Neutrino Physics in Direct Detection Dark Matter Experiments

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What do I aim at telling you?

Content of these lectures

DM direct detection experiments will be soon subject to irreducible neutrino backgrounds... Challenge for DM searches

An opportunity to study ν properties at rather low E_ν

Magnifying glass

- **LI:** Fundamental aspects of DM physics (thermal relics... WIMPs)
- **LII:** Fundamental aspects of neutrino physics
- **LIII:** DM direct detection and neutrino physics
- **LIV:** Studying BSM neutrino signals in DM detectors

Fundamental aspects of DM physics

Useful references

Biased list

- The Early Universe, Kolb & Turner
- Galaxy Formation and Evolution, Mo, Van den Bosch & White
- General relativity, R. Wald
- Modern Cosmology, S. Dodelson

Dynamics of the Early Universe-I

The dynamics should account for the Universe as we see it (LSS)

Key questions...

A. When does it happen?

B. What does it requires?

Address A

Solve Einstein equations with the aid of the cosmological principle

$$R_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

$$T_{\mu\nu} = \begin{cases} \text{Consistency with } g_{\mu\nu} \Rightarrow \text{diagonal } T_{\mu\nu} \\ \text{Isotropy} \Rightarrow \text{spatial components are equal} \\ \text{Simplest realization: Perfect fluid} \end{cases}$$

Equation of state: $p = \omega\rho$

Rad: $p = \rho/3 \quad \Rightarrow \quad \rho = \rho_0 R(t)^{-4}$

Mat: $p = 0 \quad \Rightarrow \quad \rho = \rho_0 R(t)^{-3}$

Vac: $p = -\rho \quad \Rightarrow \quad \rho = \rho_0$

Dynamics of the Early Universe-II

Einstein equations in a FRW Universe with a stress-energy tensor as that of a perfect fluid ⇒ Friedman equation

$$H^2 + \frac{k}{R^2} = \frac{8}{3}\pi G\rho$$

$\rho =$ matter + radiation + vacuum

matter = baryons+? radiation = $\gamma + \nu$

Present values ⇒ precise evolution of the Universe

$$H^2 = H_0^2 \left[\frac{\Omega_{\mathrm{m},0}}{R(t)^3} + \frac{\Omega_{\mathrm{r},0}}{R(t)^4} + \Omega_{\Lambda,0} + \frac{\Omega_{k,0}}{R(t)^2} \right]$$

$$\Omega_X = \frac{\rho_X}{\rho_C} \qquad \rho_C = \frac{3H^2}{8\pi G}$$

Evolution of scale factor:

$$t = \int_0^{R(t)} \frac{dR'}{H(t)R'(t)}$$

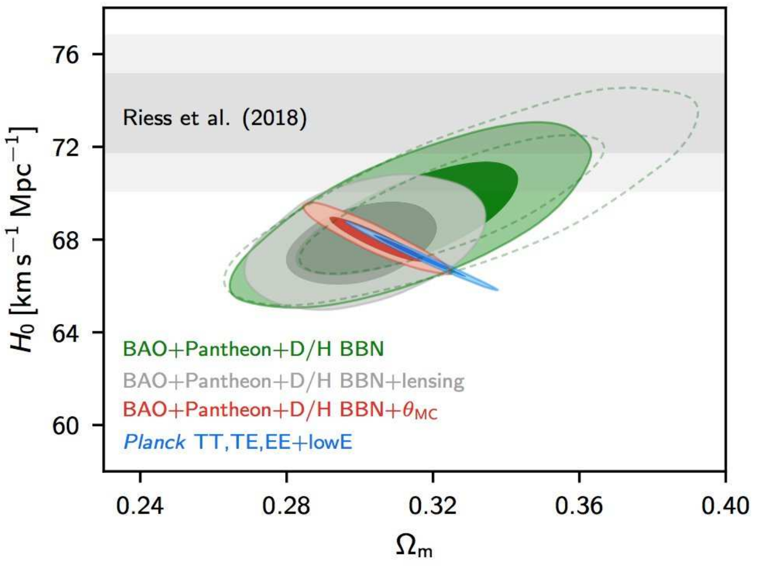
Determine evolution of $R(t)$

⇒ Evolution of the different densities

Cosmological models: PLANCK data

PLANCK satellite data provides a wealth of information on cosmological parameters

Measurements: temperature, polarization and cross power spectra



PLANCK 2018	
Parameter	TT,EE,TE+lowE+lensing+BAO (68% CL)
H_0[km/s/Mpc]	67.66 ± 0.42
Ω_Λ	0.6896 ± 0.0057
Ω_m	0.3102 ± 0.0057
Ω_k	$0.0005^{+0.0038}_{-0.0040}$
$\Omega_\mathrm{b}h^2$	0.02234 ± 0.00014
$\Omega_\mathrm{c}h^2$	0.11907 ± 0.00094
z_eq	3379 ± 22
z_rec	$7.75 \pm 0.73 \pm 22$

Cosmological data is well fitted by

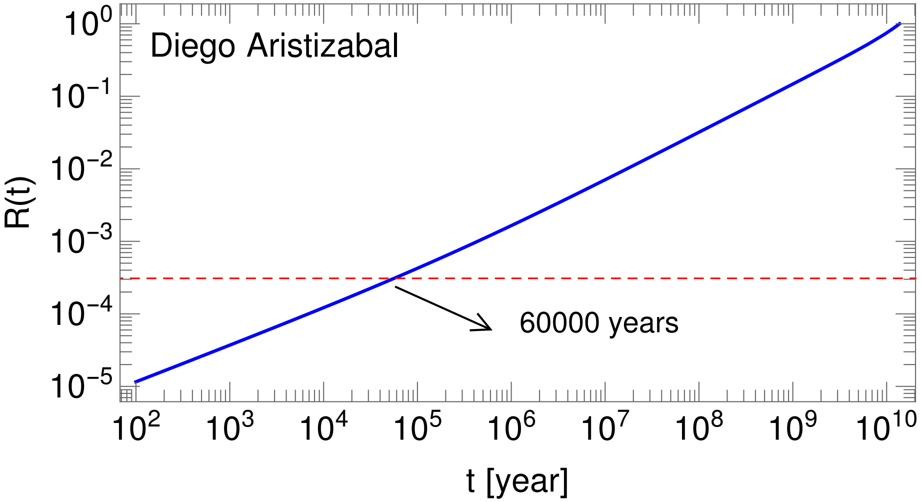
the ΛCDM cosmological model

Matter in the Universe

$$\rho_\mathrm{b}/\rho_\mathrm{m} \simeq 0.158 \qquad \rho_\mathrm{c}/\rho_\mathrm{m} \simeq 0.842$$

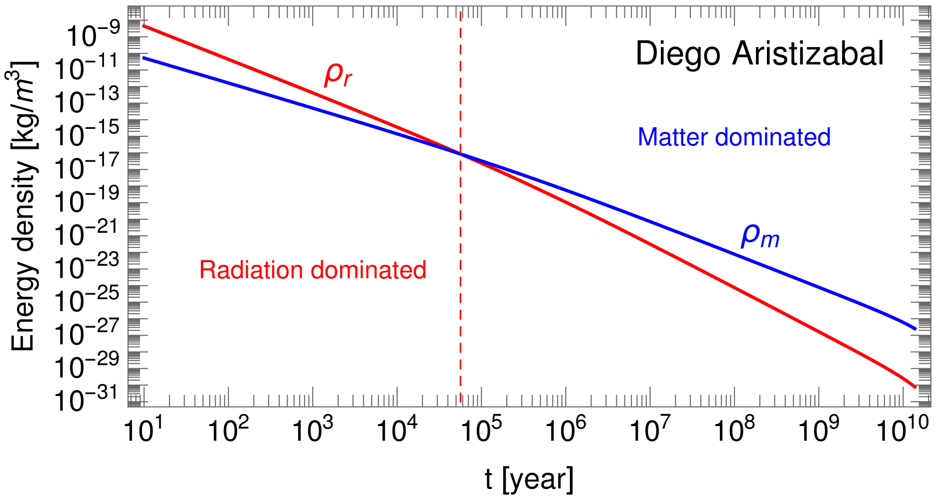
84% of the matter content is in the form of DM!

Dynamics of the Early Universe-III



Information on $R(t)$ determines the “fate” of ρ_X and fixes the time for LSS formation

Back to Friedman equation with PLANCK data



R-D-equality: $\frac{\Omega_{\text{m},0}}{R(t)^3} = \frac{\Omega_{\text{r},0}}{R(t)^4} \Rightarrow R(t_{\text{eq}}) \simeq 3\times 10^{-4}$

$t_{\text{eq}} \simeq 6\times 10^{4}$ years

Fixes the time for LSS formation!

Dynamics of the Early Universe-IV

Address B

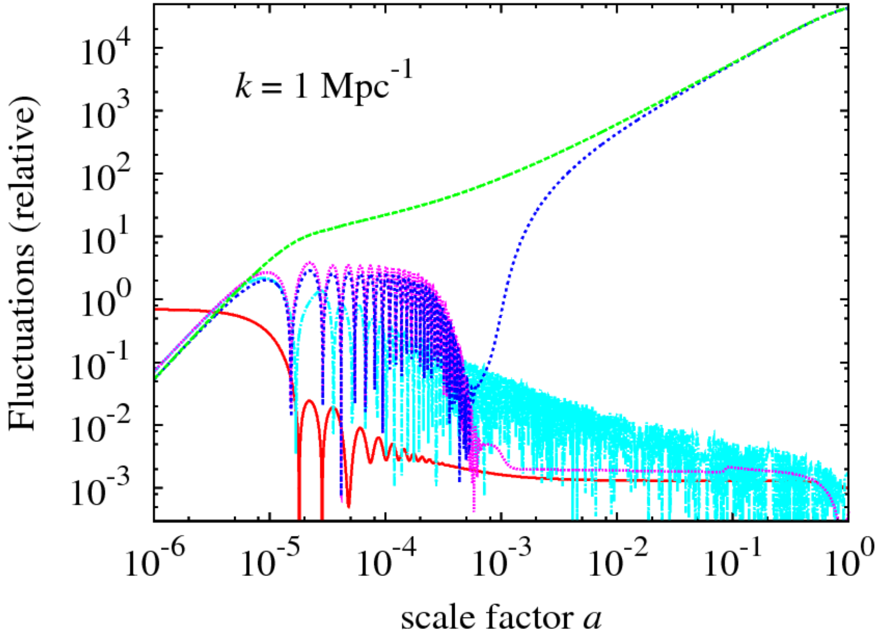
Small density perturbations are responsible for structure formation

Model-I: $H^2 = \frac{8\pi G\rho_0}{3} \quad (k=0)$

Model-II: $H^2 = \frac{8\pi G\rho_1}{3} - \frac{k}{R^2} \quad (k>0, \rho_1 > \rho_0)$

Den. Inhomo: $\delta\rho = \frac{\rho_1 - \rho_0}{\rho_0} \propto \frac{R^{-2}}{\rho_0}$

$$\delta\rho \propto \begin{cases} R^2 & \text{Radiation dominated} \\ R & \text{Mat dominated} \end{cases}$$



During MD DM perturbations grow

B perturbations only until recombination

At decoupling B fall in V_{DM}

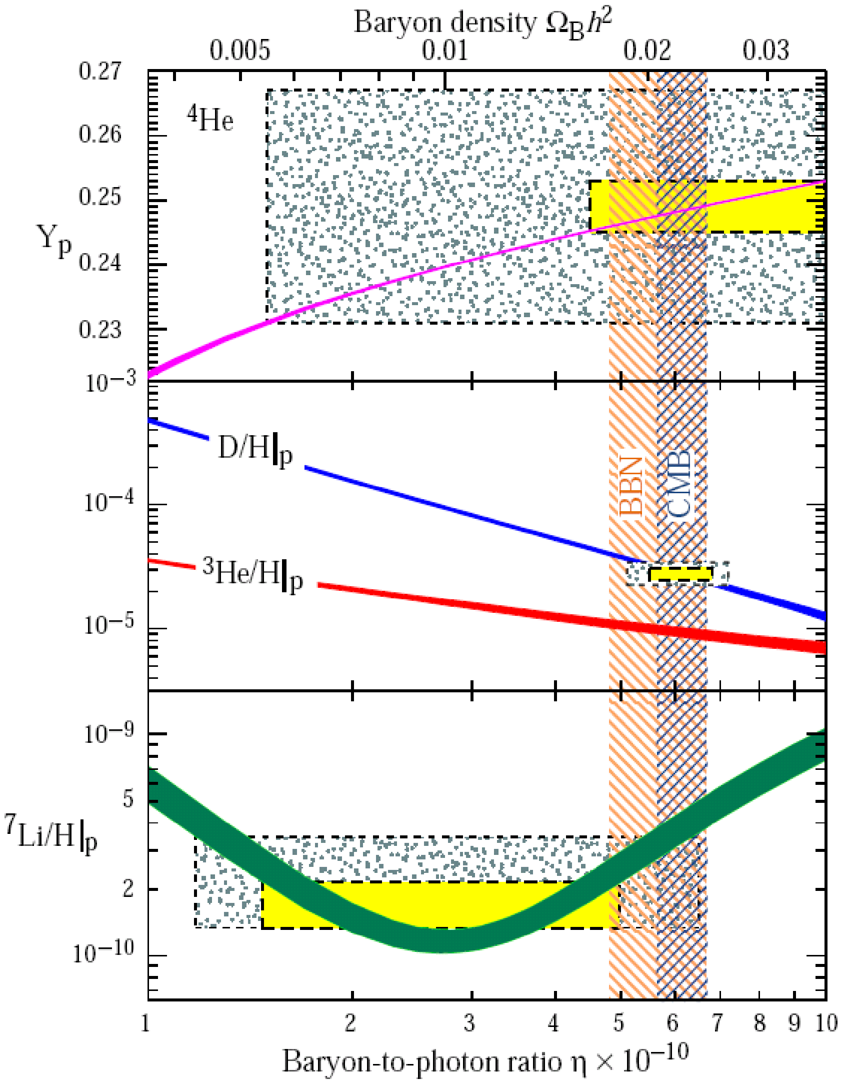
Structure formation requires DM!

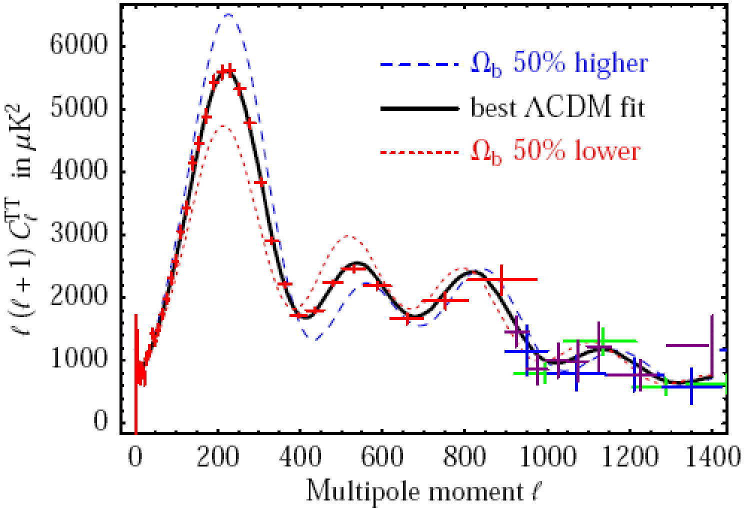
Big bang nucleosynthesis+CMB

What do I aim at telling you?

Fundamental aspects of DM physics
- Useful references
- Dynamics of the Early Universe-I
- Dynamics of the Early Universe-II
- Cosmological models: PLANCK data
- Dynamics of the Early Universe-III
- Dynamics of the Early Universe-IV
- Big bang nucleosynthesis+CMB
- Executive summary
- DM candidates
- Limits on MACHOS

Particle physics perspective





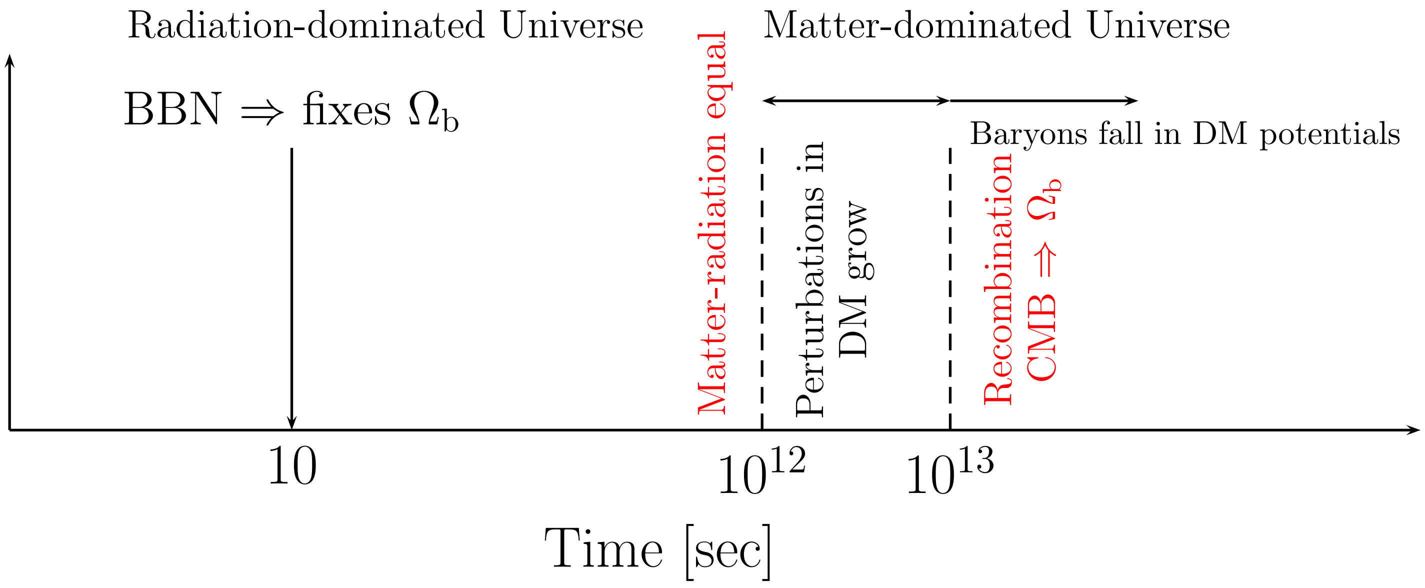
BBN+CMB: $\Omega_b h^2 \simeq 0.022$

Measurements of $\Omega_m h^2 = 0.14205 \pm 0.00090$

Reconciliation requires DM!

Executive summary

Key moments in Early Universe dynamics



Radiation-dominated Universe

Matter-dominated Universe

BBN $\Rightarrow$ fixes Ω_b

Matter-radiation equal

Perturbations in DM grow

Baryons fall in DM potentials

Recombination CMB $\Rightarrow \Omega_\mathrm{b}$

10

10^{12}

10^{13}

Time [sec]

Structure formation requires DM

$\Omega_\mathrm{b} \ll \Omega_\mathrm{m} \Rightarrow$ extra component provided by DM

Astrophysical observations (which I didn’t discuss) support the existence of DM as well

DM candidates

Two generic type of candidates exist:

Massive Compact Halo Objects (MACHOS)	**New form of matter**
Of baryonic origin	Of non-baryonic origin
Neutron stars	WIMPs
Black holes	Sterile neutrinos
Brown dwarfs	Axions
White dwarfs	Cosmic strings

Particle relics

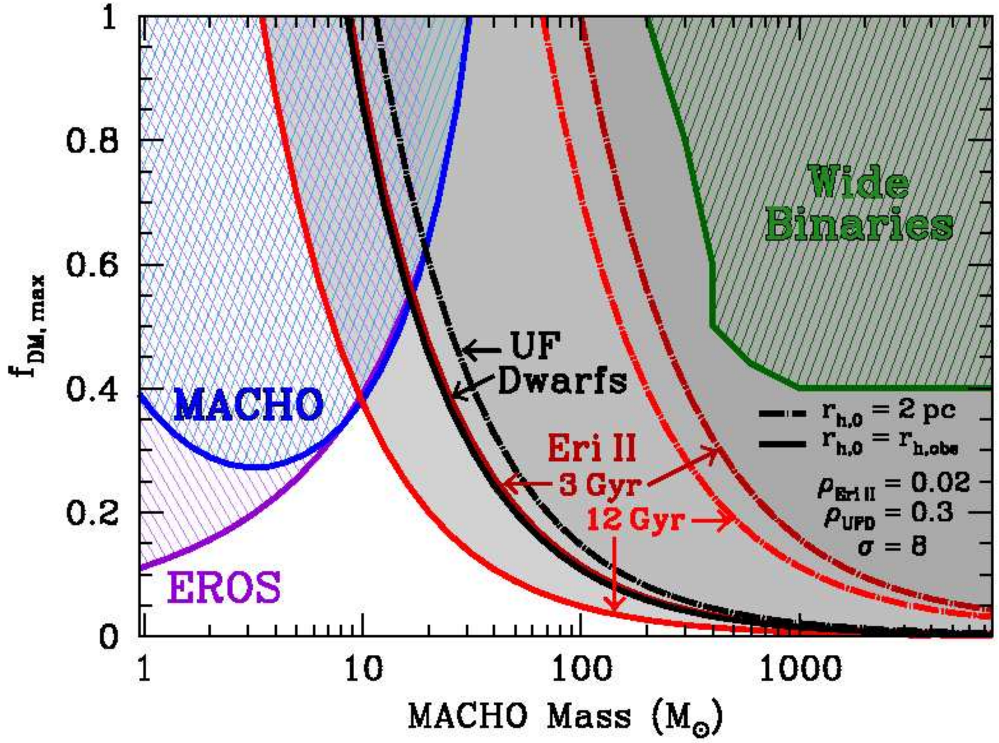
Non-thermal relics	**Thermal relics**
Non-thermally produced at early times	Thermally produced at early times
Mechanism related with e.g. inflation required	present abundance determined by freeze-out

From now on I focus on WIMPs!

Limits on MACHOS

Limits proceed from a variety of experiments most of them relying on gravitational microlensing

MACHOS (92-00), EROS-1 (90-95) & EROS-2 (96-03)



Combination of these observations

rule out $m_{\text{Macho}} \gtrsim 10^{-7} m_\odot$ as

the dominant form of DM

Particle physics perspective

DM properties

Based on the wealth of astrophysical and cosmological data properties can be derived

⇒ DM is absolutely stable or cosmologically stable with $\tau \gtrsim 10^{26}$ sec

⇒ DM does not interact with light or its interactions are suppressed

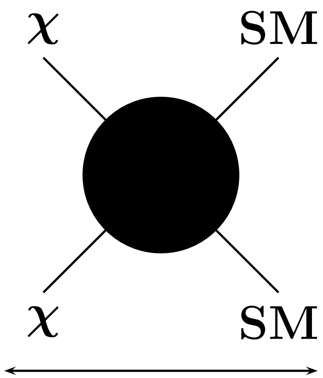
⇒ The bulk of DM must be dissipationless, a fraction can be dissipative though

⇒ Its mass can be within $[10^{-31}, 10^{48}]$ GeV (Fuzzy DM+MACHOS)

⇒ DM assumed to be collisionless. Core-cusp problem ⇒ SIDM

⇒ The bulk of DM is either cold or warm (rules out ν)

DM freeze-out



At early times plasma populated by fast processes: $\Gamma \gg H$

χ is in thermal equilibrium

At freeze-out ($\Gamma \sim H$) the species is non-relativistic

χ decouples from the heat bath, n_χ freezes

Reactions in the early Universe

What matters is the size of the reaction compared with H at a certain T

- For $\Gamma(T) \ll H(T)$ these reactions haven't (still) taken place

  $\Rightarrow$ Conservation Laws

- For $\Gamma(T) \sim H(T)$ densities have to be traced with BEqs

- For $\Gamma(T) \gg H(T)$ these reactions are in TEQ

  $\Rightarrow$ Chemical equilibrium

Boltzmann equation: Non-relativistic case

In TEQ the PDFs are known: Classically Boltzmann, at quantum level FD or BE

Decoupling does not happen in TEQ $\Rightarrow$ $f(\vec{v},\vec{x})$ should be tracked with BEqs

Non relativistic case

$$\frac{d}{dt} f(\vec{v},\vec{x}) = \underbrace{\left(\frac{\partial}{\partial t} + \frac{d\vec{x}}{dt}\cdot\vec{\nabla}_x + \frac{d\vec{v}}{dt}\cdot\vec{\nabla}_v\right)}_{\hat{L}_{\text{NR}}\equiv\text{Liouville operator}} f(\vec{v},\vec{x})$$

Liouville Theorem

No dynamics $\Rightarrow$ N is conserved

Collision-less BEq: $\hat{L}_{\text{NR}} f = 0$

Collisions: $\hat{L}_{\text{NR}}[f] = \hat{C}[f]$, $C \equiv$ CT

At early times dynamics of all species

is relativistic $\Rightarrow$ tracking f_{DM}

requires a relativistic description

PDF depends on the four-vectors: (x^μ, p^μ)

Derivation wrt $d f(x^\mu, p^\mu)/dt$ $\Rightarrow$ **breaks covariance**

$\Rightarrow$ Derivation wrt an affine parameter λ

Relativistic Liouville operator

Relativistic case

$$\frac{d}{d\lambda} f = \left(\frac{\partial}{\partial x^\mu} \frac{dx^\mu}{d\lambda} + \frac{\partial}{\partial p^\mu} \frac{dp^\mu}{d\lambda} \right) f$$

Geo. Eq: $$\frac{d^2 x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta} \frac{dx^\alpha}{d\lambda} \frac{dx^\beta}{d\lambda} = 0$$

$$p^\alpha = \frac{dx^\alpha}{d\lambda} \quad \Rightarrow \quad \frac{dp^\mu}{d\lambda} = -\Gamma^\mu_{\alpha\beta} p^\alpha p^\beta$$

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

⇒ Gravitation enters via the affine connection

⇒ BEq: $\hat{L}_R[f] = C[f]$

⇒ In a flat Universe simple form

FRW Universe

$$f = f(|\vec{p}|, t) = f(E, t)$$

$$\Gamma^t_{tt} = 0$$

$$\Gamma^r_{tr} = \Gamma^\theta_{t\theta} = \Gamma^\phi_{t\phi} = \dot{R}/R = H$$

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

Boltzmann Equation in a FRW Universe

$$\boxed{E\frac{\partial f}{\partial t} - \frac{\dot{R}}{R}|\vec{p}|^2\frac{\partial f}{\partial E} = \hat{C} f}$$

$$n = \frac{g}{(2\pi)^3}\int d^3p\; f(E,t)$$

See blackboard

$$\boxed{\frac{dn}{dt} + 3\frac{\dot{R}}{R}n = \frac{g}{(2\pi)^3}\int \frac{d^3p}{E}\hat{C} f}$$

$$\boxed{\text{RHS: Collision term: } \psi + a + b + \cdots_{\mathrm{i}} \leftrightarrow i + j + \cdots}$$

$$\text{RHS} = -\prod_{\mathrm{i}}\prod_{\mathrm{f}}\int d\Pi_{\mathrm{i}}\, d\Pi_{\psi}\, d\Pi_{\mathrm{f}}(2\pi)^4\delta^4(P_{\mathrm{i}} - P_{\mathrm{f}})\underbrace{\left[|\mathcal{M}_{\mathrm{i}\to\mathrm{f}}|^2 f_{\mathrm{i}} f_{\psi}(1 \pm f_{\mathrm{f}}) - (\mathrm{i} \to \mathrm{f})\right]}_{\text{Accounts for asymmetries} \Rightarrow \text{CPV}}$$

⇒ Factors $1 \pm f_{\mathrm{f}}$: Bose enhancement or Pauli blocking: $\to 1$

⇒ In general a network of BEqs is required... But

⇒ Typically only track n_{ψ} (all others are in TEQ: kin+chem)

What do I aim at telling you?

Fundamental aspects of DM physics

Particle physics perspective
- DM properties
- DM freeze-out
- Boltzmann equation: Non-relativistic case
- Relativistic Liouville operator
- Boltzmann Equation in a FRW Universe
- The CP-conserving $2 \leftrightarrow 2$ case
- Production of a relic abundance-II

The CP-conserving $2 \leftrightarrow 2$ case

$$\boxed{\psi\bar{\psi} \leftrightarrow X\bar{X}}$$

$\Rightarrow$ Assume interactions of ψ and $\bar{\psi}$ are CP-conserving

$\Rightarrow$ All thermal distributions are Maxwell-Boltzmann

Scale out the expansion effect

$\Rightarrow$ Use s as a fiducial quantity:

$$s\dot{Y} = \dot{n} + 3\frac{\dot{R}}{R}n$$

Take into account entropy conservation:

$$x \equiv \frac{m}{T} \quad \Rightarrow \quad \frac{d}{dt}\left(\frac{R}{x}\right) = 0 \quad \Rightarrow \quad \text{Jacobian:}\frac{dx}{dt} = H\,x$$

Energy conservation: $f_X^{\text{Eq}} f_{\bar{X}}^{\text{Eq}} = f_\psi^{\text{Eq}} f_{\bar{\psi}}^{\text{Eq}}$

Boltzmann equation

$$\boxed{\frac{dY_\psi}{dx} = -\frac{x\,s}{H(m)}\langle\sigma|\vec{v}|\rangle\left(Y_\psi - Y_\psi^{\text{Eq}}\right)}$$

Thermally-averaged cross section

$$\langle\sigma|\vec{v}|\rangle = \frac{1}{(n^{\text{Eq}})^2}\int d\Pi_\psi d\Pi_{\bar{\psi}} d\Pi_X d\Pi_{\bar{X}} (2\pi)^4 |\mathcal{M}|^2 f_X^{\text{Eq}} f_{\bar{X}}^{\text{Eq}}$$

$\mathcal{M}$: Contains particle physics model information

Production of a relic abundance-II

Numerical solution is required... But don't get me wrong

Before using computers **understand the physics!**

Otherwise is not physics **is just a technician job!**

Entropy density dominated by the contribution of relativistic species

$$s = \frac{2\pi^2}{45} g_\star T^3$$

Thermally-averaged xsec: $\langle \sigma |\vec{v}| \rangle = \sigma_0 \left(\frac{T}{m}\right)^n$

$n = 0 \rightarrow$ s-wave annihilation

$n = 1 \rightarrow$ p-wave annihilation