Karlsruhe Institute of Technology

Perspectives on the Detection of Supersymmetric Dark Matter

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General remark

- No time to discuss details in 30‘
- No signals seen sofar in experiments, but DM exists. Are experiments not sensitive enough or is our paradigm about search for DM wrong?
- Talk will concentrate on the main paradigm (DM as thermal relic from supersymmetric early universe) and compare this with experiments

- For details on DM searches check recent talks:
  - Eleni Aprile, Iris Gebauer, Yeongduk Kim, Carsten Rott, ICRC2017, Busan, South-Korea)
  - Eric Charles, Christoph Weniger, 13th Rencontres de Vietnam, Quy Nhon, Vietnam, 2017

- At this conference: (25.8.2017)
  - Overview direct DM searches by Giuliana Fiorillo
  - Overview indirect DM searches by Aldo Morselli

Outline

- What do we know about Dark Matter (DM)?
- Why is Supersymmetry so interesting for DM?
- How to search for DM?
- Status of present and perspectives of future DM searches:
  - Present and future limits of direct DM searches
  - Present LHC limits
  - Discussion on „hot topic“ of Fermi GeV excess

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

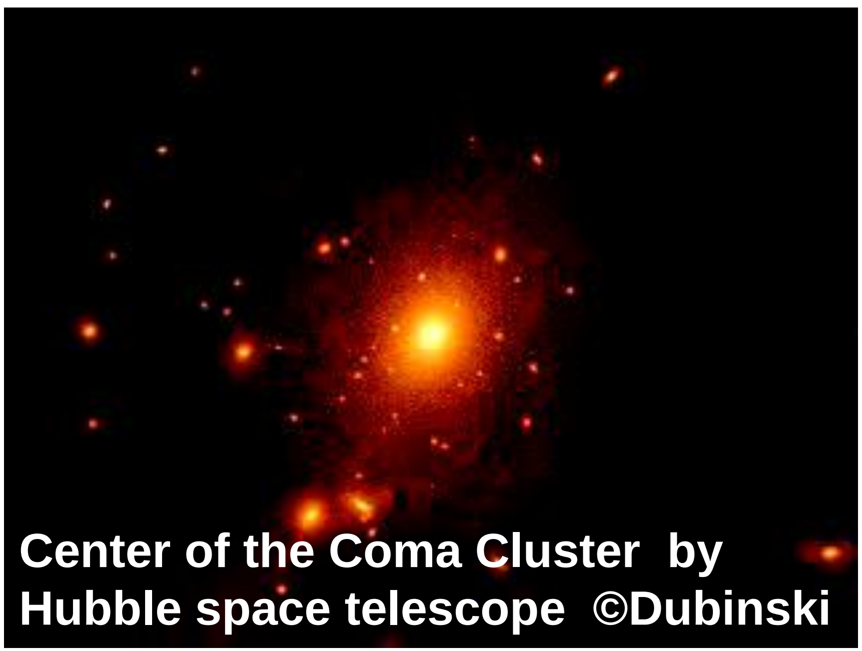
Therefore DM consists of WIMPs
(Weakly Interacting Massive Particles)

Wimps are Neutrinos? No, Galaxies cluster on small scales (in gravitational potential wells of DM)⇒ DM = non relativistic ("Cold DM").
Neutrinos would be "warm" or "hot" DM.⇒
WIMPs ARE NEW PARTICLES outside Standard Model
NOT PRODUCED AT ACCELERATORS.
BEST EVIDENCE FOR PHYSICS BEYOND THE SM!

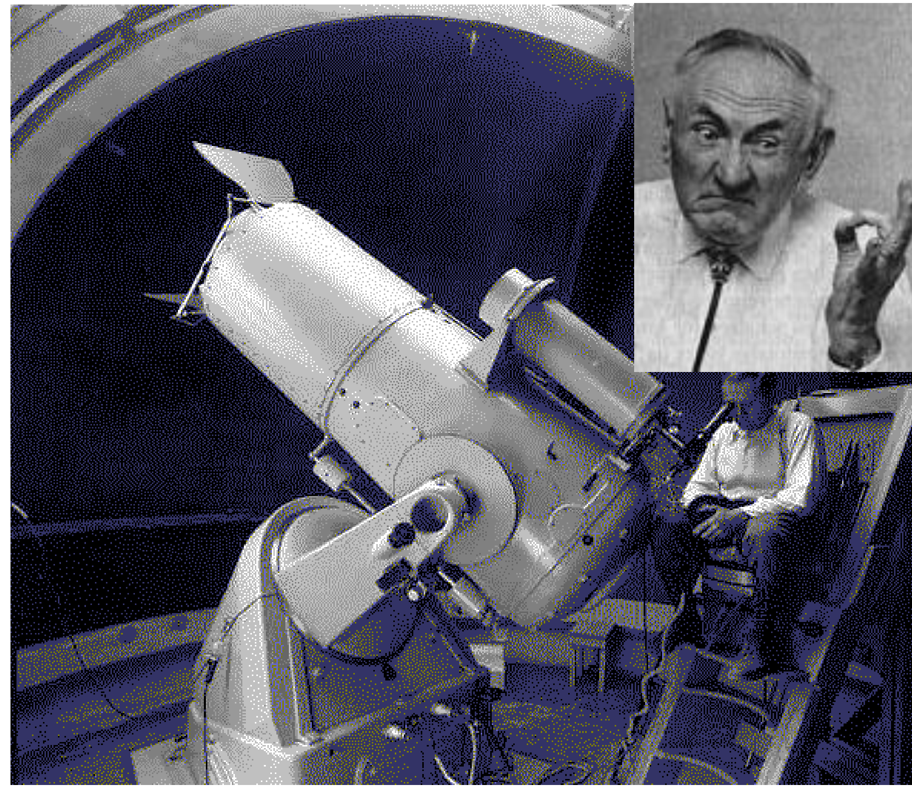
Concept of DM since 1922

History of DM

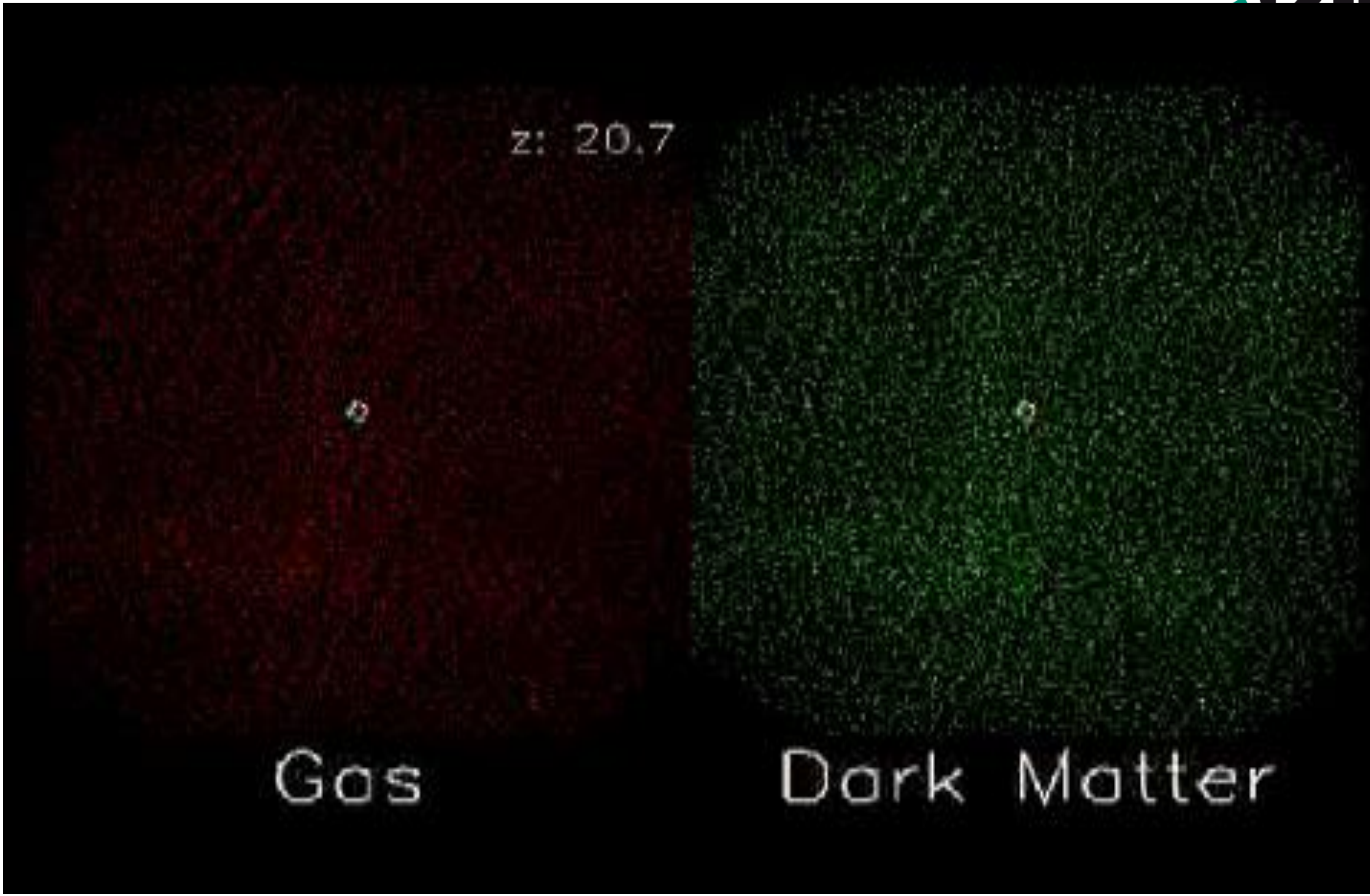
1922 Kapteyn proposes dark matter to explain gravitational effects.
Student van Oort proposes stars fall into potential wells of DM
1933 Zwicky concludes existence of DM from Coma cluster of galaxies



Center of the Coma Cluster by Hubble space telescope ©Dubinski

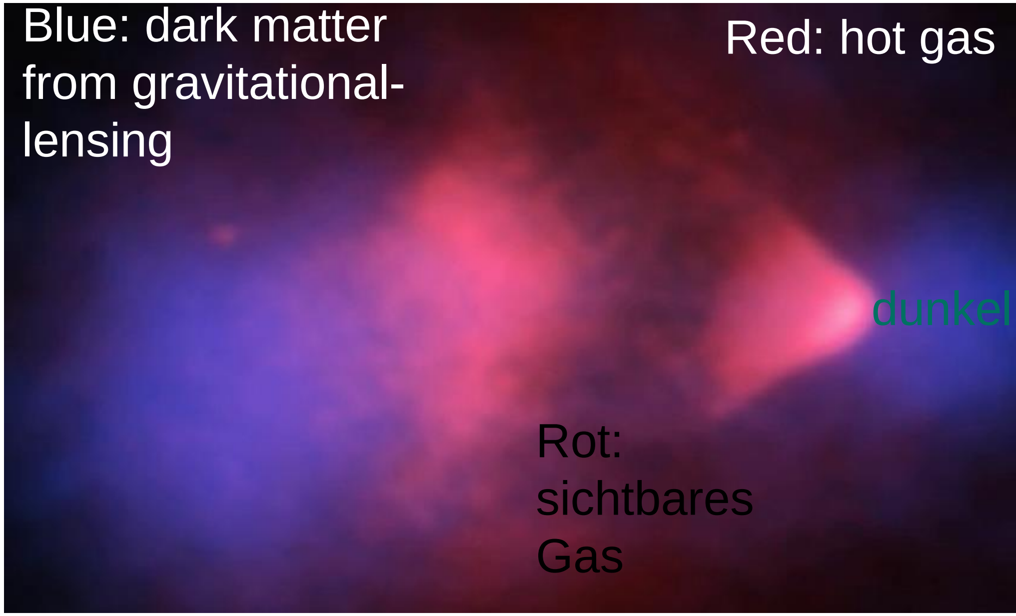


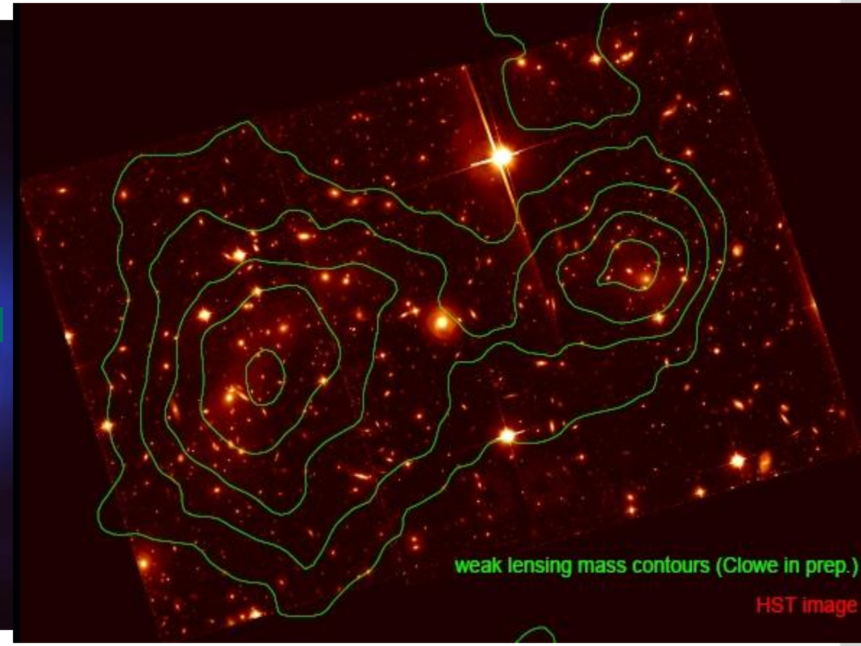
DM attracts galaxies with more force->higher speed. But still bound!
Zwicky was first one to connect potential and kinetic energy using virial theorem



From M. Steinmetz, Potsdam

Colliding Clusters Shed Light on Dark Matter

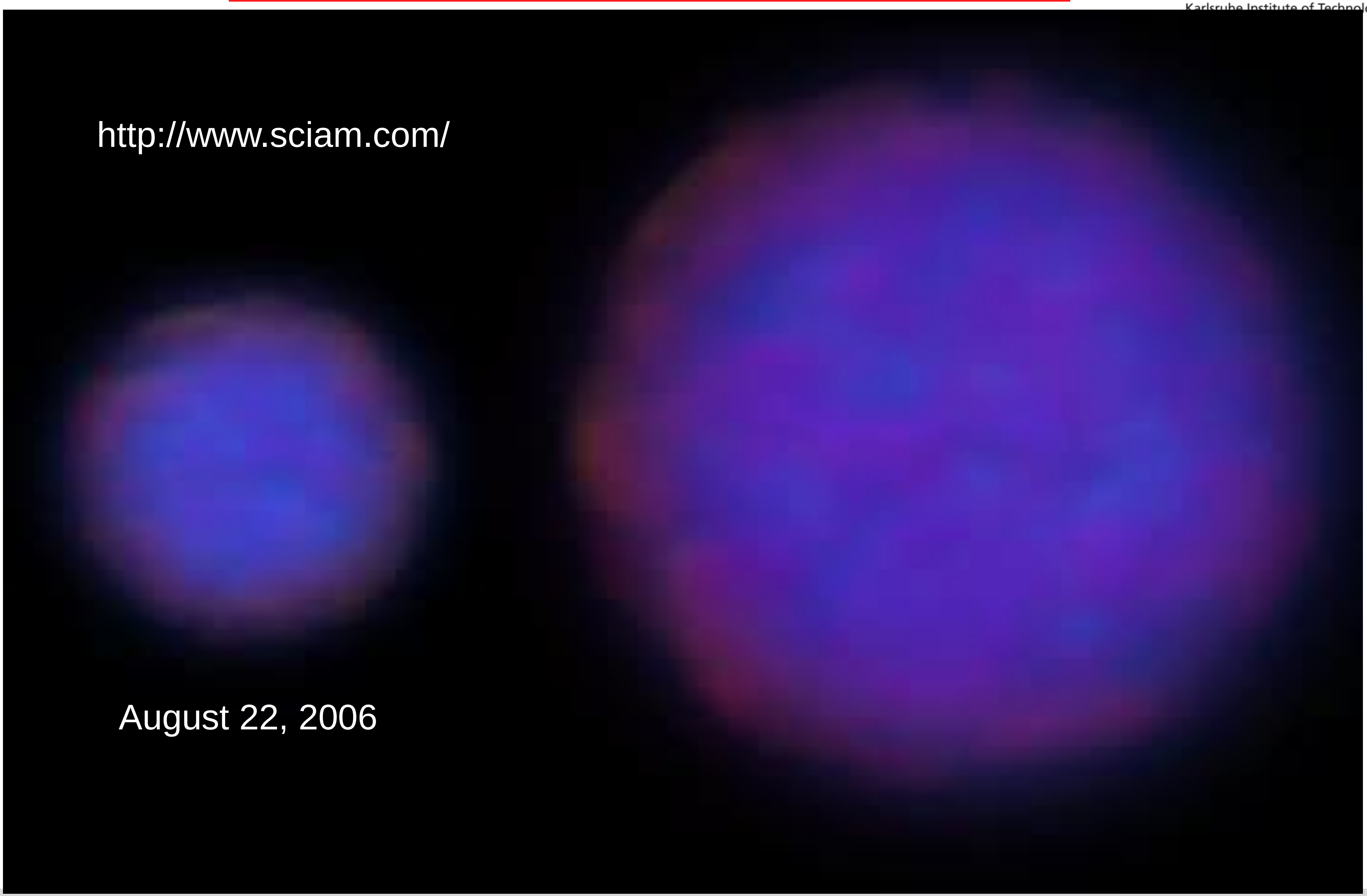




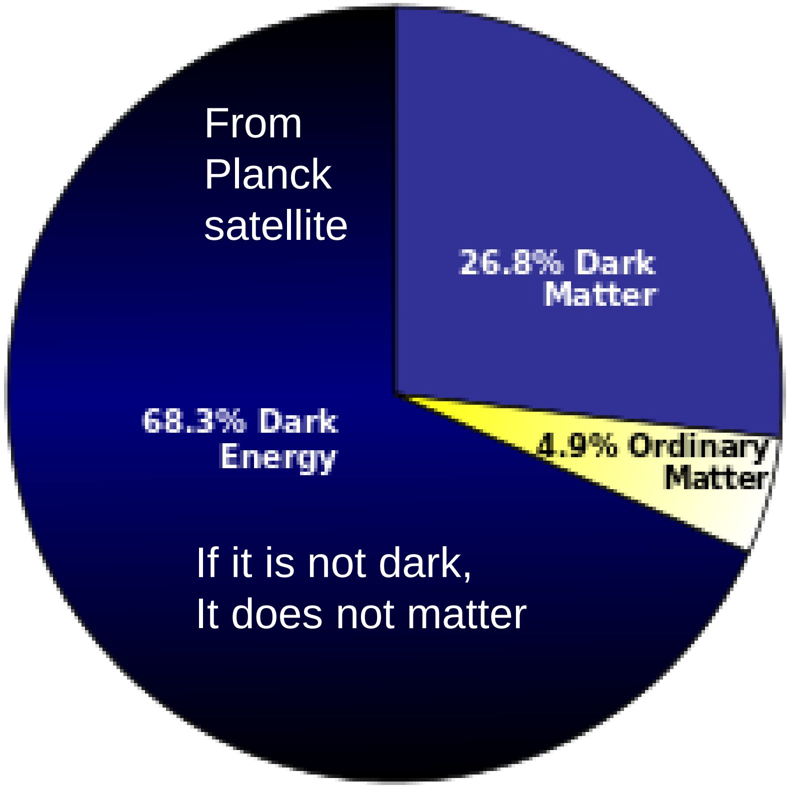
Observations with bullet cluster:

- **Chandra X-ray telescope shows distribution of hot gas**
- **Hubble Space Telescope and others show distribution of dark matter from weak gravitational lensing**
- **Distributions are clearly different after collision-> dark matter is weakly interacting!**

Simulation of “Colliding Clusters”



84% of Matter is Dark Matter



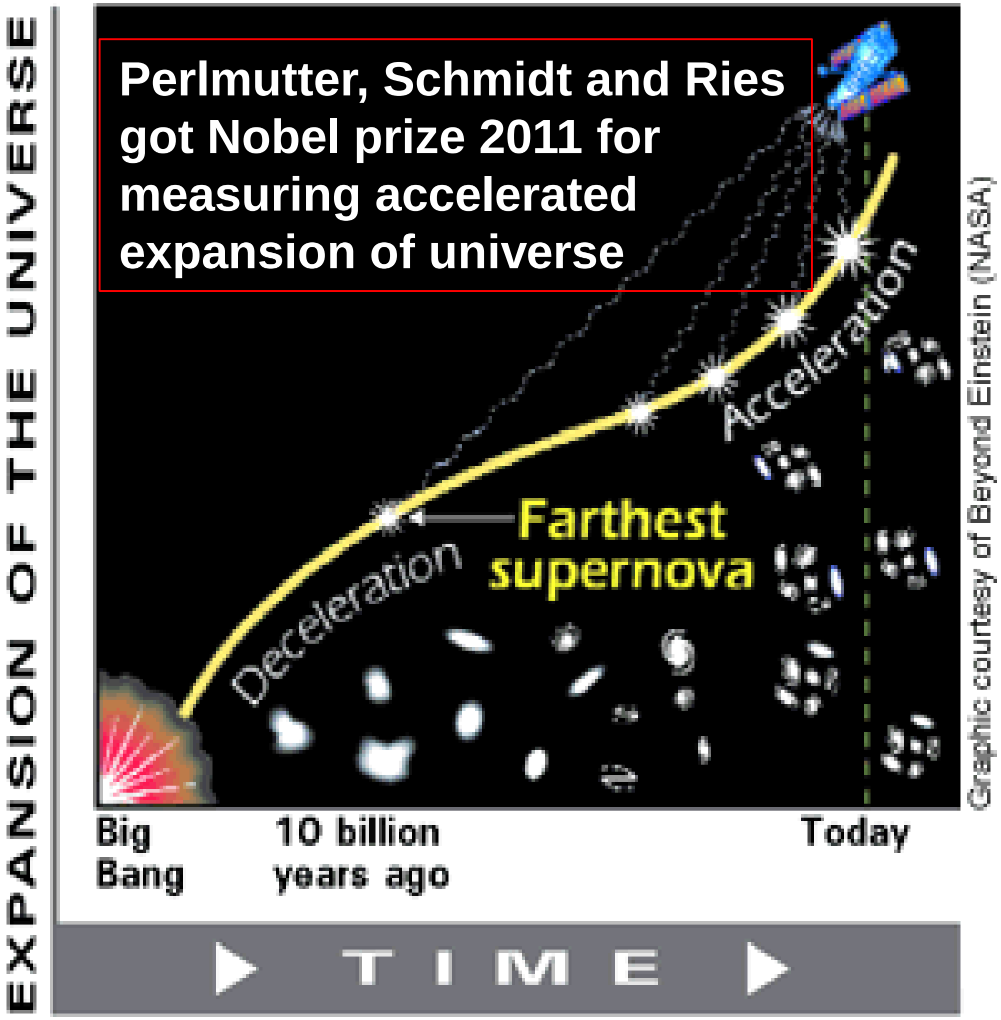
The „complete“ SM describes only 4.9% of the energy in our universe.

We know it is only 4.9% from Cosmic Microwave Background (photons: 412/cm^3 everywhere for a CMB temperature of 2.7 K)

Repulsive gravity is caused by a constant energy density, like vacuum energy (Higgs field?) or a cosmological constant

The dark side divided in two classes:
Dark Matter with attractive gravity
Dark Energy with repulsive gravity
(Nobel prize 2011)

Evolution of the universe



R(t) determined by gravity

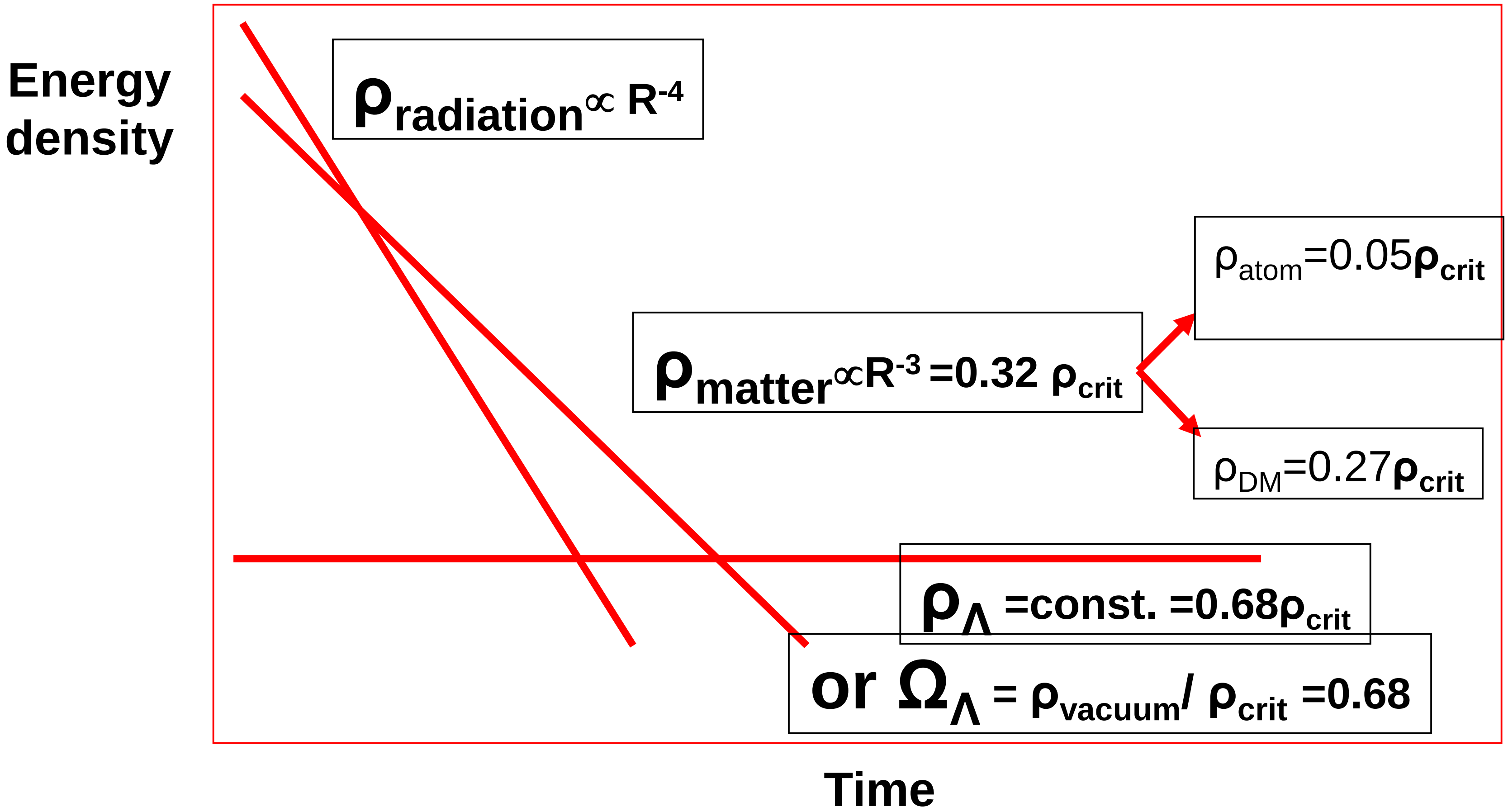
It can be reconstructed from SNIa supernovae remnants, since R can be determined from luminosity and velocity (= slope dR/dt) from the Doppler shift.

One observes first a decelerating phase (attractive gravity) followed by an accelerating phase (repulsive gravity).

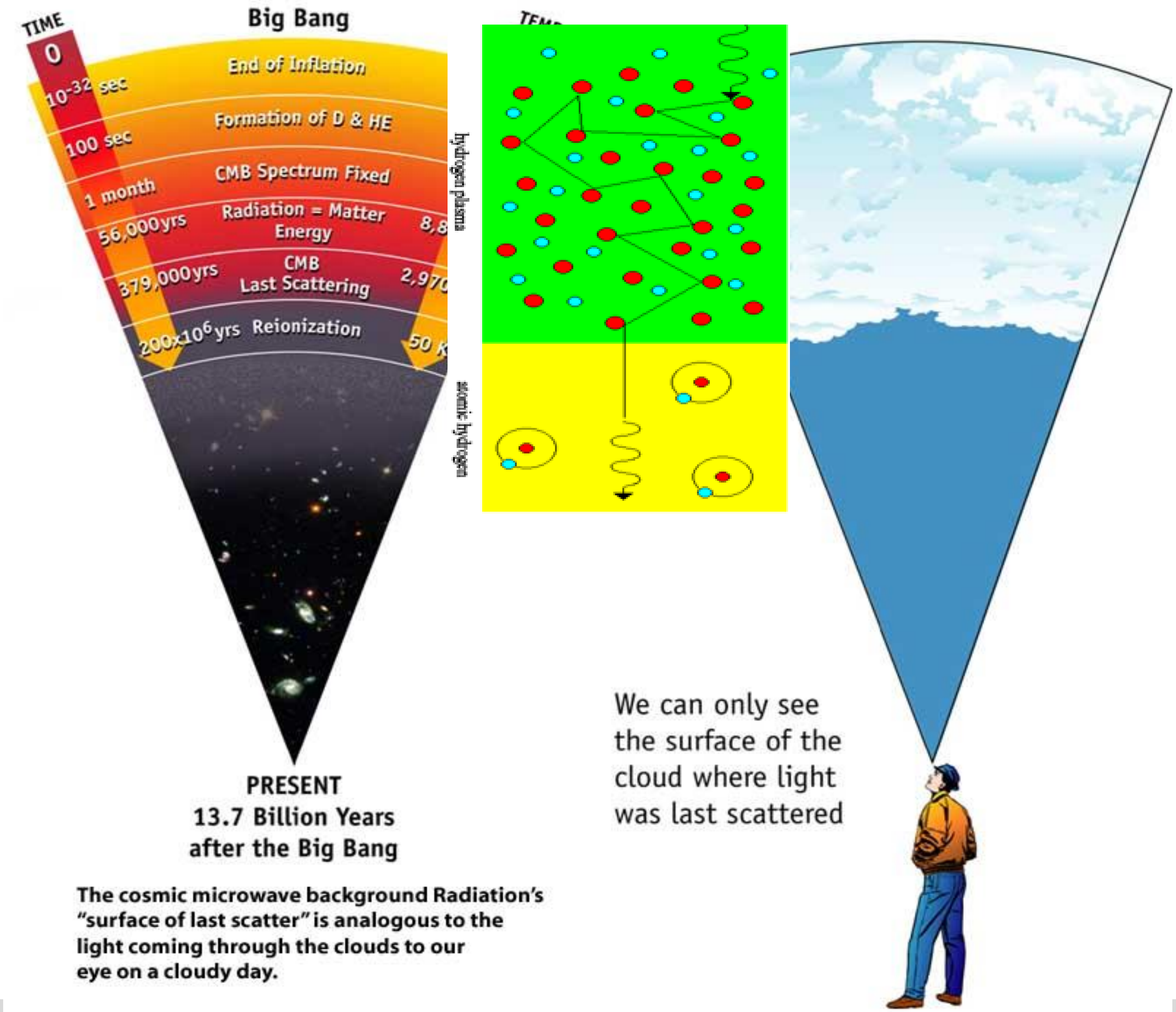
Gravity repulsive if constant energy density (= vacuum energy?) dominates.

Can be calculated with non-rel. Newtonian mechanics

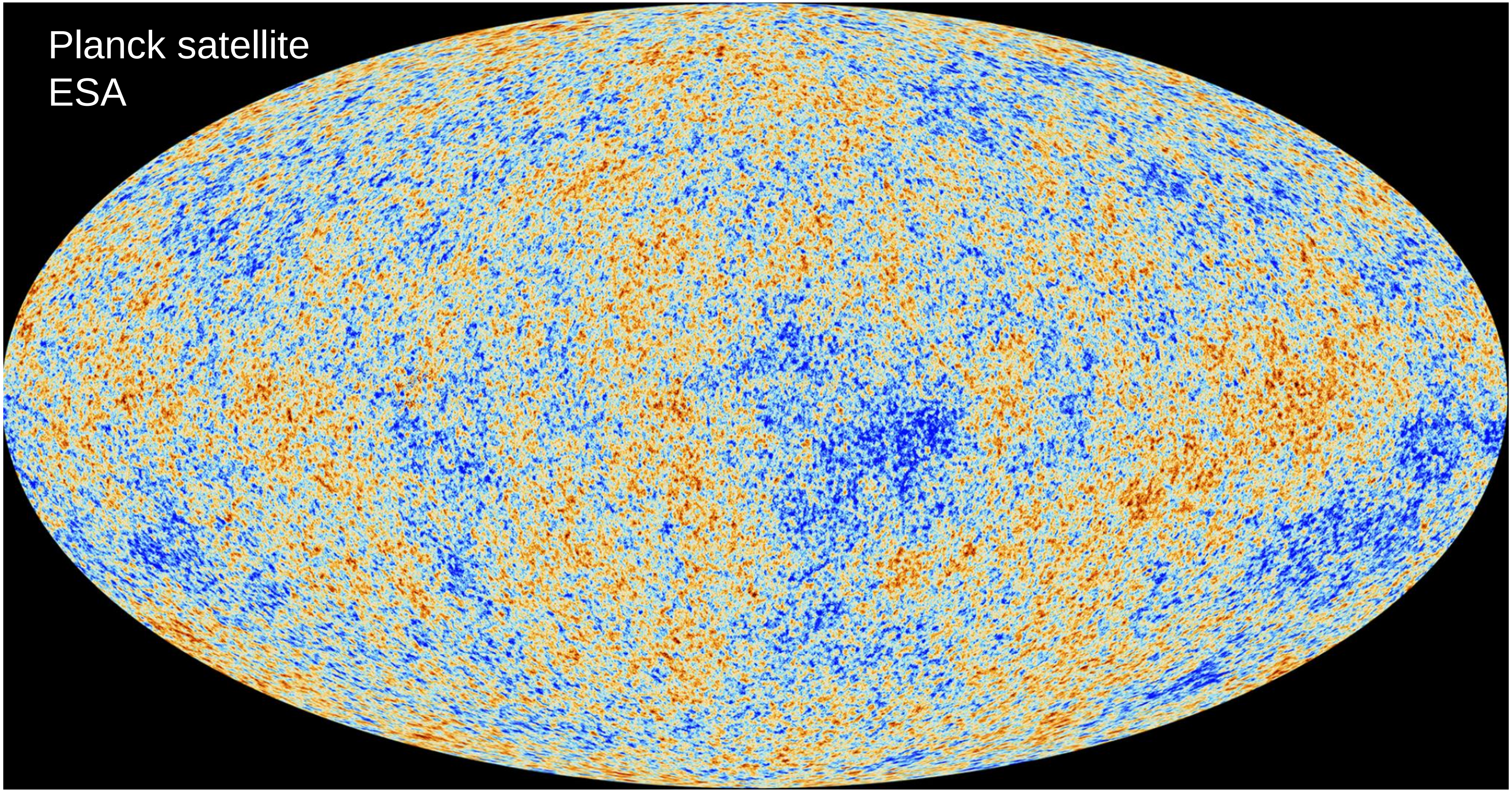
Energy density components in an expanding universe



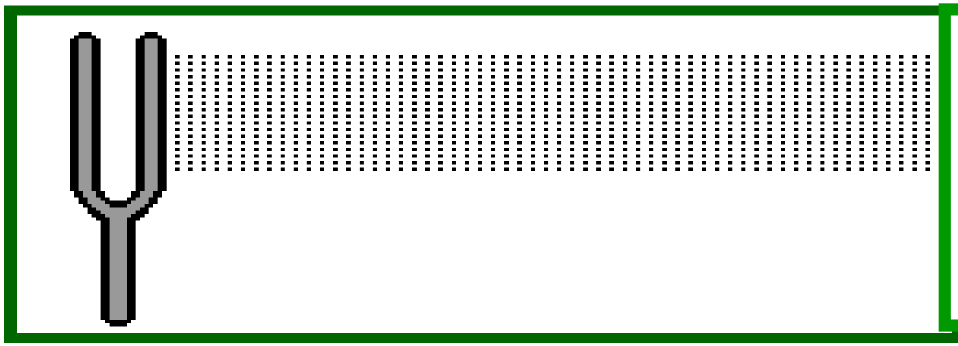
Light from early universe visible as cosmic microwave background (CMB)

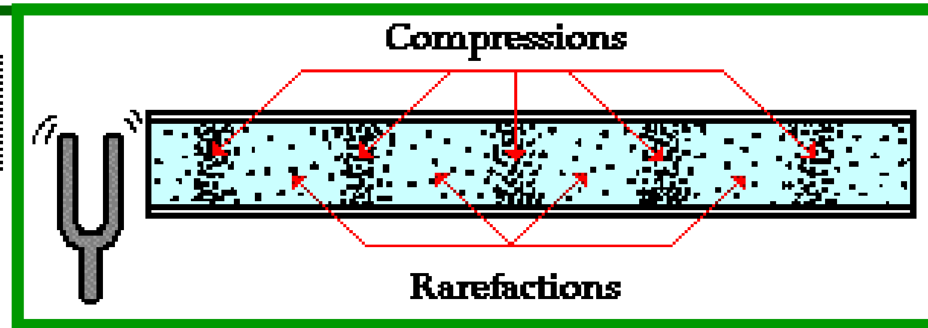


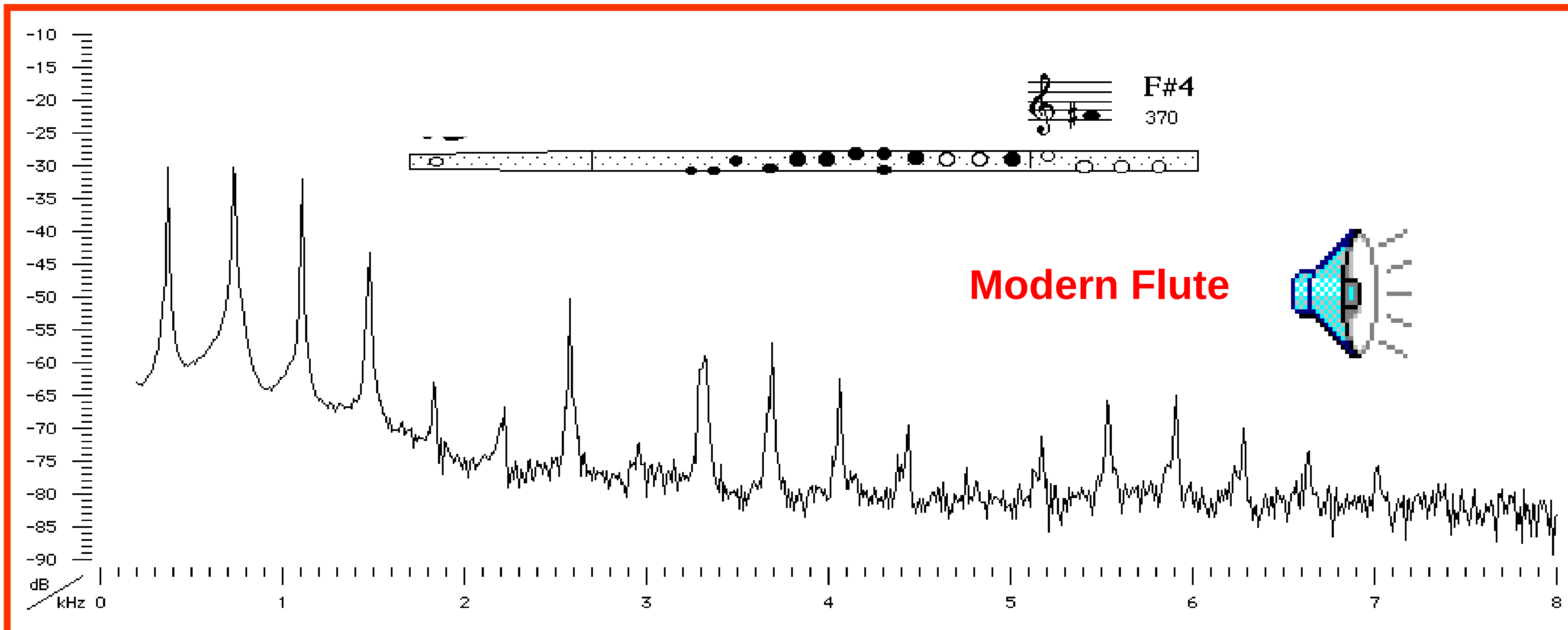
Density fluctuations in Cosmic Microwave Background



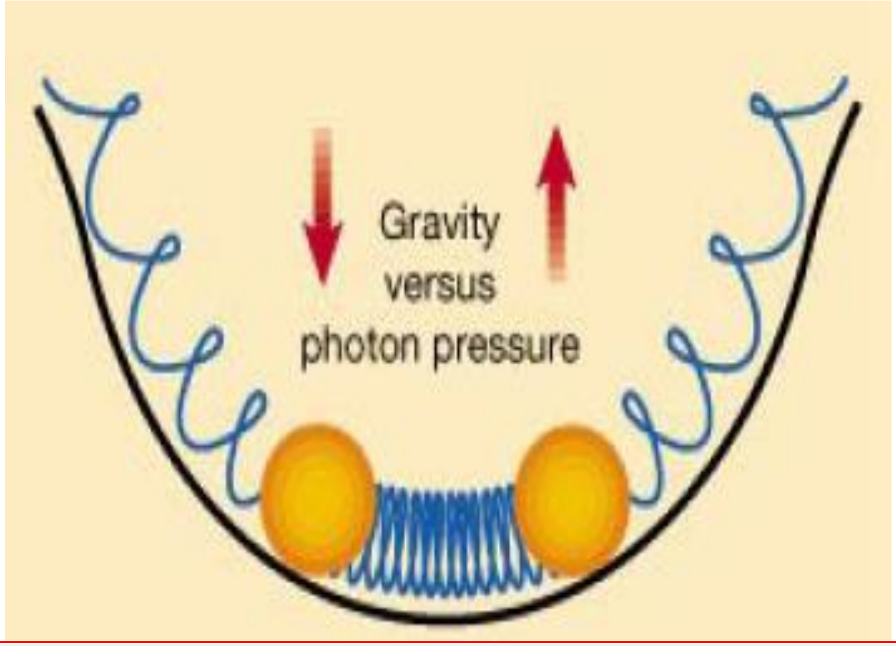
Acoustic waves ARE density fluctuations







Model of acoustic waves in early universe

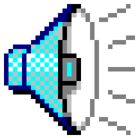


Model of acoustic waves:

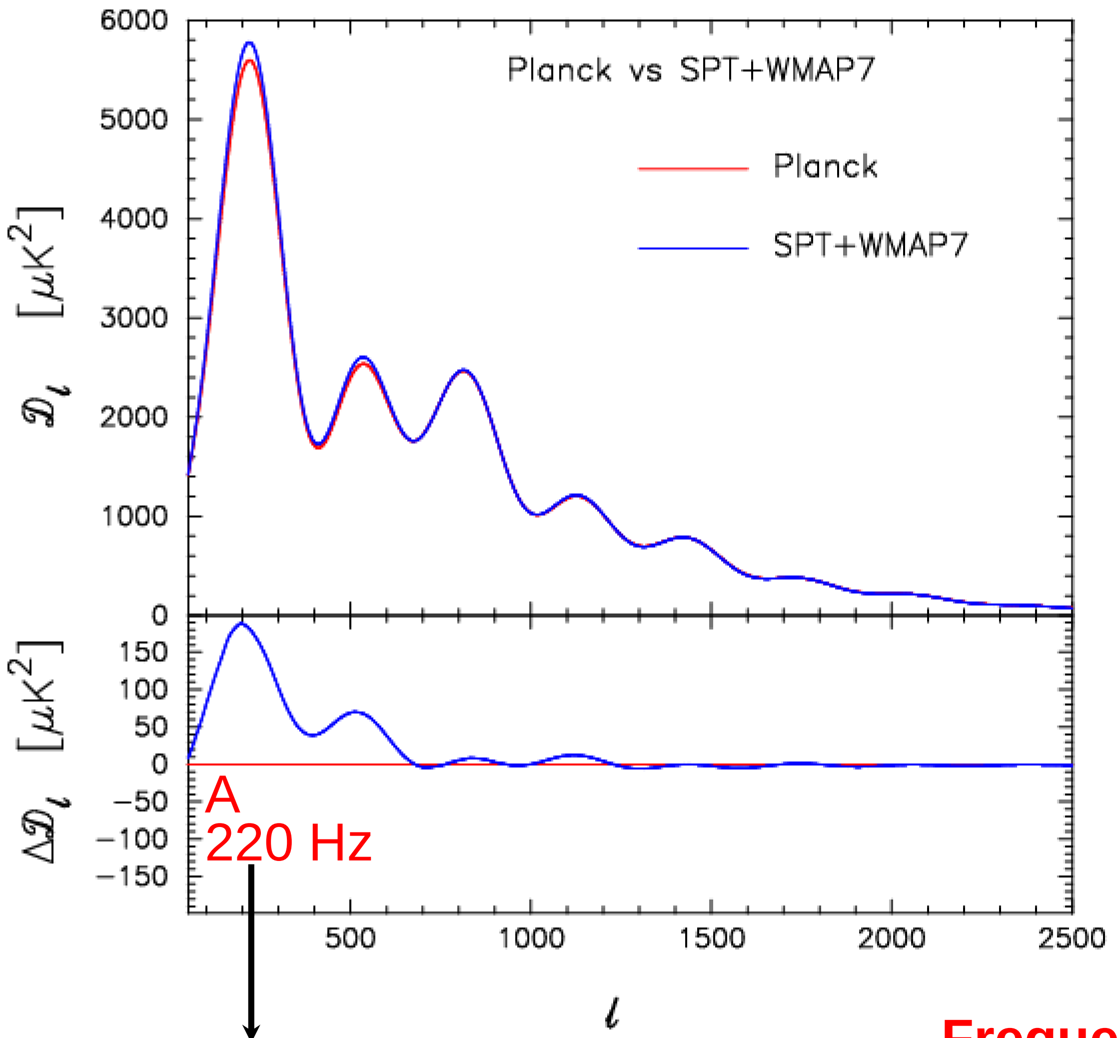
DM determines depth of potential well
Baryons (yellow) fall into well
Photon pressure (spring) drives them out of well
(till universe cooled down enough that baryons catch electrons and become neutral, so no interactions with photons anymore->decoupling 379.000 yrs after the big bang)

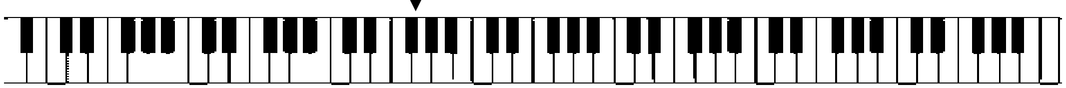
Sound of Big Bang after 379.000 years

©Mark Whittle



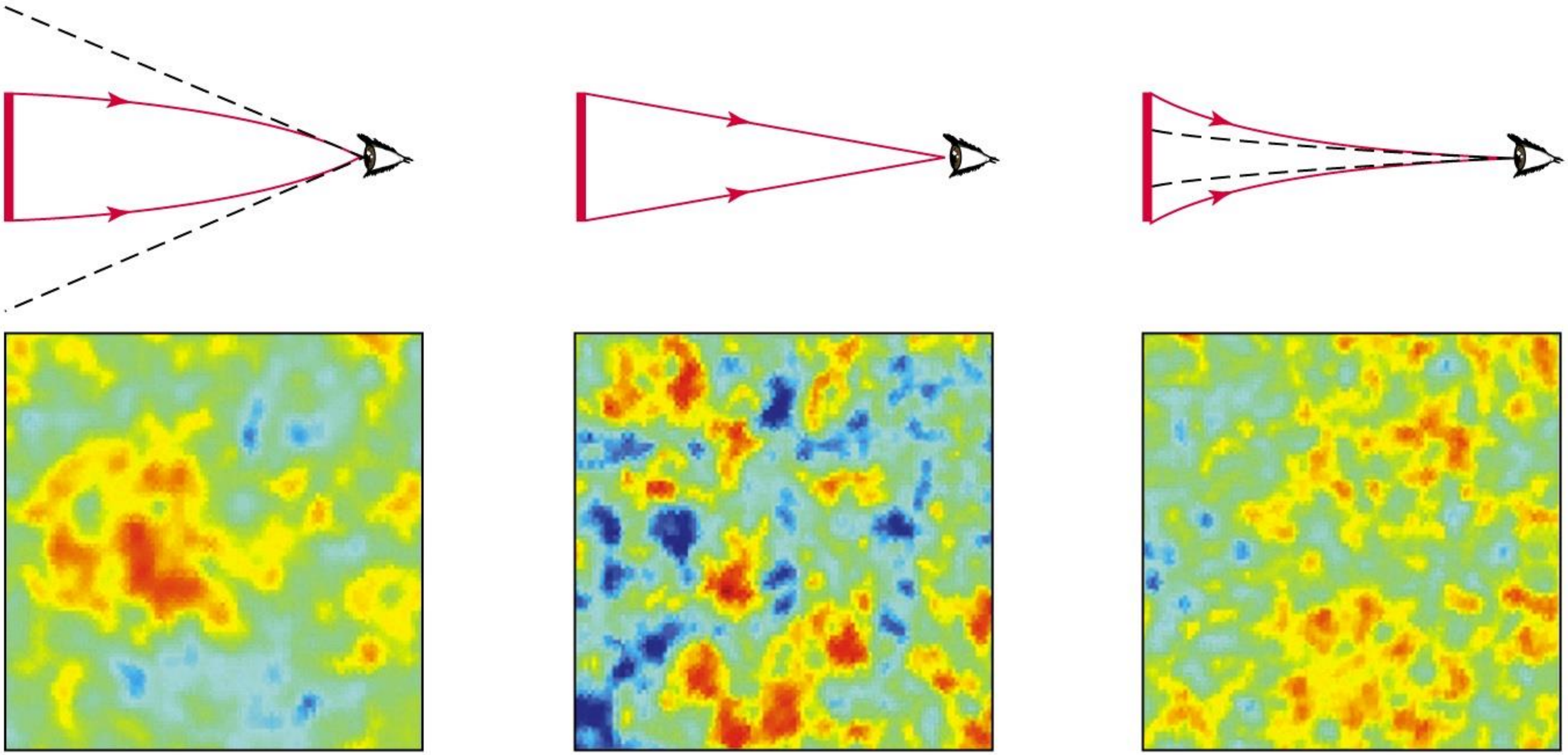
(transposed by 50 octaves**)**





Frequency (in Hz)

Position of first acoustic peak determines curvature of universe



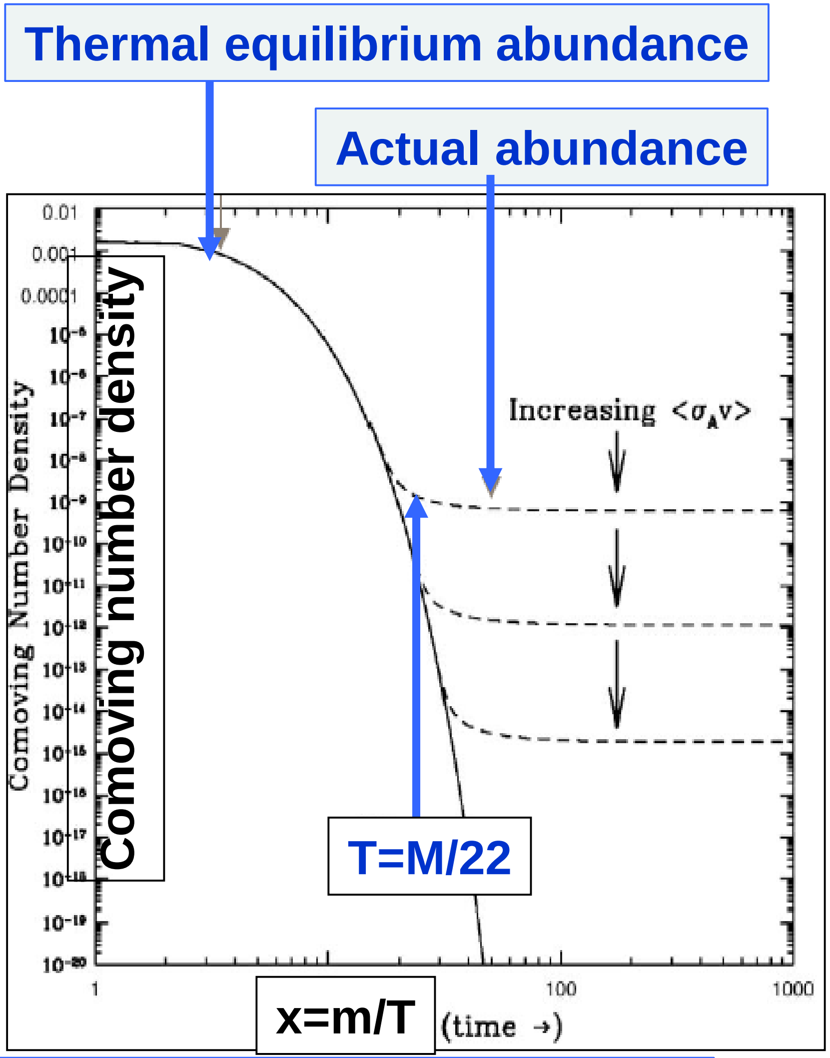
a If universe is closed, "hot spots" appear larger than actual size

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

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

CMB analyzer: https://wmap.gsfc.nasa.gov/resources/camb_tool/index.html

Paradigm: WIMPs are thermal relics from early universe



Steigman, Ann. Rev. Nucl. Part. Sci. 1979

T>>M: $f+\bar{f} \to M+\bar{M}$; $M+\bar{M} \to f+\bar{f}$
T<M: $M+\bar{M} \to f+\bar{f}$
T=M/22: M decoupled, stable density
(when annihilation rate ≅ expansion rate,
i.e. $\Gamma = \langle\sigma v\rangle n\chi(x_{fr}) \cong H(x_{fr})$!)

WMAP -> $\Omega h^2 = 0.113 \pm 0.009$ ->
$\langle\sigma v\rangle = 2.10^{-26}\ cm^3/s$

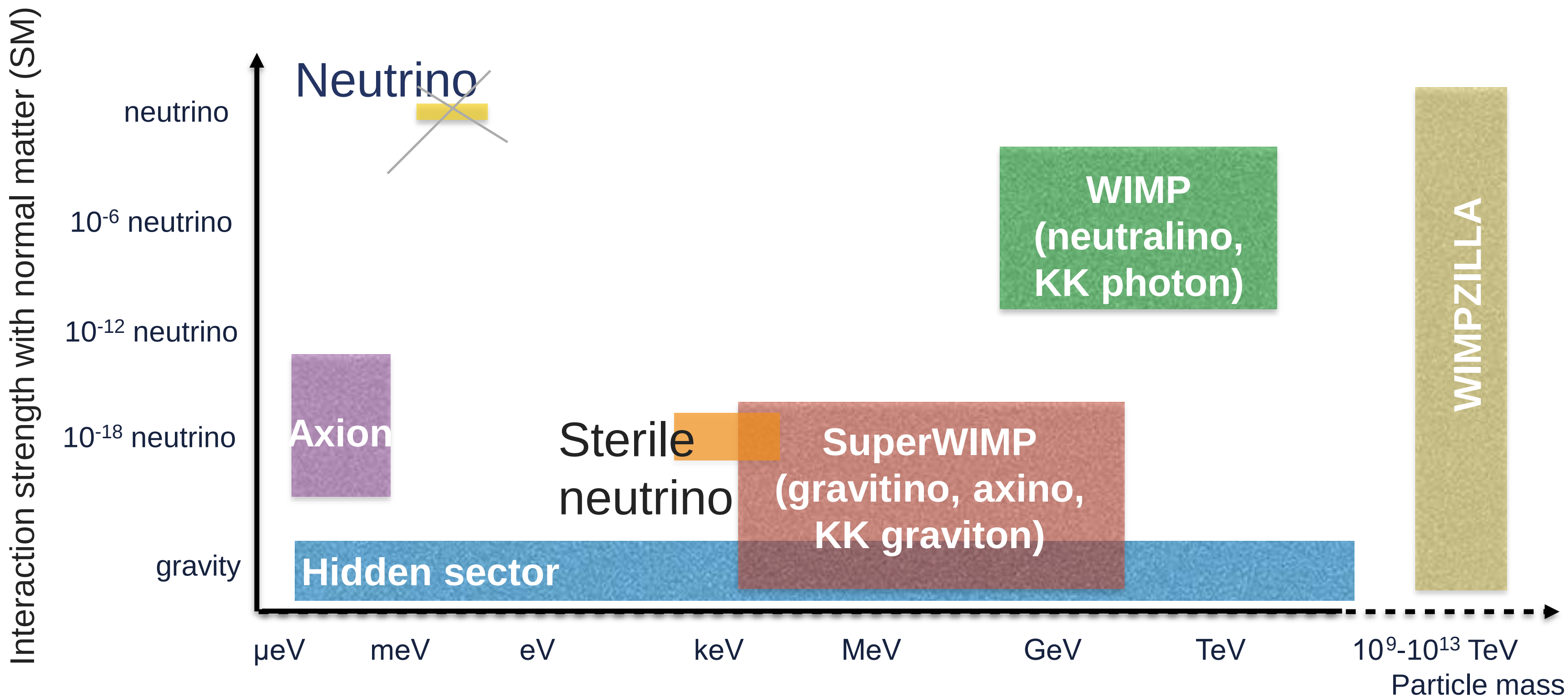
DM increases in galaxies:
≈1 WIMP/coffee cup ≈10^5 <ρ>.
DMA ($\propto\rho^2$) restarts again..

Annihilation into lighter particles, like quarks -> π_0 -> gammas-rays

Only assumption in this analysis:
WIMP = THERMAL RELIC!

WIMP candidates

- Mass and cross section of WIMP candidates span many orders of magnitude
- Concentrate on neutralino, which can provide correct relic density (WIMP miracle)
- (Neutralino = Lightest Supersymmetric Particle)



Baudis, KIT 2017

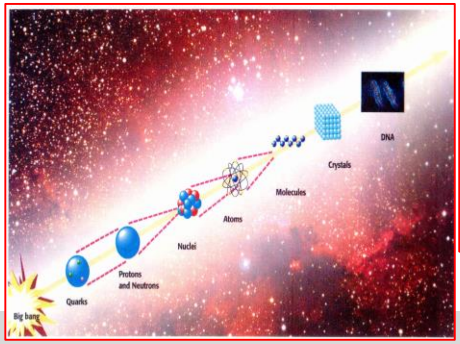
What is SUSY?

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

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

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

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



In modern theories particles are excitations of strings in 10-dimensional space (String theory)

Particle spectrum in SUPERSYMMETRY

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Alternative to Heavy Neutrinos: Neutralinos

The hypothesis of supersymmetry holds that every boson should have a fermionic partner, and vice versa.

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 ($\tilde{\gamma}$)	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

If R-parity is conserved, the lightest sparticle (LSP) must be stable.
Best dark matter candidate, similar to heavy Majorana neutrino, is

Neutralino = C_1 Photino + C_2 Zino + C_3 Higgsino

Fundamental Questions

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Particle Physics

- What is the origin of mass?
  (SUSY predicts Higgs mechanism)
- Why hydrogen atom neutral?
  (SUSY connects leptons and quarks)

Why forces so different strength?
  (radiative corrections)

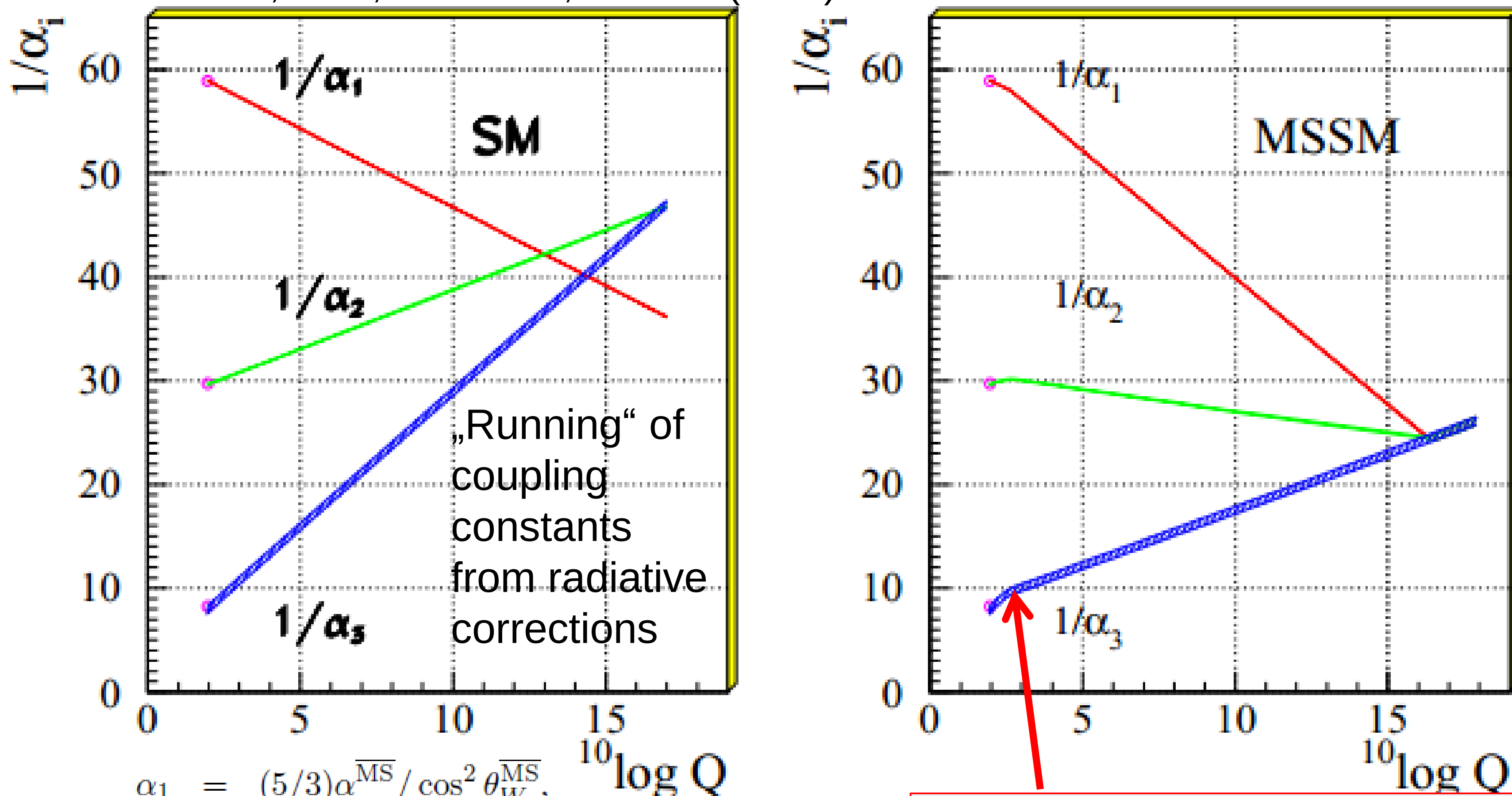
Cosmology

- Why more matter than antimatter ?
  (Sacharov conditions fulfilled)
- What is dark matter?
  (Lightest SUSY particle)
- How did galaxies form?
  (Baryons fall into DM potential wells)

Magic solution: SUPERSYMMETRIC GRAND UNIFIED THEORIES

Unification with SUSY possible

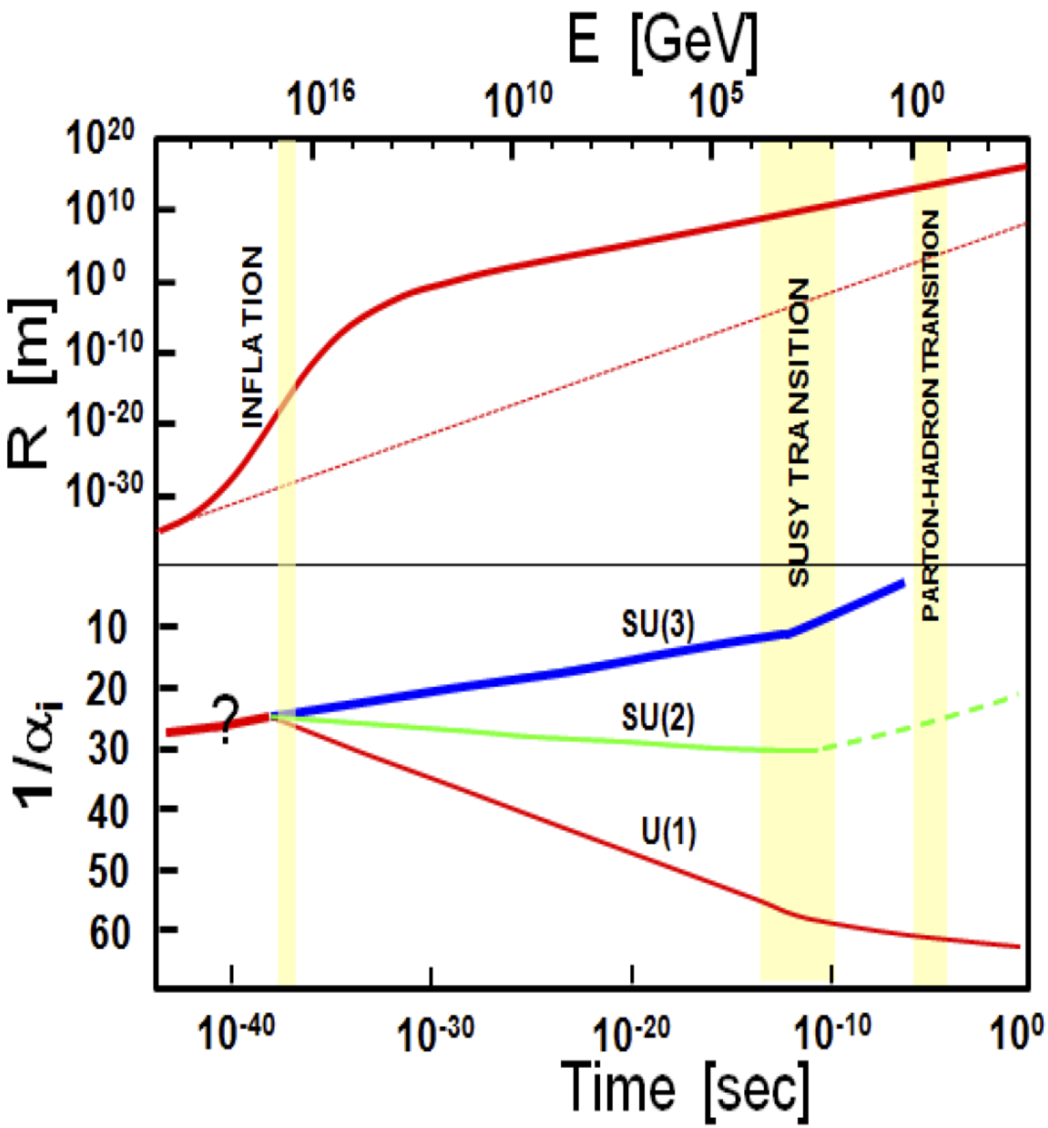
Amaldi, WdB, Fürstenau, PL B260(1991)



$$\alpha_1 = (5/3)\alpha^{\overline{MS}} / \cos^2\theta_W^{\overline{MS}},$$
$$\alpha_2 = \alpha^{\overline{MS}} / \sin\theta_W^{\overline{MS}},$$
$$\alpha_3 = \alpha_s^{\overline{MS}},$$

Unification possible with SUSY scale around 1 TeV (all interactions equally strong)

Time evolution of Universe



Idea:

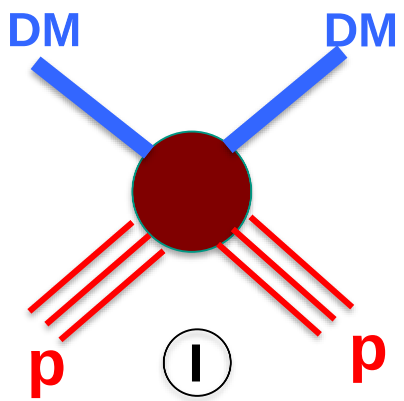
High vacuum density of a scalar field in early universe during breaking of GUT would provide a burst of inflation by „repulsive“ gravity.

Otherwise no explanation why the universe has matter, is flat and is isotropic.

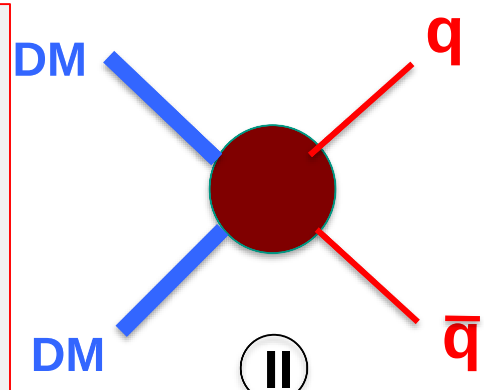
Discovery of Higgs field as origin of ewsb important, especially that it was found in range predicted by SUSY (<130 GeV)

How to detect dark matter?

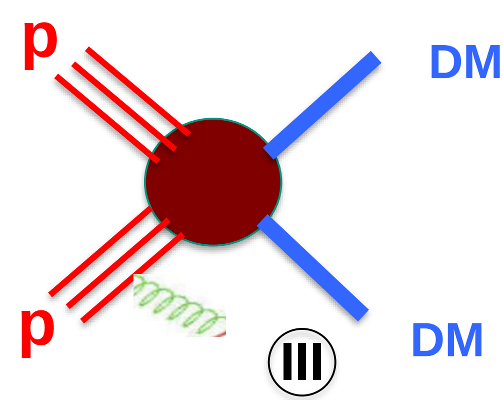
DIRECT



INDIRECT



COLLIDER



σ < 10^{-46} cm^2 from direct DM searches

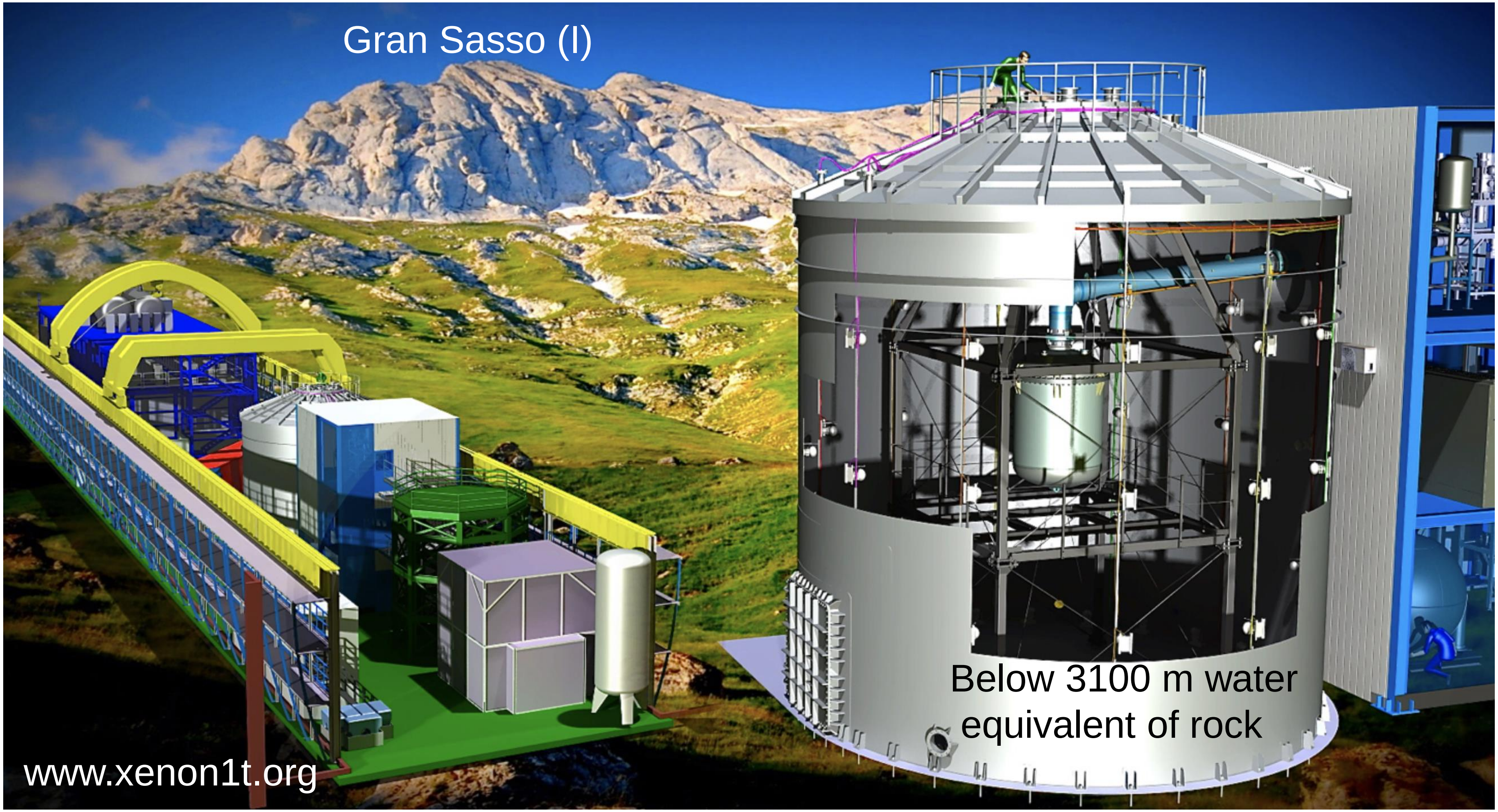
σ ≈ 10^{-35} cm^2 from relic density Ω
(assuming thermal relic)

σ < 10^{-44} cm^2 DM from tag by Z or monojet

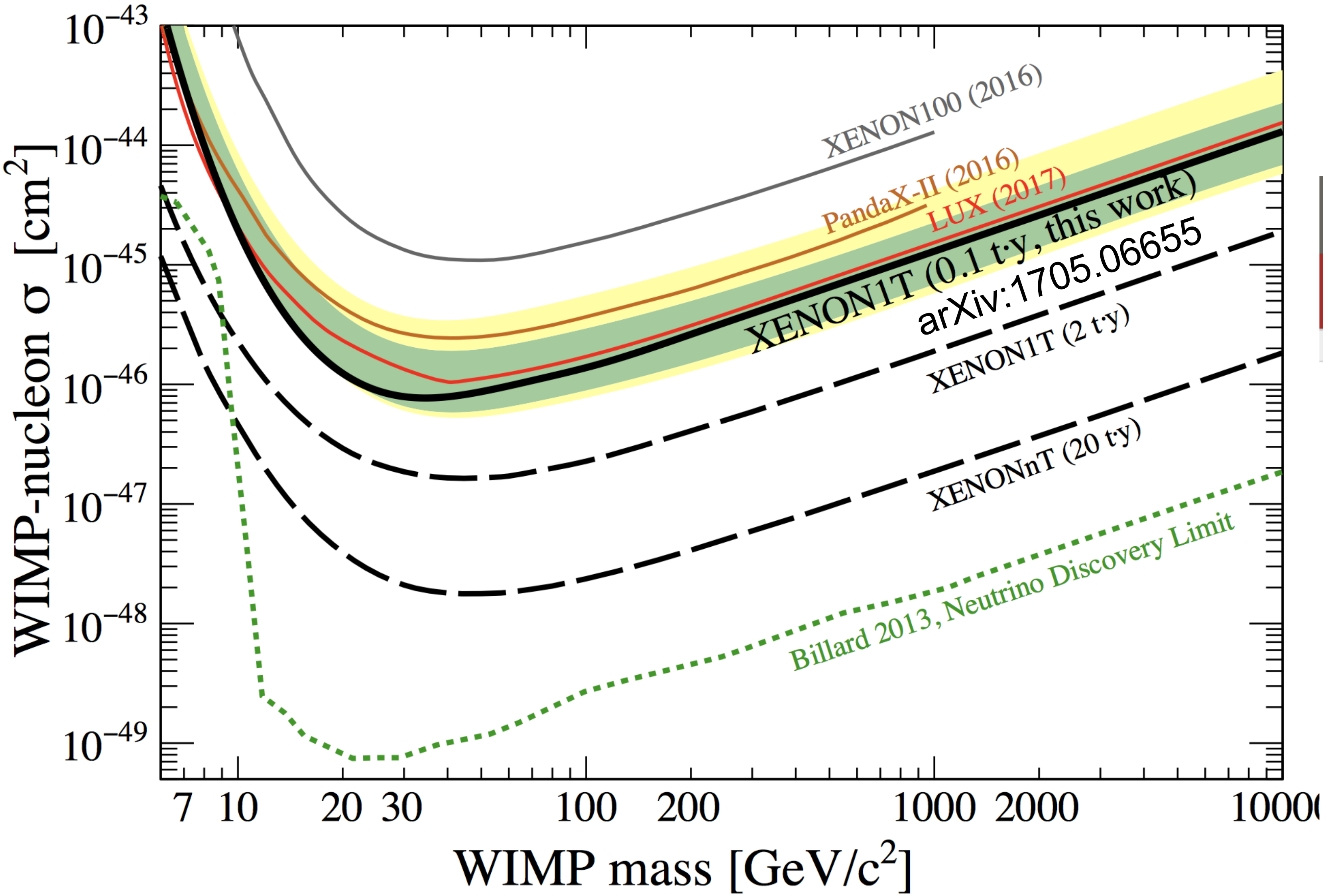
In blob: only Z or Higgs particles to explain neutral and weak interactions
But 11 orders of magnitude between I and II most easily explained by Higgs exchange, since Higgs couples only weakly to light quarks

Higgs Portal models: in III Higgs is portal between visible and invis. sector!
(see Kanemura, Matsumoto,Nabeshima, Okada arXiv:1005.5651)
SUSY with singlet Higgs: NMSSM (DM = „singlino-like“)

The XENON1T detector



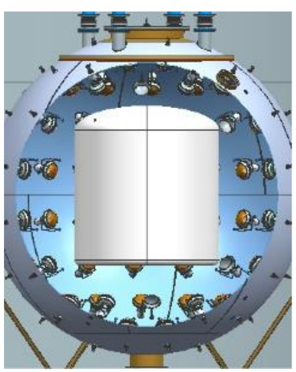
Limits from XENON detectors



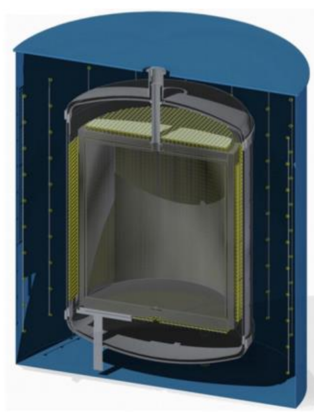
New and future noble liquid detectors

- Acquiring science data: XENON1T 3.3 t LXe, DEAP-3600 3.6 t LAr
- Approved LXe: LUX-ZEPLIN 7t, XENONnT 7t
- Proposed LAr: DarkSide-20k; Proposed LXe: XMASS 5t
- Design & R&D: DARWIN 50 t LXe; ARGO 300 t LAr, DEAP-50T LAr

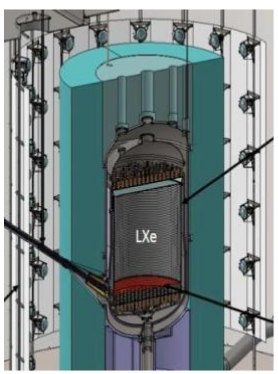
XENONnT: 7t LXe



DarkSide: 20 t LAr



DEAP-50T: 50 t LAr



LZ: 7t LXe

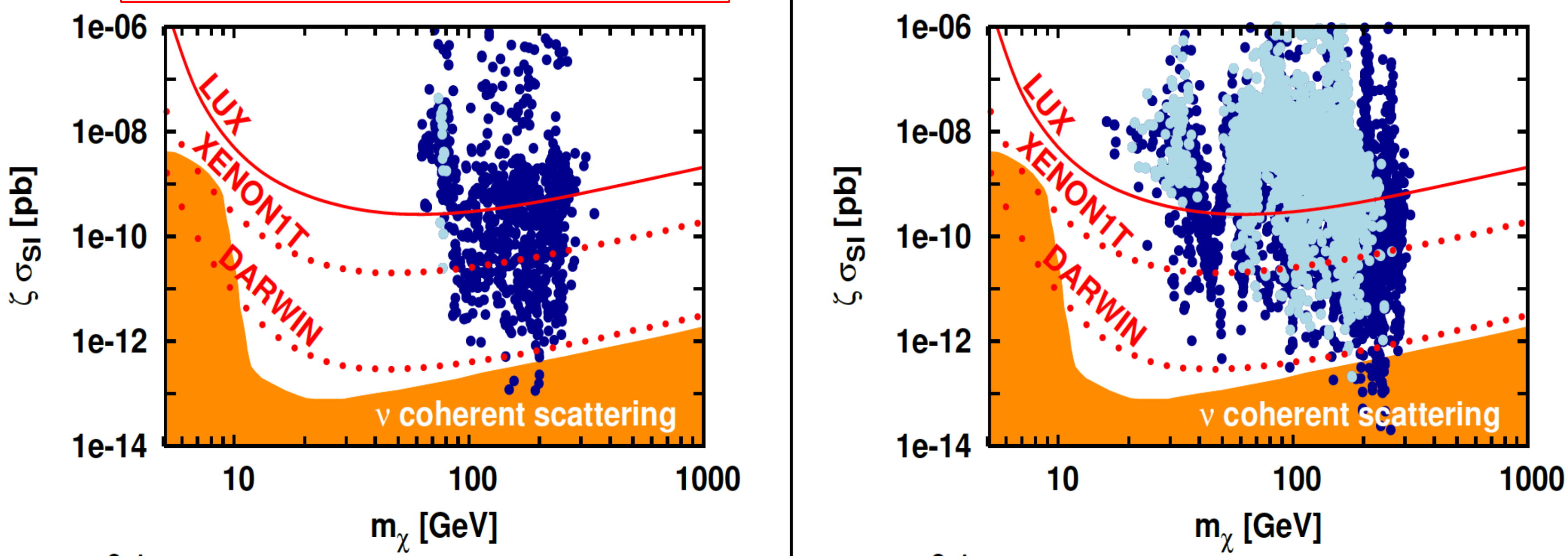
DARWIN: 50 t LXe

L. Baudis, KIT, 2017

Future sensitivity for NMSSM

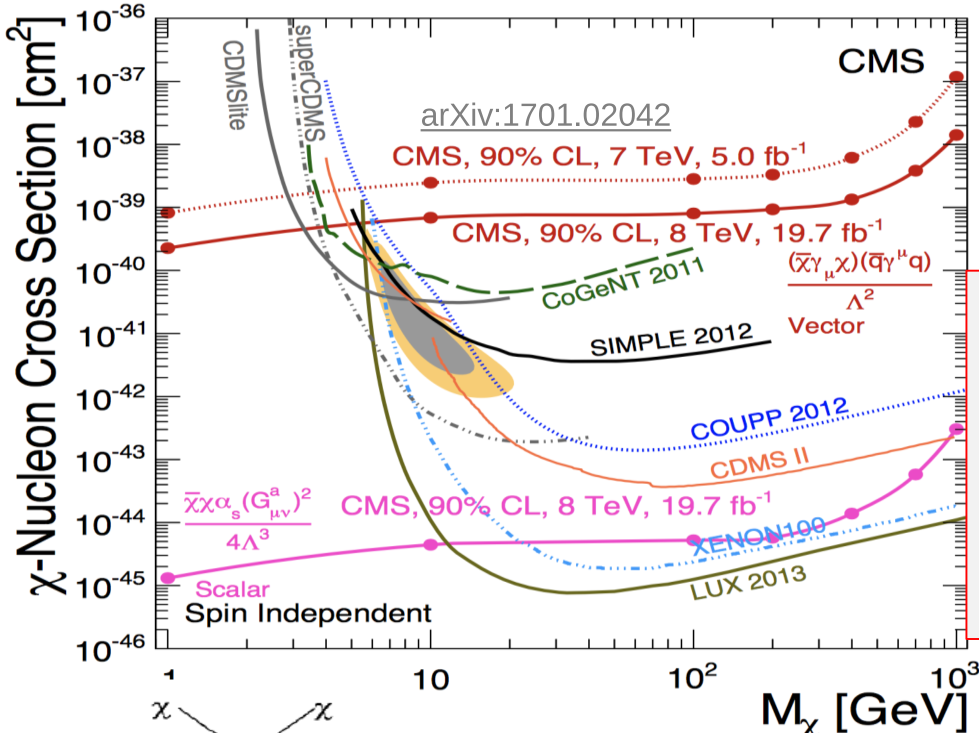
LSP= Higgsino,
predicted DM < observed DM
(dark blue ponts)
ς = pred/obs relic density

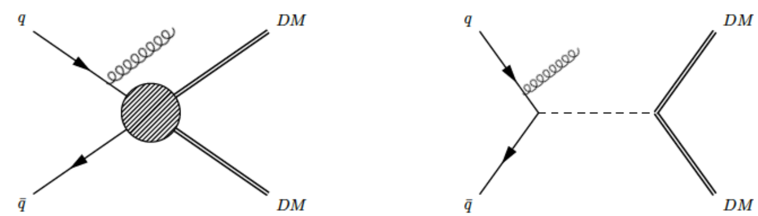
LSP= Singlino,
predicted DM ≈ observed DM
(light blue points)



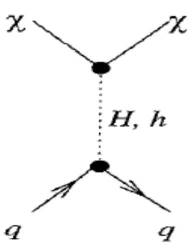
Beskidt, WdB, Kazakov, **PL B771 (2017) 611,** **arXiv:1703.01255**

LHC limits from monojets (or Z) with missing energy

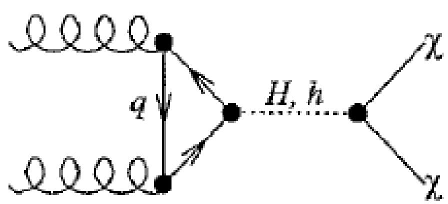




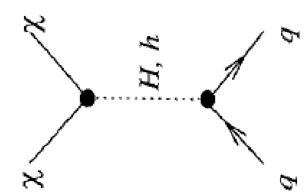
Beware: LHC data interpreted within non-renormalizable effective theories (assuming propagator mass heavy). Not true, so not valid. Wait for realistic comparison within single model using (main) diagrams below



Direct scattering: light quarks,coherence, form factors

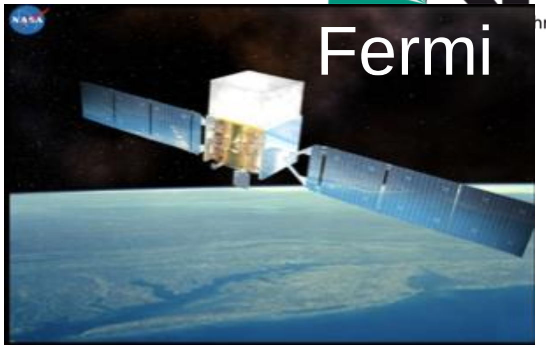


LHC: Loops with heavy quarks

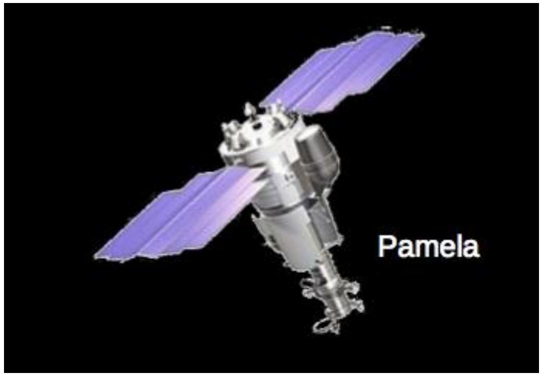


Annihilation: mainly into b-quark pairs

Annihilation signals



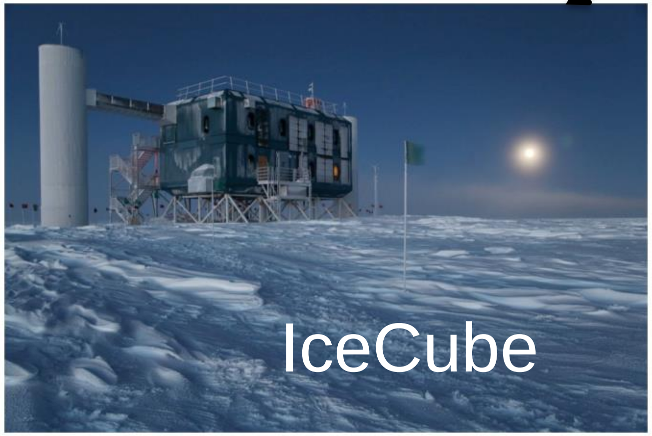
Charged particles

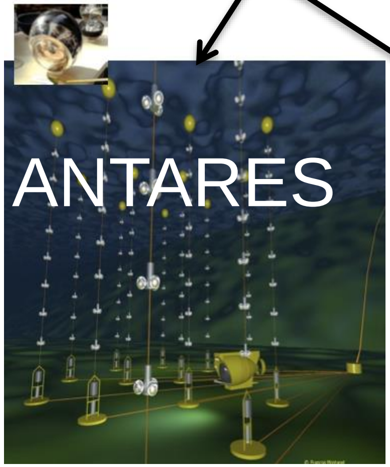


GAMMA-RAYS

See Carsten Rott
@ICRC2017 for details

Neutrinos





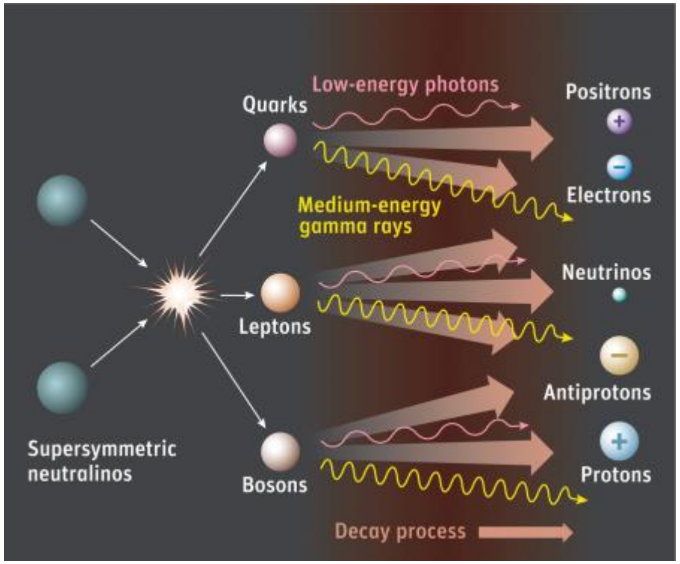
Indirect DM searches

- Annihilation of neutralinos

→ 30-40 photons per annihilation...

- Expect measurable signal in the diffuse component
- Compare expected photon-fluxes and spectra with measured fluxes

Strongest anomaly: Fermi GeV excess



- Background components:

- pion decays
- Inverse Compton Effect
- Bremsstrahlung
- isotropic background

Note 1: spectrum from all particles In DM annihilation known from e+e- annihilation data from LEP collider

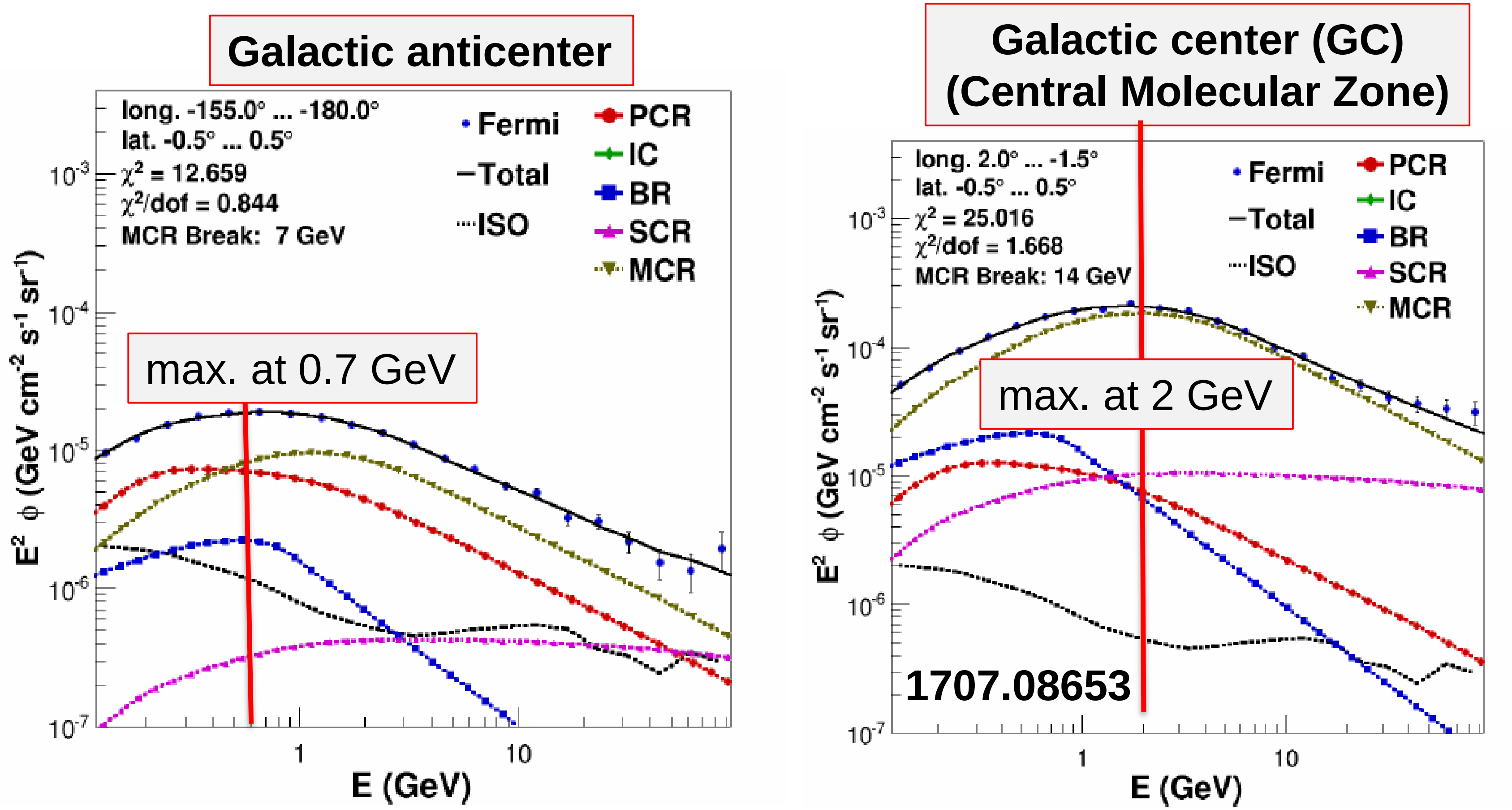
Note 2: charged particles will not point back to DM source, so difficult to interpret. Concentrate on gamma-rays

Fermi GeV excess papers

(adapted from Weniger, Rencontres du Vietnam, 2017)

Goodenough & Hooper, arXiv:0910.2998 (proposing DM)
- Vitale & Morselli, 2009
- Hooper & Goodenough, Phys. Lett. B697 (2011) 412
- Hooper & Linden, Phys. Rev. D84 (2011) 123005
- Boyarsky, Malyshev & Ruchayskiy, Phys. Lett. B705 (2011) 165
- Abazajian & Kaplinghat, PRD 86 (2012) 083511
- Hooper & Slatyer, Phys. Dark Univ. 2 (2013) 118
- Gordon & Macias, Phys. ReV. D88 (2013) 083521
- Macias & Gordon, PRD 89 (2014) 063515
- Abazajian, Canac, Horiuchi, Kaplinghat, Phys. Rev. D90 (2014) 023526
- Cholis, Evoli, Calore, Linden, Weniger, Hooper, JCAP 1512 (2015) 12
- Calore, Cholis & Weniger, JCAP 1503 (2015) 038
- Zhou, Liang, Huang, Li, Fan, Chang, Phys. Rev. D91 (2015) 123010
- Gaggero, Taoso, Urbano, Valli & Ullio, JCAP 1512 (2015) 056
- Daylan, Finkbeiner, Hooper, Linden, Portillo et al., Physics of Dark Universe 12 (2016) 1 (DM)
- De Boer, Gebauer, Neumann, Biermann, arXiv:1707:08653, PRD, August, 2017 (Molecular Clouds)
- Huang, Ensslin & Selig, JCAP 1604 (2016) 030
- Carlson, Linden, Profumo, Phys. Rev. D94 (2016) 063504
- Bartels, Krishnamurthy, Weniger, Phys. Rev. Lett. 116 (2016) (Millisecond pulsars)
- Macis, Gordon, Crocker, Coleman, Paterson, arXiv:1611.06644
- Lee, Lisanti, Safdi, Slatyer, Xue, Phys. Rev. Lett. 116 (2016) 5 (Millisecond pulsars)
- Ajello et al. 2016, Astrophys. J. 819, 44
- Ackermann et al., 2017, Astrophys. J. 840, 43
- Ajello et al., 2017, arXiv:1705.00009 + others + many theory papers

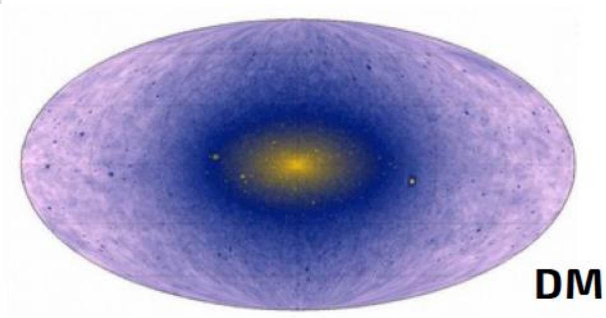
What is the Fermi GeV excess?



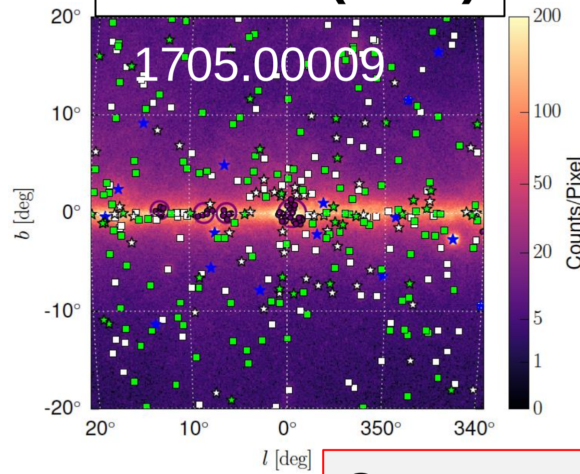
(Note: spectrum in GC dominated by spectrum from CMZ, which peaks at 2 GV, Presumably because of suppression of low energy protons by energy losses and/or magnetic cutoffs)

Possible new sources

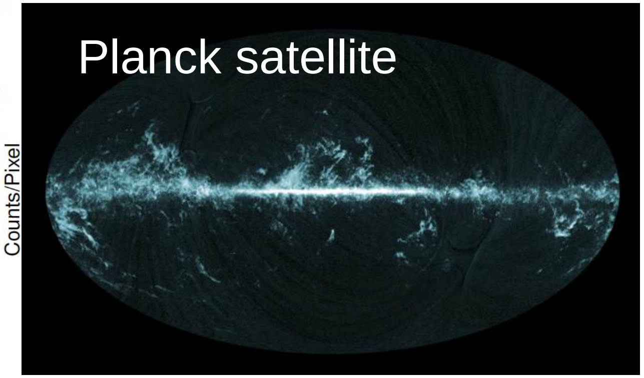
DM



Millisecond Pulsars (MSP)



Molecular Clouds (MC)



Pro:
All have spectra peaking around 2 GeV
All have maximum intensity at GC
MSP and MC „speckled“ intensities (observed-> no DM)
All have sharp decrease in latitude (all consistent with DM profile)

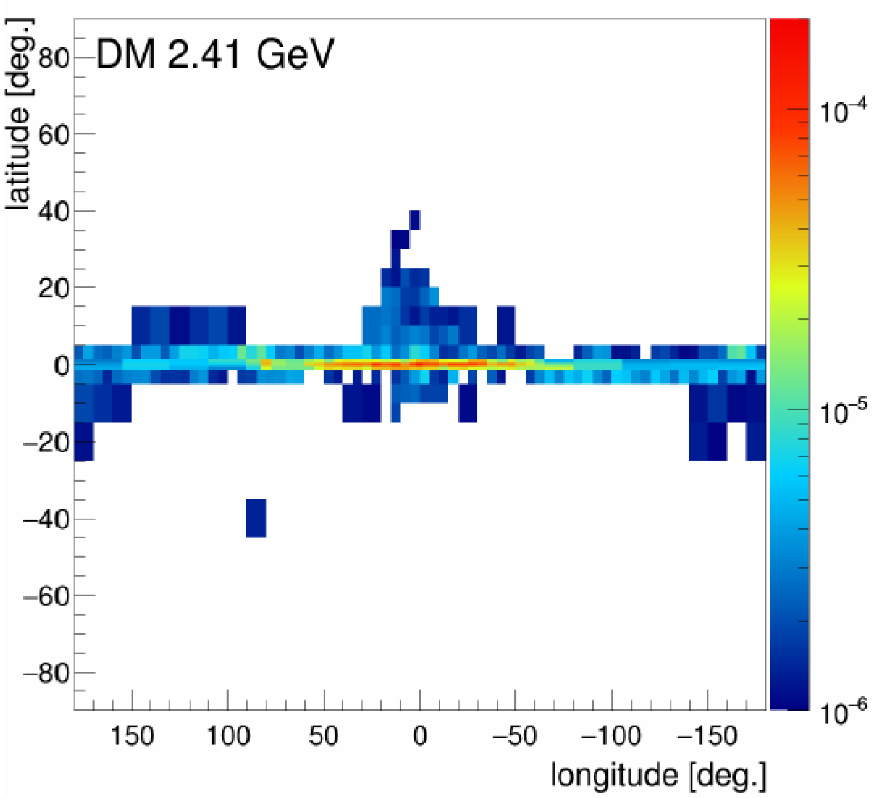
Contra:
MSP mostly unresolved (66 clearly obs.
Need ≈3500 in disk, ≈1300 in bulge,
but consistent with detection efficiency
-> large uncertainty

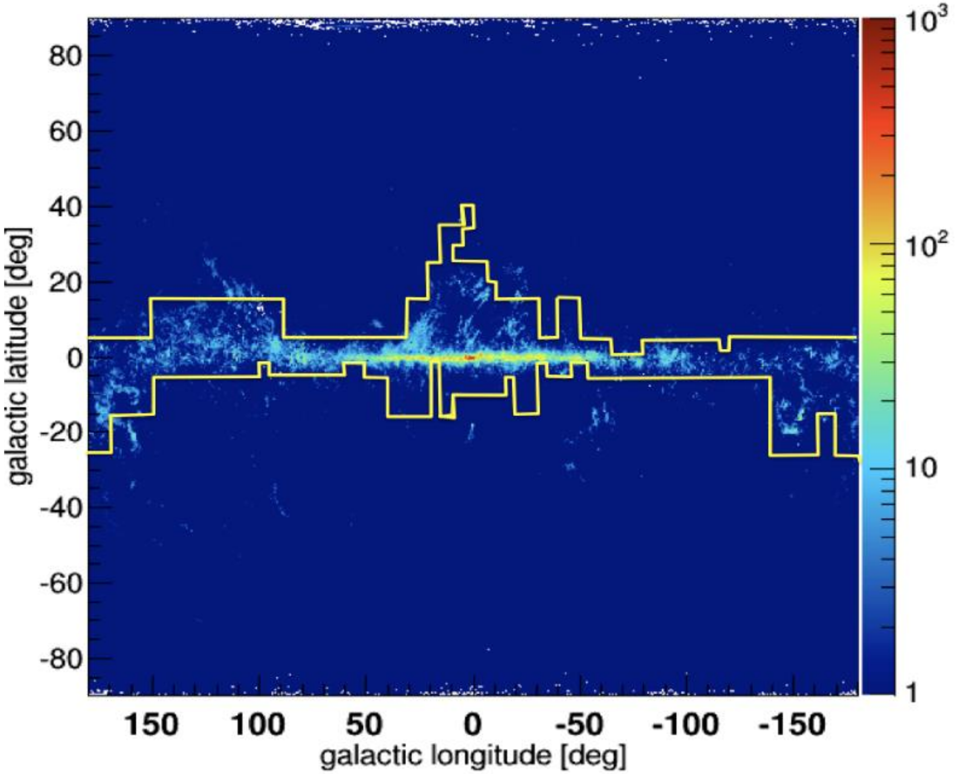
Excess oberved in Galactic disk away from center -> no DM

Distinguish by morphology and spectral fit quality

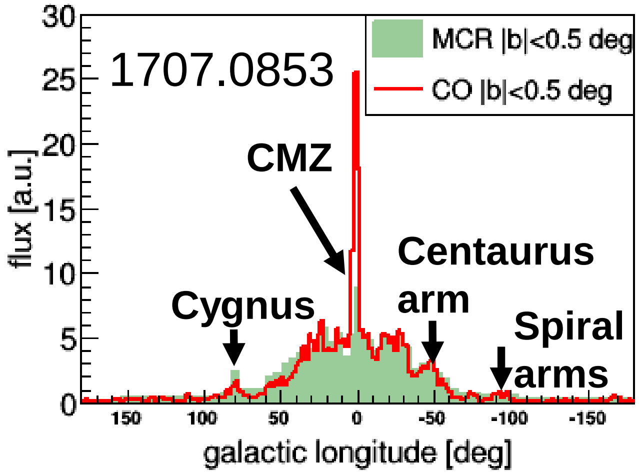
Excess follows CO distribution

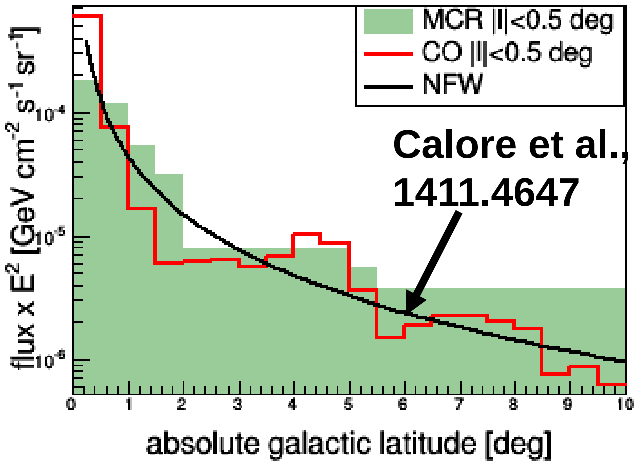
WdB + 1707.08653





CORRELATION BETWEEN MCR AND CO ROTATION LINES





CO surveys are the primary way of identifying molecular clouds (low J transitions).
We use the Planck measurements on the CO J 2 →1 emission.

Planck 2013 results. XIII. Galactic CO emission", Astron. Astrophys. 571 (2014) A13

The MCR template traces molecular clouds.

Along latitude the GeV-excess shows the morphology of a generalized NFW profile.

Conclusion on GeV excess

- Using a fit based on energy templates we find that the GeV excess is compatible with the emission of π^0 decay inside molecular clouds.

- We compared the dark matter hypothesis and the molecular cloud hypothesis to explain Fermi GeV excess.

- The molecular cloud hypothesis is preferred for the following reasons:
  - it provides better fits if the whole sky and all energies are considered
  - both hypotheses follow the CO profile instead of a NFW profile
  - the CMZ shows a strong excess in the Galactic Center in a longitudinal extended rectangular profile of $l \times b = 4^o \times 1^o$ instead of a spherical DM profile

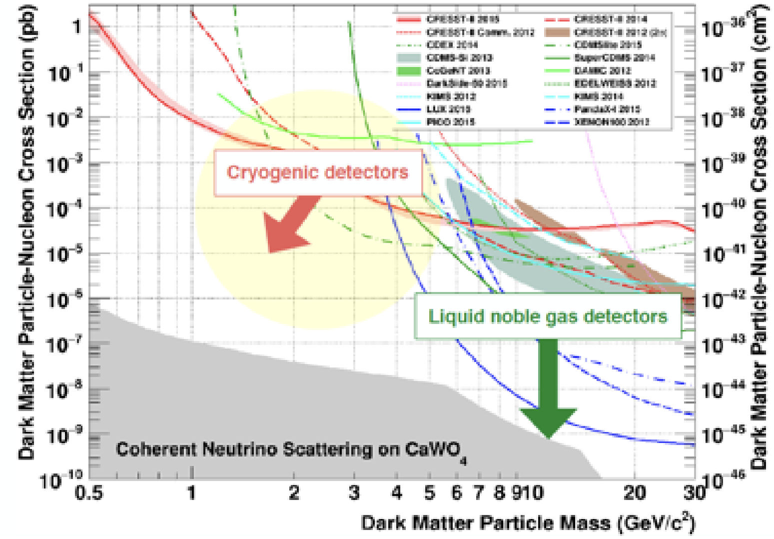
Summary

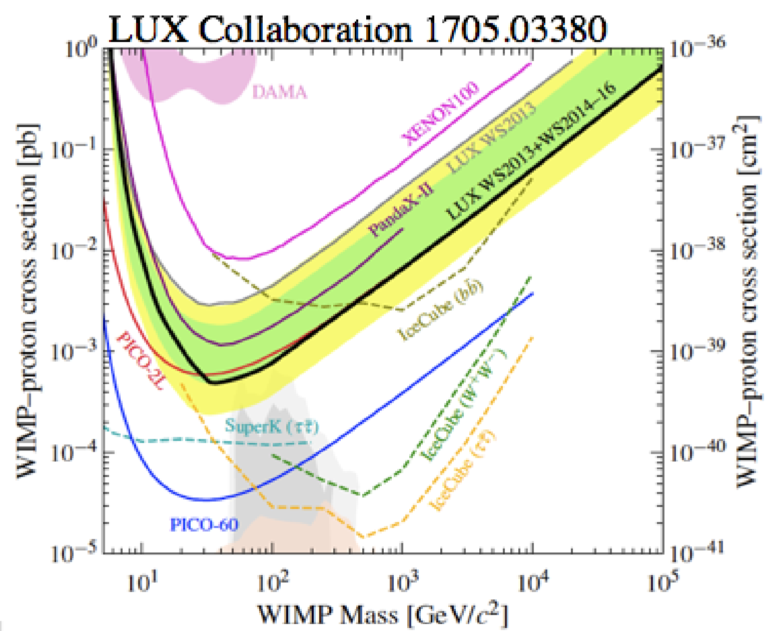
- No signals from elusive DM observed so far (except for gravity)
- Future experiments expected to be order of magnitude more sensitive
  - Direct DM searches: DARWIN 50 t LXe; ARGO 300 t LAr, DEAP-50T Lar, Pico, Icecube,
    (see Fiorelli´s talk)
  - Indirect DM searches: FERMI, CTA, DAMPE,
    (see Morselli´s talk)
  - LHC: 3000 fb^{-1} instead of 30 fb^{-1} at present

Future direct DM detection

Carsten Rott, ICRC2017

- Liquid Nobel Gases making rapid progress
    - Moving towards multi ton scales
    - Neutrino Floor in reach
- Bubble Chambers proves to be extremely competitive for SD searches (PICO, …)
- Impressive progress in exploring light DM region with cryogenic detectors (CRESST-III, CDMSLite, …)
- DAMA Anomaly to be resolved in the near future
- Directional DM to go below the neutrino floor
- Next generation experiments are going beyond single purpose





Future indirect DM detection