Initial conditions for simulations of arbitrary modified gravity, beyond quasi-static approximations

Wessel Valkenburg
CERN

Based on [Valkenburg & Hu (2015), JCAP]

Message

- How to generate positions, masses, pressures for linearly perturbed (im)perfect fluid
- Use our code for IC of your future simulation

$$\frac{ds^2}{a(\tau)^2} = -(1+2A)d\tau^2 - 2B_i d\tau\, dx^i + \left[(1+2H_L)\eta_{ij} + 2h^T_{ij}\right] dx^i dx^j$$

Linear PT

Perturbation Theory

$$U^\mu = dx^\mu/\sqrt{-ds^2},\ U^\mu U_\mu = -1$$

$$\bar{U}^i = 0, \text{ and } \partial_i \delta U^i \equiv \theta$$

$$n^\mu = -nU^\mu$$

$$\nabla_\mu n^\mu = 0, \qquad \text{[number conservation]}$$

$$\bar{n} \propto a^{-3},$$

$$\dot{\Delta}_n = -\,(\theta + 3\dot{H}_L), \qquad \text{[linear order]}$$

$$\frac{ds^2}{a(\tau)^2} = -(1+2A)d\tau^2 - 2B_i d\tau\, dx^i + \left[(1+2H_L)\eta_{ij} + 2h^T_{ij}\right] dx^i dx^j$$

Linear PT

Perturbation Theory

$U^\mu = dx^\mu/\sqrt{-ds^2}$, $U^\mu U_\mu = -1$

$\bar{U}^i = 0$, and $\partial_i \delta U^i \equiv \theta$

$$n^\mu = -nU^\mu$$

$\nabla_\mu n^\mu = 0,$ [number conservation]

$\bar{n} \propto a^{-3},$

GR:

$$\dot{\Delta}_n = -\,(\theta + 3\dot{H}_L),$$

Newtonian:

$$\dot{\Delta}_n^{\text{Newt}} = -\theta^{\text{Newt}}$$

$$\frac{ds^2}{a(\tau)^2} = -(1+2A)d\tau^2 - 2B_i d\tau\, dx^i + \left[(1+2H_L)\eta_{ij} + 2h^T_{ij}\right] dx^i dx^j$$

Linear PT

Perturbation Theory

$$U^\mu = dx^\mu/\sqrt{-ds^2},\; U^\mu U_\mu = -1$$

$$\bar{U}^i = 0, \text{ and } \partial_i \delta U^i \equiv \theta$$

$$n^\mu = -nU^\mu$$

$$\nabla_\mu n^\mu = 0, \qquad \text{[number conservation]}$$

$$\bar{n} \propto a^{-3},$$

GR:

$$\dot{\Delta}_n = -\left(\theta + 3\dot{H}_L\right),$$

Newtonian:

$$\dot{\Delta}_n^{\rm Newt} = -\theta^{\rm Newt}$$

$$\Delta_n^{\text{any gauge}} = \Delta_n^{\rm Newt} + \mathcal{O}(\mathcal{H}/k)$$

$$\frac{ds^2}{a(\tau)^2} = -(1+2A)d\tau^2 - 2B_i d\tau\, dx^i + \left[(1+2H_L)\eta_{ij} + 2h^T_{ij}\right] dx^i dx^j$$

Linear PT

Perturbation Theory

$U^\mu = dx^\mu/\sqrt{-ds^2}$, $U^\mu U_\mu = -1$

$\bar{U}^i = 0$, and $\partial_i \delta U^i \equiv \theta$

$n^\mu = -nU^\mu$

$\nabla_\mu n^\mu = 0$, [number conservation]

$\bar{n} \propto a^{-3}$,

GR:

$$\dot{\Delta}_n = -\left(\theta + 3\dot{H}_L\right),$$

Newtonian:

$$\dot{\Delta}_n^{\rm Newt} = -\theta^{\rm Newt}$$

$$\Delta_n^{\rm any\ gauge} = \Delta_n^{\rm Newt} + \mathcal{O}(\mathcal{H}/k)$$

$$\theta^{\rm any\ gauge} + 3\dot{H}_L \to \theta^{\rm Newt}$$

$$\frac{ds^2}{a(\tau)^2} = -(1+2A)d\tau^2 - 2B_i d\tau\, dx^i + \left[(1+2H_L)\eta_{ij} + 2h^T_{ij}\right] dx^i dx^j$$

Linear displacement field

$$\delta x^i = \int d\tau\, u^i = \int d\tau\, \frac{\nabla^i}{\nabla^2}\theta$$

$$\frac{ds^2}{a(\tau)^2} = -(1+2A)d\tau^2 - 2B_i d\tau\, dx^i + \left[(1+2H_L)\eta_{ij} + 2h_{ij}^T\right] dx^i dx^j$$

Linear displacement field

$$\delta x^i = \int d\tau\, u^i = \int d\tau\, \frac{\nabla^i}{\nabla^2}\theta$$

$$\delta x^{i\ \mathrm{Newt}} = \int d\tau\, \frac{\nabla^i}{\nabla^2}\theta^{\mathrm{Newt}} = -\frac{\nabla^i}{\nabla^2}\Delta_n$$

$$\frac{ds^2}{a(\tau)^2} = -(1+2A)d\tau^2 - 2B_i d\tau\, dx^i + \left[(1+2H_L)\eta_{ij} + 2h^T_{ij}\right] dx^i dx^j$$

Linear displacement field

$$\delta x^i = \int d\tau\, u^i = \int d\tau\, \frac{\nabla^i}{\nabla^2}\theta$$

$$\delta x^{i\ \mathrm{Newt}} = \int d\tau\, \frac{\nabla^i}{\nabla^2}\theta^{\mathrm{Newt}} = -\frac{\nabla^i}{\nabla^2}\Delta_n$$

If only CDM:

$$\delta x^{i\ \mathrm{Newt}} = -\frac{\nabla^i}{\nabla^2}\Delta_n = -\frac{\nabla^i}{\nabla^2}\Delta_\rho = -\nabla^i \Phi^{\mathrm{Newt}}$$

$$\frac{ds^2}{a(\tau)^2} = -(1+2A)d\tau^2 - 2B_i d\tau\, dx^i + \left[(1+2H_L)\eta_{ij} + 2h^T_{ij}\right] dx^i dx^j$$

Linear displacement field

$$\delta x^i = \int d\tau\, u^i = \int d\tau\, \frac{\nabla^i}{\nabla^2}\theta$$

If $\hat{\theta}_{\vec{k}}(\tau) = D(\tau)\hat{\theta}^0_{\vec{k}}$ $\longrightarrow$ $\delta x^i(\tau) = D(\tau)\delta x^i_0$

$$\frac{ds^2}{a(\tau)^2} = -(1+2A)d\tau^2 - 2B_i d\tau\, dx^i + \left[(1+2H_L)\eta_{ij} + 2h^T_{ij}\right] dx^i dx^j$$

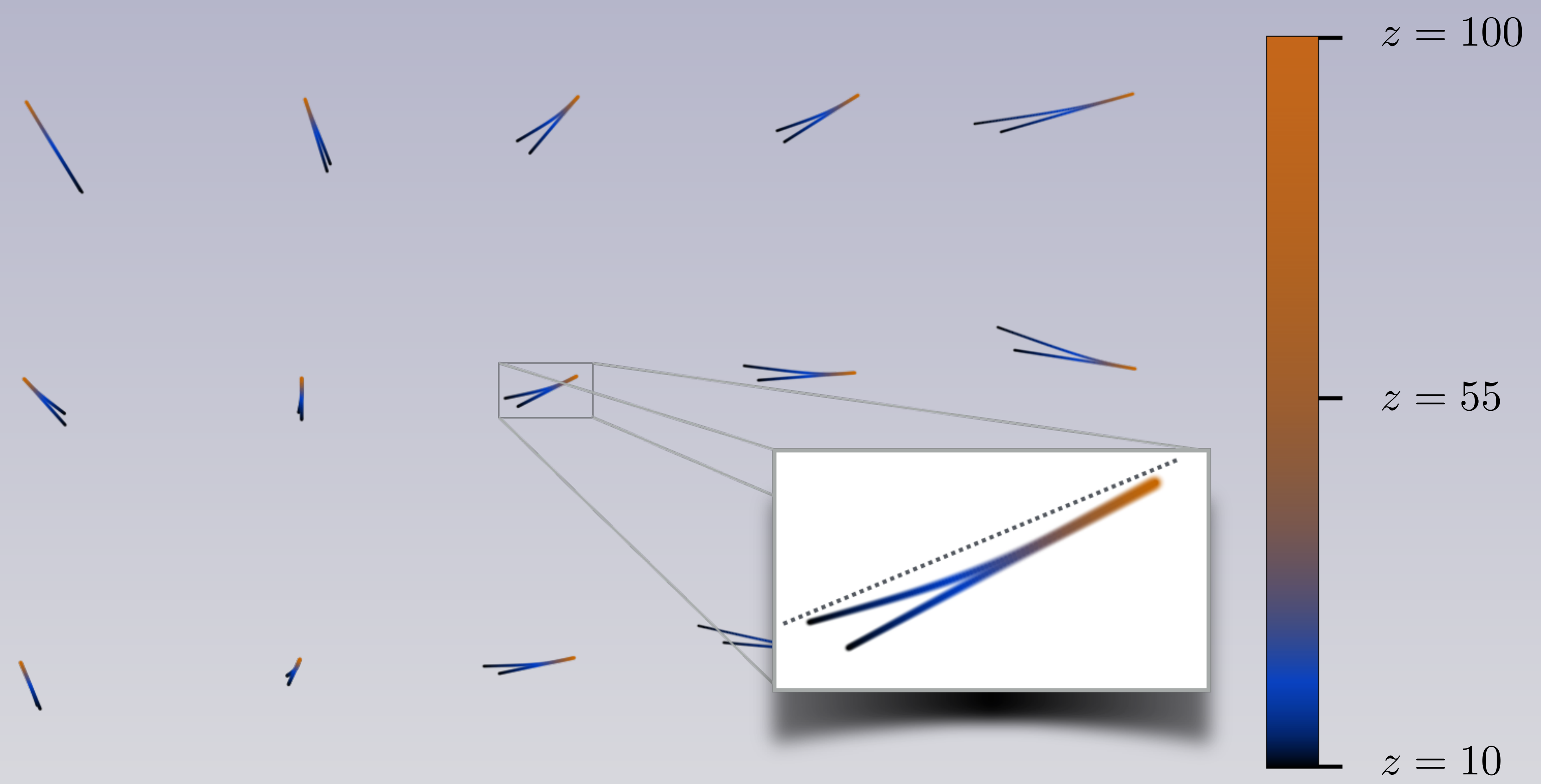
Linear displacement field

$$\delta x^i = \int d\tau\, u^i = \int d\tau\, \frac{\nabla^i}{\nabla^2}\theta$$

If $\hat{\theta}_{\vec{k}}(\tau) = D(\tau)\hat{\theta}^0_{\vec{k}}$ ⟶ $\delta x^i(\tau) = D(\tau)\delta x^i_0$

If $\hat{\theta}_{\vec{k}}(\tau) = D(\tau, \vec{k})\hat{\theta}^0_{\vec{k}}$ ⟶ $\delta x^i(\tau) = D(\tau, \vec{x})\delta x^i_0$

Scale dependent growth in DM: curves



These are linear perturbations for a viable EFTofMG parameter set (EFTCamb). Hence, the straight-line Zel'dovich Approximation cannot be used when simulating general MG.

Anything that is not DM

$$
\begin{aligned}
m =& \frac{\bar{\rho}}{\bar{n}} \left(1 + \Delta_\rho - \Delta_n\right), \\
T =& \frac{\bar{P}}{\bar{n}} \left(1 + \Delta_P - \Delta_n\right) = \frac{\bar{\rho}}{\bar{n}} \left(w + \frac{\delta P}{\delta \rho} \Delta_\rho - w \Delta_n\right)
\end{aligned}
$$

Anything that is not DM

Generate from $P_n(k)$

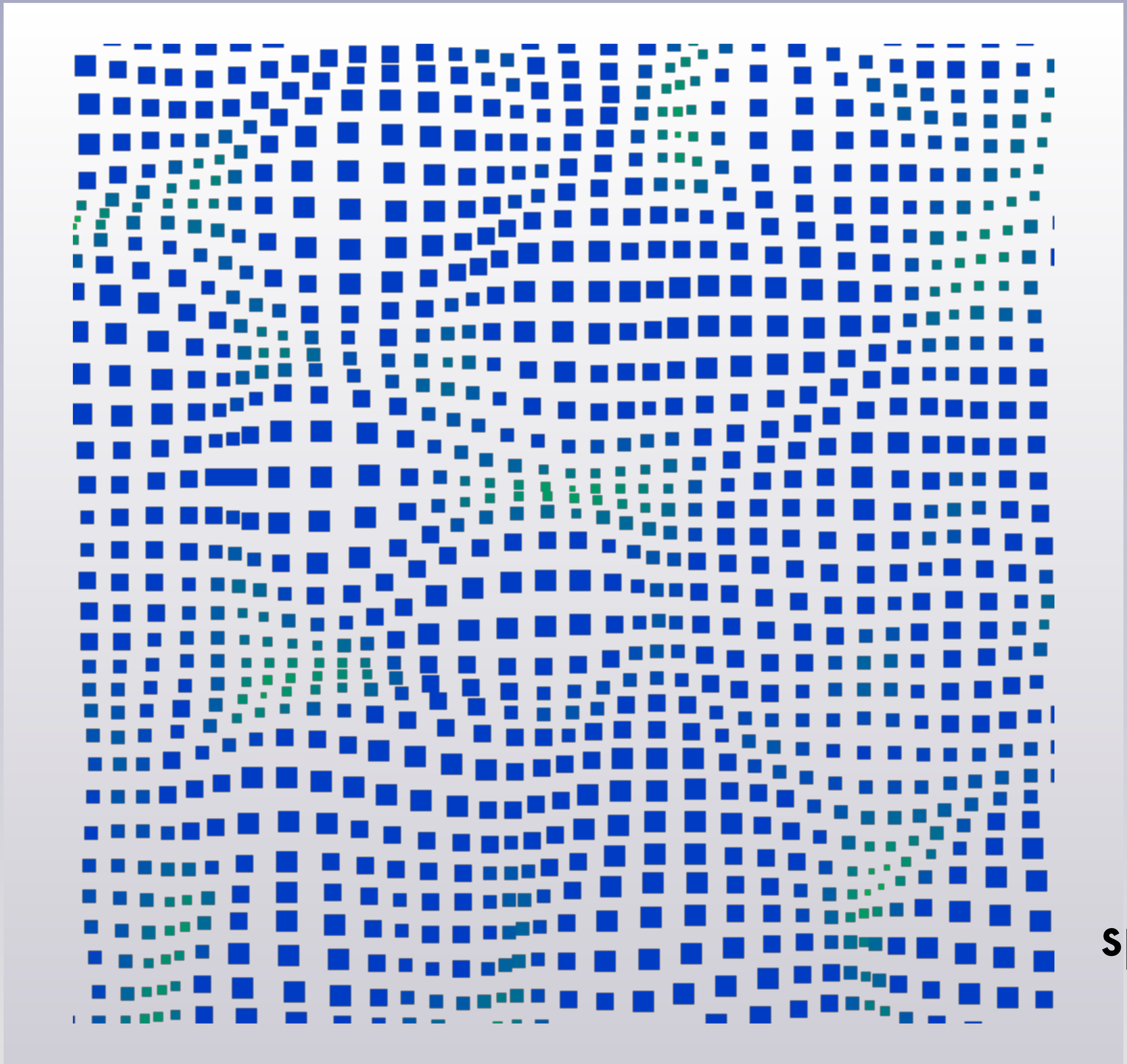
$$m = \frac{\bar{\rho}}{\bar{n}}\left(1 + \Delta_\rho - \Delta_n\right),$$

$$T = \frac{\bar{P}}{\bar{n}}\left(1 + \Delta_P - \Delta_n\right) = \frac{\bar{\rho}}{\bar{n}}\left(w + \frac{\delta P}{\delta \rho}\Delta_\rho - w\Delta_n\right)$$

Generate from $P_{rho}(k)$

Generate from $P_P(k)$

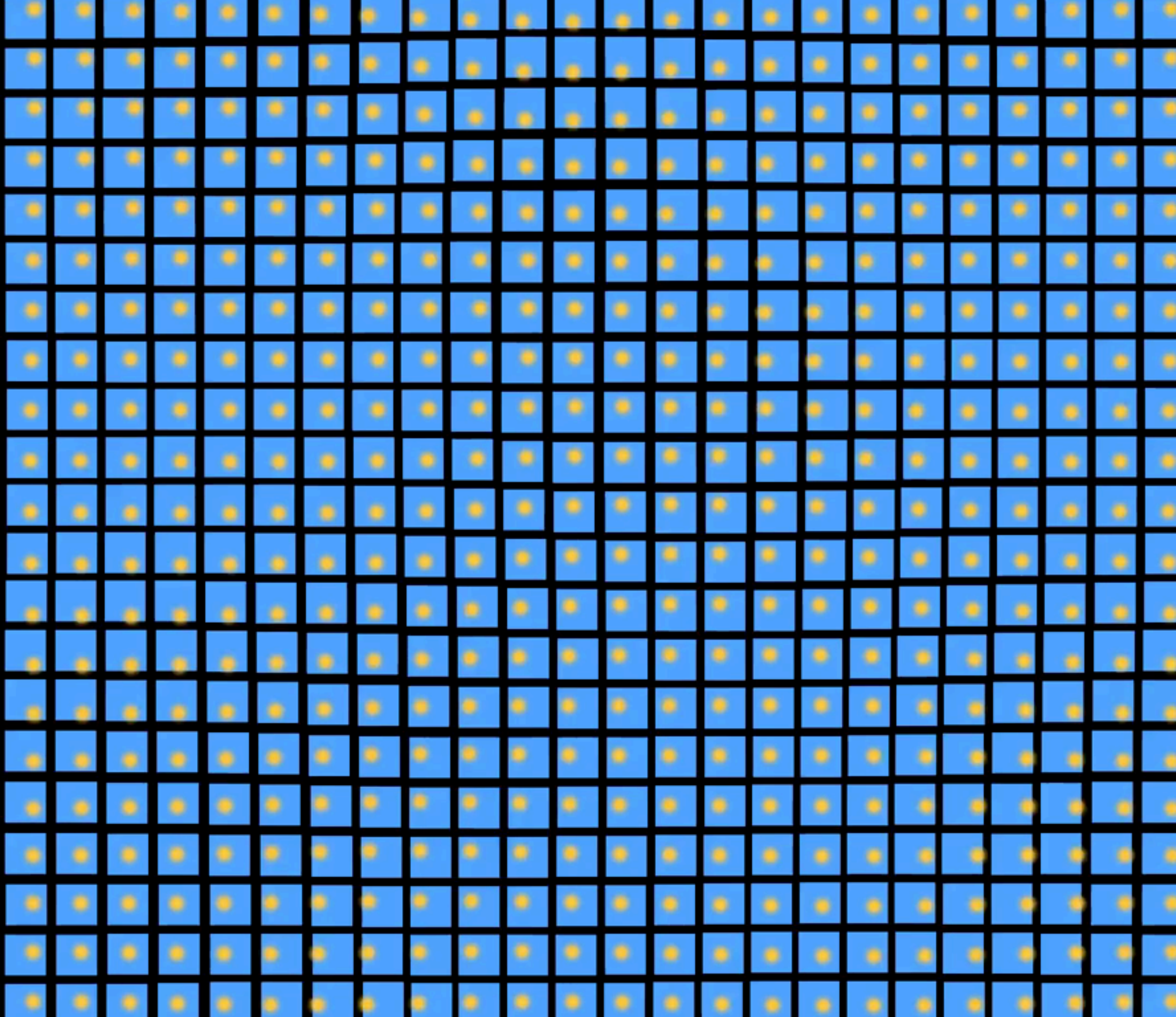
Just some imperfect fluid

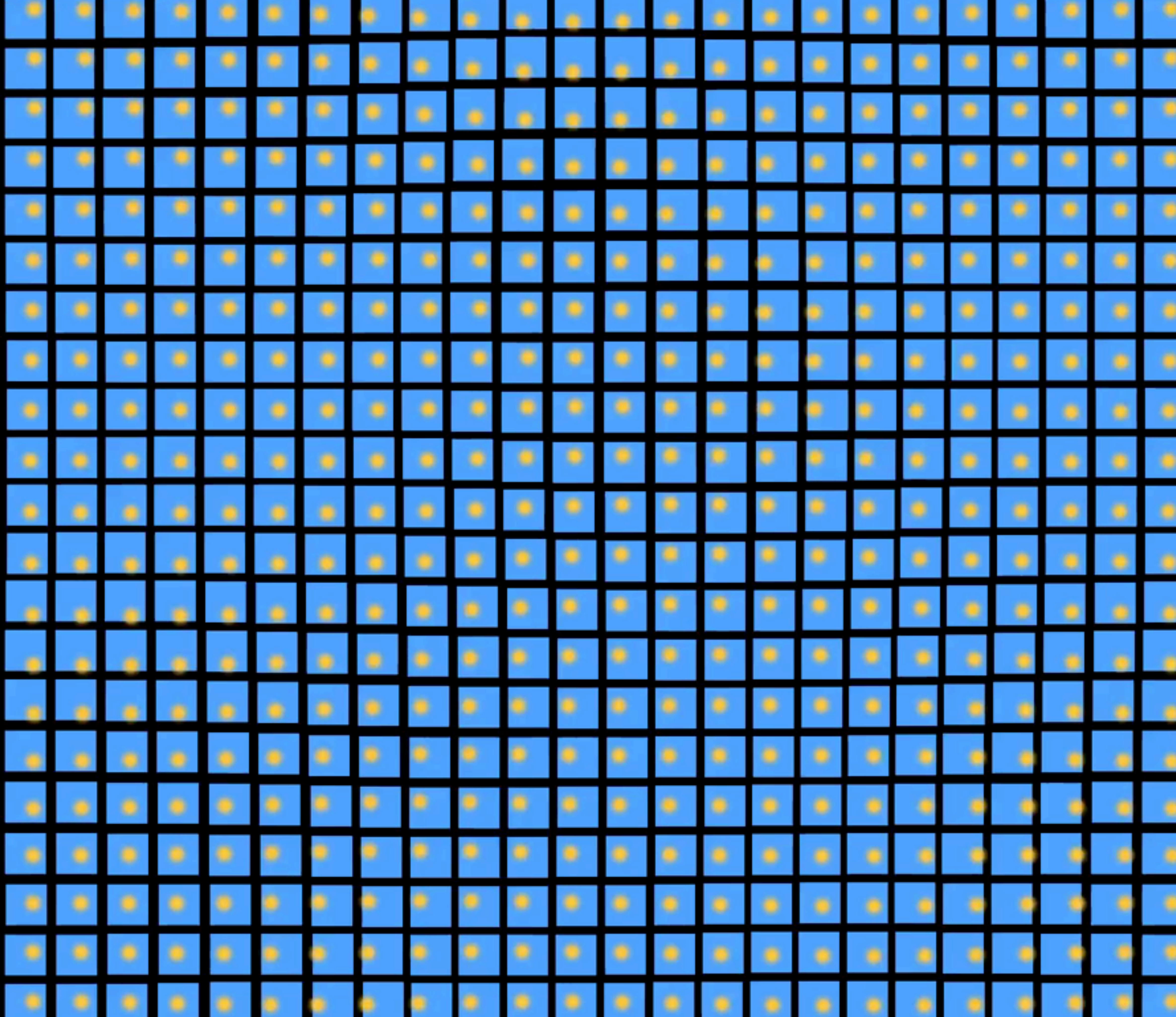


Size = mass

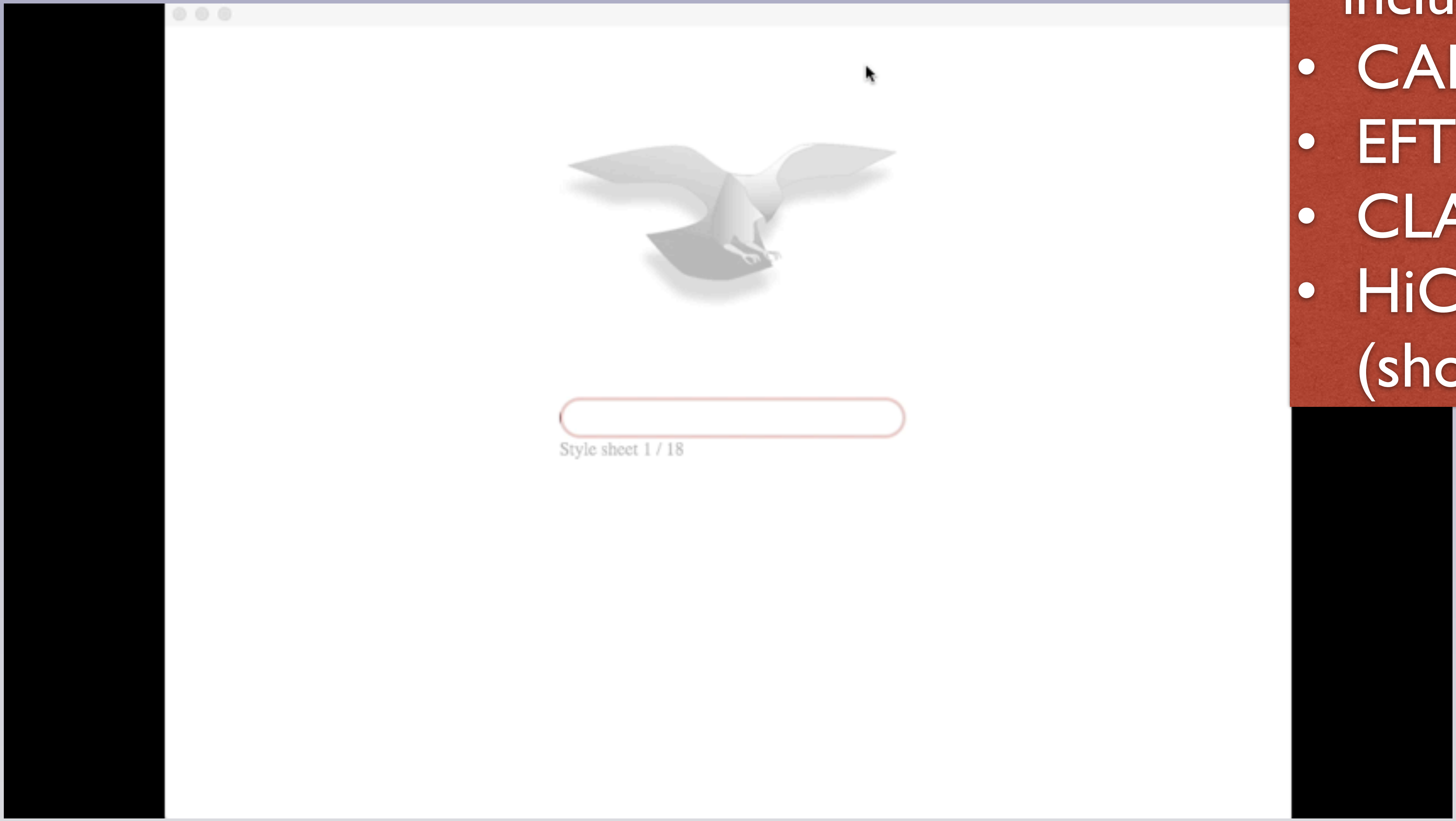
Color = internal energy

Amplitudes from spectra from EFTCamb





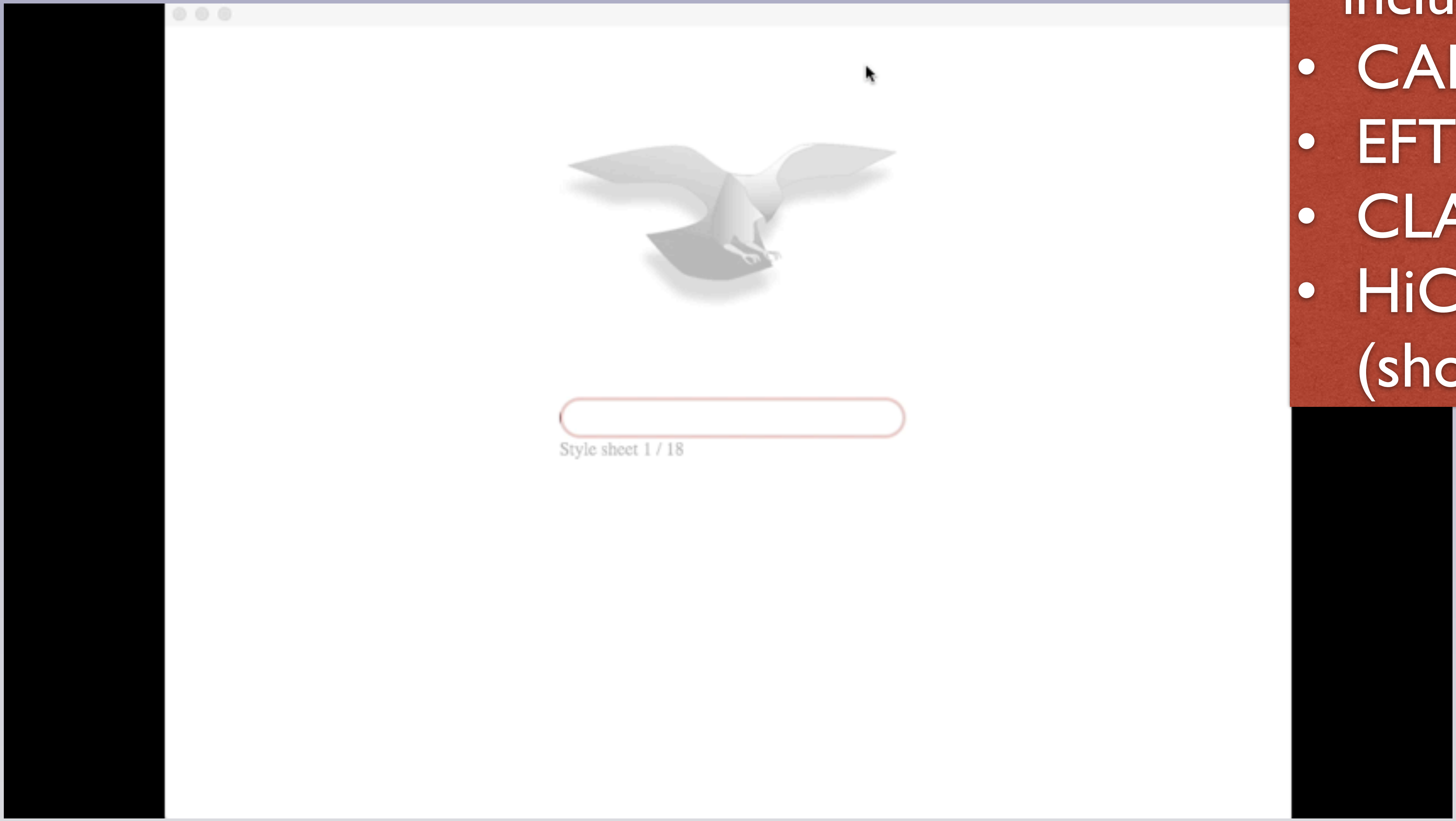
FalconIC



Links with (and renders all fields included in)

- CAMB
- EFTCAMB
- CLASS
- HiClass (should!)

FalconIC



Links with (and renders all fields included in)

- CAMB
- EFTCAMB
- CLASS
- HiClass (should!)

Summary

- Imperfect fluid: m(x) and T(x)
- Toward nonlinear simulations
- Code for ICs available:
  http://falconb.org
  http://git.falconb.org