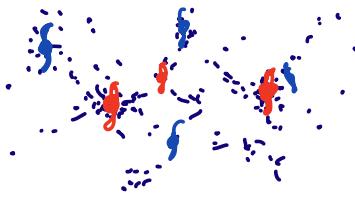


Lecture 4

So far we have been focusing on DM in real space.
In reality, we observe galaxies in redshift space.



EFT methods are applicable
in all situations!

Identify relevant d.o.f.

Identify relevant symmetries

Identify relevant expansion parameters

} Write down the e.o.m.

For DM, we didn't have to start from Vlasov equation.

Think about VLDM!

Relevant d.o.f. $\rightarrow \delta_g(\vec{x}, t) = \frac{p_g(\vec{x}, t) - \bar{p}_g(t)}{\bar{\rho}_g(t)}$

Symmetries:

We have to give up mass and momentum conservation



In redshift space $\uparrow^{\hat{n}}$ \rightarrow can't be same
lose isotropy.

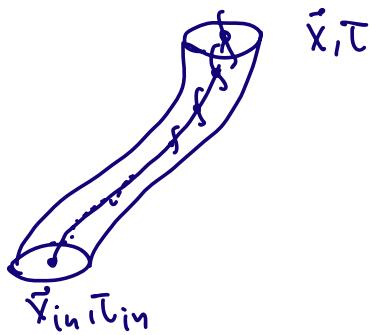
Equivalence principle still holds!

Expansion parameters: the same as for DM.

Biased tracers

time scale for all fluctuations $\sim H^{-1}$

$$\delta_g^{\text{model}}(\vec{x}, \tau) = \int_{\tau_{\text{lin}}}^{\tau} d\tau' \left[C_\delta(\tau, \tau') \delta_{NL}(\vec{x}_{\text{fe}}(\tau'), \tau') + C_{\delta^2} \cdot \delta_{NL}^2 + C_{\text{tide}} (\partial_i \partial_j \phi)^2 + \dots + C_{\sigma^2} \cdot \frac{\nabla^2 \delta_{NL}}{k_M^2} + \dots \right]$$



$$\delta_{NL}(\vec{x}_{\text{fe}}(\tau'), \tau') =$$

$$\delta_{NL}(\vec{x}) + (\tau - \tau') \frac{D}{D\tau} \delta_{NL}(\vec{x}) + \dots$$

$$\frac{D}{D\tau} = \frac{\partial}{\partial \tau} + \vec{v} \cdot \vec{\nabla}_x$$

$$\begin{aligned} \delta_g^{\text{model}}(\vec{x}, \tau) &= b_1(\tau) \delta_{\text{ne}}(\vec{x}, \tau) + \frac{b_2(\tau)}{2} \left(\delta_{\text{ne}}^2 - \langle \delta_{\text{ne}}^2 \rangle \right) \\ &\quad + b_{G_2} \underbrace{\left[(\partial_i \partial_j \phi)^2 - 1 \right]}_{\equiv G_2} + \dots + b_{\sigma^2} \nabla^2 \delta + \dots \end{aligned}$$

$$\delta_g^{\text{model}} [\delta^{(1)}], \quad \delta_{NL} = \delta^{(1)} + \delta^{(2)} + \dots \quad \hookrightarrow \int F_2 \delta^{(1)} \delta^{(1)}$$

$$\delta_g^{\text{model}}(\vec{k}, \tau) = b_1 \delta^{(1)}(\vec{k}) + \int_{\vec{q}_1, \vec{q}_2} Y_2(\vec{q}_1, \vec{q}_2; b_1) \delta^{(1)}(\vec{q}_1) \delta^{(1)}(\vec{q}_2)$$

$$Y_2(\vec{q}_1, \vec{q}_2) = b_1 F_2(\vec{q}_1, \vec{q}_2) + \frac{b_2}{2} + b_{G_2} \left(\frac{(\vec{q}_1 \cdot \vec{q}_2)^2}{q_1^2 q_2^2} - 1 \right)$$

$$F_2(\vec{q}, \vec{k}-\vec{q}) \Big|_{q \gg k} \sim \frac{k^2}{q^2} \quad \text{mass and momentum conservation}$$

$$Y_2(\vec{q}, \vec{k}-\vec{q}) \Big|_{q \gg k} \sim \text{const.}$$

$$\delta_g = \delta_g^{\text{model}} + \epsilon \quad P_e(k) \approx \text{const.}$$

\hookrightarrow noise

RSD.

$$\begin{array}{c} \vec{s} \\ \downarrow h \\ \vec{x} \end{array} \quad \vec{s} = \vec{x} + \frac{\vec{\sigma} \cdot \hat{n}}{h} \hat{n}$$

$$(1 + \delta_g^s(\vec{s})) d^3 \vec{s} = (1 + \delta_g(\vec{x})) d^3 \vec{x}$$

$$\left| \frac{\partial \vec{r}}{\partial \vec{x}} \right| \rightarrow \text{find } \delta_g^s(\vec{s}) \text{ in terms of } \begin{matrix} \delta_g(\vec{x}) \\ [\delta_g(\vec{x}) \cdot \vec{U}] \end{matrix}$$

In linear theory:

$$\delta_g^s(k) = (b_1 + f \mu^2) \delta^{(1)}(\vec{k}) \quad \mu = \hat{k} \cdot \hat{n}$$

$$P_{gg}^{s, \text{lin}}(k, \mu) = (b_1 + f \mu^2)^2 P_{\text{lin}}(k)$$

Power spectrum multipoles

$$P_e(k) = \frac{2\ell+1}{2} \int_{-1}^1 d\mu P_g^s(k, \mu) \cdot P_e(\mu)$$

\hookrightarrow Legendre polynomials

The full 1-loop RSD model for galaxies

Finite number of fixed momentum dependent templates
A handful of free parameters.

$$P_{\text{gg,RSD}}(z, k, \mu) = Z_1^2(\mathbf{k}) P_{\text{lin}}(z, k) + 2 \int_{\mathbf{q}} Z_2^2(\mathbf{q}, \mathbf{k} - \mathbf{q}) P_{\text{lin}}(z, |\mathbf{k} - \mathbf{q}|) P_{\text{lin}}(z, q) \\ + 6Z_1(\mathbf{k}) P_{\text{lin}}(z, k) \int_{\mathbf{q}} Z_3(\mathbf{q}, -\mathbf{q}, \mathbf{k}) P_{\text{lin}}(z, q) \\ + P_{\text{ctr,RSD}}(z, k, \mu) + P_{\epsilon\epsilon, \text{RSD}}(z, k, \mu),$$

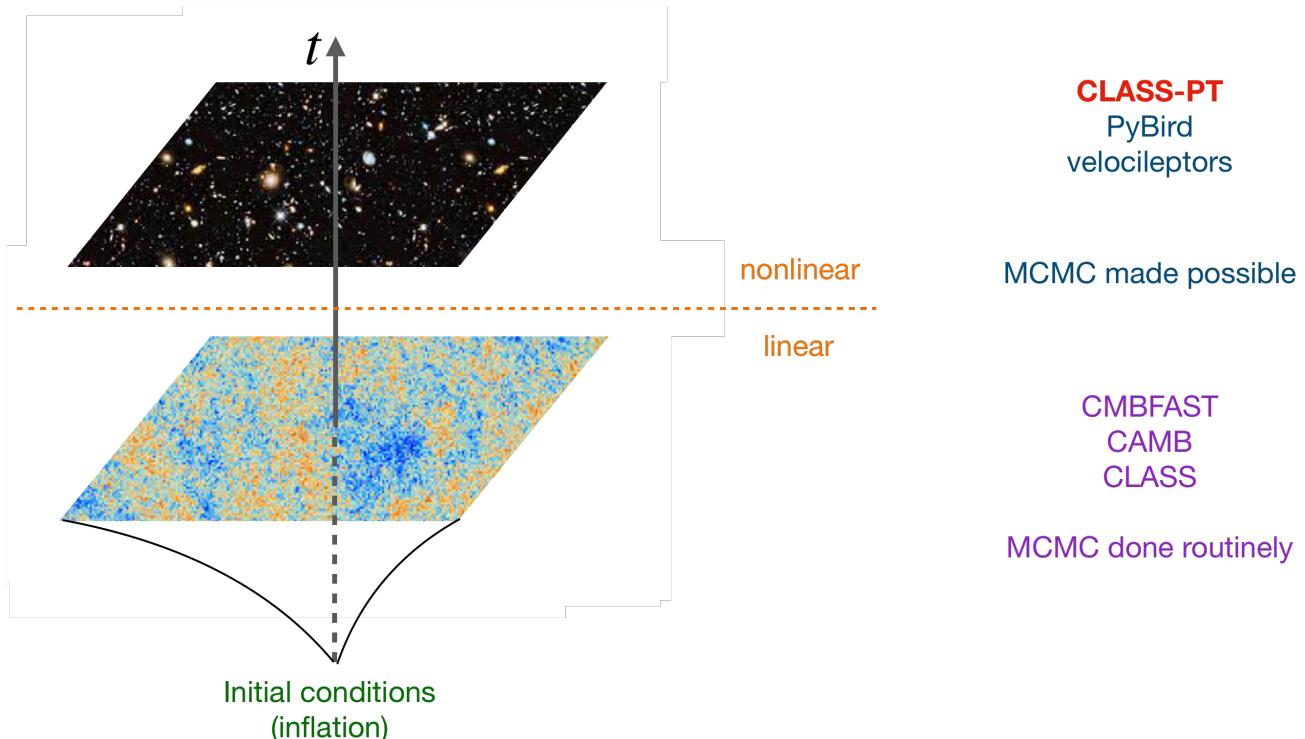
$$Z_1(\mathbf{k}) = b_1 + f\mu^2, \\ Z_2(\mathbf{k}_1, \mathbf{k}_2) = \frac{b_2}{2} + b_{G_2} \left(\frac{(\mathbf{k}_1 \cdot \mathbf{k}_2)^2}{k_1^2 k_2^2} - 1 \right) + b_1 F_2(\mathbf{k}_1, \mathbf{k}_2) + f\mu^2 G_2(\mathbf{k}_1, \mathbf{k}_2) \\ + \frac{f\mu k}{2} \left(\frac{\mu_1}{k_1} (b_1 + f\mu_2^2) + \frac{\mu_2}{k_2} (b_1 + f\mu_1^2) \right),$$

$$\Sigma^2(z) \equiv \frac{1}{6\pi^2} \int_0^{k_S} dq P_{\text{nw}}(z, q) \left[1 - j_0 \left(\frac{q}{k_{\text{osc}}} \right) + 2j_2 \left(\frac{q}{k_{\text{osc}}} \right) \right] \\ \delta\Sigma^2(z) \equiv \frac{1}{2\pi^2} \int_0^{k_S} dq P_{\text{nw}}(z, q) j_2 \left(\frac{q}{k_{\text{osc}}} \right) \\ \Sigma_{\text{tot}}^2(z, \mu) = (1 + f(z)\mu^2(2 + f(z)))\Sigma^2(z) + f^2(z)\mu^2(\mu^2 - 1)\delta\Sigma^2(z)$$

$$P_{\text{gg}}(z, k, \mu) = (b_1(z) + f(z)\mu^2)^2 \left(P_{\text{nw}}(z, k) + e^{-k^2\Sigma_{\text{tot}}^2(z, \mu)} P_{\text{w}}(z, k)(1 + k^2\Sigma_{\text{tot}}^2(z, \mu)) \right) \\ + P_{\text{gg, nw, RSD, 1-loop}}(z, k, \mu) + e^{-k^2\Sigma_{\text{tot}}^2(z, \mu)} P_{\text{gg, w, RSD, 1-loop}}(z, k, \mu).$$

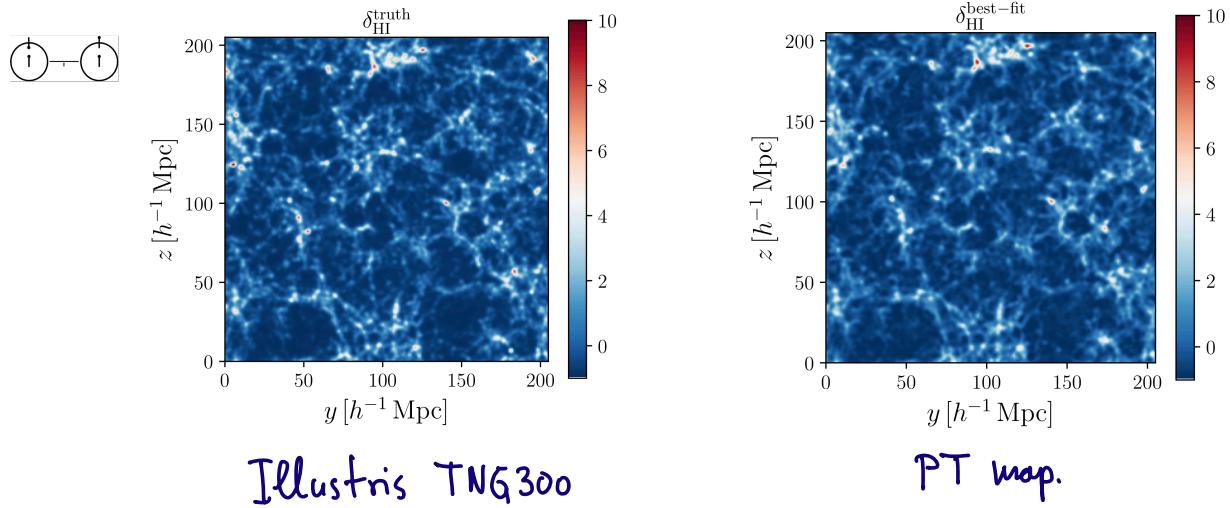
Parameters: $(\omega_b, \omega_{\text{cdm}}, h, A^{1/2}, n_s, m_\nu) \times (b_1 A^{1/2}, b_2 A^{1/2}, b_{G_2} A^{1/2}, P_{\text{shot}}, c_0^2, c_2^2, \tilde{c})$

Fast extensions of linear codes that compute all observables in $O(1 \text{ sec})$

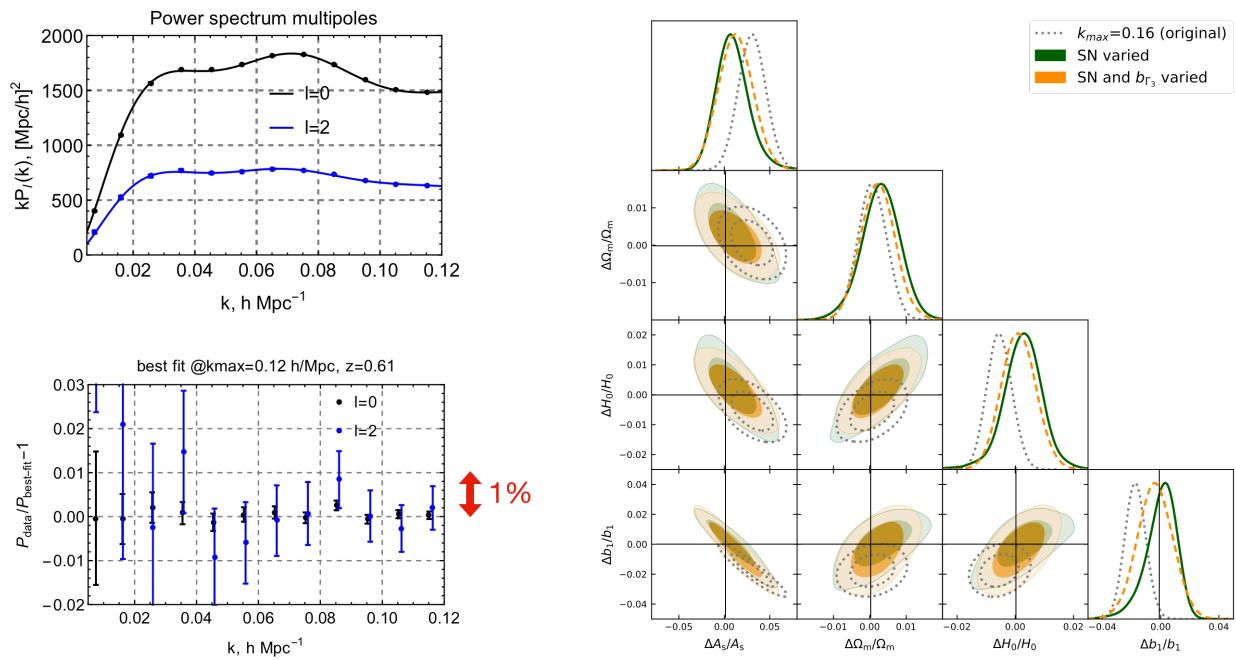


How well does it work for galaxies in redshift space?

the same ICs → PT map
hydro simulation

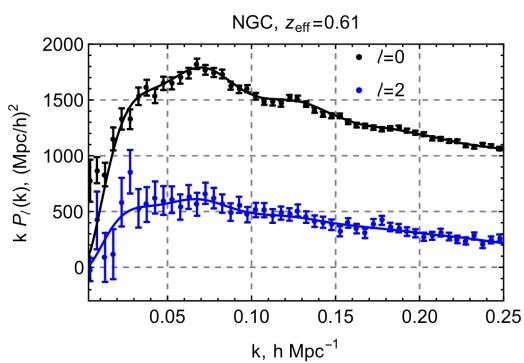


Blind analysis, very large volume ~ 600 (Gpc/h) 3 , realistic galaxies



We can apply this in the real data!

Galaxy map

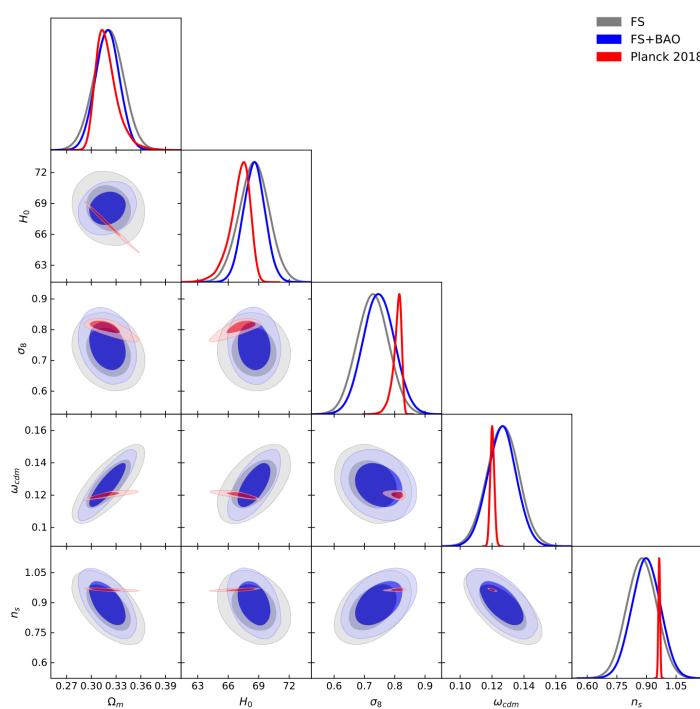


Full-shape analysis

Similar to CMB, directly measures “shape” parameters



all cosmological parameters
no CMB input needed



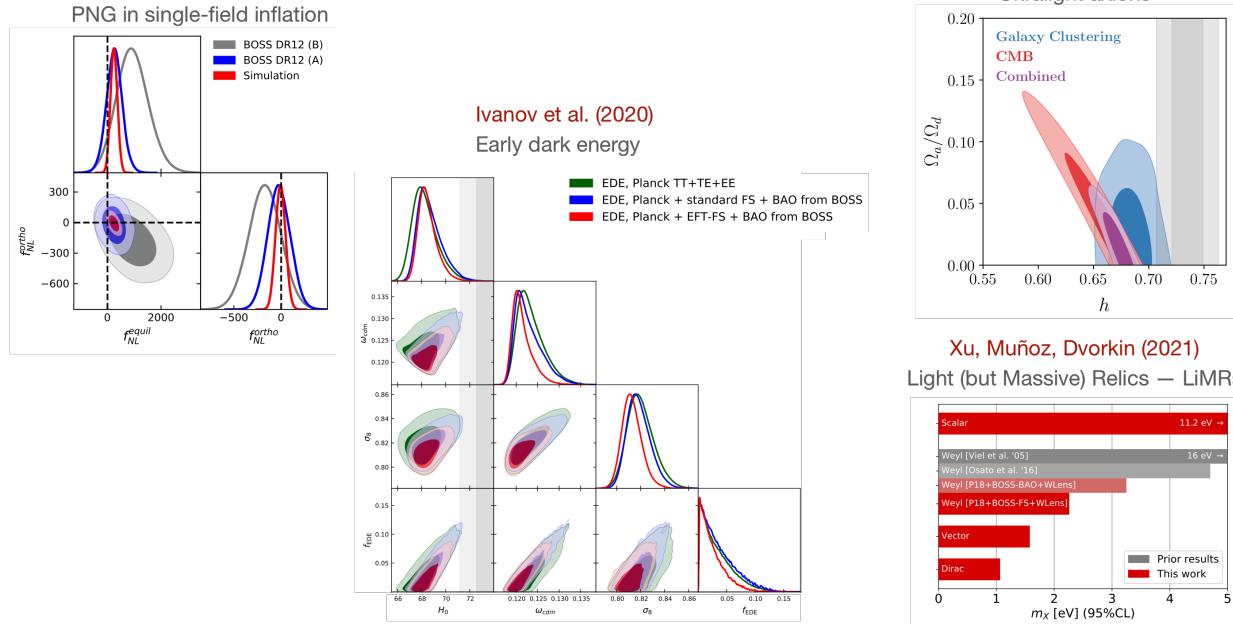
$$H_0 = 68.6 \pm 1.1 \text{ km/s/Mpc}$$

$$H_0 = 67.8 \pm 0.7 \text{ km/s/Mpc}$$

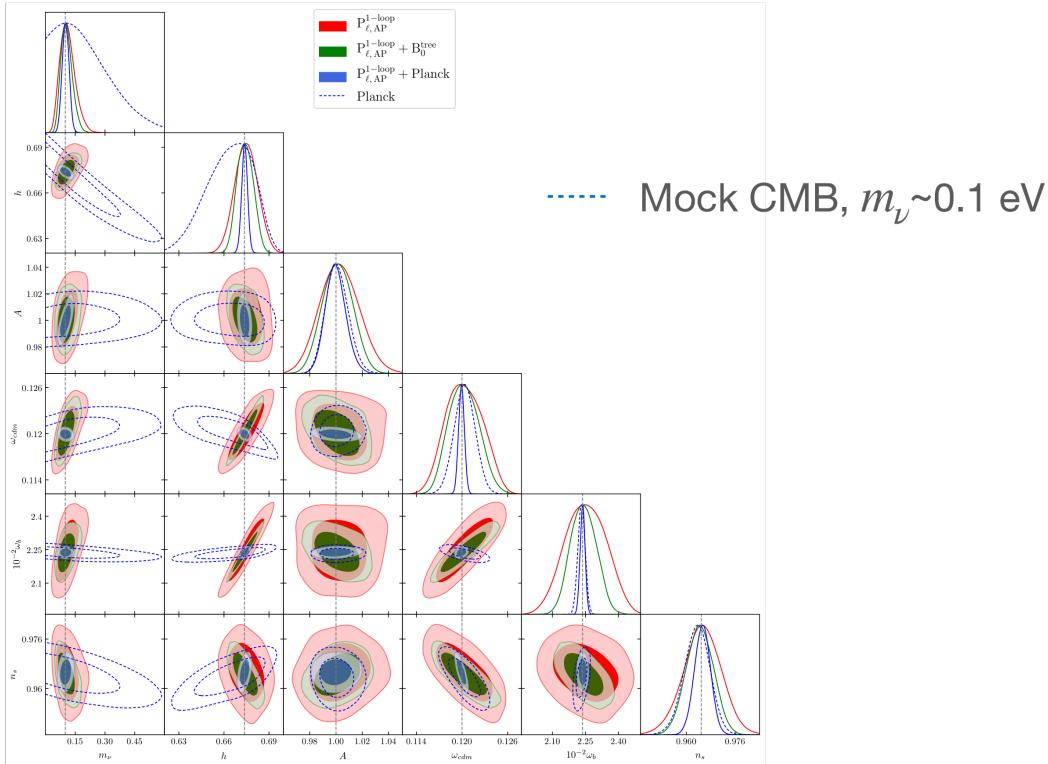
Beyond Λ CDM

Cabass, Ivanov, Philcox, MS, Zaldarriaga (2022)

Laguë, Bond, Hložek, Rogers, Marsh, Grin (2021)



Forecast for a DESI / Euclid - like survey



Future

Theory : beyond Λ CDM models , higher order/loop computations , perturbative forward modeling, new estimators , beyond galaxy clustering, different statistics...

Implementation: better algorithms to compute loops, faster , simpler, more optimal codes

Data analysis: optimization , masks, covariances, data compression , new observables...