The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2354-3

Summer School on Cosmology

16 - 27 July 2012

Dark Matter

M. Cirelli
CERN & CNRS Saclay

July 2012

ICTP summer school in cosmology - Trieste

Dark Matter

(slides are for support only)

Marco Cirelli

(CERN-TH & CNRS IPhT Saclay)

in collaboration with:
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N.Fornengo (Torino)
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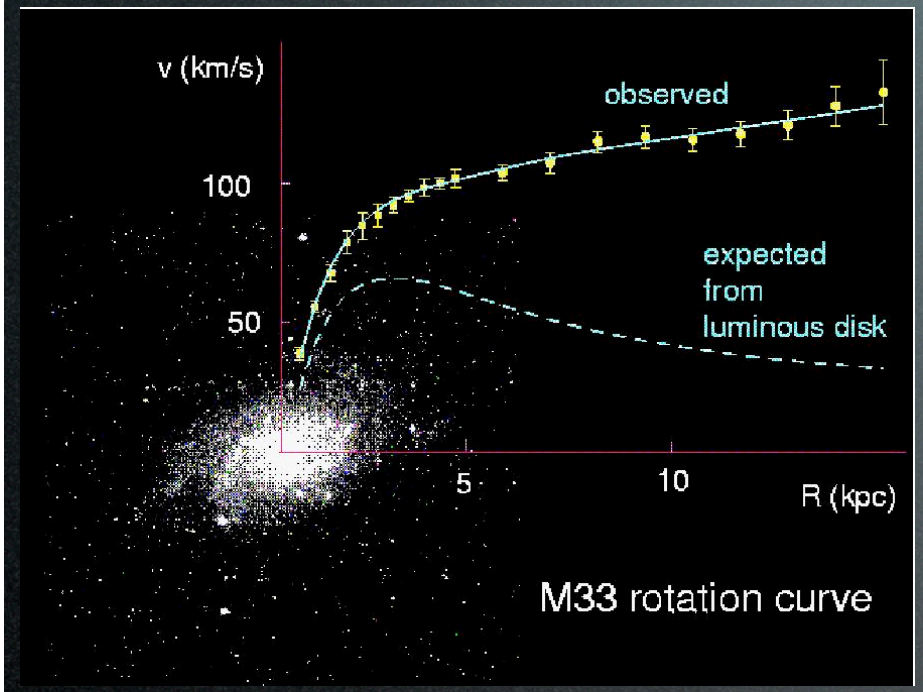
R.Franceschini (Pisa)
M.Raidal (Tallin)
M.Kadastik (Tallin)
Gf.Bertone (IAP Paris)
M.Taoso (Padova)
C.Bräuninger (Saclay)
P.Panci (L'Aquila + Saclay + CERN)
F.Iocco (Saclay + IAP Paris)
P.Serpico (CERN)

Reviews on Dark Matter:

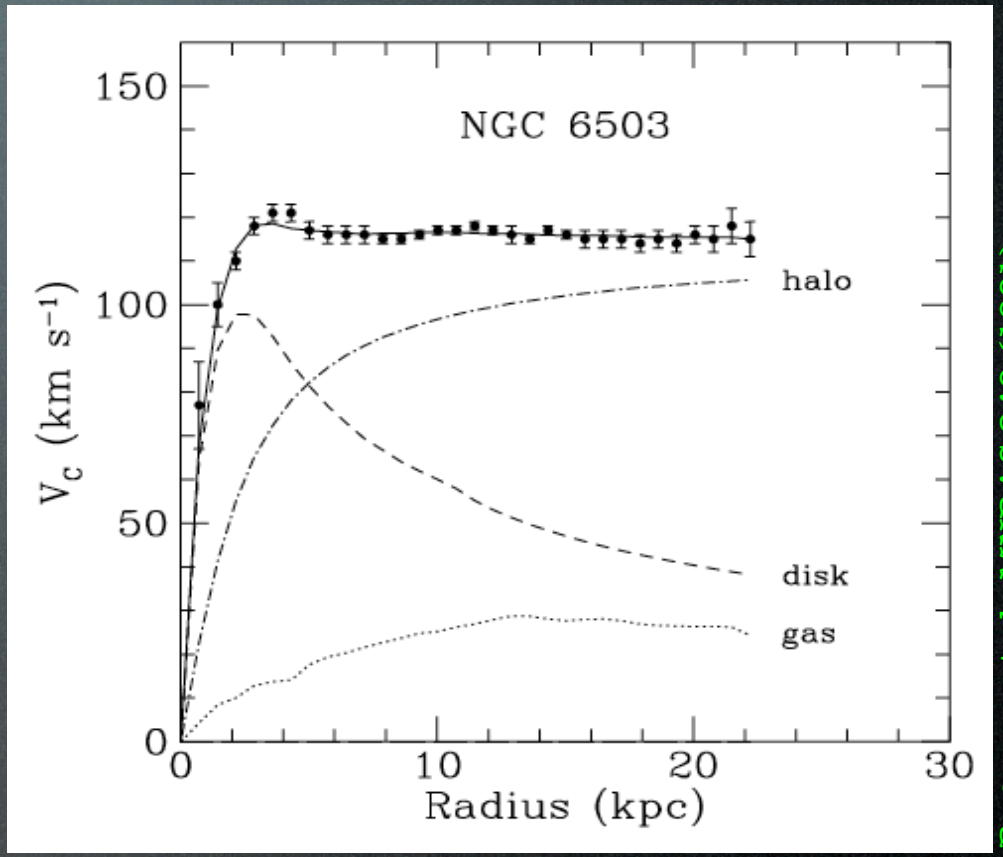
Jungman, Kamionkowski, Griest, Phys.Rept. 267, 195-373, 1996
Bertone, Hooper, Silk, Phys.Rept. 405, 279-390, 2005
Einasto, 0901.0632
Cirelli, Strumia arXiv: yymm.nnnn (*upcoming*)

Evidences & ‘cosmology’

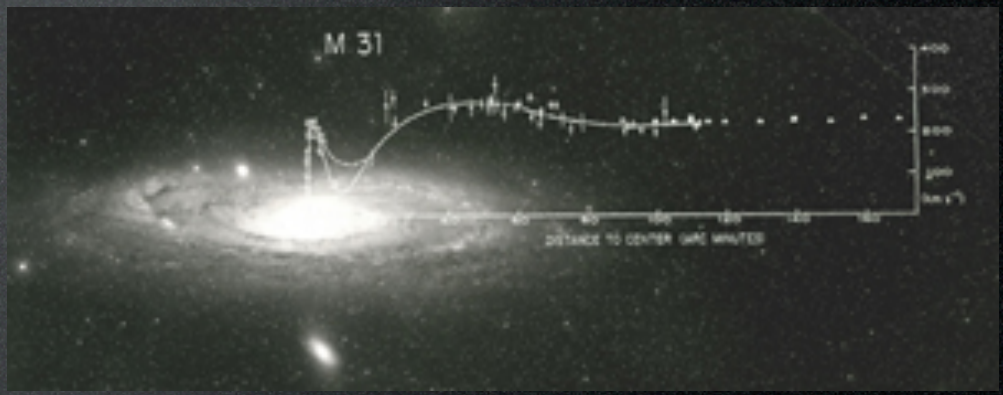
The Evidence for DM



Corbelli e Salucci , MN 2000



Begeman et al., MNRAS 249 (1991)



The Evidence for DM

"bullet cluster" - NASA
astro-ph/0608247

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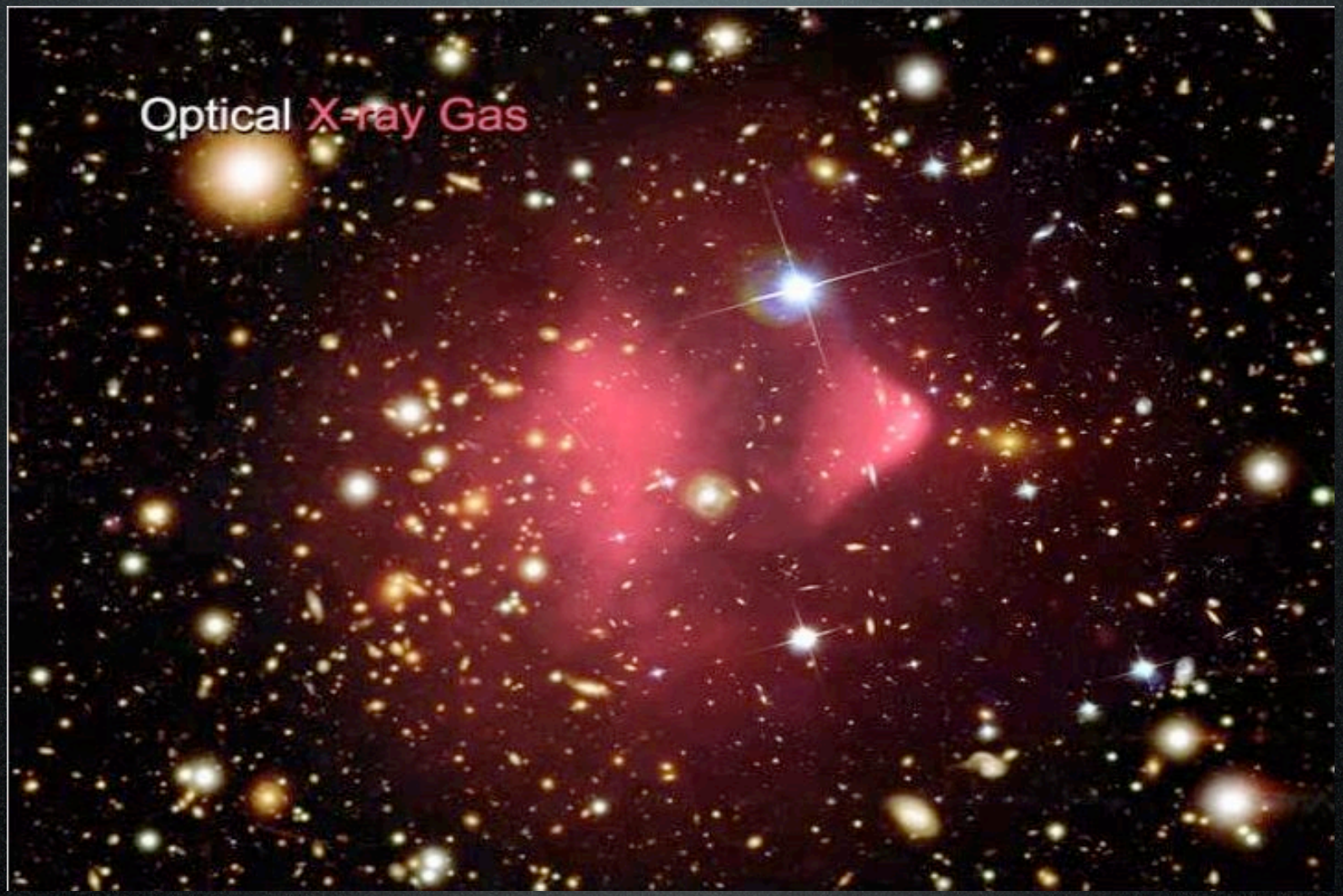

"bullet cluster" - NASA
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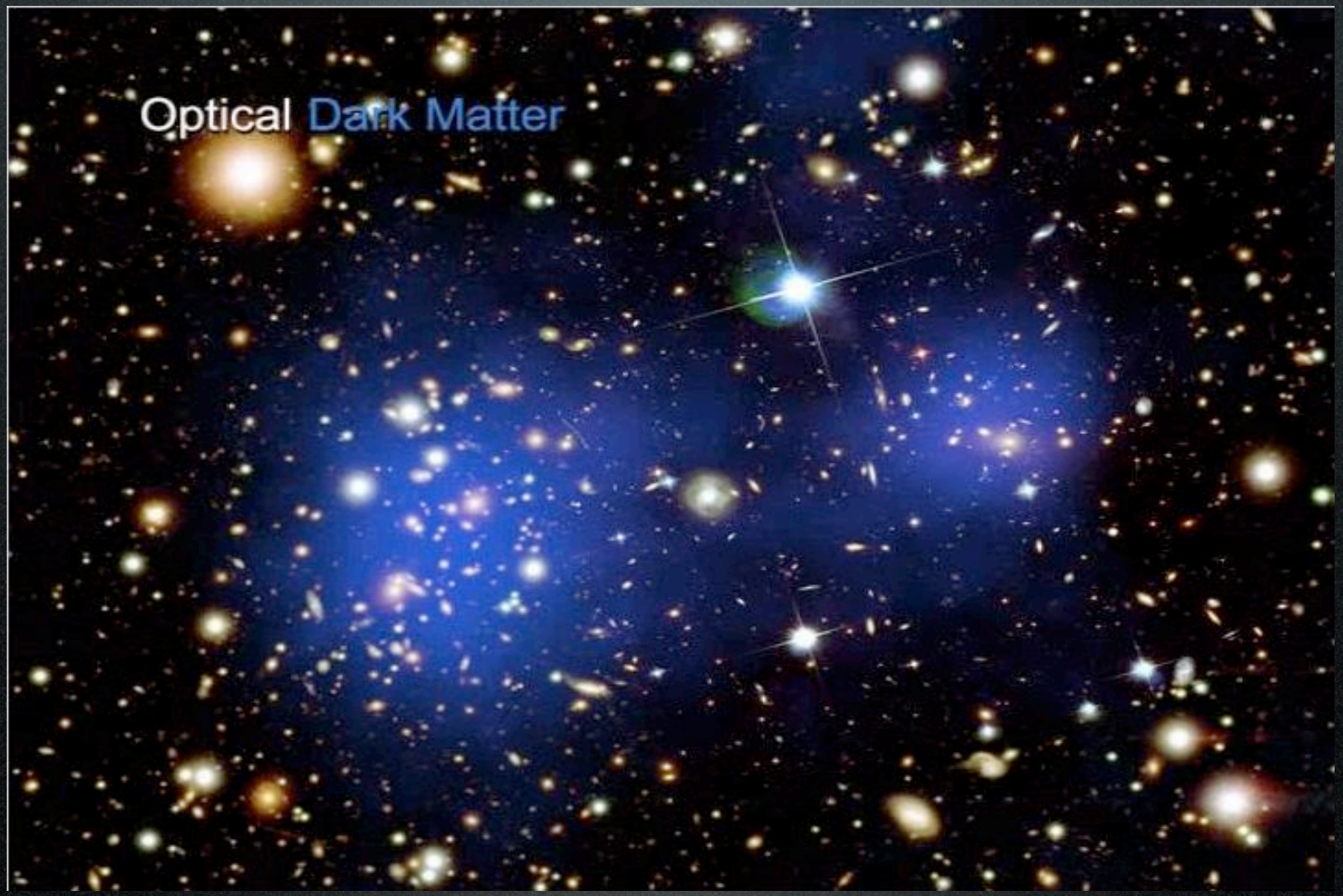

"bullet cluster" - NASA
astro-ph/0608247

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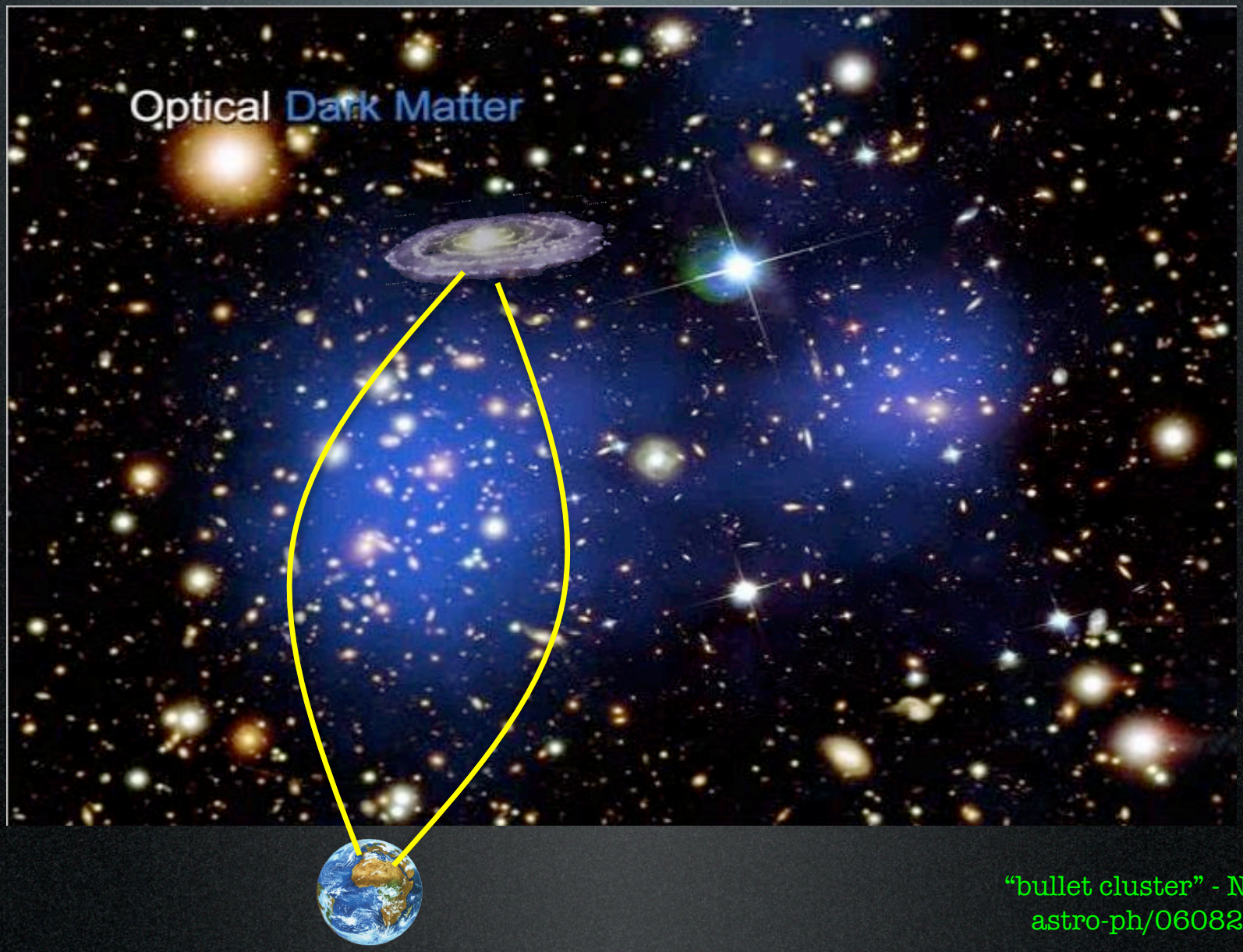

"bullet cluster" - NASA
astro-ph/0608247

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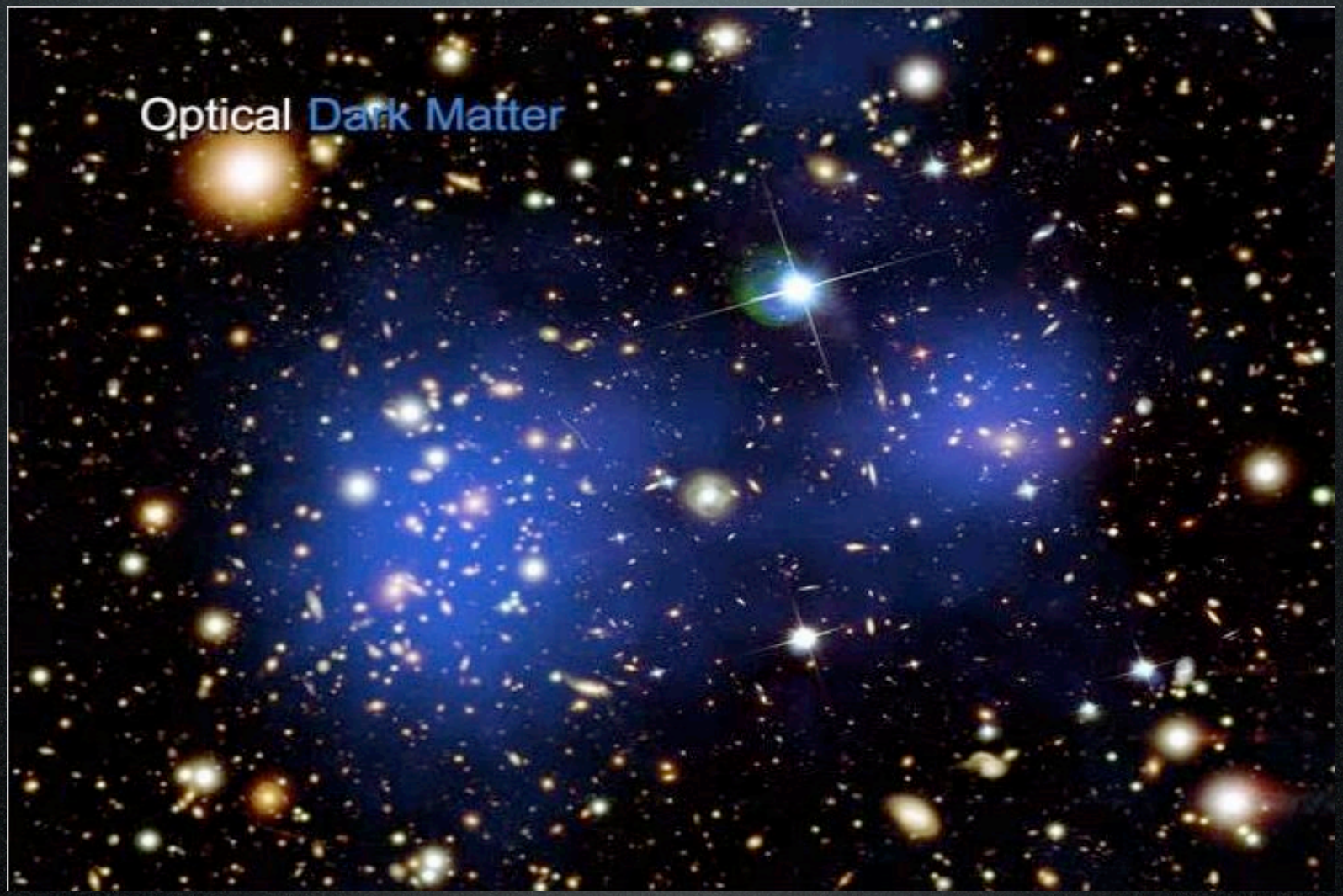

"bullet cluster" - NASA
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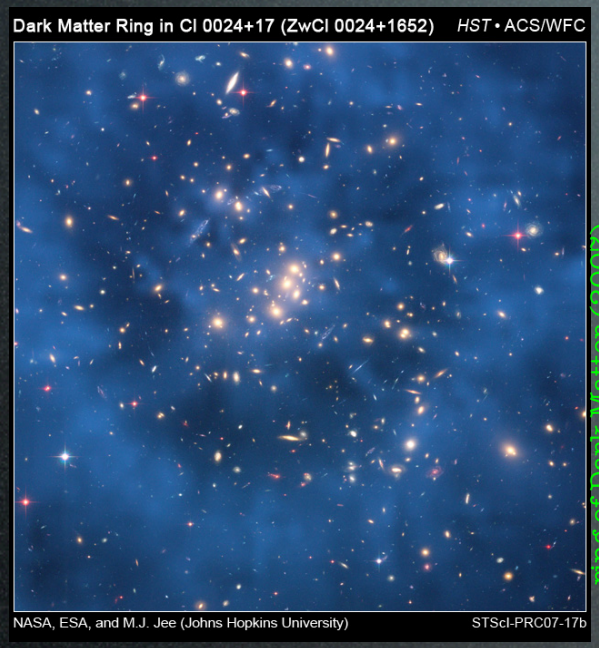
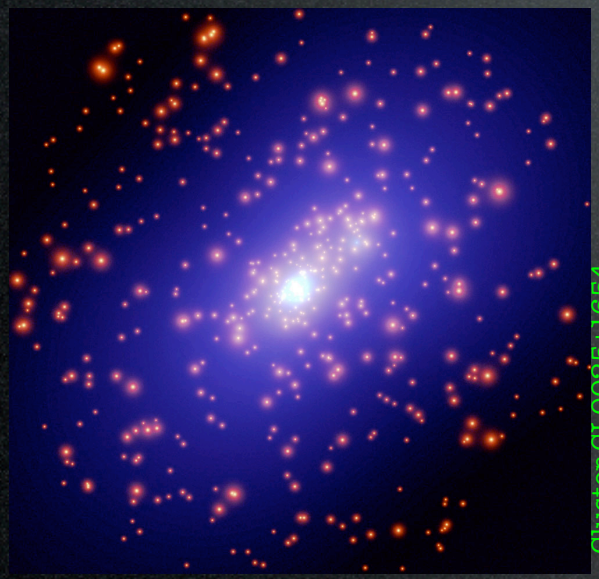
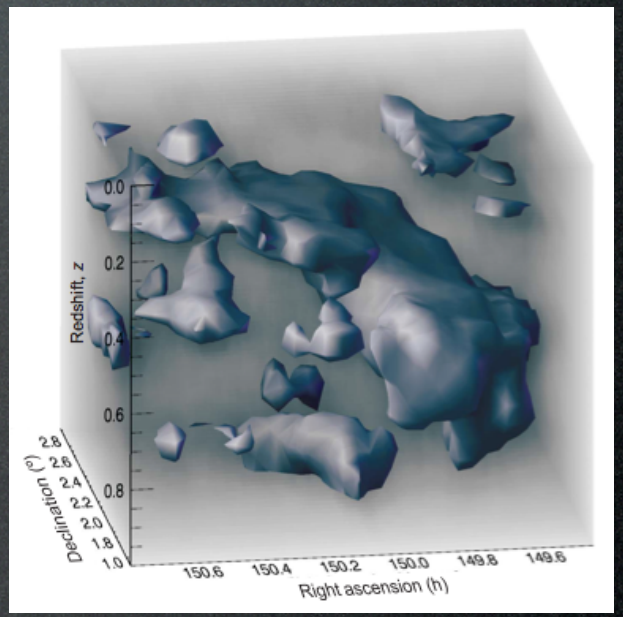


ring of Dark Matter (2007)

Abell 2744 NASA/ESA 2011



Cluster CL0025+1654



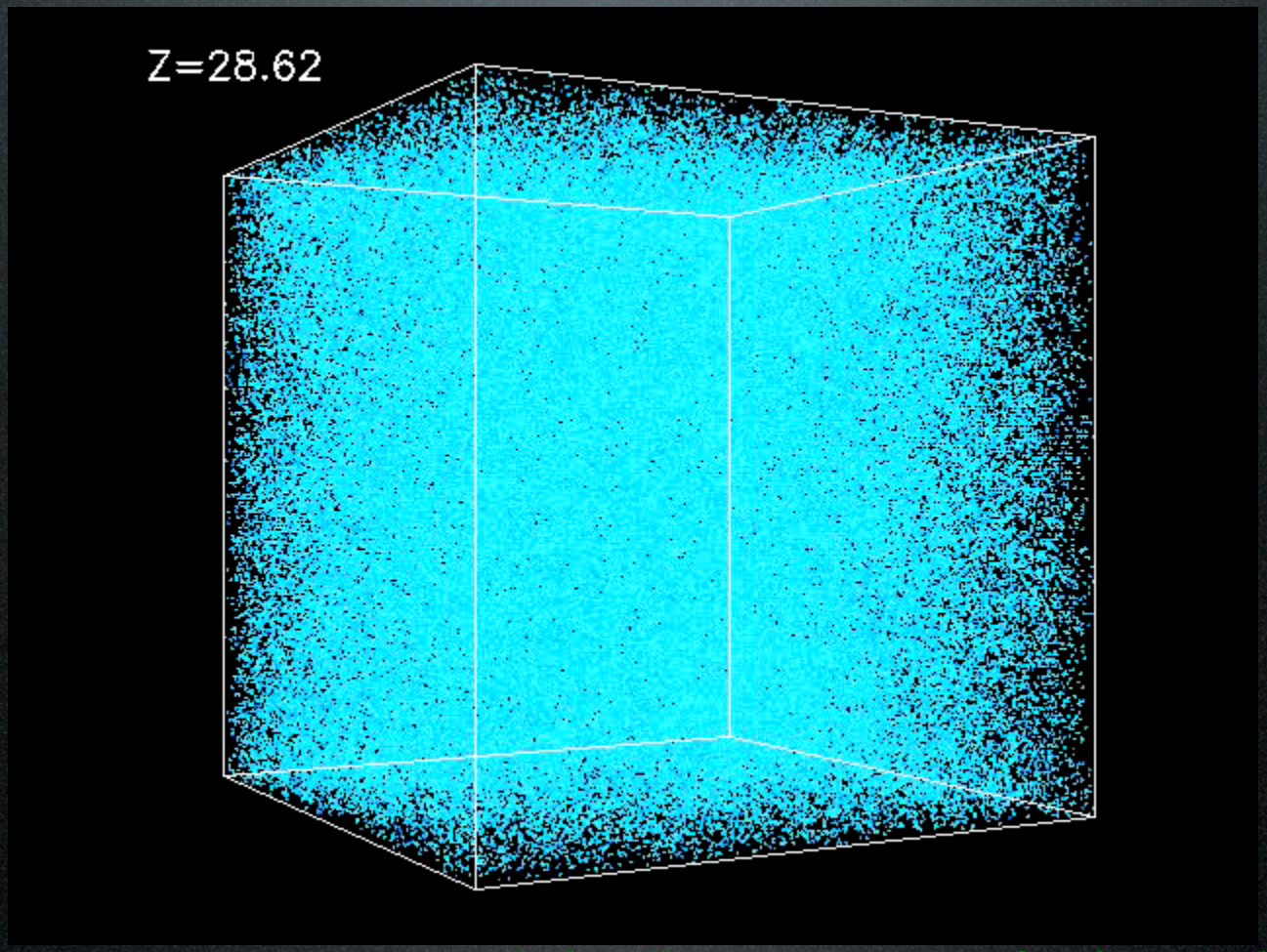
Massey et al, Nature 2007

DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box

DM N-body simulations

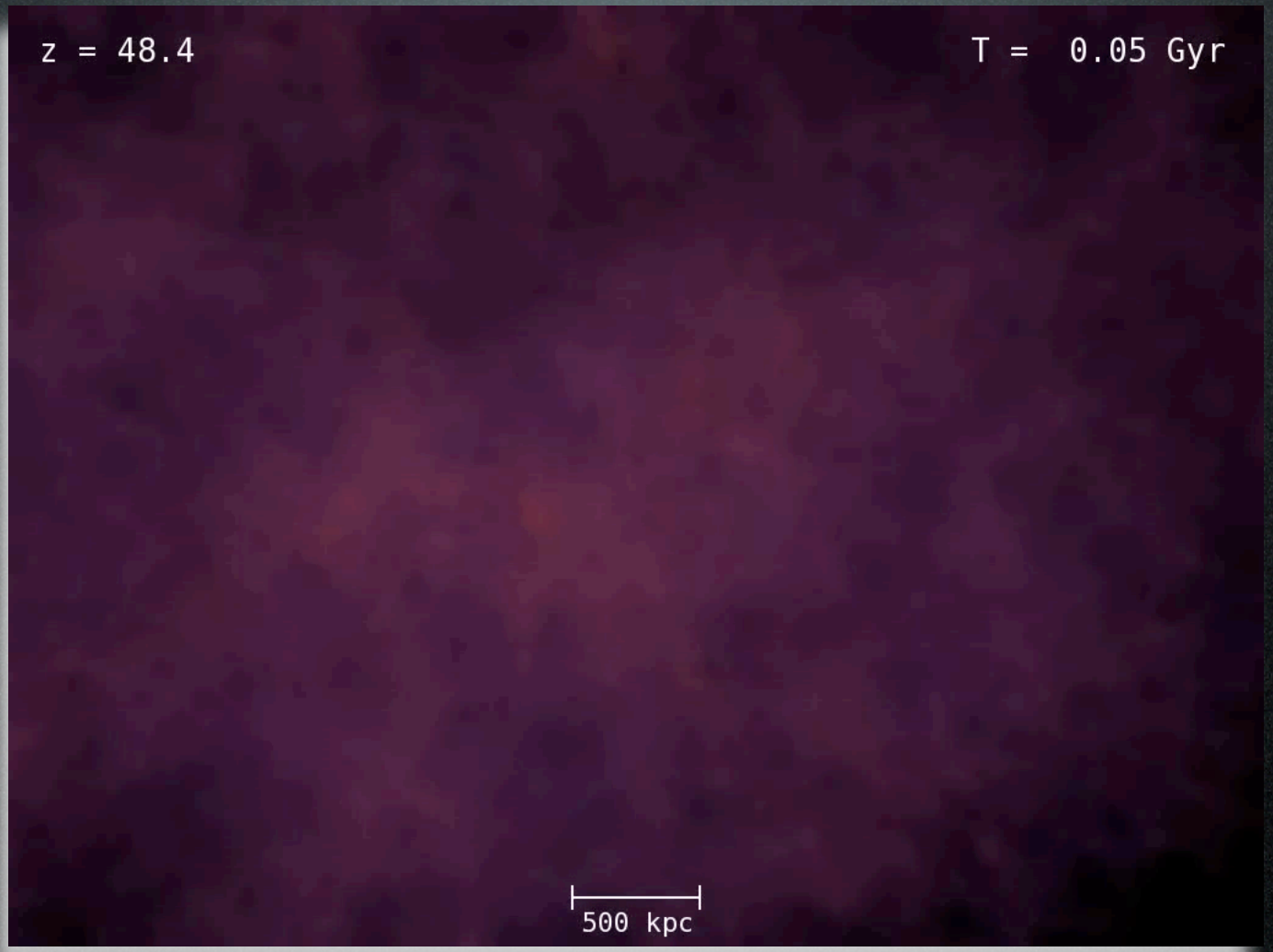
$2\ 10^6$ CDM particles, 43 Mpc cubic box



Andrey Kravtsov, cosmicweb.uchicago.edu

DM N-body simulations

Aquarius project of the VIRGO coll.:
$1.5\ 10^9$ CDM particles, single galactic halo

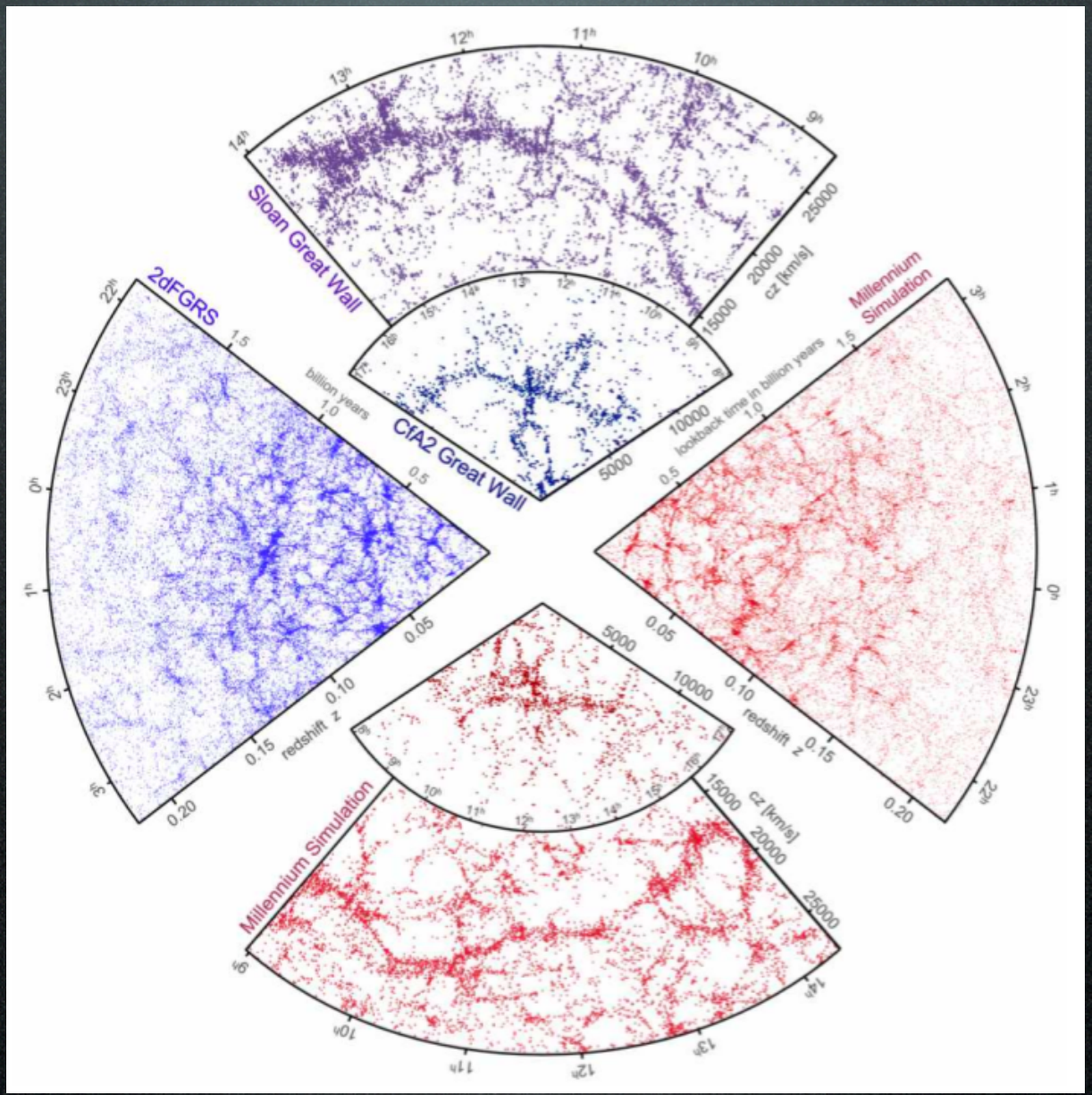


VIRGO coll., Aquarius project, www.mpa-garching.mpg.de/aquarius/

DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies, 2 billion lyr



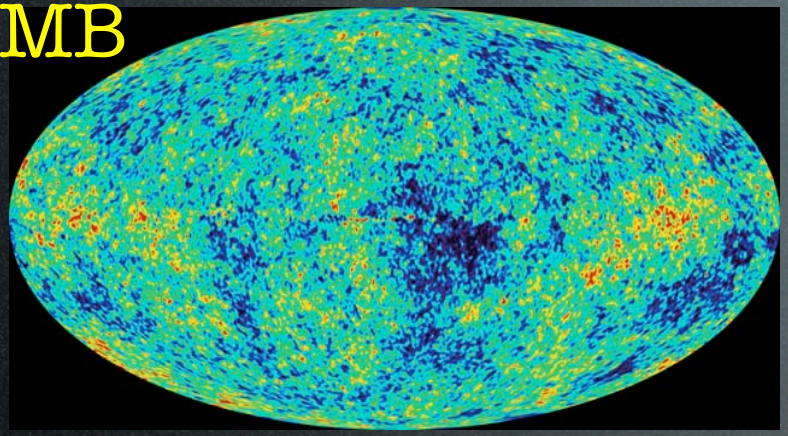
Springel, Frenk, White, Nature 440 (2006)

Of course, you have to infer galaxies within the DM simulation

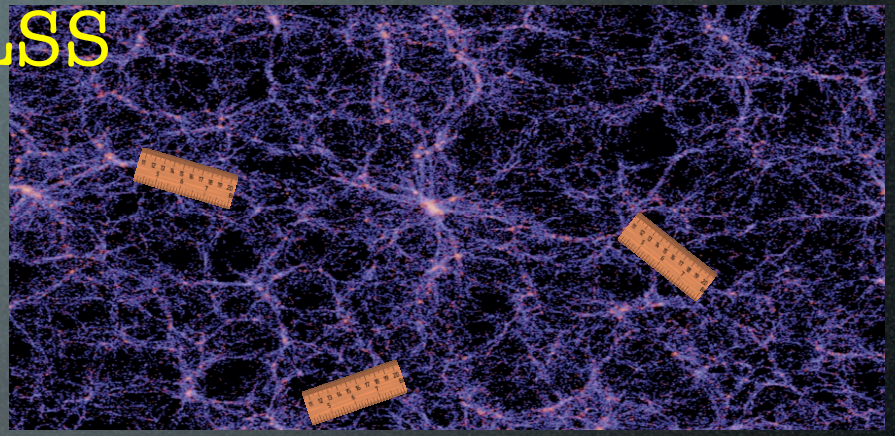
Millennium: 10^{10} particles, 500 h^{-1} Mpc

CMB & Large Scale Structure

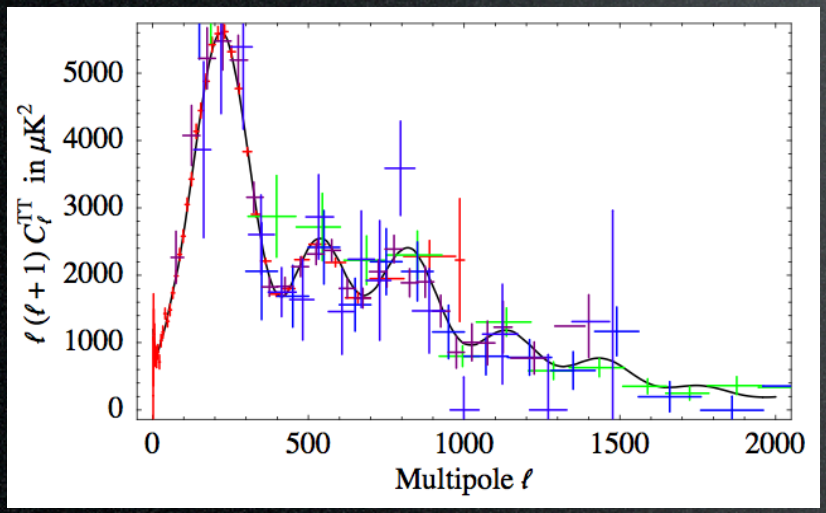
CMB

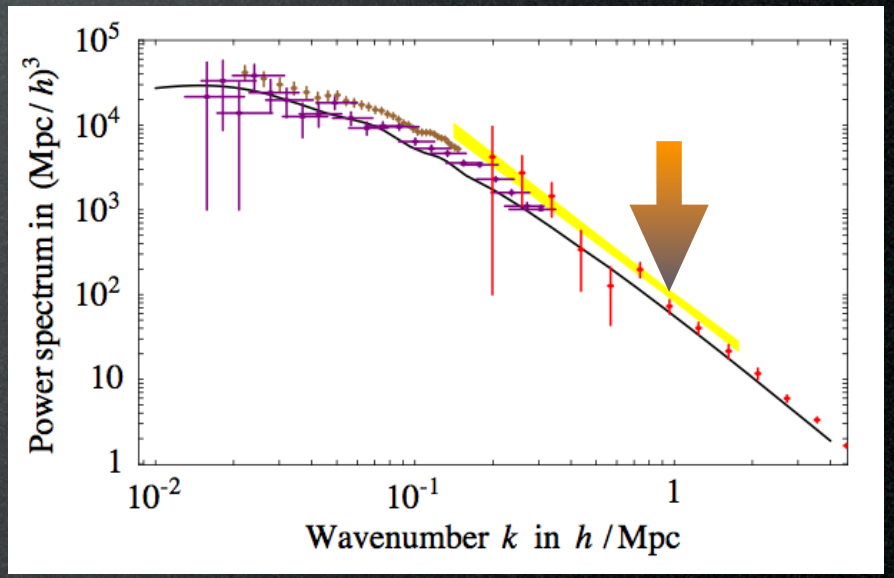


LSS



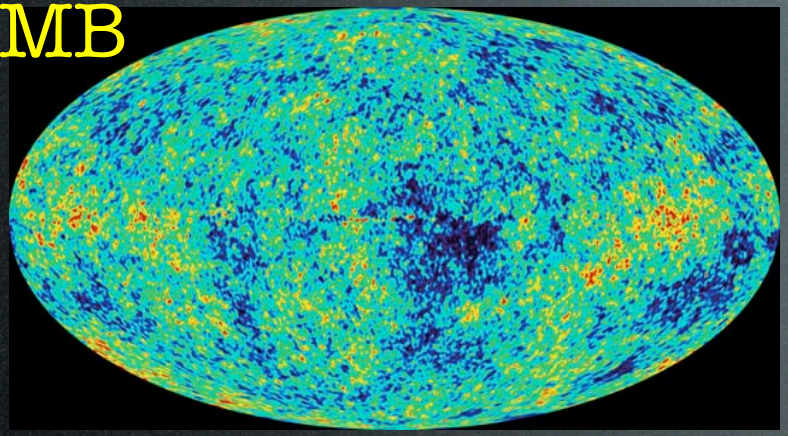
LSS matter power spectrum



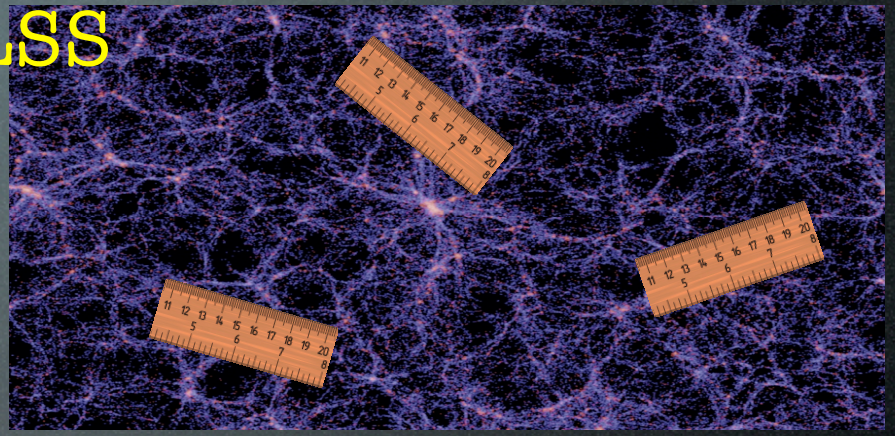


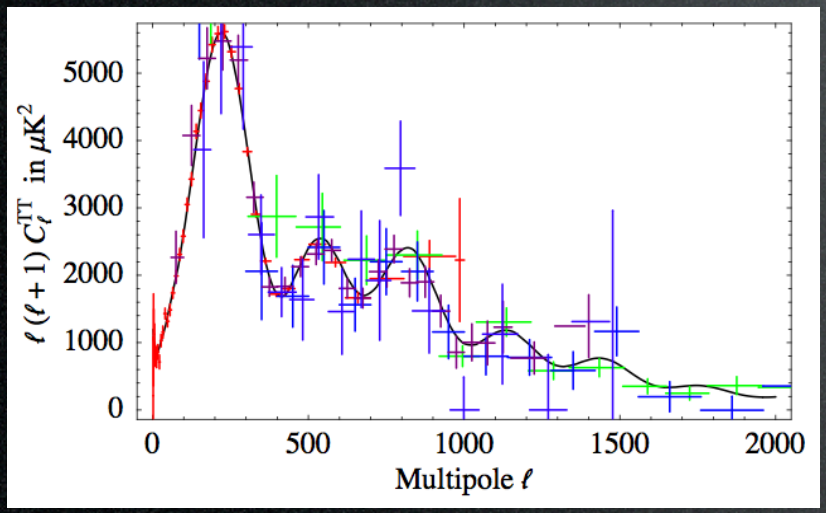
CMB & Large Scale Structure

CMB

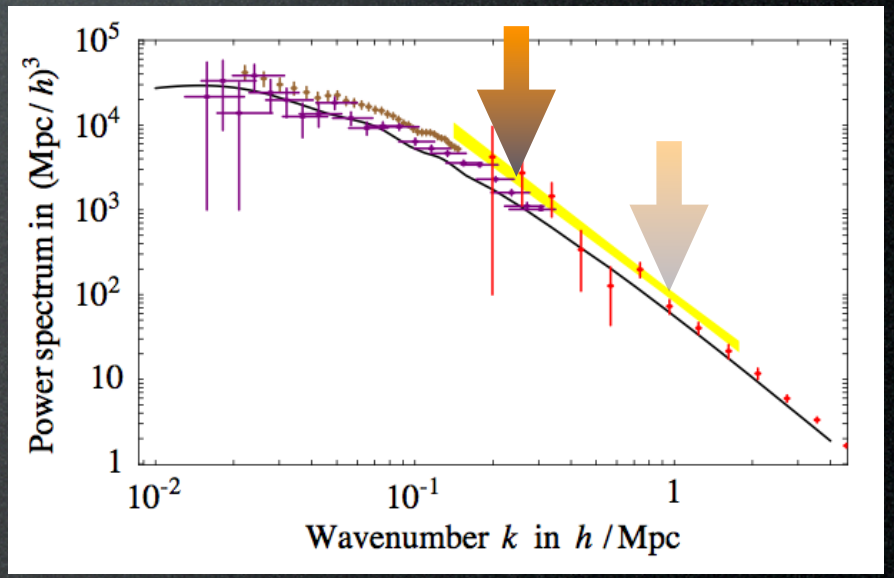


LSS



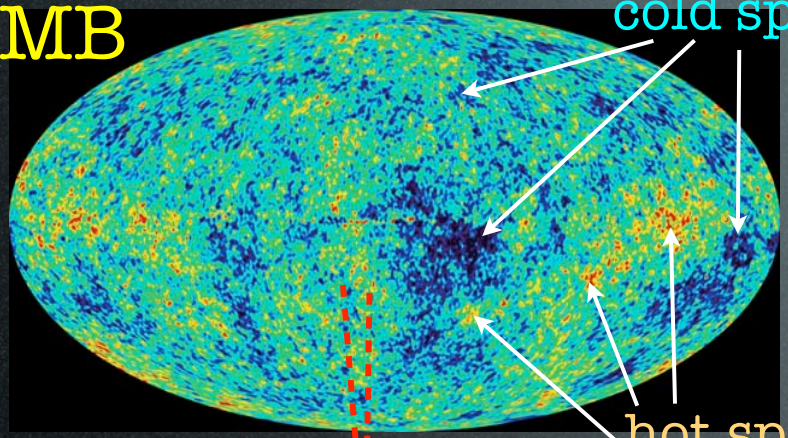


LSS matter power spectrum



CMB & Large Scale Structure

CMB

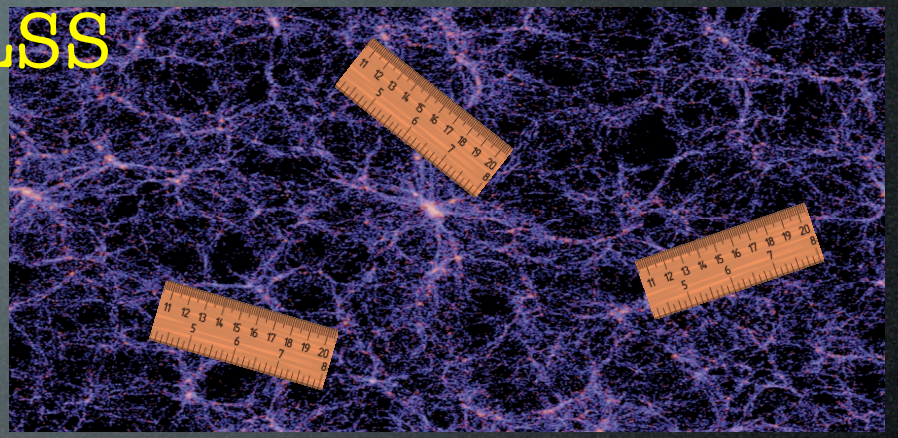


$T = 2.725° K$

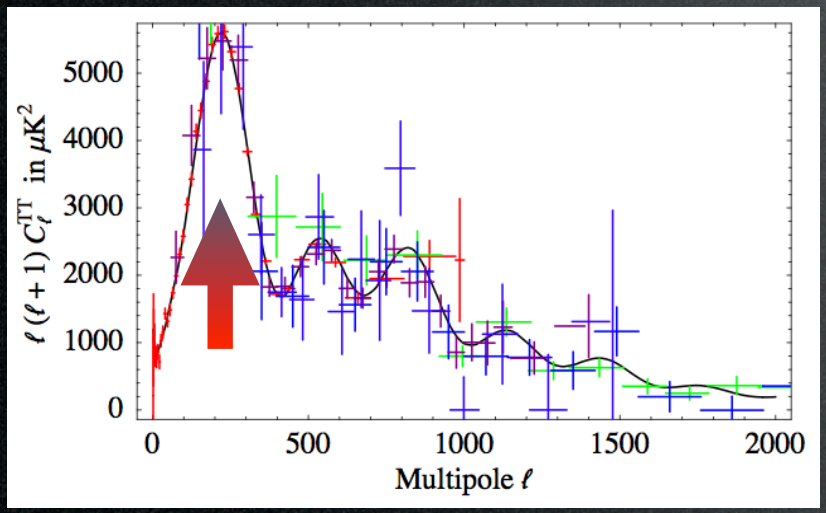
$\frac{\delta T}{T} \sim 10^{-5}$

$1°$

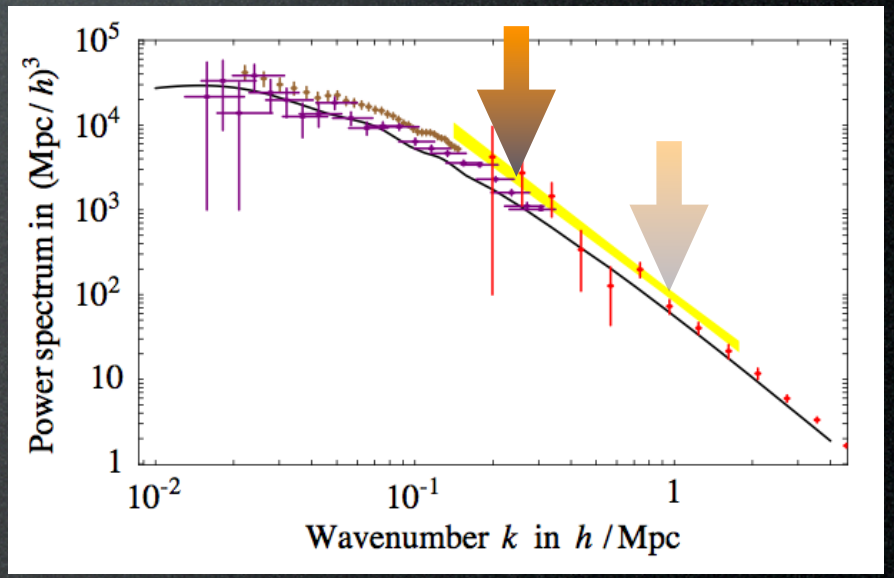
LSS



CMB spectrum

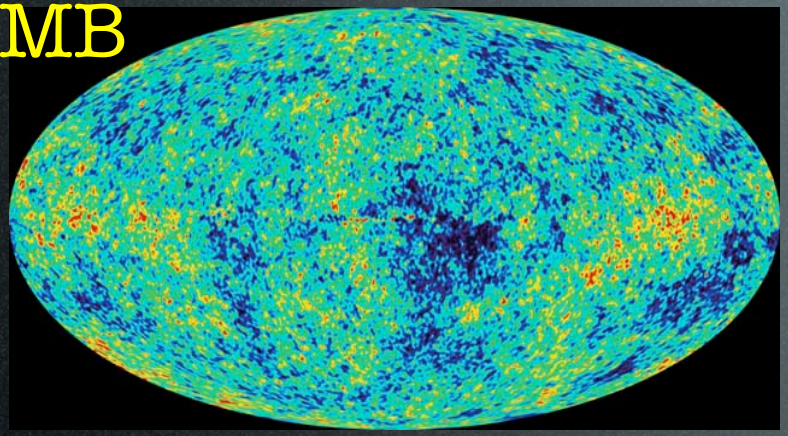


LSS matter power spectrum

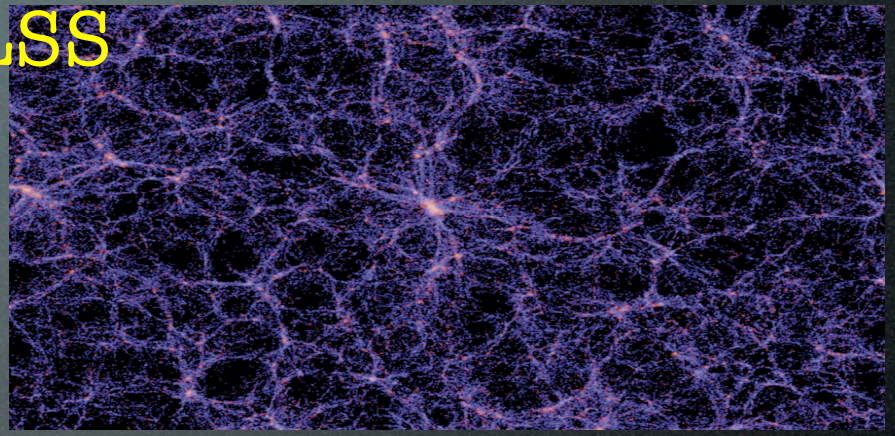


CMB & Large Scale Structure

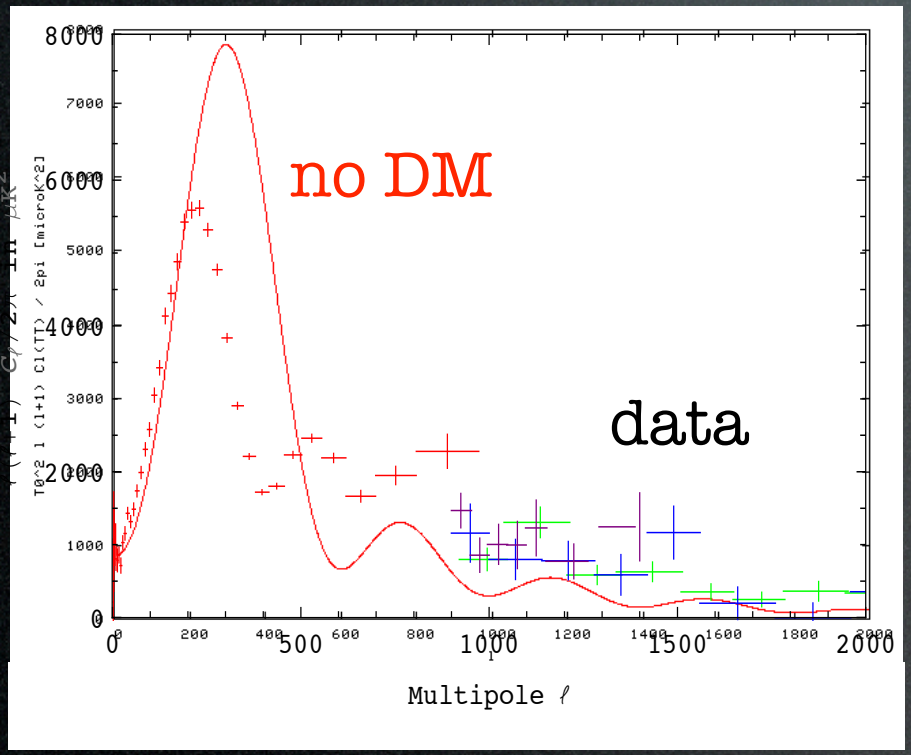
CMB



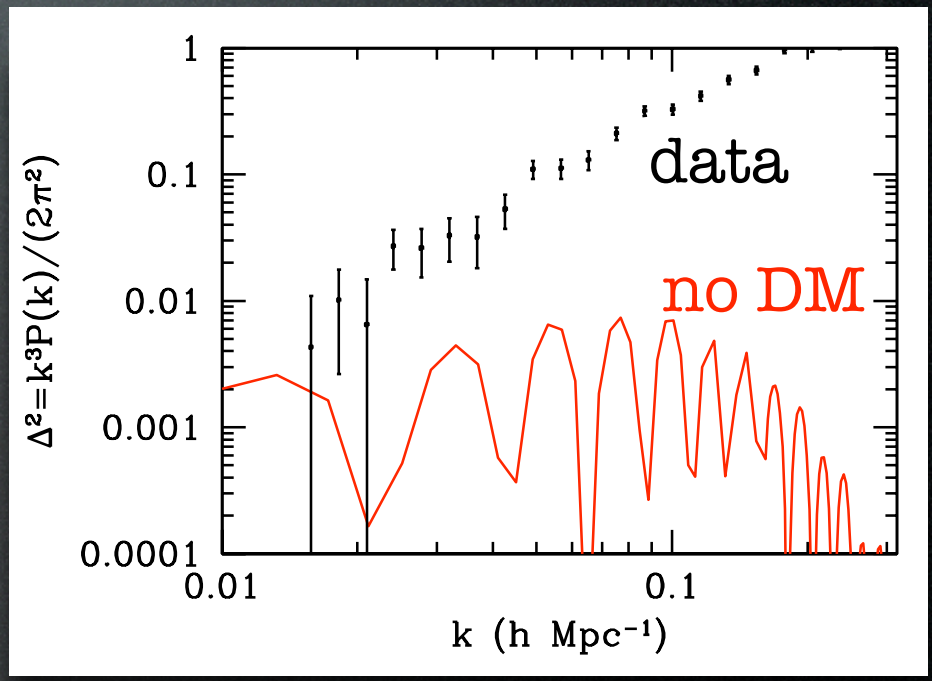
LSS



How would the power spectra be without DM? (and no other extra ingredient)



CAMB online



Dodelson, Liguori 2006

(in particular: no DM => no 3rd peak!)

(you need DM to gravitationally "catalyse" structure formation)

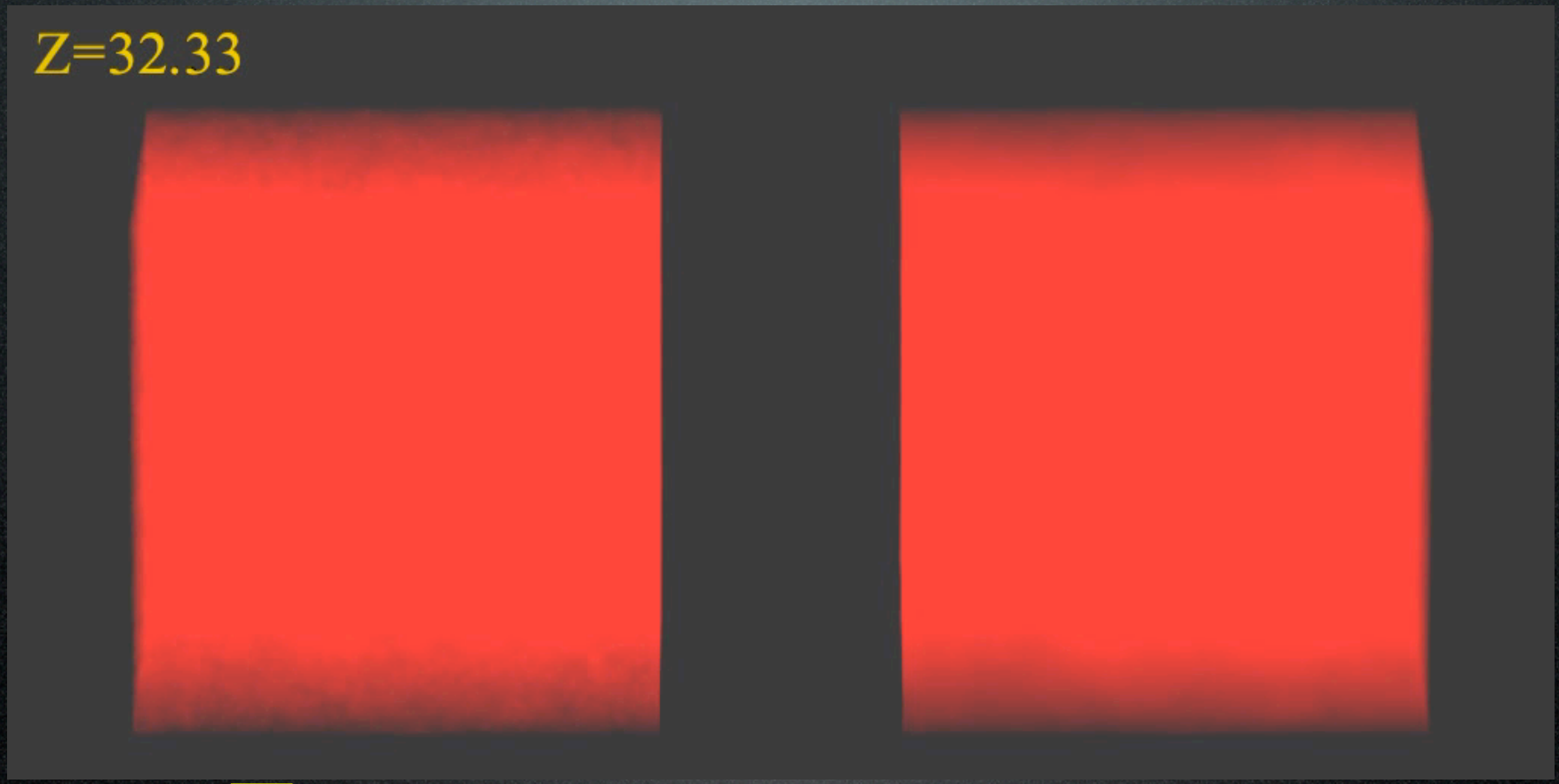
Neutrino HDM in LSS

$\sum m_\nu = 0$ $\sum m_\nu = 6.9$ eV

ΛCDM - Gadget2 - 768 Mpc^3

T.Haugboelle, S.Hannestad, Aarhus University

Neutrino HDM in LSS

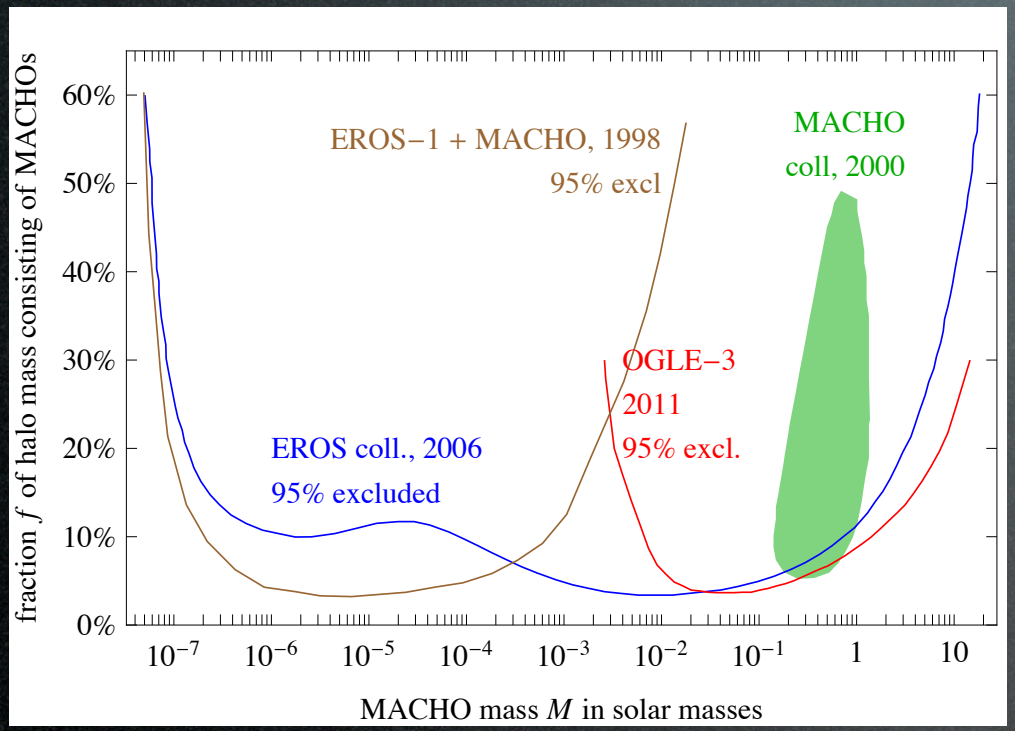


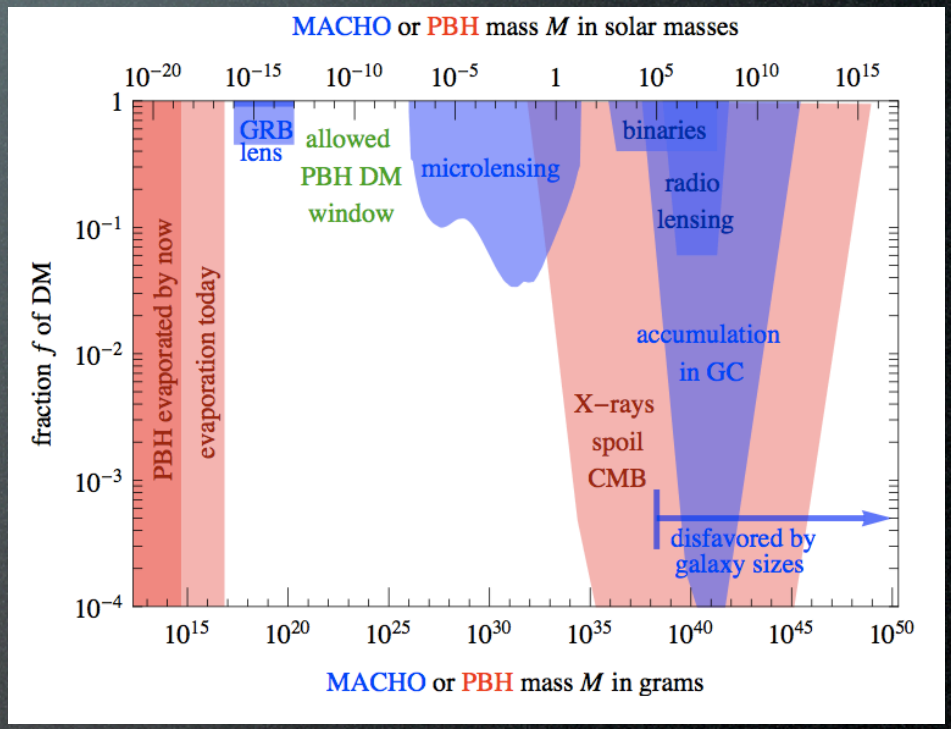
$\sum m_\nu = 0$ $\sum m_\nu = 6.9$ eV

ΛCDM - Gadget2 - 768 Mpc^3

T.Haugboelle, S.Hannestad, Aarhus University

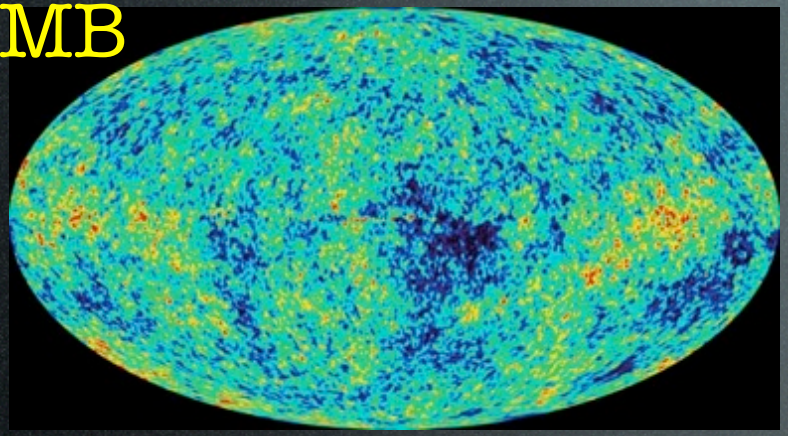
MACHOs or PBHs as DM



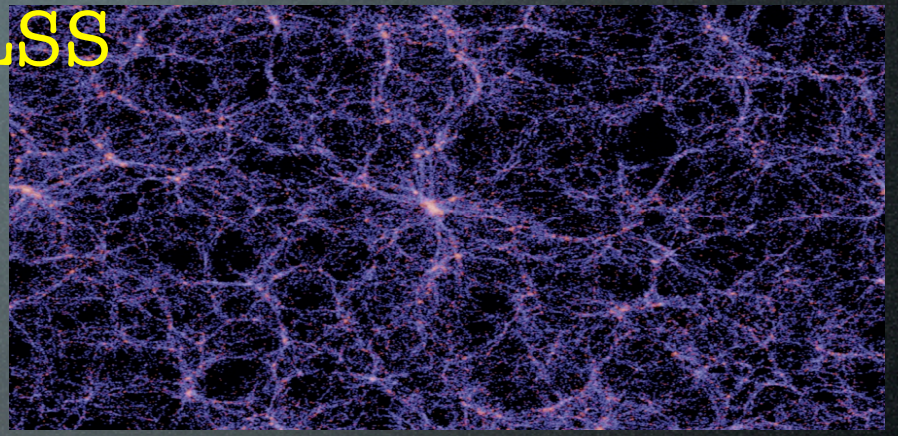


CMB & Large Scale Structure

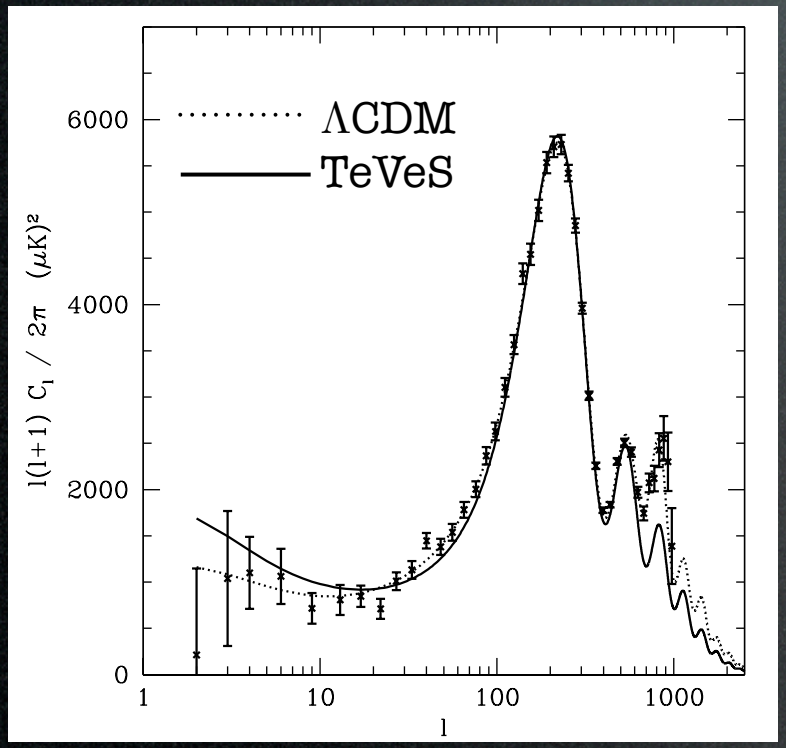
CMB



LSS

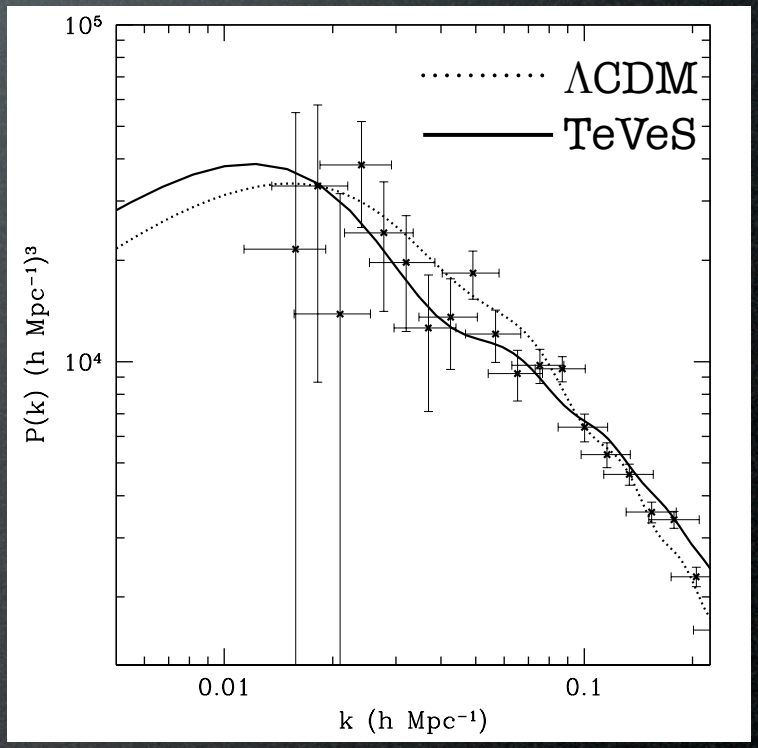


How would the power spectra be in MOND/TeVeS, without DM ?



C.Skordis, Review, 0903.3602

(in particular: no DM => no 3rd peak!)

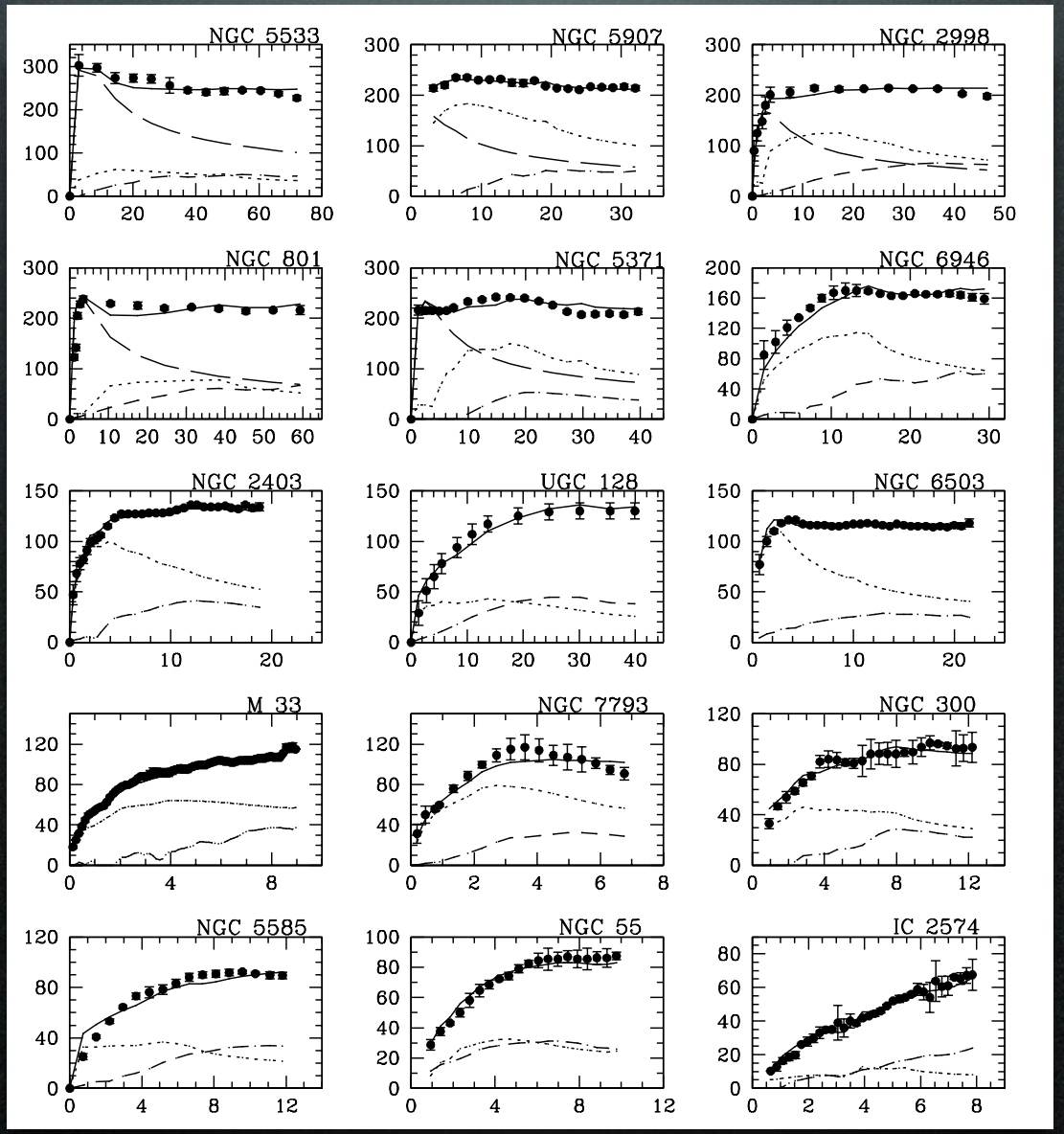


C.Skordis, Review, 0903.3602

(here you can make it)

MOND? TeVeS?

fits rotation curves very well



Sanders, McGaugh, Ann. Rev. AA, 2002

Indirect Detection

DM halo profiles

From N-body numerical simulations:

$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

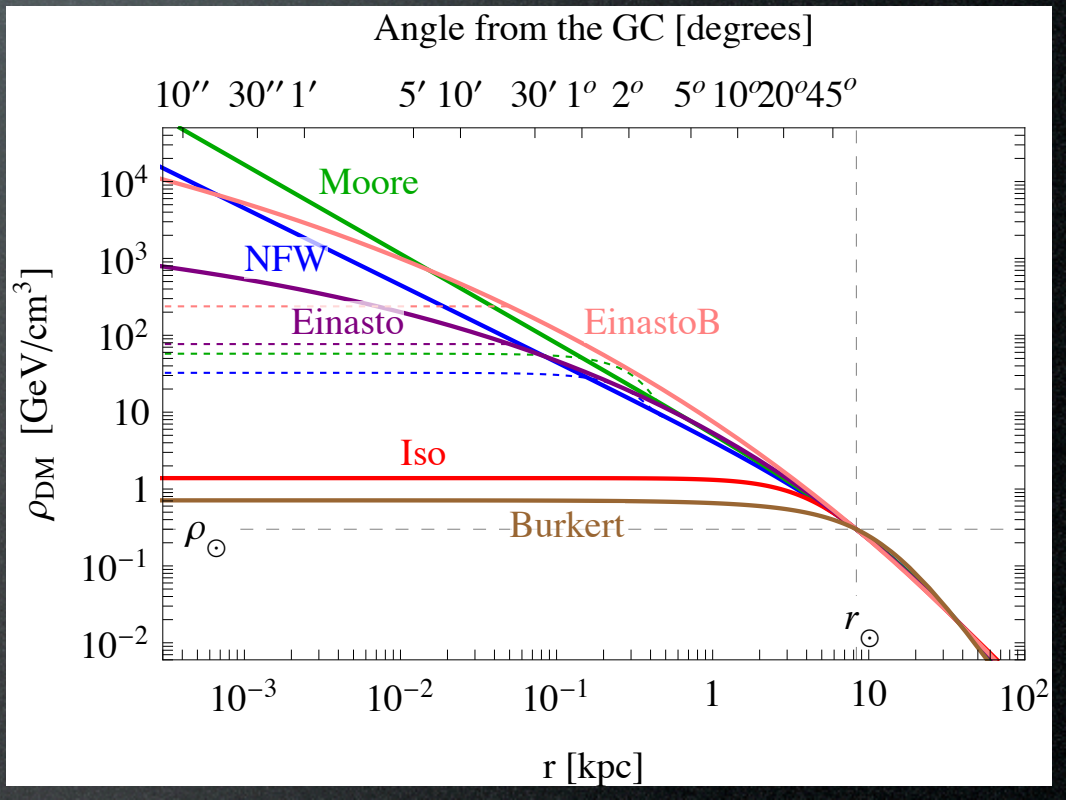
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

At small r: $\rho(r) \propto 1/r^{\gamma}$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105



6 profiles:

cuspy: NFW, Moore

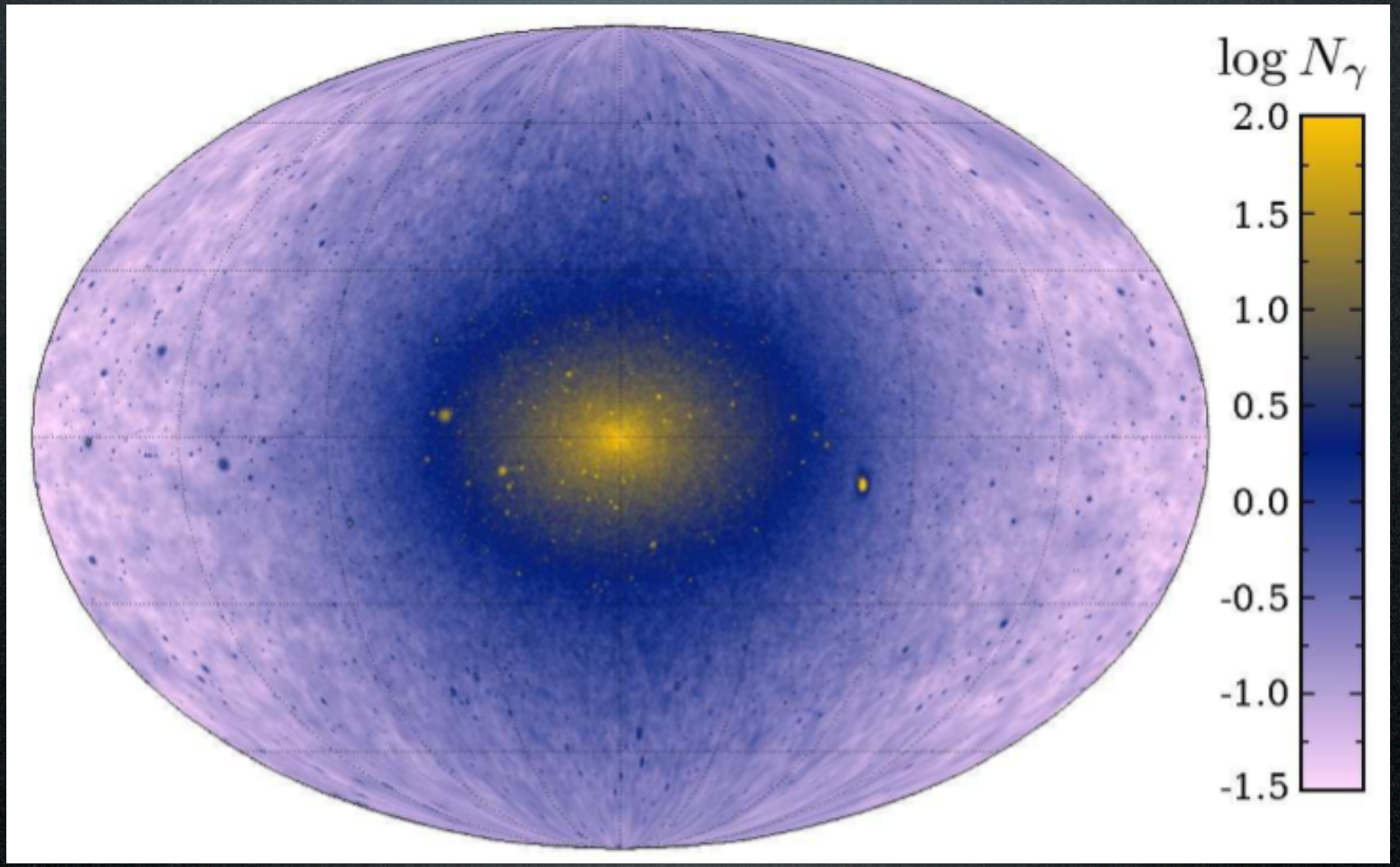
mild: Einasto

smooth: isothermal, Burkert

EinastoB = steepened Einasto

(effect of baryons?)

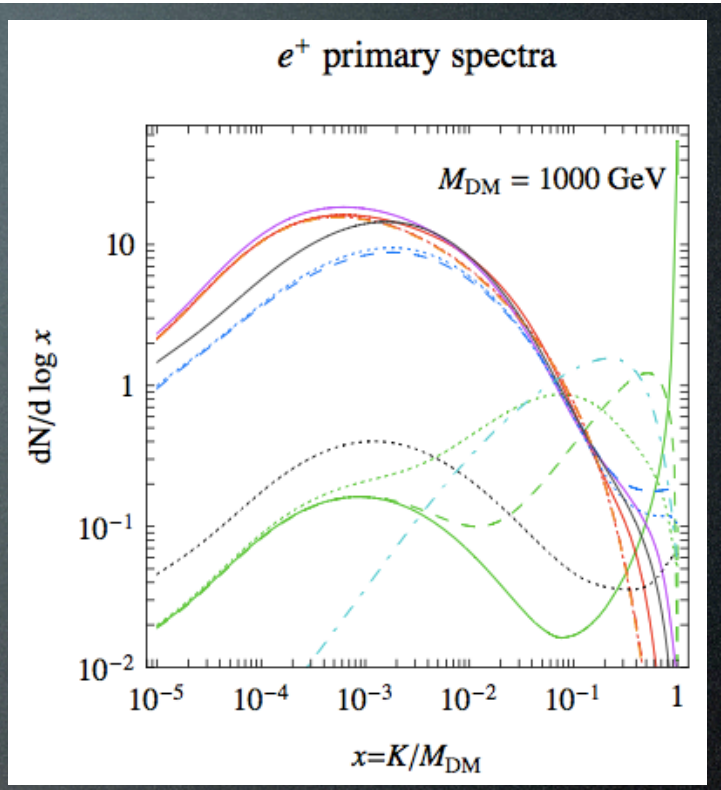
DM halo profiles

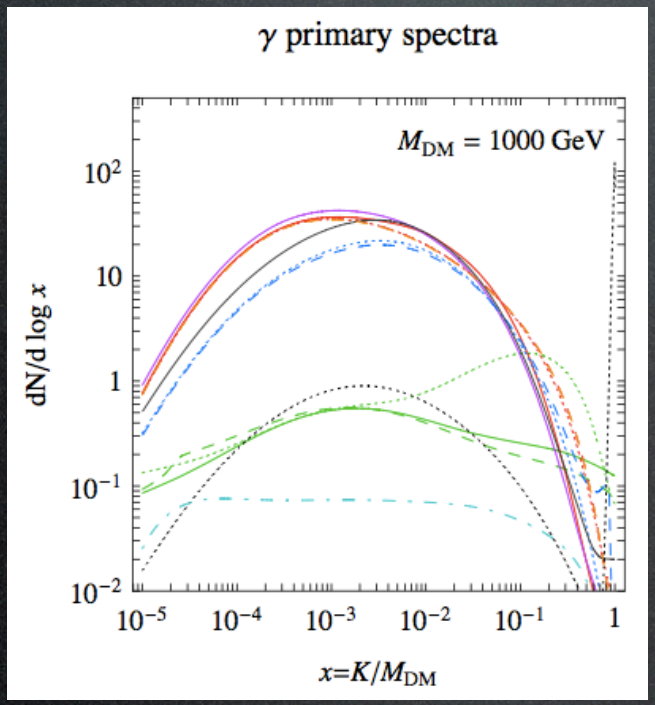


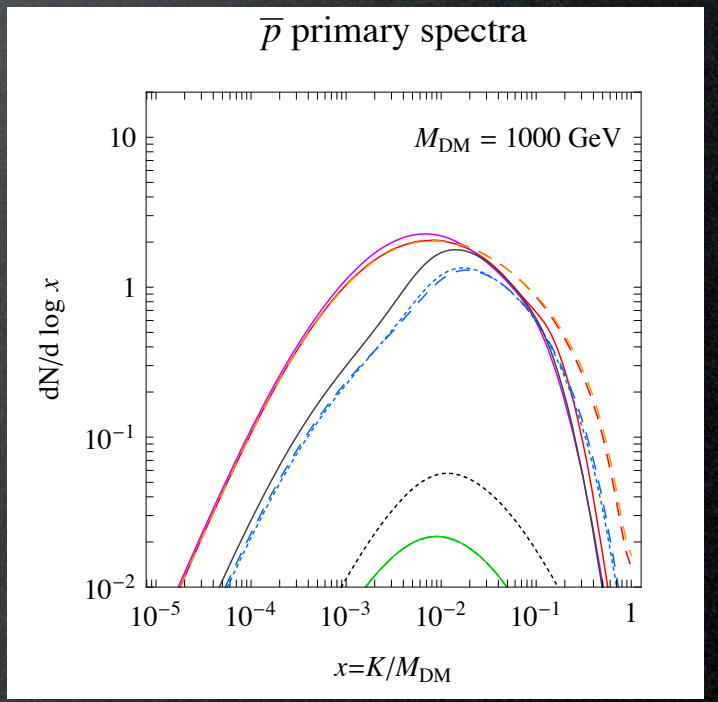
Kuhlen, Diemand, Madau 2007

Primary spectra

1012.4515 [hep-ph]



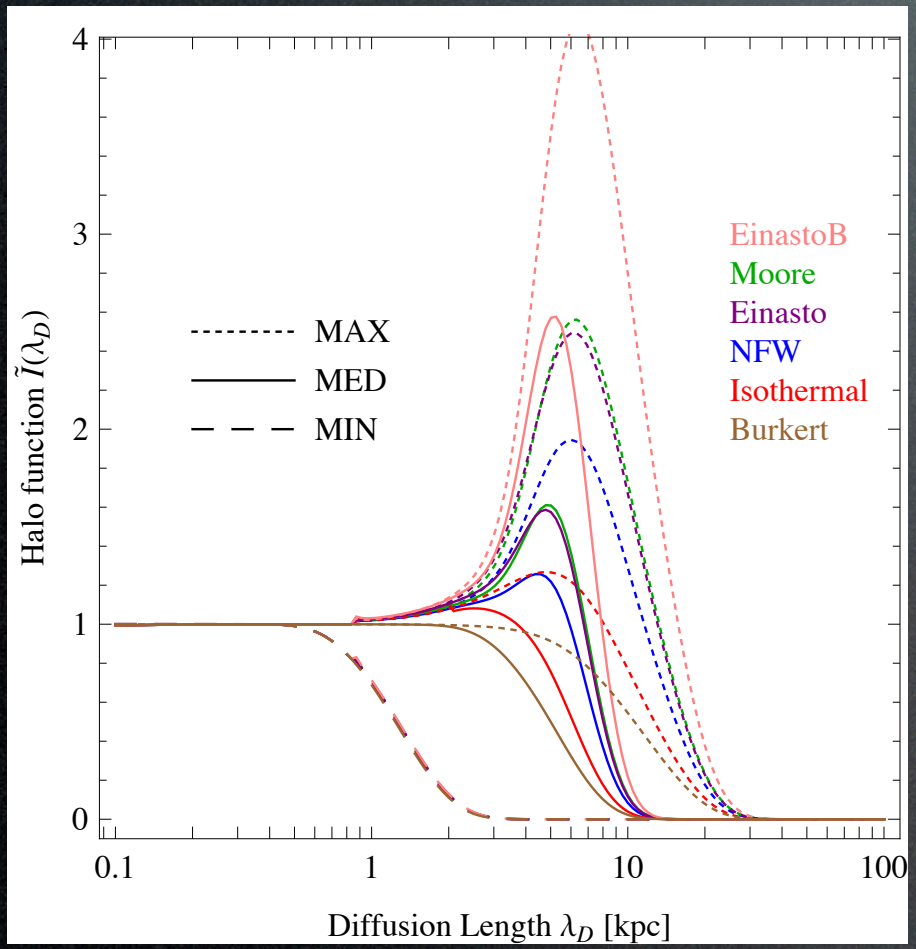




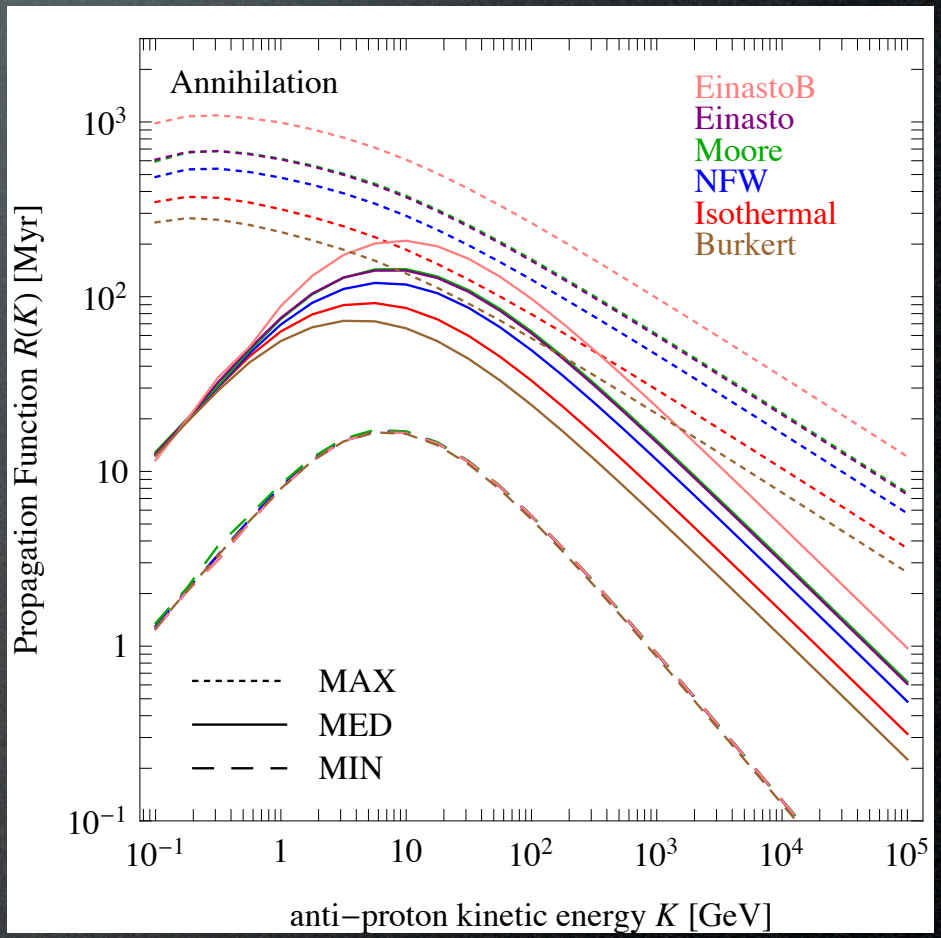
Propagated charged CRs

Model	Electrons or positrons δ	$\mathcal{K}_0$ [kpc^2/Myr]	Antiprotons (and antideuterons) δ	$\mathcal{K}_0$ [kpc^2/Myr]	$V_{\rm conv}$ [km/s]	L [kpc]
MIN	0.55	0.00595	0.85	0.0016	13.5	1
MED	0.70	0.0112	0.70	0.0112	12	4
MAX	0.46	0.0765	0.46	0.0765	5	15

electrons/positrons

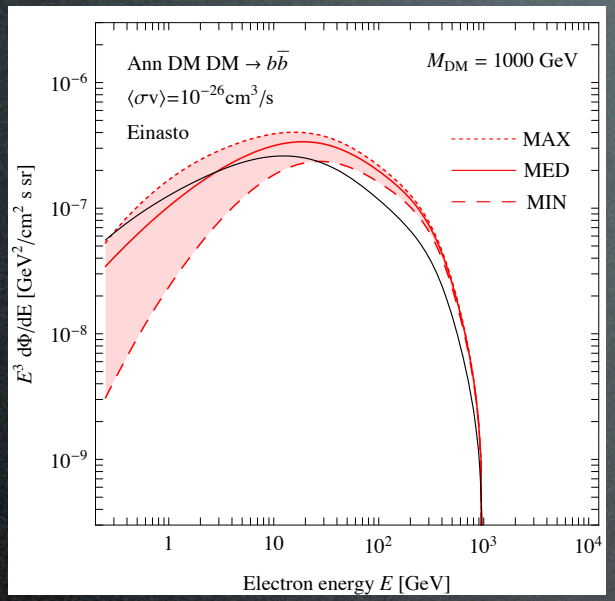


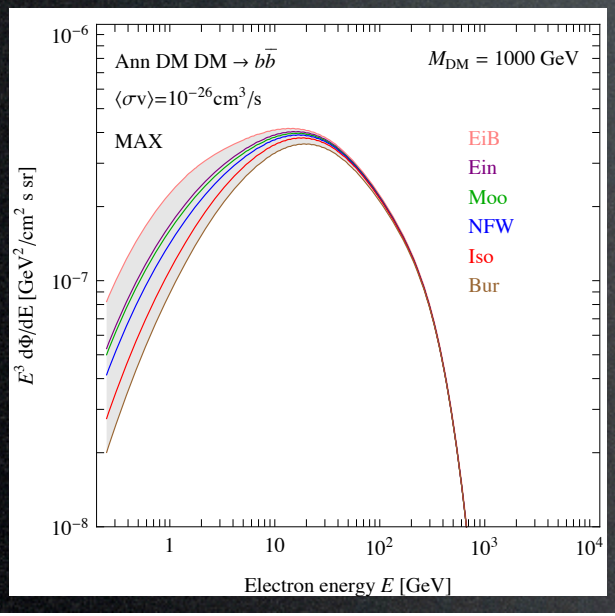
antiprotons



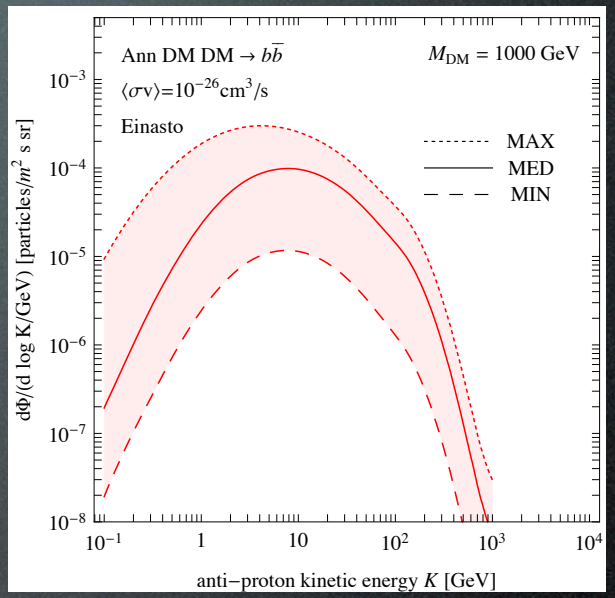
Propagated charged CRs

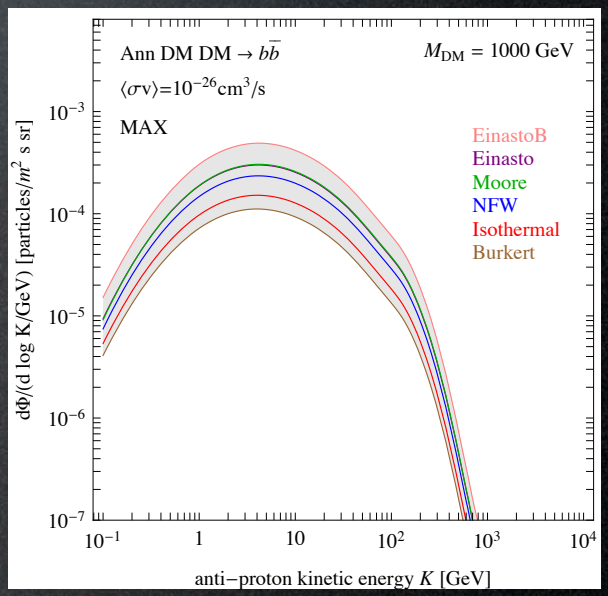
electrons/positrons





antiprotons



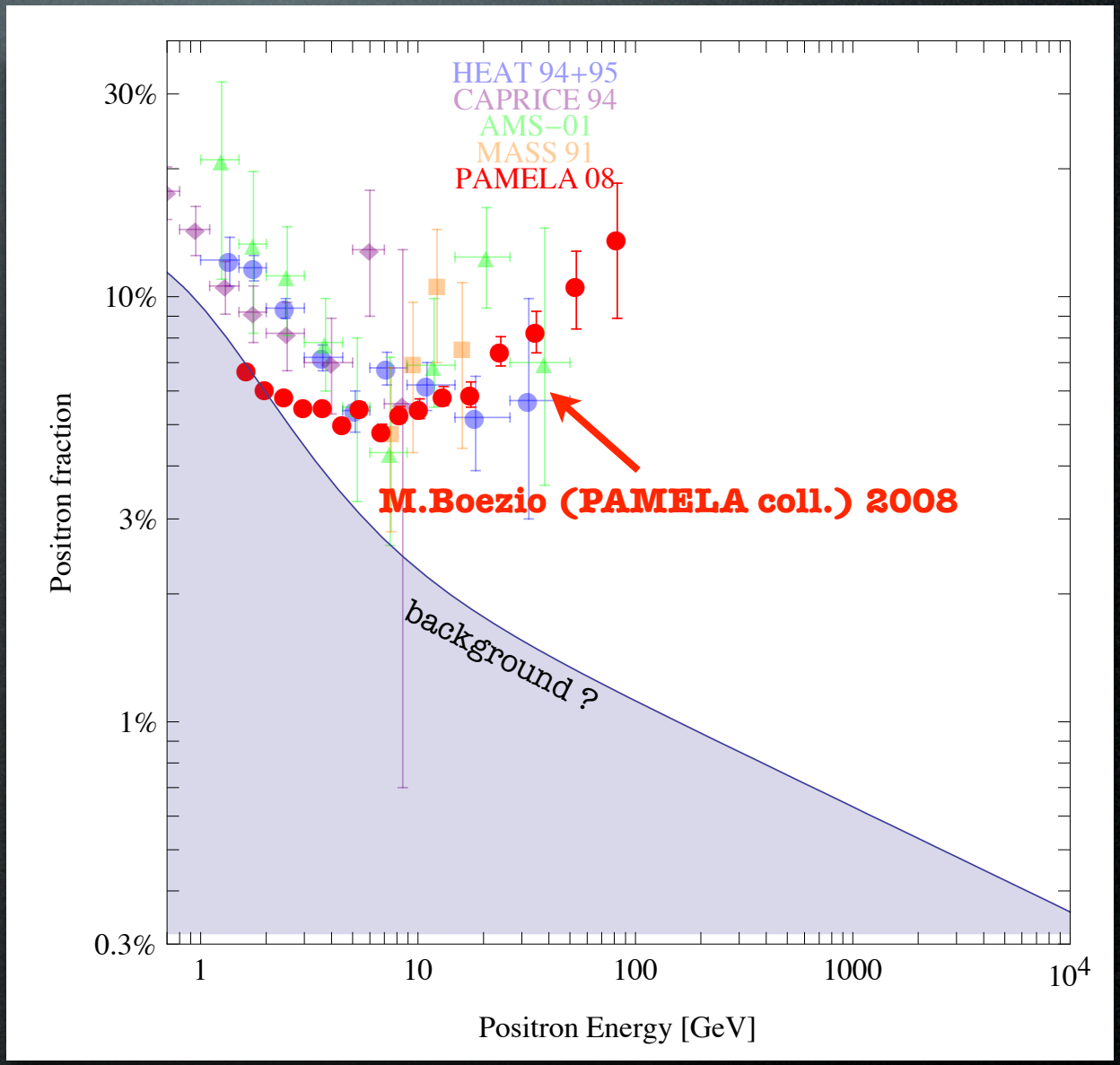


Charged particles

Positrons from PAMELA:

- steep e^+ excess above 10 GeV!
- very large flux!

positron fraction: $\dfrac{e^+}{e^+ + e^-}$

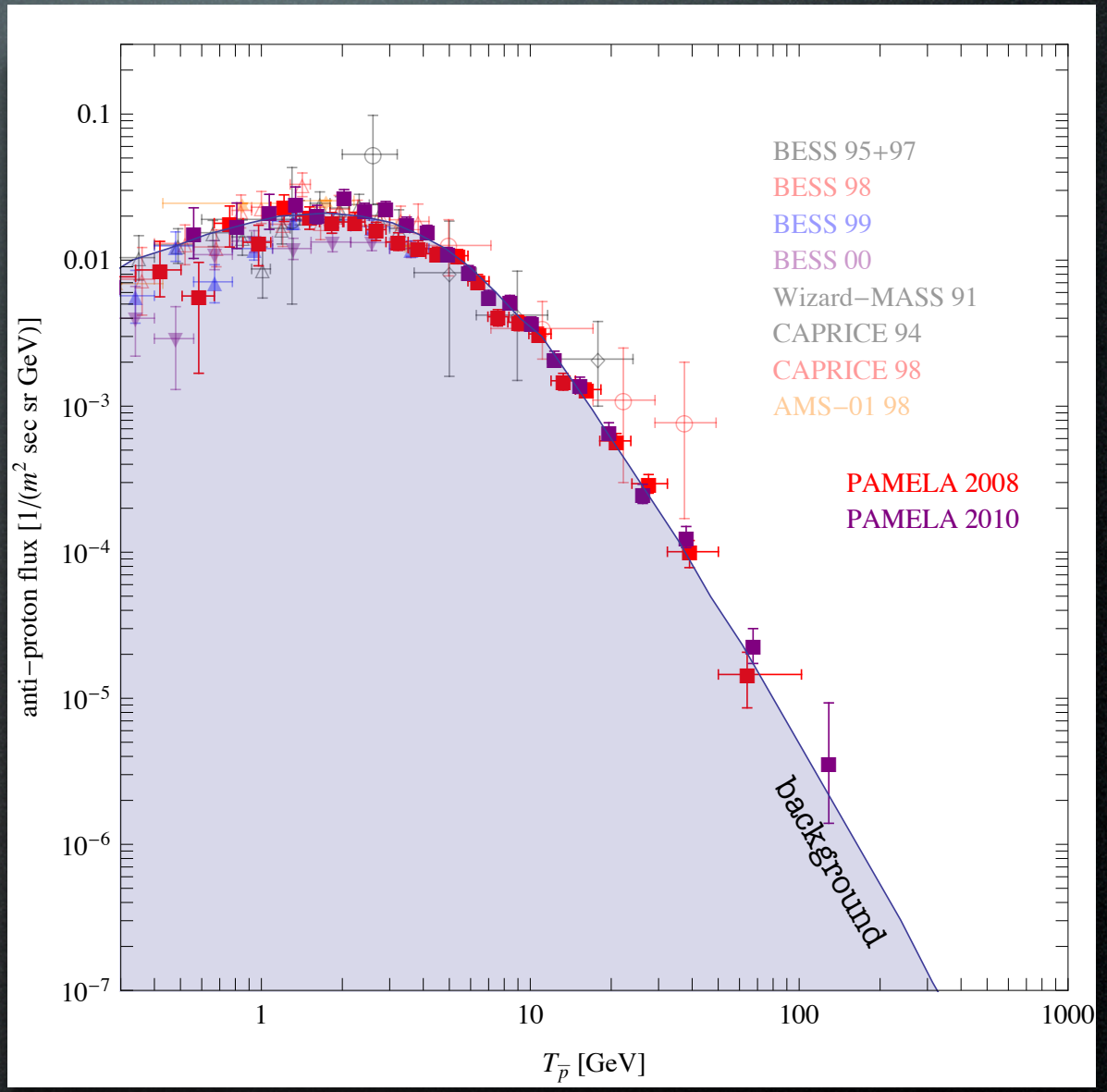


Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

Charged particles

Antiprotons from PAMELA:

- consistent with the background

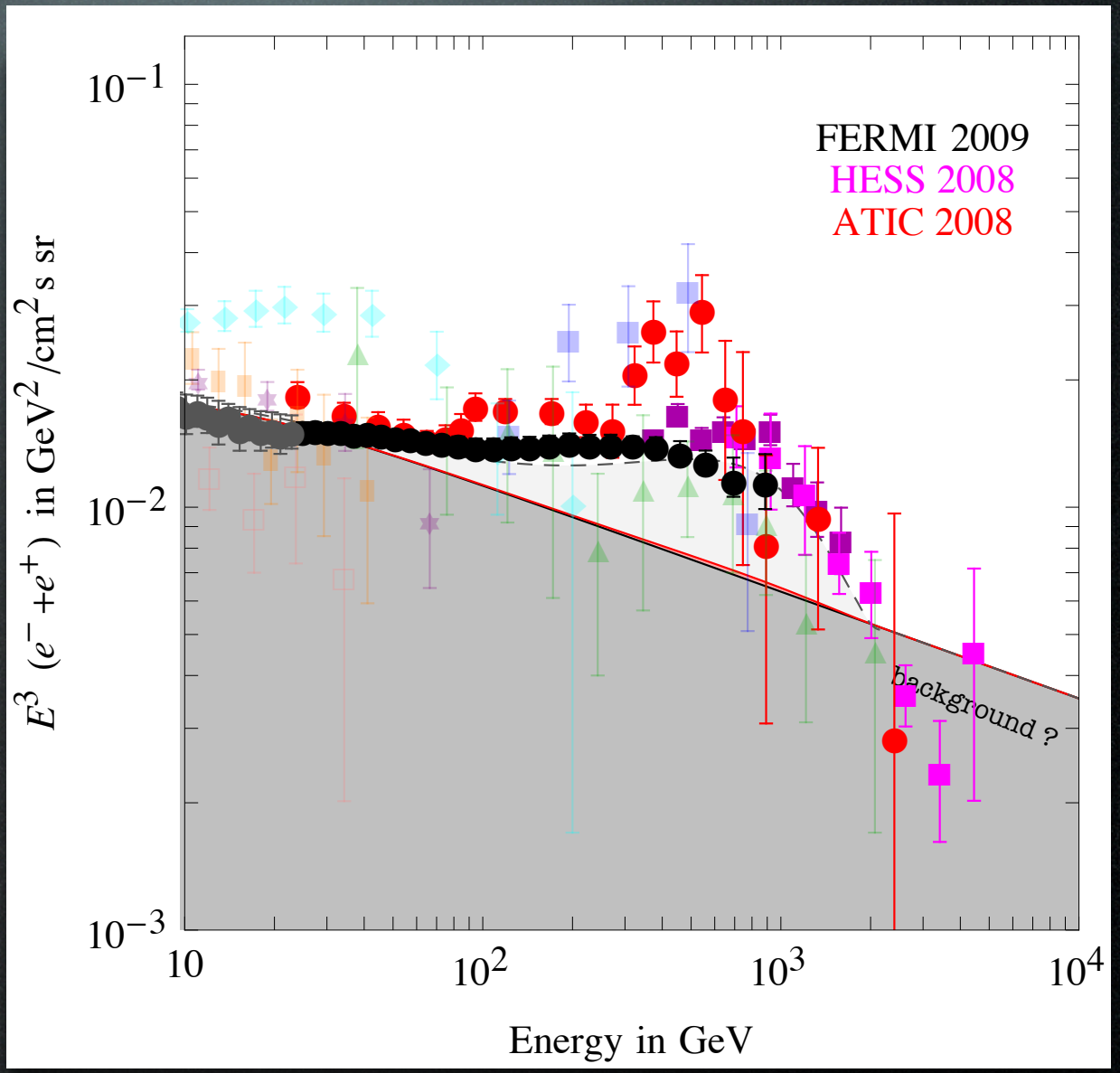


Adriani et al., PRL 105 (2010) 121101, 1007.0821

Charged particles

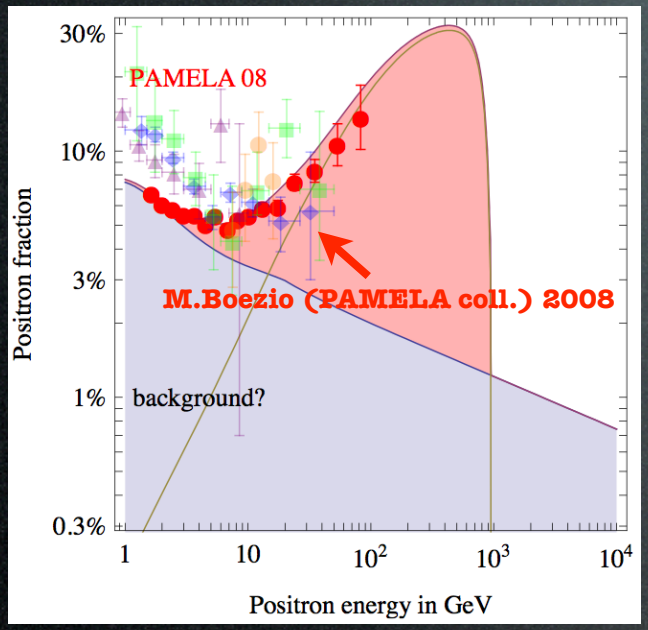
Electrons + positrons adding FERMI and HESS:

- no $e^+ + e^-$ excess
- spectrum $\sim E^{-3.04}$
- a (smooth) cutoff?

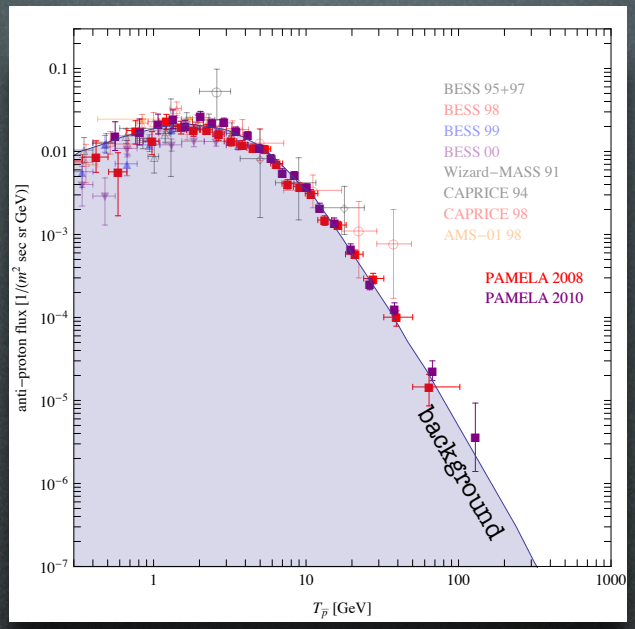


Charged particles

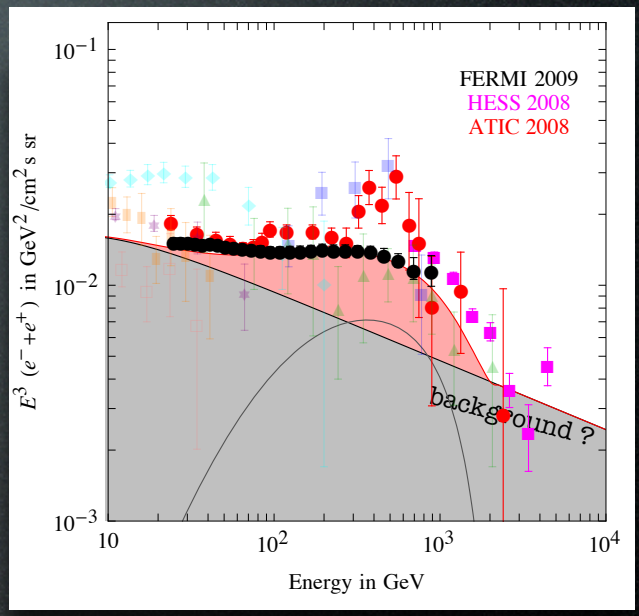
positron fraction



antiprotons



electrons + positrons

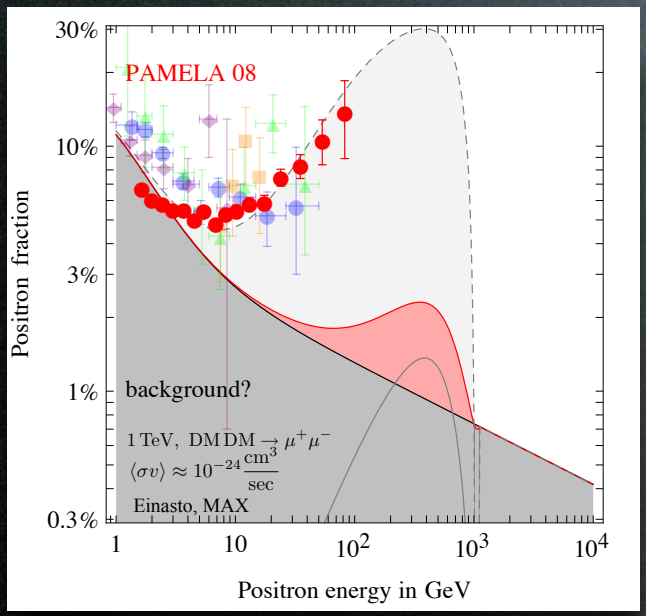


Are these signals of Dark Matter?

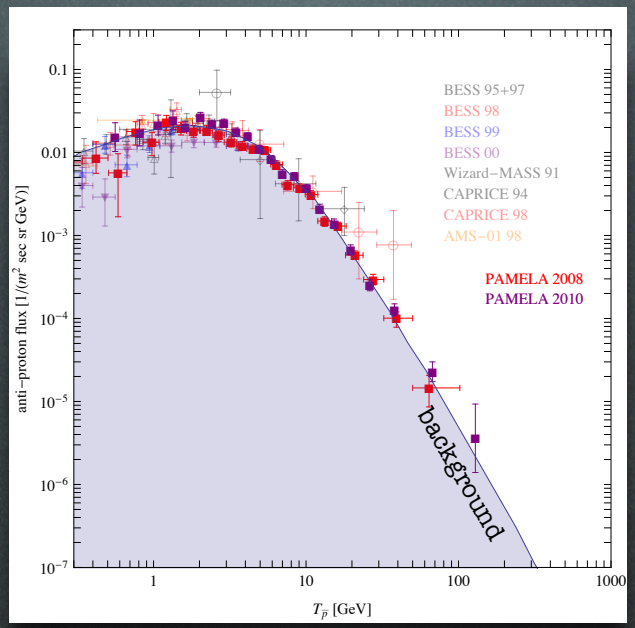
YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

Charged particles

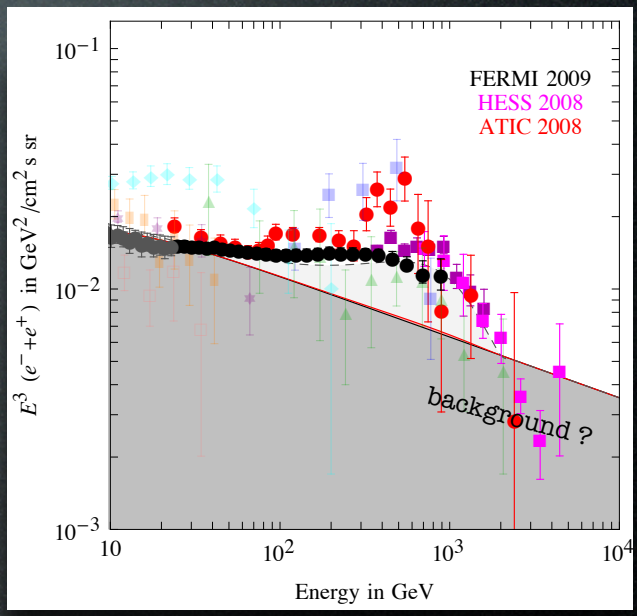
positron fraction



antiprotons



electrons + positrons



Are these signals of Dark Matter?

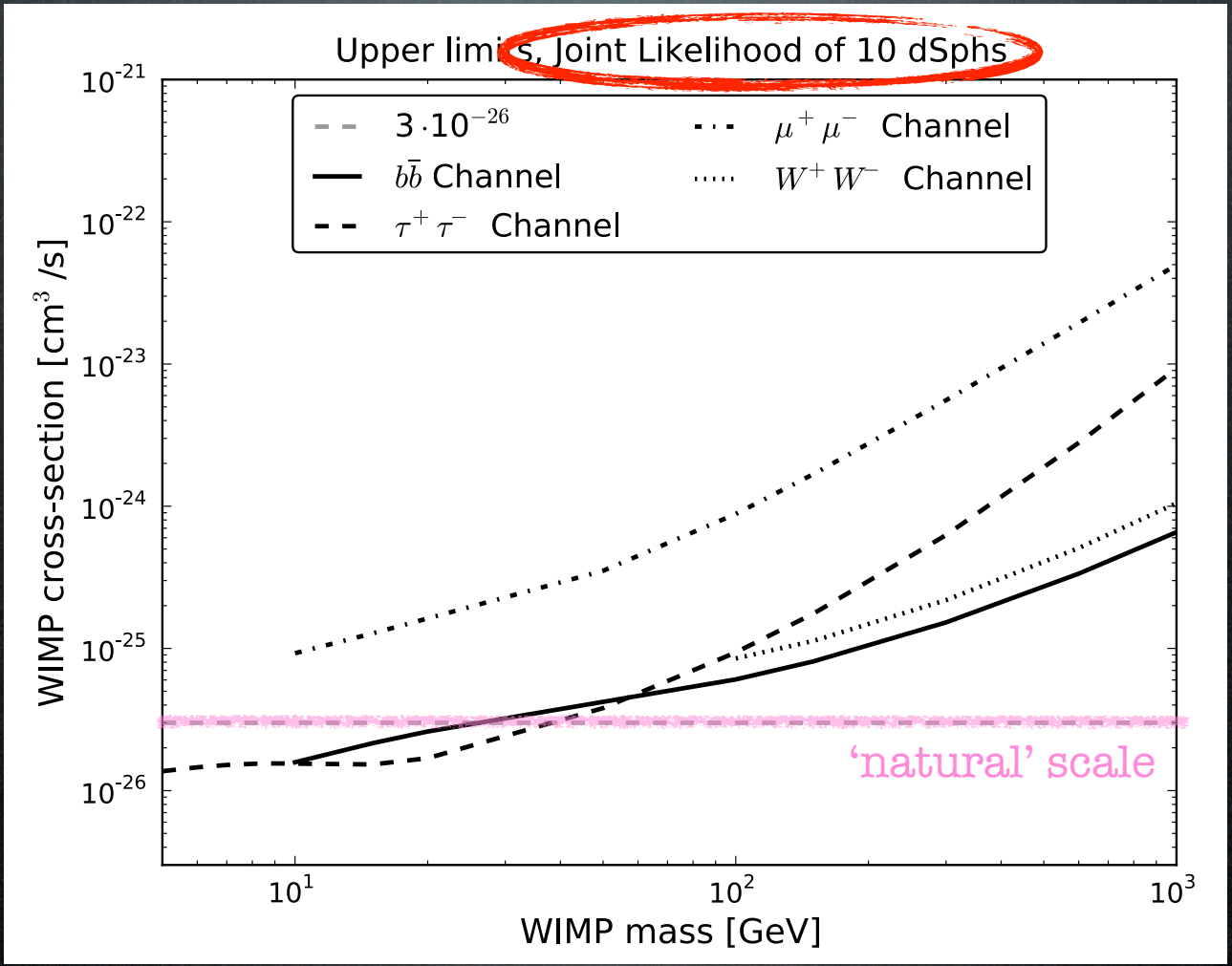
YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

NO: a formidable 'background' for future searches

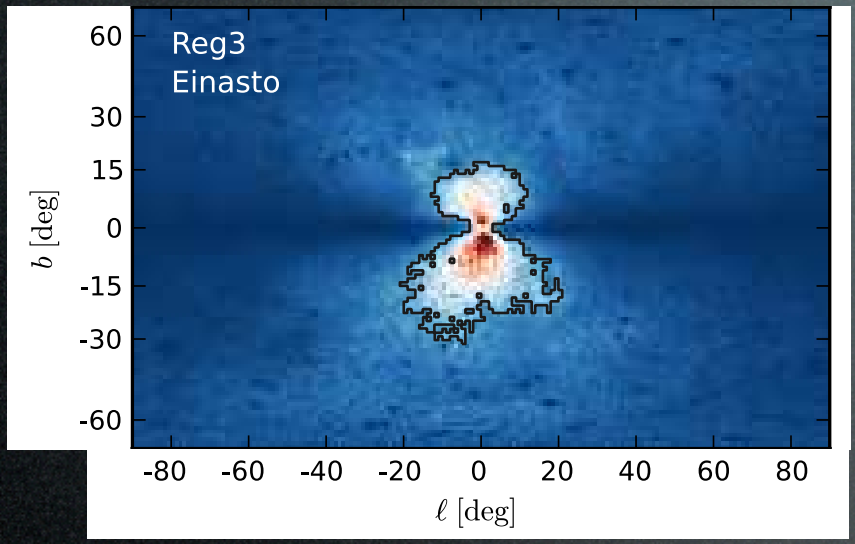
Gamma rays

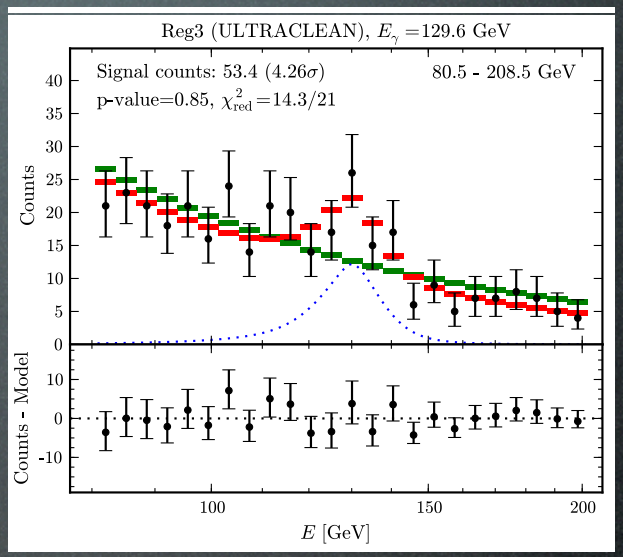
FERMI

FERMI coll., 1108.3546



Gamma rays



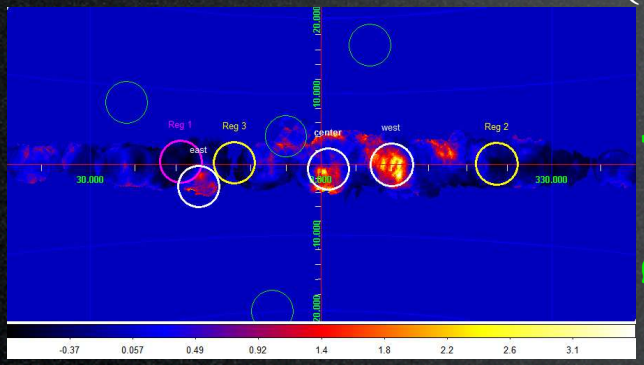


Ch. Weniger, 1204.2797

4.6σ (3.3σ with LEE)

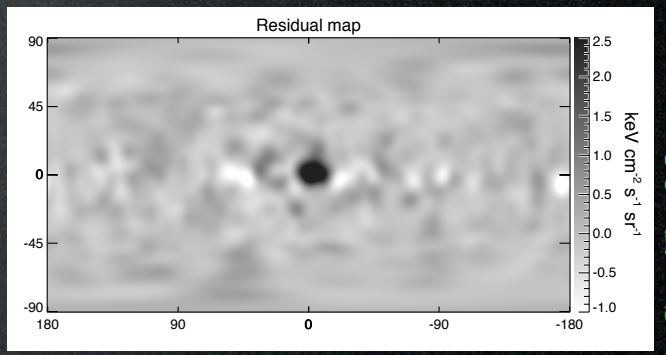
$\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} \simeq 1.3 \cdot 10^{-27} \mathrm{cm}^3/\mathrm{s}$ (large!)

Similar excesses found elsewhere (fluctuation?)



Boyarsky, Malyshev, Ruchayskyi, 1205.4700

The excess is actually (only) in the GC



Su, Finkbeiner, 1206.1616

Mmm.... A good fit requires [1] careful bkgd subtraction & [2] fitting energy spectra + angular spectra + associated signals.

Direct Detection

Direct Detection

Strategy #1: silence the Universe

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measure two quantities to discriminate Sign & Bkgd,
on event-by-event basis

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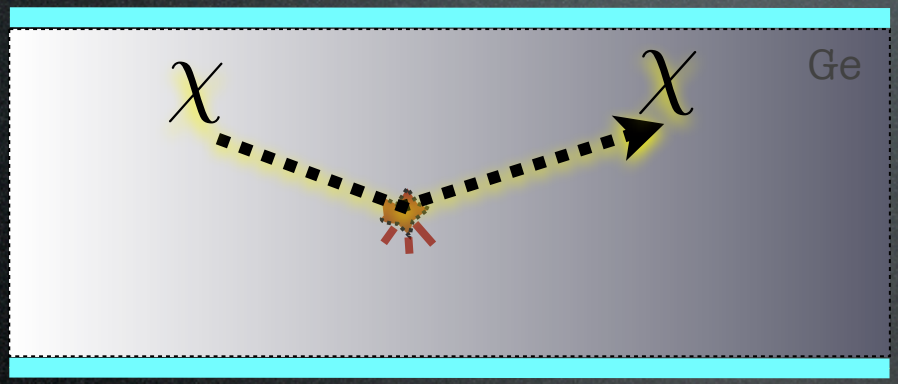
E.g. Edelweiss:



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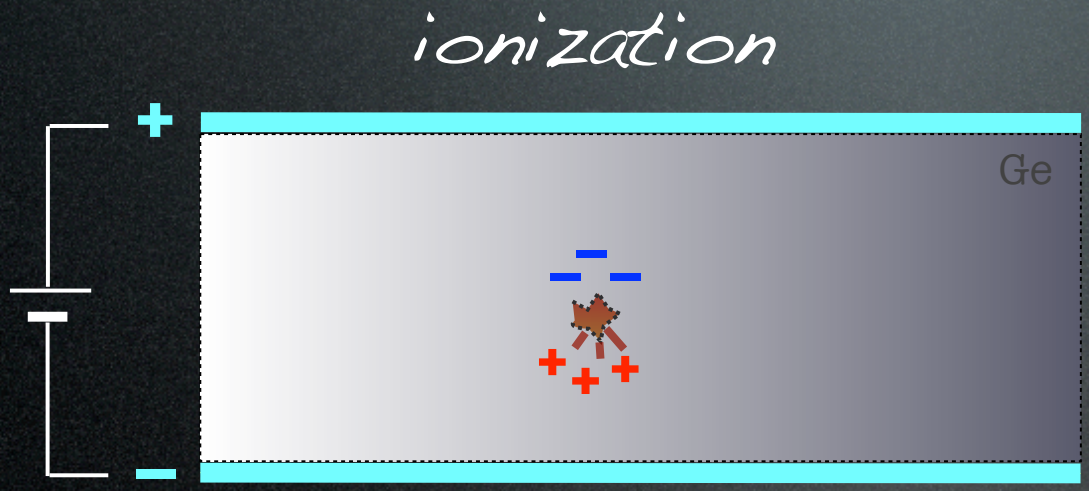

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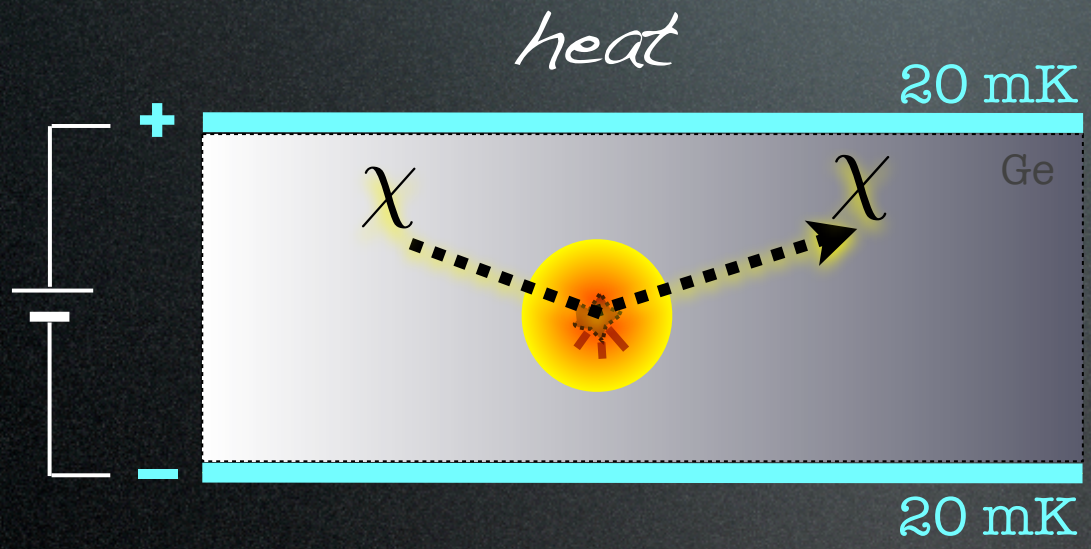

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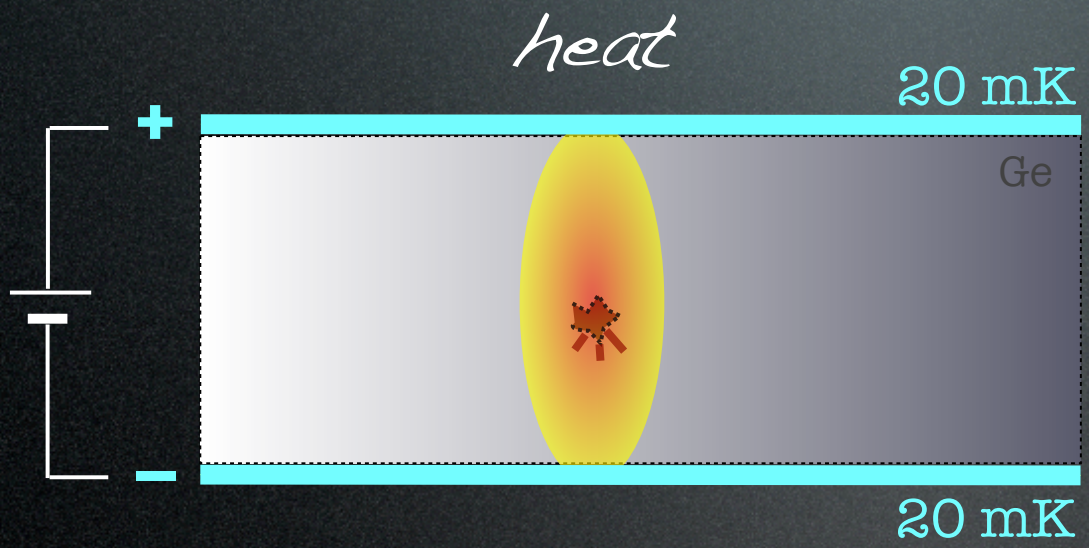

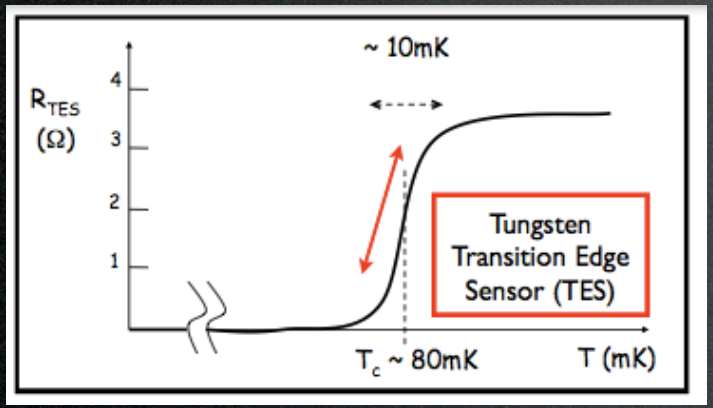

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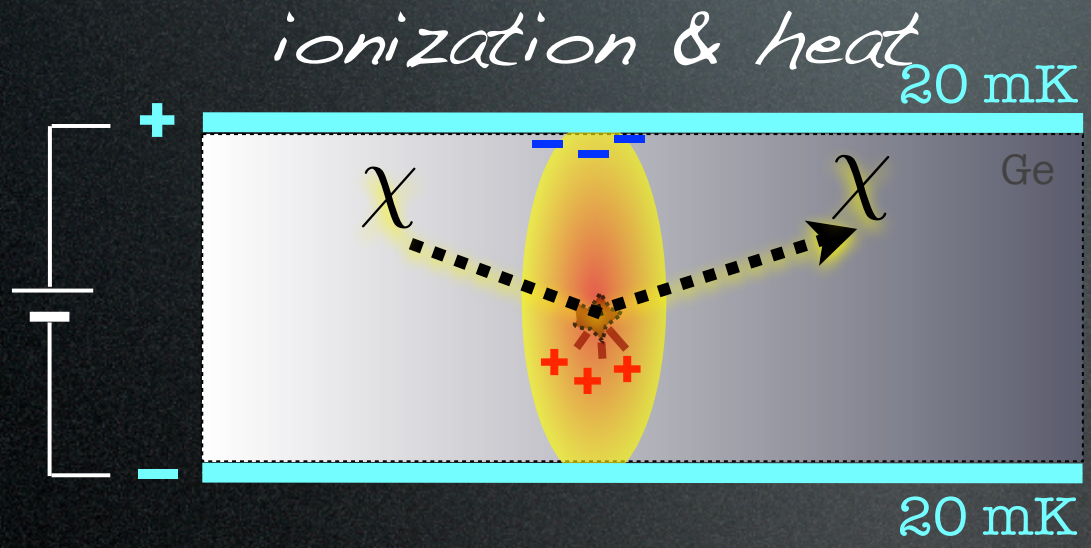

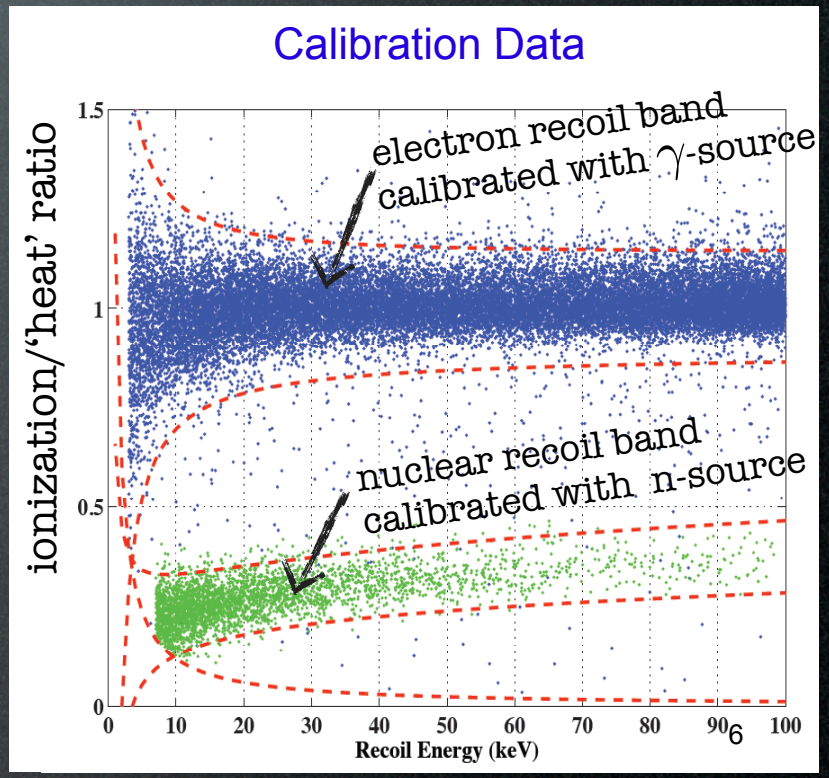

CDMS coll.

Direct Detection

Strategy #1: silence the Universe

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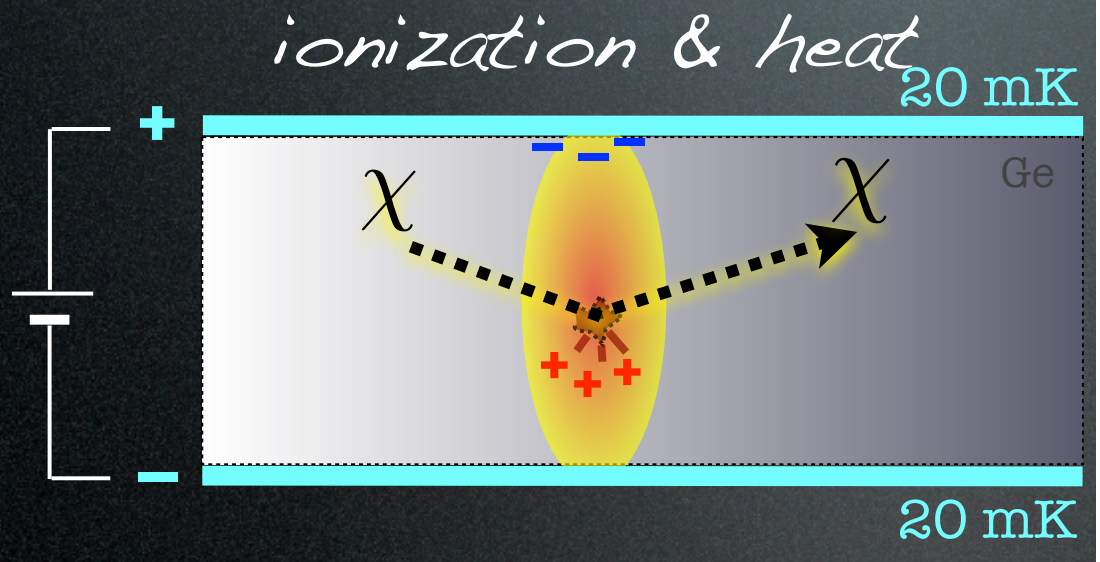
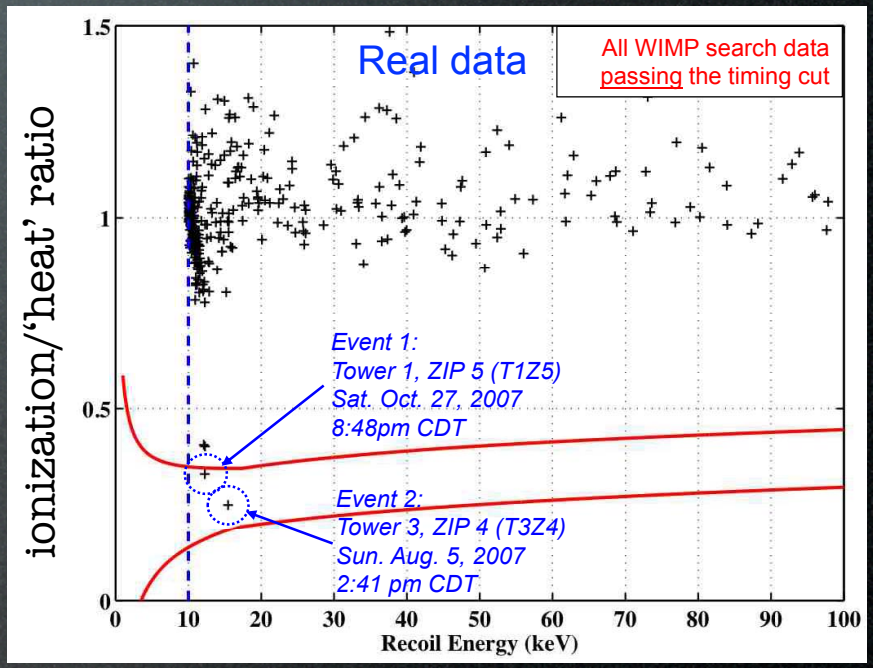
E.g. Edelweiss:





CDMS coll., Science 327 (2010), 0912.3592

Direct Detection

Strategy #2: ride the dark wave

collect all events, and detect an annual modulation

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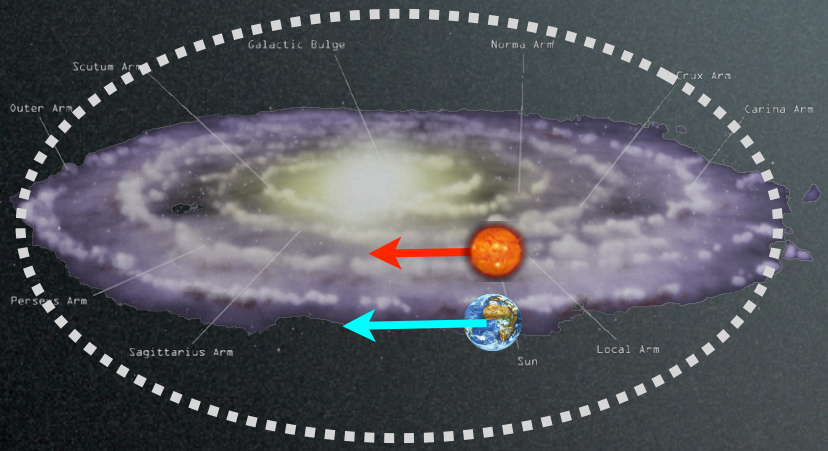

summer

Direct Detection

Strategy #2: ride the dark wave

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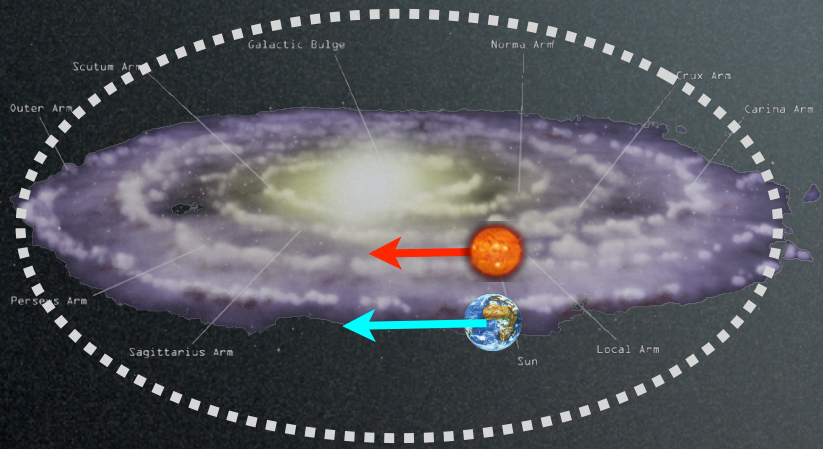
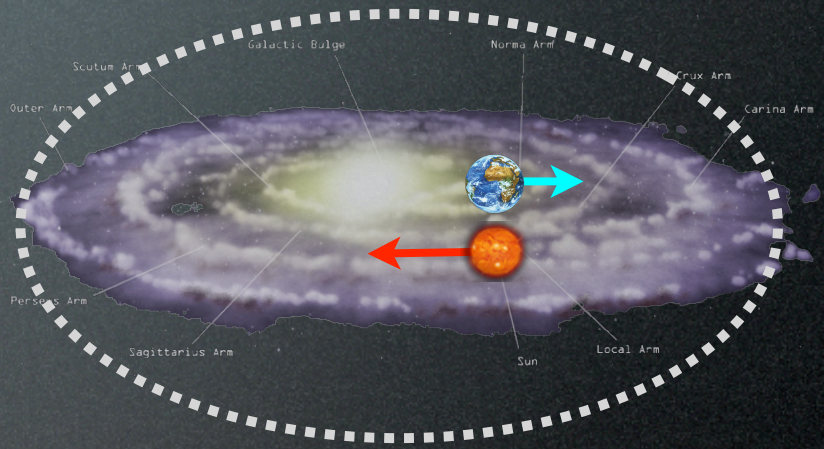


summer



winter

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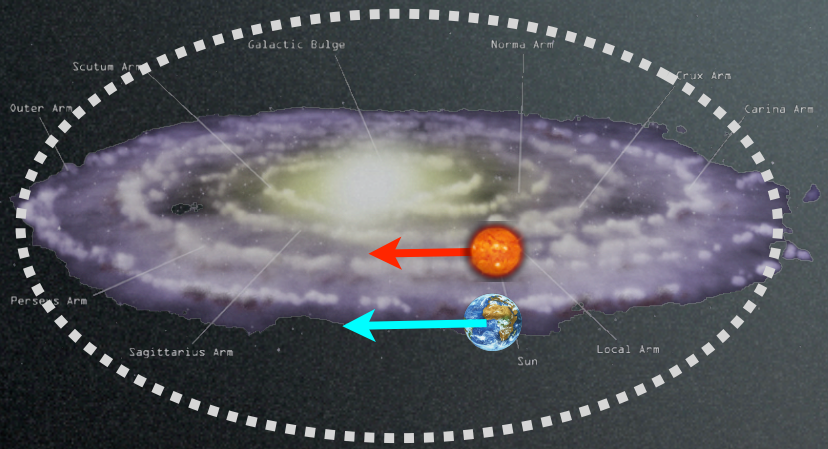
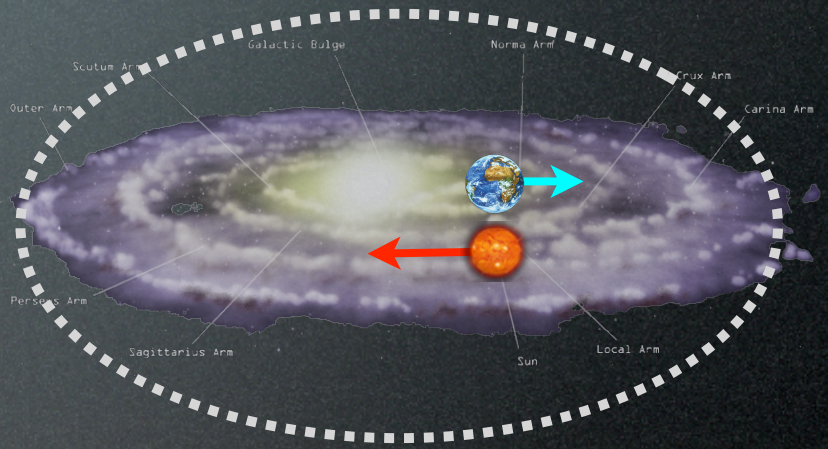
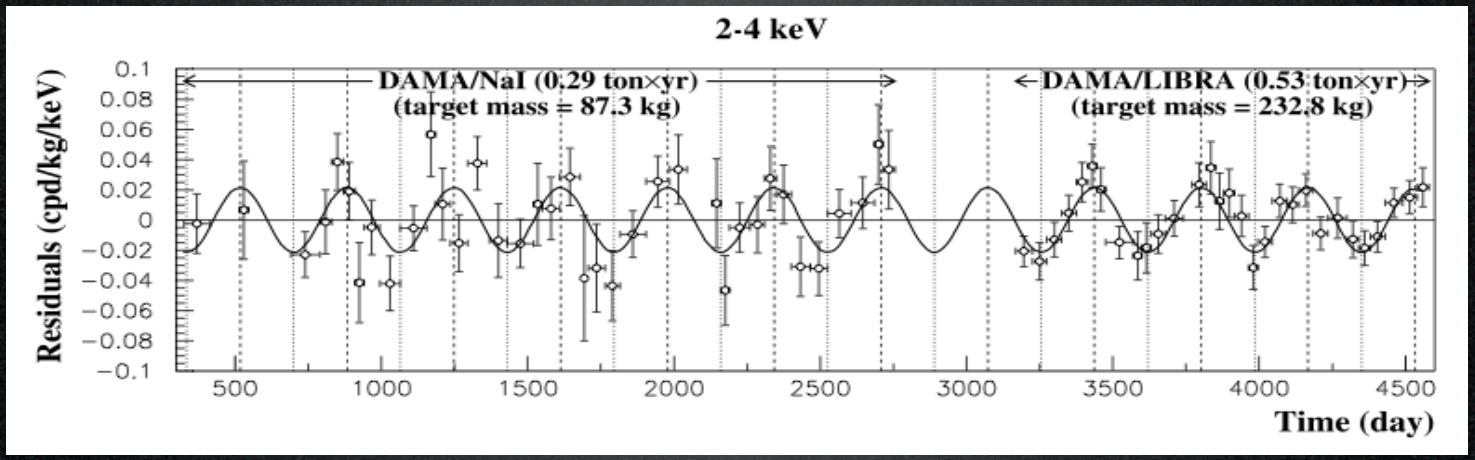


summer



winter

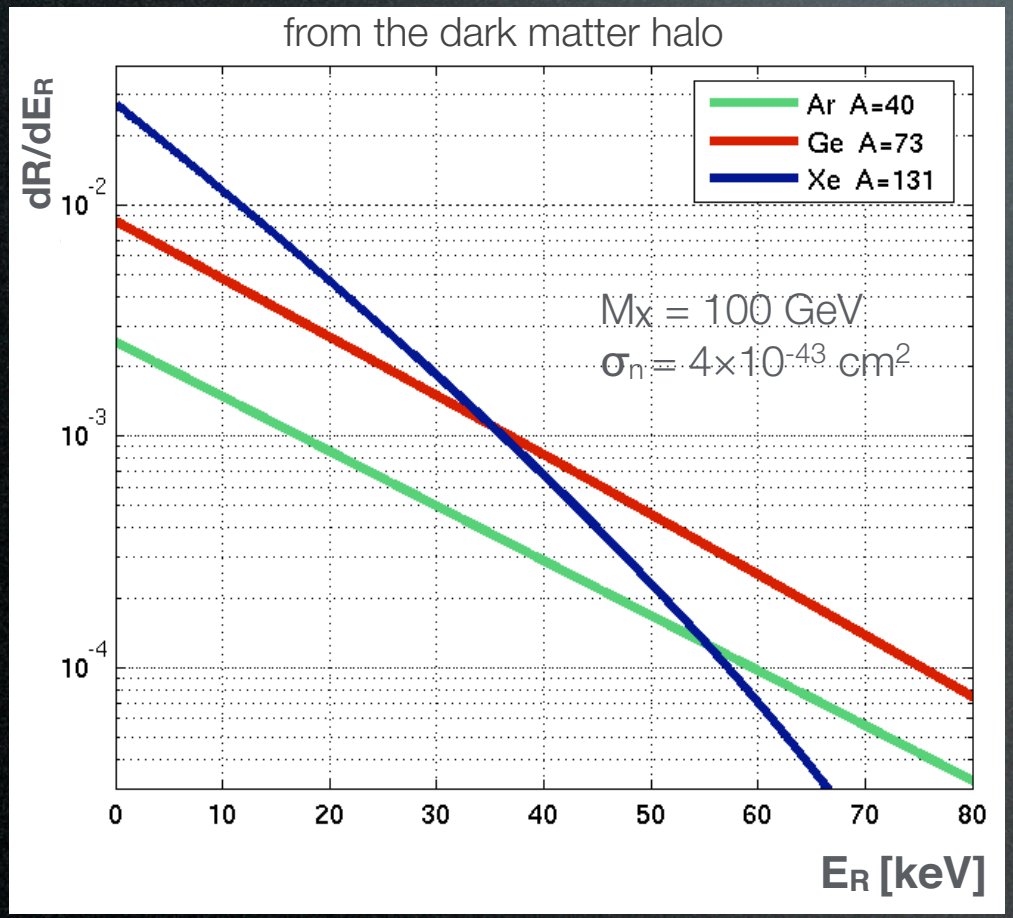


DAMA Coll., 0804.2741, 2008

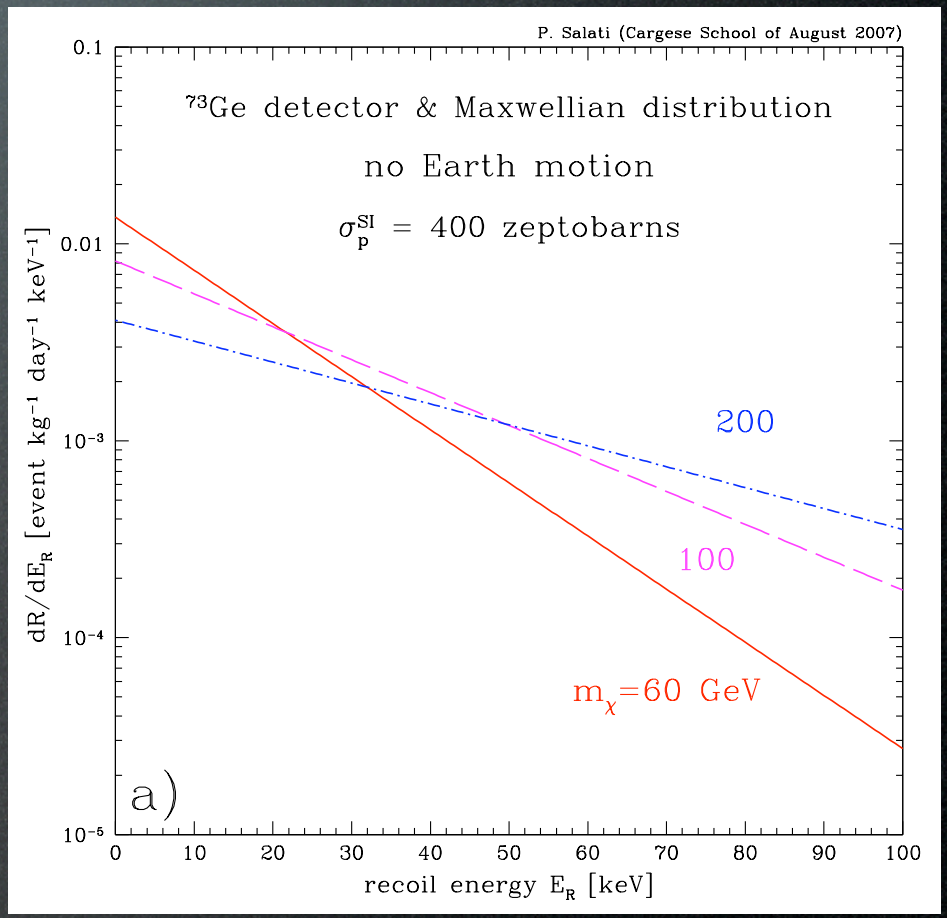
Direct Detection

Recoil spectra

fixed M_{DM}



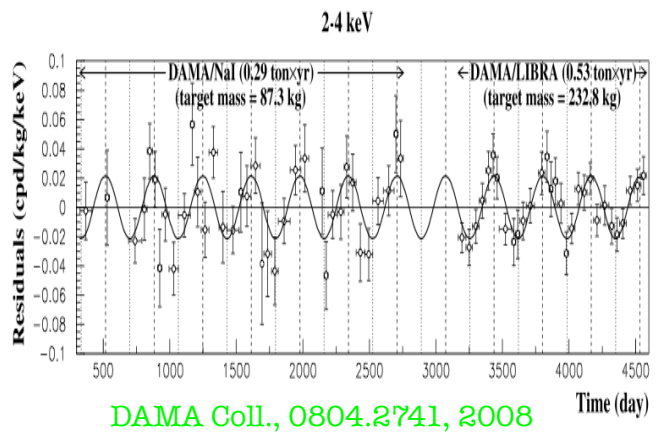
fixed M_{nucl}



Direct Detected?

DAMA/Libra

Annual modulation seen (8σ):



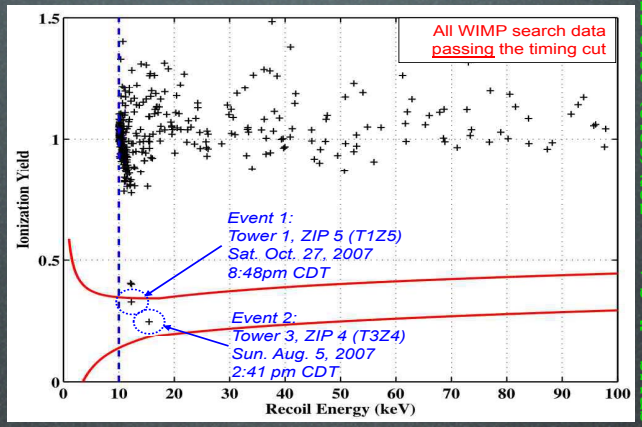
DAMA Coll., 0804.2741, 2008

CDMS

Ge+Si

2 events seen (0.6 exp'd bkgd)

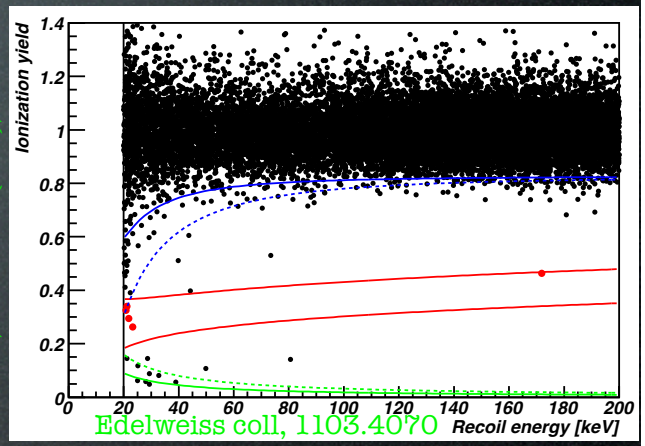
[data taking: 15 months]



CDMS coll., Science 327 (2010), 0912.3592

Edelweiss

5 events seen (3 exp'd bkgd)

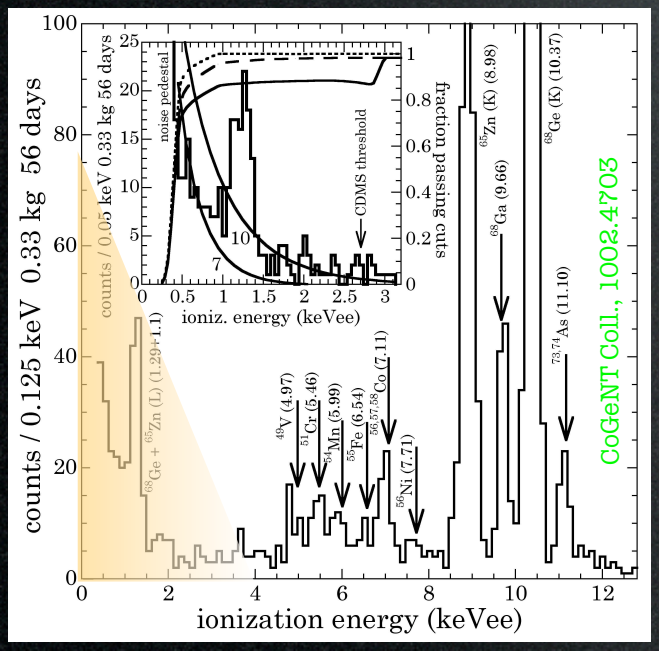


Edelweiss coll, 1103.4070

CoGeNT

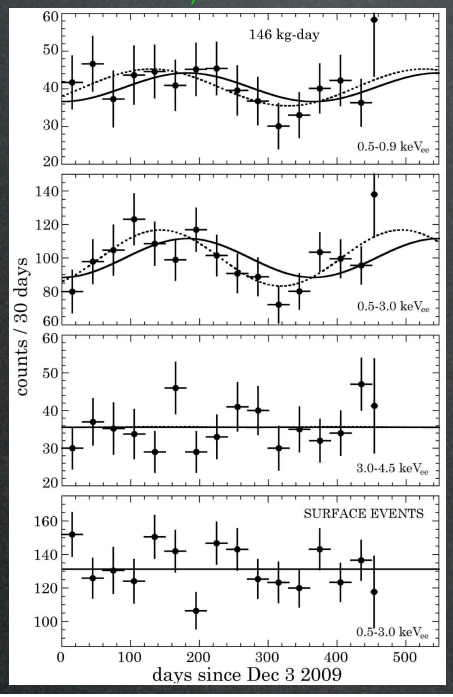
Ge

'excess of events < 3 KeVee'



CoGeNT Coll., 1002.4703

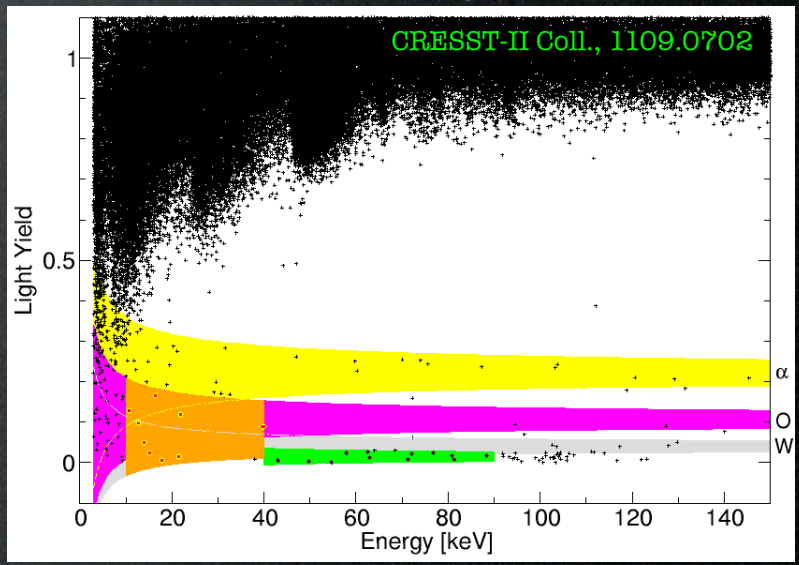
CoGeNT coll., 1106.0650



CRESST-II

$CaWO_4$

67 events seen on Oxygen,
twice the exp'd background

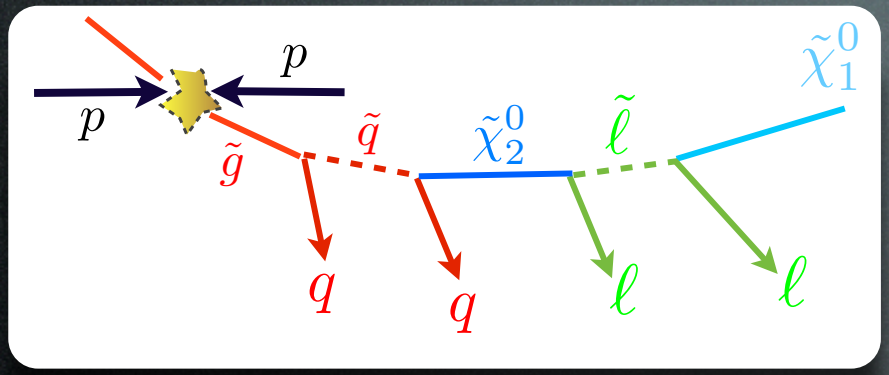


Collider Searches

Production at colliders

Search strategy 1:

look for decay subproducts of particles in the same theory



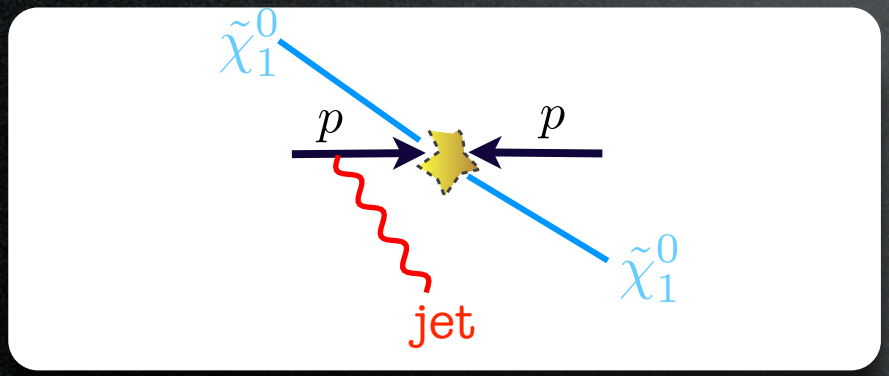
'trigger on 4j+4l+MET...'

- well studied (M_T^2...)
- model dependent

huge literature

Search strategy 2: 'monojets'

e.g. J.Goodman et al., 1008.1783



- 'new'
- more model independent