

Laboratory Astrophysics from MeV to TeV

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Like many of my colleagues in high-energy physics, I have recently been plagued by "astro-envy".

While we confirm the Standard Model with higher precision, astrophysicists have made profound discoveries about the form of the universe:

the universe is flat

there is a cosmological constant or "dark energy"

familiar matter is only 5% of the total energy content

A few weeks ago, the WMAP experiment reported a dramatic confirmation of these results from observations of the cosmic microwave background.

Should we, then, give up our accelerators and go observe the cosmos?

We should remember that observations of the universe and experiments on microscopic processes run along parallel tracks.

There is a notable history of astrophysics not only informing but also depending on microscopic measurements.

There is good reason to believe that this symbiosis will also be a part of our experience at the next generation of accelerators.

In this lecture, I would like to defend this sentiment by discussing the astrophysical importance of cross section measurements **at nuclear physics energies** and **at Higgs physics energies**.

for orientation, some basic cosmology:

Hubble constant:

$$H_0 = 100 h \text{ km/sec/Mpc}$$

from HST Cepheid observations: $h = 0.71 \pm 0.07$

Critical density: $\rho_c = 3H_0^2/8\pi G_N = 0.95 \times 10^{-29} \text{ g/cm}^3$

$$\Omega_i = \rho_i/\rho_c$$

Radiation domination \rightarrow matter domination of ρ

$$T \sim eV \quad t \sim 10^{10} \text{ sec}$$

In the radiation-dominated era,

$$H = \frac{1}{2t} = 1.66 g_*^{1/2} T^2/m_{\text{Pl}}$$

$$g_* = \begin{cases} 3.36 & \text{today } (\gamma + 3\nu) \\ 10.75 & 1 \text{ MeV} \\ 86 & 50 \text{ GeV} \end{cases}$$

From these formulae, we see that the expansion of the universe is **slow** on particle physics scales:

$$H/\alpha^2 T \sim \frac{1}{g_*^{1/2} \alpha^2} \frac{m_{\text{Pl}}}{T} \sim 10^{-3} \frac{m_{\text{Pl}}}{T}$$

e.g. $\sim 10^{-16}$ at $T \sim 100 \text{ GeV}$

So, the universe stays in thermal equilibrium,

except when there is a major change in the (effective) laws of Nature.

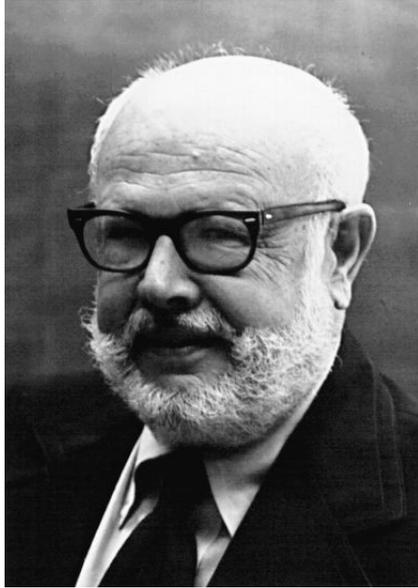
One of the classical problems of astrophysics
--- the synthesis of the elements ---
is governed by processes at the nuclear physics scale

A thermal gas of p, n, e^-, ν

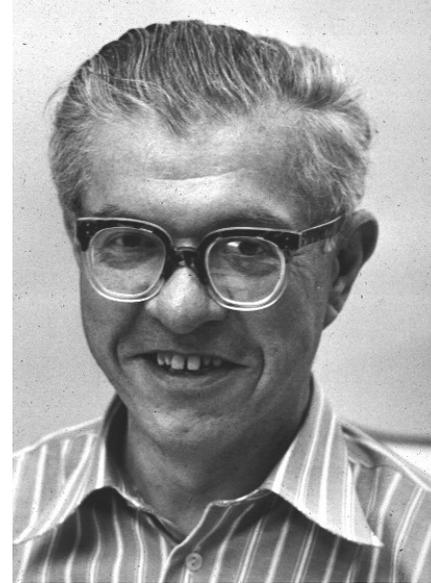
converts to H, He, D, etc.

which is then processed by fusion in stars, to He,
then to C, N, O, then to heavier elements.

Many of the leaders of this study were trained as nuclear physicists:

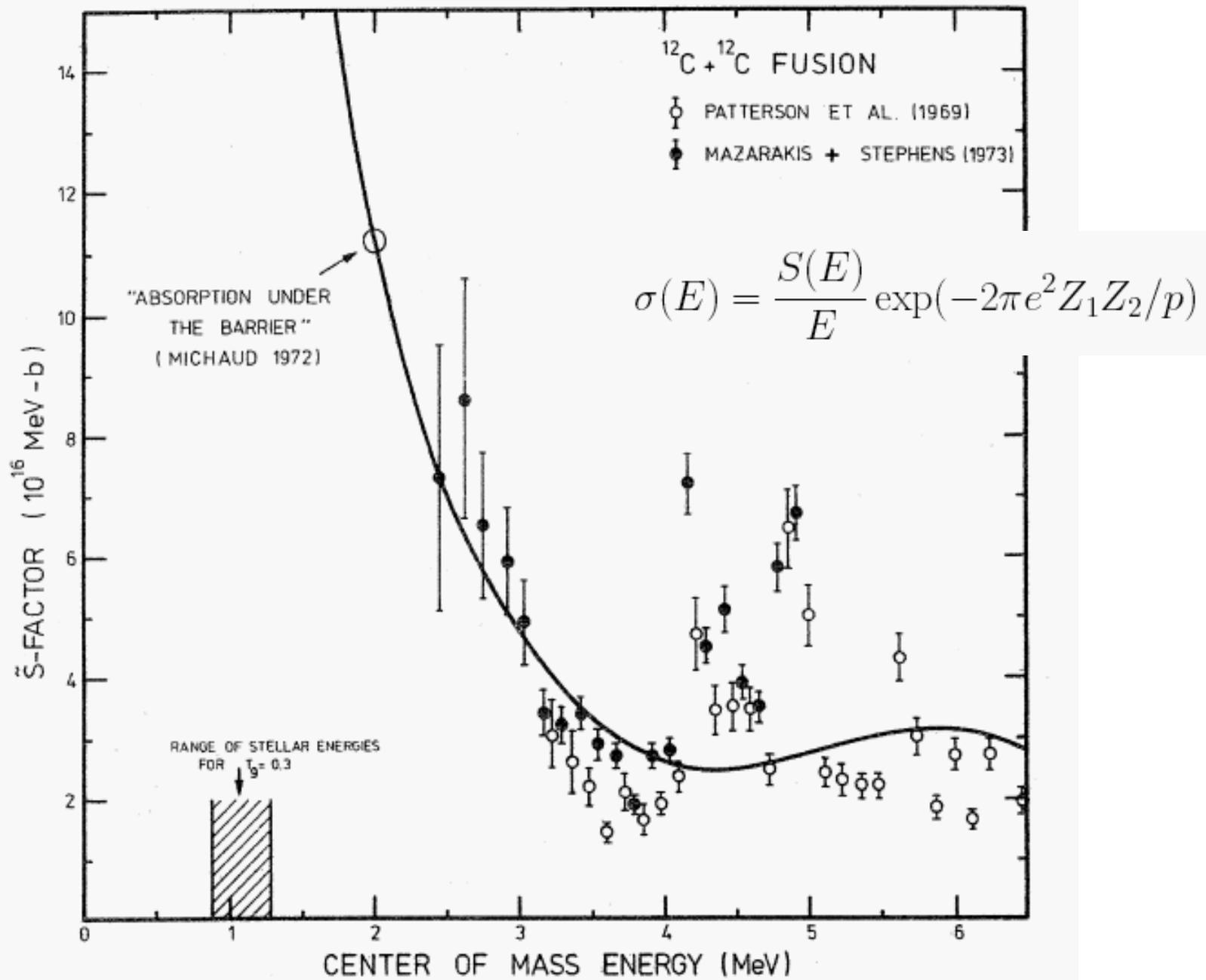


Willy Fowler



Fred Hoyle

Fowler's laboratory of experimental nuclear physics at Caltech played a central role in the understanding of stellar processes.



Primordial nucleosynthesis

There is an ultra-simple picture that does not need nuclear data. (Kolb + Turner)

rate of $p e \leftrightarrow n \nu$ equilibrium: $\Gamma/H = (T / 0.8 \text{ MeV})^3$

n to p ratio at "freeze-out": $n/p \sim e^{-(m_n - m_p)/T_f} \sim \frac{1}{6}$

bind all n into He^4 ; this gives the mass fraction:

$$Y_p = \frac{2(n/p)}{1 + (n/p)} \approx 29\%$$

accounting for free n decays lowers this to $\sim 25\%$

compare to : $0.228 < Y_p < 0.248$

It pays to do better!

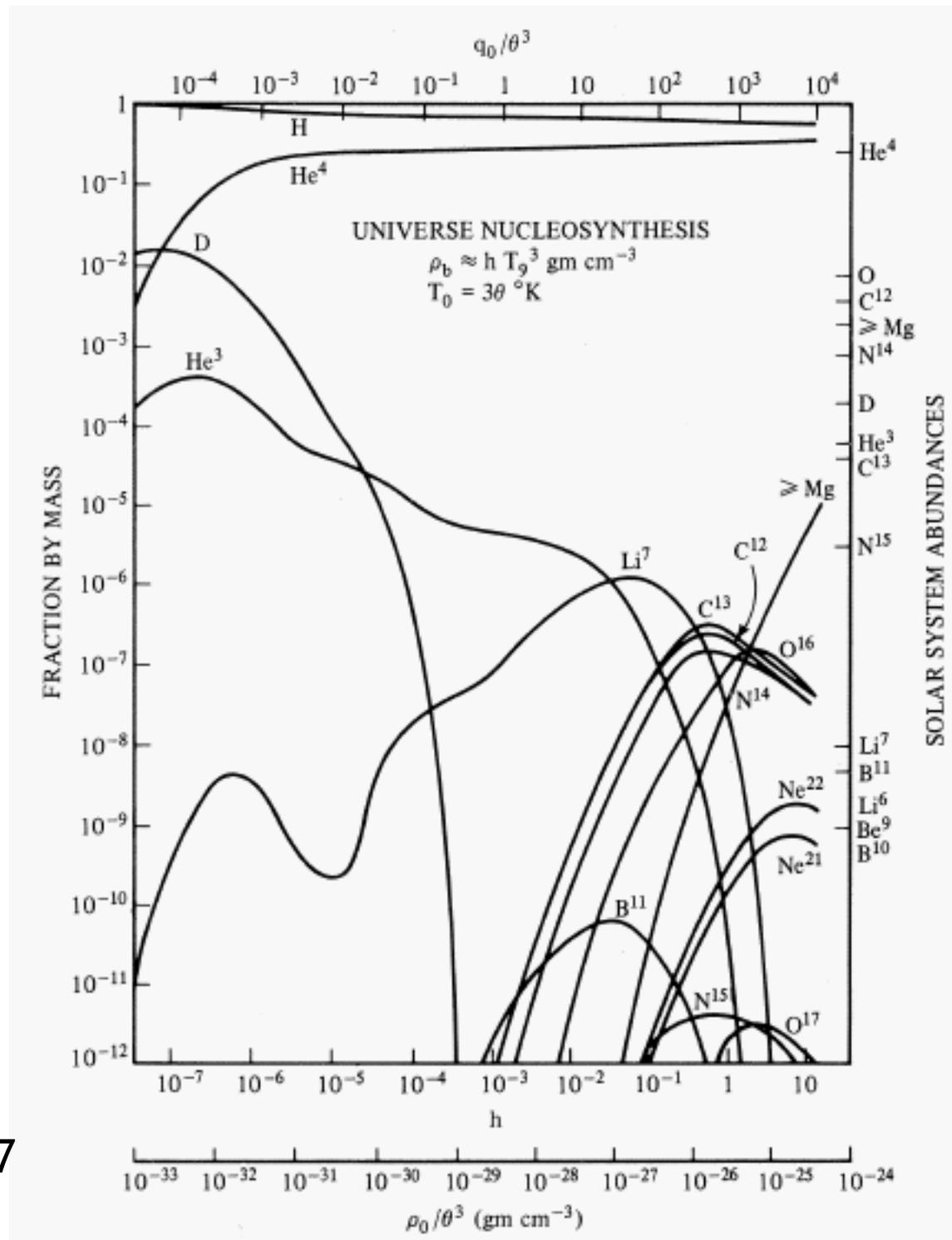
Wagoner, Fowler, and Hoyle (1967):

solving the Boltzmann equation with measured reaction rates,

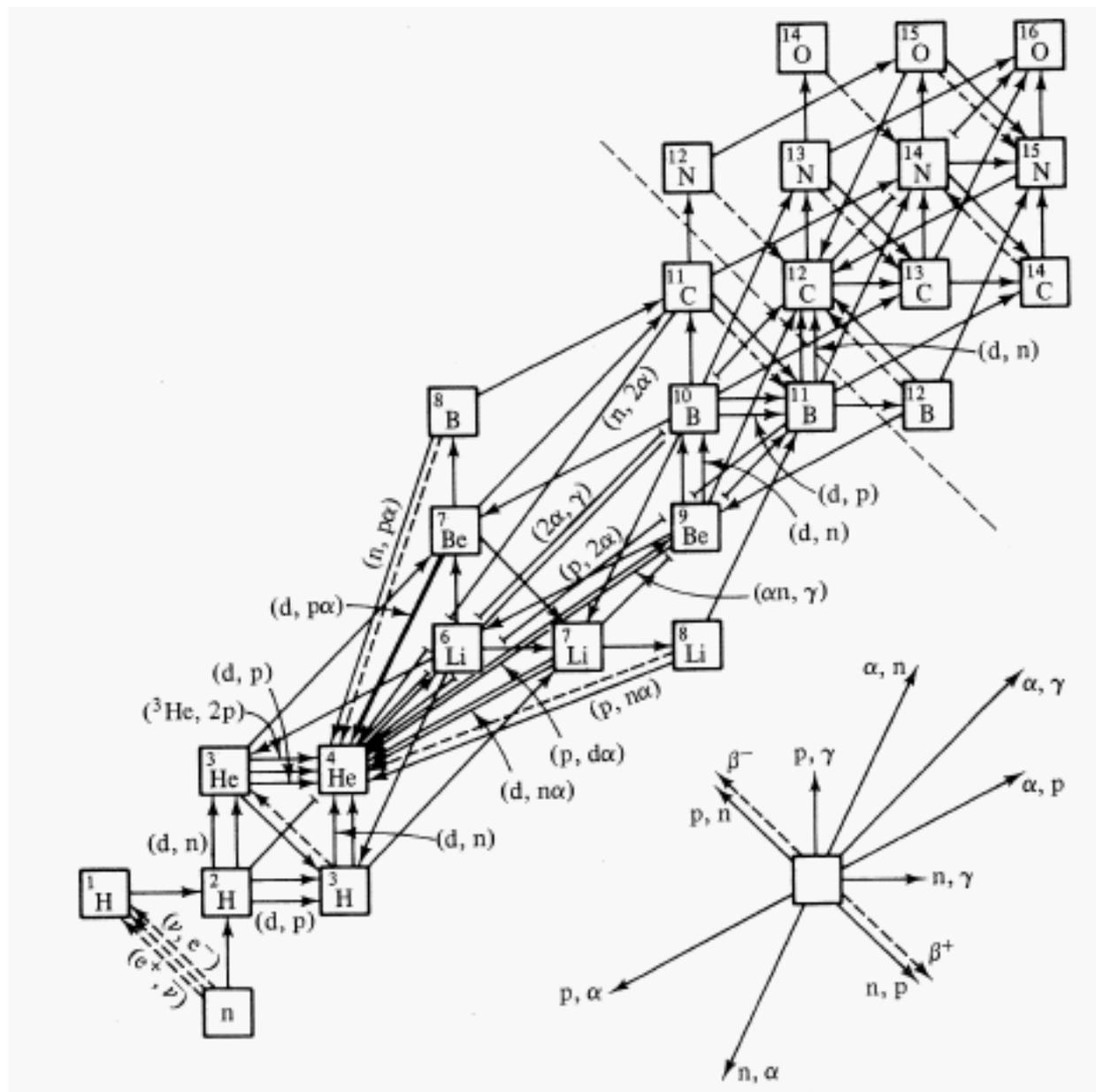
one can follow the production of less tightly bound species:

D , He^3 , Li^7 , ...

(Since there are no stable nuclei of mass 5 or 8, there is limited production of heavier species.)



Wagoner '67



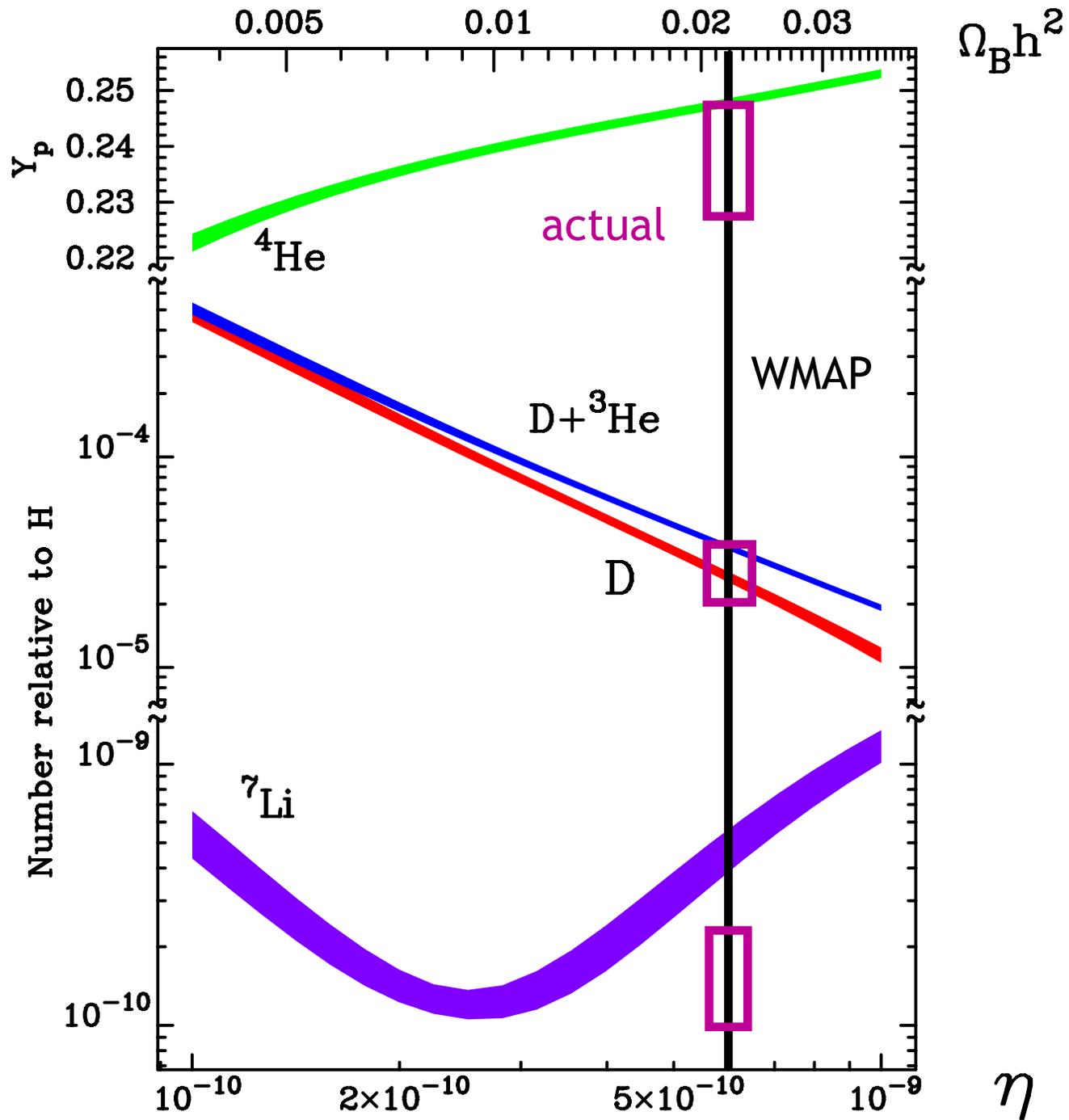
Wagoner '73

The calculations account for the primordial abundances of the major light species,

and point to a low value of the baryon density:

$$\Omega_b h^2 \sim 0.02$$

More recent improvements bring the calculation to the precision level, 1% accuracy (e.g. Lopez and Turner).



Burles,
 Nollett,
 Turner

Wagoner (1990):

"The Spites found that old (Population II) stars contain about 10 times less lithium, and the abundance does not vary with surface temperature, indicating that it had not been affected by mixing. On the other hand, new cross section data has led to an increase in the predicted primordial ${}^7\text{Li}$ abundance... Both of these changes have produced a better agreement between the predicted and observed abundances for the choice of baryon density which matches the deuterium and helium... The fact that new astrophysical and nuclear data have produced this concordance must be considered as additional evidence for the validity of the standard big bang model."

Once the basic theory of primordial nucleosynthesis is established as a reference point, observations can constrain both particle physics and astrophysical quantities:

$$\Delta g_* < 0.25 \quad ; \quad \text{this excludes:}$$

extra active neutrinos, $\Delta N_\nu < 0.3$

any other new light particle thermal at 1 MeV

late-decaying particles contributing to the γ entropy

a 10% change in G_N since $T \sim \text{MeV}$

order-1 baryon density inhomogeneities at 1 MeV

neutrino degeneracy: $\left| \frac{\mu_{\nu e}}{T} \right| < 0.1$

The Li^7 abundance plays an important role in these constraints.

The experimental determination of nuclear reaction rates is obviously central to the modelling of stellar processes.

This is a huge subject, beyond the scope of this talk,

but there is one example I cannot resist:

The nonexistence of stable nuclei with $A = 5$ and 8 hinders heavy element production not only in the early universe, but also in stars.

Salpeter suggested a way around the barrier:



but Be^8 is **unstable**, with $\tau = 10^{-16}$ sec.

Sandage and Schwarzschild found that the required ignition temperature of 2×10^8 K was too high, producing **too large red giants**:

At 1×10^8 K, "a physical process not included in the present computations should start to play an essential role."

Hoyle, then on sabbatical at Caltech, suggested that the reaction **must be assisted by a resonance in C^{12}** . Balancing the rate of the formation process with the rate of destruction:



he predicted

$$\Delta(C^{12*} - (Be^8 + He^4)) = 0.33 \text{ MeV}$$

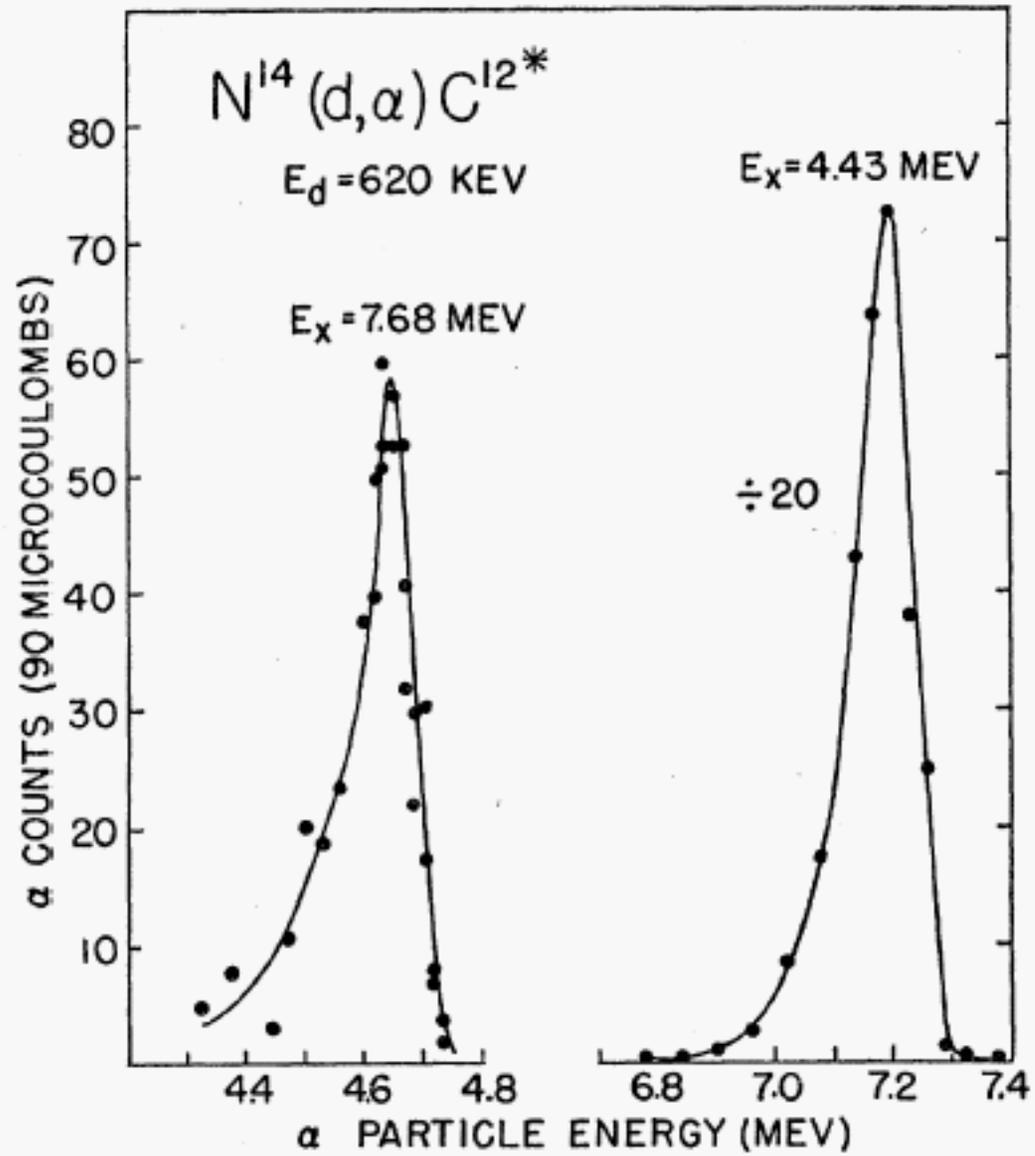
Dunbar, Pixley, Wenzel, and Whaling went into the lab and found the resonance in



at

$$\Delta = 0.31 \text{ MeV}$$

$$\Delta(C^{12*} - C^{12}) = 7.65 \text{ MeV}$$



Dunbar, Pixley, Wenzel, Whaling

So much for the past. What problems do we face now ?

From the new observations, astrophysicists have a Standard Model, the " Λ CDM model".

D. Spergel, on the WMAP results:

"The main thing we have learned is that the Standard Model accounts for the data surprisingly well."

For us, it is important that the Λ CDM model contains ingredients that pose a challenge to our community.

elements of the Λ CDM model: (according to WMAP)

flatness:

$$\Omega_{tot} = 1.02 \pm 0.02$$

from the position of the first acoustic peak in the CMB fluctuation spectrum

small density of baryons:

$$\Omega_b h^2 = 0.0224 \pm 0.0009$$

from the amplitude of the CMB spectrum

c.f. consistency of primordial nucleosynthesis: $\Omega_b h^2 = 0.01 - 0.03$

dark matter:

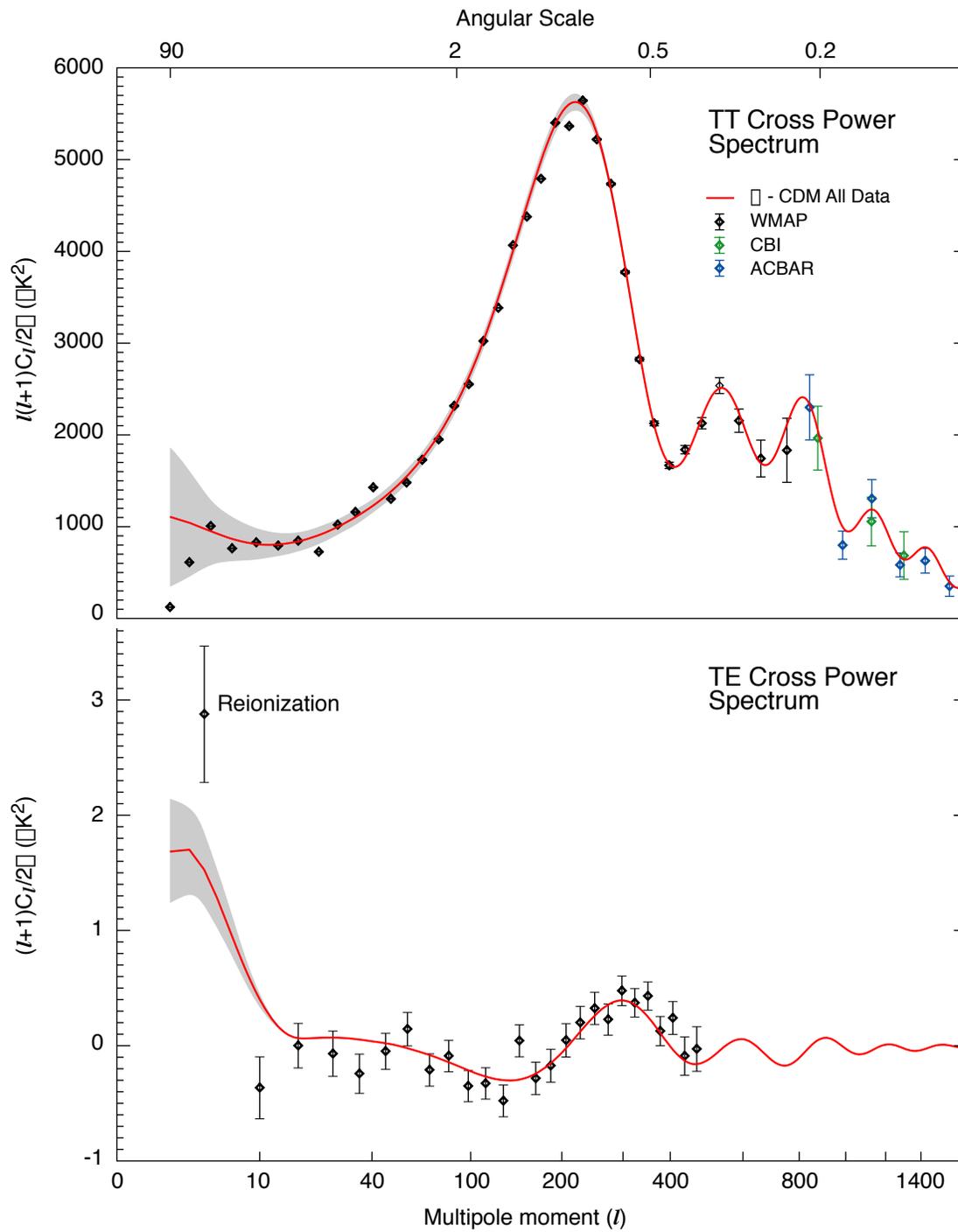
$$\Omega_m h^2 = 0.135 \pm 0.009$$

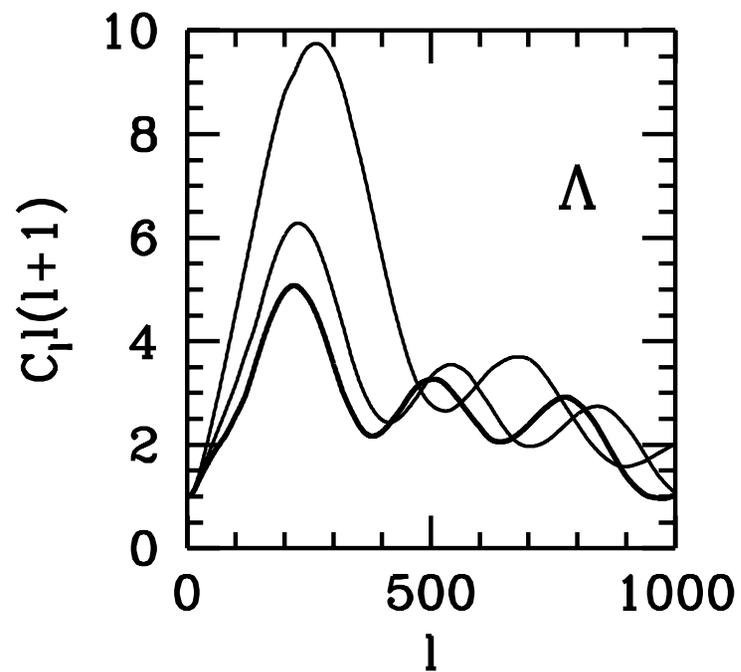
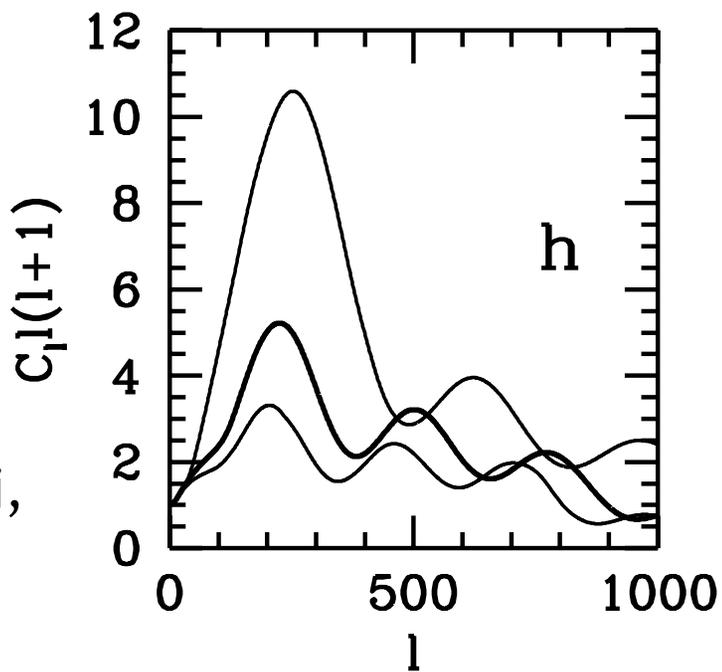
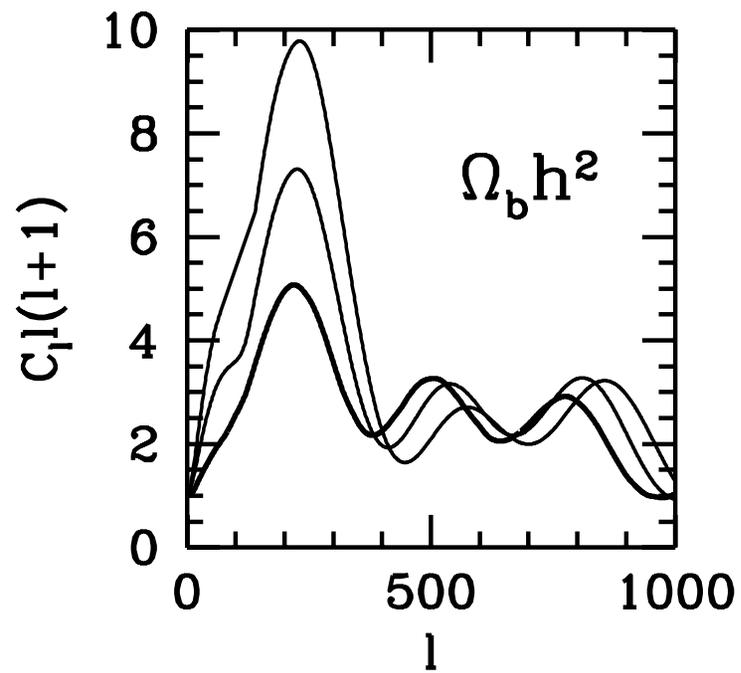
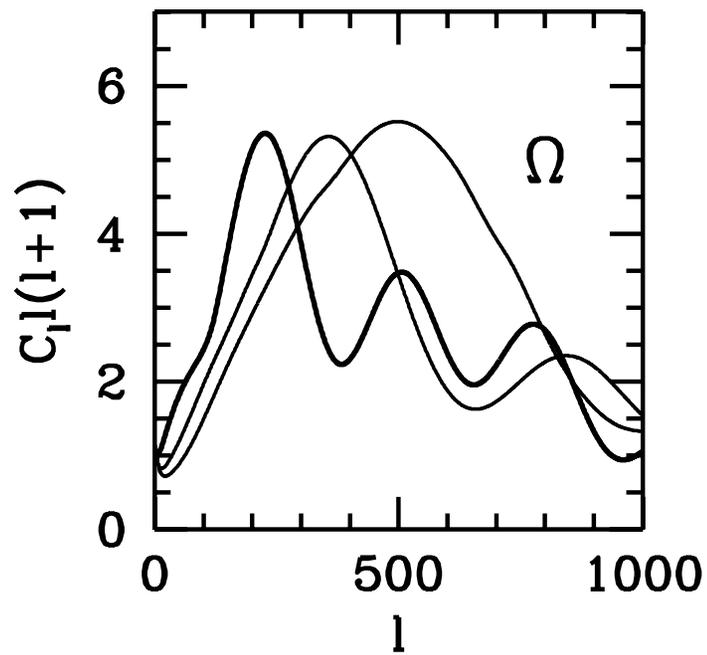
from the value of H at recombination

need for residual "dark energy":

$$\Omega_{tot} - \Omega_m = 0.73 \pm 0.03$$

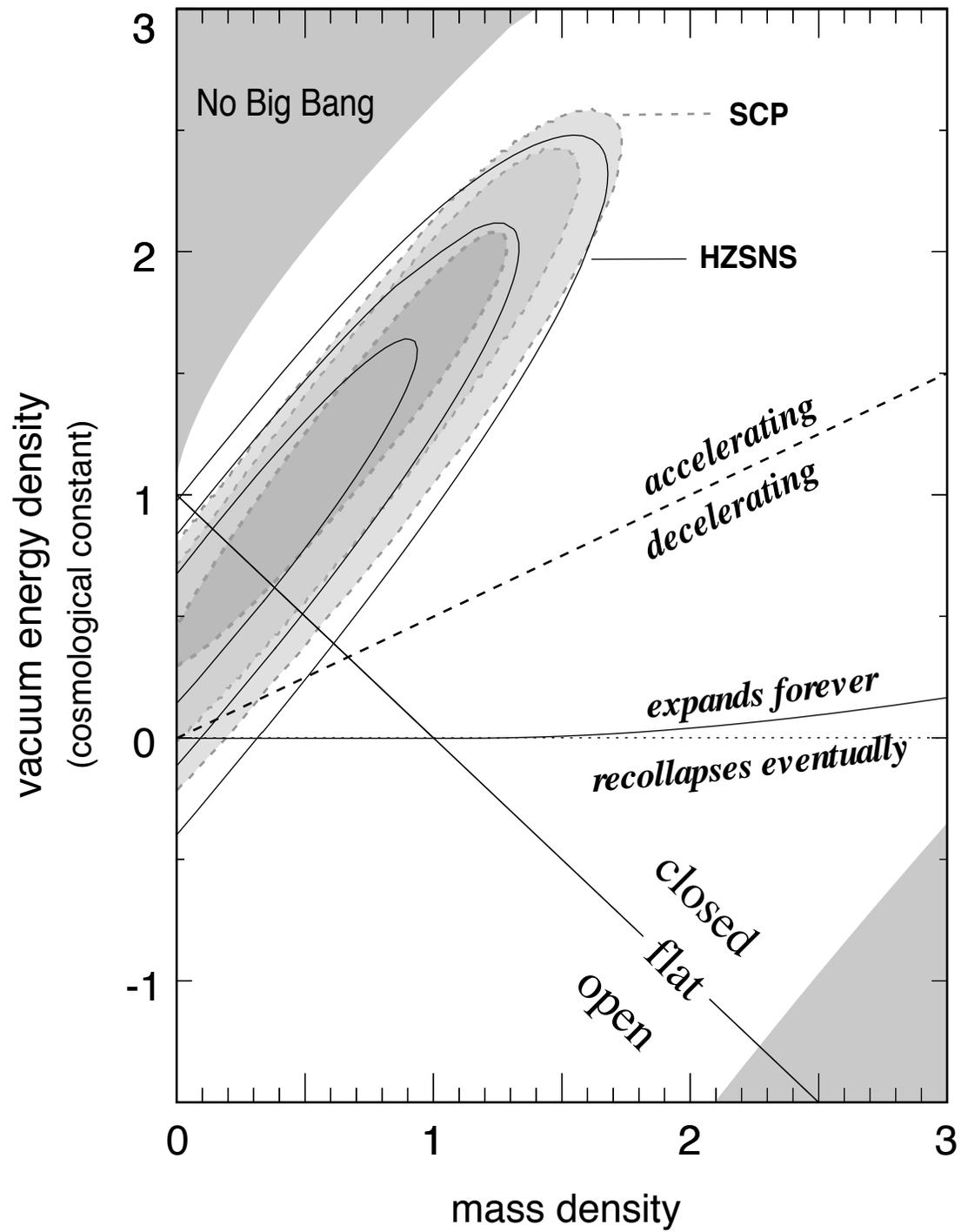
These results mesh nicely with the **supernova observations** of the acceleration of the Hubble expansion.





Jungman,
Kamionkowski,
Kosowsky,
Spergel

Perlmutter



evidence for dark matter:

rotation curves of galaxies: (Rubin and Ford)

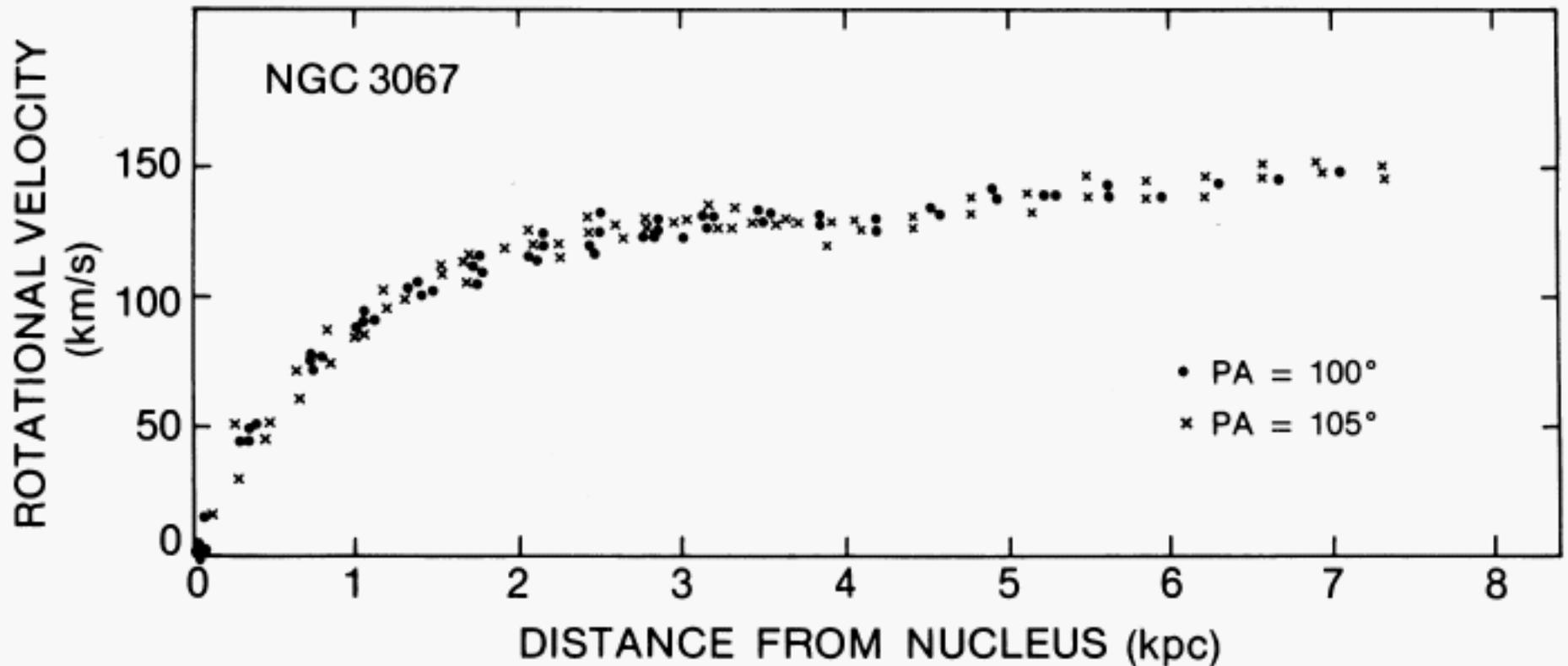
rotation velocities of stars in galaxies do not fall off
in Keplerian fashion as $1/r$.

virial theorem and mass/light of clusters (1-10 Mpc)

$$\Omega_m = \begin{cases} 0.16 \pm 0.05 & \text{Bahcall } et \text{ al.} \\ 0.19 \pm 0.06 & \text{CNOc survey} \\ 0.20 \pm 0.03 & \text{2dFGR survey} \end{cases}$$

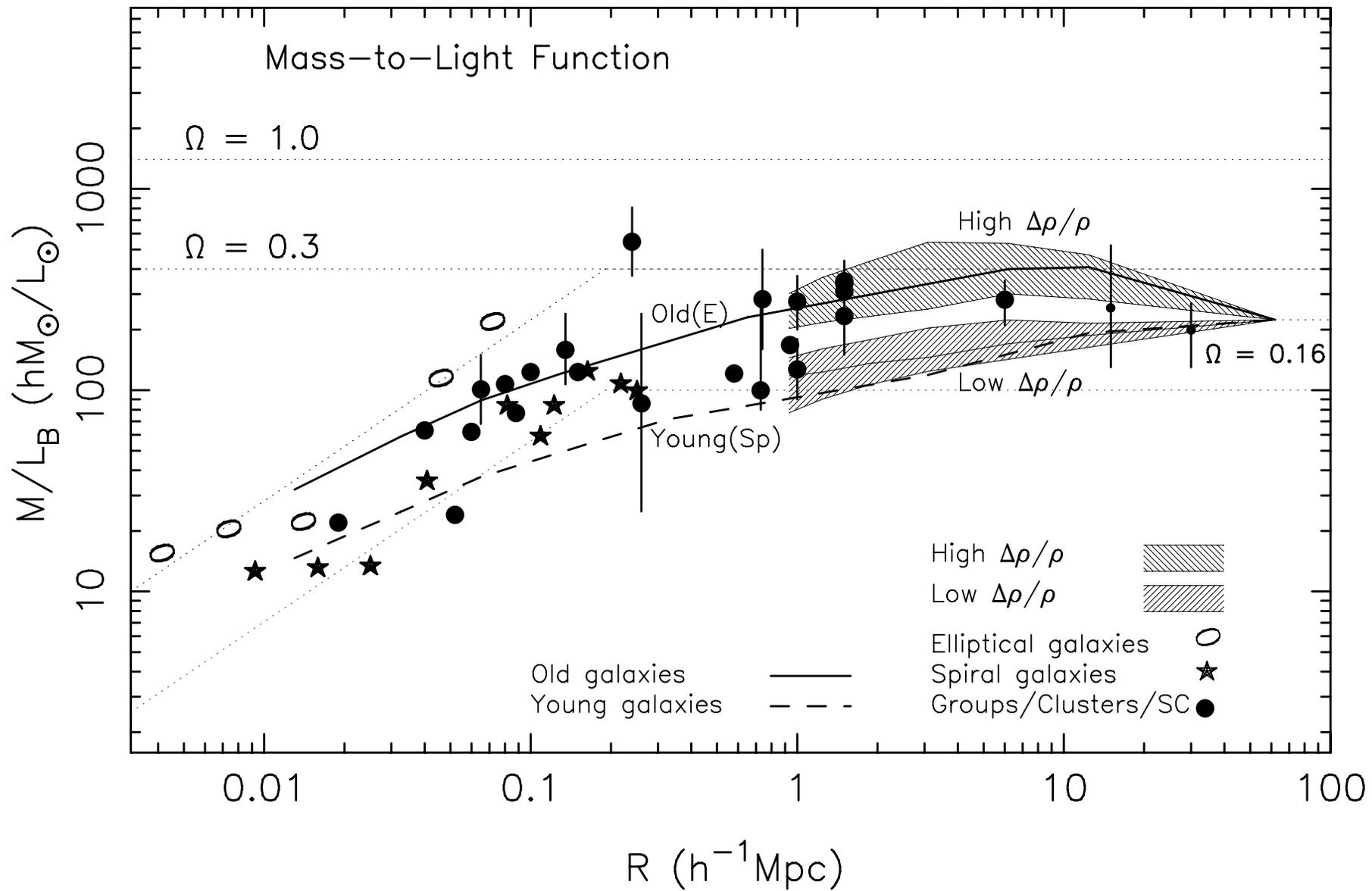
CMB fluctuations (100-1000 pc)

$$\Omega_m = 0.27 \pm 0.03 \quad \text{WMAP}$$



Rubin, Thonnard, Ford

"Such a velocity implies that 94% of the mass is located beyond the optical image; this mass has a ratio M/L_B greater than 100."



Bahcall, Cen, Davé, Ostriker, Yu

Neither dark matter nor dark energy are accounted for in our Standard Model.

Both entities challenge us:

We should provide a microscopic explanation

-- as particles --

for these constituents of the universe.

The number of astrophysical observables is limited.

For a full understanding --- the way we understand the strong and the weak interactions --- we must produce these particles in the lab.

However, dark energy and dark matter stand on very different footing.

Dark energy is truly mysterious, as I will discuss later.

Dark matter is predicted by many extensions of the Standard Model that we are already searching for in accelerator experiments.

What is required for dark matter is a new heavy particle produced in the early universe with a conserved quantum number that makes it stable for cosmological time.

Theory of such "relic" particles:

Scherrer and Turner

Boltzmann equation:
$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2)^2$$

useful variables:
$$Y = n/n_s \qquad x = m/T$$

freeze-out when
$$H \sim \langle \sigma v \rangle n_{eq}$$

then x_f is fixed by
$$1 = e^{-x_f} \left(0.04 \frac{g m_{pl} m}{g_*^{1/2} x^{1/2}} \langle \sigma v \rangle \right)$$

Henceforth, ignore Y_{eq} , follow the decrease of Y :

$$Y_\infty = 3.7 / [g_*^{1/2} m_{pl} m \int \frac{dx}{x^2} \langle \sigma v \rangle]$$

these equations lead to: (all masses in GeV)

$x_f \sim 20$ for electroweak cross sections

$$\Omega_{DM} h^2 \sim \frac{1 \times 10^9}{m_{Pl}} \frac{1}{g_*^{1/2}} \frac{x_f}{\langle \sigma v \rangle}$$

putting

$$\langle \sigma v \rangle \sim \frac{\pi \alpha^2}{m^2} \quad g_* \sim 86$$

we find

$$\Omega_{DM} h^2 \sim 9 \times 10^7 m^2$$

which gives the observed dark matter density for
 $m \sim 350$ GeV.

We already suspect that there is new physics beyond the Standard Model at $m \sim 100$ GeV.

The reason for this is that we need new physics to explain electroweak symmetry breaking.

The minimal Higgs model is a parametrization, not an explanatory theory.

To have a mechanism for electroweak symmetry breaking, we need **new ingredients** beyond the simple Higgs scalar.

Now astrophysicists tell us that those ingredients must exist !

What is the next step ? Find the particle, measure its mass, confirm the required relic matter density ?

The story may not be so simple. To see this, it is worth studying in some detail the example of **supersymmetry**.

Supersymmetry can contain a naturally conserved quantum number, **R-parity**

$$R = (-1)^{3B+L+2J}$$

such that **superpartners have R = -1**. Then **the lightest superpartner is stable**. This should be a neutral particle. The **lightest neutralino** and the **sneutrino** are possible candidates.

Start by making a very simple estimate of the dark matter density for a stable neutralino.

I assume:

the neutralino is the **superpartner of the U(1) gauge boson**
(no mixing with wino, higgsino)

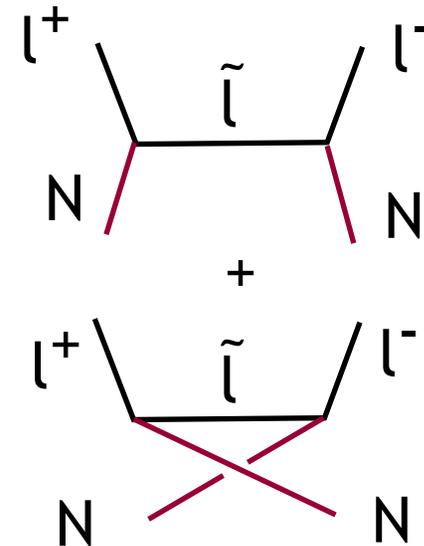
the neutralino **annihilates to leptons** ($m(\tilde{l}) \ll m(\tilde{q})$)

sleptons are degenerate and unmixed, and

$$m_N \sim m(\tilde{l}_R) \ll m(\tilde{l}_L)$$

Then

$$\sigma v = \frac{3}{32} \frac{\pi \alpha^2}{\cos^4 \theta_w} \frac{1}{m_N^2} v^2$$



from the earlier formulae, noting that $\sigma v \sim v^2$

$$\Omega_N h^2 = \frac{1 \times 10^9}{m_{\text{Pl}}} \frac{1}{g_*^{1/2}} \frac{x_f^2/3}{\langle \sigma/v \rangle}$$

propagator

then

$$\Omega_N h^2 = (\Omega_{DM} h^2) \cdot \left(\frac{m_N}{50 \text{ GeV}} \right)^2 \cdot \left[\frac{m_N^2 + m_{\tilde{\ell}}^2}{m_N^2} \right]^4$$



3 features are apparent:

We can obtain roughly the right dark matter density.

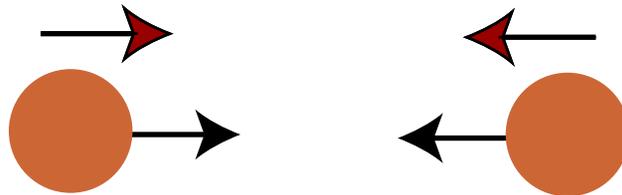
It is easy to obtain too much dark matter.

The theory has sensitive dependence and tradeoffs among parameters.

It is worth remarking on the fact that $\sigma v \sim v^2$:

Goldberg

By Fermi statistics, neutralinos annihilate in the s-wave as



This produces a spin 0 state for the final leptons



Production of this state is helicity-suppressed:

$$\sigma(\text{s-wave}) \sim m_\ell^2 / m_N^2 \ll v^2$$

This suppression can be removed by "co-annihilation":

e.g. let $m(\tilde{\tau})$ be within 10-15% of m_N . Then

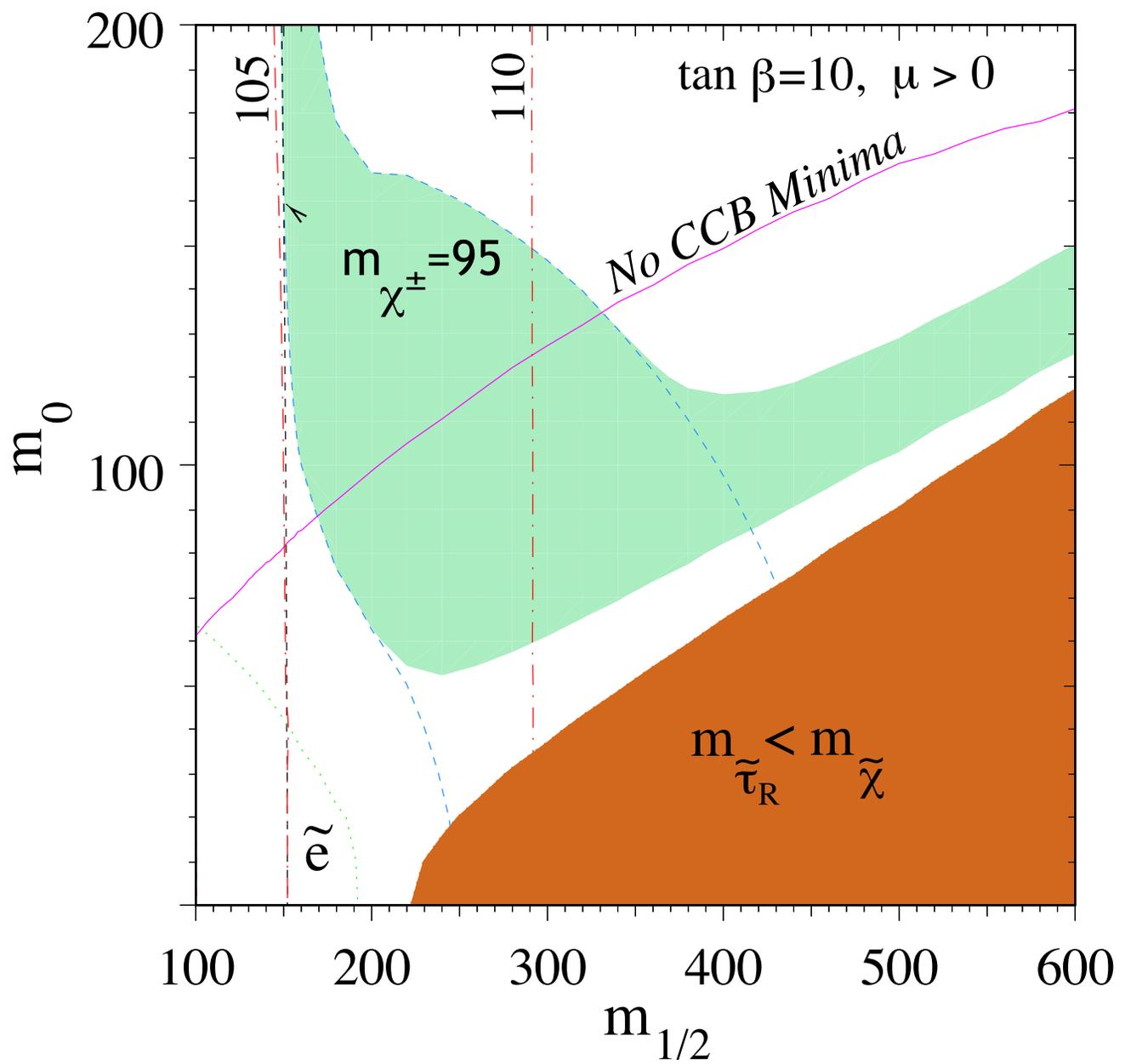
$$\frac{\sigma(\tau\bar{N} \rightarrow \tilde{\tau}\gamma)}{\sigma(\bar{N}\bar{N} \rightarrow \tau^+\tau^-)} \sim \left(\frac{T}{m_N}\right)^{3/2} e^{m_N/T} \quad \text{Greist and Seckel}$$

and N densities remain at their equilibrium ratio as both species annihilate

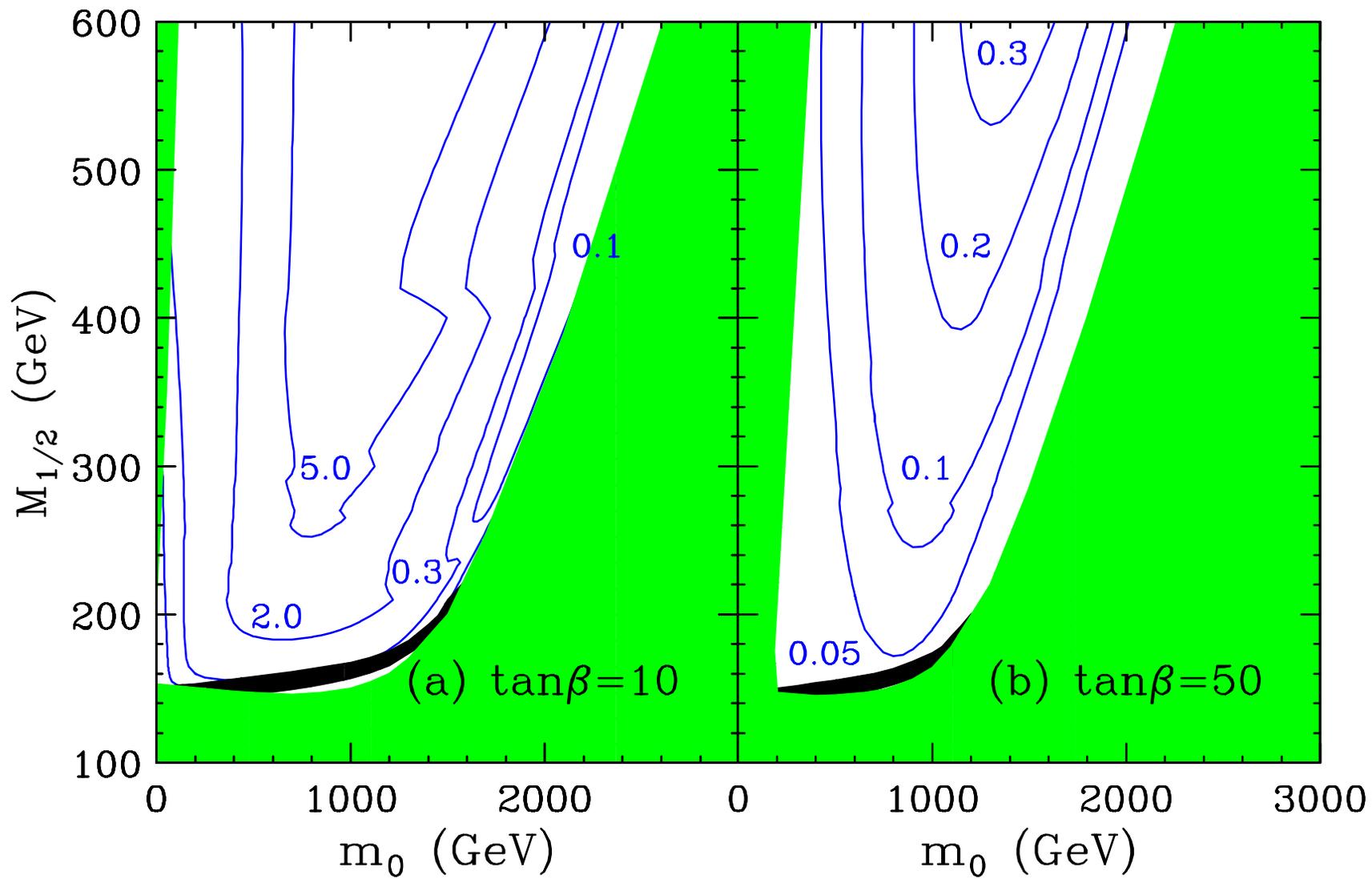
$$\tilde{\tau}\bar{N} \rightarrow \tau + \gamma, Z^0 \quad \text{is not helicity-suppressed.}$$

In this narrow band, Ω_N changes by order 1 or more.

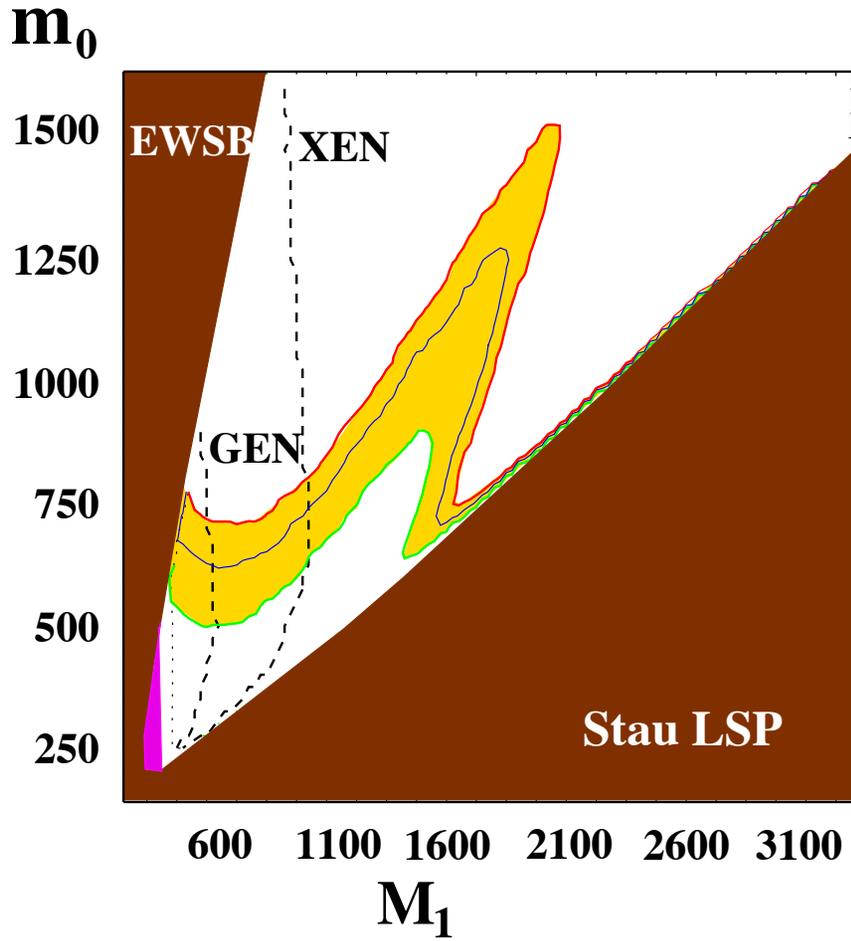
In an increasingly narrow band about $m_N \sim m(\tilde{\tau})$, both particles can become heavy while Ω_N stays constant.



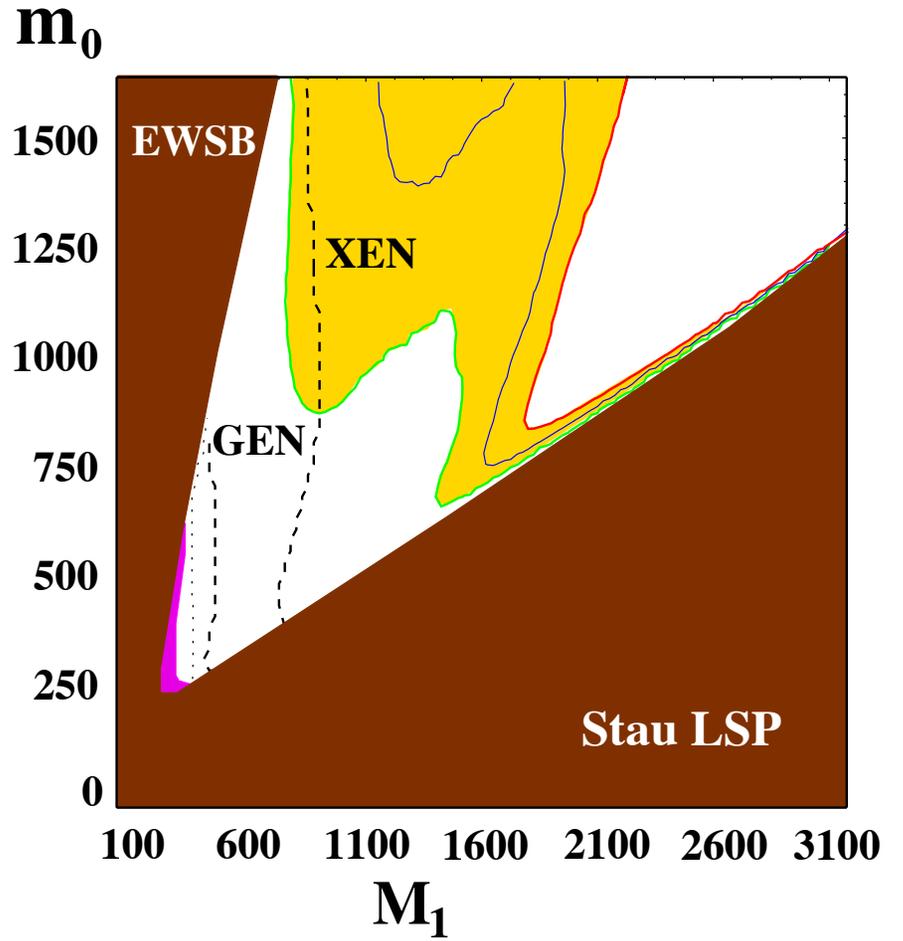
Ellis, Falk, Olive, Srednicki



Feng, Matchev, Wilczek



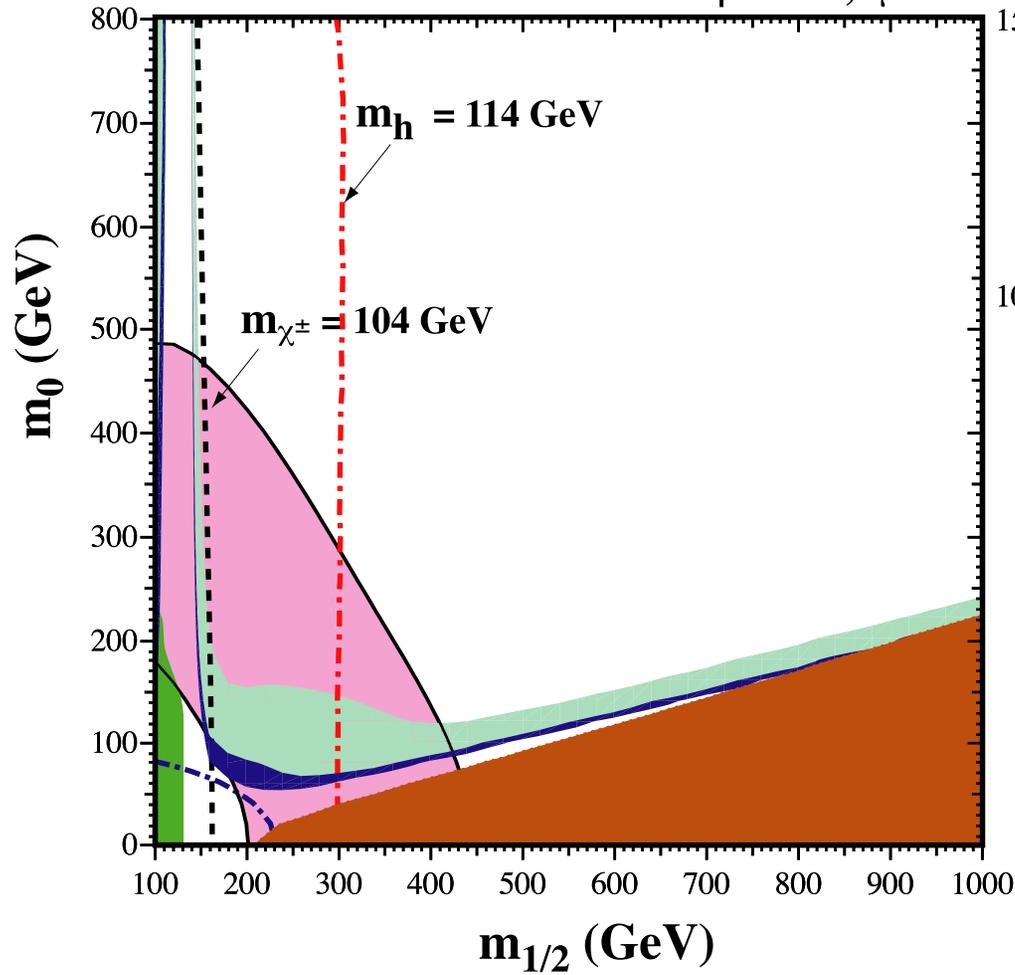
$$M_2/M_1 = 1.0$$



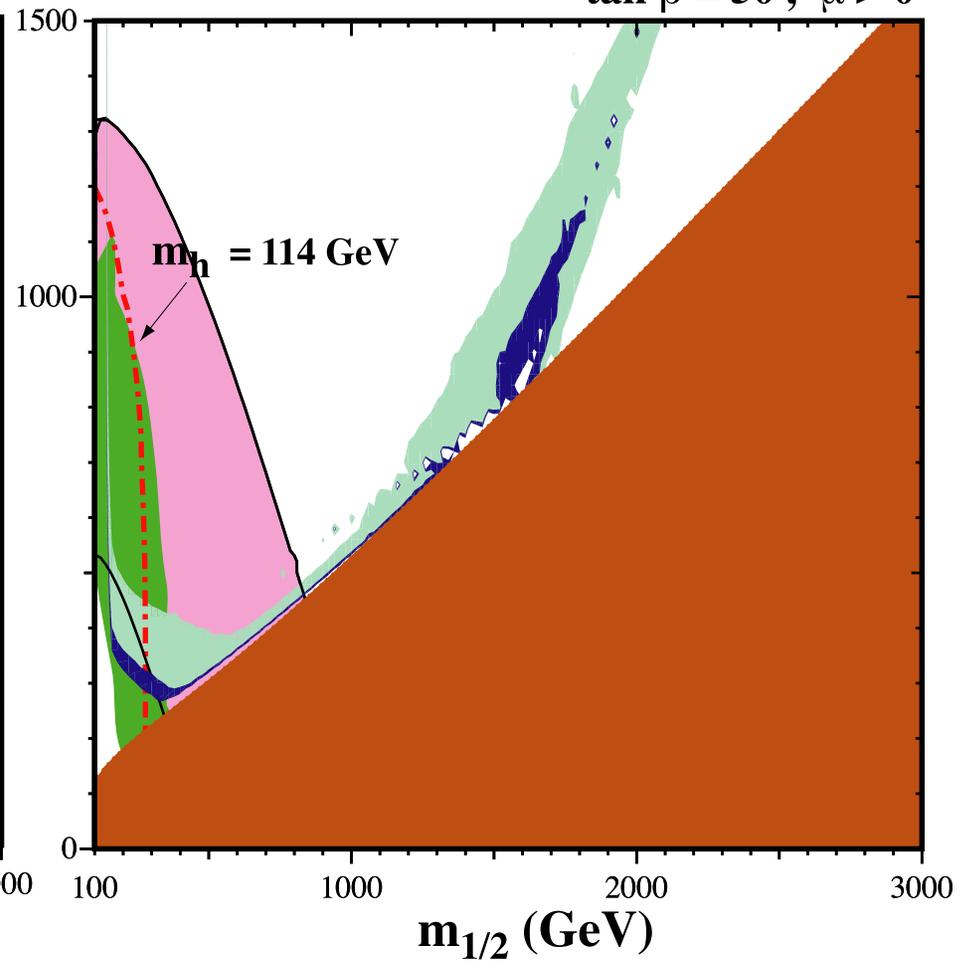
$$M_2/M_1 = 0.6$$

Birkedal-Hansen and Nelson

$\tan \beta = 10, \mu > 0$



$\tan \beta = 50, \mu > 0$



Ellis, Olive, Santoso, Spanos

How will we find the true kinetic equations that determine \square_N in Nature ?

The first step is to discovery supersymmetry at the Tevatron or LHC.

But then we will only be ready to begin.

Since SUSY is a weak-coupling theory, we do not need explicit cross section measurements as a function of energy. But we do need to determine the relevant parameters of the SUSY Lagrangian with high precision.

It is important to note that the parameters on which σ_N depends most sensitively

$$m_N, \quad m(\tilde{\tau}), \quad m(\tilde{l}), \quad m_1/m_2,$$

and mixing angles of N and $\tilde{\tau}$

are just those that are most difficult to measure at the LHC.

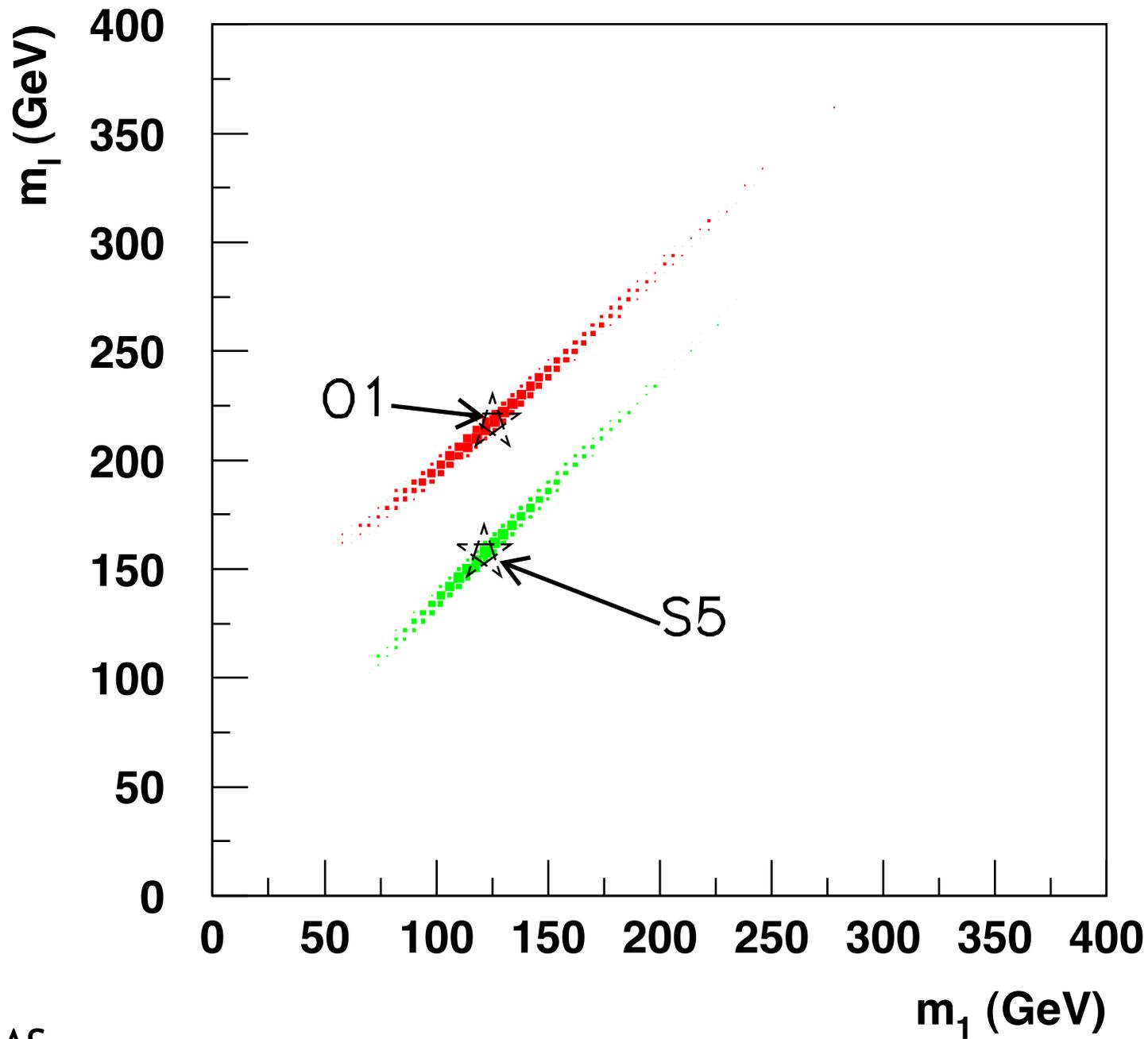
On the other hand, the e^+e^- linear collider reactions

$$e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}^- \rightarrow \tau^+\tilde{N}\tau^-\tilde{N}$$

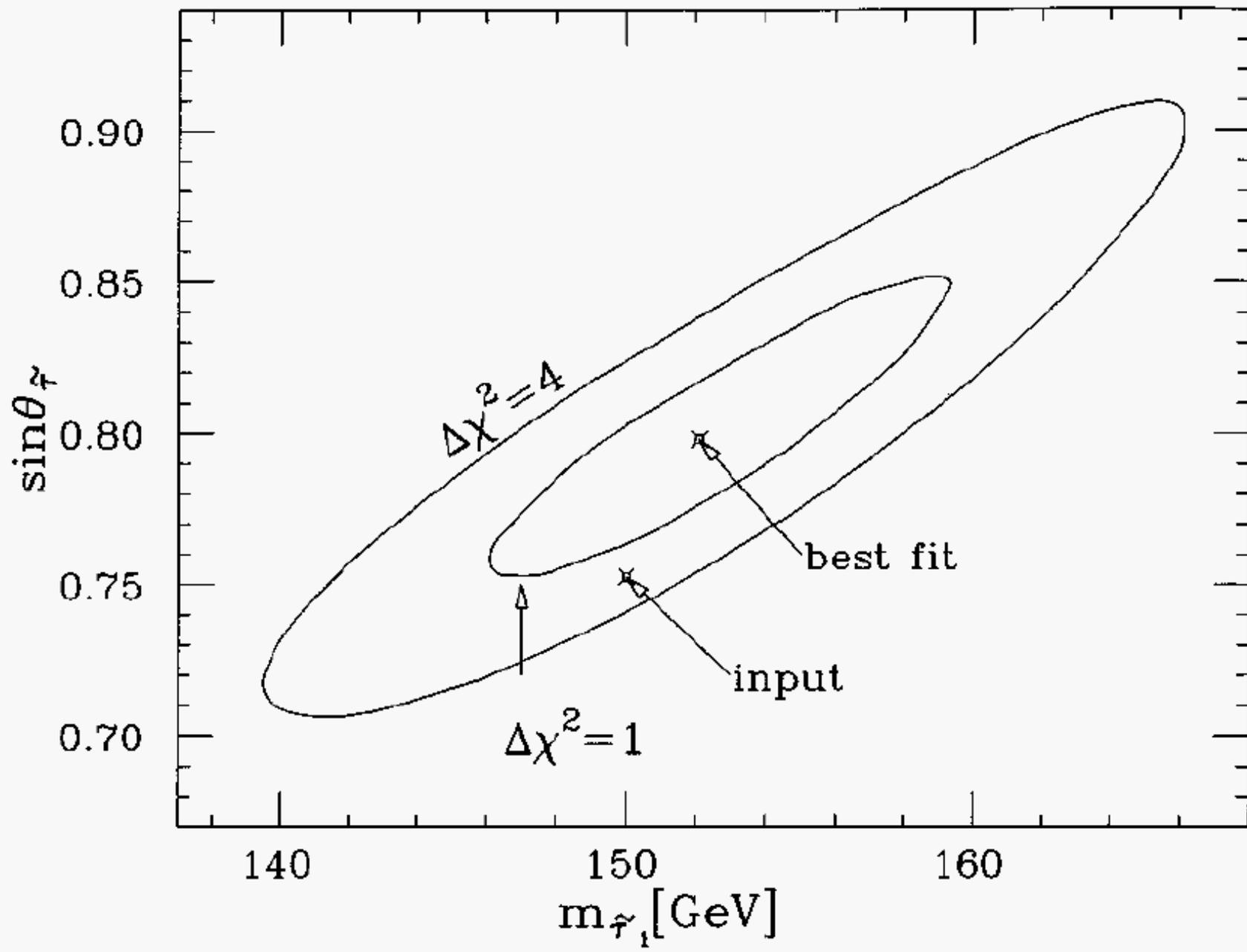
$$e^+e^- \rightarrow \tilde{e}^+\tilde{e}^- \rightarrow e^+\tilde{N}e^-\tilde{N}$$

access the same parameters that are important for neutralino annihilation.

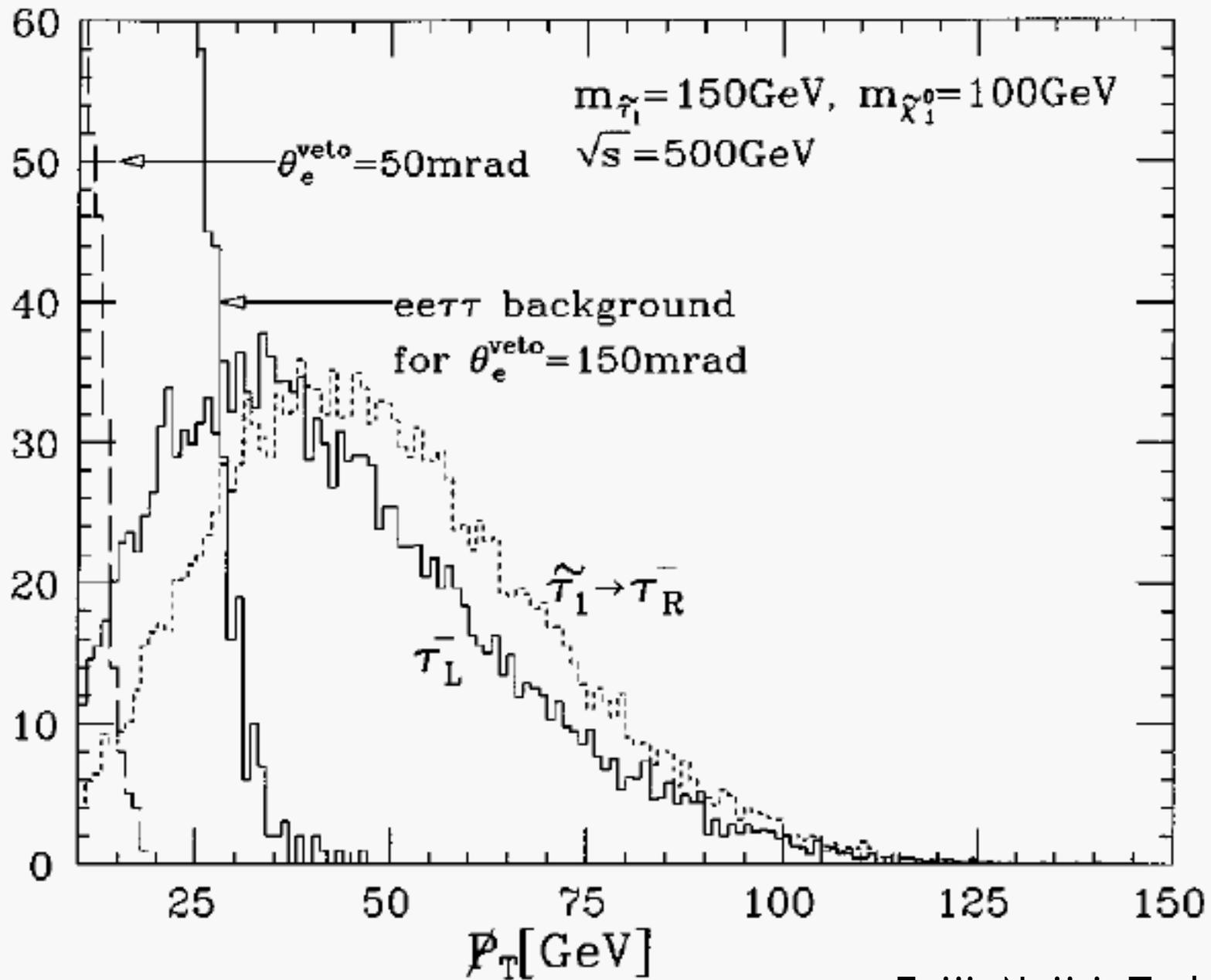
Fujii, Nojiri, Tsukamoto
Dutta, Kamon



ATLAS



\cancel{P}_T Distribution of Signal and Background



SUSY is an illustration of how the solution to the problem of electroweak symmetry breaking can also provide a solution to the problem of dark matter.

But it is not unique in this respect.

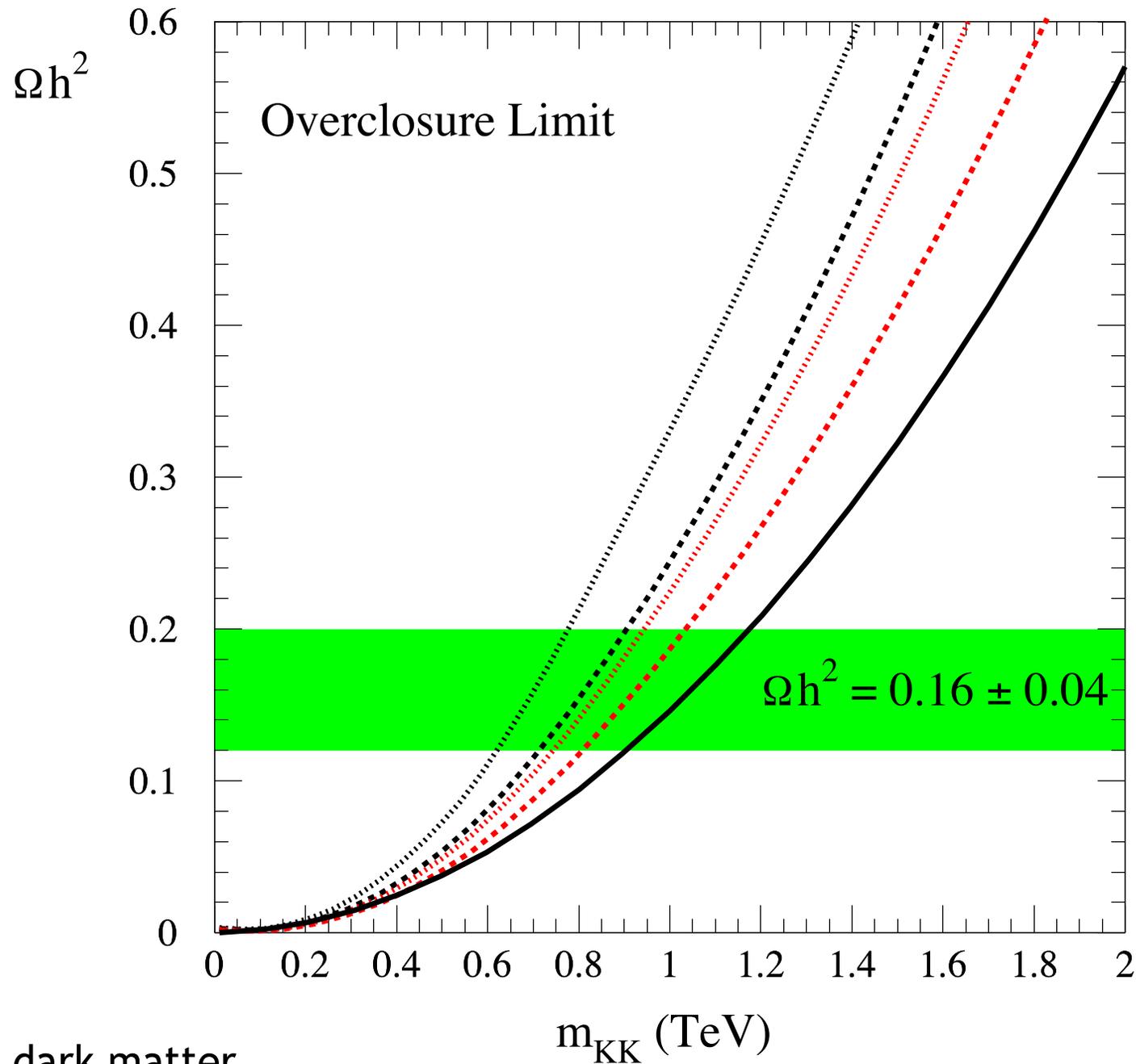
TeV-scale "universal" extra dimensions provide an alternative:

new particles: Kaluza-Klein excitations

$$m_n^2 = p_5^2 = \left(\frac{2\pi n}{L}\right)^2$$

conserved quantity: KK parity P_5

dark matter candidates: γ_1 or B_1 , ν_1



B₁ dark matter

Servant and Tait

Again, the experimental particle physics needed to understand the physics of the dark matter density is challenging.

All particles with $n = +1, -1$ are approximately degenerate, so co-annihilation is an important issue.

Cheng, Matchev, and Schmaltz have called this scenario "bosonic supersymmetry"

because the general properties of collider reactions strongly resemble those of SUSY. To distinguish the cases, it is important to measure the spins of the new particles.

Both of these features call for precision measurements at an e^+e^- linear collider.

It is also important to be aware that there is one type of model for dark matter in which there are no important signatures at accelerators:

a particle produced at high density in an early epoch by vacuum orientation or high-dimension operators, e.g.

axion or moduli dark matter

Dark energy:

For dark energy, it is more difficult to point to a specific role for accelerator experiments,

because theorists find this question **totally baffling**

We measure

$$\Lambda_0 = [2 \times 10^{-3} \text{ eV}]^4$$

We do not understand why phase transitions that we know took place in the early universe do not contribute:

$$\begin{array}{ll} \text{EWSB} : & \Delta\Lambda_H \sim (100 \text{ GeV})^4 \sim 10^{54} \Lambda_0 \\ \chi\text{SB} : & \Delta\Lambda_\chi \sim (300 \text{ MeV})^4 \sim 10^{44} \Lambda_0 \end{array}$$

Explanations for dark energy with a scalar field that will relax to zero energy density ("quintessence") require that this field be **highly decoupled from the Standard Model**:

e.g., if

$$\frac{1}{\alpha_s(Q)} = \frac{1}{\alpha_s(U)} + \frac{b_0}{2\pi} \log \frac{Q}{m_U} + a \frac{\phi}{m_{\text{Pl}}}$$

we find

$$\Lambda_{QCD} \sim \exp\left[\frac{2\pi}{b_0} a \frac{\phi}{m_{\text{Pl}}} \right]$$

so that

$$\Delta\Lambda_\chi \sim 10^{44} \left(1 + 3.3a \frac{\phi - \phi_0}{m_{\text{Pl}}} \right) \cdot \Lambda_0$$

Nevertheless, there are two positive things to say:

First, models of quintessence, Λ relaxation
--- and also models of inflation ---
require very flat potentials.

In quantum field theory, it is not trivial to have flat potentials;
this is the gauge hierarchy problem.

Mechanisms for making potentials flat include:

supersymmetry -- moduli have exact degeneracies

extra dimensions -- branes can have potentials
exponentially small in their separation

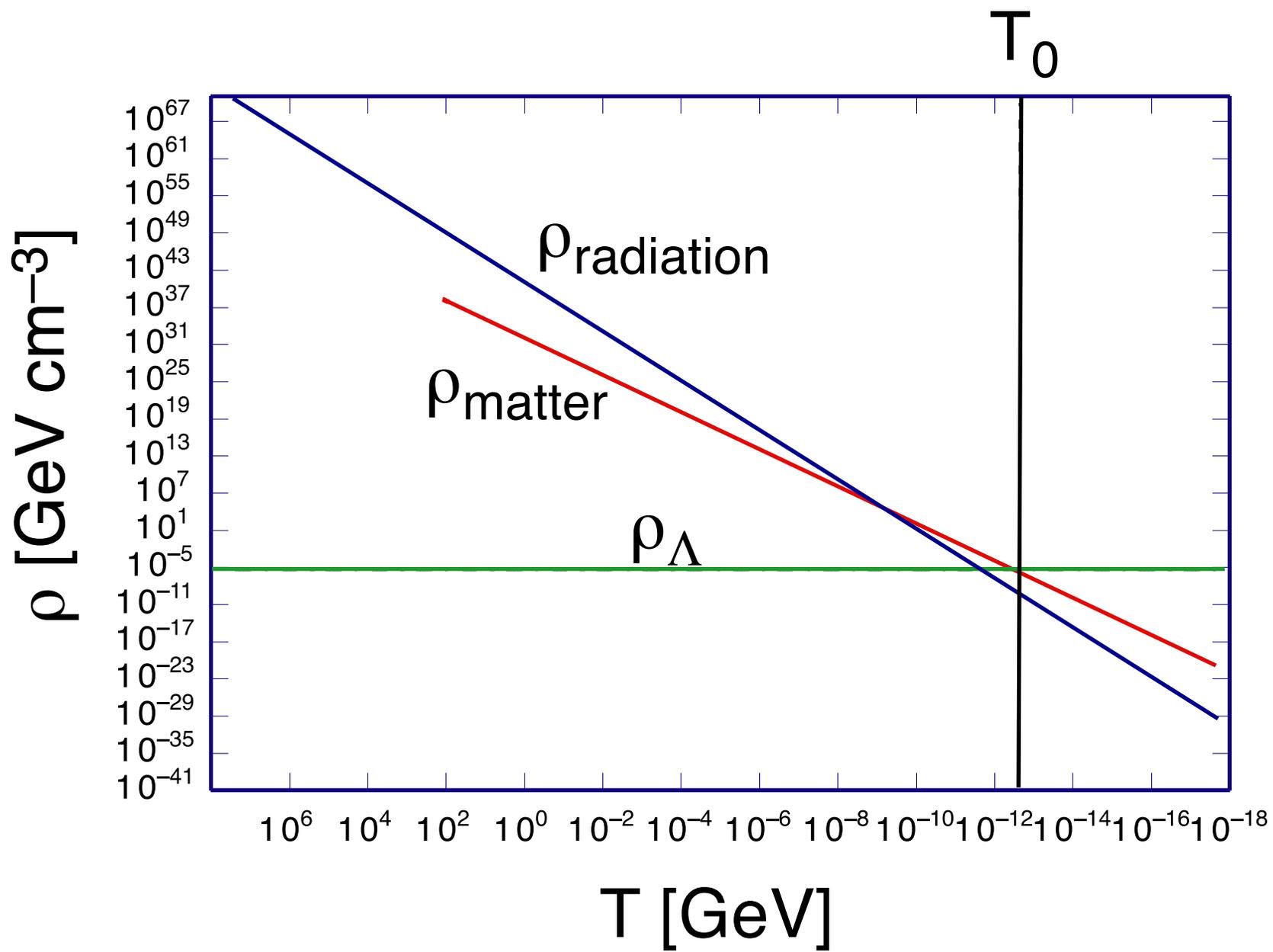
Discovery of either of these phenomena at the 100 GeV energy
scale would tell us what track we should be on.

The second comes from an often-heard question:

Why are we now at the special time in cosmology when

$$\Omega_m \sim \Omega_\Lambda \quad ?$$

In fact, on a larger scale, there is a **triple coincidence**, since, only recently, radiation dominated.



Arkani-Hamed, Hall, Kolda, Murayama

Arkani-Hamed, Hall, Kolda, Murayama propose an explanation along the following lines. Parametrically:

radiation-dominated era:

$$\rho \sim T^4$$

matter-dominated era:

$$\rho \sim m \cdot \left(\frac{m^2}{m_{\text{Pl}} \langle \sigma v \rangle} \right) \cdot \left(\frac{T}{m} \right)^3$$

$$\rho \sim \frac{m_{EW}^2}{m_{\text{Pl}}} T^3$$

AHKM propose that there is a similar formula for the cosmological constant:

$$\rho \sim \left(\frac{m_{EW}^2}{m_{\text{Pl}}} \right)^4$$

$$\frac{m_{EW}^2}{m_{\text{Pl}}} \sim 10^{-3} \text{ eV}$$

The reason for the coincidence is that both ρ_m and ρ_Λ are determined by the electroweak scale.

In the past, laboratory measurements of particle masses and cross sections have had a **strong symbiotic interaction** with cosmology.

We can expect this relationship to continue as we explore the physics of electroweak symmetry breaking. We look forward to

Discovery of the dark matter particle

Parameter measurements for the kinetic theory of dark matter abundance

Clues to the origin of dark energy