New physics from n-point correlations of large-scale structure, gravitational waves and the cosmic microwave background

Goals:

Include effects of new physics

Development of cross- power and bispectra for LSS–GW–CMB

Analysis of higher order correlations including relativistic effects

Università degli Studi di Padova
Dipartimento di Fisica e Astronomia "Galileo Galilei"

New physics from n-point correlations of large-scale structure, gravitational waves and the cosmic microwave background

Software goals:

Adaptation of existing codes that calculate Large Scale Structure observables in standard cosmology, to allow for new physics effects, including integration with Markov Chain Monte Carlo packages. Development of user interface taking the linear cosmology evolution as input.

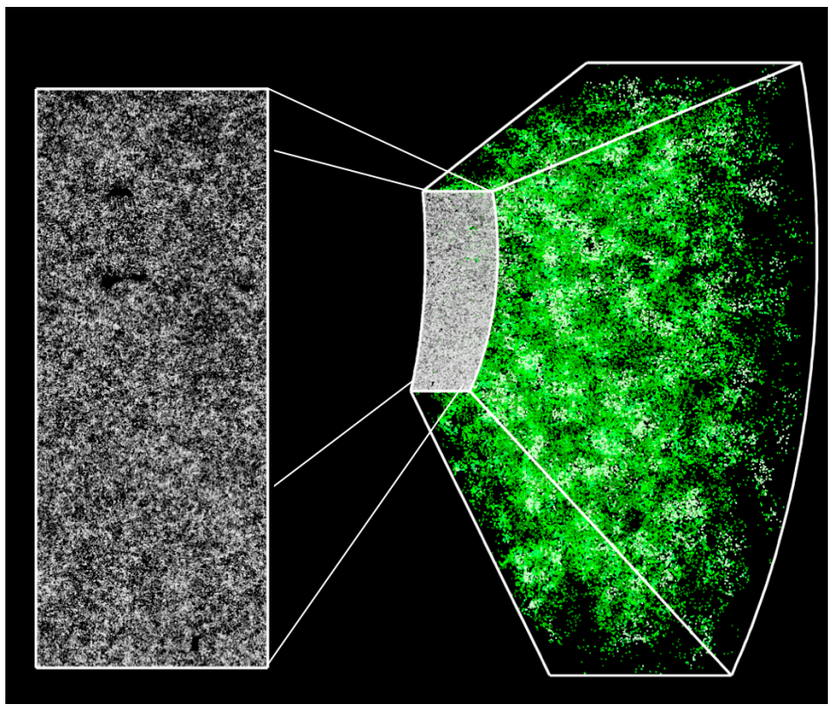
Numerical and simulation-based analyses of cross-correlations of Large Scale Structure with Gravitational Wave and CMB data

Development of a machine learning algorithm for the study of relativistic effects in LSS and GW data

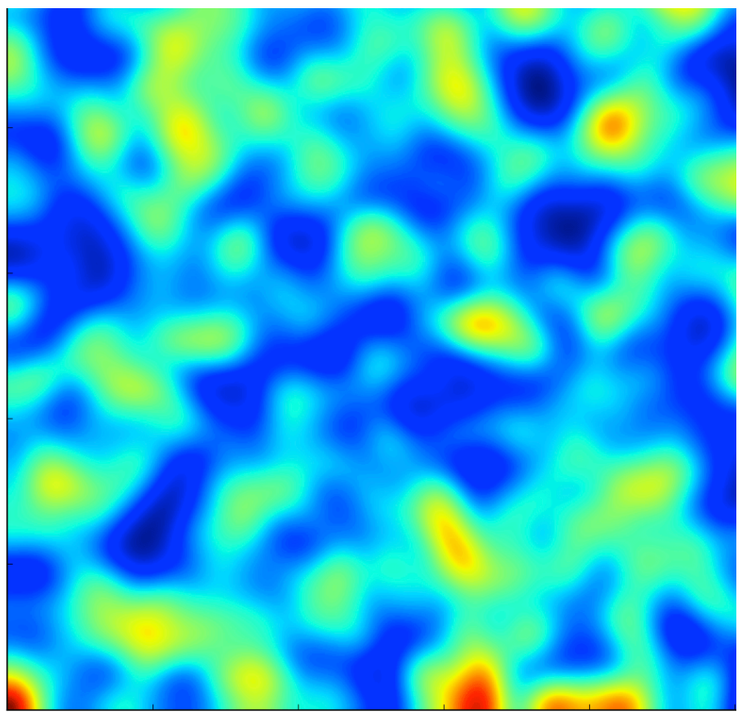
Università degli Studi di Padova
Dipartimento di Fisica e Astronomia "Galileo Galilei"

Multi-messenger cosmology

Galaxies — resolved and IM



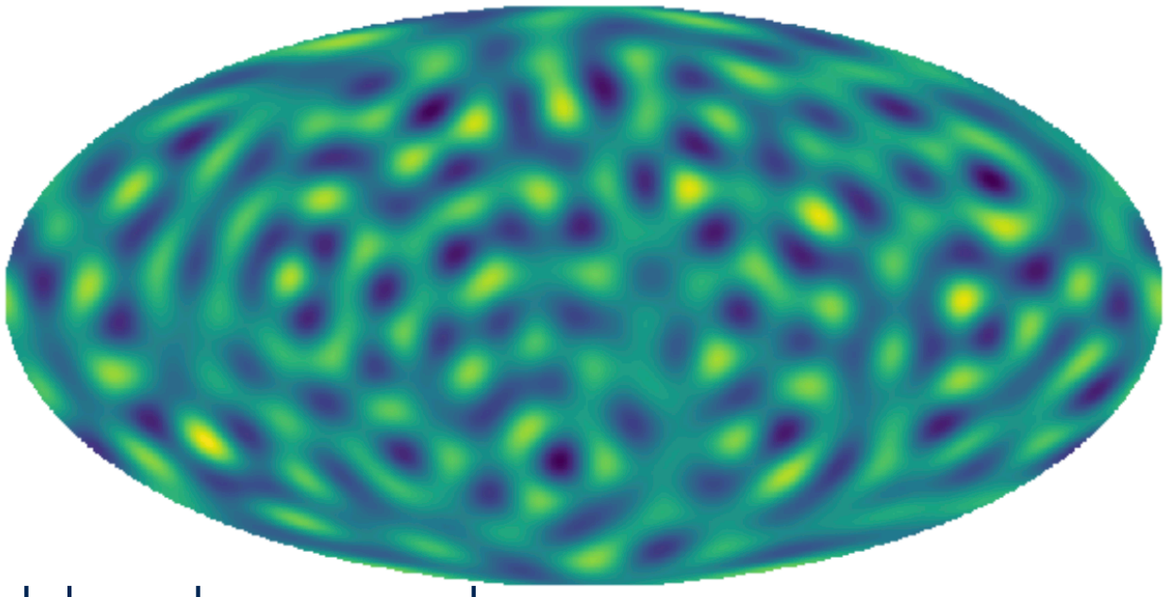
X



X

X

X

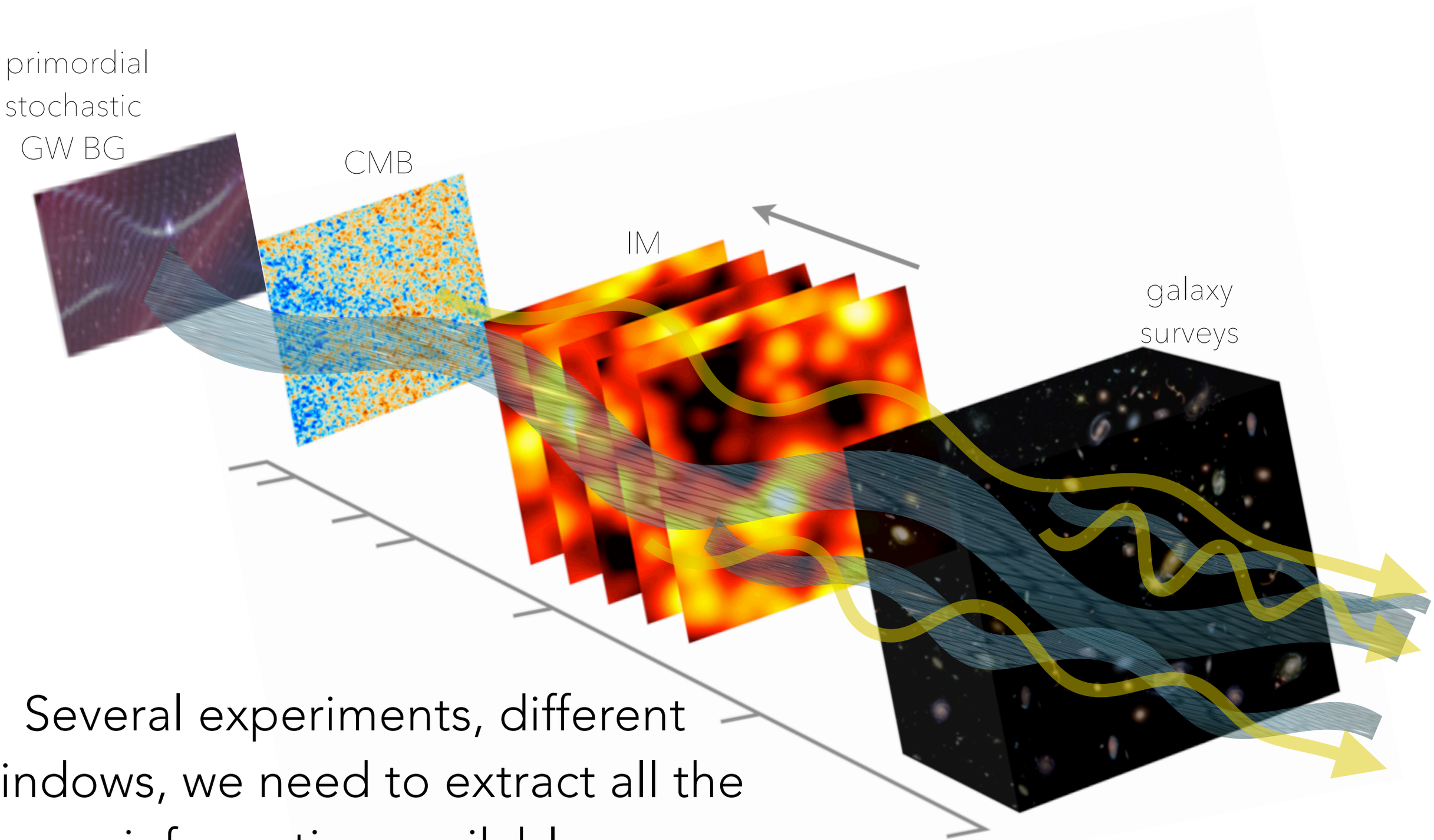


GW — resolved and background

Università degli Studi di Padova

Dipartimento di Fisica e Astronomia "Galileo Galilei"

Cross-correlations LSS—GW—CMB



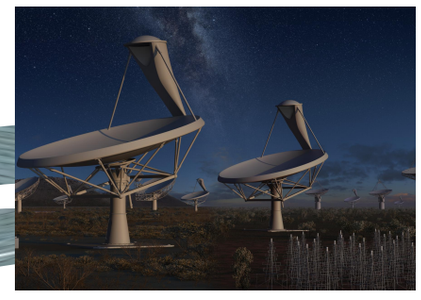
Several experiments, different windows, we need to extract all the information available

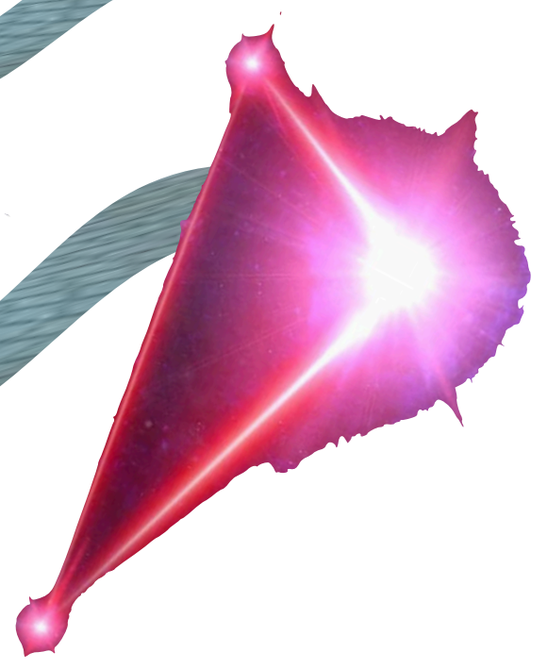
Università degli Studi di Padova
Dipartimento di Fisica e Astronomia "Galileo Galilei"

GW stochastic backgrounds

stellar black holes

PBHs

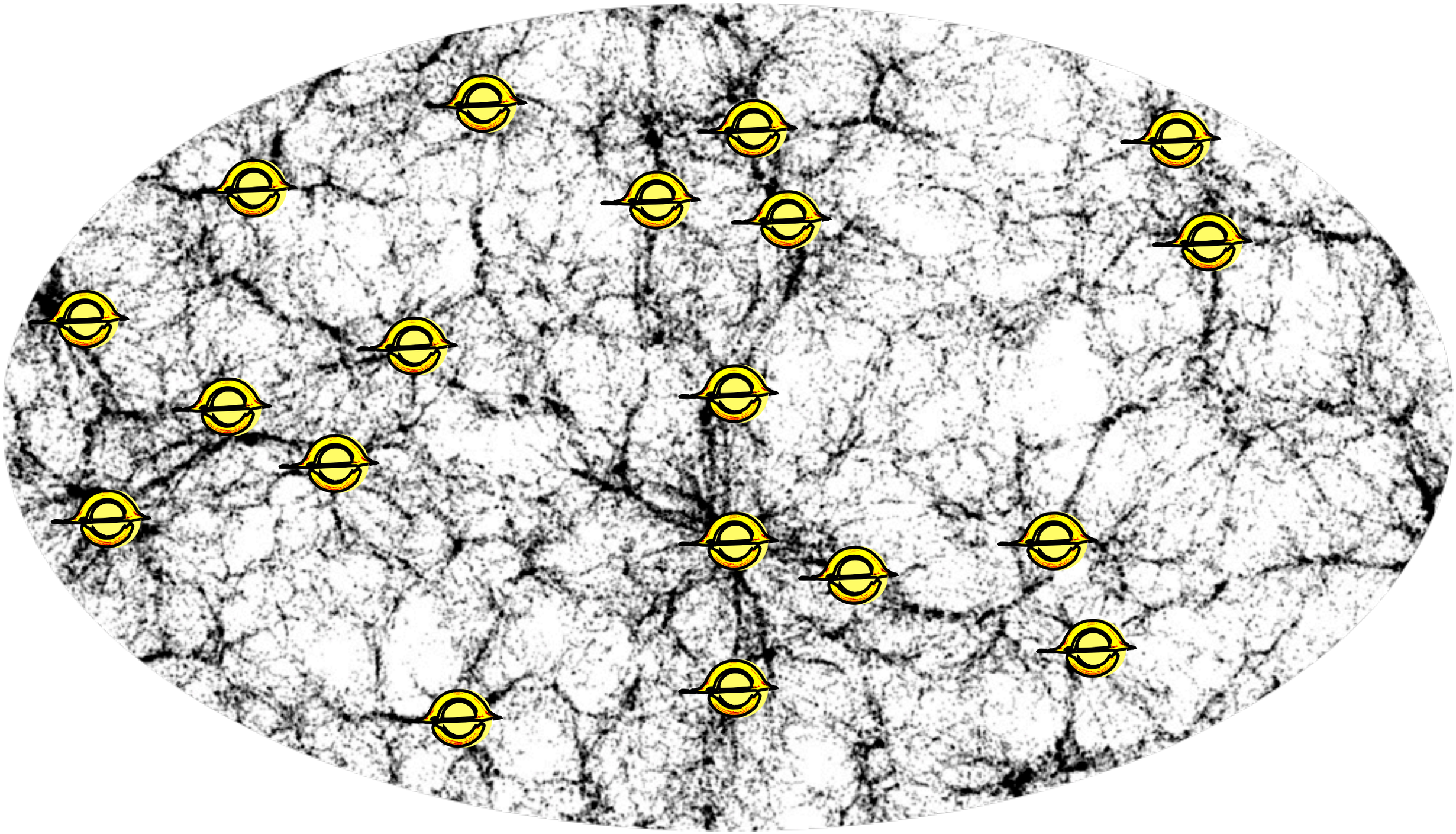




GW-matter interactions

Università degli Studi di Padova
Dipartimento di Fisica e Astronomia "Galileo Galilei"

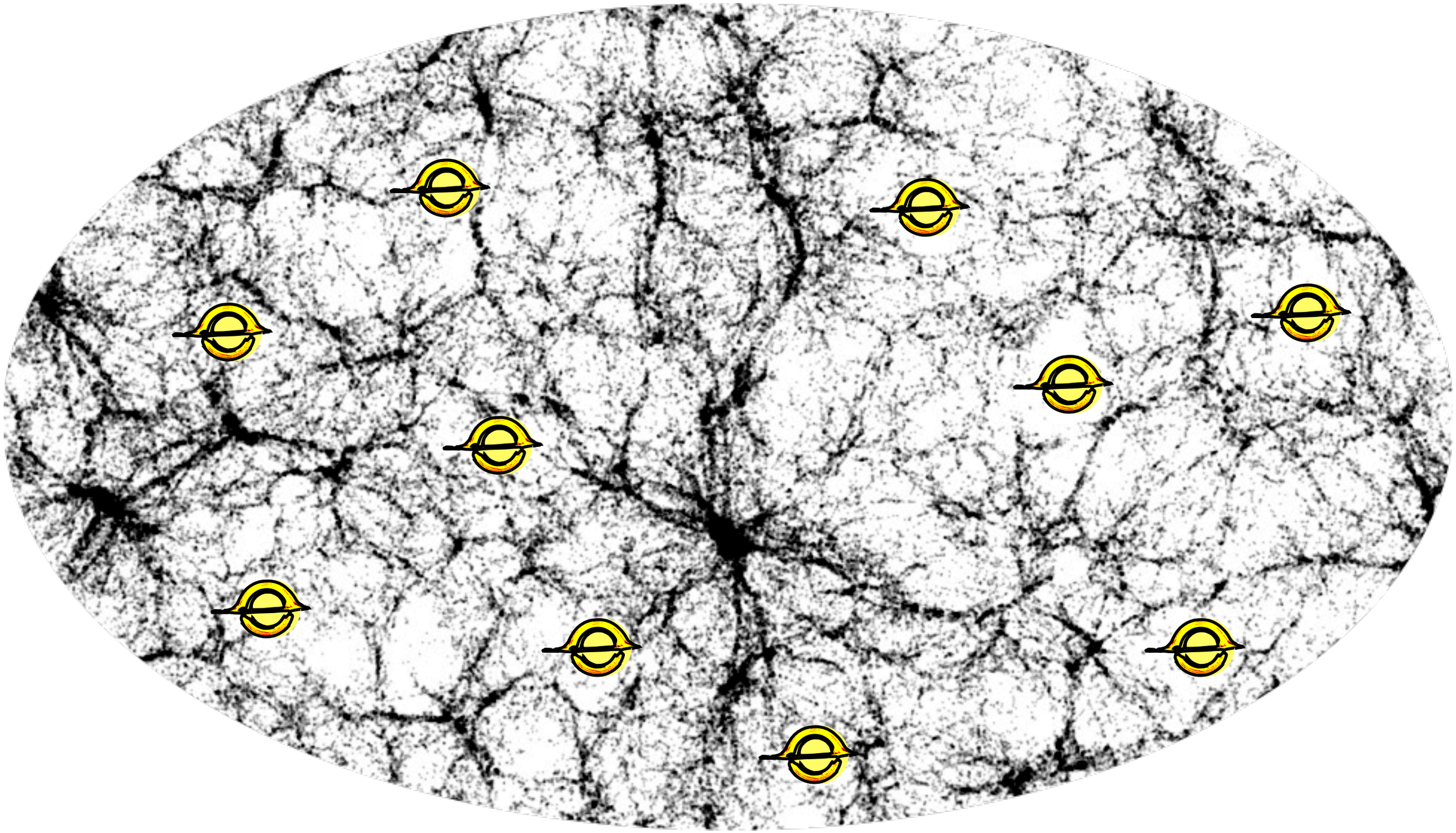
GW x LSS



UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Fisica e Astronomia "Galileo Galilei"

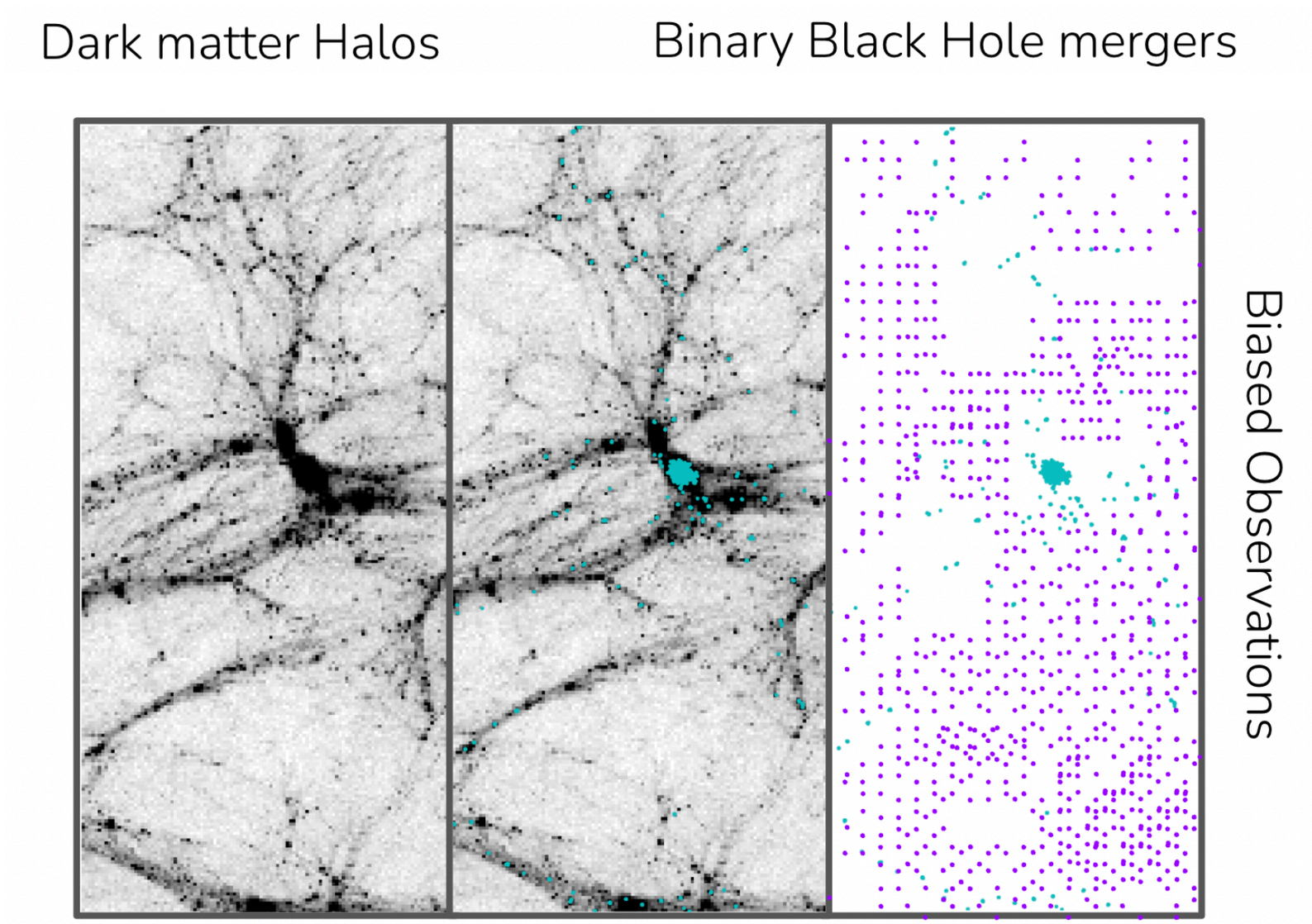
GW x LSS



Different populations cluster differently

UNIVERSITÀ DEGLI STUDI DI PADOVA
Dipartimento di Fisica e Astronomia "Galileo Galilei"

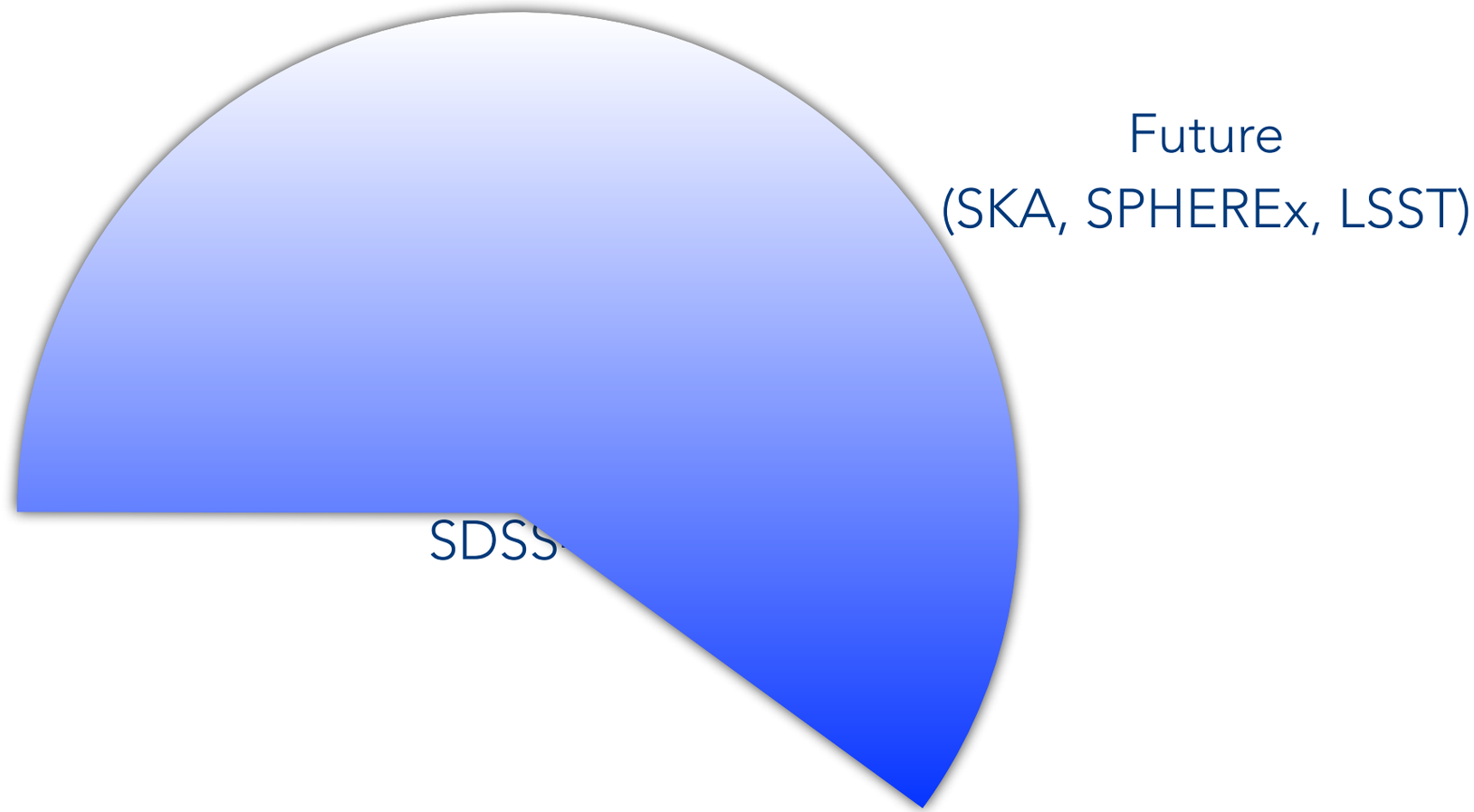
Machine learning techniques for binary black hole merger studies



Machine learning to populate dark matter simulations with compact object mergers and discriminate between models

Università degli Studi di Padova
Dipartimento di Fisica e Astronomia "Galileo Galilei"

LSS on ultra-large scales: relativistic effects



We are going to probe much larger volumes in the next few years

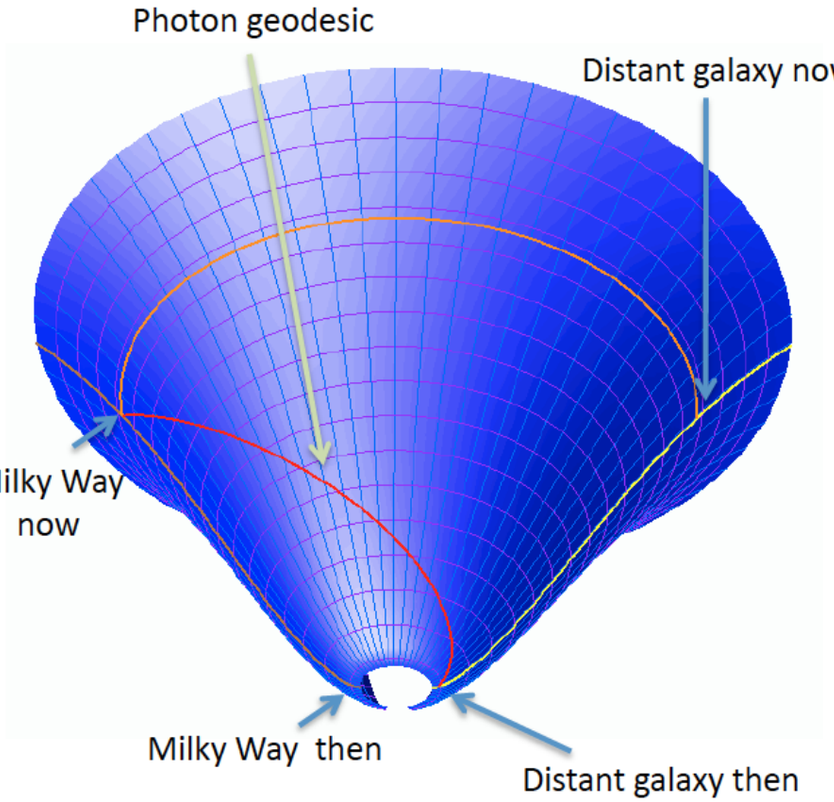
When looking at very large scales the plane-parallel, Newtonian description is not anymore accurate

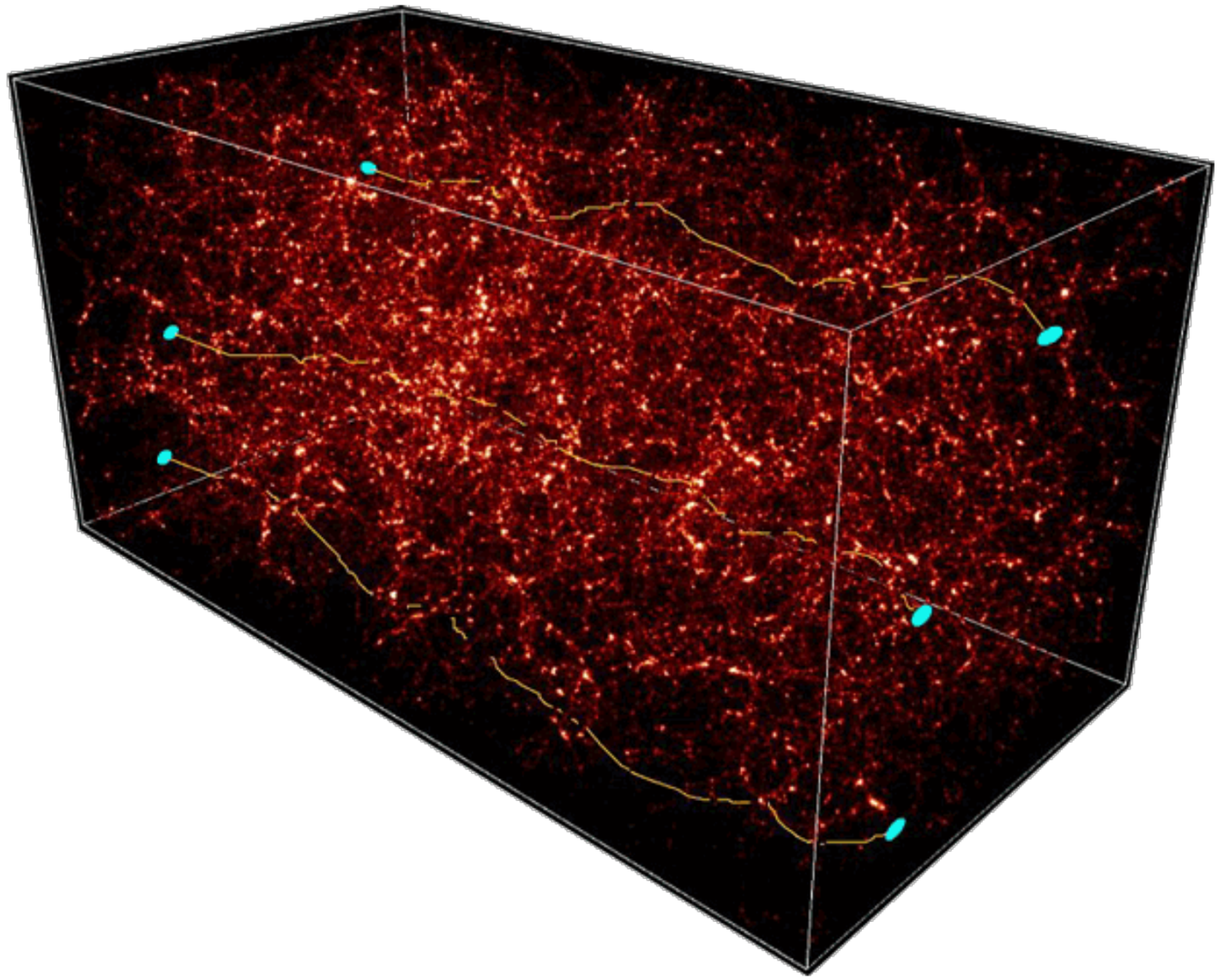
We need to include General Relativistic corrections

Università degli Studi di Padova
Dipartimento di Fisica e Astronomia "Galileo Galilei"

Higher order LSS correlations

We need to include relativistic corrections





Università degli Studi di Padova
Dipartimento di Fisica e Astronomia "Galileo Galilei"

Higher order LSS correlations

bispectrum – full analytical theory

$$
\begin{aligned}
\Delta_g^{(2)} &= \delta_g^{(2)} + \left[b_e - 2\mathcal{Q} - \frac{\mathcal{H}'}{\mathcal{H}^2} - (1-\mathcal{Q})\frac{2}{\bar{\chi}\mathcal{H}}\right]\Delta\ln a^{(2)} - (1-\mathcal{Q})\left(2\Psi^{(2)} + \frac{1}{2}\hat{h}_\parallel^{(2)}\right) - (1-\mathcal{Q})\frac{2}{\bar{\chi}}T^{(2)} - 2(1-\mathcal{Q})\kappa^{(2)} \\
&+\Phi^{(2)} + \frac{1}{\mathcal{H}}\Psi^{(2)\prime} - \frac{1}{2\mathcal{H}}\hat{h}_\parallel^{(2)\prime} - \frac{1}{\mathcal{H}}\partial_\parallel^2 v^{(2)} - \frac{1}{\mathcal{H}}\partial_\parallel \hat{v}_\parallel^{(2)} + 2(-1+2\mathcal{Q})\Phi\delta_g^{(1)} - \frac{2}{\mathcal{H}}\delta_g^{(1)}\partial_\parallel^2 v + \frac{2}{\mathcal{H}}\delta_g^{(1)}\Phi' + (\partial_\parallel v)^2 \\
&+\frac{2}{\mathcal{H}}\left(2\mathcal{Q} + \frac{\mathcal{H}'}{\mathcal{H}^2}\right)\Phi\Phi' + \left(-5 + 4\mathcal{Q} + 4\mathcal{Q}^2 - 4\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}}\right)\Phi^2 - \frac{2}{\mathcal{H}}\left(1 + 2\mathcal{Q} + \frac{\mathcal{H}'}{\mathcal{H}^2}\right)\Phi\partial_\parallel^2 v + \frac{2}{\mathcal{H}^2}(\Phi')^2 + \frac{2}{\mathcal{H}^2}\left(\partial_\parallel^2 v\right)^2 \\
&+\frac{4}{\mathcal{H}}\partial_\parallel v\partial_\parallel\Phi - \frac{2}{\mathcal{H}^2}\Phi\partial_\parallel^3 v - \frac{2}{\mathcal{H}}\Phi\partial_\parallel\Phi + \frac{2}{\mathcal{H}^2}\Phi\frac{\mathrm{d}\Phi'}{\mathrm{d}\bar{\chi}} - \frac{2}{\mathcal{H}^2}\partial_\parallel v\frac{\mathrm{d}\Phi'}{\mathrm{d}\bar{\chi}} - \frac{2}{\mathcal{H}^2}\Phi\partial_\parallel^2\Phi - \frac{4}{\mathcal{H}^2}\partial_\parallel^2 v\Phi' + \frac{2}{\mathcal{H}}\left(1 + \frac{\mathcal{H}'}{\mathcal{H}^2}\right)\partial_\parallel v\partial_\parallel^2 v \\
&+\frac{2}{\mathcal{H}^2}\partial_\parallel v\partial_\parallel^2\Phi + \frac{2}{\mathcal{H}}\left(1 - \frac{\mathcal{H}'}{\mathcal{H}^2}\right)\partial_\parallel v\Phi' + \frac{2}{\mathcal{H}}\partial_{\perp i}v\partial_\perp^i\Phi - \frac{4}{\mathcal{H}}\partial_{\perp i}v\partial_\perp^i\partial_\parallel v + \left(-1 + \frac{4}{\bar{\chi}\mathcal{H}}\right)\partial_{\perp i}v\partial_\perp^i v + \frac{2}{\mathcal{H}^2}\partial_\parallel v\partial_\parallel^3 v \\
&+\left\{\left[-2b_e - 4\mathcal{Q} + 4b_e\mathcal{Q} - 8\mathcal{Q}^2 + 8\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}} + 4\frac{\partial\mathcal{Q}}{\partial\ln\bar{a}} + 2\frac{\mathcal{H}'}{\mathcal{H}^2}(1-2\mathcal{Q}) + \frac{4}{\bar{\chi}\mathcal{H}}\left(-1 + \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}}\right)\right]\Phi\right. \\
&+2\left[b_e - 2\mathcal{Q} - \frac{\mathcal{H}'}{\mathcal{H}^2} - \frac{2}{\bar{\chi}\mathcal{H}}(1-\mathcal{Q})\right]\delta_g^{(1)} - \frac{2}{\mathcal{H}}\frac{\mathrm{d}\delta_g^{(1)}}{\mathrm{d}\bar{\chi}} + \frac{2}{\mathcal{H}}\left[-b_e + 2\mathcal{Q} + \frac{\mathcal{H}'}{\mathcal{H}^2} + \frac{2}{\bar{\chi}\mathcal{H}}(1-\mathcal{Q})\right]\partial_\parallel^2 v - \frac{4}{\mathcal{H}}\mathcal{Q}\partial_\parallel\Phi \\
&+\frac{2}{\mathcal{H}}\left[-2 + b_e - \frac{\mathcal{H}'}{\mathcal{H}^2} - \frac{2}{\bar{\chi}\mathcal{H}}(1-\mathcal{Q})\right]\Phi' + 4\left[-\left(b_e - b_e\mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}} - \frac{\partial\mathcal{Q}}{\partial\ln\bar{a}}\right) + \frac{\mathcal{H}'}{\mathcal{H}^2}(1-\mathcal{Q})\right. \\
&\left.\left.+\frac{1}{\bar{\chi}\mathcal{H}}\left(1 - \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}}\right)\right]\left(\frac{T^{(1)}}{\bar{\chi}} + \kappa^{(1)}\right)\right\}\Delta\ln a^{(1)} + \left\{-b_e + b_e^2 + \frac{\partial b_e}{\partial\ln\bar{a}} + 6\mathcal{Q} - 4\mathcal{Q}b_e + 4\mathcal{Q}^2 - 4\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}}\right. \\
&-4\frac{\partial\mathcal{Q}}{\partial\ln\bar{a}} + (1 - 2b_e + 4\mathcal{Q})\frac{\mathcal{H}'}{\mathcal{H}^2} - \frac{\mathcal{H}''}{\mathcal{H}^3} + 3\left(\frac{\mathcal{H}'}{\mathcal{H}^2}\right)^2 + \frac{6}{\bar{\chi}}\frac{\mathcal{H}'}{\mathcal{H}^3}(1-\mathcal{Q}) + \frac{2}{\bar{\chi}^2\mathcal{H}^2}\left(1 - \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}}\right) \\
&\left.+\frac{2}{\bar{\chi}\mathcal{H}}\left[1 - 2b_e - \mathcal{Q} + 2b_e\mathcal{Q} - 4\mathcal{Q}^2 + 4\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}} + 2\frac{\partial\mathcal{Q}}{\partial\ln\bar{a}}\right]\right\}\left(\Delta\ln a^{(1)}\right)^2 + 4\left[+\frac{1}{\mathcal{H}}\left(1 - \frac{\mathcal{H}'}{\mathcal{H}^2}\right)\Phi' + \frac{1}{\mathcal{H}}\partial_\parallel\Phi\right. \\
&+\frac{1}{\mathcal{H}}\left(1 + \frac{\mathcal{H}'}{\mathcal{H}^2}\right)\partial_\parallel^2 v + \frac{1}{\mathcal{H}^2}\partial_\parallel^2\Phi + \frac{1}{\mathcal{H}^2}\partial_\parallel^3 v - \frac{1}{\mathcal{H}^2}\frac{\mathrm{d}\Phi'}{\mathrm{d}\bar{\chi}}\Big]I^{(1)} + \left[-\frac{4}{\bar{\chi}}(1-\mathcal{Q})\delta_g^{(1)} - 2\partial_\parallel\delta_g^{(1)} - \frac{4}{\bar{\chi}\mathcal{H}}(1-\mathcal{Q})\Phi'\right. \\
&+\frac{4}{\bar{\chi}}\left(-1 + \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}}\right)\Phi + 2(1-2\mathcal{Q})\partial_\parallel\Phi + \frac{4}{\bar{\chi}\mathcal{H}}(1-\mathcal{Q})\partial_\parallel^2 v + \frac{2}{\mathcal{H}}\partial_\parallel^3 v. - \frac{2}{\mathcal{H}}\partial_\parallel\Phi'\Big]T^{(1)} \\
&+\left(1 - \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}}\right)\left[\frac{2}{\bar{\chi}^2}\left(T^{(1)}\right)^2 + \frac{4}{\bar{\chi}}T^{(1)}\kappa^{(1)}\right] + 4\left[-\left(1 - \mathcal{Q} - 2\mathcal{Q}^2 + 2\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}}\right)\Phi + \frac{1}{\mathcal{H}}(1-\mathcal{Q})\partial_\parallel^2 v\right. \\
&\left.-\frac{1}{\mathcal{H}}(1-\mathcal{Q})\Phi' - (1-\mathcal{Q})\delta_g^{(1)}\right]\kappa^{(1)} + (1-\mathcal{Q})\vartheta_{ij}^{(1)}\vartheta^{ij(1)} + 2\left(1 - \mathcal{Q} + 2\mathcal{Q}^2 - 2\frac{\partial\mathcal{Q}}{\partial\ln\bar{L}}\right)\left(\kappa^{(1)}\right)^2 - 2(1-\mathcal{Q})\left|\gamma^{(1)}\right|^2 \\
&+4\left[\frac{\bar{\chi}}{\mathcal{H}}\left(\partial_{\perp i}\Phi' - \partial_{\perp i}\partial_\parallel^2 v\right) + \bar{\chi}\partial_{\perp i}\delta_g^{(1)} + \bar{\chi}\partial_{\perp i}\Phi - 2\bar{\chi}(1-\mathcal{Q})\partial_{\perp i}\Phi + \frac{1}{\mathcal{H}}(1-\mathcal{Q})\partial_{\perp i}\Delta\ln a^{(1)}\right]S_\perp^{i(1)} \\
&-4(1-\mathcal{Q})S_\perp^{i(1)}S_\perp^{j(1)}\delta_{ij} + 2\left[\frac{2}{\bar{\chi}\mathcal{H}}\partial_{\perp i}v - \frac{\bar{\chi}}{\mathcal{H}}\partial_{\perp i}\Phi' + \frac{\bar{\chi}}{\mathcal{H}}\partial_{\perp i}\partial_\parallel^2 v - \frac{2}{\mathcal{H}}\partial_{\perp i}\partial_\parallel v - \bar{\chi}\partial_{\perp i}\delta_g^{(1)} + \bar{\chi}(1-2\mathcal{Q})\partial_{\perp i}\Phi\right]\partial_\perp^i T^{(1)} \\
&+4\mathcal{Q}^{(1)}\left[\Phi - \left(1 - \frac{1}{\bar{\chi}\mathcal{H}}\right)\Delta\ln a^{(1)} + \frac{1}{\bar{\chi}}T^{(1)} + \kappa^{(1)}\right] + 8(1-\mathcal{Q})\left\{\int_0^{\bar{\chi}}\mathrm{d}\tilde{\chi}\left[-\Phi\tilde{\partial}_{\perp m}S_\perp^{m(1)} + \left(\frac{\mathrm{d}\Phi}{\mathrm{d}\tilde{\chi}} - \frac{1}{\tilde{\chi}}\Phi\right)\kappa^{(1)}\right]\right. \\
&\left.\left.-\frac{1}{\bar{\chi}}\int_0^{\bar{\chi}}\mathrm{d}\tilde{\chi}\left(\Phi^2 + \Phi' T^{(1)} + 2\Phi\kappa^{(1)} + \tilde{\chi}\tilde{\partial}_{\perp i}\Phi\tilde{\partial}_\perp^i T^{(1)}\right) + \frac{1}{\bar{\chi}}\int_0^{\bar{\chi}}\mathrm{d}\tilde{\chi}\,(\bar{\chi} - \tilde{\chi})\left[-2\Phi\tilde{\partial}_{\perp m}S_\perp^{m(1)} + 2\left(\frac{\mathrm{d}\Phi}{\mathrm{d}\tilde{\chi}} - \frac{1}{\tilde{\chi}}\Phi\right)\kappa^{(1)}\right]\right\}.
\end{aligned}
$$

We need a way to reduce analytical complexity

Use machine learning to identify relevant contributions


Università degli Studi di Padova


Dipartimento di Fisica e Astronomia "Galileo Galilei"

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Dipartimento di Fisica e
Astronomia
"Galileo Galilei"