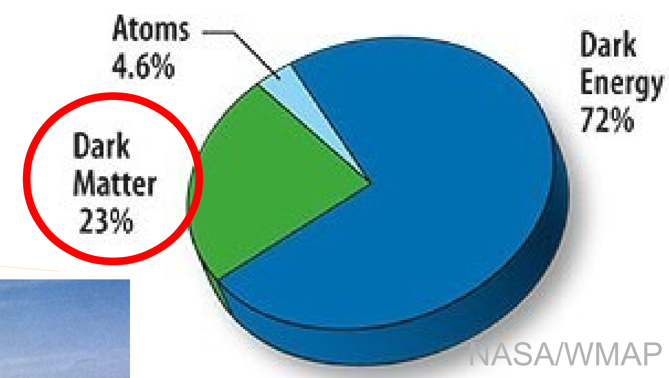
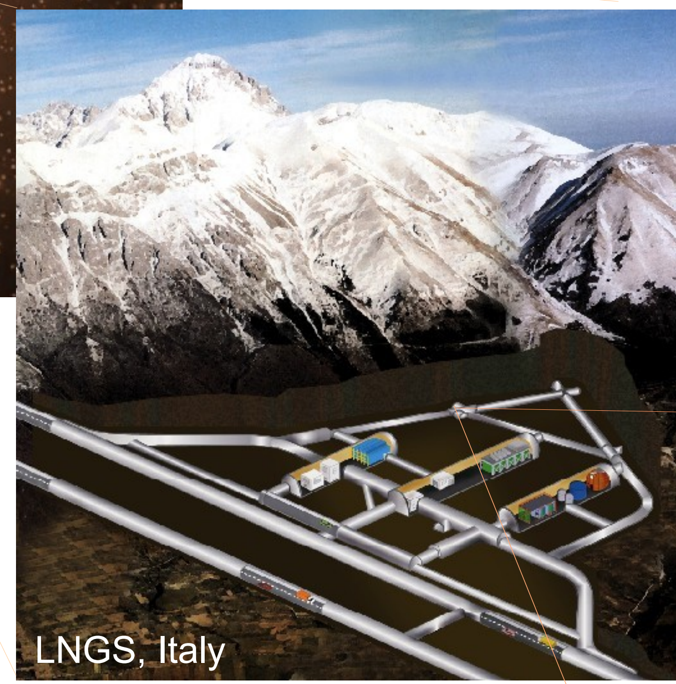
Searches for Dark Matter





Lecture for *Astroteilchenschule*

Obertrubach-Bärnfels
October 11-13, 2011

Uwe Oberlack

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Part 1:
Introduction
Accelerator & Indirect Searches

Outline of Lectures at Astroteilchenschule

Part 1

- Evidence for Dark Matter
- WIMP Dark Matter
- Accelerator Searches
- Indirect Searches

Outline of Lectures at Astroteilchenschule

Part 2

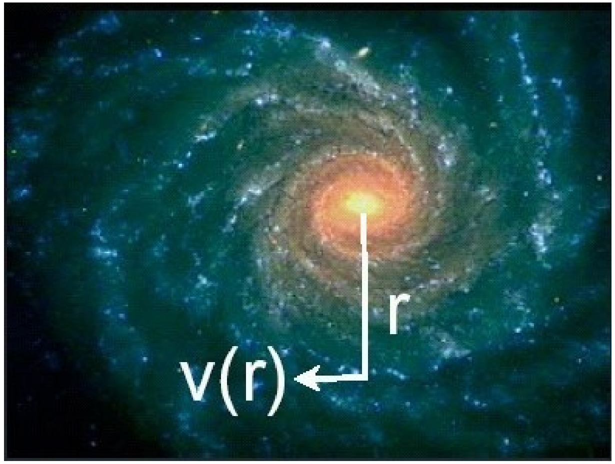
- Direct Detection Technique
  - Kinematics
  - Energy Spectrum
  - Astro, Nuclear, Particle Physics Inputs
- Experimental backgrounds
- Detector techniques:
  - Noble liquids
  - Cryogenic germanium
  - Cryogenic scintillating crystals
  - Superheated liquids

Outline of Lectures at Astroteilchenschule

Part 3

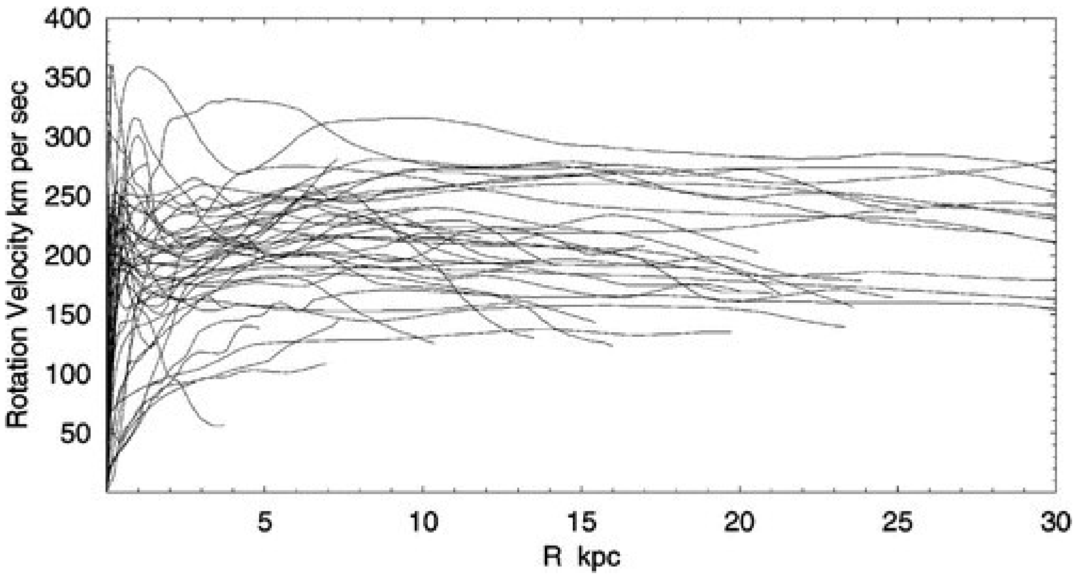
- Signals (?)
  - DAMA / LIBRA annual modulation
  - CoGeNT
  - CRESST-II
- and Limits
  - CDMS-II
  - EDELWEISS-II
  - COUPP
  - XENON100
- Future

Evidence for Dark Matter in Spiral Galaxies

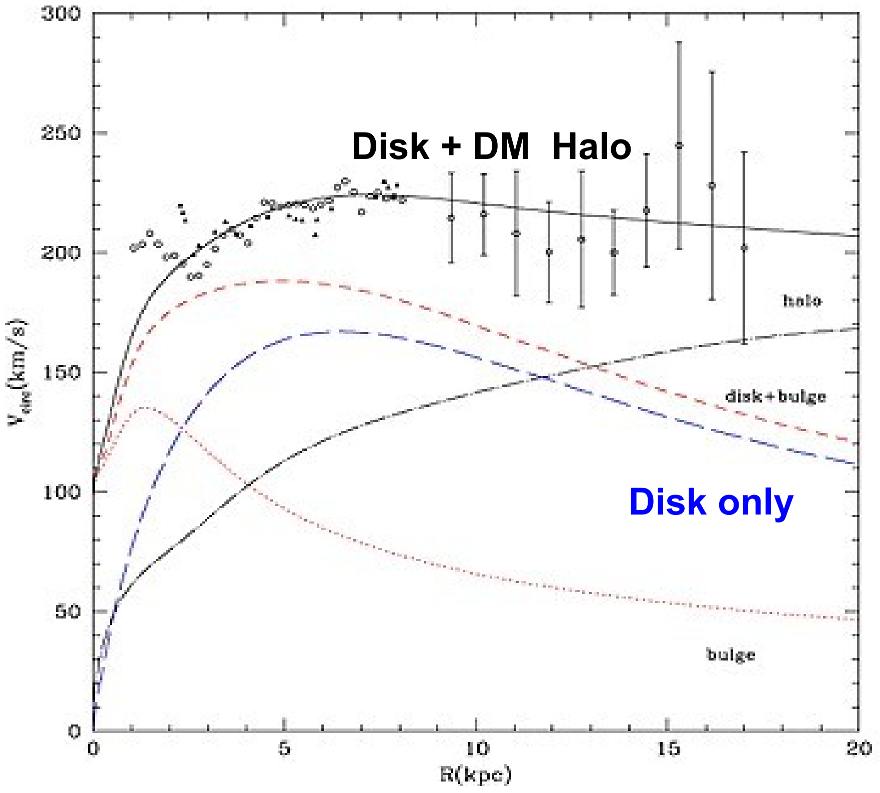


Rotation curves (orbital velocity vs. galactocentric radius) remain flat well beyond the edge of the visible disk in spiral galaxies.

$$\left.\begin{array}{lcl} v(R) & = & \sqrt{GM(R)/R} \\ v(R) & \approx & const \end{array}\right\} \Rightarrow \left\{\begin{array}{lcl} M(R) & \propto & R \\ \rho(R) & \propto & R^{-2} \end{array}\right.$$



Rotation curves of nearby galaxies
(Sofue & Rubin ARAA 2001)



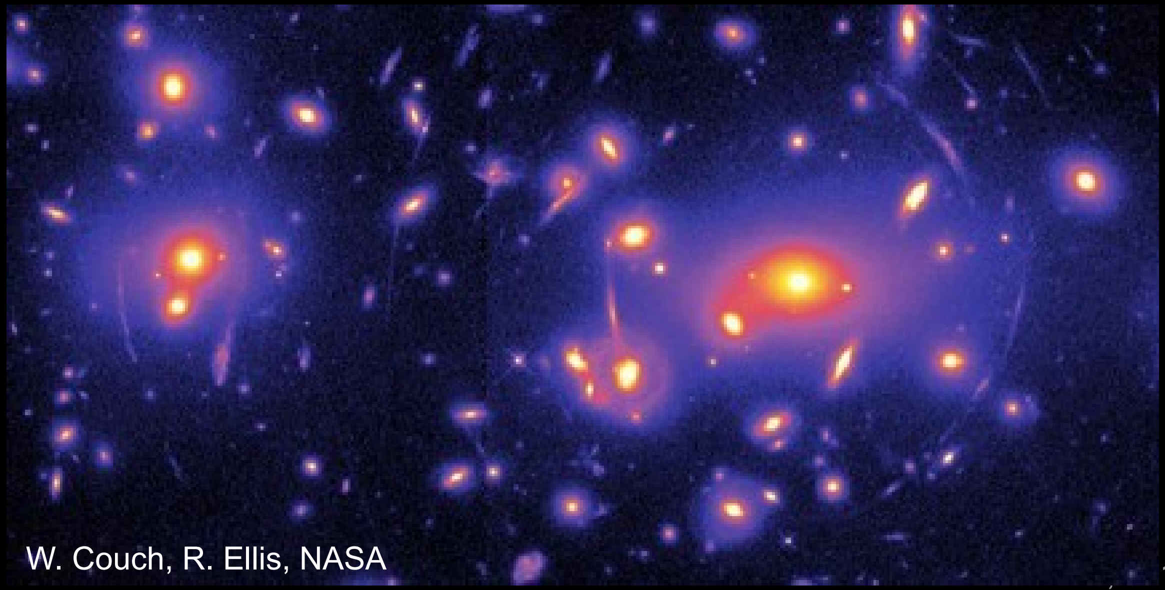
Rotation curve of the Milky Way
(A. Klypin et. al, ApJ. 573, 2002)

Evidence for Dark Matter in Galaxy Clusters

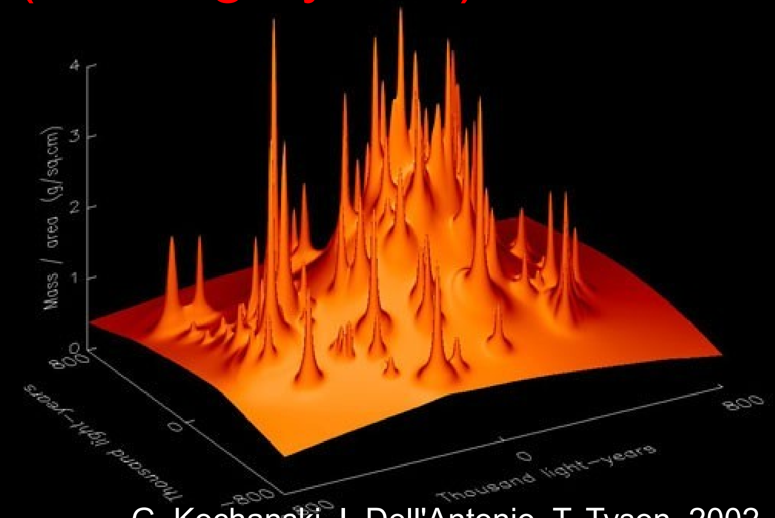
- Orbital velocities of galaxies exceed escape velocity estimated from visible mass in galaxies (Zwicky 1933).
- X-ray gas: pressure too great for visible mass. Traces gravitational potential.
- Gravitational lensing: measures total mass distribution in galaxy clusters.

NOAO/Kitt Peak: Uson, Dale
NASA/CXC/IoA: Allen et al.

Scale: ~10^{22} m (~10^{6} lightyears)

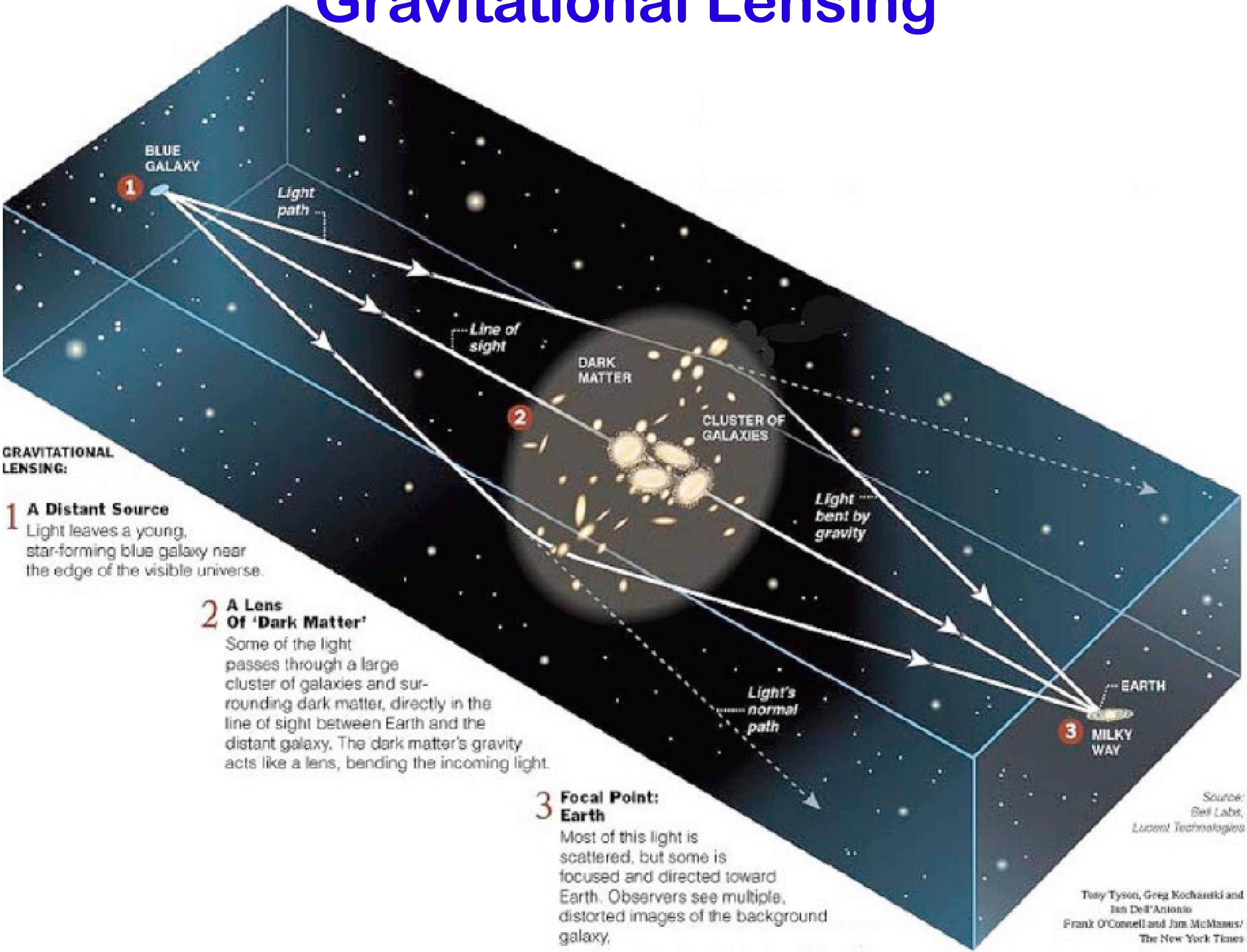


W. Couch, R. Ellis, NASA



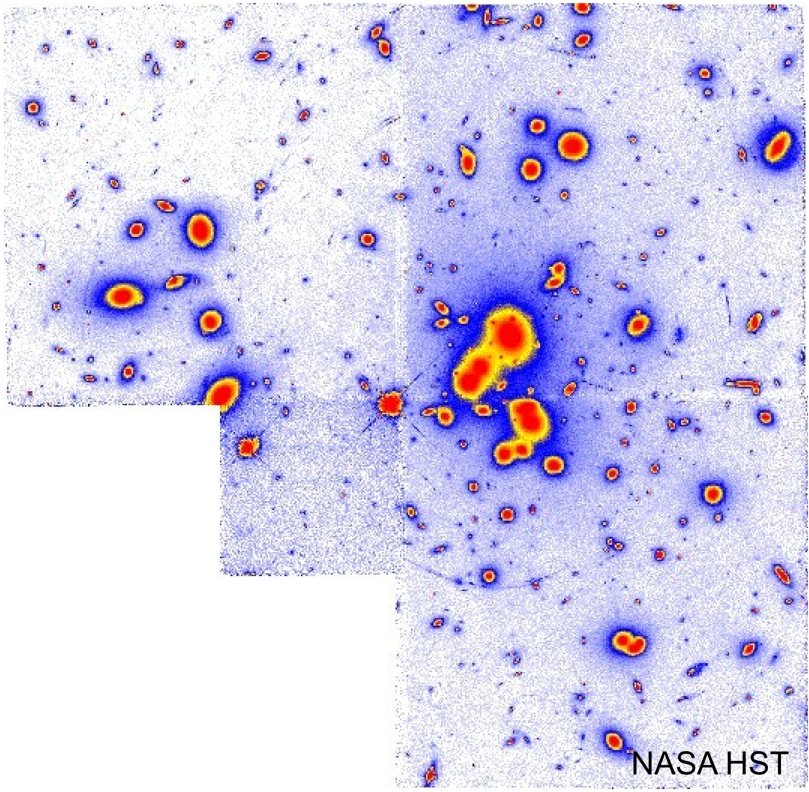
G. Kochanski, I. Dell'Antonio, T. Tyson, 2002

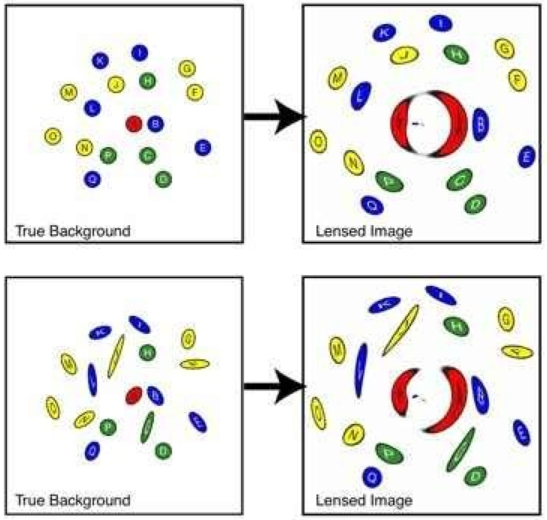
Gravitational Lensing



Weak Lensing

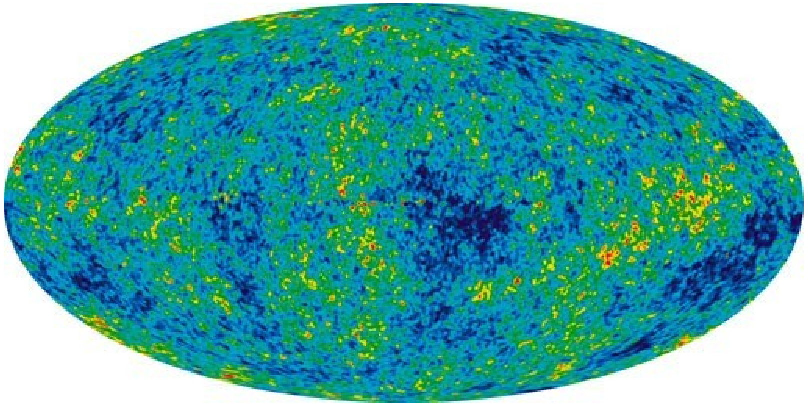
- Line of sight near galaxy cluster: strong lensing (long arcs)
- Further out: weaker distortions, but more abundant. → weak lensing
- Measure **total** mass distribution in galaxy clusters



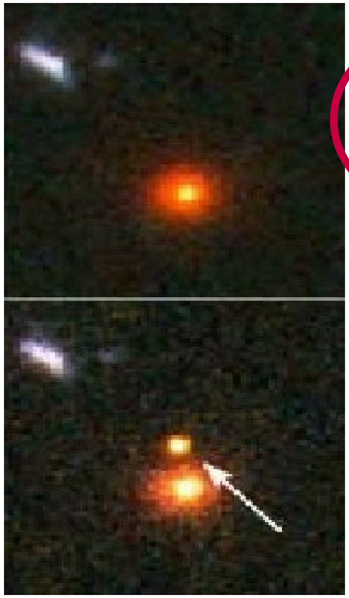


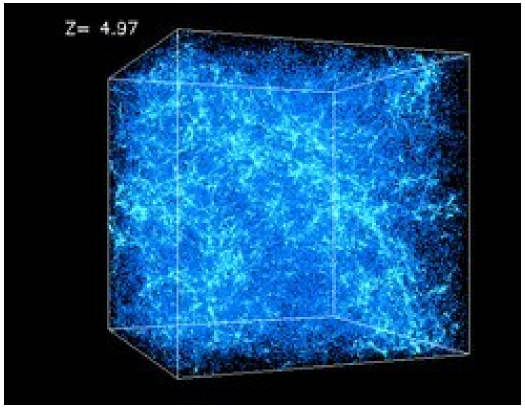
Bullet cluster
blue: total mass distribution from weak lensing

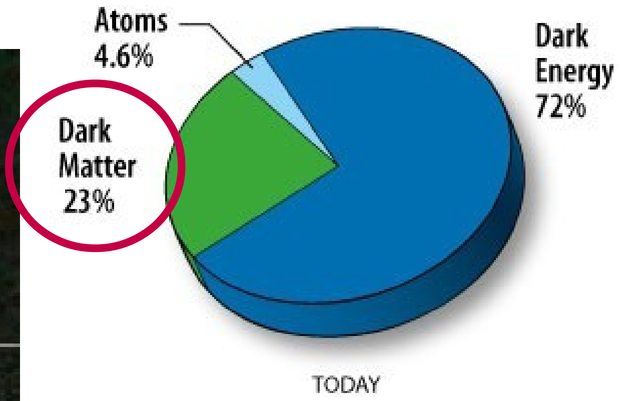
Evidence for Dark Matter from Cosmology

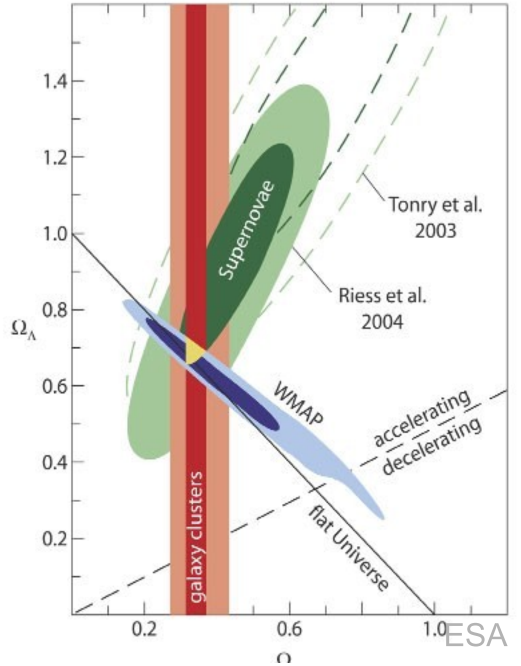


- Cosmic Microwave Background.
  - Uniformity at age 380,000 yr.
  - Flatness of the universe (with H_0 or other)
  - Baryon density, etc.
- Supernovae as standard candles.
  - Expansion history of the universe.
- Galaxy surveys (wide or deep) and Simulations of structure formation.
  - Large scale structure.
  - Early structure formation.
    First stars. Quasars and galaxies.
- Big Bang Nucleosynthesis and light element abundances observed in the early universe.
  - Limit on baryon density, consistent with CMB.
- Galaxy clusters
- Baryon Acoustic Oscillations
  - standard ruler
- ...









ESA

(

a brief excursion into the Dark Universe

Supernovae Ia and Cosmology

Observation: (1998/1999)

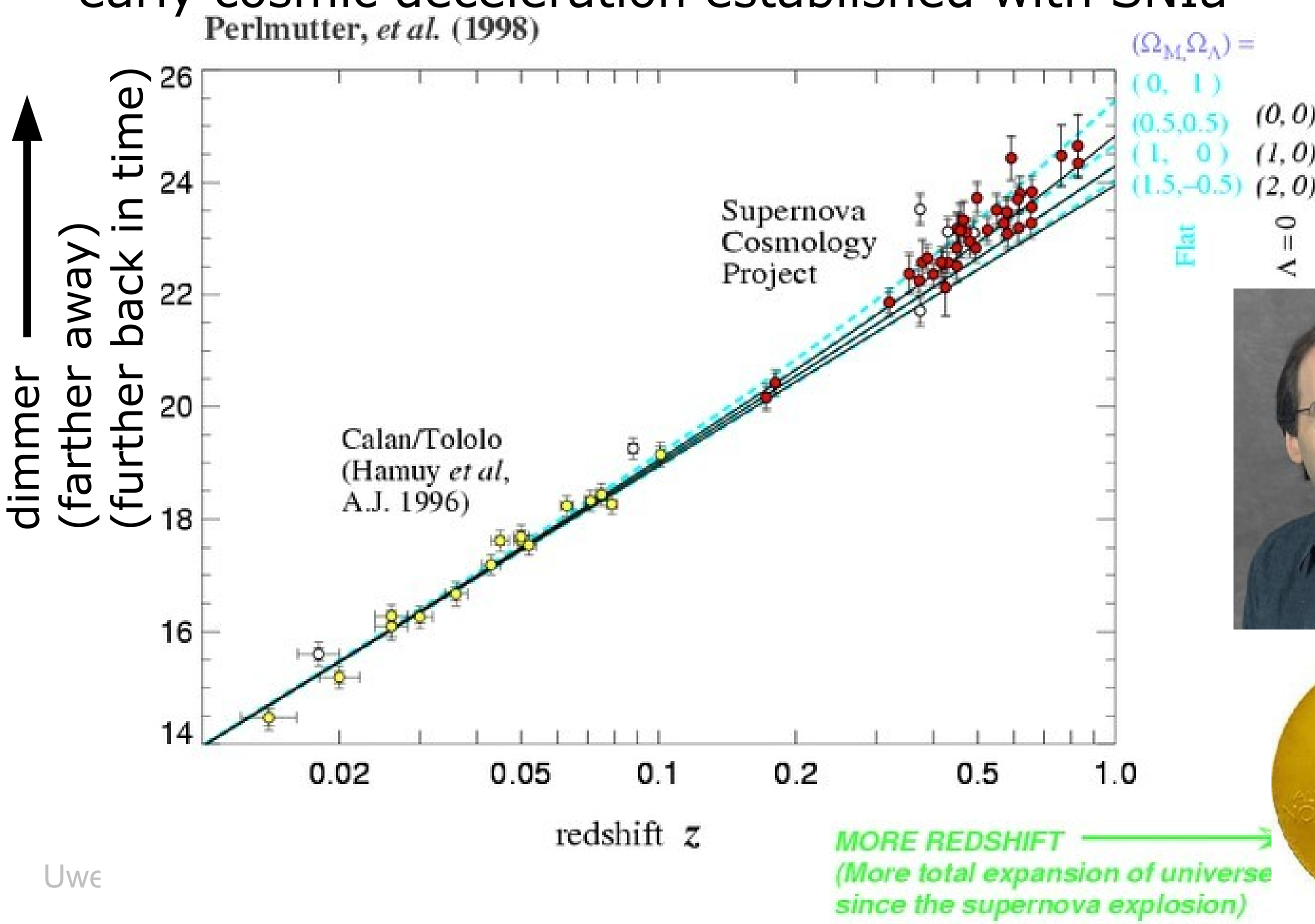
- At redshift $z > 0.3$ SN Ia are dimmer than expected from local sample of SN:

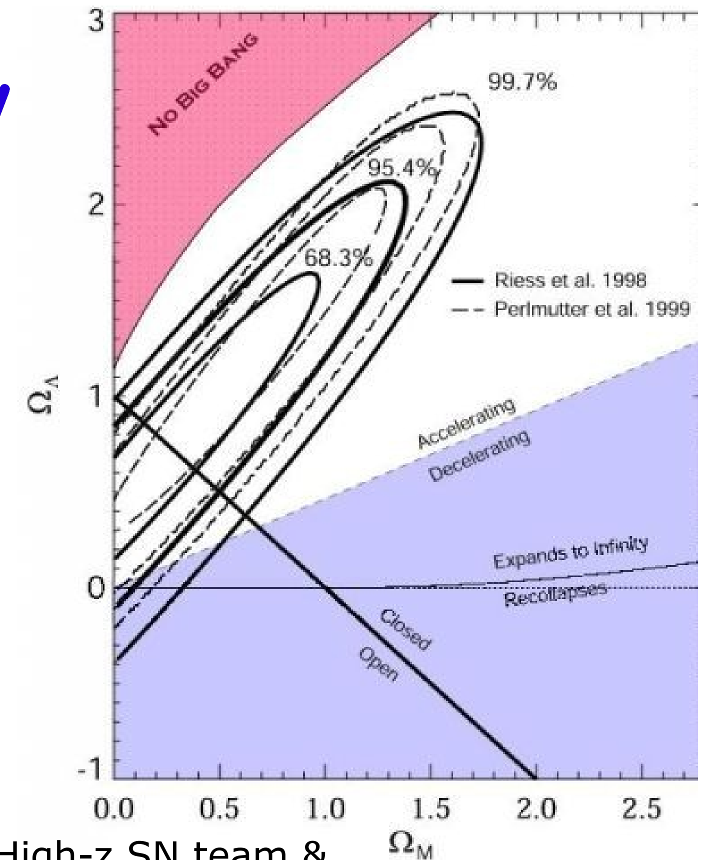
Interpretation:

- The universe was expanding more slowly in the past, i.e. the expansion is accelerating today.

Further observations at higher z (2004):

early cosmic deceleration established with SNIa





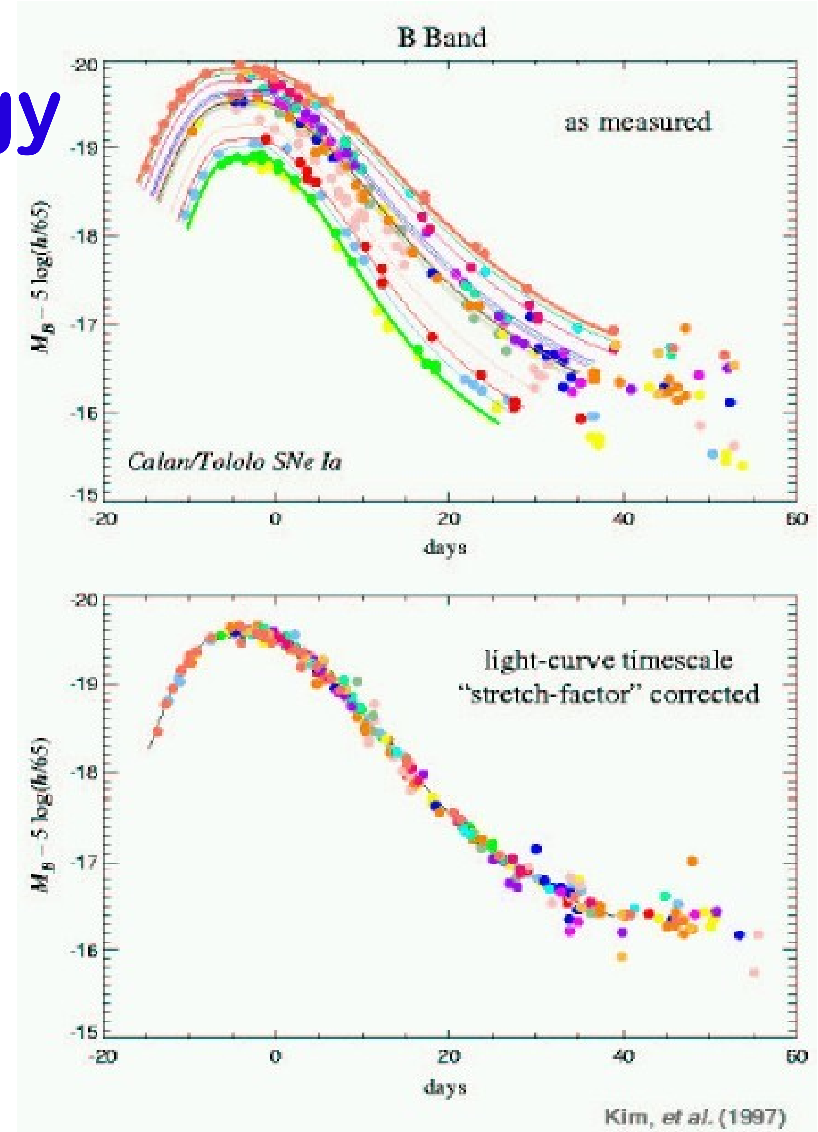
High-z SN team &
Supernova Cosmology Project

2011 Nobel Prize in Physics
Saul Perlmutter
Brian P. Schmidt
Adam G. Riess

Supernovae Ia and Cosmology

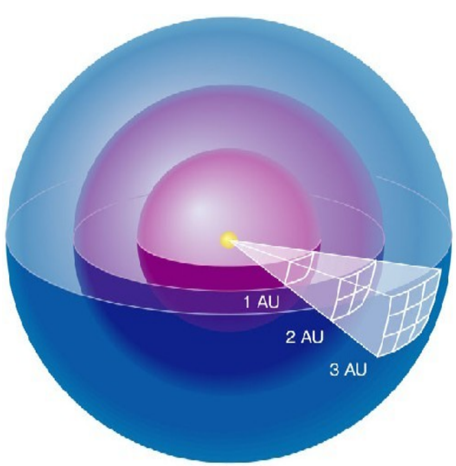
- Measurement of redshift z and peak flux of a large sample of White Dwarf (thermonuclear) supernovae (SN type Ia)
- Correct peak flux for intrinsic variations and reddening using
  - shape of light curve
  - colors
- Derive peak luminosity by comparison with local supernovae
  → "standard candle"
- Calculate luminosity distance

$$D_L = \sqrt{\frac{L}{4\pi F}}$$



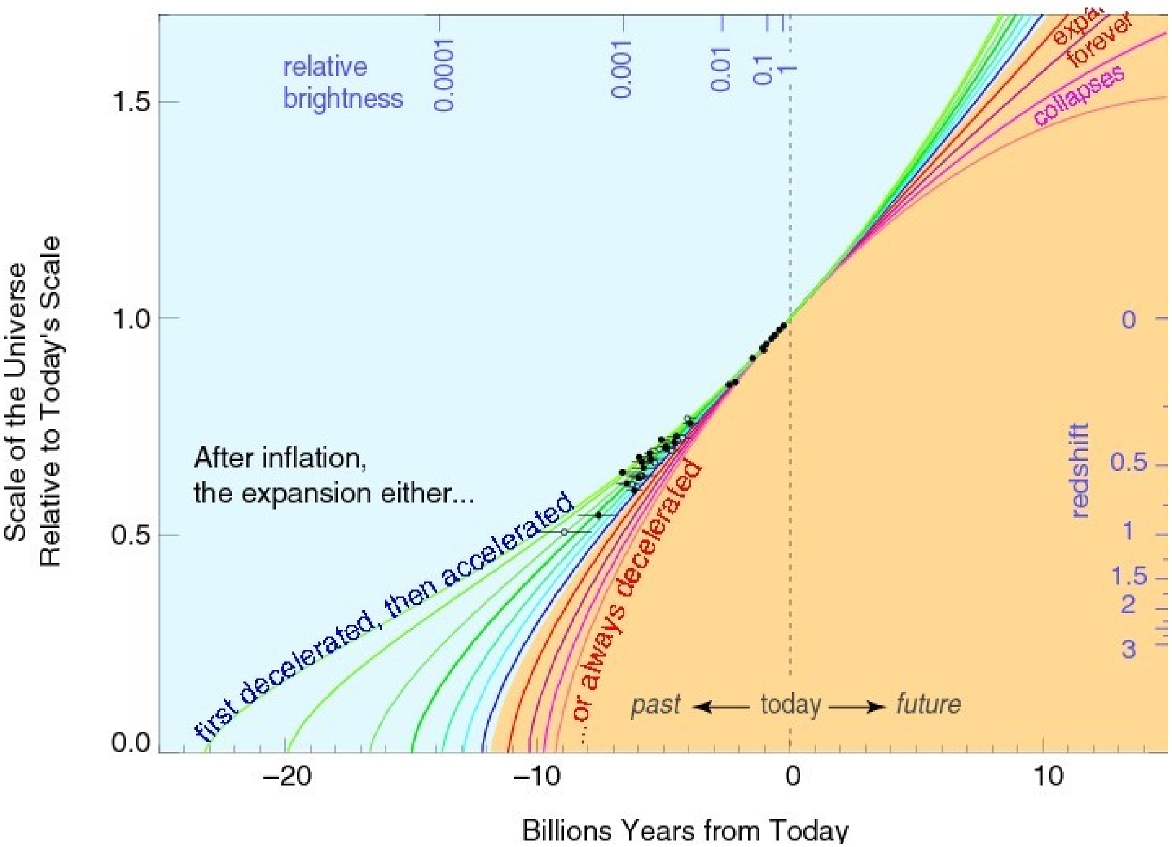
- Fit cosmological model (defining expansion history) in D_L and z:

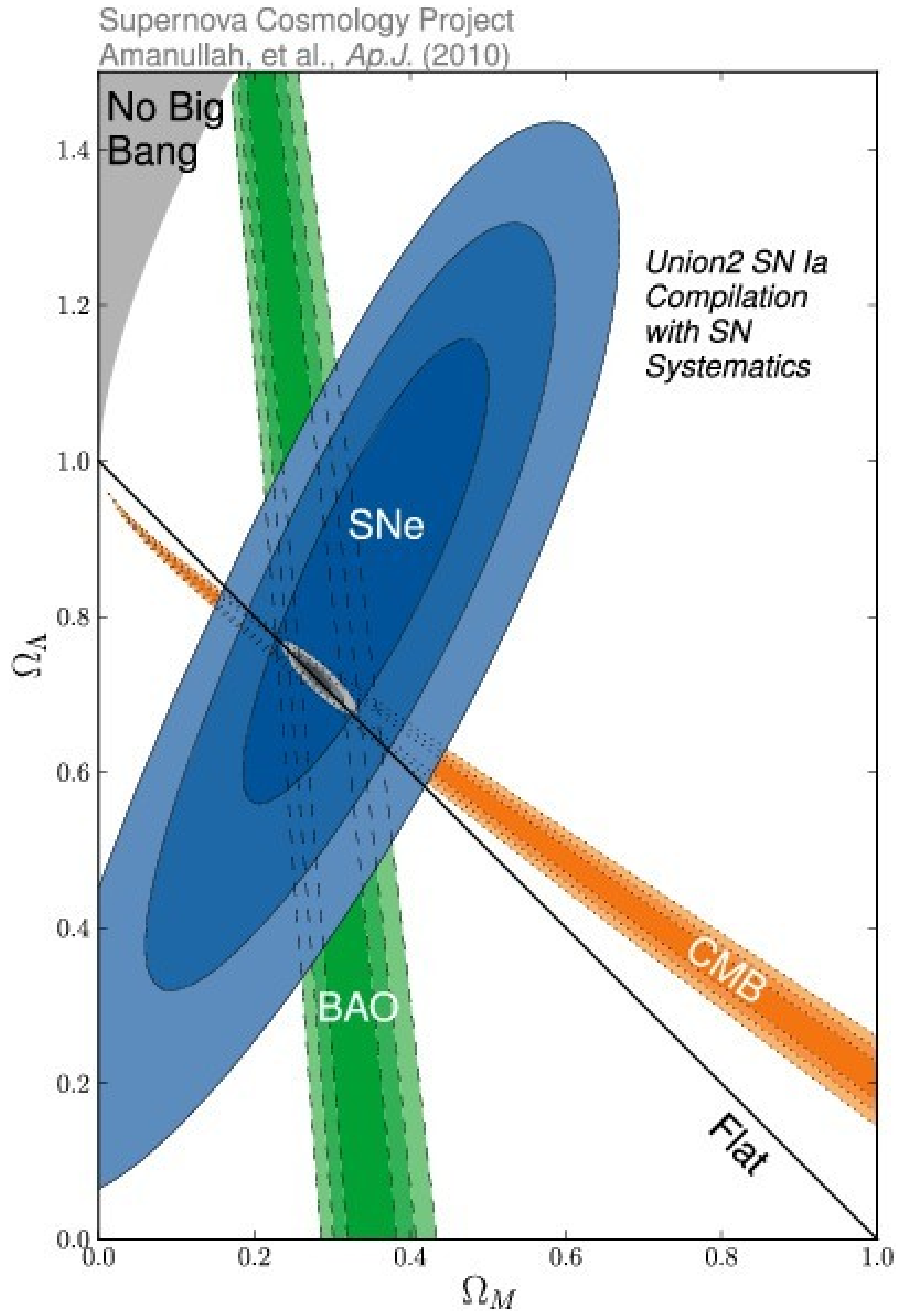
$$D_L = cH_0^{-1}(1+z)|\Omega_k|^{-1/2}\,\mathrm{sinn}\left\{|\Omega_k|^{1/2} \times \int_0^z dz[(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2}\right\}$$



Das ΛCDM-Modell und Supernovae Ia (Überblick)

- 1998: Supernovae Ia erscheinen bei großen Distanzen dunkler als erwartet.
- Hinweis auf beschleunigte Expansion des Universums heute.
- Beobachtungen von CMB und SN Ia sind "orthogonal" im Parameterraum: $\Omega_\Lambda - \Omega_m$: SN Ia, $\Omega_\Lambda + \Omega_m$: CMB





BAO: Baryonic Acoustic Oscillations

Dark Matter is non-baryonic.

Multipole Expansion of CMB

WMAP after dipole subtraction

Expansion in spherical harmonics:

$$T(\vec{n}) = T_0 \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{m=+\ell} a_{\ell m} Y_{\ell m}$$

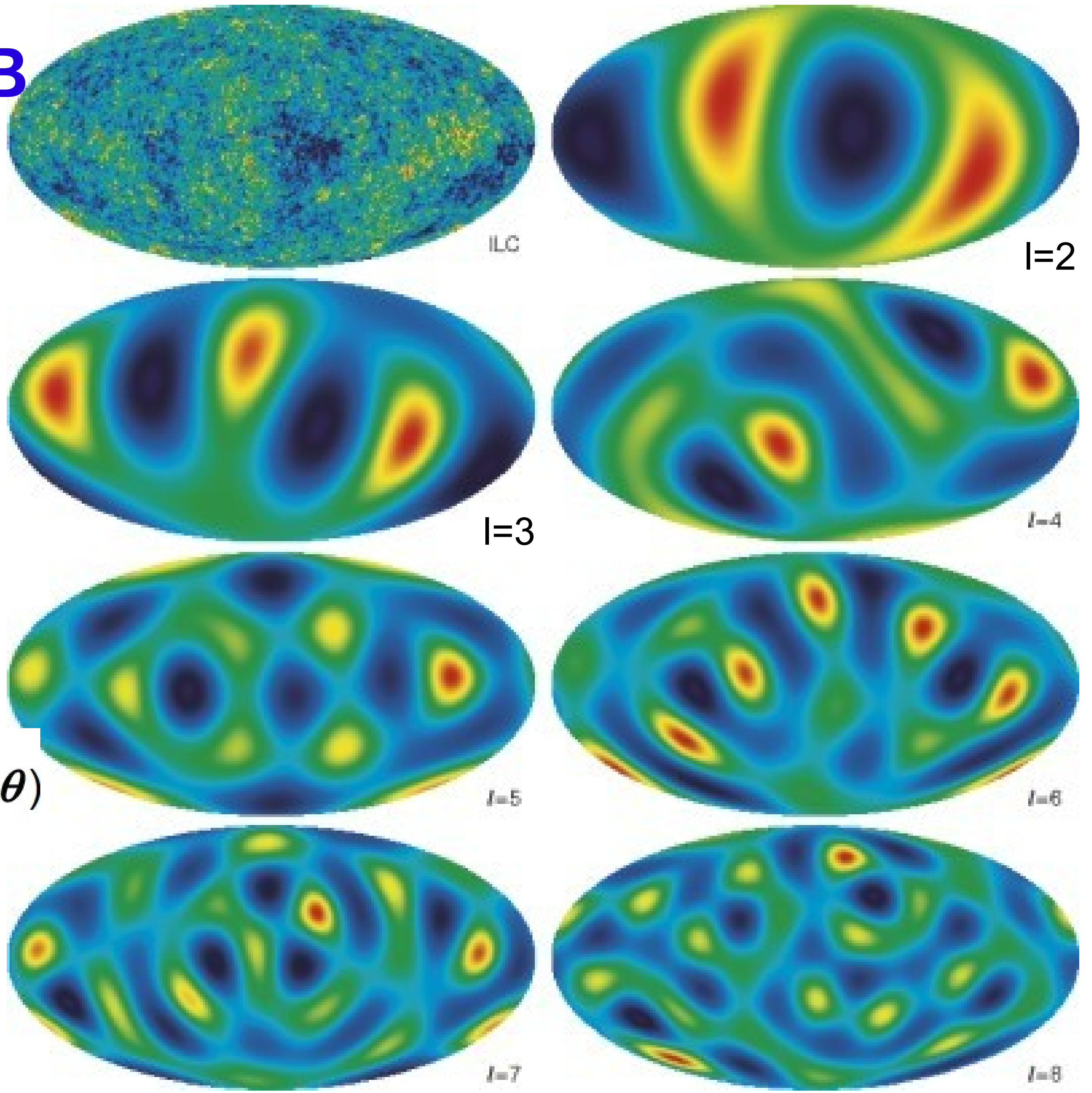
Pair correlation function:

$$C(\theta) = \left\langle \left(\frac{\Delta T(\vec{n})}{T_0} \right) \left(\frac{\Delta T(\vec{m})}{T_0} \right) \right\rangle$$

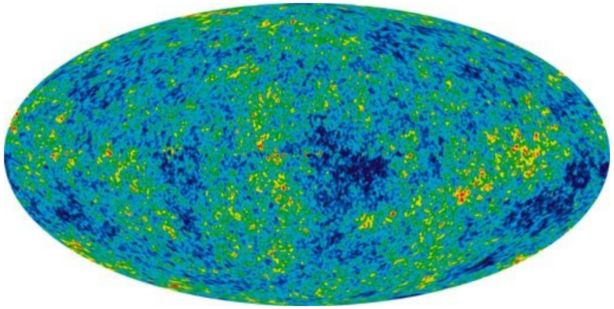
$$C(\boldsymbol{\theta}) = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) C_\ell P_\ell(\cos\boldsymbol{\theta})$$

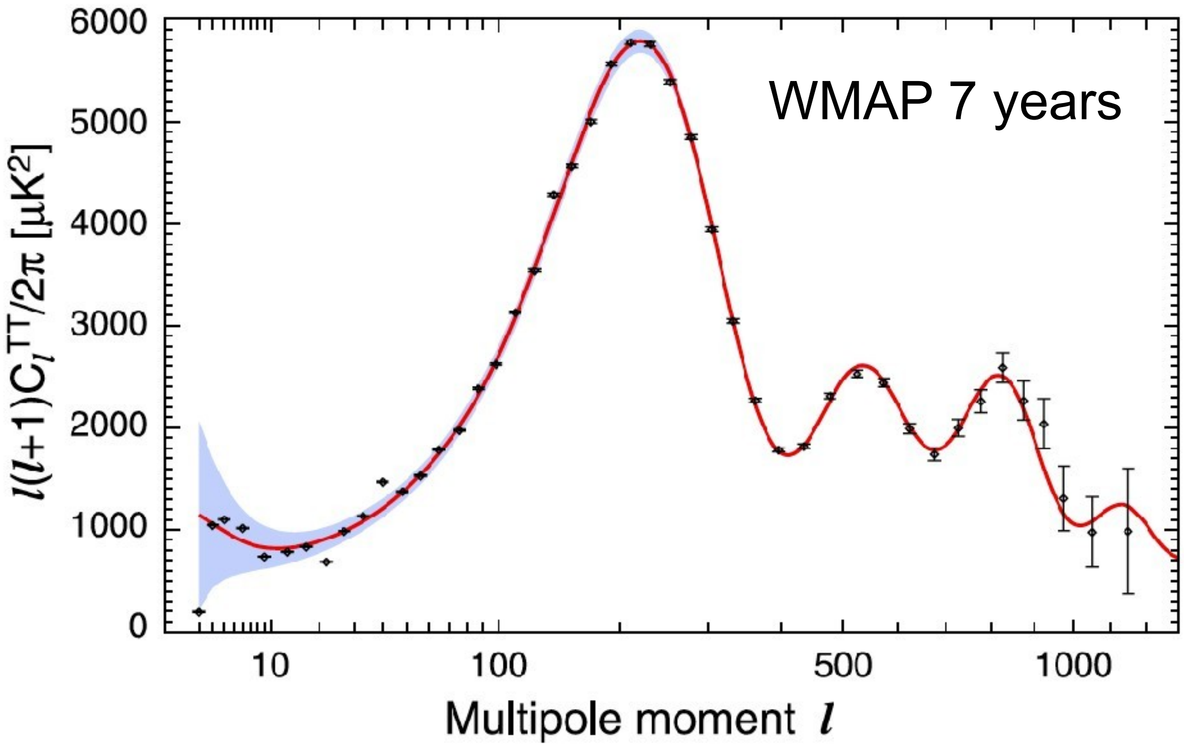
$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

$$(\Delta T)^2 = l\,(l+1)\,\frac{C_l}{2\,\pi}$$



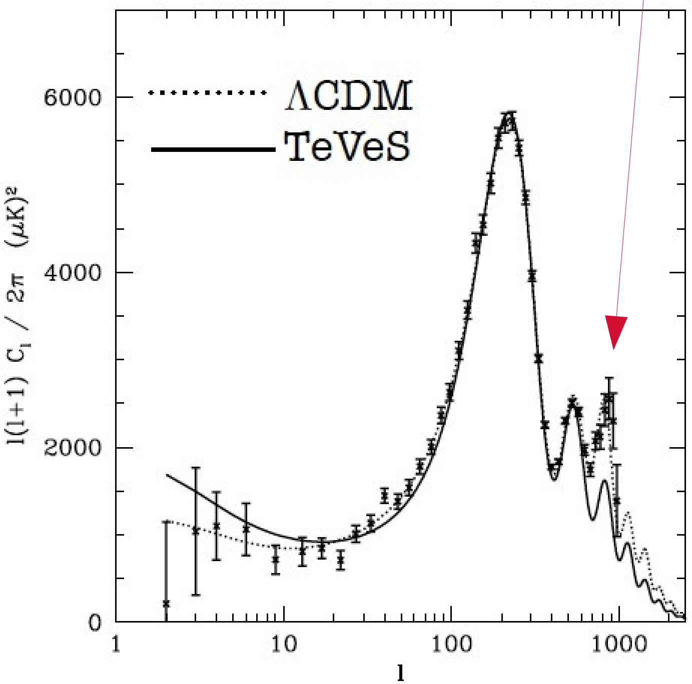
Non-baryonic Dark Matter



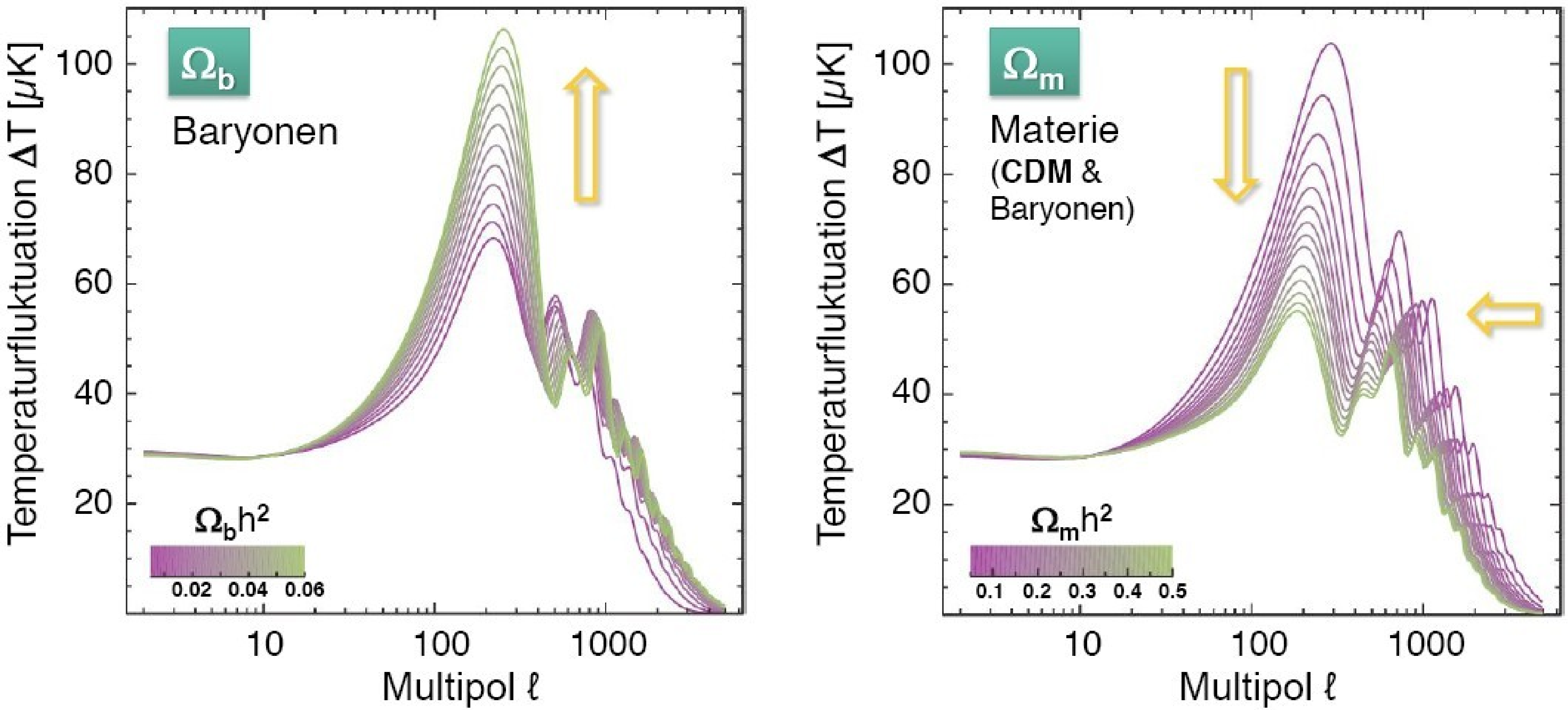


- Relative strength of acoustic peaks provides Ω_m and Ω_b independently.
- One can also test for alternative theories of gravitation (e.g., TeVeS): no alternative theory can do without Dark Matter.

3rd peak only with Dark Matter

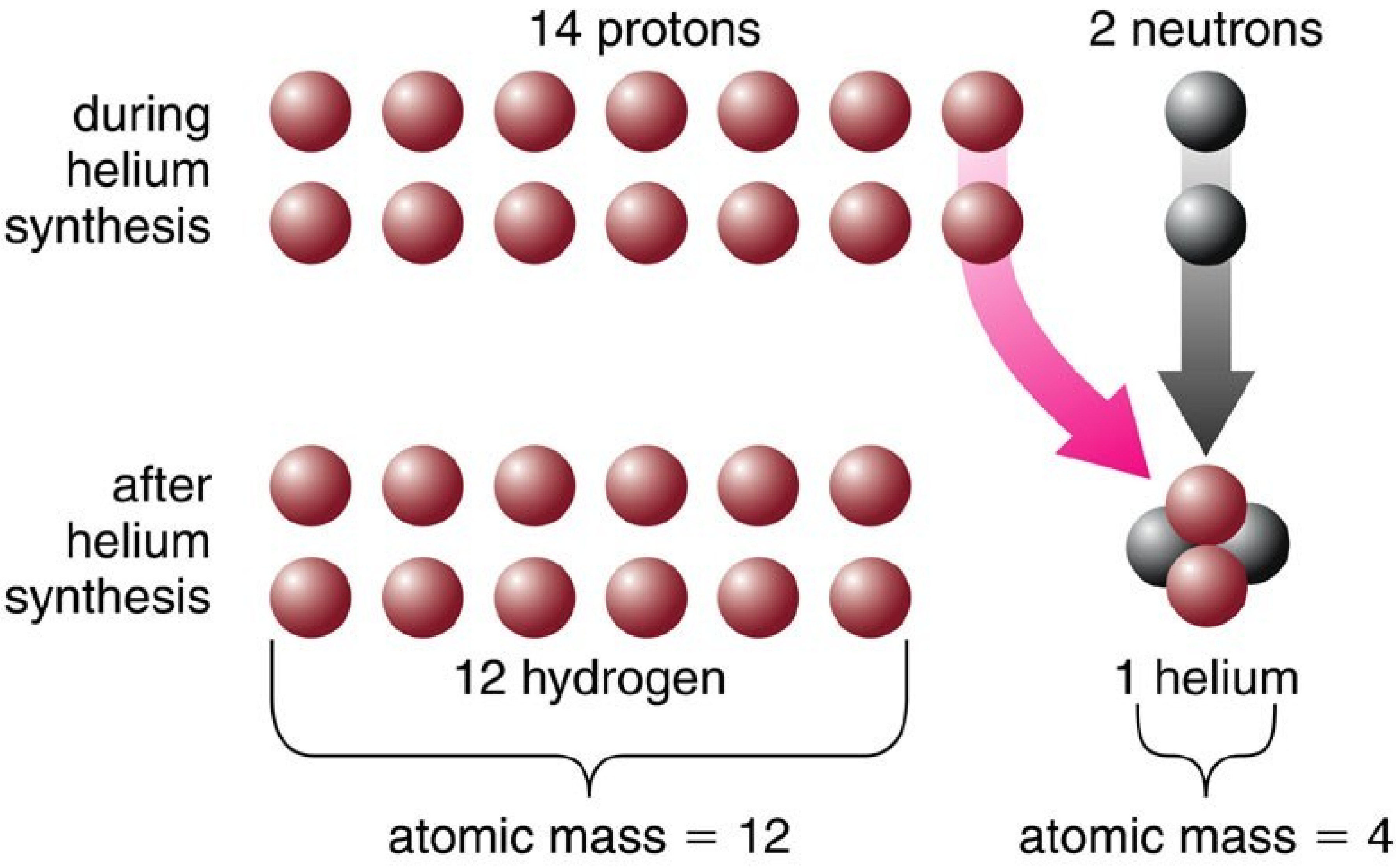


CMB Power Spectrum & Baryon Density



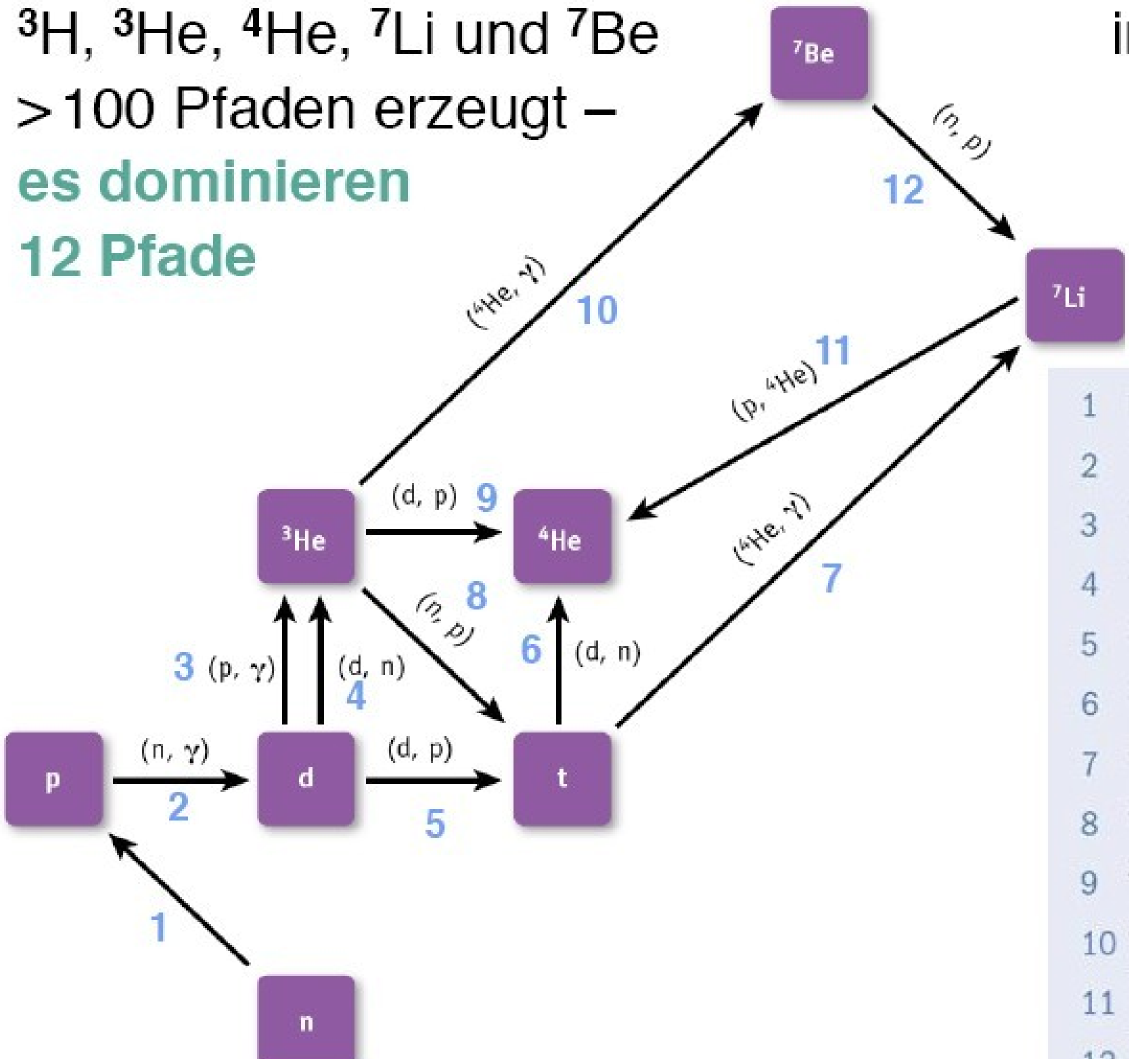
Primordial Nucleosynthesis

Big Bang Nucleosynthesis BBN

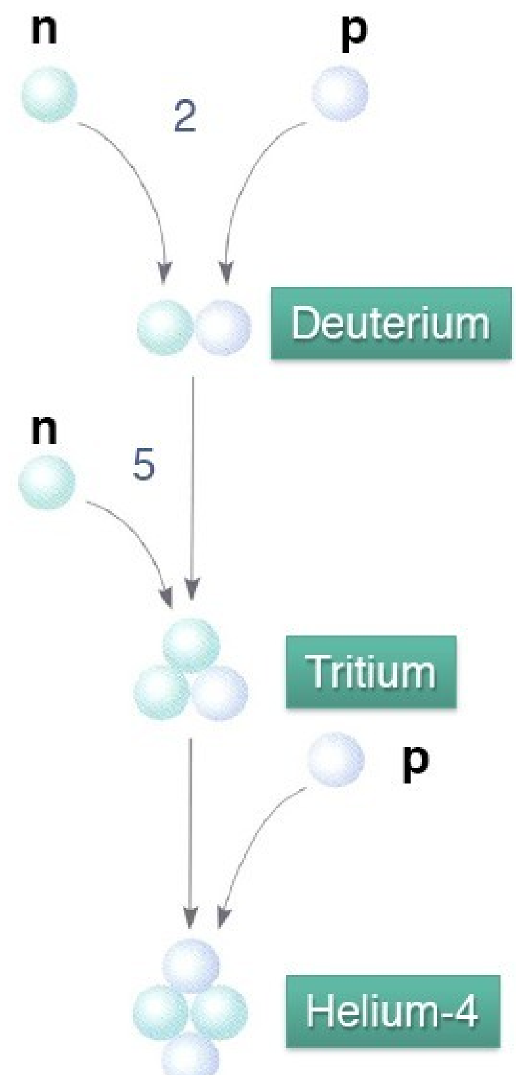


Big Bang Nucleosynthesis

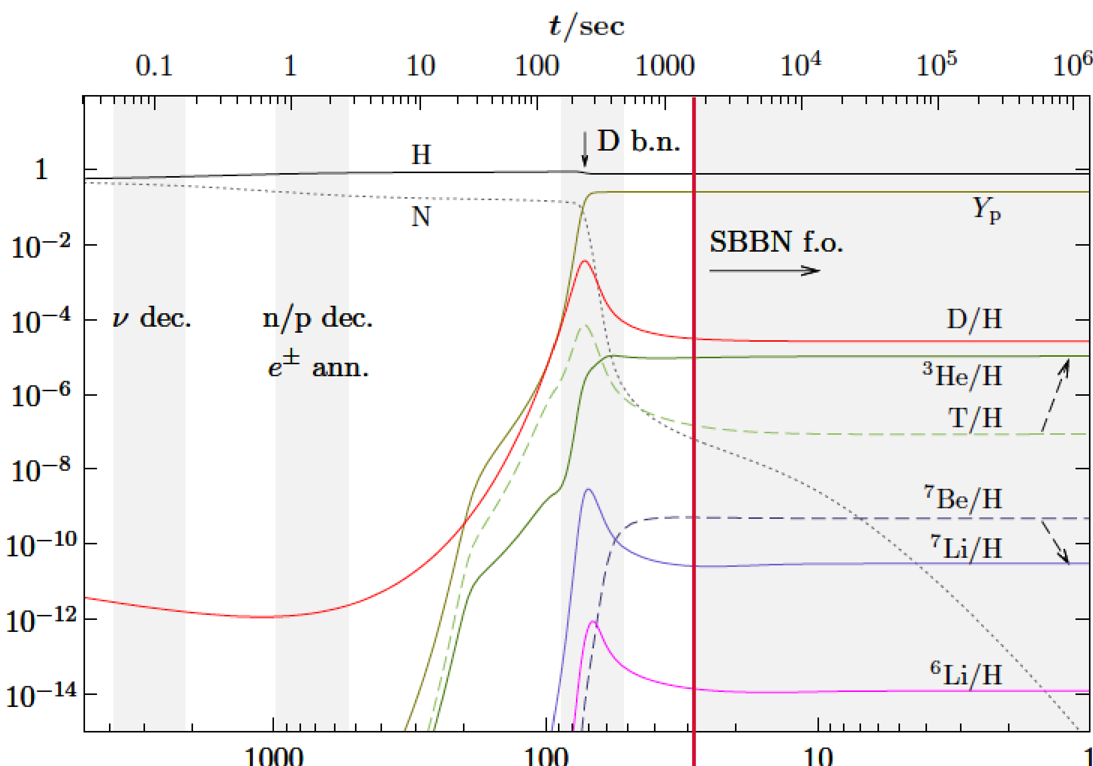
in den ersten 3 Minuten werden in der BBN aus p und n ^3H, ^3He, ^4He, ^7Li und ^7Be in über >100 Pfaden erzeugt –
es dominieren 12 Pfade



1	$n \longrightarrow {}^1H + e^- + \bar{\nu}$
2	${}^1H + n \longrightarrow {}^2H + \gamma$
3	${}^2H + {}^1H \longrightarrow {}^3He + \gamma$
4	${}^2H + {}^2H \longrightarrow {}^3He + n$
5	${}^2H + {}^2H \longrightarrow {}^3H + {}^1H$
6	${}^2H + {}^3H \longrightarrow {}^4He + n$
7	${}^3H + {}^4He \longrightarrow {}^7Li + \gamma$
8	${}^3He + n \longrightarrow {}^3H + {}^1H$
9	${}^3He + {}^2H \longrightarrow {}^4He + {}^1H$
10	${}^3He + {}^4He \longrightarrow {}^7Be + \gamma$
11	${}^7Li + {}^1H \longrightarrow {}^4He + {}^4He$
12	${}^7Be + n \longrightarrow {}^7Li + {}^1H$



BBN – Model Calculations



M. Pospelov & J. Pradler, 2010
Ann.Rev.Nucl.Part.Sci. 60:539-568

^{4}He/H ~ 0.25

D/H ~10^{-5}

^{7}Li/H ~ 10^{-10}

End of BBN

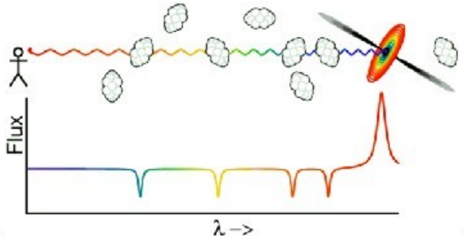
End BBN: energie of nucleons becomes too low to tunnel through the Coulomb potential.

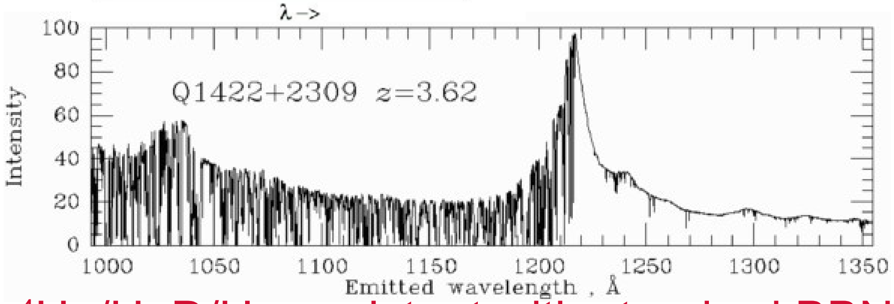
Model Calculation:

- Variation of $\eta_B = n_B/n_\gamma$
  - either determination of n_B (result: consistent with CMB)
  - or measurement with CMB as input: $\eta_B = (6.23 \pm 0.17) \times 10^{-10}$
- Neutron lifetime τ_n
- Test of new physics:
  e.g., number of neutrino generations

BBN – Comparison with Observations

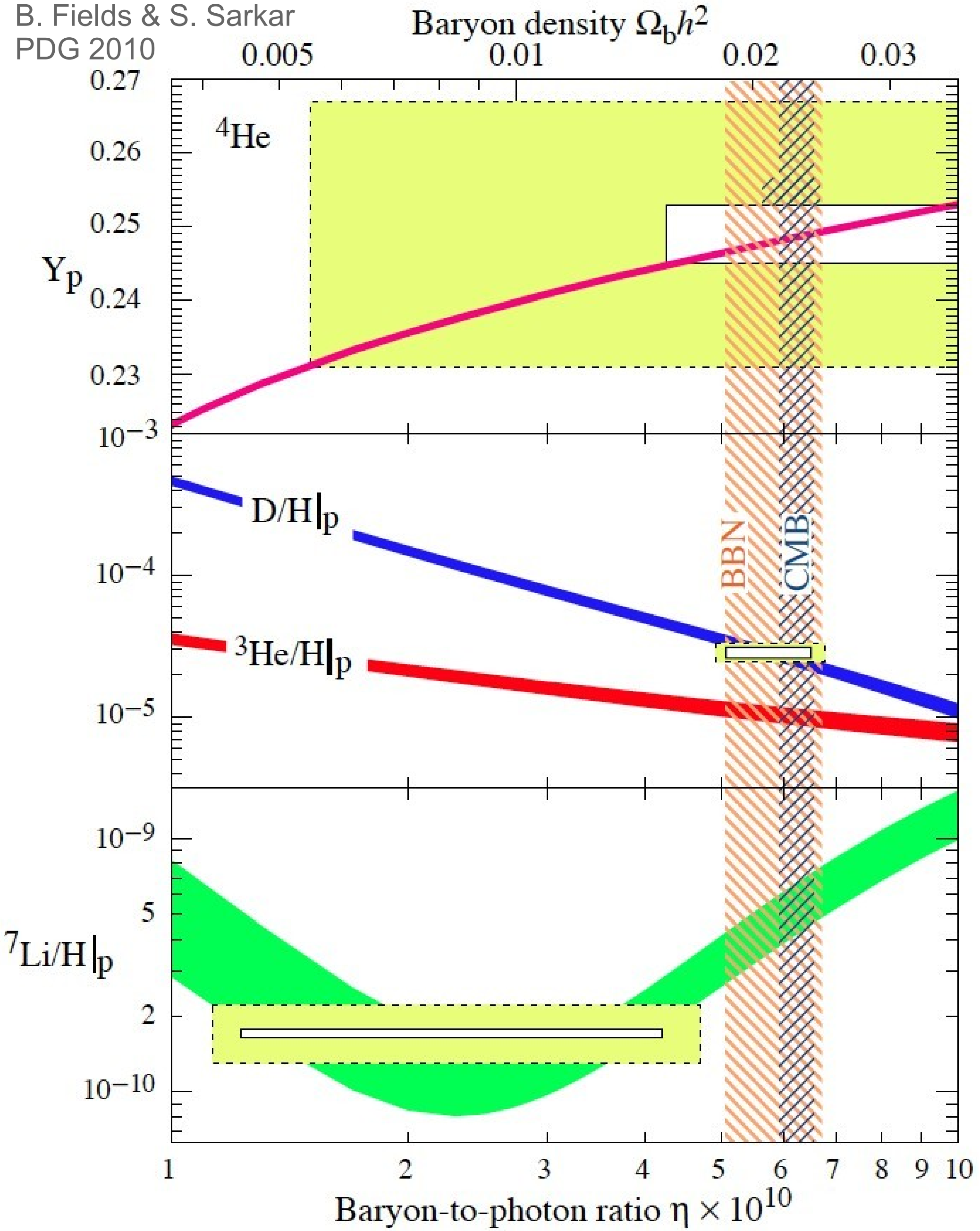
- CMB Observations:
  - T = (2.725 ± 0.001) K
    $\rightarrow n_\gamma = 411\ \mathrm{cm}^{-3}$
  - Ω_B from fit of η_b to abundance data
    $\rightarrow \eta_b = (6.23 \pm 0.17) \times 10^{-10}$
- Quasar spectra: (Lyman-α forest)



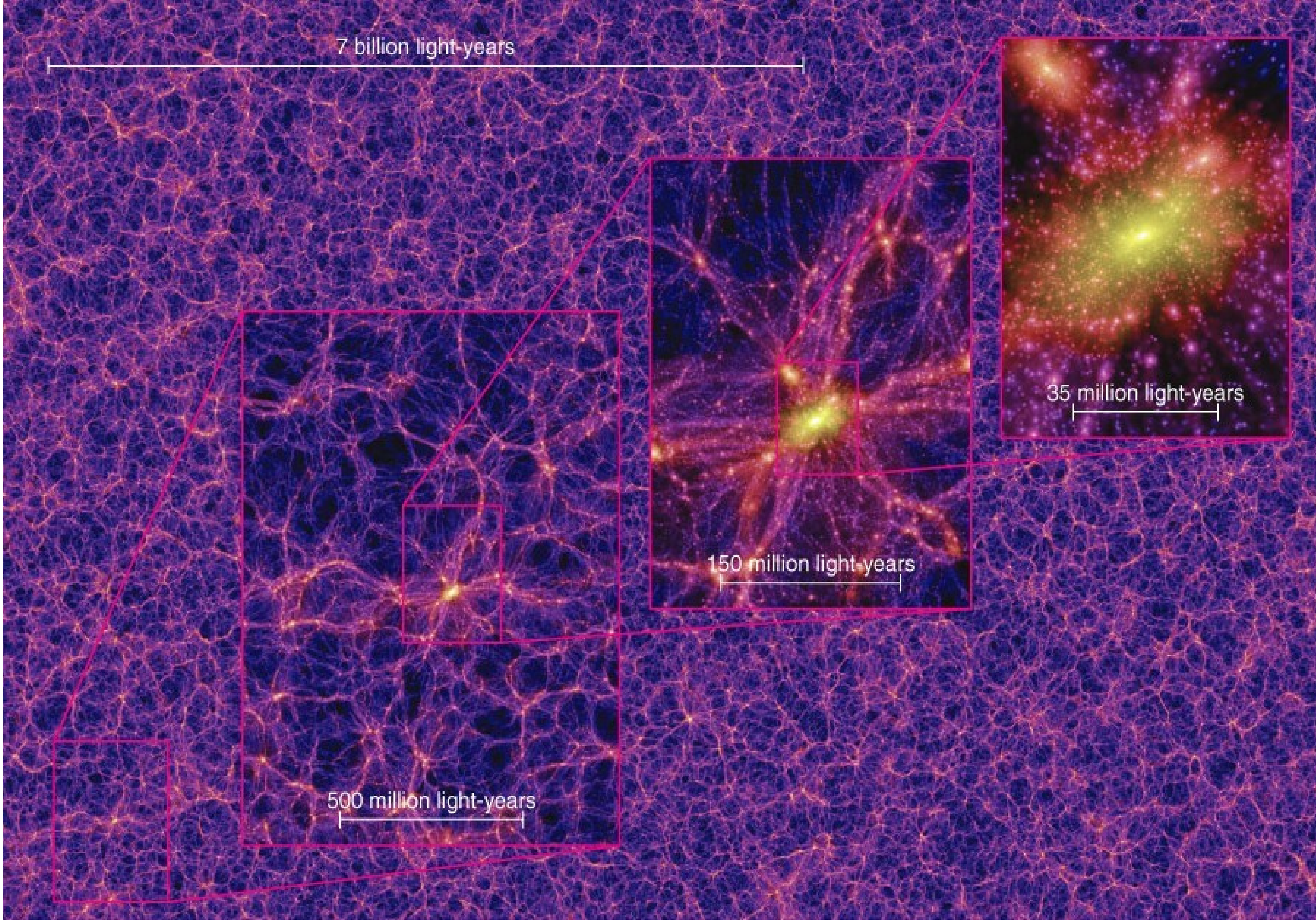


- ^{4}He/H, D/H consistent with standard BBN.
  D-absorption from line shape.
- Lithium problem:
  ^{7}Li/H somewhat inconsistent.
  Indication of non-standard physics?
  Problems with measurements?

B. Fields & S. Sarkar
PDG 2010

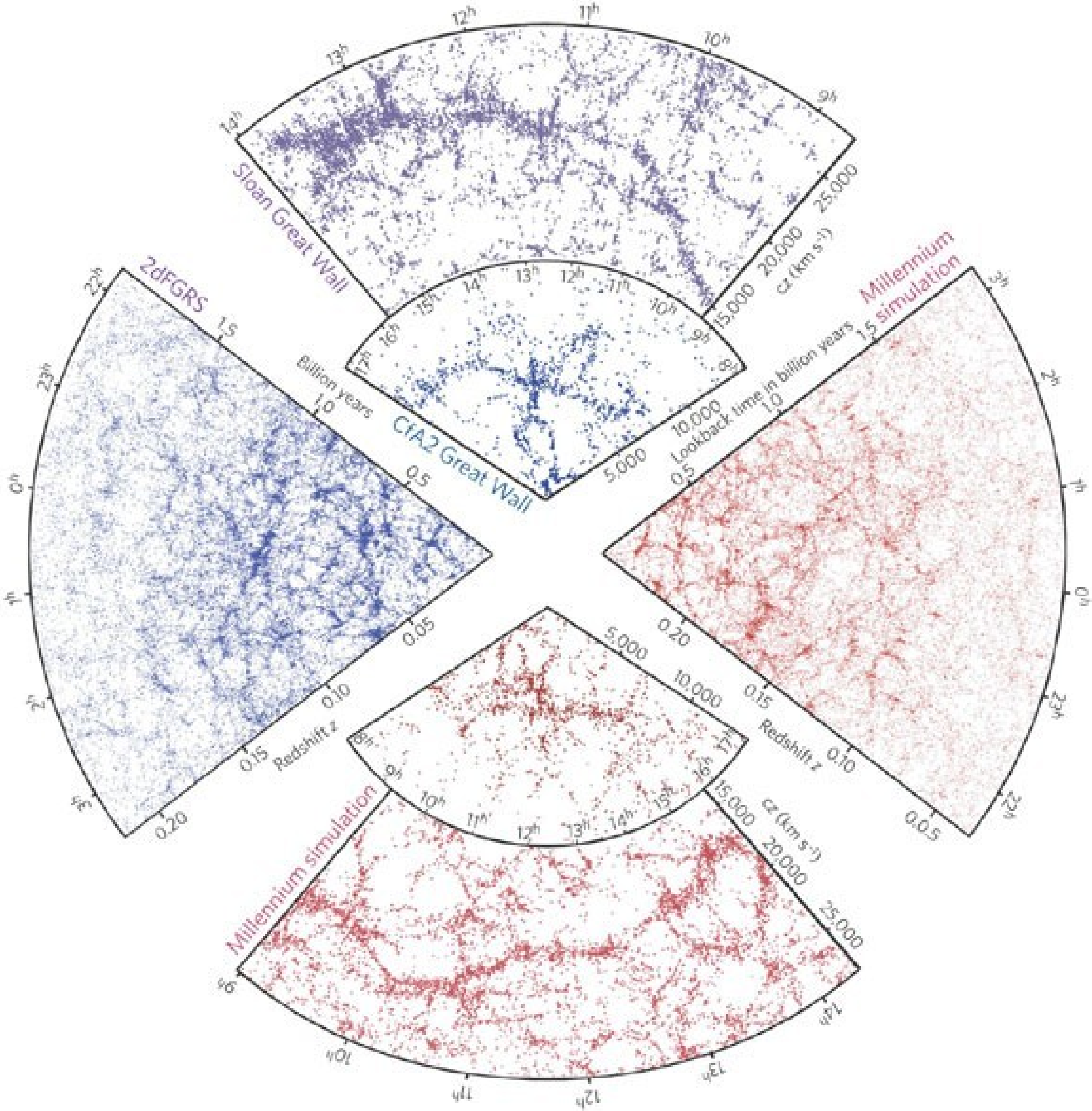


Dark Matter is non-relativistic (cold).



Structures in galaxy maps look very similar to the ones found in models in which dark matter is “cold” (traveling at $v \ll c$) and not interacting, supporting WIMPs as Dark Matter candidates.

Cold Dark Matter – Structure formation



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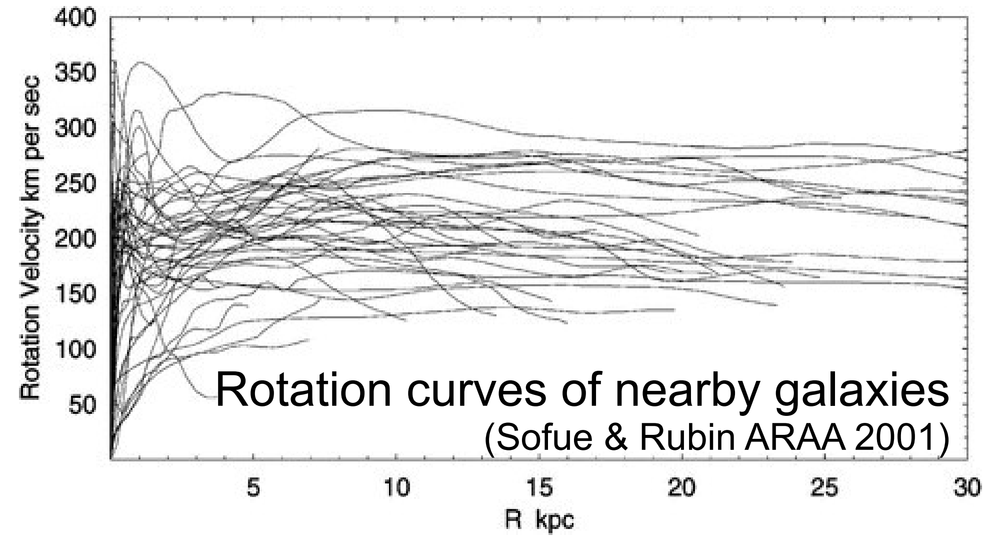
Summary: Evidence for Dark Matter
at Different Astrophysical Scales

Spiral Galaxies Scale: ~10^{21} m

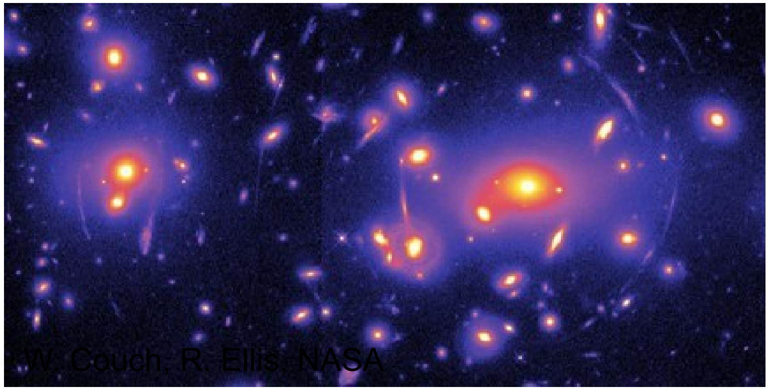
Rotation curves remain flat far beyond the edge of the visible disk.

$$\left.\begin{array}{lcl} v(R) & = & \sqrt{GM(R)/R} \\ v(R) & \approx & const \end{array}\right\} \Rightarrow \left\{\begin{array}{lcl} M(R) & \propto & R \\ \rho(R) & \propto & R^{-2} \end{array}\right.$$



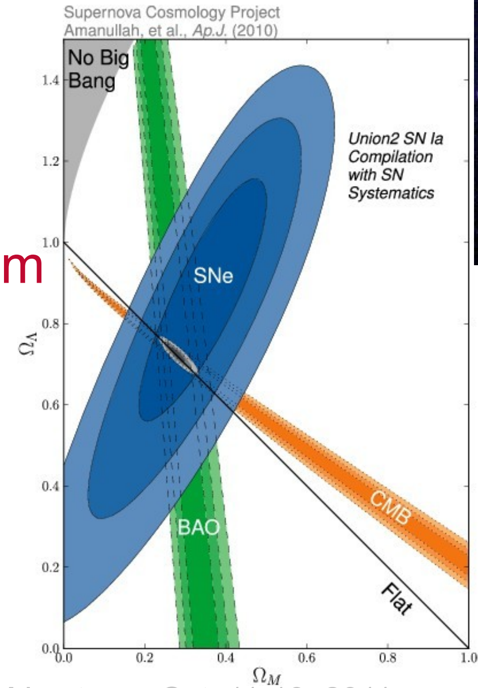
Galaxy Clusters Scale: ~10^{22} m

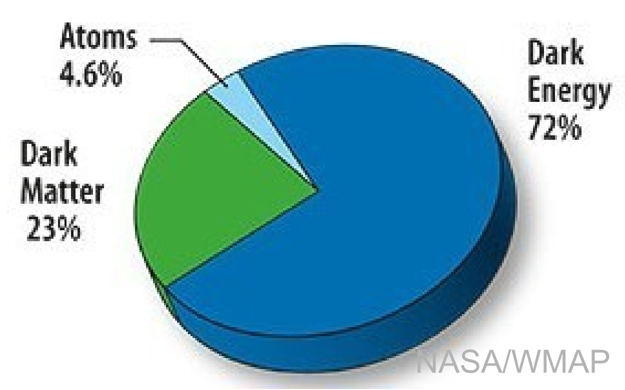
- Orbital velocities of galaxies (Zwicky's discovery in 1933)
- X-ray gas
- Gravitational lensing



The Dark Universe - Scale: ~10^{26} m

- CMB: Ω_{tot}=1.0
- CMB, BBN: Ω_b=0.045
- Galaxy clusters: Ω_m=0.27
- Supernovae Ia: Ω_m, Ω_Λ
- Structure formation: cold DM



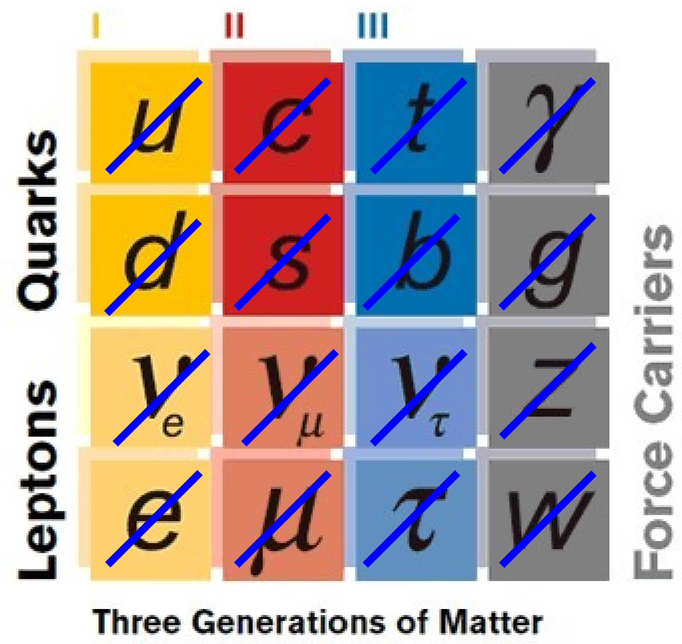


Physics beyond SM!

What do we know about Dark Matter?

- Gravitationally interacting
  - How we know about Dark Matter
- Stable or long-lived
  - $\Omega_{DM} = 0.23$
- Cold or warm - not hot (relativistic)
  - Structure formation, CMB
- Non-baryonic
  - CMB, Big Bang nucleosynthesis
- Electrically neutral
  - Dark Matter

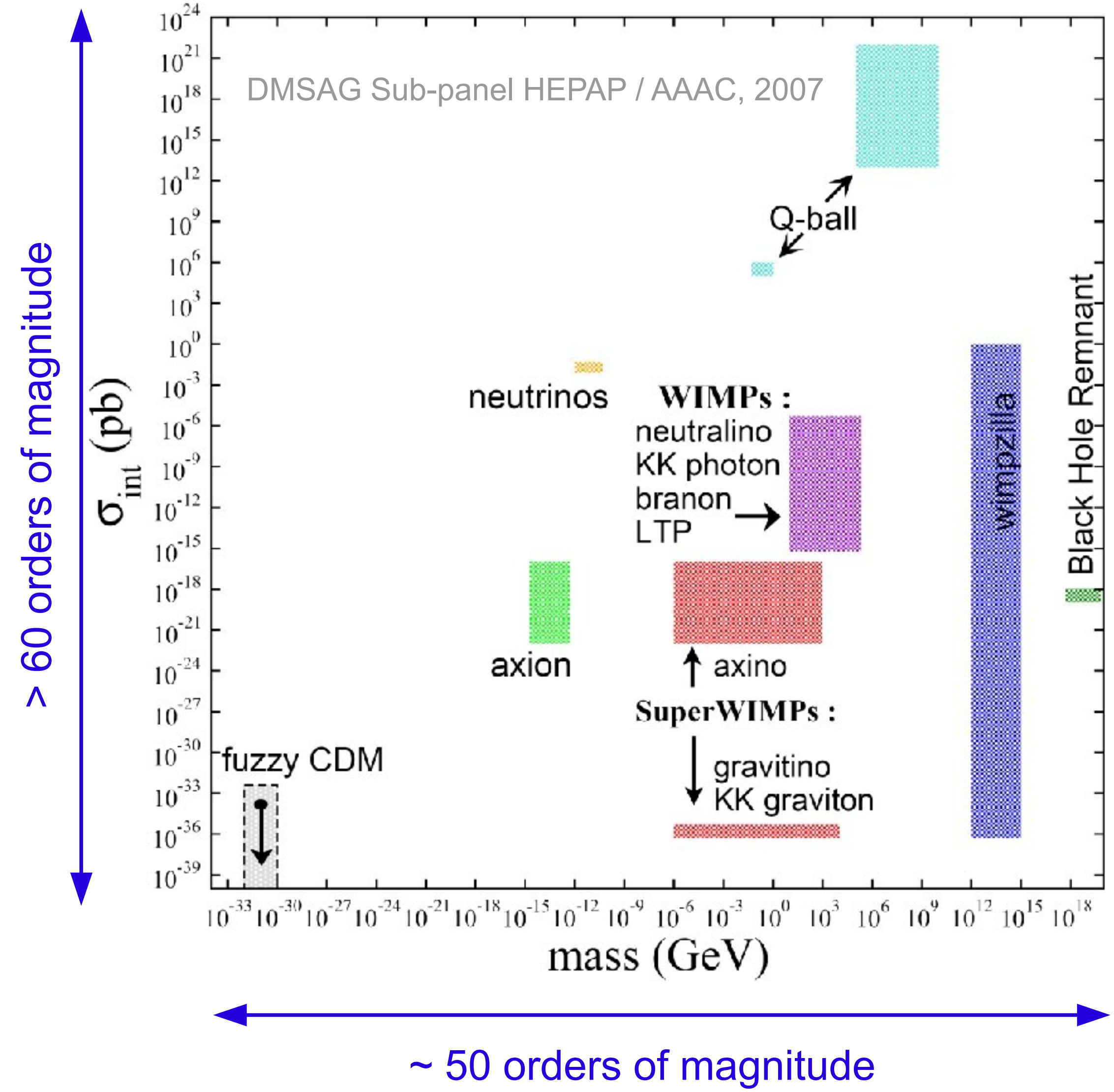
The Standard Model



Dark Matter requires physics beyond the Standard Model.

What do we know about Dark Matter?

- Gravitationally interacting
  - How we know about Dark Matter
- Stable or long-lived
  - $\Omega_{DM} = 0.23$
- Cold or warm - not relativistic
  - Structure formation, CMB
- Non-baryonic
  - CMB, Big bang nucleosynthesis
- Electrically neutral
  - Dark Matter
- Additional constraints from accelerator searches, direct and indirect searches.



This still leaves many options.

Where to start? Look for “well motivated” candidates.

The Appeal of Weakly Interacting Massive Particles (WIMPs): A Thermal Relic at just the Right Density

$$\frac{dn_\chi}{dt} = -3\,H\,n_\chi - \langle \sigma_{\mathrm{eff}}\, v \rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2 \right)$$

Decrease due to universe expansion

Boltzmann equation

$$\chi + \chi \leftrightarrow 2\gamma$$
$$\chi + \chi \leftrightarrow \mathrm{f} + \bar{\mathrm{f}}$$

① $kT >> m_\chi c^2$: equilibrium of WIMP pair creation and annihilation

② $kT < m_\chi c^2$: WIMP creation suppressed by factor $\exp(-kT/m_\chi c^2)$.

③ **Weakly Interacting**: **freeze out** when annihilation rate drops below expansion rate:

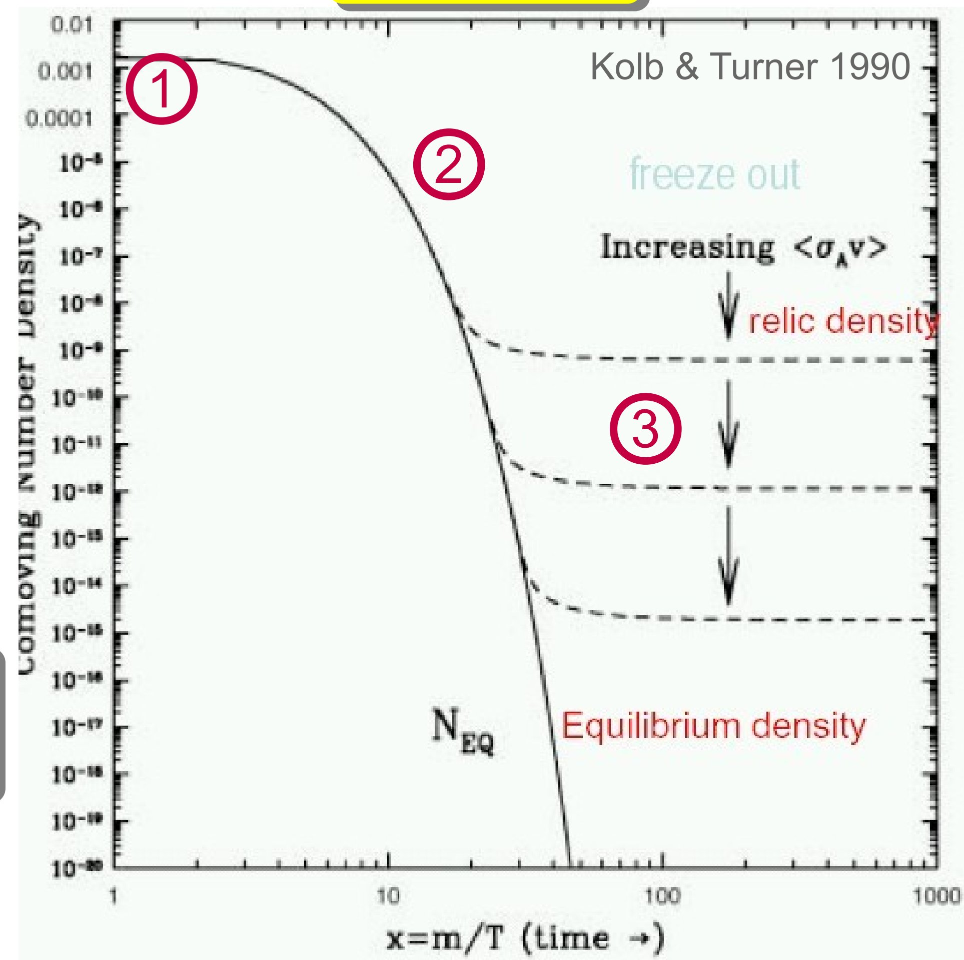
$$H > \Gamma_{ann} \sim n_\chi \langle \sigma_a\, v \rangle$$

results in **relic density**: $\Omega_\chi h^2 \approx \frac{10^{-27}\, cm^3\, s^{-1}}{\langle \sigma_a v \rangle}$

If m_χ and σ_a related to the electroweak scale

=> $\Omega_\chi h^2 \sim O(0.1)$ ✓

"WIMP miracle"

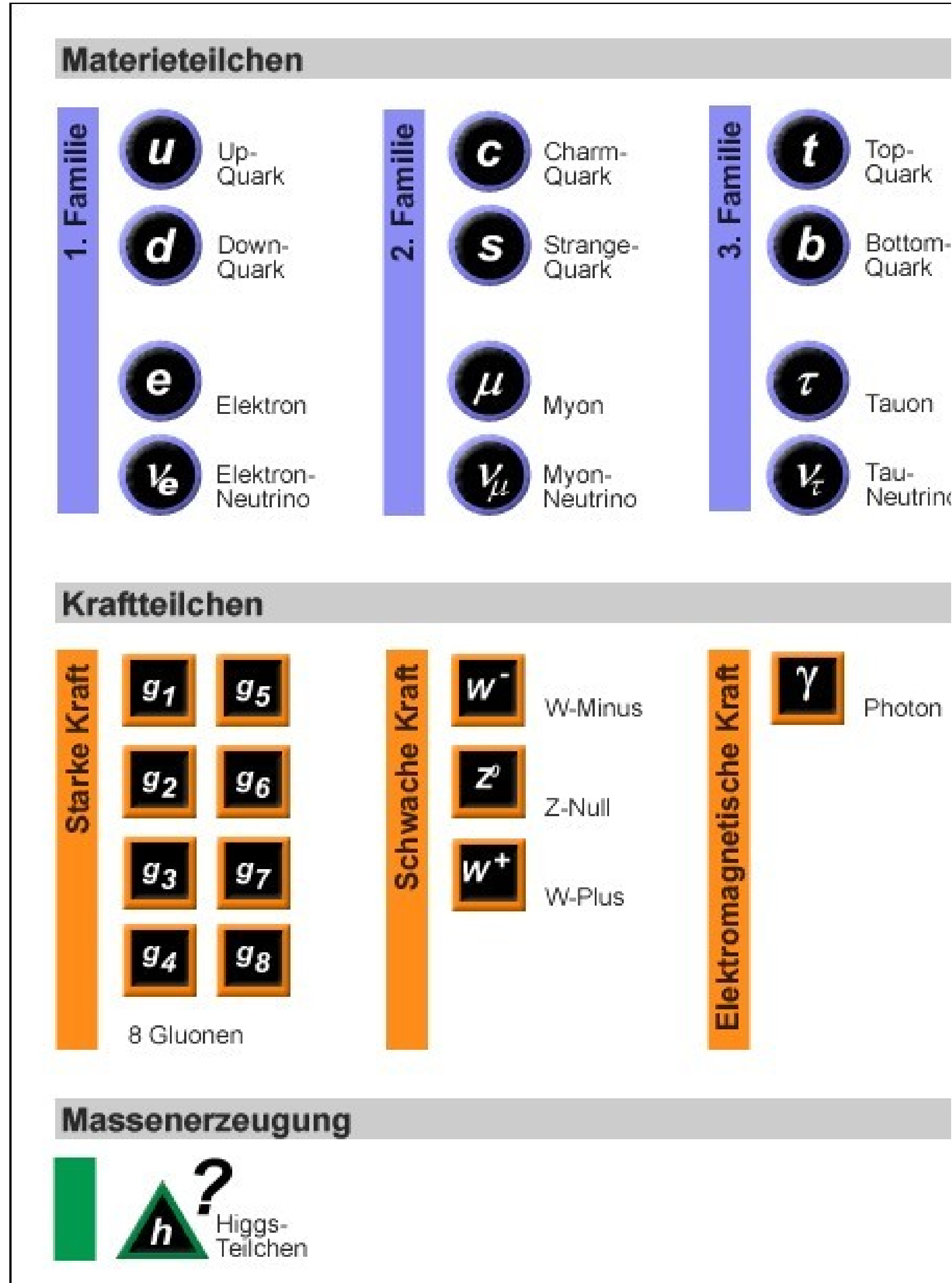


Massive particles: average WIMP velocity is non-relativistic.

Quick Reminder:

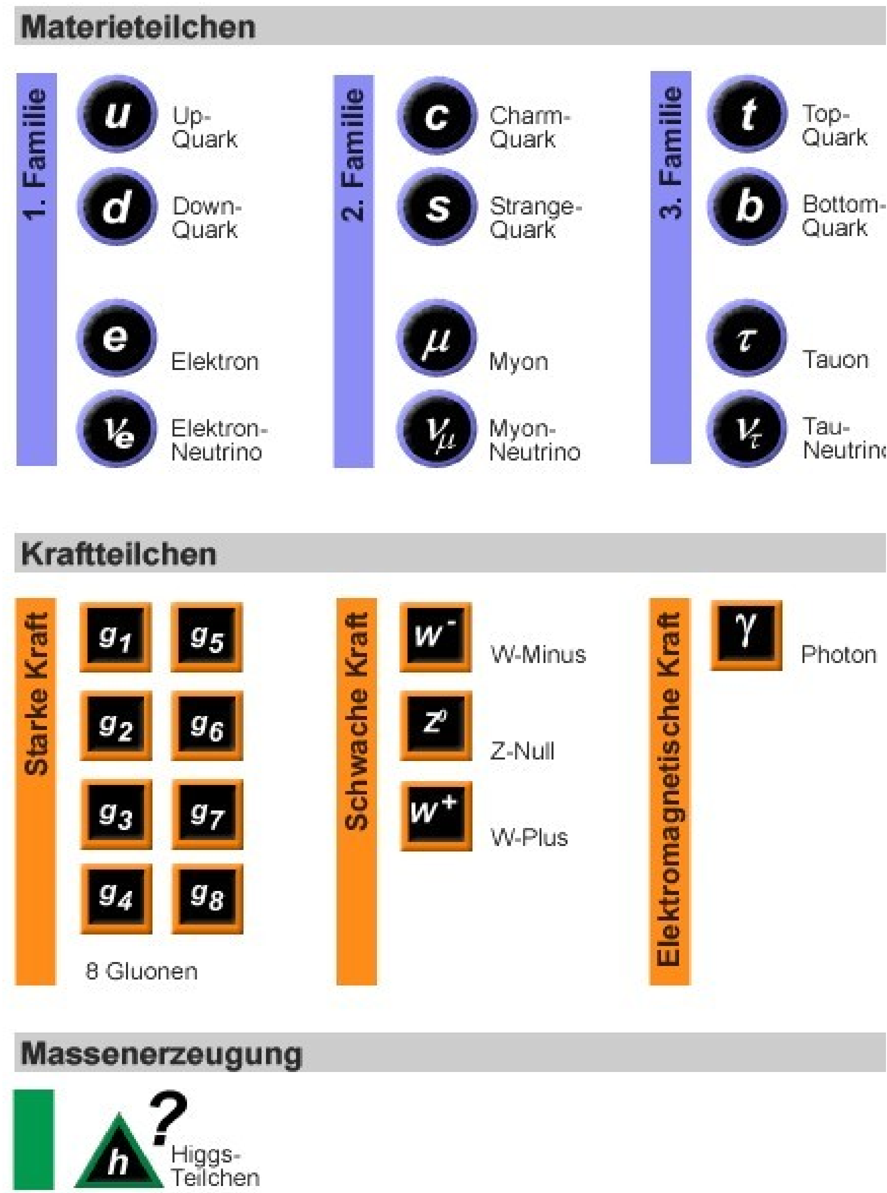
Standard Model of Particle Physics

- describes very well electroweak and strong interactions
- Symmetry:
  Gauge group SU(3)×SU(2)×U(1)
  - strong interaction: SU(3)
  - elektroweak int. SU(2)×U(1)
  - spontaneously broken to SU(3)×U(1)
- Electroweak symmetry breaking (EWSB) through non-vanishing vacuum expectation value of a fundamental scalar field (Higgs field) at ~100 GeV.
- Associated with the Higgs field, a Higgs boson is expected. Searched for at Tevatron (Fermi-Lab, ended Sep. 2011) und LHC (CERN).
- SM says nothing about gravity.
- Considered to be an effective low-energy field theory of a more fundamental theory at higher energies.



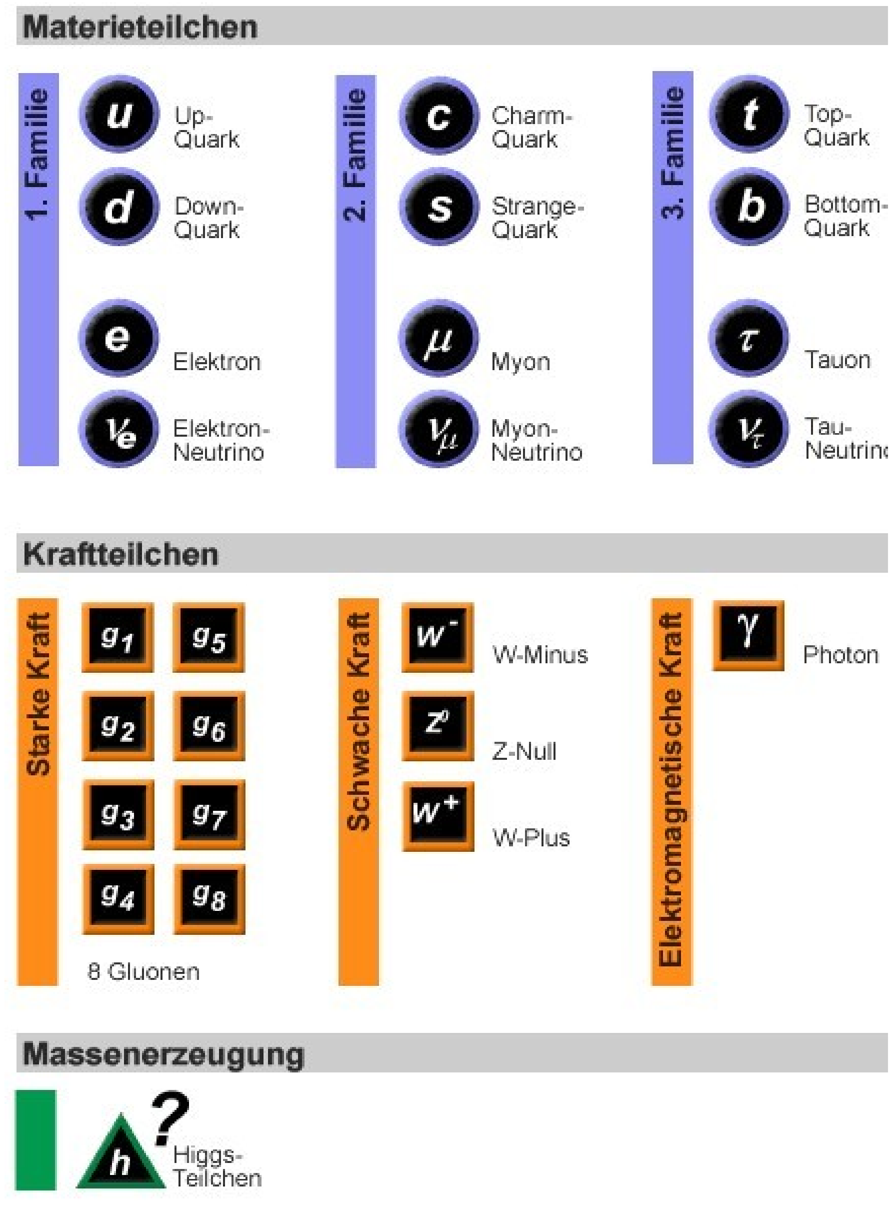
Problems of the Standard Model (SM)

- **Hierarchy Problem**:
  - In order to be relevant for EWSB, Higgs boson should have mass m~O(100 GeV). Radiation corrections to the Higgs mass depend quadratically on a cut-off energy Λ, since masses of the fundamental scalar field are not constrained by chiral or gauge symmetry.
  - To get an effective masse O(100 GeV), the scalar mass parameter m_0 must be fixed with a precision of $(m/\Lambda)^2$. For instance: Λ at GUT-scale (~10^{16} GeV): fine tuning with a precision of 10^{-28} necessary! This is allowed in principle, but is considered unnatural.



Problems of the Standard Model (SM)

- **Unification of Gauge Coupling Constants**
  see SUSY & Unification (later)
- **Existence of Three Families and mass spectra of Fermions**
  - unexplained in SM
  - free parameters
- **Cosmology**
  - SM provides no candidate for cold Dark Matter.
  - Value of cosmological constant, interpreted as vacuum energy, overestimated by ~120 orders of magnitude
  - SM provides no candidate for an Inflaton field, responsible for exponential expansion of the universe (Inflation) in the early universe.
  - Even though SM fulfills the Sakharov-Criteria, the predicted baryon asymmetry through electroweak phase transition is too small.

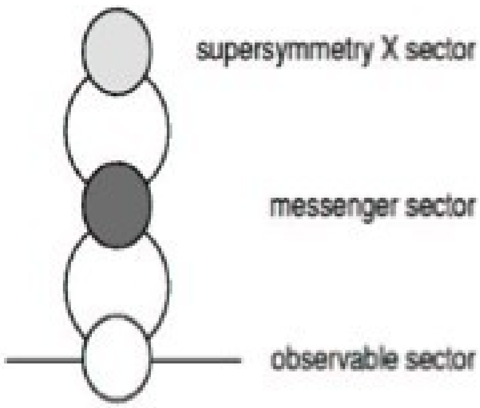


Supersymmetrie - SUSY

- Hypothetische neue **Raumzeit-Symmetrie**:
  - zu jedem elementaren Fermion gibt es einen bosonischen Superpartner (spin 0) sfermions: squarks (sup, sdown, ..., stop) & sleptons (selectron, sneutrino, …, stau)
  - zu jedem Eichboson und dem Higgs-Boson gibt es einen fermionischen Superpartner (spin ½): photino, zino, wino, gluino, higgsino.
  - Spindifferenz: $\Delta s = ½$
  - SUSY-Operator: Q |boson> = |fermion>, Q |fermion> = |boson>
- Neutrale Teilchen sind **Majorana-Teilchen**, d.h. ihre eigenen Anti-Teilchen
- SUSY fordert auch, dass die Superpartner die gleiche Masse haben. Nicht beobachtet! → **Symmetrie gebrochen**.
  z.B.: Elektron: 511 keV, selectron nicht beobachtet bis ~100 GeV.
- **R-Parität**: multiplikative Quantenzahl, die in vielen SUSY-Modellen eine Erhaltungsgröße ist.
  - Experimenteller Befund:
    Proton ist stabil gegen Zerfall $p \rightarrow \pi^0 + e^+$ mit Halbwertszeit > 10^{32} a.
  - $R = (-1)^{(2S+3B+L)}$: Spin S, Baronenzahl B, Leptonenzahl L
    +1 für SM-Teilchen, -1 für SUSY-Teilchen.
  - Falls R Erhaltungsgröße:
    - SUSY-Teilchen können nicht ausschliesslich in SM-Teilchen zerfallen.
    - Das leichteste SUSY-Teilchen muss stabil sein.
      → *Lightest supersymmetric particle* LSP natürlicher Kandidat für Dunkle Materie!

Brechung der Supersymmetrie

- Beobachtung: SUSY bei Energien unterhalb von ~100 GeV gebrochen
- Beschreibung der Symmetriebrechung durch explizite SUSY-brechende Terme in der Lagrange-Dichte.
  - Annahme: lediglich eine phänomenologische Beschreibung der effektiven Theorie bei niedriger Energie ("emerging theory")
  - Folge einer *spontanen* Symmetriebrechung in einer noch unbekannten fundamentalen Theorie

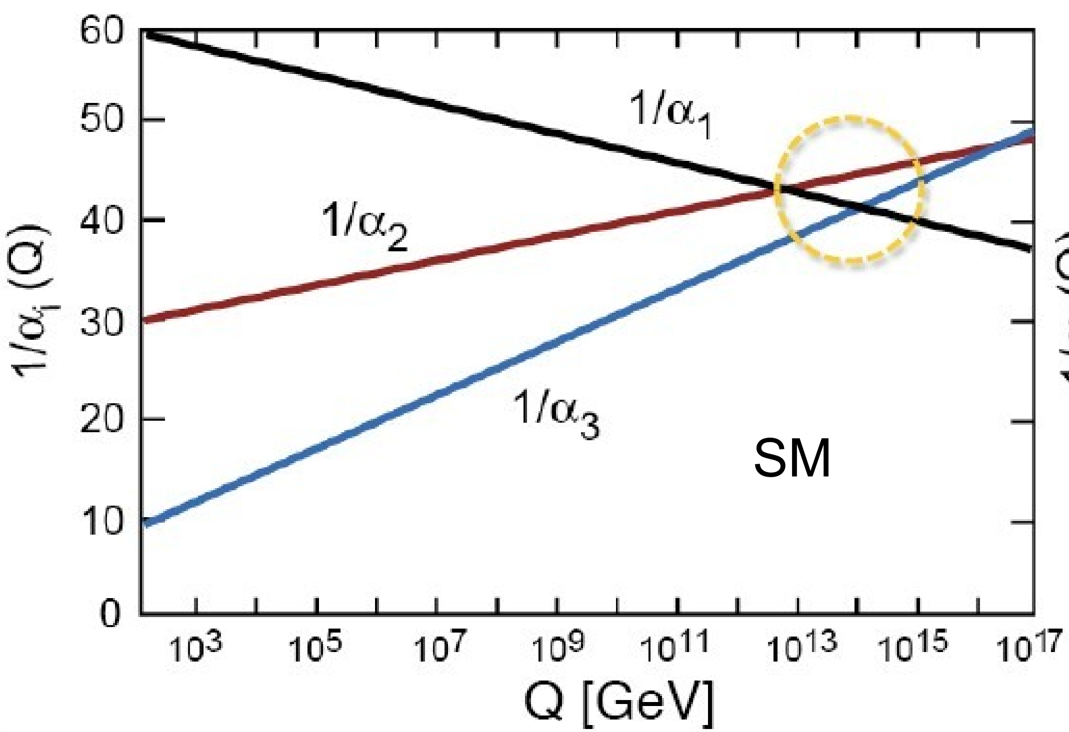


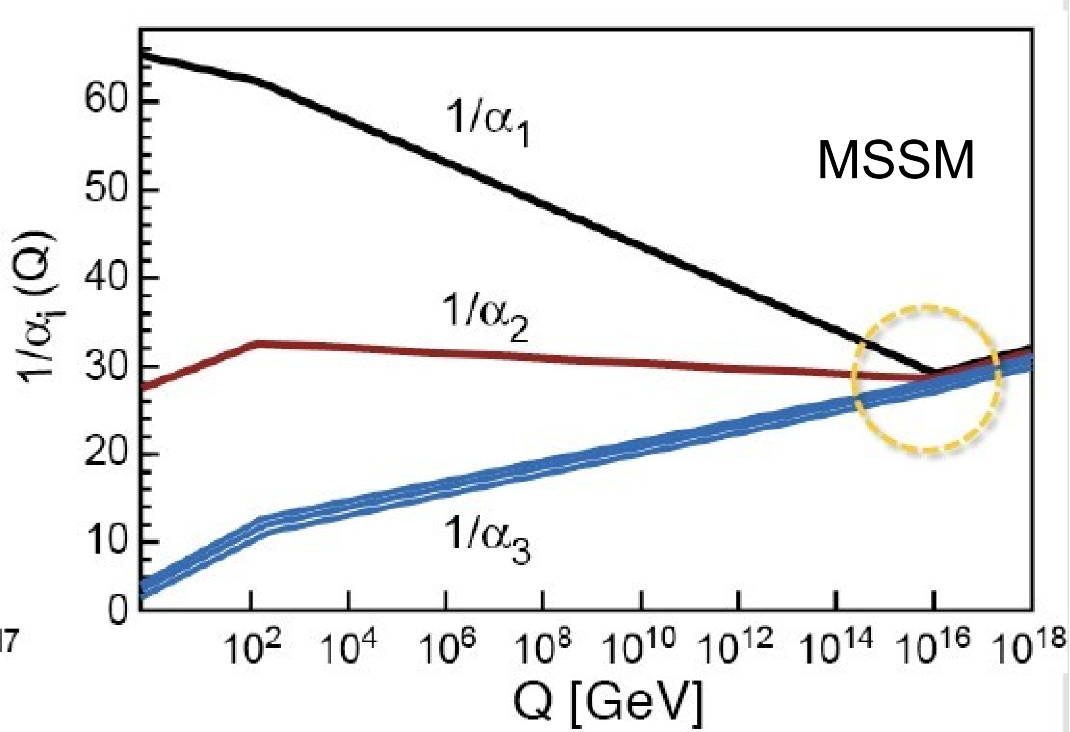
- Annahme: fundamentale Theorie besteht aus mind. zwei Sektoren:
  - der beobachtbare Sektor (SM und Superpartner)
  - der "versteckte" (hidden) Sektor, in dem spontane SUSY-Brechung stattfindet.
- Ein dritter Satz an Feldern (mediator or messenger fields) vermittelt die spontane SUSY-Brechung an den beobachtbaren Sektor. Verschiedene Ansätze:
  - Vermittlung über Gravitation (gravity mediation: Supergravity)
    Kopplung $\rightarrow 0$ für $M_{Pl} \rightarrow \infty$
  - Vermittlung über Eichfelder (gauge mediation)
    Kopplung über Schleifendiagramme (loop level) mit neuen Feldern, die SM-Quantenzahlen besitzen.
  - Vermittlung über extra Dimensionen (bulk mediation)
    beobachtbarer und versteckter Sektor befinden sich auf verschiedenen 4-dim. Raumzeit-Hyperflächen (Branes) in einem höherdimensionalen Raum (Bulk).
    Vermittelndes Feld: Bulk-Feld. SM-Felder auf den beobachtbaren Sektor beschränkt.
- Klassifikation nicht immer eindeutig, z.B.:
  Gravitation als "Bulk"-Feld: Überlapp mit Vermittlung über Gravitation

SUSY & Vereinheitlichung der Kräfte

- Grand Unified Theories (GUTs):
  Vereinigung von starker Ww mit elektromagnetischer und schwacher Ww
- Erwartung: Stärke der Eichkopplungen soll in einem Punkt bei $M_{GUT}<M_{Pl}$ zusammenkommen.
- Standard-Modell: kein gemeinsamer Schnittpunkt aller drei Kopplungen
- Minimal SUSY (MSSM): gemeinsamer Schnittpunkt bei $M_{GUT} = 2 \cdot 10^{16}$ GeV

α_1: elektromagnetisch, α_2: schwach, α_3: stark

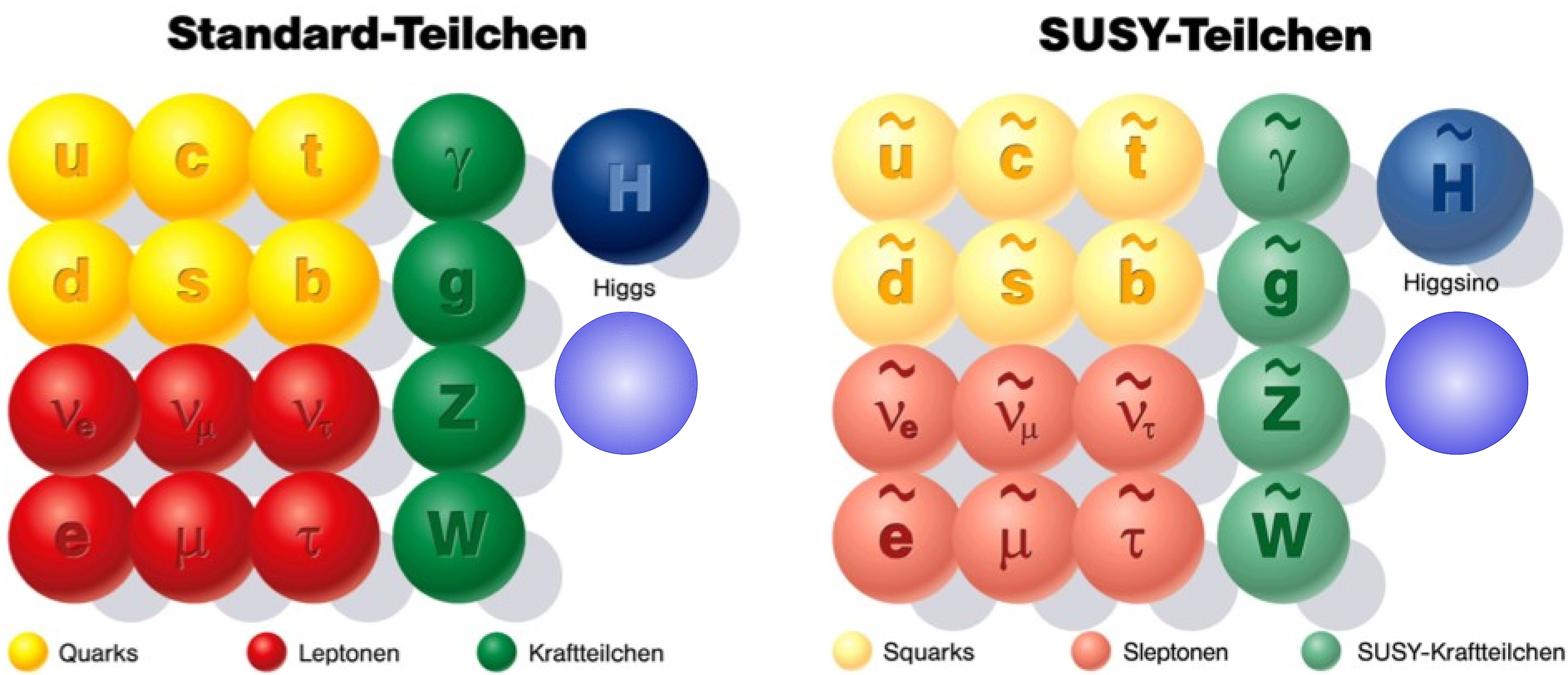




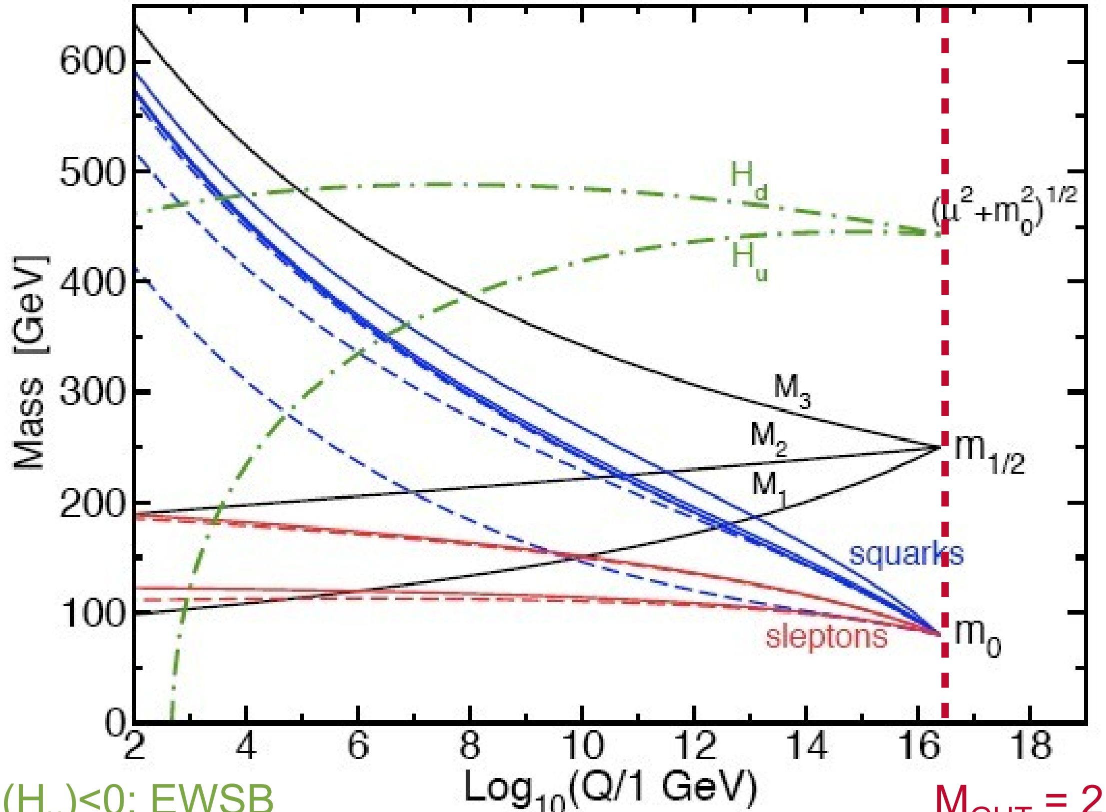
SUSY - MSSM

MSSM: Minimales Supersymmetrisches Standard Modell

- 105 (!) neue physikalische Parameter: (e.g., PDG http://pdg.lbl.gov/, Supersymmetry Part I)
  - Massen (Skalare, Gauginos,…)
  - Benötigt 2 Higgs-Bosonen im SM + 2 Higgsinos
  - CP-Phasen
  - Mischungswinkel (z.B. für Neutralinos & Charginos), …



Constrained Minimal Supersymmetric Standard Model CMSSM



m(H_u)<0: EWSB

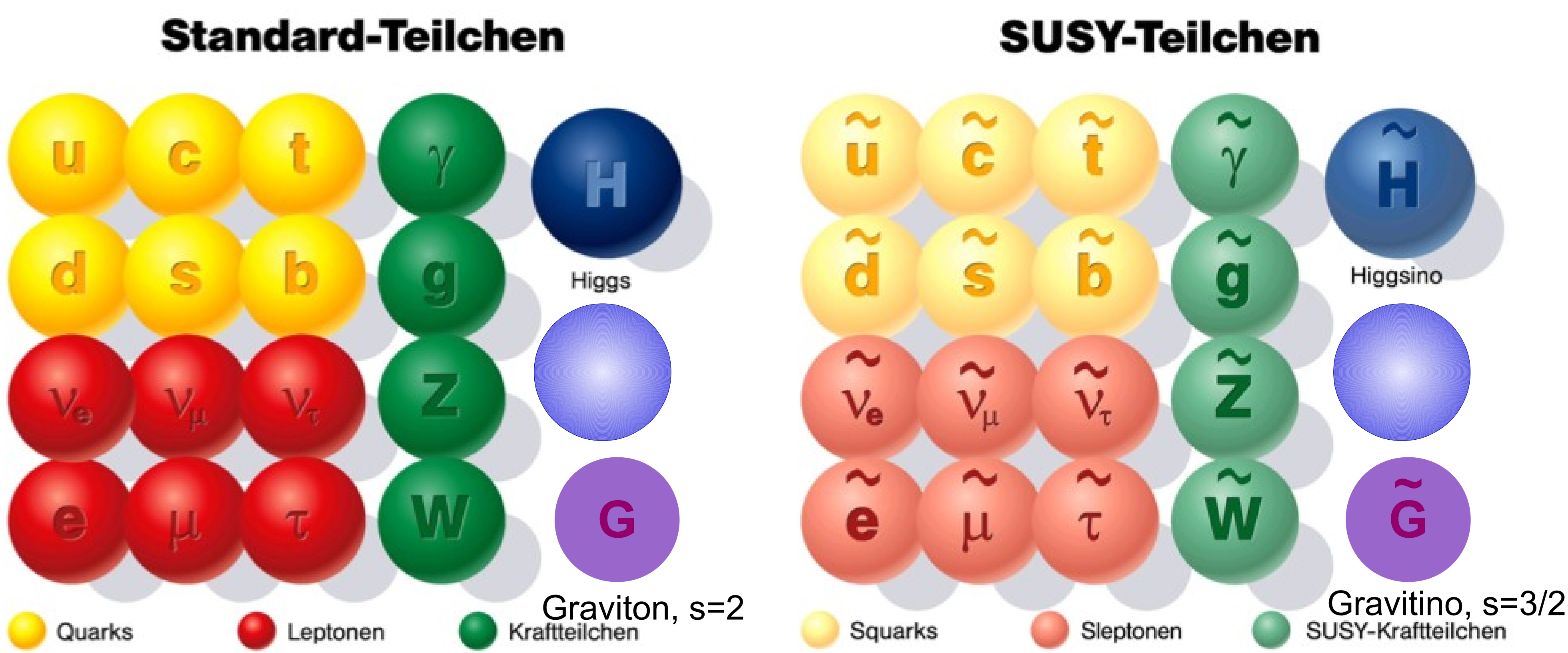
M_{GUT} = 2.5×10[16] GeV

- An der supersymmetrischen GUT-Skala werden die folgenden Parameter als gleich angenommen:
  - Alle weich supersymmetrie-brechenden skalaren Massen m_0 (alle Flavors an der GUT-Skala)
  - Alle Gaugino-Massen $m_{1/2}$
  - Alle weich supersymmetrie-brechenden trilinearen Parameter A_0

- Reduktion auf 5 neue physikalische Parameter, die an der GUT-Skala definiert werden:
  - m_0: universelle supersymmetrie-brechende skalare Masse
  - $m_{1/2}$: universelle supersymmetrie-brechende Gaugino-Masse
  - A_0: universelle supersymmetrie-brechende trilineare skalare Wechselwirkung
  - tan β: Verhältnis der Vakuum-Erwartungswerte der zwei Higgs-Doublets
  - Vorzeichen(μ). μ: Massenparameter des supersymmetrischen Higgsinos. Betrag(μ) festgelegt durch elektroschwache Symmetriebrechung (EWSB)

SUSY - Minimal Supergravity Model mSUGRA

- Supergravitation (SUGRA): Einbeziehung der Gravitation.
  SUSY wird von globaler zu lokaler Eichsymmetrie.
- Gravitino ist Superpartner des Gravitons: DM-Kandidat.
- Phänomenologisch sind minimal SUGRA (mSUGRA) und CMSSM weitgehend äquivalent. (more details later)



mSUGRA: WMAP-erlaubte Parameterbereiche

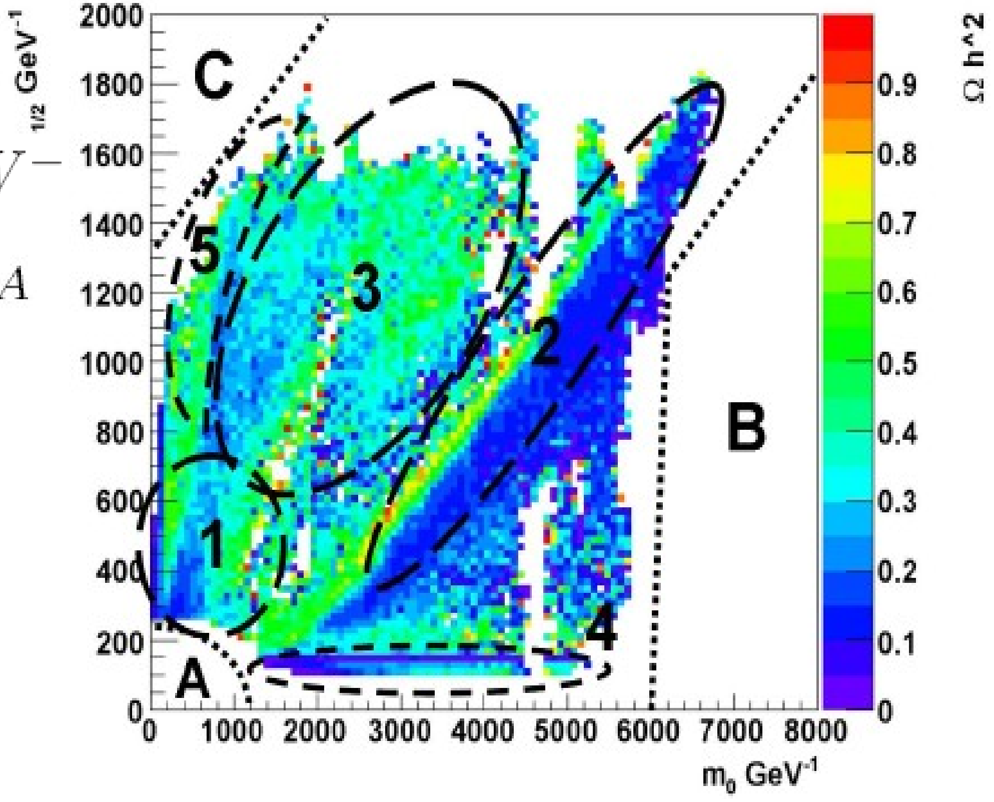
Einschränkungen aus WMAP-Daten (CMB), verschiedene Annihilations- und Co-Annihilationskanäle

Fünf charakteristische Regionen des mSUGRA-Parameterbereichs:

1. Bulk Region: $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to q\bar{q}$
2. focus-point-Region: $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to ZZ$
   oder $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to W^+ W^-$
3. A-Resonanz-Region: $2m_\chi \approx m_A$
   $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to A \to b\bar{b}$
4. h-Resonanz-Region: stark von top-Quarkmasse abhängig
5. Stau-Koannihilationsregion:

$$m_{\tilde{\chi}_1^0} \approx m_{\tilde{\tau}_1}$$

z.B. $\tilde{\chi}_1^0 \tilde{\tau}_1 \to \tau^* \to \tau\gamma$



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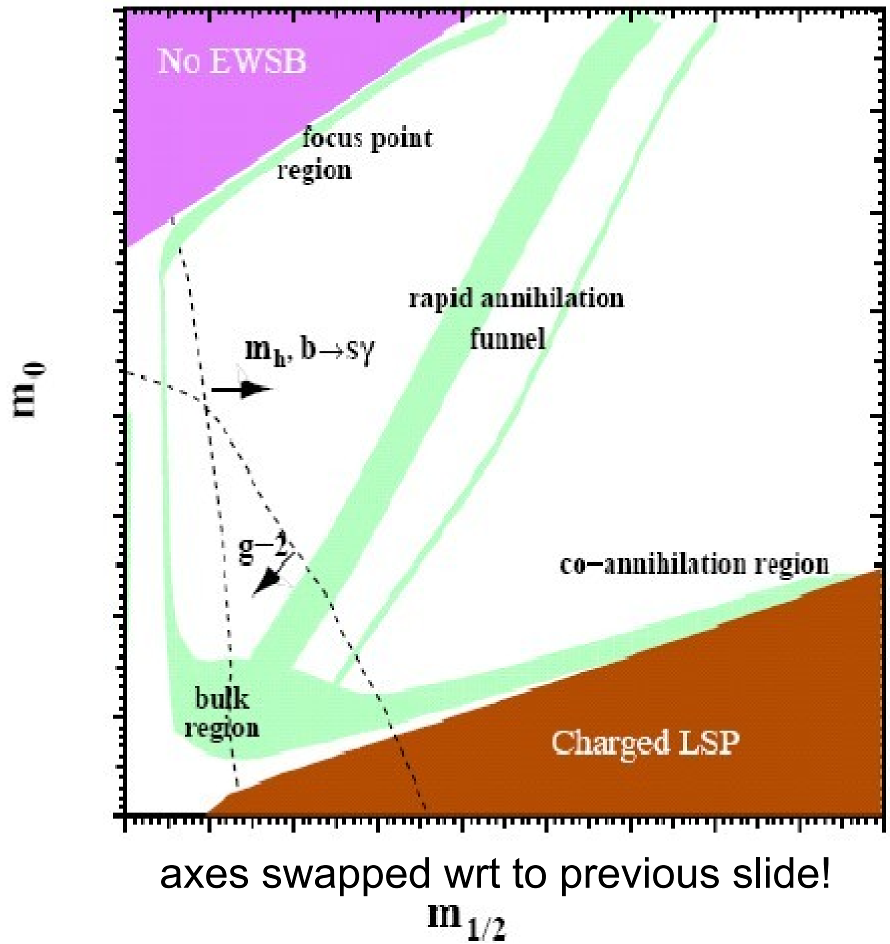


axes swapped wrt to previous slide!

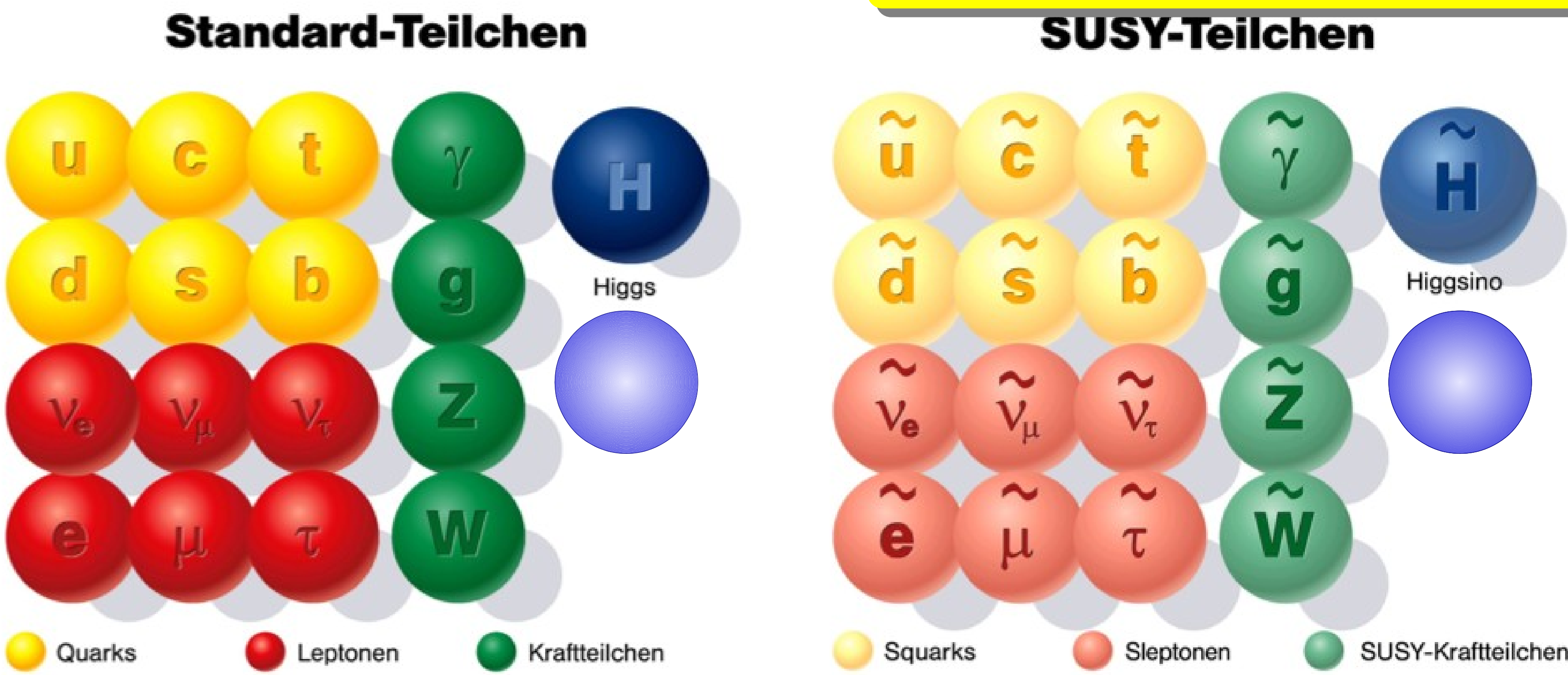
SUSY – Dunkle Materie - Kandidaten

- Schwach wechselwirkend (WIMP): Neutralino, sneutrino
  sneutrino durch Beobachtung als DM-Kandidat ausgeschlossen
- Superschwach wechselwirkend: Gravitino, Axino

Beobachtbare Masseneigenzustände::
4 Neutralinos, 2 Charginos
DM-Kandidat: leichtestes Neutralino

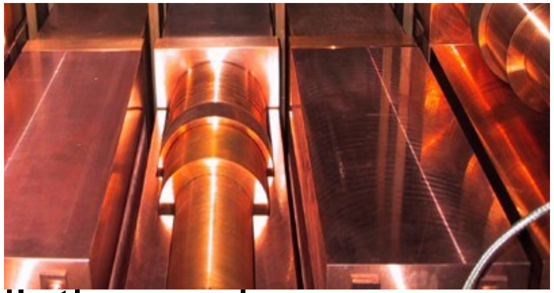
Neutralino: $\chi_1^0 = N_{11}\,\tilde{\gamma} + N_{12}\,\tilde{Z}^0 + N_{13}\,\tilde{H}_1^0 + N_{14}\,\tilde{H}_2^0$

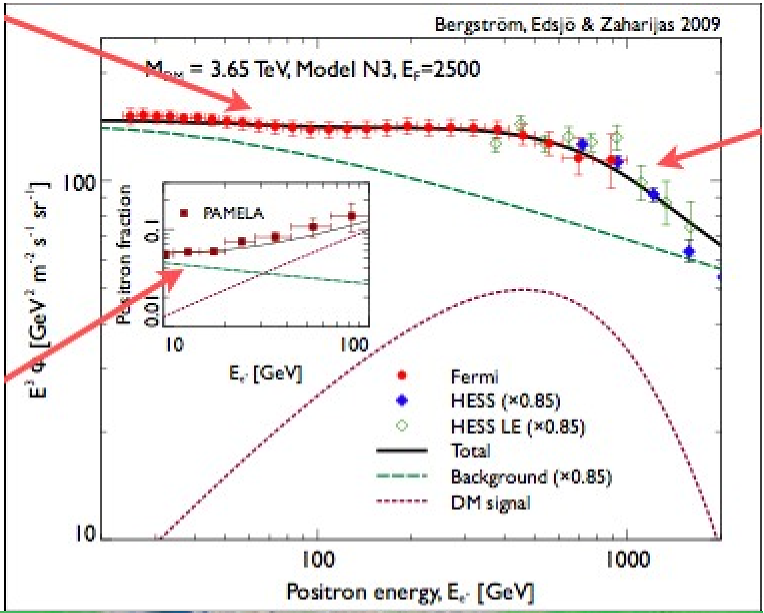
oder $\chi_1^0 = N'_{11}\,\tilde{B} + N'_{12}\,\tilde{W}^3 + N_{13}\,\tilde{H}_1^0 + N_{14}\,\tilde{H}_2^0$



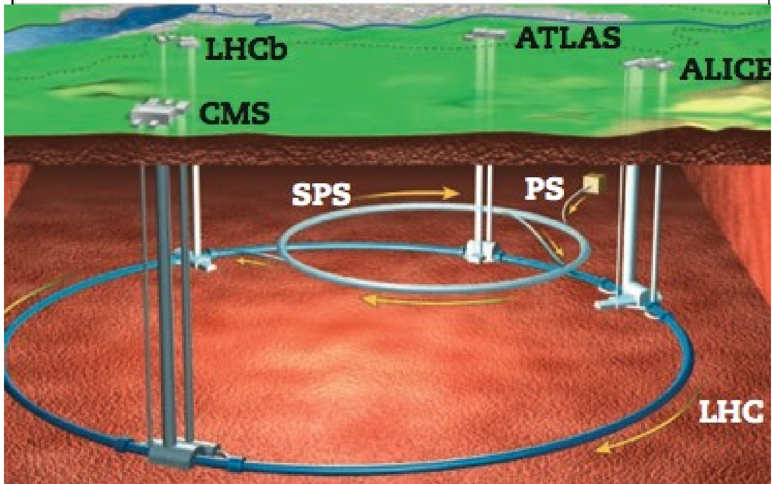
Dark Matter Detection Methods

- Astrophysics / Cosmology:
  Measurement of Gravitational Effects.
  - Rotation curves of spiral galaxies
  - Orbital velocities of galaxies in clusters (Zwicky 1933)
  - Colliding clusters (Bullet cluster)
  - Large scale structure, lensing
- **Direct Detection:**
  - **WIMP scattering**
  - Axion searches, ...





- Indirect Detection: from annihilation or decay
  - Cosmic rays
    PAMELA positrons?
    Fermi, ATIC, HESS electrons? Anti-deuterons?
  - Neutrinos
  - Gamma-rays
- Accelerator-based Creation and Measurement:
  - Missing energy / momentum (+ jets + lepton(s))
  - Search for (possibly) DM-related particles
    (SUSY, extra dimensions, dark photon)



Production and Decay of SUSY Particles

If scalar masses not too heavy, squark gluino production via strong interaction dominant

SUSY Signatures

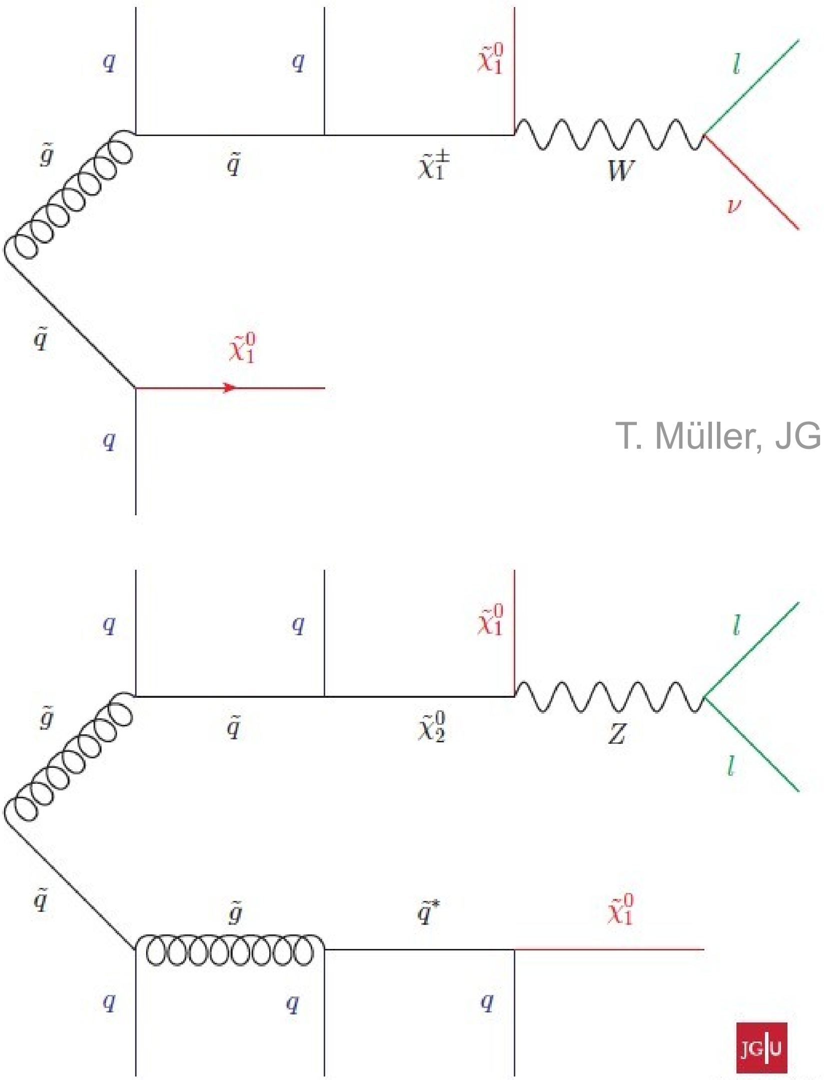
Pairs of squarks and/or gluinos decay via long cascades resulting in

- **Hard jets** from decays of gluinos and squarks
- **Missing transverse energy** due to the 2 LSPs escaping detector
- possibly **Leptons** from chargino, neutralino and slepton decays

$\Rightarrow$ $\boxed{n \text{ leptons} + k \text{ jets} + \not{E}_T}$

Leptonic final states

- Decays of charginos and neutralinos via (real or virtual) W and Z bosons
- Also decays via sleptons ($\tilde{\tau}_1$) possible



T. Müller, JGU

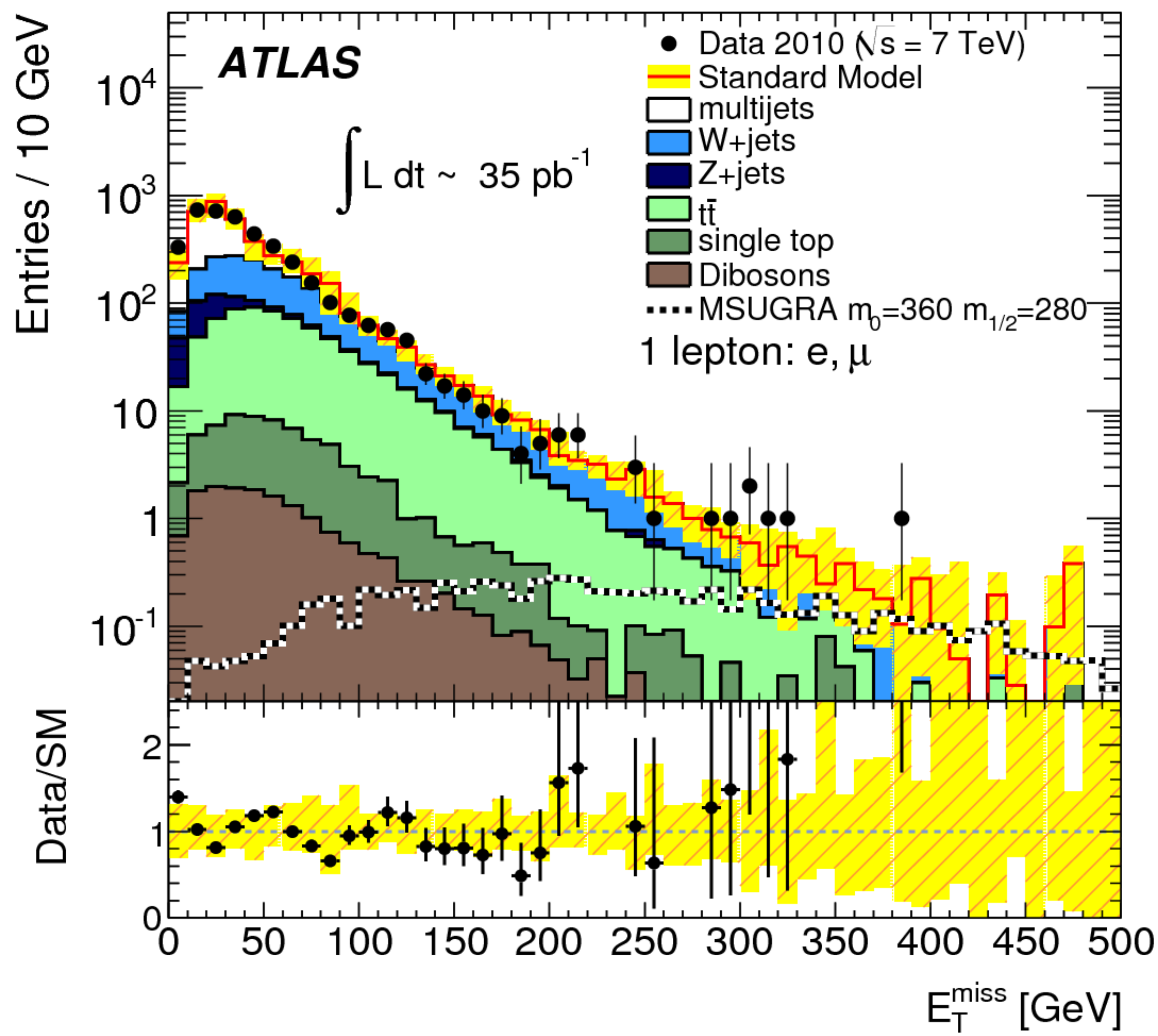
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Searches for DM at the LHC (Initial Results)

Example: ATLAS searches for squarks and gluinos

ATLAS-CONF-2011-064

- Final states with
  - jets
  - missing transverse momentum
  - and zero or one lepton
- Integrated luminosity: 35 pb^{-1}
- Electron and muon channel combined
- Yellow bands: uncertainty on the Monte Carlo prediction from finite MC statistics and from jet energy scale uncertainty
- MSUGRA/CMSSM with $\tan\beta = 3$, $A_0 = 0$, $\mu > 0$: squarks and gluinos of equal mass excluded < 815 GeV (95% CL)



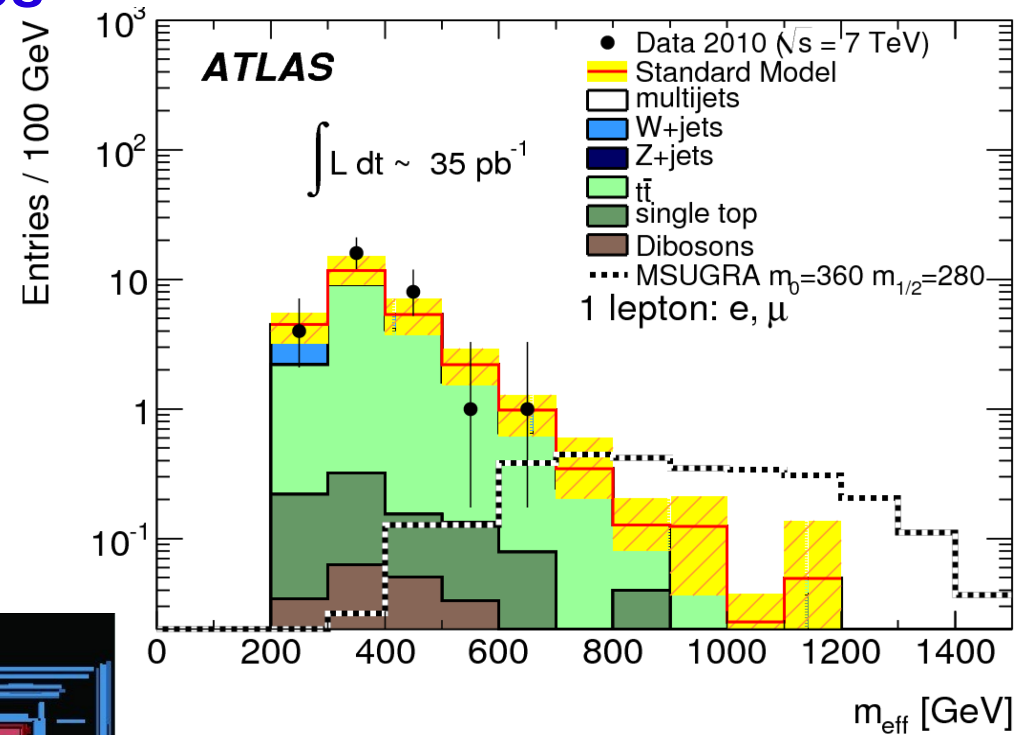
courtesy of V. Büscher, JGU

Searches for DM at the LHC

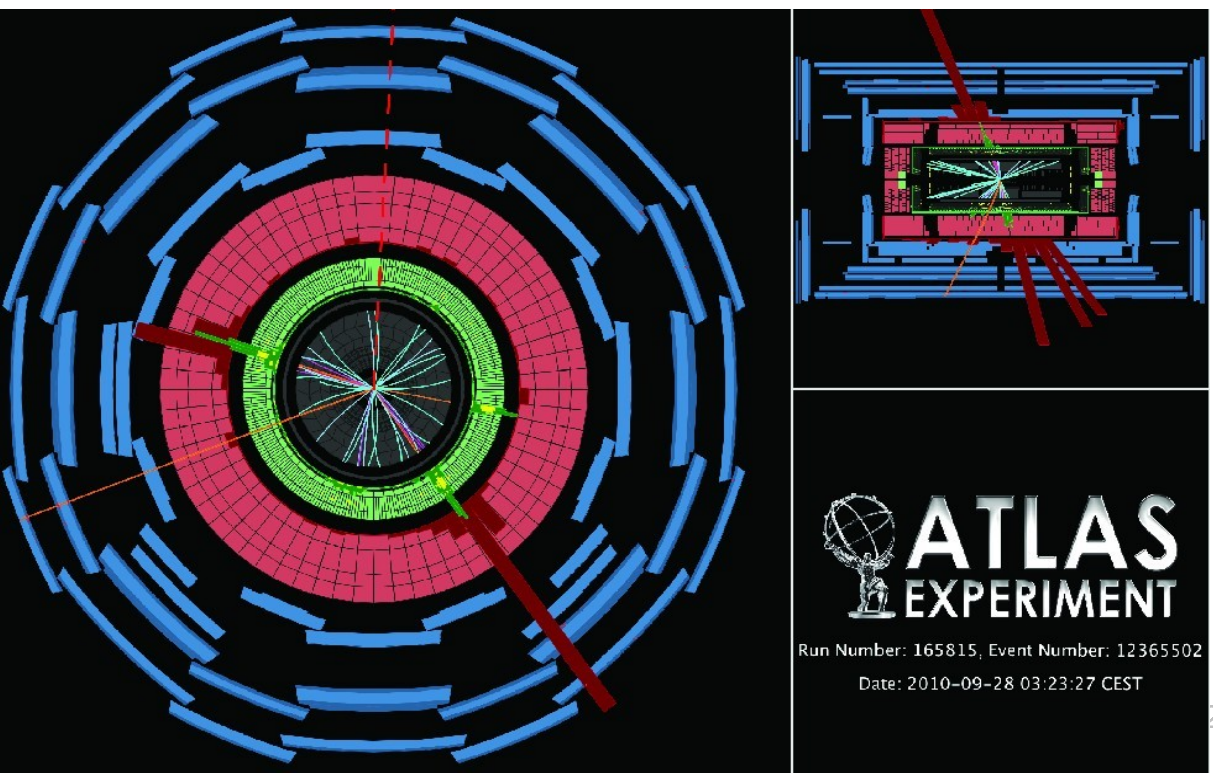
Searches for squarks and gluinos

- Effective mass distribution
  - after final selection criteria except for the cut on the effective mass itself
  - Electron and muon channel combined
  - Yellow bands: uncertainty on the Monte Carlo prediction from finite MC statistics and from jet energy scale uncertainty

ATLAS-CONF-2011-064



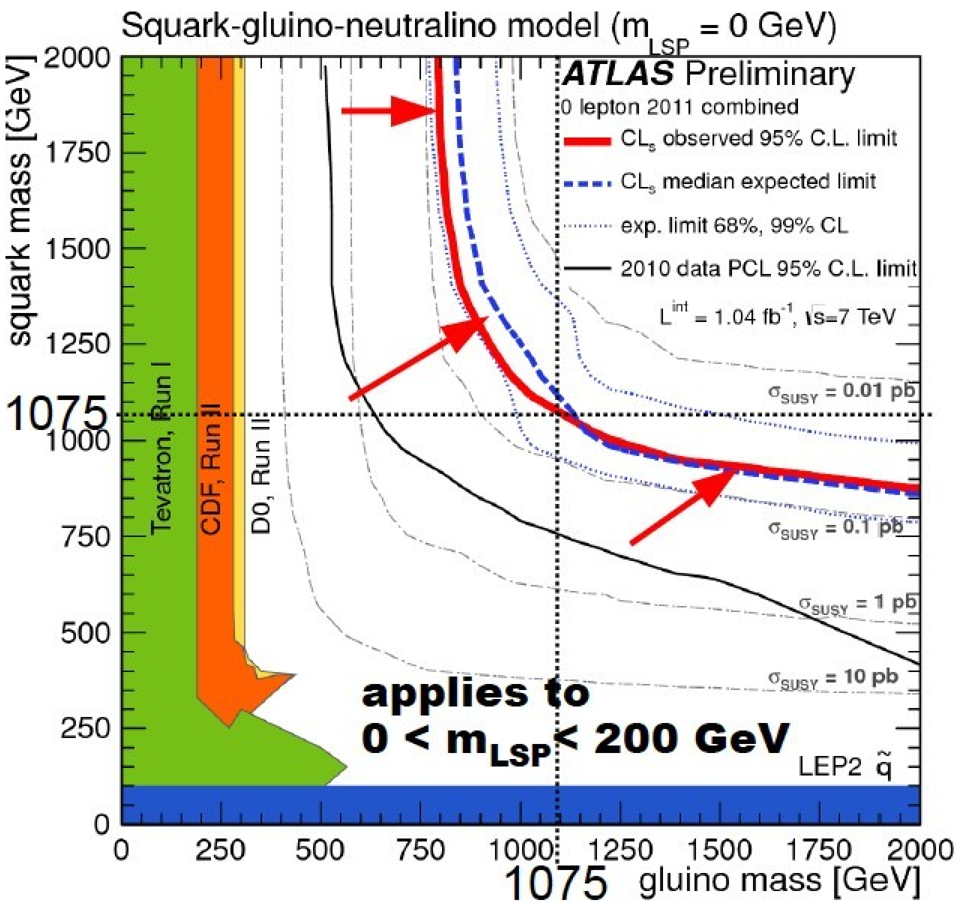
ATLAS event display of electron event in signal region

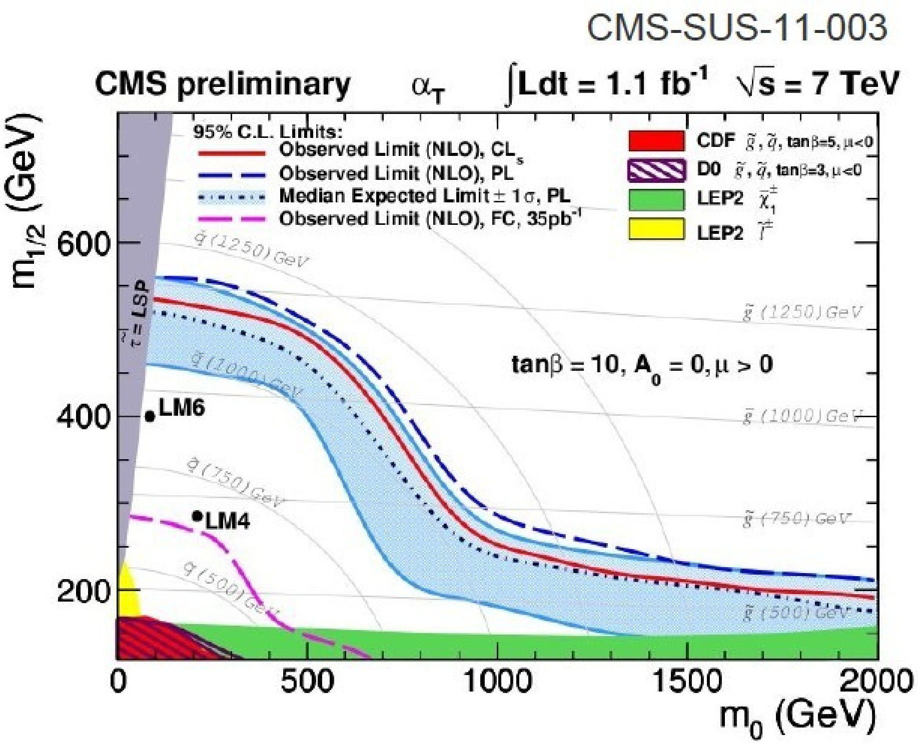


Near Future:

- 2011: On track for integrated luminosity of 5 fb^{-1}
  → ~10^2 higher statistics!

SUSY (mSugra) LHC Limits as of late August 2011

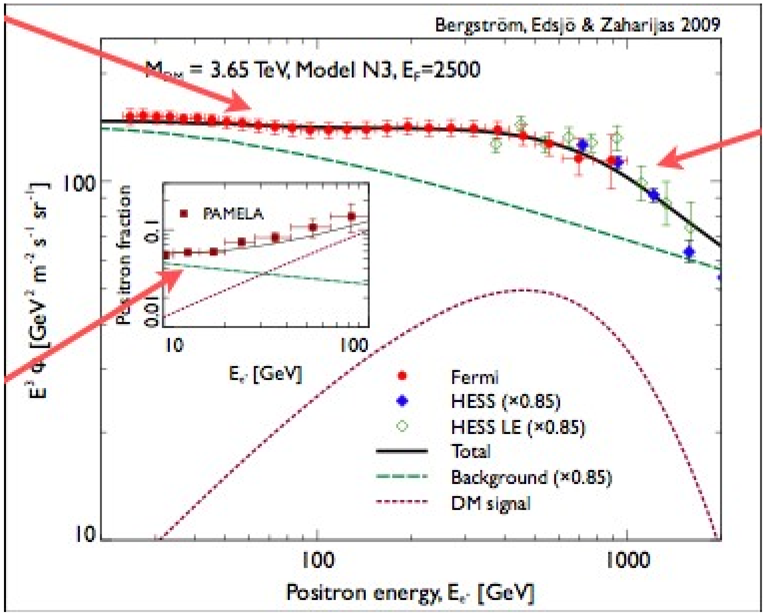




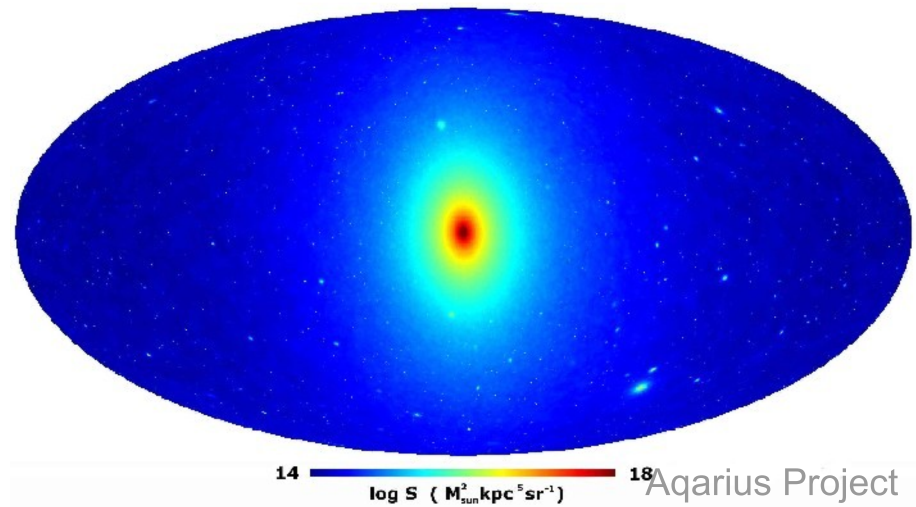
H. Bachacou, Lepton-Photon 2011

Indirect Dark Matter Searches
Tracing Products of DM Annihilation or Decay

Cosmic rays

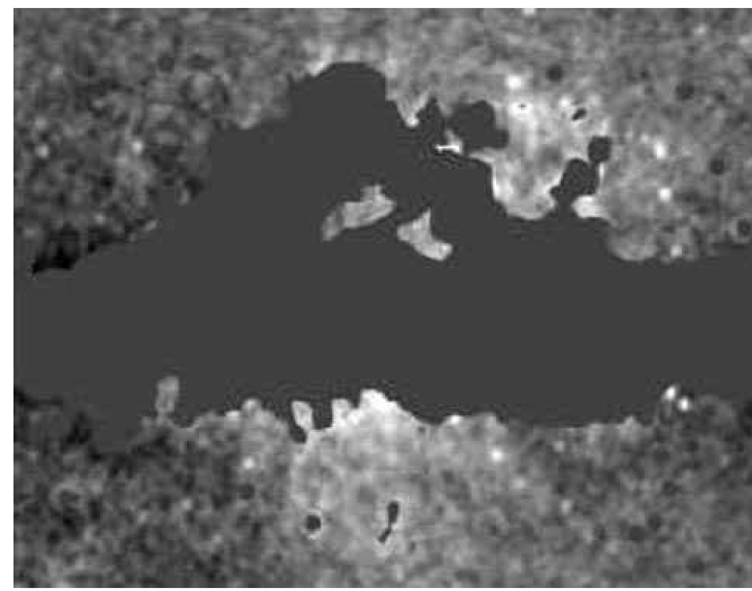


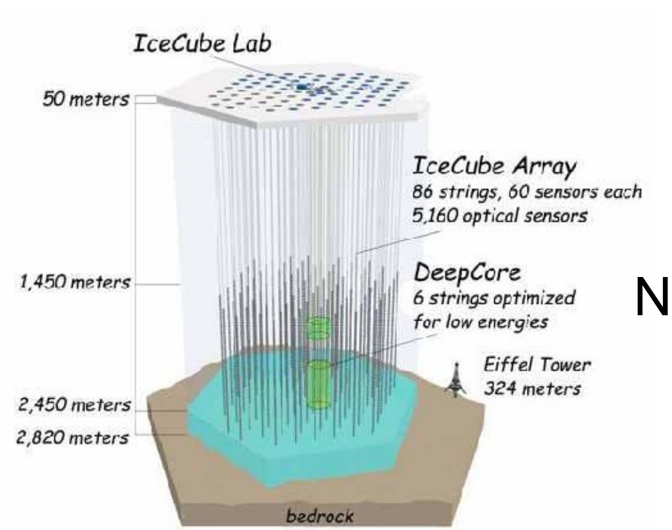
Gamma-rays



Aqarius Project

Other e.m. radiation





Neutrinos

Production of Secondary Particles

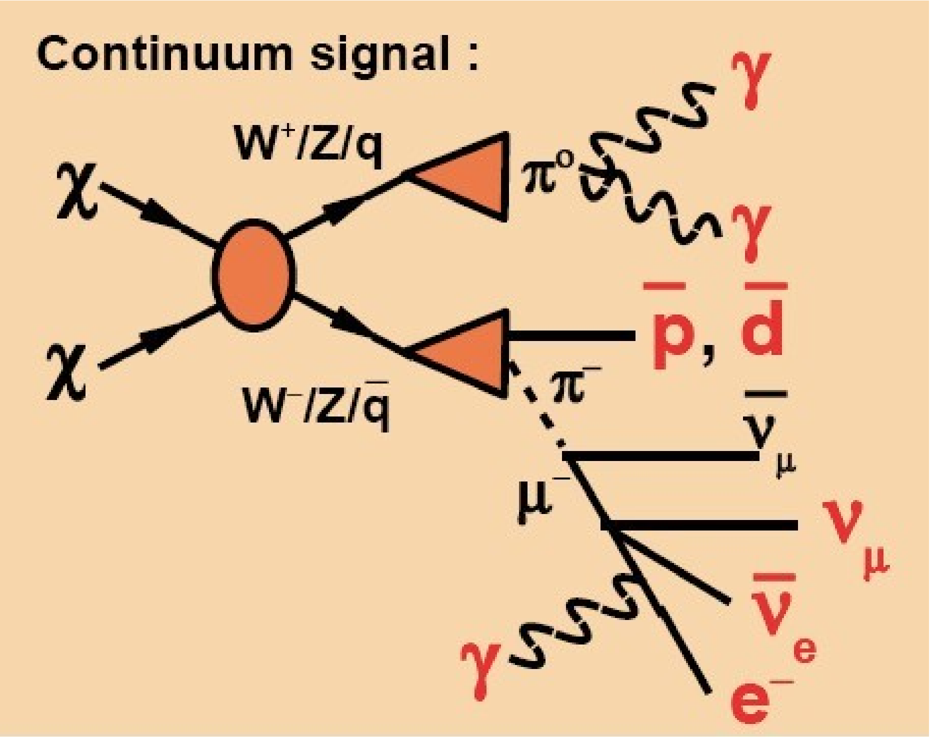
Annihilation of DM: Flux ∝ n_{DM}^2

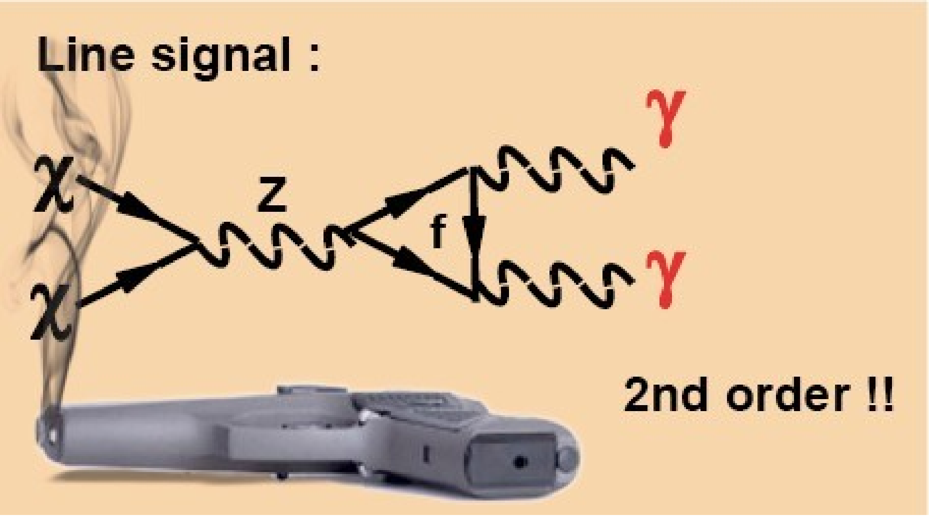
Typically leading to:

- heavy fermions
- Gauge bosons
- Higgs Bosons

- Decay or fragmentation of annihilation products
  - charged particles: electrons, protons, deuterons, and their anti-particles
  - neutral particles: Neutrinos, Gamma-rays
- Relativistic electrons & positrons:
  - Synchrotron radiation
  - Bremsstrahlung
  - Inverse Compton effect

Some DM candidates may decay: Flux ∝ n_{DM}





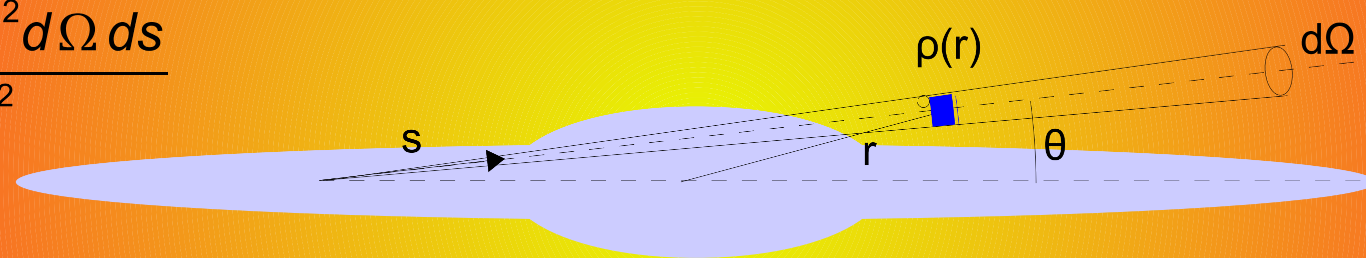
Expected Annihilation Flux

- Rate of WIMP annihilations in a volume

$$dV = s^2 d\Omega ds: \quad \langle \sigma_a v \rangle \frac{n_{DM}^2}{2} dV \qquad \text{Number of WIMP pairs in } dV:\ N(N-1)/2$$

- leads to contribution in flux through an area *dA perpendicular* to the line of sight:

$$dF = \frac{\langle \sigma_a v \rangle n_{DM}^2 s^2 d\Omega ds}{8\pi s^2}$$

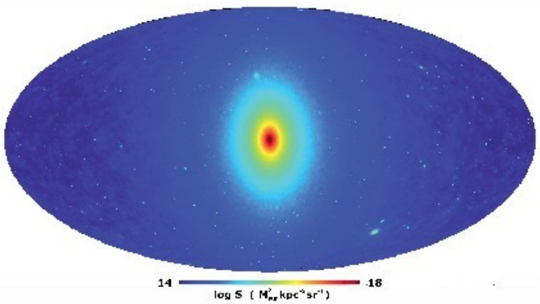


- Intensity: from integral along line of sight

$$I(E,\theta) = \frac{\langle \sigma_a v \rangle}{8\pi m_{DM}^2} \frac{dN_\gamma}{dE} \int \rho_{DM}^2 ds$$

- Number of photons per annihilation in Energieintervall *dE* (spectra from particle physics model): $\frac{dN_\gamma}{dE}$

Expected Gamma-ray Flux

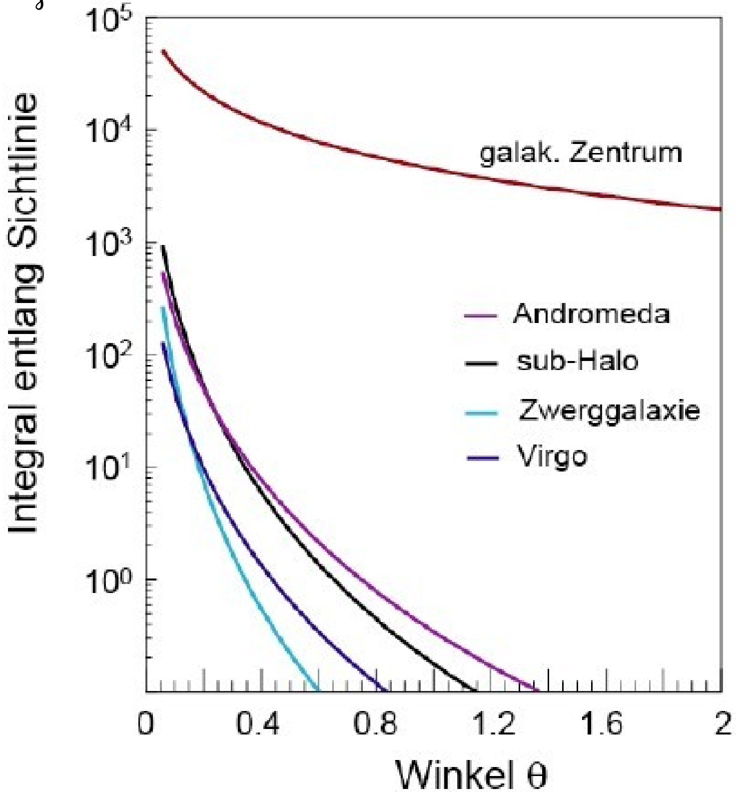


- Typical Intensities:

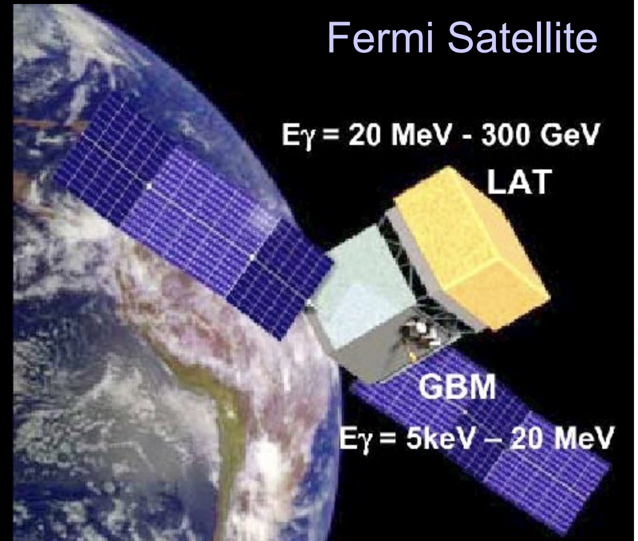
$$I(\theta, E_\gamma) = 0{,}94 \times 10^{-10}\, cm^{-2}\, s^{-1}\, sr^{-1}\, \frac{dN_\gamma}{dE} \left(\frac{\langle \sigma v \rangle}{10^{-26}\, cm^3\, s^{-1}} \right) \left(\frac{100\ \mathrm{GeV}}{m_\chi} \right)^2 J(\theta)$$

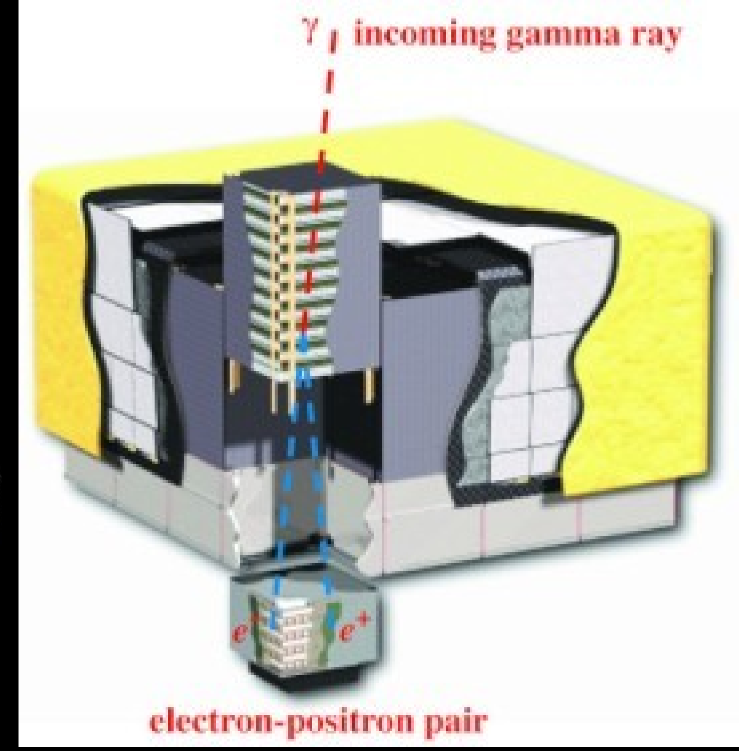
$$J(\theta) = \frac{1}{8{,}5\ \mathrm{kpc}} \left(\frac{1}{0{,}3\ \mathrm{GeV/cm^3}} \right)^2 \int_{\text{line of sight}} \rho^2(r(s,\theta))\, ds$$

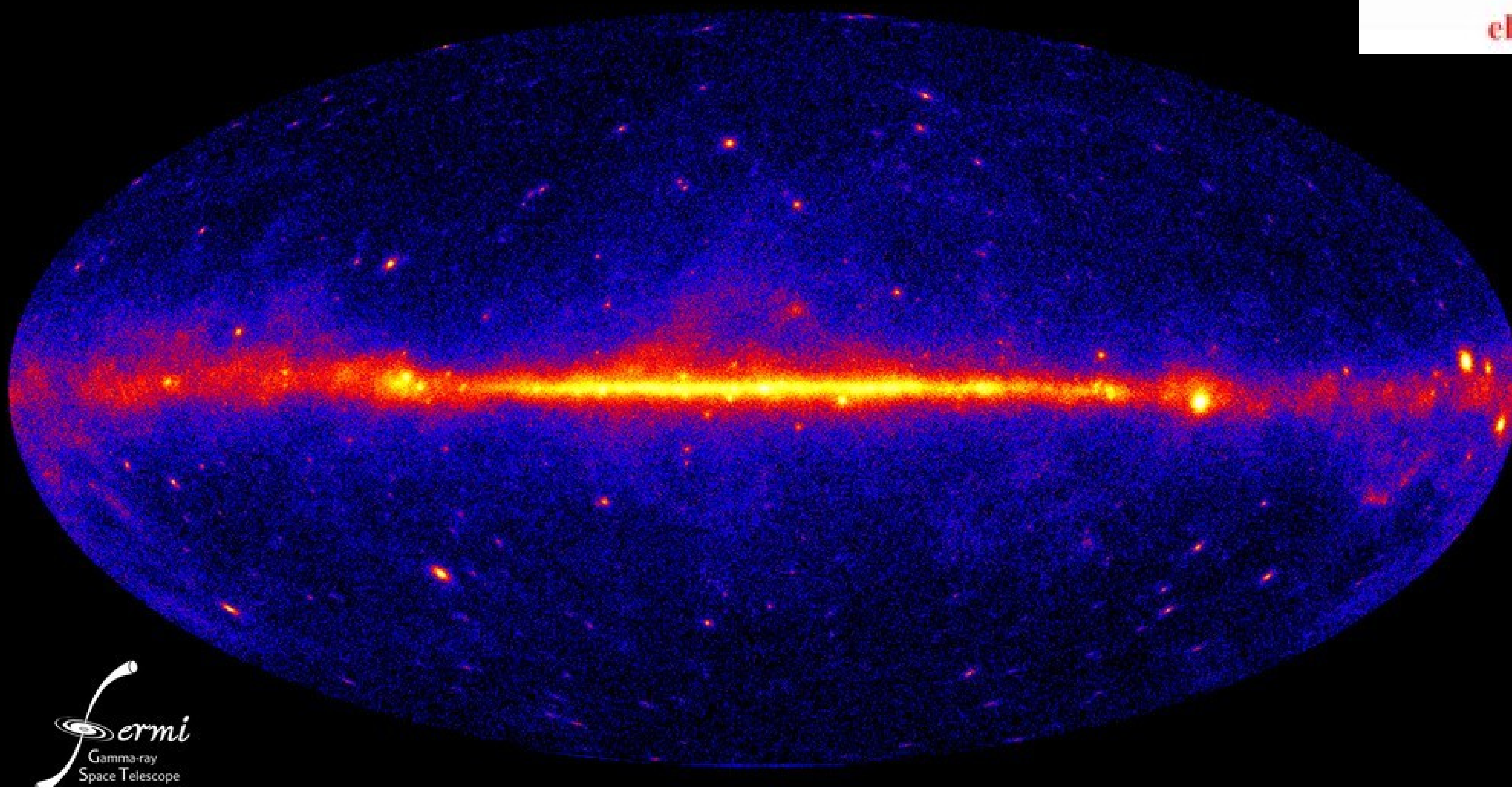
with: $\int \frac{dN_\gamma}{dE} dE = N_\gamma$



Fermi: Gamma Radiation at GeV Energies

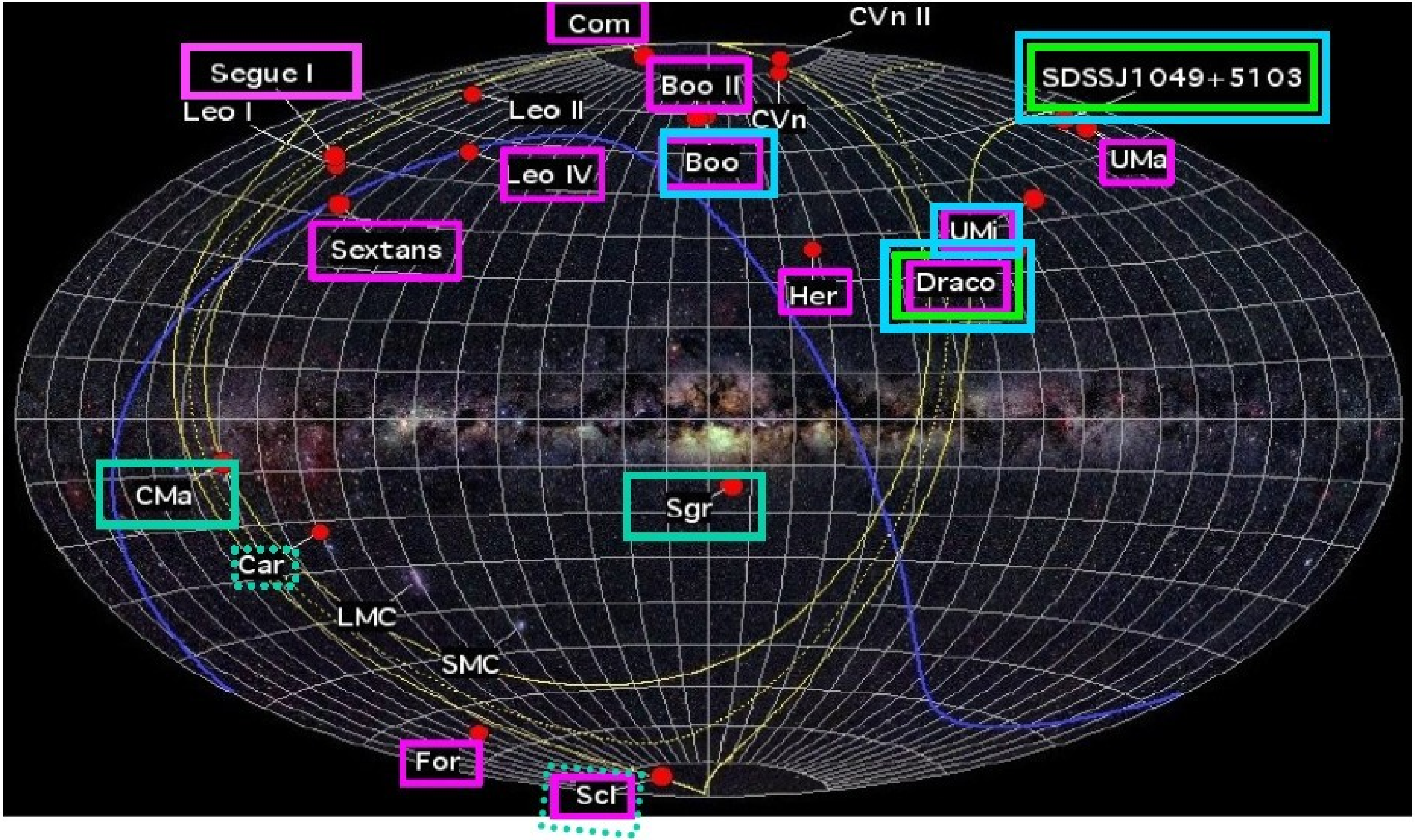






Dwarf Spheroids probed in Gamma-Rays

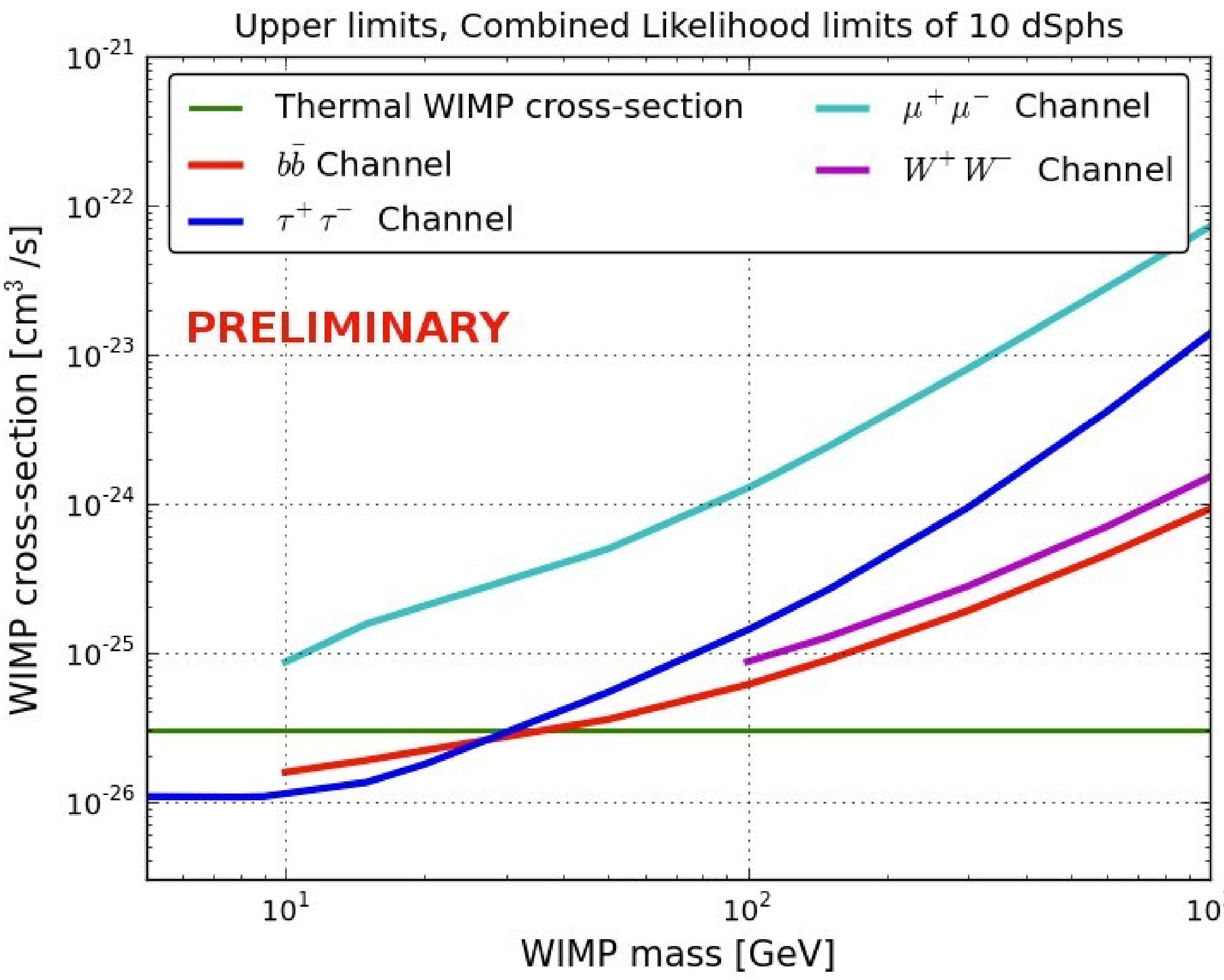
Fermi H.E.S.S. MAGIC Veritas



H.E.S.S. in prep.

Combined analysis of Milky Way satellites with Fermi

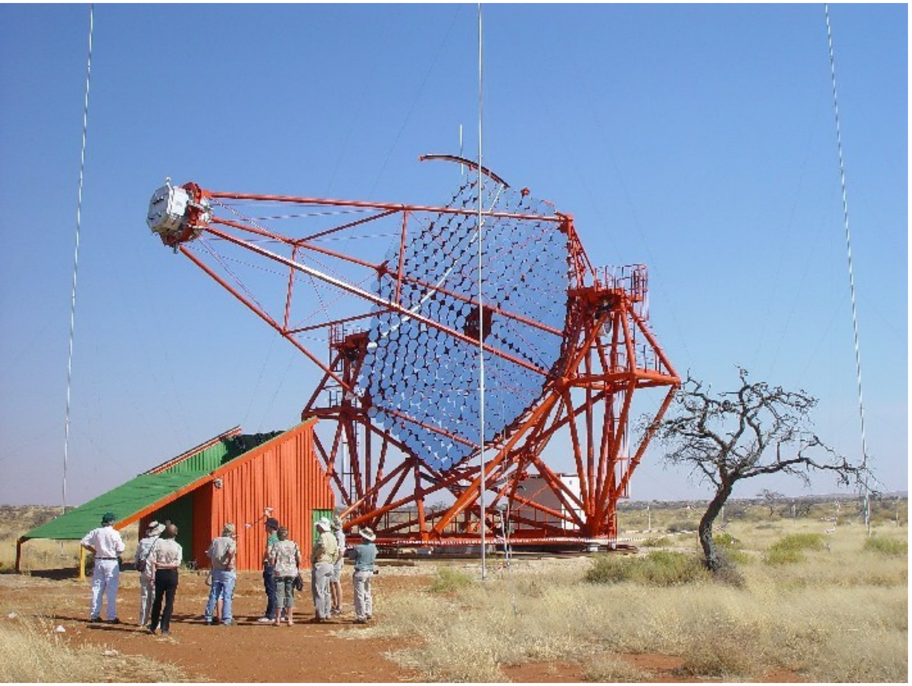
Maja Llena Garde, Fermi Symp. 2011



3×10^{-26} cm³/s

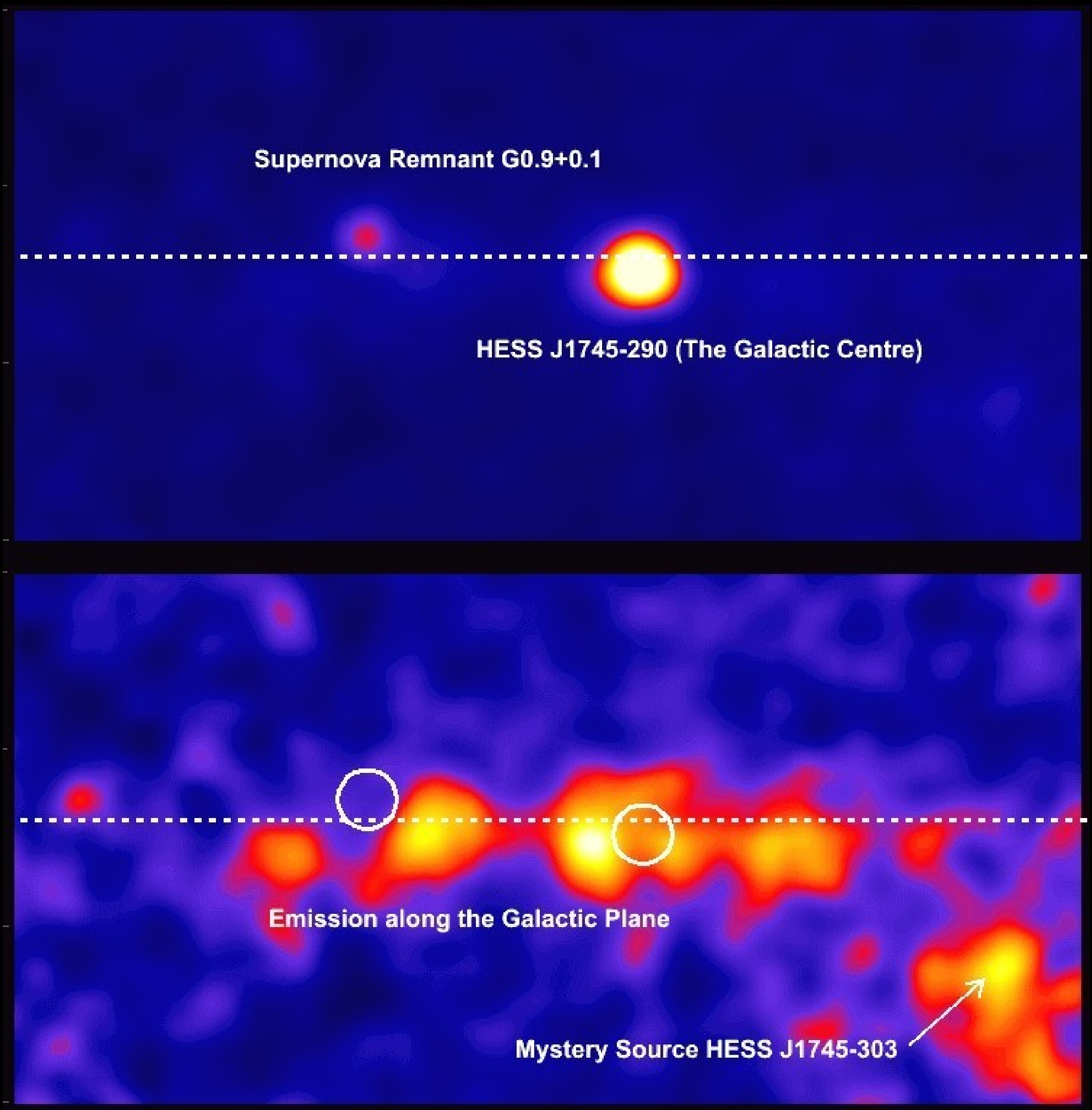
- Relevante Grenzen bei niedrigen WIMP-Massen für zwei Zerfallskanäle

HESS: TeV Gamma Radiation



- Imaging Air Cherenkov Telescope (IACT) in Namibia
- 4 identical telescopes, 13 m diameter, 120 m baseline
- Measures Cherenkov radiation of particle showers in the atmosphere, initiated by high energy gamma rays in the upper atmosphere
- <0,1° angular resolution, 5° field of view

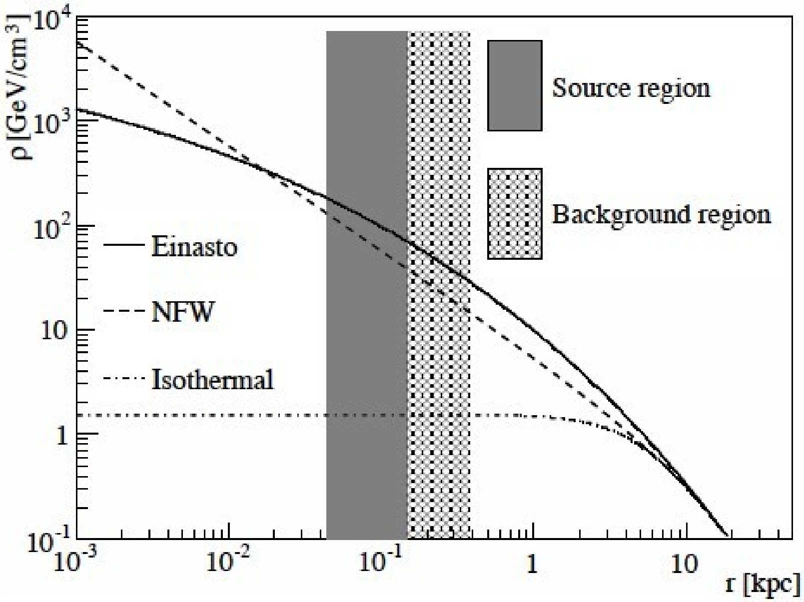
HESS: Inner Galaxy in TeV Region

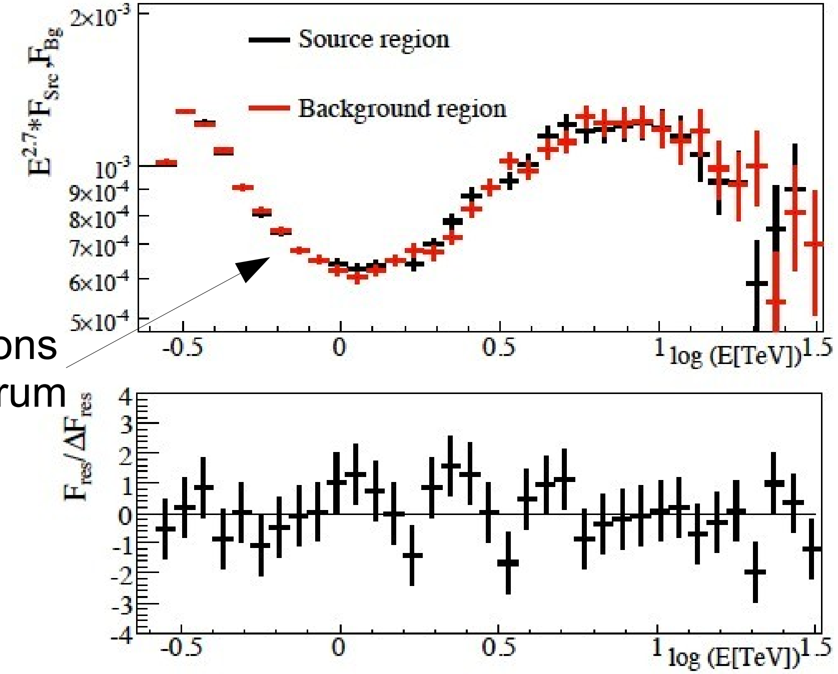


dominant point source in the galactic center

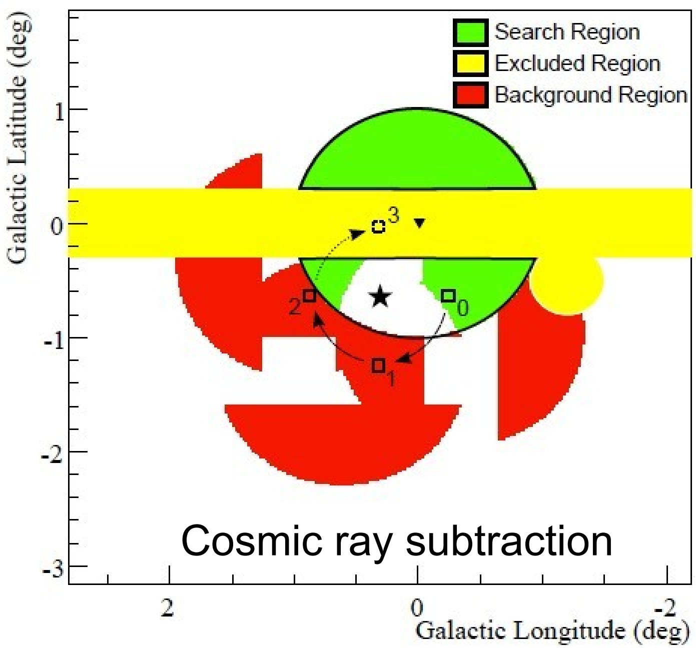
After subtraction of the two dominant point sources: diffuse emission along the galactic plane → interesting astrophysics, but not DM

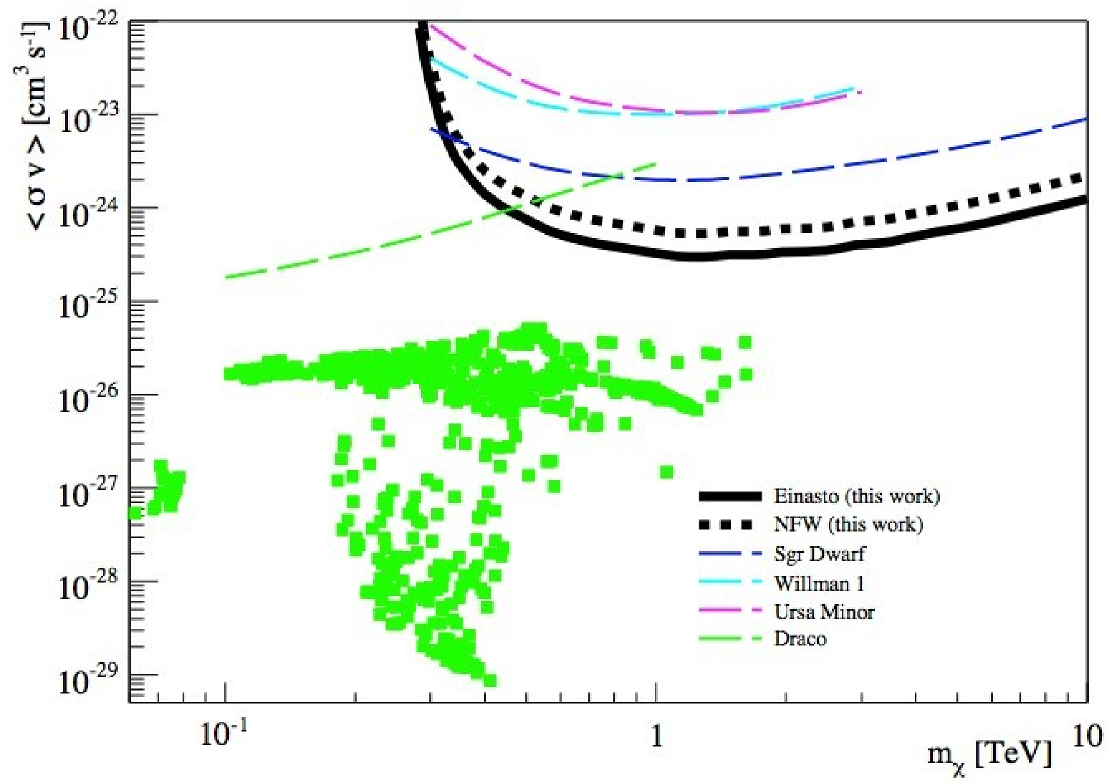
HESS Dark Matter Limits





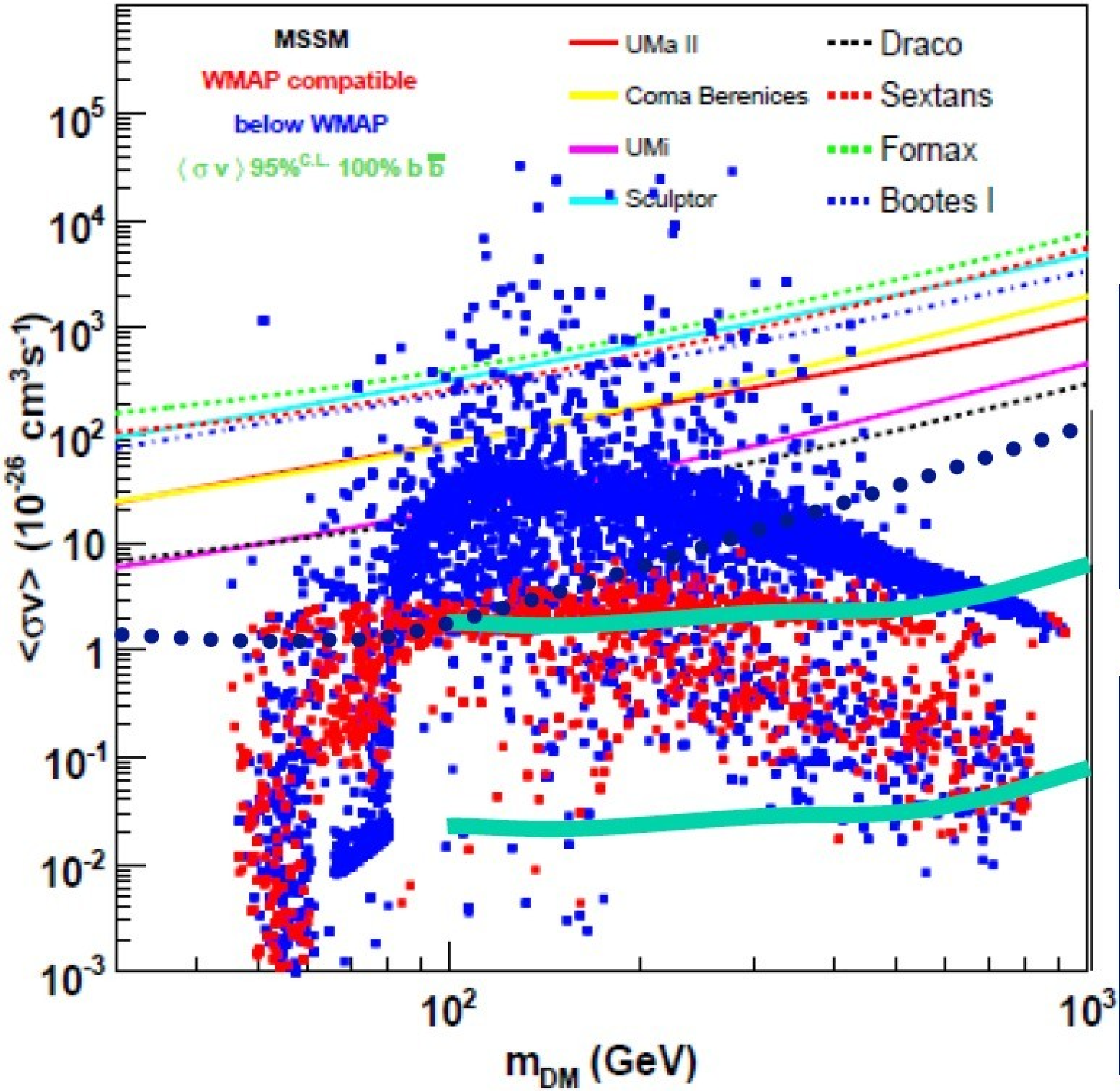
Efficiency variations modify CR spectrum





arXiv:1103.3266

Expectations for the end of the decade with CTA (ultra-high energies)



CTA Sag, NFW, 20 h (based on CTA Design study simulations). NB: 5 σ

PRELIMINARY!

CTA halo (~100h)

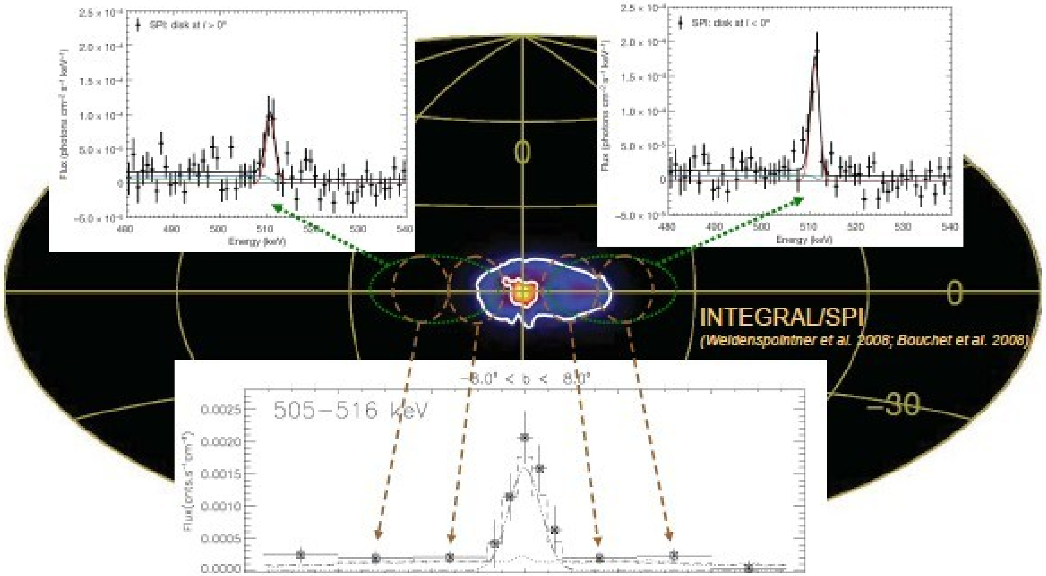
(if halo sensitivity improvment comparable to Sag dwarf improvement)

Aquarius

J. Conrad, IDM 2010

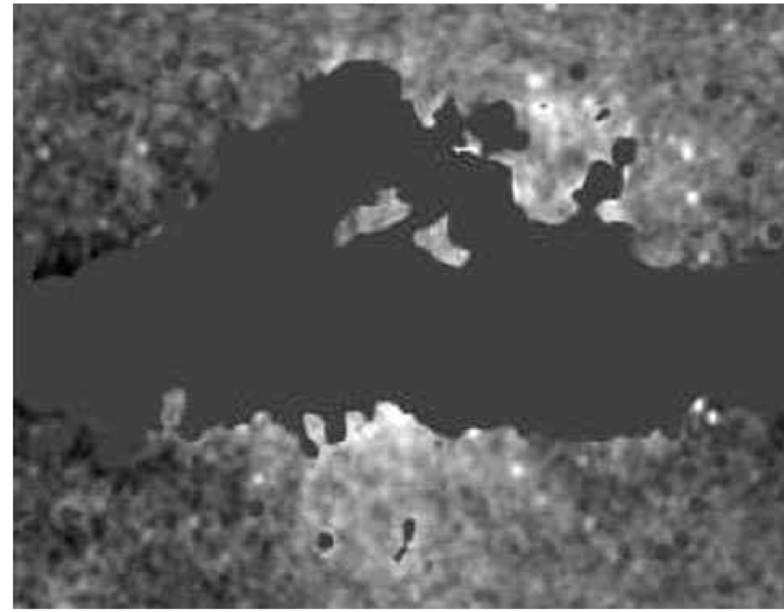
Positrons in the Galactic Bulge

511 keV Emission



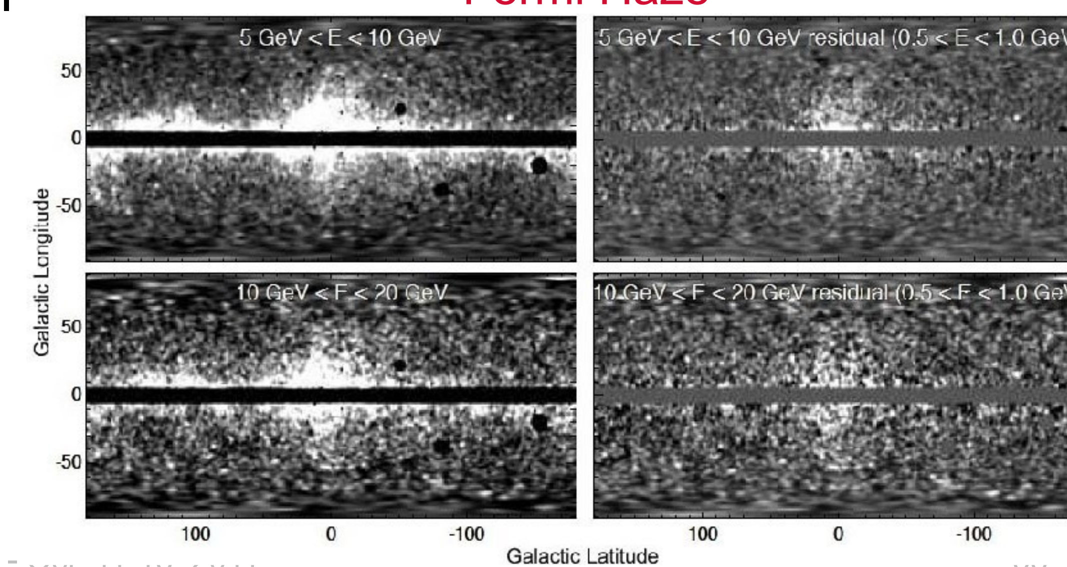
Diehl & Leisung arXiv:0906.1503

CMB Haze Finkbeiner et al.



- Surprises in various maps of celestial emissions: 511 keV, synchrotron emission, high-energy gamma-rays.
- DM scenarios have been proposed.
- However, very difficult to disentangle from astrophysics.
- Dark force could naturally result in e+/e- excesses from DM annihilation

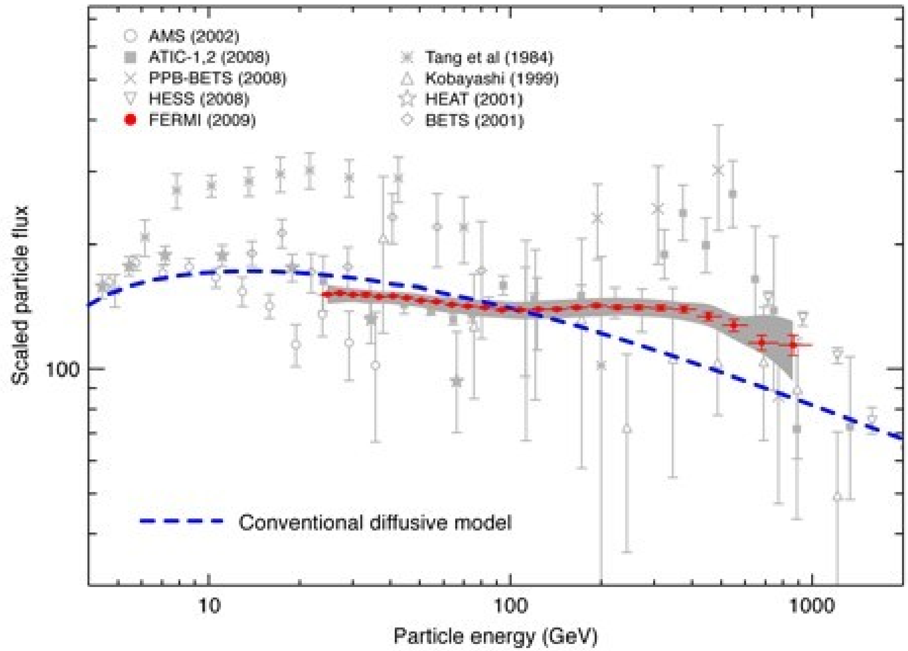
Fermi Haze

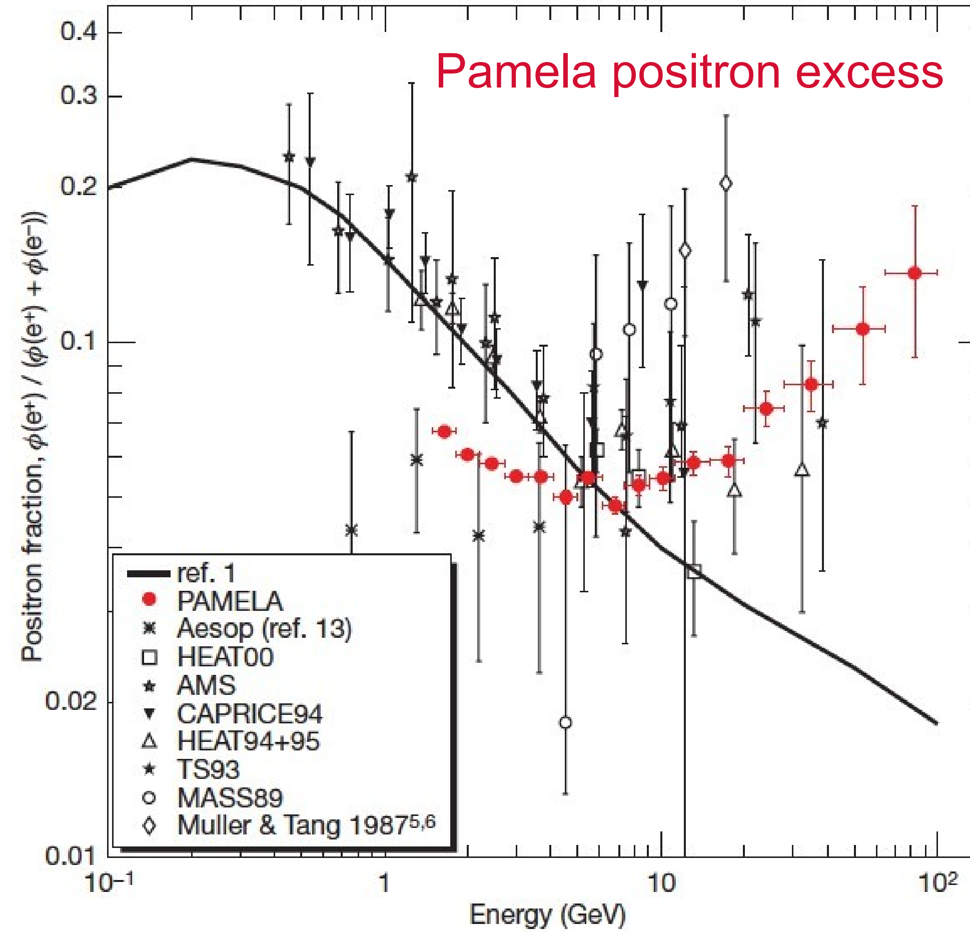


Dobler et al., ApJ 717, 825 (2010).

Positron Excess in Local Cosmic Rays

- Unexpected large positron excess
- Fermi electron (+positron) flux also shows an enhancement





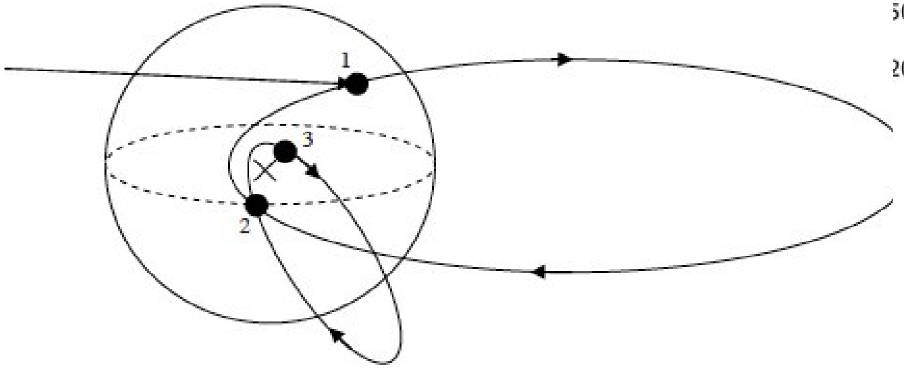
Adriani et al., Nature 458, 607 (2009)

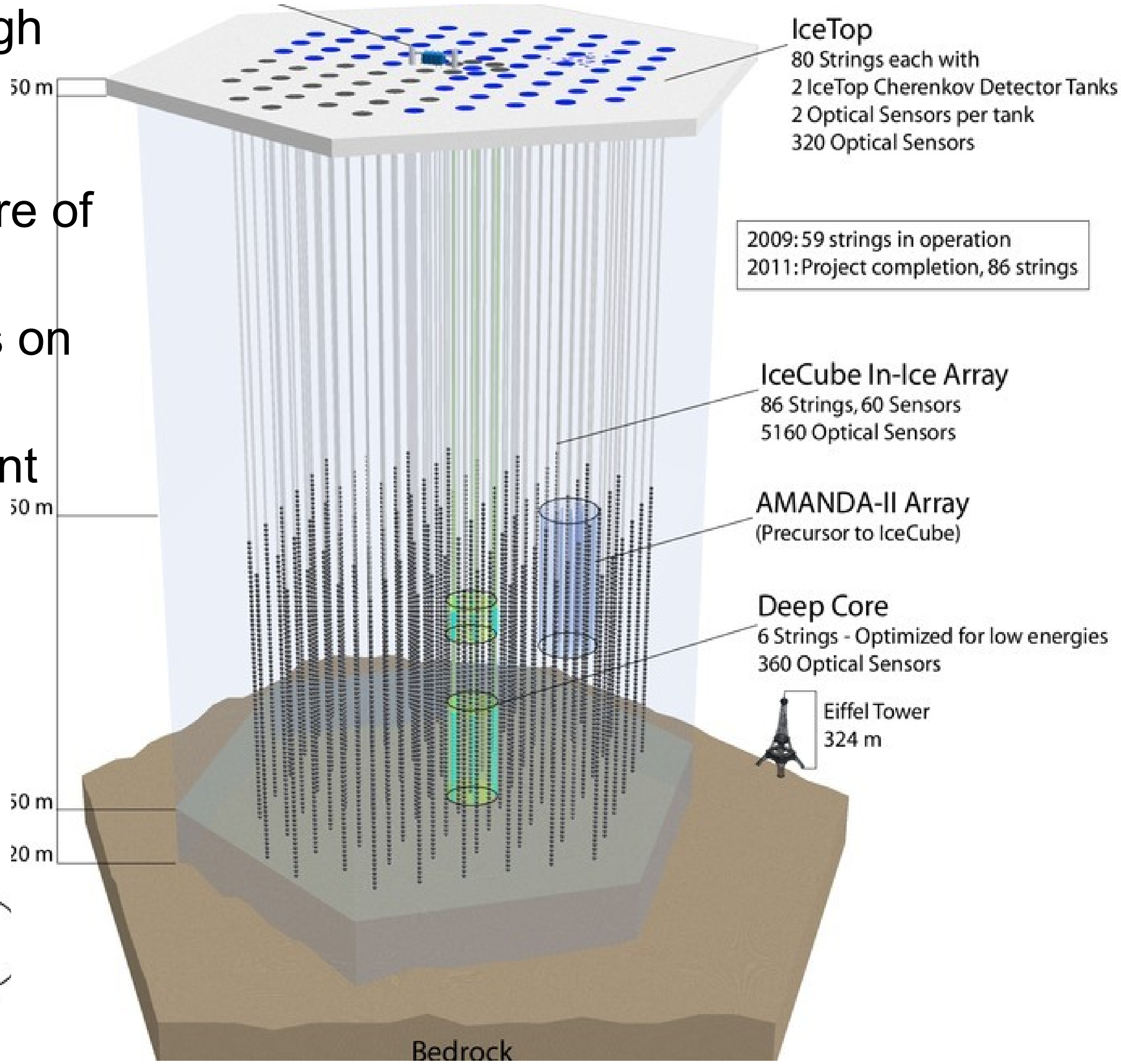
- Dark Matter? (very large signal)
- Astrophysics? "Local" pulsars could produce the excess.
- Outlook: AMS-02 launched 16-May-2011

Indirect DM Searches – Neutrinos with IceCube

courtesy of K. Wiebe & L. Köpke, JGU

- Capture of DM in the Sun through scattering
- Annihilation results in neutrinos, which can escape the dense core of the Sun
- WIMP annihilation rate depends on WIMP-nucleon scatter rate
- Most powerful for spin-dependent interactions
- Energy thresholds:
  - IceCube: 100 GeV
  - DeepCore: 10 GeV

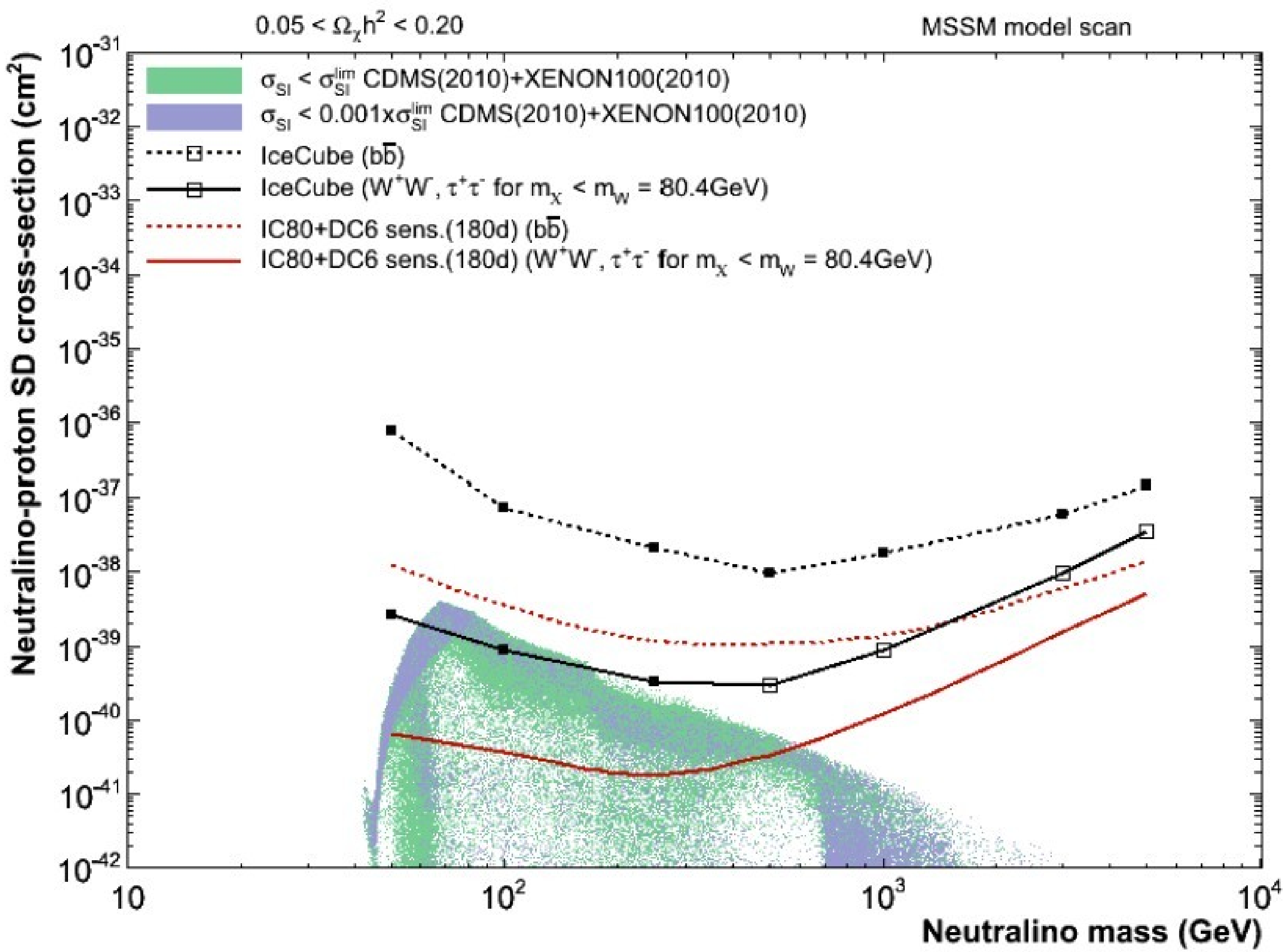




Indirect DM Searches – Neutrinos with IceCube

Spin-dependent vs. Spin-independent Interactions

courtesy of K. Wiebe
& L. Köpke, JGU



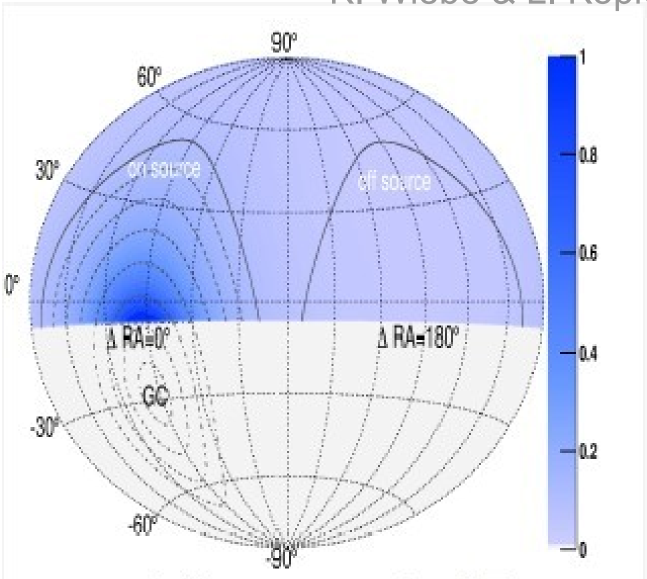
Indirect DM Searches – Neutrinos with IceCube

Galactic Halo and Dwarf Galaxies

K. Wiebe & L. Köpke, JGU

- Dark Matter in galactic halo:
  - enhanced neutrino flux expected near galactic center
  - galactic center in southern sky
  - down going analysis (DeepCore)
- Dwarf spheroidal galaxies
  - high mass-to-light ratio → large DM density
  - point-source search performed in Mainz
  - advantage over ground-based gamma telescopes: continuous observation → large exposure

- However, without boost factors, signals may be too small by factor ~10^2.



relative expected Flux