The inert Higgs doublet model

Preparatory talk for Michael Gustafsson

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December 06, 2012

Part I
The inert doublet model

Two observations & the standard view

1. **Hierarchy problem:**
   - The Higgs mass (m_h) gets quadratically divergent loop contributions
   - Main one from the t quark: $\delta m_h^2 \simeq m_h^2$ if the cutoff $\Lambda_t \lesssim 3.5 m_h$
   - To avoid fine-tuning, new physics (*e.g.*, SUSY) must be introduced to cancel δm_h^2

2. **Electroweak precision tests (EWPT):**
   - These point to a light Higgs, with $m_h < 186$ GeV
   - Today we think that the Higgs is (apparently) indeed light, with $m_h \simeq 125$ GeV (so $\Lambda_t \approx 400$ GeV)

1 + 2 lead to the standard view:
divergence-cancelling new physics should be accessible at the LHC

An alternative: a heavy Higgs?

Is a heavy Higgs (~ 500 GeV) possible anyway?
(After all, the 125 GeV resonance might be something else, or a (*very* rare) fluctuation)

With a heavy Higgs ...

- Higher "naturalness" cutoff (*i.e.*, where $\delta m_h^2 \approx m_h^2$) at $\Lambda_t \gtrsim 1.5$ TeV
- Need a modified electroweak theory below Λ_t that allows a heavy Higgs to bypass the EWPT ...
- ... while keeping naturalness and perturbativity

Solution:
introduce an inert doublet scalar,
i.e., a second Higgs without a vev or coupling to matter

Let us look first at the SM with a heavy Higgs ▶

Improved naturalness

- The SM is highly sensitive to the UV cutoff via m_h
- The energy scale at which the divergence-cancelling physics should appear can be estimated by

$$m_h^2 \simeq \delta m_h^2 \qquad \text{("naturalness condition")}$$

with the one-loop quadratic contribution

$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2$$

$$\alpha_t = \frac{3m_t^2}{4\pi^2 v^2} \, , \quad \alpha_g = -\frac{6m_W^2 + 3m_Z^2}{16\pi^2 v^2} \, , \quad \alpha_h = -\frac{3m_h^2}{16\pi^2 v^2}$$

- v: Higgs vev (174 GeV)
- Λ_i: cutoffs on momenta of virtual t, gauge bosons, Higgs

$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2$$

Demanding that, individually,

$$|\alpha_i| \, \Lambda_i^2 \lesssim m_h^2 \ ,$$

is equivalent to demanding low sensitivity of m_h^2 to cutoffs, *i.e.*,

$$\left| \frac{\partial \log m_h^2}{\partial \log \Lambda_i^2} \right| = \frac{|\alpha_i| \, \Lambda_i^2}{m_h^2} \lesssim 1$$

These result in (at saturation)

$$\Lambda_t \simeq 3.5 m_h \ , \quad \Lambda_g \simeq 9 m_h > \Lambda_t \ , \quad \Lambda_h \approx 1.3 \text{ TeV}$$

	m_h	Λ_t	observable at LHC?
Light Higgs	125 GeV	400 GeV	yes
Heavy Higgs	$\gtrsim 400$ GeV	$\gtrsim 1.4$ TeV	yes (unless m_h too large)

How high can m_h be? – perturbativity

- The quartic interaction $\lambda |H|^4$ becomes stronger with m_h
- One-loop RG equation for the coupling λ:

$$\frac{d\lambda}{d\ln\Lambda} = \frac{3\lambda^2}{2\pi^2} + \text{(smaller gauge boson, top contributions)}$$

- λ evolves as

$$\lambda(\Lambda) = \frac{\lambda_{\text{phys}}}{1 - \frac{3\lambda_{\text{phys}}}{2\pi^2}\ln\frac{\Lambda}{1.36 m_h}}$$

with $\lambda_{\text{phys}} \equiv \lambda(1.36 m_h) = m_h^2/(4v^2)$

- It blows up at the Landau pole

$$\Lambda_L = 1.36 m_h \exp\left(\frac{2\pi^2}{3\lambda_{\text{phys}}}\right)$$

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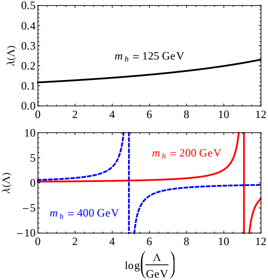

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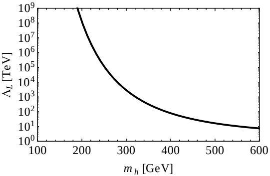
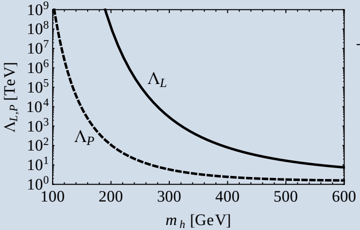


- However, perturbativity breaks down before Λ_L
- We define the perturbativity scale Λ_P at which the one-loop correction to λ reaches 30% of the tree-level value,

$$\Lambda_P = 1.36 m_h \exp\left(0.3 \frac{2\pi^2}{3\lambda_{\text{phys}}}\right)$$

- Require that $\Lambda_P > 1.5$ TeV
- For $m_h \lesssim 600$ GeV, we are safe:



m_h [GeV]	Λ_P [TeV]	Λ_L [TeV]
125	2.4×10^{21}	7.5×10^6
400	2.4	80
500	1.8	16
600	1.6	7.5

Electroweak precision tests

- How about the EWPT, which predict a light Higgs?

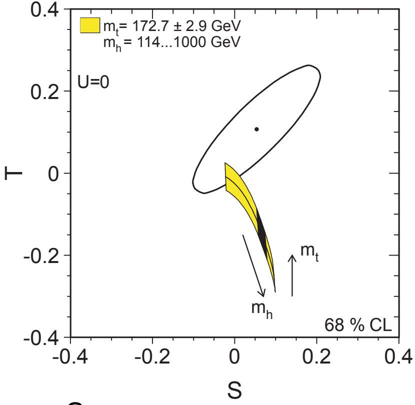
Peskin-Takeuchi parameters (S, T, U): measurable quantities that parametrise potential new physics contributions to EW radiative corrections

- Defined in terms of the self-energies of the γ, Z, and W
- Reference: $S = T = U = 0$ for the SM
- EWPT affected by m_h through contributions to S, T:

$$T \simeq -\frac{3}{8\pi c^2} \ln \frac{m_h}{m_Z} \quad , \qquad S \simeq \frac{1}{6\pi} \ln \frac{m_h}{m_Z}$$

- From fits to S, T, one expects a light Higgs: $m_h \lesssim 200$ GeV

BARBIERI, HALL, RYCHKOV, PRD **74**, 015007 (2006)



- $m_h = 400$ GeV excluded at 99.9% C.L.
- However, a heavy Higgs *can* be consistent with EWPT *if* there is new physics that:
  1. produces a compensating $\Delta T > 0$; and
  2. a small ΔS
- For $m_h = 400 - 600$ GeV, we need

$$\Delta T \approx 0.25 \pm 0.1$$

So,

> if H is heavy, there must be new physics that produces ΔT
> – this is the new physics that the LHC would study

The model

Add to the SM a doublet H_2 which is invariant under $\mathbb{Z}_2$, *i.e.*,

$$H_2 \to -H_2$$

New potential:

$$V = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

- H_1 is the SM Higgs
  – acquires a vev and gives masses to W, Z, and fermions
- H_2 is an inert doublet
  – does **not** acquire a vev or couples to fermions, but **has** weak and quartic interactions

V bounded from below

$\Rightarrow$ the minima, $H_1 = (0,\ v)$, $H_2 = (0,\ 0)$, are global and stable

We perturb them as

$$H_1 = \begin{pmatrix} \phi^+ \\ v + (h + i\chi)/\sqrt{2} \end{pmatrix} \quad , \quad H_2 = \begin{pmatrix} H^+ \\ (S + iA)/\sqrt{2} \end{pmatrix}$$

Scalar spectrum:

SM Higgs	h	$m_h \approx 400 - 600$ GeV	$\lambda_1 = m_h^2 / \left(4v^2\right) \approx 2$
charged inert	$H^\pm$	$m_H^2 = \mu_2^2 + \lambda_H v^2$	$\lambda_H = \lambda_3$
neutral inert	S	$m_S^2 = \mu_2^2 + \lambda_S v^2$	$\lambda_S = \lambda_3 + \lambda_4 + \lambda_5$
neutral inert	A	$m_A^2 = \mu_2^2 + \lambda_A v^2$	$\lambda_A = \lambda_3 + \lambda_4 - \lambda_5$

Seven parameters:

$$\underbrace{m_h\ ,\ \ m_H\ ,\ \ m_A\ ,\ \ m_S}_{\text{physical masses}}\ ,\ \ v\ ,\ \ \lambda_2\ ,\ \ \lambda_3$$

The Lightest Inert Particle (LIP)

- Since the $\mathbb{Z}_2$ parity is unbroken, the lightest inert particle (LIP) will be stable …
- … and constitute a dark matter candidate
- To avoid conflicts with the stringent limits on charged relics, it is assumed that the LIP is neutral

$\therefore$ LIP $= A$ or S, with mass $m_{\mathsf{L}} = m_A$ or m_S

Making the IDM perturbative

- λ_2 affects only the self-interactions between inert particles – assume $\lambda_2 \lesssim 1$
- The SM w/ 500 GeV Higgs is perturbative up to ~ 1.8 TeV – we want the same for the IDM
- To achieve this, in the RGE of λ_1,

$$16\pi^2 \frac{d\lambda_1}{d\log\Lambda} = 24\lambda_1^2 + 2\lambda_3^2 + 2\lambda_3\lambda_4 + \lambda_4^2 + \lambda_5^2 \ ,$$

we make the extra terms $\leq 50\%$ of the SM term $24\lambda_1^2$, *i.e.*,

$$\left|2\lambda_3\left(\lambda_3+\lambda_4\right)+\lambda_4^2+\lambda_5^2\right| \lesssim 50$$

- $\Delta T > 0$ will need additionally $\lambda_4 < 0$ and λ_5 small, *i.e.*,

$$|\lambda_4| \lesssim \lambda_3 \lesssim 7$$

Making the IDM natural

- The IDM is also a natural theory only up to some cutoff
- One-loop quadratic corrections to m_h^2:

$$\text{SM:} \qquad \delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2$$

$$\text{IDM:} \qquad \delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_{11} \Lambda_{H_1}^2 + \alpha_{12} \Lambda_{H_2}^2$$

$$\alpha_{11} = -\frac{3\lambda_1}{4\pi^2} \;, \quad \alpha_{12} = -\frac{2\lambda_3 + \lambda_4}{8\pi^2} \;, \quad \alpha_{t,g} \text{ as before}$$

- Naturalness ($\delta m_h^2 \approx m_h^2$) conditions for the first three terms:

for $m_h \gtrsim 400$ GeV: $\Lambda_t \simeq \Lambda_g \gtrsim 1.5$ TeV , $\Lambda_{H_1} \approx 1.3$ TeV

– in analogy, we also demand $\Lambda_{H_2} \gtrsim 1.5$ TeV

- Requiring that $\alpha_{12} \Lambda_{H_2}^2 \lesssim m_h^2$ constrains

$$|2\lambda_3 + \lambda_4| \lesssim 9$$

Satisfying the electroweak precision tests

- Recall the heavy Higgs contribution to T:

$$T \simeq -\frac{3}{8\pi c^2} \ln \frac{m_h}{m_Z}$$

- Compensated by the contribution from the inert doublet:

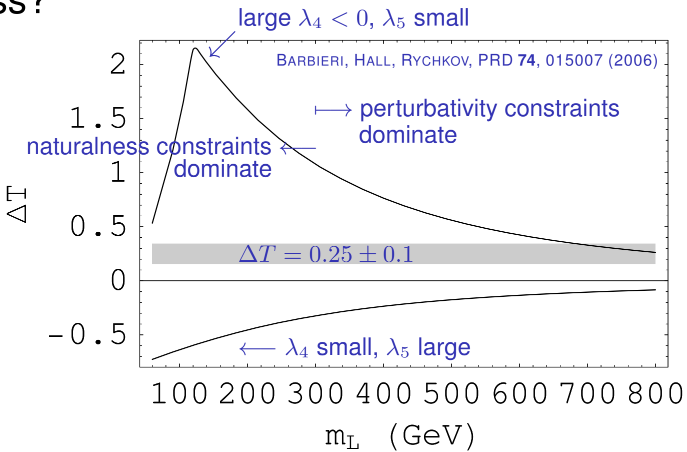
$$\Delta T \simeq \frac{1}{24\pi^2 \alpha v^2} \left(m_H - m_A\right) \left(m_H - m_S\right)$$

- Requiring that $\Delta T = 0.25 \pm 0.1$ constrains the spectrum,

$$\left(m_H - m_A\right) \left(m_H - m_S\right) = \left(120^{+20}_{-30}\right) \text{ GeV}^2$$

- H must be heavier than A and S in order for $\Delta T > 0$
- $|\Delta S| \lesssim 0.04$ for $m_{A,S} = 100 - 800$ GeV

Success?



Yes – in a large region of the parameter space, $\Delta T > 0$ and is of the typical size needed to compenste for the heavy Higgs

Production and decay of the inert particles – *at LEP*

- $\mathbb{Z}_2$ conserved $\Rightarrow$ inert particles can only be pair-produced
- The production cross section at LEP was

$$\sigma\left(e^+e^- \to SA\right) = \left(\frac{g}{2c_W}\right)^4 \left(\frac{1}{2} - 2s_W^2 + 4s_W^4\right) \frac{1}{48\pi s} \frac{\left(1 - 4m^2/s\right)^{3/2}}{\left(1 - m_Z^2/s\right)^2}$$
$$\approx 0.2 \text{ pb}$$

for $\sqrt{s} = 200$ GeV (assuming $\Delta m \equiv m_{\text{NL}} - m_{\text{L}} \ll m_{\text{L}}$)

- Let A be the heavier state; so

$$A \to S + Z^* \to \text{ dilepton events} + \text{ missing energy}$$

For $\Delta m \lesssim 10$ GeV, σ is below the limits set by LEP2

Production and decay of the inert particles – *at LHC*

Production: $\begin{cases} pp \to W^* \to HA \text{ or } HS \\ pp \to Z^* (\gamma^*) \to SA \text{ or } H^+H^- \end{cases}$

Decay: $\begin{cases} H \to AW \text{ or } SW \\ A \to SZ^{(*)} \end{cases}$

- Best signal: final state with charged leptons
- For $m_h = 400 - 600$ GeV and $m_{\text{L}} = 60 - 75$ GeV:
  - HA, HS production:

$$\left.\begin{array}{l} \sigma\,(pp \to HA \text{ or } HS) \approx 0.25 \text{ pb} \\ \text{BR}\,(\geq 3e \text{ or } \geq 3\mu) \approx 1.5\% \end{array}\right\} \sigma_{\text{signal}} \approx 3.5 \text{ fb}$$

  - H^+H^- production: $\sigma_{\text{signal}} \approx 0.35$ fb
- Background WW $(\to e, \mu)$ and ZZ $(\to \tau^+\tau^- \to e, \mu)$: $\sigma_{\text{bg}} \approx 20$ fb

$\therefore$ Luminosity $\mathcal{L} \sim 30$ fb^{-1} needed (currently, 21 fb^{-1} collected)

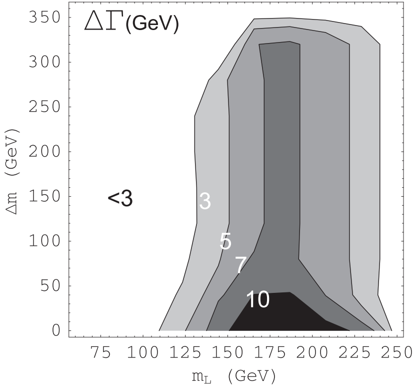
The Higgs width

- Existence of new states inferred indirectly from increase of the width of h
- New decay channels:

$$h \to SS, AA, H^+H^-$$

- Width of a 500 GeV SM Higgs: $\Gamma_{\text{SM}} \approx 68$ GeV
- Increase in the width of h:

BARBIERI, HALL, RYCHKOV, PRD **74**, 015007 (2006)



$$\Delta\Gamma = \frac{v^2}{16\pi m_h}\left[\lambda_S^2\left(1-\frac{4m_S^2}{m_h^2}\right)^{1/2} + \lambda_A^2\left(1-\frac{4m_A^2}{m_h^2}\right)^{1/2} + 2\lambda_3^2\left(1-\frac{4m_H^2}{m_h^2}\right)^{1/2}\right]$$

If $\Delta\Gamma \gtrsim 0.1\Gamma_{\text{SM}} \approx 7$ GeV, LHC might observe it

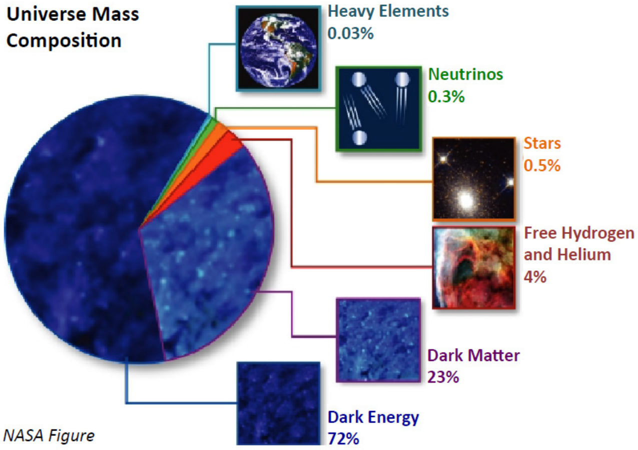
Summary – Part I

- Although data point to a light Higgs ($m_h \lesssim 186$ GeV), a heavy Higgs ($m_h \gtrsim 400$ GeV) is possible
- It forces a shift in the EW precision observables T, $S \dots$
- ... which, in the inert doublet model (IDM), is compensated by a new doublet (vev-less, inert)
- Four inert scalars added (two charged, two neutral)
  – possible dark matter candidates (see Part II)
- Most promising collider signal: trilepton + missing energy
- LHC might be able to observe / constrain the IDM
  – see talk by Michael Gustafsson next week

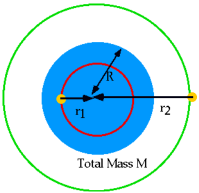
Part II
Dark matter and the inert doublet

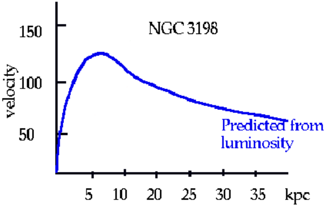
What is dark matter?

What is dark matter?



Rotation curves





http://people.physics.carleton.ca/~watson/Physics/Astrophysics/galaxies/4901_galaxies3.html

Predicted from Keplerian law:

$$v = \sqrt{\frac{GMr^2}{R^3}}$$

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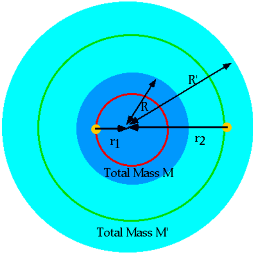

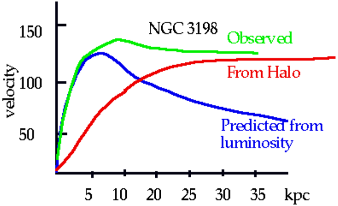

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Predicted from Keplerian law:

$$v = \sqrt{\frac{GMr^2}{R^3}}$$

But: observed is a flat curve
Explanation: matter M' in the halo that is not observed

$$v = \sqrt{\frac{GM}{r} + \frac{GM'r^2}{R'^3}}$$

Dark matter (DM) is needed to explain the flat rotation curve of galaxies (Rubin *et al.*, 1980)

- DM constitutes $\sim 80\%$ of the matter in the Universe
- Nonbaryonic DM are based on the Cold Dark Matter hypothesis (CDM = slow, weakly interacting matter)
- Possible constituents:
  - **Axions:** very light particles with a specific type of self-interaction; solve the strong CP problem in QCD, not detected
  - **MACHOs:** Massive Compact Halo Objects (*e.g.*, BH, NS, WD, very faint stars, planets)
  - **WIMPs:** **Weakly Interacting Massive Particles**; no currently known particle
  - **LIP:** **Lightest Inert Particle**

The inert doublet model and DM

LIP as a CDM candidate:

- For $m_{\mathrm{L}} \gtrsim m_W$:
  - includes most of the region of parameter space by naturalness
  - annihilation into gauge bosons
  - cross section $\sigma_{\mathrm{ann}} v_{\mathrm{rel}} \sim 100 - 130\,\mathrm{pb}$ for $m_{\mathrm{L}} \sim 400\,\mathrm{GeV} - m_W$
  - relic density $\Omega h^2 \lesssim 0.02 - 0.002$
  - LIP only a sub-dominant component of DM
- For $m_{\mathrm{L}} < m_W$:
  - thermal equilibrium is maintained via p-wave suppressed coannihilations of S and A into fermions
  - thermally averaged cross section $\langle \sigma_{\mathrm{coann}} v_{\mathrm{rel}} \rangle \sim 60 - 80\,\mathrm{pb}$ for $m_{\mathrm{L}} = 60 - 80$ GeV
  - $\Omega h^2 \approx (0.5 - 2.5) \times 10^{-2}$
- Observed value of Ωh^2: $\Delta m \approx 8 - 9\,\mathrm{GeV}$ for $m_{\mathrm{L}} = 60 - 73\,\mathrm{GeV}$

WIMPs

- Interact through the weak force and gravity
- Cannot be seen directly
- Properties like neutrinos but more massive
- Annihilation of WIMPs produces neutrinos

Abundances

- Observed cosmological abundance of DM can be explained by the chemical “freeze-out” of a thermal relic
  - thermal relic is in local thermodynamic equilibrium (LTE) at early times
  - “freeze-out”: for very small abundances, equilibrium can no longer be maintained
- Equilibrium abundance depends on the ratio of the mass of the particle to the temperature, $x = m/T$

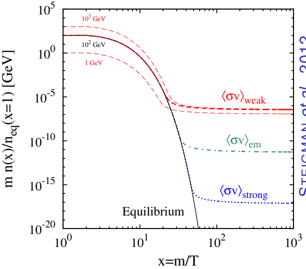
A stable WIMP χ with

- mass m
- spin 1/2 Majorana fermion
- degrees of freedom $g_\chi = 2$
- produced thermally during the early evolution of the Universe

evolves as

$$\frac{dn}{dt} + 3Hn = \frac{d(na^3)}{a^3 dt} = \langle \sigma v \rangle (n_{\mathrm{eq}}^2 - n^2)$$

- n: number density of χ's
- n_{eq}: equilibrium density
- a: cosmological scale factor
- Hubble parameter $H = a^{-1} da/dt$
- $\langle \sigma v \rangle$: cross section



STEIGMAN *et al.*, 2012

Degrees of freedom contributing to energy density:

$$g_\rho \equiv \sum_{\mathrm{B}} g_{\mathrm{B}} \left(\frac{T_{\mathrm{B}}}{T_\gamma} \right)^4 + \frac{7}{8} \sum_{\mathrm{F}} g_{\mathrm{F}} \left(\frac{T_{\mathrm{F}}}{T_\gamma} \right)^4$$

B $\equiv$ bosons, F $\equiv$ fermions

For thermodynamic equilibrium, $T_{\mathrm{B,F}} = T_\gamma$

For relativistic particles which are decoupled from the photons:

- g_ρ is associated with the total energy density
- g_s is associated with the total entropy density

$$g_s \equiv \sum_{\mathrm{B}} g_{\mathrm{B}} \left(\frac{T_{\mathrm{B}}}{T_\gamma} \right)^3 + \frac{7}{8} \sum_{\mathrm{F}} g_{\mathrm{F}} \left(\frac{T_{\mathrm{B}}}{T_\gamma} \right)^3$$

As the entropy $S \equiv sa^3$ is conserved in the absence of phase transitions, n can be replaced by $Y \equiv n/s$, *i.e.*,

$$\frac{dY}{dx} = \frac{s\langle\sigma v\rangle}{Hx}\left[1 + \frac{1}{3}\frac{d(\ln g_s)}{d(\ln T)}\right](Y_{\mathrm{eq}}^2 - Y^2)$$

Source of uncertainty and model dependence from $g\,(T)$

We can use

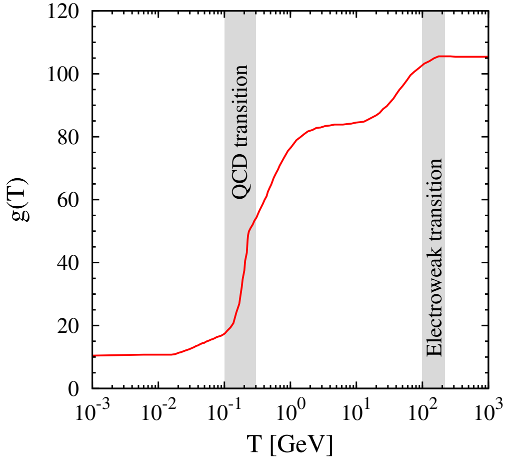
$$g = g_\rho = g_s$$

because, for

- 10 MeV $\lesssim m \lesssim 10$ TeV; and
- the particle content of the SM,

one finds that $T_{\mathrm{B}} = T_{\mathrm{F}} = T$

Effective number of interacting, relativistic degrees of freedom, $g(T)$:



STEIGMAN, DASGUPTA, BEACOM, PRD **86**, 023506 (2012)

Improved analytical treatment – early evolution

Solve

$$\frac{dY}{dx} = \frac{s\langle\sigma v\rangle}{Hx}\left[1 + \frac{1}{3}\frac{d(\ln g_s)}{d(\ln T)}\right](Y_{\text{eq}}^2 - Y^2)$$

taking into account the evolution of $g\,(T)$

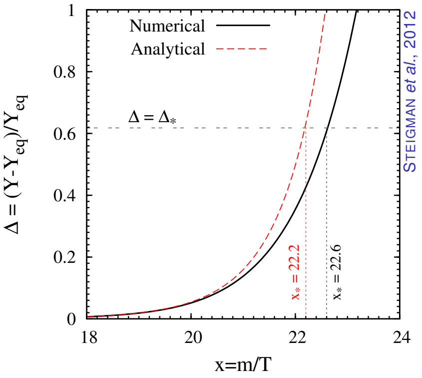
Early evolution:

- $n \approx n_{\text{eq}}$
- $Y \equiv (1+\Delta)Y_{\text{eq}}$, with Δ the departure from equilibrium

$$\frac{\Delta(2+\Delta)}{(1+\Delta)} \approx \frac{1.25\times 10^{-35} g^{1/2}}{\langle\sigma v\rangle m}\left(\frac{(x-3/2)e^x}{x^{1/2}}\right)$$

Δ : departure of the WIMP abundance from equilibrium

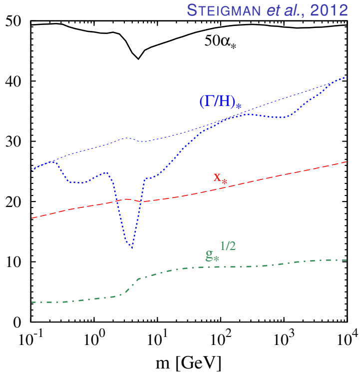
For $m = 100\,$GeV and $\langle \sigma v \rangle = 2.2 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$:



Due to approximations, the analytical value underestimates x_* by about 2%.

Intermediate matching point between early and late evolution:

$$x_* + \ln(x_* - 1.5) - 0.5 \ln x_* = 20.5 + \ln(10^{26} \langle \sigma v \rangle) + \ln m - 0.5 \ln g_*$$



No freeze–out for $x = x_*$

Approach to freeze–out:

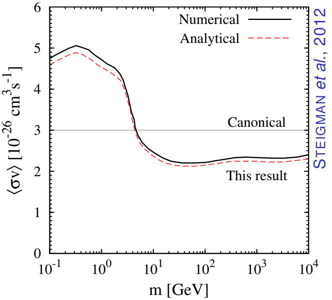
$$\frac{dY}{dx} = -\frac{s\langle \sigma v \rangle}{Hx} \left[1 + \frac{1}{3} \frac{d(\ln g)}{d(\ln T)} \right] Y^2$$

$$\frac{Y_f}{Y_*} = \frac{1}{1 + \alpha_* (\Gamma/H)_*}$$

Relic abundance

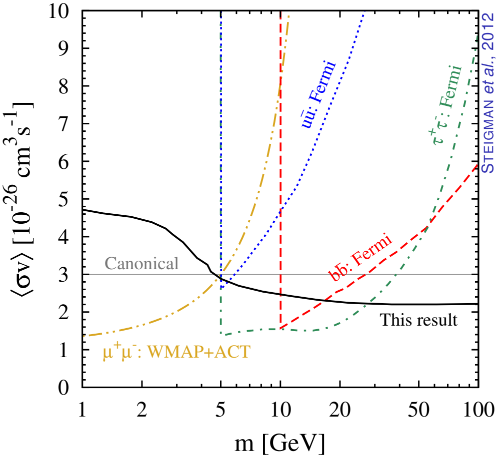
From Y_f/Y_*, we find the cosmological WIMP mass fraction $\Omega = (mY_f s_0)/\rho_{crit}$:

$$\Omega h^2 = \frac{9.92 \times 10^{-28}}{\langle \sigma v \rangle} \left(\frac{x_*}{g_*^{1/2}} \right) \left(\frac{(\Gamma/H)_*}{1 + \alpha_* (\Gamma/H)_*} \right)$$



◀ $\langle \sigma v \rangle$ as a function of WIMP mass, for relic abundance $\Omega h^2 = 0.11$

Fermi-LAT limits on thermal WIMP annihilation $\langle \sigma v \rangle$



Direct DM detection experiments

- **DAMA/LIBRA, Italy:** searching for annual variation of the number of detection due to the motion of the Earth around the Sun
- **CoGeNT, USA**
- **CRESST-II, Italy**: aiming at detection of WIMPs via elastic scattering off nuclei in CaWO4 crystals

Summary – Part II

The thermal cross section $\langle\sigma v\rangle$...

- ... can be calculated with great precision ($\lesssim$ few %)
- ... is not independent of the WIMP mass for masses $\lesssim$ 10 GeV
- ... is nearly independent of mass for larger WIMP masses
- ... is $\sim$ 40 % smaller than the canonical value usually adopted in the literature

The Lightest Inert Particle in the inert doublet model
can be a dark matter candidate

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Backup slides

Definitions of S, T, U

Defined in terms of the self-energies of the γ, Z, and W, *i.e.*,

$$\alpha S = 4 s_w^2 c_w^2 \left[\Pi'_{ZZ}(0) - \frac{c_W^2 - s_W^2}{s_W c_W} \Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0) \right]$$

$$\alpha T = \frac{1}{m_W^2} \Pi_{WW}(0) - \frac{1}{m_Z^2} \Pi_{ZZ}(0)$$

$$\alpha U = 4 s_w^2 \left[\Pi'_{WW}(0) - c_W^2 \Pi'_{ZZ}(0) - 2 s_W c_W \Pi'_{Z\gamma}(0) - s_W^2 \Pi'_{\gamma\gamma}(0) \right]$$

In practice,

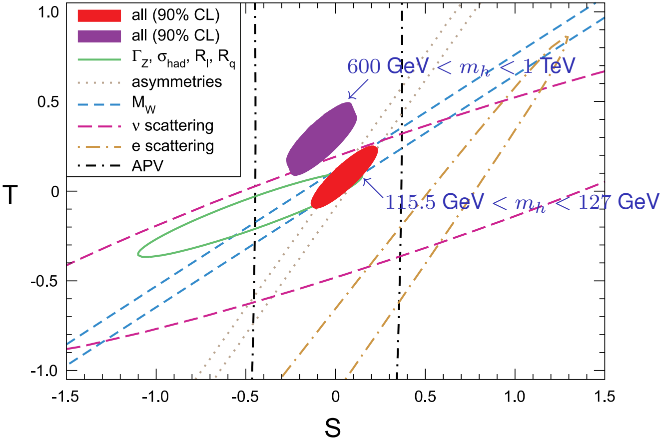
$$m_Z^2 = m_{Z0}^2 \frac{1 - \hat{\alpha}(m_Z) T}{1 - G_F m_{Z0}^2 S / 2\sqrt{2}\pi}$$

$$m_W^2 = m_{W0}^2 \frac{1}{1 - G_F m_{W0}^2 (S+U) / 2\sqrt{2}\pi}$$

m_{Z0}, m_{W0}: SM masses in terms of m_t and m_h ($\overline{\text{MS}}$ scheme)

- S, T, U describe many types of heavy physics
- Expected to be $\mathcal{O}(1)$ in the presence of new physics
- Not useful to describe new physics that couple directly to ordinary fermions
  – *e.g.*, heavy Z', mixing with exotic fermions, leptoquarks
- S: measures the difference between the number of left-handed and right-handed fermions with weak isospin
  – constrains fourth-generation fermions
- T: measures isospin violation
  – *e.g.*, mass difference between b and t
- U: most types of new physics yield $U = 0$
  – counter-example: anomalous triple gauge vertices

Updated S, T bounds



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