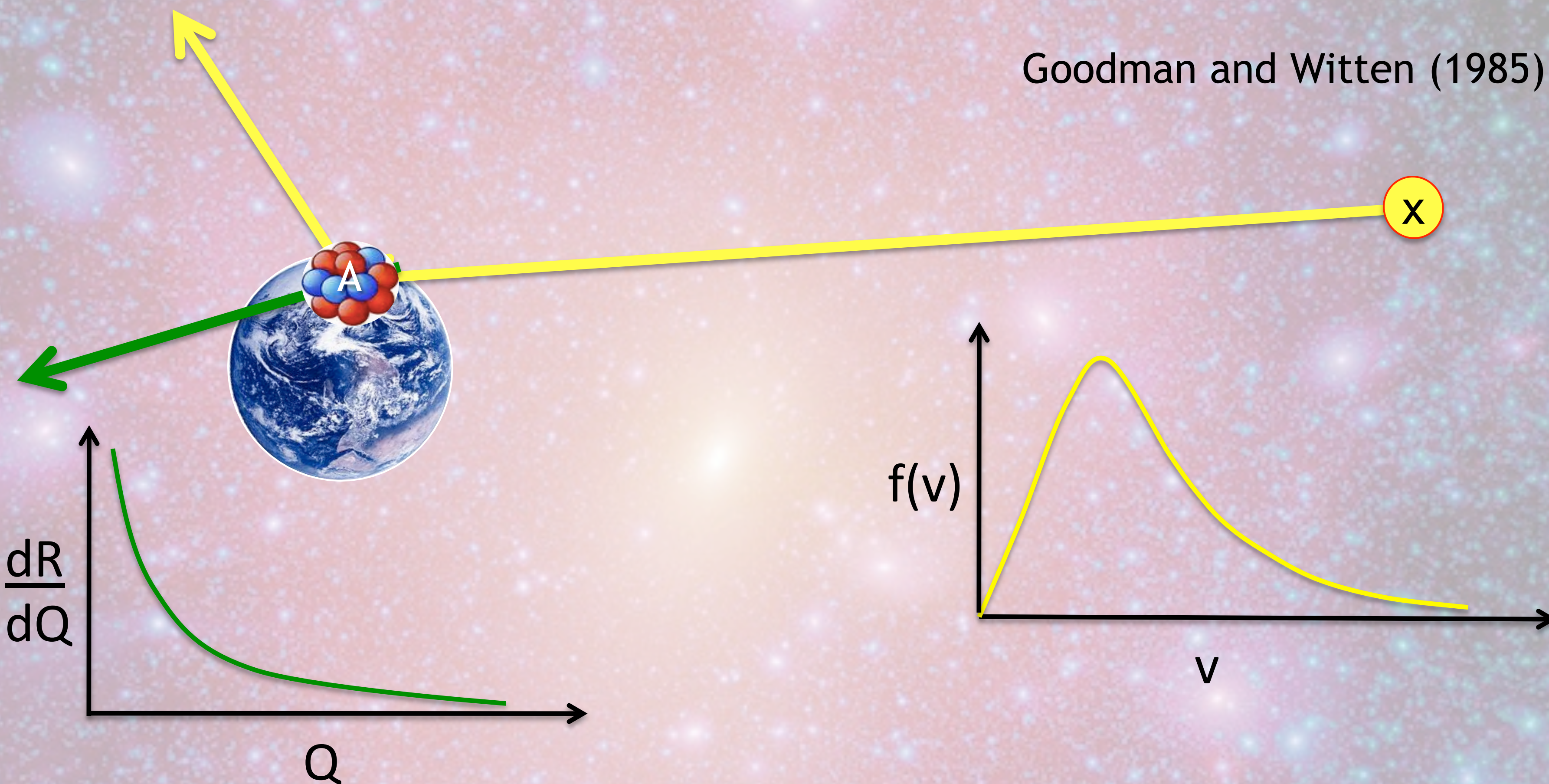
Looking for DM

Probing DM Properties



Direct Detection

Goodman and Witten (1985)



$$\frac{dR}{dQ} = \frac{\rho_0 \sigma_n}{2\mu^2 m} A^2 F(Q)^2 \int_{\sqrt{\frac{mQ}{2\mu^2}}}^{\infty} dv \, \frac{f_1(v)}{v}$$

Rates and Kinematics

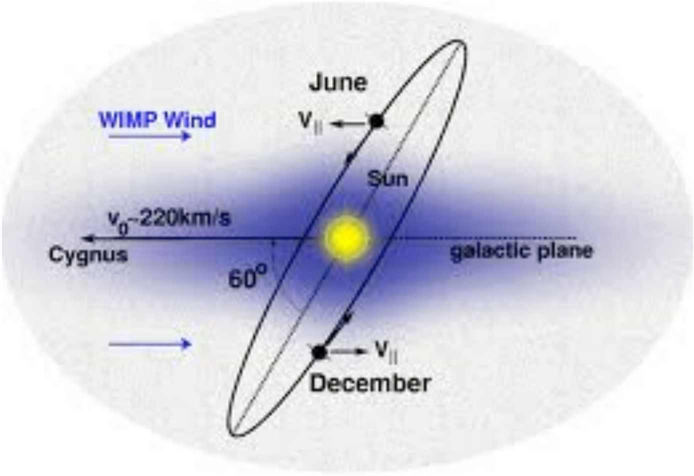
$$R \sim 1\mathrm{yr}^{-1}\,\frac{N}{\mathrm{ton}}\,\frac{\rho}{\mathrm{GeV cm}^{-3}}\,\frac{100\,\mathrm{GeV}}{m}\,\frac{\sigma}{10^{-42}\,\mathrm{cm}^2}\,\frac{\langle v\rangle}{100\,\mathrm{km/s}}$$

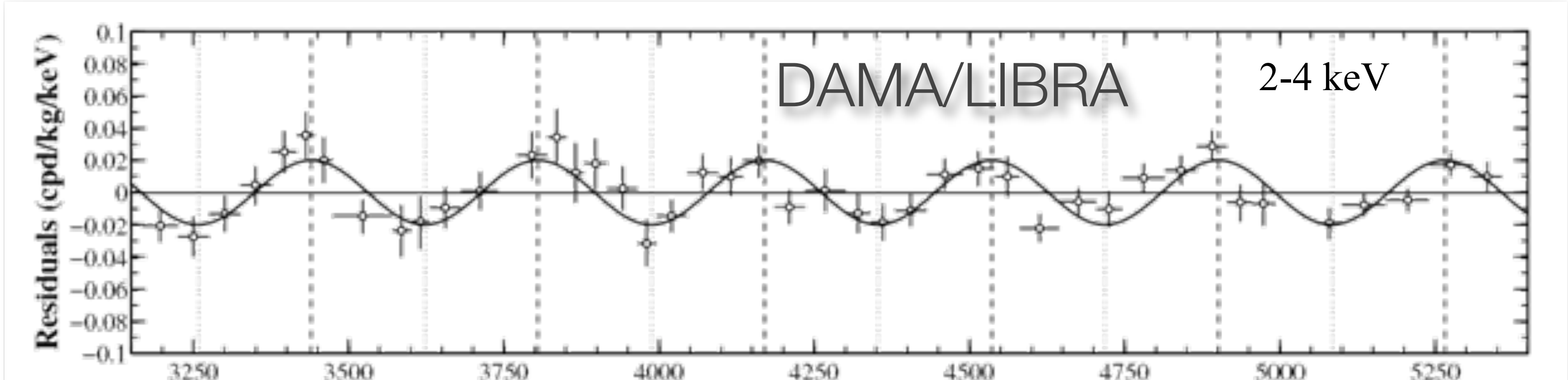
$$Q = (1-\cos\theta)\mu^2 v^2/A \sim (1-100)\,\mathrm{keV}$$

Very low signal rates with very low energies!

Direct Detection Experiments

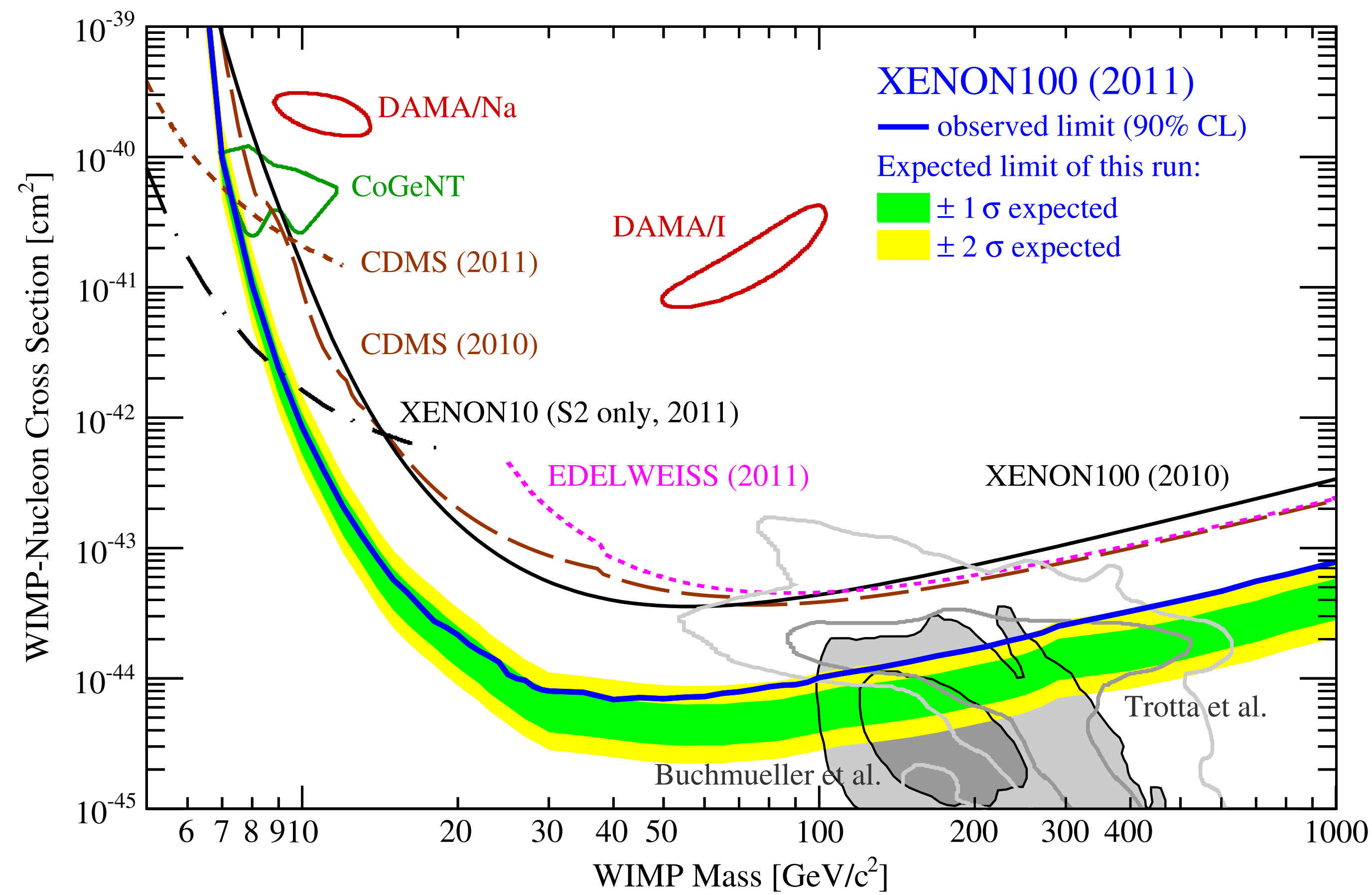
Have we discovered DM?





R.Bernabei et al, Eur.Phys.J. **C67** (2010)

Global Picture



No Consistent Scenario!

Fresh off the press!

Sizing-up the WIMPs of Milky Way : Deriving the velocity distribution of Galactic Dark Matter particles from the rotation curve data

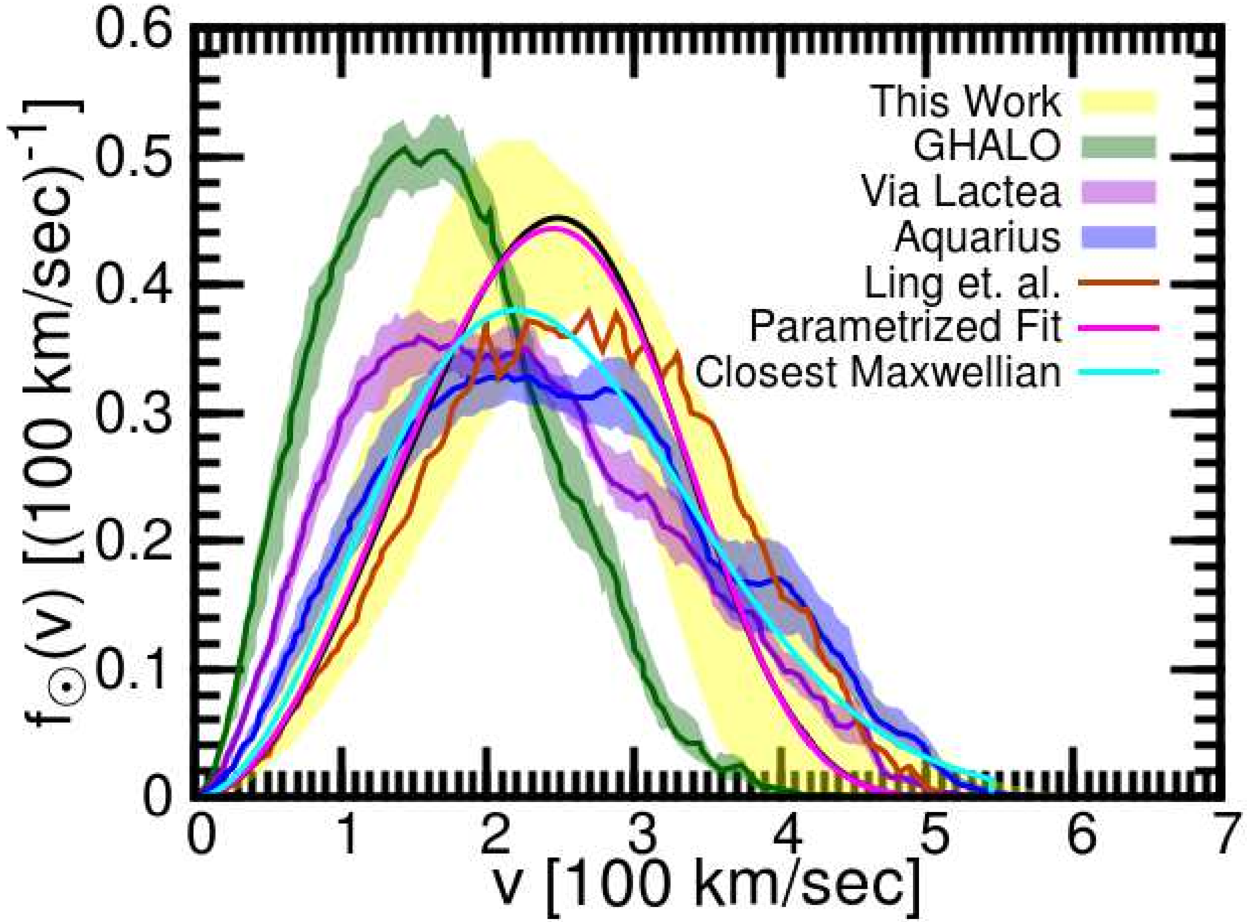
Pijushpani Bhattacharjee[1*], Soumini Chaudhury[1†], Susmita Kundu[1‡] and Subhabrata Majumdar[2§]
[1] *AstroParticle Physics & Cosmology Division and Centre for AstroParticle Physics, Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700064. India*
[2] *Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005. India*

The velocity distribution function (VDF) of the hypothetical Weakly Interacting Massive Particles (WIMPs), currently the most favored candidate for the Dark Matter (DM) in the Galaxy, is determined directly from the rotation curve data of the Galaxy assuming isotropic VDF. This is done by "inverting" — using Eddington's method — the Navarro-Frenk-White universal density profile of the DM halo of the Galaxy, the parameters of which are determined, by using Markov Chain Monte Carlo (MCMC) technique, from a recently compiled set of observational data on the Galaxy's rotation curve extended to distances well beyond the visible edge of the disk of the Galaxy. The derived most-likely local isotropic VDF strongly differs from the Maxwellian form assumed in the "Standard Halo Model" (SHM) customarily used in the analysis of the results of WIMP direct-detection experiments. A parametrized (non-Maxwellian) form of the derived most-likely local VDF is given. The astrophysical "g-factor" that determines the effect of the WIMP VDF on the expected event rate in a direct-detection experiment can be lower for the most-likely VDF than that for the closest Maxwellian VDF by as much two orders of magnitude at the lowest WIMP mass threshold of a typical experiment.

$$\mathcal{F}(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\left[\int_0^{\mathcal{E}} \frac{d\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{d^2\rho}{d\Psi^2} + \frac{1}{\sqrt{\mathcal{E}}}\left(\frac{d\rho}{d\Psi}\right)_{\Psi=0}\right]$$

Very Promising New Strategy!

f(v) from Rotation Data



Bhattacharjee, Chaudhuri, Kundu, Majumdar (2012)

Deriving f(v) from Direct Detection

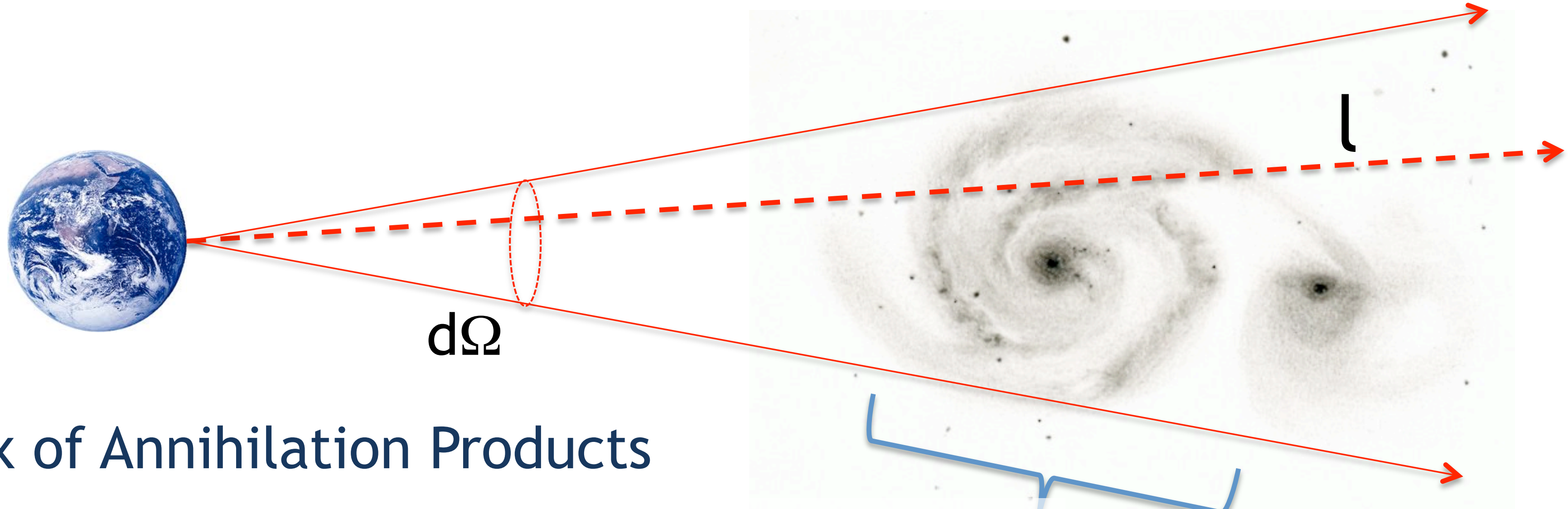
$$\frac{dR}{dQ}(Q) = \frac{N_0}{m_N}\frac{\rho_X}{m_X}\int_{v_{min}(Q)}^{\infty} dv \frac{d\sigma}{dQ}(Q,v) v f_1(v)$$

What is the best that one can do?

Usually assume both a particle physics model and a parametrization for f(v) and set limits / measure the parameters. Can one do better?

Drees and Shan (2007)
Fox, Kribs, Tait (2009)

Indirect Detection



Flux of Annihilation Products

DM density

$$\frac{d\Phi}{dE} = \int d\Omega \int dl\, \rho^2(l,\Omega) \times \frac{\langle \sigma v \rangle}{8\pi m^2} \sum \left(\frac{dN}{dE} B_f \right)$$

DM annihilation

Sources, Messengers

Sun

Milky Way

Dwarf Galaxies

Galaxy Clusters

Diffuse

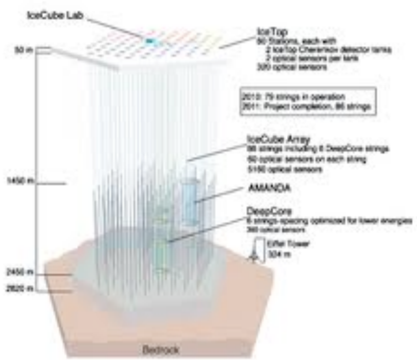
Neutrinos

Gamma Rays

(Anti)-Electrons

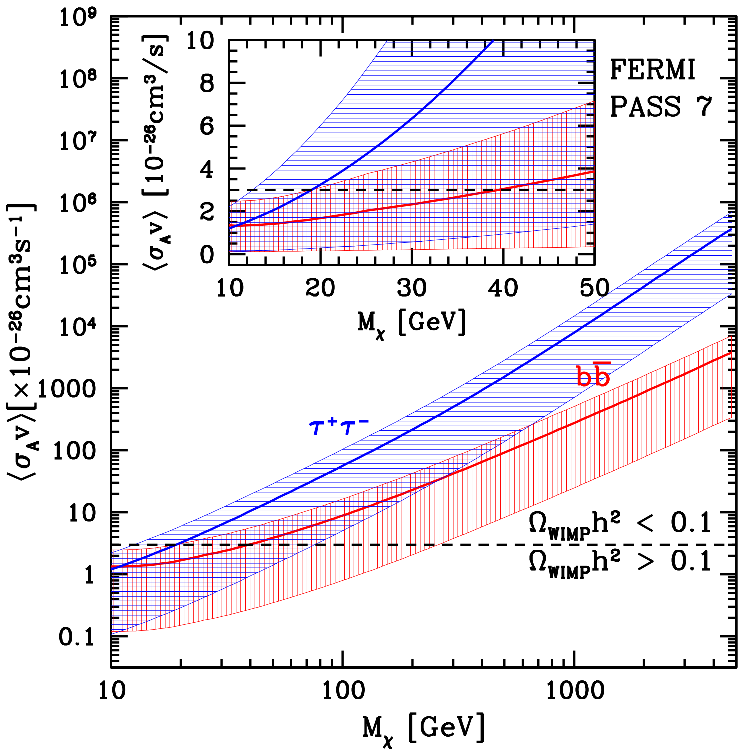
(Anti)-Protons

Indirect Detection Experiments



- Neutrinos
  - Super-K, KamLAND, …
  - IceCube, Pingu
  - Baikal, KM3NeT, LAGUNA
- Gamma Rays
  - Fermi
  - MAGIC, HESS, VERITAS, CTA
- Anti-Matter
  - PAMELA, ATIC, AMS, GAPS, …
- Others
  - Radio, X-ray

DM in Dwarf Galaxies



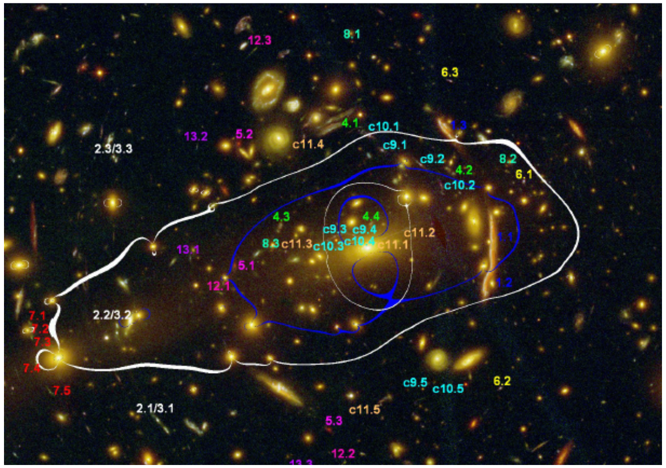
Geringer-Sameth and Koushiappas (2011)
Fermi Collaboration (2011)

Are we in the Endgame?

Crucial to use precise <σv> to set limits at low-m

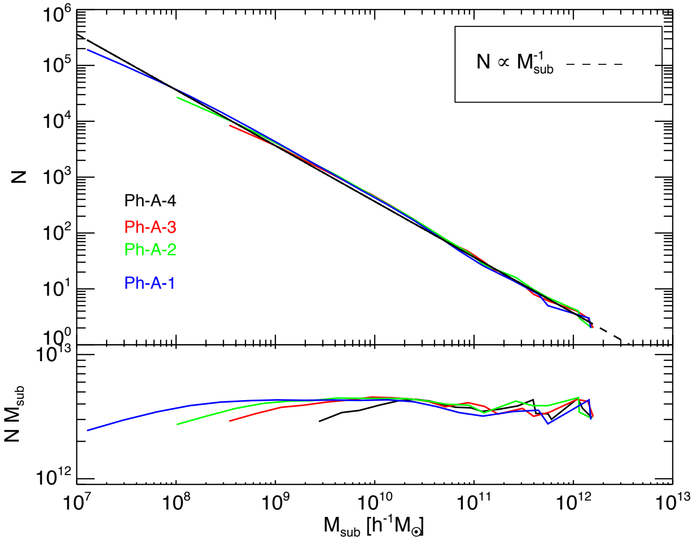
Steigman, Dasgupta, Beacom (2012)

DM in Clusters



LOT OF SUBSTRUCTURE

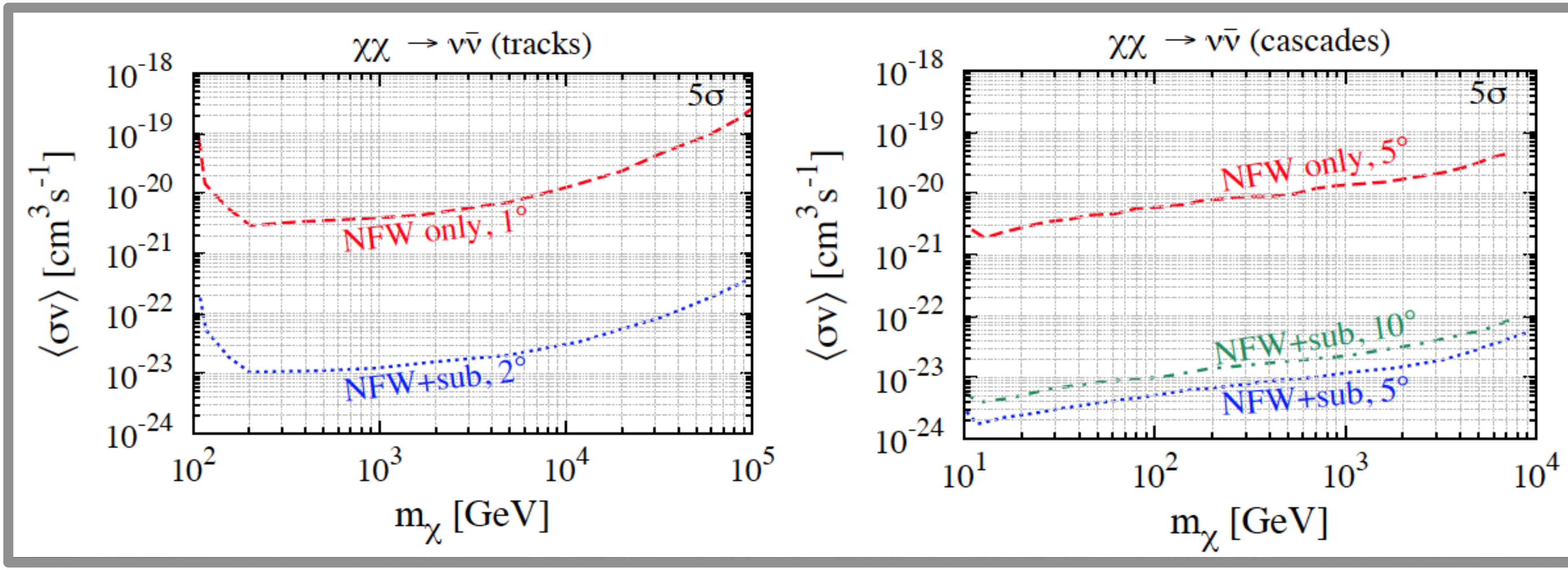
Cluster Lensing in CLASH



LOT OF SUBSTRUCTURE

Phoenix Simulations of Clusters (Springel et al.)

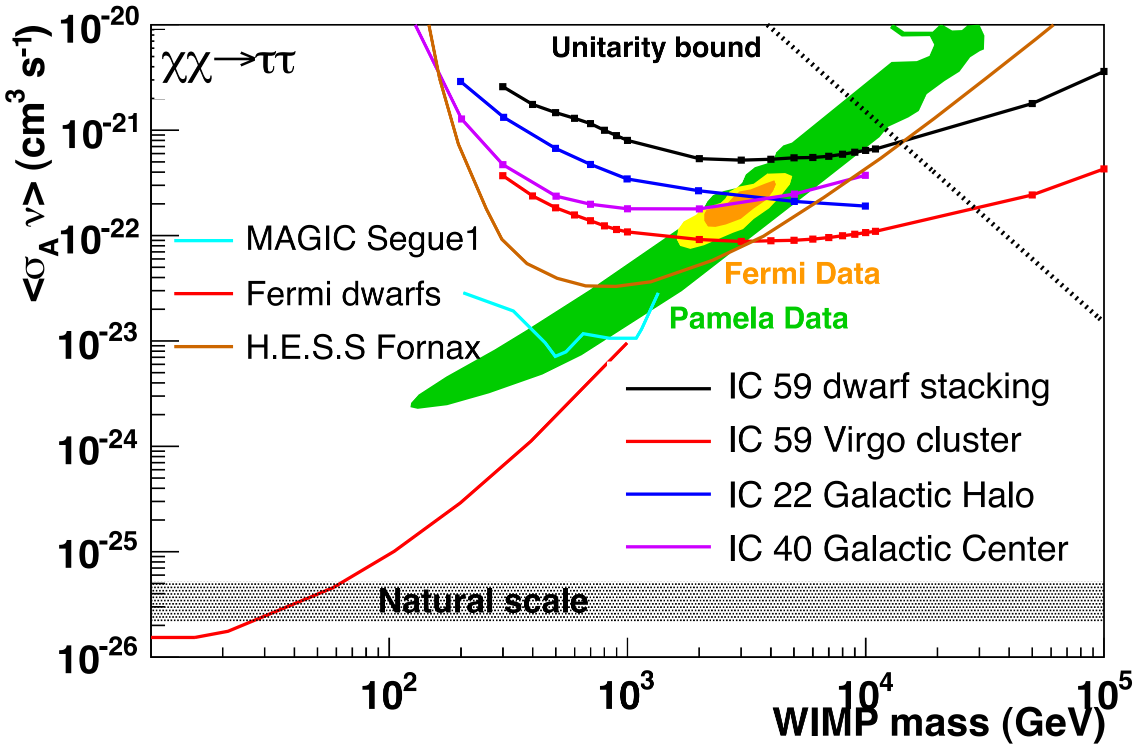
IceCube Sensitivity



Dasgupta and Laha (2012)

Clusters are the best targets for IceCube

IceCube Preliminary Results



C. Rott, for IC (2012)

Very similar to our results!

Recent Excitement and Future Prospects

arXiv:1204.2797v2 [hep-ph] 8 Aug 2012

A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

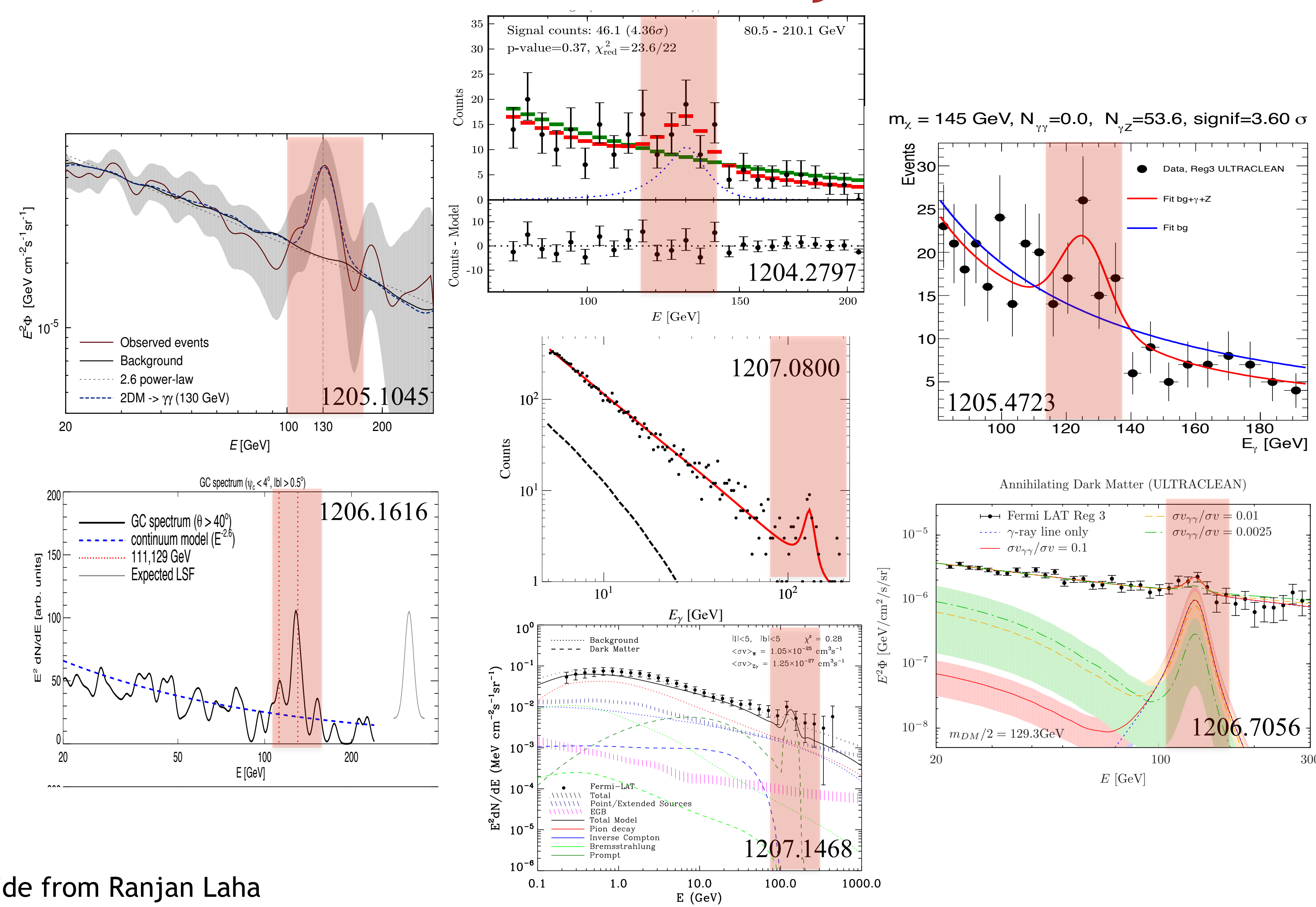
Christoph Weniger

Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany

E-mail: weniger@mppmu.mpg.de

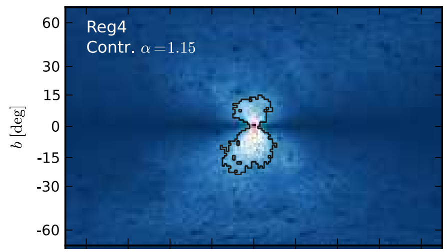
Abstract. The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 300 GeV. Besides updating to 43 months of data, we use a new data-driven technique to select optimized target regions depending on the profile of the Galactic dark matter halo. In regions close to the Galactic center, we find a 4.6σ indication for a gamma-ray line at $E_\gamma \approx 130$ GeV. When taking into account the look-elsewhere effect the significance of the observed excess is 3.2σ. If interpreted in terms of dark matter particles annihilating into a photon pair, the observations imply a dark matter mass of $m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}$ GeV and a partial annihilation cross-section of $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}$ cm^3 s^{-1} when using the Einasto dark matter profile. The evidence for the signal is based on about 50 photons; it will take a few years of additional data to clarify its existence.

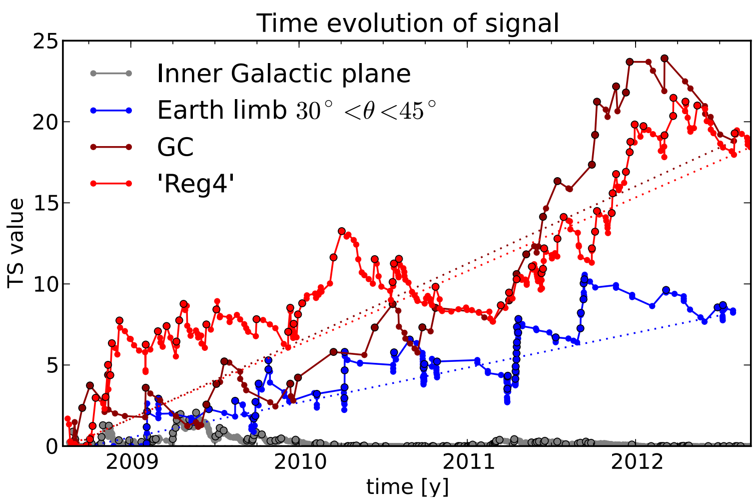
130 GeV Gamma Ray Line at GC

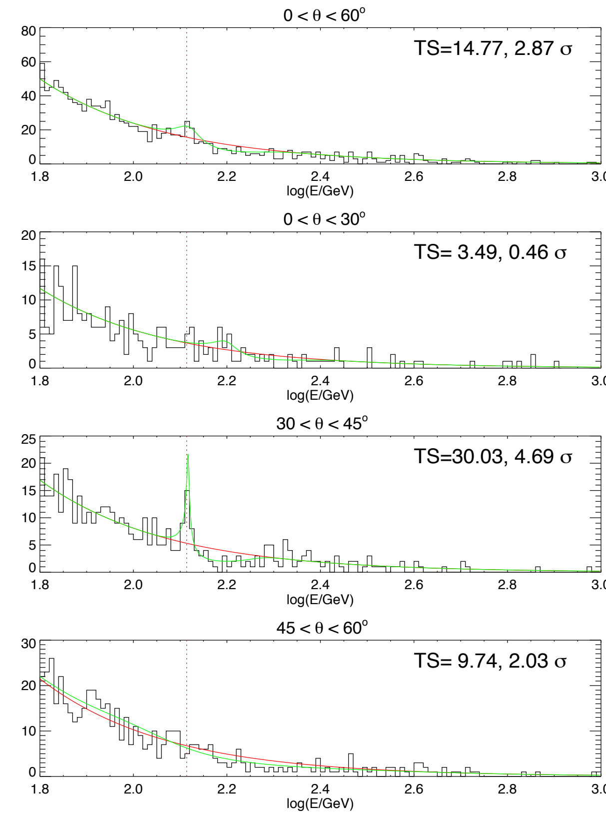


Slide from Ranjan Laha

Systematics



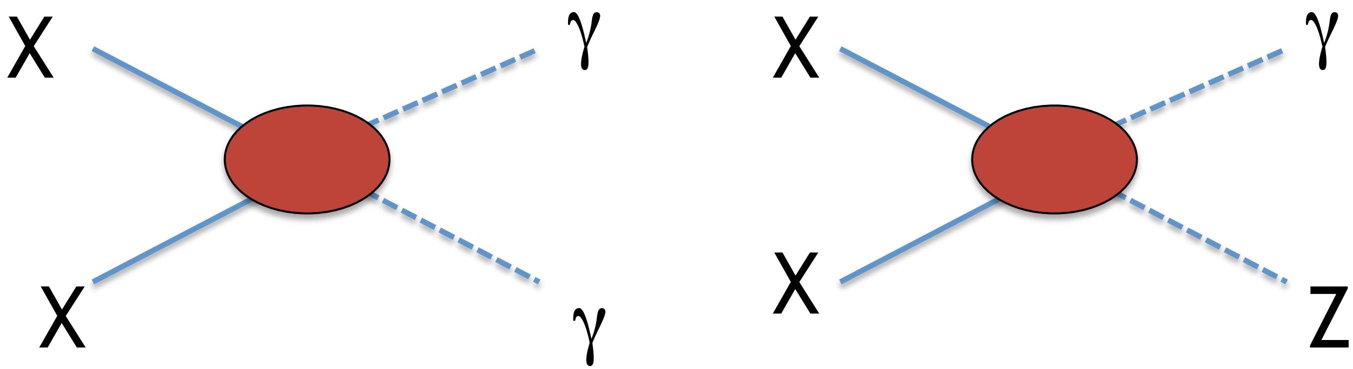




Earth Limb Photons?

Finkbeiner, Su, Weniger (2012)
Hector, Tempel, Raidal (2012)

γZ versus $\gamma\gamma$



Z must decay to charged pairs.
They will radiate via synchrotron!

Laha, Ng, Dasgupta, Horiuchi (2012)

Radio Fluxes from DM Products

$$K(E)\nabla^2 n_e(E,\mathbf{r}) + \frac{\partial}{\partial E}\left[b(E,\mathbf{r}) n_e(E,\mathbf{r})\right] = -S(E,\mathbf{r}),$$

$$n_e(E,\mathbf{r}) = -\frac{\int_E^{m_\chi} dE' \; S(E',\mathbf{r})}{b(E,\mathbf{r})}.$$

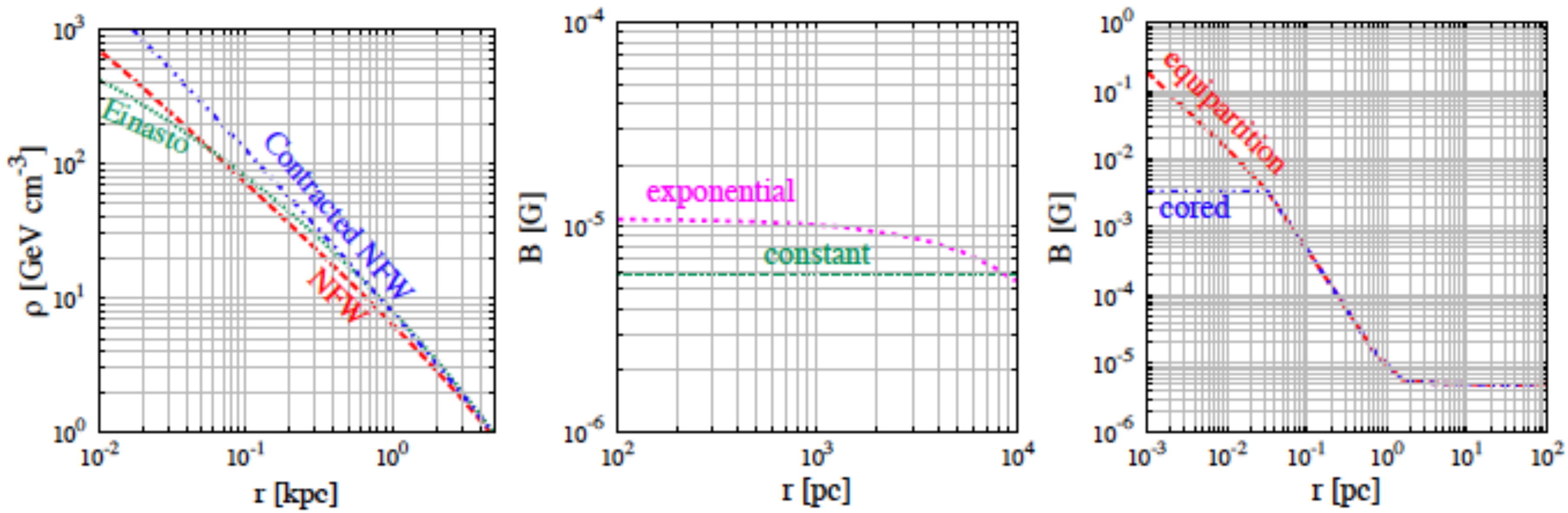
$$\left.\frac{dE}{dt}\right|_{\rm sync} = \frac{4}{3}\sigma_T\, c\, U_{\rm mag}(\mathbf{r})\gamma^2\beta^2 = 3.4\times 10^{-17}\ {\rm GeV\,s^{-1}}\left(\frac{E}{\rm GeV}\right)^2\left(\frac{B(\mathbf{r})}{3\,\mu{\rm G}}\right)^2$$

Close to GC Diffusion is Slow

$$F_\nu = \frac{1}{4\pi(8.5\ {\rm kpc})^2}\frac{\langle\sigma v\rangle}{2m_\chi^2}\int dV\,\rho_\chi^2 E\int_E^{m_\chi}\frac{dN}{dE'}dE'$$

Laha, Ng, Dasgupta, Horiuchi (2012)

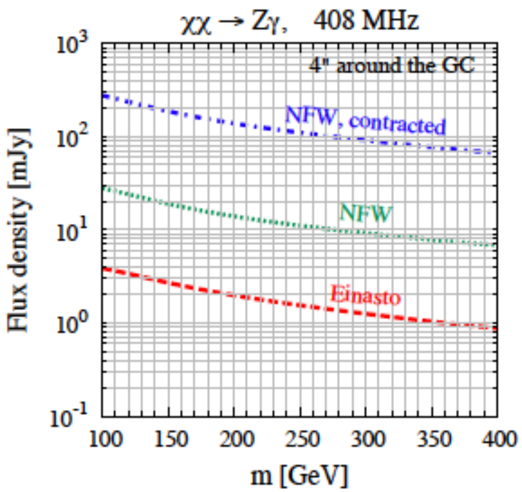
Modeling the Galactic Center

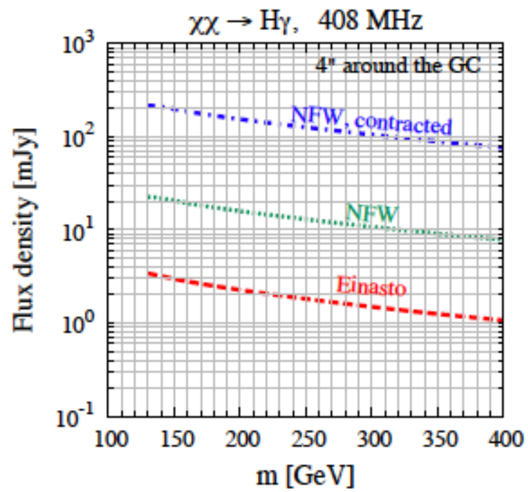


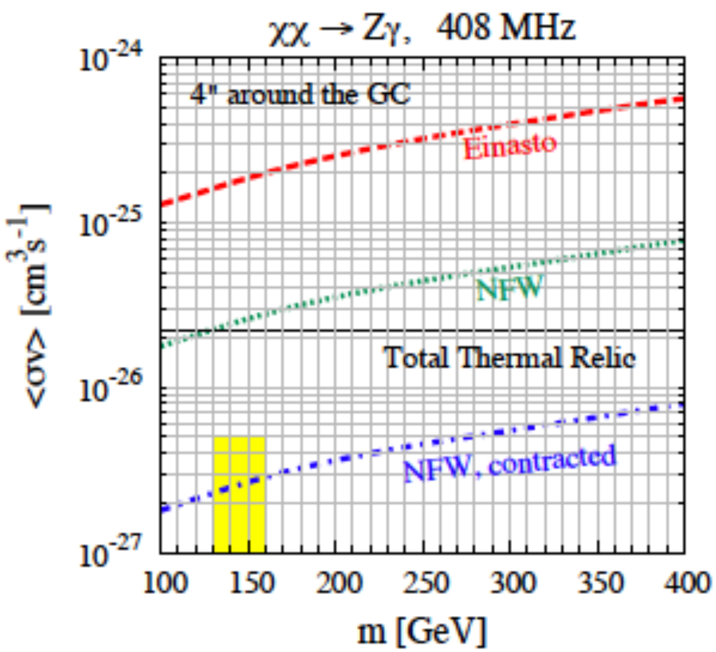
Large Uncertainties: Taken into Account

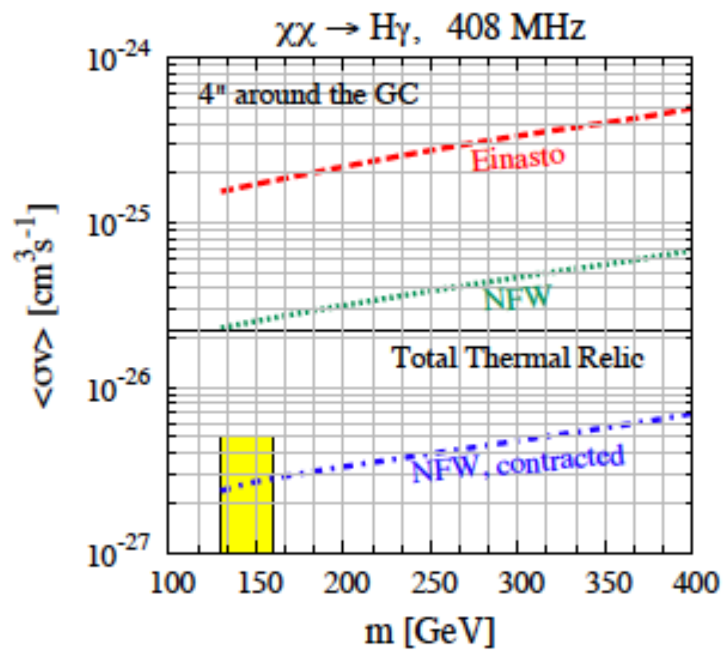
Laha, Ng, Dasgupta, Horiuchi (2012)

Radio Fluxes and Constraints

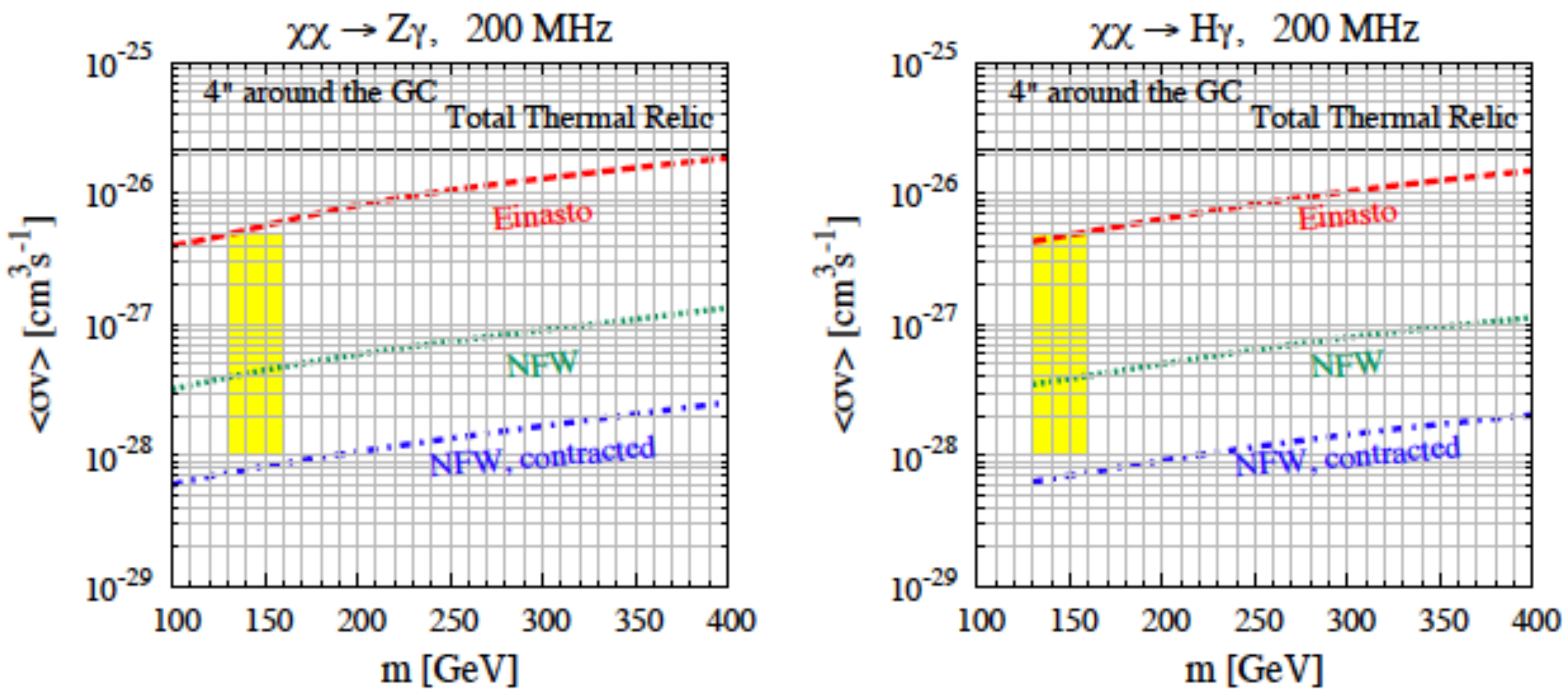








Near Future LOFAR Forecast



Fully testable in 6 hours of LOFAR observation

Laha, Ng, Dasgupta, Horiuchi (2012)

Lots of activity in store …

Ranjan Laha

Shunsaku Horiuchi

John Beacom

Kenny Ng

Kohta Murase

Gary Steigman

Three Key Questions

Why do we need Dark Matter?

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What sets its abundance?

Thermal Relic/Asymmetry/…

How are we probing it?

Direct, Indirect, …