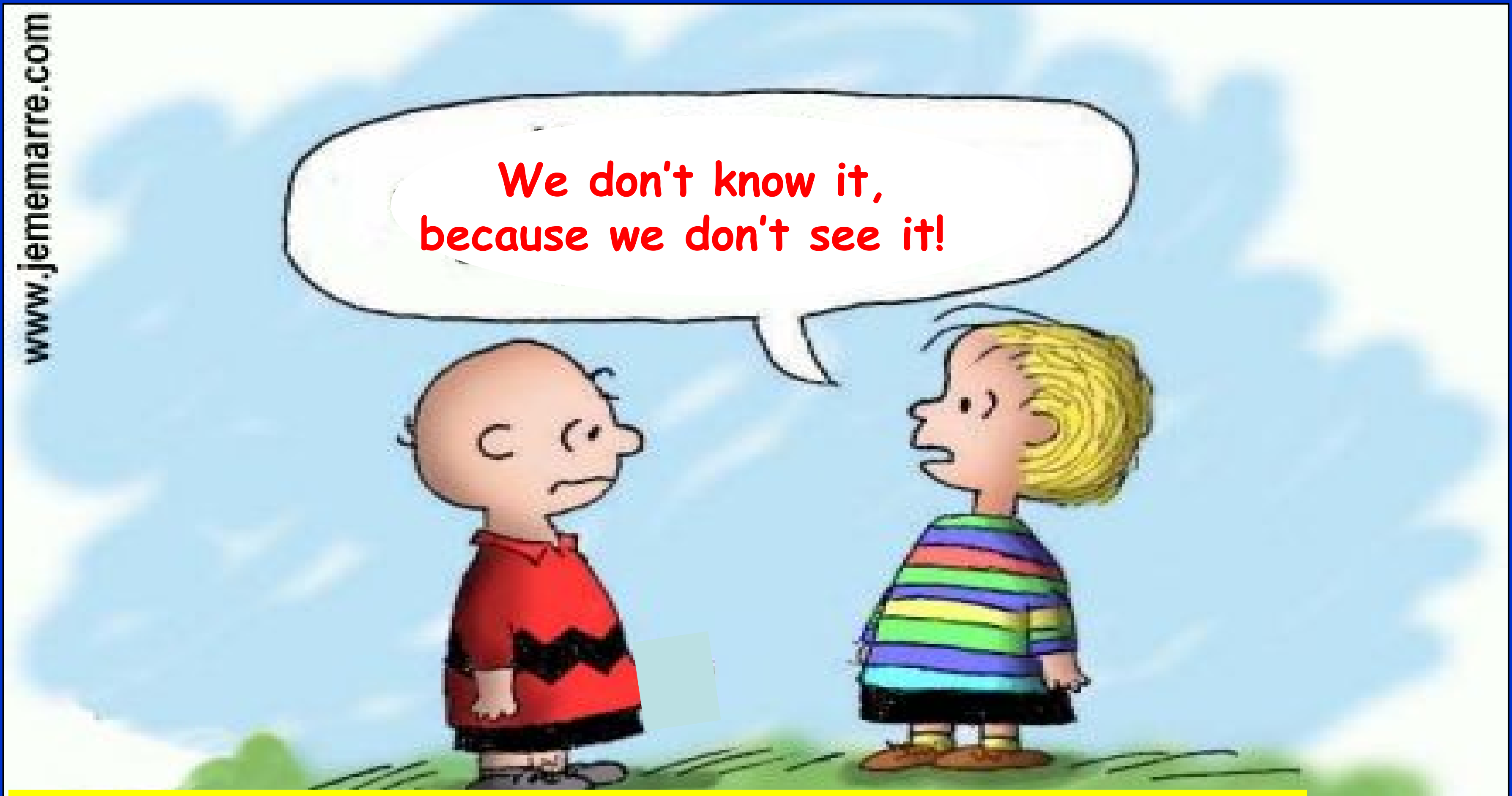
Dark Matter: what is it?



WdB, C. Sander, V. Zhukov, A. Gladyshev, D. Kazakov, EGRET excess of diffuse Galactic Gamma Rays as Tracer of DM, astro-ph/0508617, A&A, 444 (2005) 51

Dark Matter: what is it?

Outline:

LECTURE 1+2: Evidence for Dark Matter from cosmology
Indirect Dark Matter detection

LECTURE 3: Is DM the SUPERSYMMETRIC Partner of CMB?
Expectations for Direct Dark Matter detection

The Big Bang and its energy

Cosmology

↕

Astroparticle physics
Astronomy

↕

Particle physics

Big Bang →

13.7 billion years

95% of energy in universe of unknown nature

1 ps

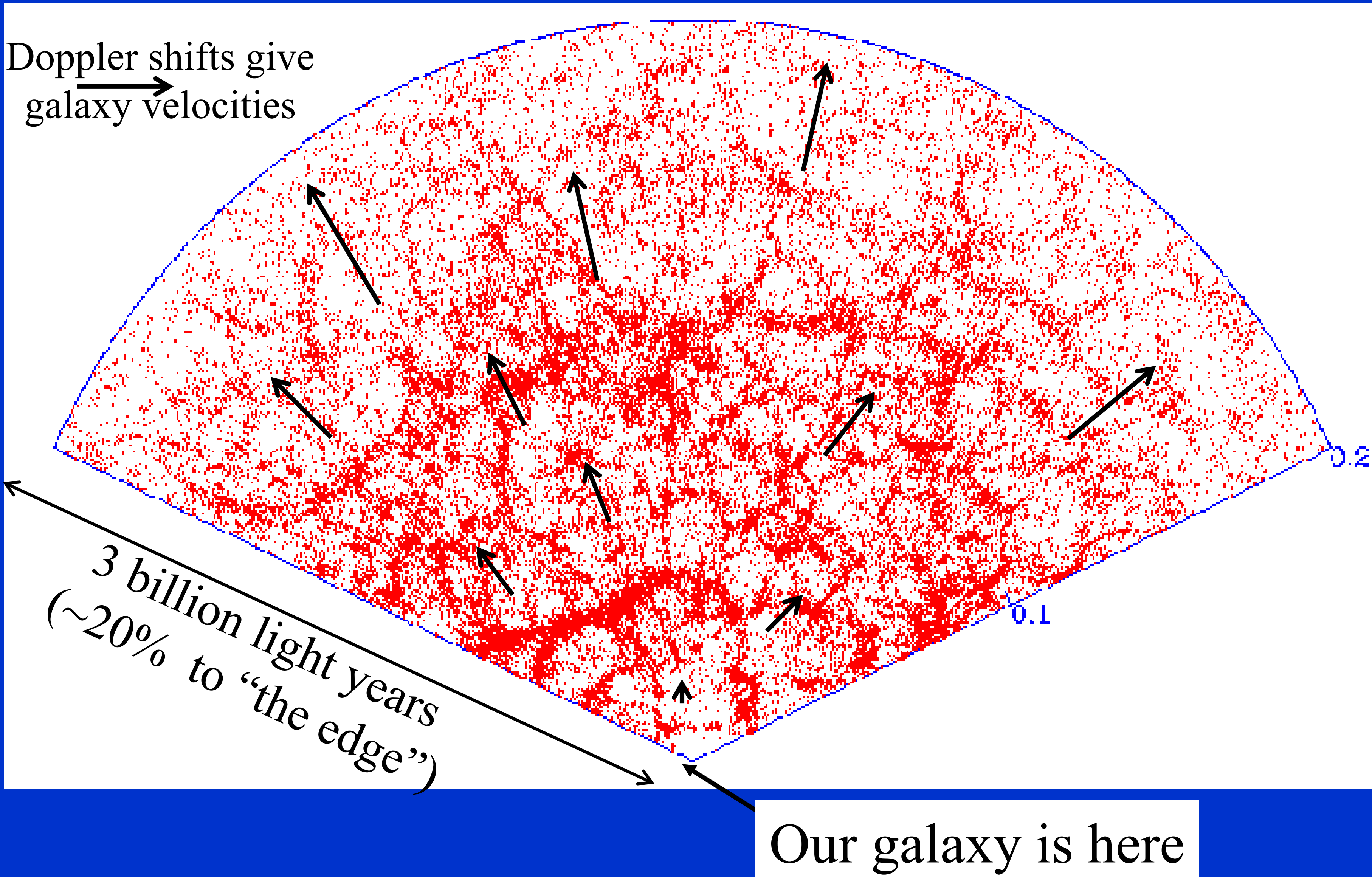
10^{-34} s

Universe is a very active place

During this lecture:

10^8 stars are created (in 10^{11} *galaxies*)
The sun loses by radiation 10^{10} tons of its weight
The sun radiates 10^{23} kWh
The earth receives 10^{14} kWh
This is the equivalent of 10^{13} Euros
The energy prices are clearly too high

SDSS : ⅓ million galaxies



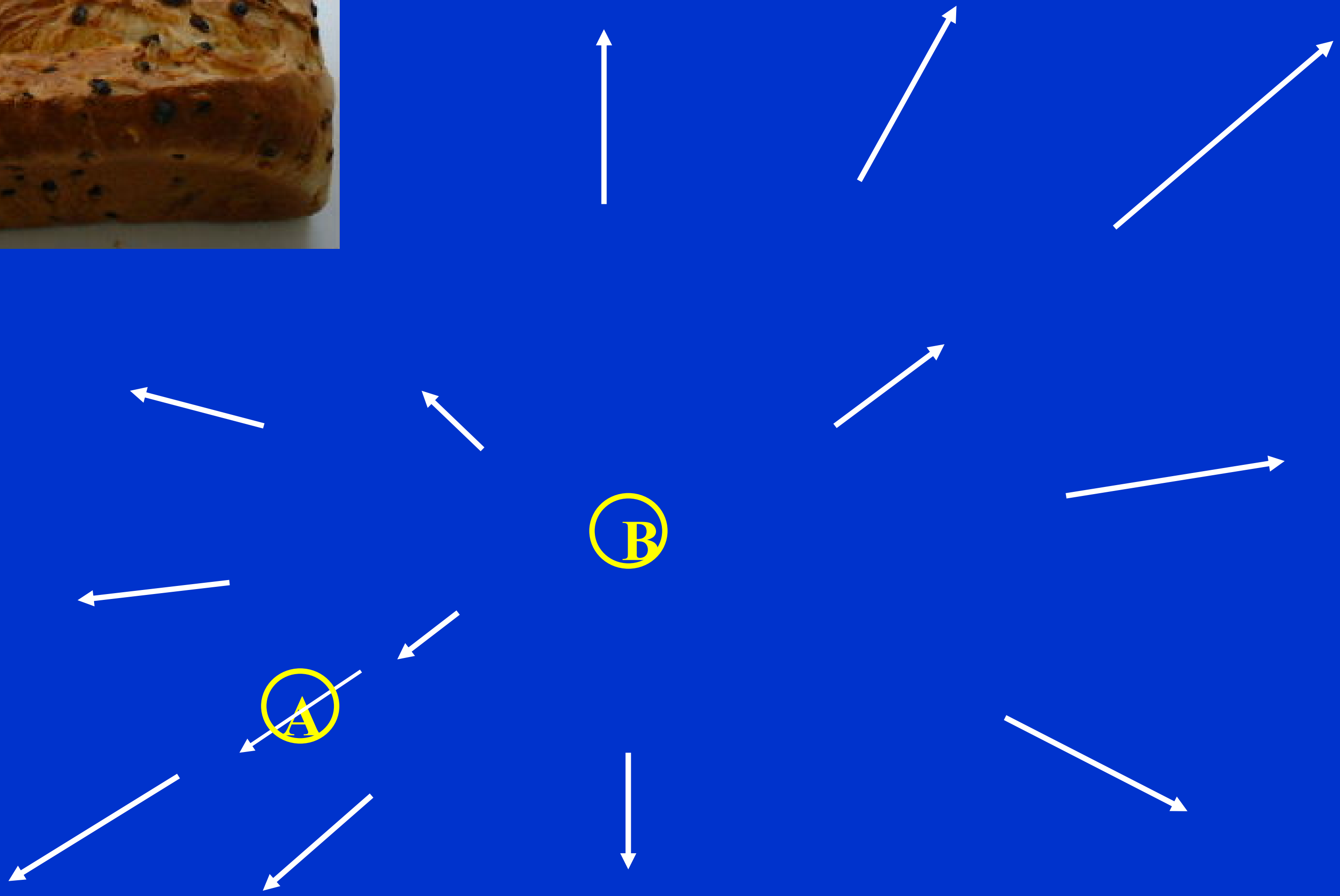
The Universe is

EXPANDING

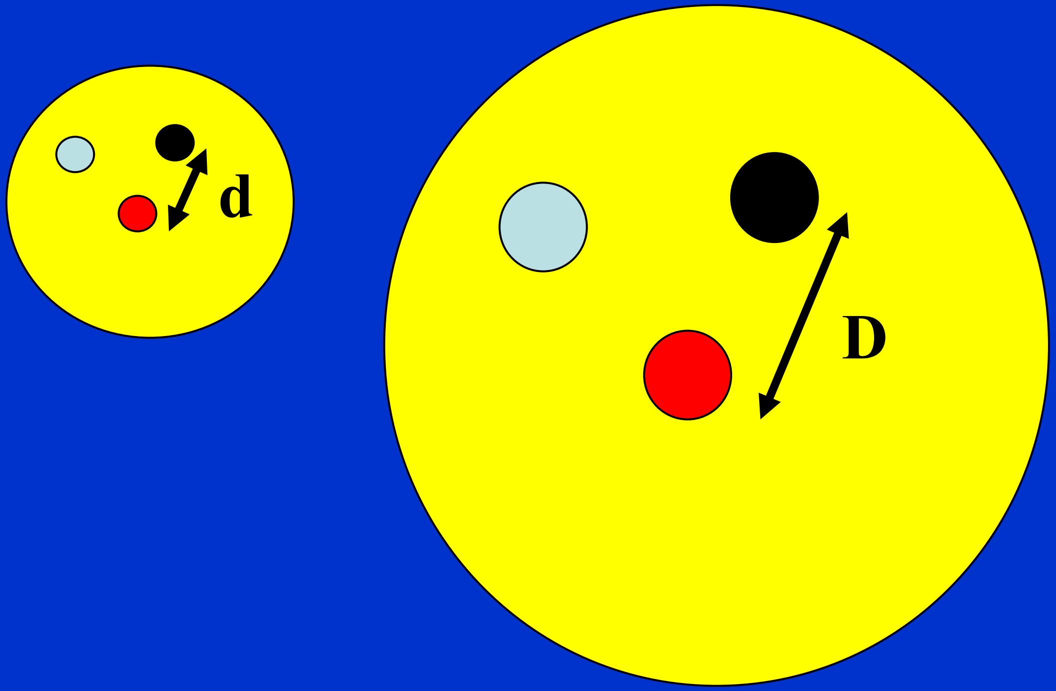
(discovered already by Hubble some 80 years ago!)

View from galaxy A

View from galaxy B



Hubble's law in "comoving coordinates"



Hubble's law:

$D = S(t)\, d \quad (1)$

Differentiate⇒

$\dot{D} = \dot{S}(t)\, d \quad (2)$

oder

$\dot{D} = v = \dot{S}(t)/S(t)\, D$

or $v = HD$

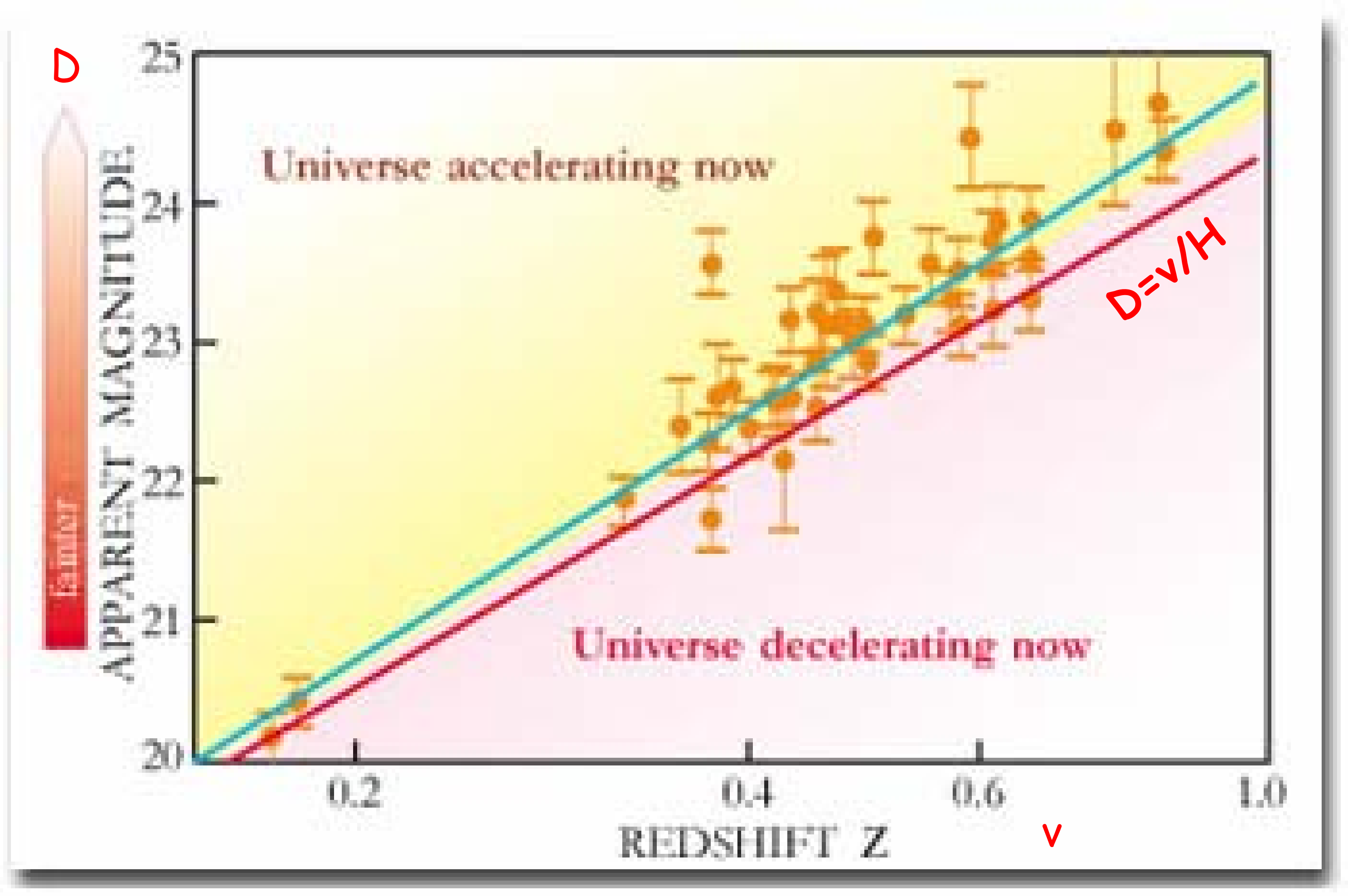
with $H = \dot{S}(t)/S(t)$

$D = S(t)\, d$

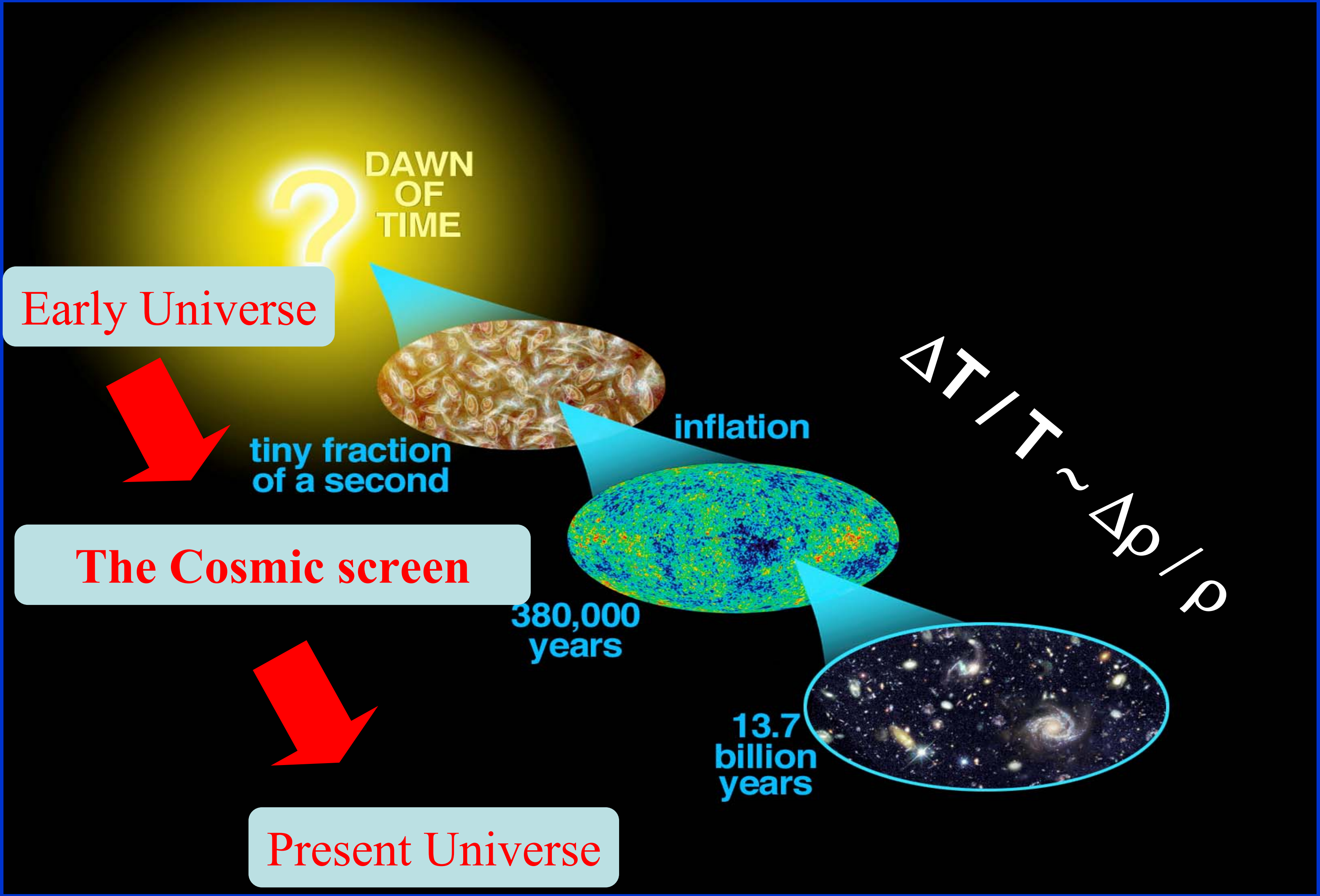
S(t) = time dependent scale factor

Real coordinates from time-independent comoving coordinates by multiplication by S(t)

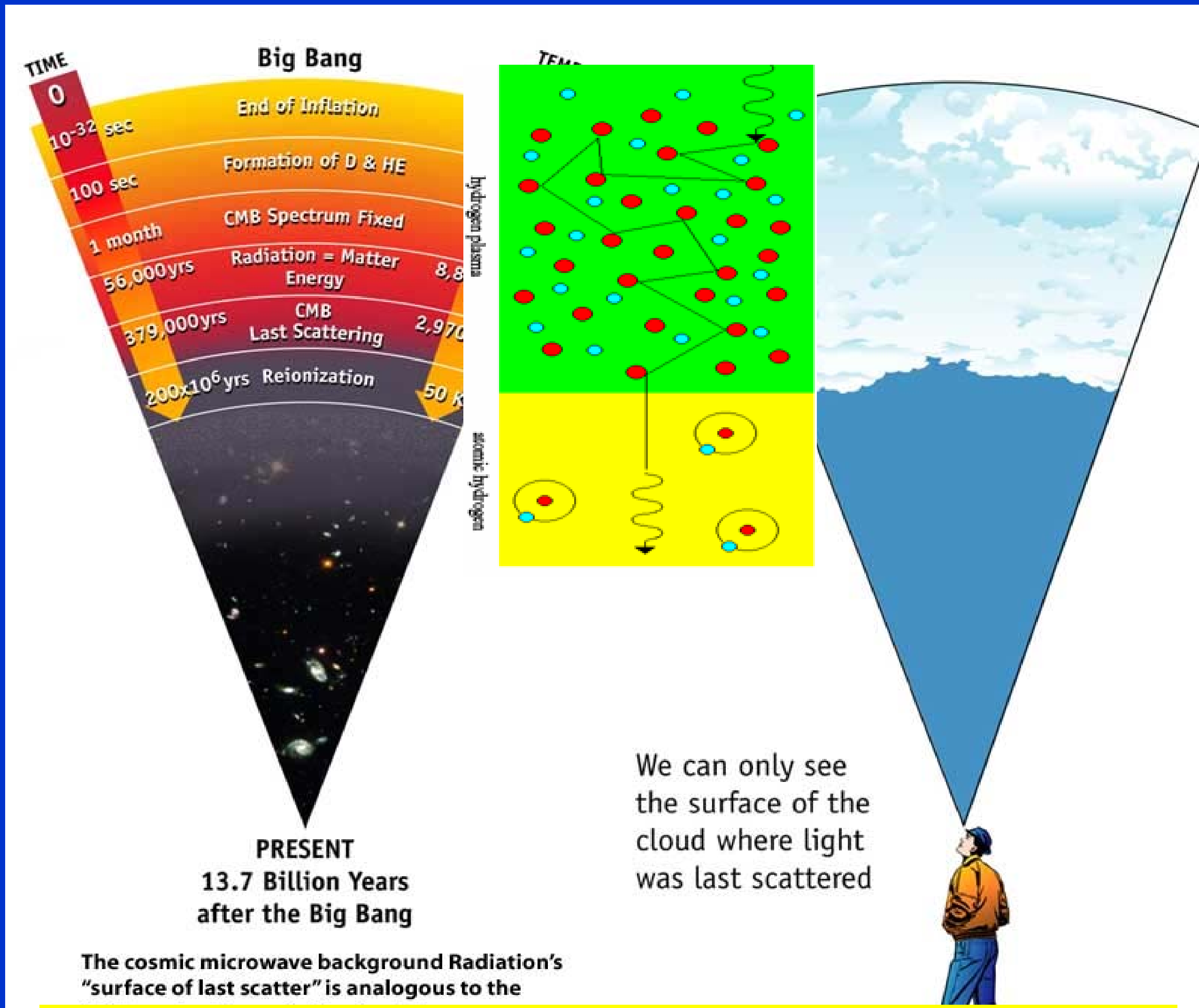
Hubble diagram from SN Ia data



Evolution of the universe

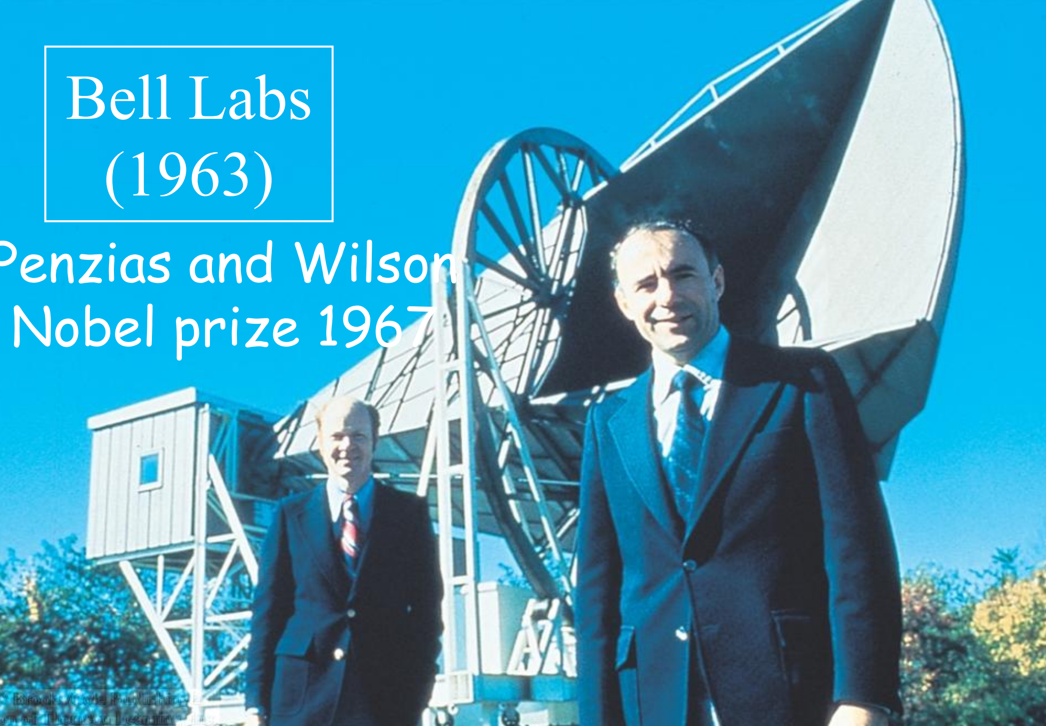


Light from early universe visible as cosmic microwave background (CMB)



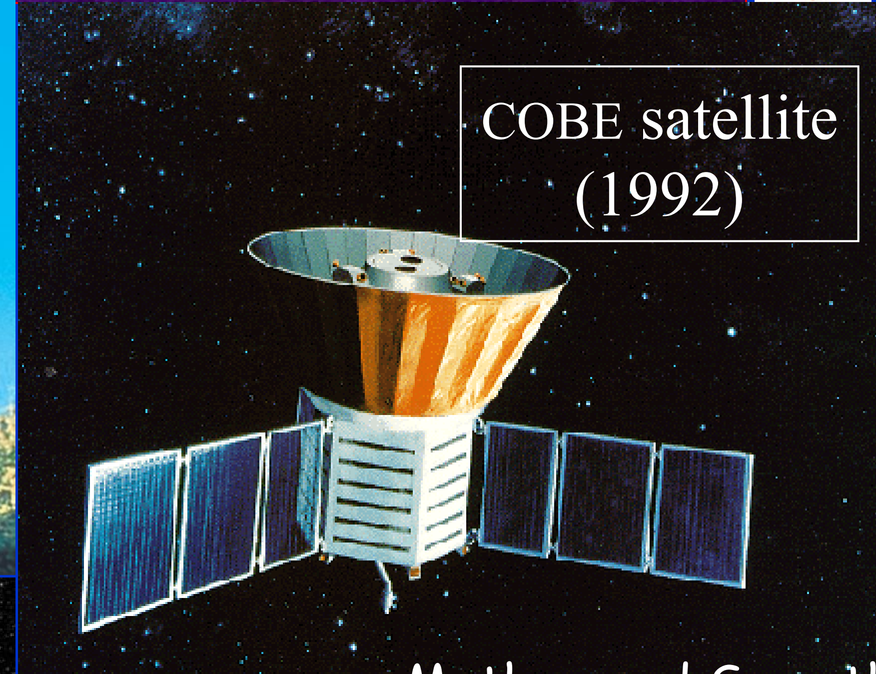
CMB perfect for tracing flatness of universe

Observing the Microwave Background

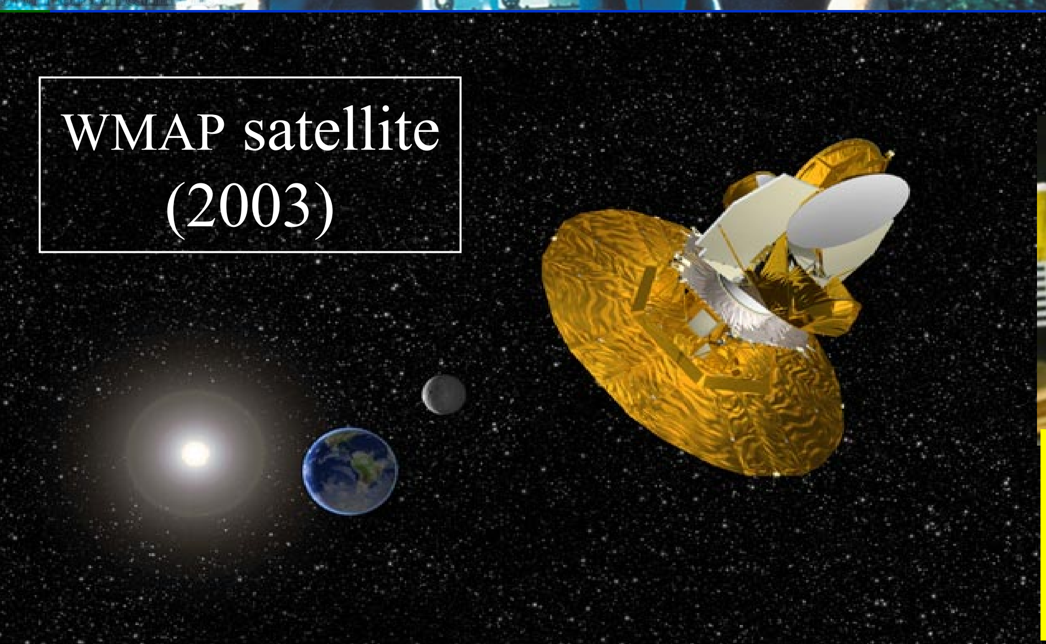


Bell Labs (1963)

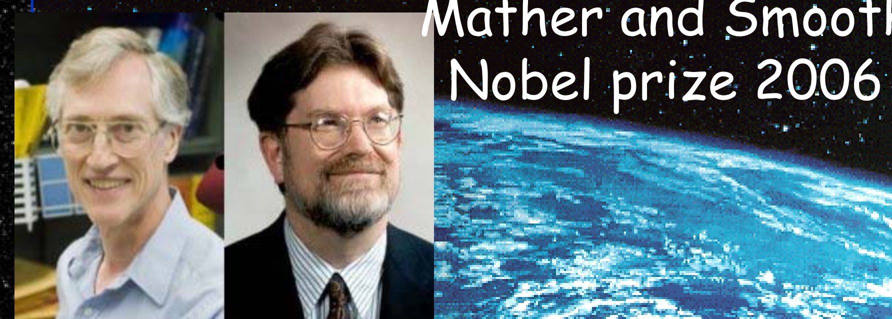
Penzias and Wilson Nobel prize 1967



COBE satellite (1992)



WMAP satellite (2003)

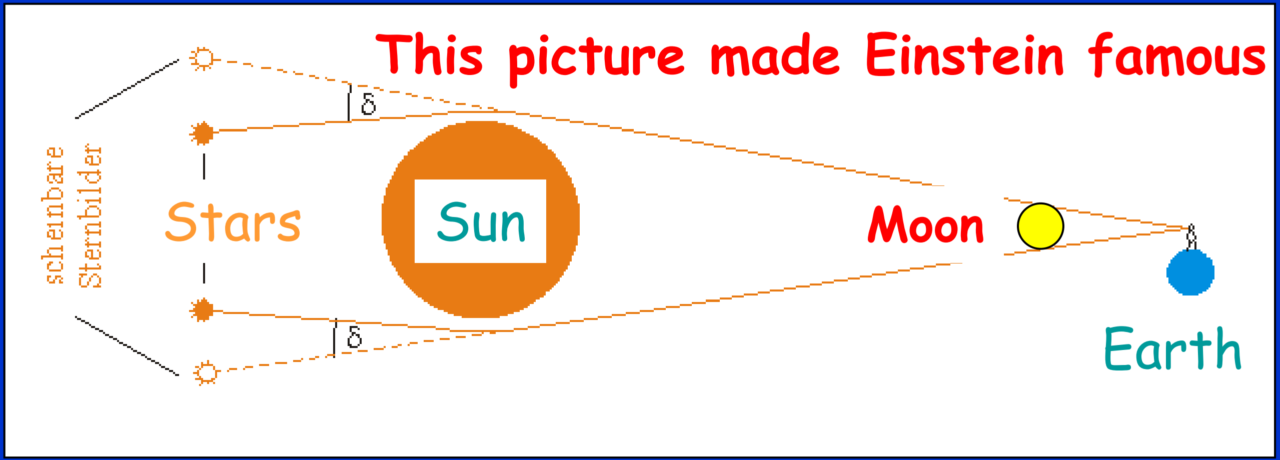


Mather and Smooth Nobel prize 2006

2003:WMAP: universe is flat, which implies an energy density $\rho_{critical}=2.10^{-29}$ g/cm^3

How do we measure the energy density of the universe?

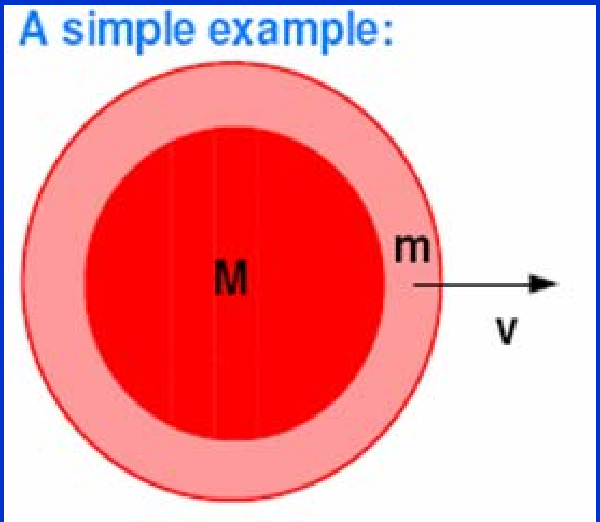
In principle: the bending of light determines the energy density.
In a flat universe the light moves on straight lines, which corresponds to the critical energy density



In 1919 moon in front of sun (eclipse), so Eddington could observe positions of stars behind the sun (expeditions to West-Africa and Brasil) According to Newton the angle : δ=0.87 Grad
According to Einstein: δ= 2 x 0.87 Grad
because of additional time dilatation by gravity

Light on straight lines, if average energy zero or universe "FLAT"

What is the critical density? (i.e. E=0)



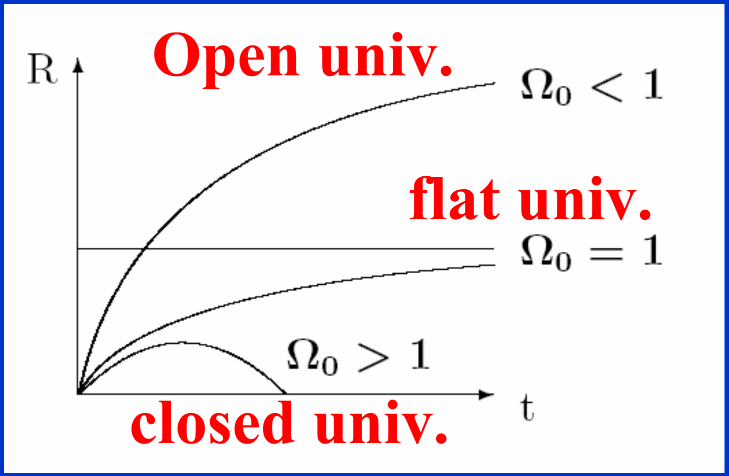
$$E_{tot} = \frac{1}{2} m \dot{R}^2 - \frac{GmM}{R}$$

$$M = \frac{4}{3}\pi R^3 \rho$$

$$H=\dot{R}/R$$

$$E_{tot}=0 \Rightarrow H^2=8\pi G\rho_{crit}/3$$
$$\rho_{crit}=3H^2/8\pi G=2.10^{-29}\ g/cm^3$$

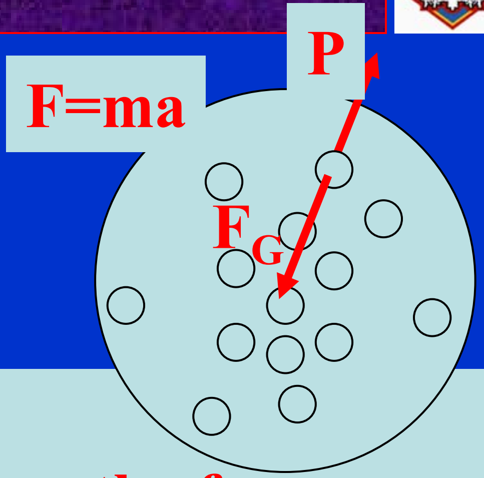
Define dimensionless density parameter: $\Omega=\rho/\rho_{crit}=8\pi G/3H^2$



Compare with rocket with U<T, U=T und U>T

Flatness of universe proven by measuring angular size of acoustic horizon at decoupling

Why acoustic waves in early universe?



Define: $\delta=\Delta\rho/\rho$

From Newton`s F=ma:
$\delta`` + (\text{pressure-gravity})\,\delta=0$

Solution:
pressure small: $\delta=ae^{bt}$, i.e. exponential growth of δ (->gravitational collapse)
pressure large: $\delta=ae^{ibt}$, i.e. oscillation of δ (acoustic waves)

Horizon-crossing: Waves on large scales enter region of causal contact (= horizon) later, i.e. small scales (large $k=2\pi/\lambda$) start to grow first or MORE POWER at large k:

$$P(k)\propto k^n,\ n=\text{powerindex}$$

(n=1 expected from Inflation, WMAP: n=0.98±0.04!

So not all wavelengths have same amplitude, but some wavelengths have more “power”

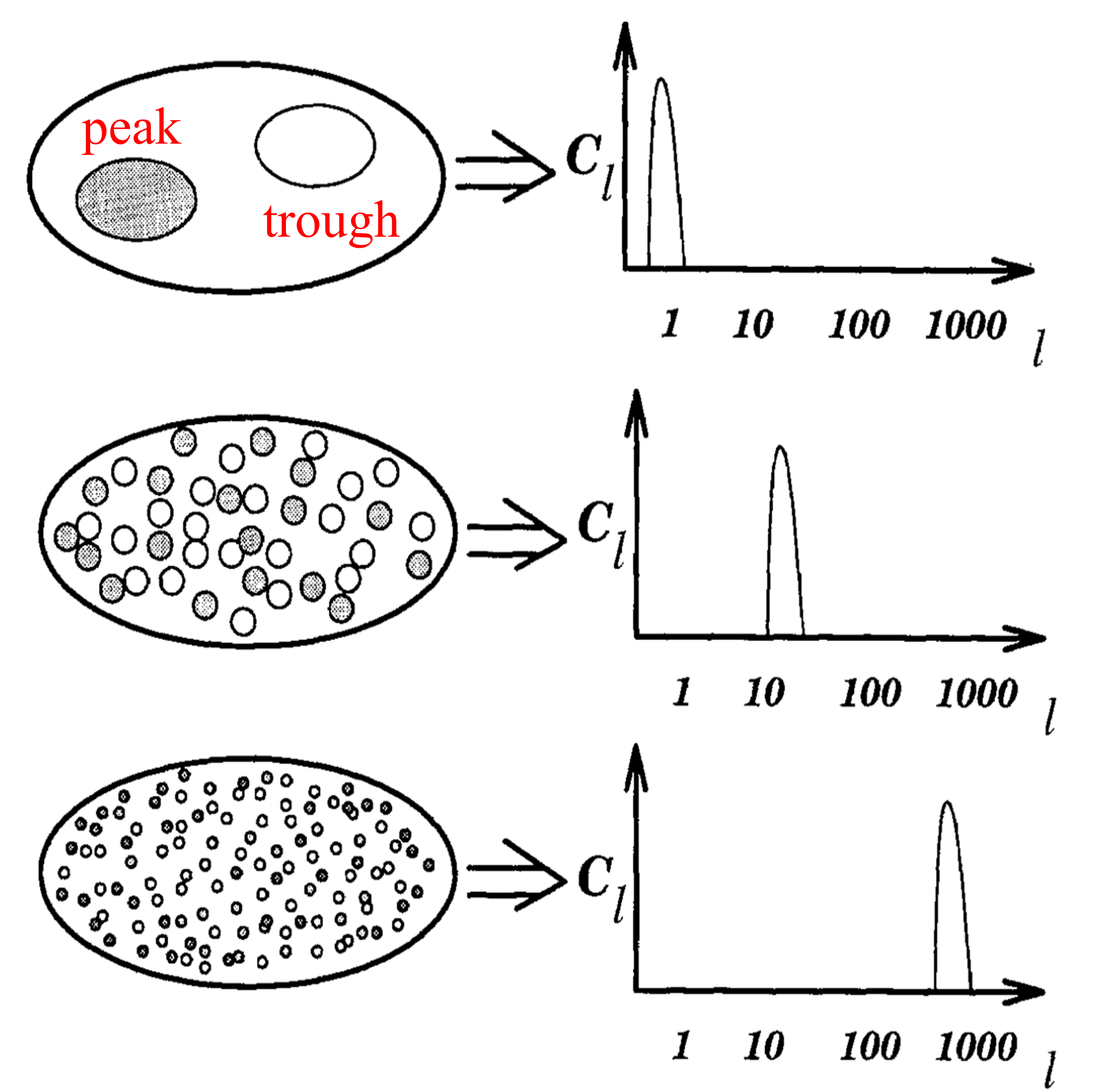
How to measure power spectra?

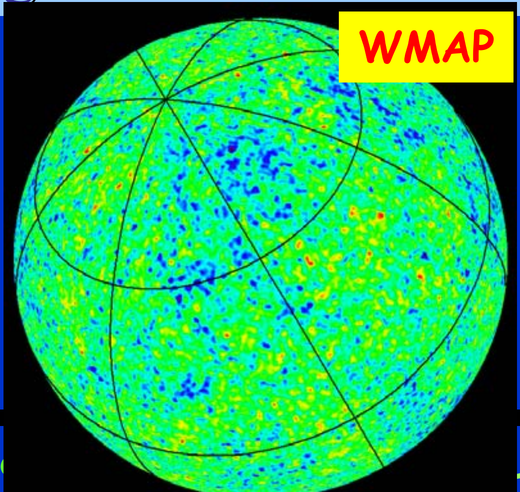
Cannot follow waves in time.

Instead use the wave's spatial appearance

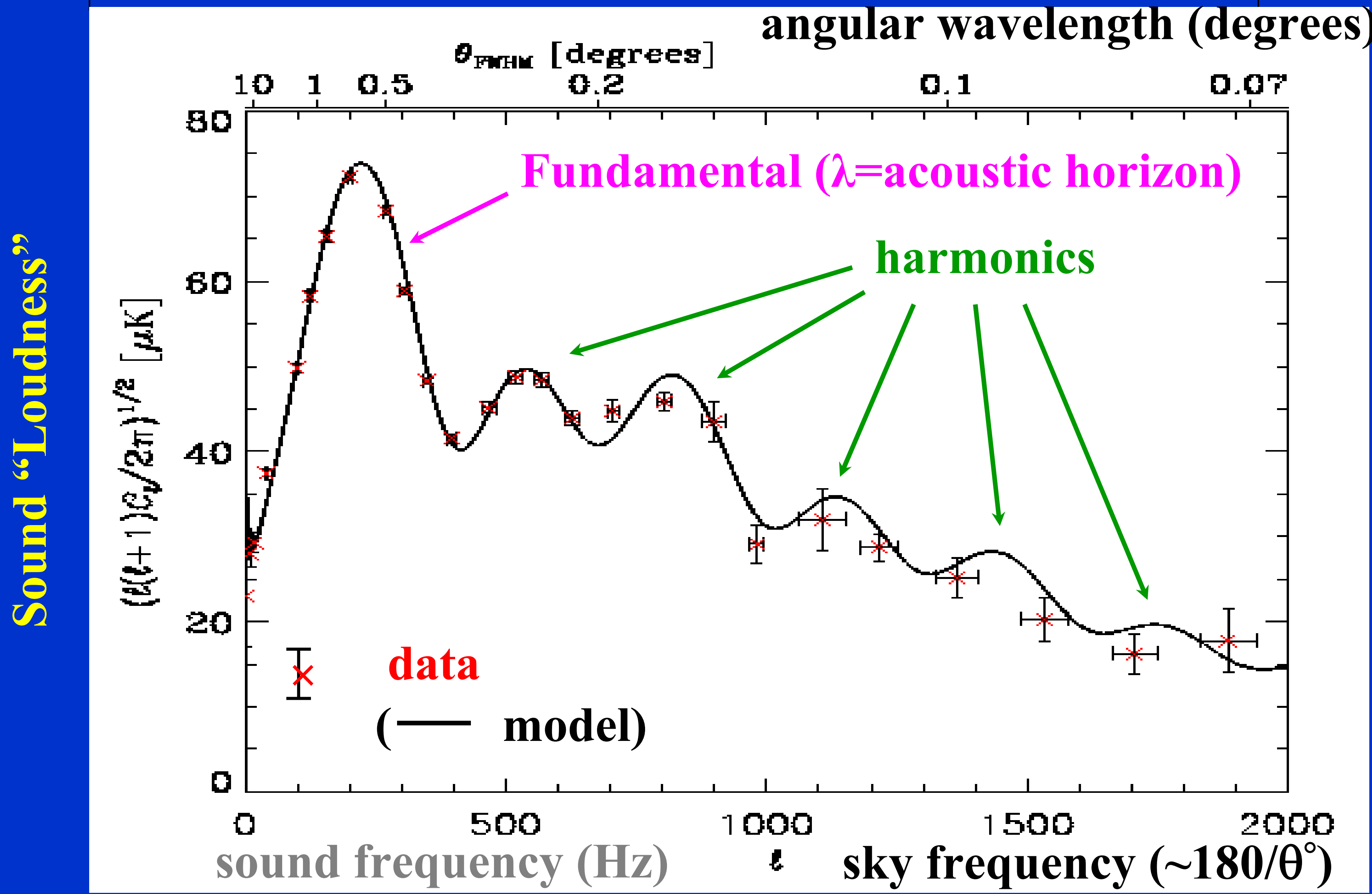
Evaluate spatial power spectrum, of waves on the sphere.

"frequency" is spherical angular harmonic: ℓ





The Observed Sound Spectrum



Sound as Diagnostic

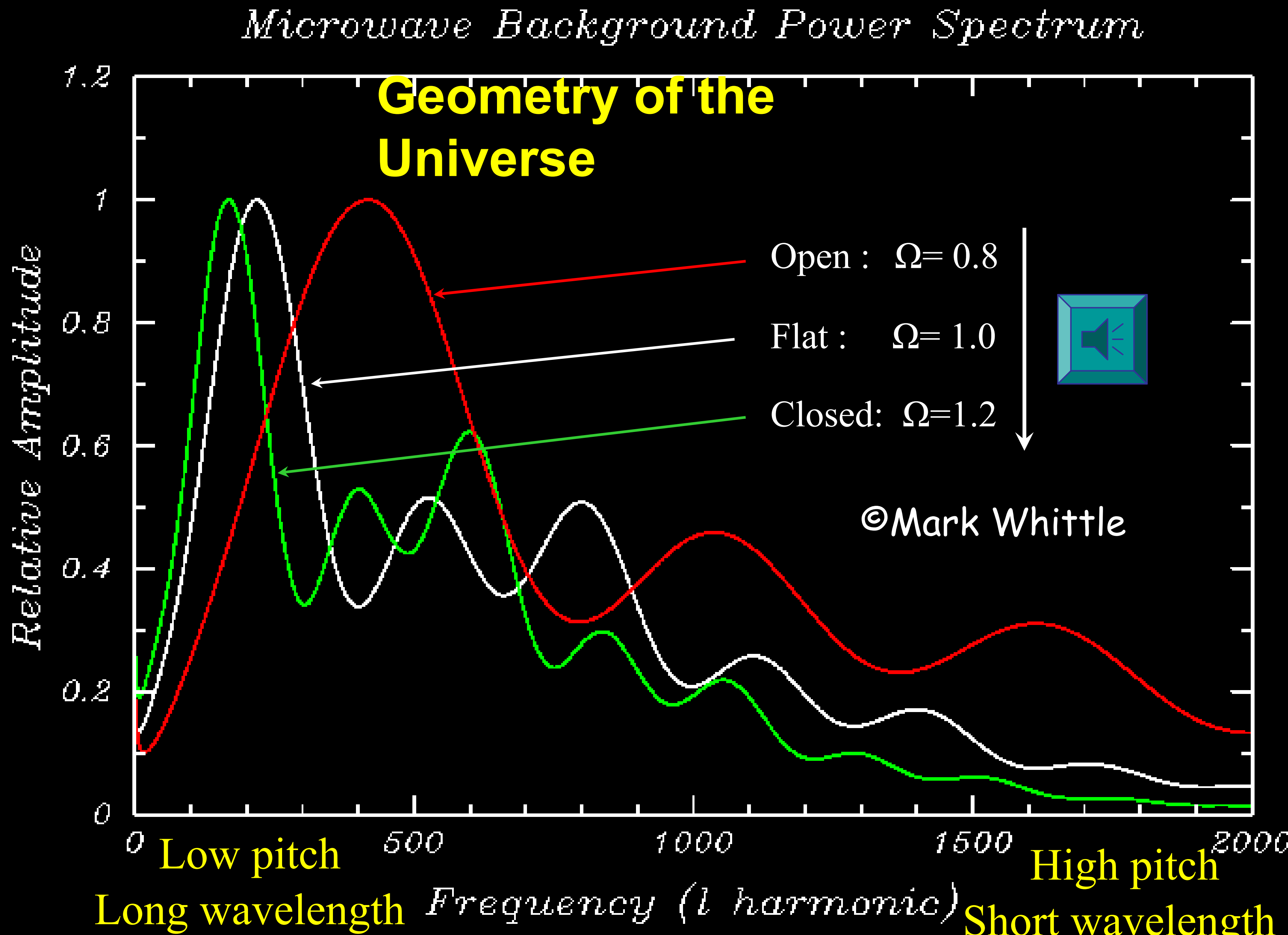
Quality of sound reveals the nature of an object

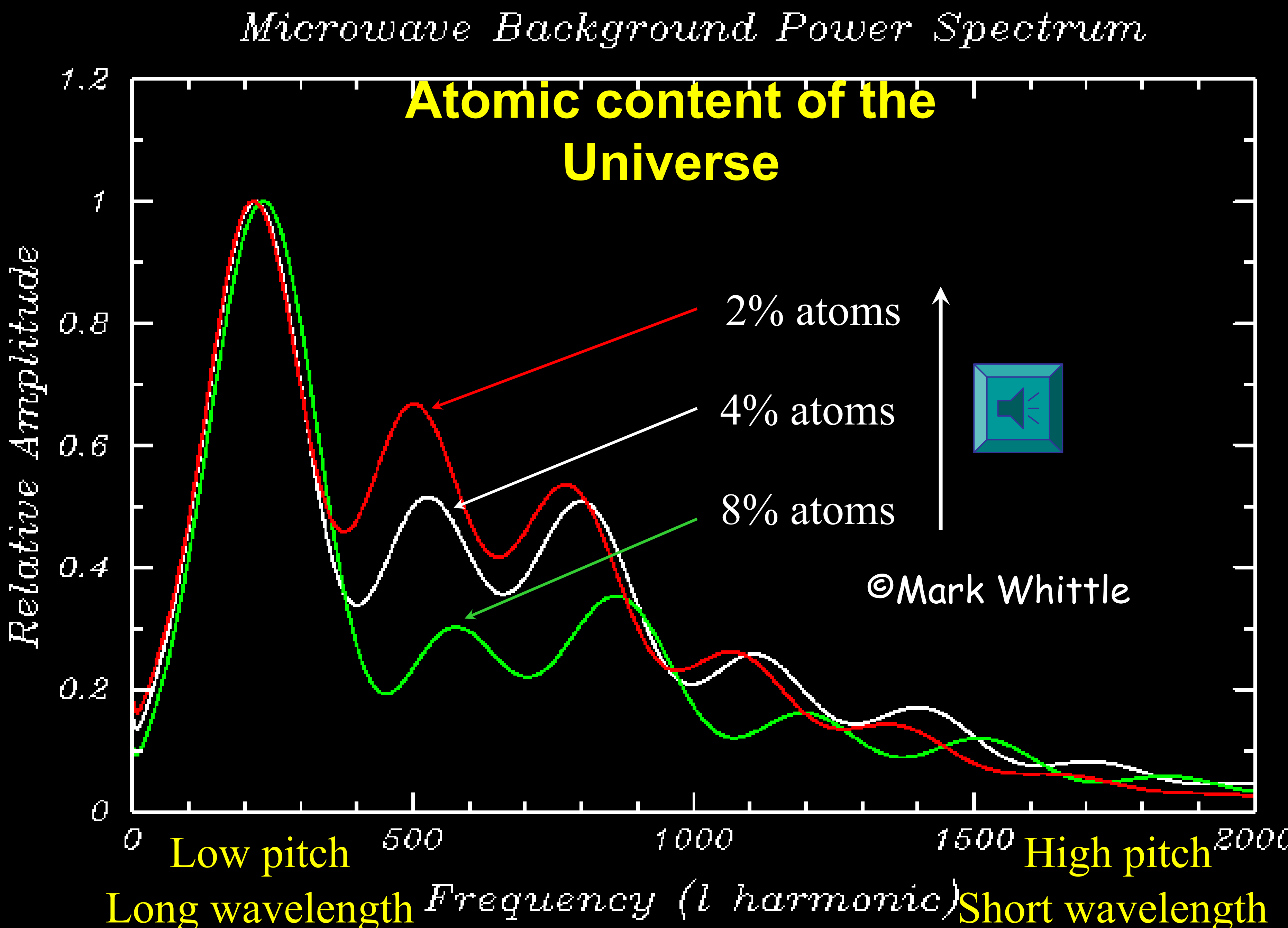
True also for the Universe:

- The sound spectrum reveals many properties
- Use computer simulations to match data
- Two examples: baryon fraction; total density

See homepage: Mark Whittle
University of Virginia

Geometry of the Universe




Microwave Background Power Spectrum
Atomic content of the Universe
2% atoms
4% atoms
8% atoms
©Mark Whittle
Relative Amplitude
1.2
1
0.8
0.6
0.4
0.2
0
0
500
1000
1500
2000
Low pitch
High pitch
Long wavelength
Frequency (l harmonic)
Short wavelength

Could one really have heard the early universe?

What frequencies can we hear ?

20 – 20,000 waves per second (Hertz)

v. deep v. high

What's the Cosmic pitch ??

1 wave every 20,000 – 200,000 yrs !!

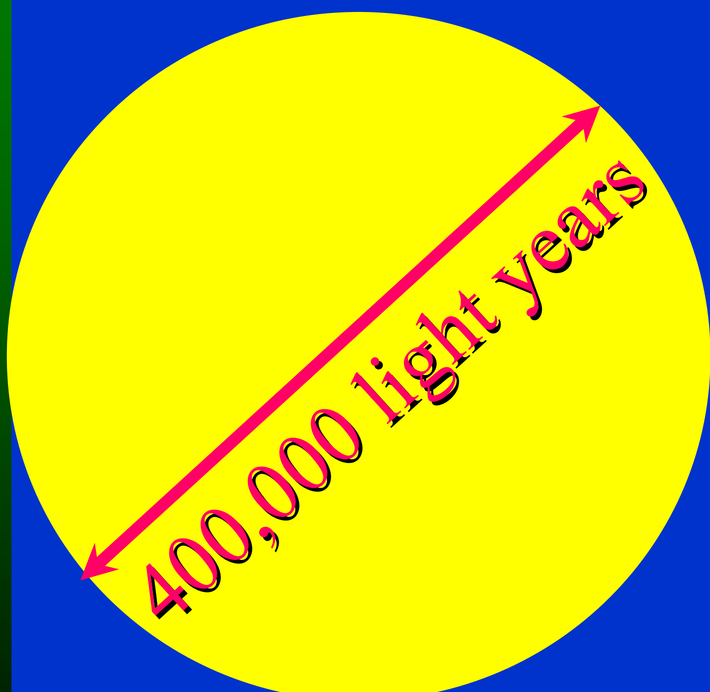
Too deep to hear, by about 50 octaves!

©Mark Whittle

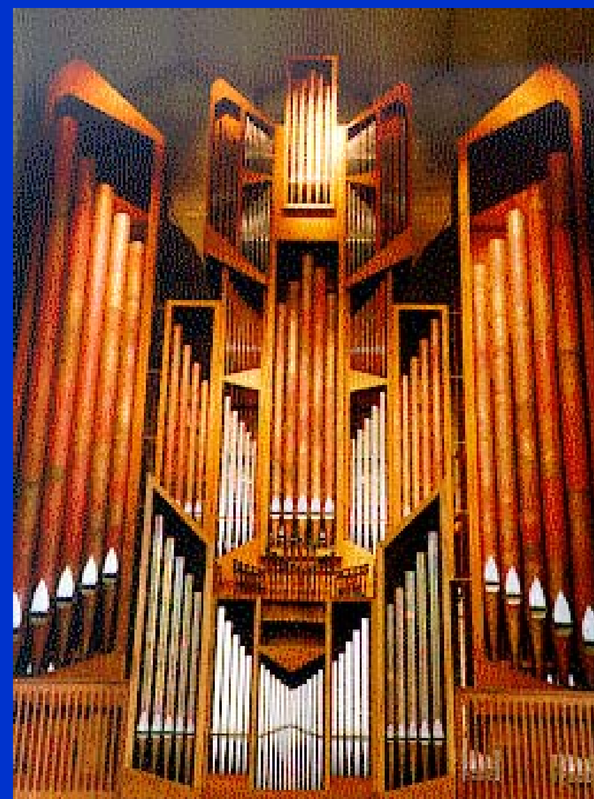
Why is the primordial sound so deep?

Because the Universe is so: **BIG**

Universe



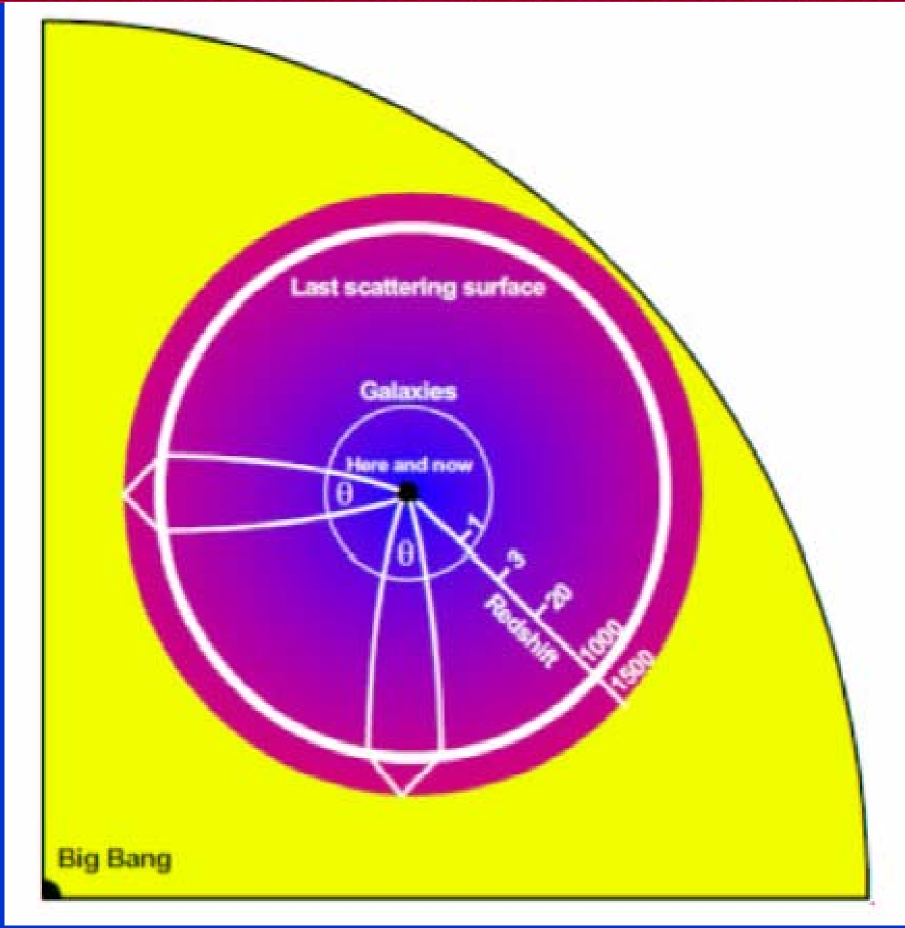
Cathedral Organ

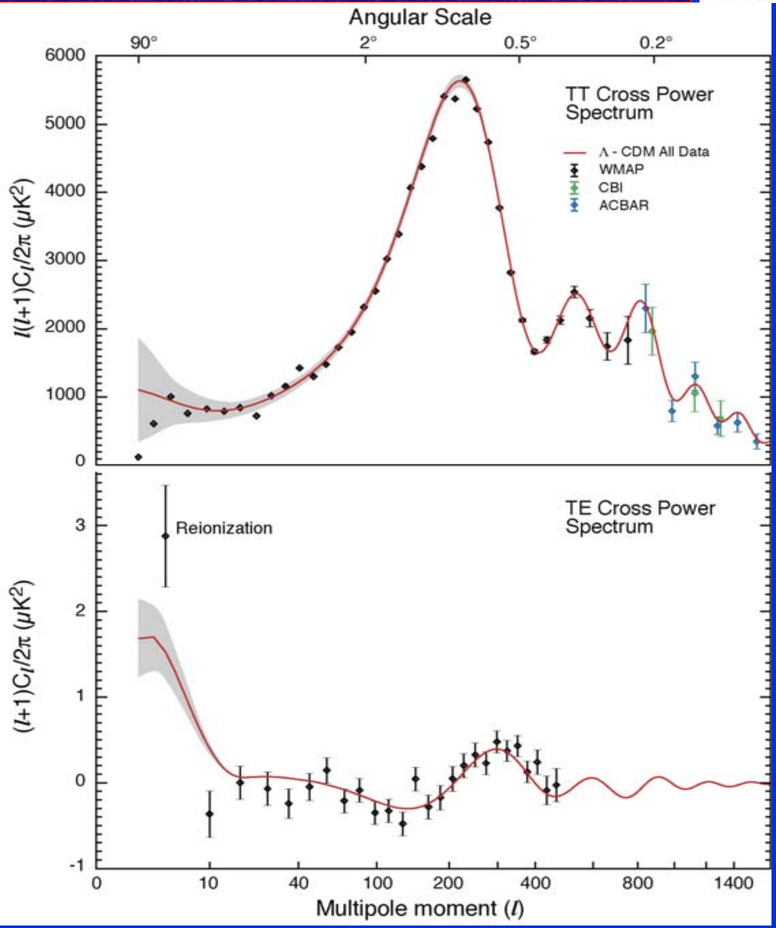


Pan Pipes

©Mark Whittle

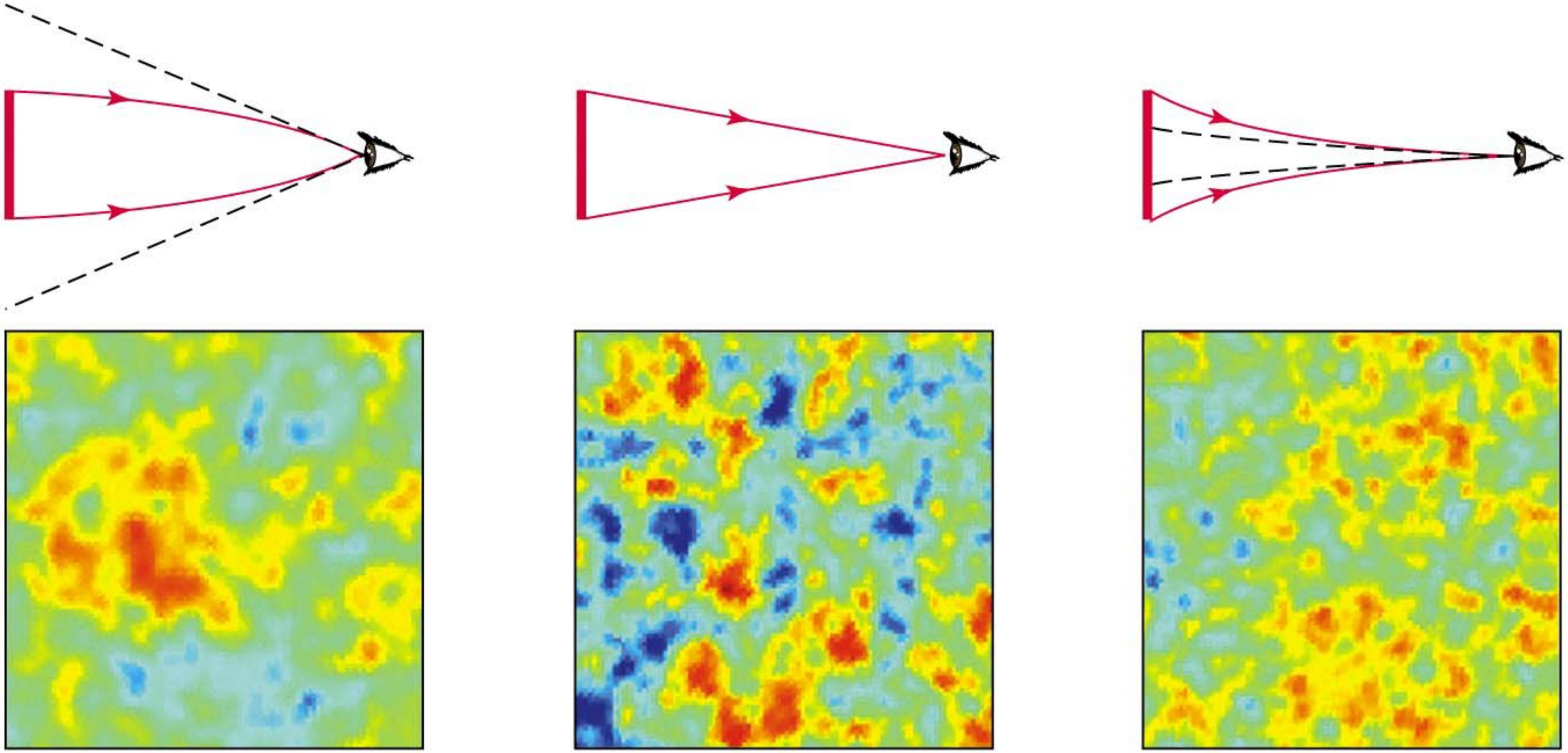
Acoustic peaks from WMAP





Density fluctuations (DF) develop as acoustic waves: contraction by gravity counter-acted by pressure. They grew coherently and can be observed under angles below 1° as temperature fluctuations in the CMB -> opening angle and peaks sensitive to all parameters, like flatness Ω_{tot}, expansion rate Ω_v, Ω_b...

Position of first acoustic peak determines curvature of universe

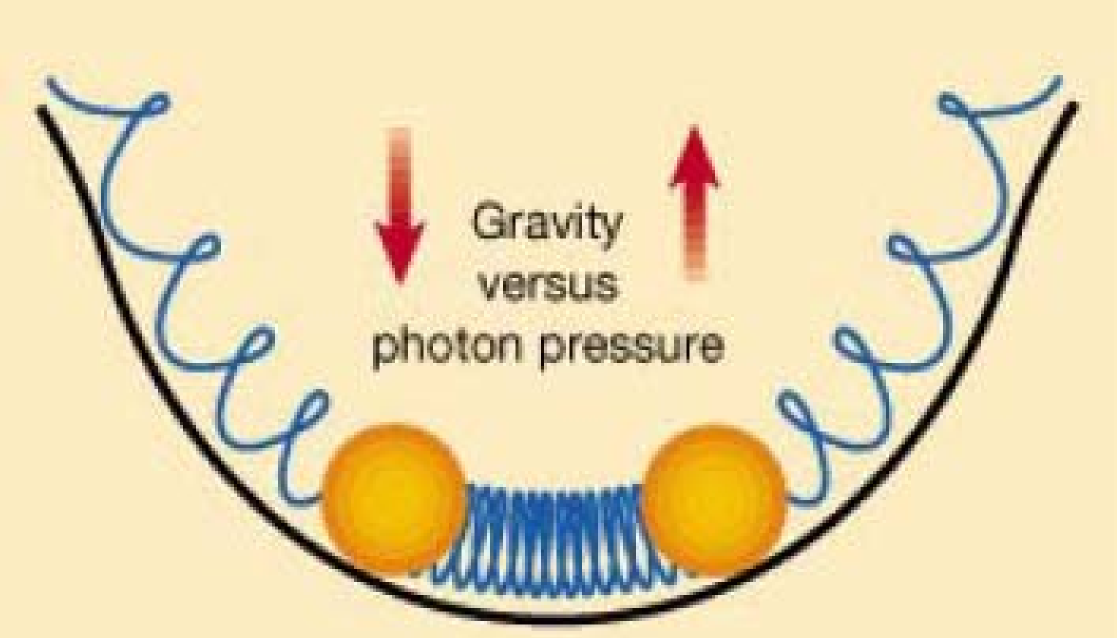


a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

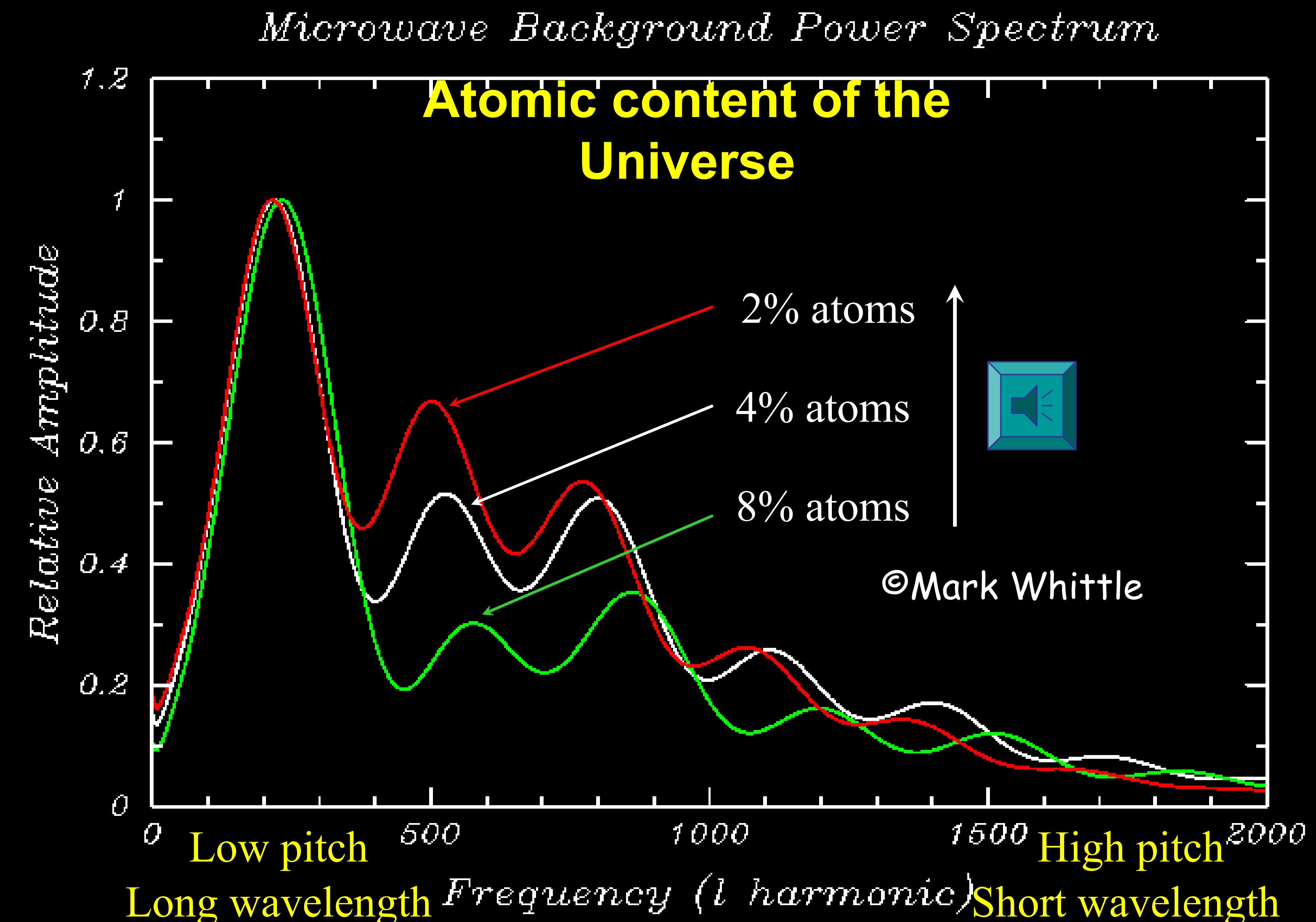
Model of acoustic waves in early universe



Model of acoustic waves:

DM determines depth of potential well
Baryons (yellow) fall into well
Photon pressure (spring) drives them out of well

More baryons: more damping, less amplitude, less power
More neutrinos: free streaming reduces depth of well-> less amplitude -> less power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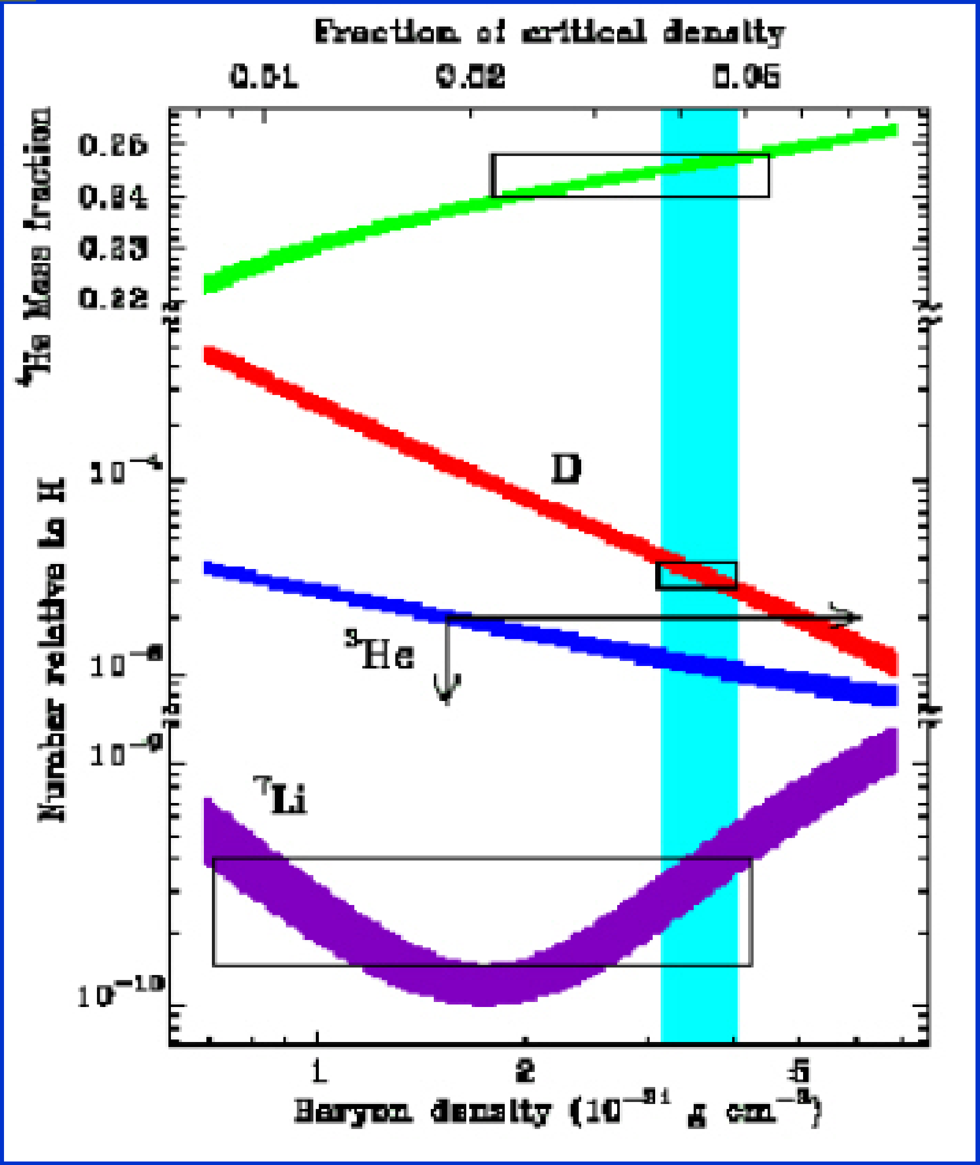
0.2
0
0
500
1000
1500
2000
Low pitch
Long wavelength
High pitch
Short wavelength
Frequency (l harmonic)

How does this compare with the visible matter?

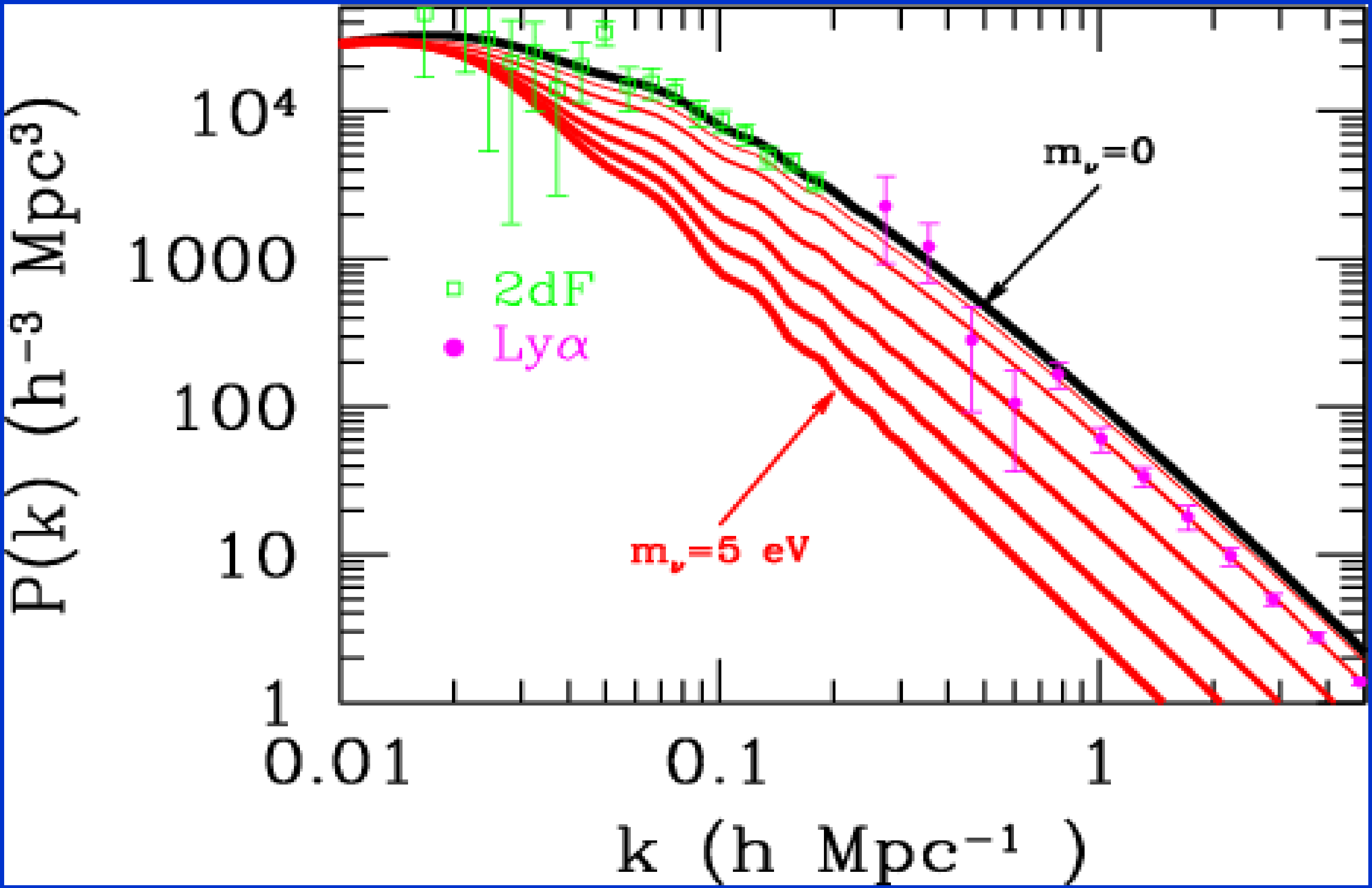


From the relative fraction of nuclei one finds that the density of atoms is only about 4% of the critical density.

(in agreement with other observations, like the acoustic peaks in the CMB)

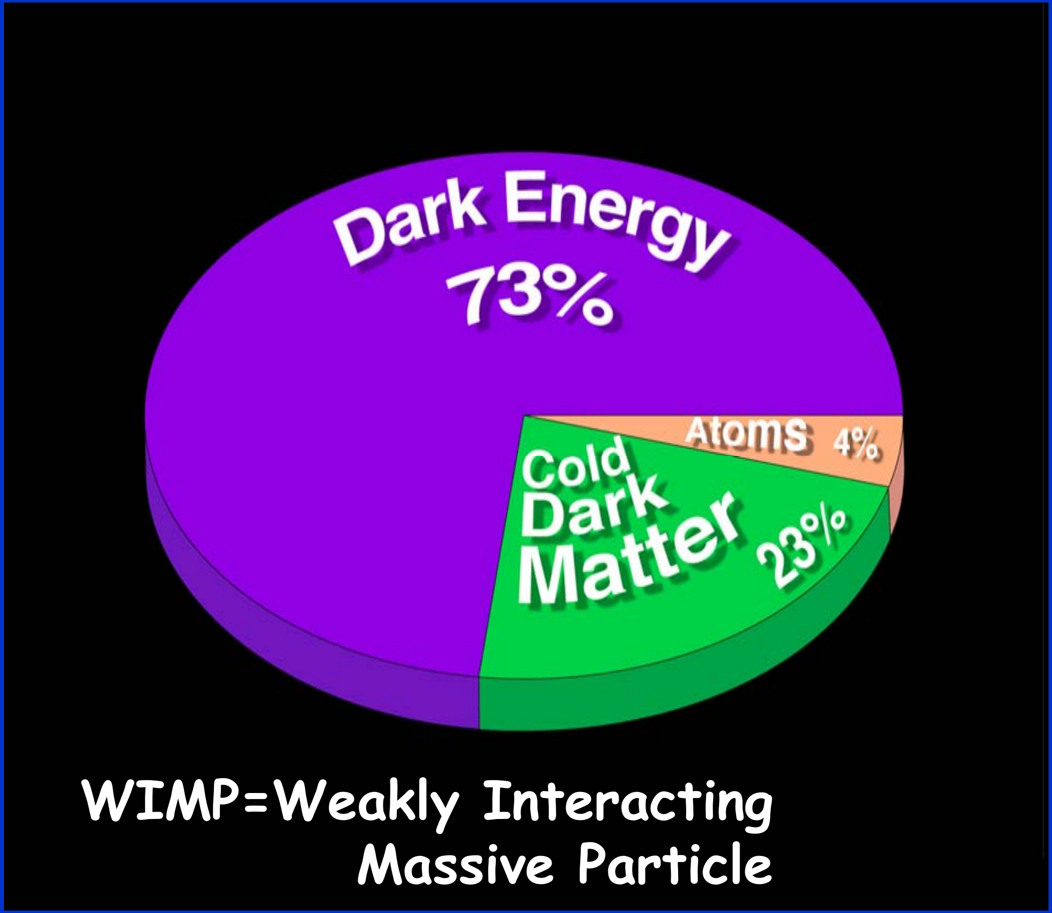
What is the other 96% of invisible energy made off?

Power spectrum at small scales sensitive for neutrino masses!



Neutrino mass < 0.23 eV (all ν's same mass, 95% C.L.)

Energy content of the Universe



We know the invisible 96% has 2 components:

One with repulsive gravity –called dark energy (73%)-

one with normal gravity, called dark matter (23%)

$\Omega = \rho/\rho_{crit}$ 1.0±0.04

$\Omega_M = \rho_M/\rho_{crit}$

$\Omega_{CDM} = \rho_{CDM}/\rho_{crit}$

$\Omega_\Lambda = \rho_\Lambda/\rho_{crit} = 73\%$

$\Omega = \Omega_M + \Omega_{CDM} + \Omega_\Lambda = 1$

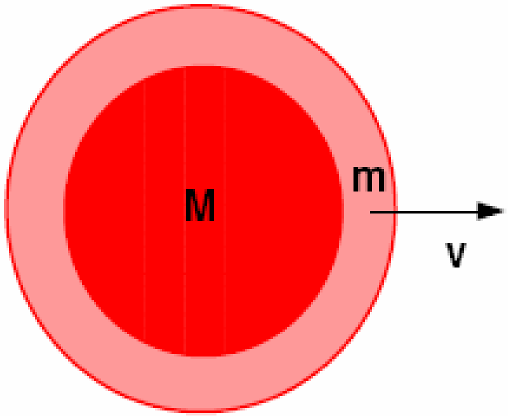
Questions

1. **How can it happen that gravity becomes repulsive?**
2. **How does one measure acceleration of universe?**

   (acceleration will determine how much dark energy (DE) compared with dark matter (DM), since total acceleration is sum of positive acceleration from DE and negative acc. from DM)

Repulsive Gravity if energy density is constant as expected for vacuum energy

A simple example:



$$E_{tot} = \frac{1}{2}m\dot{R}^2 - \frac{GmM}{R}$$

Differentiate with respect to t and use $\dot{E}_{tot} = 0$, $M = \frac{4}{3}\pi R^3 \rho$:

$$\dot{R}\ddot{R} - \frac{4\pi G}{3}\left[2\rho R\dot{R} + \dot{\rho}R^2\right] = 0$$

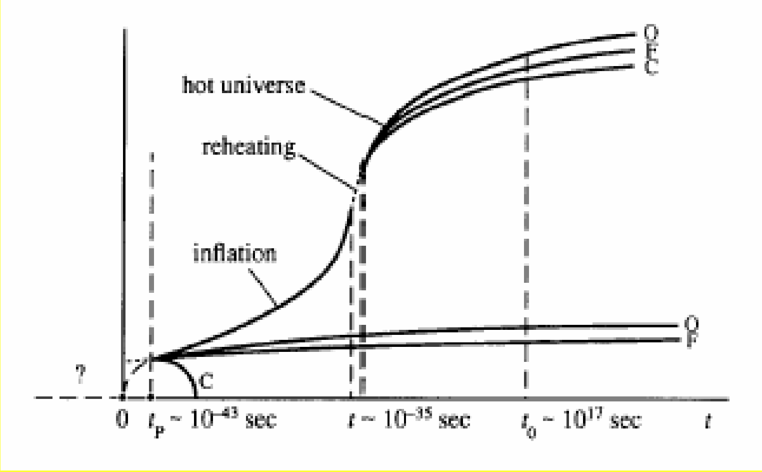
Two solutions for acceleration $\ddot{R}$:

$\ddot{R} = \frac{-4\pi G}{3}\rho R$, if $\rho = c/R^3$

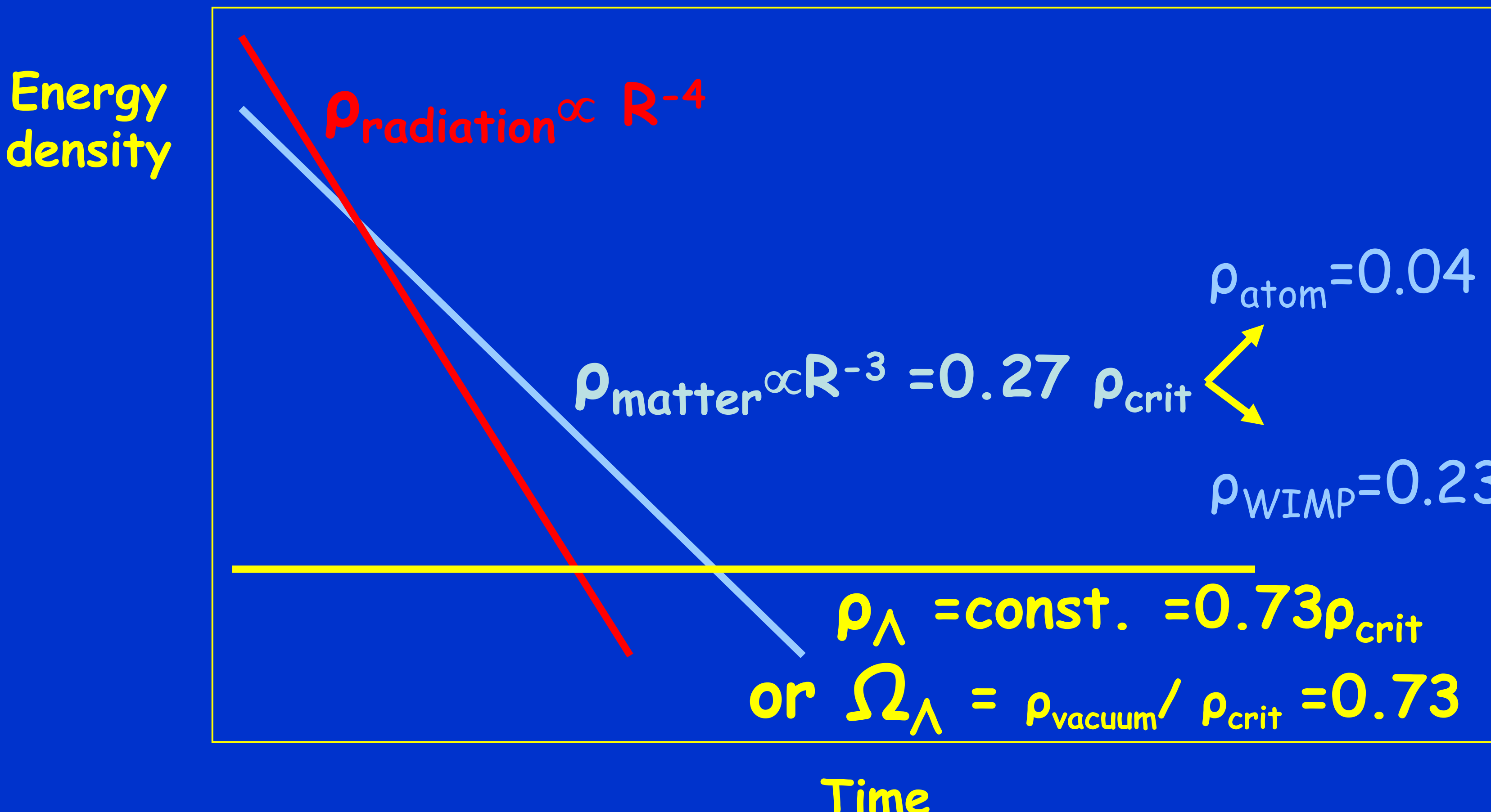
$\ddot{R} = \frac{+8\pi G}{3}\rho R$, if $\rho = \mathrm{const.}$

Solution 2 $\Rightarrow$ **INFLATION**, since $R = ce^{+t/\tau}$ with $\tau = \sqrt{3/8\pi\, G\rho} = 10^{-37}$ s at GUT energies $\Rightarrow$

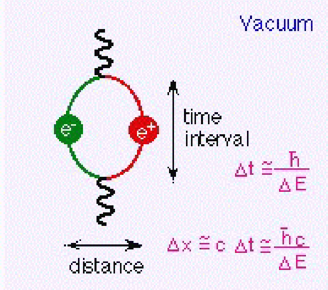
Radius of Universe doubles every $\tau \ln 2 = 3 \cdot 10^{-37}$ s after phase transition!

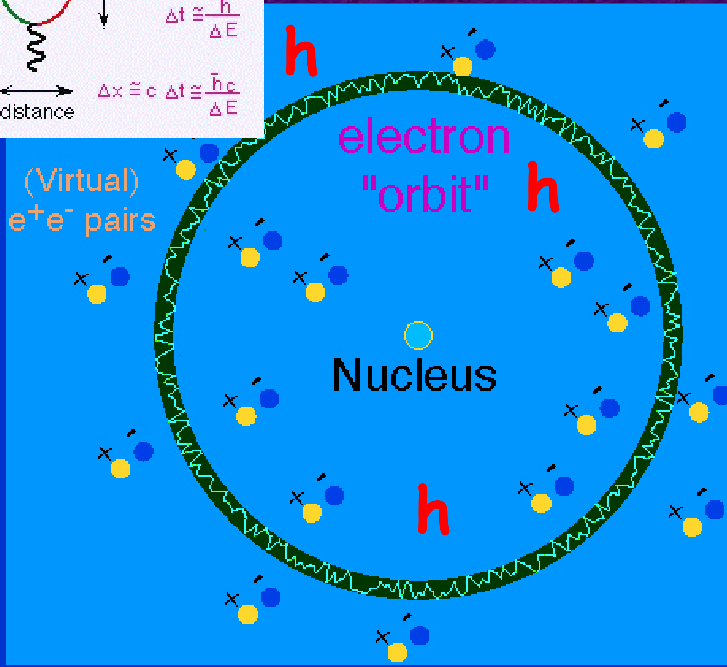


Energy density components in expanding universe



What is vacuum energy?





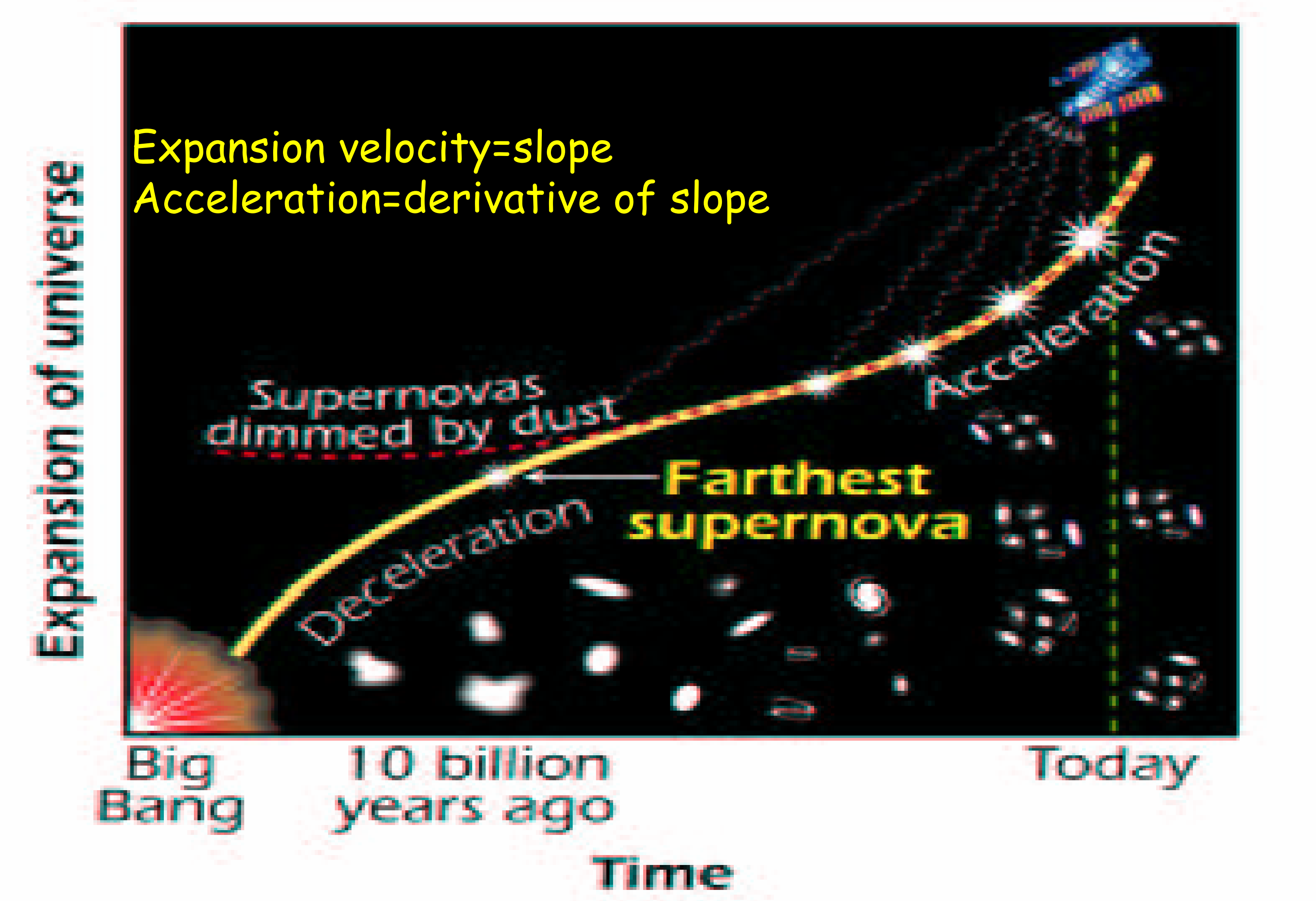
Vacuumfluctuations observed in
1) Lamb shift
2) Casimir effect
3) Running coupling constants
4) Repulsive gravity

Calculation of vacuum energy
10^{115} GeV/cm^3 in Standard Model
10^{50} GeV/cm^3 in Supersymmetry

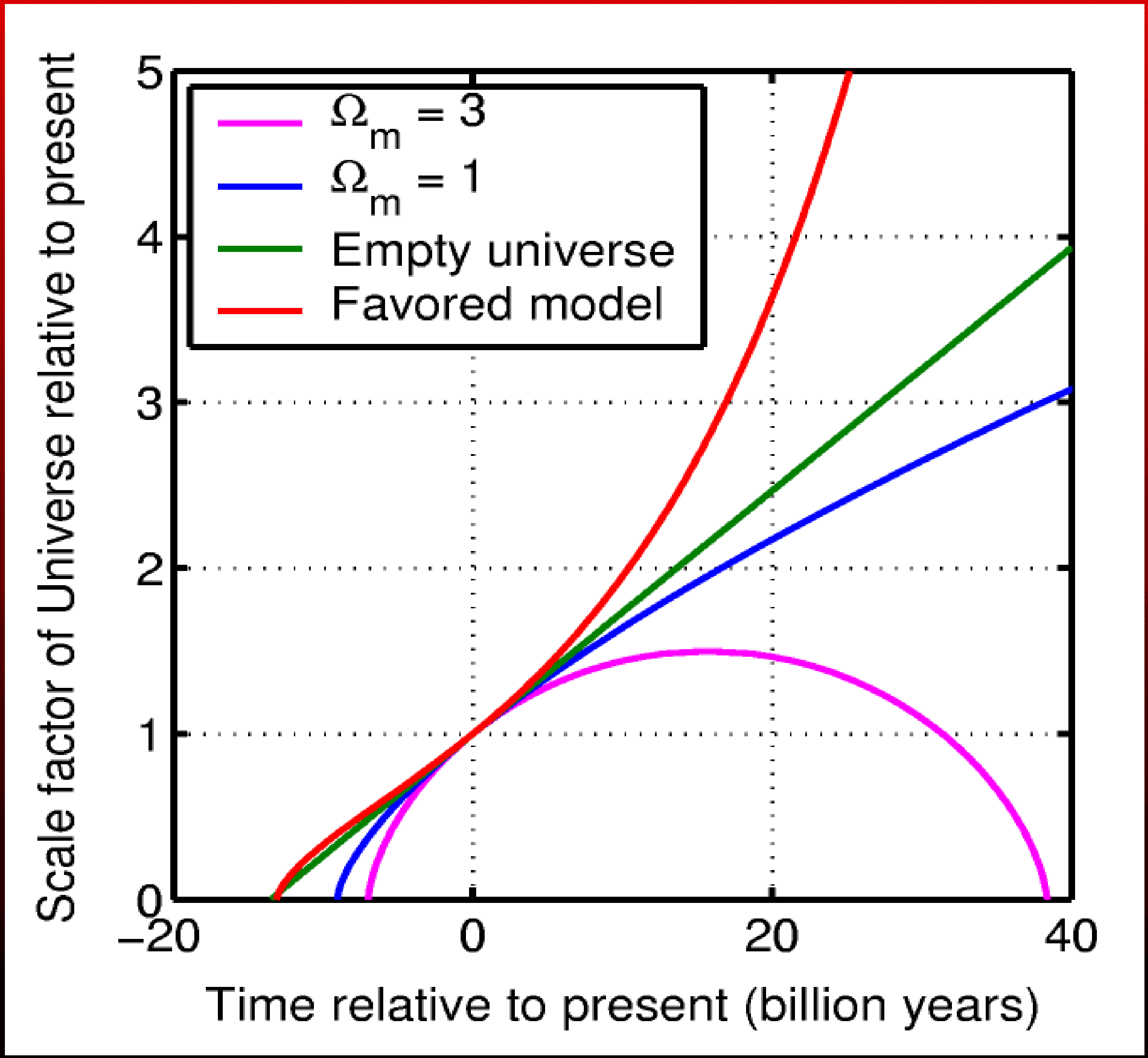
Measured vacuum energy: 10^{-5} GeV/cm^3

Why is vacuum so empty?

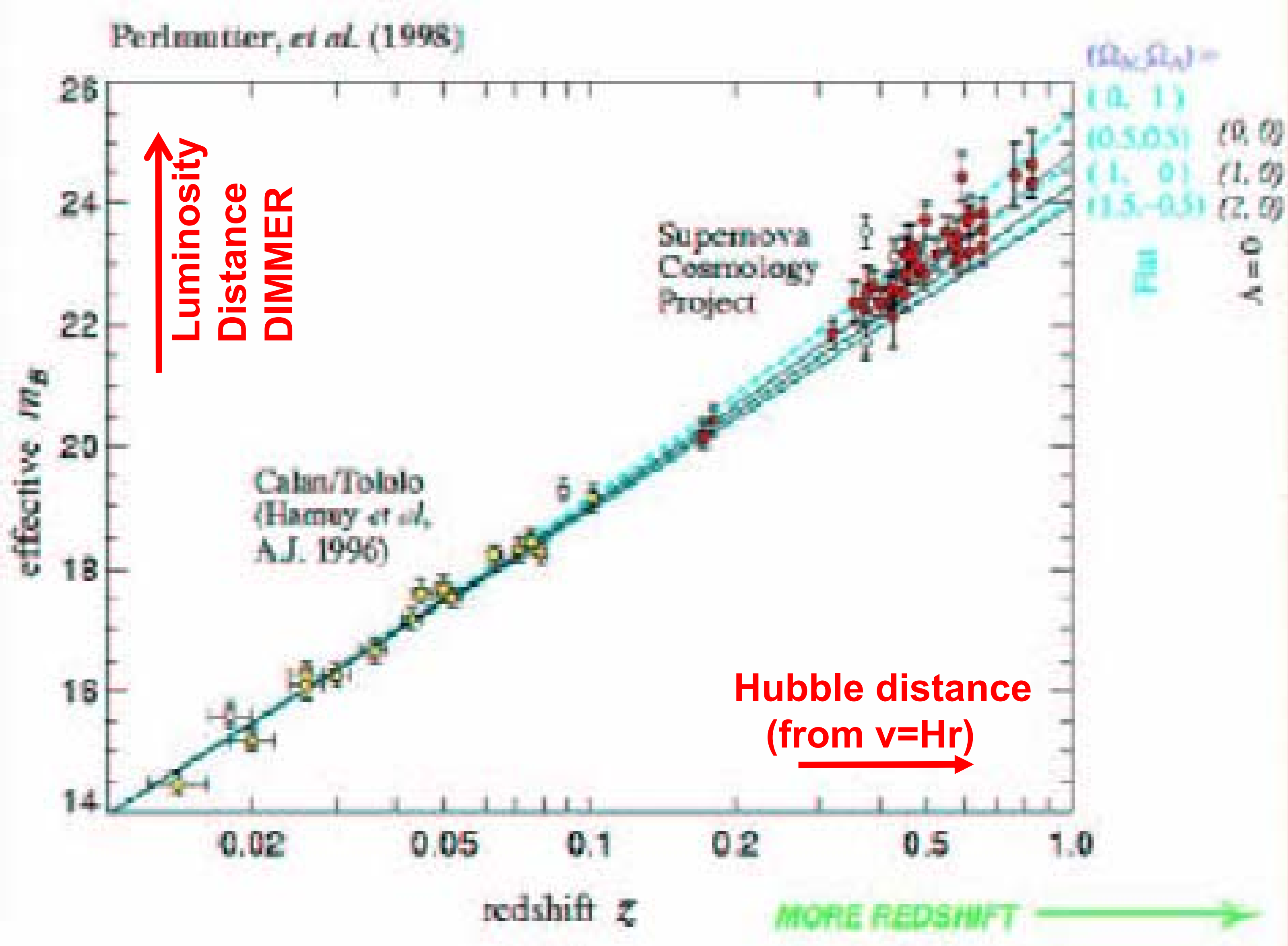
First evidence for vacuum energy in universe: ACCELERATION of universe



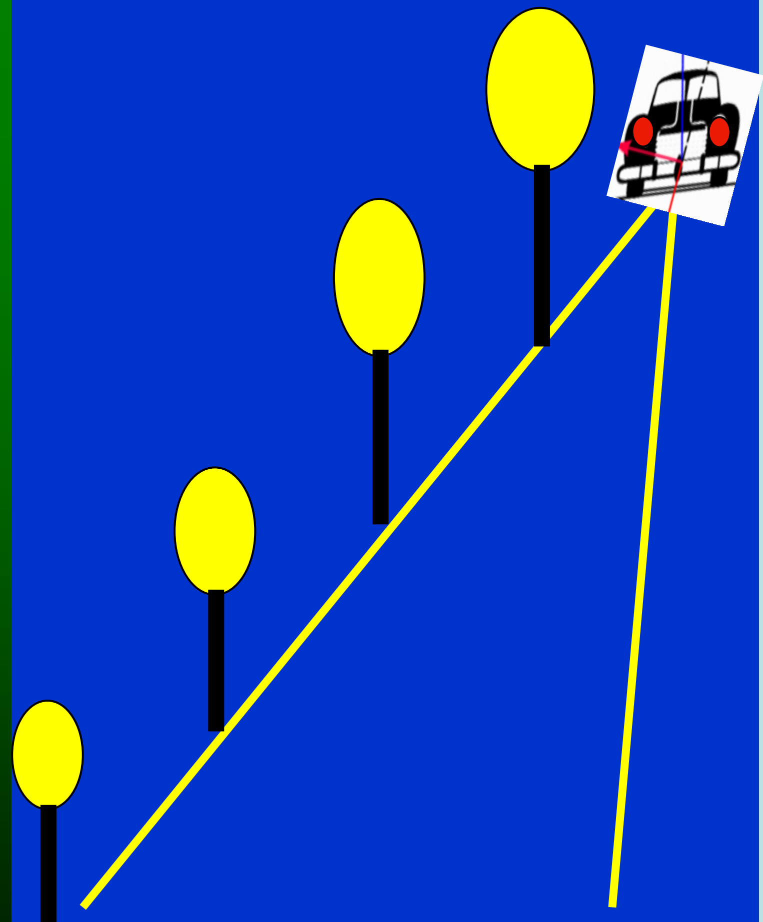
Expansion History of the Universe



SN1a as tracer of the Universe



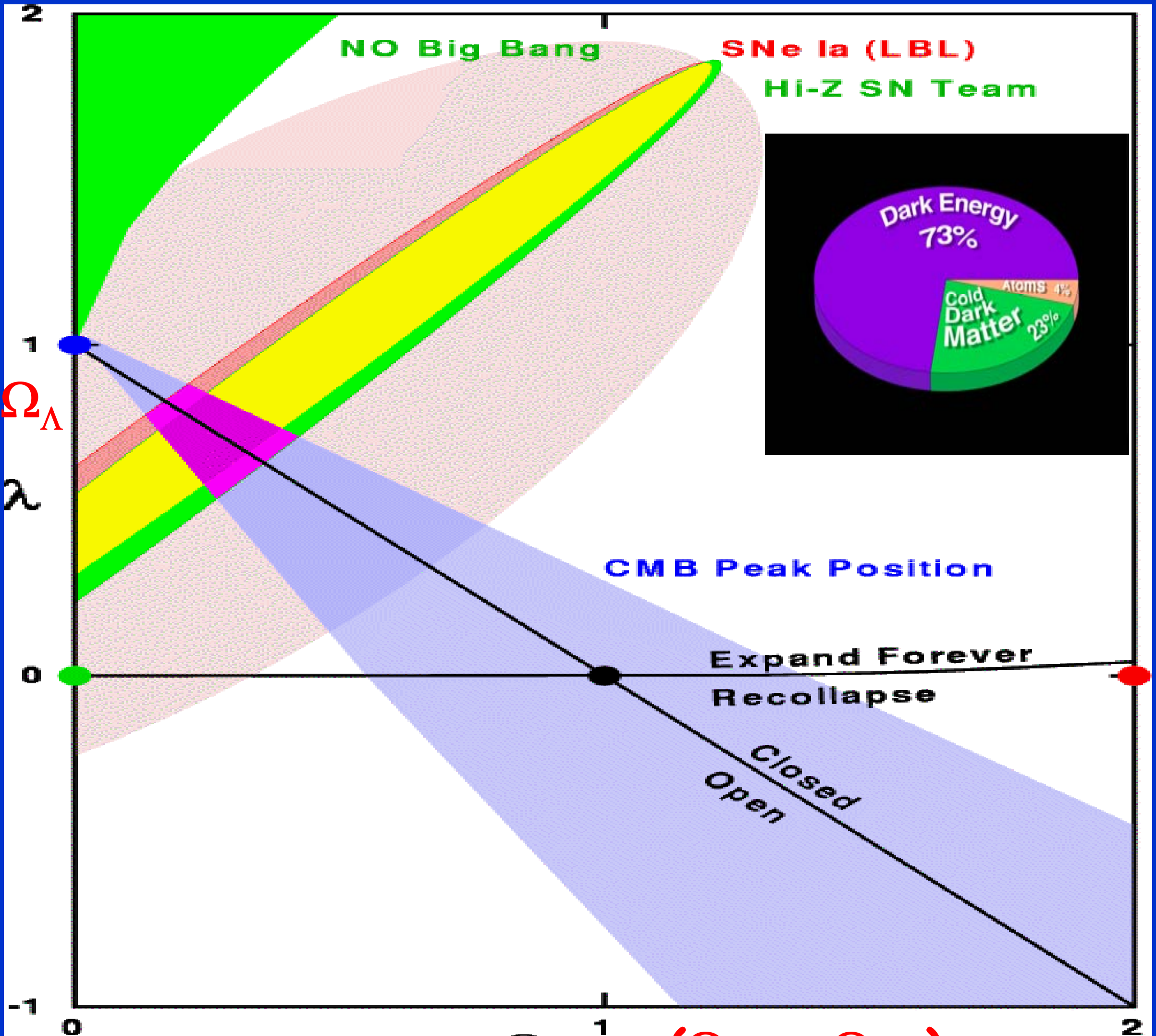
SNIa compared with Porsche rolling up a hill



SNIa data very similar to a dark Porsche rolling up a hill and reading speedometer regularly, i.e. determining v(t), which can be used to reconstruct $x(t) = \int v(t)dt$.
(speed ⇒ distance, for universe Hubble law)
This distance can be compared later with distance as determined from the luminosity of lamp posts (assuming same brightness for all lamp posts)
(luminosity ⇒ distance, if SN1a treated as 'standard' lamp posts)

If the very first lamp posts are further away than expected, the conclusion must be that the Porsche instead of rolling up the hill used its engine, i.e. additional acceleration instead of decelaration only.
(universe has additional acceleration (by dark energy) instead of decelaration only)

Combine CMB with SNIa data



$\Omega_M = (\Omega_{SM} + \Omega_{DM})$

SNIa sensitive to accelleration, i.e.

$acc = \Omega_\Lambda - (\Omega_{SM} + \Omega_{DM})$ or

$\Omega_\Lambda = acc + (\Omega_{SM} + \Omega_{DM})$

CMB sensitive to overall density, i.e.

$\Omega_\Lambda + \Omega_{SM} + \Omega_{DM} = 1$ or

$\Omega_\Lambda = 1 - (\Omega_{SM} + \Omega_{DM})$

What is Dark Matter?

a) DM is neutral (else electric fields)
b) DM is weakly interacting (else it would clump in galactic center as baryonic matter
c) DM is massive, since it determines rotation curves

Therefore DM consists of WIMPs
(Weakly Interacting Massive Particles)

WIMPs are neutrinos? No, neutrinos would be "warm" or "hot" DM, but this is excluded by powerspectrum of galaxy surveys.

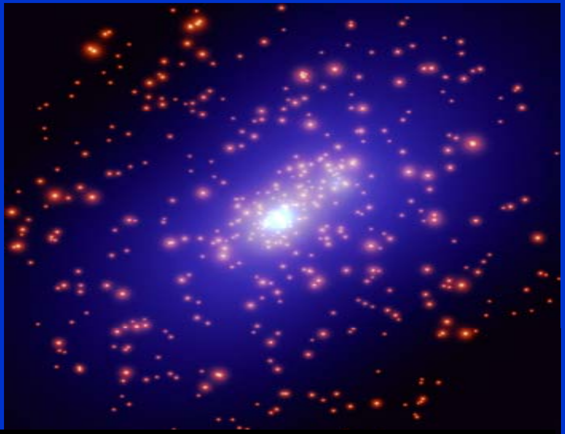
WIMPs MUST BE NEW PARTICLES outside Standard Model and NOT PRODUCED AT ACCELERATORS.
(cannot be produced directly with small WIMP-nucleon x-section)

What is known about Dark Matter?

- 95% of the energy of the Universe is non-baryonic
  23% in the form of Cold Dark Matter
- Dark Matter enhanced in Galaxies and Clusters of Galaxies but DM widely distributed in halo-> DM must consist of weakly interacting and massive particles -> WIMP's
- Annihilation with $<\sigma v> = 2.10^{-26}$ cm^3/s, if thermal relic

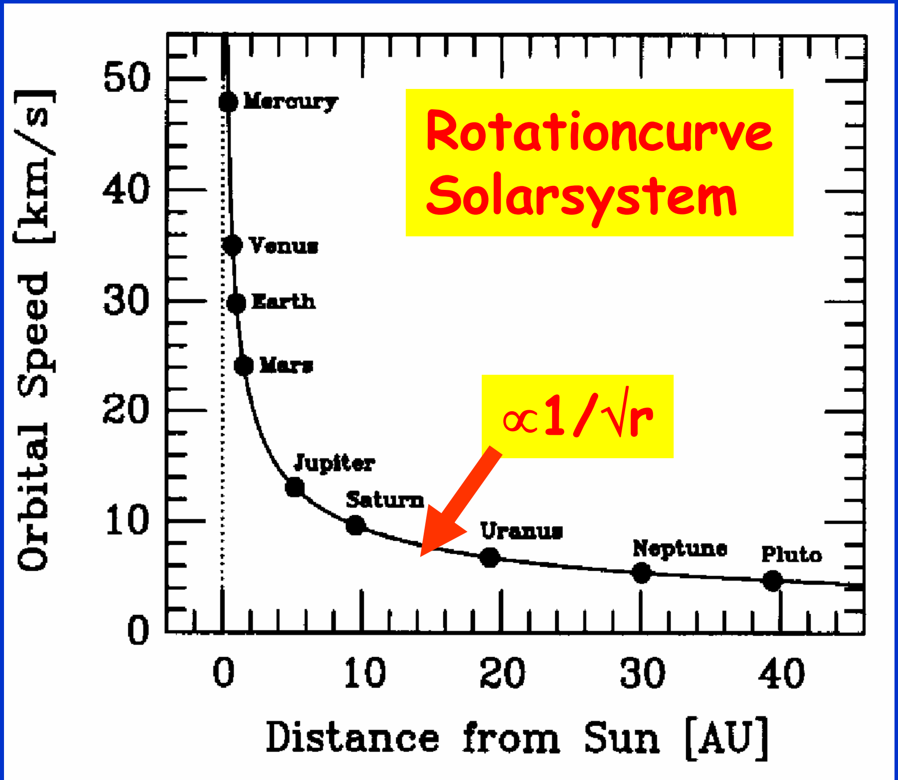
From CMB + SN1a + surveys

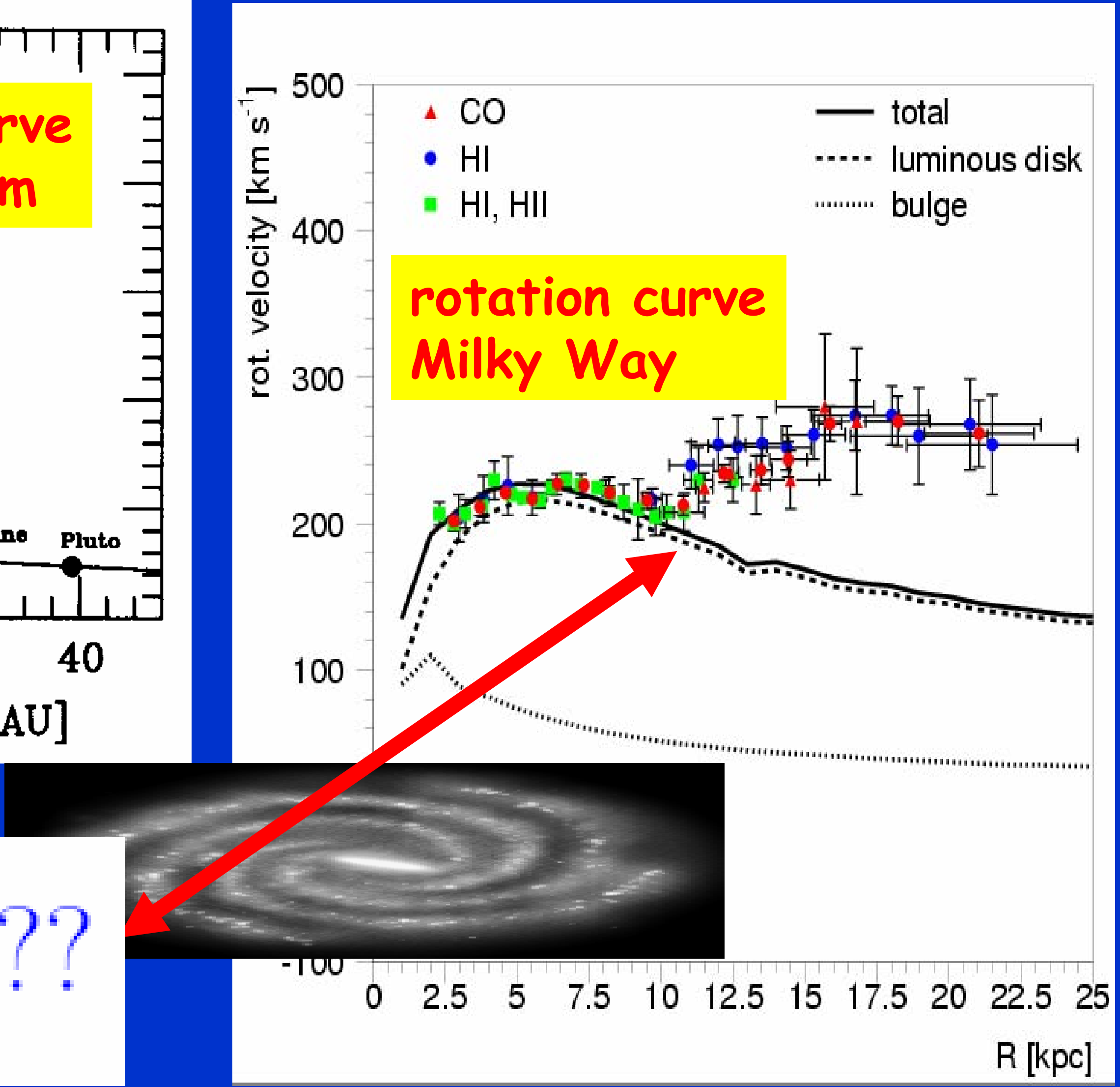
If it is not dark
It does not matter



DM halo profile of galaxy cluster from weak lensing

Do we have Dark Matter in our Galaxy?





$$\frac{mv^2}{r} \neq \frac{GmM}{r^2} ??$$

DM density in our Galaxy

Dark, since we do not see it

Non-baryonic, else it would interact and cluster like the visible matter

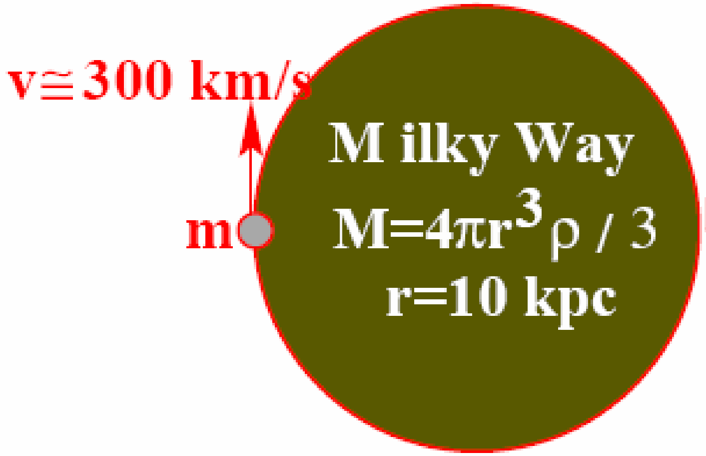
Need: WIMPS (Weakly Interacting Massive Particles)

Candidate: Neutralinos predicted by Supersymmetry

Local Density: on average 1 neutralino/ coffee cup (may be clustering)

$$mv^2/r = GmM/r^2$$

$$\rho = \frac{v^2}{\frac{4\pi}{3} r^2 G_N}$$

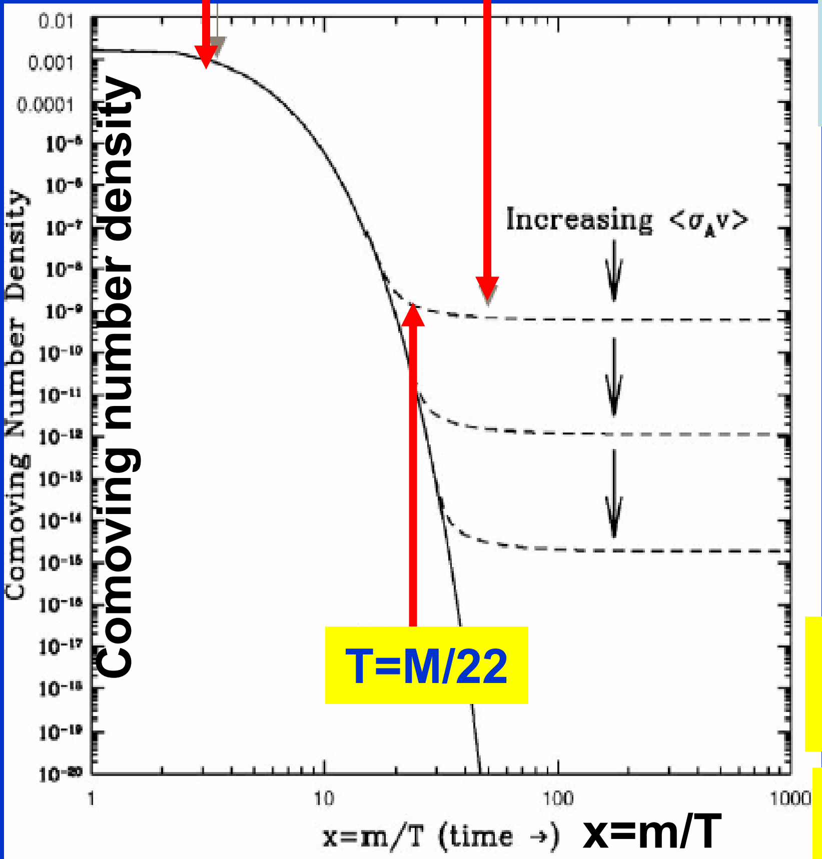


$$\rho \cong 2.10^{-24} \ g/cm^3$$

$$\cong 100 \ GeV/100 \ cm^3$$

$$\cong 10^5 \rho_{crit}$$

Expansion rate of universe determines WIMP annihilation cross section



Jungmann,Kamionkowski, Griest, PR 1995

T>>M: $f+\bar{f}$->$M+\bar{M}$; $M+\bar{M}$->$f+\bar{f}$
T<M: $M+\bar{M}$->$f+\bar{f}$
T=M/22: M decoupled, stable density
(wenn Annihilationrate ≅ Expansions-rate, i.e. $\Gamma=<\sigma v>n\chi(x_{fr}) \cong H(x_{fr})$!)

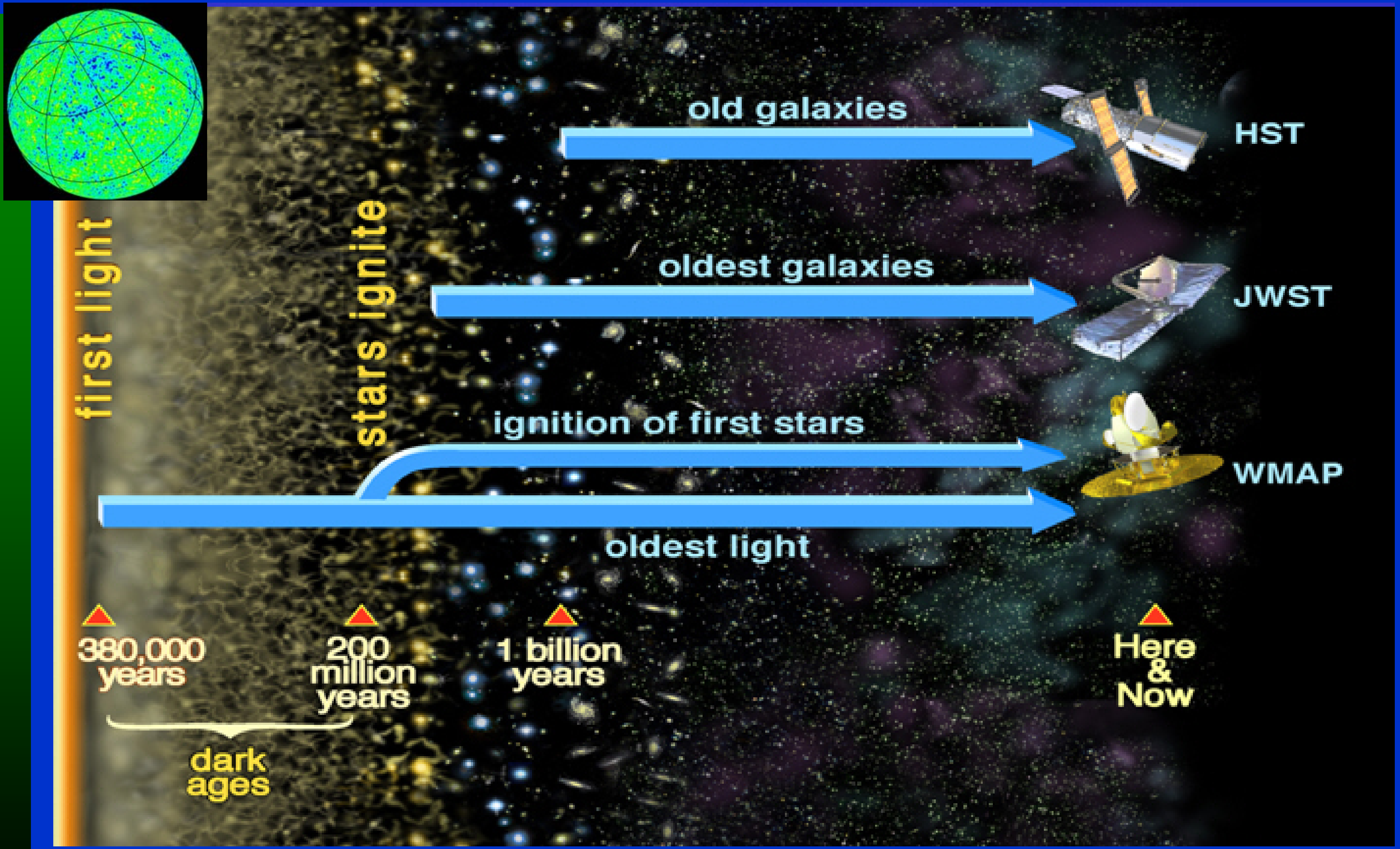
WMAP -> $\Omega h^2=0.113\pm0.009$ -> $<\sigma v>=2.10^{-26}$ cm^3/s

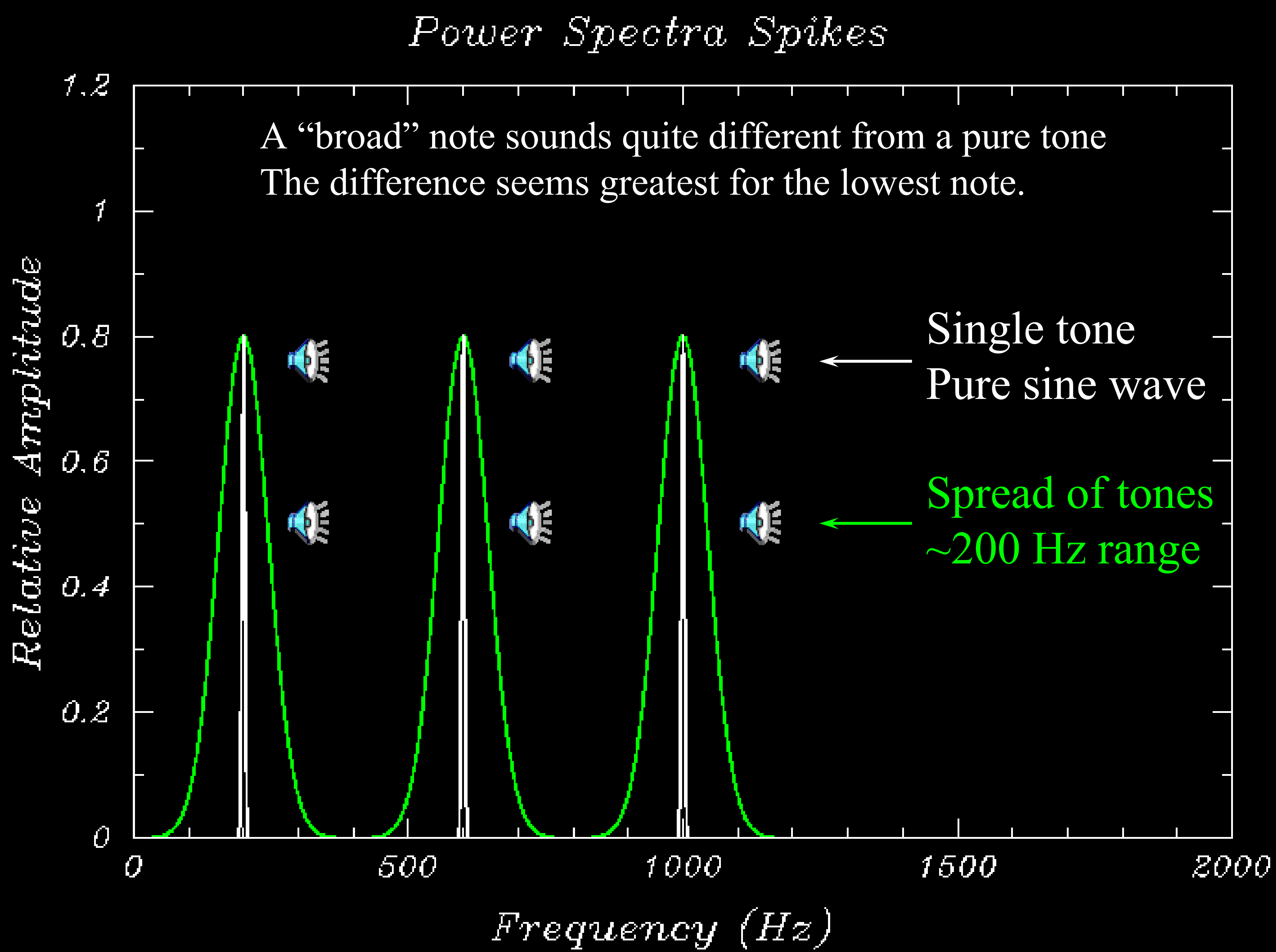
DM increases in Galaxies:
≈1 WIMP/coffee cup ≈10^5 $<\rho>$.
DMA ($\propto\rho^2$) restarts again..

Annihilation into lighter particles, like quarks and leptons -> π_0's -> Gammas!

Only assumption in this analysis:
WIMP = THERMAL RELIC!

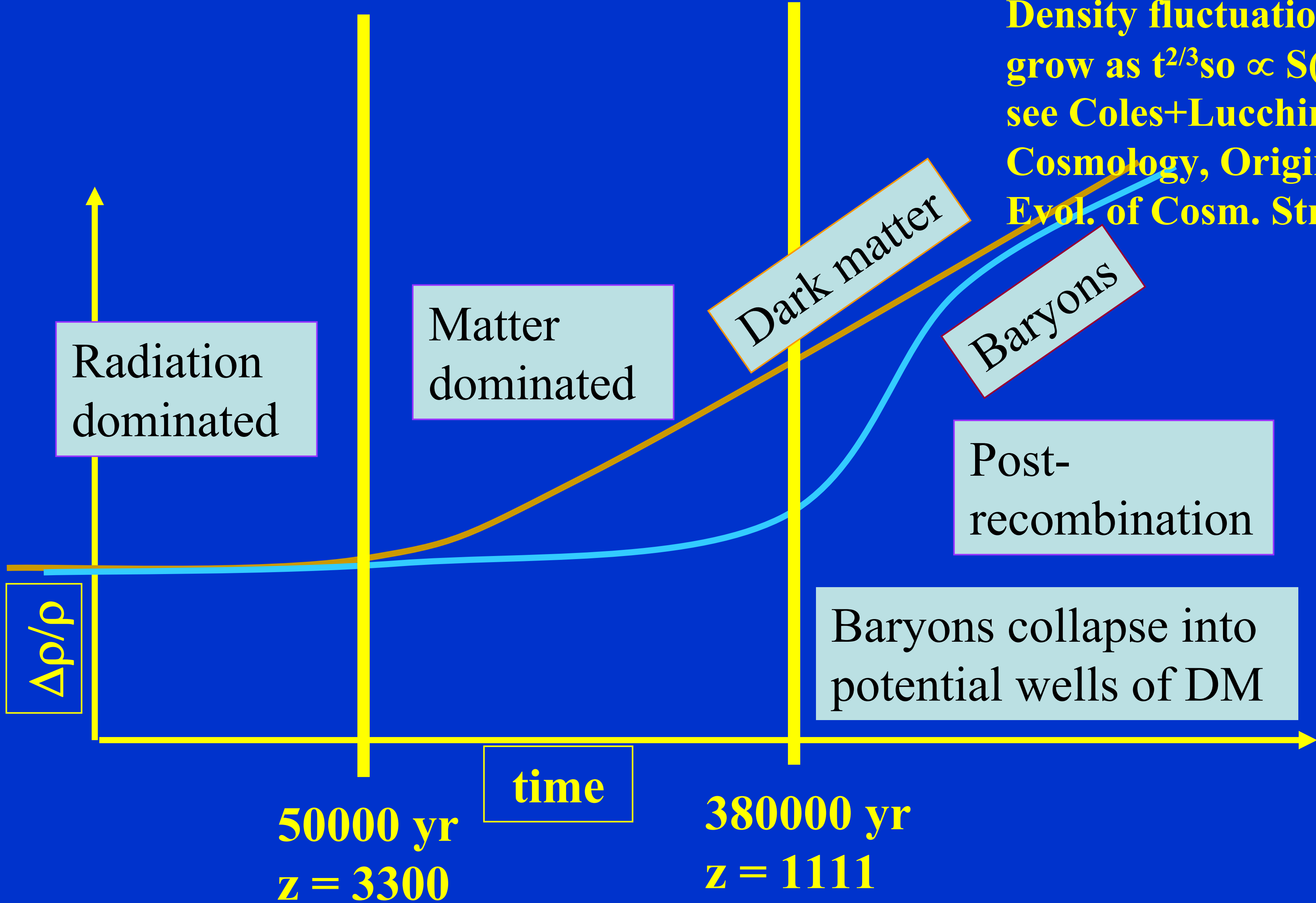
Observations of the universe




Power Spectra Spikes
A "broad" note sounds quite different from a pure tone
The difference seems greatest for the lowest note.
Single tone
Pure sine wave
Spread of tones
~200 Hz range
Relative Amplitude
Frequency (Hz)
0
0.2
0.4
0.6
0.8
1
1.2
500
1000
1500
2000

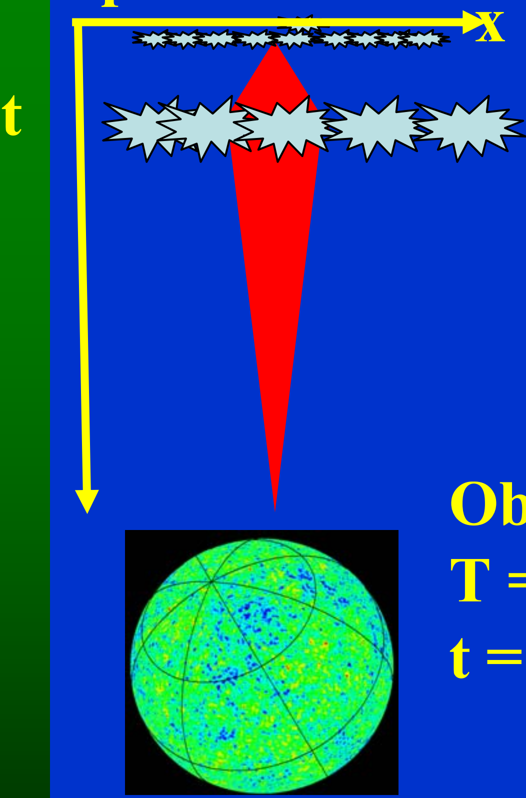
Early formation of stars only possible with DM!

Density fluctuations grow as $t^{2/3}$so ∝ S(t), see Coles+Lucchin, Cosmology, Origin a Evol. of Cosm. Struct



Position of first acoustic peak

Space-time



Inflation

Decoupling:
$T = 3000$ K
$t = 3.8 \; 10^5$ y

Observed now:
$T = 2.7$ K
$t = 13.8 \; 10^9$ y

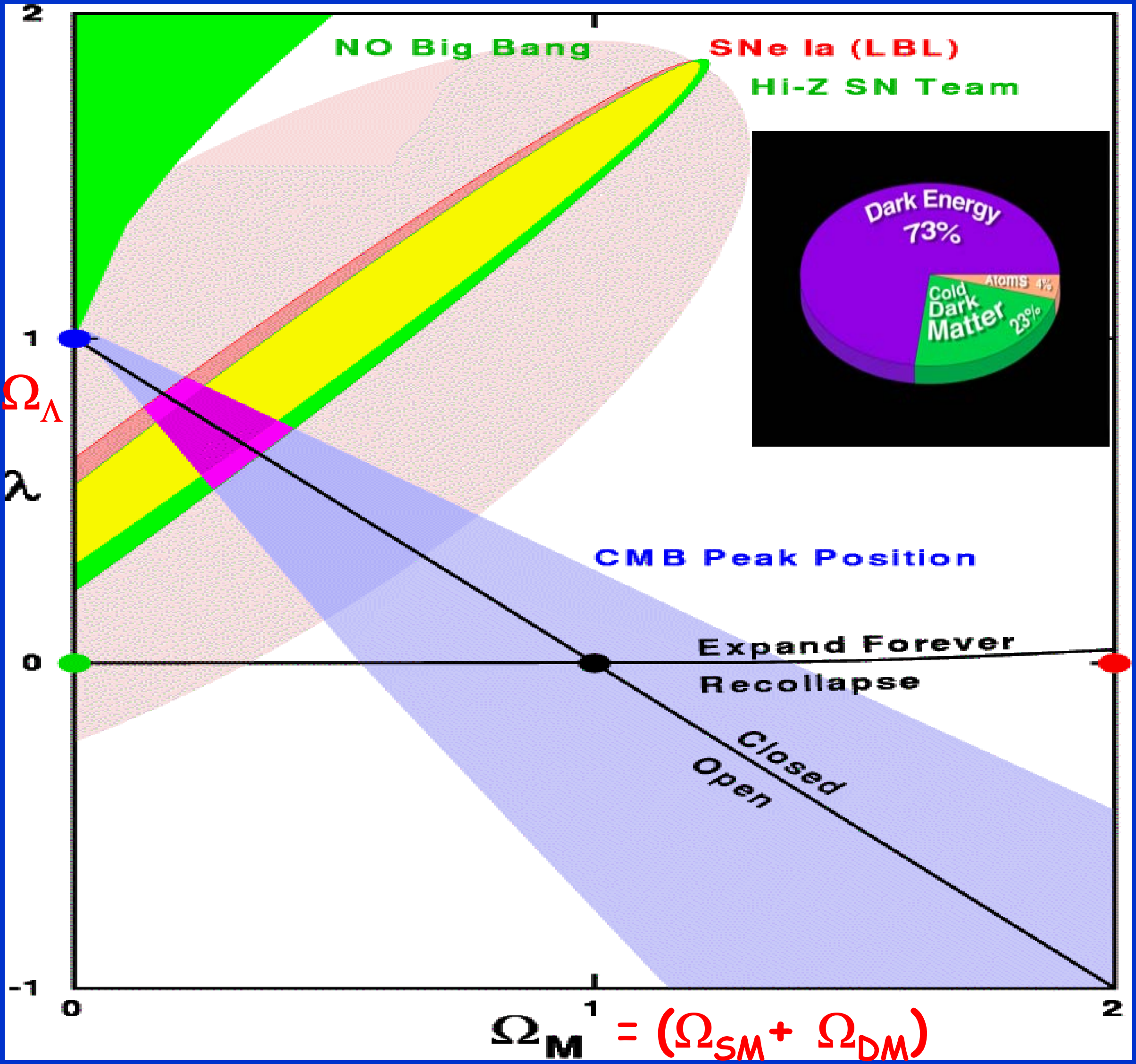
First acoustic peak= fundamental mode seen at 1^0, second harmonic at 0.5^0 third at 0.25^0,..

Acoustic horizon expected to yield maximum density contrast, since it corresponds to growing of density fluctuation for maximum time, i.e. from t=0 to recombination time trec.

Acoustic horizon at recombination time
c_s * trec
Observation now (t_0 =13.8 10^9 yr) under angle $\theta = c_s * t_{rec} * (1+z) / c*t_0$, where (1+z) represent scale factor of universe between trec and now, which scales with inverse of temperatures:
1+z=Trec/T0= 3000/2.7 =1100
With trec = 3,8 10^5 yr and acoustic speed $c_s = c/\sqrt{3}$ for a relativ. plasma:
$\theta = 0.0175 = 1^0$ (plus (small) ART correct.)

Remind: $c_s^2 \equiv dp/d\rho = c^2/3$, da $p = 1/3\, \rho c^2$

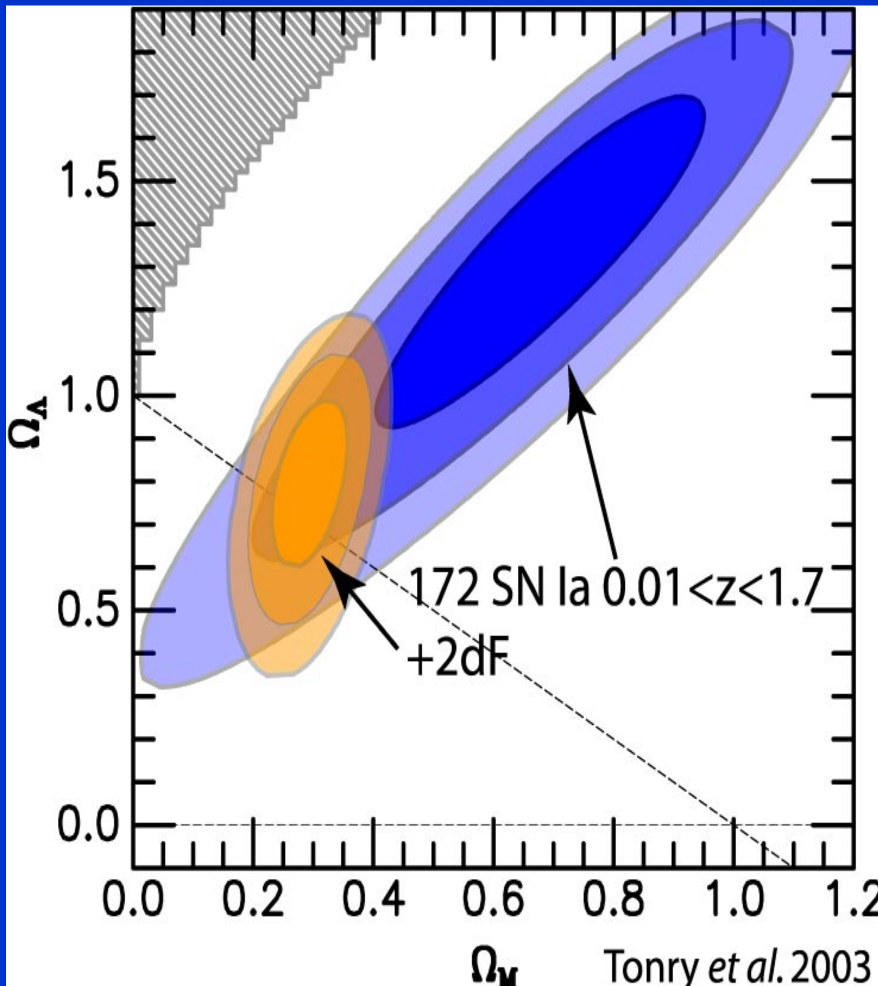
Combine CMB with SNIa data

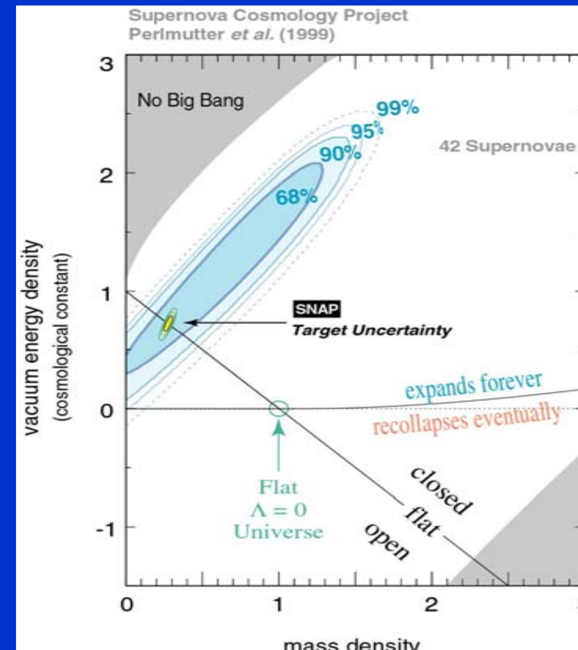


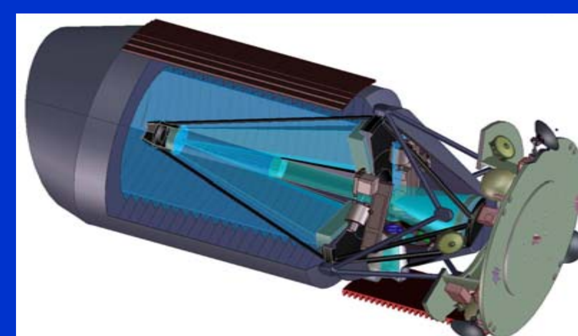
SNIa sensitive to acceleration, i.e.
$acc=\Omega_\Lambda - (\Omega_{SM}+ \Omega_{DM})$ or
$\Omega_\Lambda = acc + (\Omega_{SM}+ \Omega_{DM})$

CMB sensitive to overall density, i.e.
$\Omega_\Lambda + \Omega_{SM} + \Omega_{DM}=1$ or
$\Omega_\Lambda = 1 - (\Omega_{SM} + \Omega_{DM})$

Present and projected Results from SN1a







Expectations from SNAP satellite

SN Ia & Ω_0=1 & w=-1:
Ω_m = 0.28 ± 0.05

Conclusion sofar

IF DM particles are thermal relics from early universe they can annihilate with cross section as large as

$$\langle \sigma v \rangle = 2.10^{-26}\ cm^3/s$$

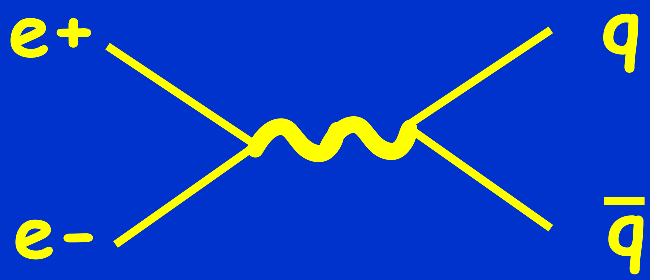
which implies an enormous rate of gamma rays from π_0 decays (produced in quark fragmentation)
(Galaxy=10^{40} higher rate than any accelerator)

Expect large fraction of energetic Galactic gamma rays to come from DMA in this case.
Remaining ones from $p_{CR}+p_{GAS} \to \pi_0 + X$, $\pi_0 \to 2\gamma$
(+some IC+brems)

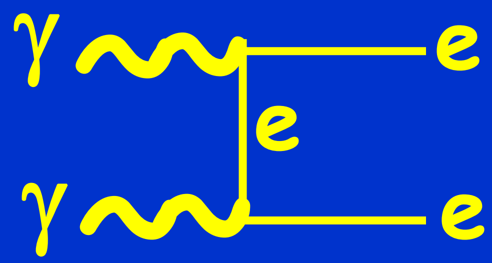
This means: Galactic gamma rays have 2 components with a shape KNOWN from the 2 BEST studied reactions in accelerators: background known from fixed target exp.
DMA known from e+e- annihilation (LEP)

How do particles annihilate?

LEP collider:
e+e- annihilation



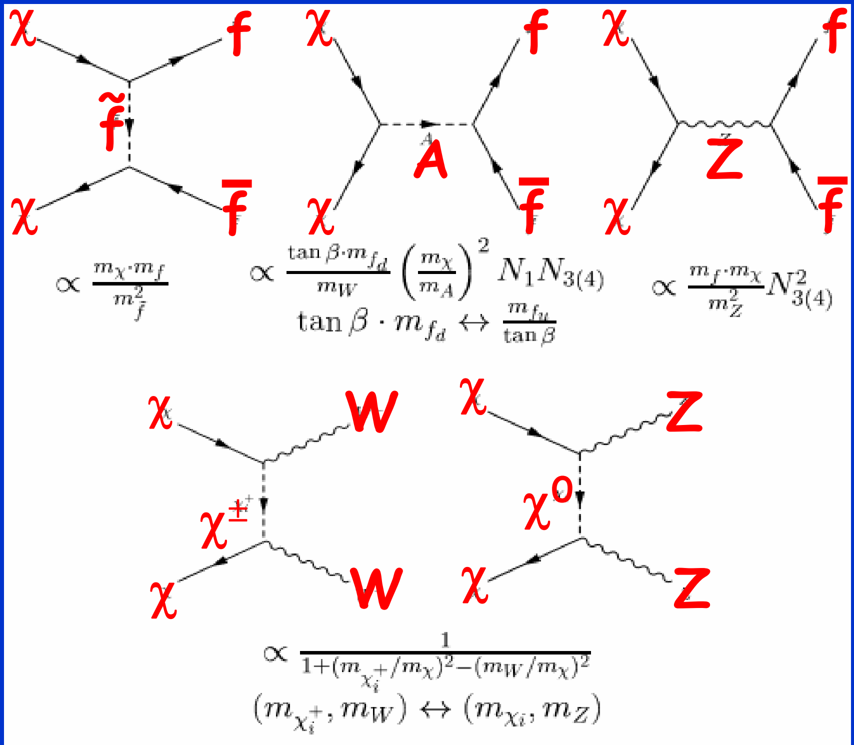
photon annihilation

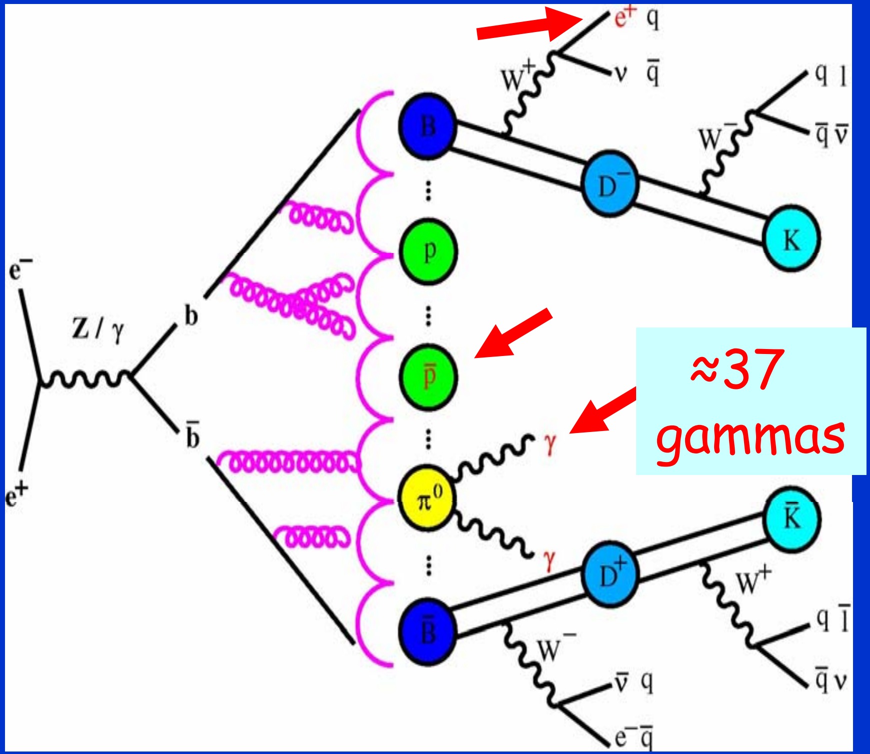


In CM: Eq=Ee
monoenergetic quarks
from monoenergetic leptons

Quarks fragment into jets,
mostly light mesons: $\pi+$, $\pi-$, $\pi0$
$\pi0$ decays 100% into 2 photons
So as many photons as charged particles
from annihilation
On averaged: 37 photons pro annihilation
into quarks at LEP
Spectral shape VERY WELL MEASURED

Example of DM annihilation (SUSY)





Dominant
$\chi + \chi \Rightarrow A \Rightarrow$ b bbar quark pair
Sum of diagrams should yield
$<\sigma v> = 2.10^{-26}$ cm³/s to get
correct relic density

Quark fragmentation known!
Hence spectra of positrons, gammas and antiprotons known!
Relative amount of γ,p,e+ known as well.

The dark connection between Canis Major, Monoceros Stream, Sagit., gas flaring, the rotation curve and the EGRET excess

From EGRET excess of diffuse Galactic gamma rays

- Determination of WIMP mass
- Determination of WIMP halo (= standard halo + DM ring)

Confirmation:

- Rotation curve
- Canis Major/Monoceros stream
- Sagittarius streams
- Gas flaring

PREDICTIONS

- for LHC (if SUSY)
- for direct searches
- for solar neutrinos

Ingredients to this analysis

Astronomers: Rotation curve, Tidal streams, Gas flaring

↕

Astrophysics: Cosmics, Gamma rays

↕

Cosmology: 23%DM, thermal history of WIMPs, Annihilation cross section, Tidal disruption of dwarf

↕

Particle Physics: Gamma ray spectra for BG + DMA

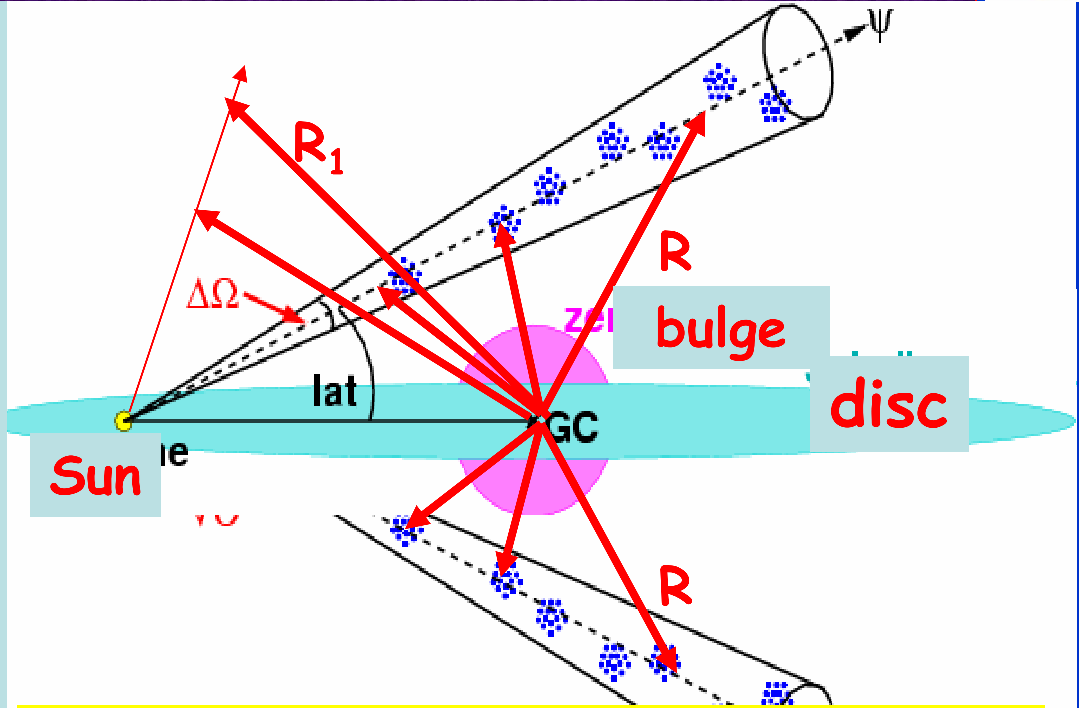
Basic principle for indirect dark matter searches

From rotation curve:

Forces: $mv^2/r=GmM/r^2$
or M/r=const. for v=cons.
and
$\rho \propto (M/r)/r^2$
$\rho \propto 1/r^2$
for flat rotation curve

Expect highest DM density
IN CENTRE OF GALAXY

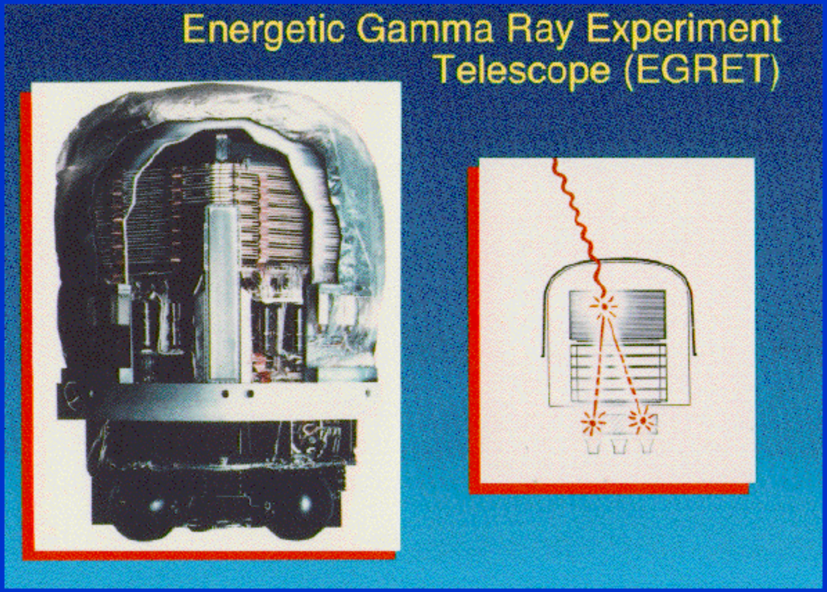
Divergent for r=0?
NFW profile $\propto 1/r$
Isotherm profile const.



IF FLUX AND SHAPE MEASURED IN ONE DIRECTION, THEN FLUX AND SHAPE FIXED IN ALL (=180) SKY DIRECTIONS!!!

THIS IS AN INCREDIBLE CONSTRAINT, LIKE SAYING I VERIFY THE EXCESS AND WIMP MASS WITH 180 INDEPENDENT MEAS.

EGRET on CGRO (Compton Gamma Ray Observ.)
Data publicly available from NASA archive



Instrumental parameters:

Energy range: 0.02-30 GeV
Energy resolution: ~20%
Effective area: 1500 cm^2
Angular resol.: <0.5^0

Data taking: 1991-1994

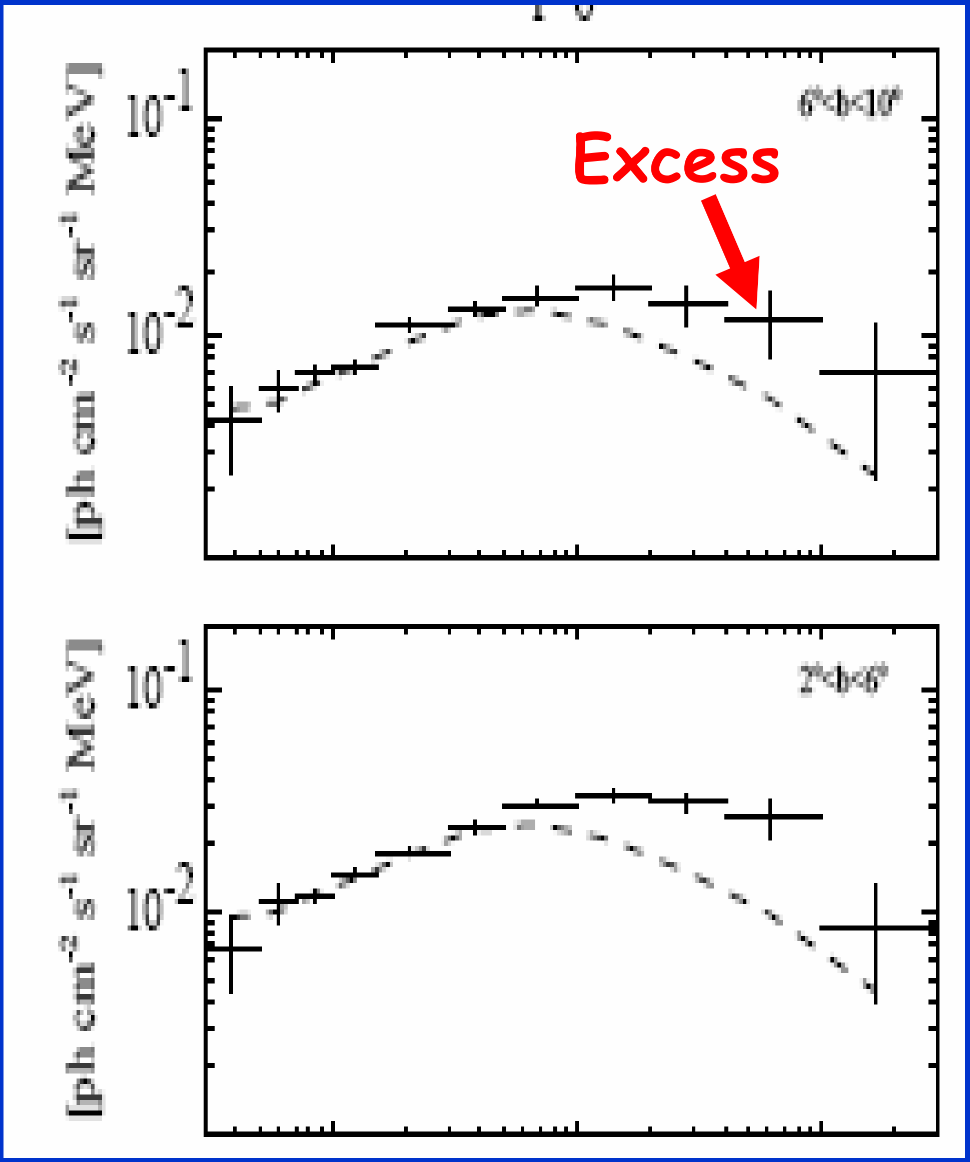
Main results:
Catalogue of point sources
Excess in diffuse gamma rays

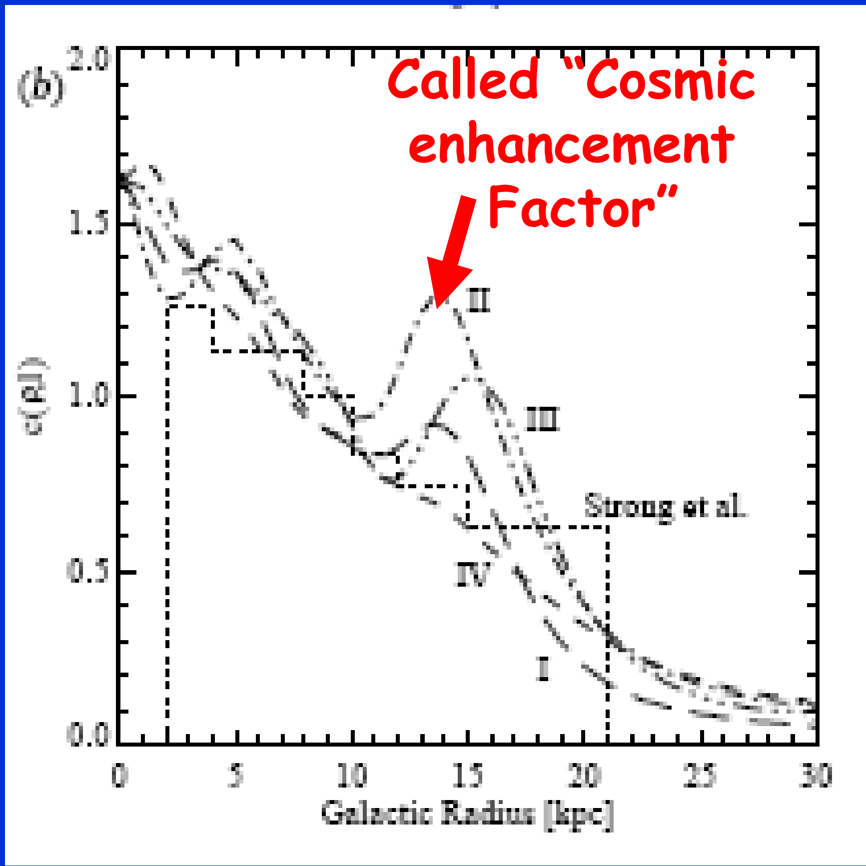
EGRET OBSERVATIONS OF THE DIFFUSE GAMMA-RAY EMISSION FROM THE GALACTIC PLANE

S. D. Hunter,[1] D. L. Bertsch,[1] J. R. Catelli,[1,2] T. M. Dame,[3] S. W. Digel,[4] B. L. Dingus,[1,5] J. A. Esposito,[1,5] C. E. Fichtel,[1] R. C. Hartman,[1] G. Kanbach,[6] D. A. Kniffen,[7] Y. C. Lin,[8] H. A. Mayer-Hasselwander,[6] P. F. Michelson,[8] C. von Montigny,[1,9] R. Mukherjee,[1,5] P. L. Nolan,[8] E. Schneid,[10] P. Sreekumar,[1,5] P. Thaddeus,[3] and D. J. Thompson[1]
Received 1995 June 13; accepted 1996 December 5

However, above about 1 GeV the integral intensity predicted by the model is about 60% less than the observed intensity. Although the explanation of this excess is unclear, uncertainties in the neutral pion production function or variations in the cosmic-ray spectrum with Galactic radius may partially account

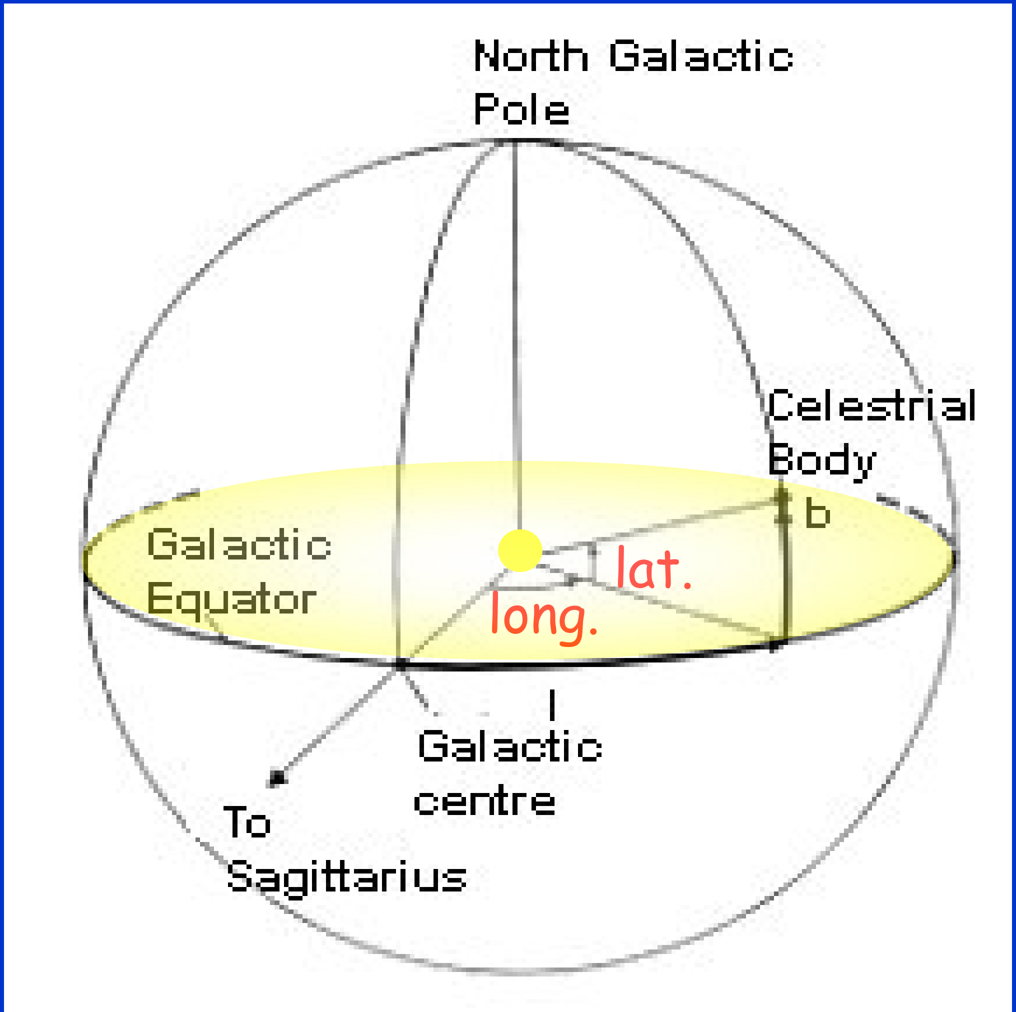
Two results from EGRET paper





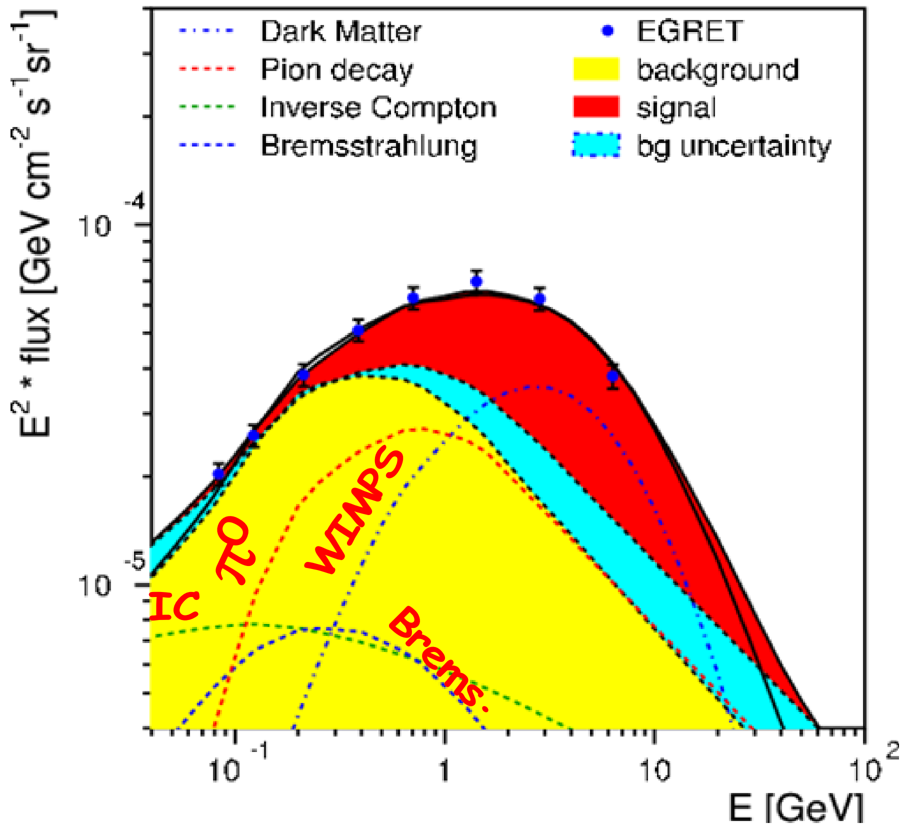
Enhancement in ringlike structure at 13-16 kpc

Galactic coordinates: longitude l and latitude b

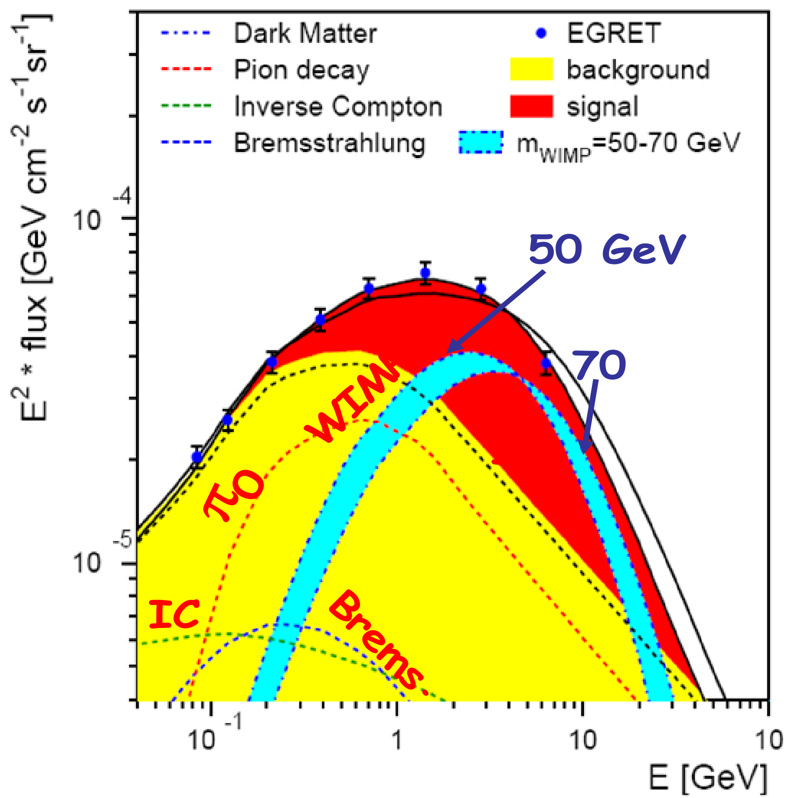


(l,b)=(0,0)=Galactic Centre
(l,b)=(0,90)=North Galactic Pole

Background + signal describe EGRET data!

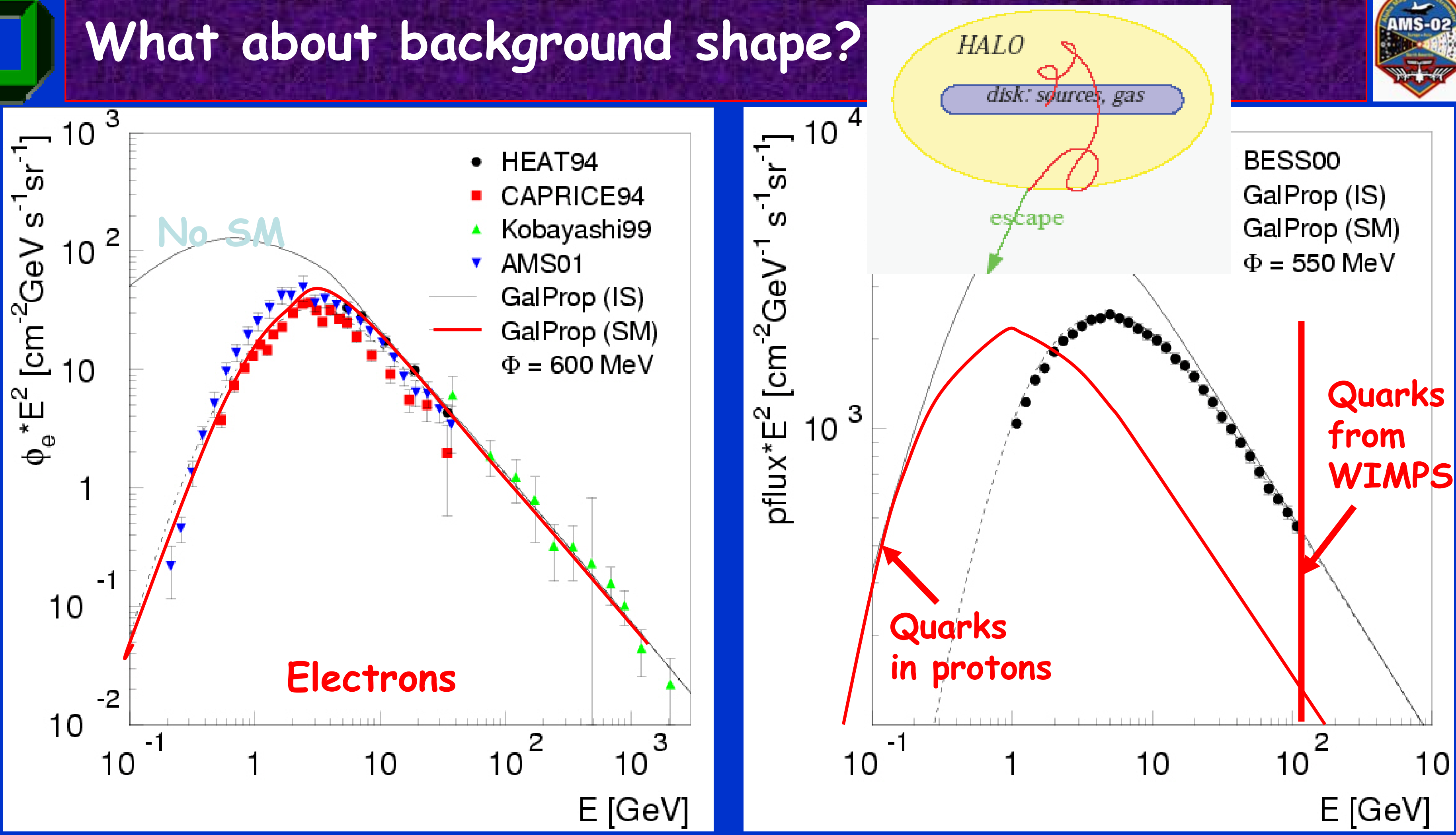


Blue: background uncertainty



Blue: WIMP mass uncertainty

What about background shape?



Background from nuclear interactions (mainly p+p-> π^0 + X -> γ + X

inverse Compton scattering (e-+ γ -> e- + γ)

Bremsstrahlung (e- + N -> e- + γ + N)

Shape of background KNOWN if Cosmic Ray spectra of p and e- known

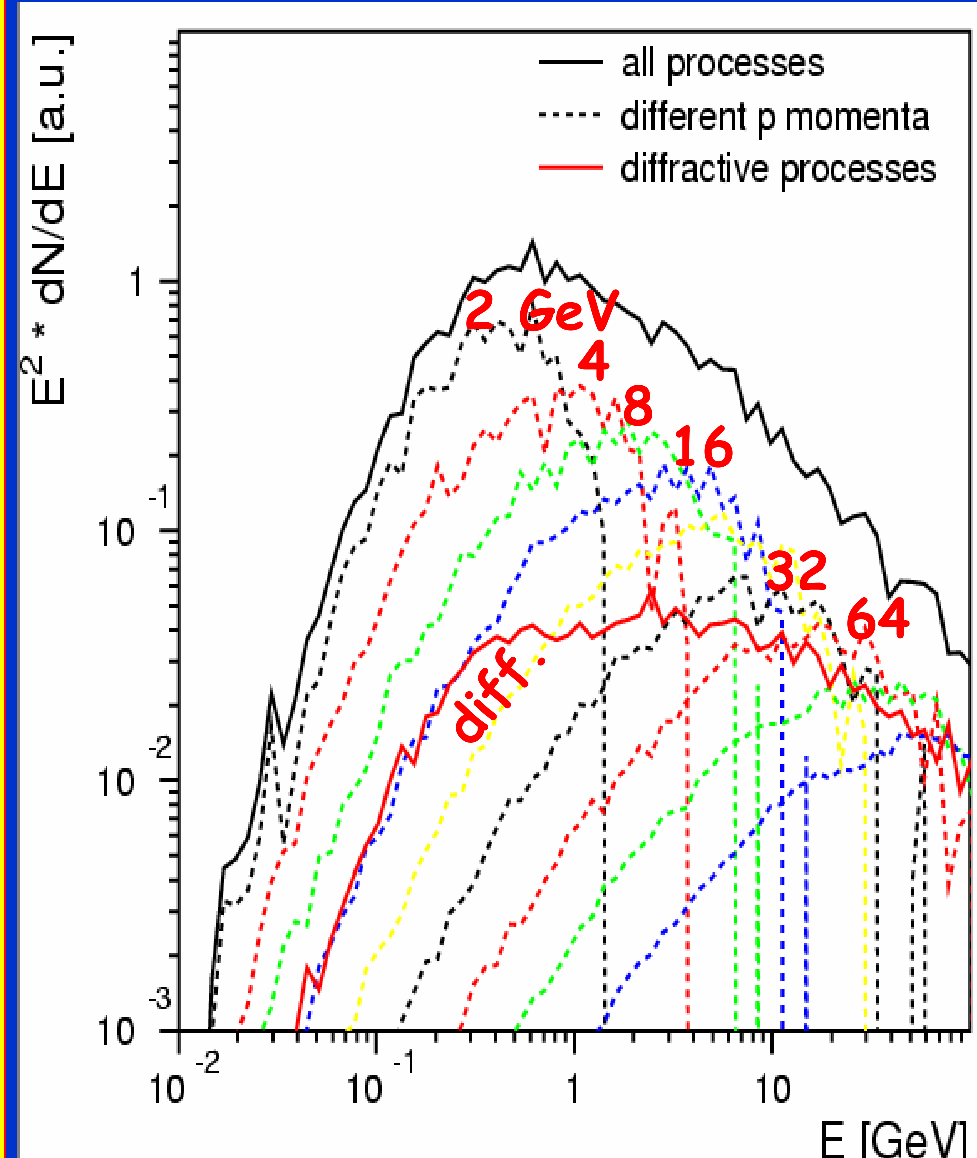
Contribution from various hadronic processes

PYTHIA processes:

11	f+f' -> f+f' (QCD)	2370
12	f+fbar -> f'+fbar'	0
13	f+fbar -> g + g	0
28	f+g -> f + g	2130
68	g+g -> g + g	1510
53	g+g -> f + fbar	20
92	Single diffractive (XB)	1670
93	Single diffractive (AX)	1600
94	Double diffractive	700
95	Low-pT scattering	0

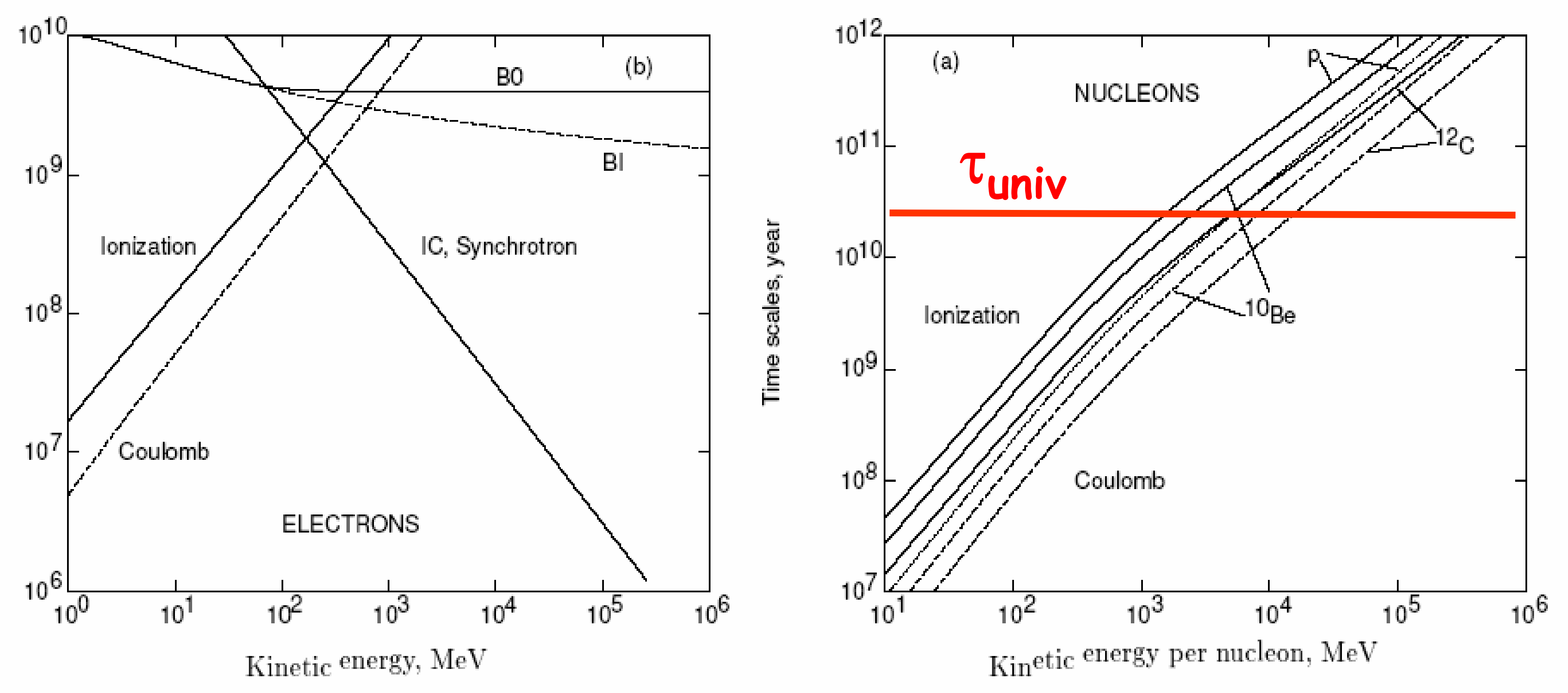
Prompt photon production:

14	f+fbar -> g+γ	0
18	f+fbar -> γ +γ	0
29	f+g -> f +γ	1
115	g+g -> g + γ	0
114	g+g -> γ + γ	0



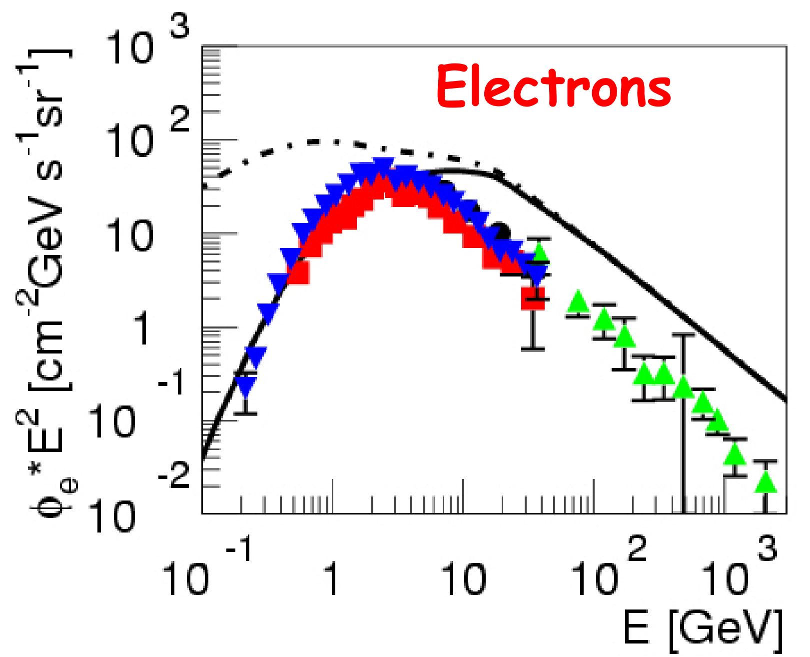
Energy loss times of electrons and nuclei

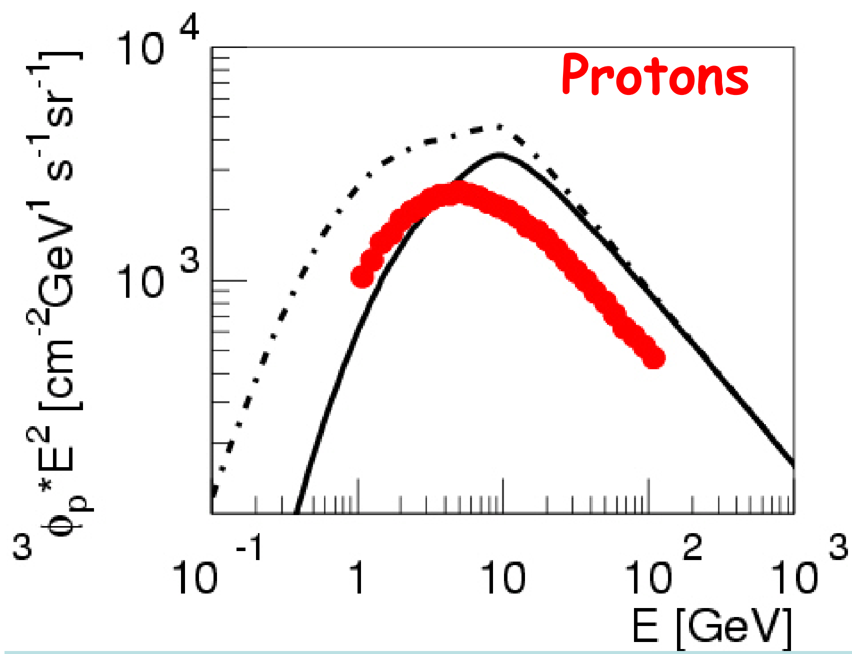
$$\tau^{-1} = 1/E\ dE/dt$$

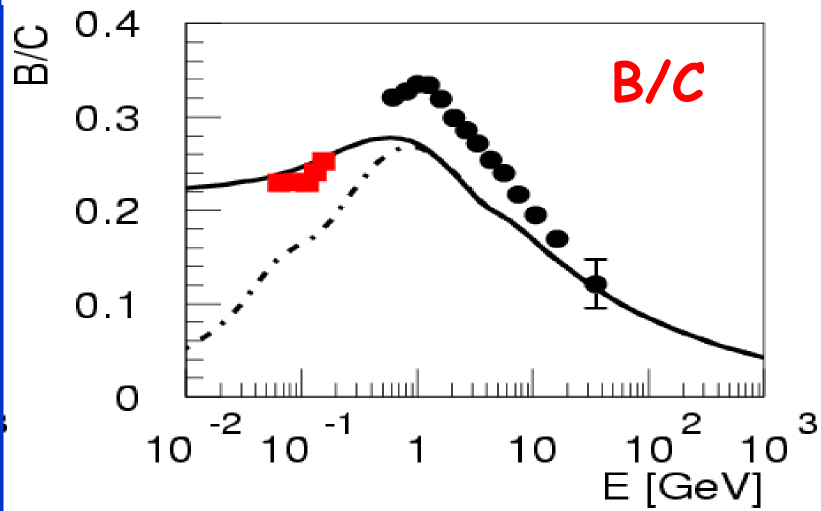


Protons diffuse much faster than energy loss time, so expect SAME shape everywhere. Indeed observed: outer Galaxy can be fitted with same shape as inner Galaxy.

Astrophysics solution: Optimize e,p spectra to fit gammas
"Optimized Model" from Strong et al. astro-ph/0406254



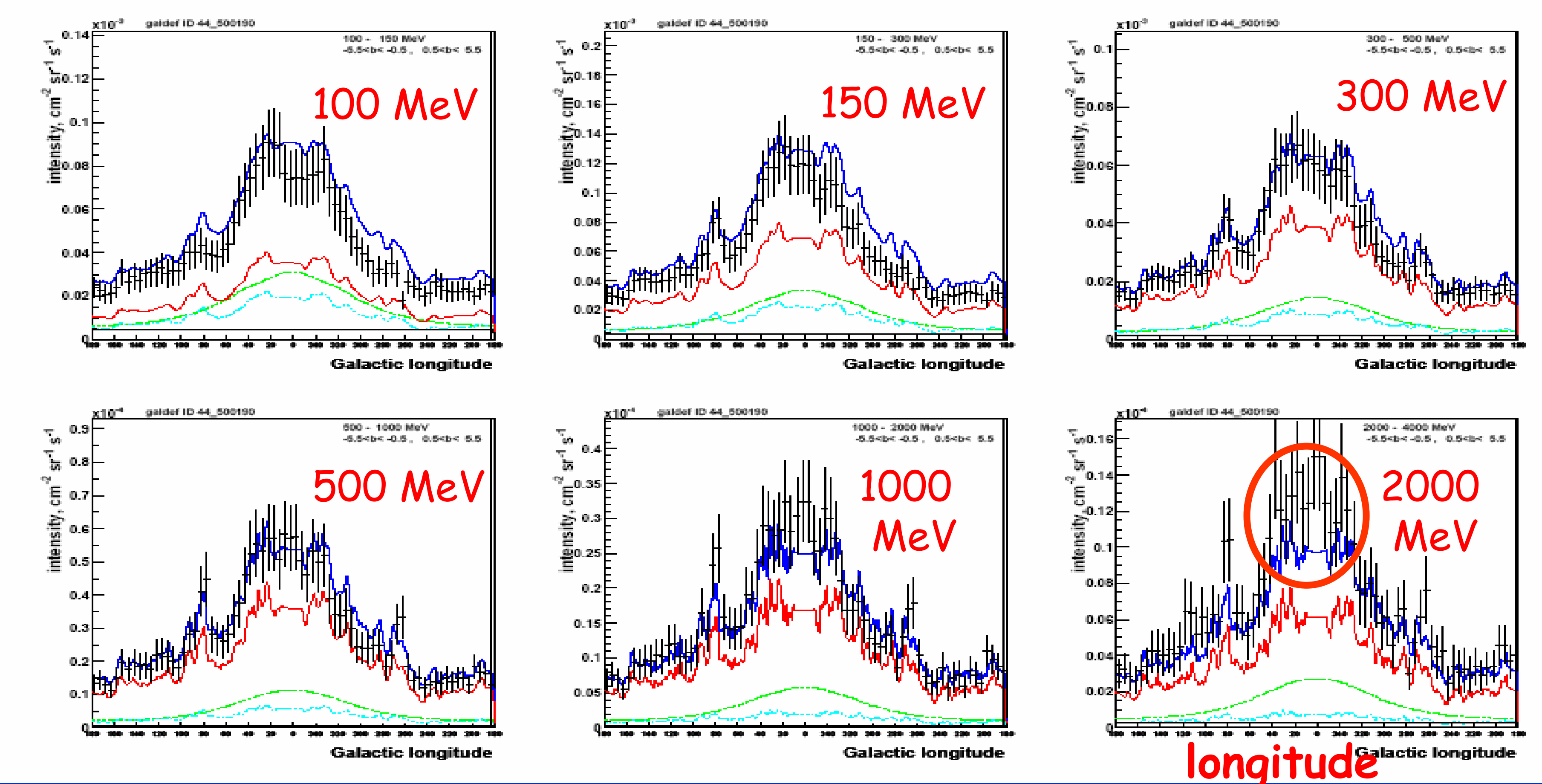




Proton and electron spectra tuned to fit gamma ray data. B/C need different tuning….

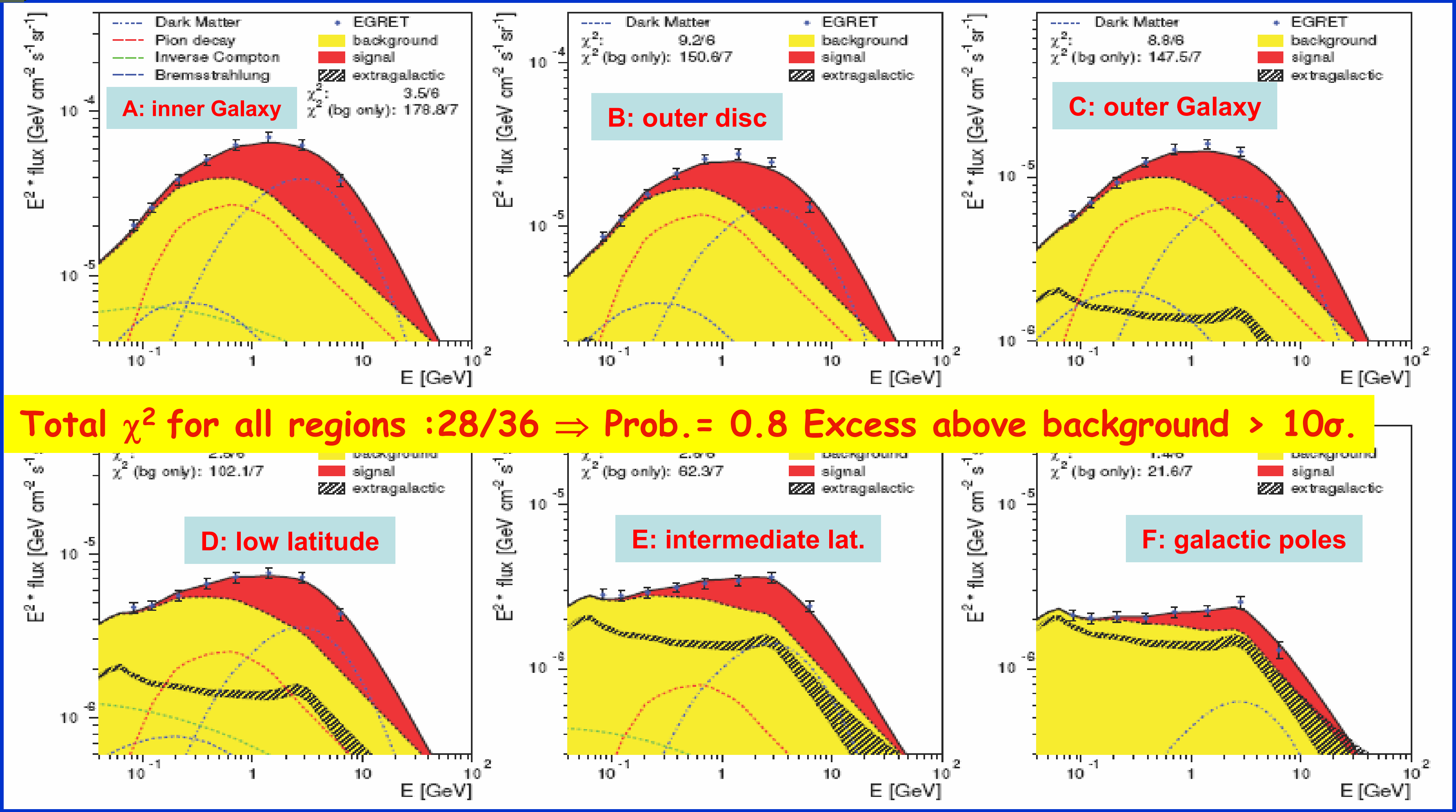
Still no good description of gamma rays.

From original paper on Optimized Model Strong et al. astro-ph/0406254



Problem with conventional models: data at low energy overestimated, Data at high energy still underestimated (30%). At expense of not fitting local CR spectra or assuming very peculiar injection spectra.

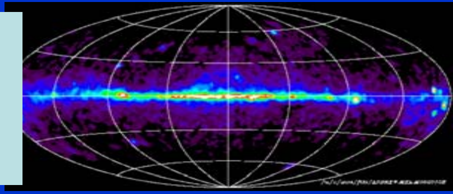
Analysis of EGRET Data in 6 sky directions



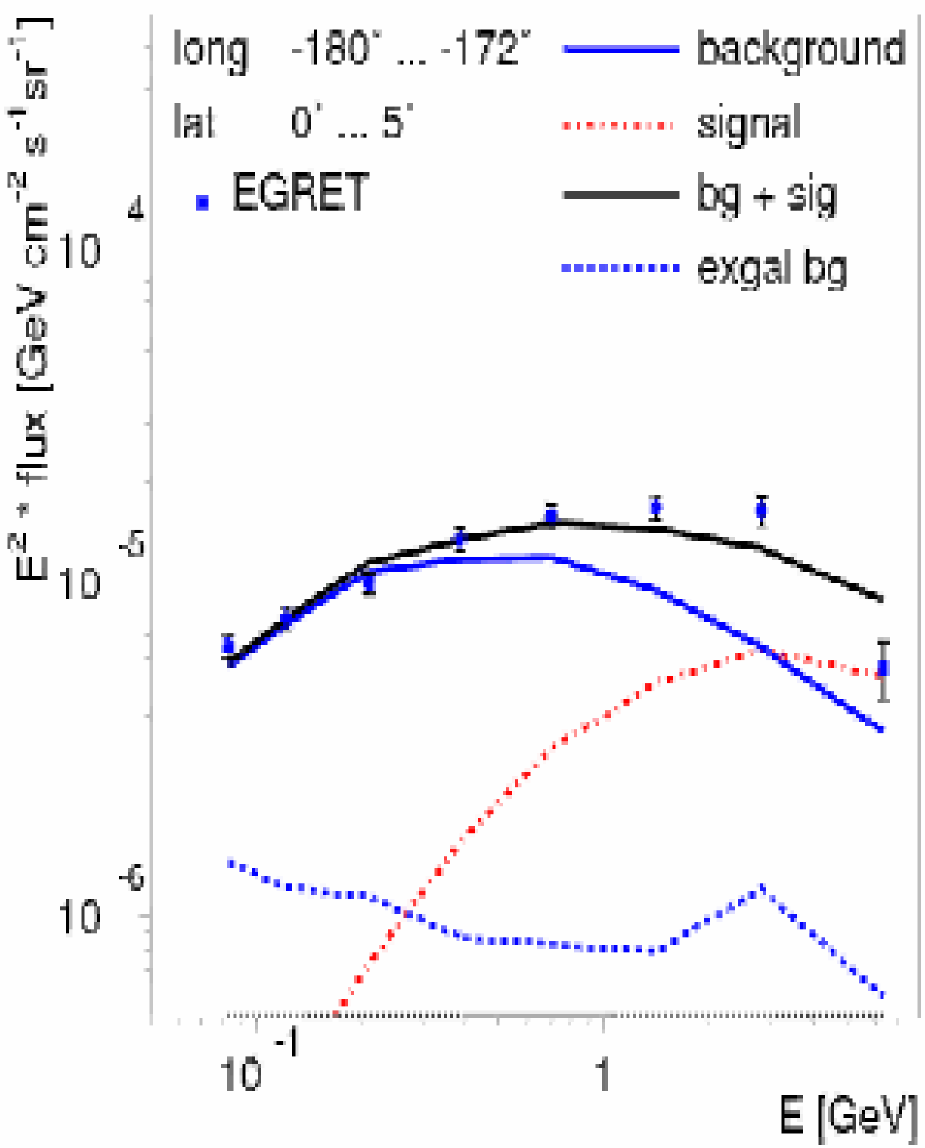
Total χ^2 for all regions :28/36 $\Rightarrow$ Prob.= 0.8 Excess above background > 10σ.

A: inner Galaxy ($l=\pm30^0$, $|b|<5^0$)
B: Galactic plane avoiding A
C: Outer Galaxy

D: low latitude ($10-20^0$)
E: intermediate lat. ($20-60^0$)
F: Galactic poles ($60-90^0$)



Fits for 180 instead of 6 regions

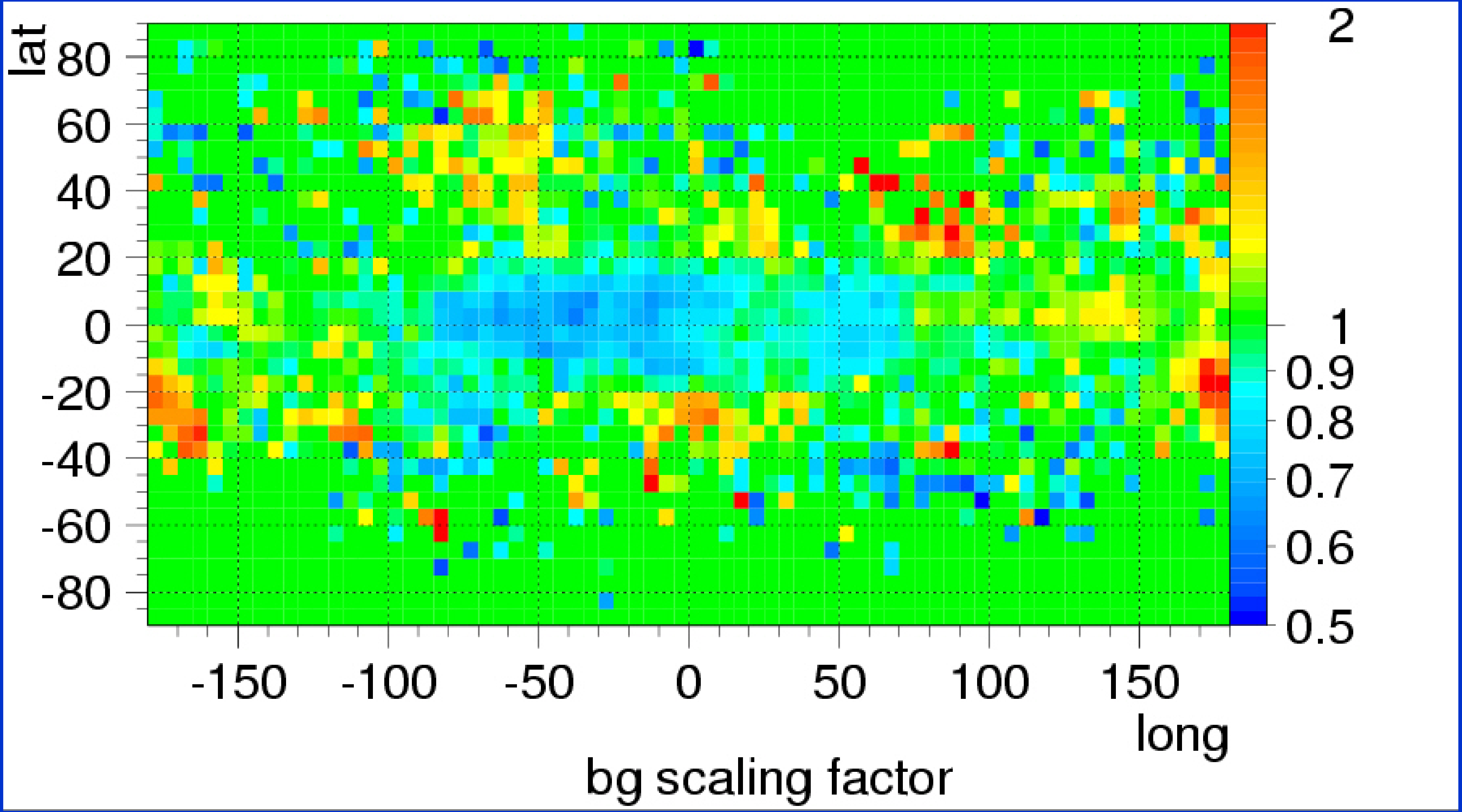


180 regions:
8^0 in longitude ⇒ 45 bins
4 bins in latitude ⇒ $0^0 < |b| < 5^0$
$5^0 < |b| < 10^0$
$10^0 < |b| < 20^0$
$20^0 < |b| < 90^0$ ⇒
4x45=180 bins ⇒
>1400 data points.
Reduced $\chi^2 \approx 1$ with 7% errors
BUT NEEDED IN ADDITION to
$1/r^2$ profile, substructure
in the form of 2 doughnut-like
rings in the Galactic disc!

ONE RING COINCIDES WITH
ORBIT FROM CANIS MAJOR
DWARF GALAXY which loses
mass along orbit by tidal forces

OTHER RING coincides with H_2 ring

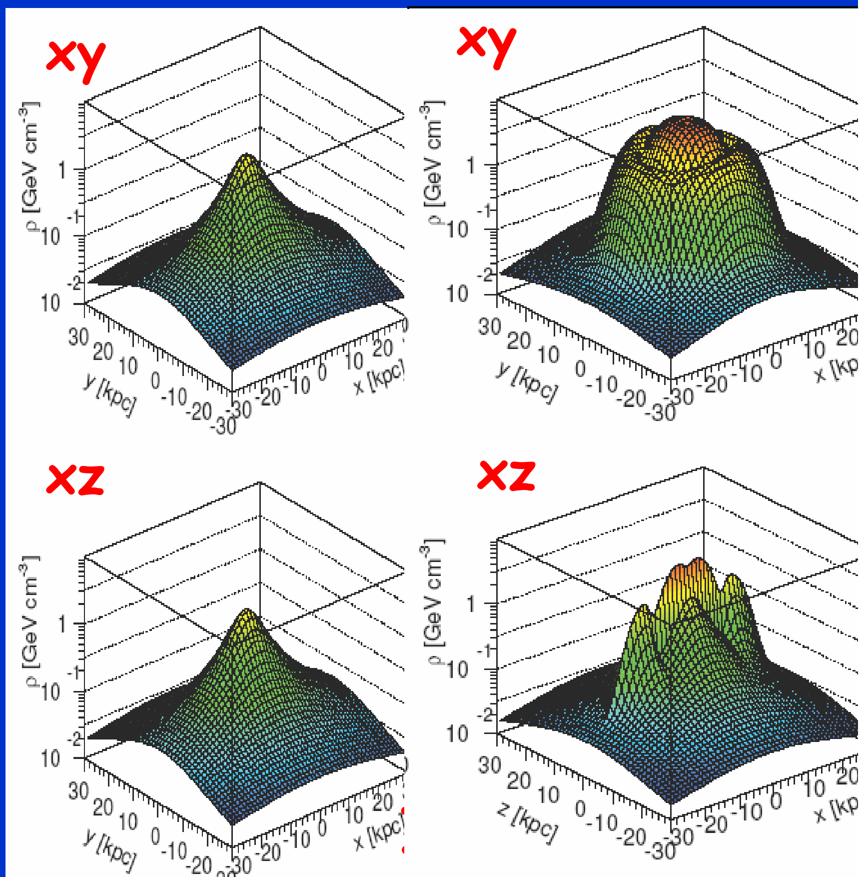
Background scaling factors agree with expectations of gas- and CR densities



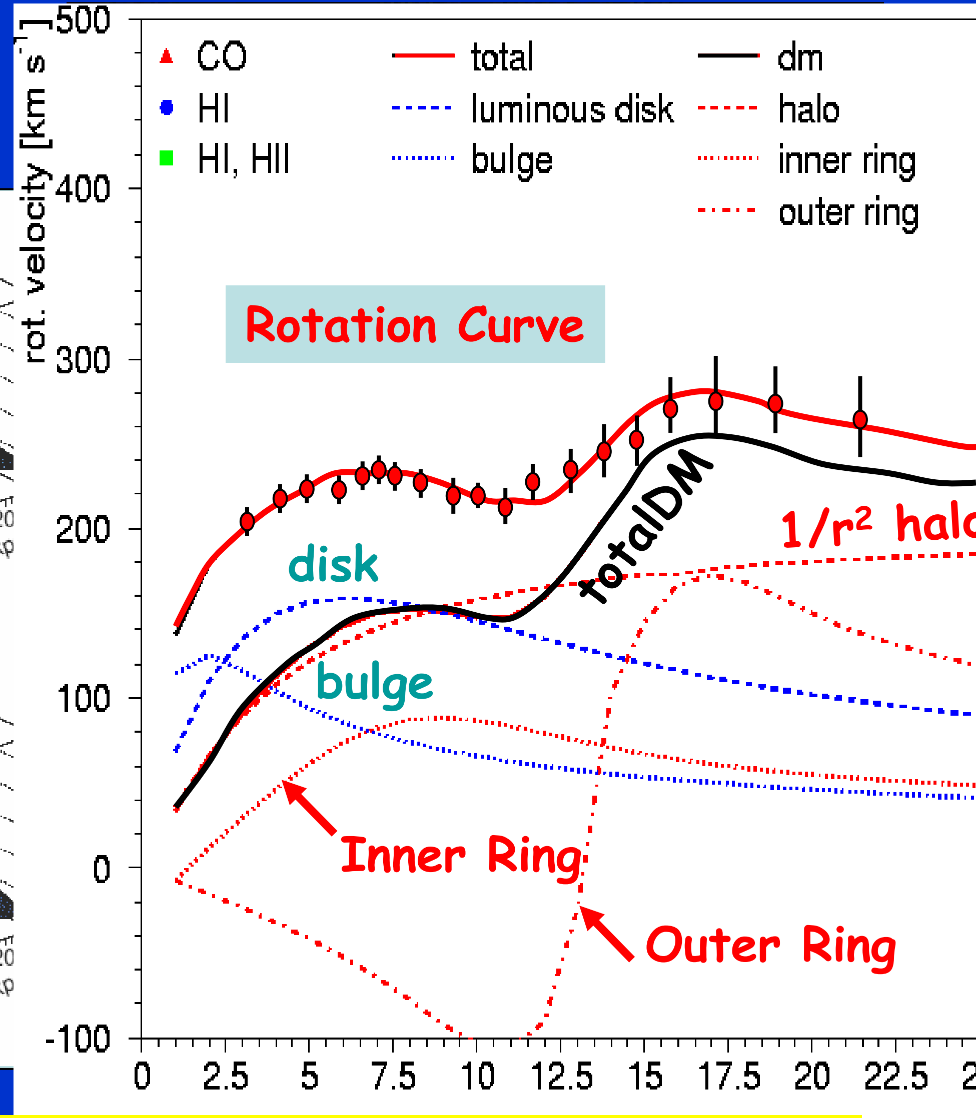
Background scaling factor = Data between 0.1 and 0.5 GeV/GALPROP
GALPROP = computer code simulating our galaxy (Moskalenko, Strong)

Dark Matter distribution

Expected Profile | **Observed Profile**

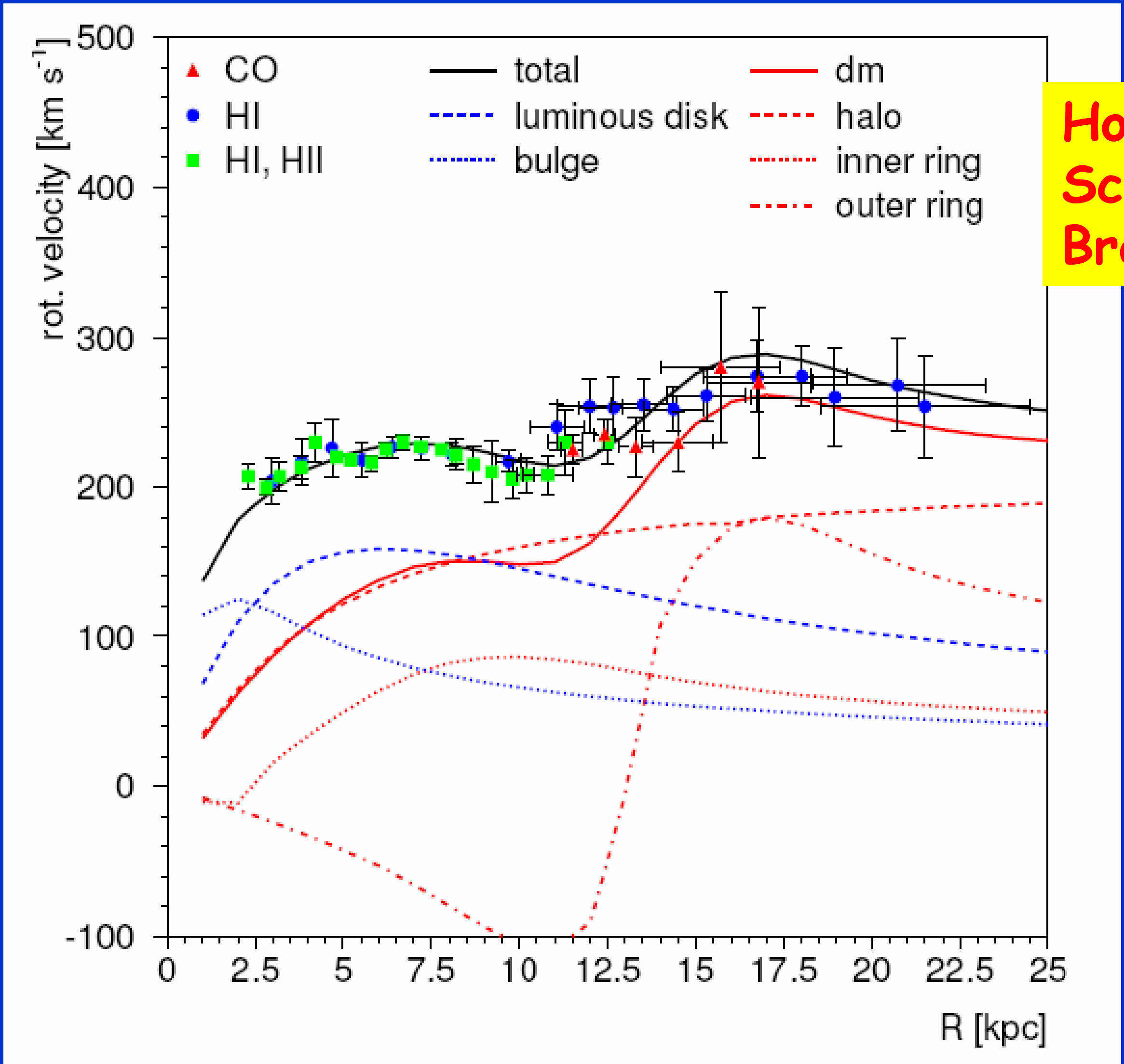


Halo profile



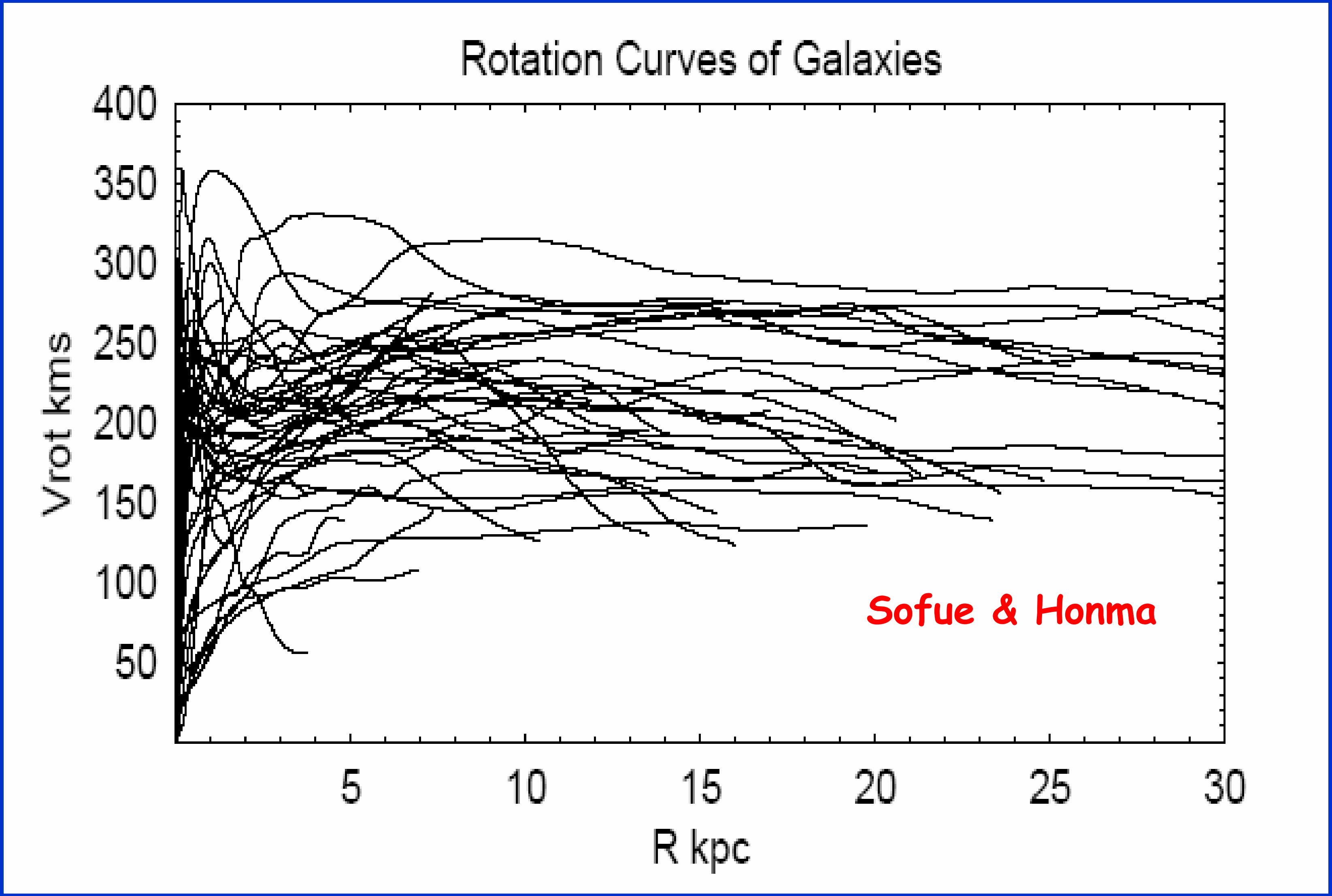
Normalize to solar velocity of 220 km/s

Rotation curve of Milky Way

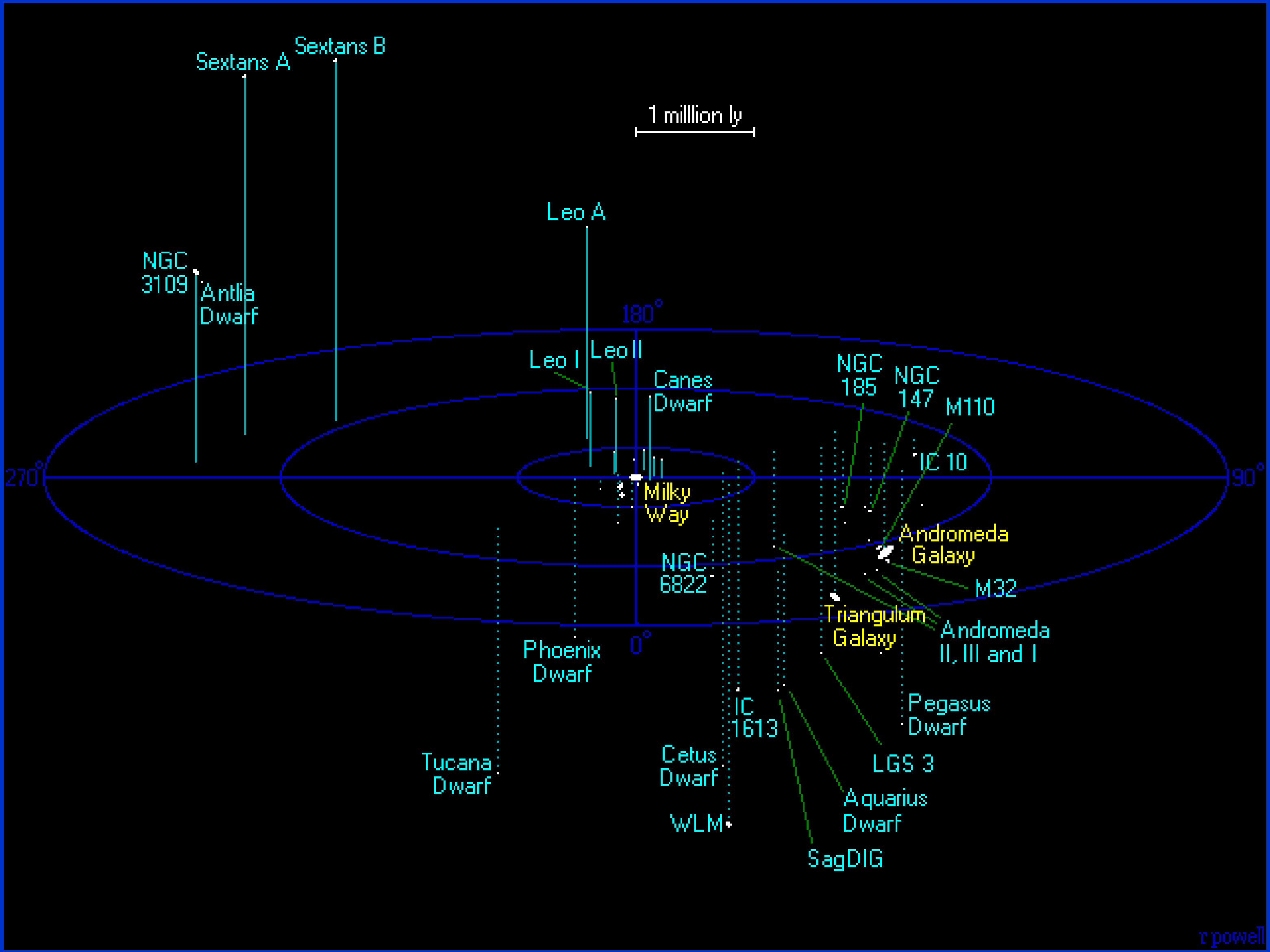


Honma & Sofue (97)
Schneider &Terzian (83)
Brand & Blitz(93)

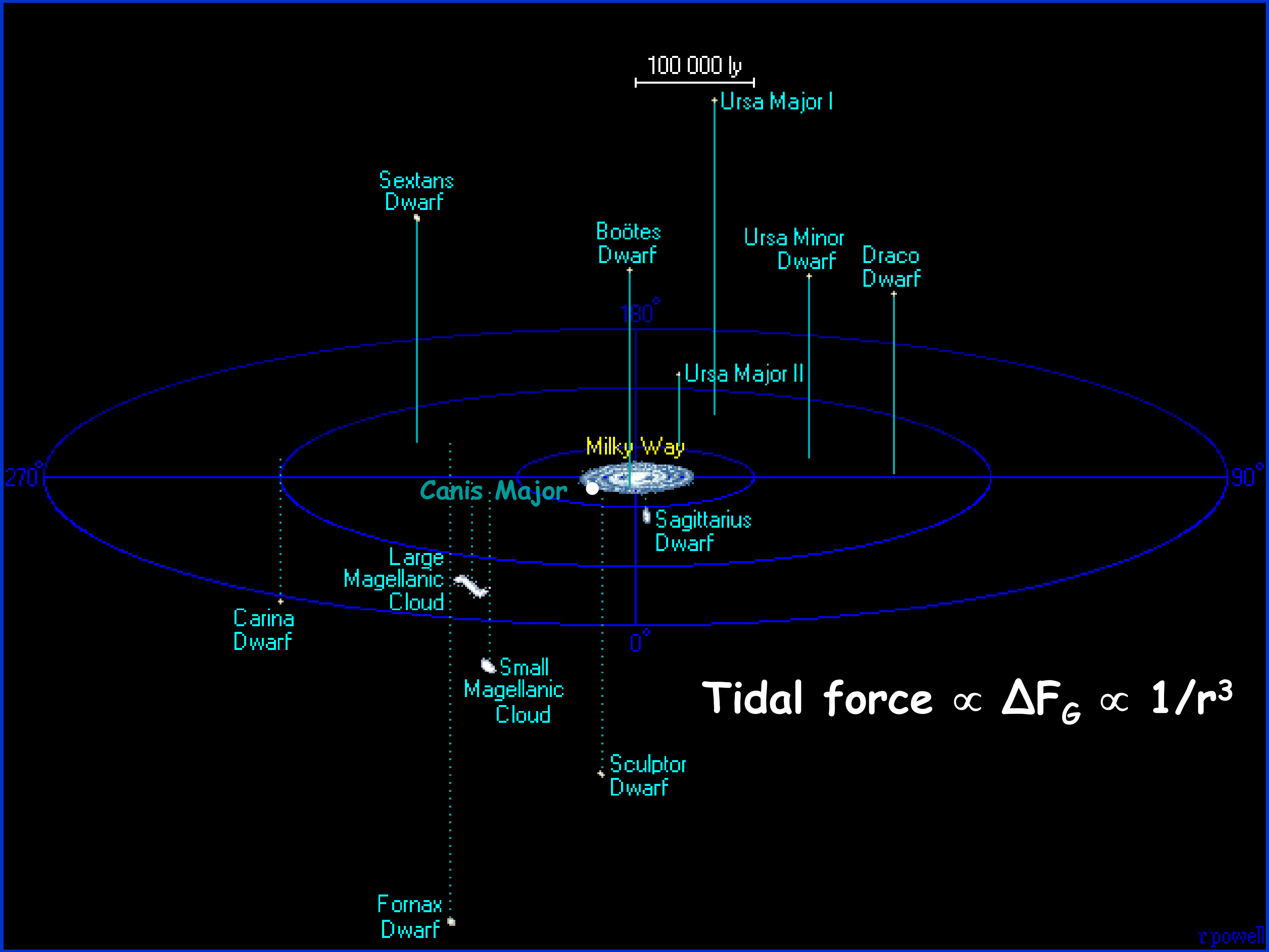
Do other galaxies have bumps in rotation curves?



The local group of galaxies

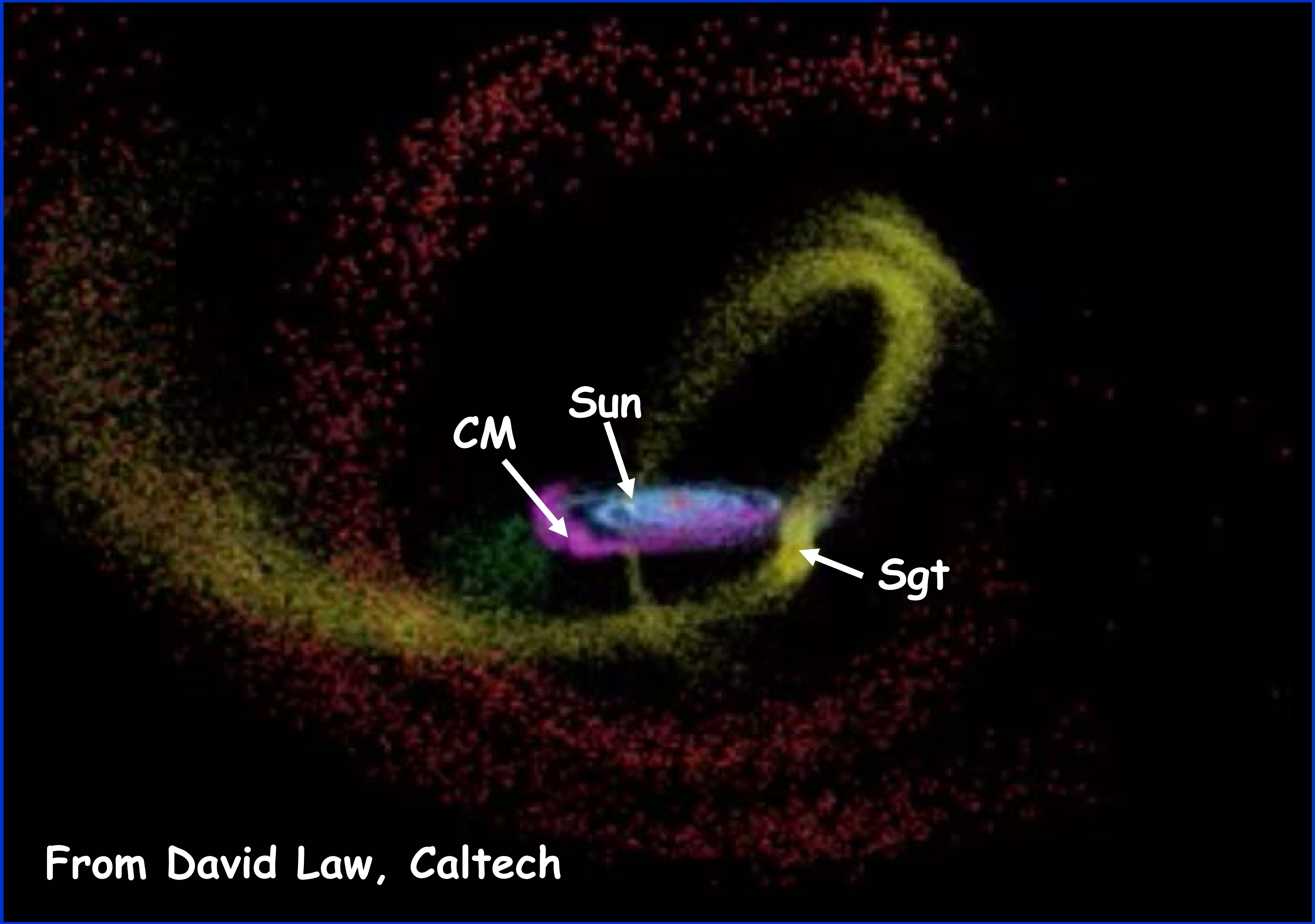


The Milky Way and its 13 satellite galaxies

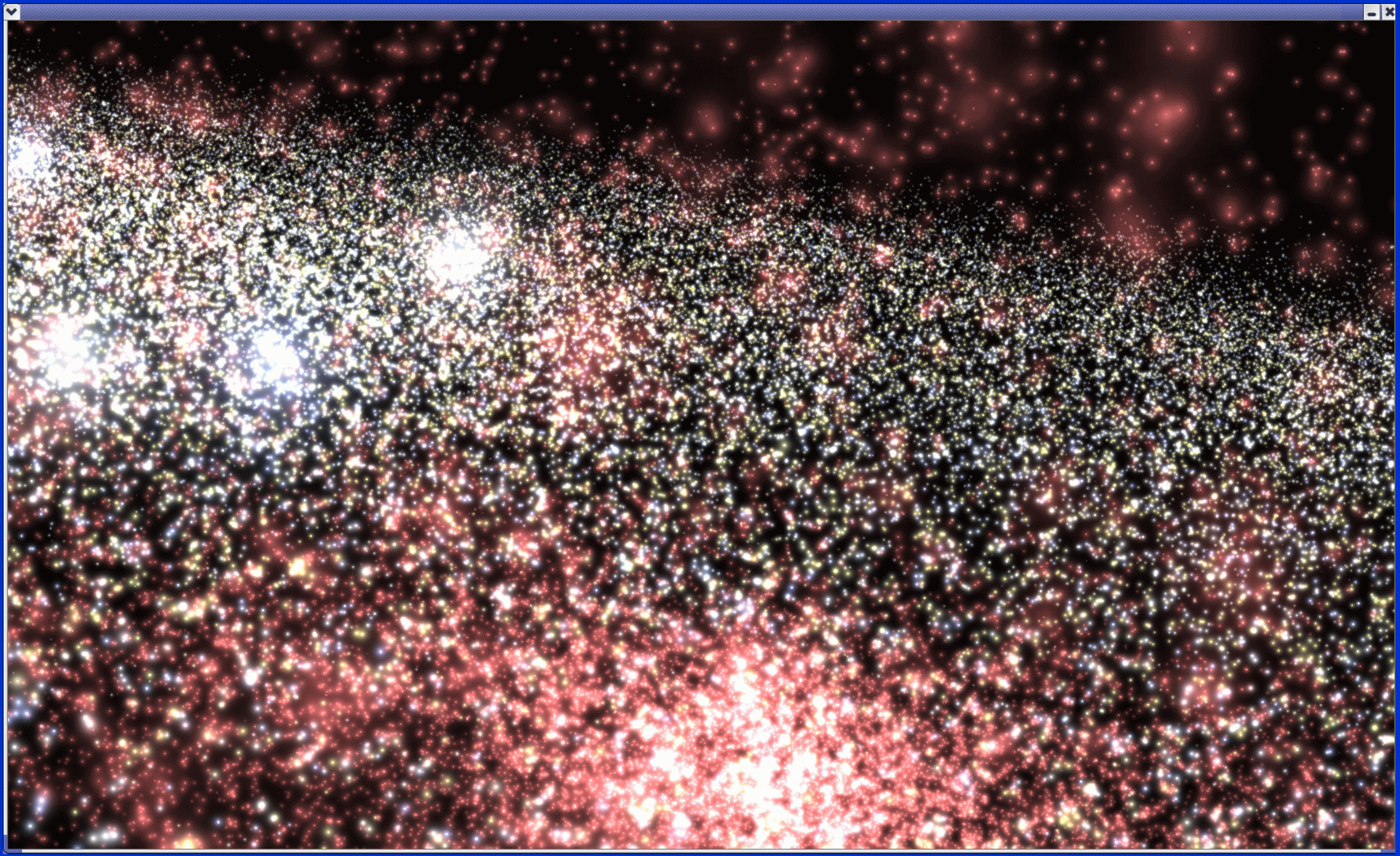


Tidal force $\propto \Delta F_G \propto 1/r^3$

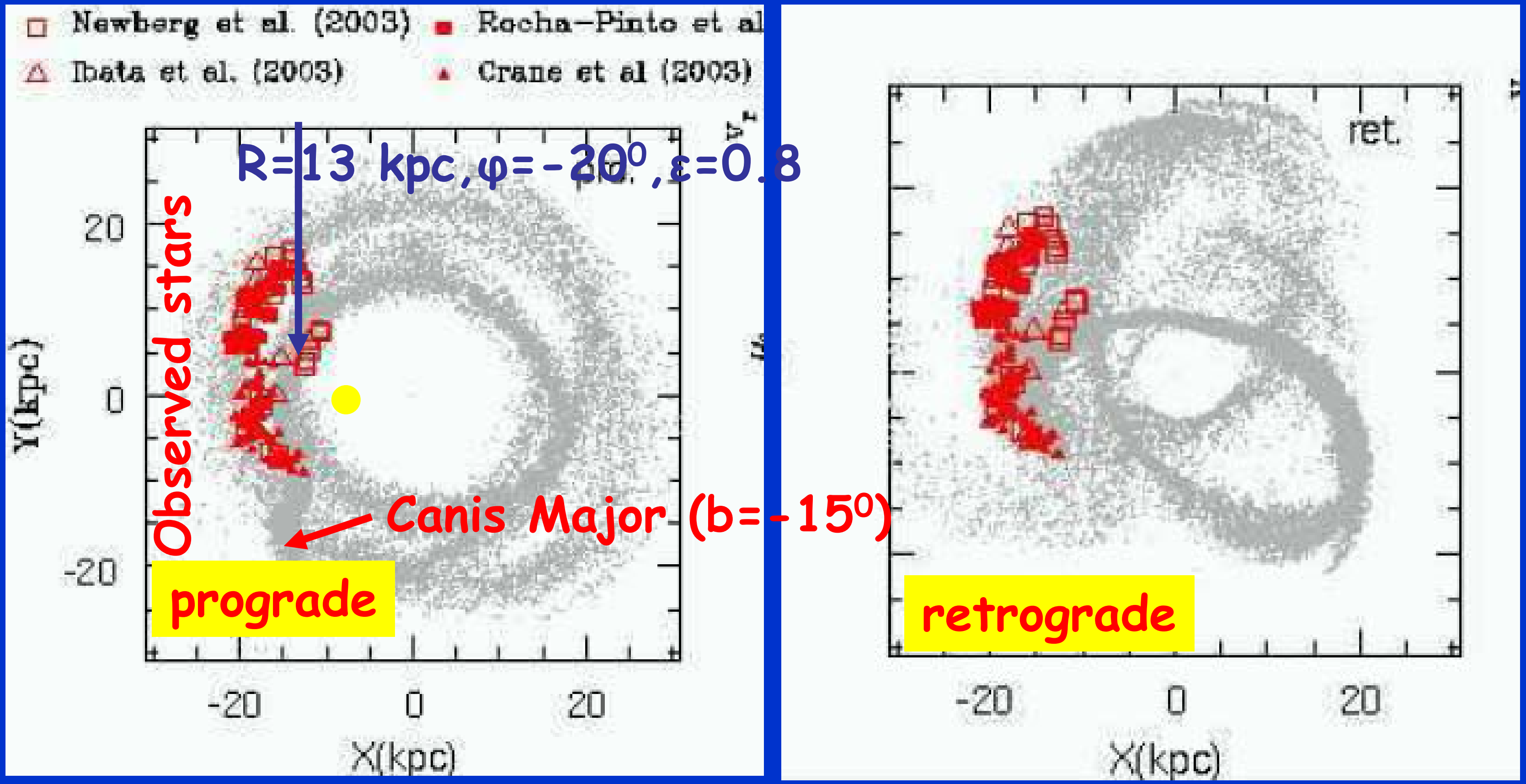
Tidal streams of dark matter from CM and Sgt



Artistic view of Canis Major Dwarf just below Galactic disc

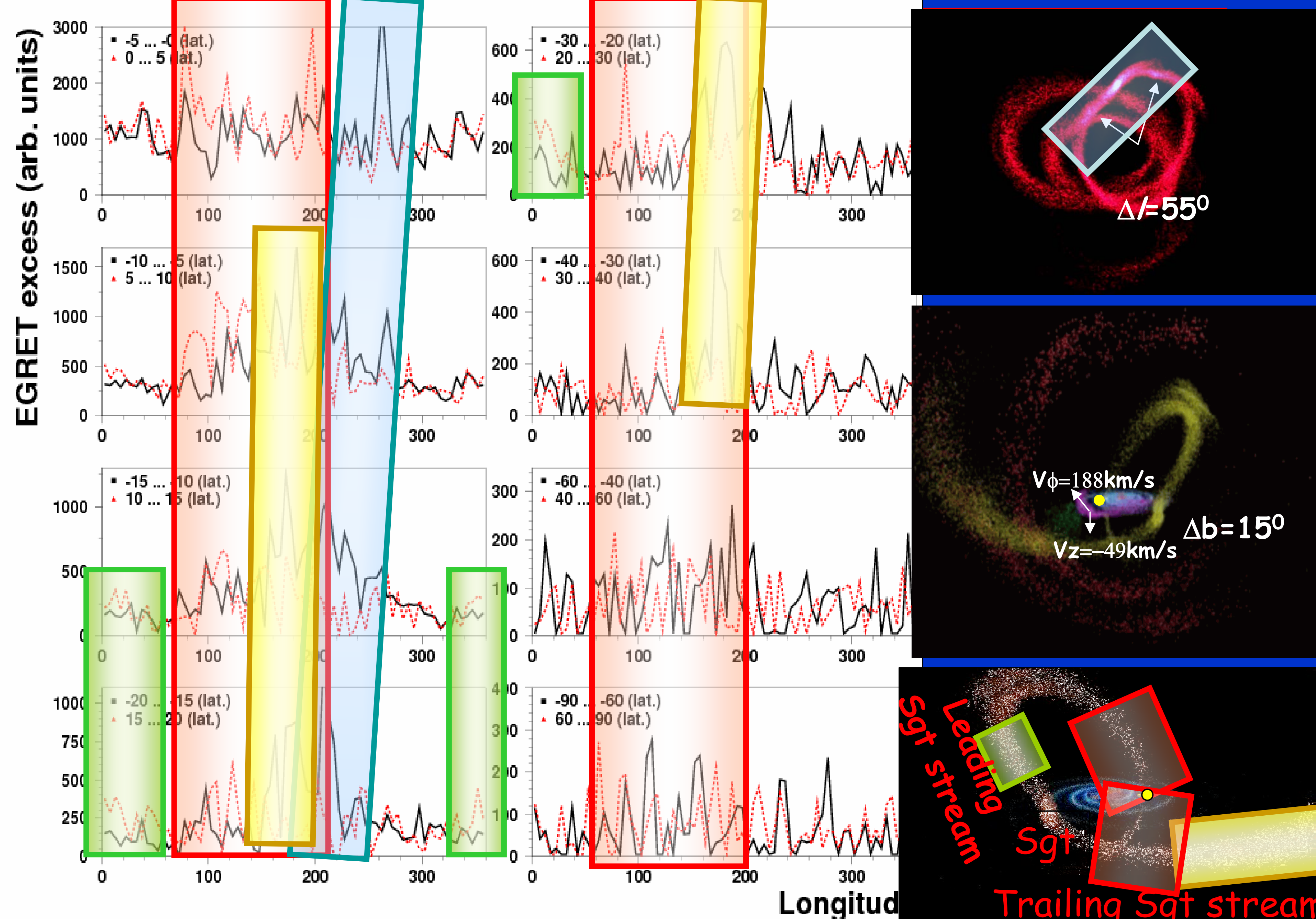


N-body simulation from Canis-Major dwarf galaxy



A comprehensive model for the Monoceros tidal stream

J. Peñarrubia[1], D. Martínez-Delgado[1], H.W. Rix[1], M.A Gómez-Flechoso[2], J. Munn[3], H. Newberg[4], E.F. Bell[1], B. Yanny[5], D. Zucker[1], E. K. Grebel[6]


EGRET excess (arb. units)
-5 ... -0 (lat.)
0 ... 5 (lat.)
-10 ... -5 (lat.)
5 ... 10 (lat.)
-15 ... -10 (lat.)
10 ... 15 (lat.)
-20 ... -15 (lat.)
15 ... 20 (lat.)
-30 ... -20 (lat.)
20 ... 30 (lat.)
-40 ... -30 (lat.)
30 ... 40 (lat.)
-60 ... -40 (lat.)
40 ... 60 (lat.)
-90 ... -60 (lat.)
60 ... 90 (lat.)
Longitud
Δl=55⁰
Vϕ=188km/s
Vz=−49km/s
Δb=15⁰
Leading Sgt stream
Sgt
Trailing Sgt stream

Conclusion

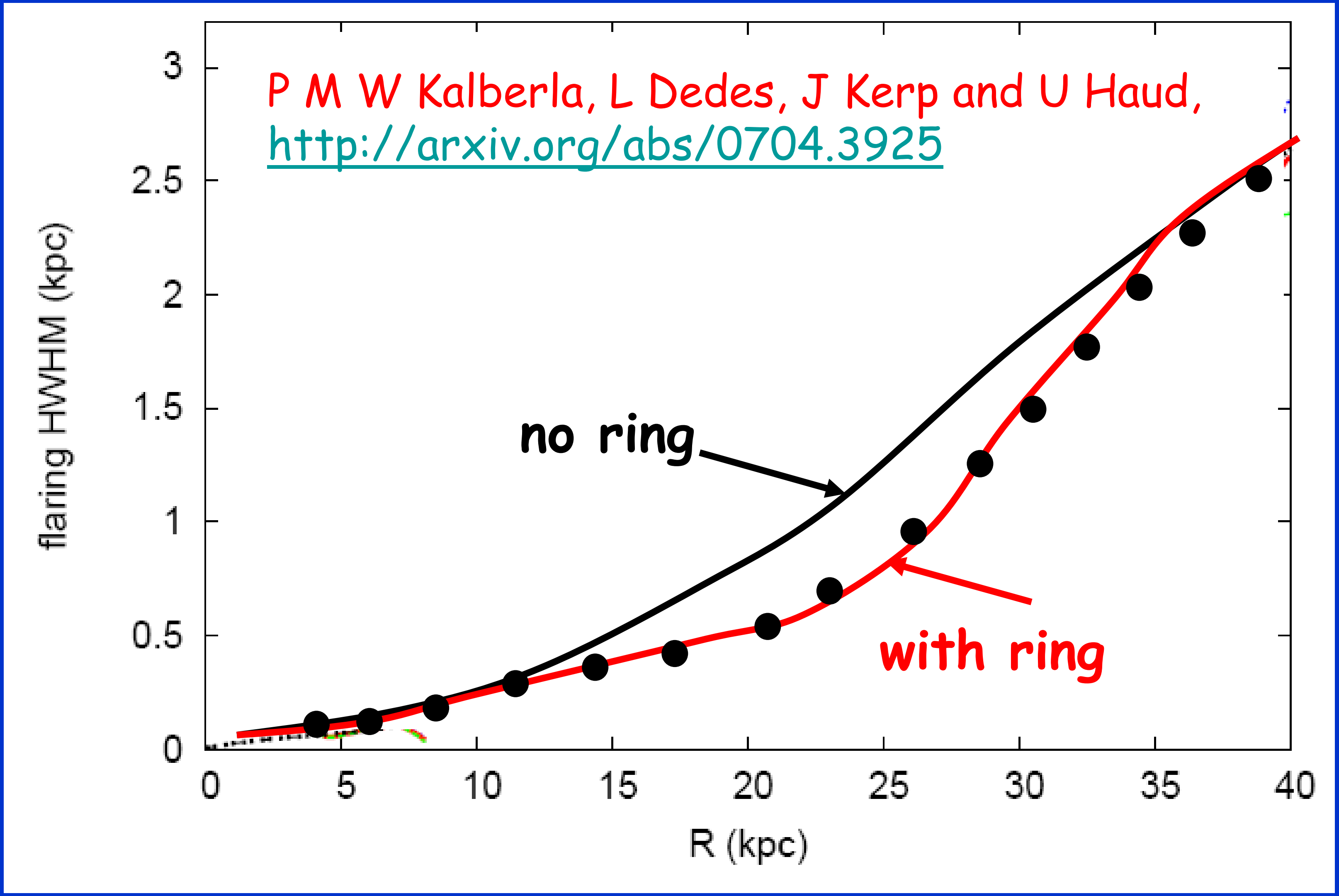
Comparing gamma rays above and below Galactic disk is excellent way to search for tidal streams, since systematic errors cancel and foreground from diffuse part of halo should be the same

Result: one finds a clear correlation between excess of diffuse gamma rays and KNOWN positions of tidal streams of two nearest satellite galaxies

Summary: all proposed indirect searches see signal:

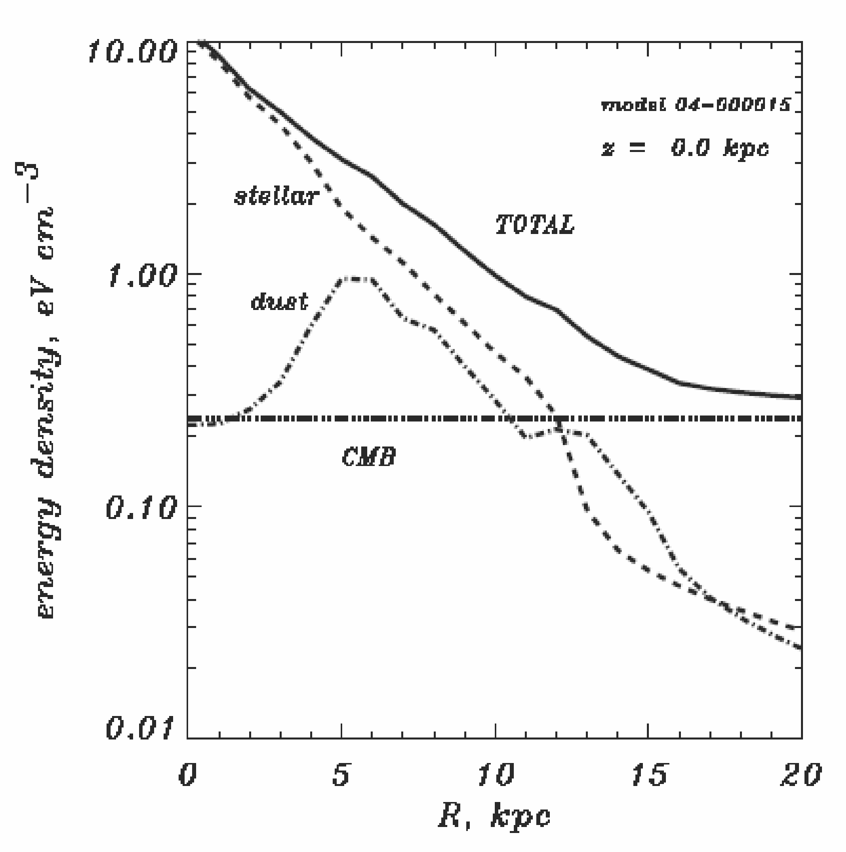
- galactic centre
- galactic poles
- galactic anticentre
- nearest satellite galactic streams

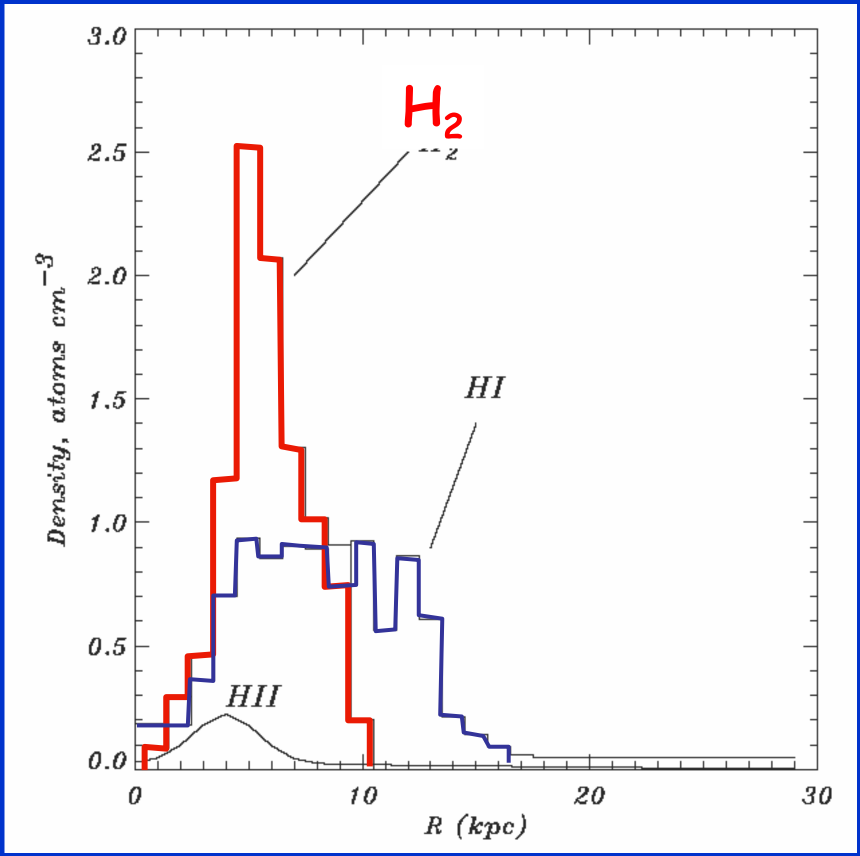
Gas flaring in the Milky Way



Gas flaring needs EGRET ring with mass of $2.10^{10} M_\odot$!

Inner Ring coincides with ring of dust and H_2 -> gravitational potential well!

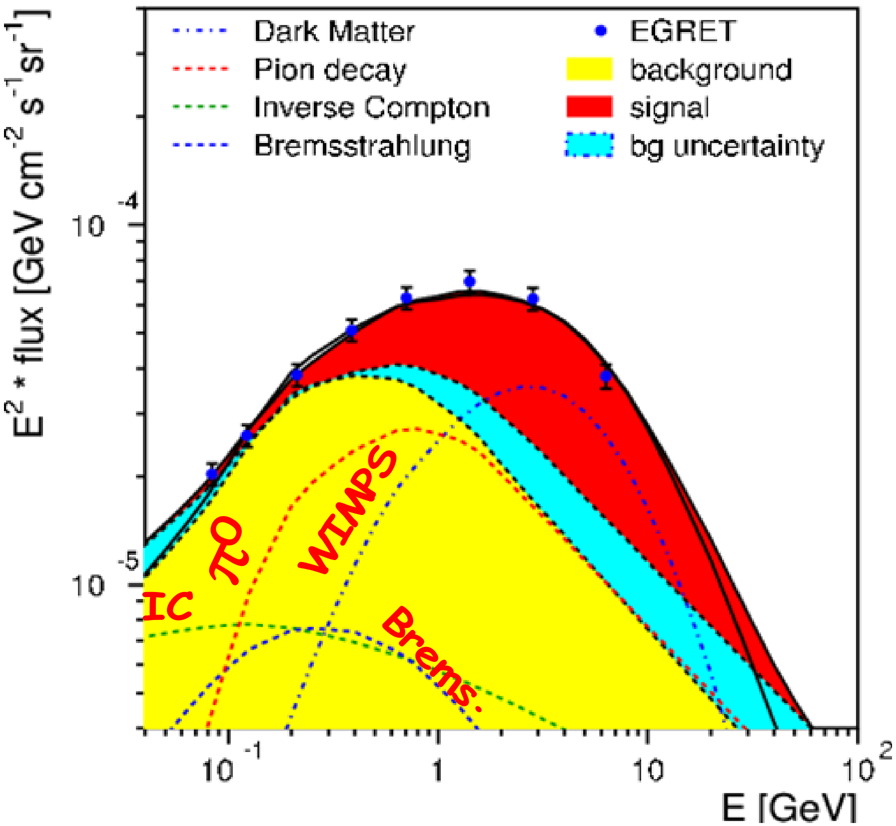


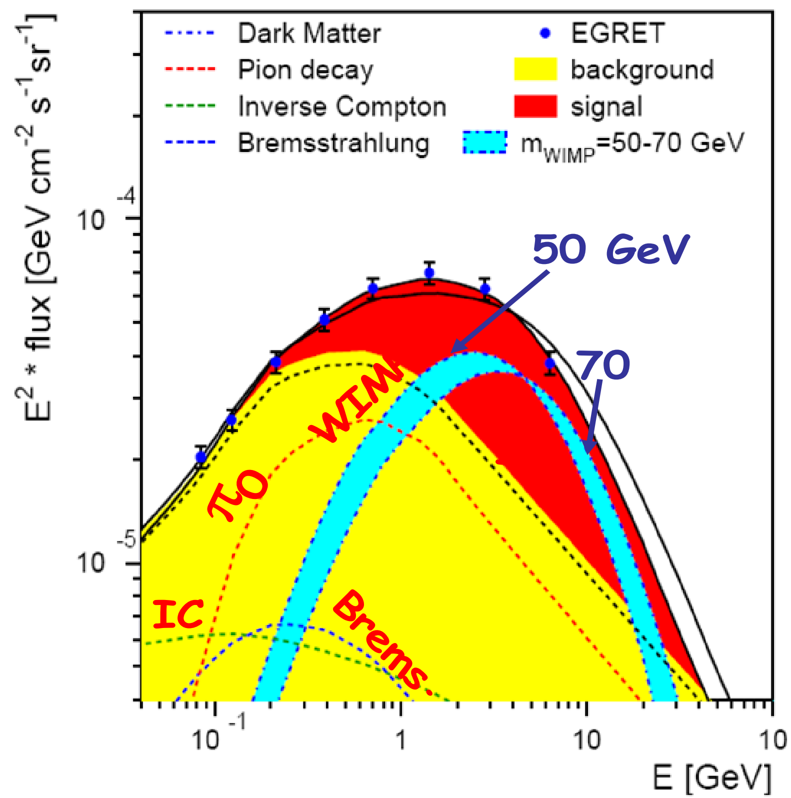


Enhancement of inner (outer) ring over $1/r^2$ profile 6 (8).
Mass in rings 0.3 (3)% of total DM

4 kpc coincides with ring of neutral hydrogen molecules!
$H+H \to H_2$ in presence of dust-> grav. potential well at 4-5 kpc.

Background + signal describe EGRET data!



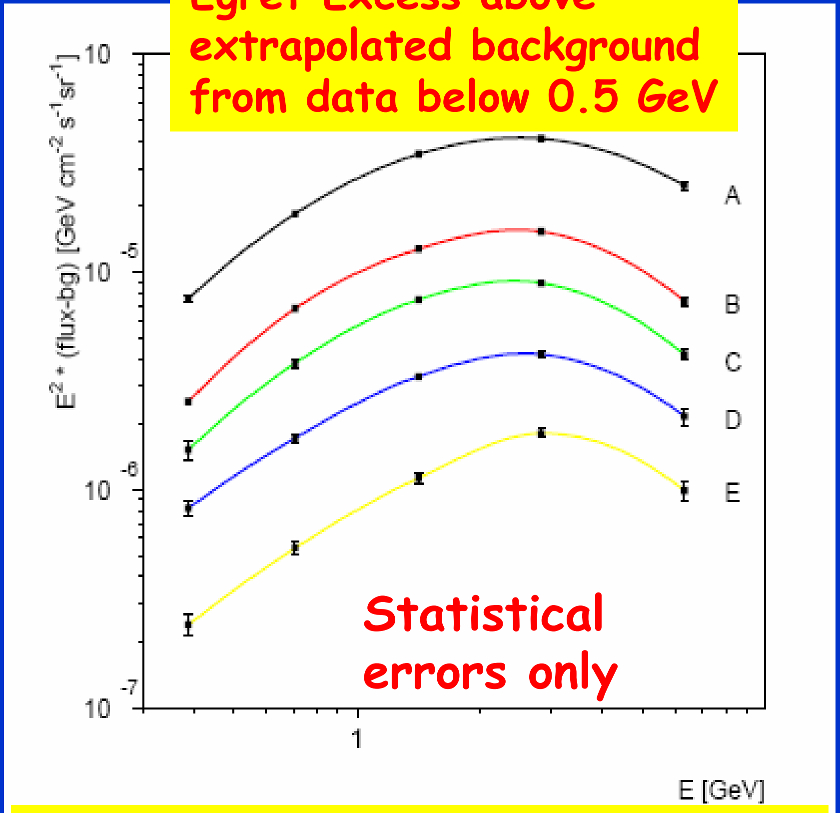


Blue: background uncertainty

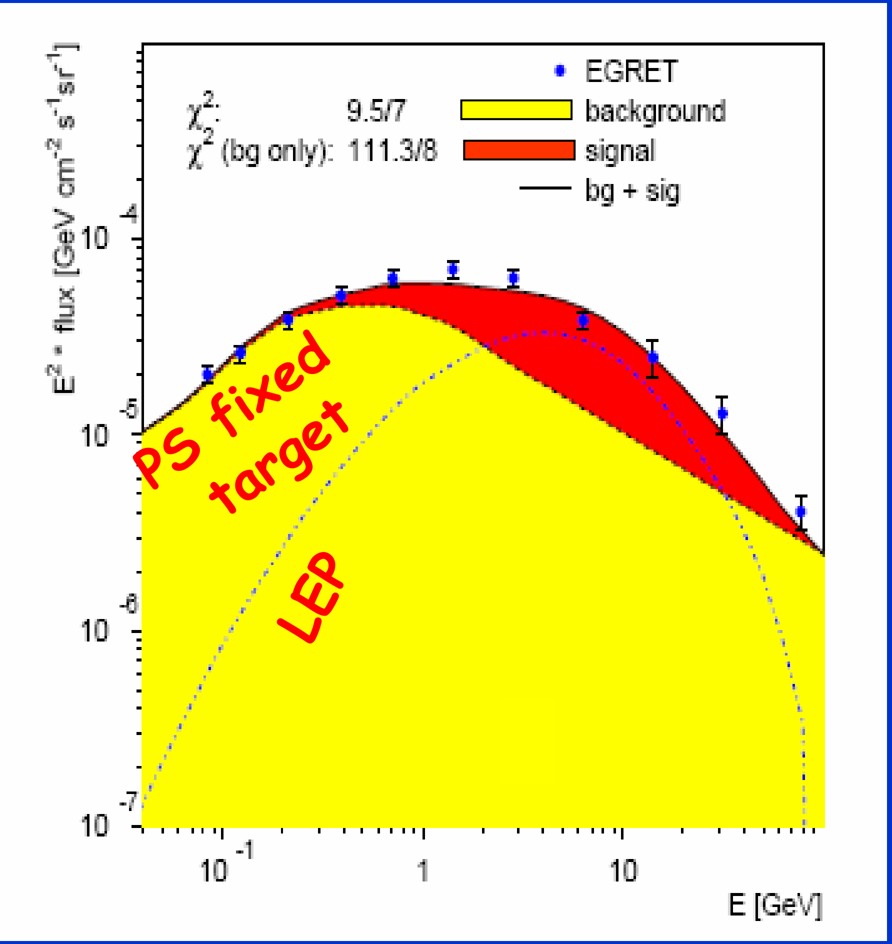
Blue: WIMP mass uncertainty

Excess of Diffuse Gamma Rays has same spectrum in all directions compatible with WIMP mass of 50-100 GeV

Egret Excess above extrapolated background from data below 0.5 GeV

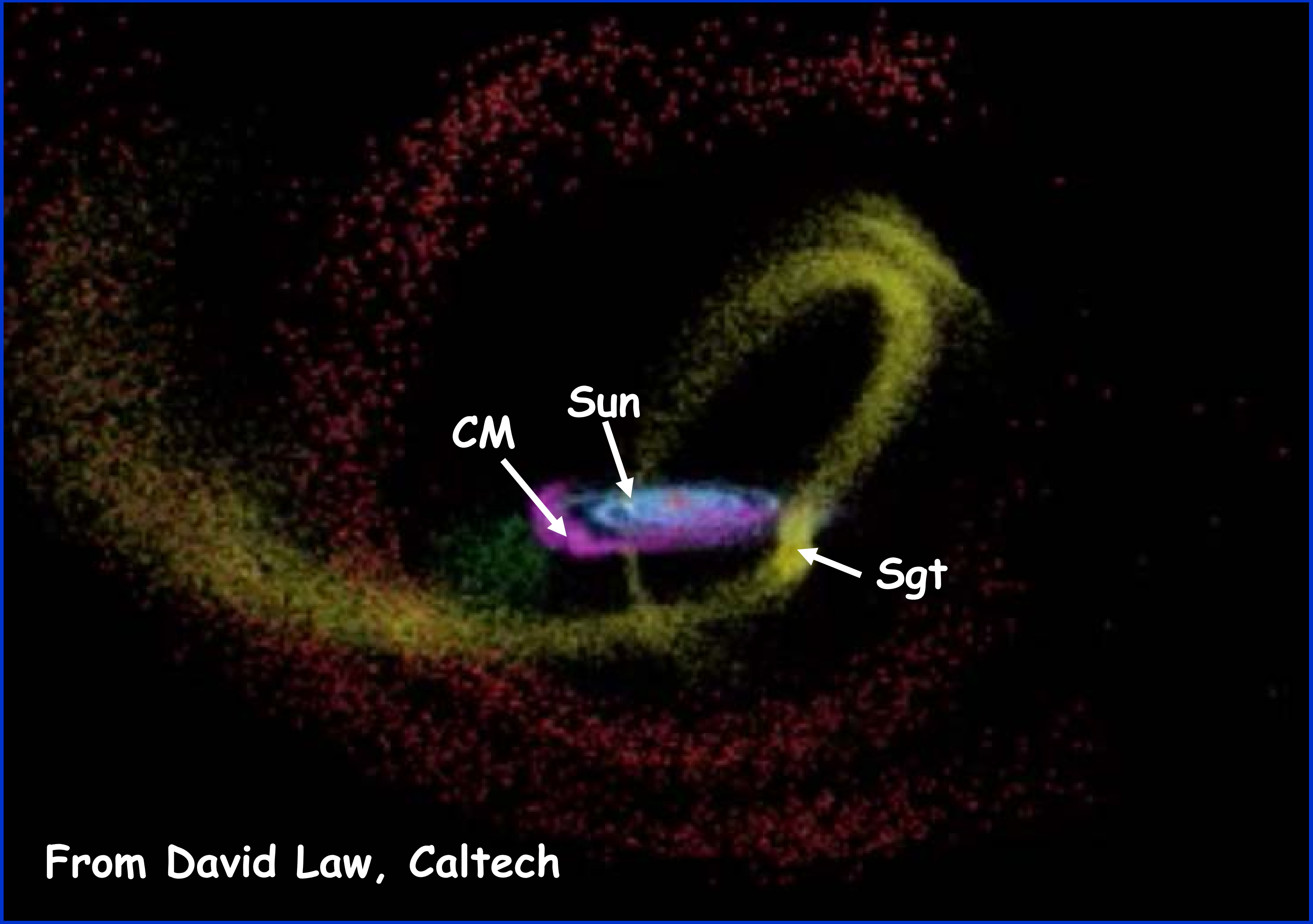


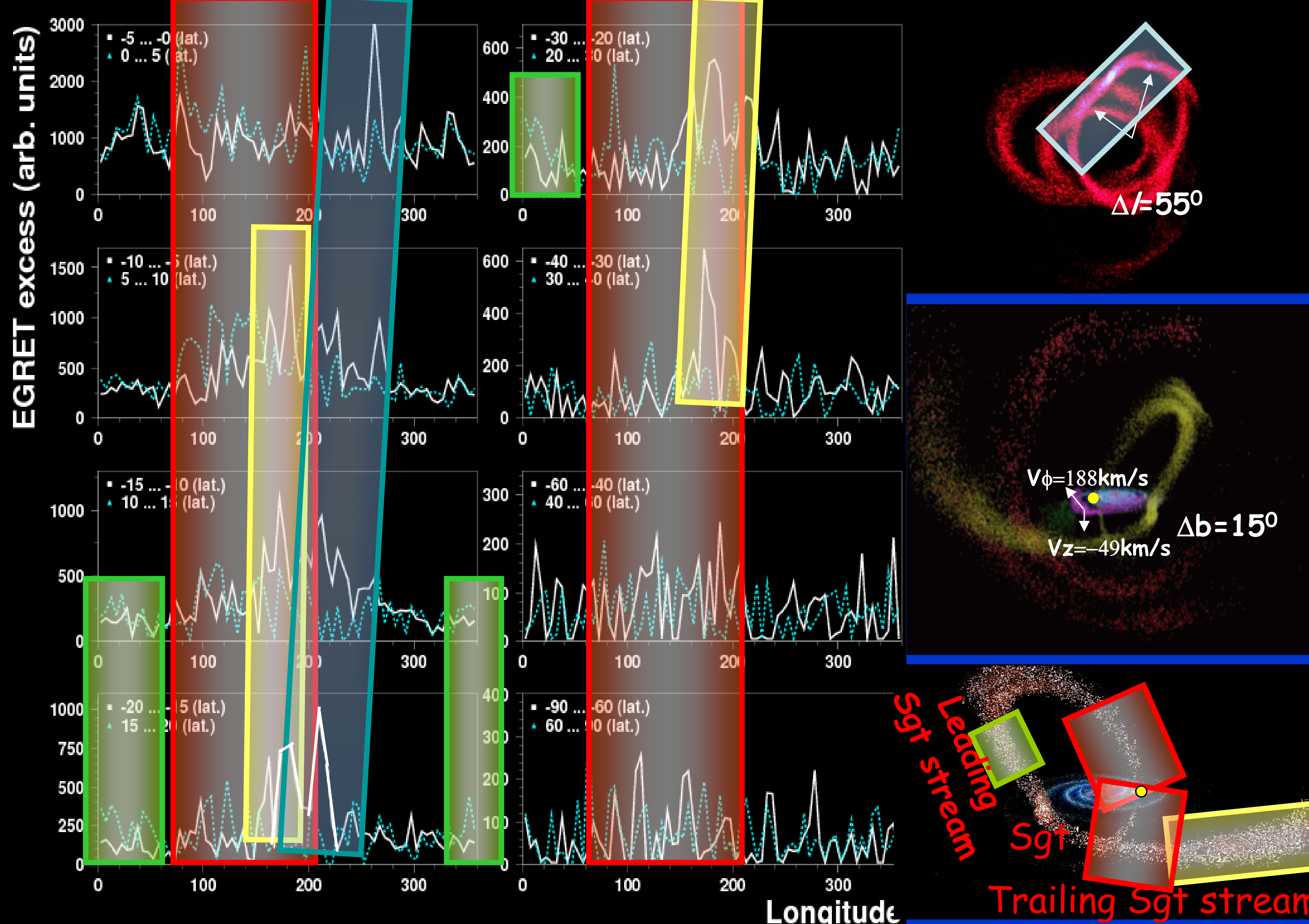
Excess same shape in all regions implying same source everywhere



Important: if experiment measures gamma rays down to 0.1 GeV, then normalizations of DM annihilation and background can both be left free, so one is not sensitive to absolute background estimates, BUT ONLY TO THE SHAPE, which is much better known.

Tidal streams of dark matter from CM and Sgt




EGRET excess (arb. units)
Longitude
Δl=55°
Vϕ=188km/s
Vz=−49km/s
Δb=15°
Leading Sgt stream
Sgt
Trailing Sgt stream

8 physics questions answered SIMULTANEOUSLY if WIMP = thermal relic

- Astrophysicists:

  What is the origin of "GeV excess" of diffuse Galactic Gamma Rays? A: DM annihilation
- Astronomers:

  Why a change of slope in the galactic rotation curve at $R_0 \approx 11$ kpc? A: DM substructure

  Why ring of stars at 13 kpc?

  Why ring of molecular hydrogen at 4 kpc?

  Why S-shape in gas flaring?
- Cosmologists: How is DM annihilating? A: into quark pairs

  How is Cold Dark Matter distributed? A: standard profile + substructure
- Particle physicists:

  Is DM annihilating as expected in Supersymmetry?

  A: Cross sections perfectly consistent with mSUGRA for light gauginos, heavy squarks/sleptons

Do antiproton data exclude interpretation of EGRET data?

Bergstrom et al. astro-ph/0603632, Abstract:

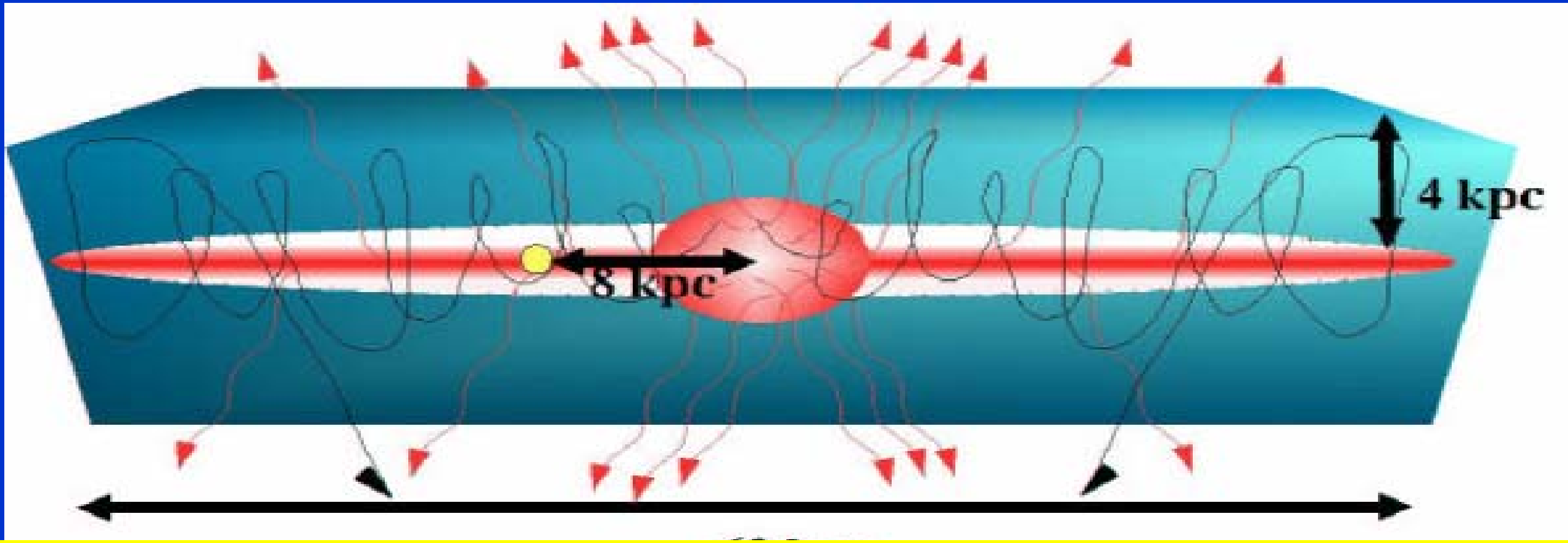
we investigate the viability of the model using the DarkSUSY package to compute the gamma-ray and antiproton fluxes. We are able to show that their (=WdB et al) model is excluded by a wide margin from the measured flux of antiprotons.

Problem with DarkSUSY (DS):

1) Flux of antiprotons/gamma in DarkSUSY: O(1) from DMA.
   However, $O(10^{-2})$ from LEP data
   Reason: DS has diffusion box with isotropic diffusion ->
   DMA fills up box with high density of antiprotons
2) Priors of DARKSUSY.(and other propagation models as well):
   a) static galactic magnetic fields are negligible
   b) gas is smoothly distributed
   c) propagation in halo and disk are the same

ALL priors likely wrong and can change predictions for DM seaches by ORDER OF MAGNITUDE (and still ok with all observations!)

One propagation model of our Galaxy



GALAXY IS BIG STORAGE TANK FOR ANTIPROTONS IN DARKSUSY and GALPROP

Primary particles by supernovae explosions, pulsars, ...

Secondary particles nuclear interactions.

Diffusion parameters determined from sec./prim. ratios, e.g. B/C ratio

Halo size determined from radioactive isotopes, e.g $^{10}Be/^{9}Be$ ratio ($\tau(^{10}Be) = 1.6 \cdot 10^6$ yr)

Another propagation model including static magnetic fields and gas clouds and anisotropic diffusion

CONFINEMENT AND ISOTROPIZATION OF GALACTIC COSMIC RAYS BY MOLECULAR-CLOUD MAGNETIC MIRRORS WHEN TURBULENT SCATTERING IS WEAK

BENJAMIN D. G. CHANDRAN
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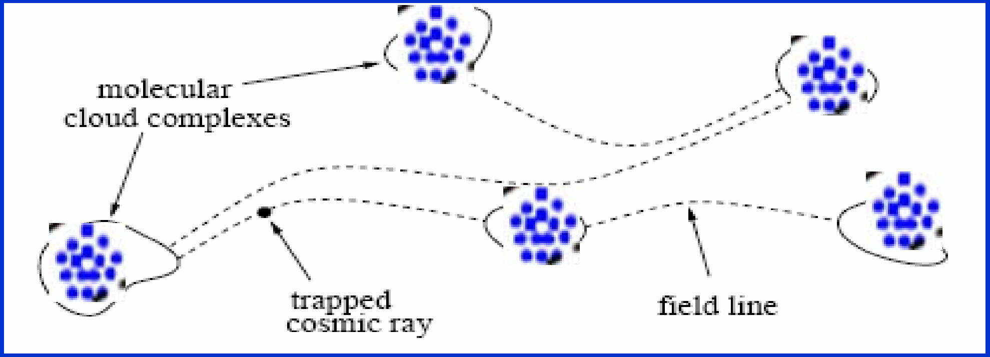
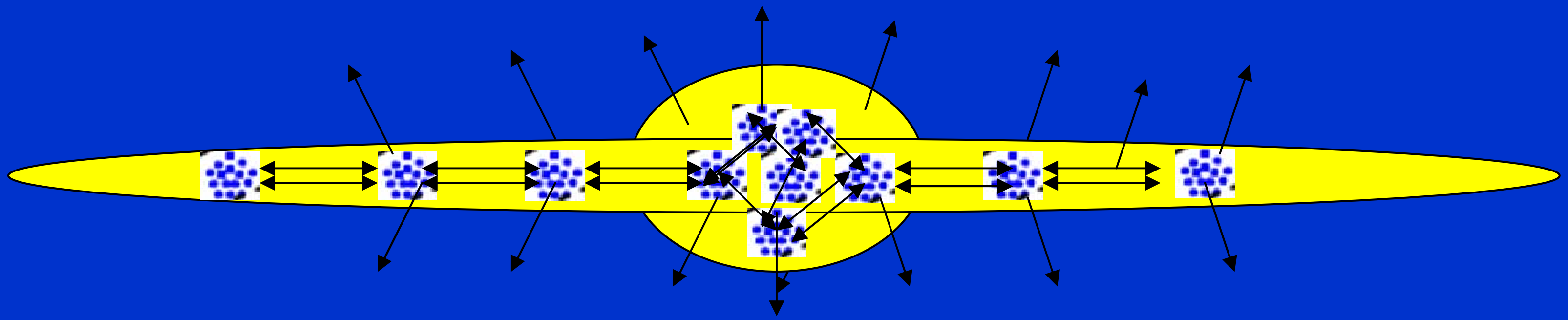
Received 1998 June 25; accepted 1999 August 6

it is shown that Galactic cosmic rays can be effectively confined through magnetic reflection by molecular clouds,

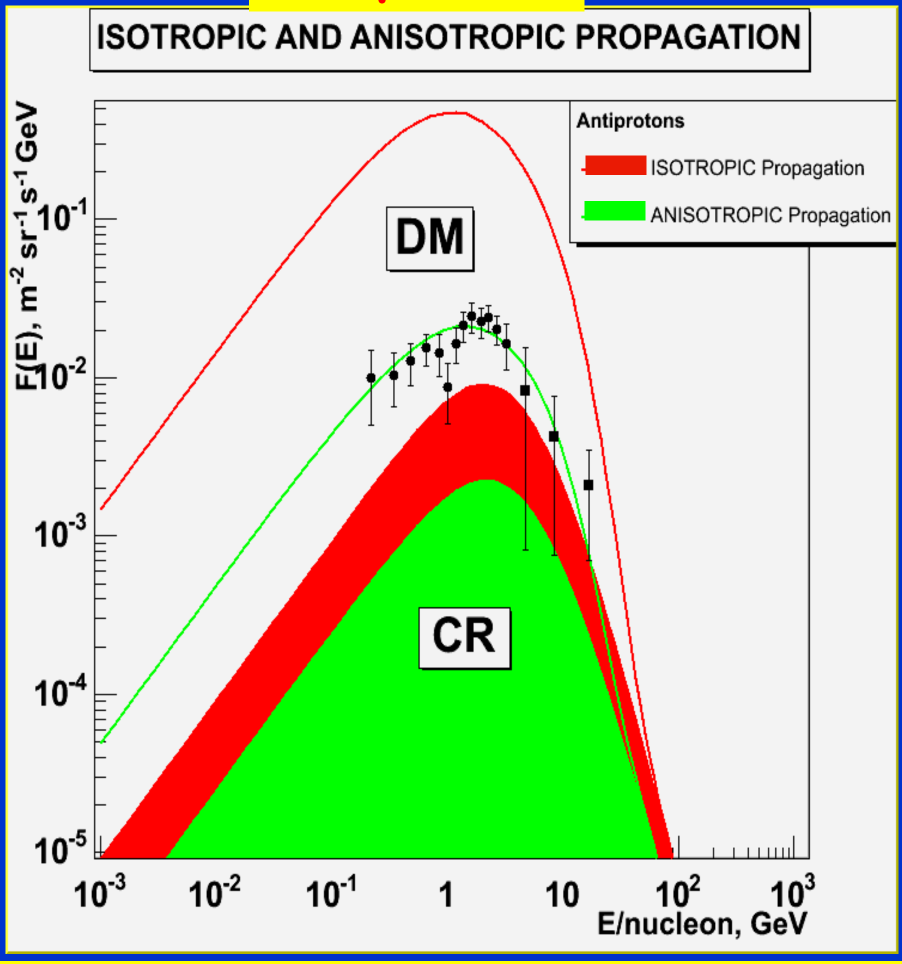




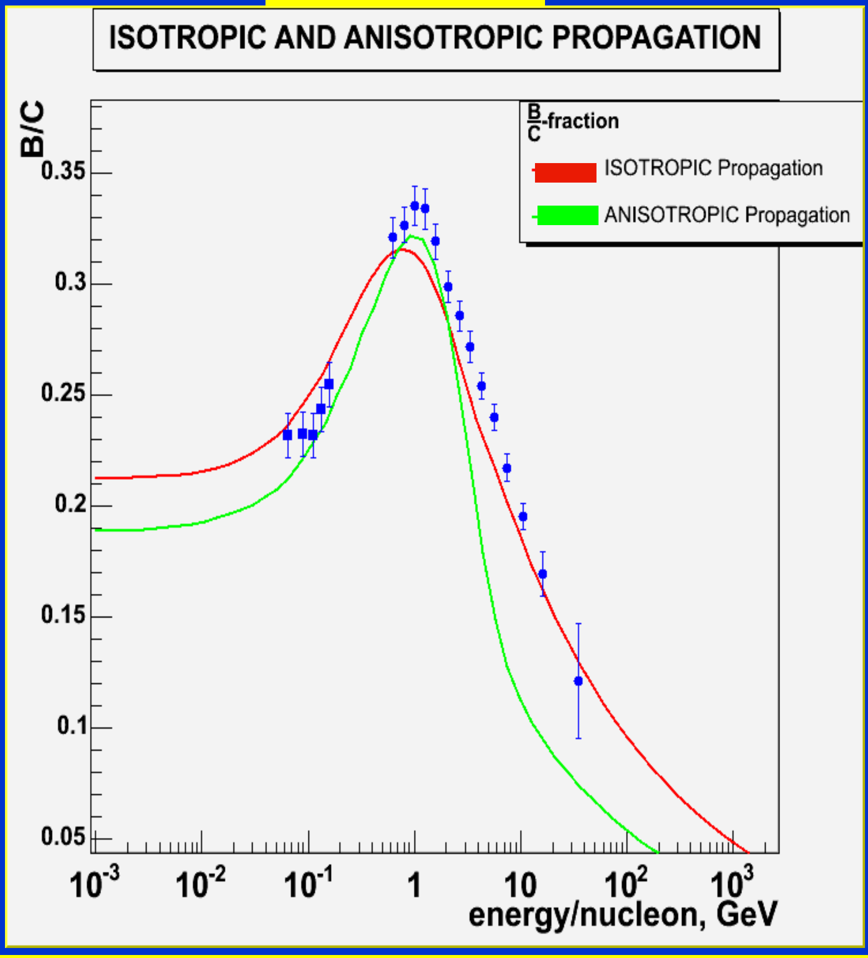
Integral excess of positrons in bulge because positrons are trapped in magnetic mirrors between gas clouds

Preliminary results from GALPROP with isotropic and anisotropic propagation

Antiprotons



B/C ratio



Summary: with anisotropic propagation you can send charged particles whereeever you want and still be consistent with B/C and $^{10}Be/^{9}Be$

Summary

>>10σ EGRET excess shows intriguing hint that:

WIMP is thermal relic with expected annihilation into quark pairs

DM becomes visible by gamma rays from fragmentation
(30-40 gamma rays of few GeV pro annihilation from π_0 decays)

Results rather model independent, since only KNOWN spectral shapes of signal and background used, NO model dependent calculations of abs.fluxes. Different shapes or unknown experimental problems may change the gamma ray flux and/or WIMP mass, BUT NOT the distribution in the sky.

SPATIAL DISTRIBUTION of annihilation signal is signature for DMA which clearly shows that EGRET excess is tracer of DM by fact that one can construct rotation curve and tidal streams from gamma rays.

DM interpretation strongly supported independently by gas flaring

What about supersymmetry?

EGRET excess does not say anything about SUSY,
it only shows that the excess is coming from
the annihilation of 60 GeV MONOENERGETIC quarks!
BUT one can check consistency with SUSY.

E.g. can a WIMP mass of 60 GeV yield an annihilation cross section as expected from WMAP+cosmology?

SUSY07 in Karlsruhe next month

- SUSY07 Home
- Program
- PreSUSY07 - Summer School
- Public Lecture
- Important Dates
- Registration
- Payment Information
- Abstract Submission
- My Contributions
- List of registrants

The 15th International Conference on Supersymmetry and the Unification of Fundamental Interactions

Karlsruhe, Germany
July 26 - August 1, 2007

Deadline for hotel reservation
25th June, 2007

PreSUSY07 - Summer School

Introductory lectures

- Basics of Supersymmetry - *D.I. Kazakov (Dubna)*
- Basics of Higgs Physics - *S. Heinemeyer (Santander)*
- Basics of Physics at the LHC - *H.A. Baer (Tallahassee)*
- Basics of Direct Dark Matter Searches - *J. Jochum (Tübingen)*
- Basics of Indirect Dark Matter Searches - *W. de Boer (Karlsruhe)*
- Basics of Cosmology - *E.W. Kolb (Fermilab)*
- From Symmetry to Supersymmetry - *J. Wess (Munich)*
- The Universe is a Strange Place - *F. Wilczek (MIT)*

Karlsruhe, July 23-25, 2007

Program for SUSY2007, Karlsruhe, July 26 - August 1, 2007.

Thursday, 26.7.2007		
9:00-9:15	Welcome	Detlef Loehe (Prorector Univ. Karlsruhe)
9:15-10:00	Supersymmetry, from its Beginning to its Deformation	Julius Wess (MPI, Munich)
10:00-10:30	break	
10:30-11:15	Status of Cosmology	Edward Kolb (Univ. of Chicago)
11:15-12:00	Anticipating a New Golden Age	Frank Wilczek (MIT)
Friday, 27.7.2007		
9:00-9:30	Status of the LHC	Lyn Evans, CERN
9:30-10:00	SUSY at the LHC (Theory)	Bhaskar Dutta, Texas A&M Univ.
10:00-10:30	Higgs at the LHC (Theory)	Abdelhak Djouadi, Univ. Paris-sud
10:30-11:00	break	
11:00-11:30	SUSY at the LHC (Experimental)	Maria Spiropulu (CERN)
11:30-12:00	Higgs at the LHC (Experimental)	Karl Jakobs (Freiburg Univ.)
12:00-12:30	SM Backgrounds to SUSY Searches	Michelangelo Mangano (CERN)

Tuesday, 31.7.2007		
9:00-9:30	Strings and Particle Physics	Hans-Peter Nilles (Bonn Univ.)
9:30-10:00	Strings and Cosmology	Andrei Linde (Stanford Univ.)
10:00-10:30	Colliders and Cosmology	Keith Olive (Univ. of Minnesota)
10:30-11:00	break	
11:00-11:30	Inflation and Unification	Qaisar Shafi (Bartol Research Inst.)
11:30-12:00	Present and Future of Neutrino Masses	Guido Drexlin (KIT, Karlsruhe)
12:00-12:30	SUSY and Seesaw	Antonio Masiero (Univ. of Padua)

Wednesday, 1.8.2007		
9:00-9:30	DM Candidates	Frank Daniel Steffen (MPI Munich)
9:30-10:00	Direct DM Searches	Laura Baudis (RWTH Aachen)
10:00-10:30	Indirect DM Searches	Dan Hooper (Fermilab)
10:30-11:00	break	
11:00-11:45	Extra Dimensions	Lisa Randall (Harvard Univ.)
11:45-13:00	Outlook	John Ellis (CERN)

Fundamental questions of modern physics

Particle physics	Cosmology
What is the origin of mass?	What is Dark Matter?
Why forces different strength?	What is Dark Energy?
Why hydrogen atom neutral?	Why no antimatter?
	How did galaxies form?

Magic solution: SUPERSYMMETRY

Motivation of SUSY in Particle Physics

1. Unification with Gravity
2. Unification of gauge couplings
3. Solution of the hierarchy problem
4. Higgs mechanism by radiative corrections
5. No quadratic divergencies,
   i.e. theory valid to high energies
6. Dark matter in the Universe
7. Superstrings

What is SUSY?

Supersymmetry is a Boson-Fermion symmetry, which allows to unify all forces of nature (including gravity).

SUSY can exist in nature ONLY, if there are as many bosons as fermions ⇒ Doubling the particle spectrum (Waw, Eldorado for experimental particle physicists)

$$Q \,|\, boson >=|\; fermion > \qquad Q \,|\; fermion >=|\, boson >$$

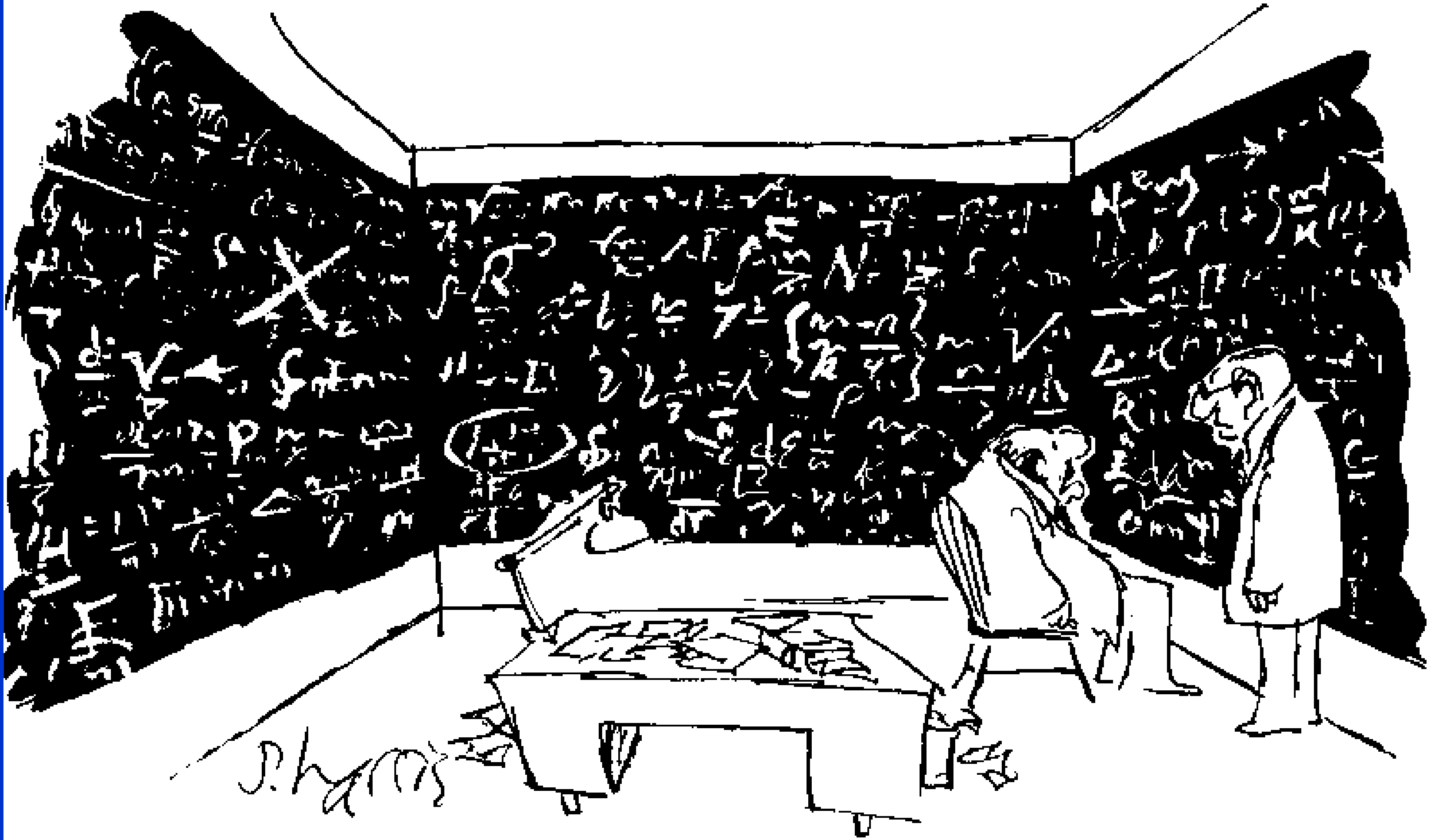
$$spin\ 2 \;\rightarrow\; spin\ 3/2 \;\rightarrow\; spin\ 1 \;\rightarrow\; spin\ 1/2 \;\rightarrow\; spin\ 0$$

$$\{Q^i_\alpha, \overline{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta} P_\mu \quad \Rightarrow \quad \{\delta_\varepsilon, \overline{\delta}_{\overline{\varepsilon}}\} = 2(\varepsilon\sigma^\mu\overline{\varepsilon})P_\mu$$

$\varepsilon = \varepsilon(x)$ local coordinate transformation.

Local translation = general relativity !

We like elegant solutions



"Whatever happened to *elegant* solutions?"

Particle spectrum in SUPERSYMMETRY

Symmetry between

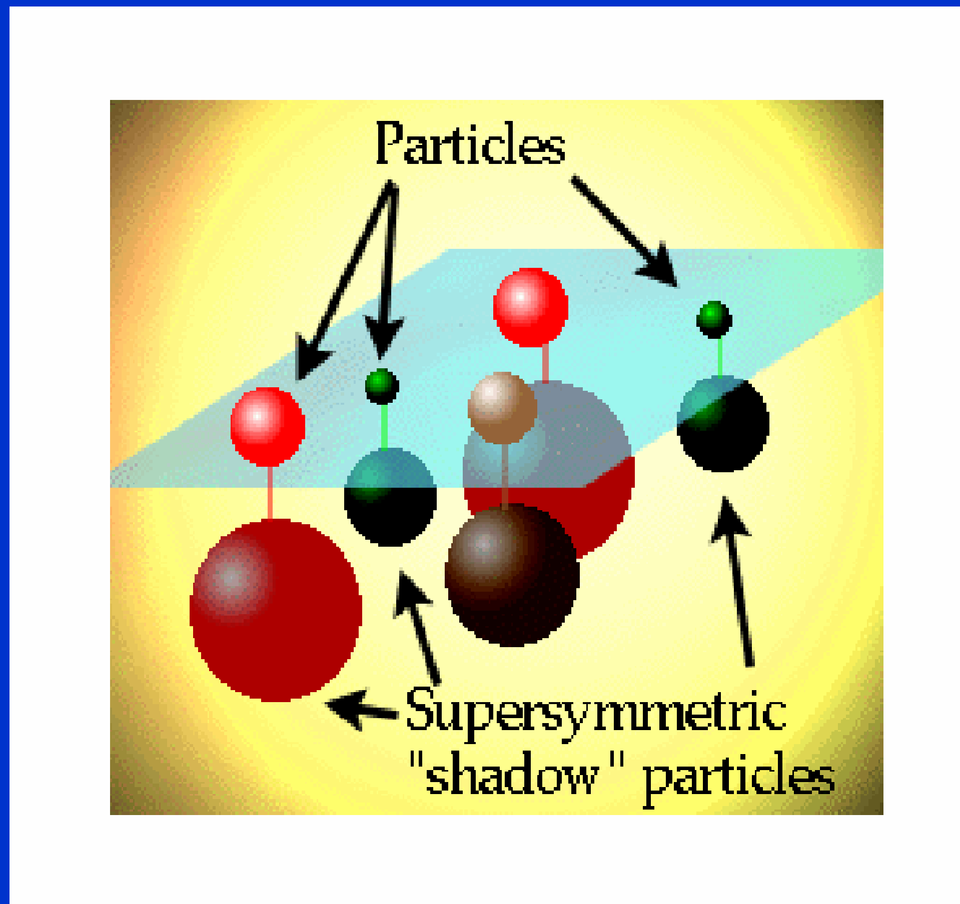
Fermions ↔ Bosons
(Matter particles) (exchange particles)

Spin	Standardparticle	Superpartner	Spin
1/2	Leptons (e, ν_e, ...) Quarks (u, d, ...)	Sleptons ($\tilde{e}$, $\tilde{\nu}_e$, ...) Squarks ($\tilde{u}$, $\tilde{d}$, ...)	0
1	Gluons $W^{\pm}$ Z^0 Photon (γ)	Gluinos Wino Zino Photino ($\tilde{\gamma}$) = WIMP	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

SUSY masses: 100 - 2000 GeV !

Lightest Supersymmetric Particle (LSP) is stable, heavy and weakly interacting
⇒ excellent Weakly Interacting Massive Particle (WIMP) ⇒ DM candidate!
R-Parity conservation: TWO SUSY particles at each vertex!
LSP mostly photinolike in MSSM ⇒ DM = supersymmetric partner of CMB

SUSY Shadow World



One half is observed!

One half is NOT observed!

Grand Unified Theories

The smallest symmetry group: $SU(5) \supset (\mathrm{SU(3)_C} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)})$

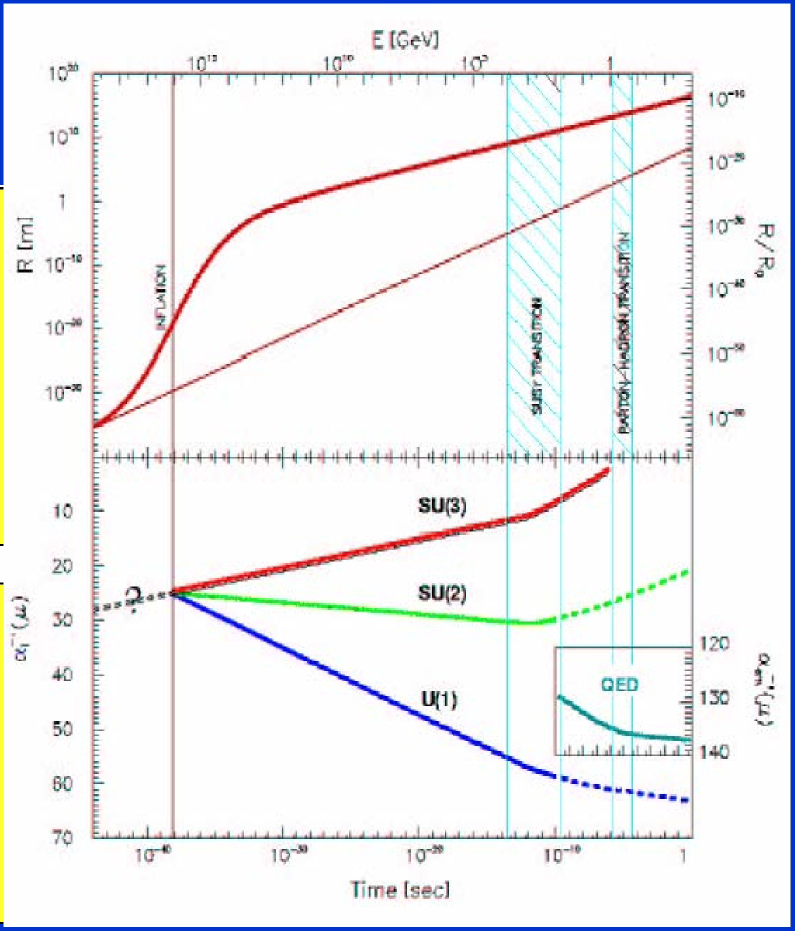
Quarks and Leptons in $\overline{5}$- and 10-plets:

$$
\begin{pmatrix} d_g^C \\ d_r^C \\ d_b^C \\ e^- \\ -\nu_e \end{pmatrix}
\qquad
\frac{1}{\sqrt{2}}
\begin{pmatrix}
0 & +u_b^C & -u_r^C & -u_g & -d_g \\
-u_b^C & 0 & +u_g^C & -u_r & -d_r \\
+u_r^C & -u_g^C & 0 & -u_b & -d_b \\
+u_g & +u_r & +u_b & 0 & -e^+ \\
+d_g & +d_r & +d_b & +e^+ & 0
\end{pmatrix}_L
$$

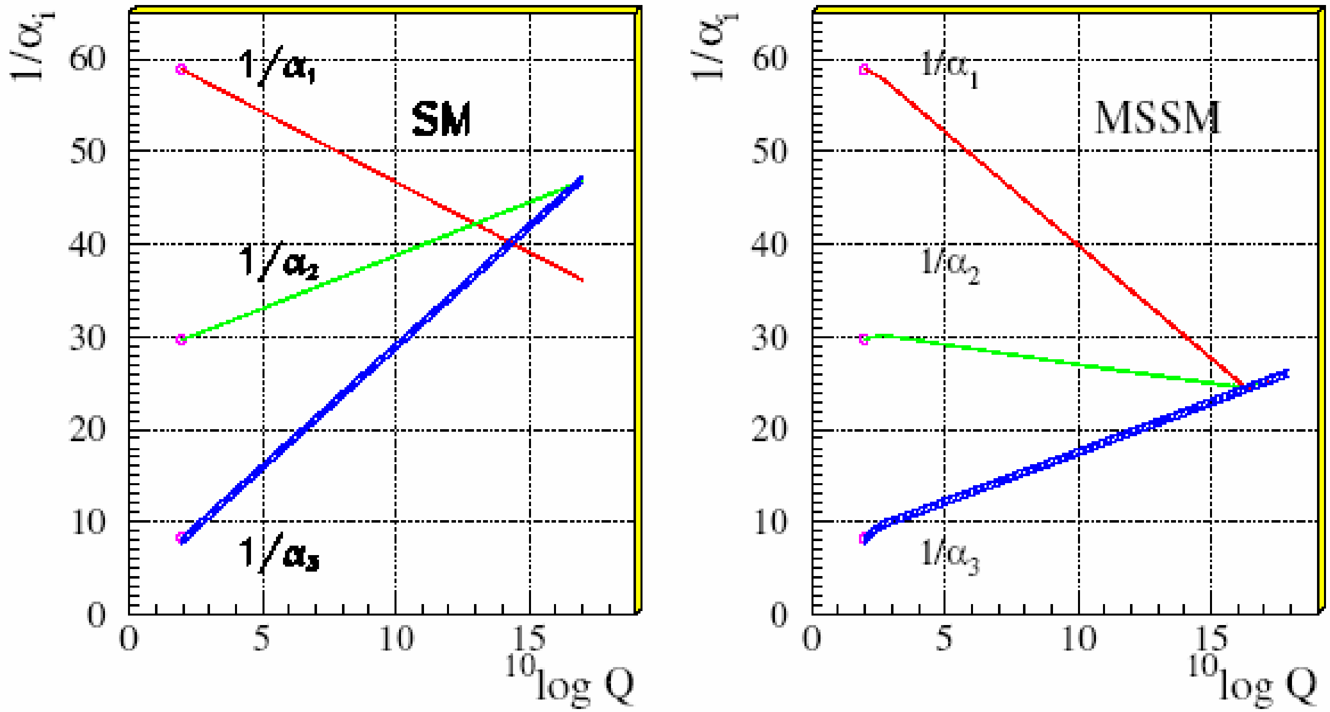
Gauge bosons in 5x5 matrices:

$$
\left(\begin{array}{ccc|cc}
G_{11} - \frac{2B}{\sqrt{30}} & G_{12} & G_{13} & X_1^C & Y_1^C \\
G_{21} & G_{22} - \frac{2B}{\sqrt{30}} & G_{23} & X_2^C & Y_2^C \\
G_{31} & G_{32} & G_{33} - \frac{2B}{\sqrt{30}} & X_3^C & Y_3^C \\
\hline
X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\
Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}}
\end{array}\right)
$$

Possible evolution of Universe



Gauge Coupling Unification in SUSY



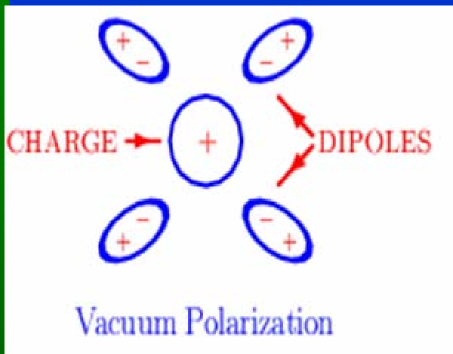
U. Amaldi, W. de Boer, H. Fürstenau, PL B260(1991)

$\alpha_1, \alpha_2, \alpha_3$ coupling constants of electromagnetic –, weak–, and strong interactions

$1/\alpha_i \propto \log Q^2$ due to radiative corrections (LO)

Why are gauge couplings running?

Answer: couplings $\propto$ charges, but bare charges shielded by quantum fluctuations

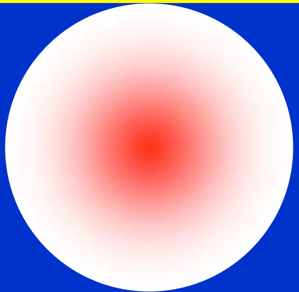


$\Rightarrow$

Spation charge distribution of electromagnetic charges (reduced at large distance because of screening by vacuum polarization)

$\Rightarrow$

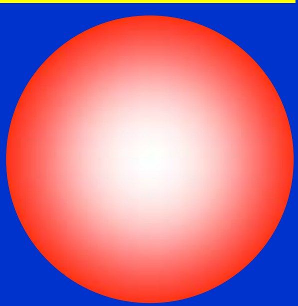
Electric charge in electron



Colour charge in proton

In strong interactions: vacuum fluctuations from gluons->qq AND gluons->gg
Latter dominates, thus enhancing colour charge at large distances (antiscreening)

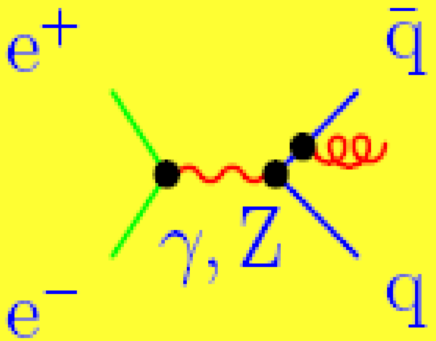
$\Rightarrow$



Because of opposite screening effects, opposite running of electromagnetic and strong interactions!

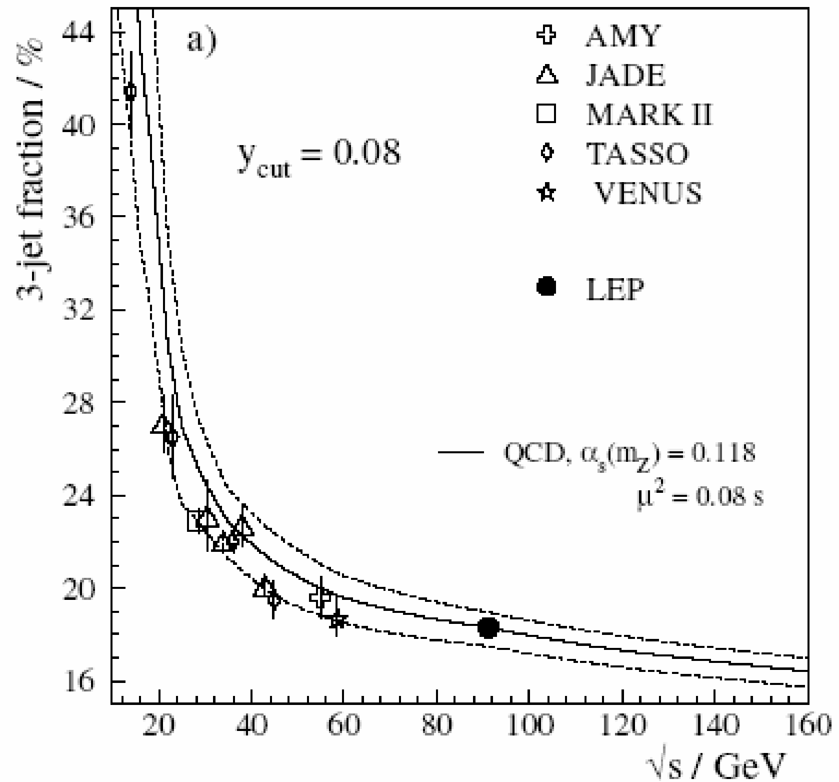
At higher energies also SUSY particles in vacuum -> change of running!

Running of Strong Coupling Constant



3-jet fraction $\propto \alpha_s$

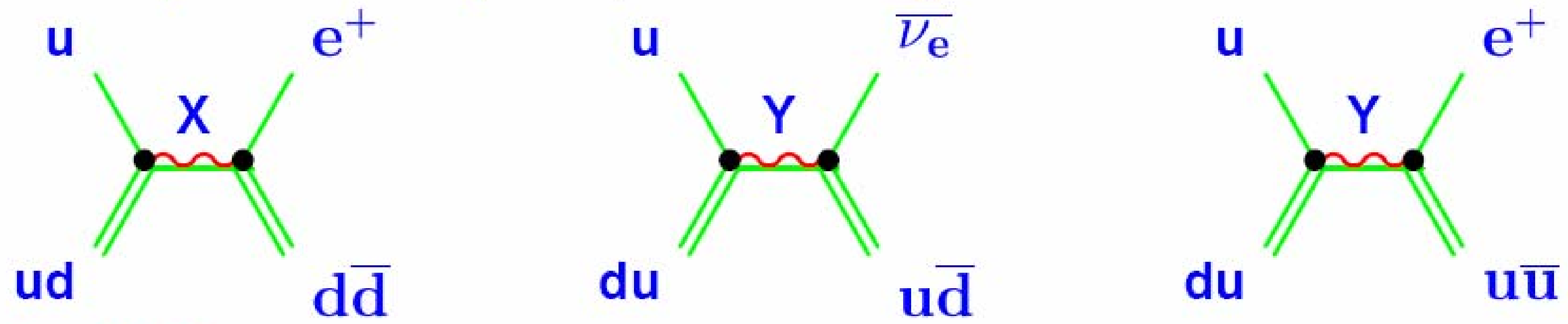
$$\propto 1/\ln E$$



From: T. Hebbeker, Phys. Rep. 217 (1992)

Proton decay expected in GUT's

X,Y bosons with charge $\pm 4/3$ and $\pm 1/3$ can induce transitions between quarks and leptons, thus leading to B- and L-violation!



Proton lifetime:

$$\tau_P \approx \frac{1}{\alpha^2(\mathrm{GUT})} \frac{M_{\mathrm{GUT}}^4}{M_P^5}$$

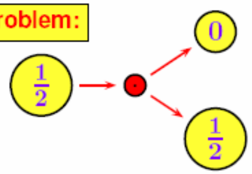
Experimental limit:

$$\tau_P \geq 5.5 \cdot 10^{32} \text{ yrs} \Rightarrow M_{\mathrm{GUT}} \geq 2 \cdot 10^{15} \text{ GeV}$$

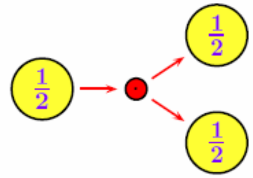
Fulfilled by MSSM, NOT SM!

R-Parity

Spin Problem:



ALLOWED→ B,L Violation



FORBIDDEN: ang. mom.

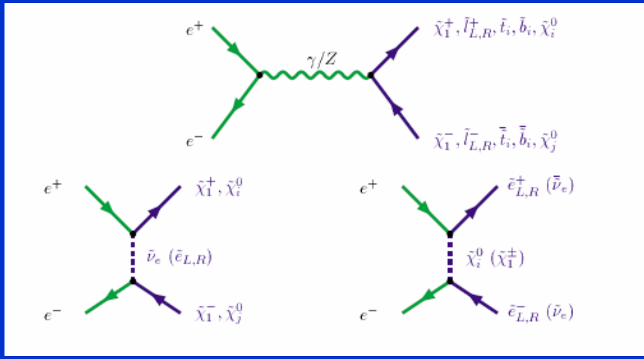
Solution: R-Parity Conservation! (multipl. quantum nr.)

$$R_p = (-1)^{3B+L+2S} = \begin{cases} +1 & \text{for } SM \text{ particles} \\ -1 & \text{for } SUSY \text{ particles} \end{cases}$$

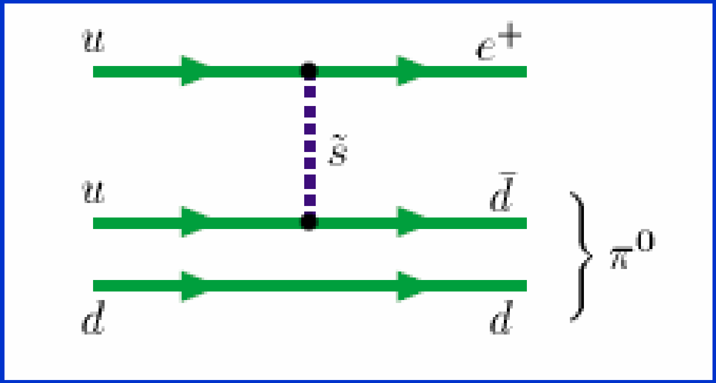
↓

LSP is stable and weakly interacting

Some production diagrams



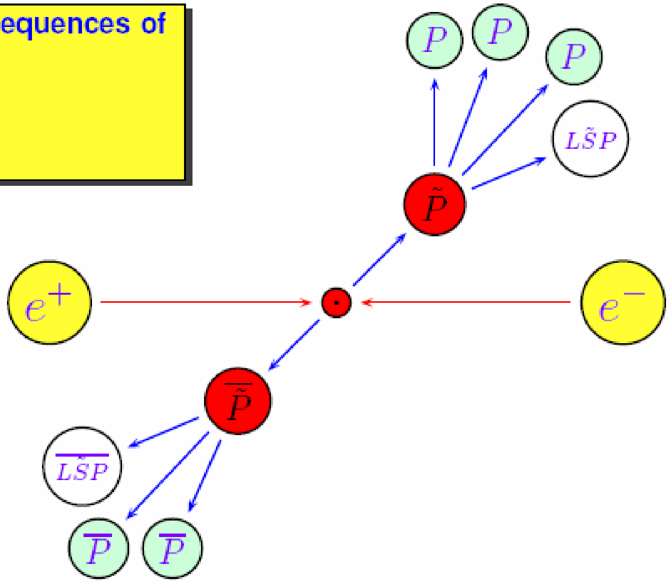
Proton decay



Experimental consequences of R-Parity:

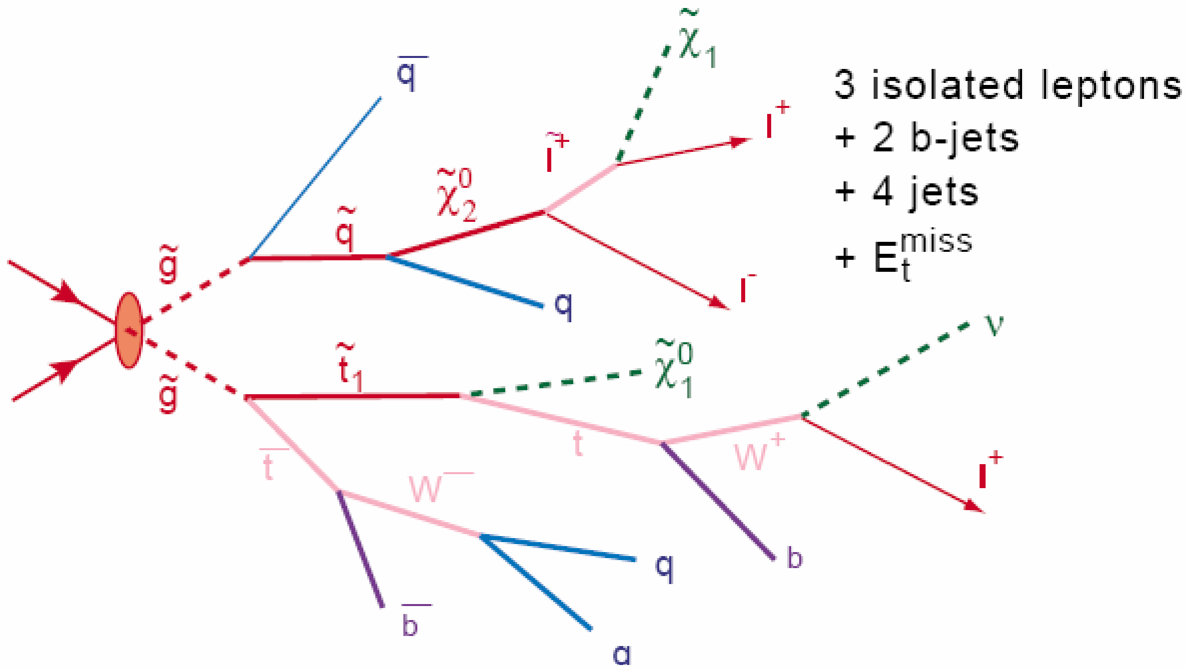
Pair Production!

$\not{E}$ SIGNATURES!



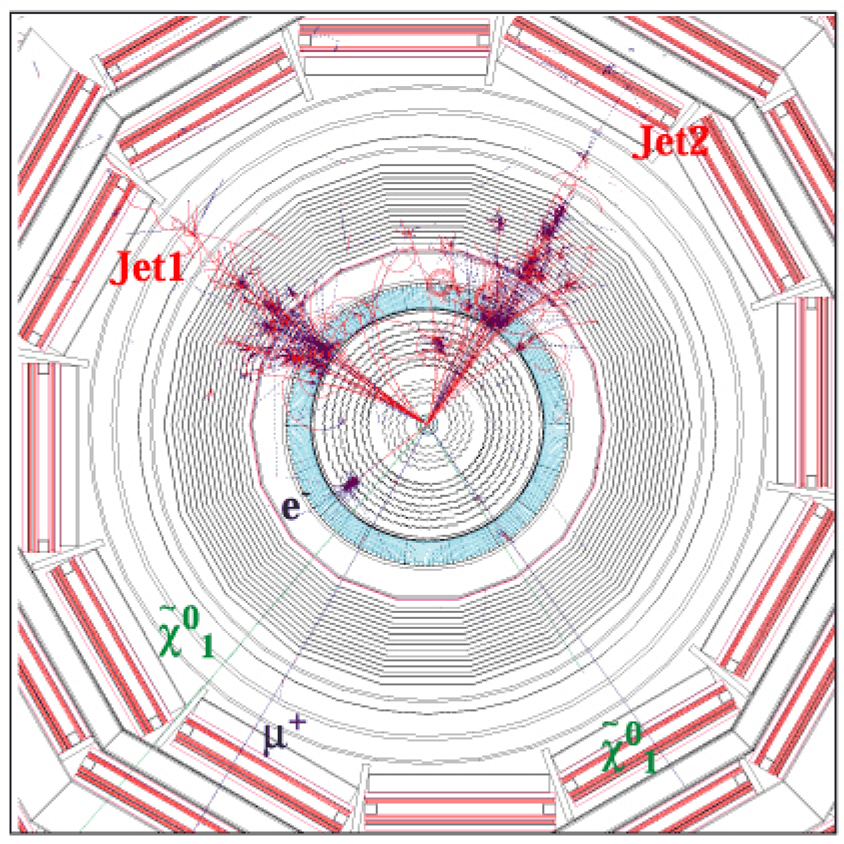
Example of SUSY production and decay chain

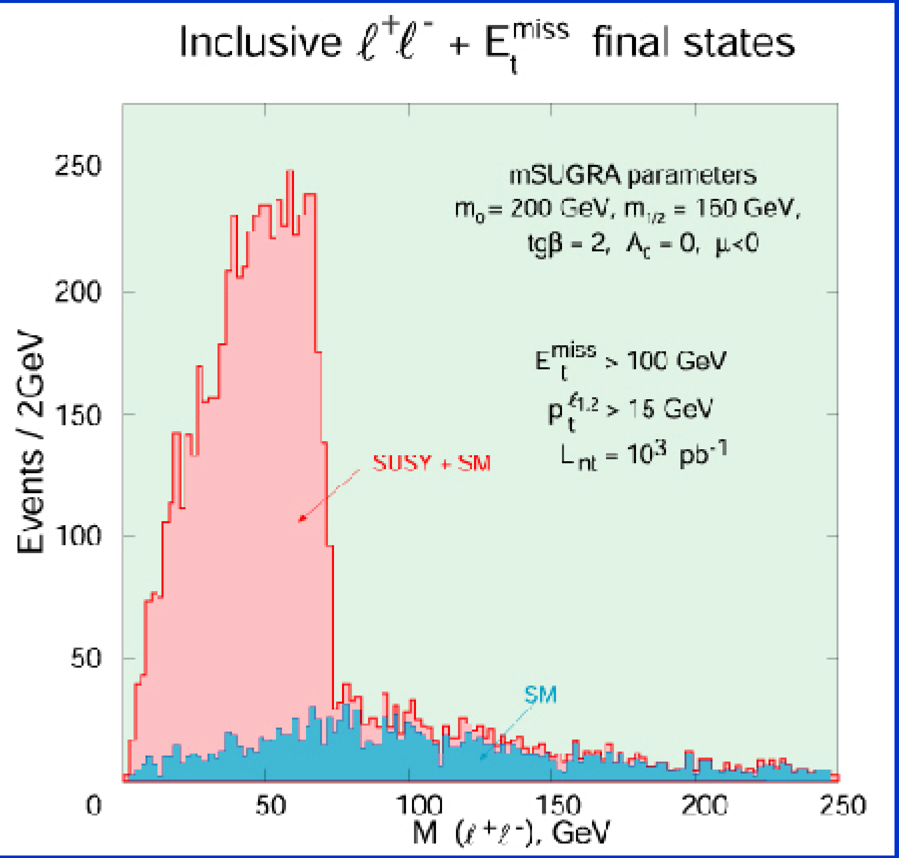
Gluino/squark production event topology allowing sparticle mass reconstruction



Such cascade decays allow to reconstruct sleptons, neutralinos, squarks, gluinos… in favorable cases with %level mass resolutions

Main SUSY signature: missing energy

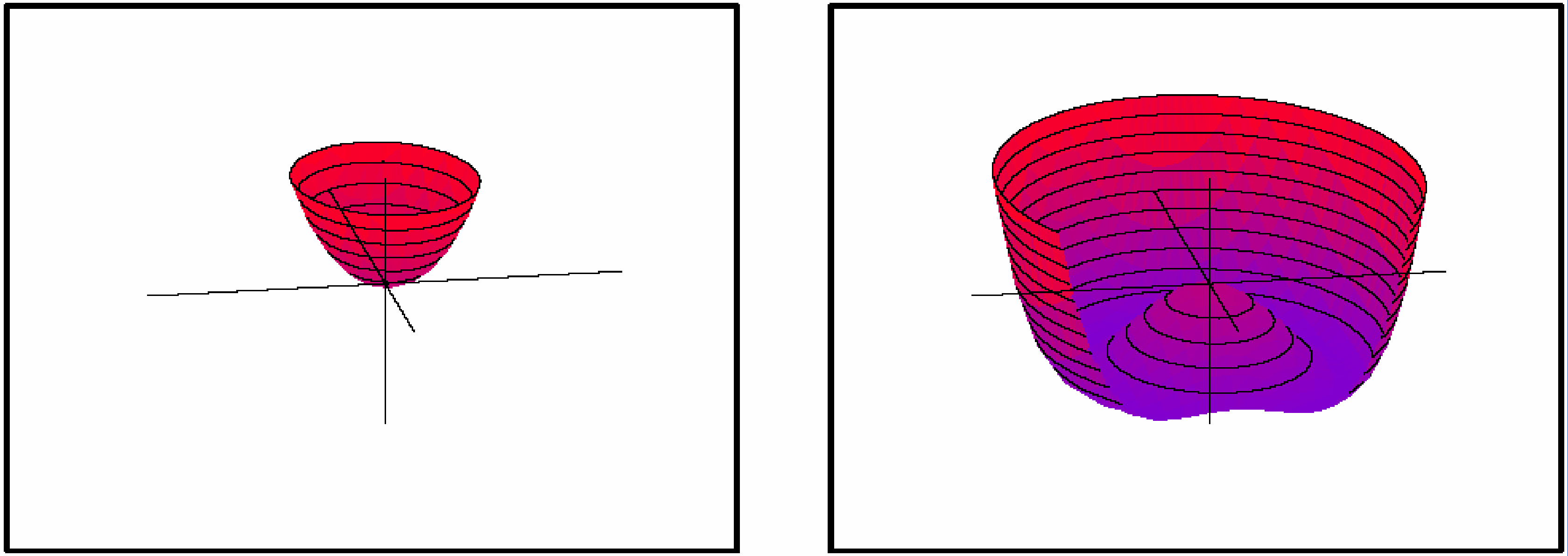




Higgs Mechanism

Potential for complex Higgs field Φ ("borrowed" from superconductivity, (Ginzburg, Landau)):
$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

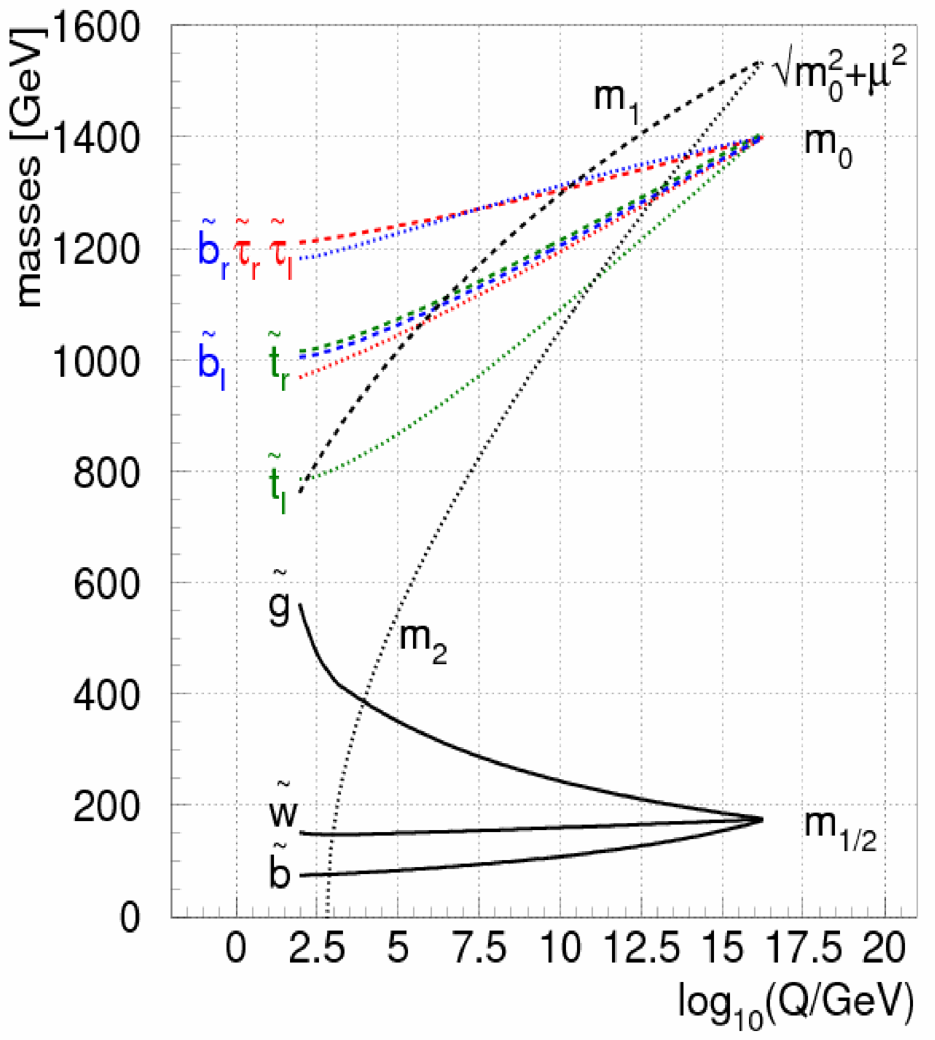
$\mu^2 > 0$: $\mu^2 < 0$



Groundstate has $|\Phi| = \sqrt{-\mu^2/(2\lambda)} \neq 0$ for $\mu^2 < 0$

Particles interact with non-zero vacuum expectation value of Higgs field (v.e.v): heavy mass means large (Yukawa) coupling constant between Higgs field and particle

Higgs mechanism in minimal mSUGRA model



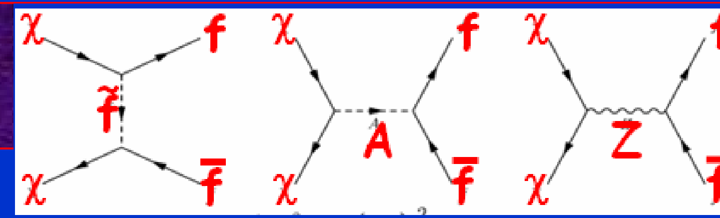
Common mass terms at GUT scales:
m_0 for scalars
$m_{1/2}$ for S=1/2 gauginos
m_1,m_2 for Higgses

Lightest supersymmetric particle = Neutralino (very similar to photino, which is S=1/2 photon)

M2 driven negative by loop diagrams, mainly from mtop
It becomes negative at electroweak Scale for 140<mtop<200 GeV.
BINGO, mtop AFTERWARDS observed to be 171 ± 3 GeV

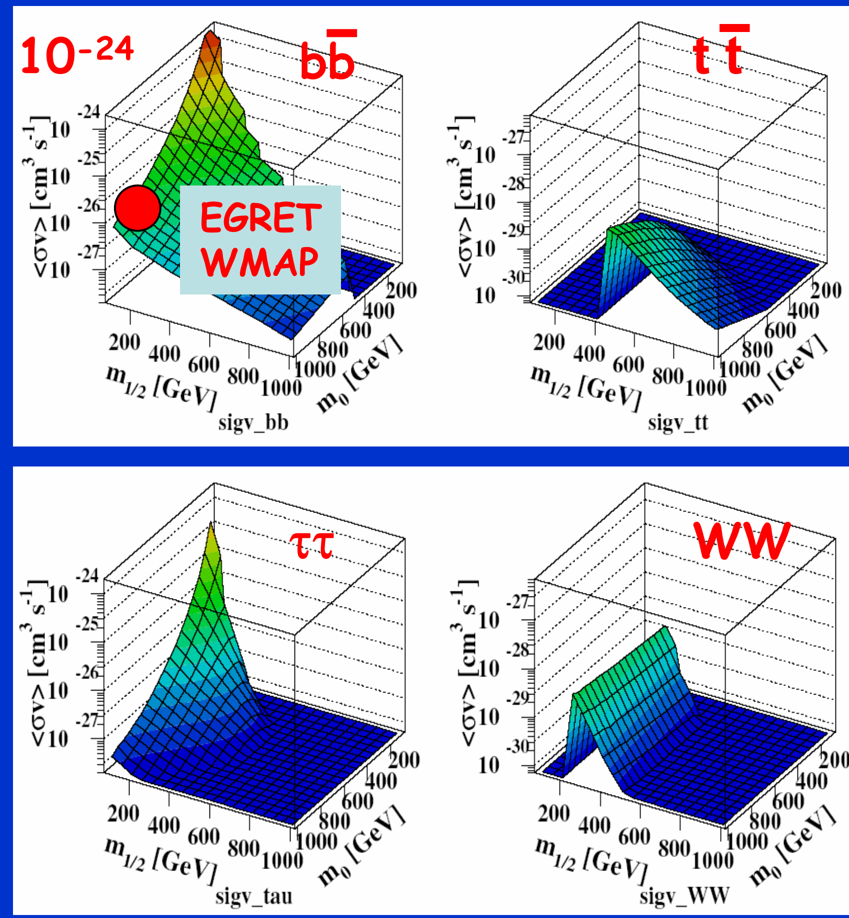
So SUSY gives you a relation between Mtop, MGUT and MZ and it works!

Annihilation cross sections in m_0-$m_{1/2}$ plane ($\mu > 0$, $A_0=0$)



Annihilation cross sections can be calculated,if masses are known (couplings as in SM). Assume not only gauge coupling unification at GUT scale, but also mass unification, i.e. all spin 0 (spin 1/2) particles have masses m0 (m1/2).

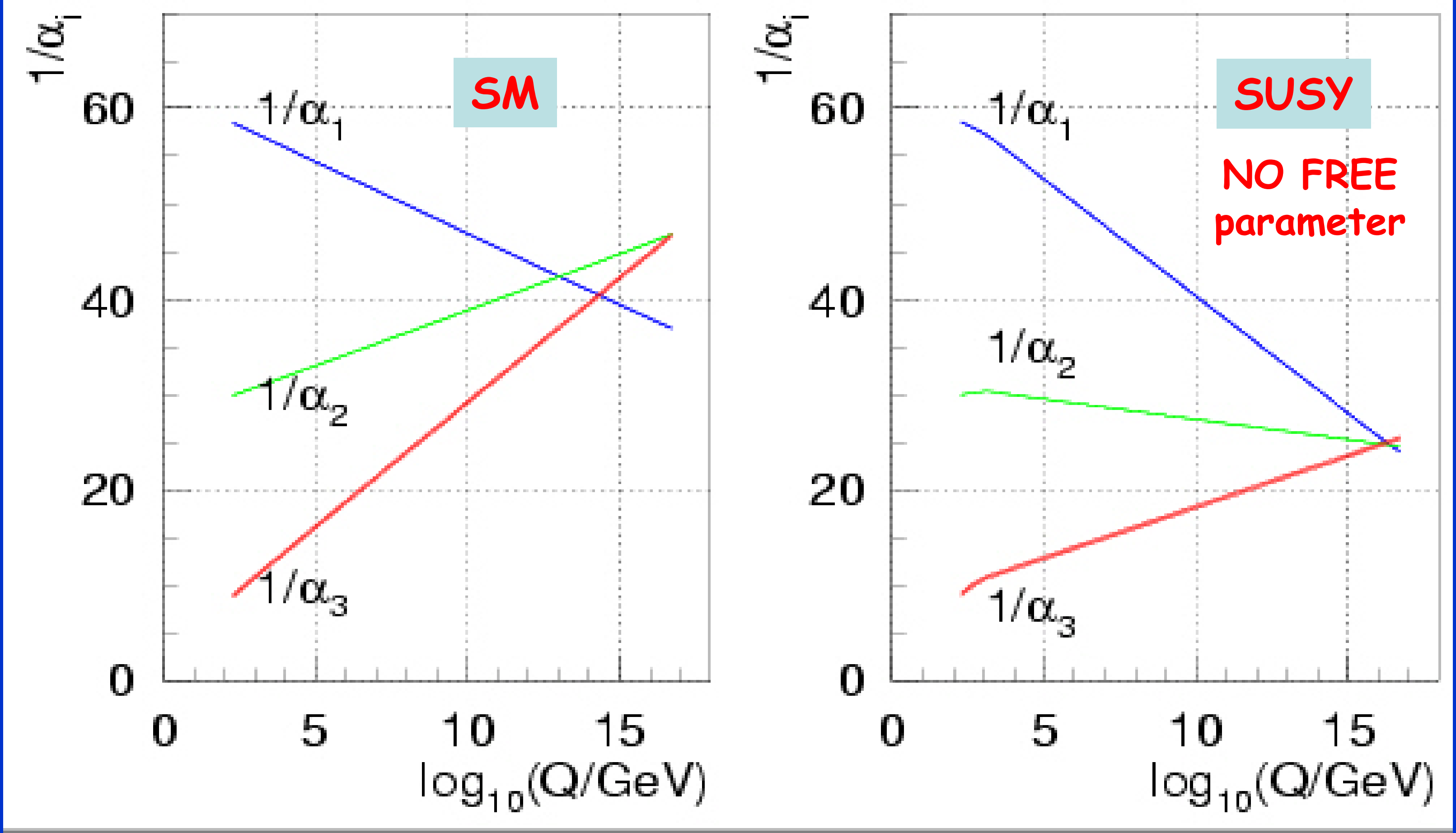
For WMAP x-section of $<\sigma v>\cong 2.10^{-26}$ cm^3/s one needs for small LSP mass (m1/2 ≈ 175 GeV) large values of (m0 ≈ 1-2 Tev) (and large tan β ≈ 50)



mSUGRA: common masses m0 and m1/2 for spin 0 and spin ½ particles

Gauge unification perfect with SUSY spectrum from EGRET

Update from Amaldi, dB, Fürstenau, PLB 260 1991

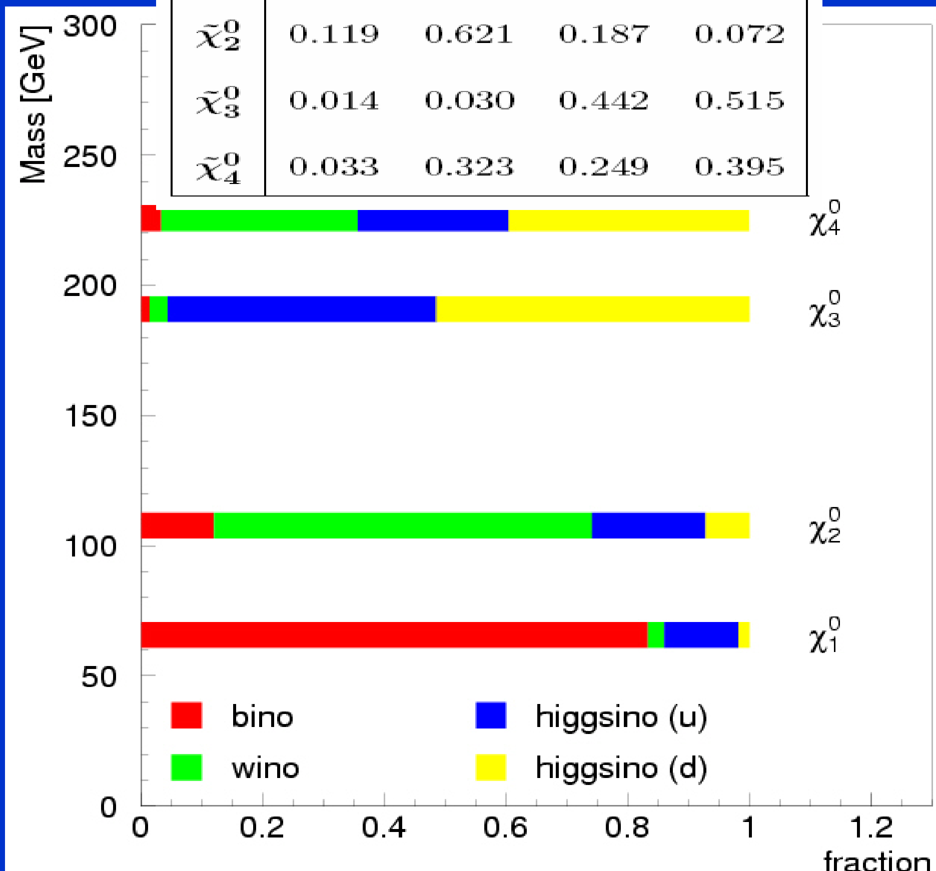


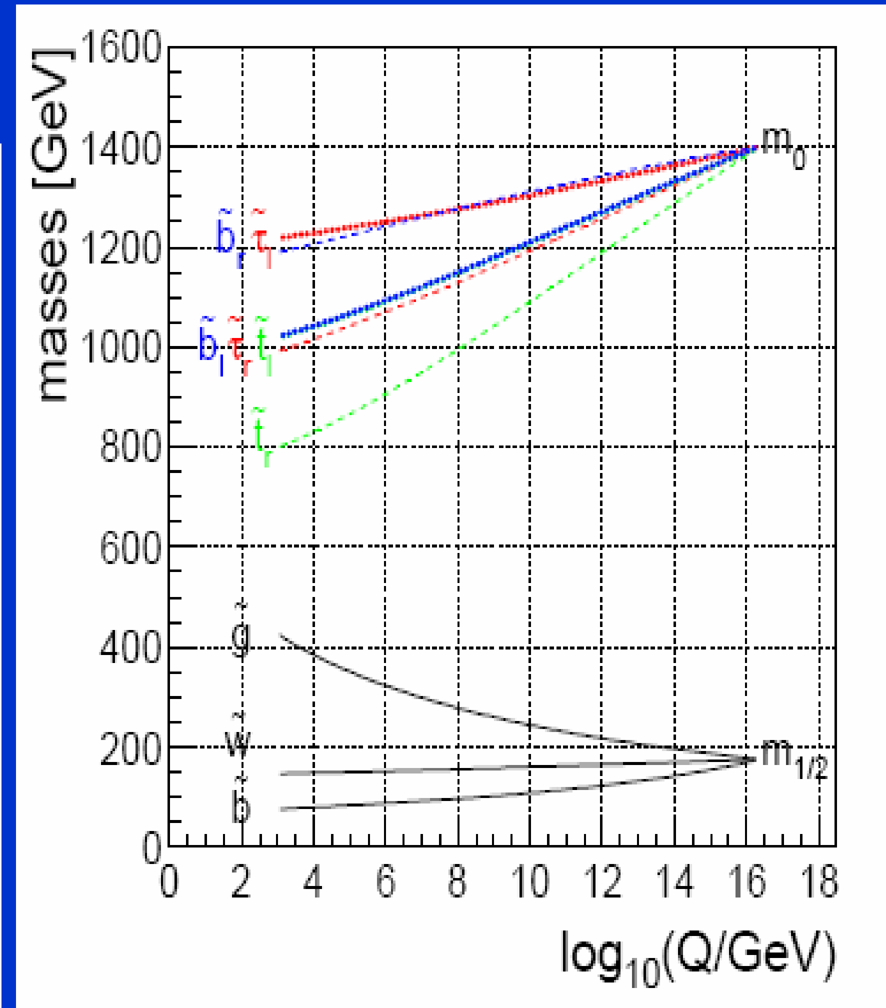
With SUSY spectrum from EGRET + WMAP data and start values of couplings from final LEP data perfect gauge coupling unification!

Also b->sγ and g-2 in agreement with SUSY spectrum from EGRET

SUSY Mass spectra in mSUGRA compatible with WMAP AND EGRET

	$\tilde{b}^0$	$\tilde{w}^0$	$\tilde{h}_1^0$	$\tilde{h}_2^0$
$\tilde{\chi}_1^0$	0.833	0.026	0.122	0.018
$\tilde{\chi}_2^0$	0.119	0.621	0.187	0.072
$\tilde{\chi}_3^0$	0.014	0.030	0.442	0.515
$\tilde{\chi}_4^0$	0.033	0.323	0.249	0.395



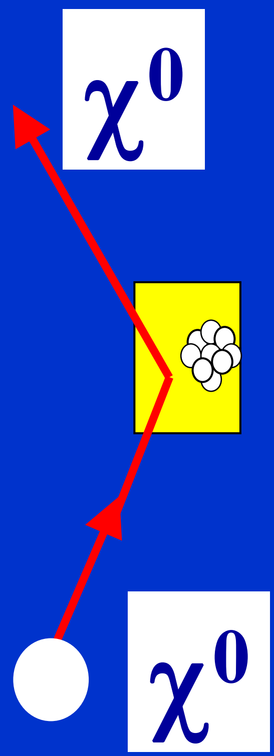


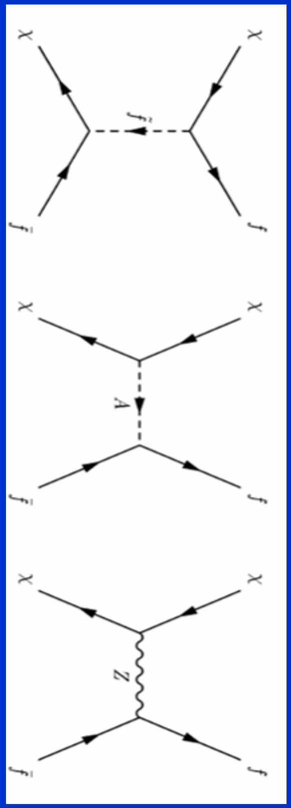
LSP largely Bino ⇒ DM may be supersymmetric partner of CMB

Charginos, neutralinos and gluinos light

Direct Detection of WIMPs

WIMPs elastically scatter off nuclei => nuclear recoils
Measure recoil energy spectrum in target



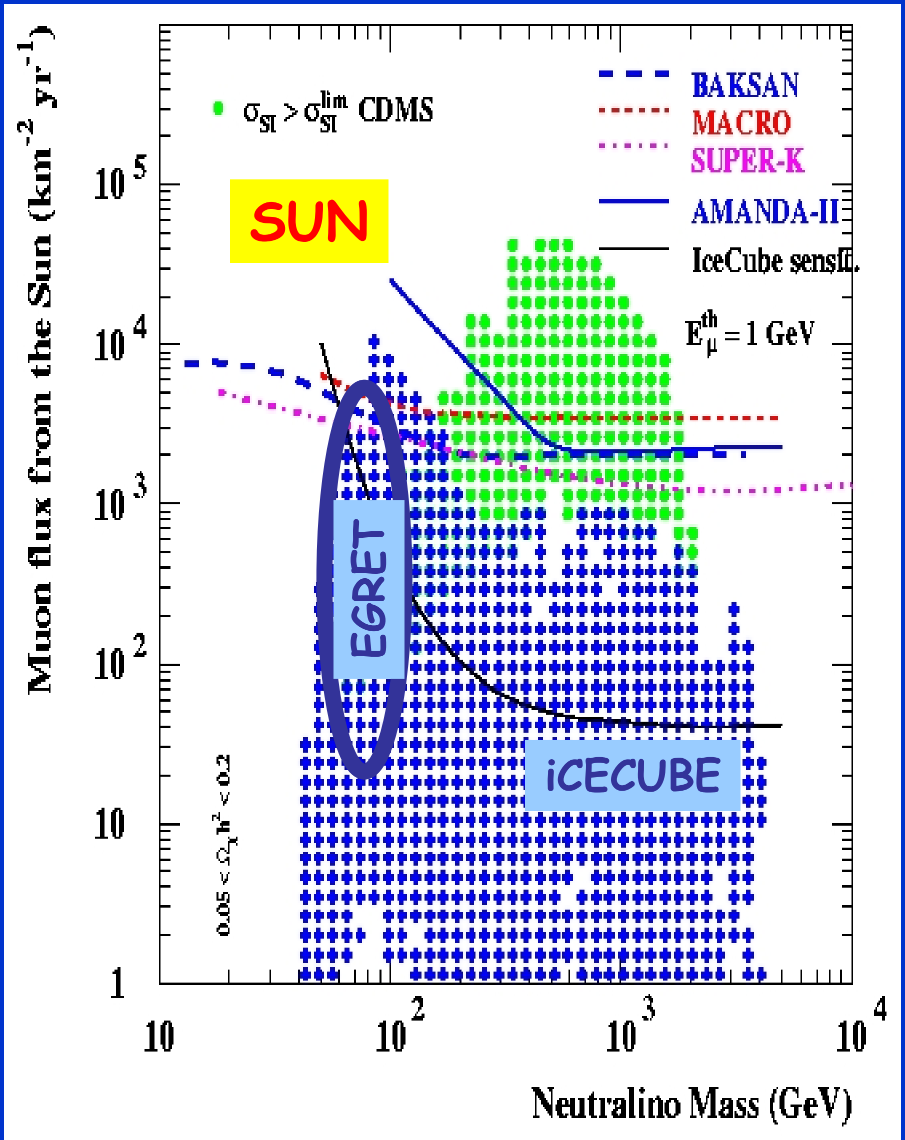


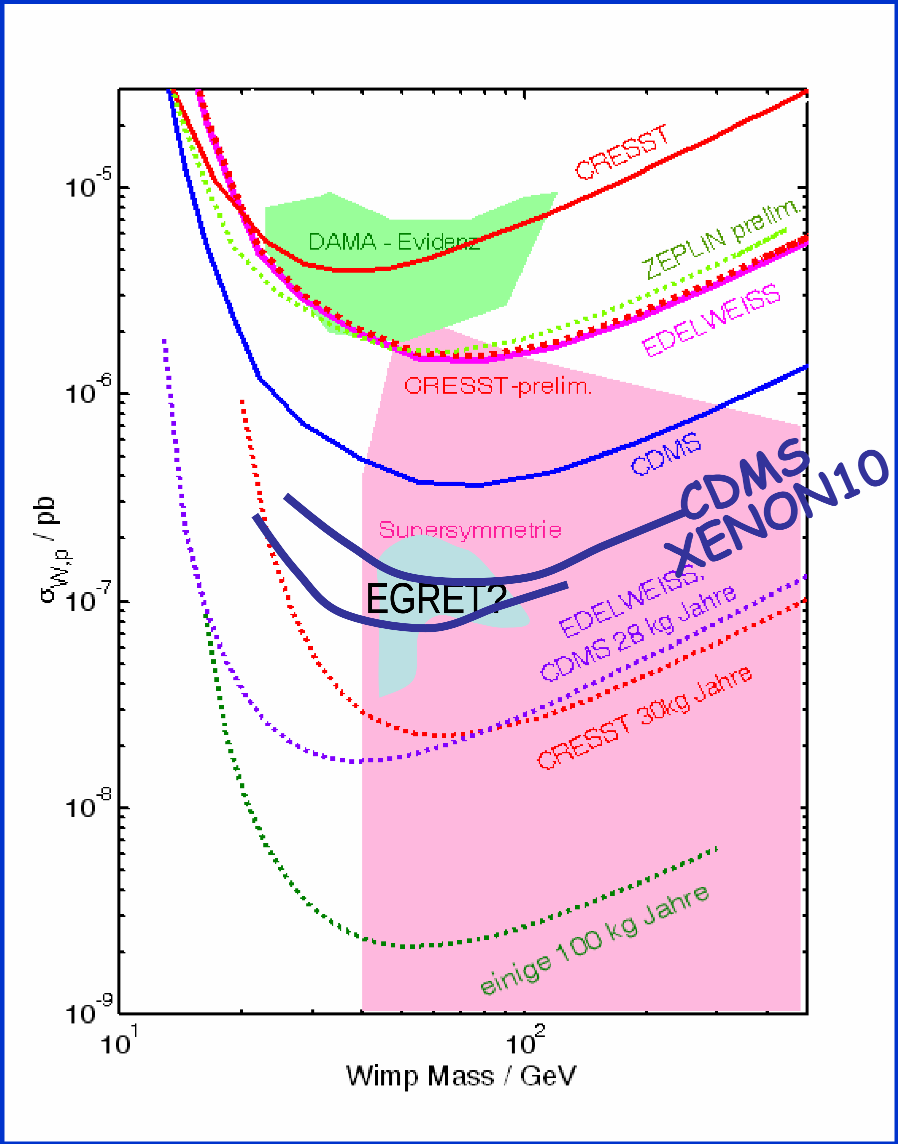
Spin dependent and indep.

Spin independent ∝
Number of nuclei²
(coherent scattering on all nuclei!)

Spin dependent

Solar neutrinos and direct DM detection





Summary on WIMP searches

Indirect detection: (SPACE EXPERIMENTS)

intriguing hint for signals from DMA for
60 GeV WIMP from gamma rays

Direct detection: (UNDERGROUND OBSERVATORIES)
expected to observe signal in near future
IF we are not in VOID of clumpy DM halo

Direct production:(ACCELERATORS (LHC 2008-2018)):
cannot produce WIMPs directly
(too small cross section), BUT IF WIMPs
are Lightest Supersymmetric Particle (LSP) THEN
WIMPs observable in DECAY of SUSY particles

IF EVERY METHOD measures SAME WIMP mass, then PERFECT.
In this case Dark Matter is the supersymmetric partner of the CMB!