Cosmology and Particle Physics

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Lecture I: The average Universe
→ Lecture II: Origins
Lecture III: The perturbed Universe

9th CLASHEP
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Plan:

II.1 – Origin of light elements

II.2 – Origin of baryons

II.3 – Origin of dark matter

II.4 – Origin of inhomogeneities

II.1- Origin of light elements

Big Bang Nucleosynthesis (BBN): one of the pillars of the Standard Cosmological Model [review 1505.01076]

- the earliest cosmological probe (~ few minutes)

- idea goes back to George Gamow and students (late 1940's)

- details involve a complicated set of nuclear reactions which can be studied with sophisticated codes

- here will present a very simplified picture of BBN

BBN in four easy time steps

a. When T>>1 MeV (t<<1 s): Universe made out of n, p, e, ν, γ
Neutrons and protons in thermal equilibrium due to the weak force

When T~ few MeV, protons and neutrons are non-relativistic with

$$\frac{n_n}{n_p} = e^{-(m_n - m_p)/T} = e^{-Q/T}$$

Notice that the neutron-proton mass difference (Q~ 1.3 MeV) is very small compared to their masses (m_n~m_p~ 1 GeV).

b. Neutrons and protons freeze out at T=0.8 MeV; their number remain constant aftwerwards (number densities ~ a^{-3}). Neutron fraction becomes:

$$X_n^{\text{f.o.}} = \frac{n_n}{n_n + n_p} = \frac{e^{-Q/T}}{1 + e^{-Q/T}}\bigg|_{T=0.8\text{MeV}} \simeq \frac{1}{6}$$

c. This number is almost frozen except for the fact that free neutrons decay with a lifetime τ_n~900 s. Hence, after freeze-out

$$X_n(t) = e^{-t/\tau} X_n^{\text{f.o.}}$$

d. Formation of helium:

$$n + p \leftrightarrow D + \gamma$$

$$D + p \leftrightarrow^3 He + \gamma$$

$$D +^3 He \leftrightarrow^4 He + p$$

^{4}He can only form when D and ^{3}He can be present – temperature must be smaller than D binding energy – T_D~ 0.06 MeV (t_D ~ 330 s)

X_n(330 s) ~ 1/8

At this point it is a good approximation to assme that all neutrons are used to make ^{4}He.

Exercise 1: show that the mass fraction in ^{4}He is:

$$Y_{He} = \frac{4n_{He}}{n_p} \sim \frac{1}{4}$$

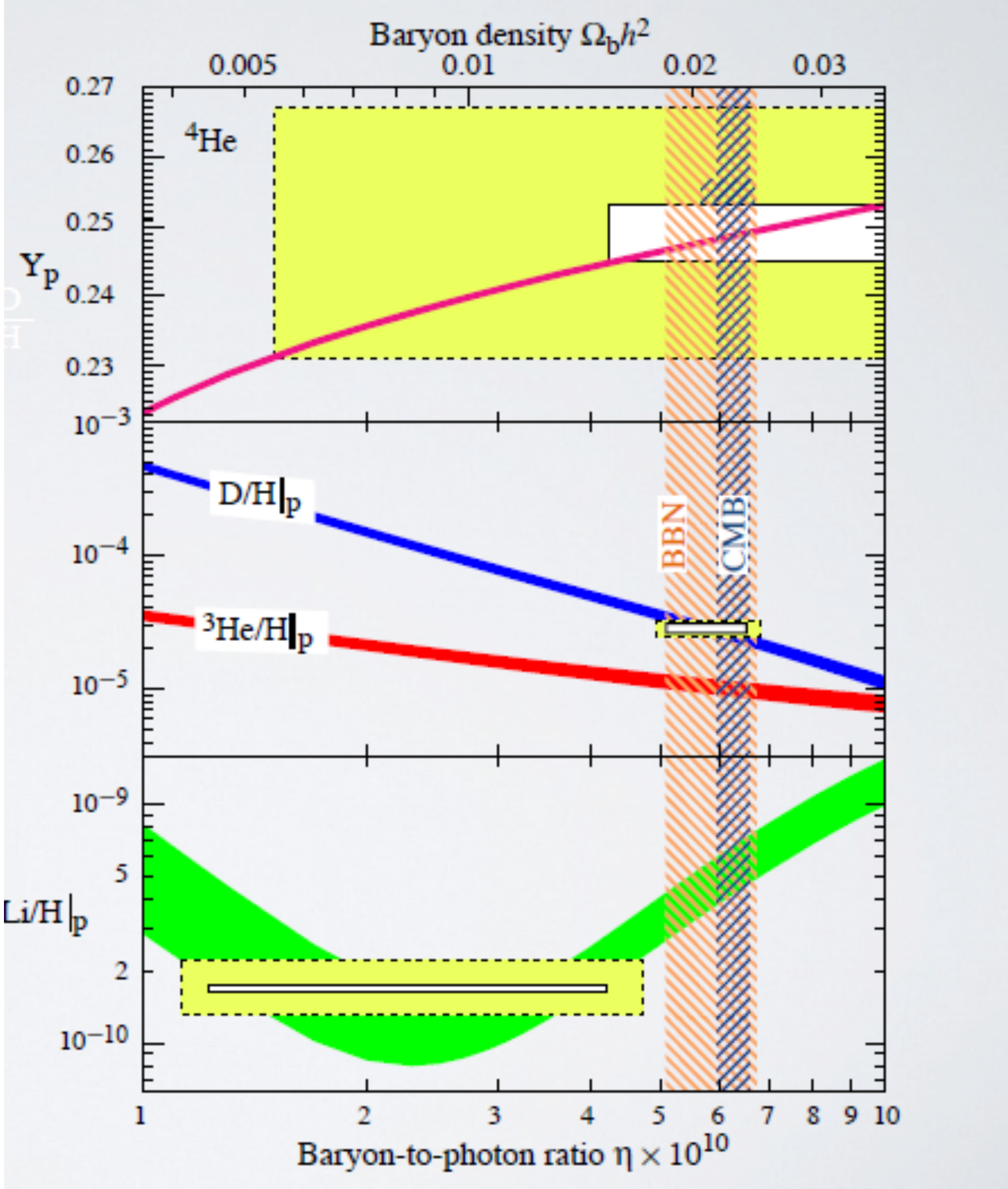
After the first 3 minutes of the Universe ~ 25% of the mass of atoms are in the form of ^{4}He. There are also small quantites of D, ^{3}He, and ^{6}Li.

These difficult measurements determine the number of baryons and the number of neutrinos in the Universe.
Good agreement with other probes (such as CMB)

Baryon-to-photon ratio:

$$\eta = \frac{n_b}{n_\gamma} = (6.10 \pm 0.04) \times 10^{-10} \qquad \text{(Planck)}$$

Deuterium abundance is very sensitive to η.



Baryon density $\Omega_b h^2$
0.005
0.01
0.02
0.03
0.27
0.26
0.25
0.24
0.23
^{4}He
Y_p
10^{-3}
10^{-4}
10^{-5}
D/H|p
^{3}He/H|p
BBN
CMB
10^{-9}
5
2
10^{-10}
Li/H|p
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio $\eta \times 10^{10}$

II.2- Origin of baryons

A very disturbing calculation for baryogenesis

Let’s estimate the freeze-out of baryons assuming a typical baryonic cross section:

$$\langle \sigma v \rangle = \frac{1}{m_\pi^2}; \ m_\pi \sim 100 \text{ MeV}$$

Freeze-out temperature: $n(T_F)\langle \sigma v \rangle = H(T_F)$

Exercise 2: show that the freeze-out temperature is given by:

$$\frac{m_N}{T_F} \simeq \ln \frac{m_N M_{\rm Pl}}{m_\pi^2} \simeq 50$$

Why is this disturbing? Because the resulting η is:

$$\eta = \left(\frac{m_N}{T_F}\right)^{3/2} e^{-m_N/T} \sim 10^{-19}!!$$

The Universe can not be baryon-antibaryon symmetric: there must exist a mechanism to create a tiny asymmetry (1 in 10^9 is enough).

How can one generate this asymmetry?

Sakharov conditions (1967!):
- baryon number violation
- C and CP violation
- Non-equilibrium process

There is no standard model of baryogenesis:
GUT’s, leptogenesis, SM

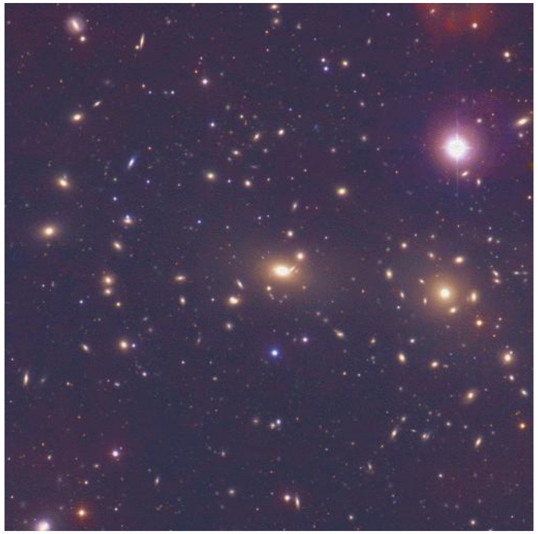
Motivates searches for new sources of CP violation (eg, LHCb, neutrino sector).

II.3- Origin of dark matter

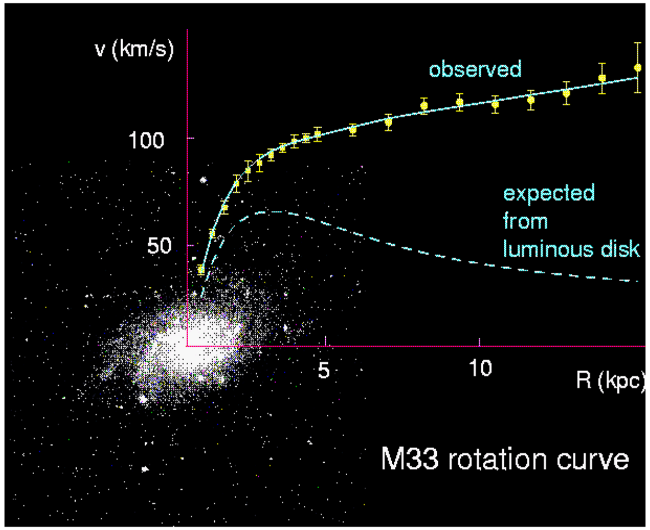
II.3.I – Observational evidences

Dark matter exists – Ω_{DM}~0.25.
Evidences from many different observations at different scales – all astronomical so far!

Dispersion velocity of galaxies in clusters (30's)

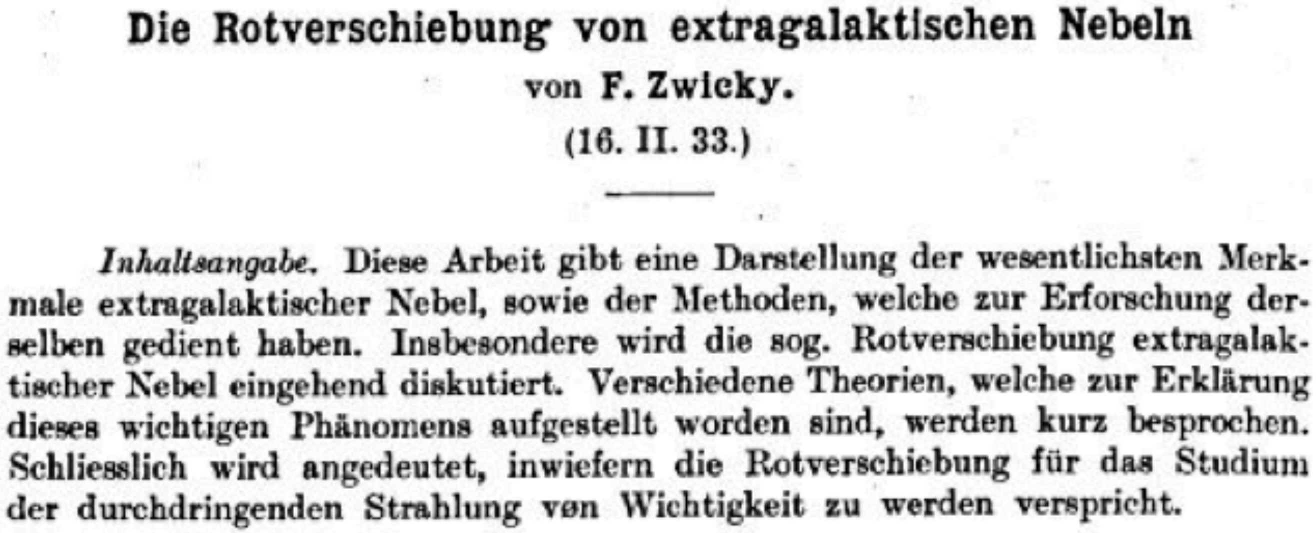


Galaxy rotation curves (70's)



Gravitational lensing

The DARK MATTER problem has been with us since the 1930's, name coined by Fritz Swicky in Helvetica Physica Acta Vol6 p.110-127, 1933



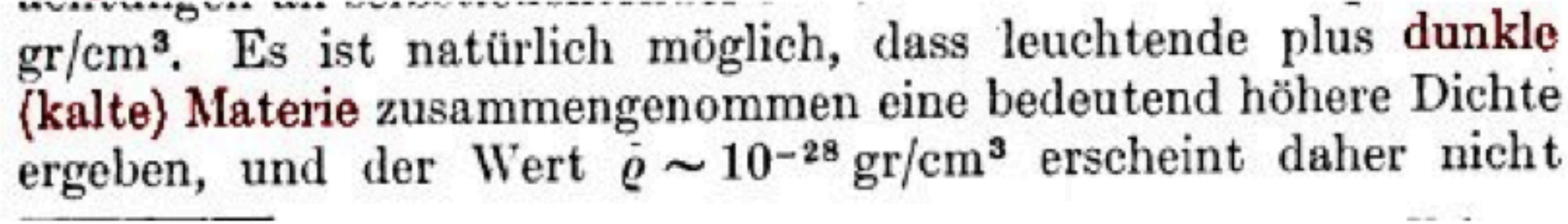
Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

On page 122

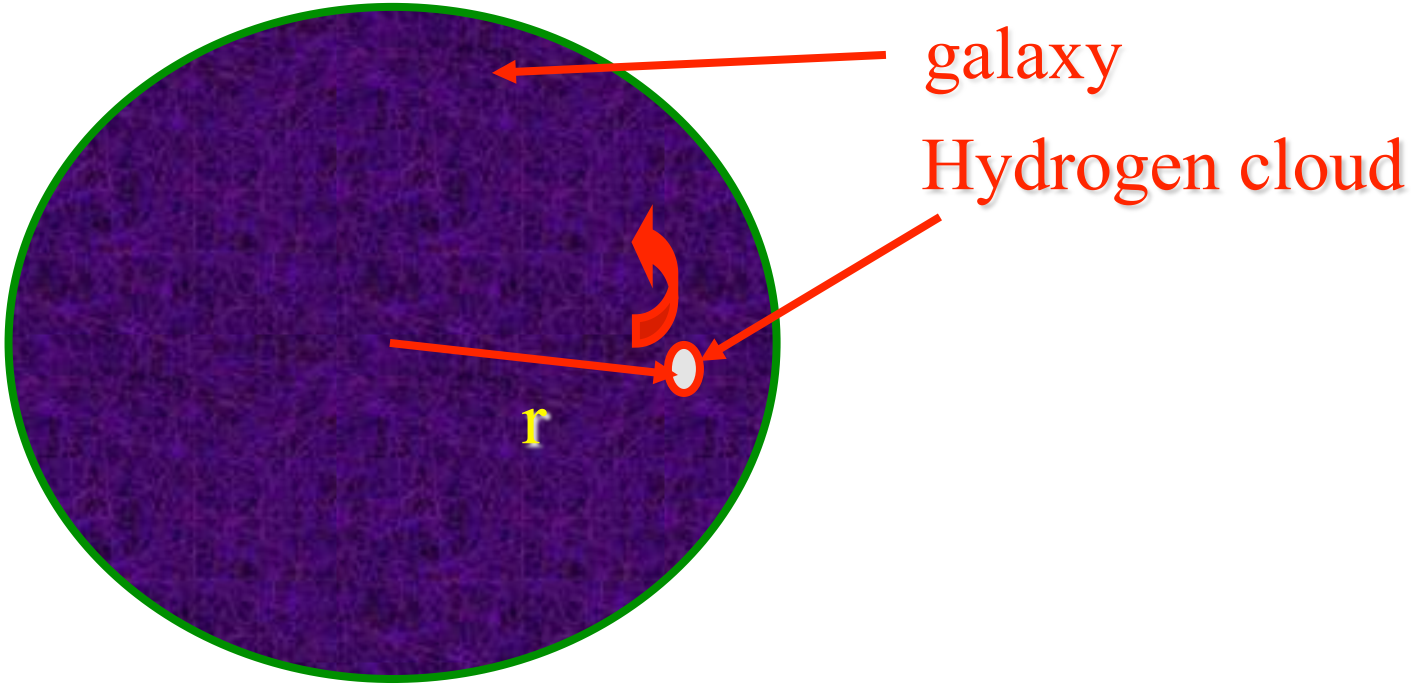


gr/cm^3. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}$ gr/cm^3 erscheint daher nicht

He used the Virial theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only

Dunkle = dark
Kalte = cold!!

Galaxy rotational curves



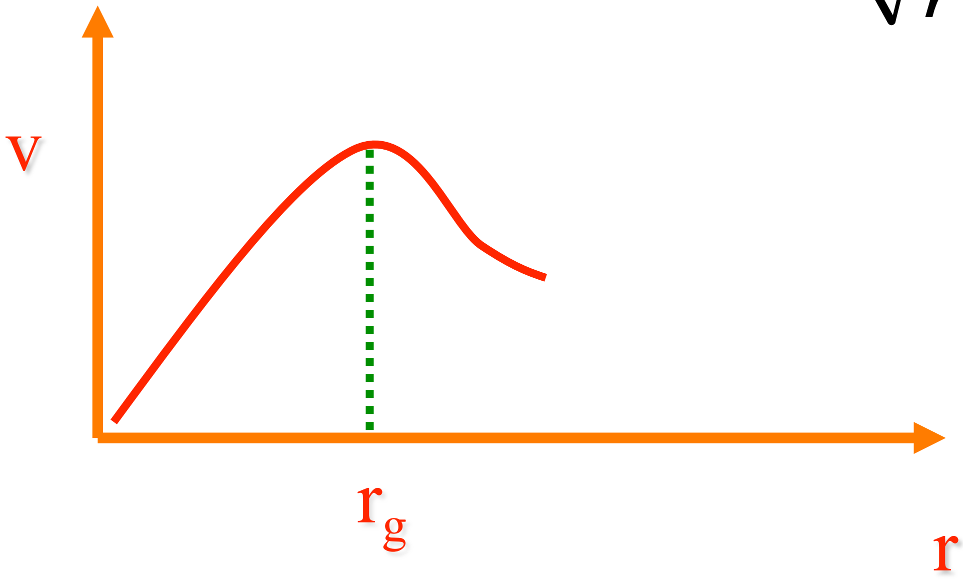
$$m\frac{v^2}{r} = \frac{GmM(r)}{r^2}$$

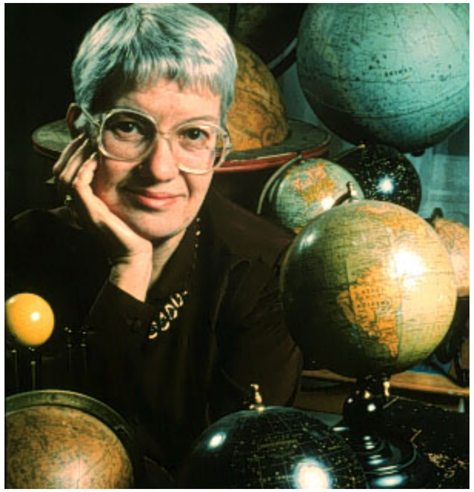
“Inside” the galaxy:

$$M(r) = \frac{4\pi}{3} r^3 \rho \Rightarrow v \propto r$$

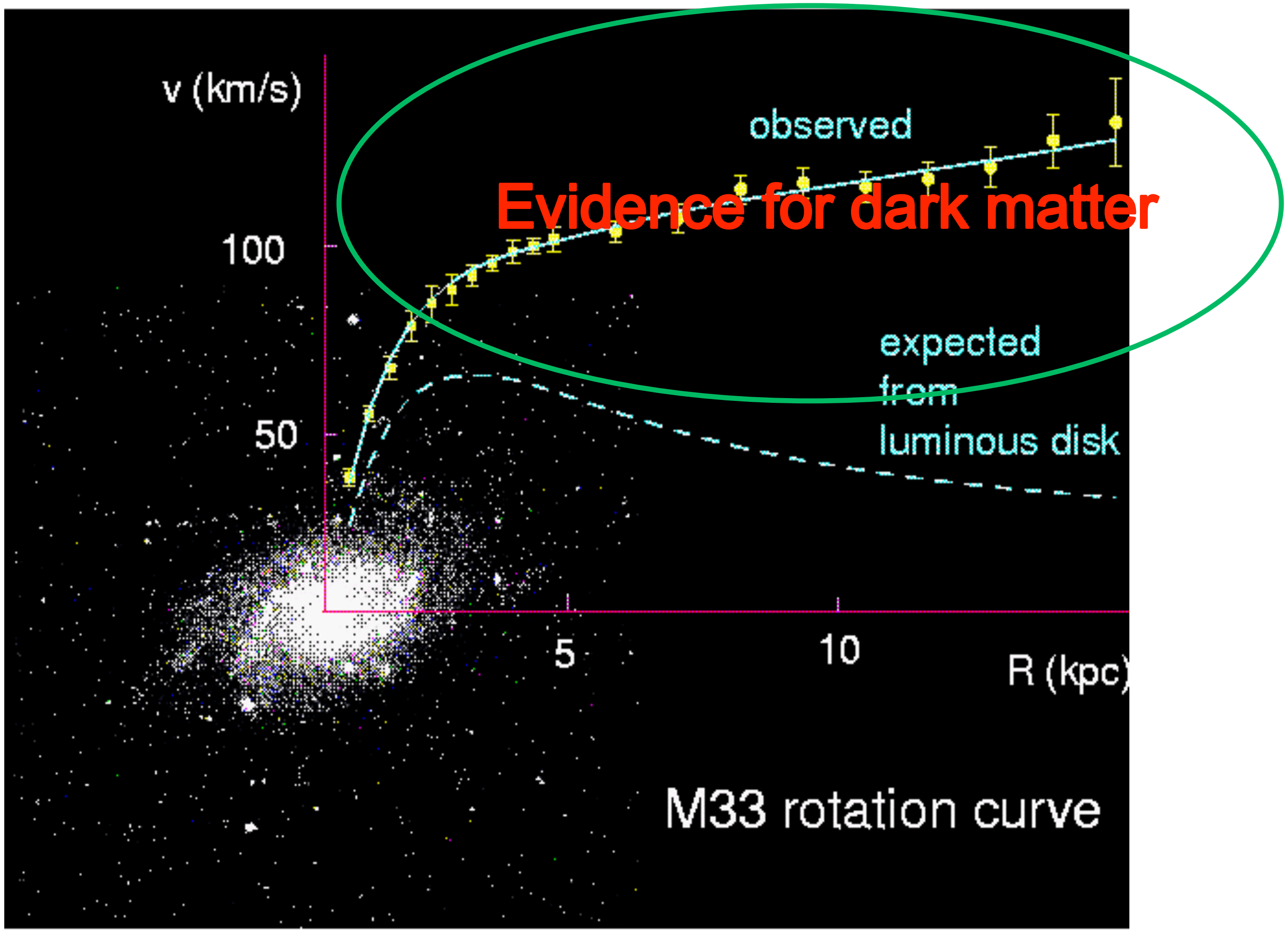
“Outside” the galaxy:

$$M(r) = M \Rightarrow v \propto \frac{1}{\sqrt{r}}$$

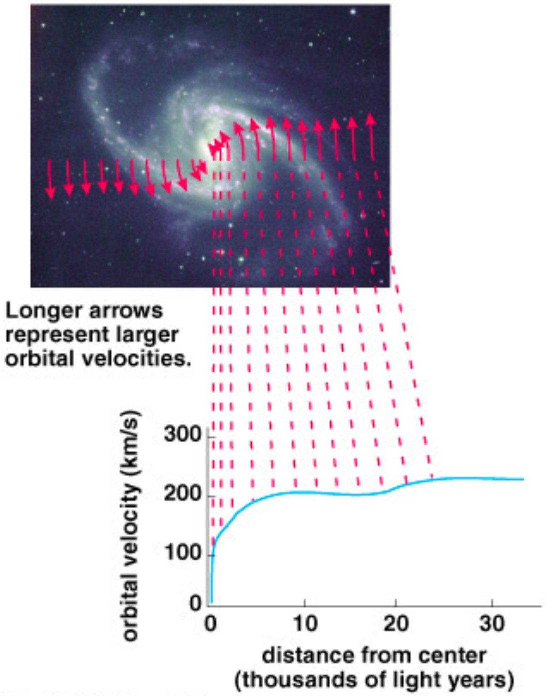


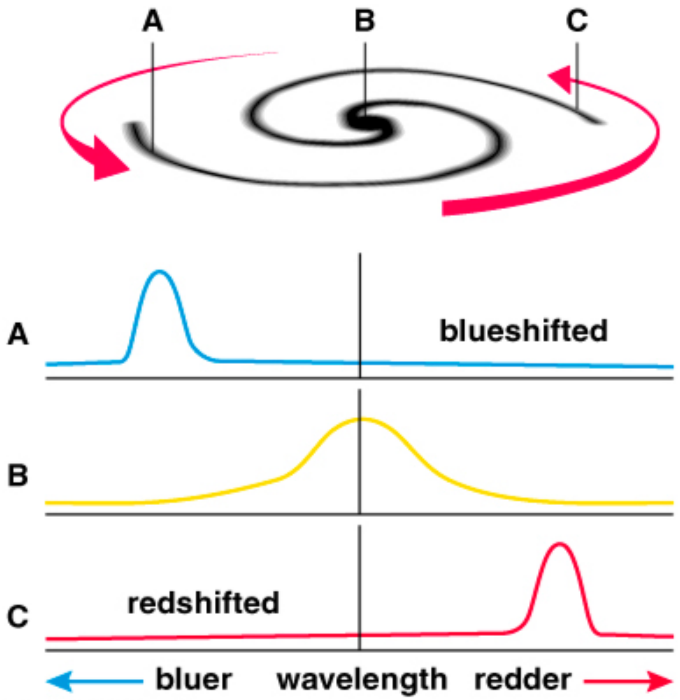


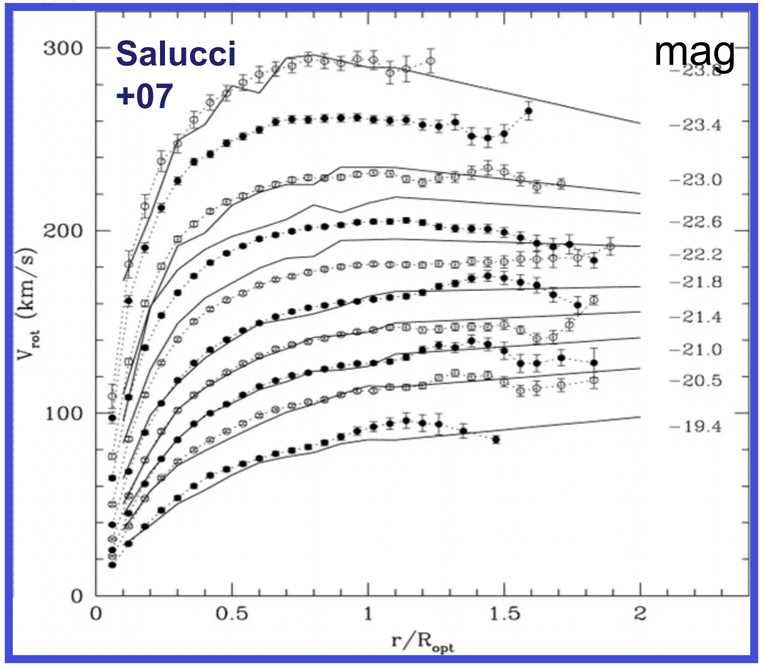
Vera Rubin
1928- 2016



1970's and 1980's



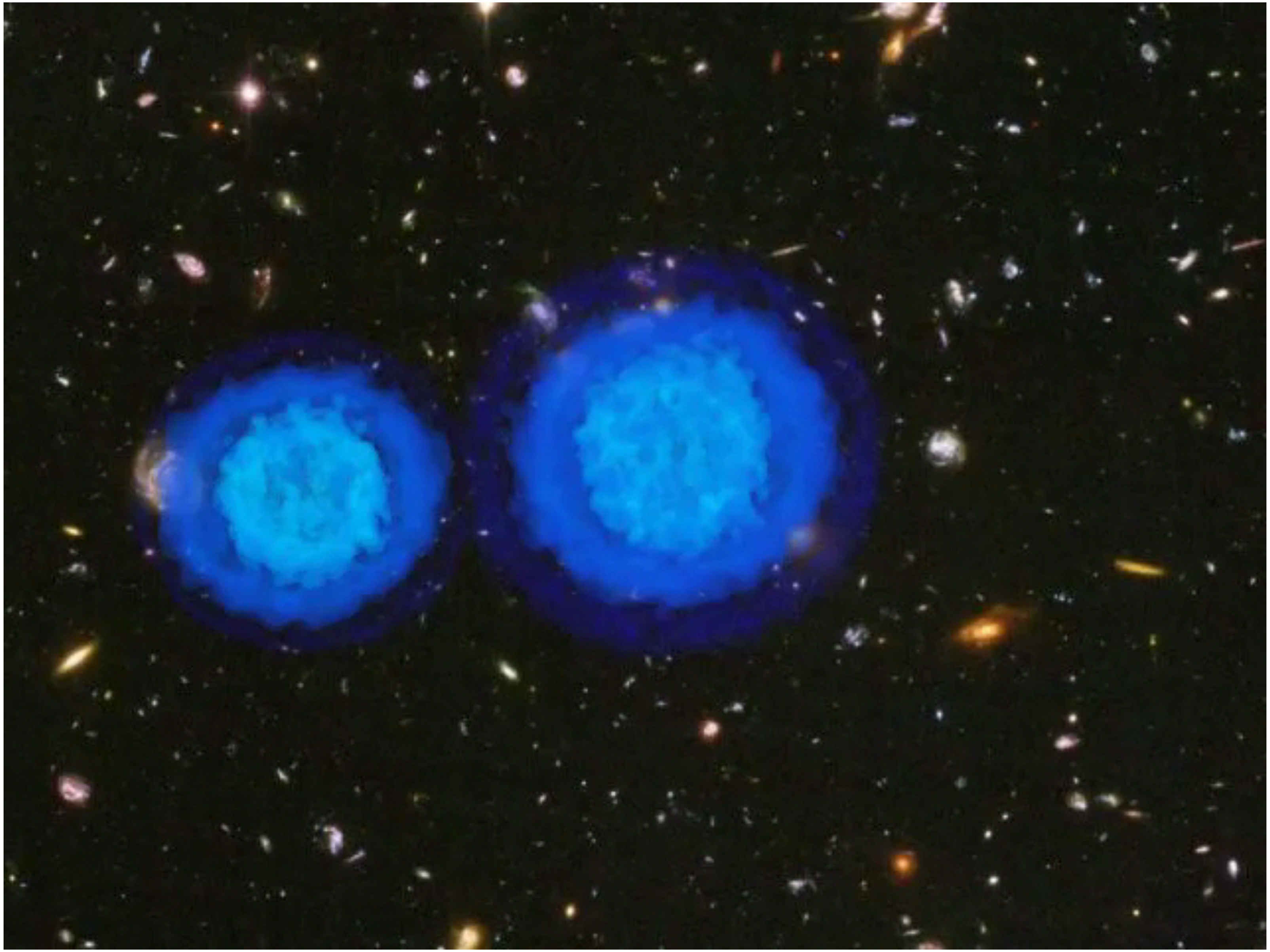




In ΛCDM scenario the density profile for virialized DM halos of all masses is empirically described at all times by the universal (NFW) profile (Navarro+96,97)

$$\rho(r)/\rho_{crit} \approx \delta \; r_s / r(1 + r/r_s)^2$$

Bullet cluster



Observational evidences for DM

I. Dynamics of clusters of galaxies

II. Rotational curves of galaxies

III. Gravitational lensing

IV. Cosmic microwave background

V. Big bang nucleosynthesis

VI. Structure formation in the universe

VII. Baryon acoustic oscillations

VIII. Bullet cluster

What is dark matter? Most possibly a stable (or very long-lived), neutral particle.

In the SM there are neutrinos but:

- they are light and $\Omega_\nu < 0.01$
- actually dark matter particles that are relativistic at decoupling are ruled out by the observations of the structure of the Universe – small scale perturbations are suppressed.

Dark matter implies physics beyond the SM

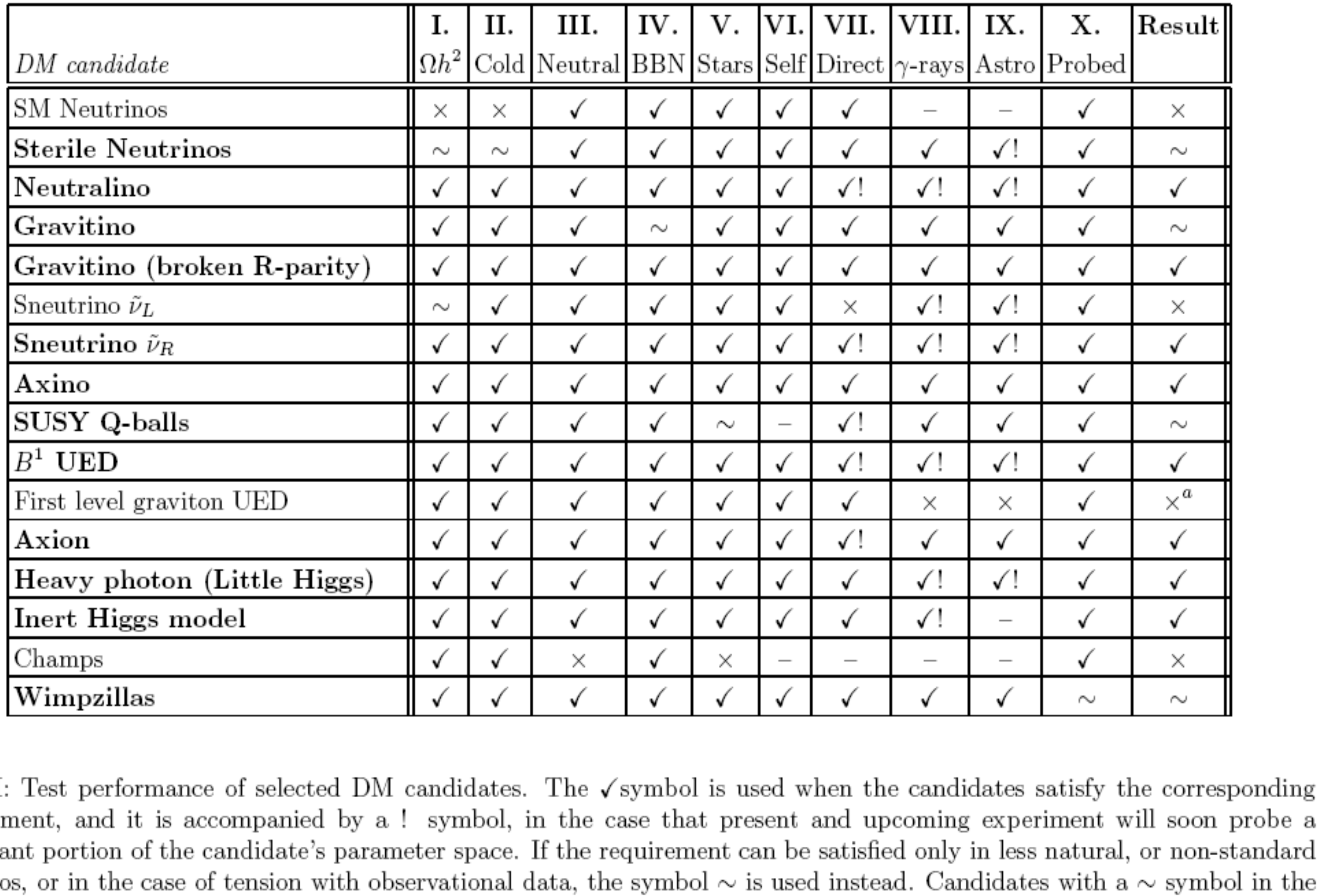
Several candidates: weakly interacting massive particles (WIMPs), new scalars (phion, inert Higgs models), ν_R, axions, primordial black holes, lightest KK particle,...

WIMPs are predicted in SUSY extensions of the SM: The lightests supersymetric particle (LSP), usually a neutralino (combination of gauginos and higgsinos).

Candidates must pass several observational constraints:

Dark matter candidates

arXiv:0711.4996



DM candidate	**I.** Ωh^2	**II.** Cold	**III.** Neutral	**IV.** BBN	**V.** Stars	**VI.** Self	**VII.** Direct	**VIII.** γ-rays	**IX.** Astro	**X.** Probed	**Result**
SM Neutrinos	×	×	✓	✓	✓	✓	✓	–	–	✓	×
Sterile Neutrinos	∼	∼	✓	✓	✓	✓	✓	✓	✓!	✓	∼
Neutralino	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Gravitino	✓	✓	✓	∼	✓	✓	✓	✓	✓	✓	∼
Gravitino (broken R-parity)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sneutrino $\tilde{\nu}_L$	∼	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
Sneutrino $\tilde{\nu}_R$	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
Axino	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SUSY Q-balls	✓	✓	✓	✓	∼	–	✓!	✓	✓	✓	∼
B^1 **UED**	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	×[a]
Axion	✓	✓	✓	✓	✓	✓	✓!	✓	✓	✓	✓
Heavy photon (Little Higgs)	✓	✓	✓	✓	✓	✓	✓	✓!	✓!	✓	✓
Inert Higgs model	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
Wimpzillas	✓	✓	✓	✓	✓	✓	✓	✓	✓	∼	∼

Table I: Test performance of selected DM candidates. The ✓symbol is used when the candidates satisfy the corresponding requirement, and it is accompanied by a ! symbol, in the case that present and upcoming experiment will soon probe a significant portion of the candidate's parameter space. If the requirement can be satisfied only in less natural, or non-standard scenarios, or in the case of tension with observational data, the symbol ∼ is used instead. Candidates with a ∼ symbol in the

II.3.2 – Thermal production of DM: the “miracle”

Disclaimer: we will present a very simple way to estimate the relic abundance of thermally produced DM particles.

For accurate estimates one must solve the appropriate Boltzmann equation with the correct thermally averaged cross section. There are specialized codes such as MicroOmegas, DarkSUSY, ...

Dark matter particles were in thermal equilibrium

$$\chi\bar{\chi} \leftrightarrow f\bar{f}, VV, \ldots$$

$$\Gamma = n\langle \sigma \, \mathrm{v} \rangle >> \mathrm{H}$$

Interaction rate

Density of particles

Scattering cross section (thermal average)

velocity

Expansion rate

If number of dark matter particles does not change (reactions that can change it are inefficient)

$$\mathrm{DM\ DM} \not\rightleftarrows \mathrm{SM\ SM}$$

Number of DM particles is frozen (out of chemical equilibrium). That happens when

$$\Gamma \approx H$$

$$\frac{dN}{dt} = \frac{d\left(a^3 n\right)}{dt} = a^3 \frac{dn}{dt} + 3a^2 \frac{da}{dt} n = 0 \Rightarrow$$

$$\frac{dn}{dt} + 3Hn = 0$$

Recall that: $H(T) \sim \frac{T^2}{M_{\rm Pl}}$

and at freeze-out:

$$n_F \sim \frac{T_F^2}{\langle \sigma v \rangle M_{\rm Pl}}$$

Since we are interested in cold dark matter, its number density at freeze-out is:

$$n_F = (m_\chi T_F)^{3/2} \, e^{-\frac{m_\chi}{T_F}}$$

Exercise 3: define $x=m_x/T$ and show that:

$$x^{1/2}e^{-x} = \frac{1}{m_\chi \langle \sigma v \rangle M_{\rm Pl}}$$

For m_x= 100 GeV, $s = G_F^2\ m_x^2$, v=0.3 show that

$$x_F \sim 30$$

Computing the dark matter relic abundance:

$$\Omega_\chi = \frac{m_\chi n_\chi(T = T_0)}{\rho_c^{(0)}}$$

Exercise 4: using $$\frac{n_\chi(T = T_0)}{T_0^3} = \frac{n_\chi(T = T_F)}{T_F^3}$$

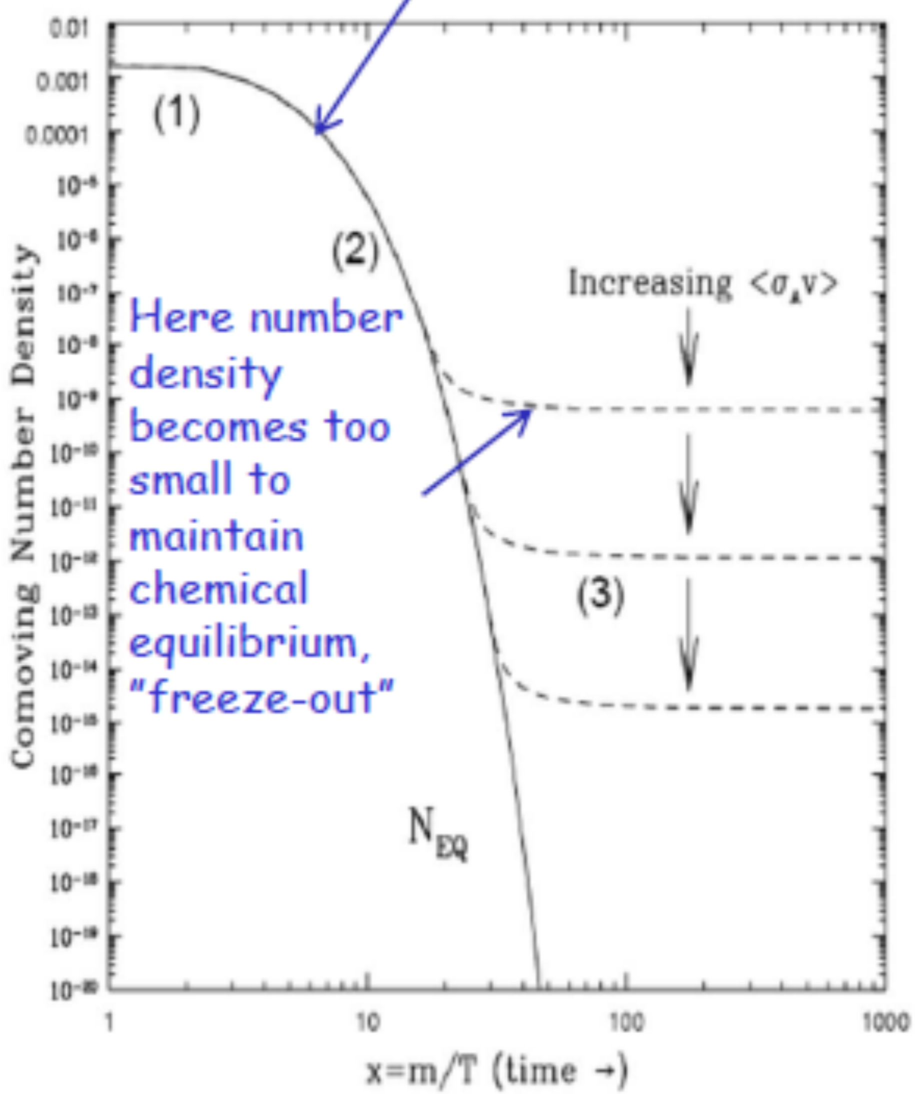
show that:

$$\Omega_\chi = \left(\frac{T_0^3}{\rho_c M_{\mathrm{Pl}}}\right)\frac{x_F}{\langle\sigma v\rangle} \sim \frac{x_F}{20}\frac{10^{-7}\ \mathrm{GeV}^{-2}}{\langle\sigma v\rangle}$$

This is the so-called “WIMP miracle”: the WIMP relic abundance is of the order of the observed one for a typical weak cross section.

Survival of the weakest: the larger the cross section, the longer the particle stays in thermal equilibrium, the smaller is its final abundance.

Equilibirium curve in early universe



Here number density becomes too small to maintain chemical equilibrium, "freeze-out"

II.3.3 – Non-standard DM model (SIMPs):

Models for dark matter usually require a discrete symmetry to render the DM particle stable.
(e.g. R-symmetry in SUSY)

Simplest model of DM: SM + extra scalar field with a Z_2 symmetry – so called Higgs portals

$$\phi \to e^{i\pi}\phi$$

It is possible to generalize the Z_2 symmetry in scalar DM models to a Z_N symmetry :

$$\phi \rightarrow e^{i\frac{2\pi}{N}}\phi$$

Simplest generalization: Z_3 symmetry

Bélanger et al (2013) – global case; Ko and Tang (2014) – local case

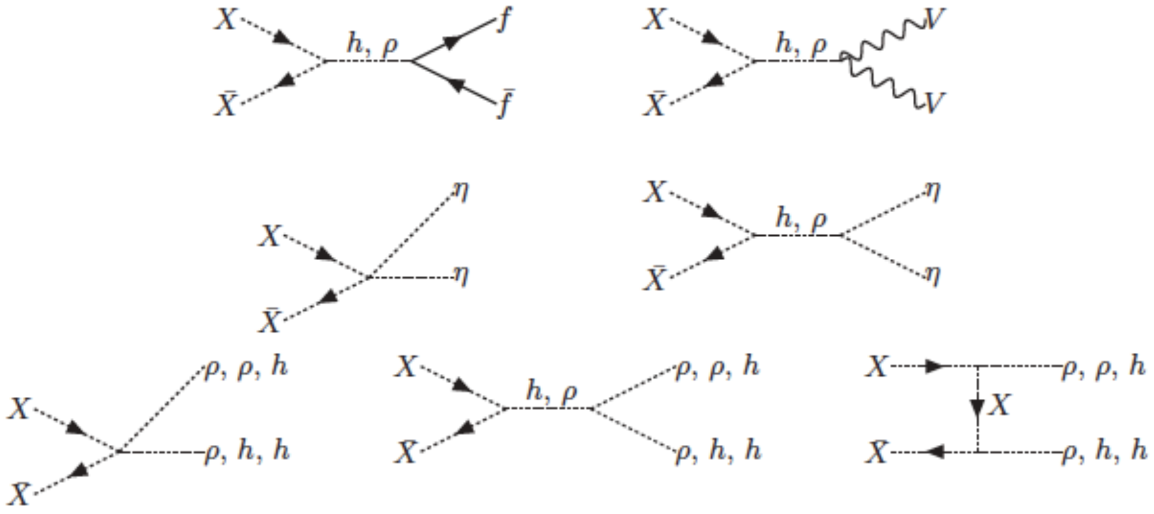
We considered a model where the dark sector has a global $U(1)_X$ symmetry spontaneously broken to Z_3 by scalar vev's.

Bernal, Garcia-Cely and RR (2015)

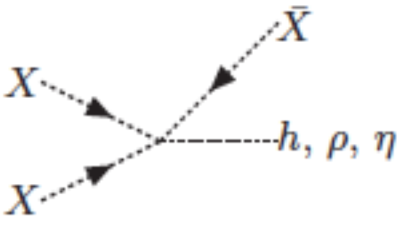
- Model implemented in FeynRules ➔ CalcHEP
- MicrOMEGAs is used for solving Boltzmann equation

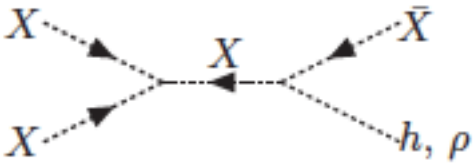
Three main processes for relic abundance:

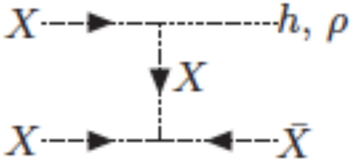
Self-annihilation:



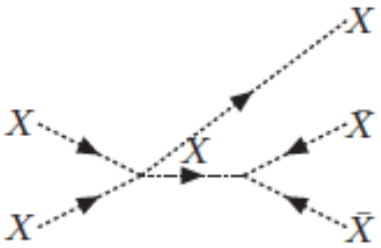
Semi-annihilation:

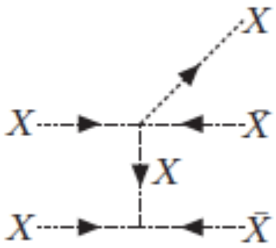


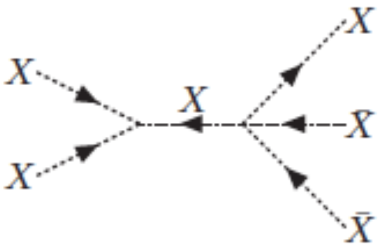




$3 \rightarrow 2$:







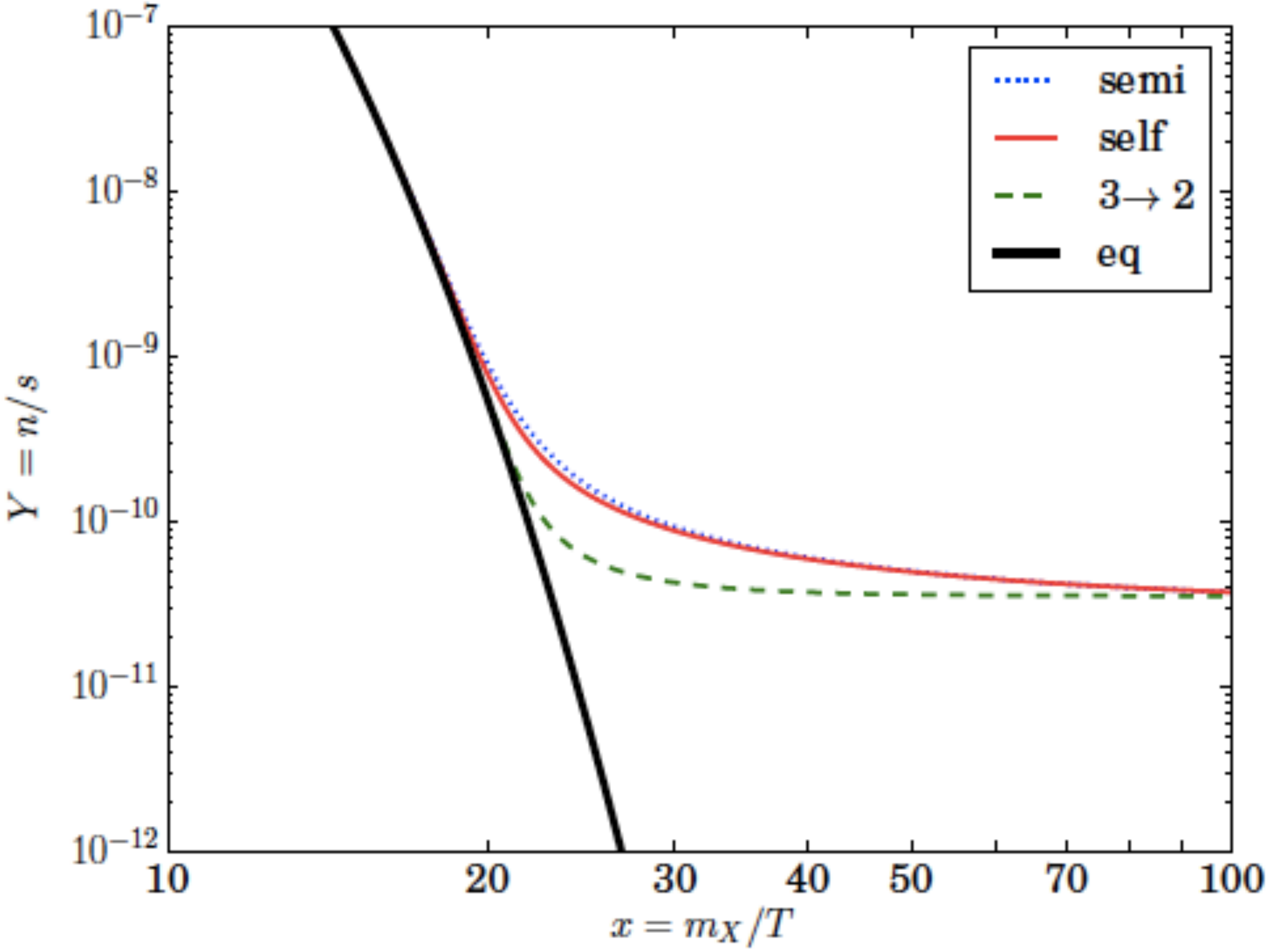
Semi-annihilation and $3 \rightarrow 2$ processes possible only because of Z_3 symmetry.

Boltzmann equation

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle_{\text{self}}\left(n^2 - n_{\text{eq}}^2\right)$$

$$\underbrace{-\,\langle\sigma v\rangle_{\text{semi}}\left(n^2 - n\,n_{\text{eq}}\right) - \langle\sigma v^2\rangle_{3\to2}\left(n^3 - n^2\,n_{\text{eq}}\right)}_{\text{New terms}}$$

Example



10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$Y = n/s$
10
20
30
40
50
70
100
$x = m_X/T$
semi
self
$3 \to 2$
eq

3→2 processes

We explore regions in parameter space where these processes are dominant.

Realization of a new mechanism for thermal dark matter production – Strongly Interacting Massive Particle (SIMP) scenario.

Hochberg, Kuflik, Volansky and Wacker (PRL 2014)

Obs: DM can be produced non-thermally – eg from the non-equilibrium decay of other particles or by coherent field oscillations (axions).

There are many searches for DM:

- direct detection in underground labs (eg LUX, CDMS, ...)
- indirect detection from DM annihilation (eg Fermi satellite)
- production at the LHC (missing energy signature)

II.4- Origin of inhomogeneities

II.4.1 – The causality problem

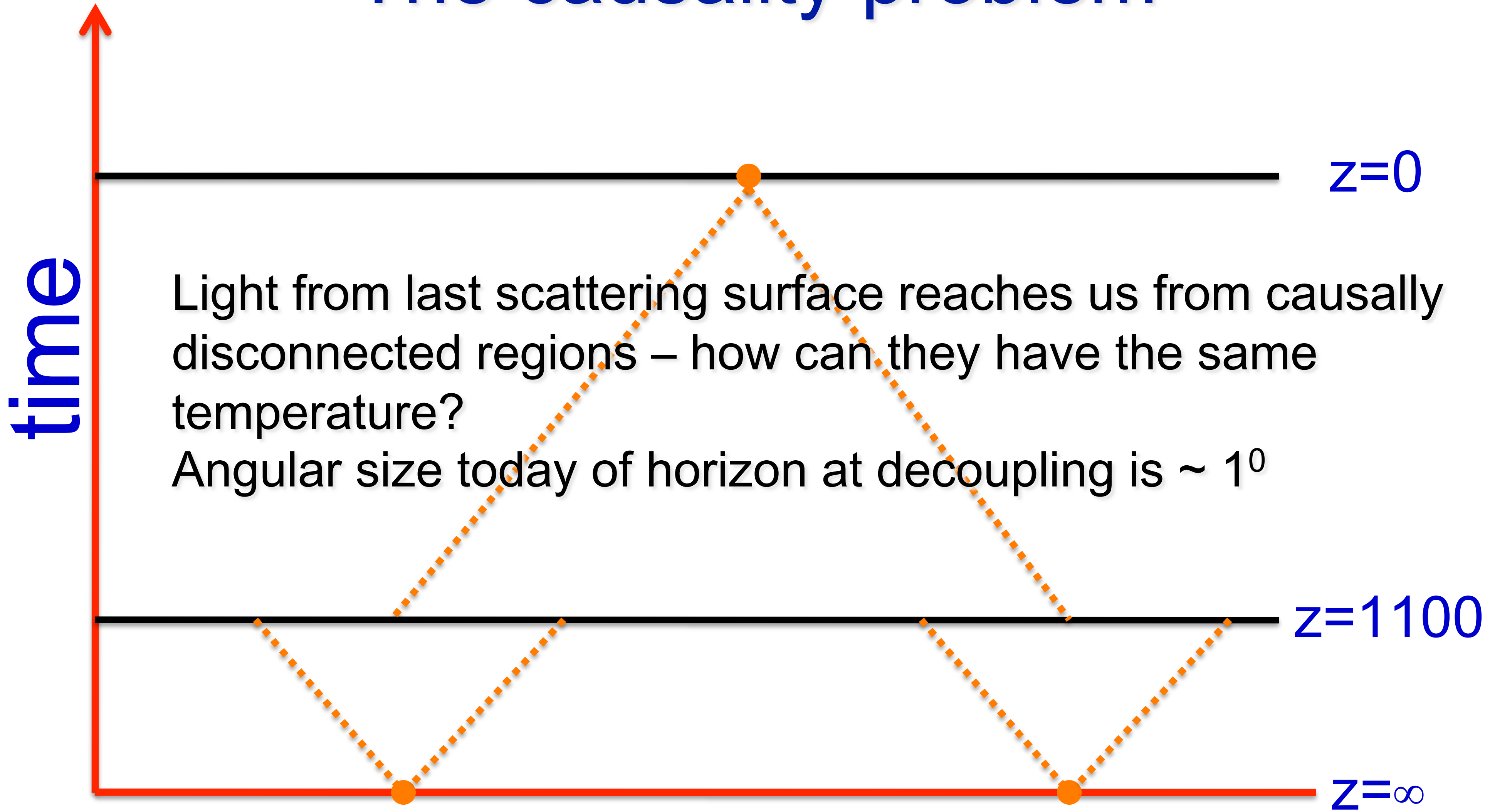
CMB is originated at the “last scattering surface” when atoms are formed and the Universe becomes transparent to radiation. Radiation decouples from matter.

This happens at z~1100 (t~380,000 years after the bang).

There are regions in the last scattering surface that were never in causal contact – no reason to have the same temperature.

Nevertheless the CMB is very uniform over the whole sky, with small variations of 1 part in 10^5! How can this be?

The causality problem



Light from last scattering surface reaches us from causally disconnected regions – how can they have the same temperature?

Angular size today of horizon at decoupling is $\sim 1^0$

II.4.2 – Inflation

Inflation is a period of very fast (exponential) expansion of the Universe.

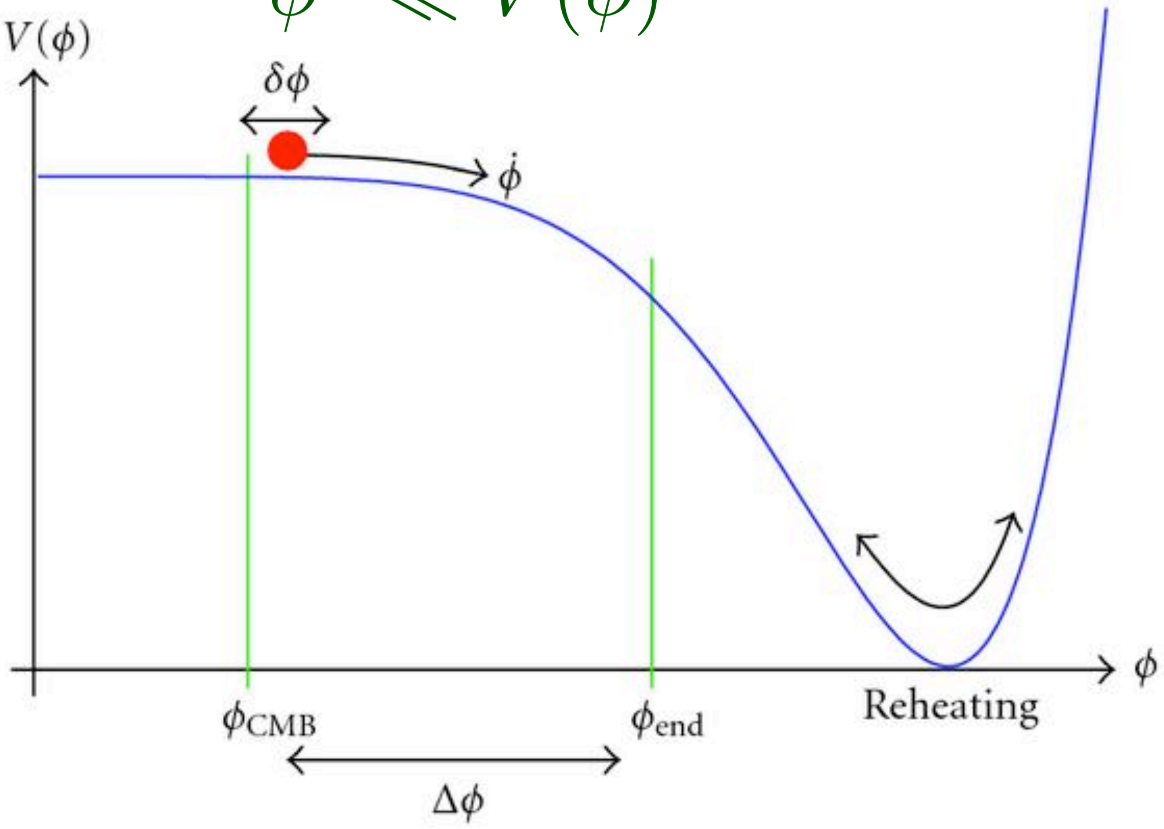
A single small patch can fill the whole horizon at decoupling.

Inflation also predicts that the Universe is spatially flat – as observed!

Inflation also provides quantum fluctuations that are the seeds for inhomogeneities in the Universe.

Basic idea: the very early Universe is dominated by the energy density of a (surprise!) scalar field – called inflaton - that is slowly rolling down in a potential.

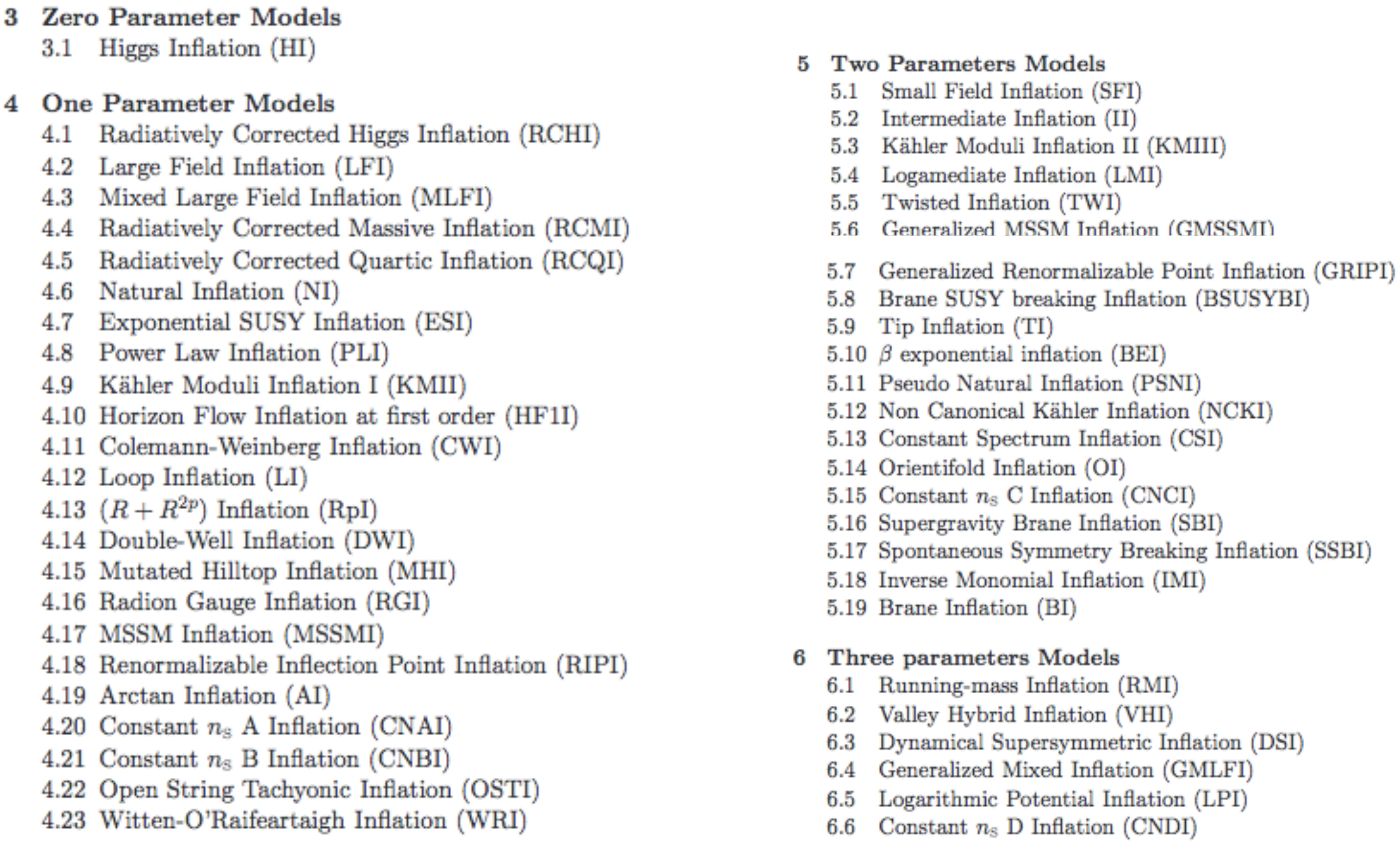
$$\dot{\phi}^2 \ll V(\phi)$$



Encyclopædia Inflationaris

http://arxiv.org/1303.3787

Jérôme Martin,[a] Christophe Ringeval[b] and Vincent Vennin[a]



Inflation must end!

Oscillating field around the minimum of the potential produces the so-called reheating of the Universe.

Oscillating field is equivalent to a gas of inflaton particles (m~10^{12} GeV) that decay into radiation (model dependent).

Actual reheating process is more complicated – possibility of preheating, etc.

The only bound on the reheating temperature T_R is that it must be larger than temperatures required by BBN (~1 GeV).

II.4.3 – How much inflation?

Let’s require that the observable Universe today of comoving size ($1/a_0 H_0$) was to fit in the comoving Hubble radius at the beginning of inflation ($1/a_i H_i$):

$$\frac{1}{a_i H_i} > \frac{1}{a_0 H_0}$$

After inflation ends (at a_e) the Universe is radiation dominated:

$$H \propto a^{-2}$$

and let's assume it is so until today. Hence

$$\frac{a_0 H_0}{a_e H_e} = \frac{a_e}{a_0} = \frac{T_0}{T_R}$$

Therefore:

$$\frac{1}{a_i H_i} > \frac{1}{a_0 H_0} = \frac{T_R}{T_0} \frac{1}{a_e H_e}$$

Finally, using that H is approximately constant during inflation ($H_i \sim H_e$) we obtain the amount the Universe has to expand during inflation:

$$\frac{a_e}{a_i} = \frac{T_R}{T_0}$$

The so-called number of e-folds is defined by:

$$N = \ln\left(\frac{a_e}{a_i}\right) = \ln\left(\frac{T_R}{T_0}\right) = 26 - 64$$

where the range arises from taking the reheating temperature from 1 to 10^{15} GeV. Usually one takes N=50.

II.4.3 – Perturbations in the Universe

Einstein equation:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Perturbed Einstein equation:

$$\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$$

Perturbations in the metric:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$$

FLRW

Can write the line element as:

$$ds^2 = (1+A)dt^2 - a(t)B_i dt dx^i - a(t)^2 \left[(\delta_{ij} + h_{ij}) dx^i dx^j \right]$$

Roughly- A: scalar perturbation, B_i: vector perturbation,
h_{ij}: tensor perturbation
[more complicated: S-V-T decomposition, gauge freedom]

Scalar perturbations: density perturbations

Vector perturbations: decay rapidly and are not important

Tensor perturbations: primordial gravitational waves

Perturbations in the energy-momentum tensor are caused by perturbation in the inflaton field:

$$\phi = \bar{\phi} + \delta\phi$$

The size of quantum fluctuations of the inflaton field during inflation is set by H:

$$\langle(\delta\phi)^2\rangle \sim \frac{H}{2\pi}$$

Inflation models are great:

- predict why the Universe is spatially flat
- solve the causality problem
- generate almost gaussian, almost scale invariant fluctuations
- generate both scalar and tensor fluctuations
- given a inflation potential one can predict the spectrum of scalar and tensor perturbations
- the scalar (density) perturbations will give rise to the large scale structure of the Universe

Spectrum of scalar and tensor perturbations

Perturbations can be decomposed in Fourier modes

$$\delta(\vec{x},t) = \int d^3k\ \delta_k(t) e^{i\vec{k}\cdot\vec{x}}$$

and the power spectrum is defined as:

$$\langle \delta_k \delta_{k'} \rangle = (2\pi)^3 \delta^3(\vec{k} - \vec{k'}) P(k)$$

Inflation predicts a primordial power spectrum of scalar and tensor perturbations:

$$P_s(k) = A_s \; k^{n_s - 1}$$

$$P_t(k) = A_t \; k^{n_t}$$

A_s, A_t: scalar and tensor amplitudes
n_s, n_t: scalar and tensor spectral indices
r: ratio of tensor to scalar amplitudes

$$r = \frac{A_t}{A_s}$$

PLANCK 2015:

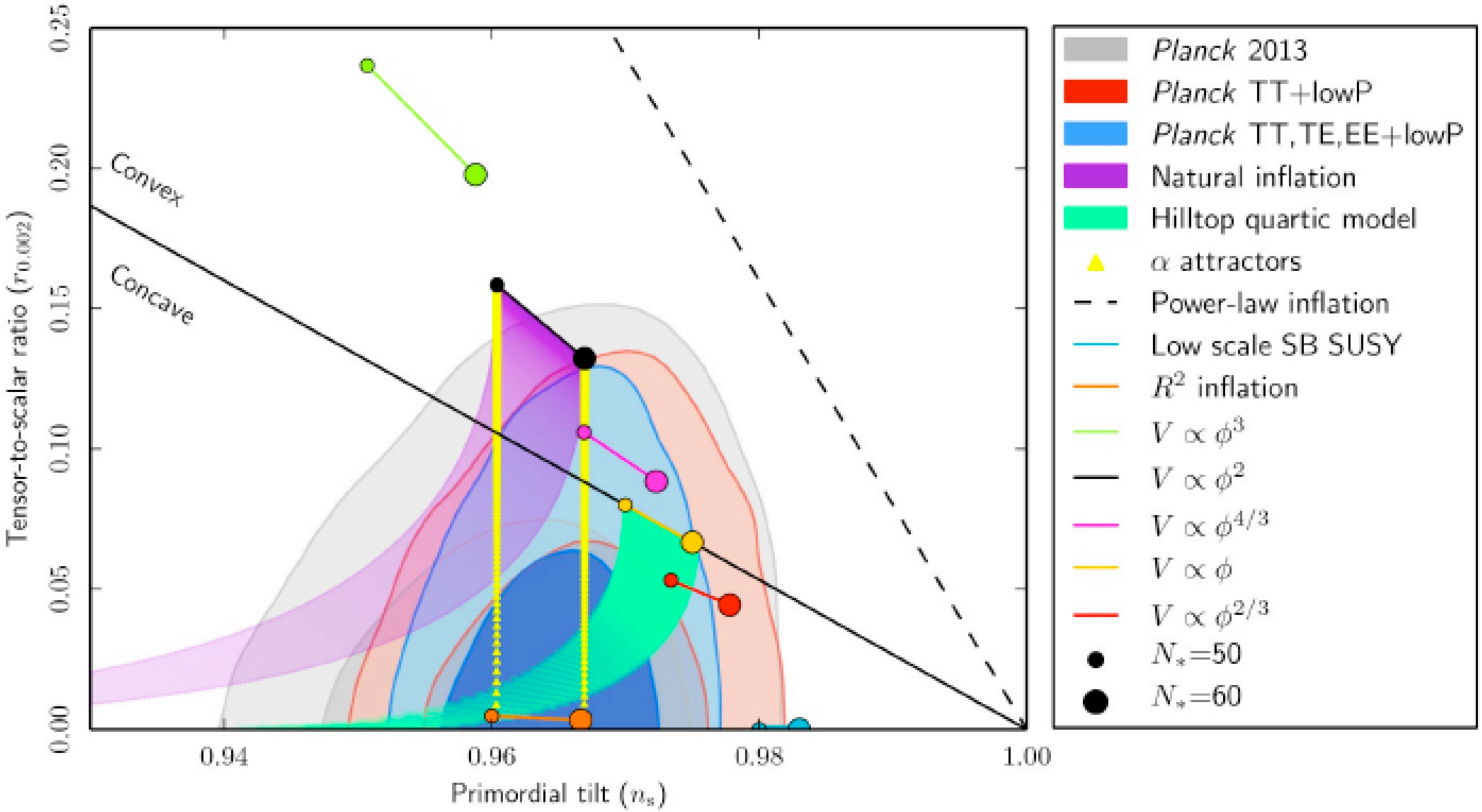


Fig. 12. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets, compared to the theoretical predictions of selected inflationary models.

r <0.12 at 95% confidence (BICEP + Planck) [1502.00612]