

Dunkle Materie

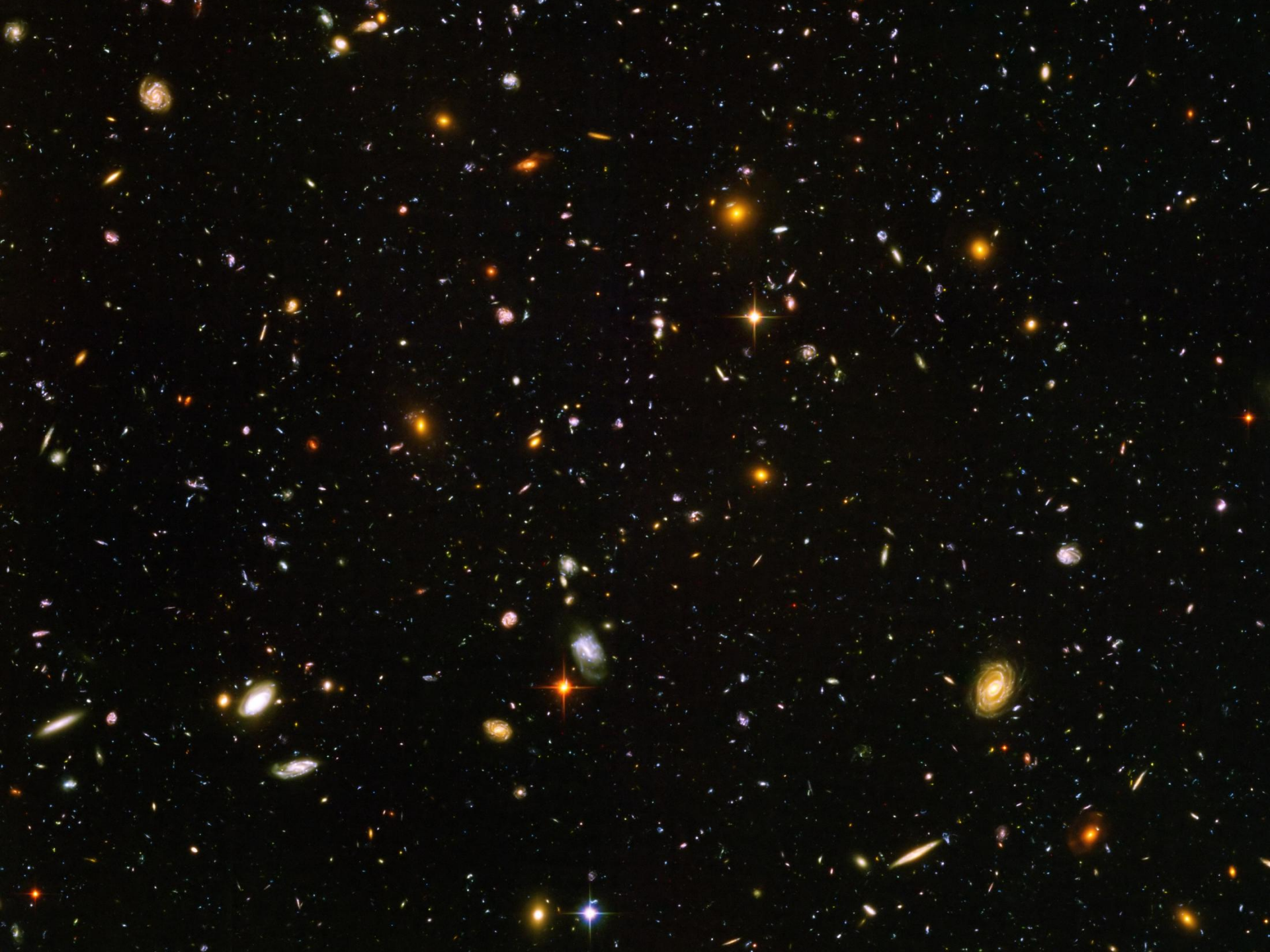
Erhellendes aus Universum und Labor



A. Straessner



- Was ist Dunkle Materie?
- Nachweis Dunkler Materie im Universum
- Suche nach Dunkler Materie “im Labor”



A deep-field astronomical image showing a vast field of galaxies and stars. The galaxies are scattered across the frame, appearing in various colors (yellow, orange, blue, purple) and shapes (spiral, elliptical, irregular). The stars are small, bright points of light, some with prominent diffraction spikes. The background is a dark, blackish space filled with these celestial objects.

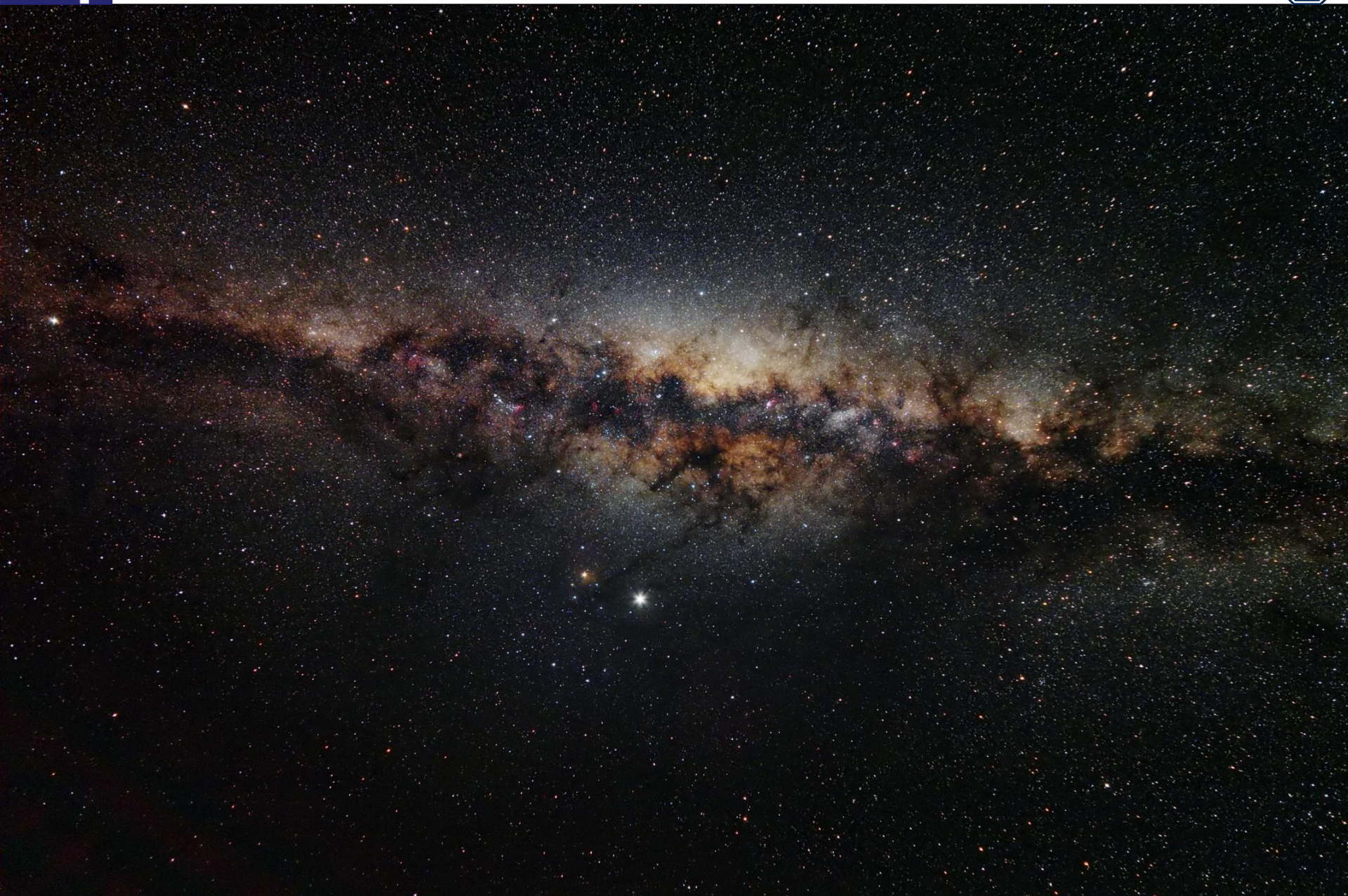
Sterne und Galaxien = leuchtende, sichtbare Materie

nicht nur sichtbares Licht, auch andere Strahlung
(Radiowellen, Infrarot, ...)

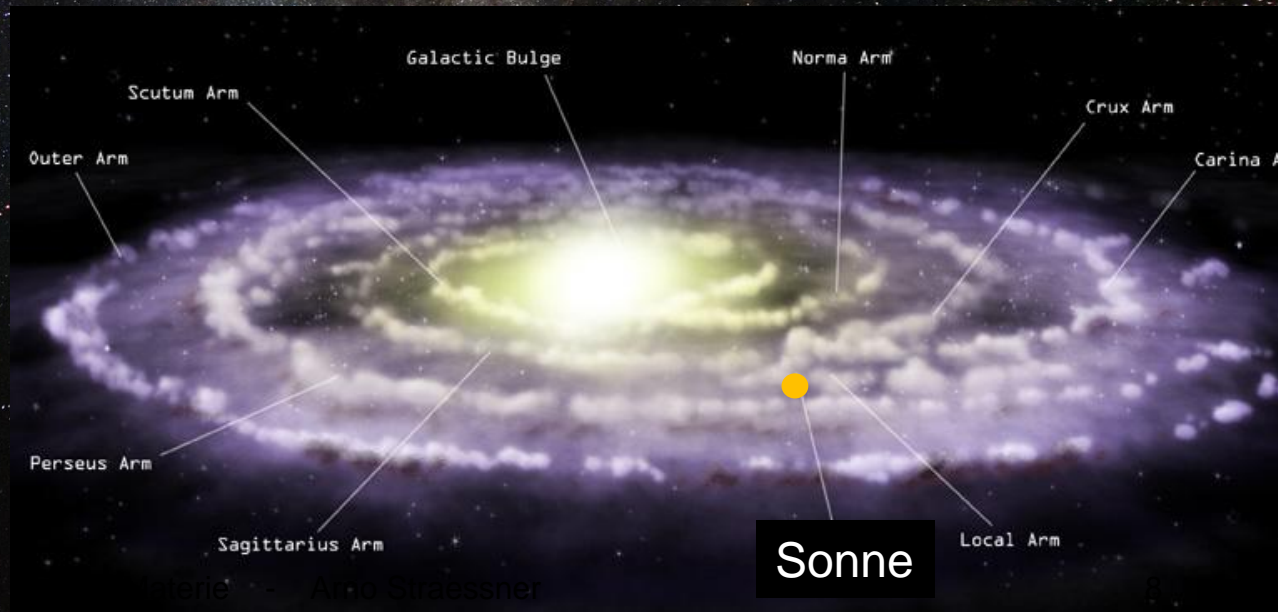
Dunkle Materie

nicht durch Strahlungsemission nachweisbar

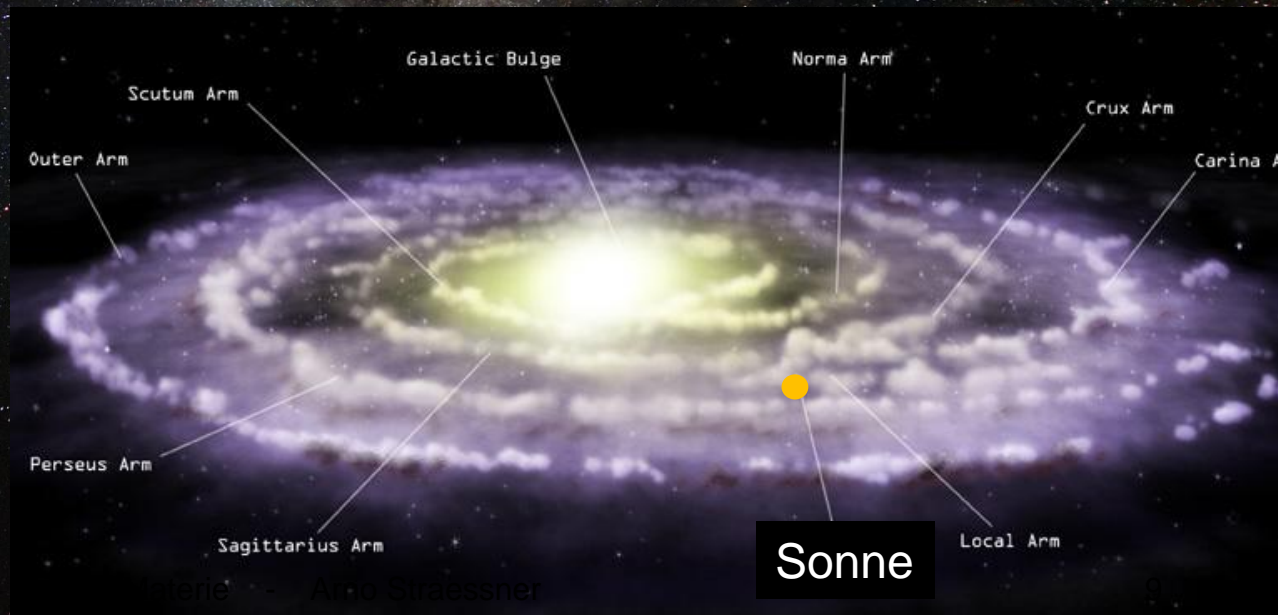
Wenn man sie nicht sieht,
woher weiß man, dass es Dunkle Materie gibt?



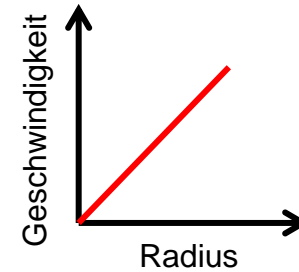
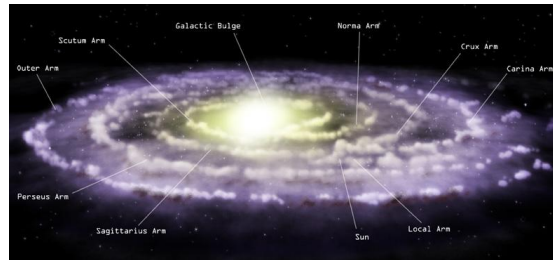
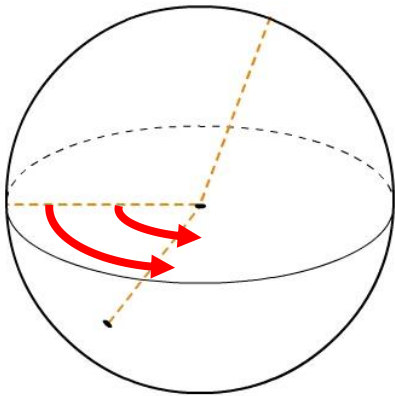
- Spiralgalaxie



- Spiralgalaxie
 - rotierende Sterne um das galaktische Zentrum
- Gravitation

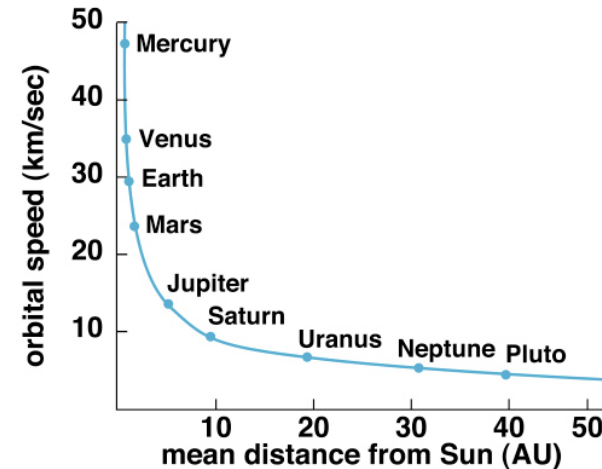
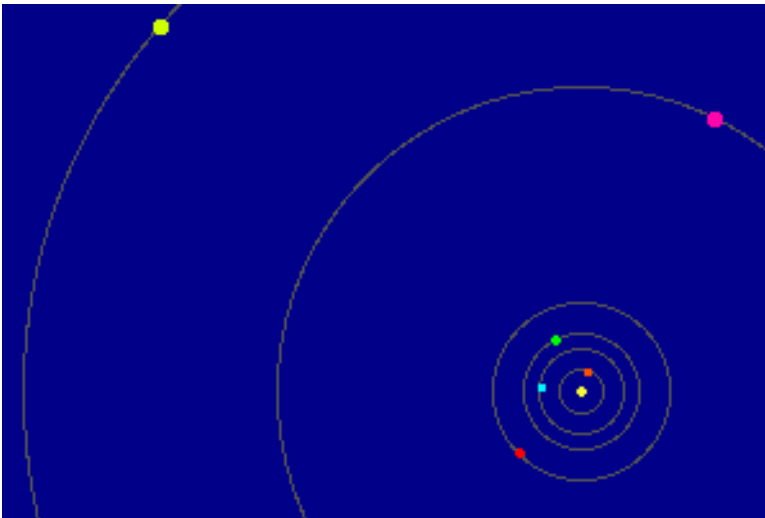


- Sterne im galaktischen Zentrum kreisen wie eine feste Kugel um Mittelpunkt



→ Geschwindigkeit nimmt linear zu mit zunehmendem Abstand vom Mittelpunkt

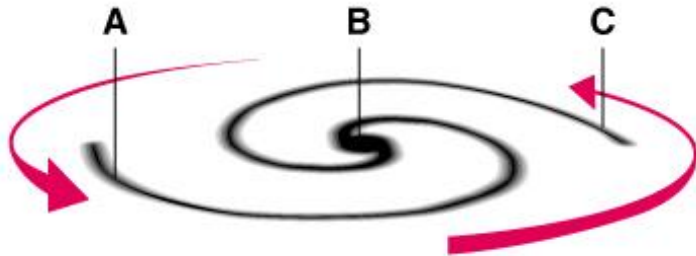
- Äußere Sterne kreisen um galaktisches Zentrum wie Planeten um die Sonne



(b)
Copyright © Addison Wesley

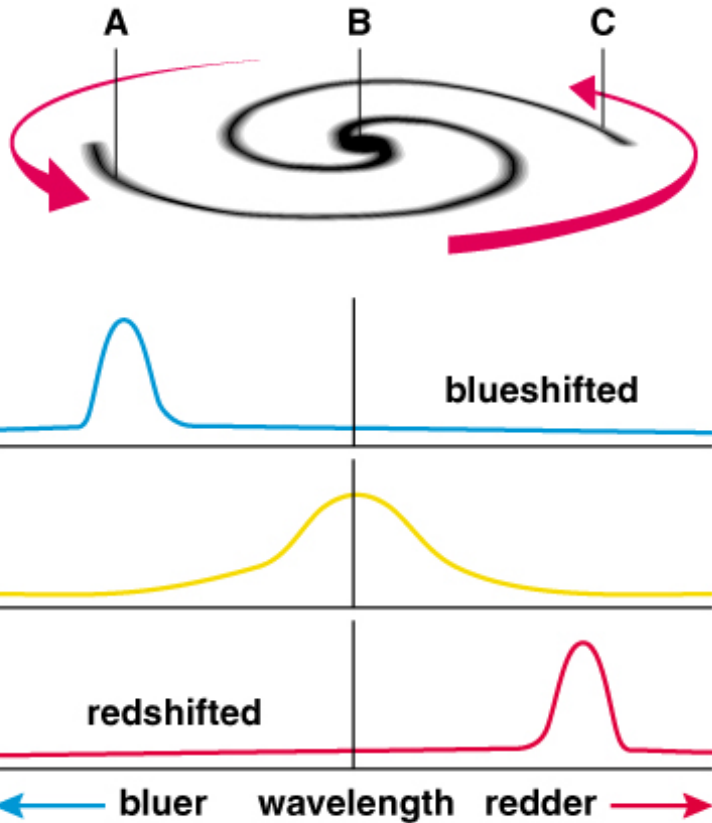
→ Geschwindigkeit nimmt mit zunehmendem Abstand ab

- Bestimmung der Bewegungsgeschwindigkeit anhand des Dopplereffekts
- Beim Martinshorn: Verschiebung der Tonhöhe:

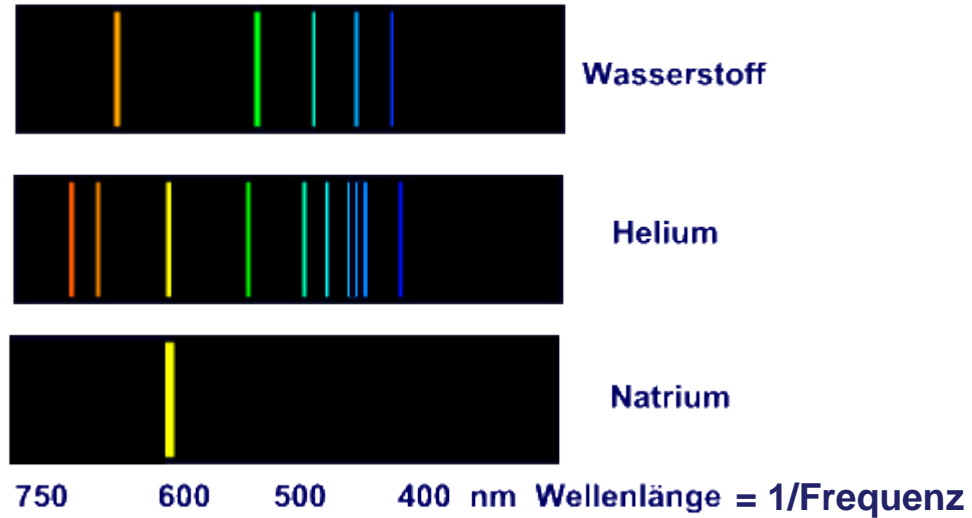


- A: Quelle bewegt sich auf Beobachter zu \rightarrow höherer Ton = höhere Frequenz
- B: Quelle entfernt sich von Beobachter \rightarrow niedrigerer Ton = niedrigere Frequenz

- Verschiebung bekannter Spektrallinien von Atomen und Molekülen

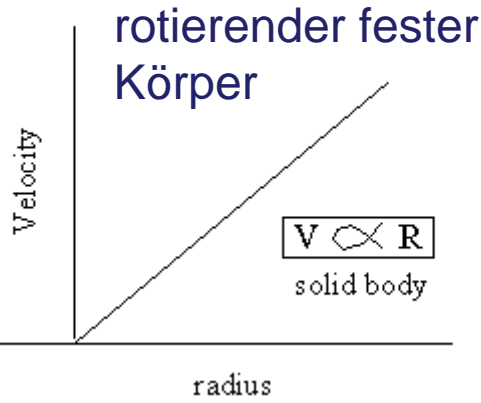
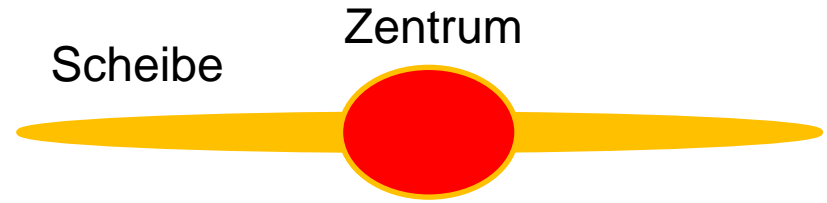
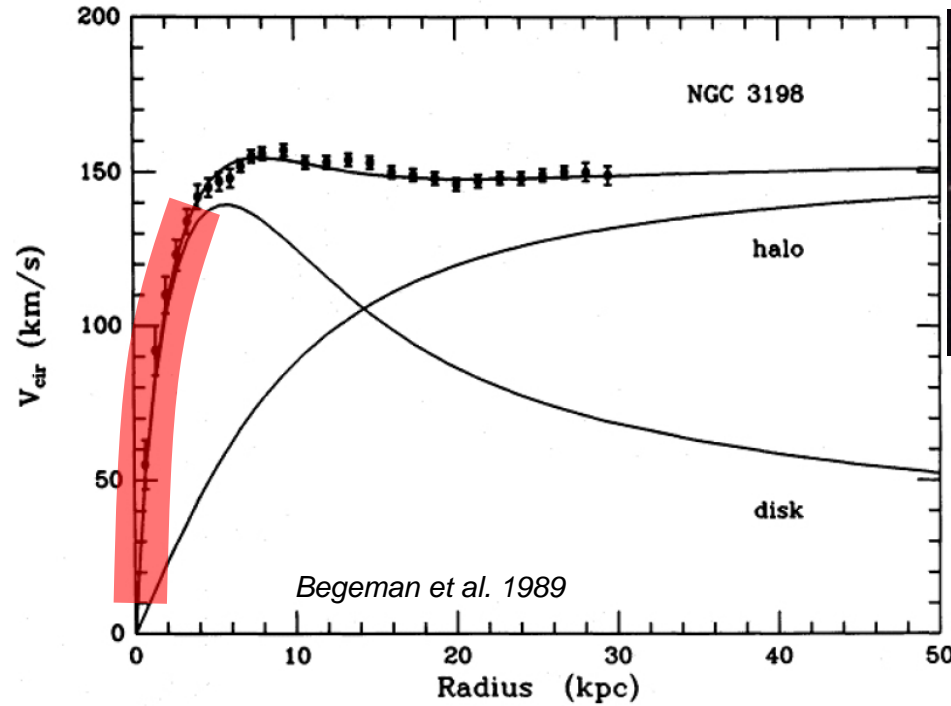


Emissionsspektren (ruhende Quelle)

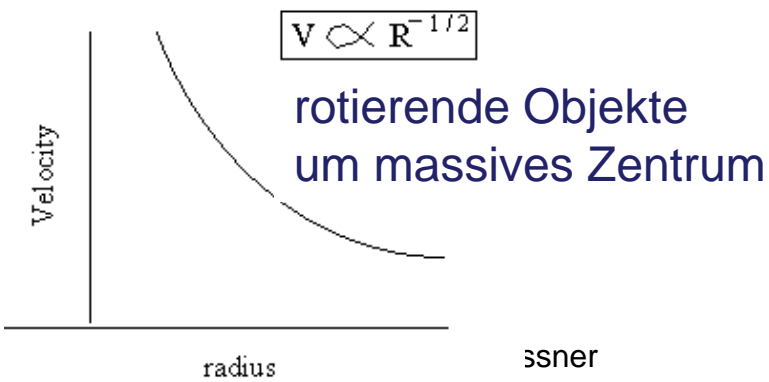
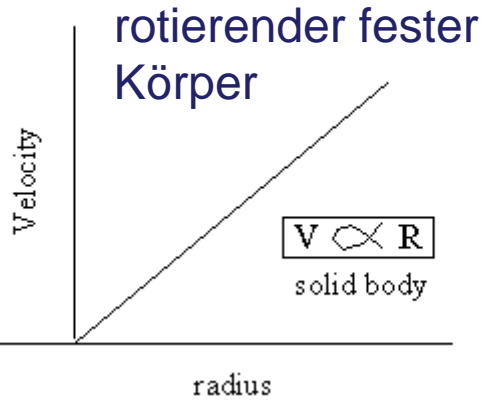
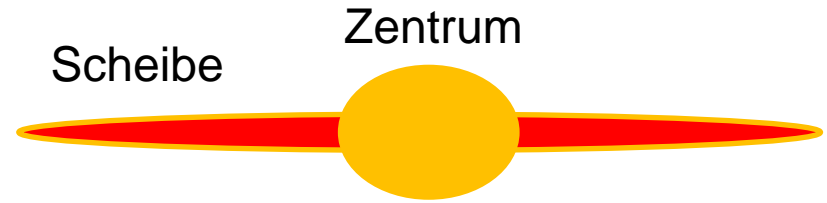
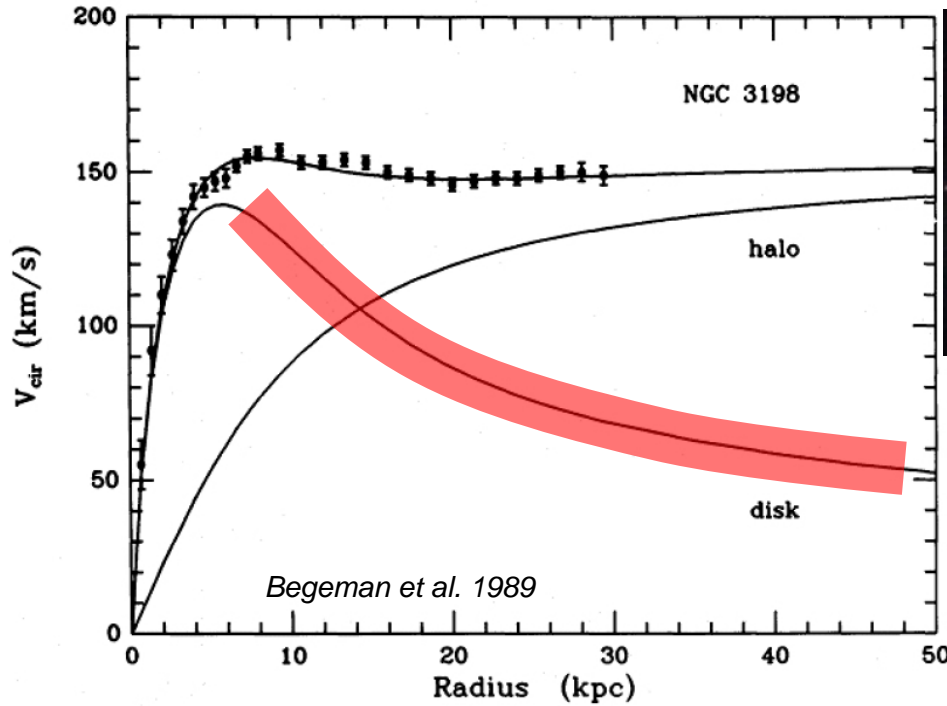


- A: höhere Frequenz: Licht wird nach "blau" verschoben
- B: niedrigere Frequenz: Licht wird "rot" verschoben

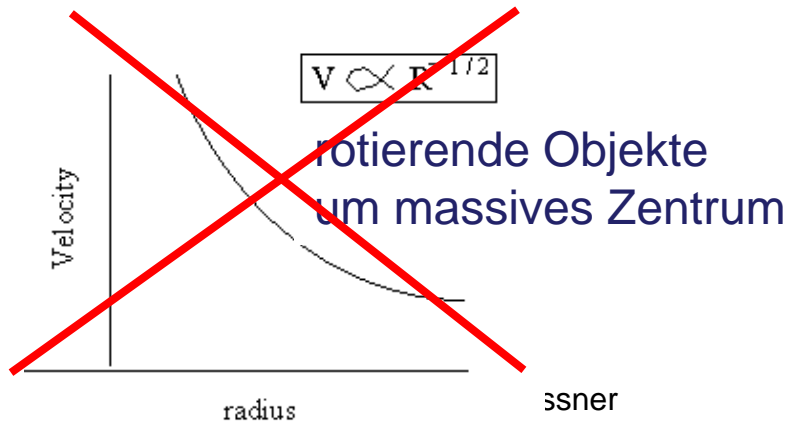
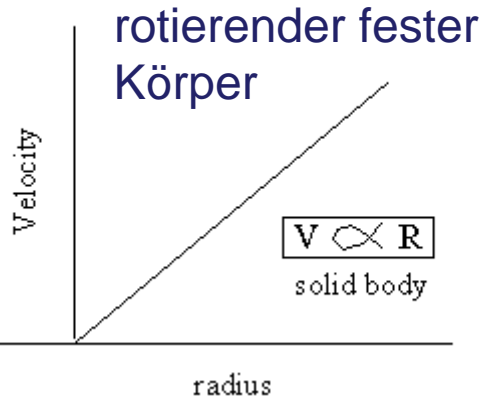
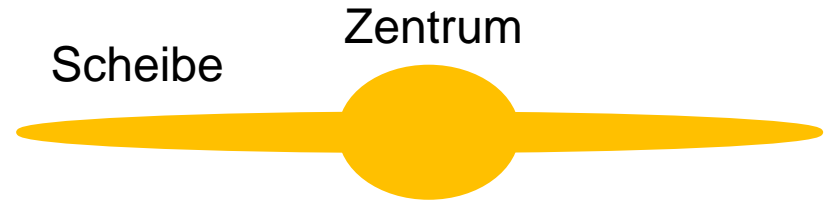
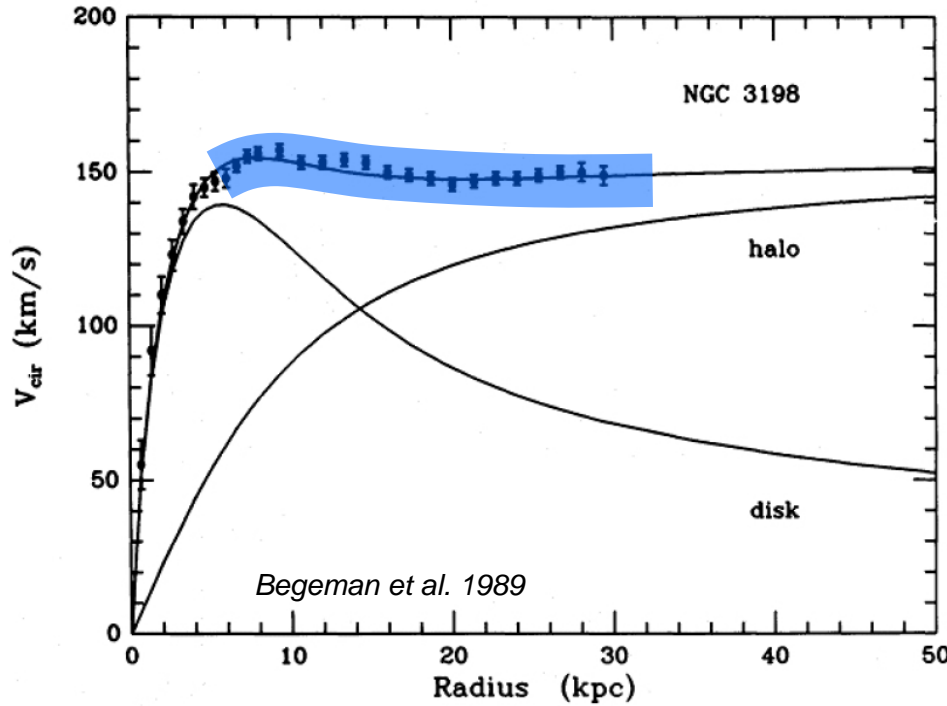
- Bestimmung der Bewegungs-Geschwindigkeit anhand des Doppler-Effekts und Verschiebung bekannter Spektrallinien von Atomen und Molekülen



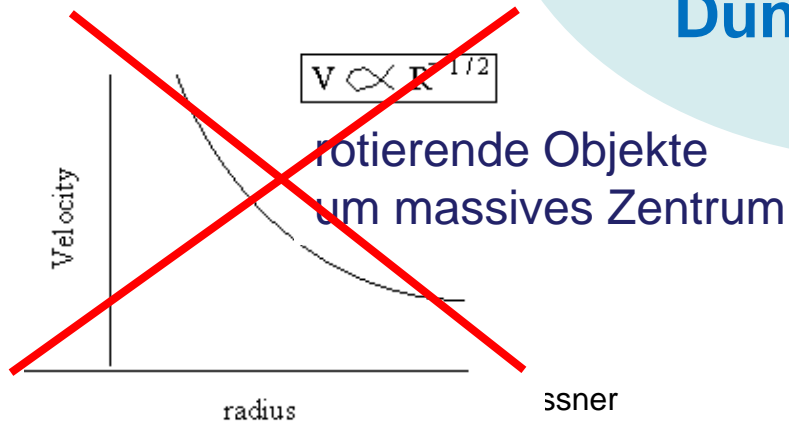
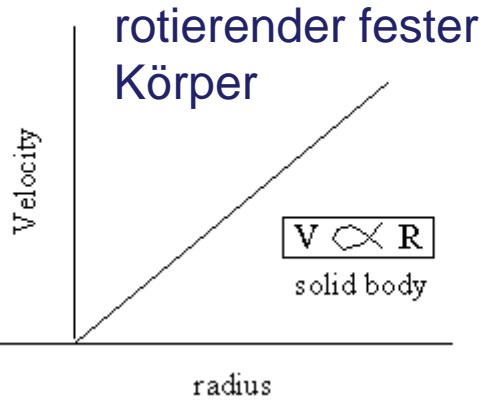
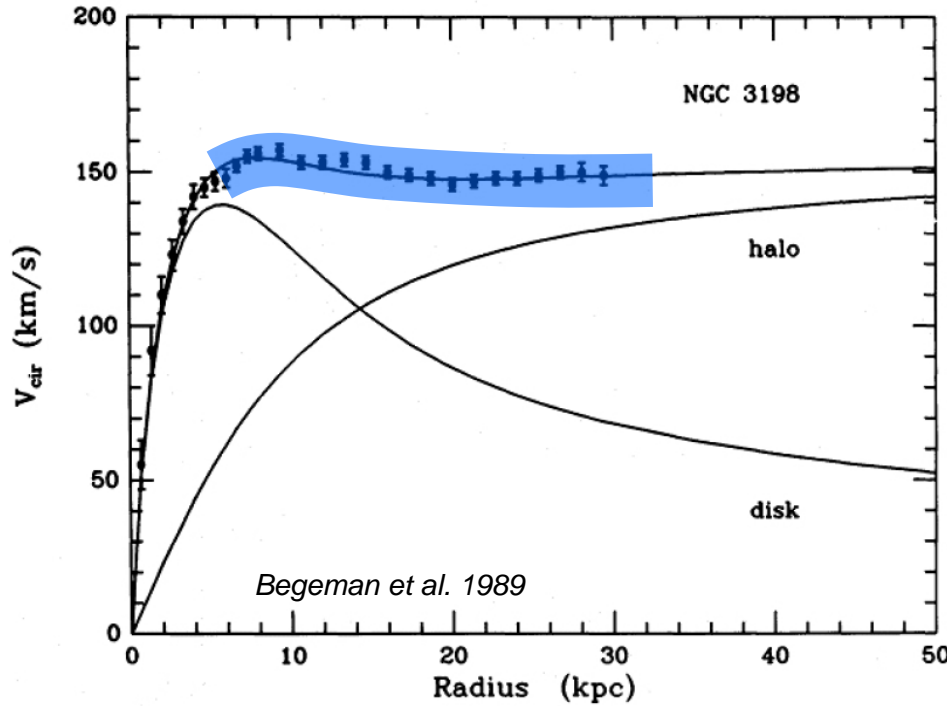
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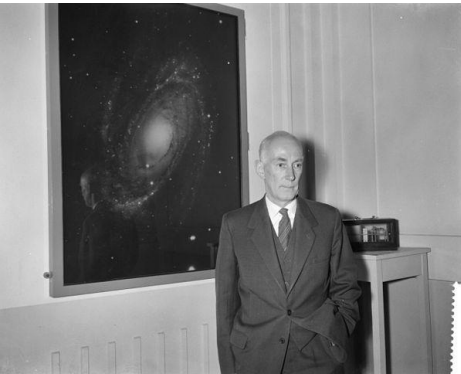


- Bestimmung der Bewegungs-Geschwindigkeit anhand des Doppler-Effekts und Verschiebung bekannter Spektrallinien von Atomen und Molekülen



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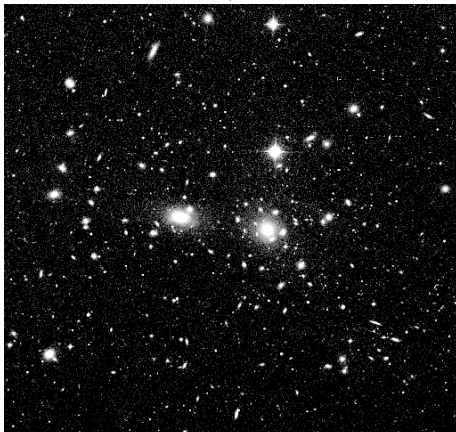
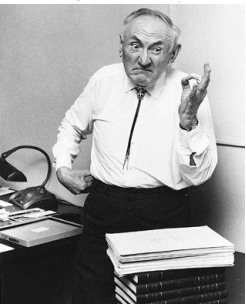


COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort*.

There is an indication that the invisible mass is more strongly concentrated to the galactic plane than that of the visible stars (Table 33).

Die Rotverschiebung von extragalaktischen Nebeln
von **F. Zwicky**.
(16. II. 33.)



- Beobachtung von Geschwindigkeiten im Sternenhaufen Coma Berenices
- Bestimmung der Masse **aller Objekte im Coma Sternenhaufen** aus Bewegungsenergie und Energie der Schwerkraft
- für **sichtbare Sterne und Galaxien** gilt:

Masse ~ Leuchtkraft

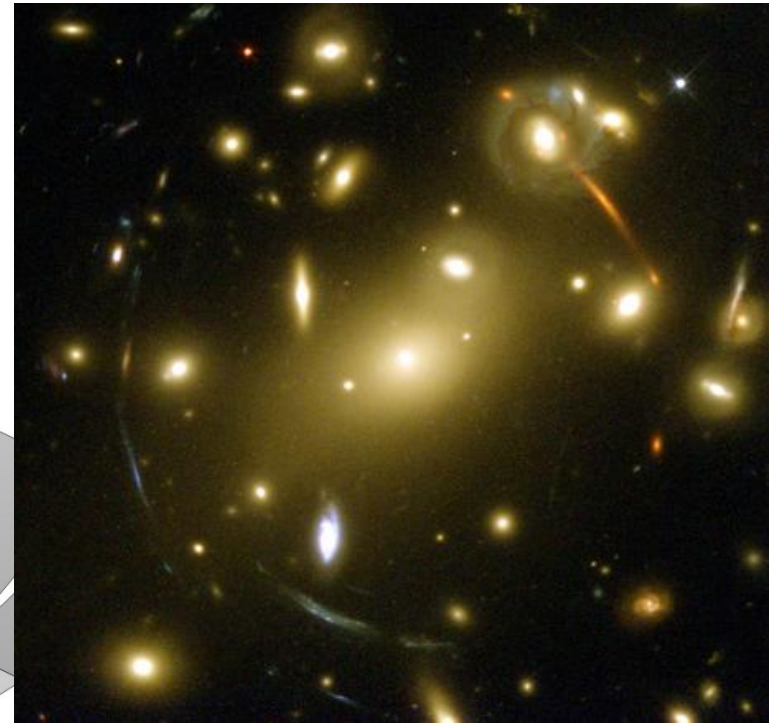
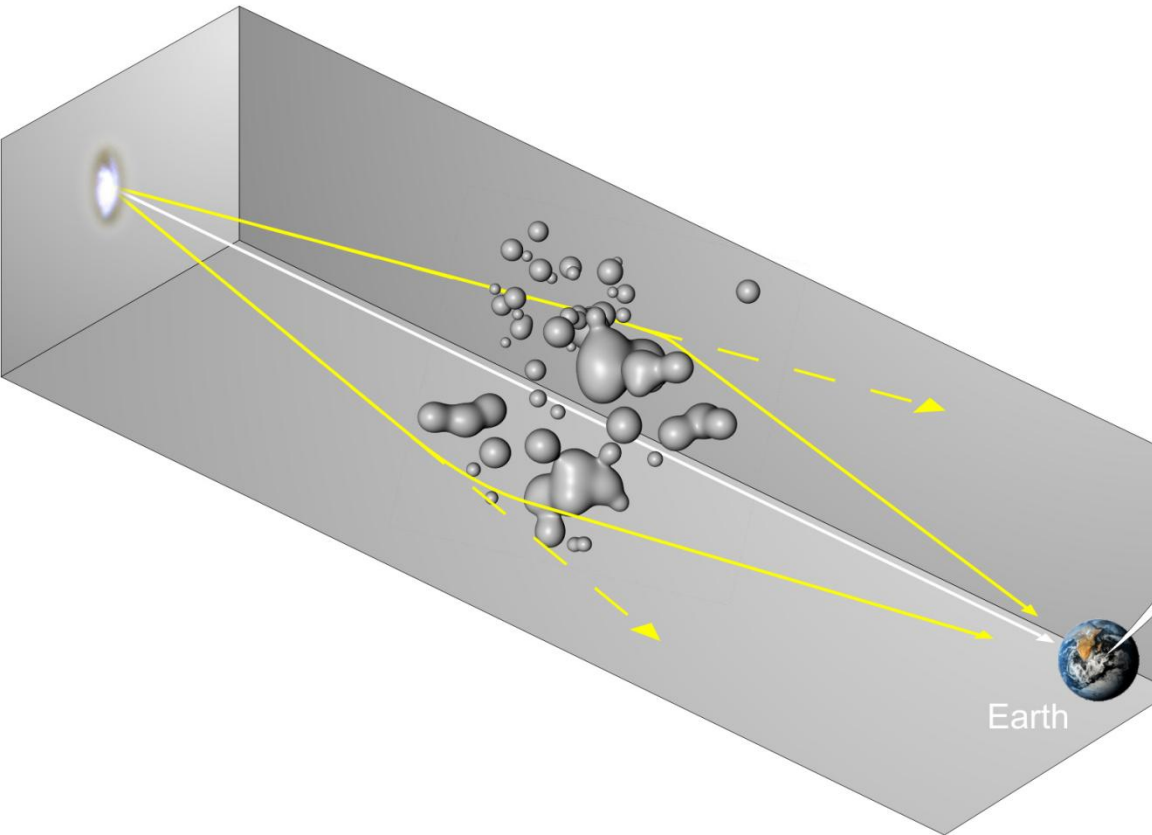
Leuchtkraft ist 400-fach kleiner ist als erwartet!

→ **Dunkle Materie**

§ 5. Bemerkungen zur Streuung der Geschwindigkeiten im Coma-Nebelhaufen.

Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

- Das Licht weit entfernter Galaxien wird im Gravitationsfeld naher Galaxien und Massenverteilungen abgelenkt wie von einer optischen Linse



- Mit dem Hubble Space Teleskop wurden solche Gravitationslinsen genau vermessen
- Ergebnis: die Masse, die zur Ablenkung nötig ist, ist größer als von den leuchtenden Objekten erwartet

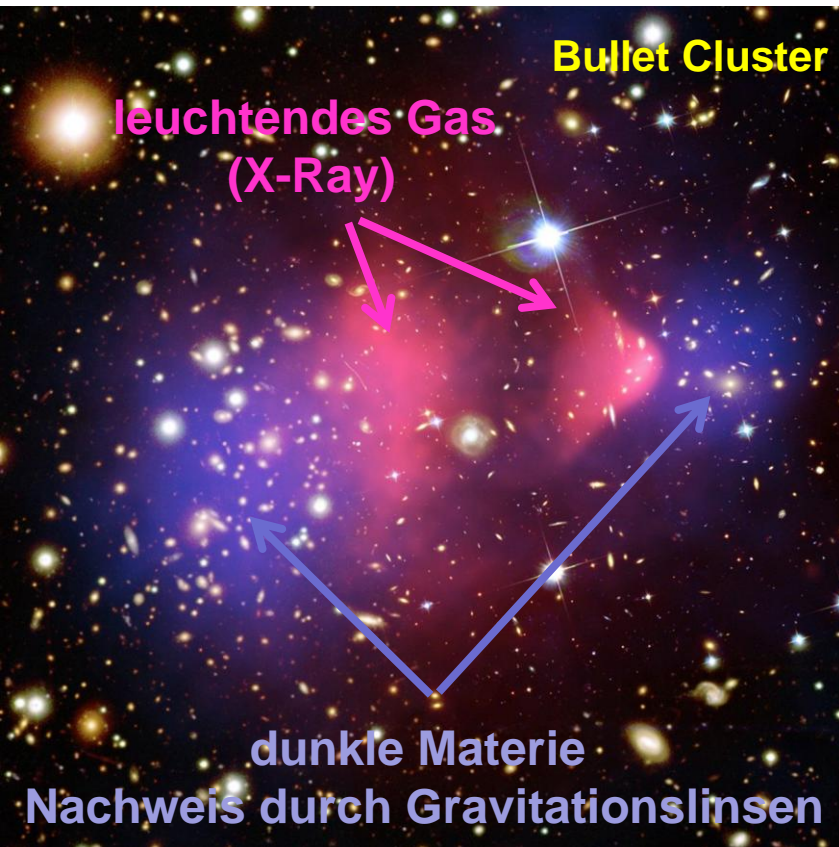
→ **Dunkle Materie**

A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER *

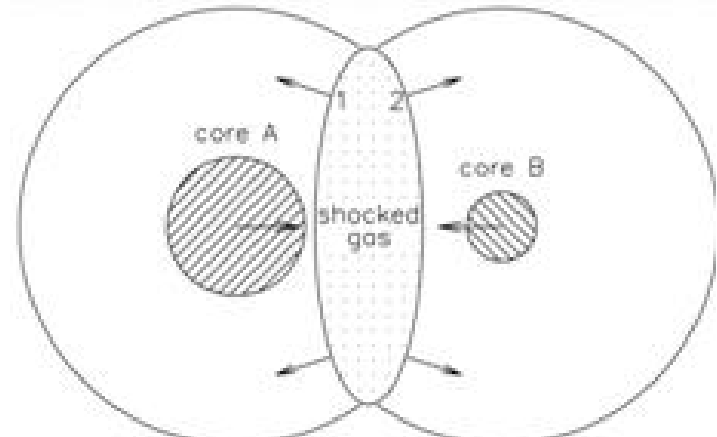
arXiv:astro-ph/0608407v1

DOUGLAS CLOWE¹, MARUŠA BRADAC², ANTHONY H. GONZALEZ³, MAXIM MARKEVITCH^{4,5}, SCOTT W. RANDALL⁴,
CHRISTINE JONES⁴, AND DENNIS ZARITSKY¹

ApJ Letters in press



- Galaxien-Cluster: Sterne, Gas, Dunkle Materie
- Heiße Gas-Wolken kollidieren
→ Nachweis im Röntgenlicht-Bereich (X-Ray)
- Sterne und Dunkle Materie durchqueren die Kollisionszone nahezu ungestört

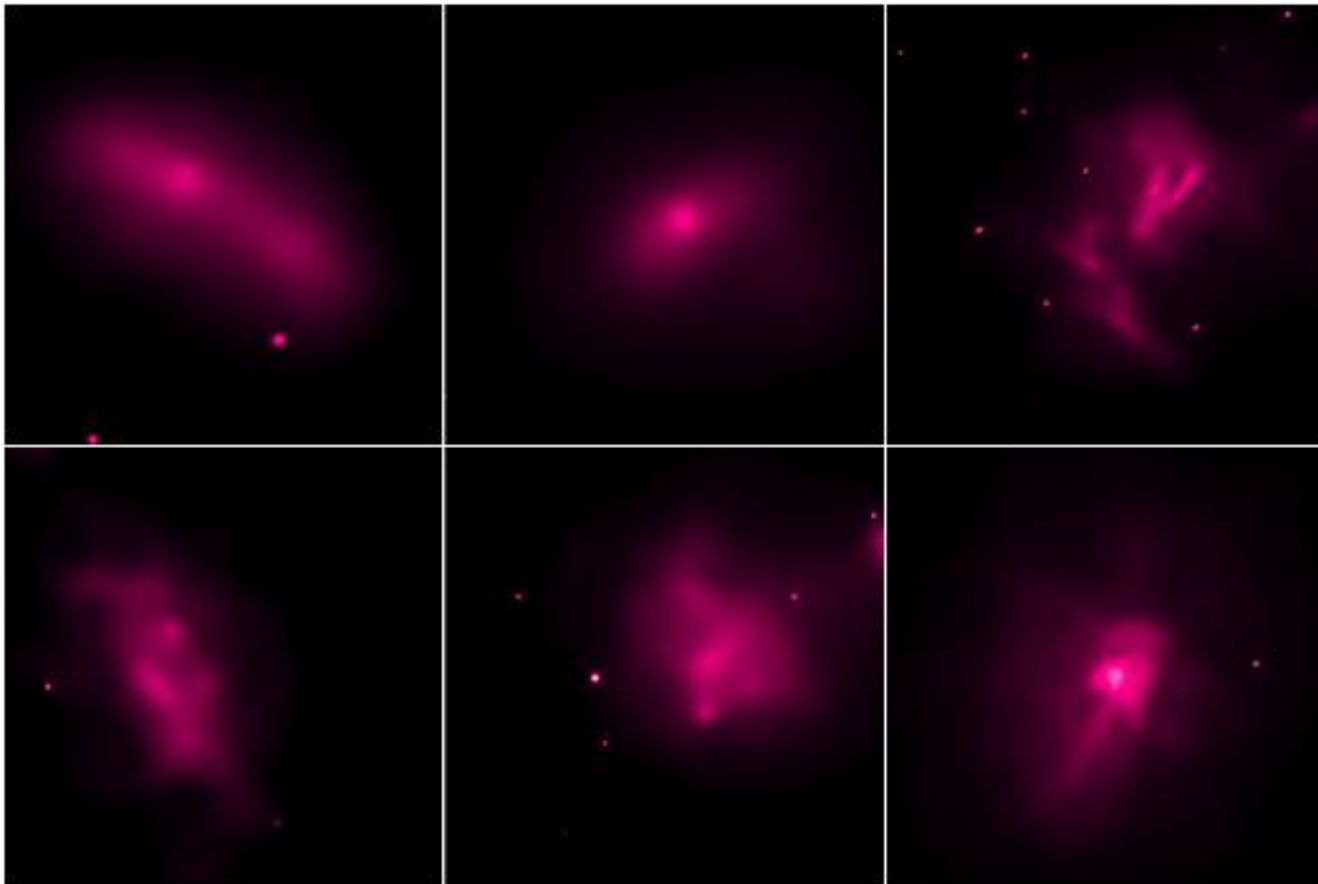


- Messung der Lichtemission der Gaswolken mit dem Chandra X-ray Observatory
- Auswertung der Gravitationslinsen mit dem Hubble Space Telescope

The nongravitational interactions of dark matter in colliding galaxy clusters

David Harvey,^{1,2*} Richard Massey,³ Thomas Kitching,⁴ Andy Taylor,² Eric Tittley²

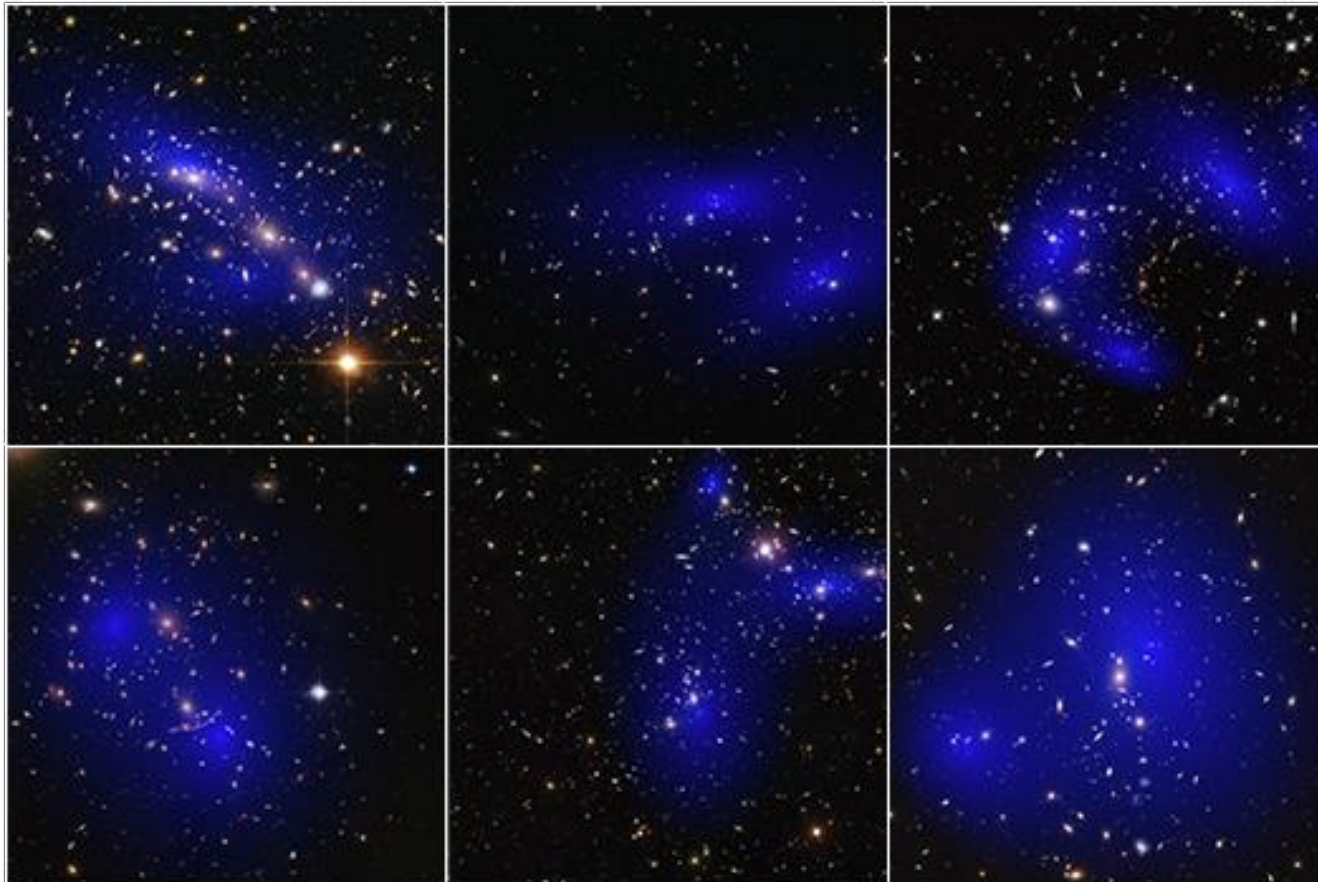
- Auswertung weiterer 72 Cluster-Kollisionen
- Wirkt zwischen den Wolken Dunkler Materie nur Gravitation oder gibt es weitere Wechselwirkungen?



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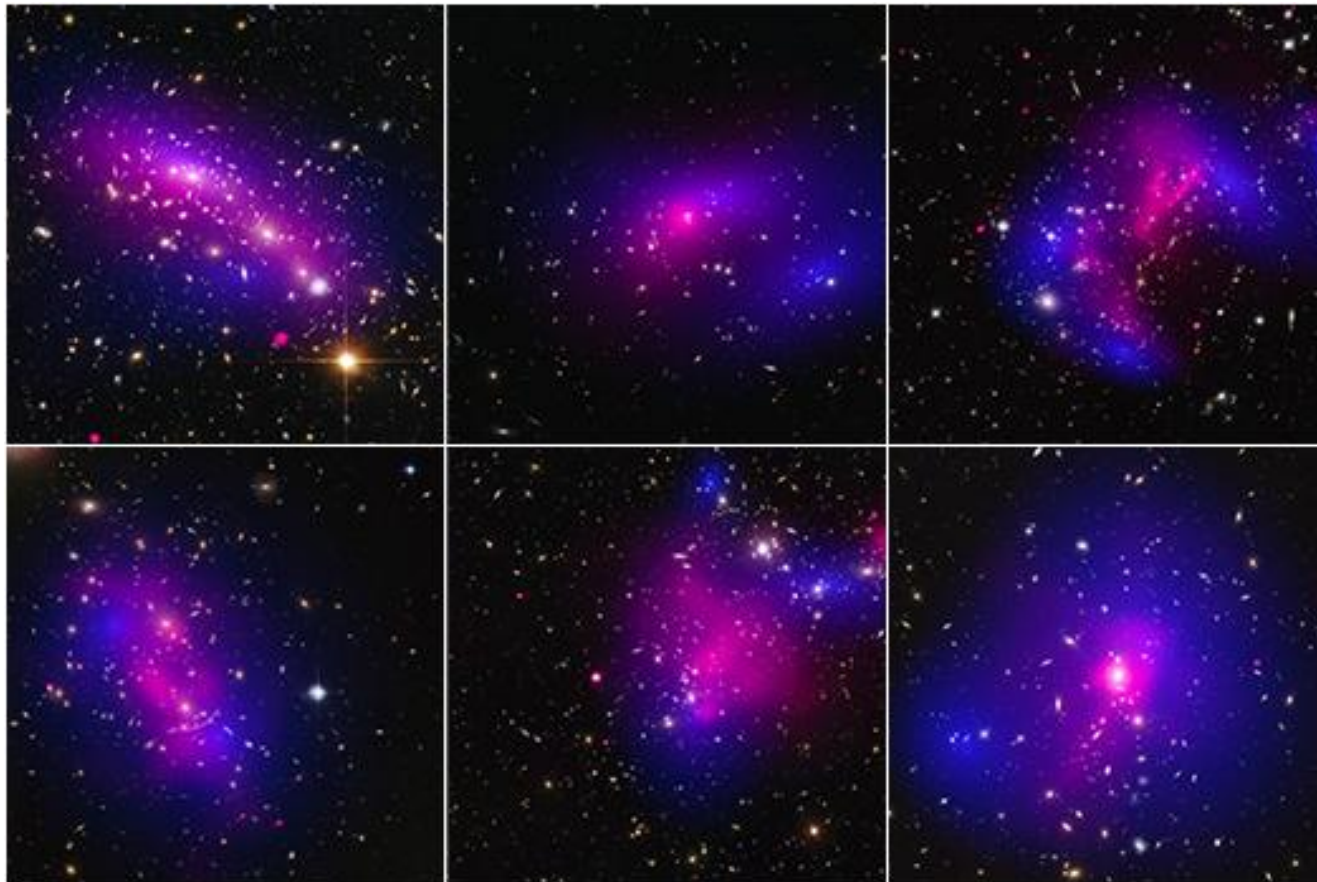
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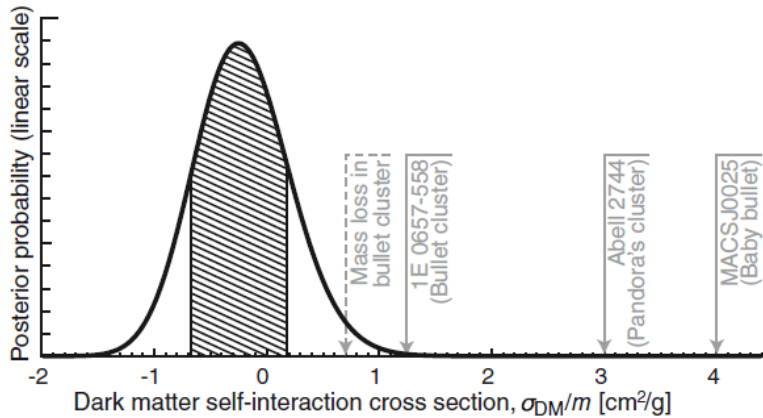
David Harvey,^{1,2*} Richard Massey,³ Thomas Kitching,⁴ Andy Taylor,² Eric Tittley²

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- Auswertung weiterer 72 Cluster-Kollisionen
- Wirkt zwischen den Wolken Dunkler Materie nur Gravitation oder gibt es weitere Wechselwirkungen?



• Ergebnis:

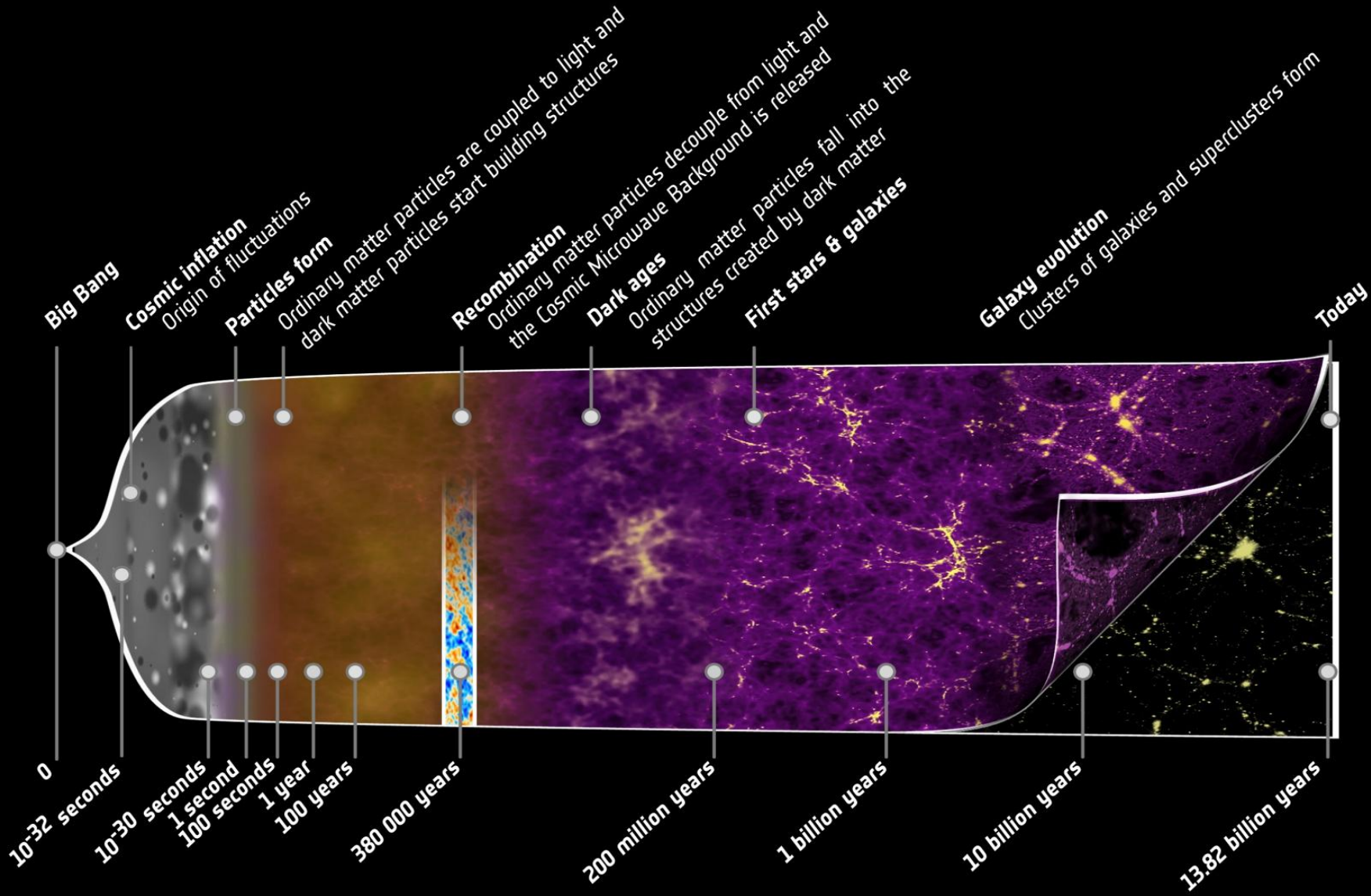
$$\sigma_{DM}/m < 0.47 \text{ cm}^2/\text{g} \text{ (95\% CL, one-tailed)}$$

- Zusätzliche Wechselwirkung zwischen den Bausteinen der Dunklen Materie ist nicht stärker als diejenige zwischen 2 kollidierenden Protonen:



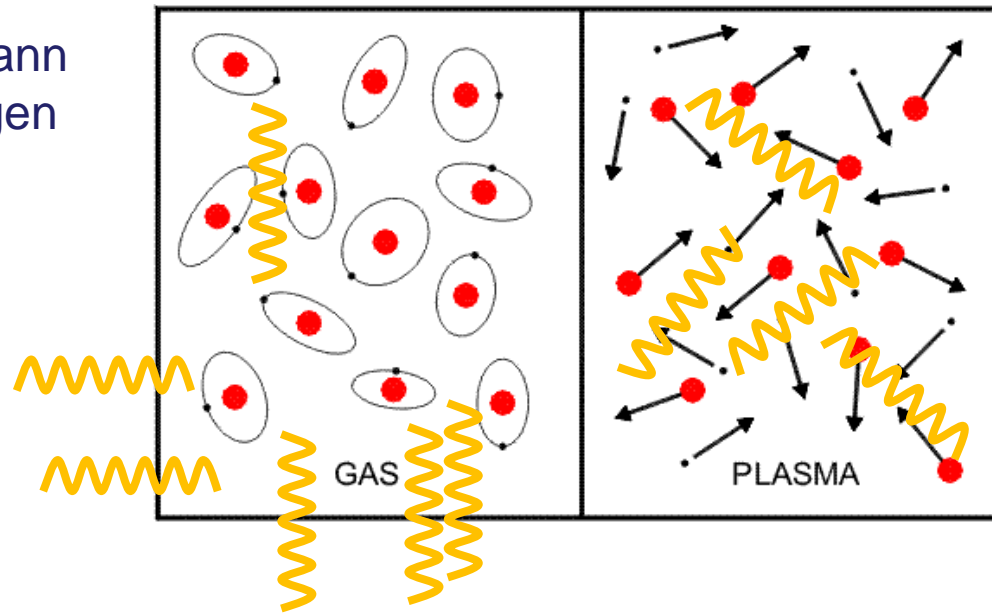
- pp-Wechselwirkung in der Teilchenphysik: "starke Wechselwirkung"

iktp Dunkle Materie und die Struktur des Universums



$T \approx 3000 \text{ K}$

$T > 3000 \text{ K}$



Atome bilden sich: Licht kann das Universum durchdringen

Alter des Universums:
~380.000 Jahre

Licht wird im Plasma geladener Teilchen gefangen

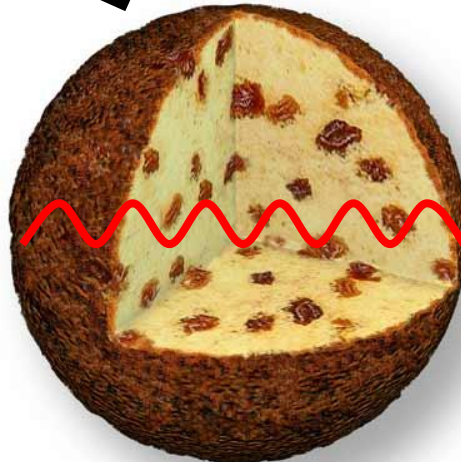
Atome bilden sich: Licht kann das Universum durchdringen

Alter des Universums:
~380.000 Jahre



Universum dehnt sich aus wie "Rosinenkuchen"

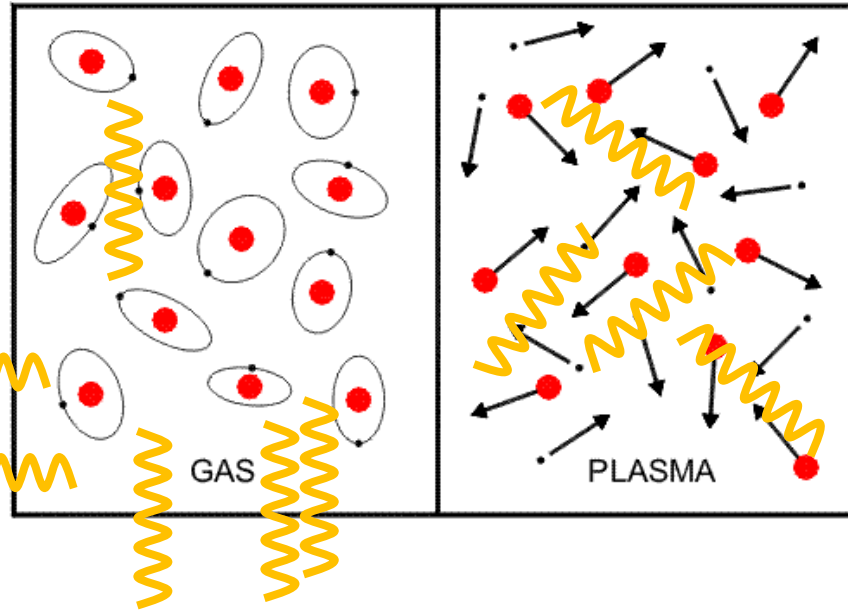
Heutiges Alter des Universums:
13.8 Milliarden Jahre



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$T \approx 3000 \text{ K}$

$T > 3000 \text{ K}$



Licht wird im Plasma geladener Teilchen gefangen

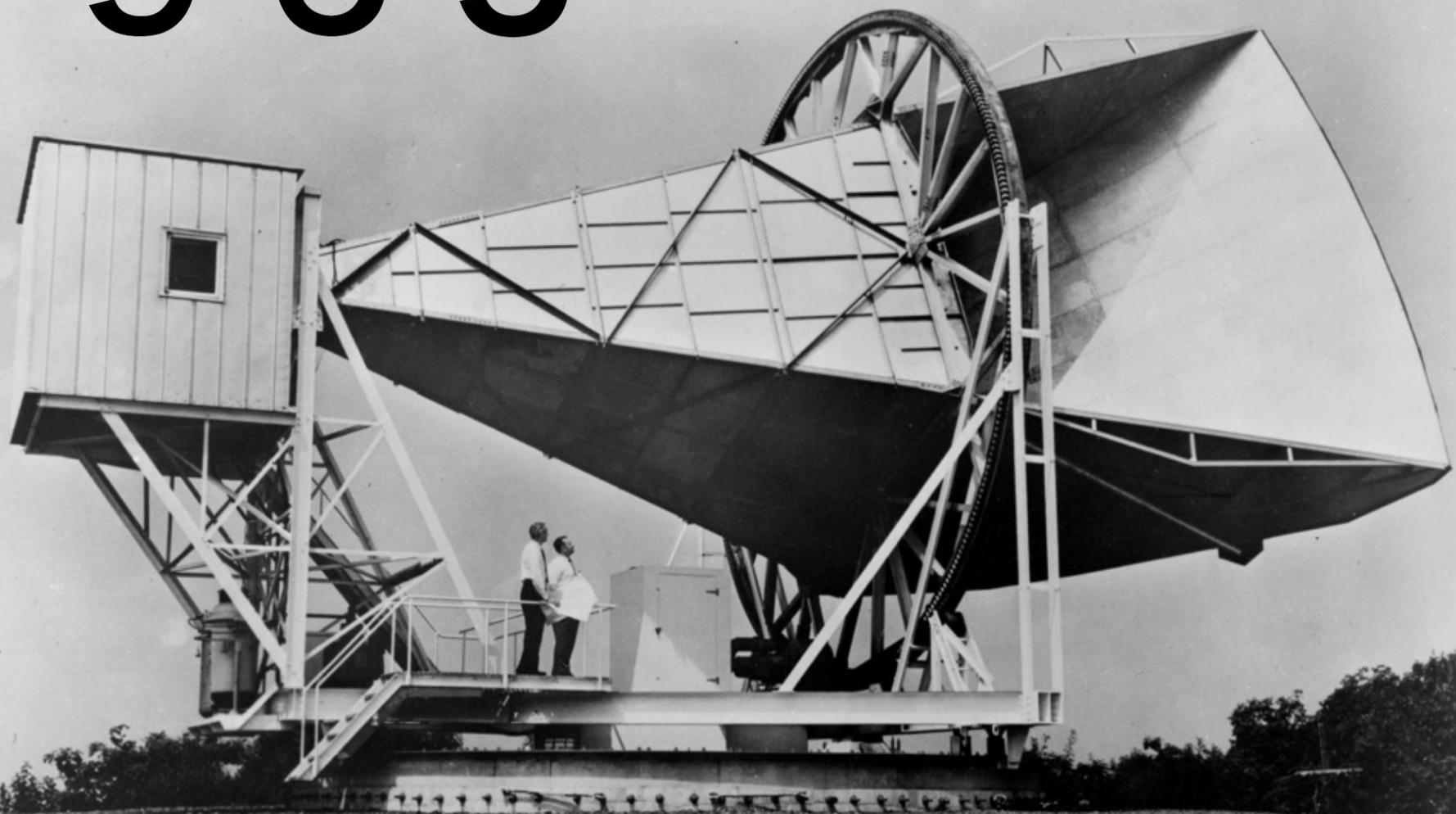
Temperaturstrahlung wird "rotverschoben" um etwa einen Faktor 1100

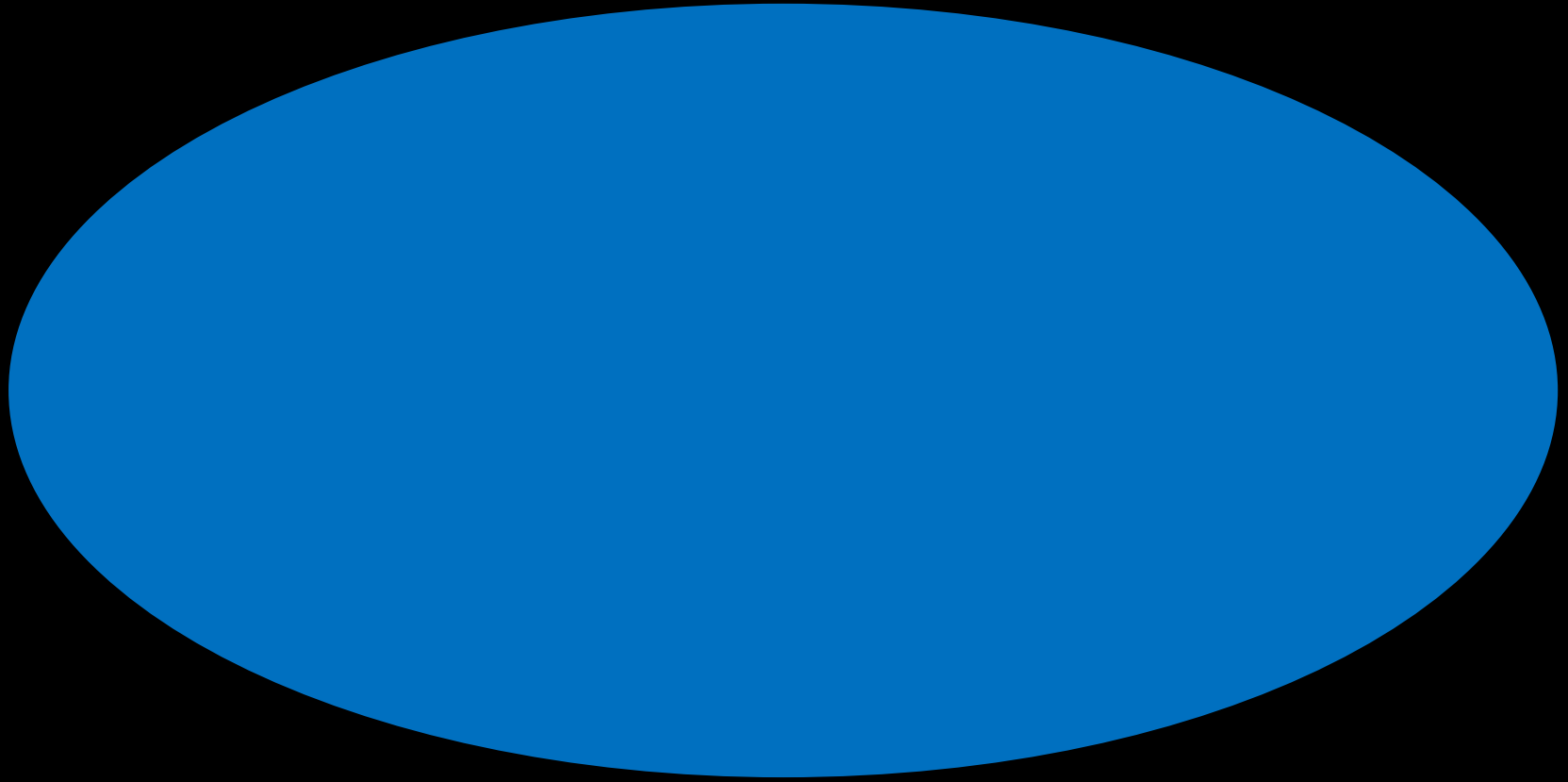
Temperaturstrahlung hat statt $T = 3000 \text{ K}$ nur noch $T = 2,7 \text{ K}$

→ **Kosmische Hintergrundstrahlung**

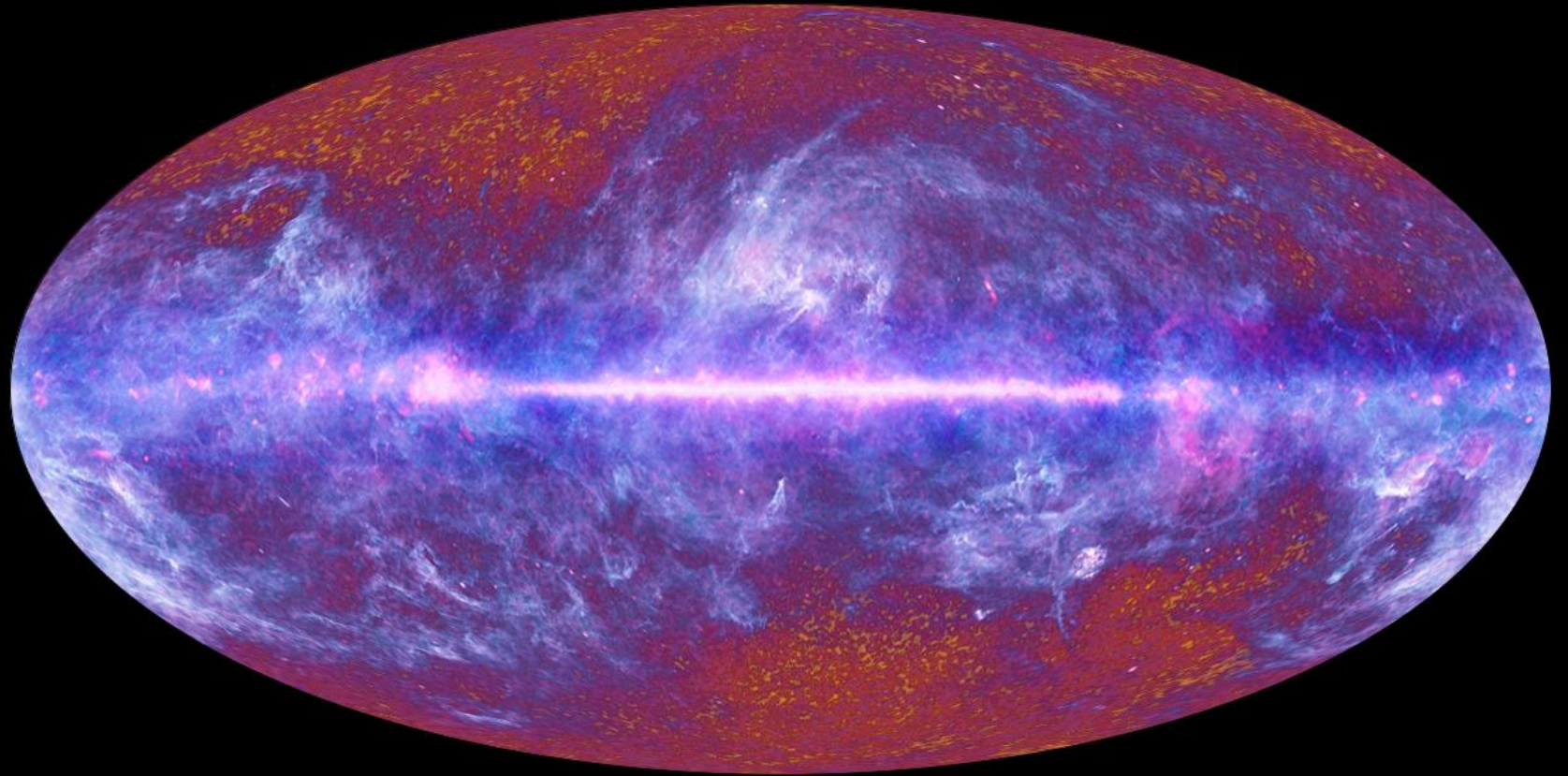
vorhergesagt 1933 (E. Regener)
erstmalig gemessen 1964 (Penzias, Wilson)

1965

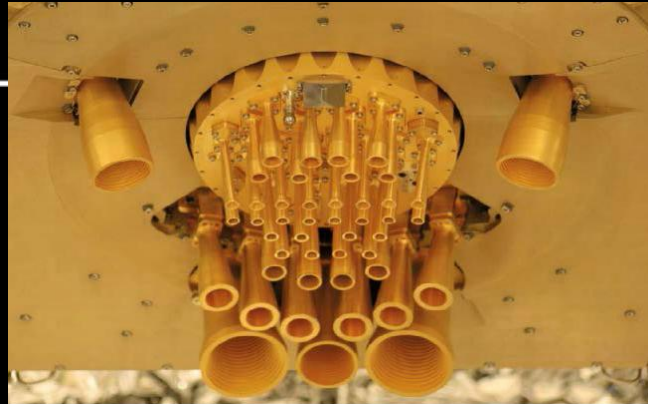




$T = 2,7 \text{ K}$



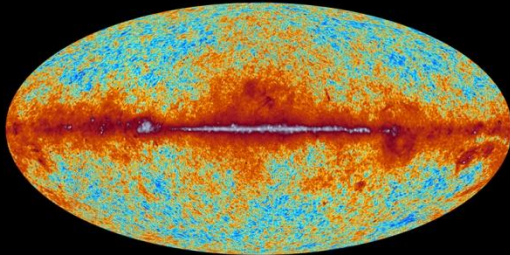
The Planck one-year all-sky survey



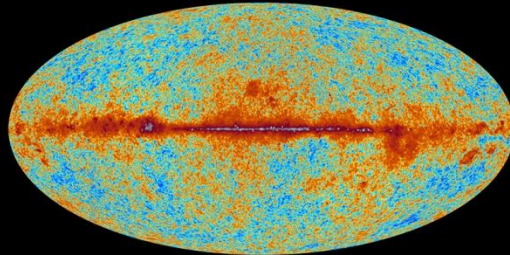


planck

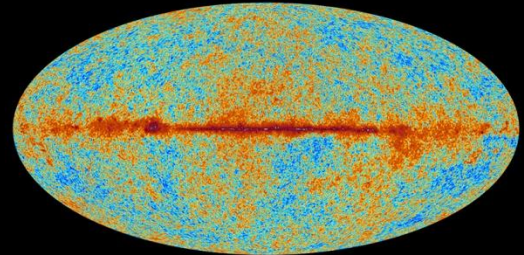
The sky as seen by Planck



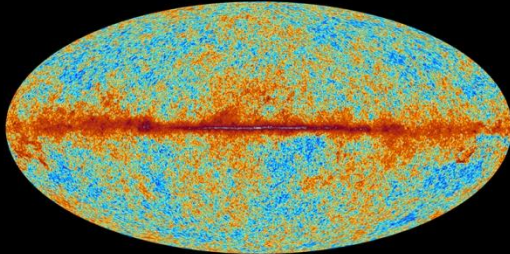
30 GHz



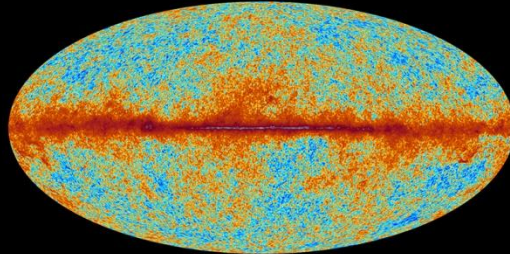
44 GHz



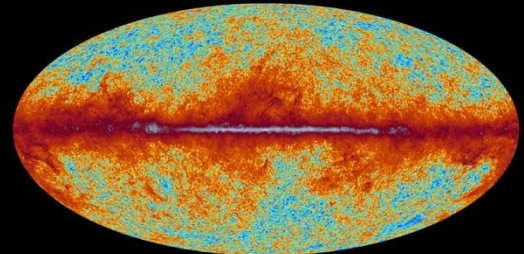
70 GHz



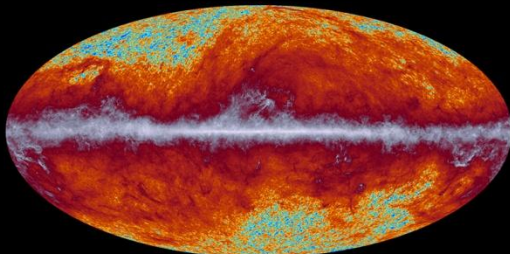
100 GHz



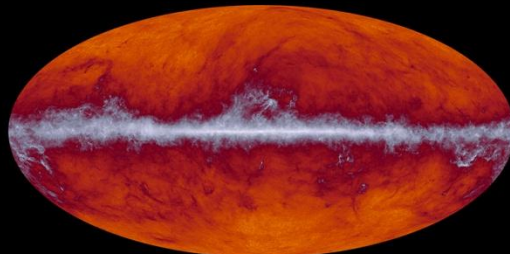
143 GHz



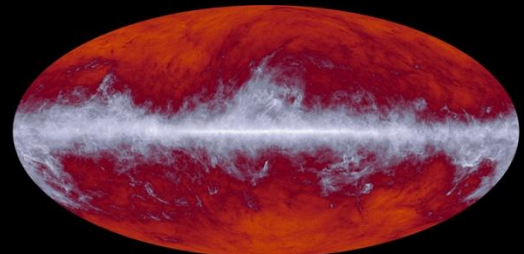
217 GHz



353 GHz

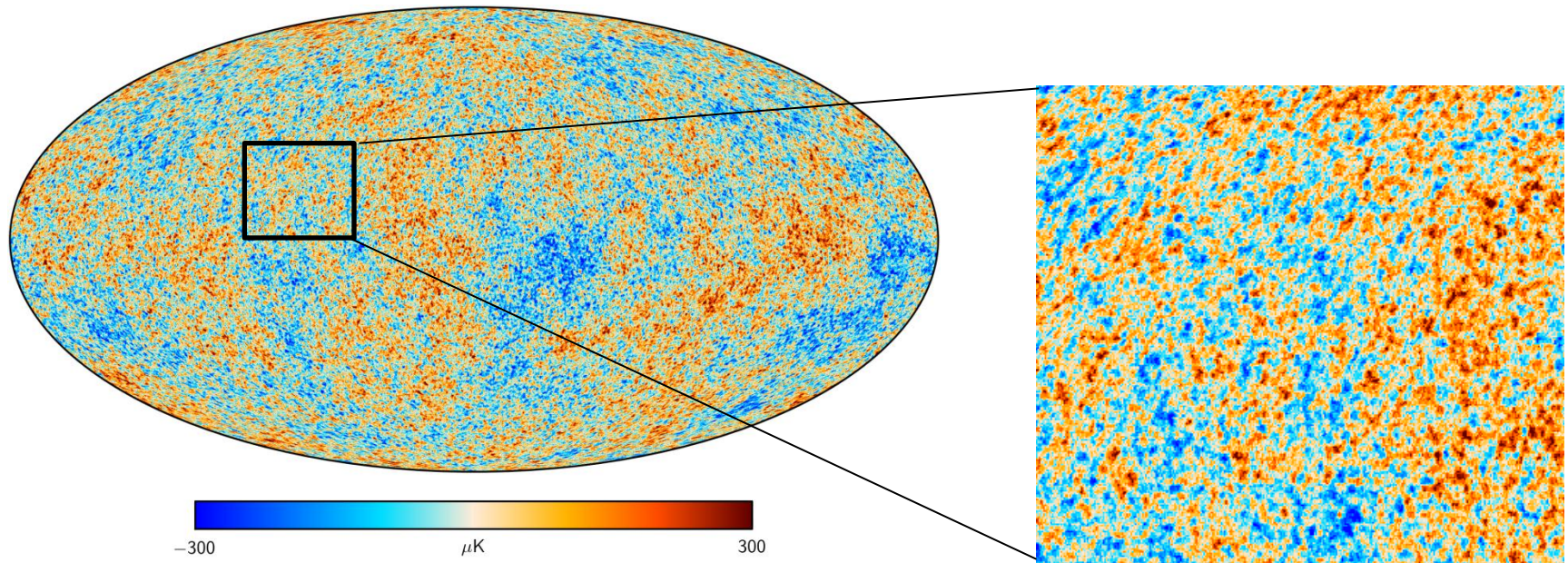


545 GHz



857 GHz

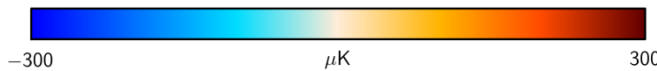
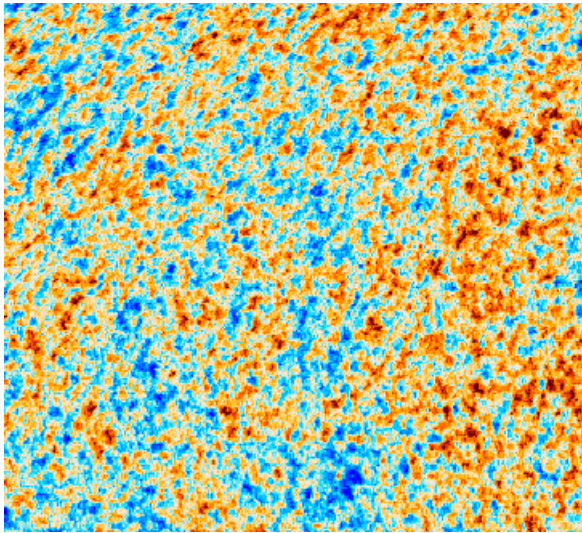
- Strahlung, welche vom "Urknall" bei der Expansion des Universum zurückgeblieben ist
- gemessen mit Planck Teleskop



- Mittlere Strahlung ist in alle Raumrichtungen gleich und entspricht einer Temperatur von $2,725 \pm 0,001$ Kelvin

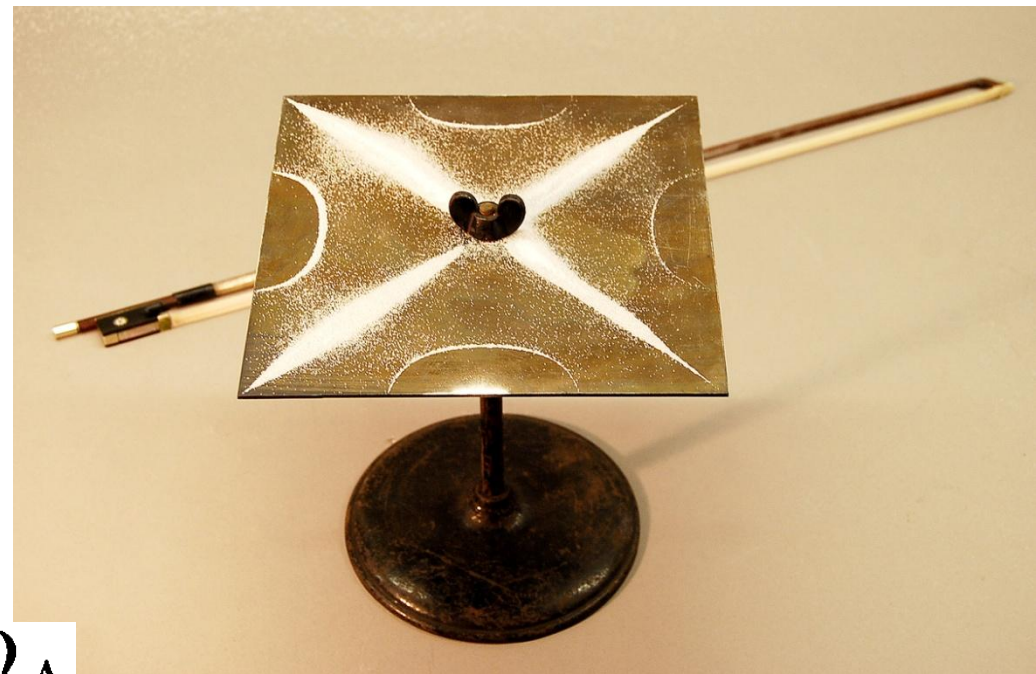
→ Zusätzliche Variationen mit Temperaturunterschieden von < 0.001 K

- Räumliche Struktur der Variationen entsprechen etwa 1° im Raumwinkel



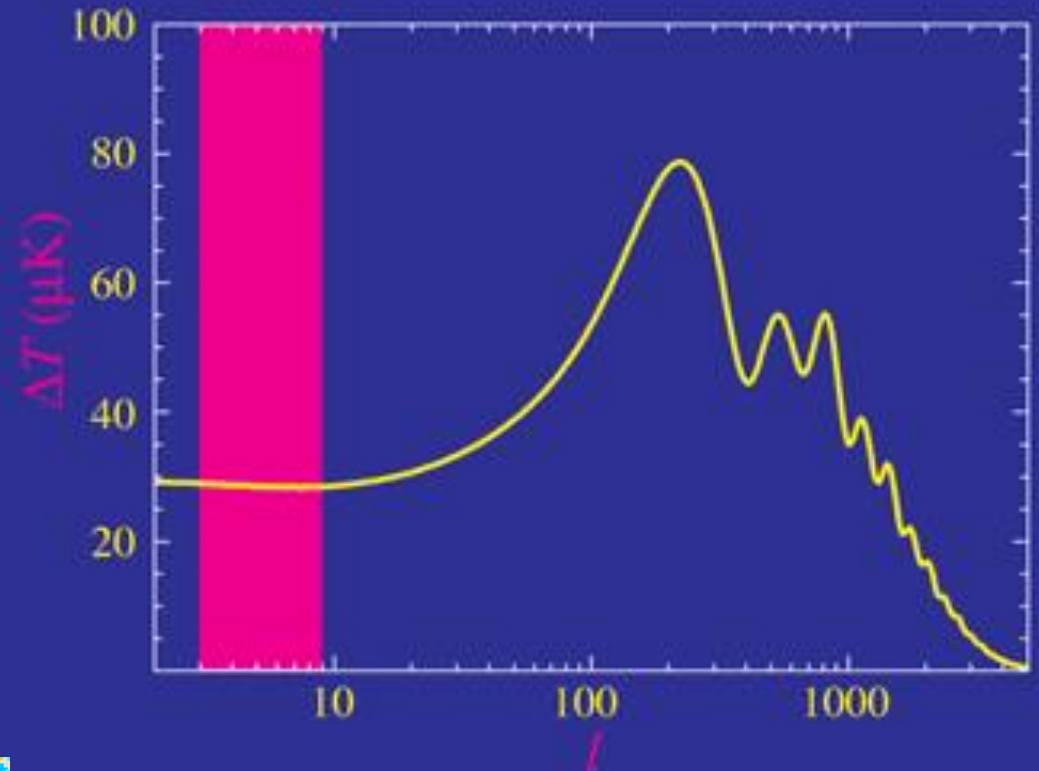
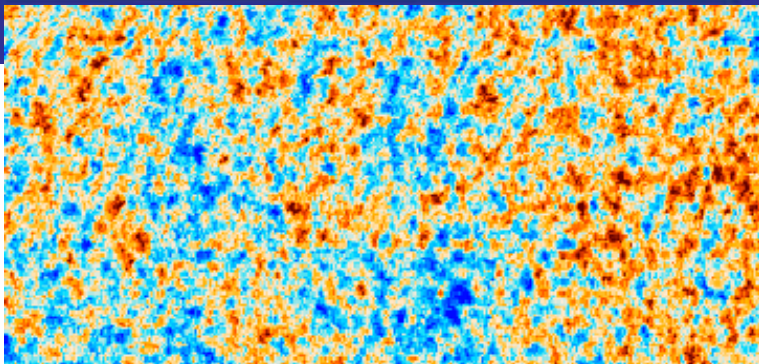
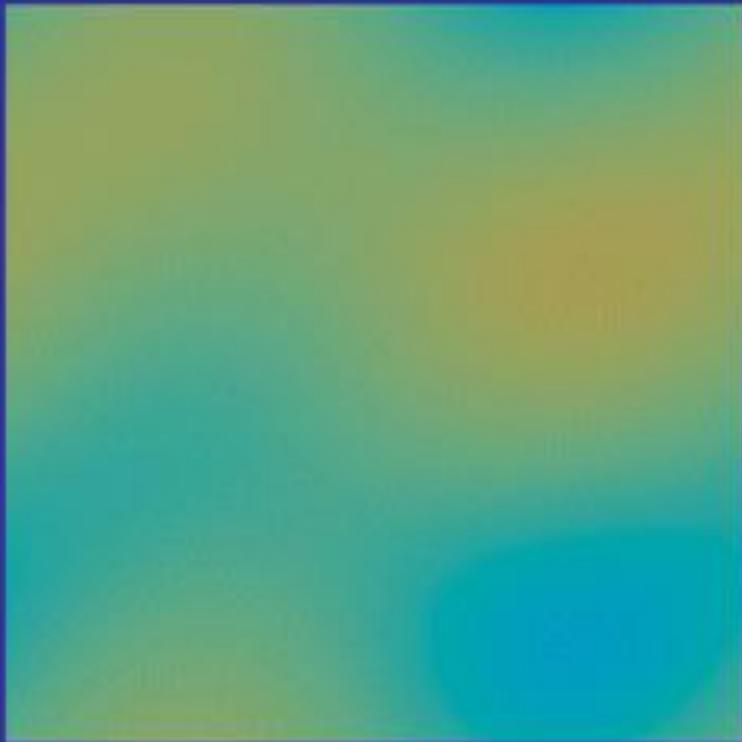
- **heißere Bereiche = hohe Dichte**
- **kühlere Bereiche = niedrige Dichte**

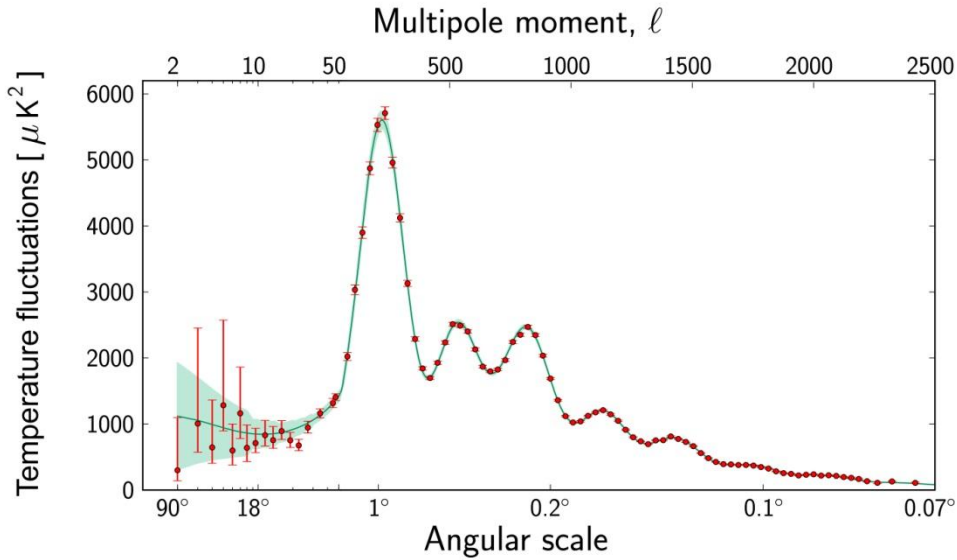
Dichteschwankungen ~ „stehende Schallwellen“



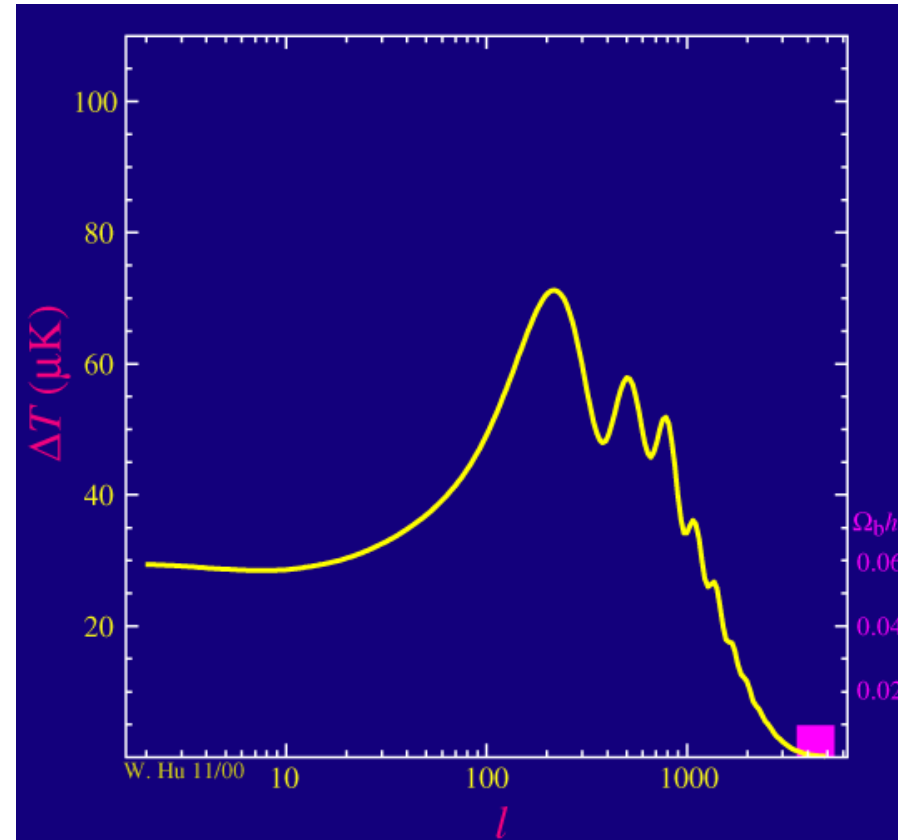
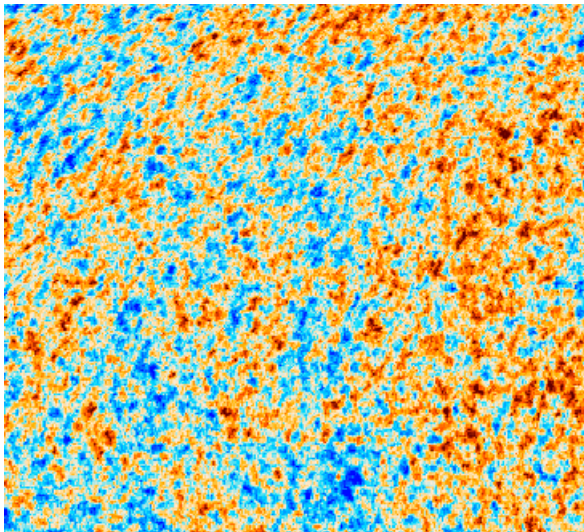
- Dichteschwankungen geben Aufschluss über Zusammensetzung der Materie- und Energiedichte

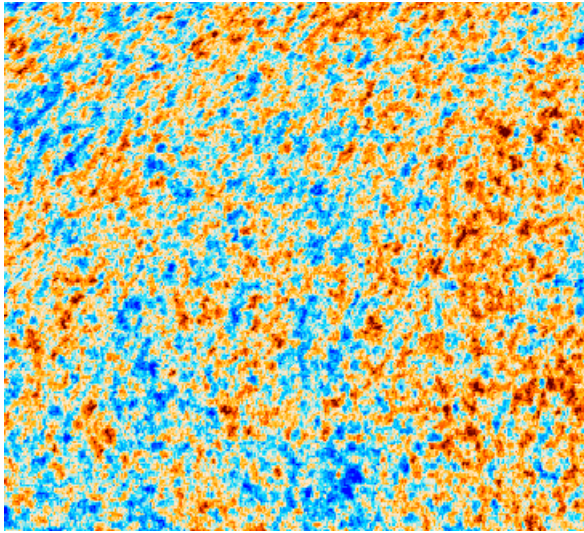
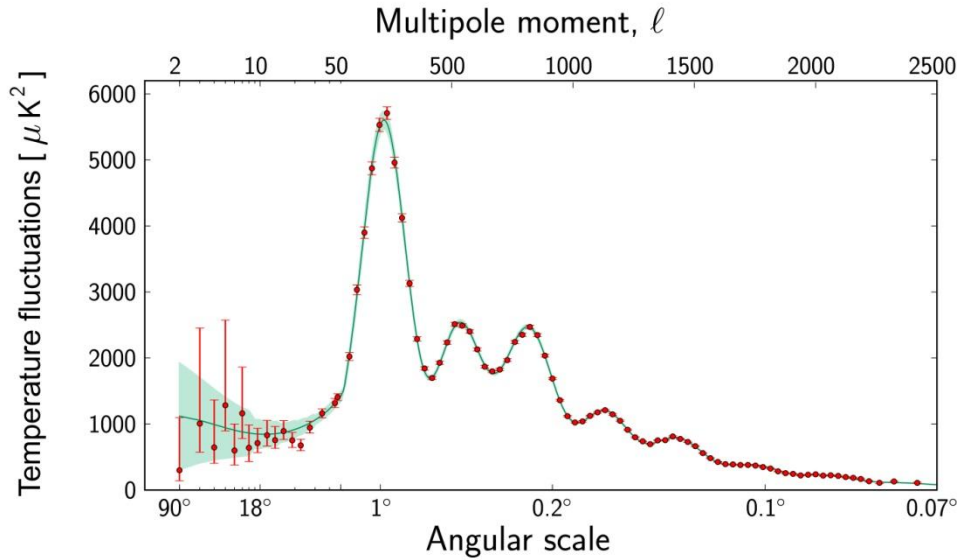
$$\Omega = \Omega_{LM} + \Omega_{DM} + \Omega_{\Lambda}$$



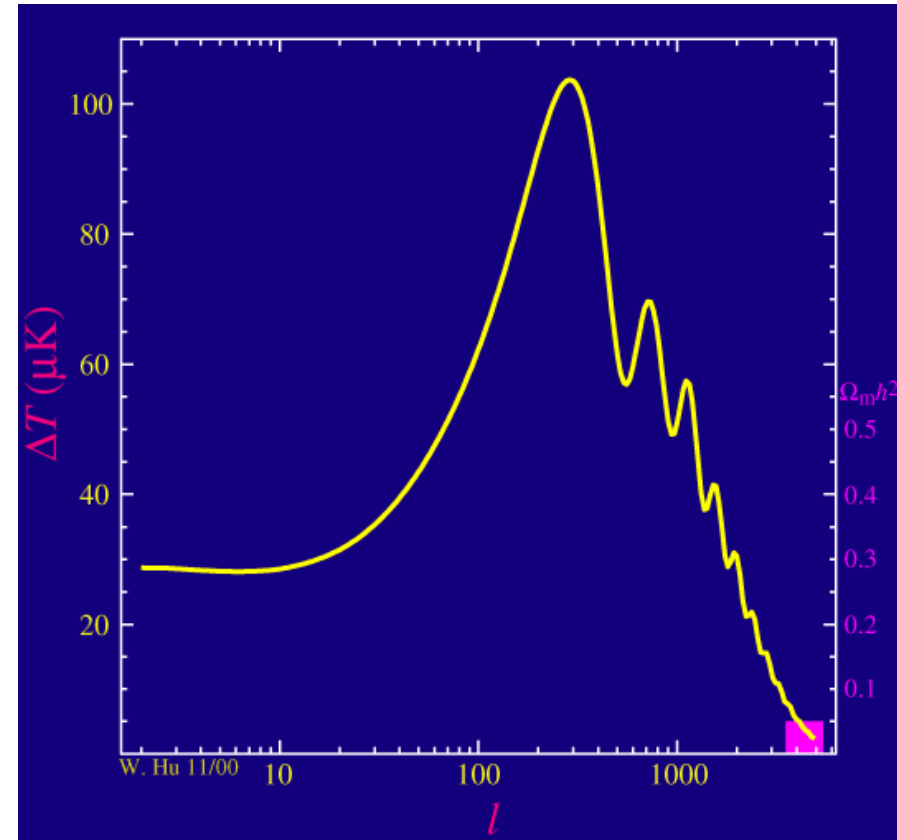


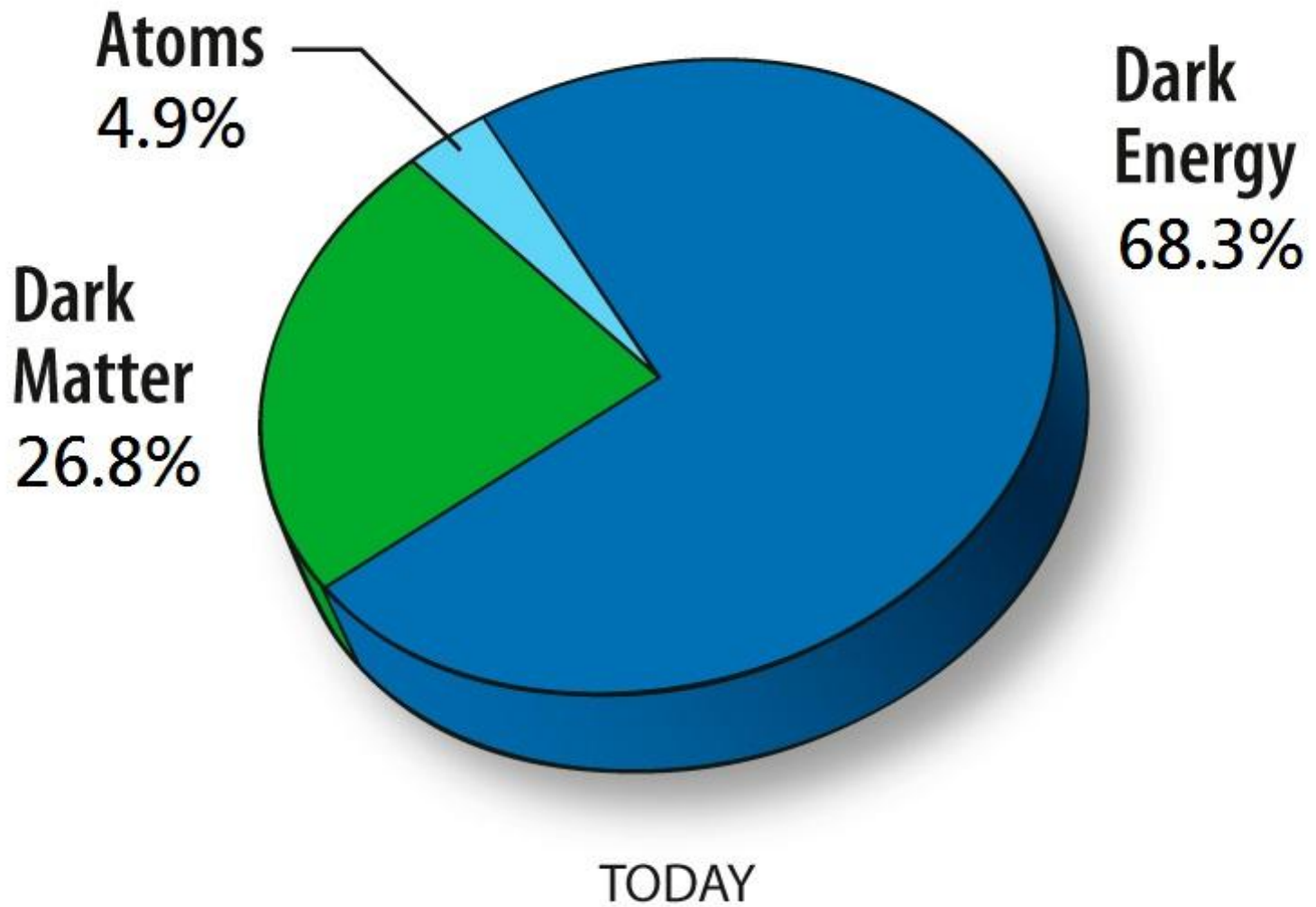
baryonische Materie \approx sichtbare Materie



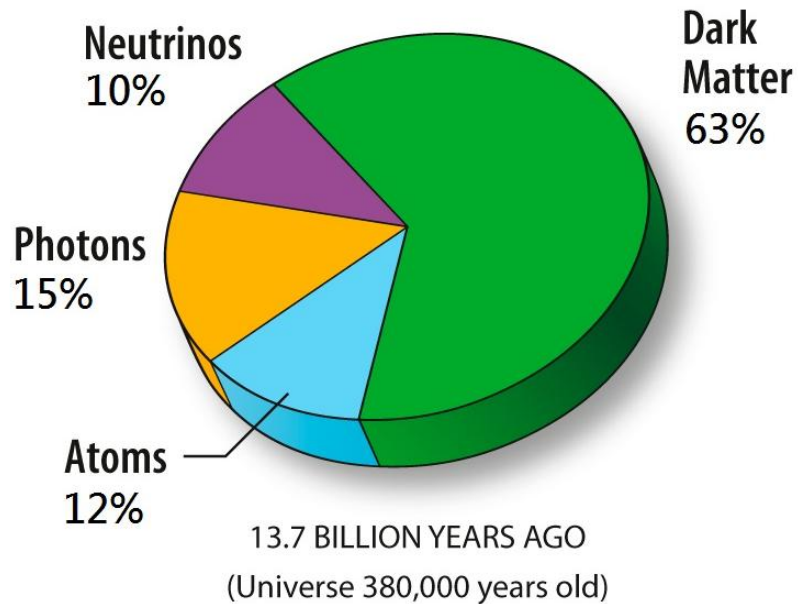


Materie = sichtbare Materie
+ Dunkle Materie

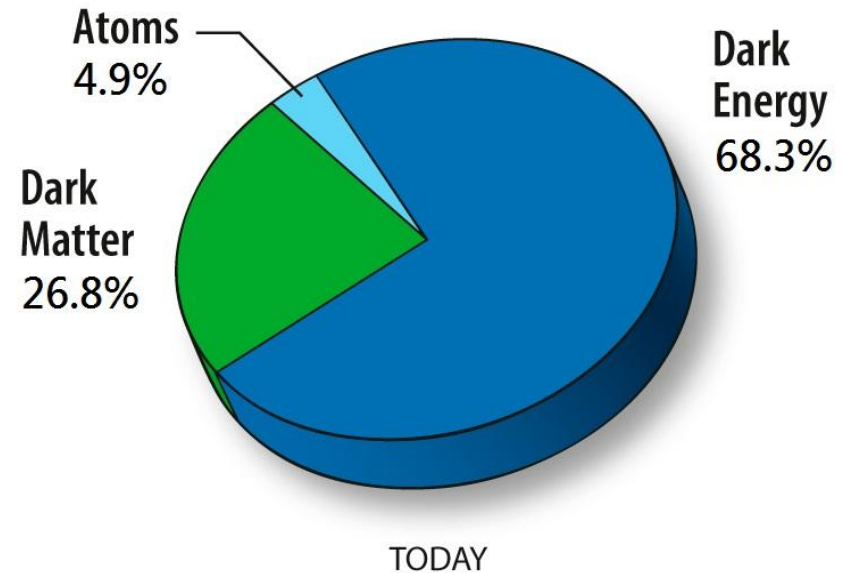




Zum Zeitpunkt der Entstehung der kosmischen Hintergrundstrahlung:

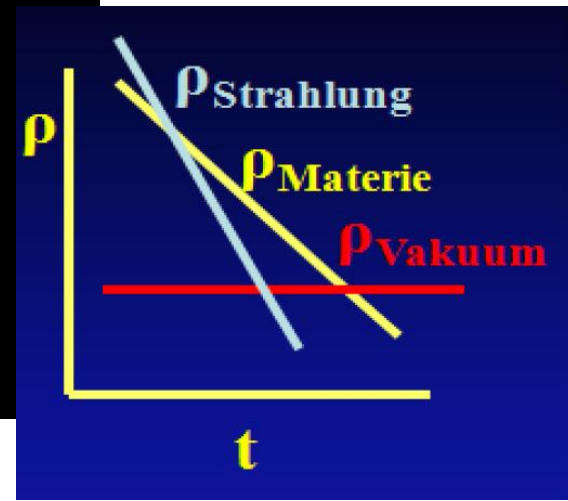
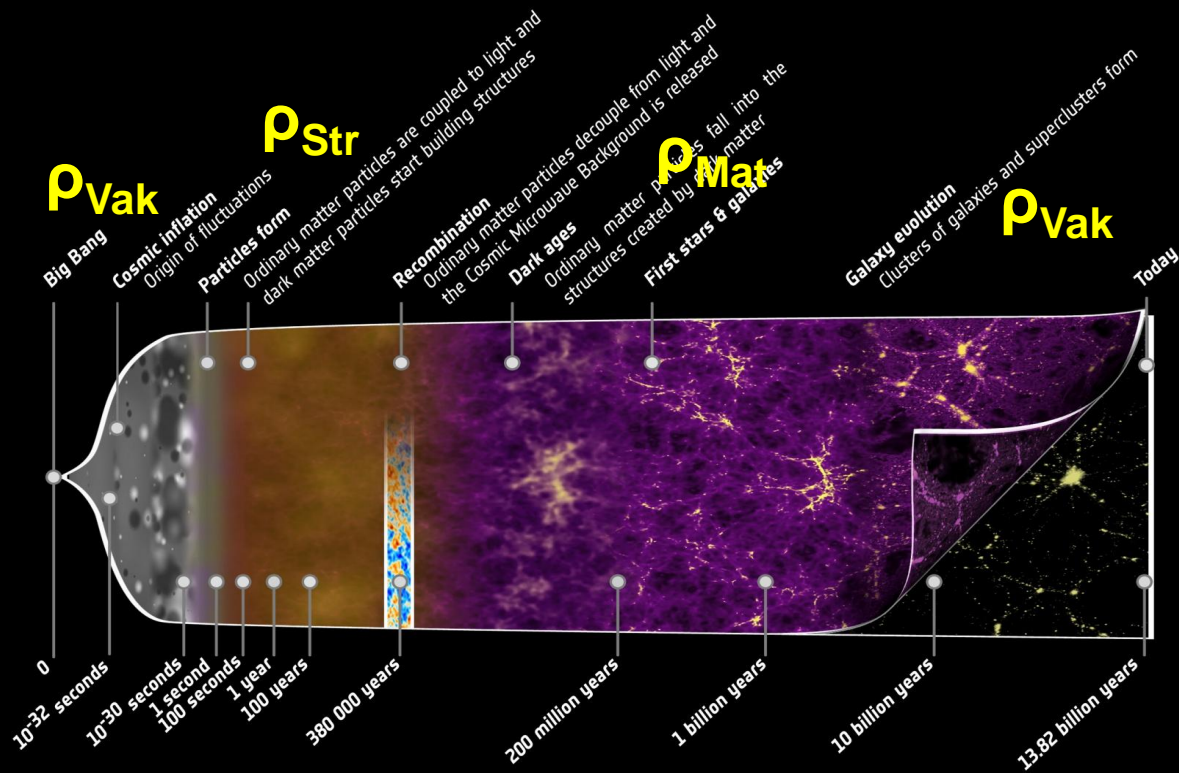


Heute:



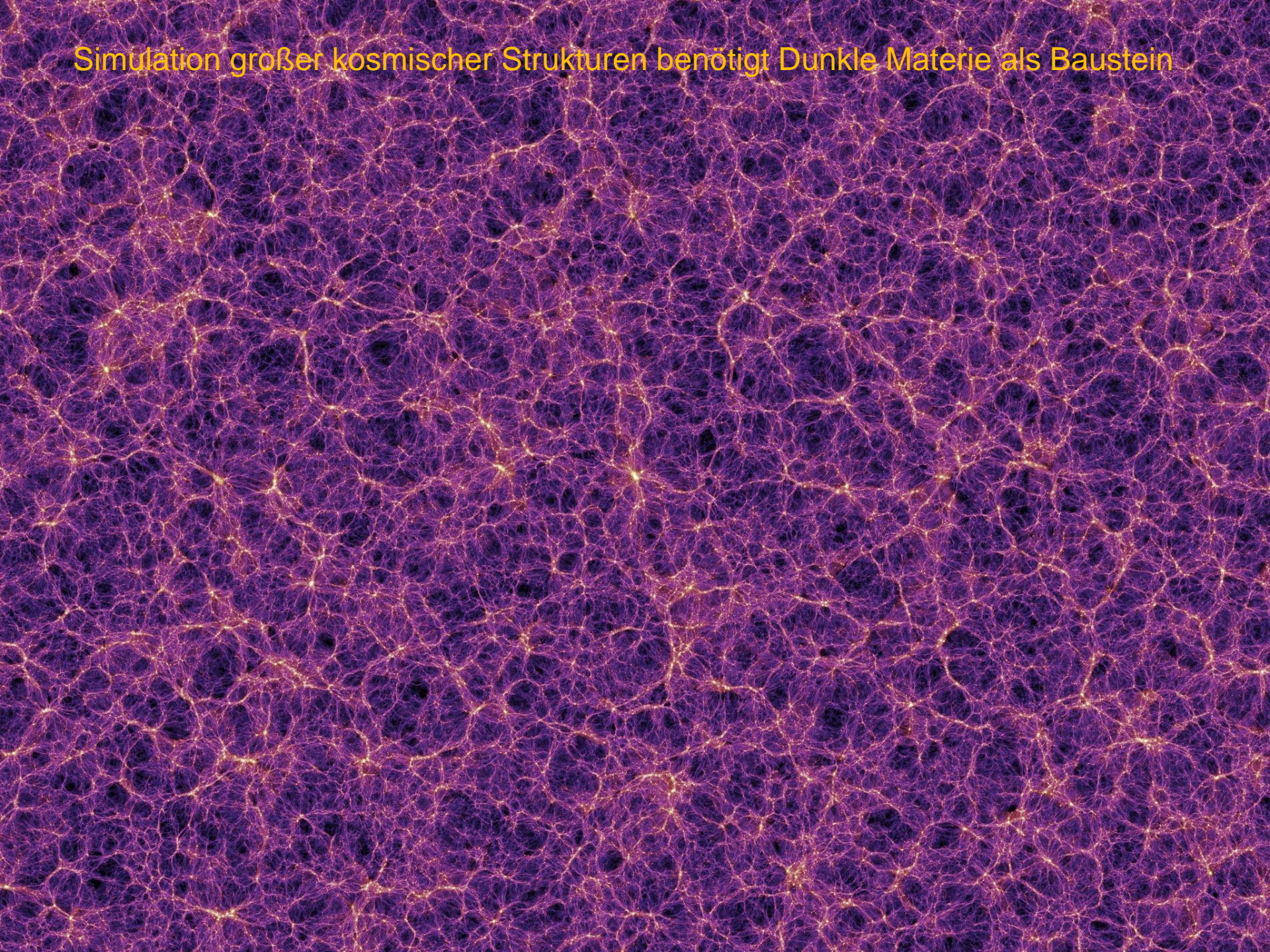
Expansions-Zeitskala
 10^{-30} s

Expansions-Zeitskala
 13 Milliarden Jahre

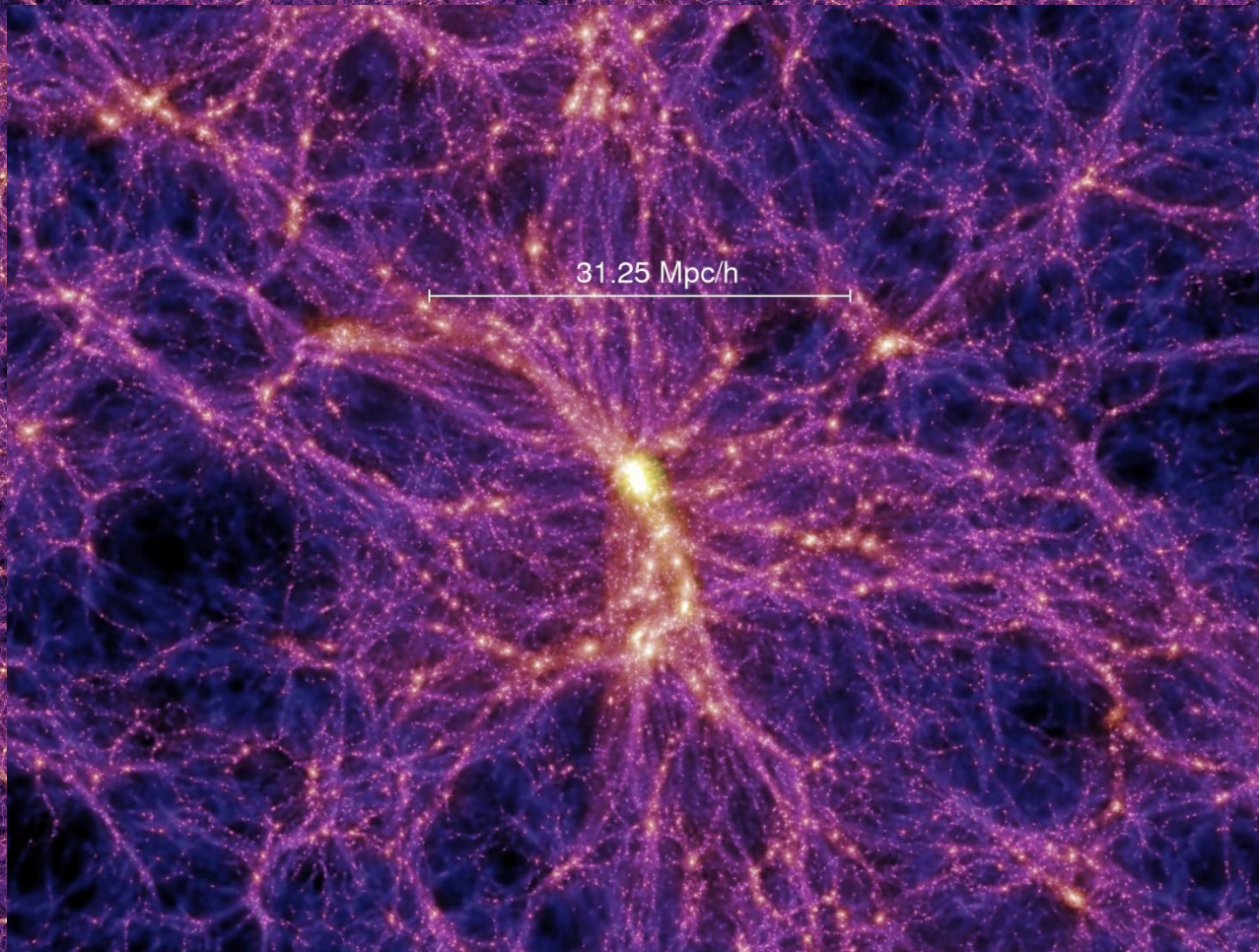


- Wenn ρ_{Vak} dominiert: exponentielle Ausdehnung
- Wenn ρ_{Str} dominiert: $a \sim t^{1/2}$
- Wenn ρ_{Mat} dominiert: $a \sim t^{2/3}$

Simulation großer kosmischer Strukturen benötigt Dunkle Materie als Baustein

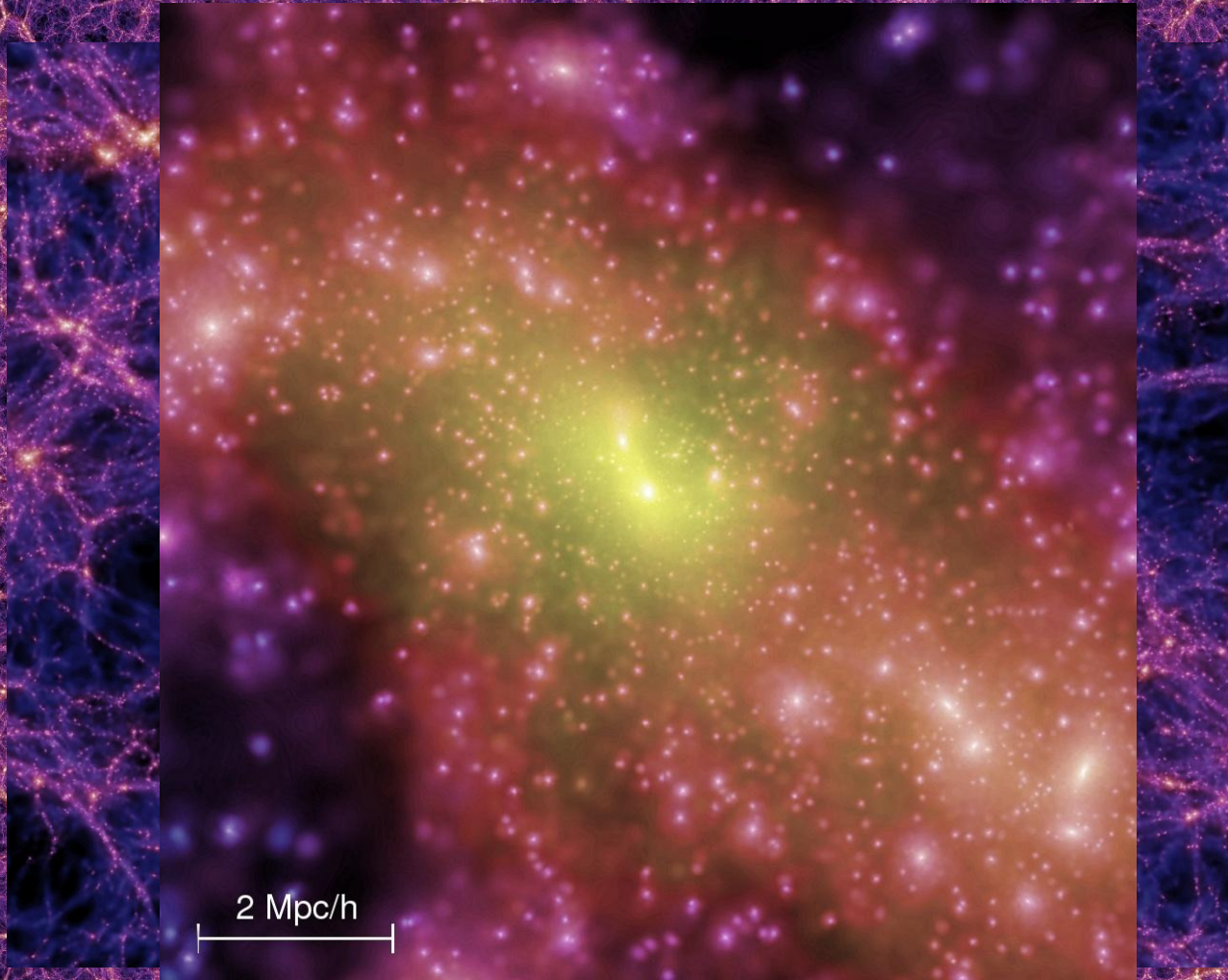


Simulation großer kosmischer Strukturen benötigt Dunkle Materie als Baustein



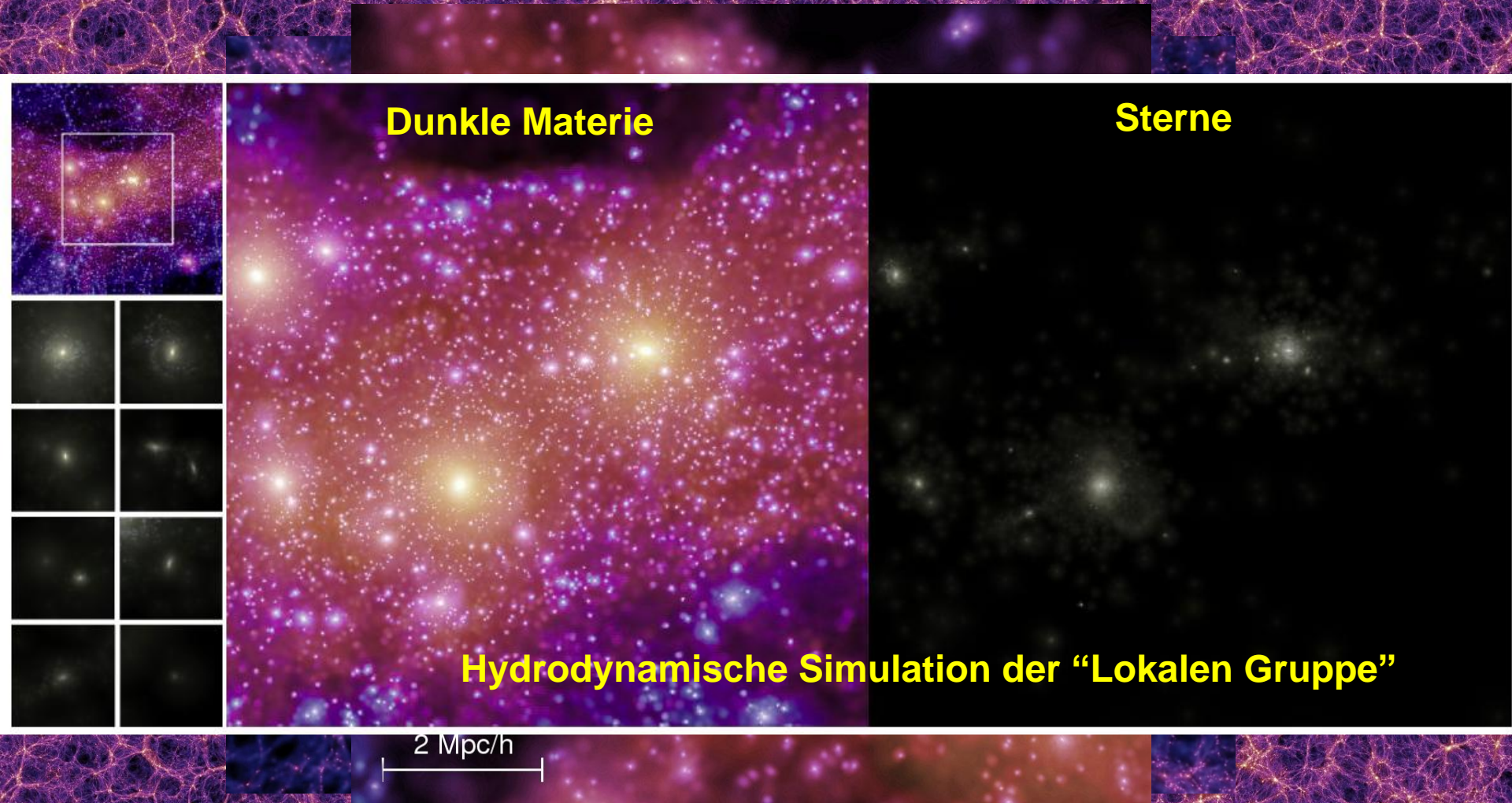
1 pc = 3×10^{15} m = 3 Lichtjahre

Simulation großer kosmischer Strukturen benötigt Dunkle Materie als Baustein



1 pc = 3×10^{15} m = 3 Lichtjahre

Simulation großer kosmischer Strukturen benötigt Dunkle Materie als Baustein



Dunkle Materie

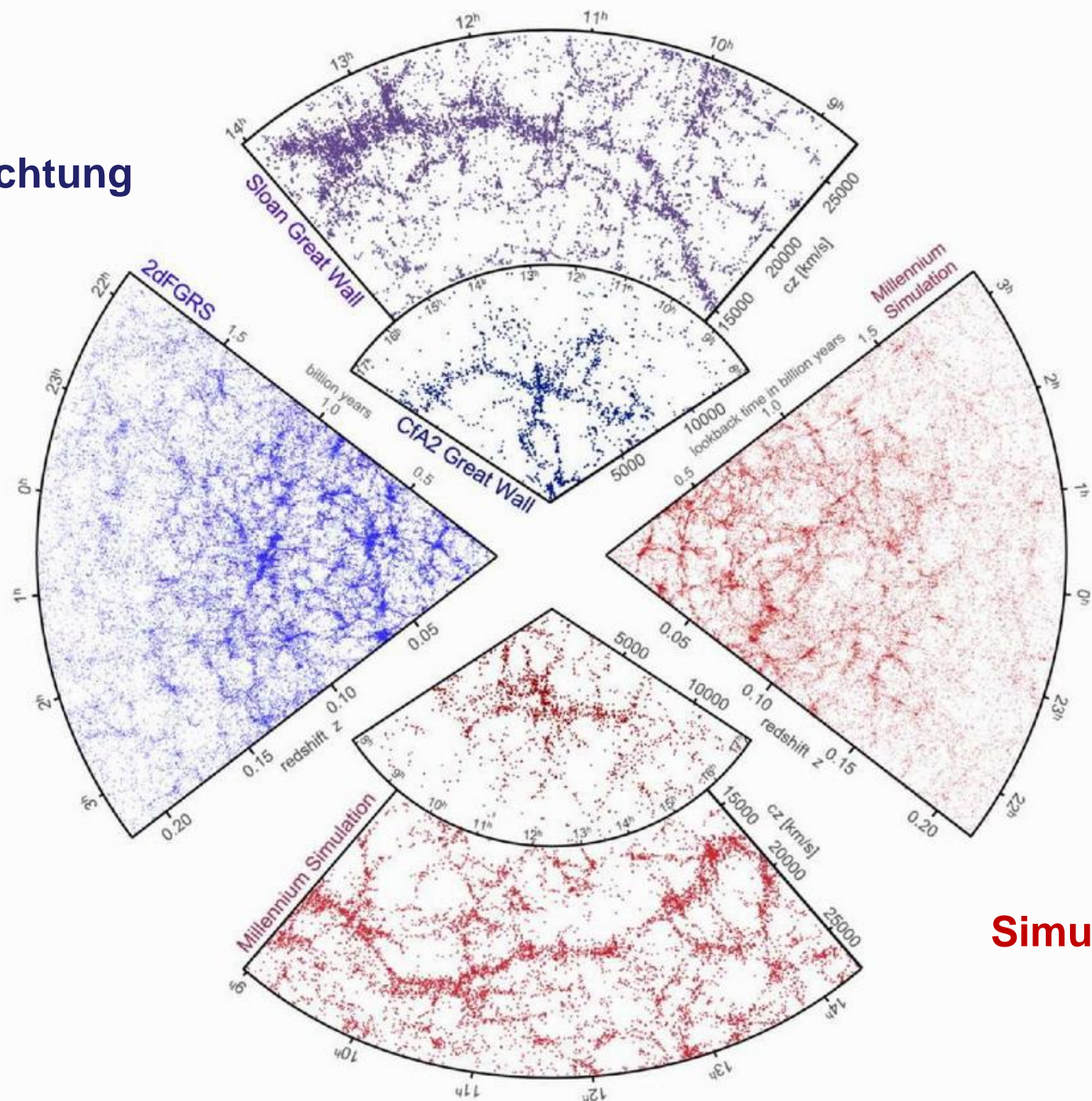
Sterne

Hydrodynamische Simulation der "Lokalen Gruppe"

2 Mpc/h

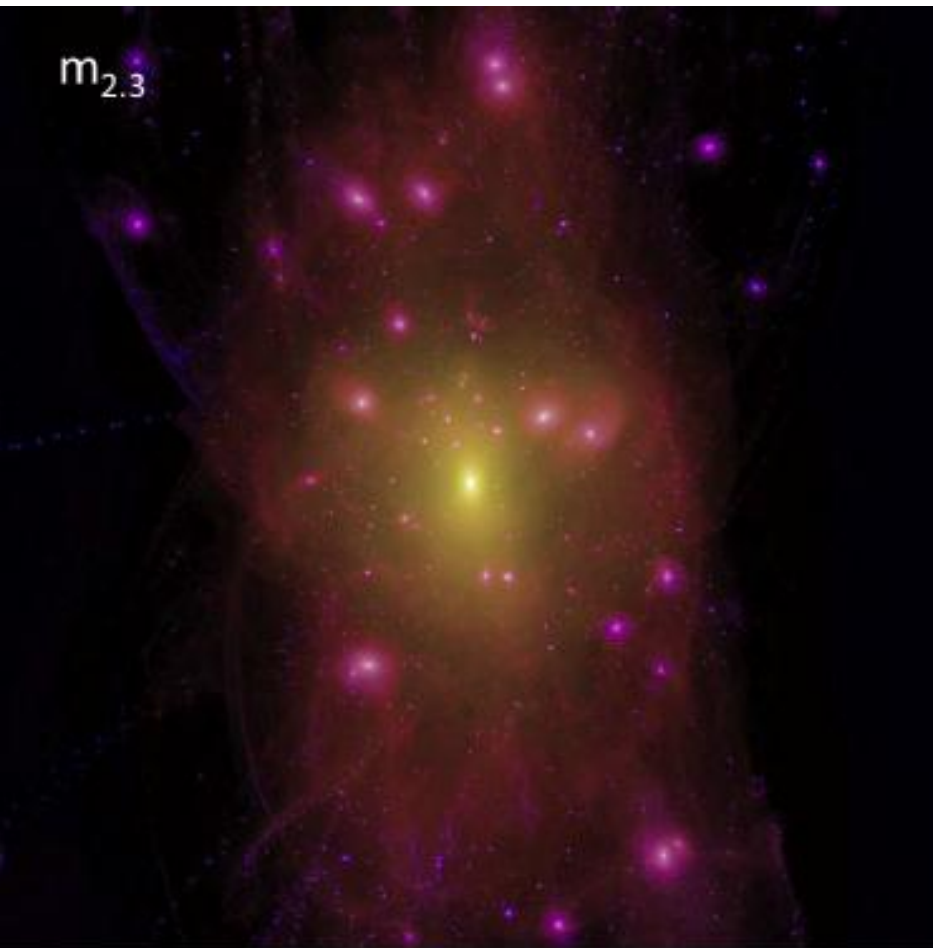
1 pc = 3×10^{15} m = 3 Lichtjahre

Beobachtung

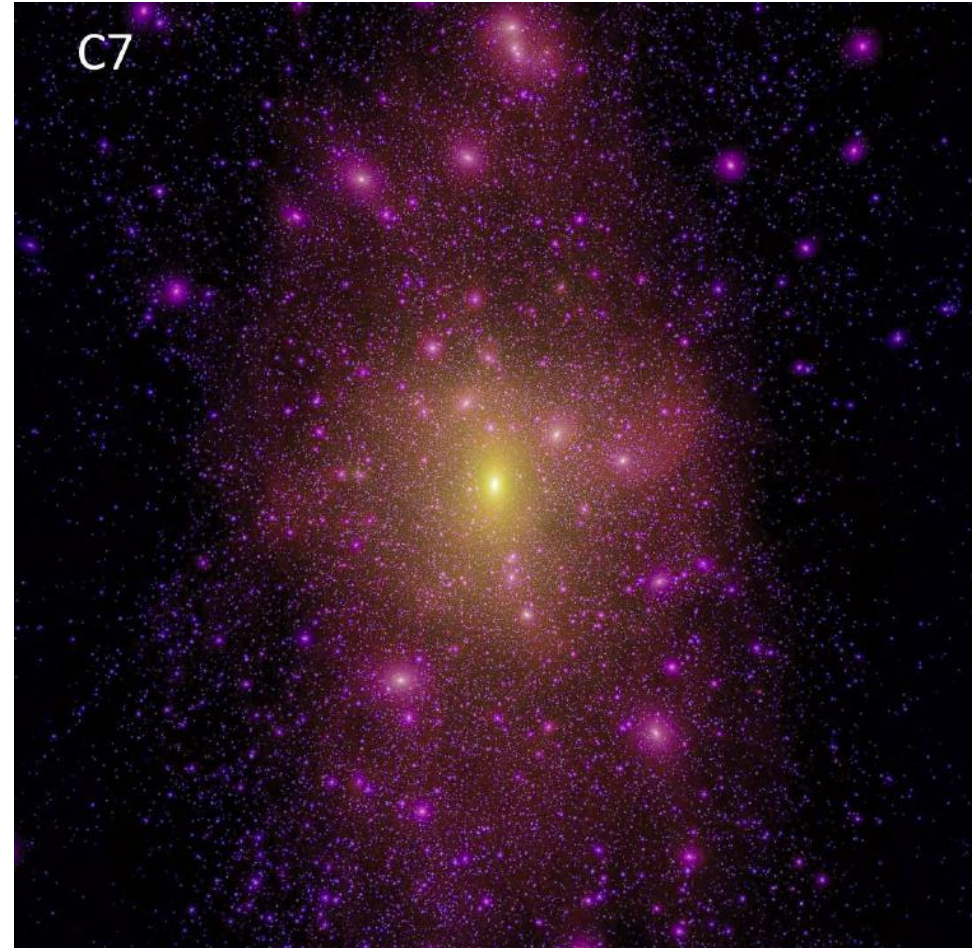


Simulation

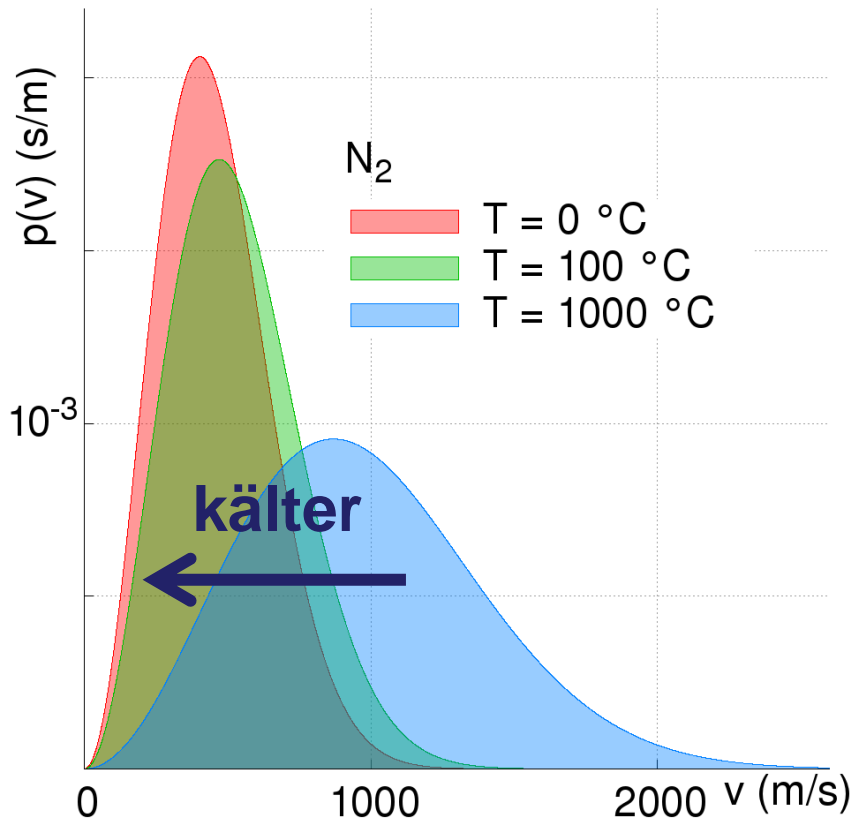
“warme” Dunkle Materie



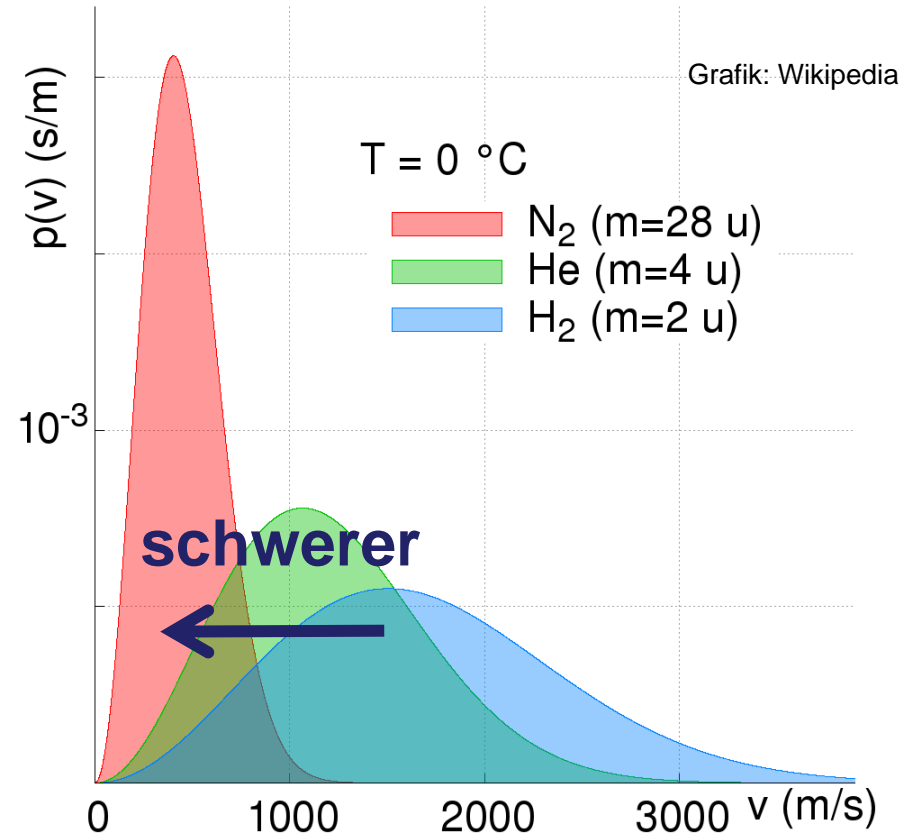
“kalte” Dunkle Materie



verschiedene Temperaturen

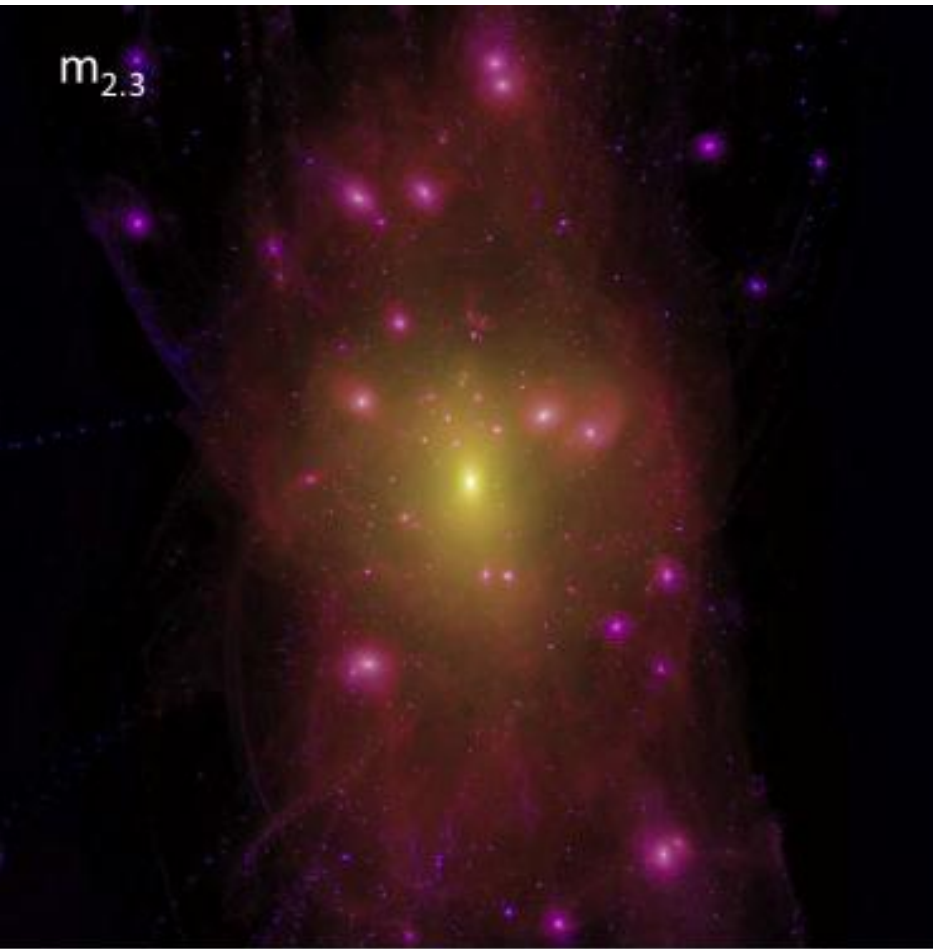


verschiedene Massen

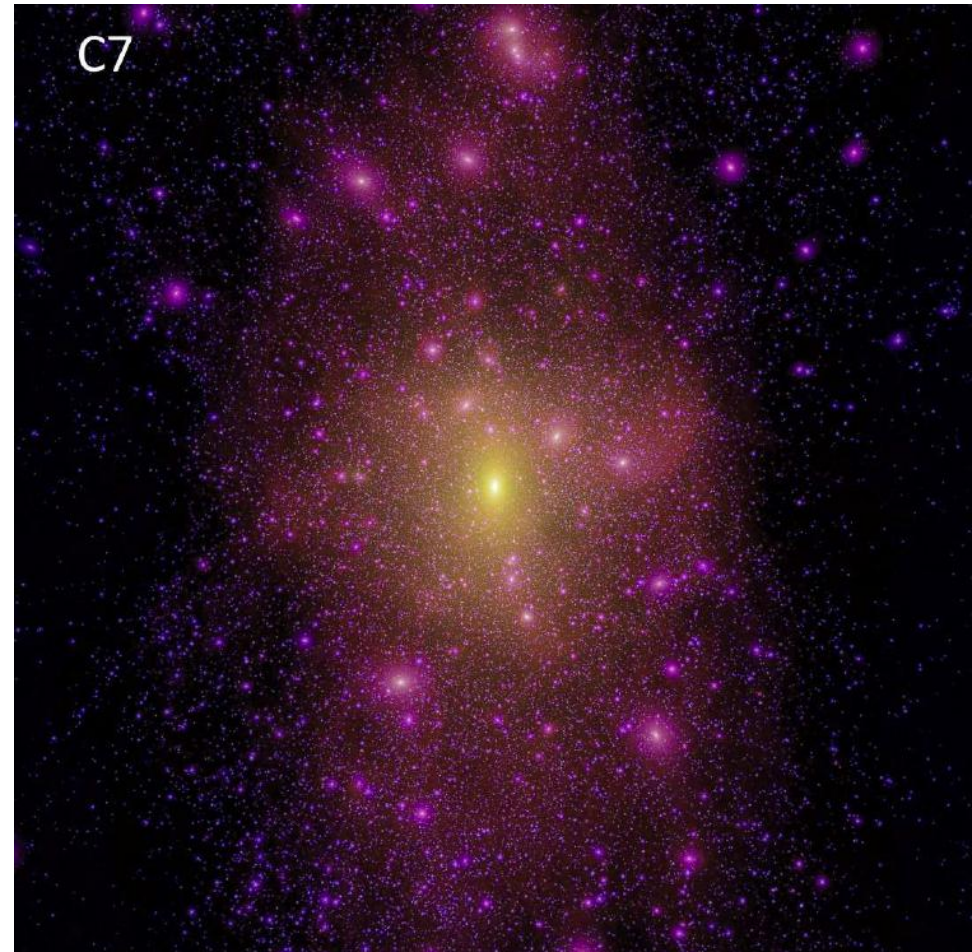


- kalt = Teilchen bewegen sich im Mittel langsamer
- äquivalent zu "kalt" = Teilchen müssen bei gegebener Energiedichte schwer sein

“warme” Dunkle Materie

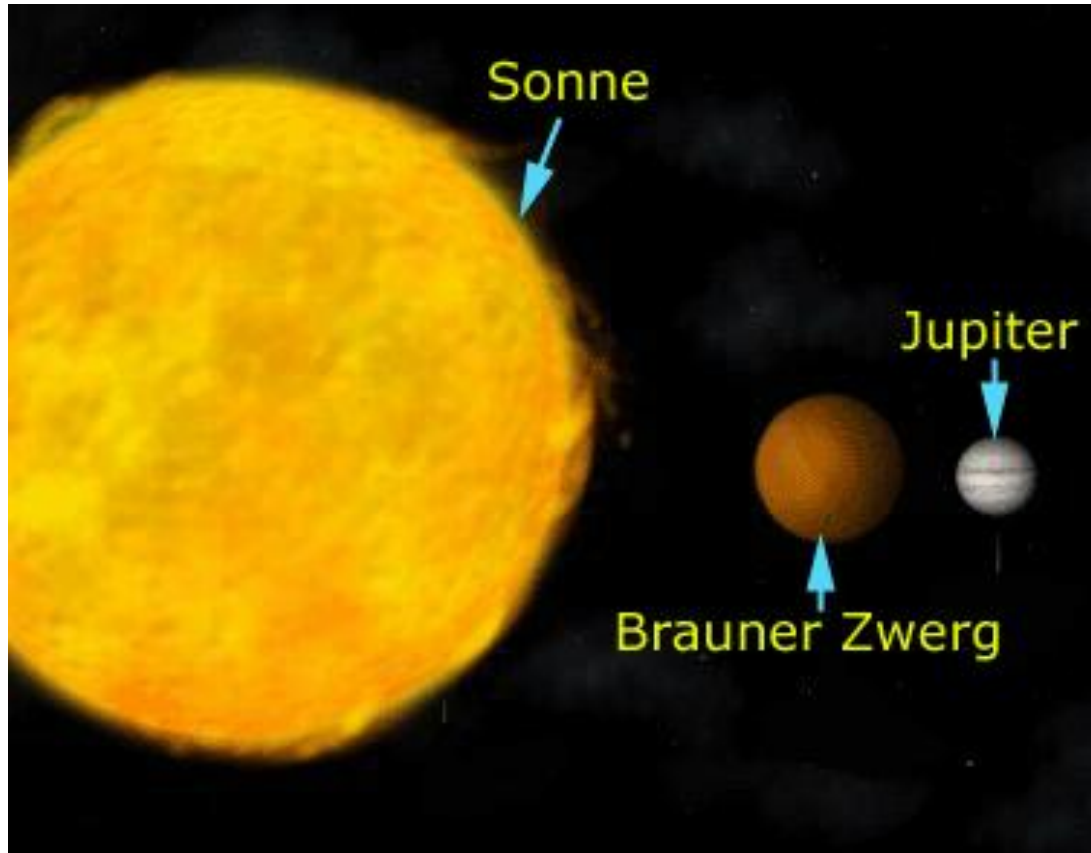


“kalte” Dunkle Materie



- beobachtete kosmische Strukturen verlangen kalte Dunkle Materie

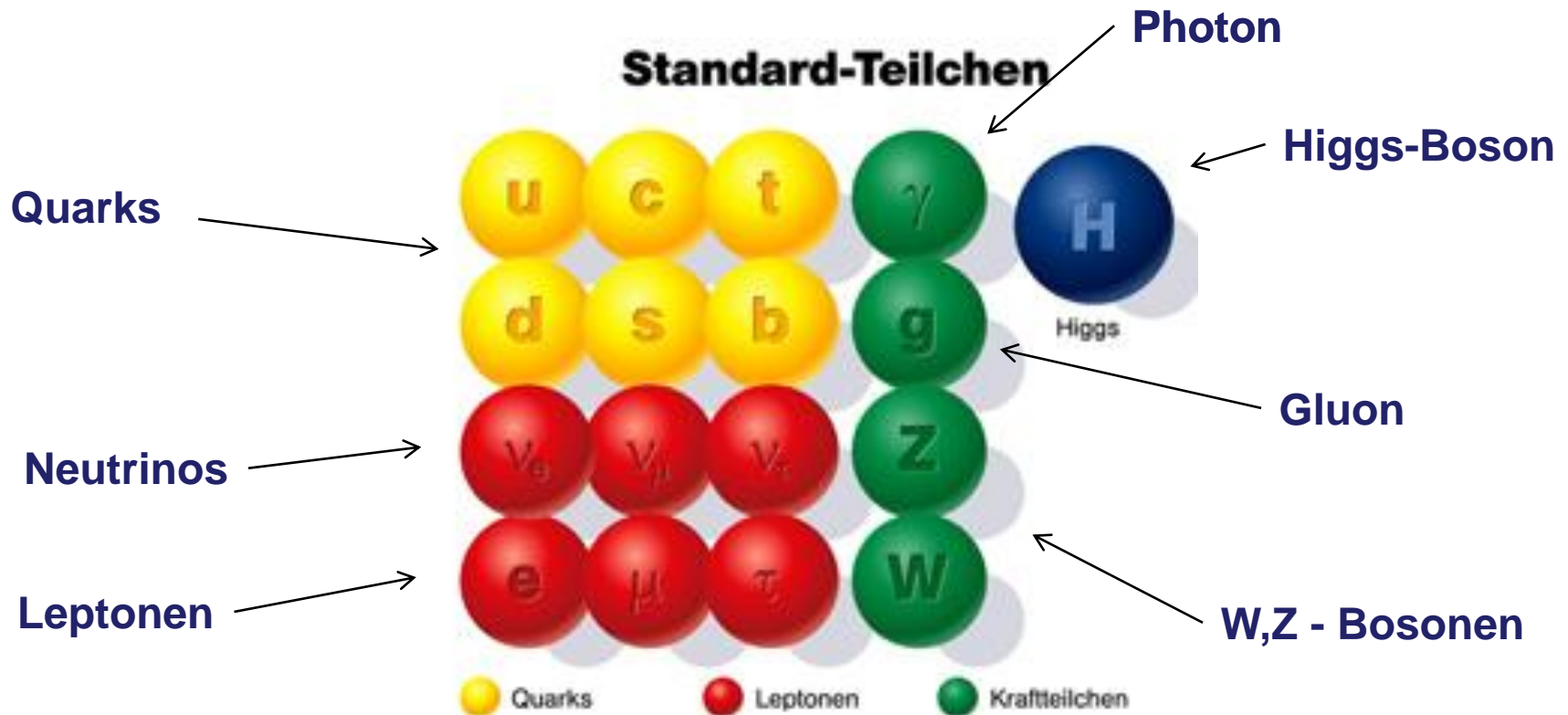
- MACHOs = Massive astrophysikalische kompakte Halo-Objekte
 - z.B. Braune Zwerge
 - nur ein kleiner Teil der dunklen Materie



• Falls es Elementarteilchen sind:

- stabil
- elektrisch neutral
- nur schwach wechselwirkend
- massiv

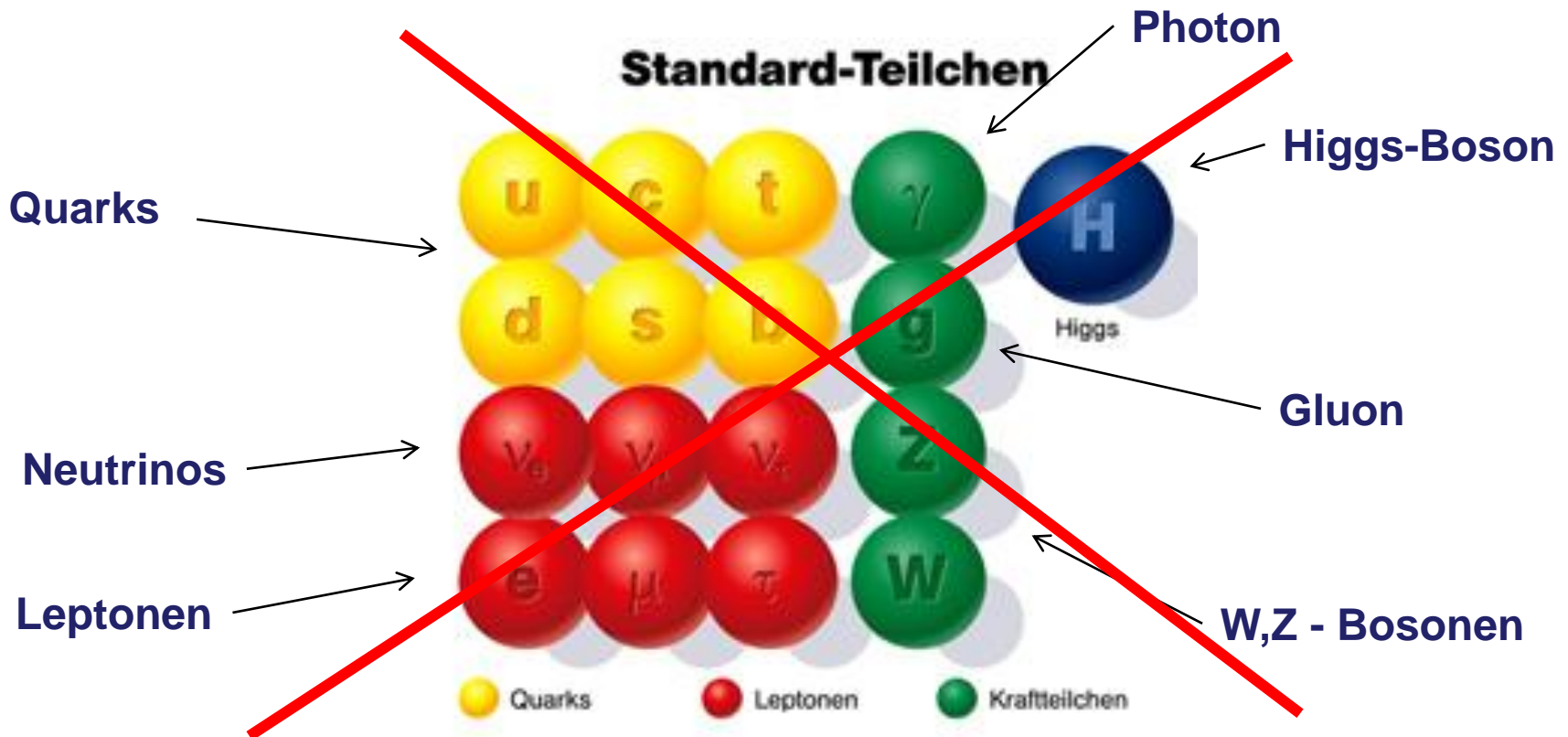
“kalte” Dunkle Materie (Cold Dark Matter)
 WIMPs = Weakly Interacting Massive Particles

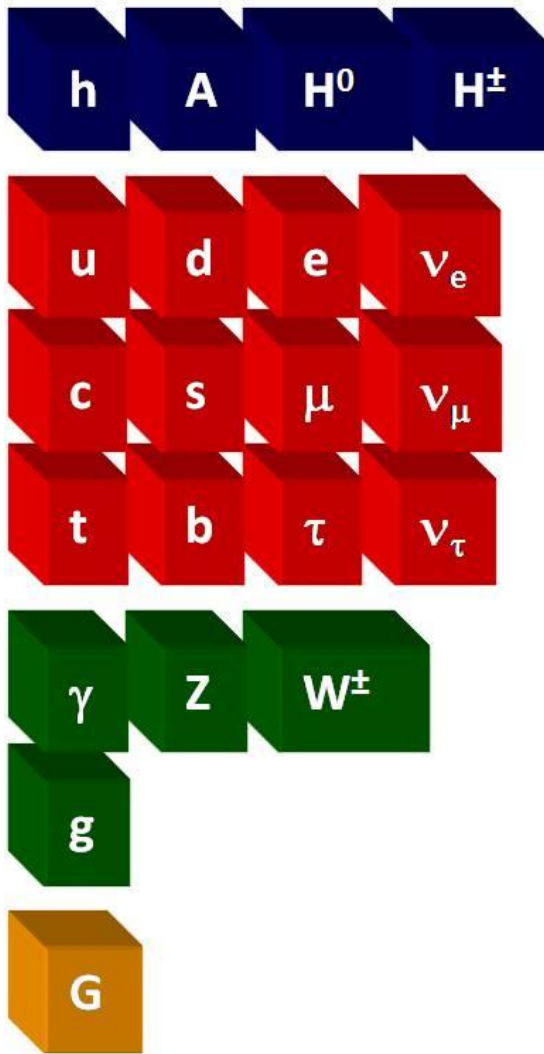


• Falls es Elementarteilchen sind:

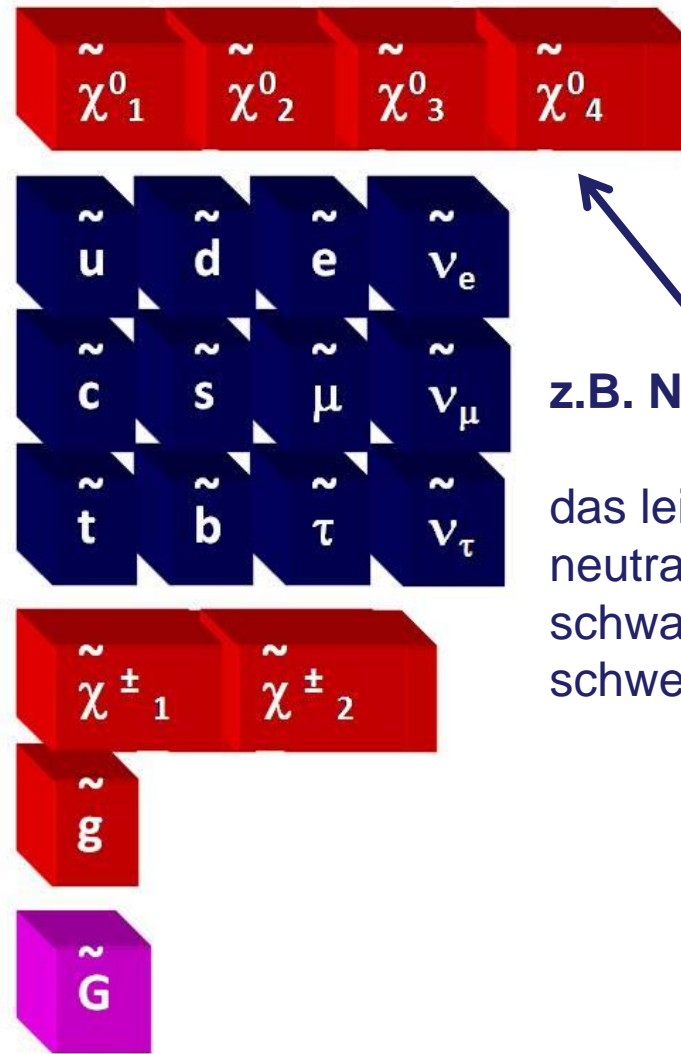
- stabil
- elektrisch neutral
- nur schwach wechselwirkend
- massiv

“kalte” Dunkle Materie (Cold Dark Matter)
 WIMPs = Weakly Interacting Massive Particles





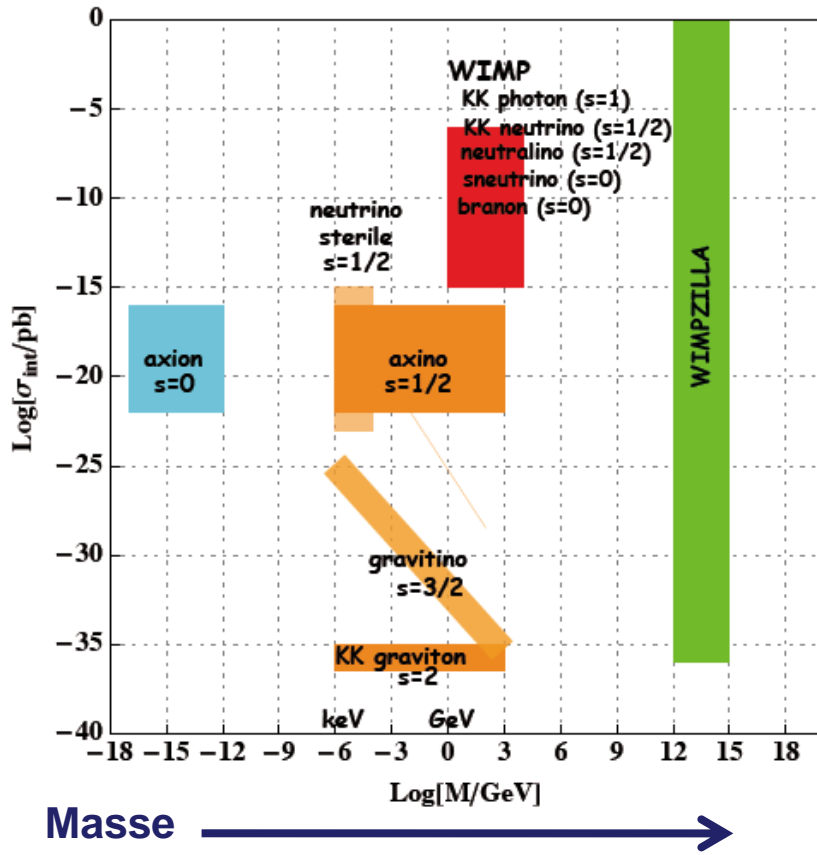
Minimal Supersymmetric Standard Model (MSSM)



z.B. Neutralinos

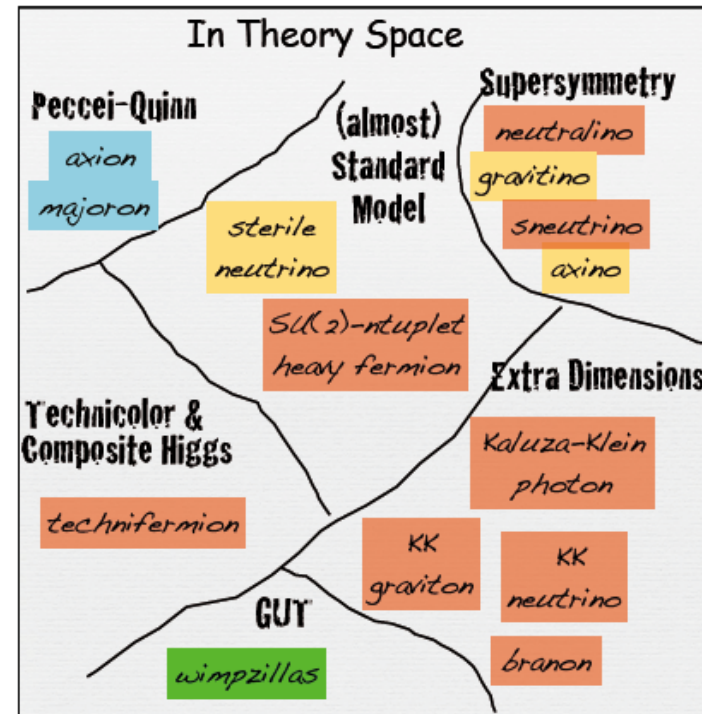
das leichteste ist stabil
neutral
schwach wechselwirkend
schwer

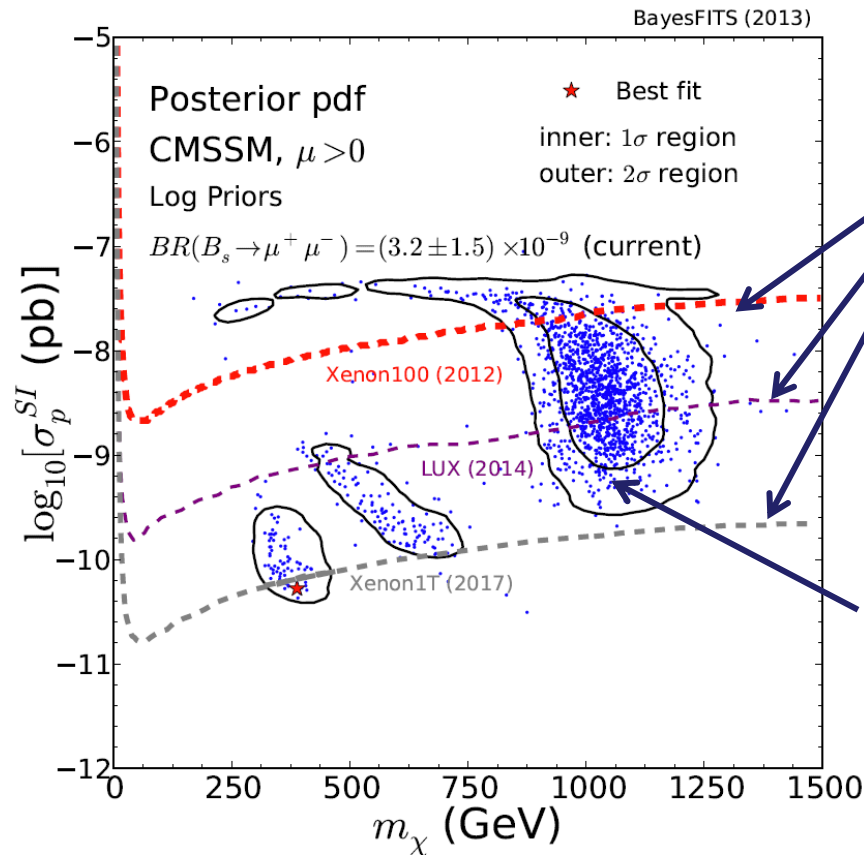
Dark Matter Candidates with $\Omega_{DM} \sim 1$



- thermal relic
- superWIMP
- condensate
- gravitationally produced or at preheating

Wechselwirkungs-wahrscheinlichkeit



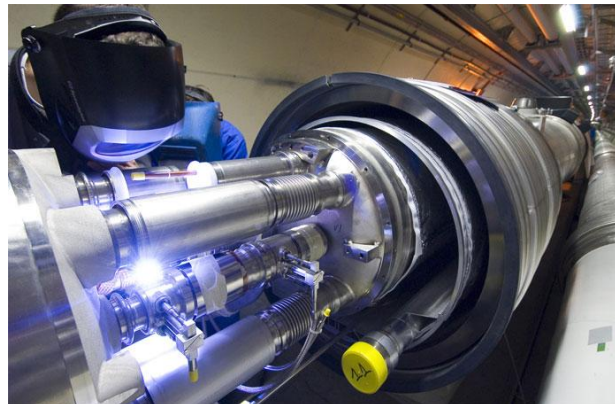
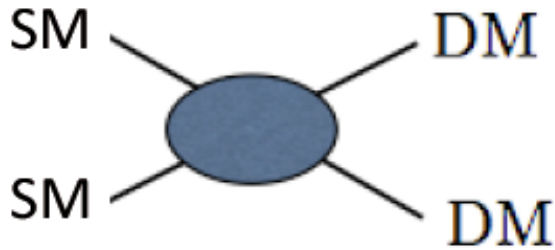
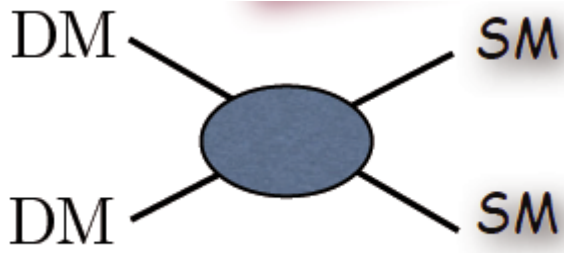
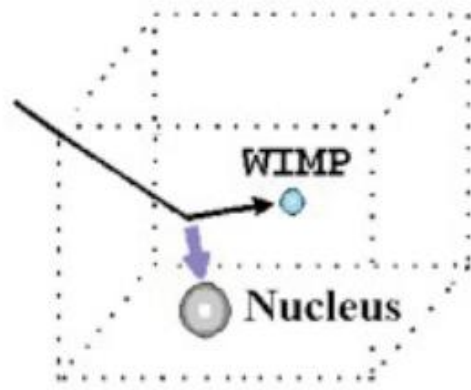
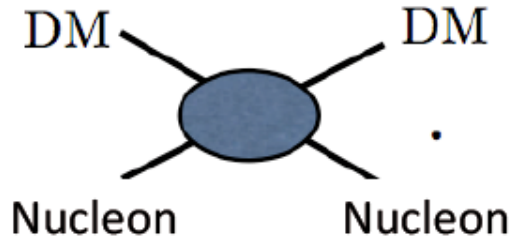


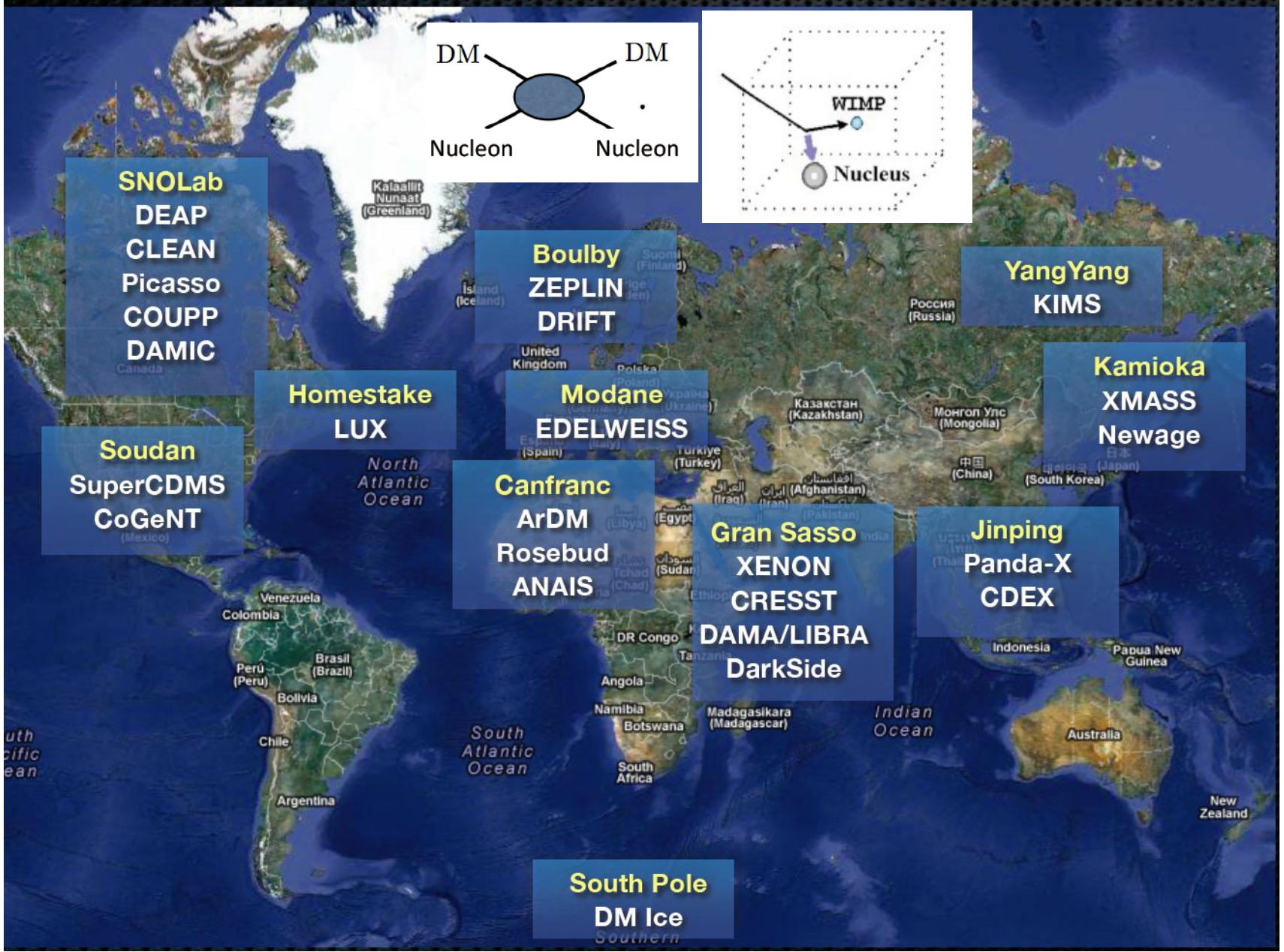
erwartete
Experimentelle
Grenzen

theoretische
Modell-Vorhersage

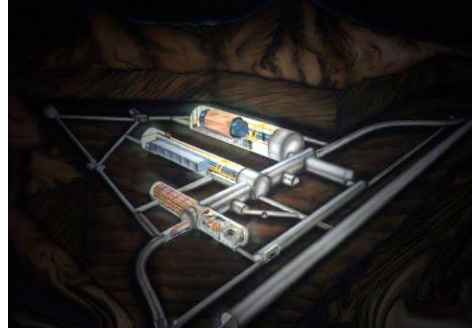
Wechsel-
wirkungs-
wahrschein-
lichkeit

Masse



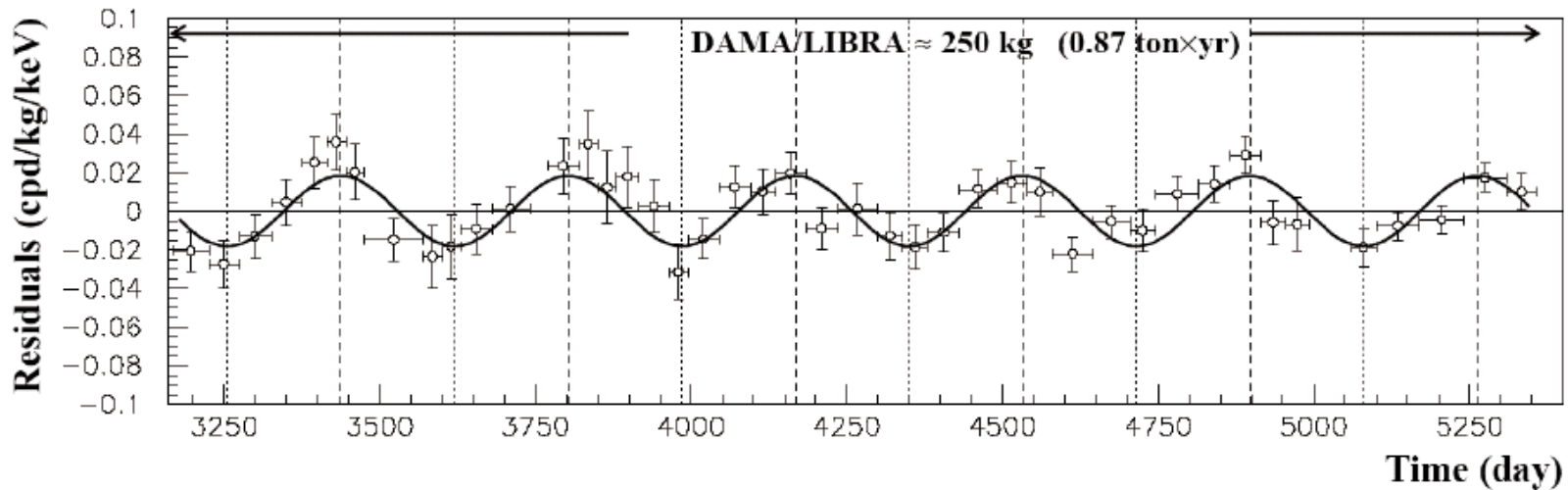


- Beispiel: DAMA/Libra-Detektor aus NaI-Kristallen im Untergrundlabor Gran Sasso (IT)



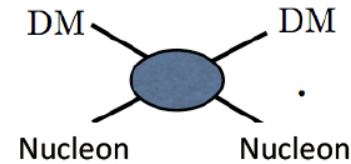
- Erde kreist um Sonne und fliegt gleichzeitig durch Hintergrund aus Dunkler Materie
- Jahreszeitliche Variation der Wechselwirkungen mit dem Teilchendetektor:

2-4 keV

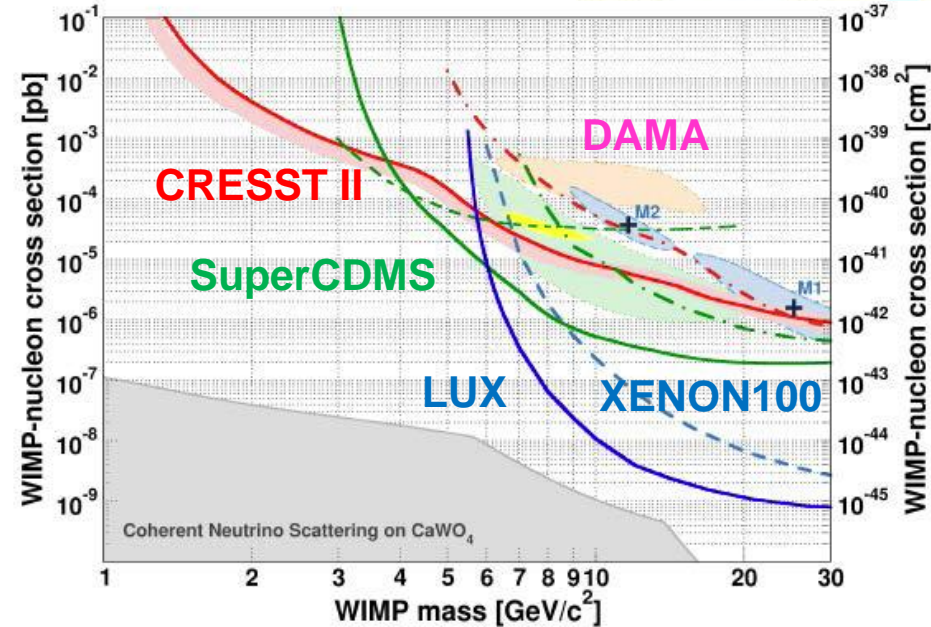
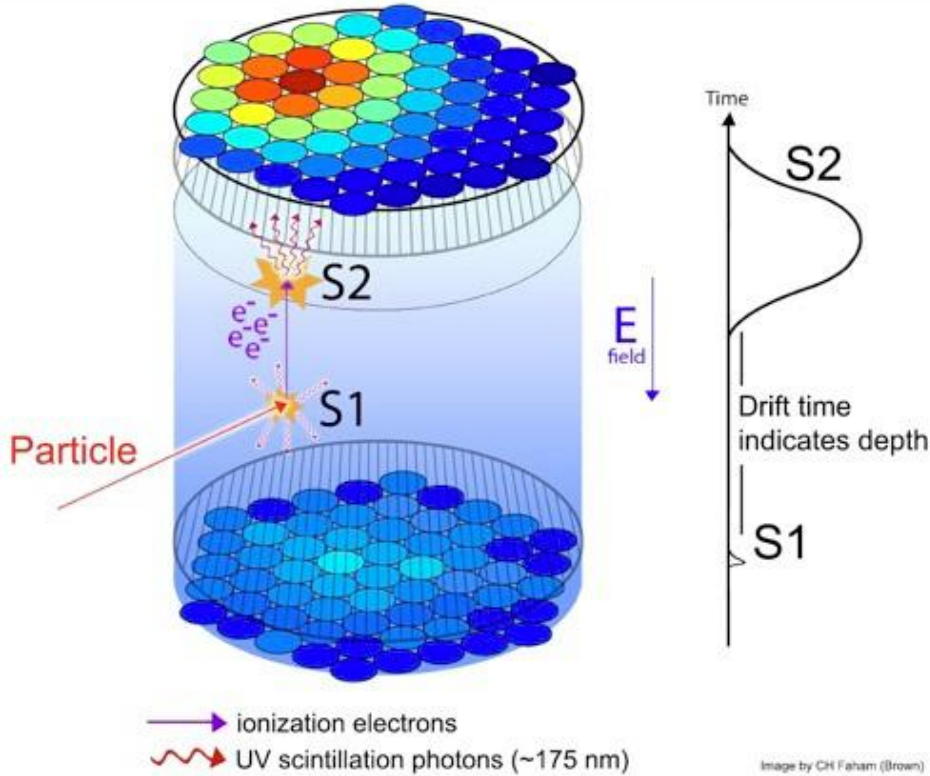


- Messung im Grenzbereich der Sensitivität des Detektors
- Ergebnisse noch nicht von anderen Experimenten bestätigt

- Beispiel: LUX-Detektor mit 120 kg flüssigem Xenon
Sanford Underground Lab South Dakota

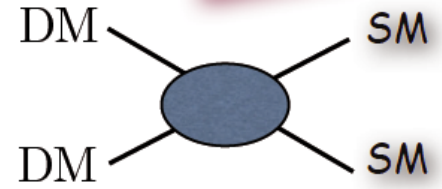
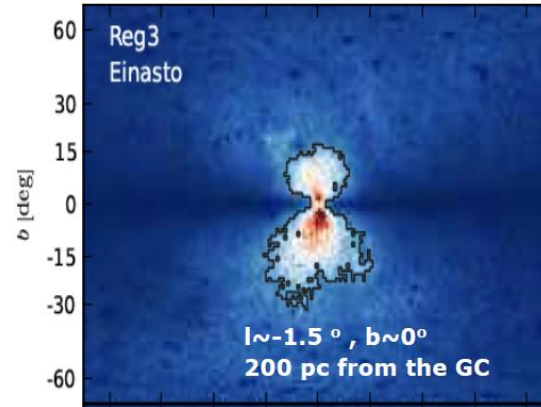
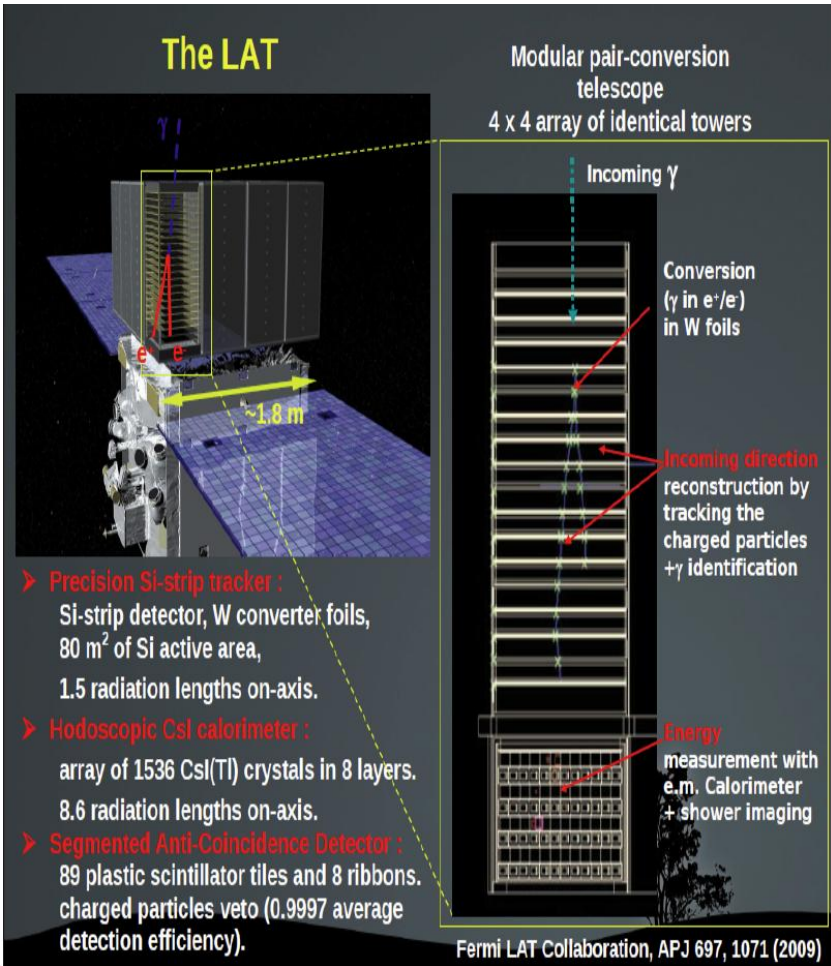


arXiv:1310.8214
arXiv:1407.3146v2



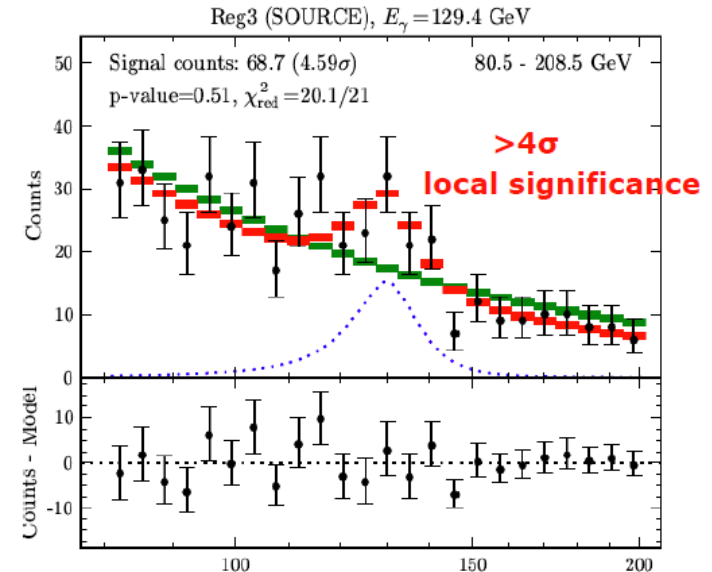
- 85 Tage Messzeit - kein Signal beobachtet
→ Dunkle Materie wechselwirkt nur sehr schwach
- Neue Ergebnisse werden 2015 erwartet, genauso von vielen anderen Experimenten in den nächsten Jahren, wobei Detektoren immer schwerer werden (1t, 2t, 5t, ...)

- Beispiel: Fermi/LAT Teleskop



- Suche nach hochenergetischen Photonen aus dem galaktischen Zentrum

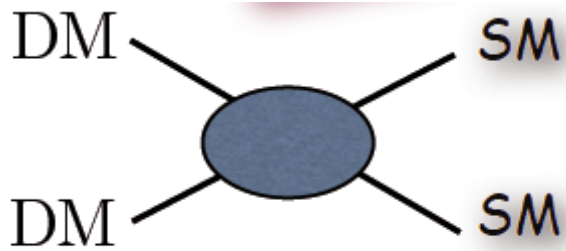
Target region : reg3 surrounding the Galactic center



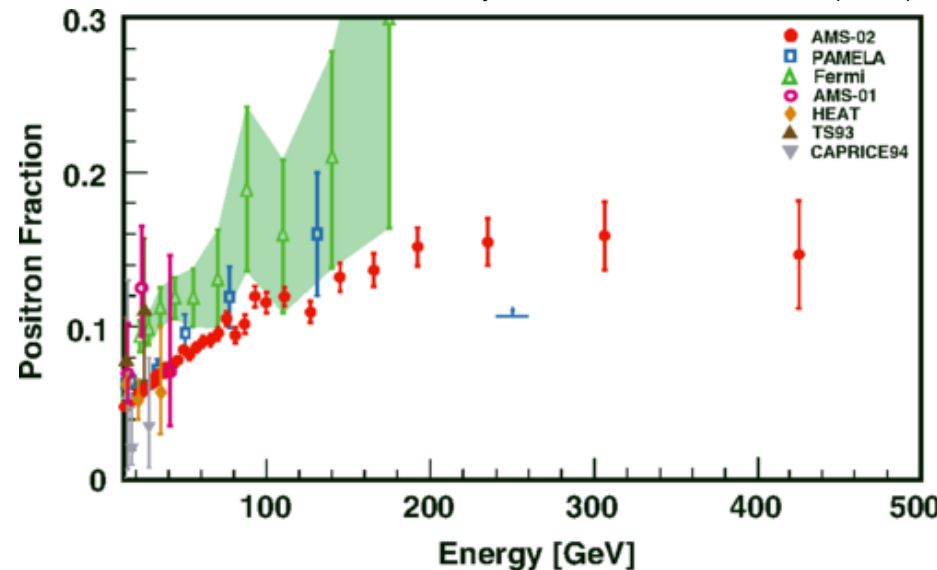
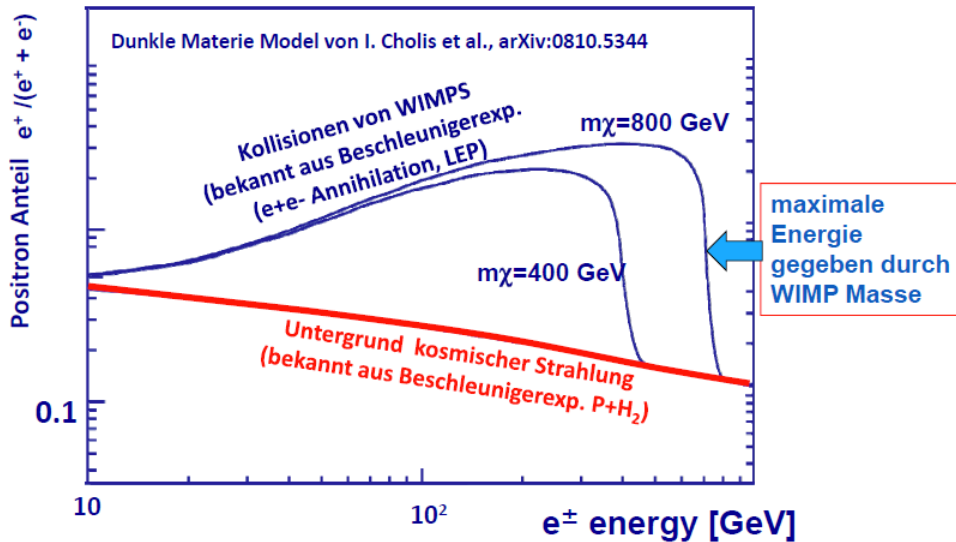
- Neue Analyse reduziert die Signifikanz auf 3.3 σ (global nur 1.6 σ)
- Astrophysikalische Quelle?

C. Weniger, JCAP 1208, 007 (2012).
Fermi-LAT Collab., M. Ackermann et al., arXiv:1305.5597.

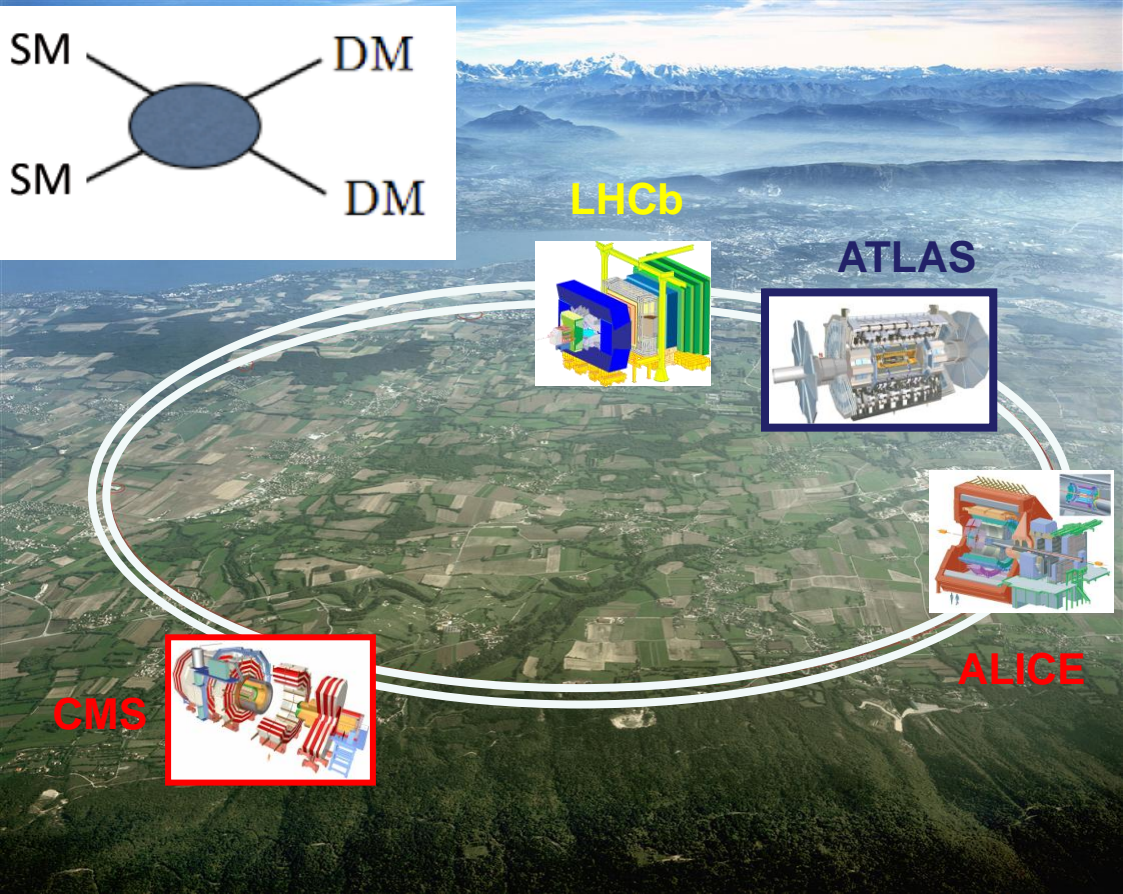
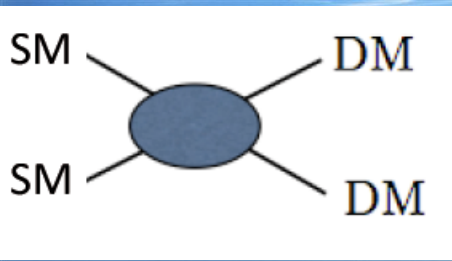
- AMS Detektor auf der ISS sieht Positronen hoher Energie – aus Annihilation von Dunkler Materie?



Phys. Rev. Lett. 113, 121101 (2014)



- Spektrum steigt an und flacht wieder ab → Dunkle Materie?
- Quelle kann auch astrophysikalischer Natur sein (Pulsar)



LHC:

26.7 km Umfang
Tunnel in 50-100 m Tiefe

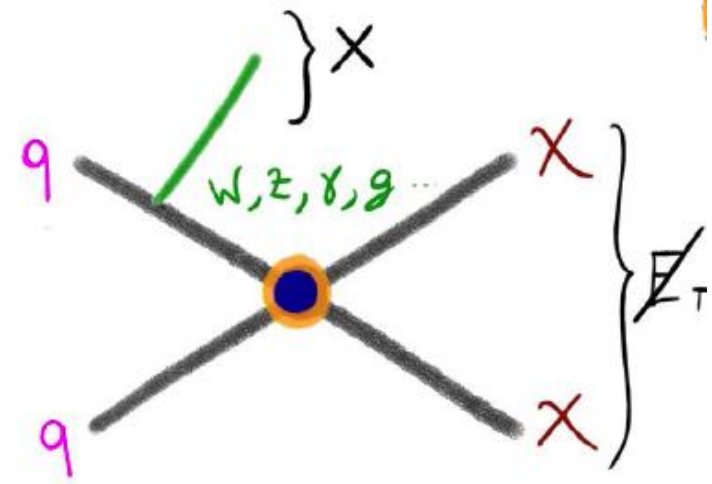
4 Teilchendetektoren

Protonen mit 99.9999991%
der Lichtgeschwindigkeit
→ 11250 Umläufe pro Sekunde

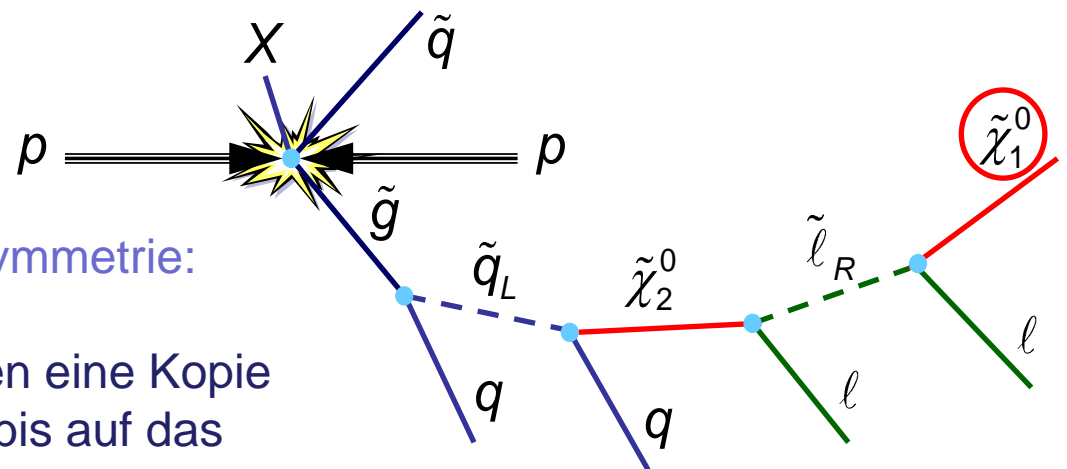


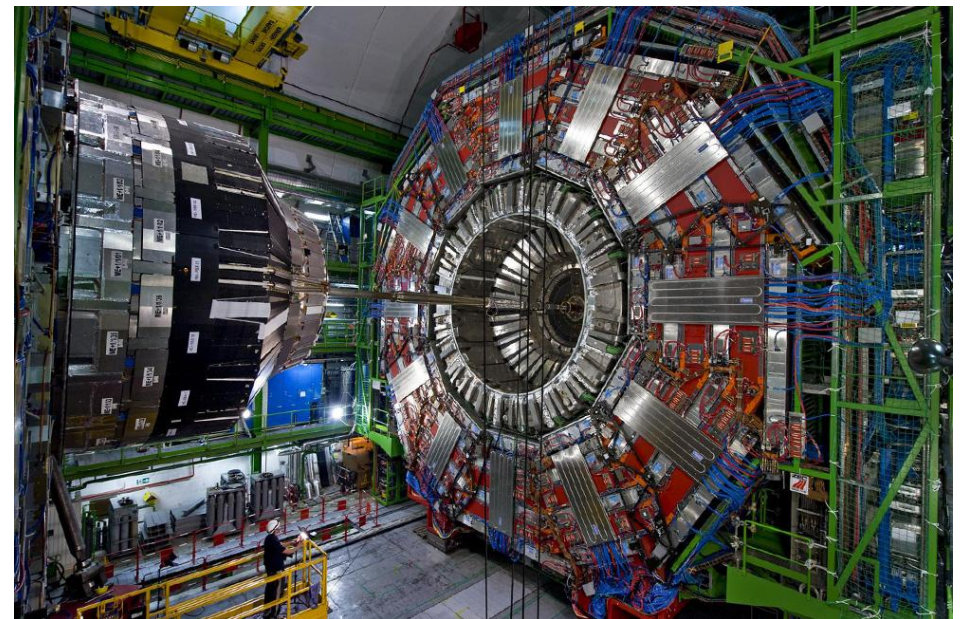
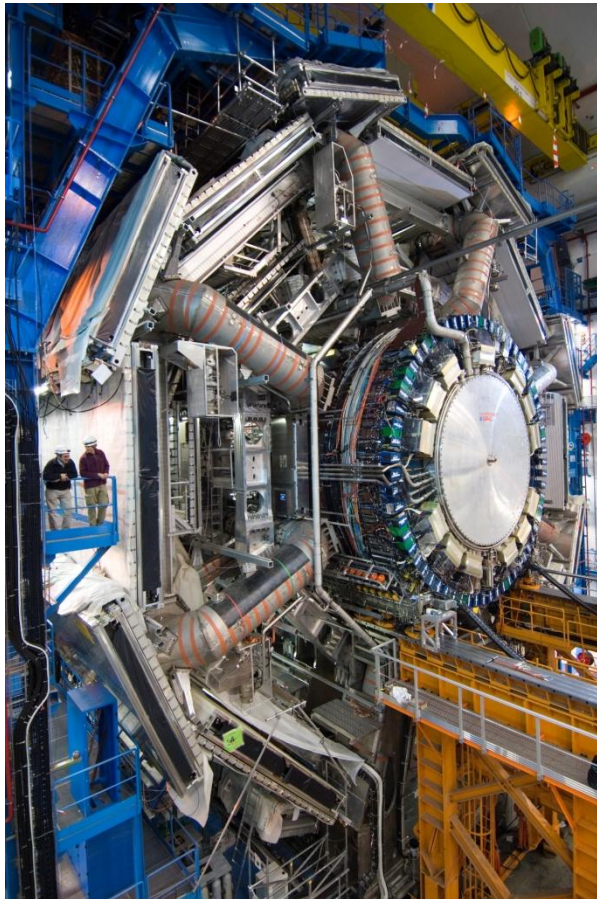
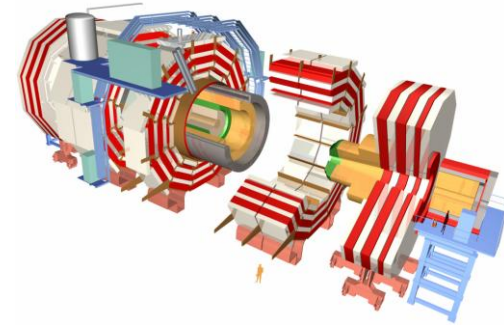
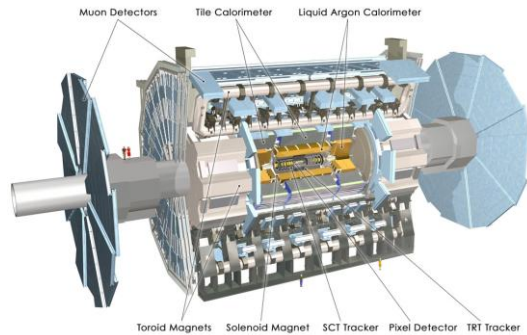
- 1100 Teilchen-Pakete mit je 10^{11} Protonen pro Strahl
- alle 50 ns eine Strahl-Kreuzung mit bis zu 40 Proton-Proton-Stößen
- Kollisionsenergie entspricht 8500 x Protonmasse

- Allgemeine Produktion Dunkler Materie zusammen mit bekannten Teilchen:

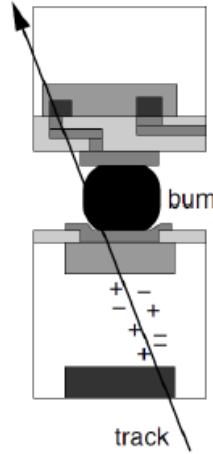
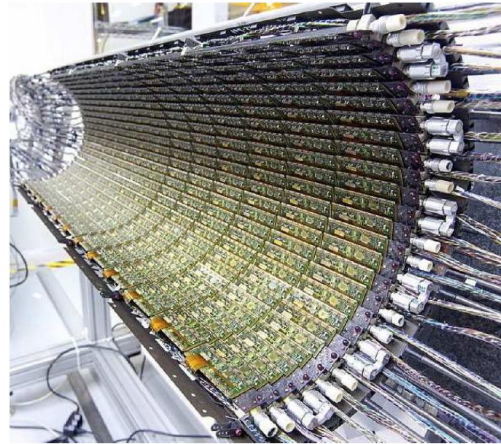


- Spezielle Modelle z.B. Supersymmetrie:
 - alle bekannten Teilchen haben eine Kopie
 - die neuen Teilchen zerfallen bis auf das leichteste supersymmetrische Teilchen
 - stabil, schwer, schwach wechselwirkend
 - Kandidat für Dunkle Materie

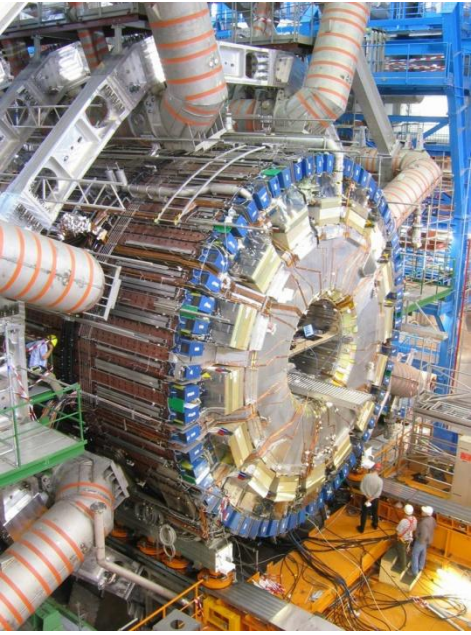
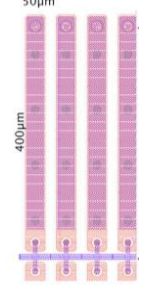




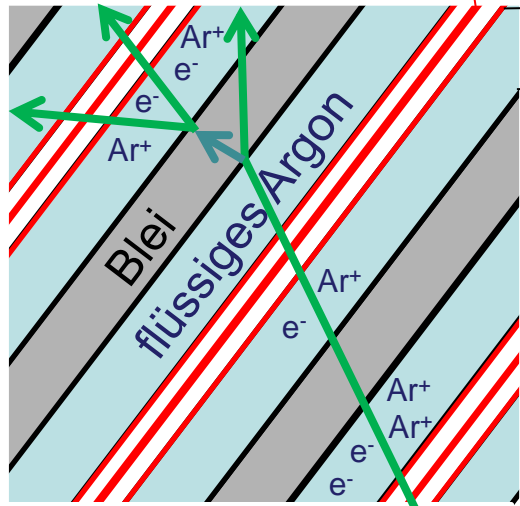
- weltweite Kollaborationen
- jeweils 3000 Physiker aus 170 Ländern
- 18 deutsche Universitäten und Forschungsinstitute sind beteiligt



80 Millionen Pixel
 $50 \times 400 \mu\text{m}^2$

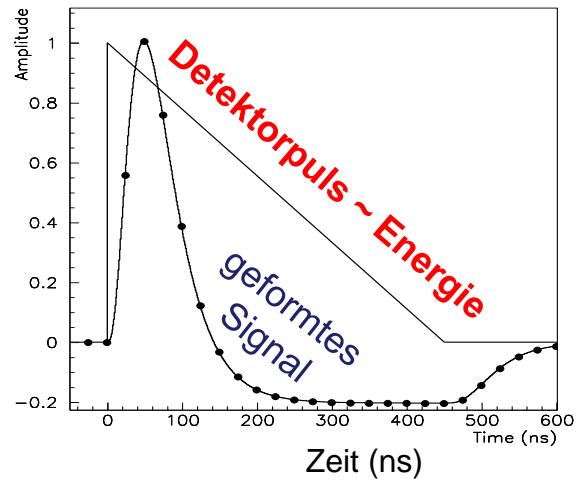


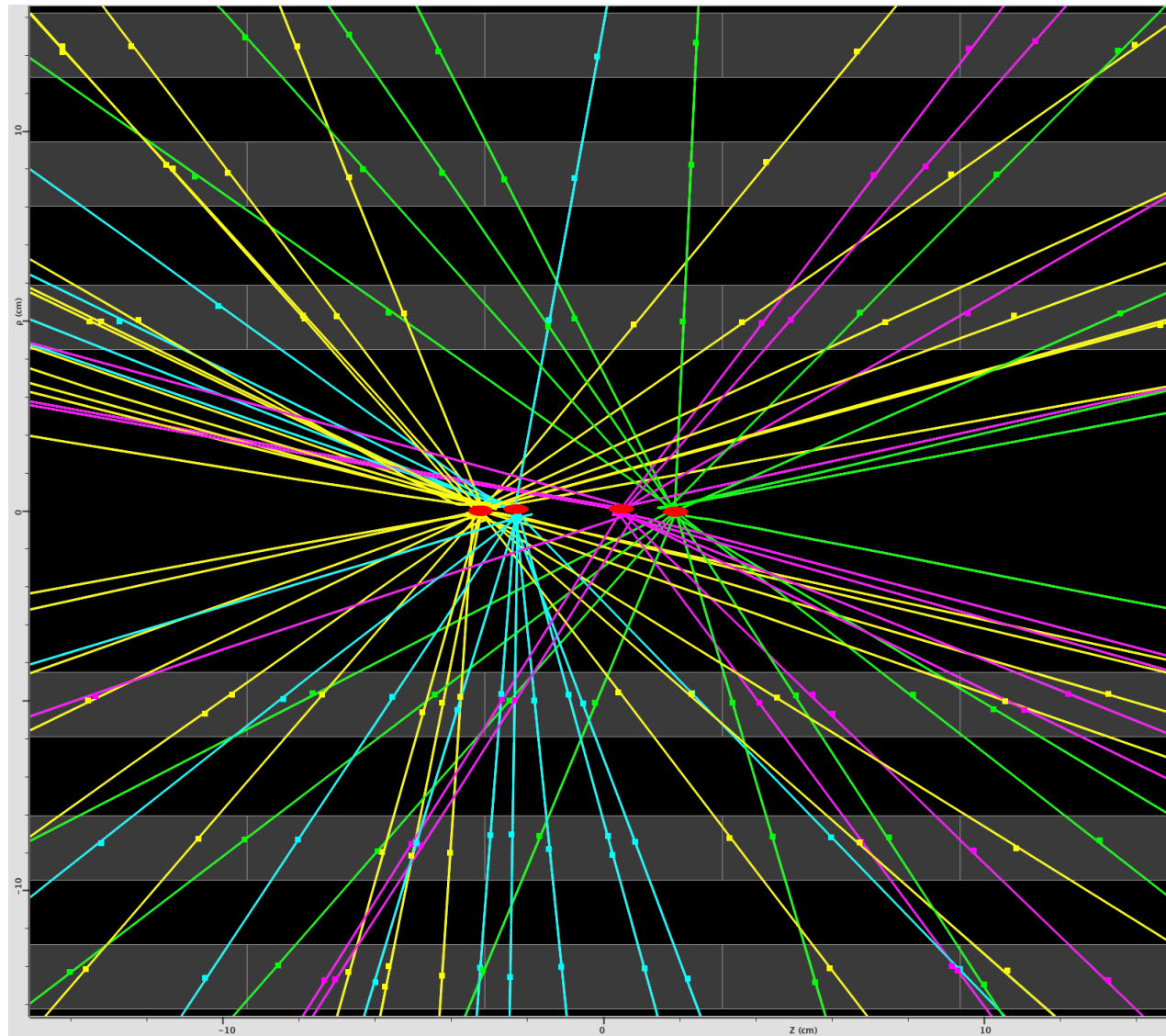
Kupferelektroden



geladenes Teilchen

Hochspannung
 und Signalauslese

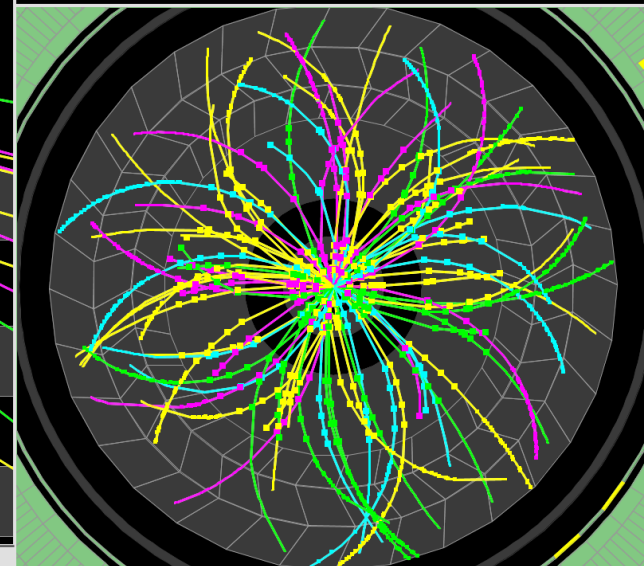




ATLAS EXPERIMENT

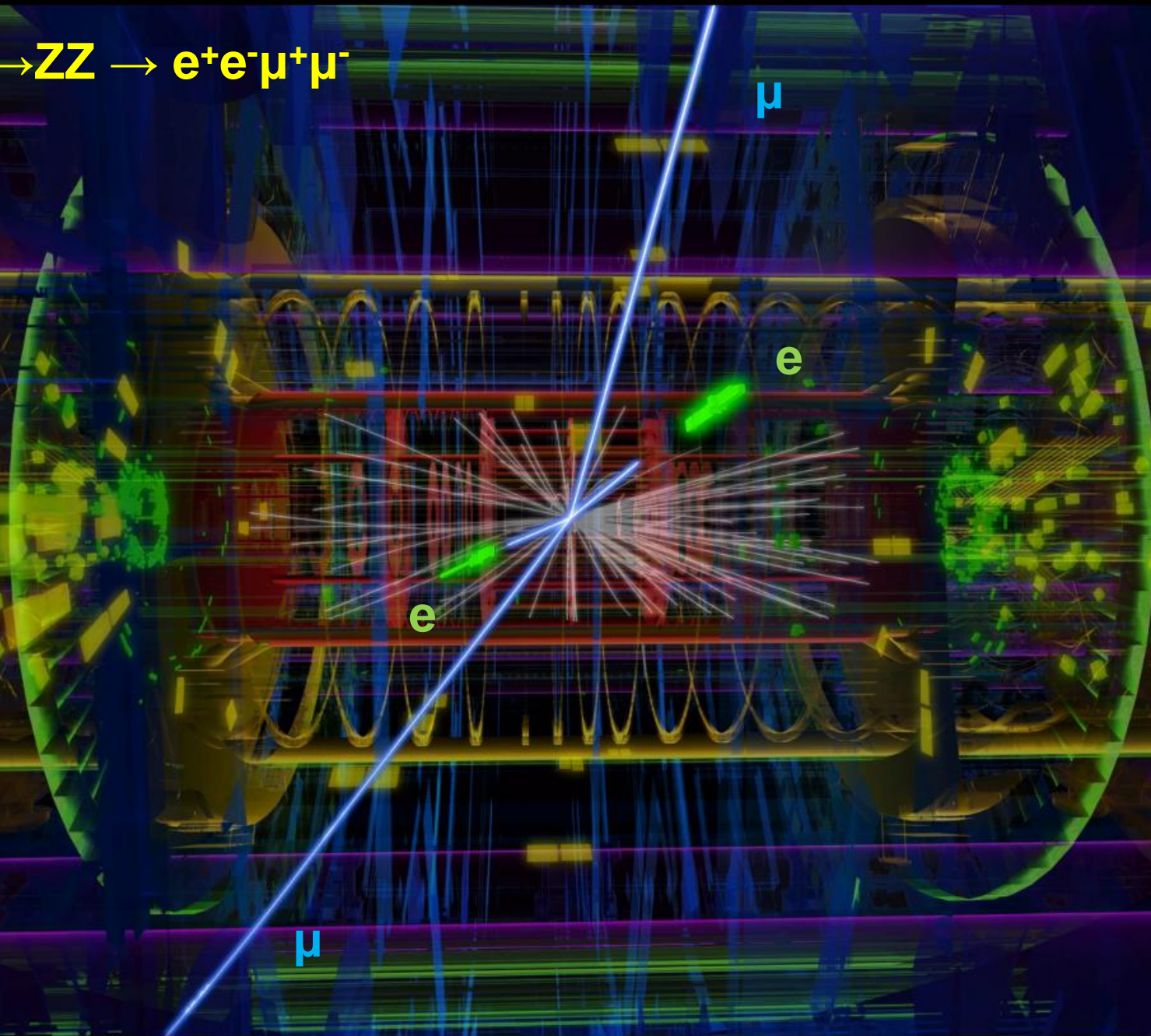
Run Number: 153565, Event Number: 4487360
 Date: 2010-04-24 04:18:53 CEST

**Event with 4 Pileup Vertices
 in 7 TeV Collisions**



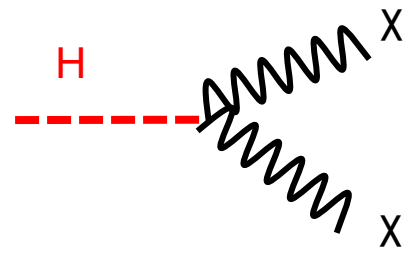
- aus der Spurkrümmung kann der Impuls der Teilchen bestimmt werden

$$H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$$

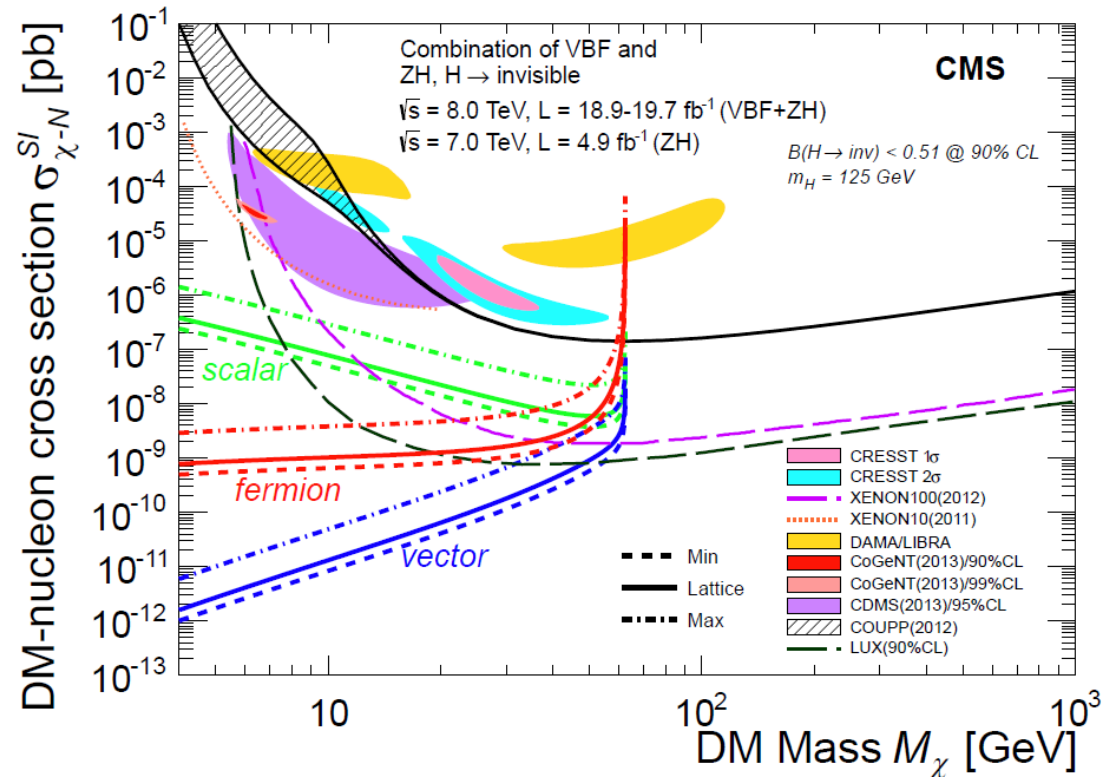


Higgs-Zerfälle in "unsichtbare" Dunkle Materieteilchen

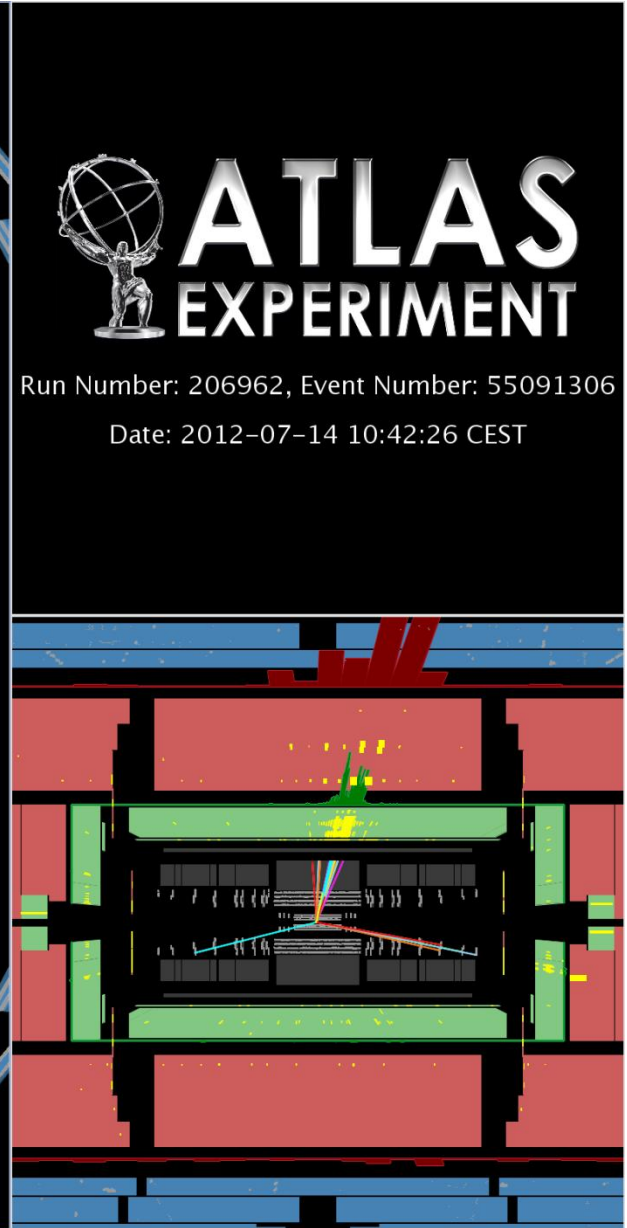
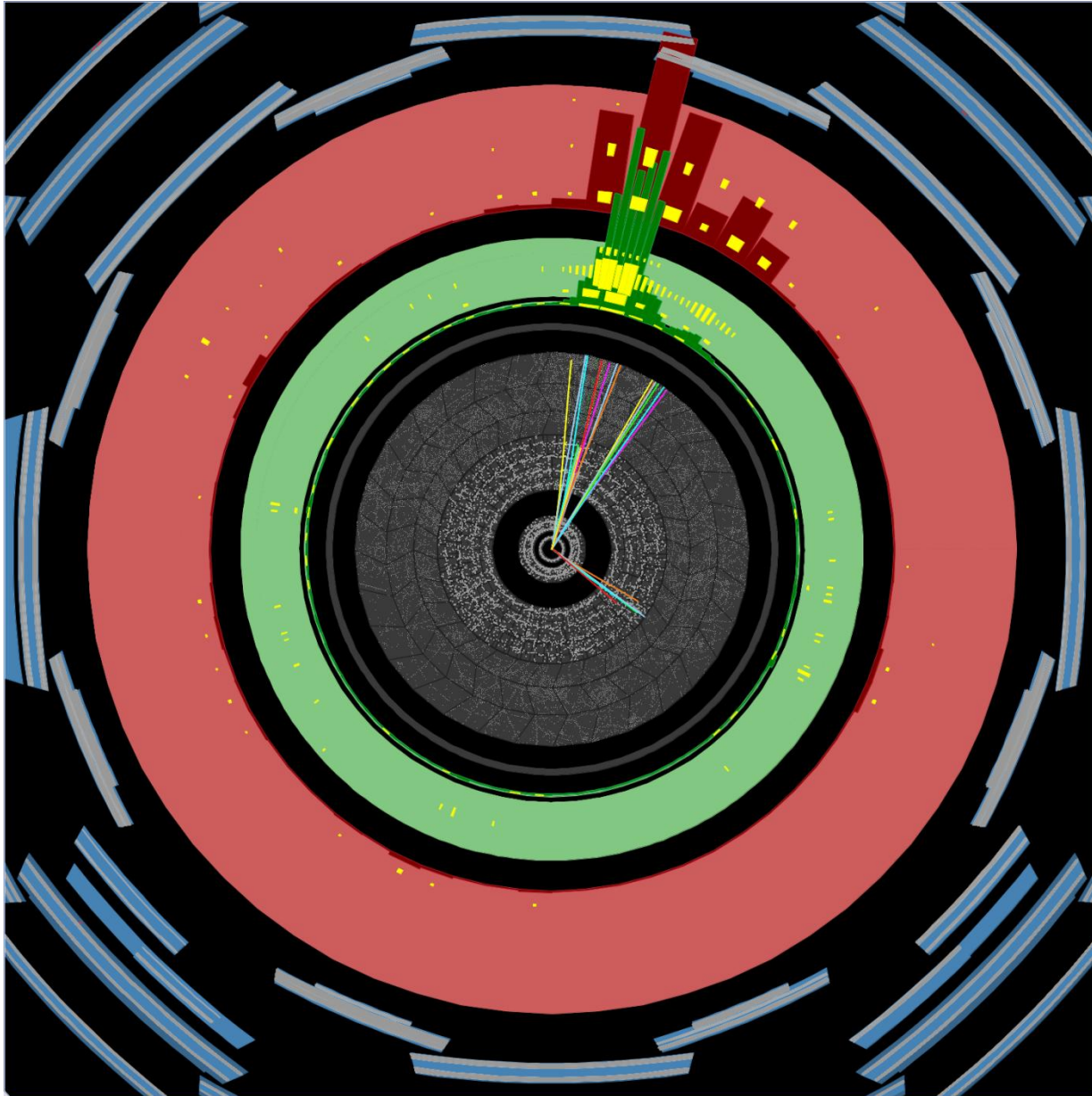
- Das Higgs-Teilchen wurde bereits sehr gut vermessen und viele Eigenschaften bestimmt
- Nahezu alle Zerfallsmoden wurden beobachtet
- Wie groß ist der Anteil "unsichtbarer" Zerfälle z.B. eventuell in Dunkle Materieteilchen?

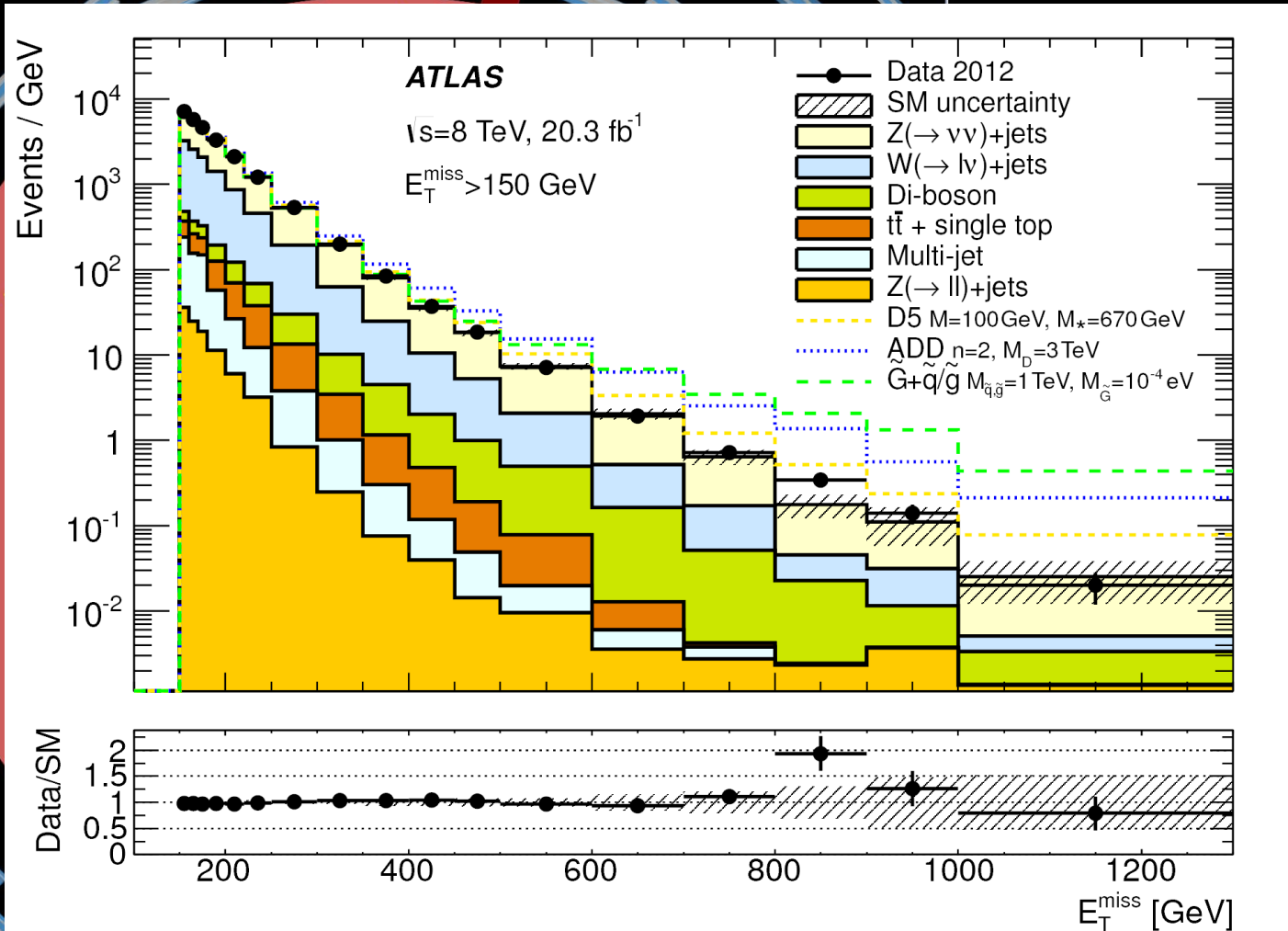


Anteil unsichtbarer Zerfälle < 37% at 95% CL (ATLAS)
 Anteil unsichtbarer Zerfälle < 58% at 95% CL (CMS)

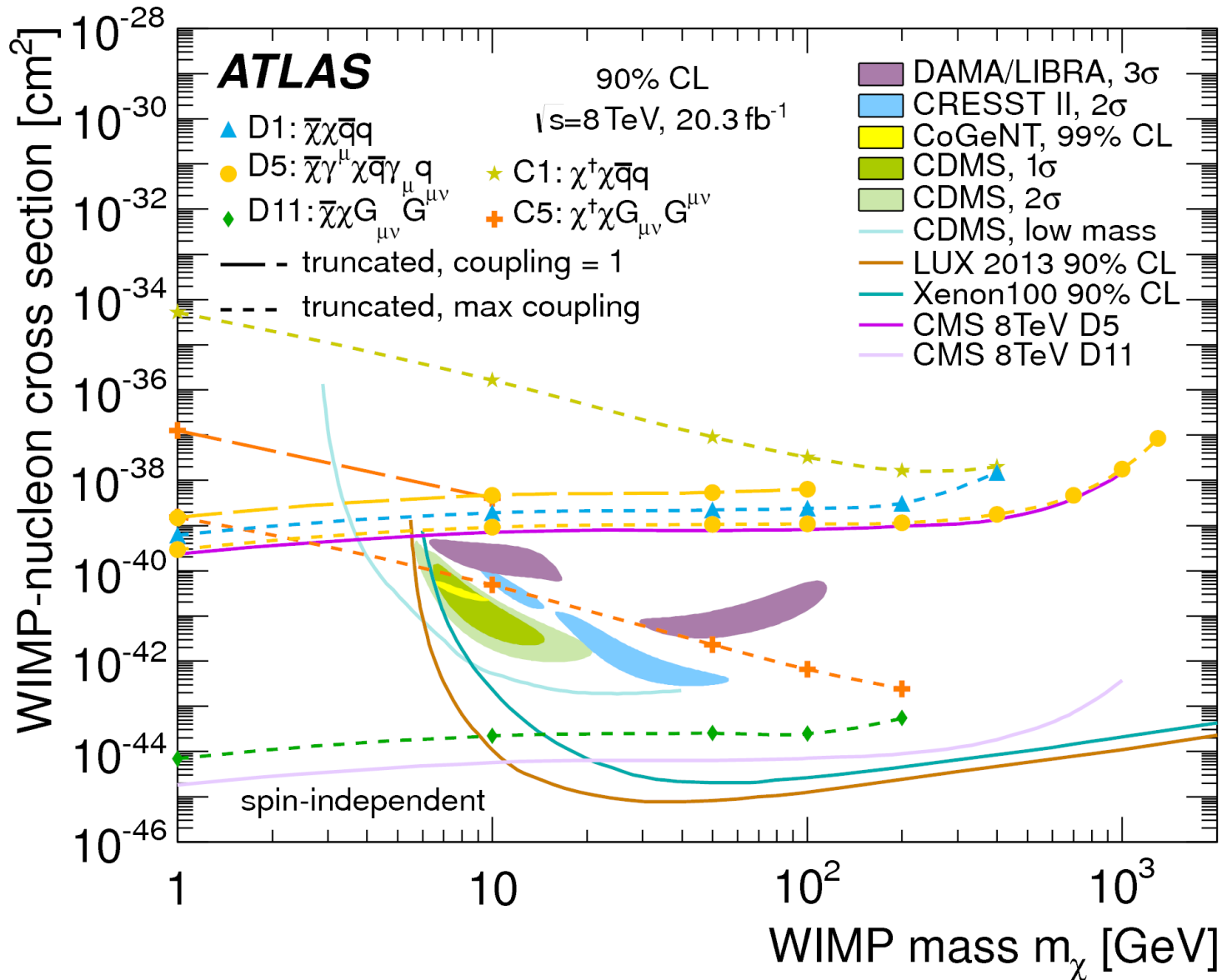


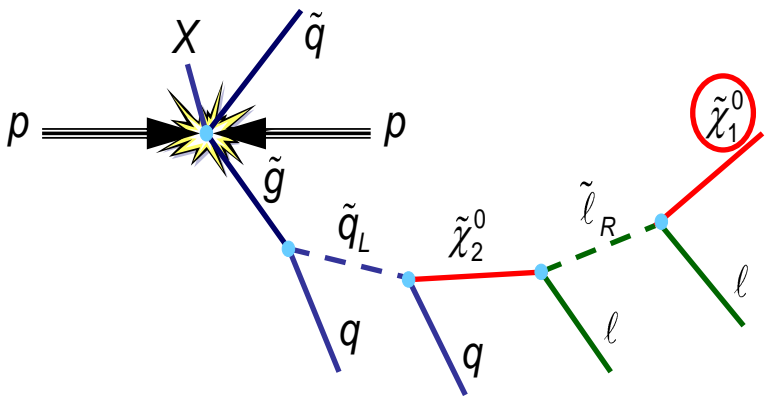
ATLAS-CONF-2014-010
 arXiv:1402.3244 (ATLAS)
 arXiv:1404.1344 (CMS)
 CMS-HIG-13-018
 CMS-HIG-13-028
 CMS-HIG-13-013



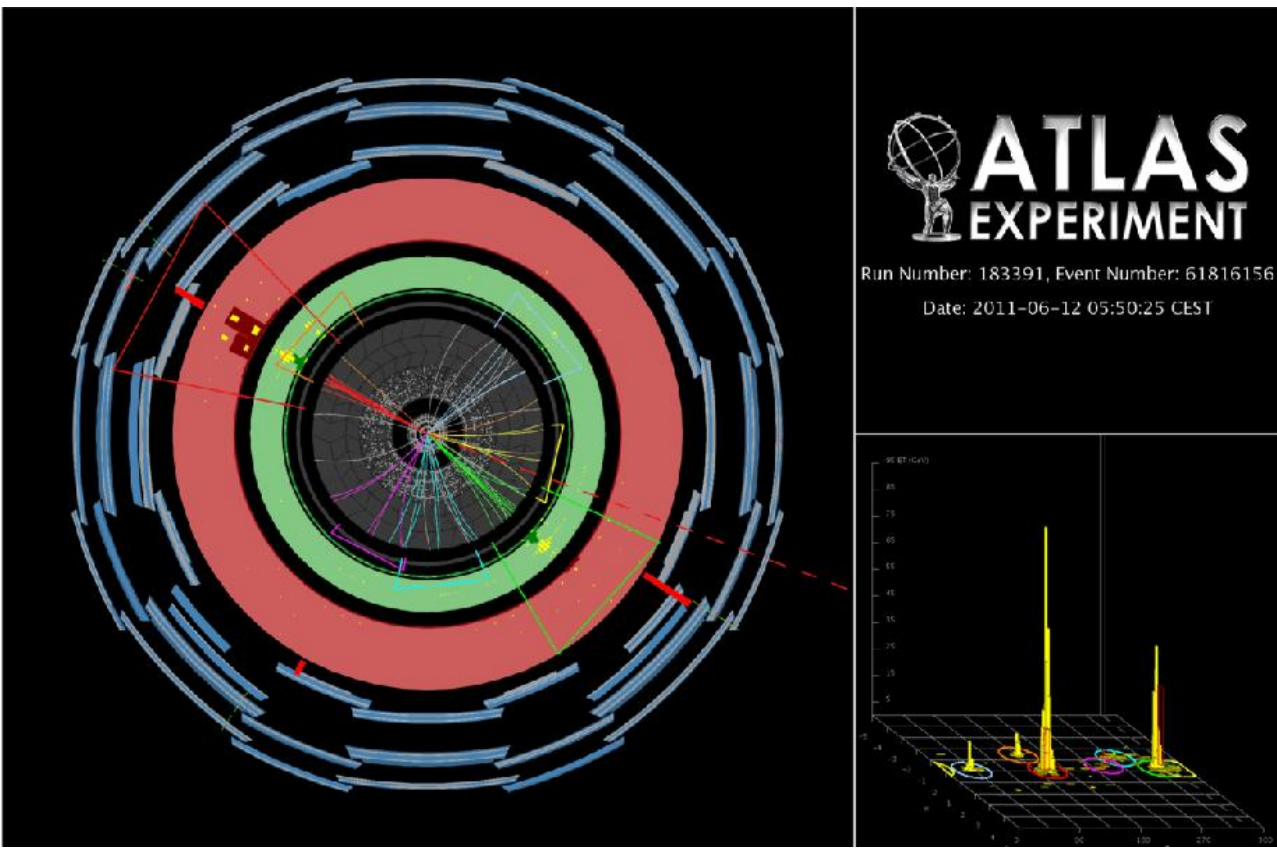


**AS
 MENT**
 number: 55091306
 42:26 CEST





- Viele Zerfallskaskaden wurden untersucht
- Bisher wurde kein signifikantes Signal von Supersymmetrie gefunden



- Ergebnis: gesuchte Teilchen müssen schwerer als etwa 1000 Protonmassen sein

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

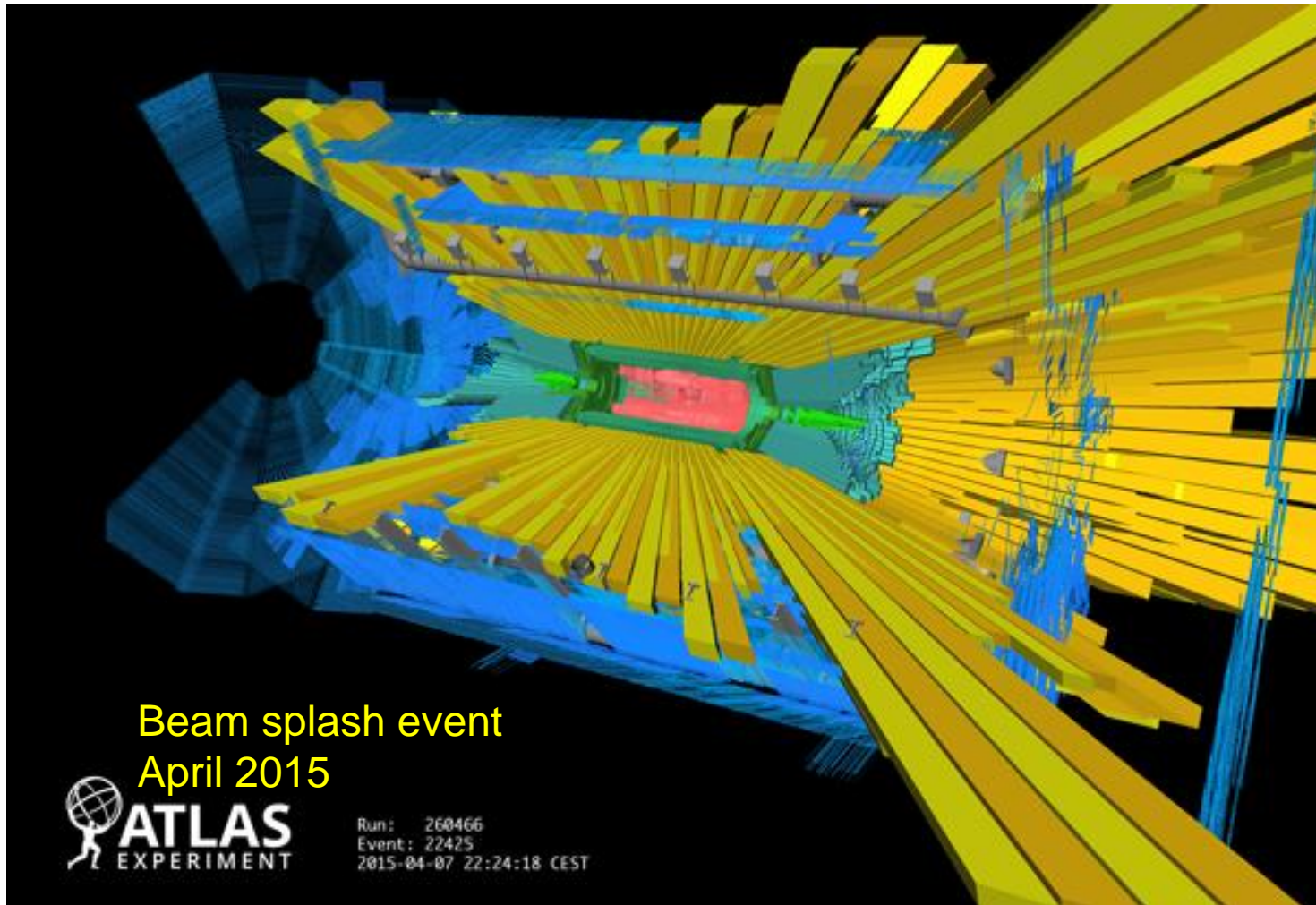
ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} d\mathcal{I} [\text{fb}^{-1}]$	Mass limit	Reference		
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_2^0$ 1.7 TeV	1405.7875	
	$\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_2^0$	0	2-6 jets	Yes	20.3	850 GeV	1405.7875	
	$\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_2^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	250 GeV	1411.1559	
	$\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_2^0$	0	2-6 jets	Yes	20.3	33 TeV	1405.7875	
	$\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 W^{\pm} \tilde{\nu}_\tau^{\pm}$	1 e, μ	3-6 jets	Yes	20	1.2 TeV	1501.03555	
	$\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_2^0 \ell \ell' (\ell' = \nu, \bar{\nu}) \tilde{\nu}_\tau^{\pm}$	2 e, μ	0-3 jets	-	20	32 TeV	1501.03555	
	GMSB (\tilde{t} NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	1.6 TeV	1407.0603	
	GGM (bino NLSP)	2 γ	-	Yes	20.3	1.8 TeV	ATLAS-CONF-2014-001	
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	619 GeV	ATLAS-CONF-2012-144	
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	900 GeV	1211.1167	
3 rd gen. \tilde{g} med.	$\tilde{g} \rightarrow b\bar{b}\tilde{t}_1^0$	0	3 b	Yes	20.1	1.5 TeV	1407.0600	
	$\tilde{g} \rightarrow t\bar{t}\tilde{t}_1^0$	0	7-10 jets	Yes	20.3	1.1 TeV	1308.1841	
	$\tilde{g} \rightarrow t\bar{t}\tilde{b}_1^0$	0-1 e, μ	3 b	Yes	20.1	34 TeV	1407.0600	
	$\tilde{g} \rightarrow b\bar{b}\tilde{t}_1^0$	0-1 e, μ	3 b	Yes	20.1	3 TeV	1407.0600	
	3 rd gen. squarks direct production	$\tilde{b}_1 \tilde{b}_1 \rightarrow b\bar{b}\tilde{t}_1^0$	0	2 b	Yes	20.1	100-620 GeV	1308.2631
		$\tilde{b}_1 \tilde{b}_1 \rightarrow b\bar{b}\tilde{t}_1^0$	2 e, μ (SS)	0-3 b	Yes	20.3	275-440 GeV	1404.2500
		$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$	1-2 e, μ	1-2 b	Yes	4.7	110-167 GeV	1209.2102, 1407.0583
		$\tilde{t}_1 \tilde{t}_1 \rightarrow W\tilde{b}_1^0$ or \tilde{t}_1^0	2 e, μ	0-2 jets	Yes	20.3	90-191 GeV	1403.4853, 1412.4742
		$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$	0-1 e, μ	1-2 b	Yes	20	215-530 GeV	1407.0583, 1406.1122
		$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$	0	mono-jet/c-tag	Yes	20.3	210-640 GeV	1407.0608
$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$		2 e, μ (Z)	1 b	Yes	20.3	90-240 GeV	1403.5222	
$\tilde{t}_1 \tilde{t}_1$ (natural GMSB)		2 e, μ (Z)	1 b	Yes	20.3	150-580 GeV	1403.5222	
$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0 + Z$		3 e, μ (Z)	1 b	Yes	20.3	290-600 GeV	1403.5222	
EW direct		$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$	2 e, μ	0	Yes	20.3	90-325 GeV	1403.5294
	$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$	2 e, μ	0	Yes	20.3	140-465 GeV	1403.5294	
	$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$	2 τ	-	Yes	20.3	100-350 GeV	1407.0350	
	$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$	3 e, μ	0	Yes	20.3	700 GeV	1402.7029	
	$\tilde{t}_1 \tilde{t}_1 \rightarrow W\tilde{b}_1^0 Z \tilde{\nu}_\tau^{\pm}$	2-3 e, μ	0-2 jets	Yes	20.3	420 GeV	1403.5294, 1402.7029	
	$\tilde{t}_1 \tilde{t}_1 \rightarrow W\tilde{b}_1^0 Z \tilde{\nu}_\tau^{\pm}$	e, μ, γ	0-2 b	Yes	20.3	250 GeV	1501.07110	
	$\tilde{t}_1 \tilde{t}_1 \rightarrow W\tilde{b}_1^0 Z \tilde{\nu}_\tau^{\pm}$	4 e, μ	0	Yes	20.3	620 GeV	1405.5086	
	Long-lived particles	Direct $\tilde{t}_1 \tilde{t}_1$ prod. long-lived \tilde{t}_1^0	Disapp. trk	1 jet	Yes	20.3	270 GeV	1310.3675
		Stable, stopped \tilde{t}_1 R-hadron	0	1-5 jets	Yes	27.9	832 GeV	1310.8584
		Stable \tilde{t}_1 R-hadron	grk	-	-	19.1	7 TeV	1411.6795
GMSB, stable $\tilde{t}_1, \tilde{t}_1^0 \rightarrow \tilde{t}_1 \tilde{t}_1 + (e, \mu)$		1-2 μ	-	-	19.1	537 GeV	1411.6795	
GMSB, $\tilde{t}_1^0 \rightarrow \gamma \tilde{t}_1$, long-lived \tilde{t}_1^0		2 γ	-	Yes	20.3	435 GeV	1409.5542	
$\tilde{\chi}_1^0, \tilde{t}_1^0 \rightarrow \tilde{g}\tilde{g}\tilde{\nu}_\tau$ (RPV)		1 μ , displ. vtx	-	-	20.3	1.0 TeV	ATLAS-CONF-2013-092	
RPV		LFV $\tilde{g}\tilde{g} \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 e, μ	-	-	4.6	1.61 TeV	1212.1272
		LFV $\tilde{g}\tilde{g} \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	1.1 TeV	1212.1272
		Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	35 TeV	1404.2500
		$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$	4 e, μ	-	Yes	20.3	750 GeV	1405.5086
	$\tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{t}_1^0$	3 $e, \mu + \tau$	-	Yes	20.3	450 GeV	1405.5086	
	$\tilde{g} \rightarrow q\bar{q}\tilde{g}$	0	6-7 jets	-	20.3	916 GeV	ATLAS-CONF-2013-091	
Other	$\tilde{g} \rightarrow t\bar{t}\tilde{t}_1^0$	2 e, μ (SS)	0-3 b	Yes	20.3	850 GeV	1404.250	
	Scalar charm, $\tilde{c} \rightarrow c\tilde{t}_1^0$	0	2 c	Yes	20.3	490 GeV	1501.01325	

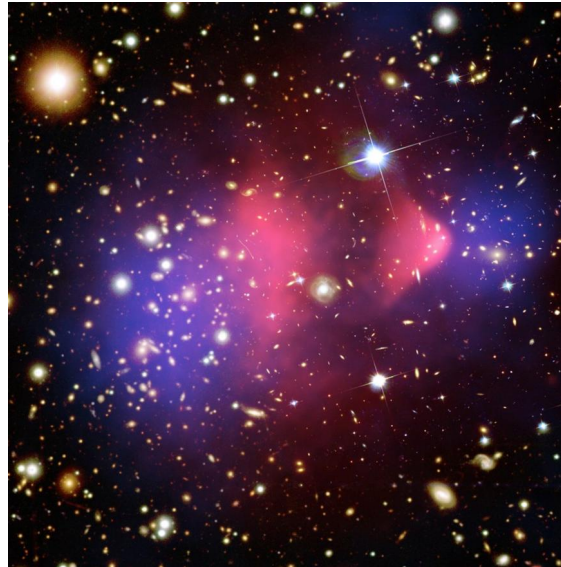
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

- LHC wurde vor 2 Wochen wieder gestartet mit doppelter Schwerpunktsenergie 13 TeV
- Teilchen mit größerer Masse können entdeckt werden

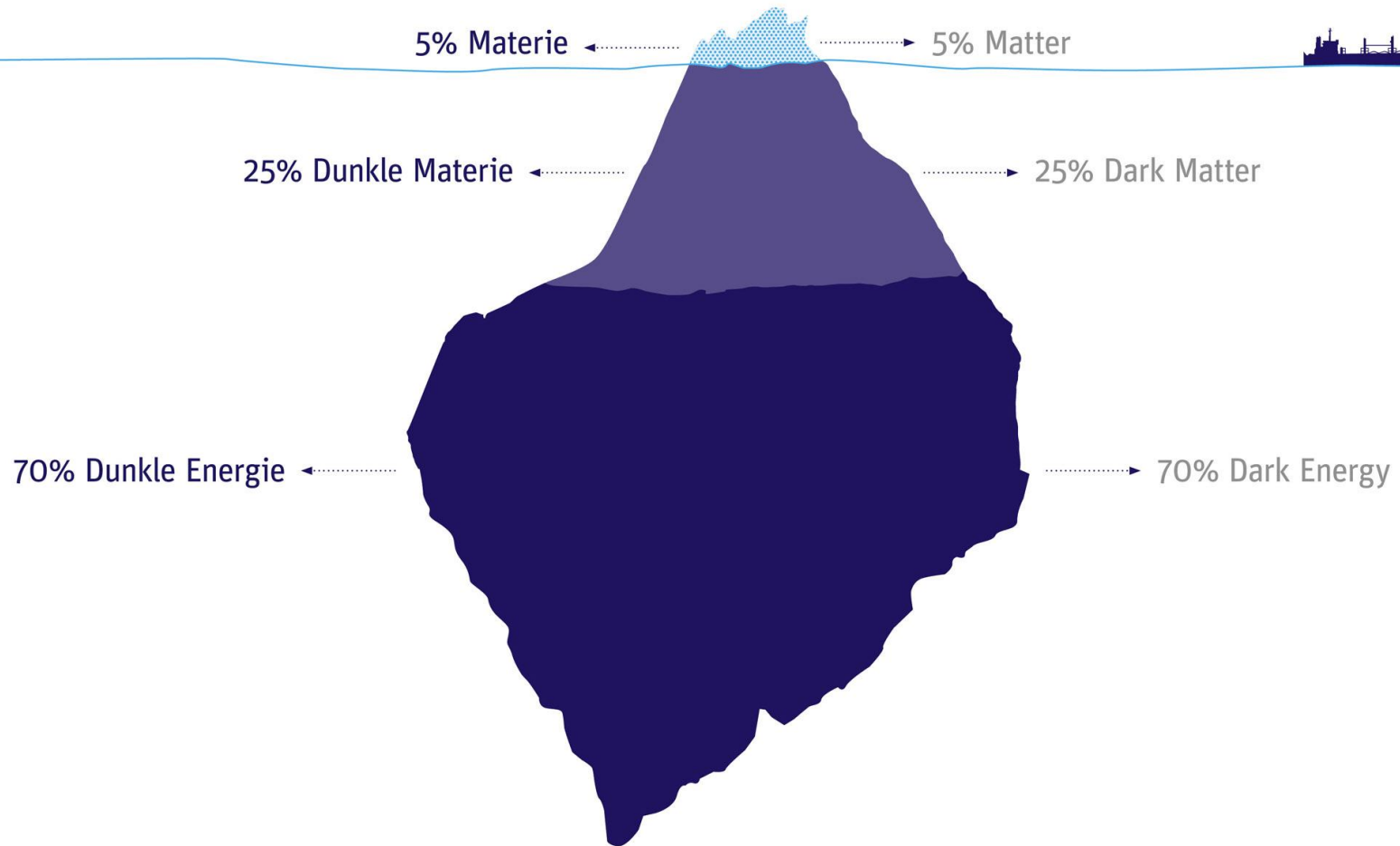


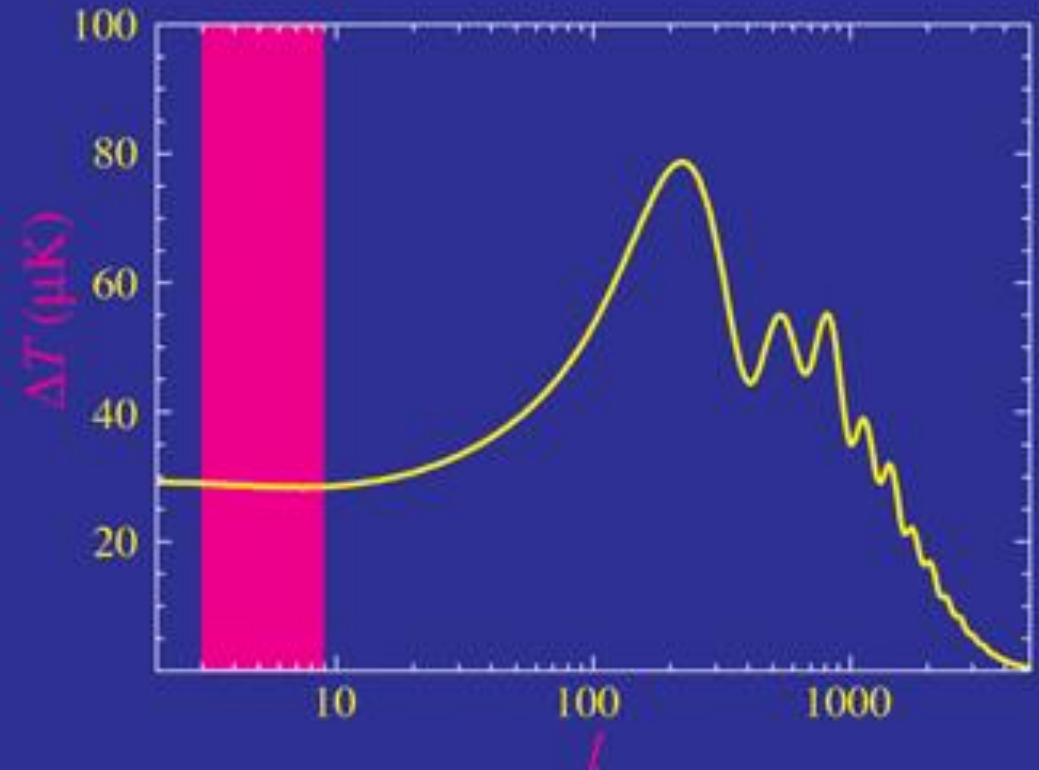
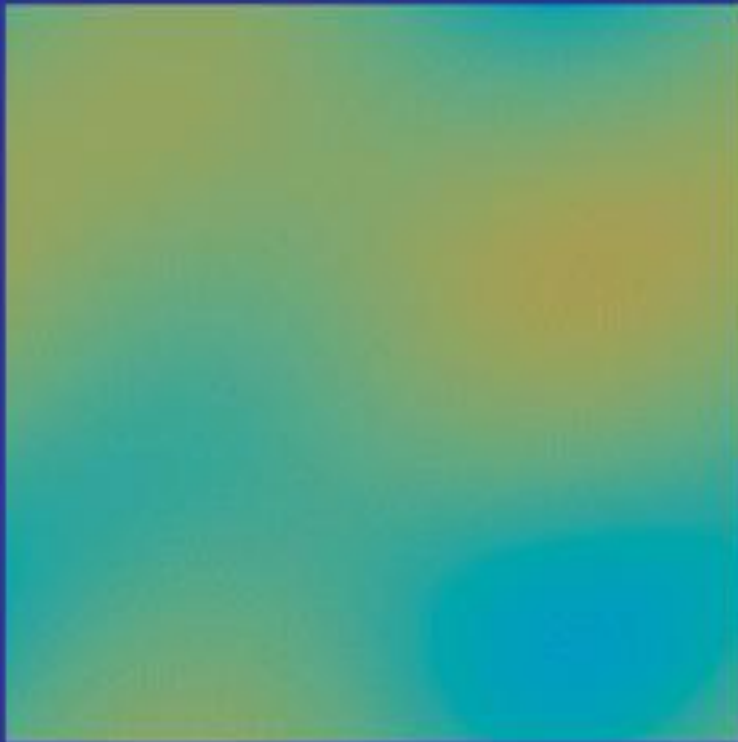
- Erste neue Ergebnisse werden in einigen Monaten erwartet

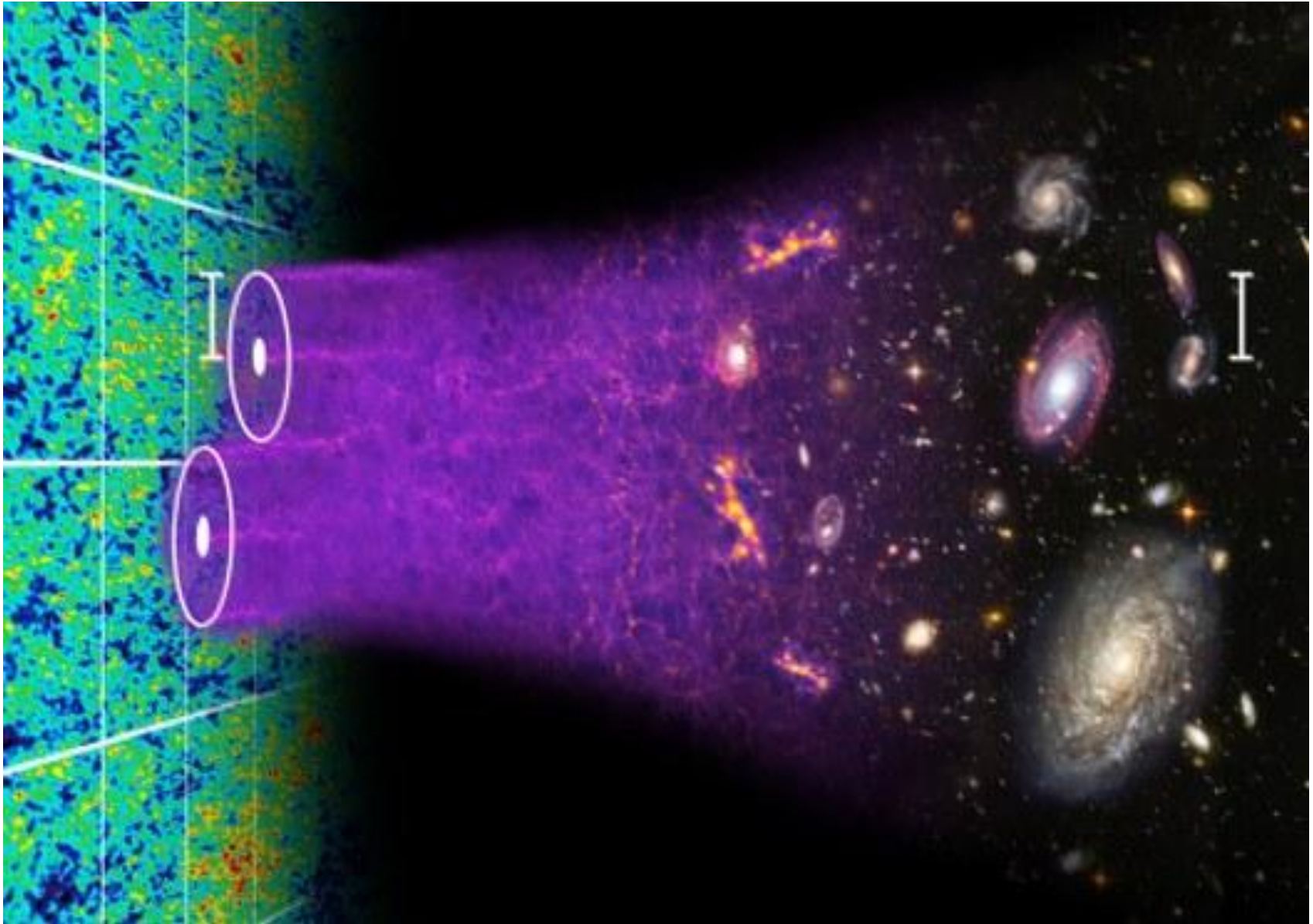
- Dunkle Materie wird im Universum mit vielen Methoden beobachtet



- Der Nachweis Dunkler Materie “im Labor” ist bisher nicht gelungen
- In den kommenden Jahren folgen viele weitere Experimente
 - mit massiveren Detektoren
 - mit besseren Teleskopen und satellitengestützten Beobachtungen
 - mit Beschleunigern bei höherer Energie

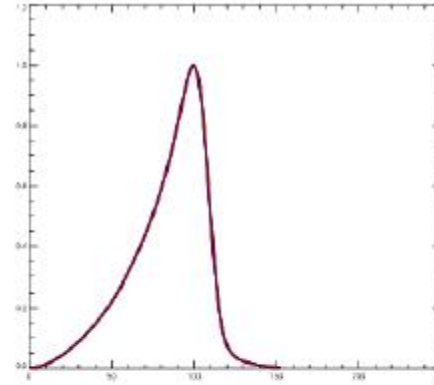
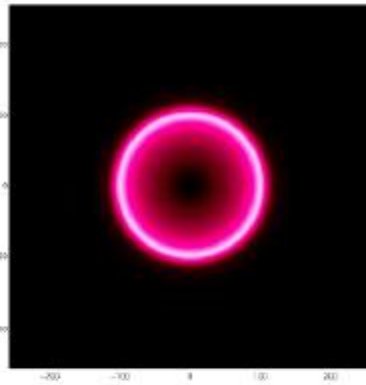
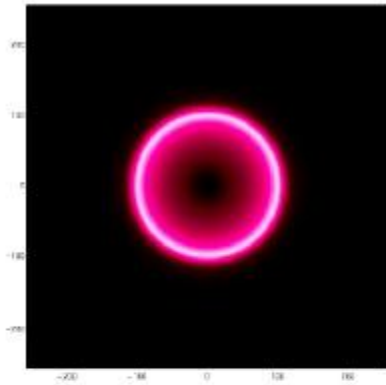




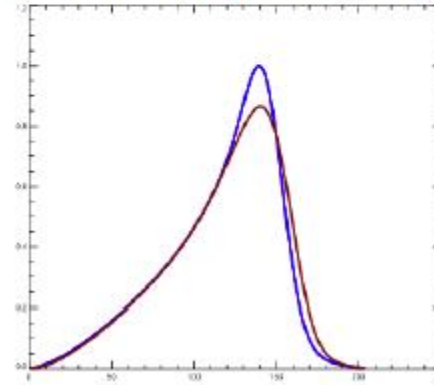
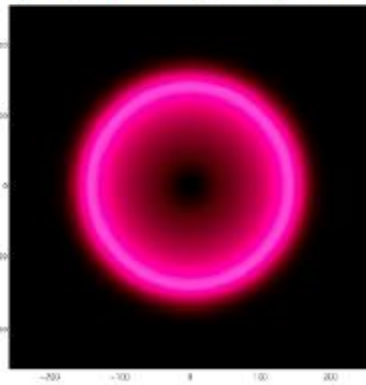
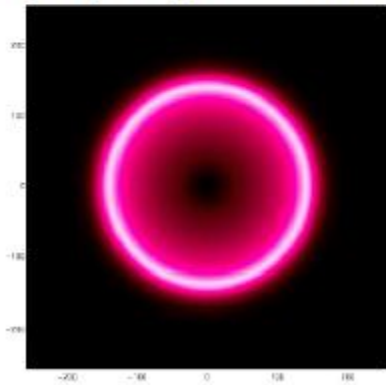


Baryondichte

Photondichte



After 10^5 years the universe has cooled enough the protons capture the electrons to form neutral Hydrogen. This decouples the photons from the baryons. The former quickly stream away, leaving the baryon peak stalled.

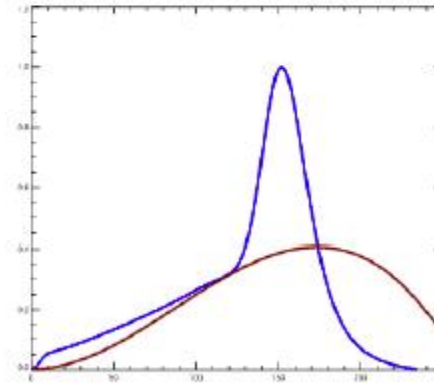
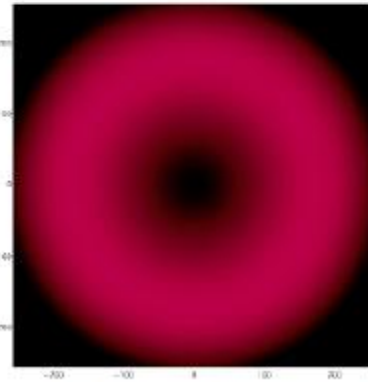
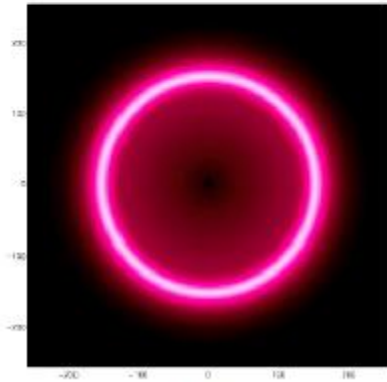
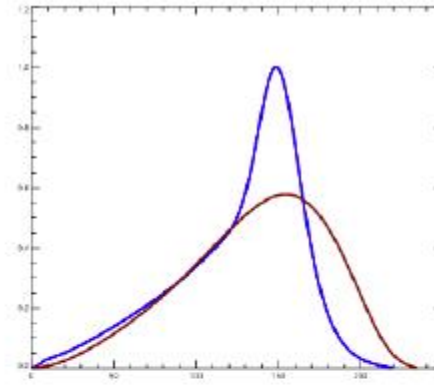
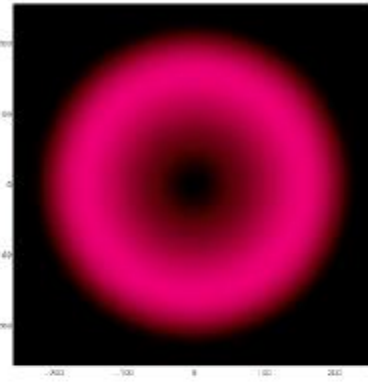
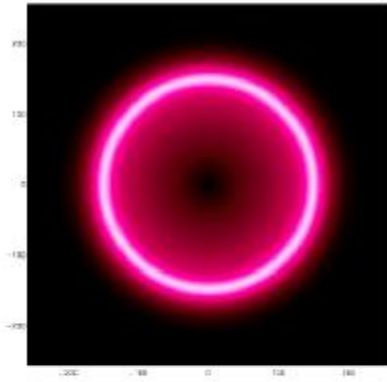


while the baryons, having lost their motive pressure, remain in place

The photons continue to stream away

Baryondichte

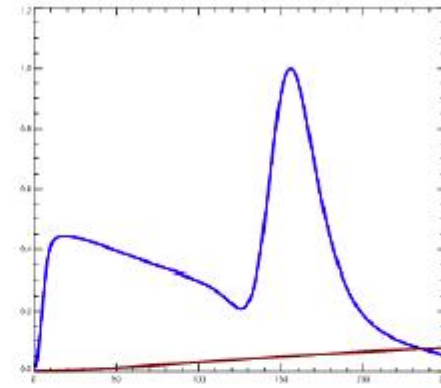
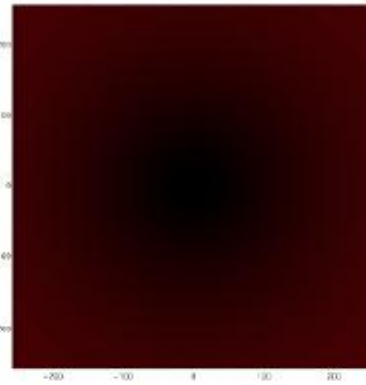
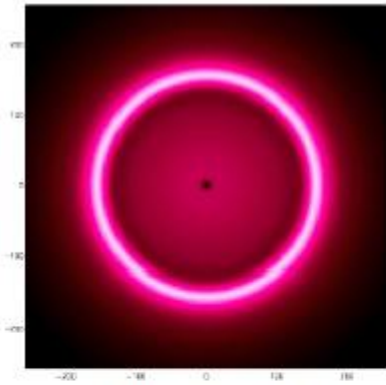
Photondichte



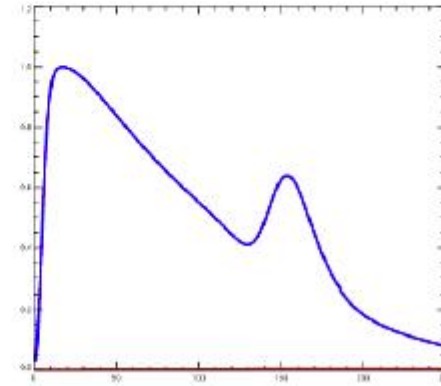
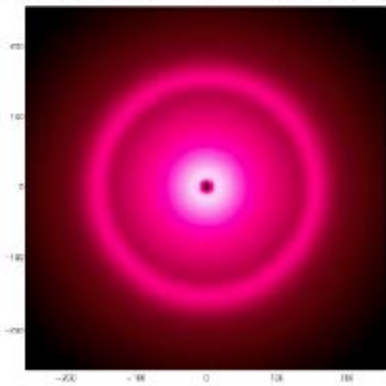
The photons have become almost completely uniform, but the baryons remain overdense in a shell 100Mpc in radius. In addition, the large gravitational potential well which we started with starts to draw material back into it.

Baryondichte

Photondichte

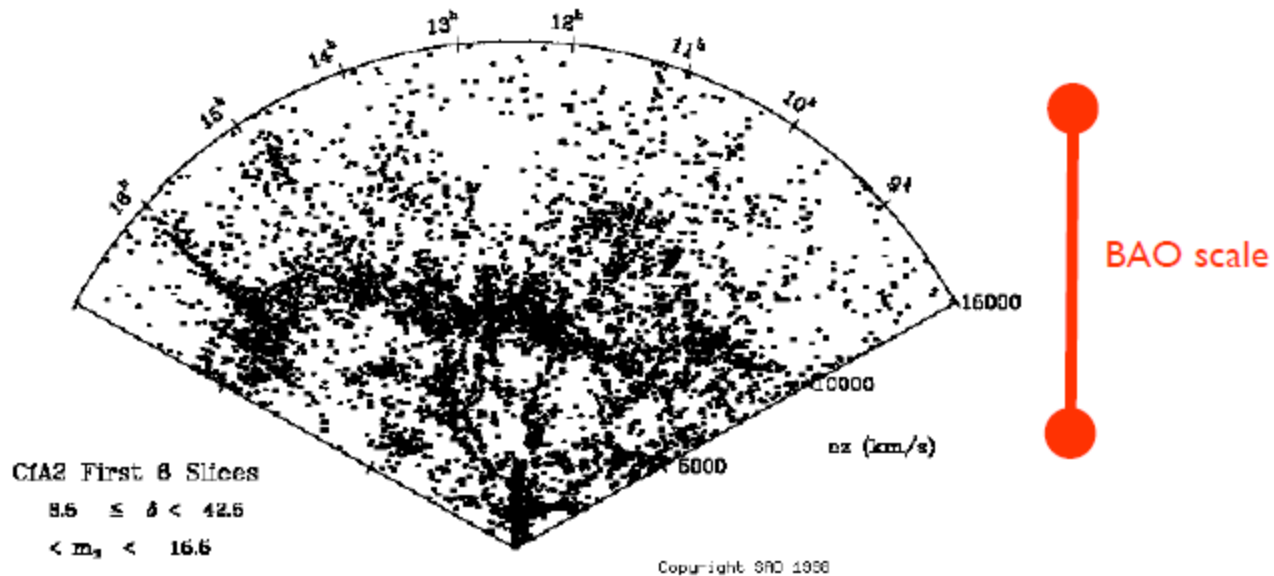


As the perturbation grows by $O(1000)$ the baryons and DM reach equilibrium densities in the ratio W_b/W_m . The final configuration is our original peak at the center (which we put in by hand) and an echo in a shell roughly 100Mpc in radius. The radius of this shell is known as the sound horizon.

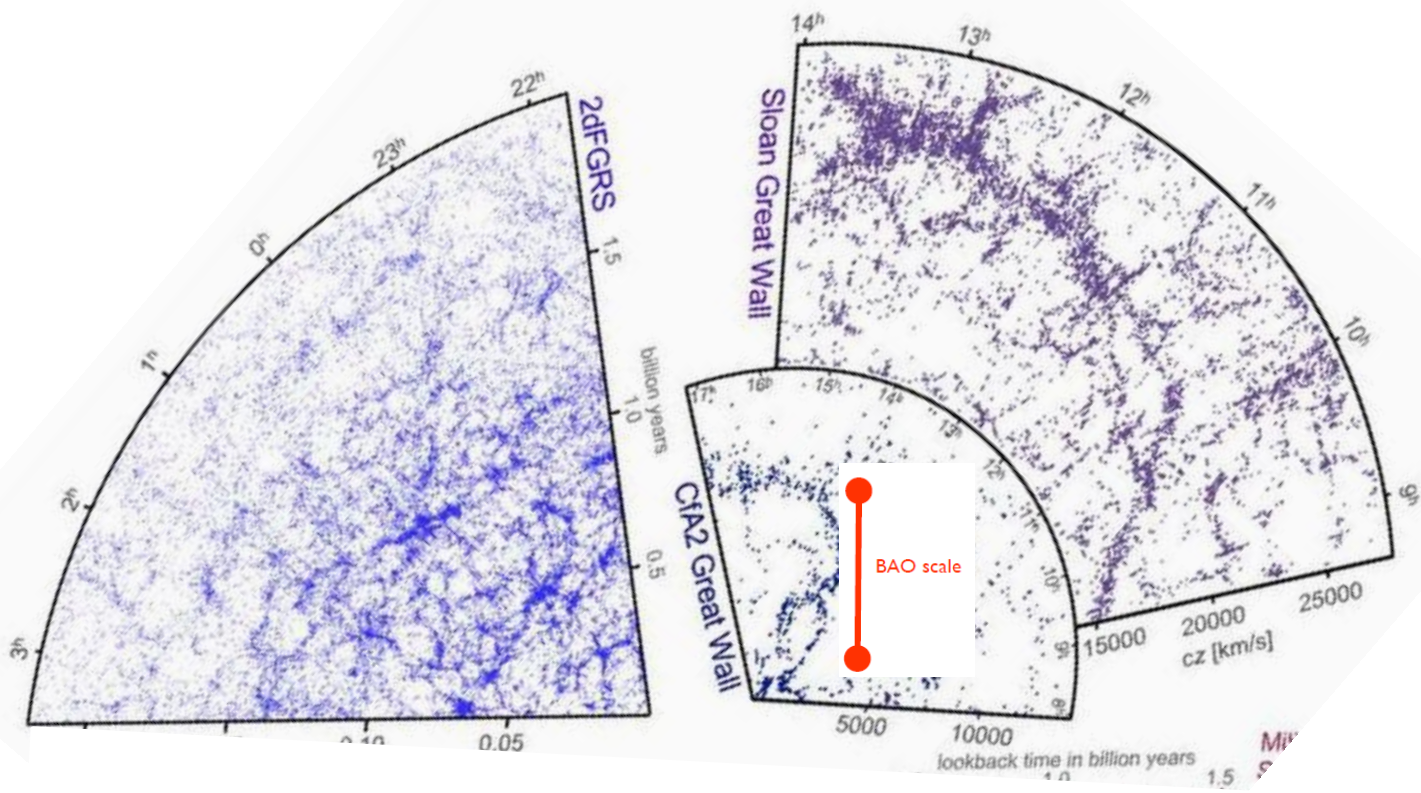


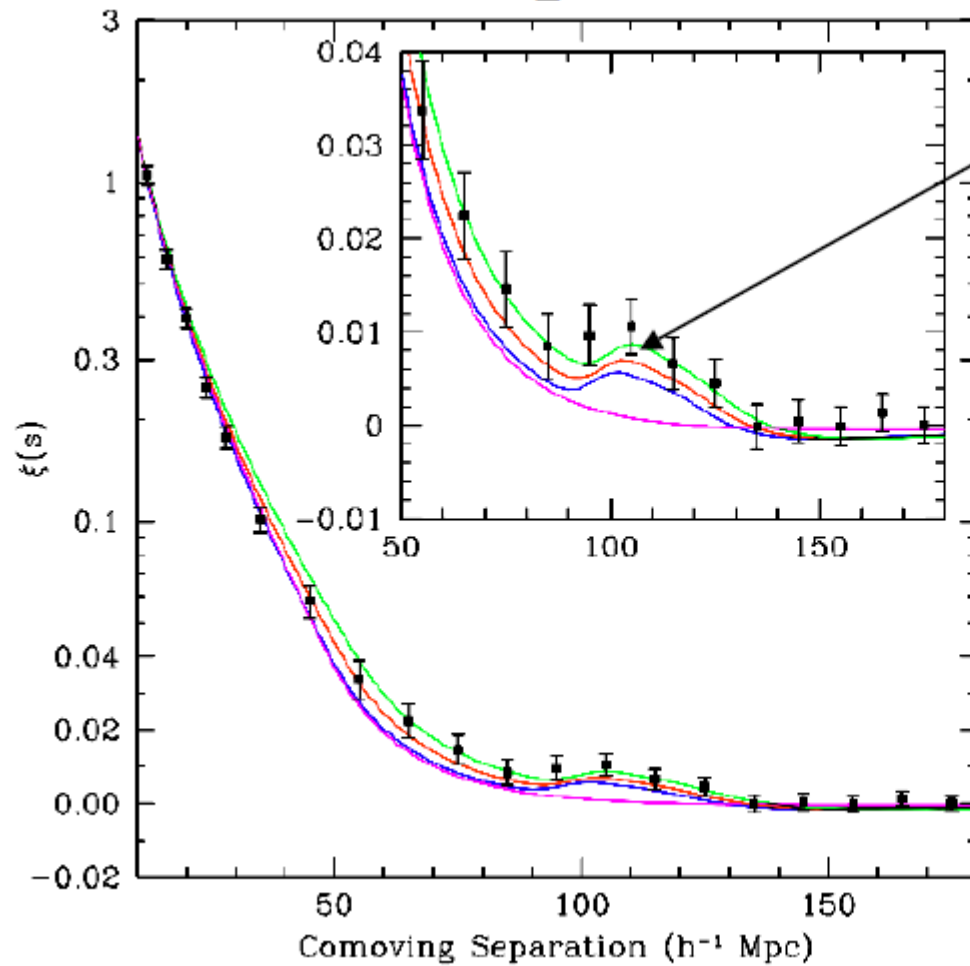
→ **Baryon-Akustische Oszillationen**

Early surveys too small



CfA2 redshift survey (Geller & Huchra 1989)
 Formally, this could “measure” BAO with a $\sim 0.05\sigma$ detection



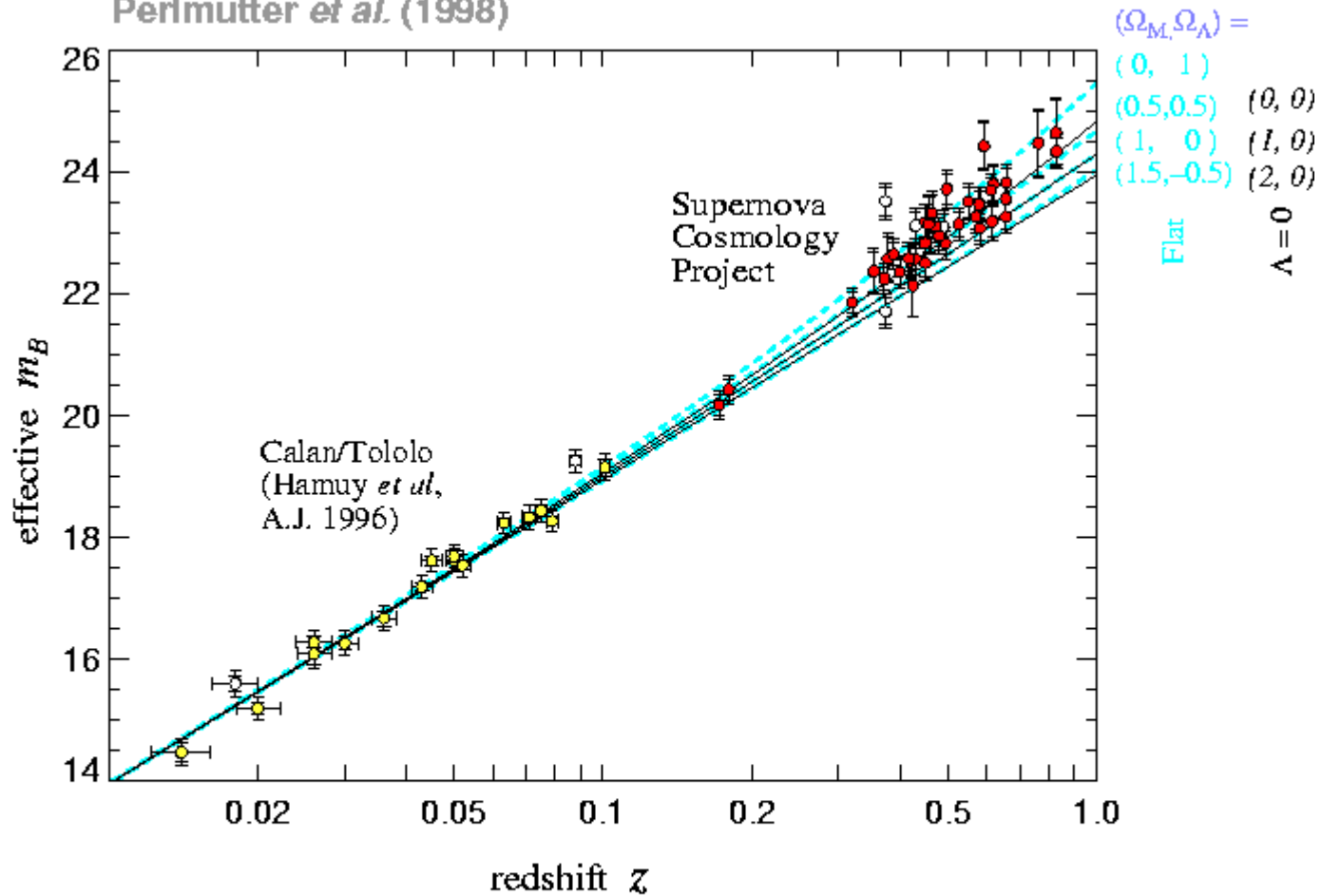


Eisenstein et al. (2005)
 detect oscillations in
 the SDSS LRG $\xi(r)$ at
 $z \sim 0.35$! Knowing s
 determines $D(z=0.35)$.

About 10% of the way
 to the surface of last
 scattering!

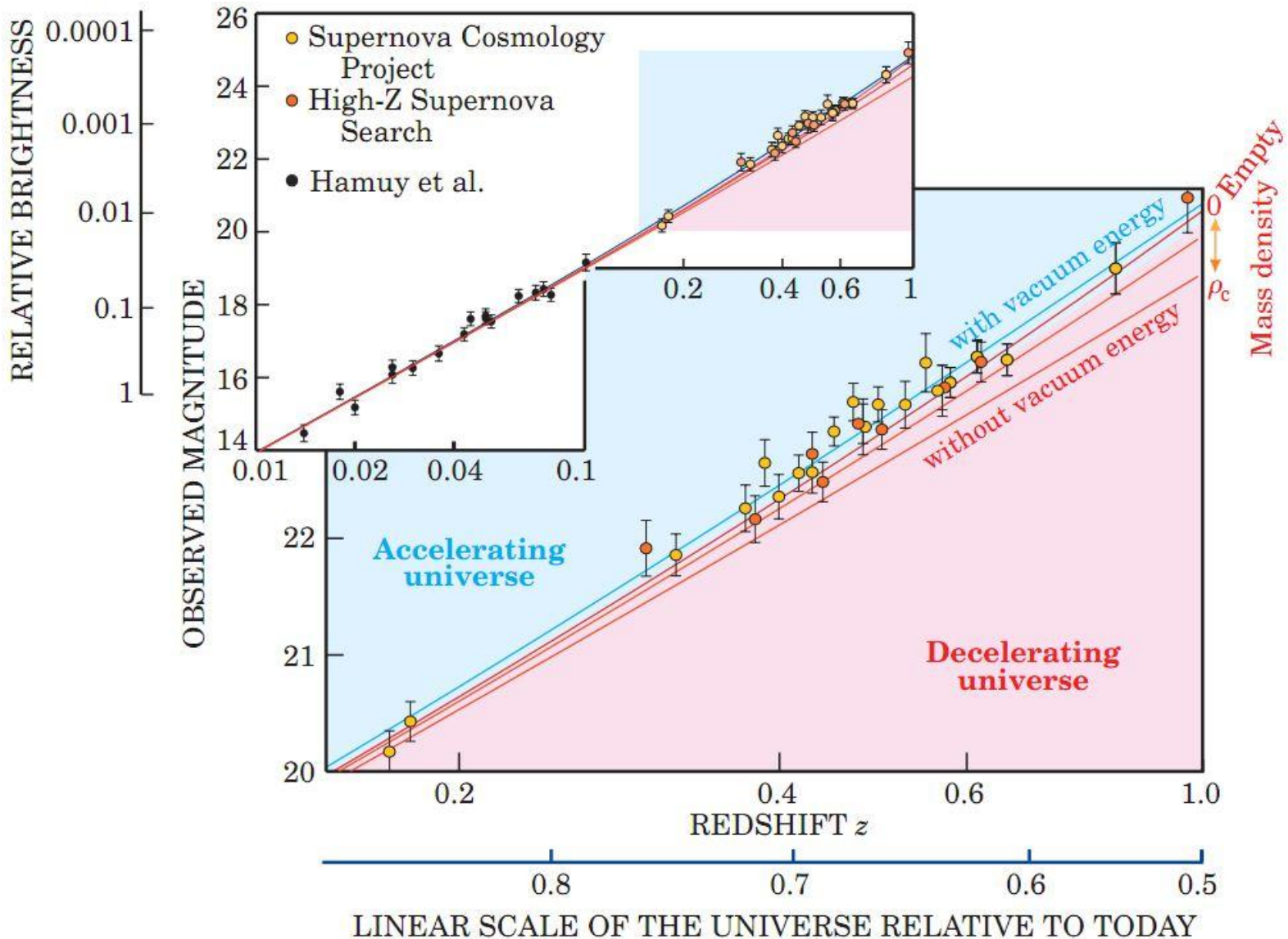
Constraints argue for
 the existence of DE, but
 do not strongly
 constrain its properties.

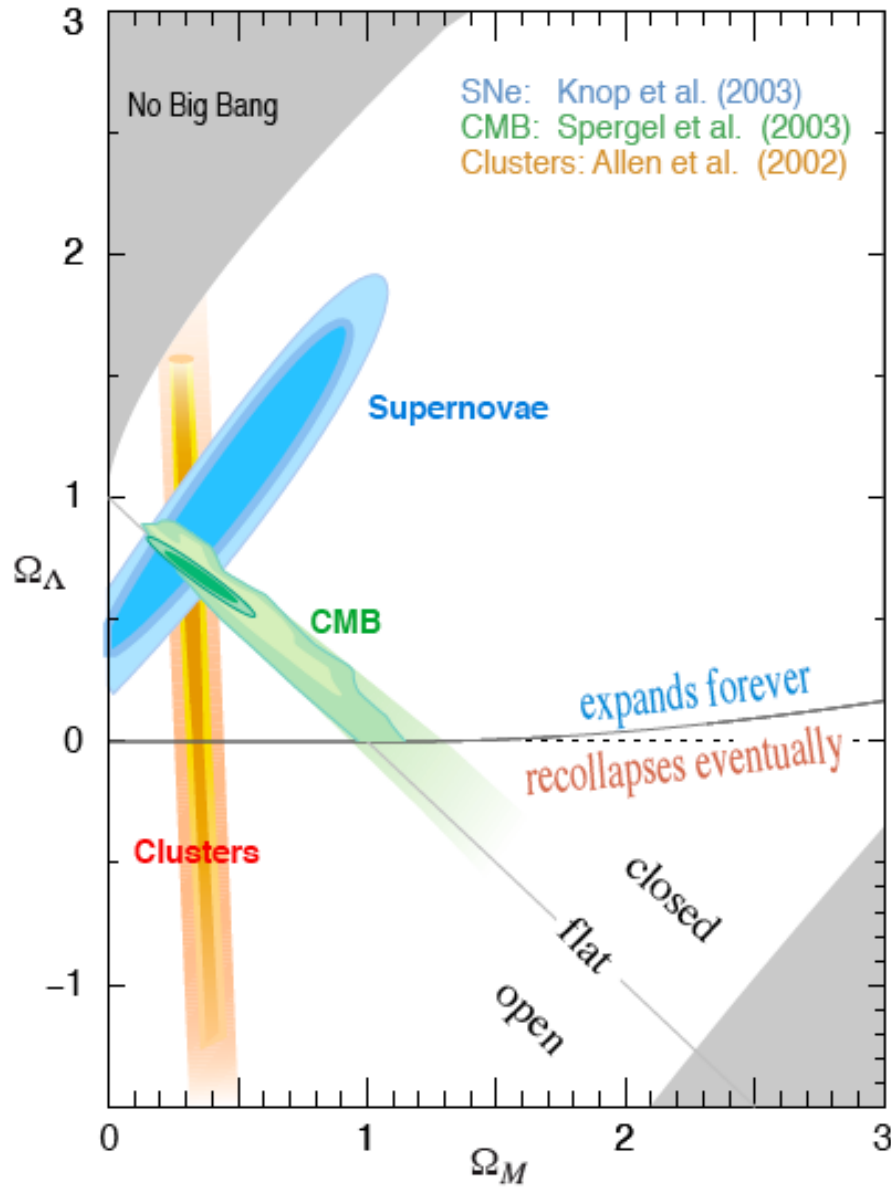
Supernova Cosmology Project Perlmutter *et al.* (1998)

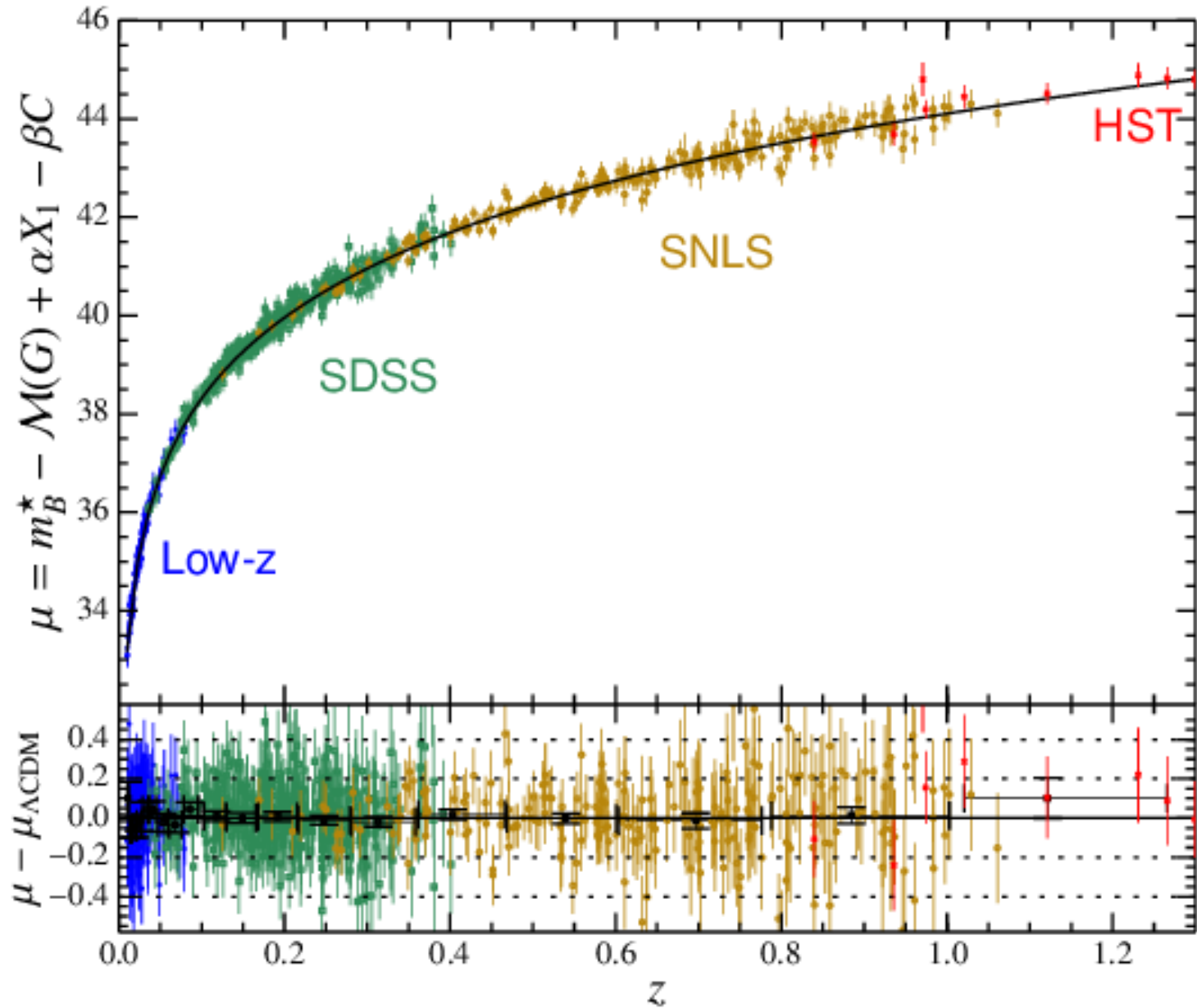


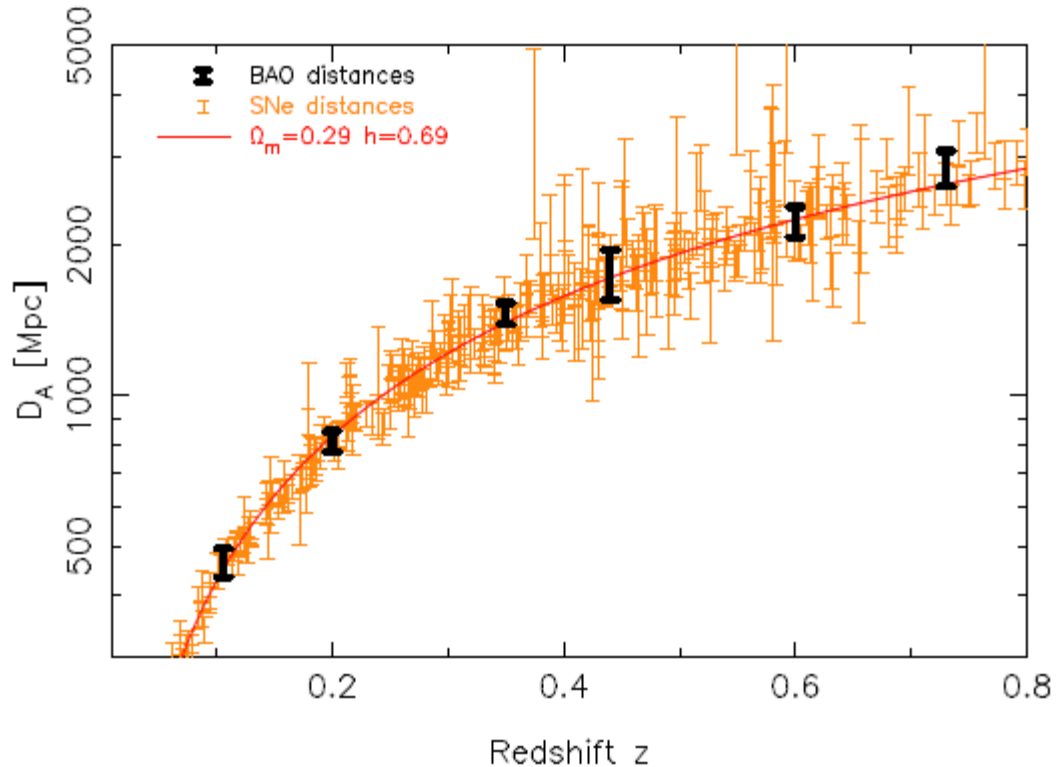
In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe: 1%



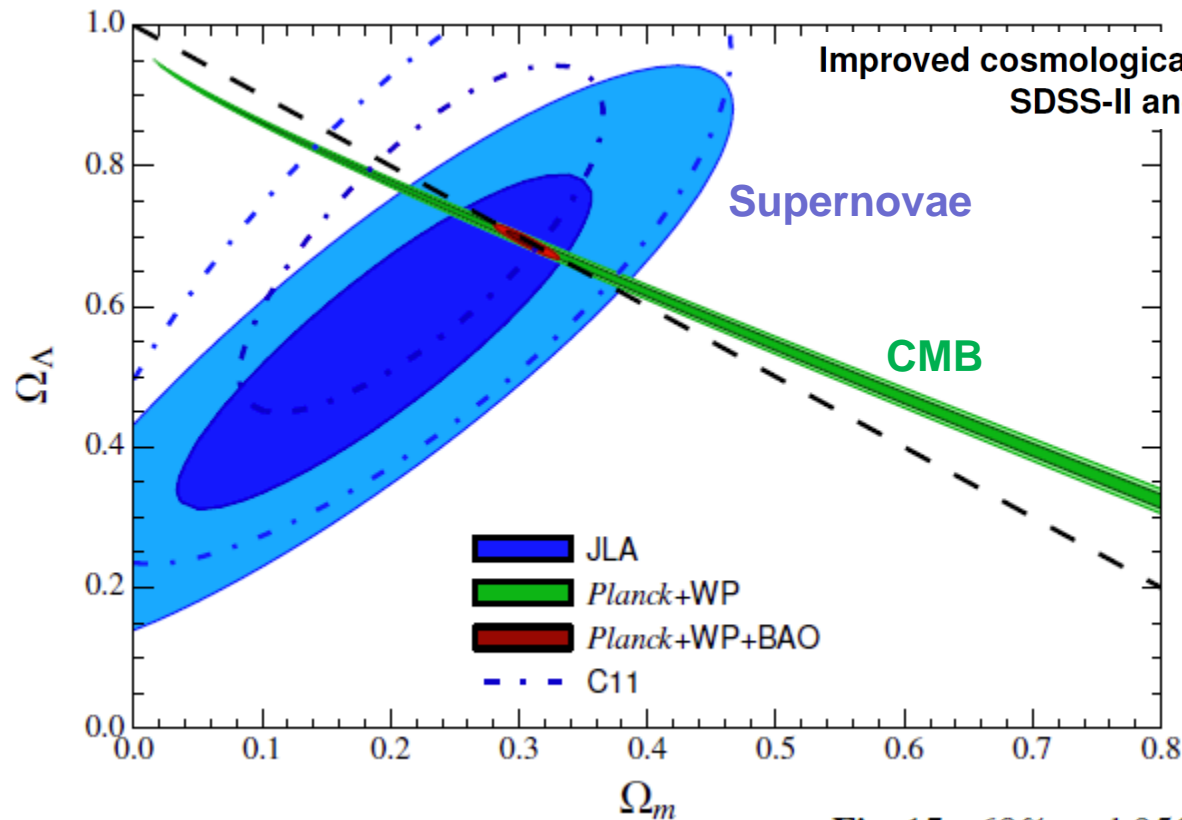






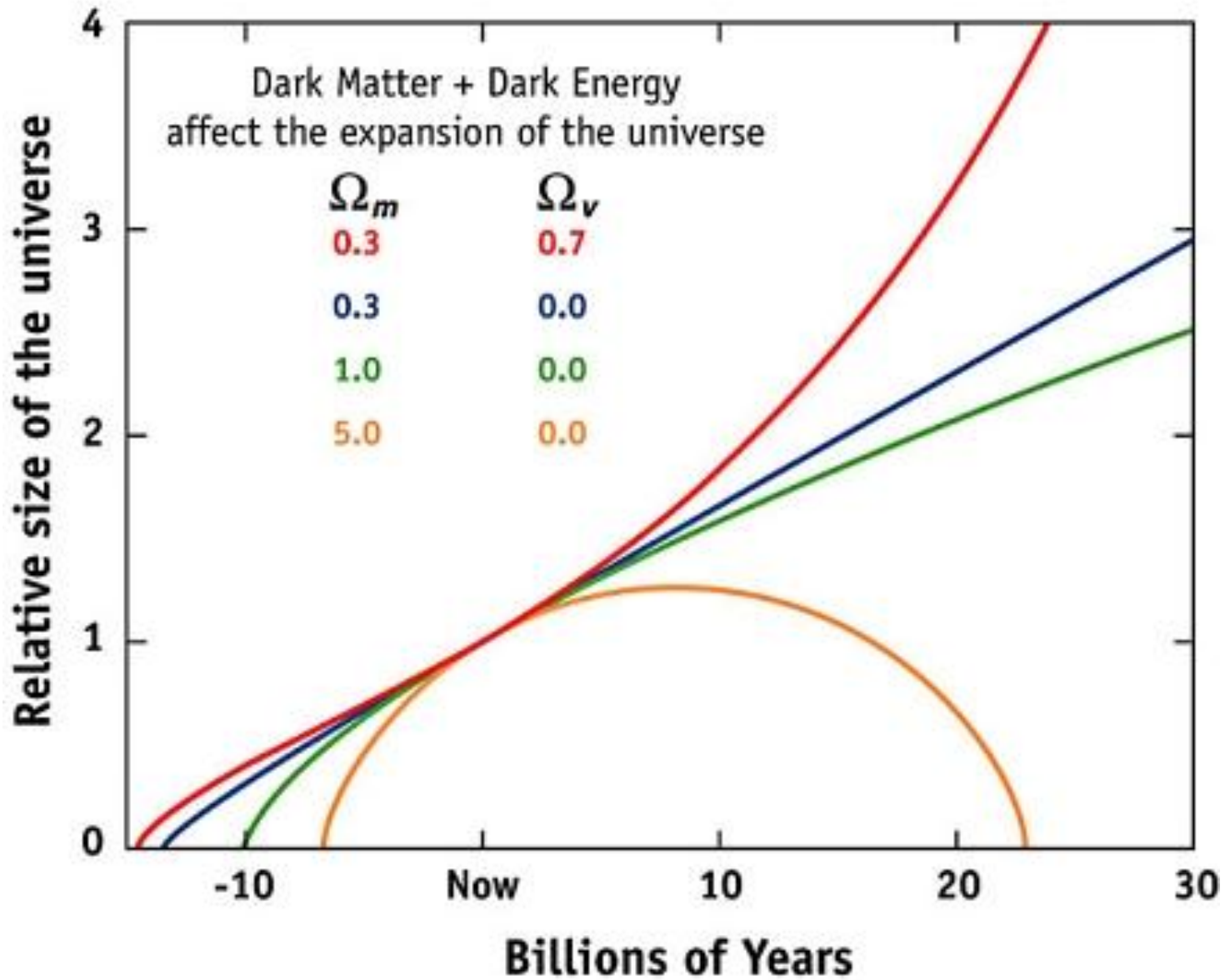
arXiv:1108.2635v1

Figure 12. Comparison of the accuracy with which supernovae and baryon acoustic oscillations map out the cosmic distance scale at $z < 0.8$. For the purposes of this Figure, BAO measurements of $D_V(z)$ have been converted into $D_A(z)$ assuming a Hubble parameter $H(z)$ for a flat Λ CDM model with $\Omega_m = 0.29$ and $h = 0.69$, indicated by the solid line in the Figure, and SNe measurements of $D_L(z)$ have been plotted assuming $D_A(z) = D_L(z)/(1+z)^2$.

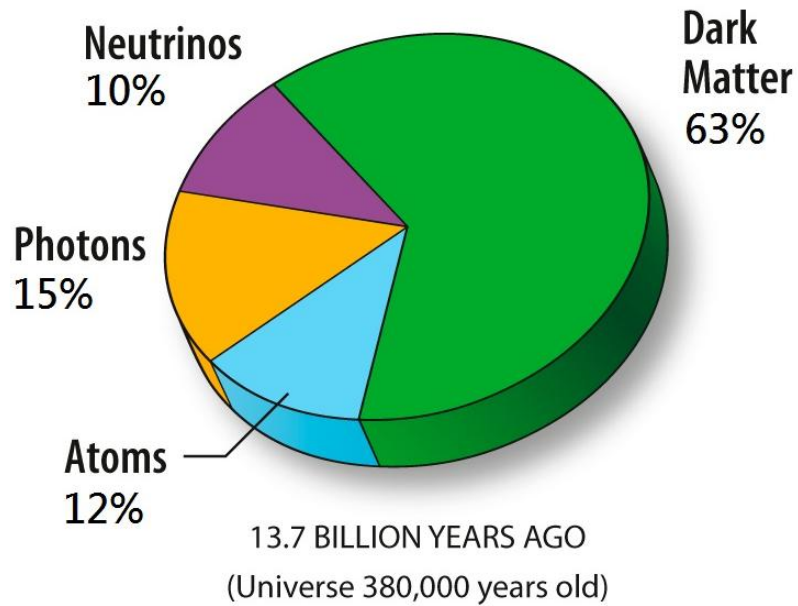


arXiv:1401.4064v2

Fig. 15. 68% and 95% confidence contours (including systematic uncertainty) for the Ω_m and Ω_Λ cosmological parameters for the Λ -CDM model. Labels for the various data sets correspond to the present SN Ia compilation (JLA), the Conley et al. (2011) SN Ia compilation (C11), the combination of *Planck* temperature and *WMAP* polarization measurements of the CMB fluctuation (*Planck*+WP), and a combination of measurements of the BAO scale (BAO). See Sect. 7.1 for details. The black dashed line corresponds to a flat universe.



Zum Zeitpunkt der Entstehung der kosmischen Hintergrundstrahlung:



Heute:

