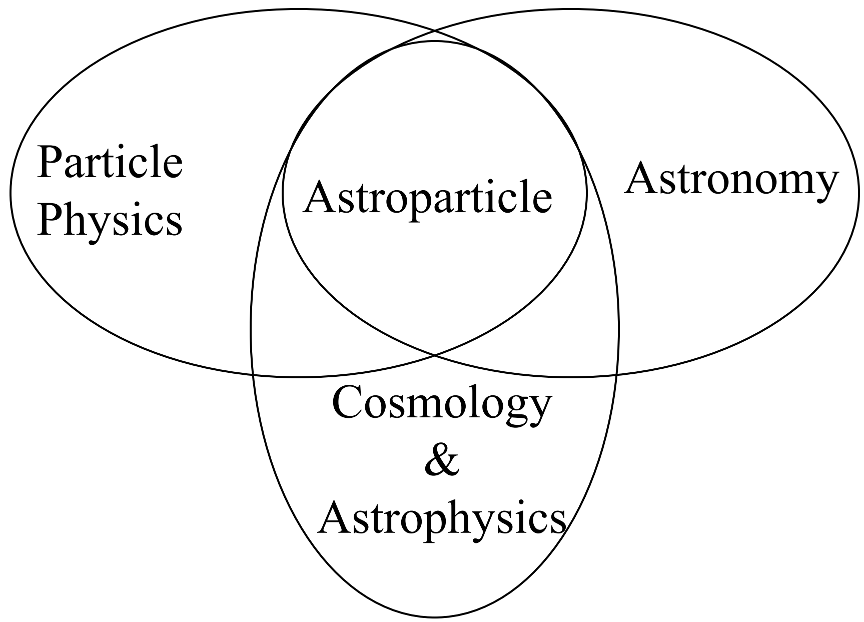
Experimental Astroparticle Physics
(a short introduction)

Alessandro De Angelis
University of Udine & INFN Trieste

29 January 2004

Lectures 1 & 2

What is Astroparticle Physics (Particle Astrophysics?)



1) Use techniques from Particle Physics to advance Astronomy

2) Use input from Particle Physics to explain our Universe, and particles from outer space to advance Particle Physics

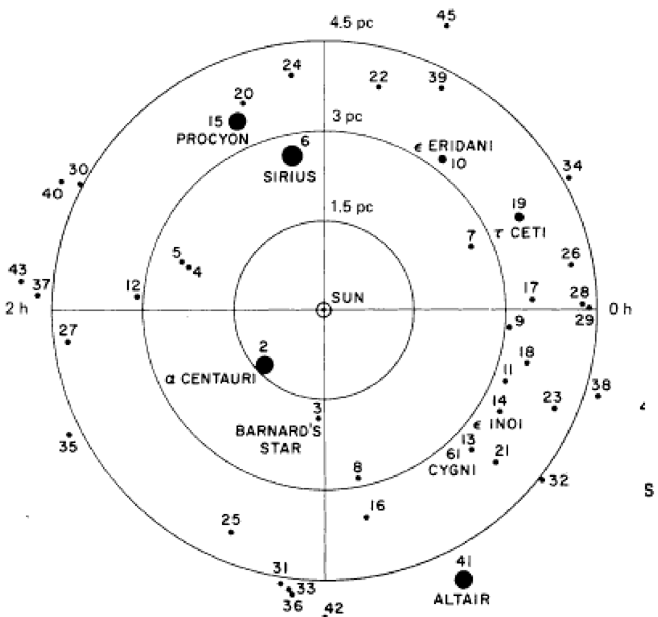
In this lecture I'll concentrate on the 2nd topic

I

A quick look to our Universe

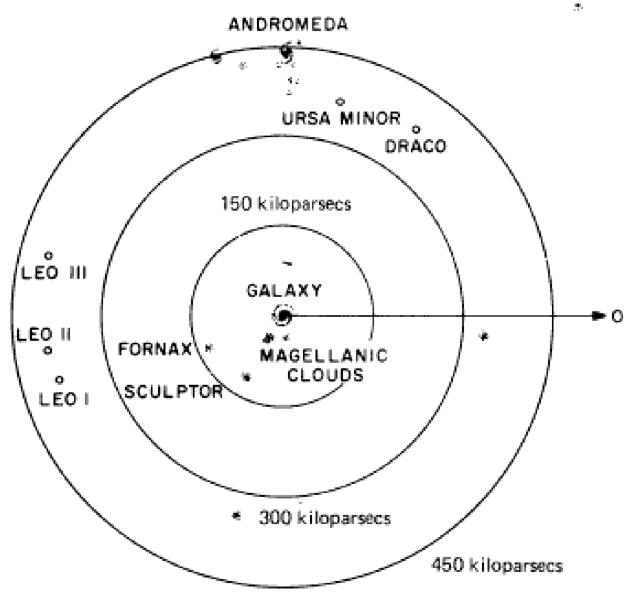
Astronomy Scales

Nearest Stars



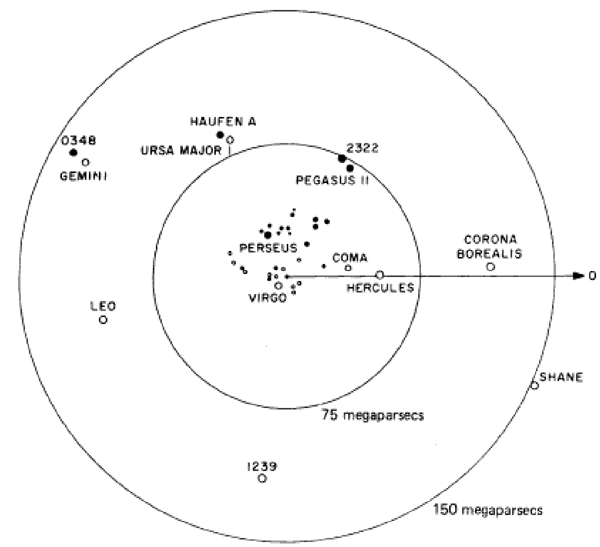
4.5 pc

Nearest Galaxies



450 kpc

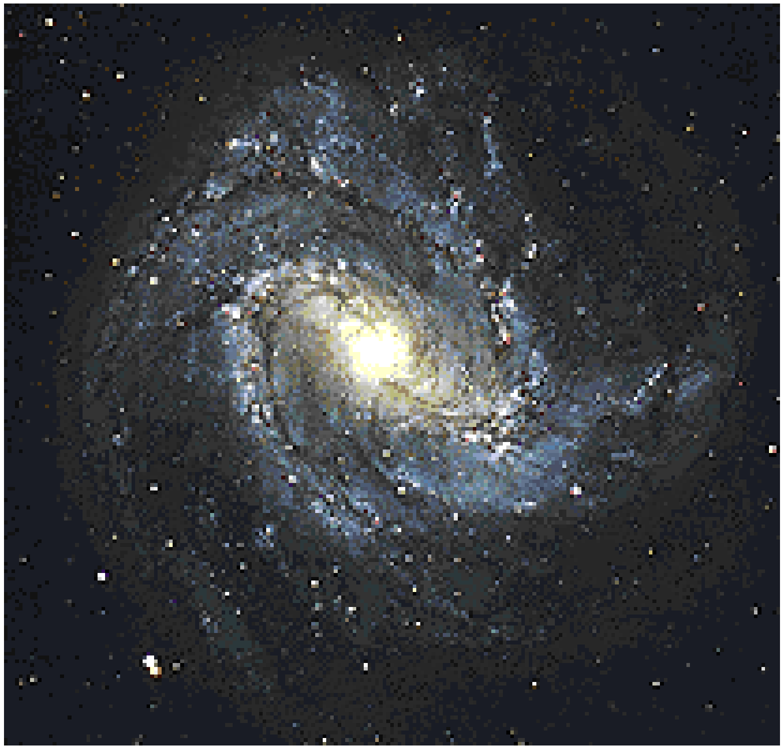
Nearest Galaxy Clusters

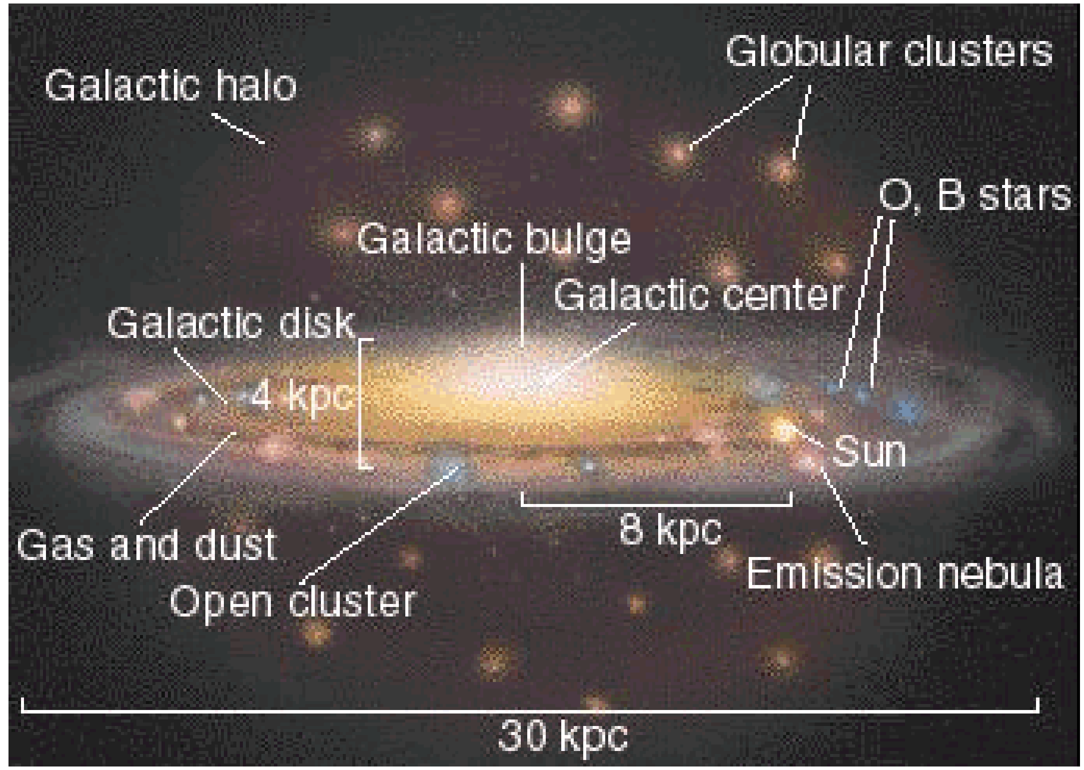


150 Mpc

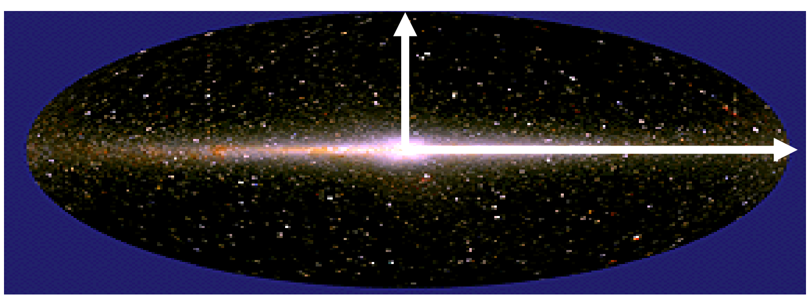
1 pc ~ 3.3 ly

Our Galaxy: The Milky Way



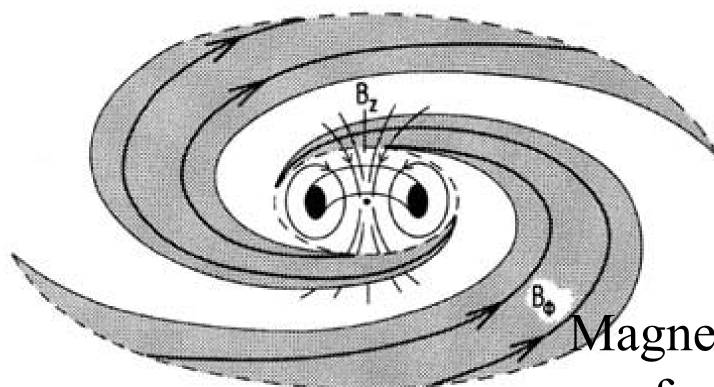


+90°



+180°

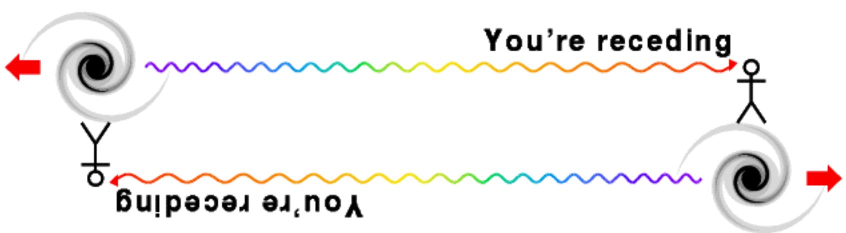
–90°



Magnetic field
~ few μG

What do we know about our Universe ?

- Many things, including the facts that…
  - Particles are coming on Earth at energies 10^8 times larger than we are able to produce…
  - The Universe expands (Hubble ~1920): galaxies are getting far with a simple relationship between distance & recession speed



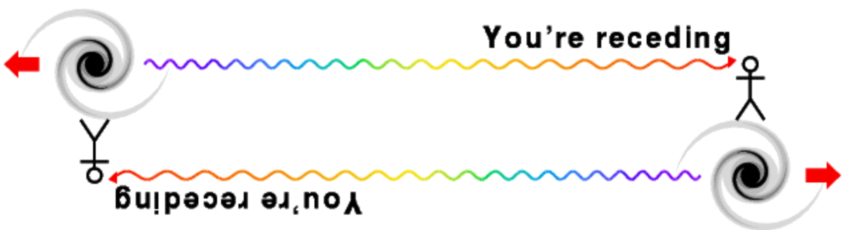
Hubble's constant (km/s/Mpc)

$$V = H_0 r$$

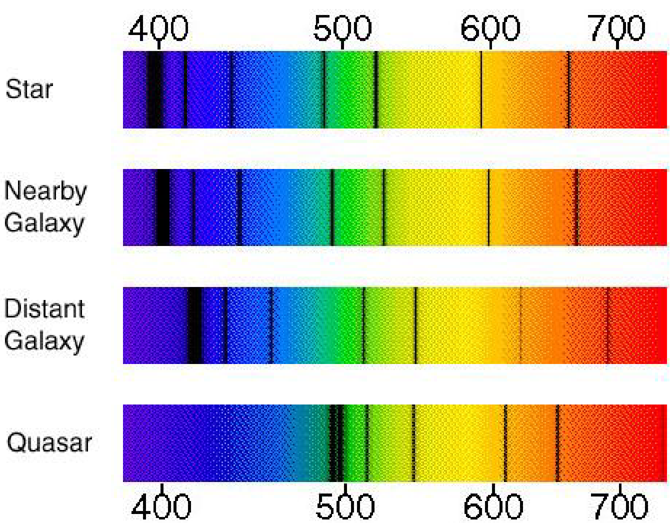
recession speed (km/s)

distance (Mpc)

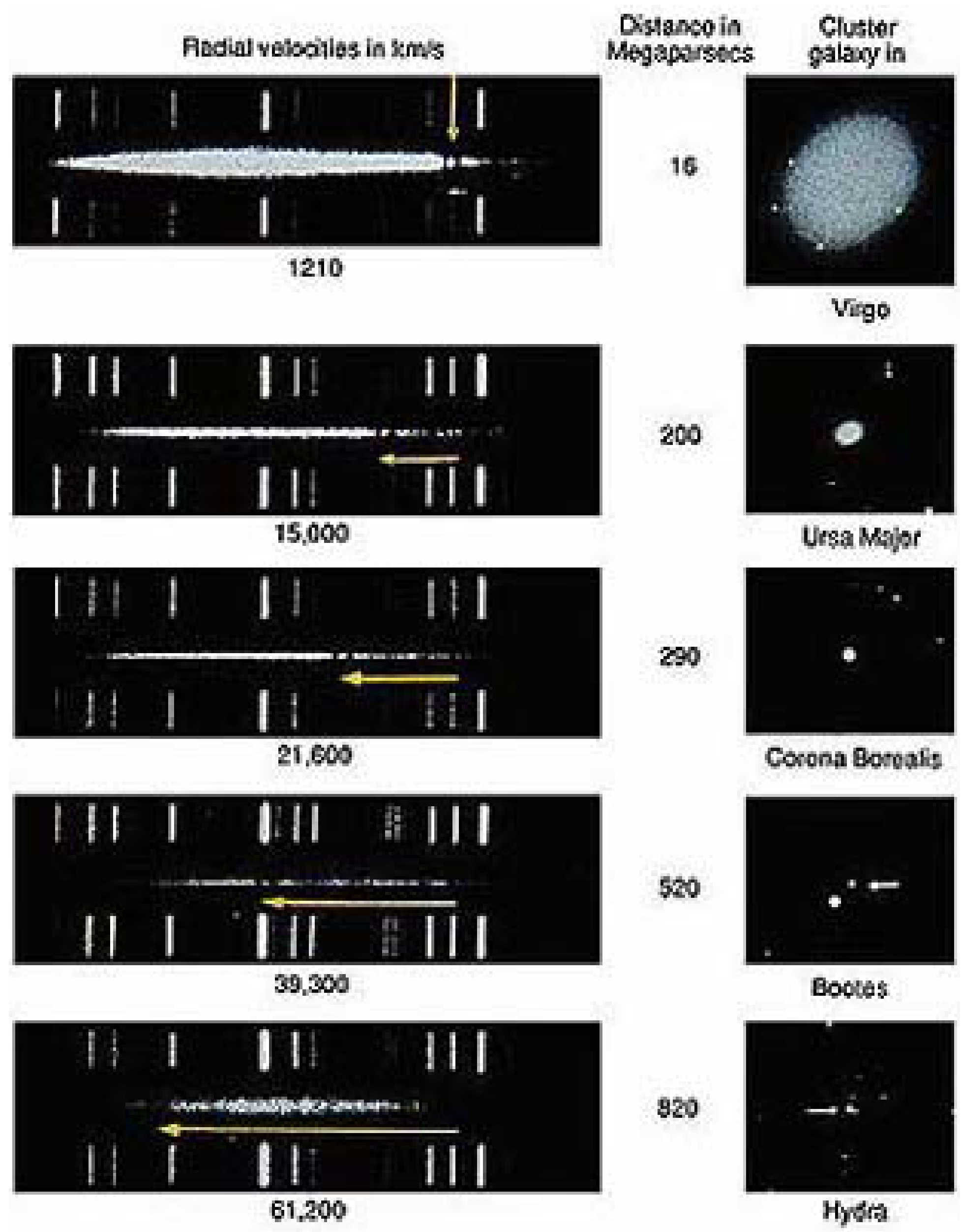
Redshift



You're receding
You're receding



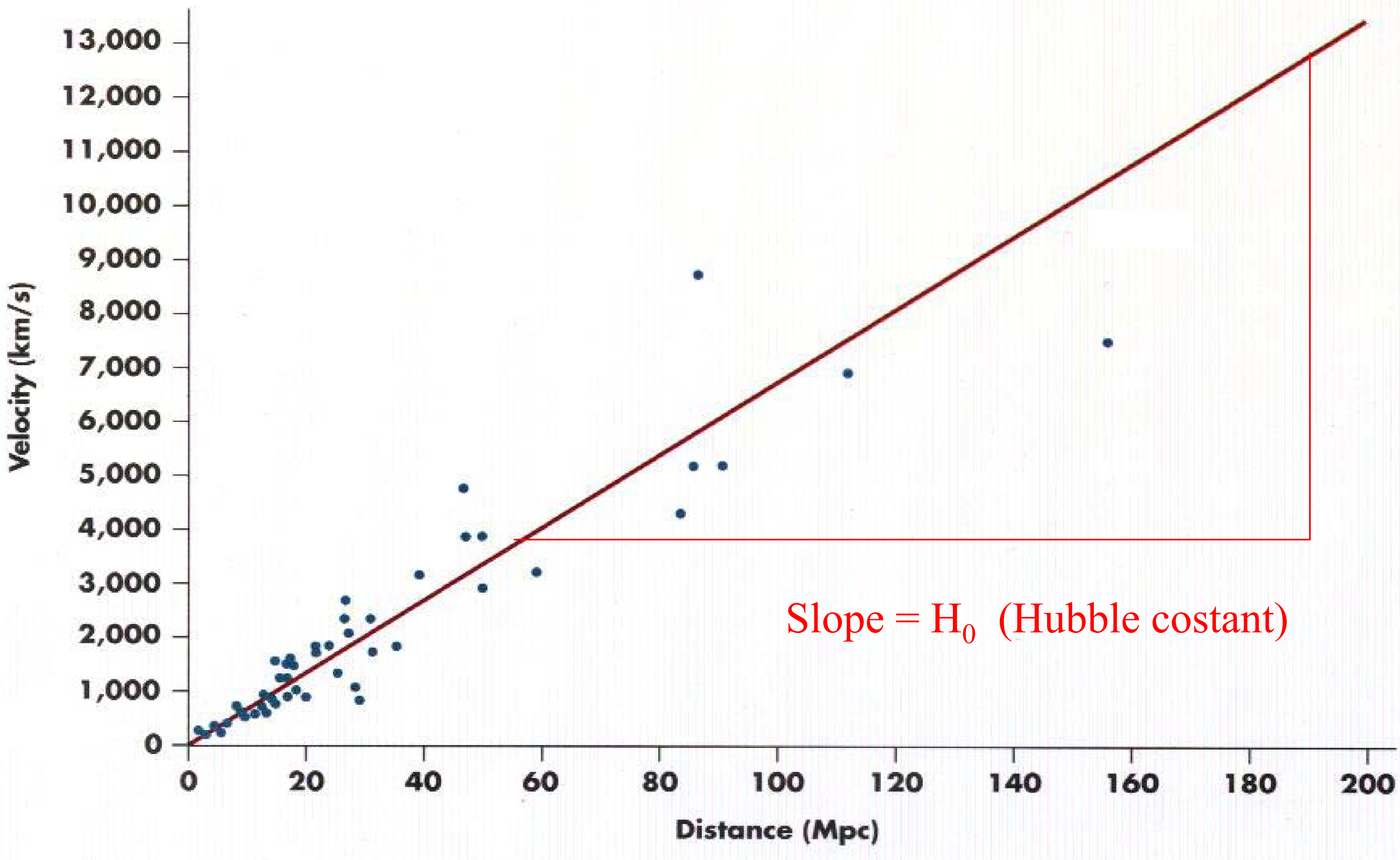
400
500
600
700
Star
Nearby Galaxy
Distant Galaxy
Quasar
400
500
600
700



Radial velocities in km/s
Distance in Megaparsecs
Cluster galaxy in
1210
16
Virgo
15,000
200
Ursa Major
21,600
290
Corona Borealis
39,300
520
Bootes
61,200
820
Hydra

Hubble's law

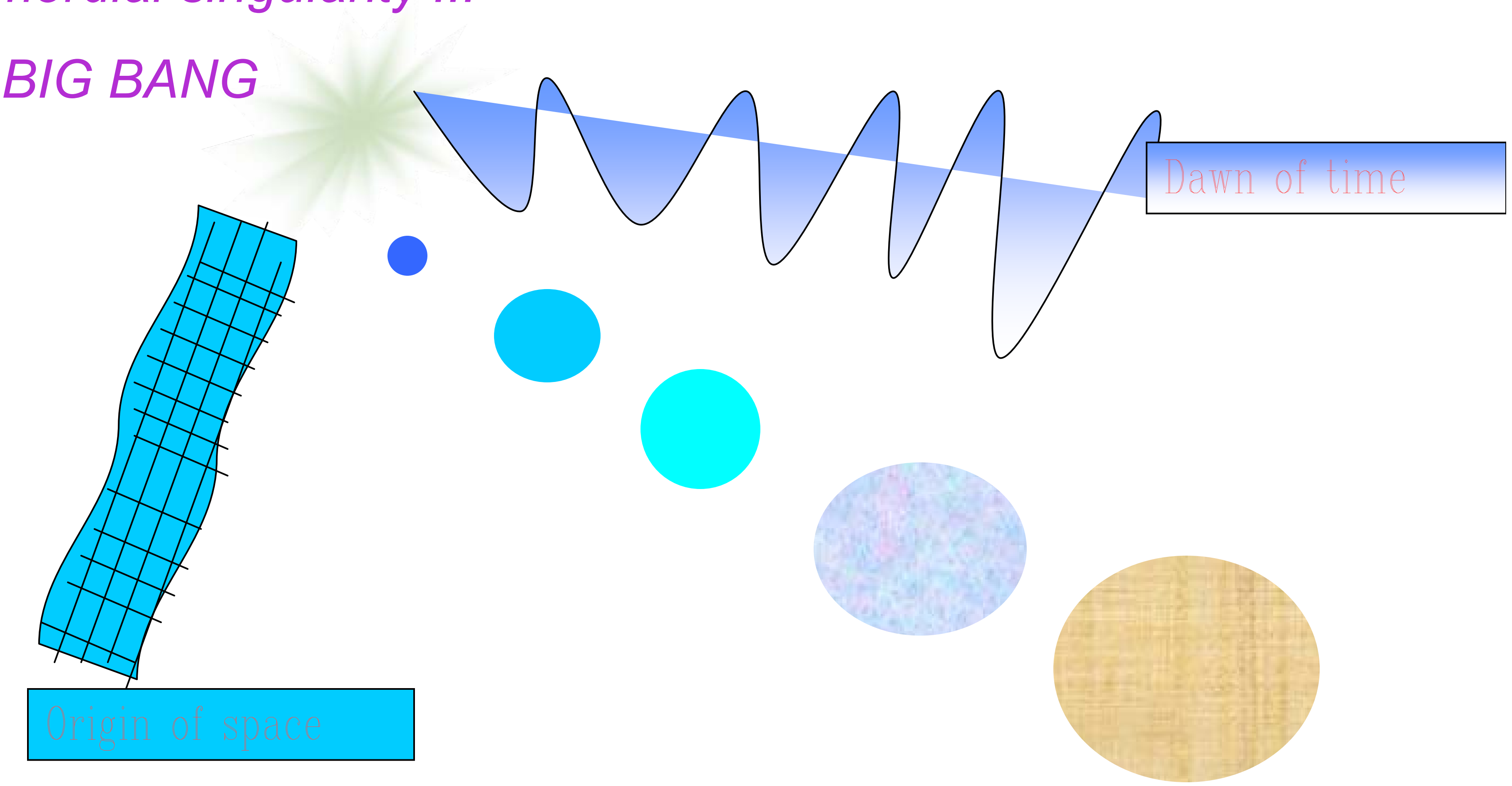
Today: H_0 = 71 ± 4 (km/s) / Mpc



Once upon a time...
our Universe was smaller

Primordial singularity !!!

=> BIG BANG



How far in time ?

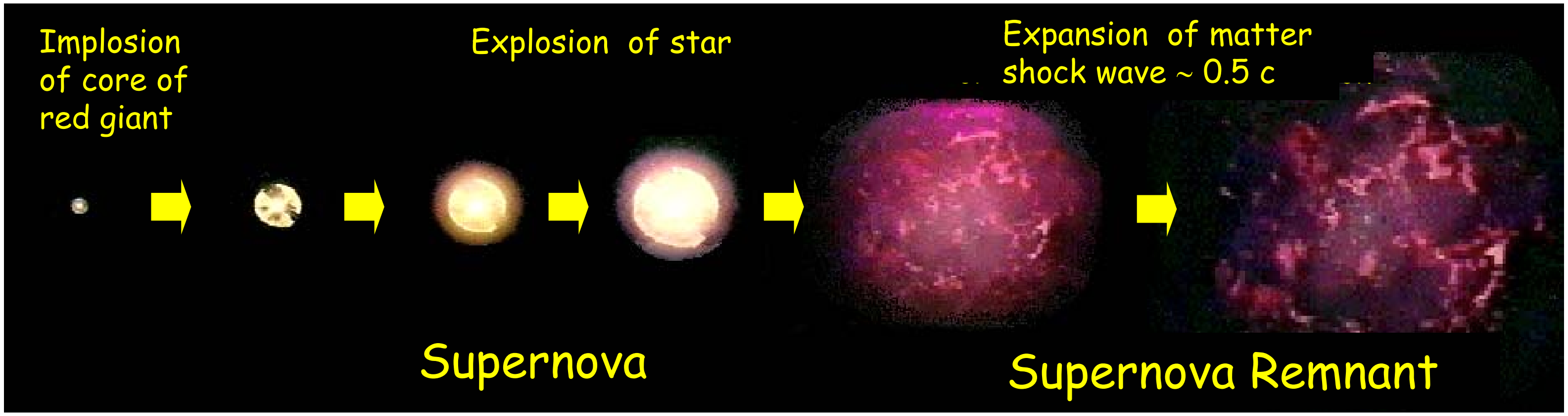
- Extrapolating backwards the present expansion speed towards the big bang

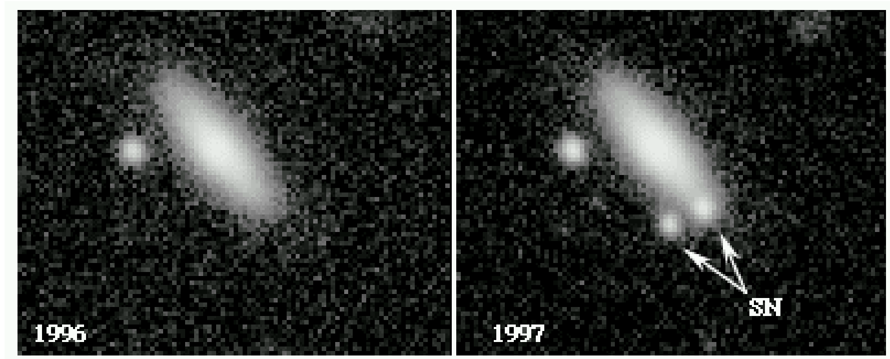
$$T \approx 1/H_0 \sim 14 \text{ billion years}$$

(note that the present best estimate, with a lot of complicated physics inside, is $T = 13.7 \pm 0.2$ Gyr)

- Consistent with the age of the oldest stars

Hubble law in 2003: supernovae





SNIa occurs at Chandra mass, 1.4 $M_{sun} \Rightarrow$ 'Standard Candle'

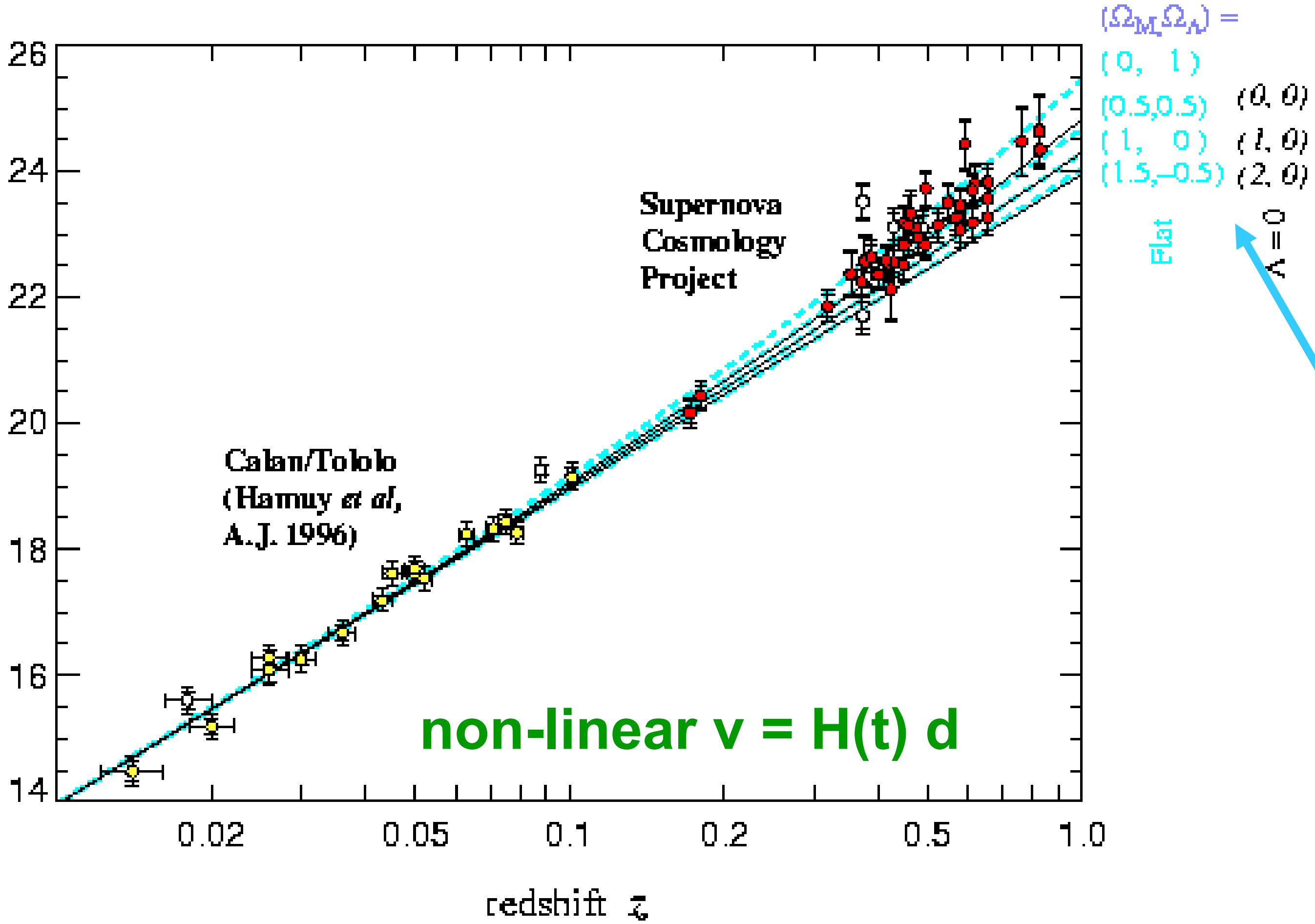
measure brightness $\rightarrow$ distance: $B = L / 4\pi d^2$

measure host galaxy redshift $\rightarrow$ get recession velocity

test Hubble's Law: $v = H\,d$, at large distances

Expansion with Supernovae Ia

effective magnitude → brightness → distance



non-linear v = H(t) d

Acceleration of universe expansion

redshift → recession velocity

Deviation from Hubble's law
The expansion accelerates
$\Omega_\Lambda \sim 0.7$

Time & temperature (=energy)

- Once upon a time, our Universe was hotter
  - Expansion requires work (and this is the most adiabatic expansion one can imagine, so the work comes from internal energy)

$$T \sim \frac{15}{\sqrt{t}} 10^9 K$$

Decoupling

Time

$\gamma \leftrightarrow$ particles+antiparticles

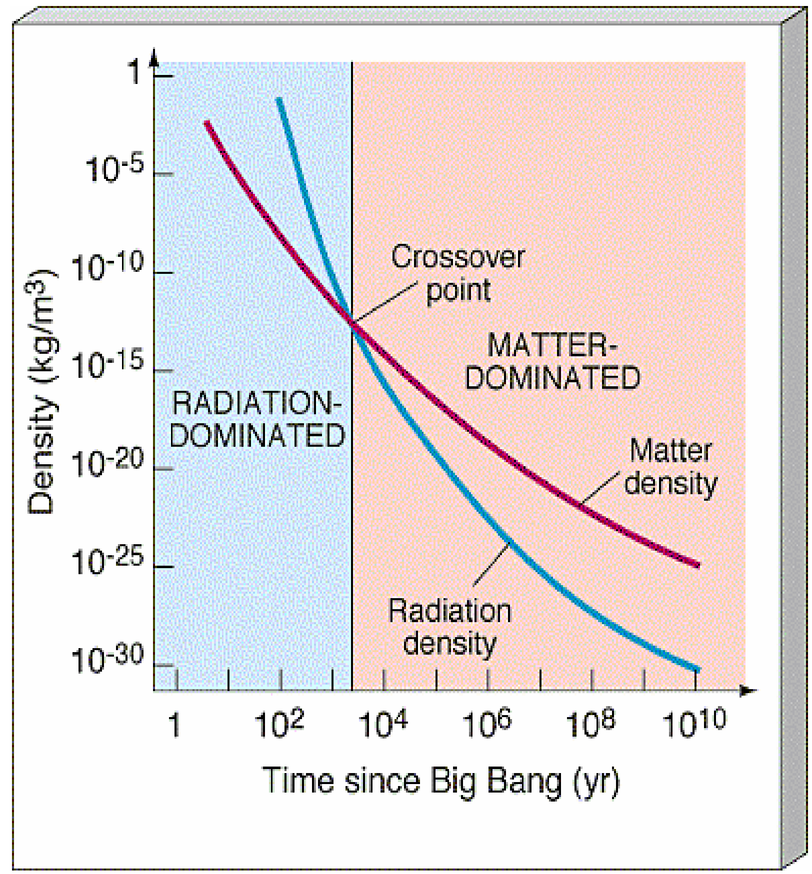
$\gamma \leftrightarrow$ proton-antiproton

$\gamma \leftrightarrow$ electron-positron

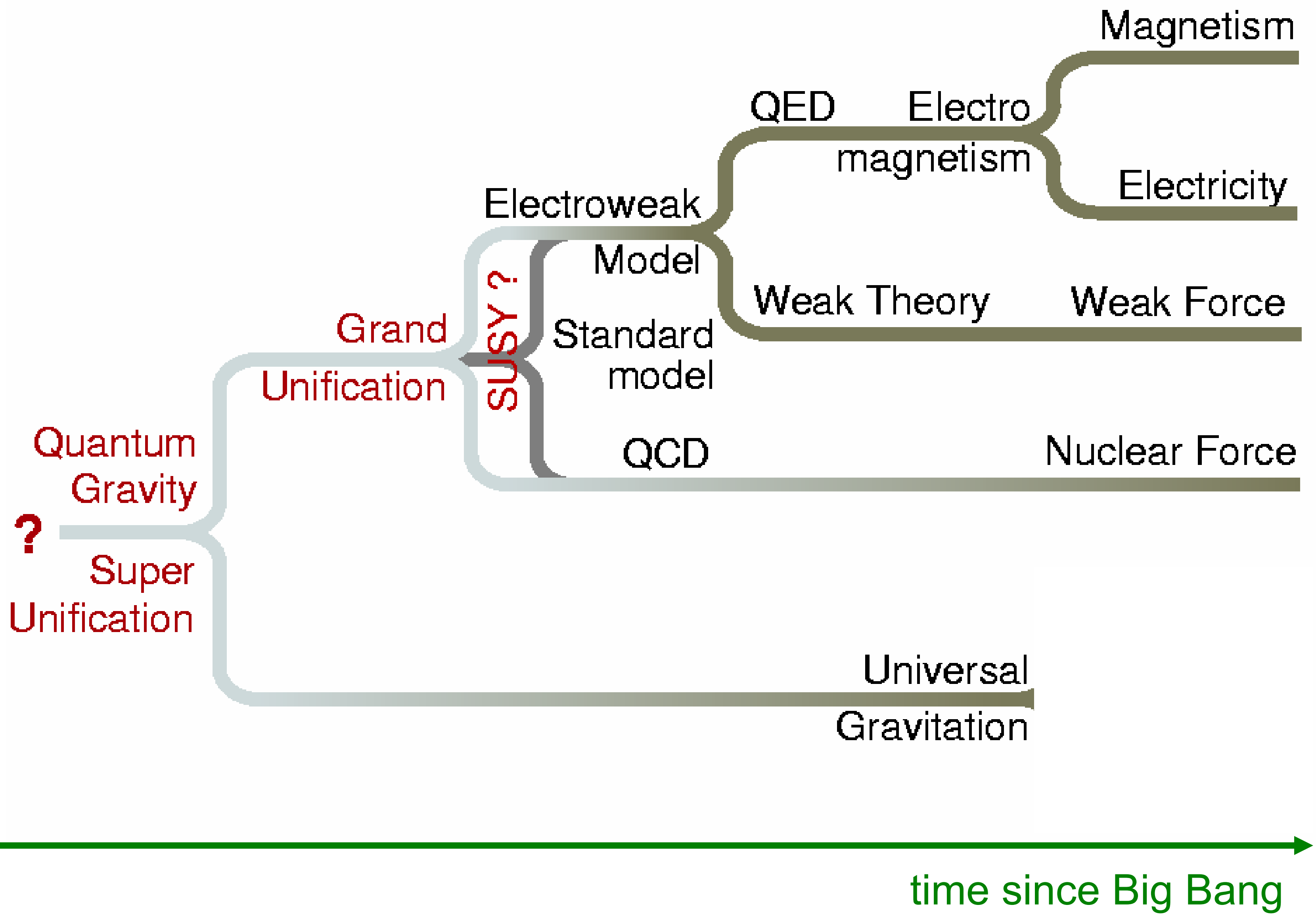
(…)

then matter became stable

Two epochs

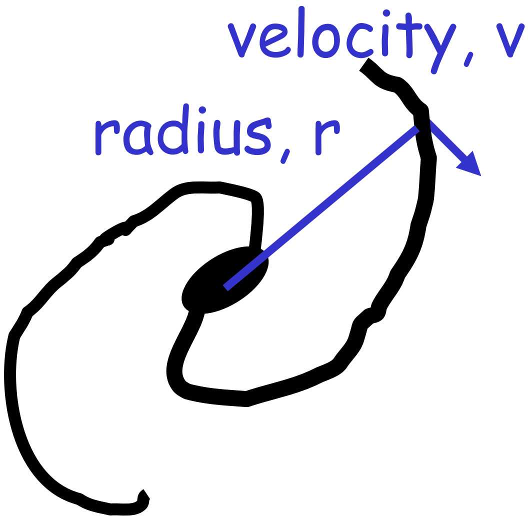


Particle Physics after Big Bang



THE QUEST FOR HIGHER ENERGIES IS ALSO A TIME TRAVEL

The Universe today: what we see is not everything

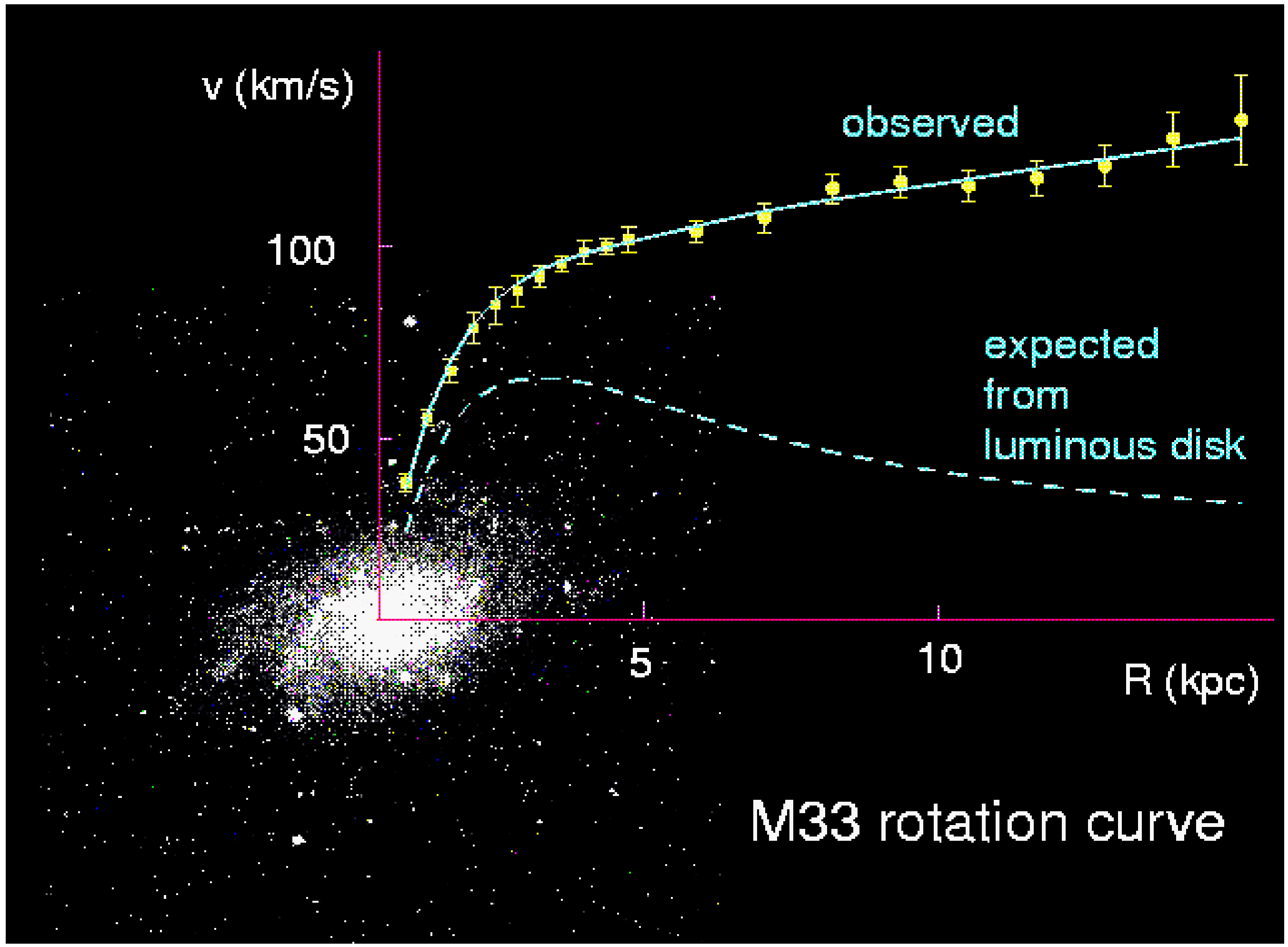


Gravity:

$G\,M(r) / r^2 = v^2 / r$

enclosed mass:

$M(r) = v^2\, r / G$



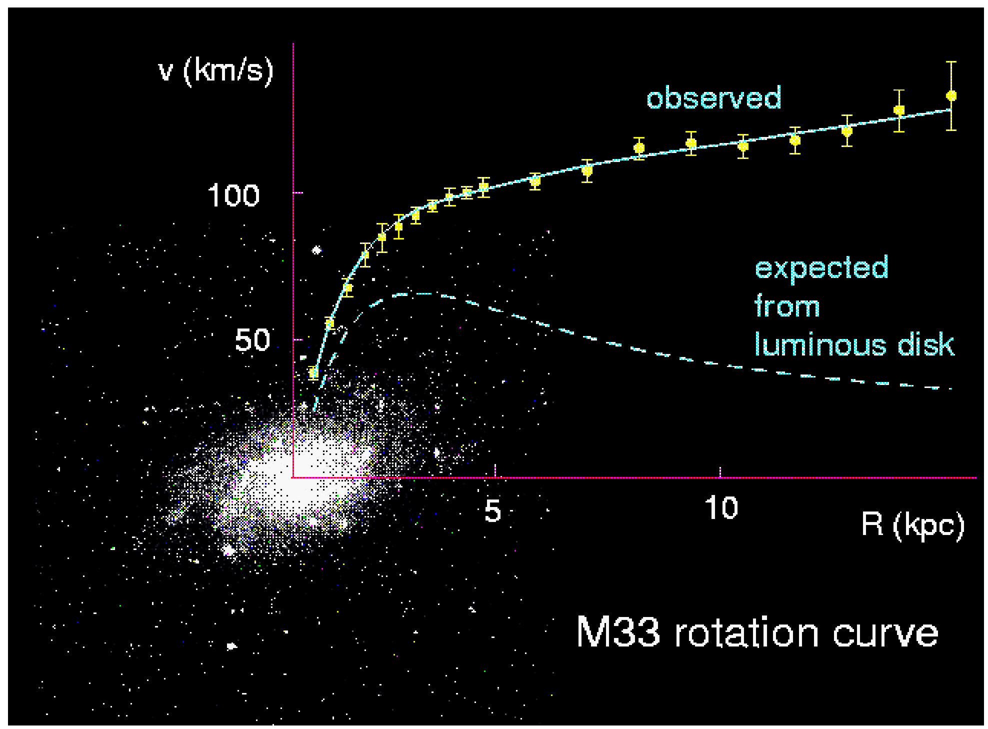
Luminous stars only small fraction of mass of galaxy

II

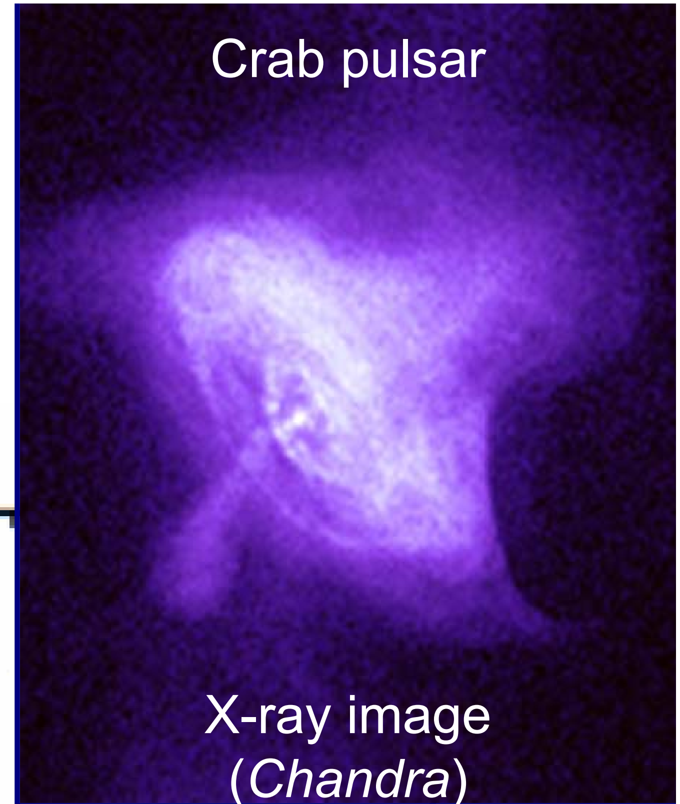
Dark matter searches

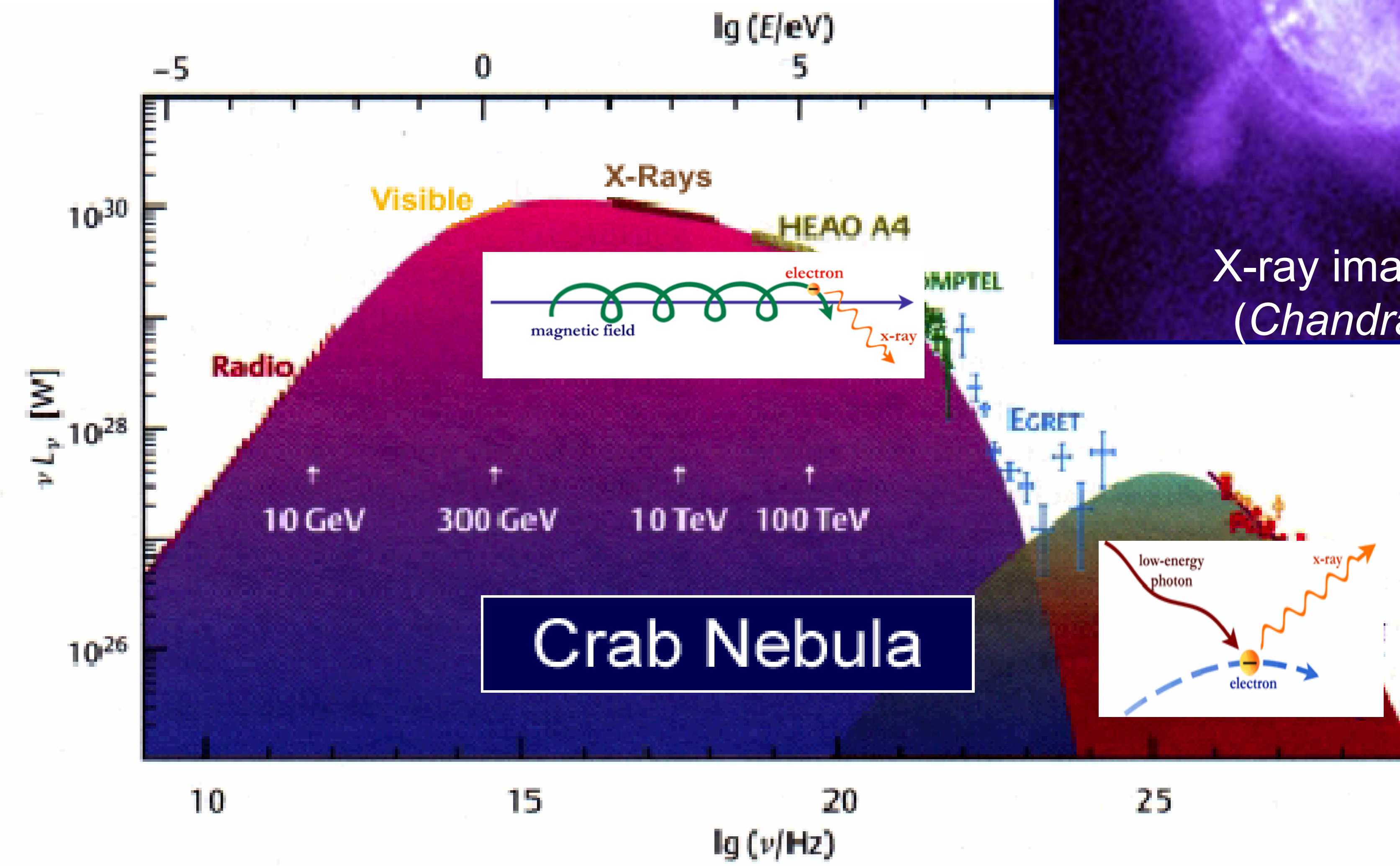
Dark matter searches

- Astronomy Dark Matter Candidates
  - Invisible macroscopic objects
    - Non-luminous objects
    - Black Holes
- Particle Dark Matter Candidates
  - Neutrinos
  - WIMPs



Many sources radiate over a wide range of wavelengths

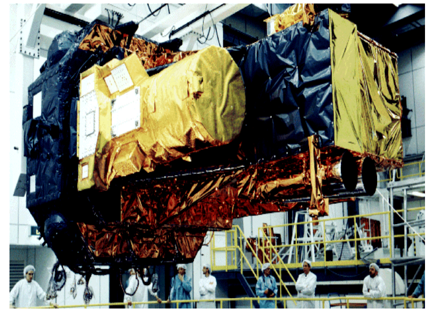




Multi Messenger Astronomy

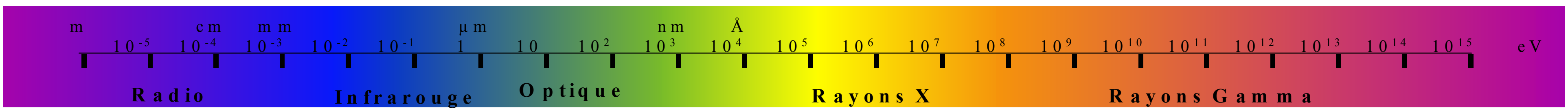
Radio Telescope
(Bonn)

Optical Telescope
(Palomar)

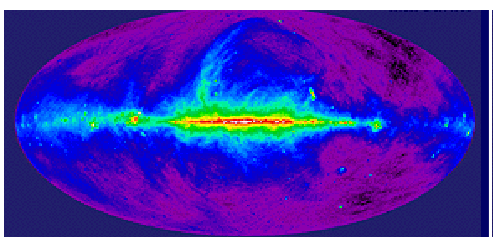


X - ray Satellite
(INTEGRAL/ESA)

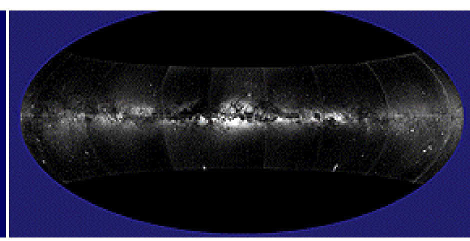
γ - ray Telescope
(CAT Pyrenees)



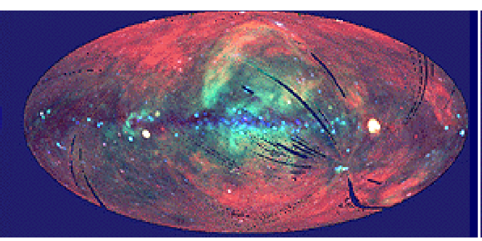
View of sky in Galactic Coordinates in four different photon wavelengths



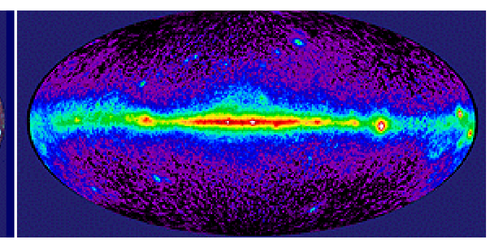
Radio



Visible light



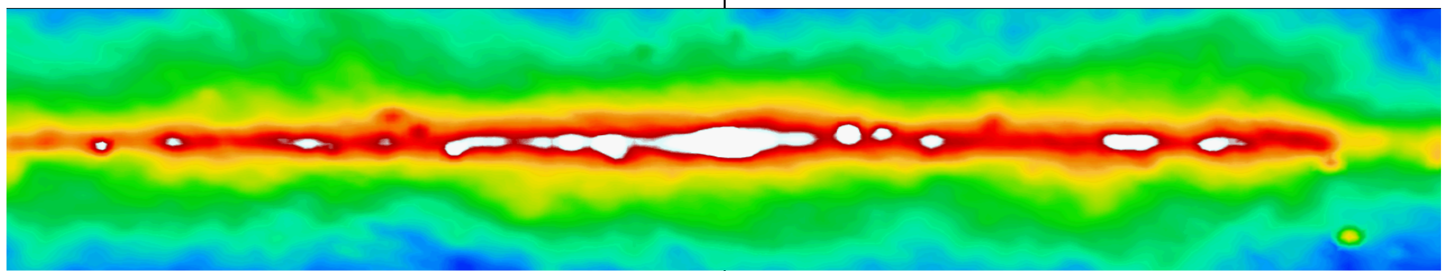
X - rays



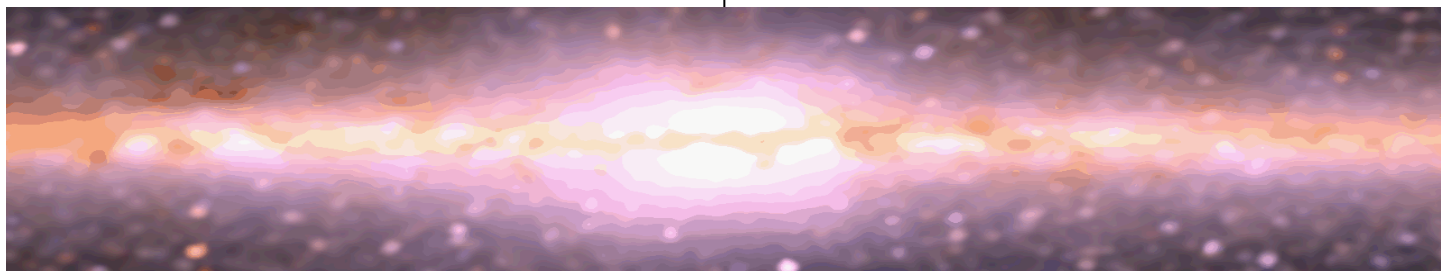
γ rays

Centre of Galaxy in Different Photon Wavelengths

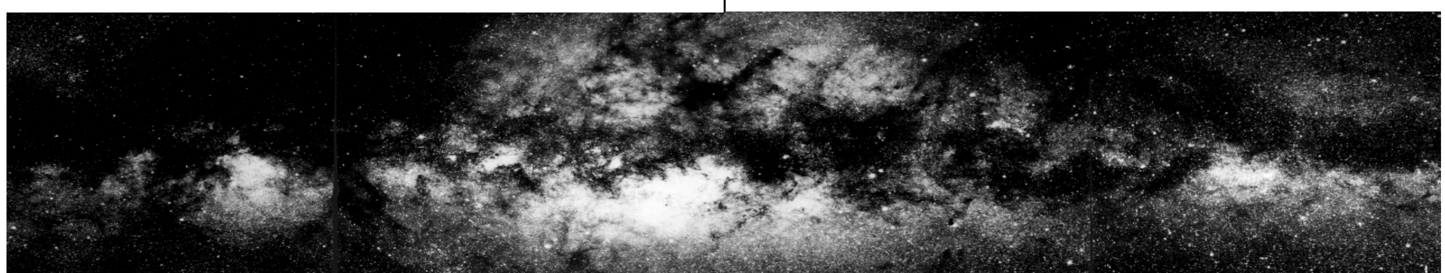
Radio 408 Mhz



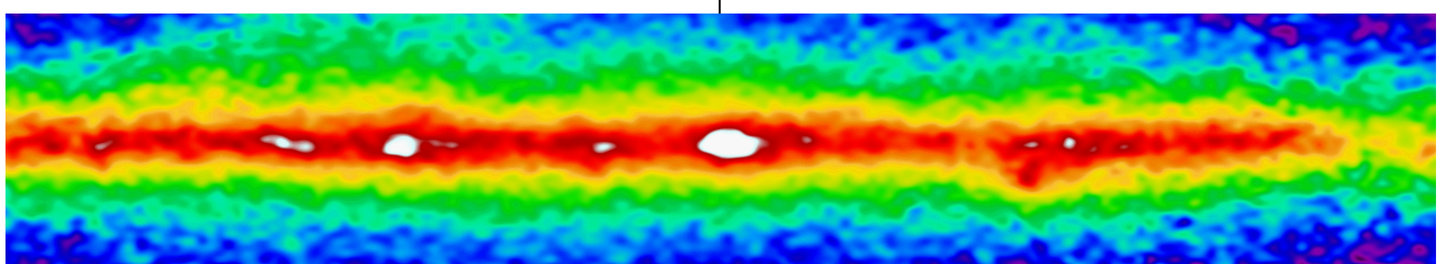
Infrared 1-3 μm



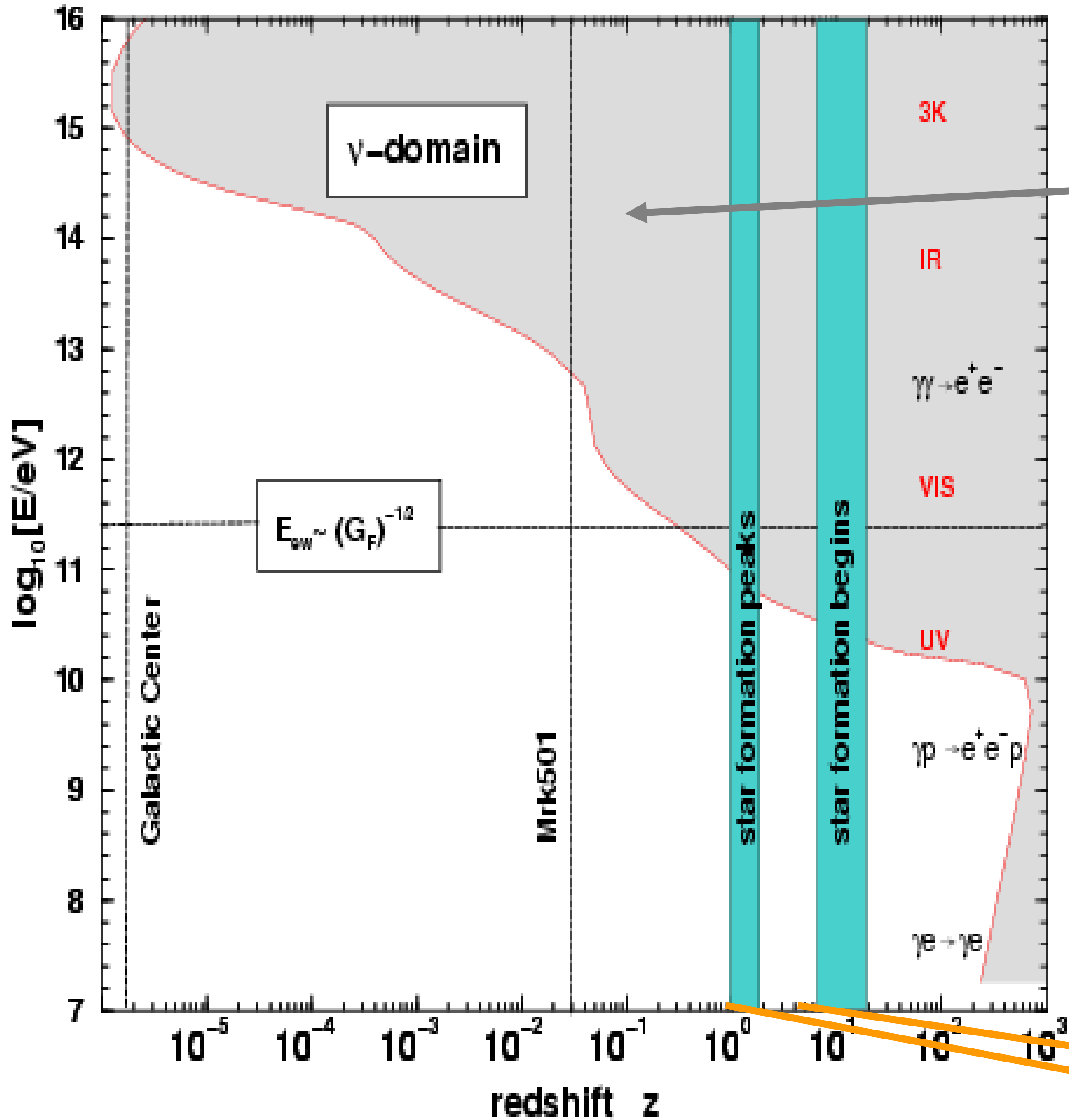
Visible Light



Gamma Rays

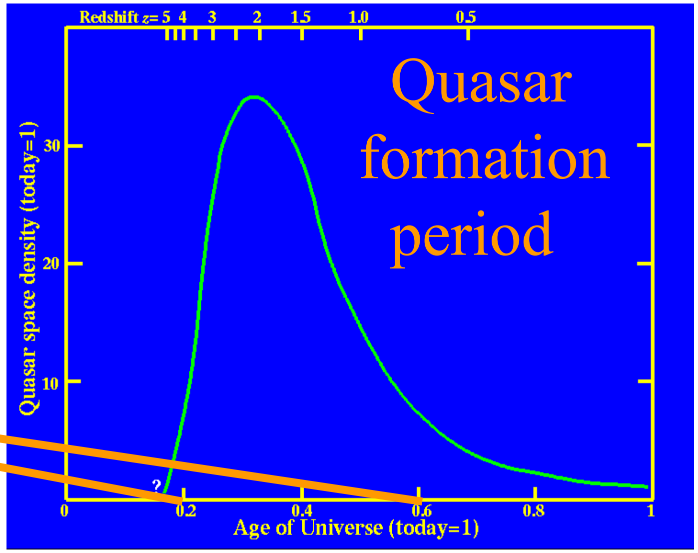


Multi-Messengers to see Whole Universe

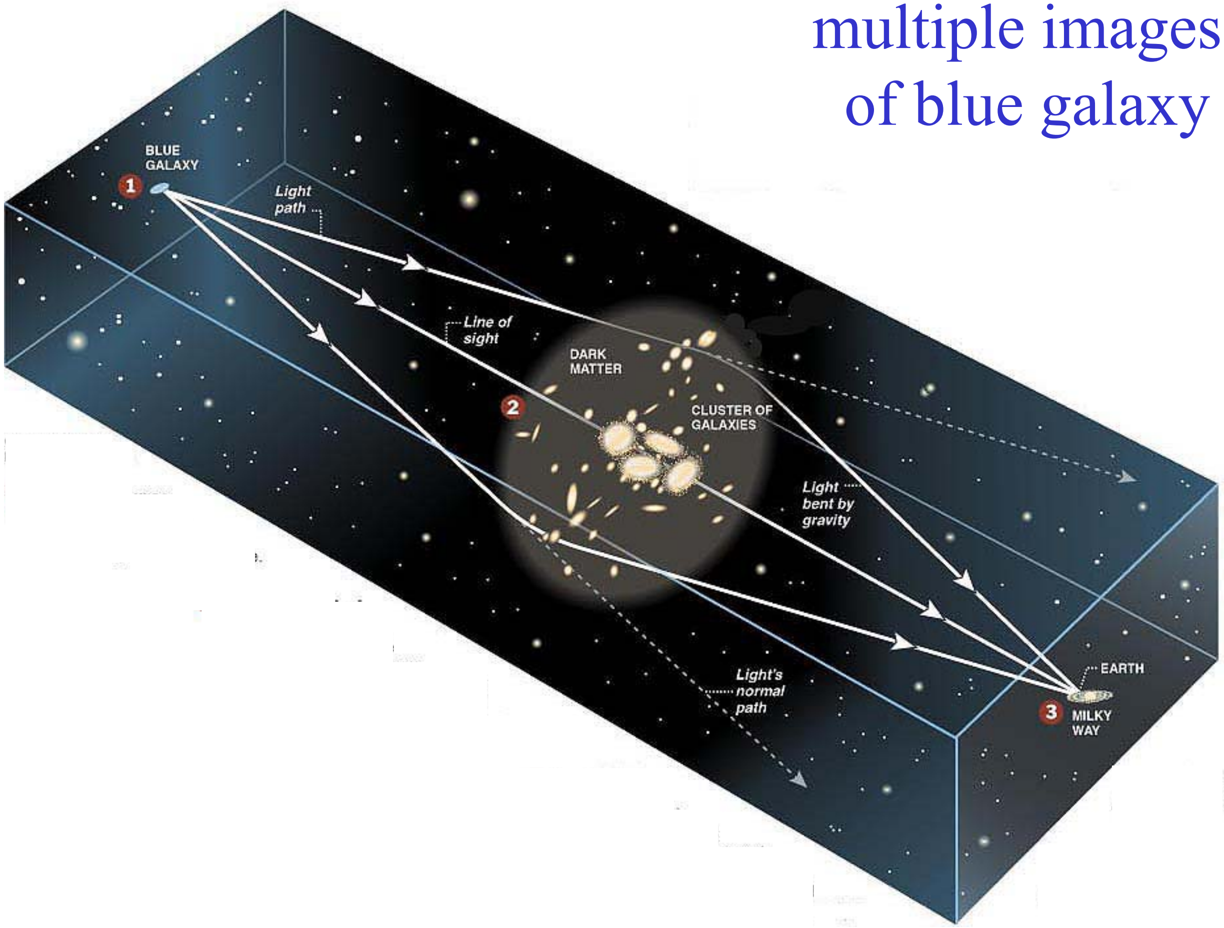


Distant universe
invisible in
high energy photons

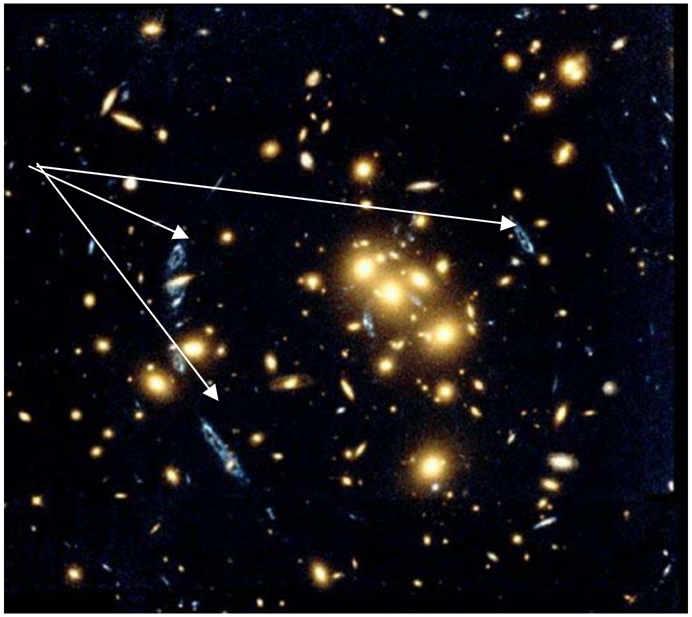
need neutrinos



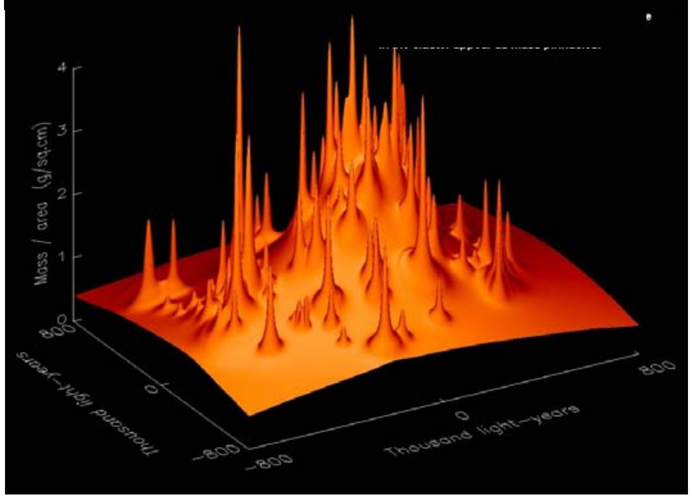
Gravitational Lensing by Dark Matter



Hubble Space Telescope
multiple images
of blue galaxy

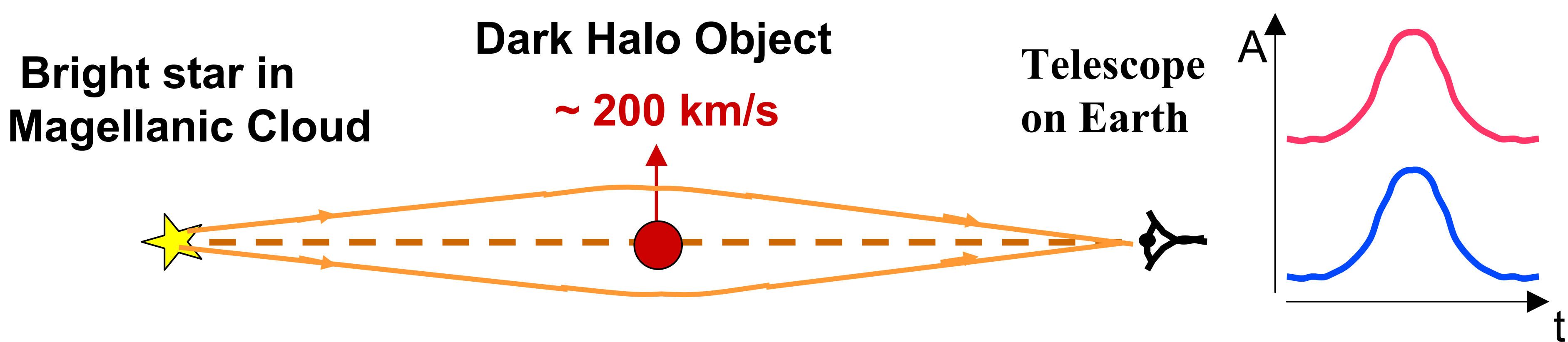


Reconstructed matter distribution



Black holes, etc.

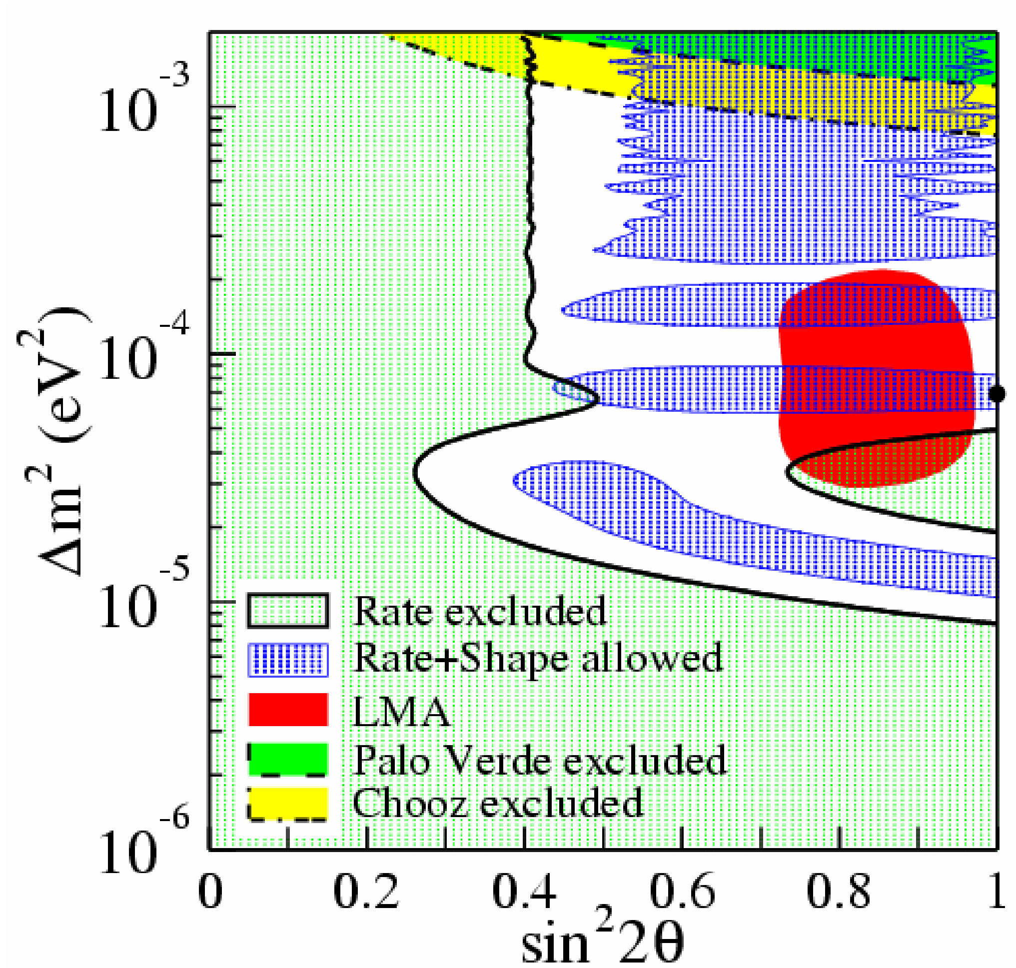
Gravitational Lensing Searches for MACHOs



Neutrino Mass is not enough

$P_{dis} = \sin^2 2\theta \sin^2(1.27\ \Delta m^2 L/E)$, Δm mass difference, θ mixing angle, E energy of ν, L oscillation length

Recent evidence of m>0 from
- -SuperKamiokande
- -SNO
- -K2K
- -KamLAND

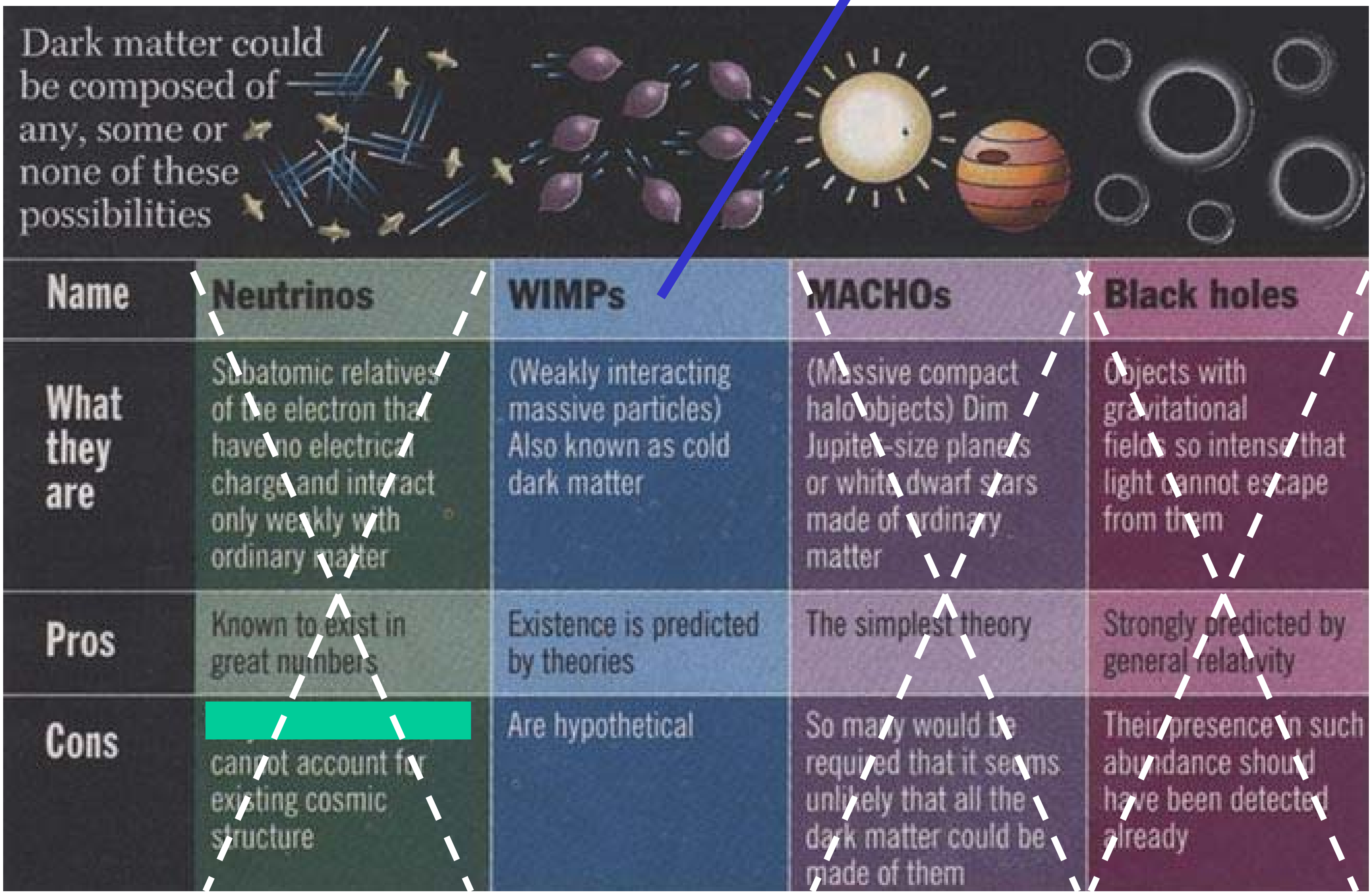


$\Delta M \sim 0.01$ eV

Mixing ~ maximal

Candidates: only WIMPS are left

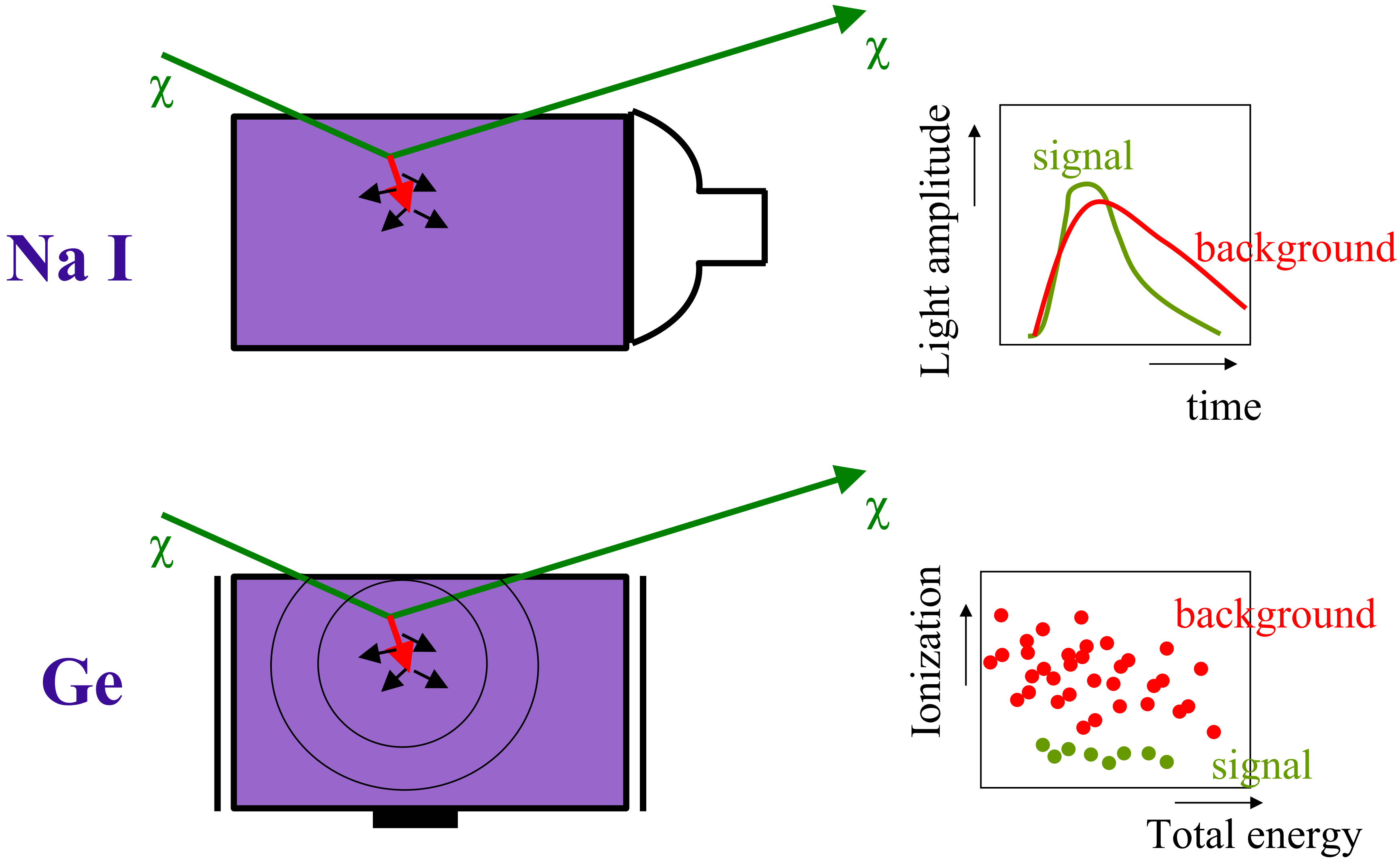
M > ~ 40 GeV
if SUSY (LEP)



Name	Neutrinos	WIMPs	MACHOs	Black holes
What they are	Subatomic relatives of the electron that have no electrical charge and interact only weakly with ordinary matter	(Weakly interacting massive particles) Also known as cold dark matter	(Massive compact halo objects) Dim Jupiter-size planets or white dwarf stars made of ordinary matter	Objects with gravitational fields so intense that light cannot escape from them
Pros	Known to exist in great numbers	Existence is predicted by theories	The simplest theory	Strongly predicted by general relativity
Cons	cannot account for existing cosmic structure	Are hypothetical	So many would be required that it seems unlikely that all the dark matter could be made of them	Their presence in such abundance should have been detected already

Direct WIMP Detection

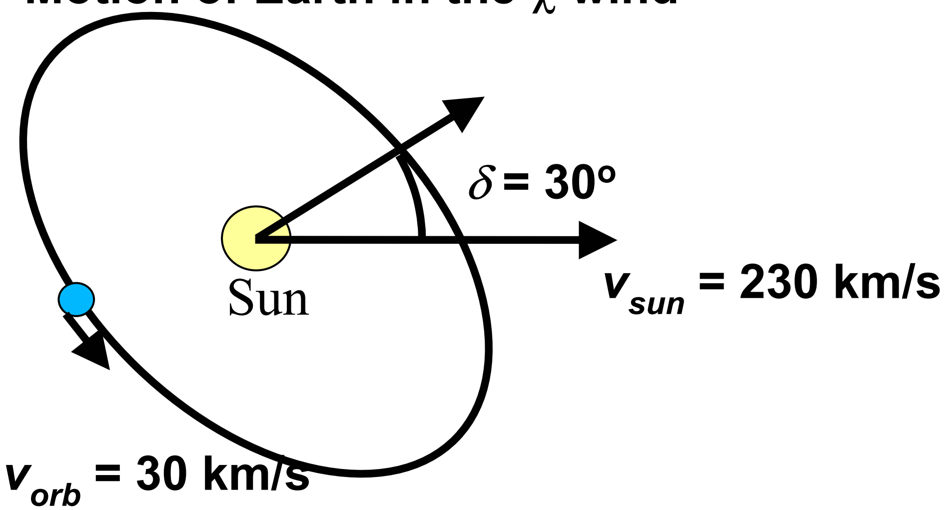
Rejection of background is the critical issue

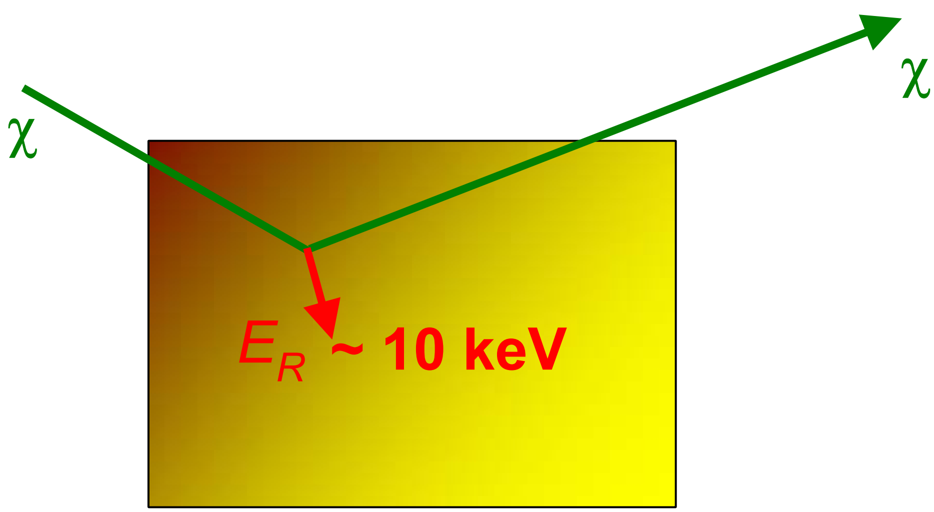


WIMP Direct Detection: modulation

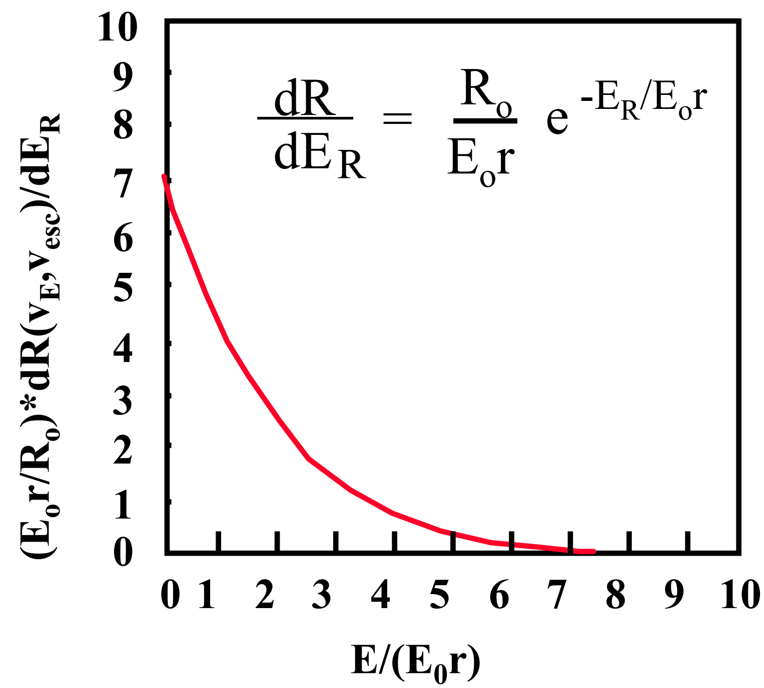
Elastic interaction on nucleus, typical χ velocity ~ 250 km/s ($\beta \sim 10^{-3}$

Motion of Earth in the χ wind





Recoil Spectrum

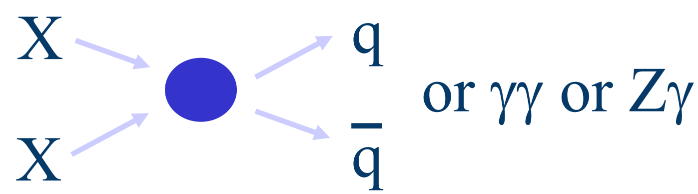


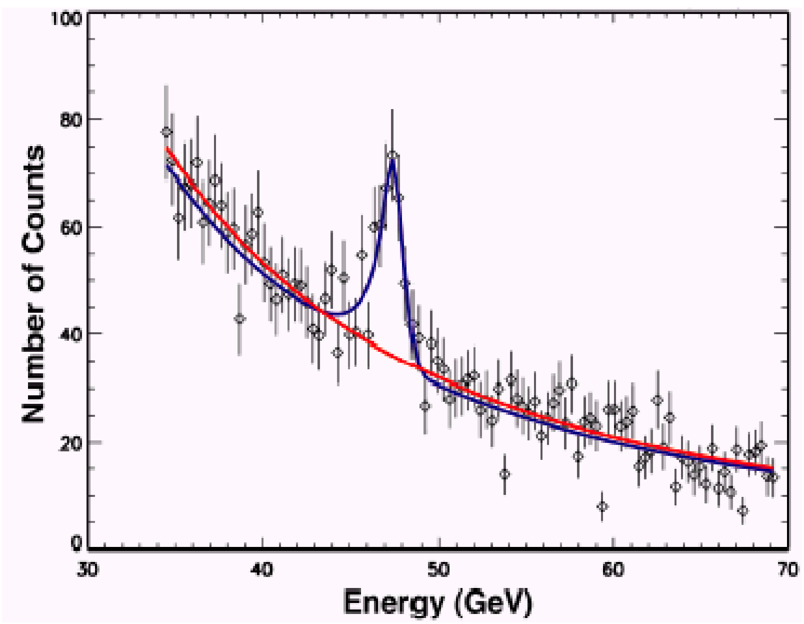
Featureless recoil energy spectrum
---> looks like electron background

But… Annual modulation

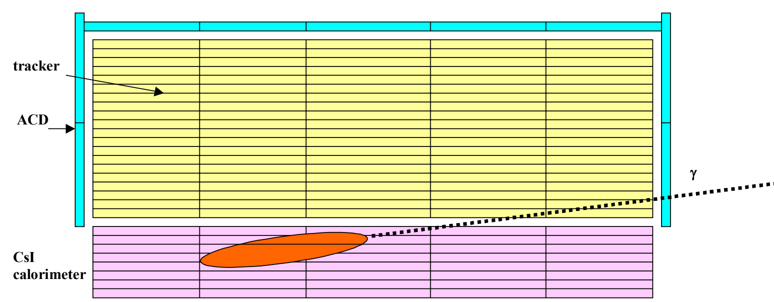
WIMPs & monochromatic γ emissions

Some dark matter candidates (e.g. SUSY particles) would lead to mono-energetic γ lines through annihilation



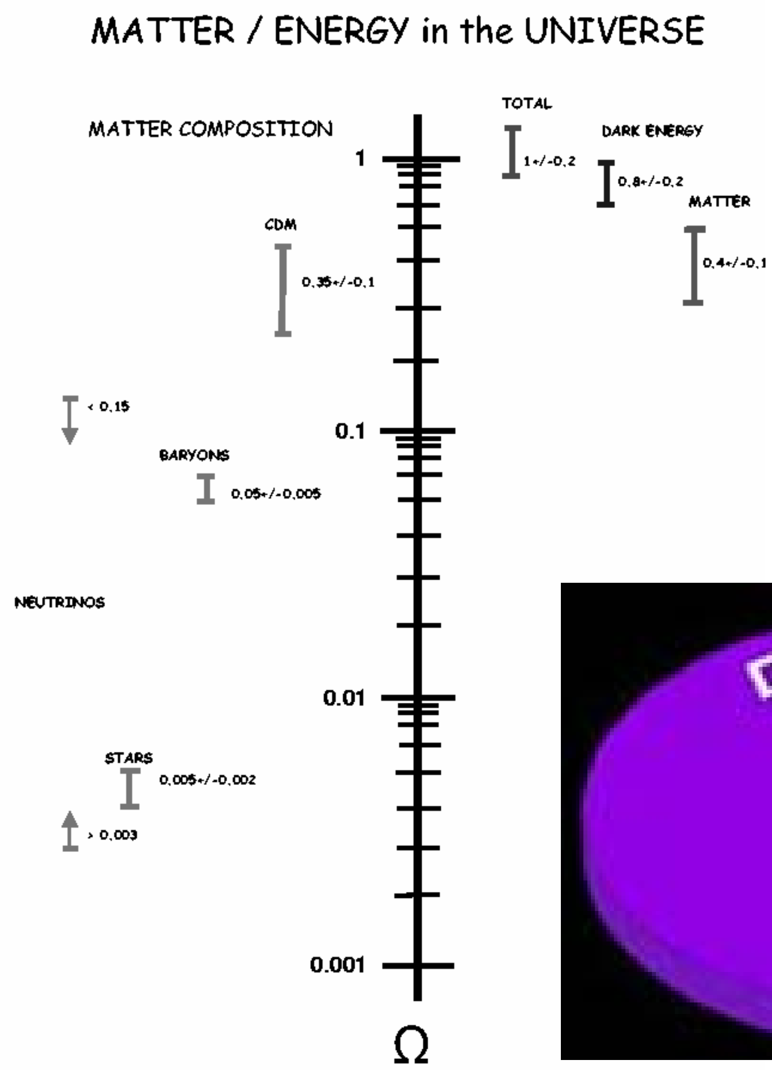


Good energy resolution in the few % range is needed



Matter/Energy in the Universe: Conclusion

Must be something new



$\Omega_{total} = \Omega_M + \Omega_\Lambda \sim 1$

matter dark energy

Matter:

$\Omega_M = \Omega_b + \Omega_\nu + \Omega_{CDM} \sim 0.3$

baryons neutrinos cold dark matter

Baryonic matter :

$\Omega_b \sim 0.04$

stars, gas, brown dwarfs, white dwarfs

Neutrinos:

$\Omega_\nu \sim 0.003$

Dark Matter :

$\Omega_{CDM} \sim 0.23$

WIMPS/neutralinos, axions