Astroparticle physics

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The application of the laws of particle physics to the macroscopic settings of cosmology and astrophysics has provided a detailed picture of how the Universe evolved from a hot and homogeneous initial state into the structures (stars, galaxies, clusters) that we observe nowadays.

Conversely, the Universe is now used as a giant laboratory to test the new models of particle physics in regimes that are out of reach for terrestrial accelerators.

Outline

Session I:

- Survey: extreme energies, extreme densities.
- Relics from the early Universe: freeze-out.

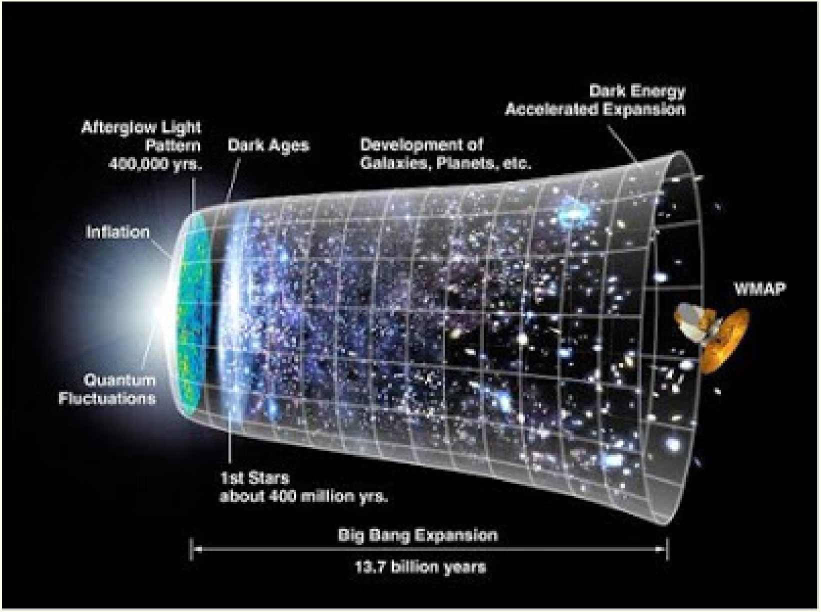
Session II:

- The most energetic particles: ultra-high energy cosmic rays.

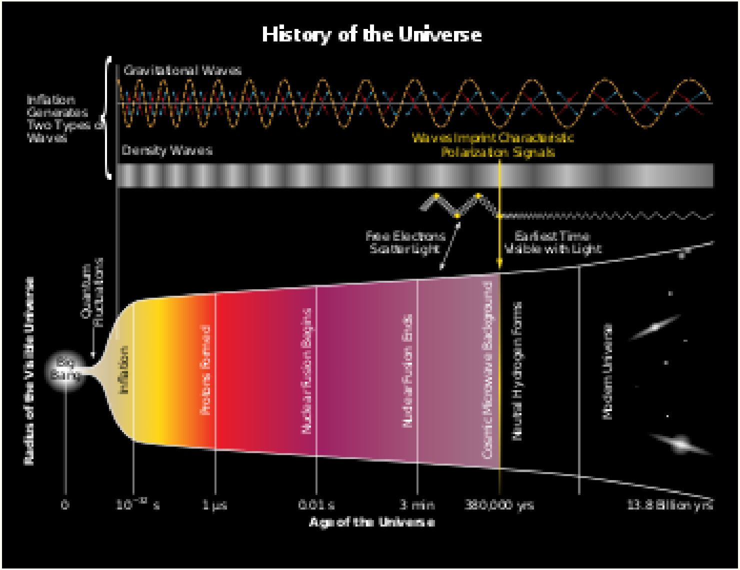
Session III:

- Gamma-ray astronomy.
- Cosmological magnetic fields.

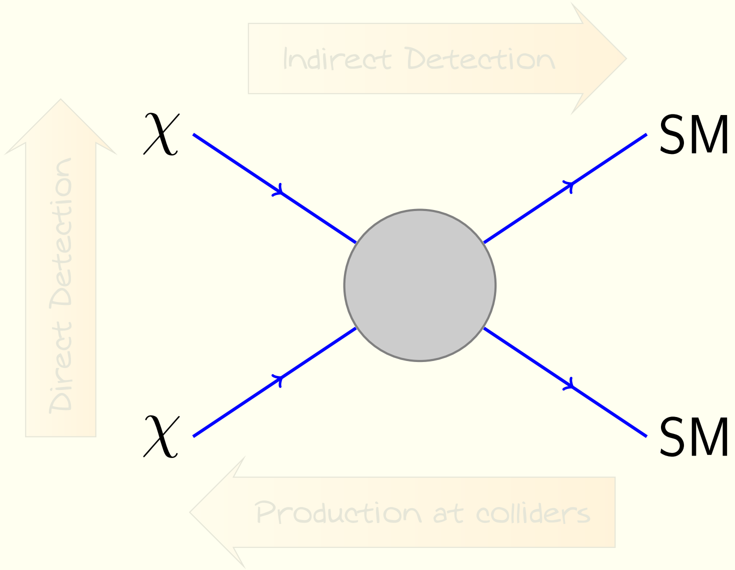
Extreme energies and extreme densities



Extreme energies and extreme densities



$T_R \gtrsim 10^{12}\,GeV$ (compare 14 TeV at the LHC!)


Indirect Detection
Direct Detection
Production at colliders
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χ
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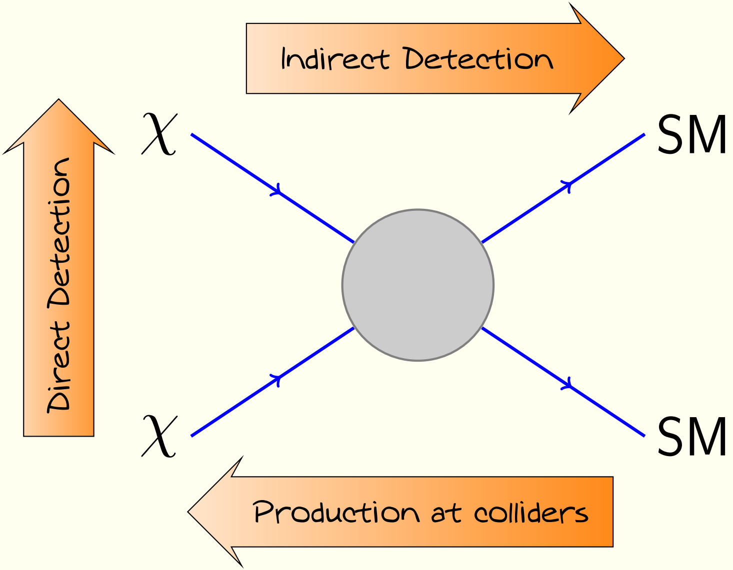
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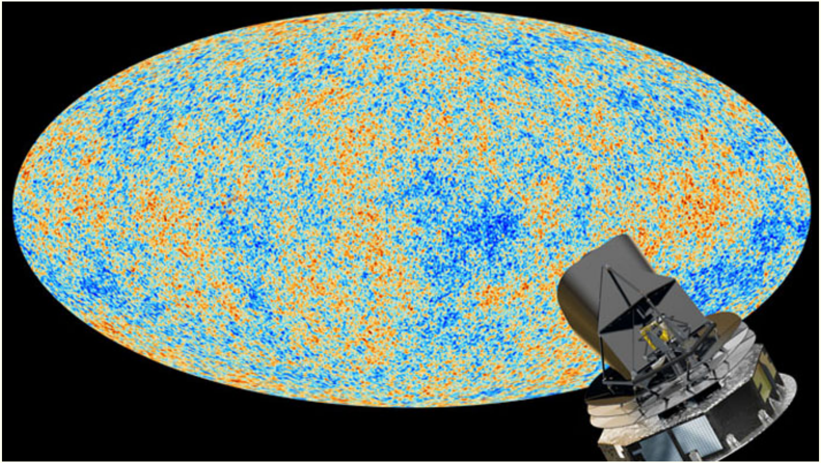

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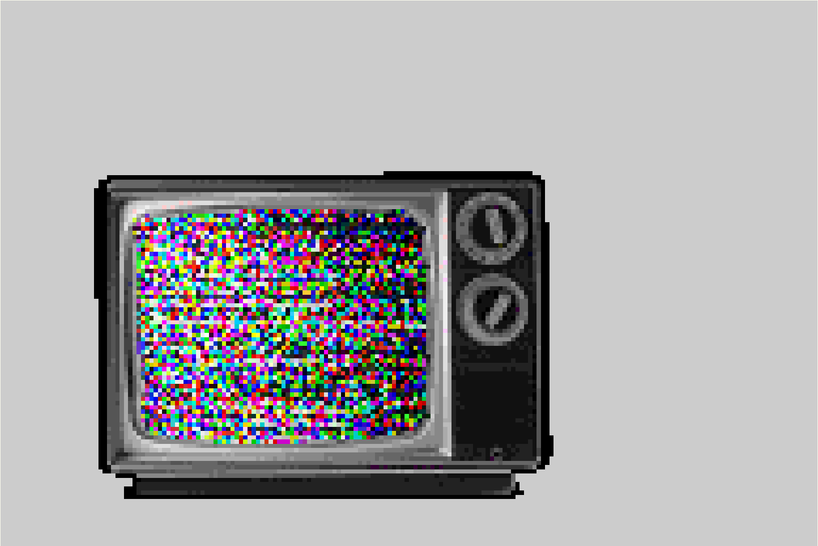

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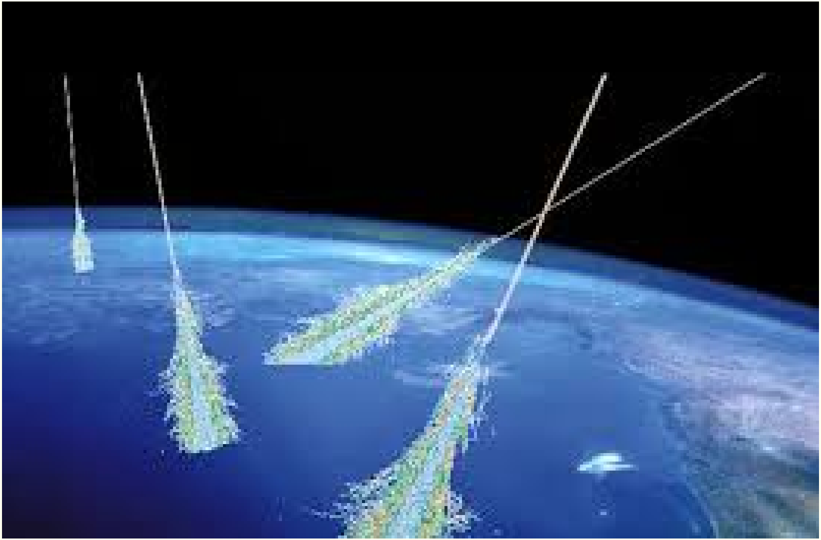
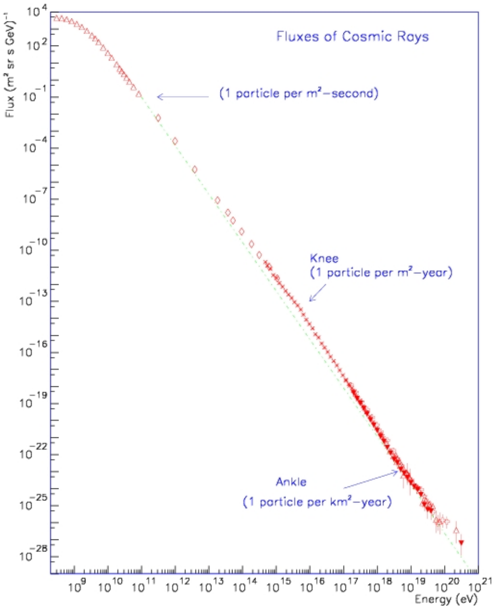


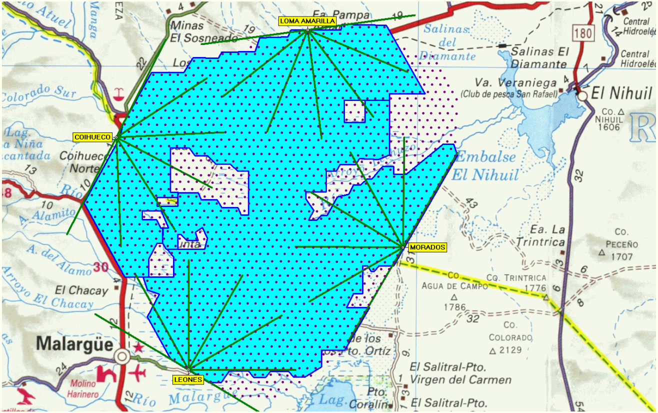


Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)

Extreme energies and extreme densities

Tobias Winchen

Extreme energies and extreme densities



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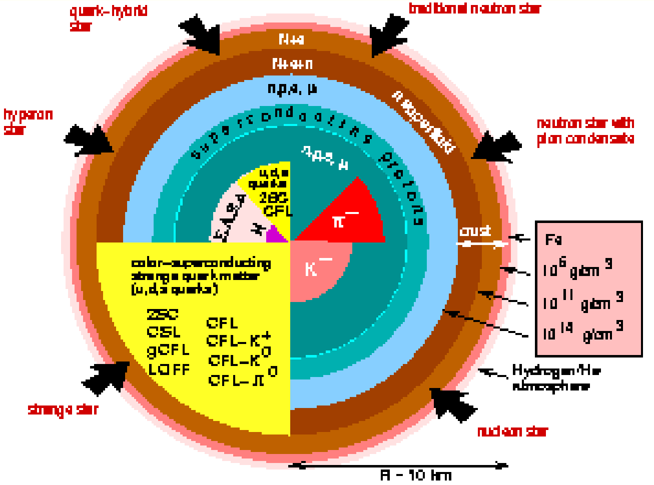
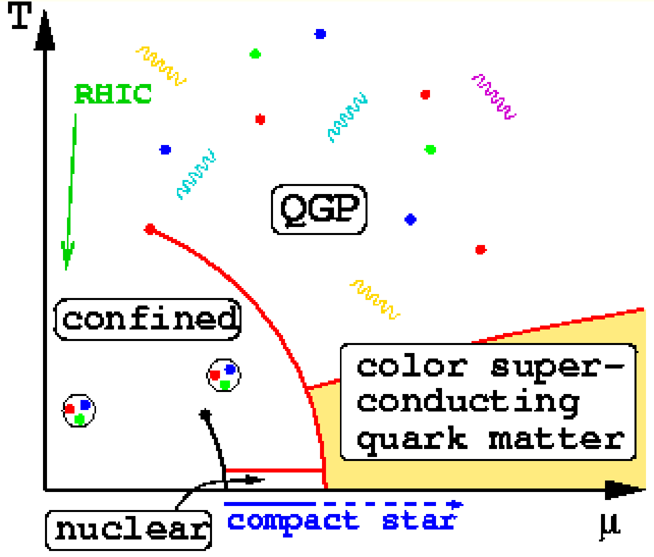


F. Weber

Extreme energies and extreme densities



M. Alford

Extreme energies and extreme densities

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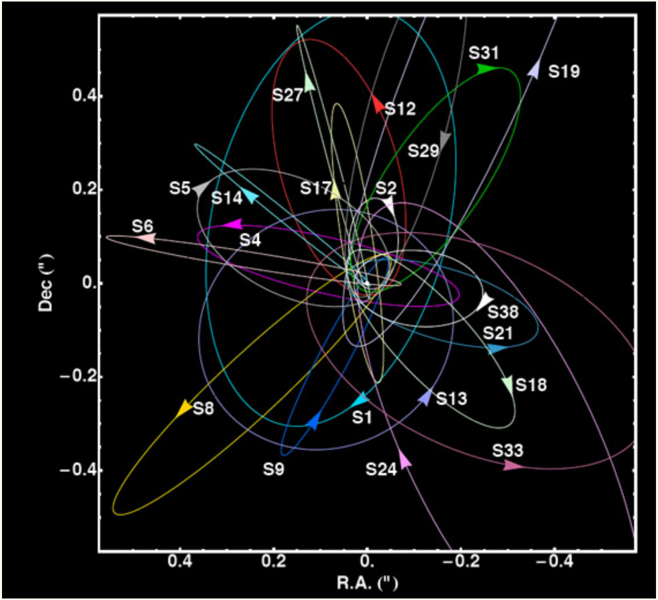

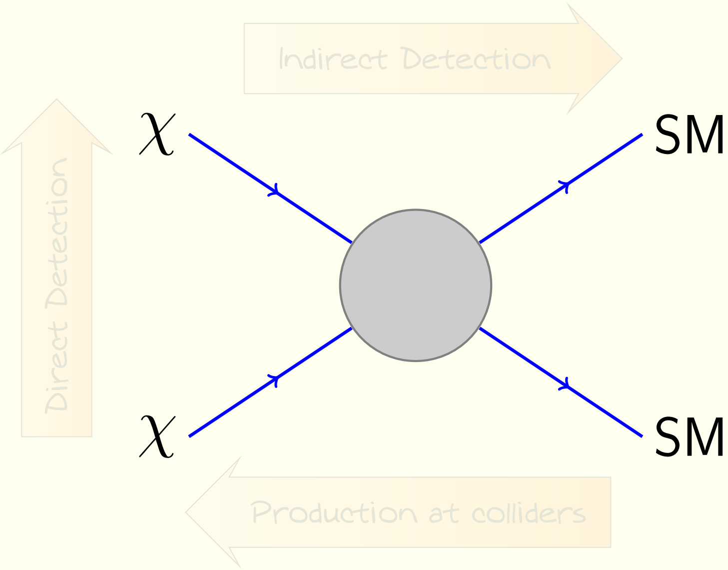

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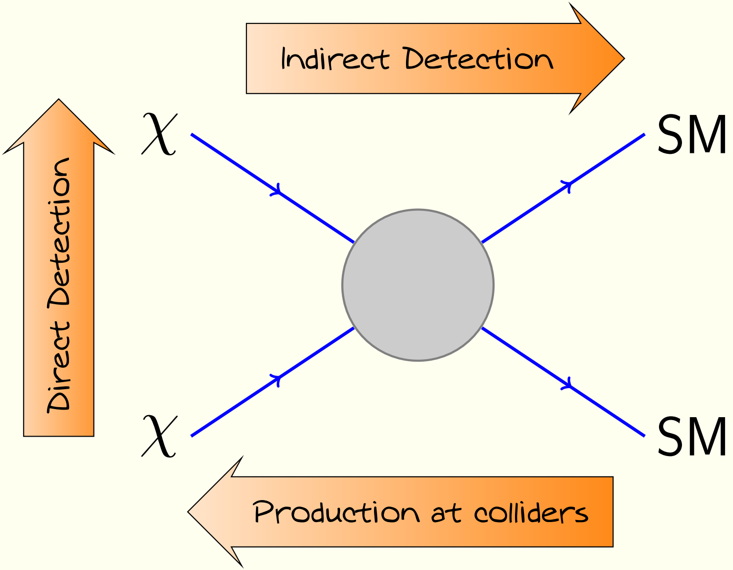
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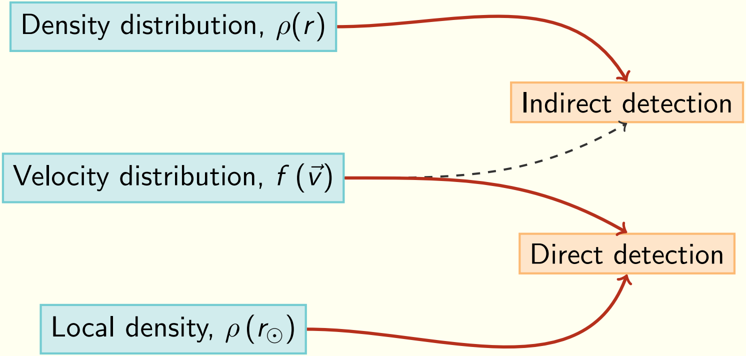
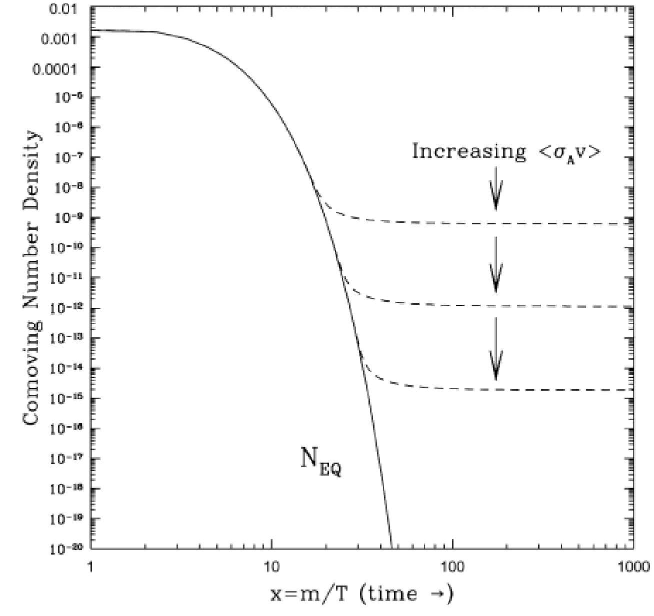
Astrophysical uncertainties



Relics from the early Universe



The distribution function

The information is contained in the phase-space distribution function:

$$\boxed{f(x,p)}$$

$$N^\mu = \int f \frac{p^\mu}{p^0} \frac{\mathrm{d}^3 p}{(2\pi)^3} \Rightarrow N^0 \equiv n$$

$$T^{\mu\nu} = \int f \frac{p^\mu p^\nu}{p_0} \frac{\mathrm{d}^3 p}{(2\pi)^3} \Rightarrow T^{00} \equiv \rho$$

$$S^\mu = -\int \left[f \log f \mp (1 \pm f) \log (1 \pm f) \frac{p^\mu}{p^0} \frac{\mathrm{d}^3 p}{(2\pi)^3} \right]$$

Bernstein 88

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This description makes sense as long as

$$\lambda = 1/p < \text{size of the universe.}$$

In the early radiation dominated epoch $H = 1.66\sqrt{g_*}\frac{T^2}{M_{\rm pl}}$ and,

$$\lambda \approx 1/T < H^{-1} \Rightarrow \boxed{T < M_{\rm pl}}$$

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The Boltzmann equation

Let us follow the variation of $f(x,p)$ along a world-line $x(\tau)$:

$$\frac{\mathrm{d}}{\mathrm{d}\tau} f(x(\tau), p(\tau)) = \frac{\partial f}{\partial x^\mu}\frac{\mathrm{d}x^\mu}{\mathrm{d}\tau} + \frac{\partial f}{\partial p^\mu}\frac{\mathrm{d}p^\mu}{\mathrm{d}\tau}.$$

If the particles only interact gravitationally (between collisions), then they follow geodesics

$$\frac{\mathrm{d}p^\mu}{\mathrm{d}\tau} = -\Gamma^\mu_{\alpha\beta} p^\alpha p^\beta,$$

and the variation of f is given by $\hat{L}[f]$ where

$$\hat{L} = p^\mu \frac{\partial}{\partial x^\mu} - \Gamma^\mu_{\alpha\beta} p^\alpha p^\beta \frac{\partial}{\partial p^\mu}.$$

The *collisionless* Boltzmann equation states that there is no net variation of f along the trajectory:

$$\boxed{\hat{L}[f] = 0}$$

Example: Robertson-Walker

In a homogeneous and isotropic flat RW Universe $f = f(E, a(t))$, and

$$\hat{L} = E\frac{\partial}{\partial t} - H|\boldsymbol{p}|^2\frac{\partial}{\partial E}$$

The most general solution is *any* function of aE, e.g.

$$\exp\left(aE/T_0\right) = \exp\left(E/(T_0/a)\right).$$

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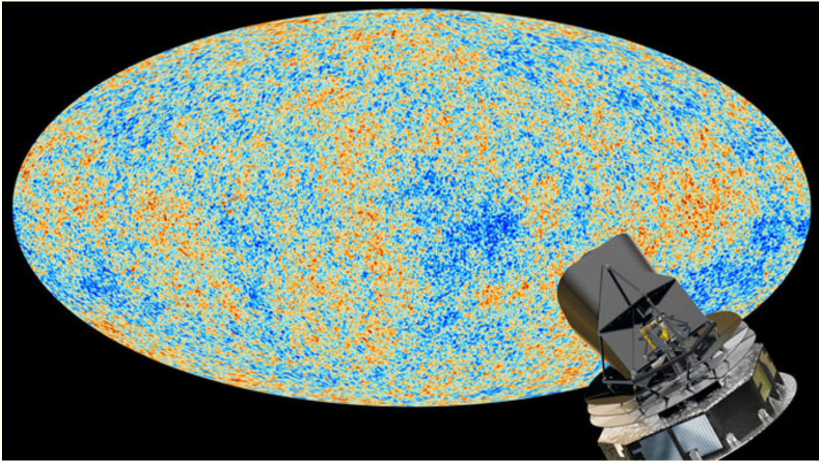

Dark matter or stars in a galaxy

We would then use the static, weak field geometry

$$\mathrm{d}s^2 = -(1+2\Phi)\,\mathrm{d}t^2 + (1-2\Phi)\,\mathrm{d}\vec{x}^2\,.$$

Since the velocities are small, $p^0 = m$, $p^i = mv^i$, and the collissionless Boltzmann equation reads

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{x}} - \frac{\partial \Phi}{\partial \vec{x}}\frac{\partial f}{\partial \vec{v}} = 0$$

Binney and Tremaine 08

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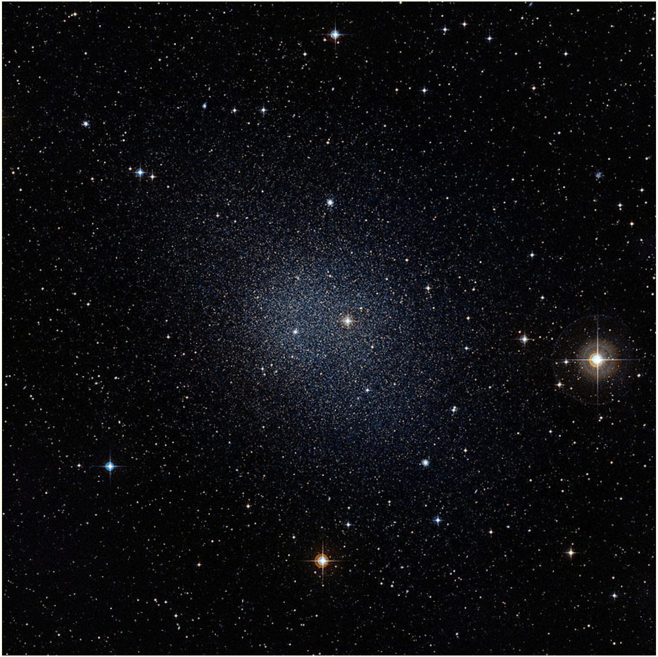

Adding collisions

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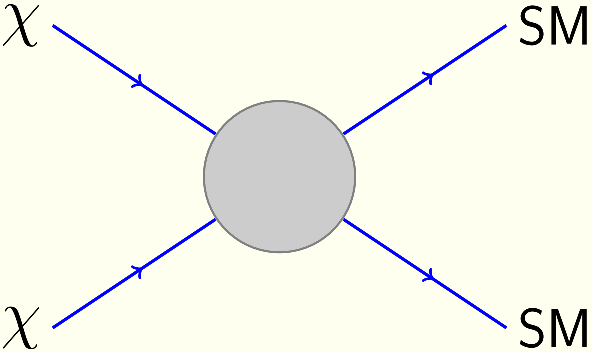

$$\hat{C}[f] = -\frac{1}{E}\int (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_a - p_b)$$

$$\times\Big[|\mathcal{M}_{12\to ab}|^2 f_1 f_2 (1 \pm f_a)(1 \pm f_b) - |\mathcal{M}_{ab\to 12}|^2 f_a f_b (1 \pm f_1)(1 \pm f_2)\Big] \quad \times$$

with $\mathrm{d}^3\Pi_i \equiv \dfrac{\mathrm{d}^3 p_i}{(2\pi)^3 2E_i}$.

Since we are looking for an equation for n,

$$\int \hat{L}[f_1]\, \mathrm{d}^3\Pi_1 = \dot{n} + 3Hn.$$

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We can typically assume that the SM annihilation products a, b, go quickly into equilibrium with the thermal background and replace $f_{a,b} \to f_{a,b}^{\mathrm{eq}}$. Detailed balance allows the replacement $f_a^{\mathrm{eq}} f_b^{\mathrm{eq}} = f_1^{\mathrm{eq}} f_2^{\mathrm{eq}}$.
We will also take advantage of the unitarity of the S-matrix:

$$\int \delta^{(4)}(p_1 + p_2 - p_a - p_b)|\mathcal{M}_{12\to ab}|^2 \, \mathrm{d}^3\Pi_a \, \mathrm{d}^3\Pi_b$$
$$= \int \delta^{(4)}(p_1 + p_2 - p_a - p_b)|\mathcal{M}_{ab\to 12}|^2 \, \mathrm{d}^3\Pi_a \, \mathrm{d}^3\Pi_b.$$

Defining the averaged total annihilation cross-section

$$< \sigma v_{M\o l} >= \frac{\int \sigma v_{M\o l} \, \mathrm{d}n_1^{\mathrm{eq}} \, \mathrm{d}n_2^{\mathrm{eq}}}{\int \mathrm{d}n_1^{\mathrm{eq}} \, \mathrm{d}n_2^{\mathrm{eq}}}$$

where the Møller velocity

$$v_{M\o l} = \sqrt{|\vec{v_1} - \vec{v_2}|^2 - \left|\vec{v_1} \times \vec{2}\right|^2},$$

we recover the familiar result

$$\boxed{\dot{n} + 3Hn = - < \sigma v_{M\o l} > \left(n^2 - n_{\mathrm{eq}}^2\right)}$$

Gondolo, Gelmini 91

One usually works with the yield $Y \equiv n/s$ as a function of $x = m/T$:

$$\frac{\mathrm{d}Y}{\mathrm{d}x} = -\frac{\lambda < \sigma v >}{x^2}\big(Y^2 - Y_{\rm eq}^2\big),$$

$$\lambda \equiv \frac{2\pi^2}{45}\frac{M_{\rm pl} g_{eff}}{1.66 g_*^{1/2}} m.$$

It can be solved analytically in the two extreme regions

$$\Delta = -\frac{Y^{\rm eq\prime}}{2f(x)Y^{\rm eq}} \quad \text{for } x \ll x_F$$

$$\Delta' = -f(x)\Delta^2 \quad \text{for } x \gg x_F$$

The last equation can be integrated between x_F and ∞ using $\Delta_{x_F} \gg \Delta_\infty$ to obtain Y_∞.

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For a heavy particle

$$< \sigma v >= a + b < v^2 > + \ldots \approx a + 6b/x$$

and we obtain the desired result

$$\Omega_X h^2 \approx \frac{10^9 GeV^{-1}}{M_{\rm Pl}} \frac{x_F}{\sqrt{g_*}} \frac{1}{a + 3b/x_F}$$
$$\approx \frac{10^{-27} cm^3 s^{-1}}{a + b/60}.$$

Unitarity bound:

$$\Omega_X \leq 1 \Rightarrow m \leq 340\ TeV$$

Griest, Kamionkowski 90

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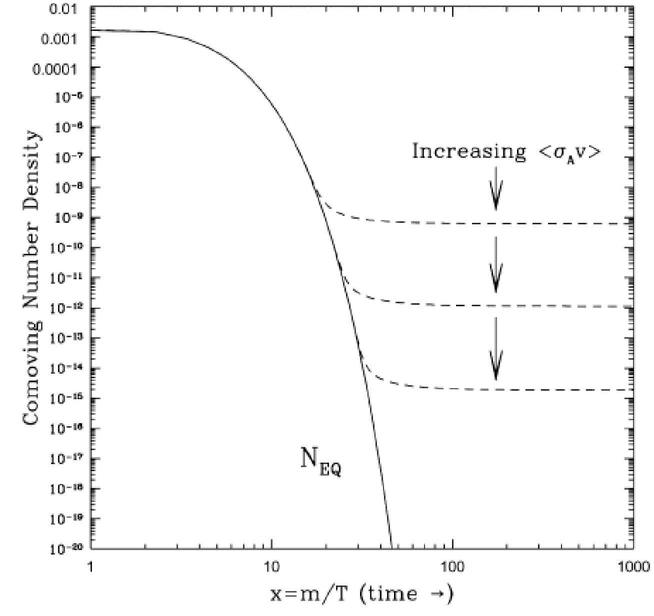

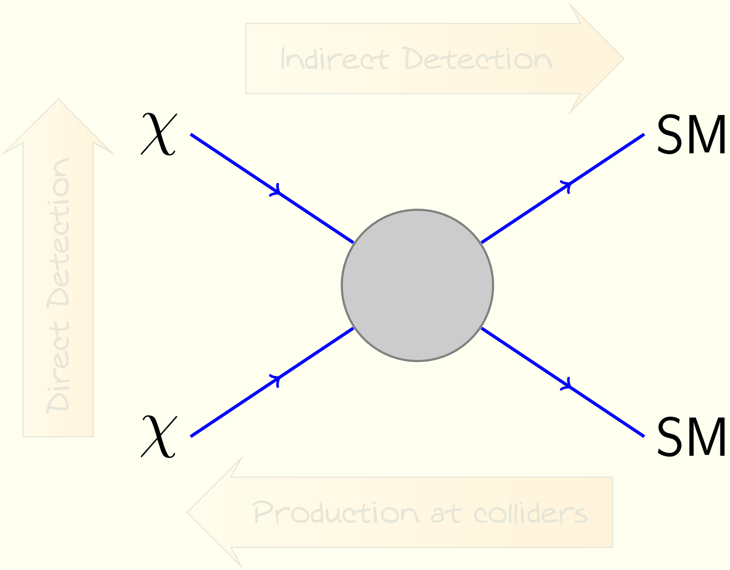

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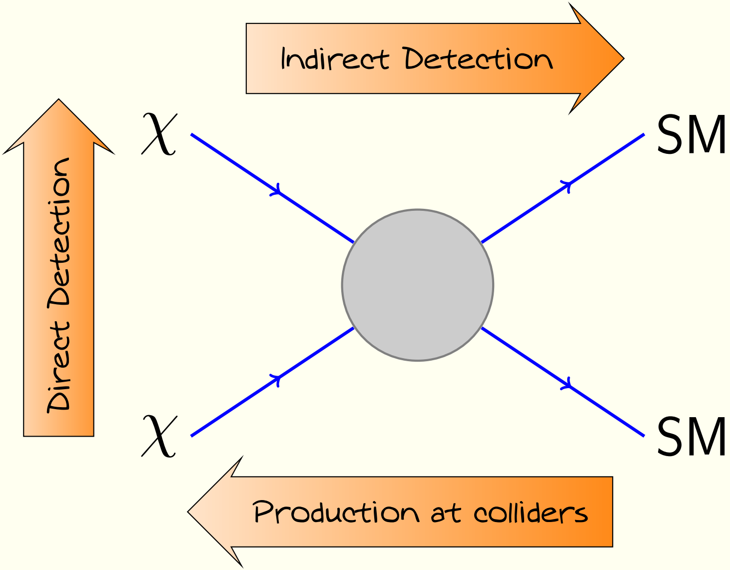
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