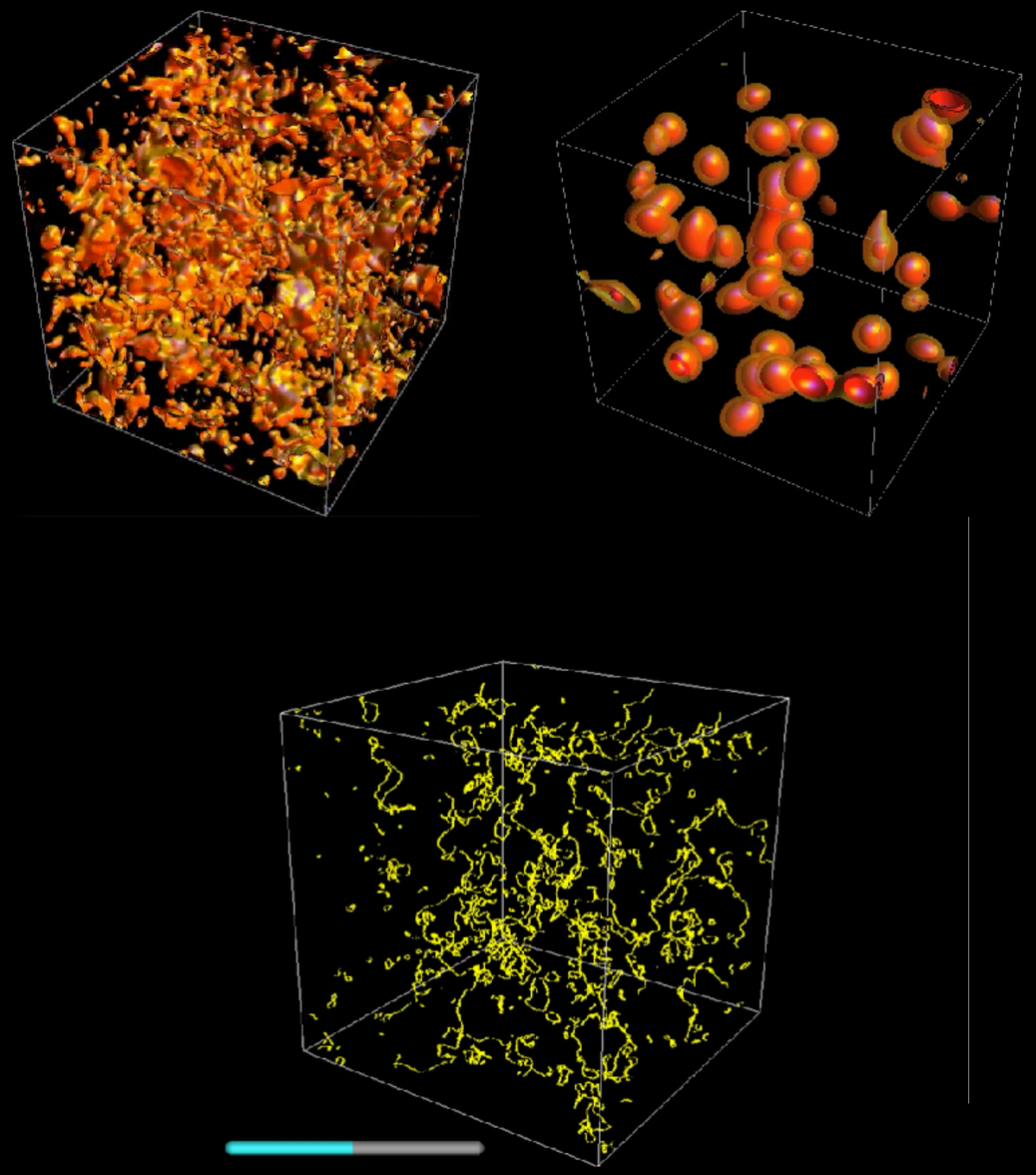
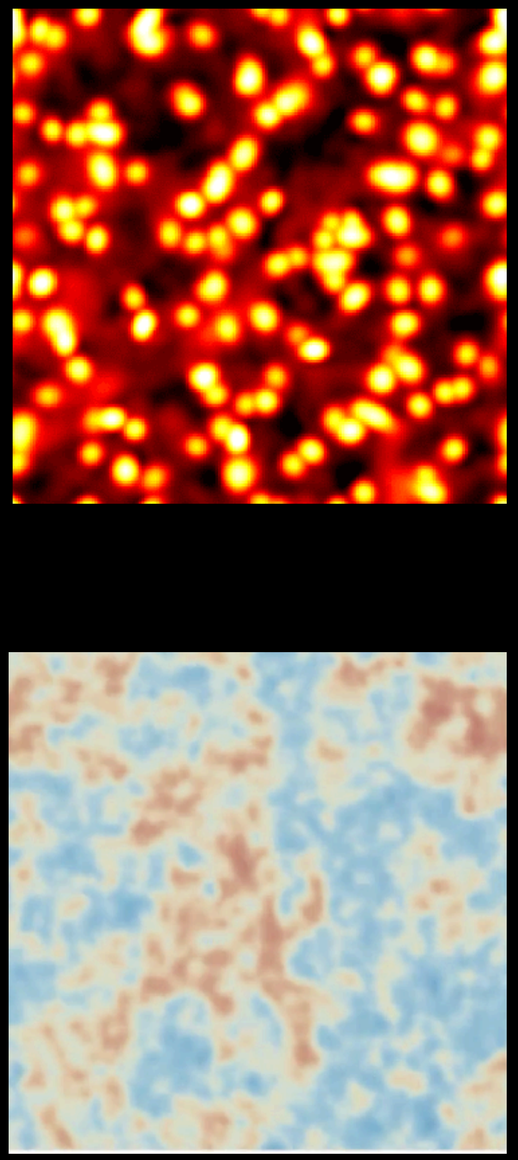
Inflation Ends, What's Next?

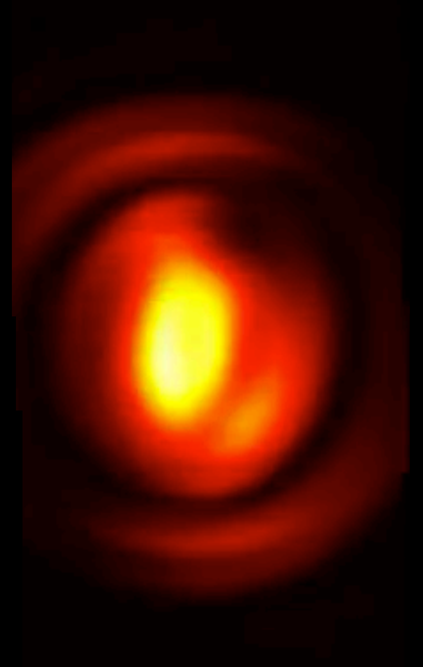
Mustafa A. Amin (RICE University)

background image: depositphotos.com

COSMO 2021







examples of nonlinear dynamics after inflation

Using a term like *non-linear* science is like referring to the bulk of zoology as the study of non-elephant animals — Stanislaw Ulam

after inflation: a few min GAP in our cosmic history

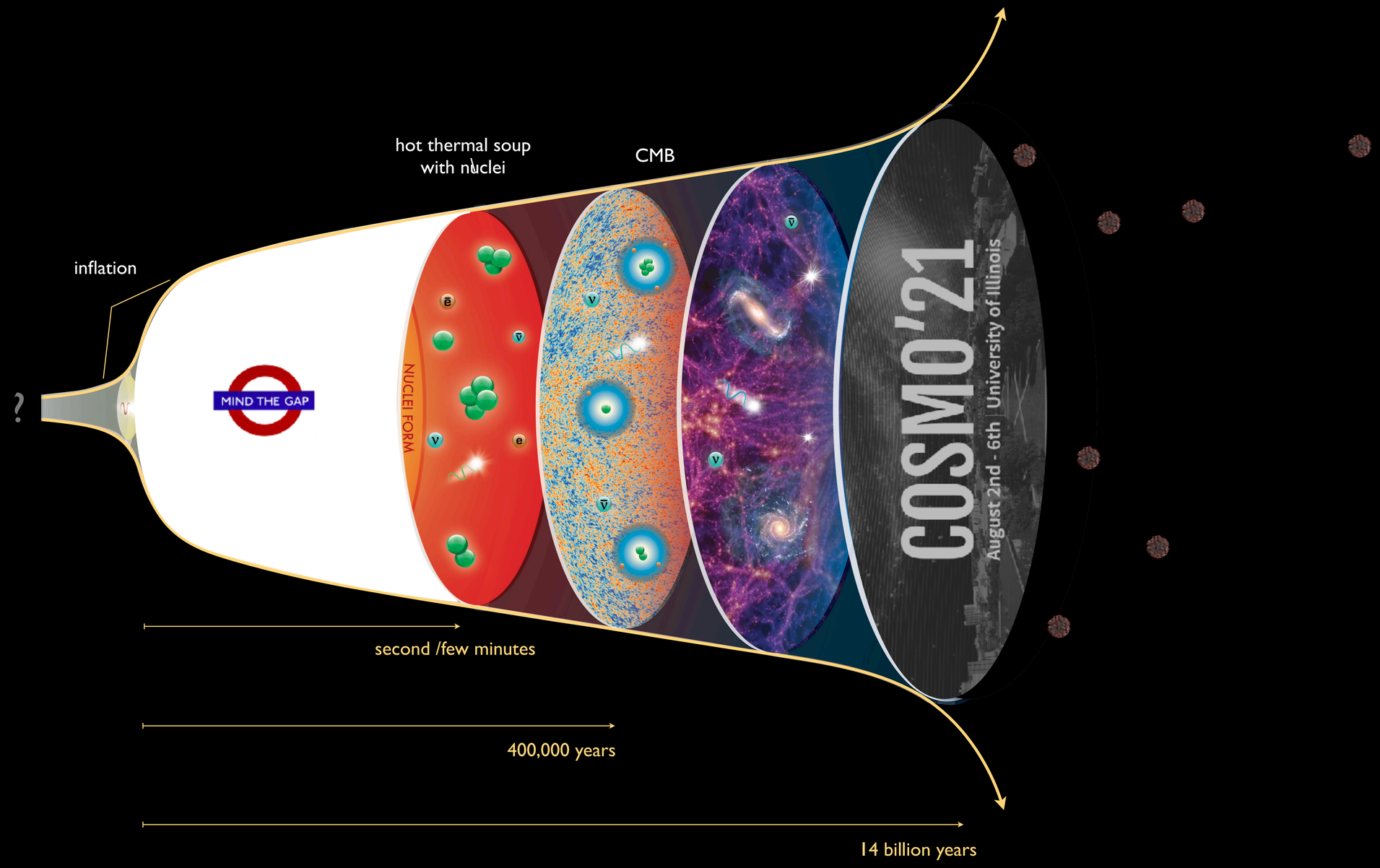
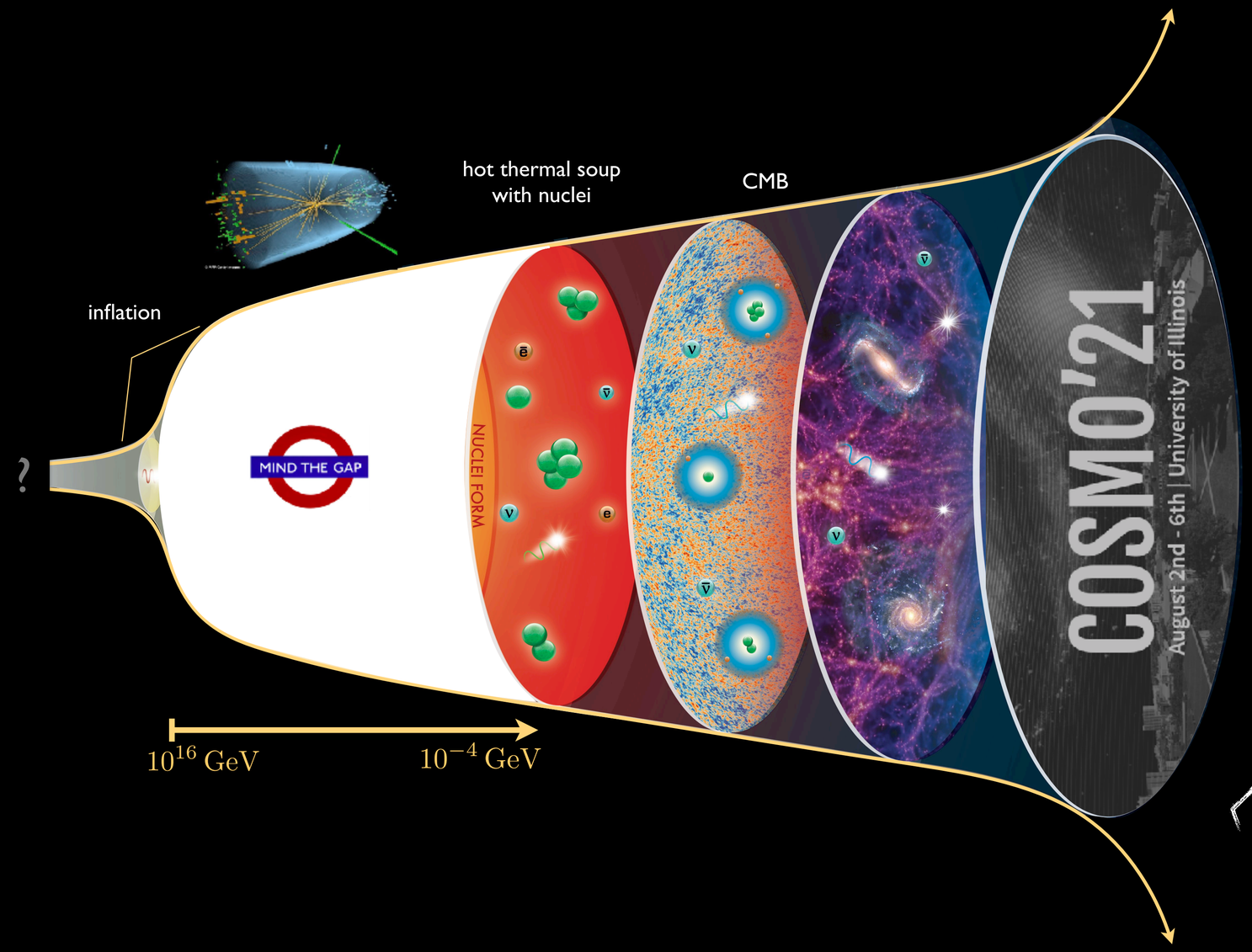
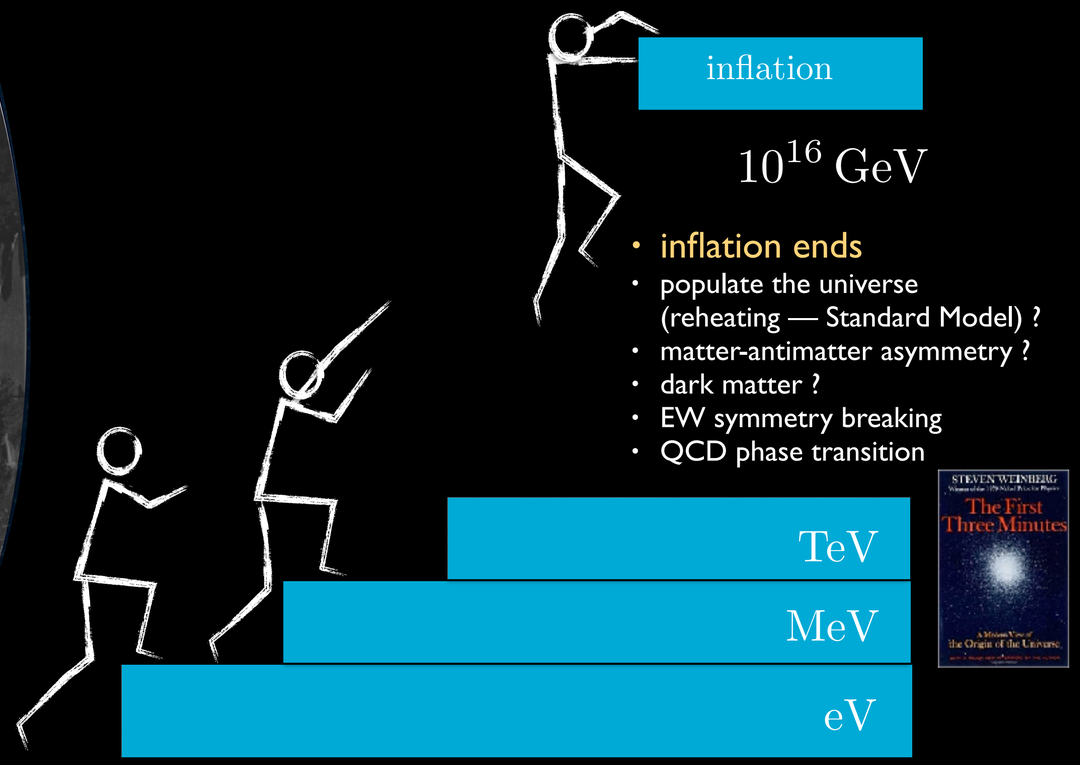


*image is my modification of the one produced by the PDG, 2014

after inflation: a huge energy GAP in our cosmic history

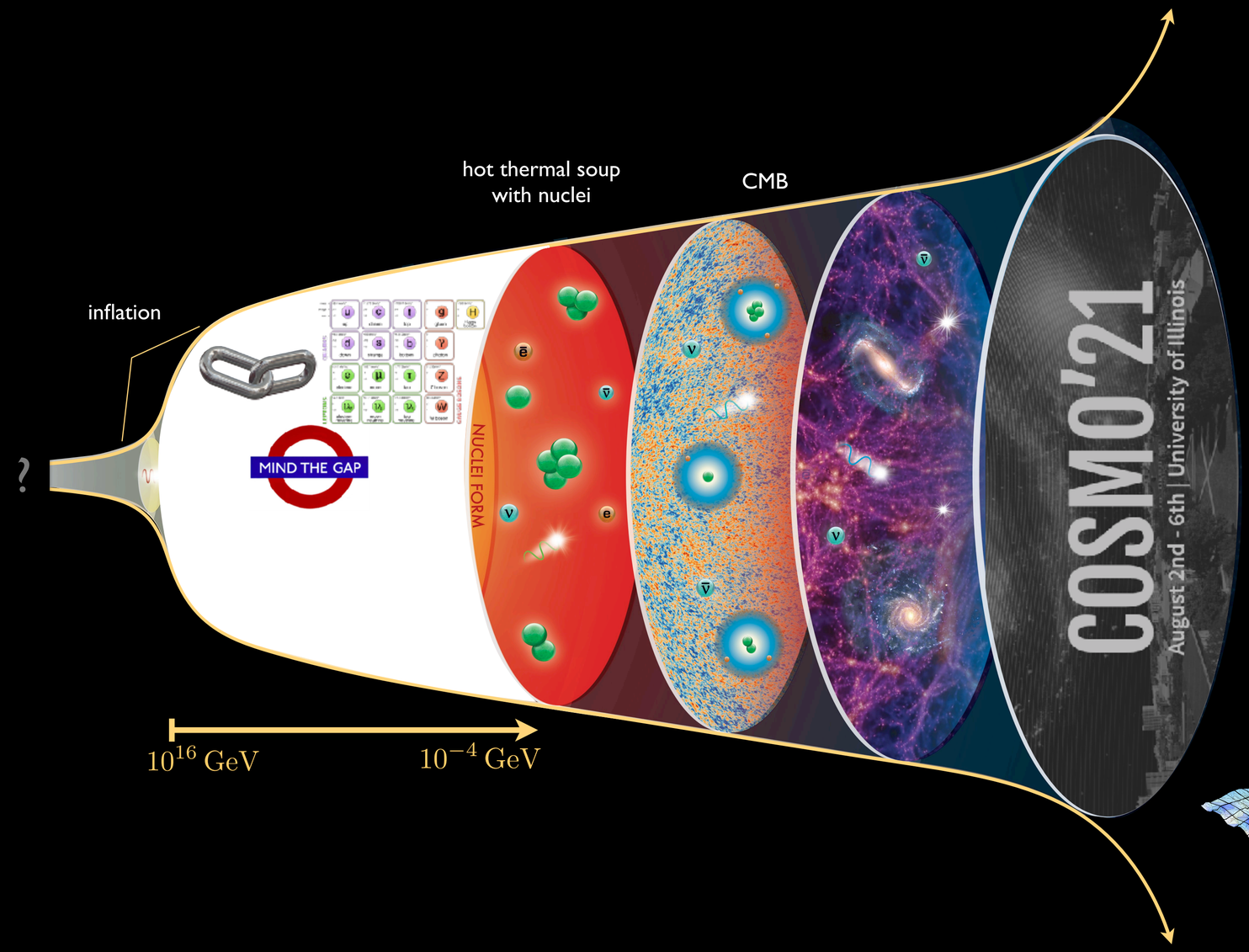


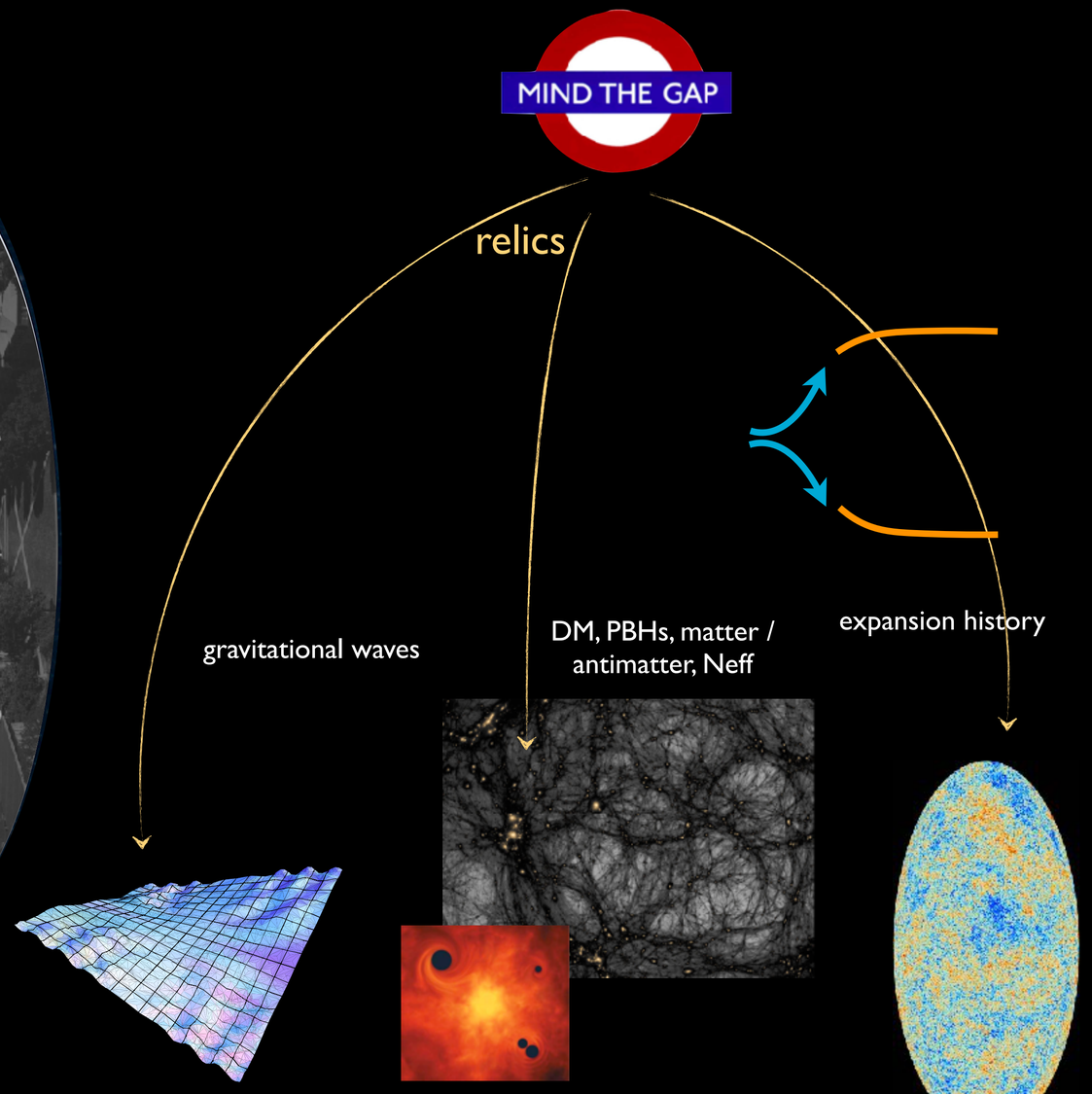


- inflation ends
- populate the universe (reheating — Standard Model) ?
- matter-antimatter asymmetry ?
- dark matter ?
- EW symmetry breaking
- QCD phase transition

*image is my modification of the one produced by the PDG, 2014

after inflation: GAP — consequences ?

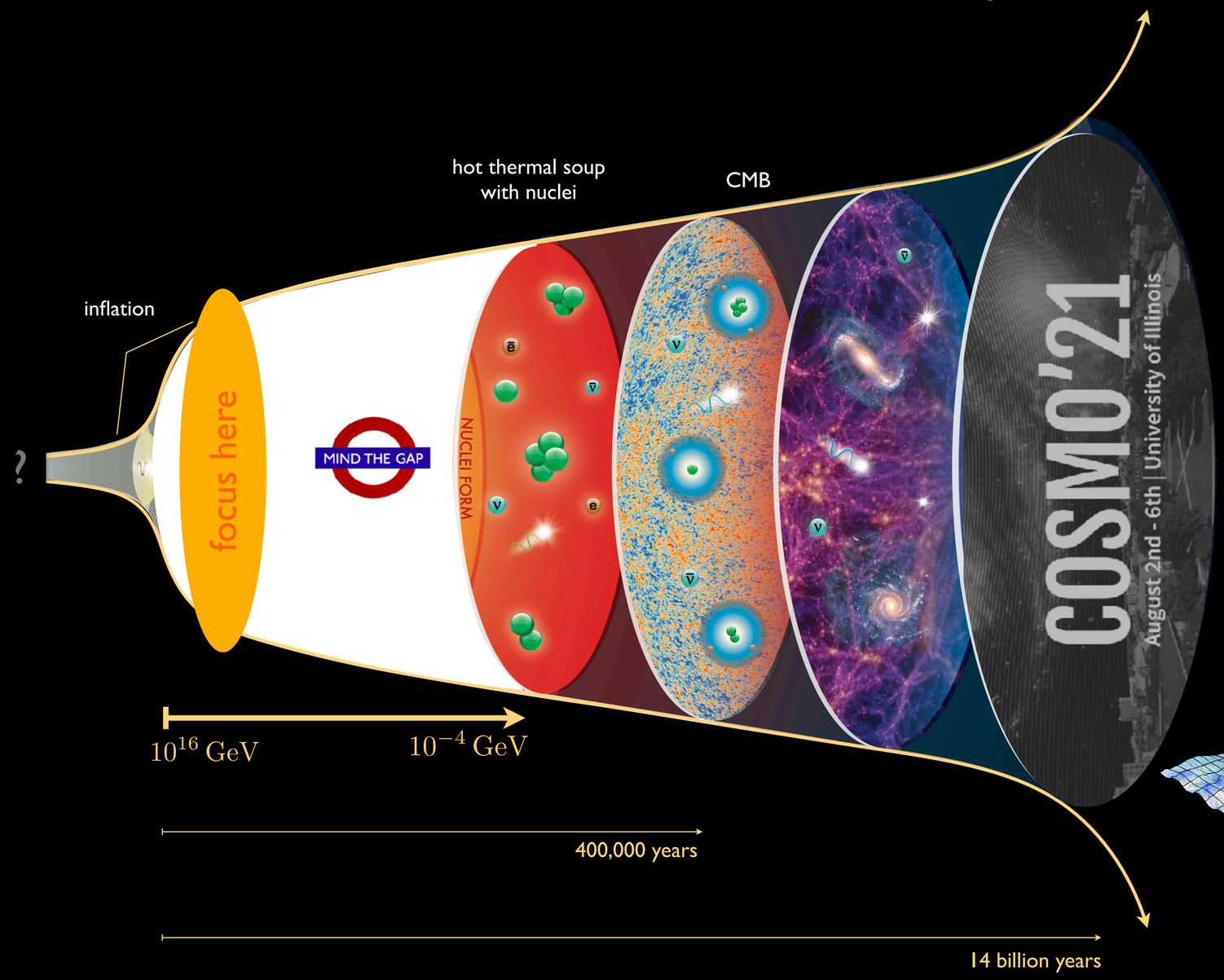


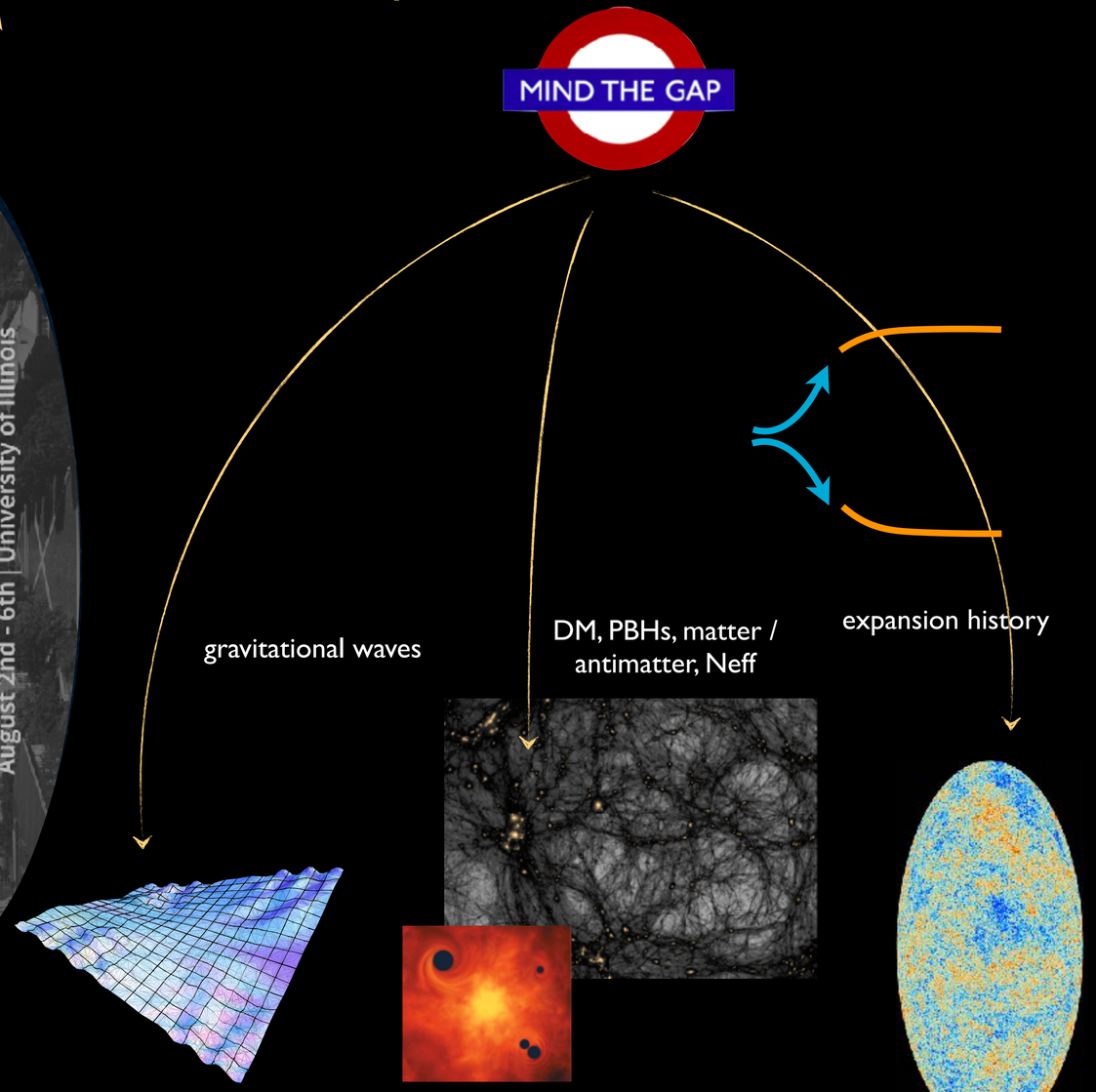


Observationally challenging because: $l \sim 1/\sqrt{H_* H_0}$

early times and small length scales (no inflationary "amplifier"), thermalization etc. But there is hope !

focus on: "soon" after the end of inflation, simple models with "universal" dynamics





much of the above phenomenology is covered in the exciting looking parallel sessions

[with apologies for works which I will be unable to cite/highlight]

For recent review: Lozanov (2019)

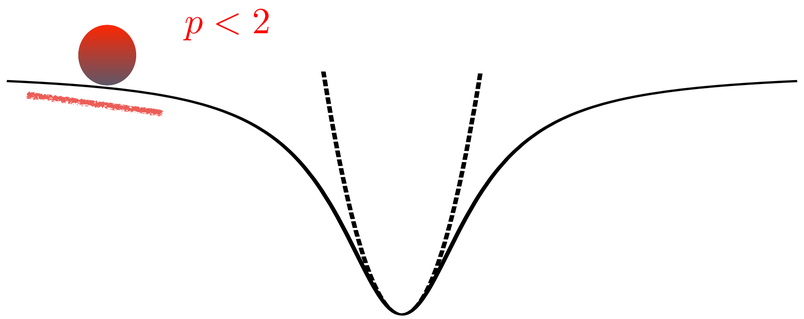
what we "know" about inflation (simplest case - scalar field driven inflation)

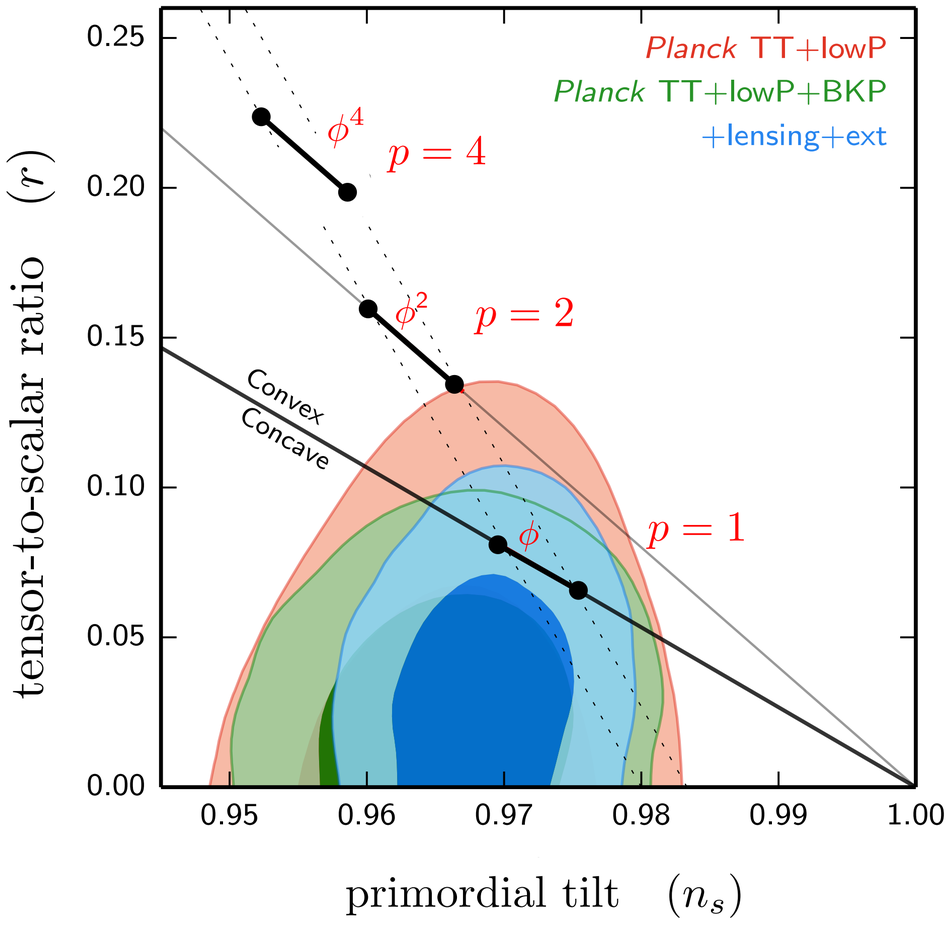
— flattened potentials

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

$V(\phi) \propto \phi^p$

$p < 2$

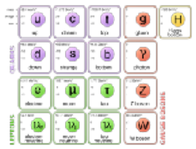




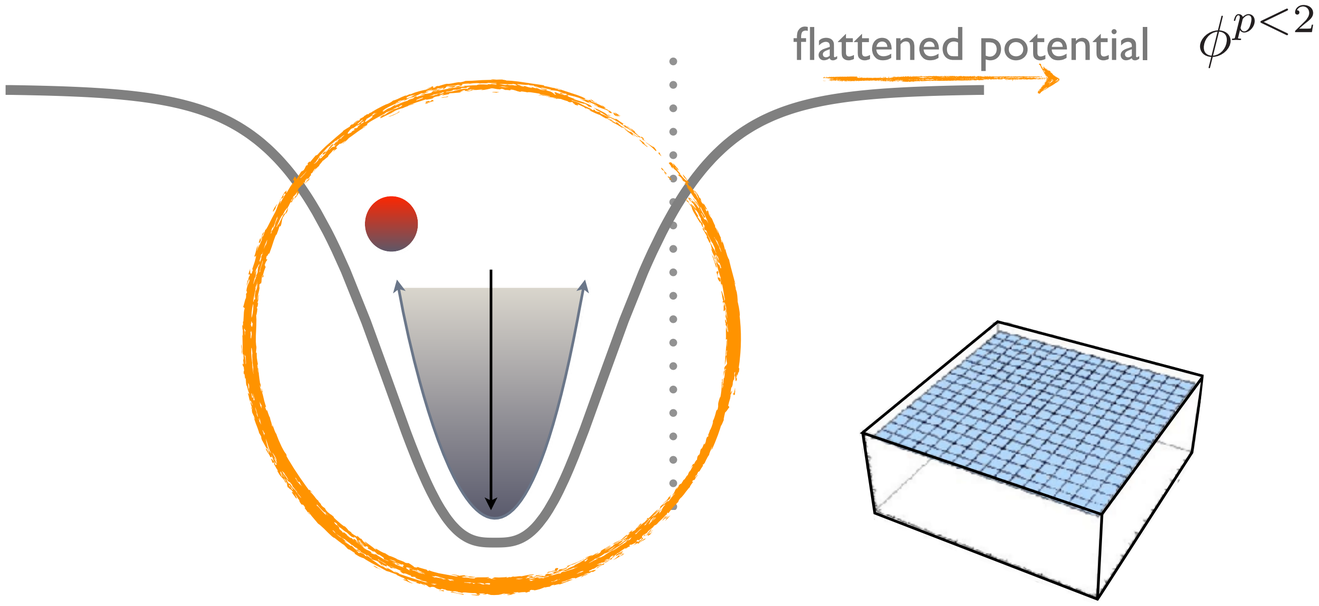
for example:
Starobinsky(1979/80), Nanopolous et. al (1983), Silverstein & Westhpal (2008), Kallosh & Linde (2013), McAllister et. al (2014) … Cliff Burgess discussed some of this elegantly earlier today

end of inflation ?

- shape of the potential (self couplings)
- couplings to other fields

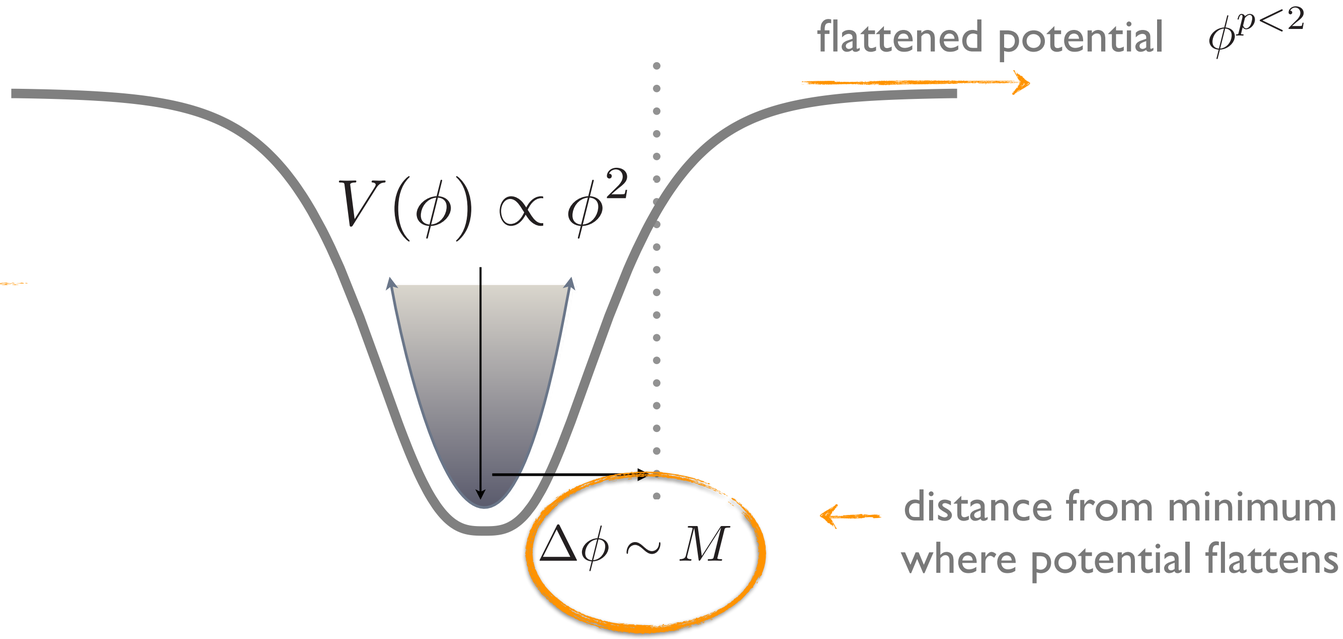


χ , ψ A_μ



end of inflation (simplest)

- shape of the potential (self couplings)
- ~~couplings to other fields~~  $\chi\ ,\psi\ A_\mu$

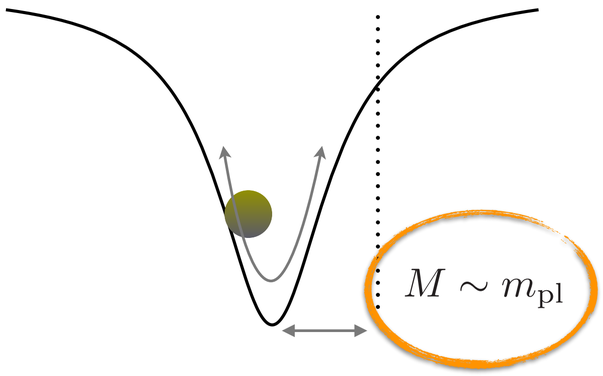


oscillating “free” scalar field: matter-dominated expansion

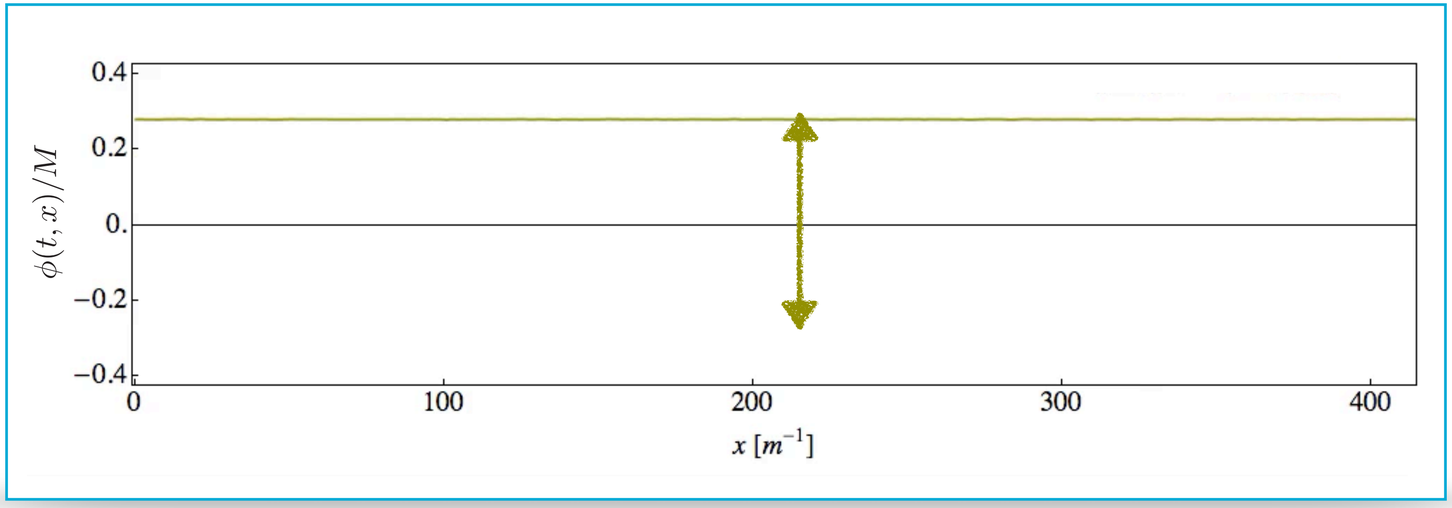
expansion ✓

self-interactions ✗

gravitational int. ✓



$$\Box\phi \approx m^2\phi$$



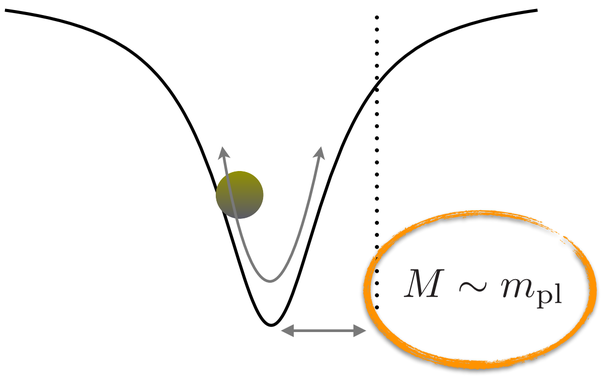
$$w \to 0$$

oscillating “free” scalar field: matter-dominated expansion +“slow” gravitational instability

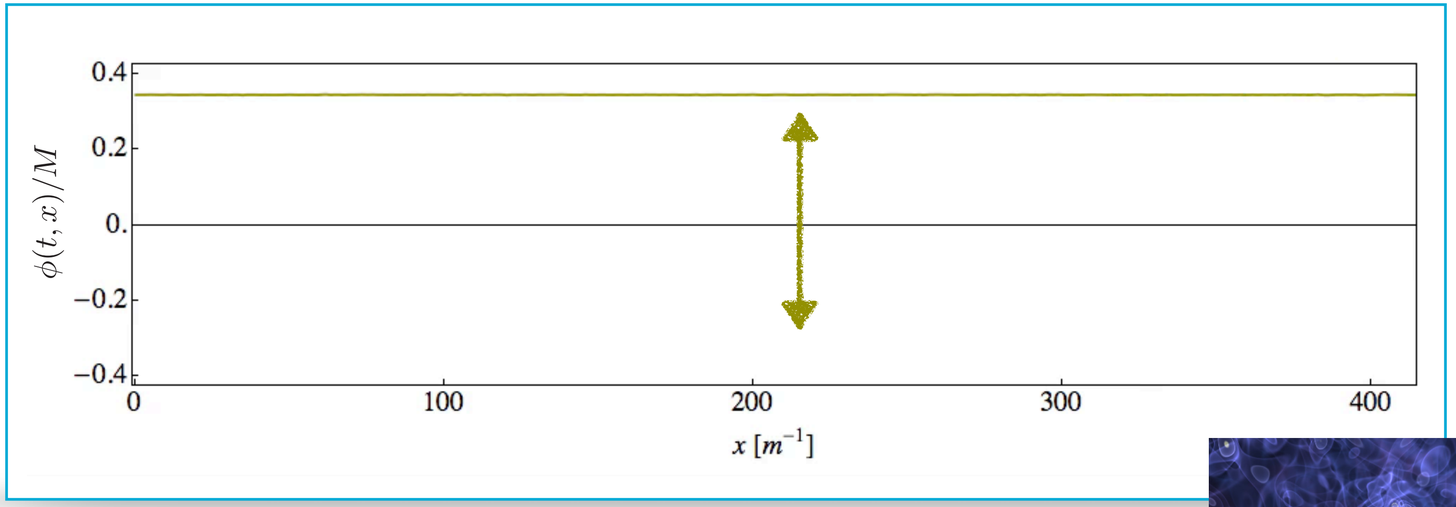
expansion ✓

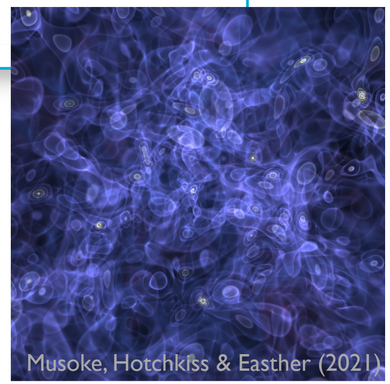
self-interactions ✗

gravitational int. ✓



$$\Box\phi \approx m^2\phi$$





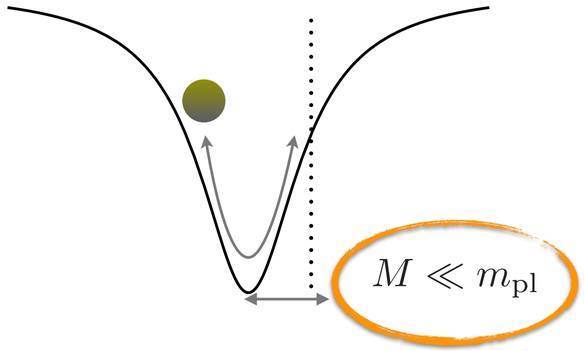
*similar to a matter dominated universe

oscillating scalar field: self-interaction driven fast instability & “oscillon” formation

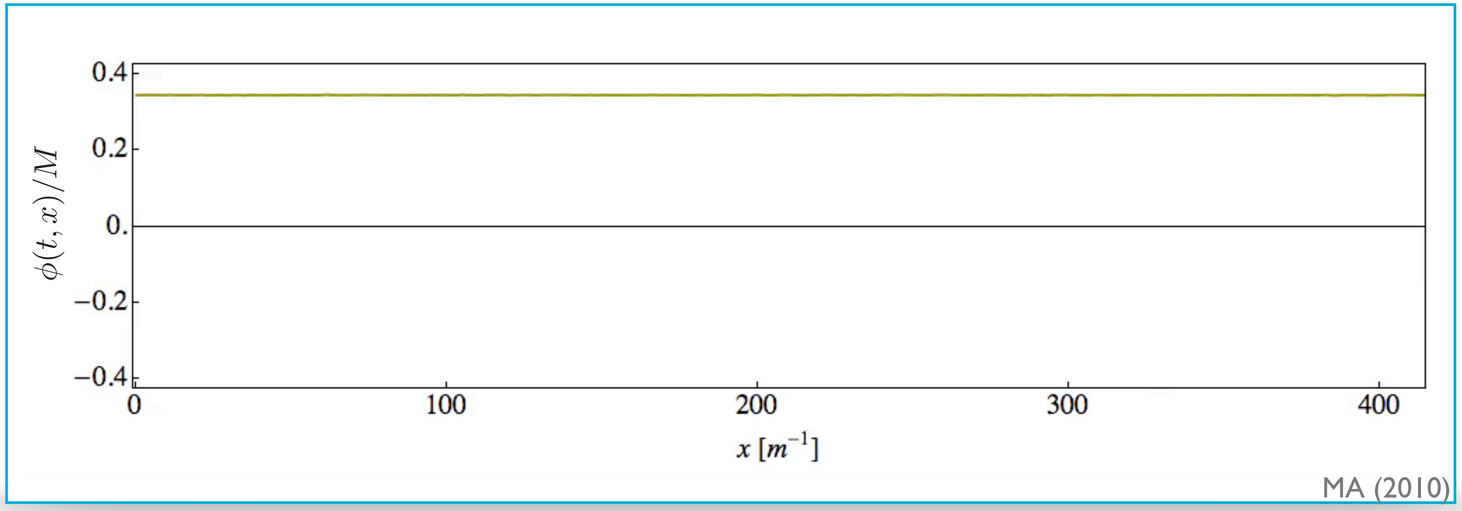
expansion ✓

self-interactions ✓

gravitational int. ✗



$$\Box\phi = V'(\phi)$$



MA (2010)

$$\frac{\text{growth-rate of fluctuations}}{\text{expansion rate}} \sim \frac{m_{\rm pl}}{M} \gg 1$$

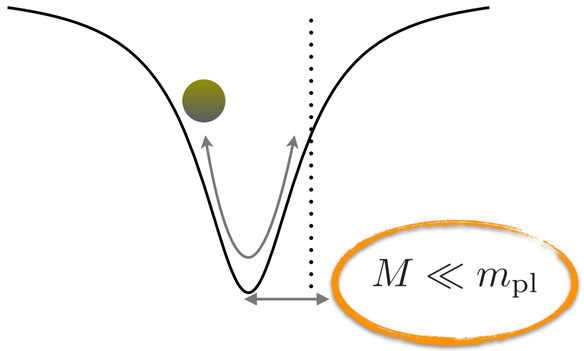
*without oscillons, but relevant for instabilities, see related (much) earlier work: Khlopov, Malomed & Zeldovich (1985)

oscillating scalar field: self-interaction driven fast instability & "oscillon" formation

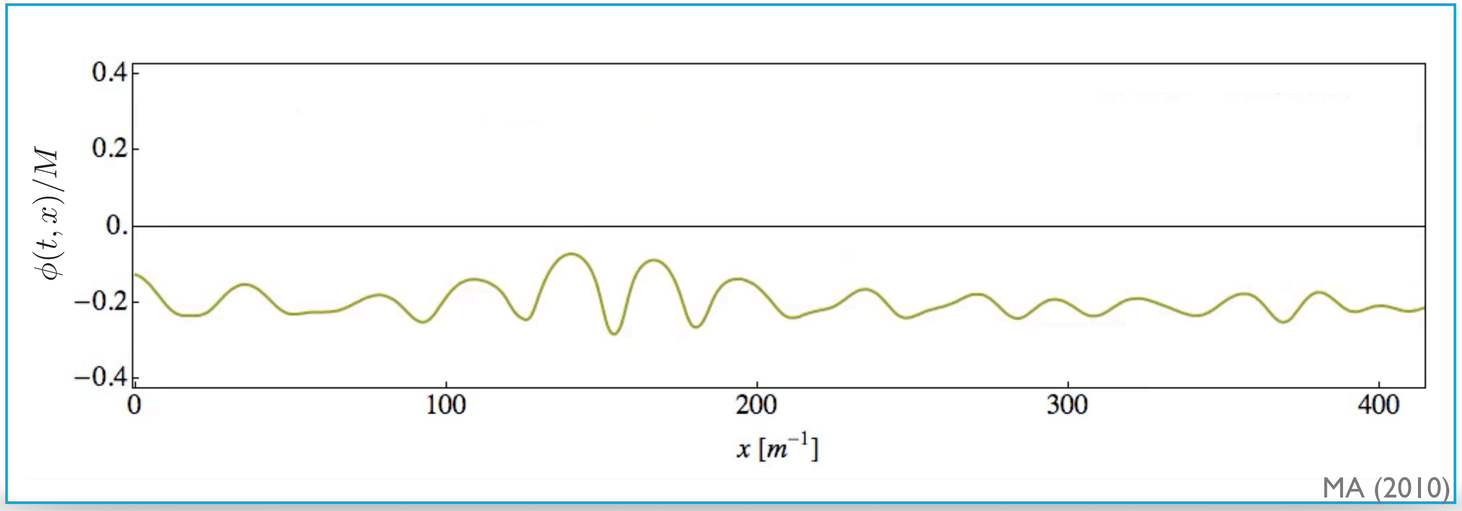
expansion ✓

self-interactions ✓

gravitational int. ✗



$$\Box\phi = V'(\phi)$$



MA (2010)

$$\frac{\text{growth-rate of fluctuations}}{\text{expansion rate}} \sim \frac{m_{\rm pl}}{M} \gg 1$$

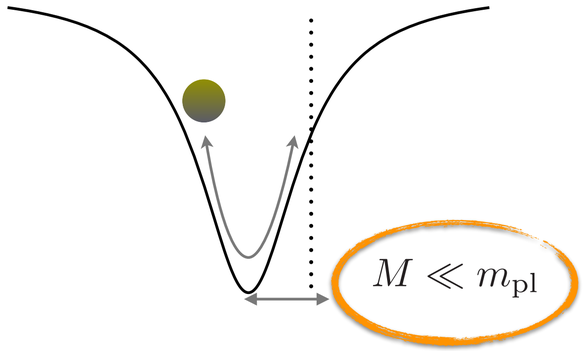
*without oscillons, but relevant for instabilities, see related (much) earlier work: Khlopov, Malomed & Zeldovich (1985)

oscillating scalar field: self-interaction driven fast instability & “oscillon” formation

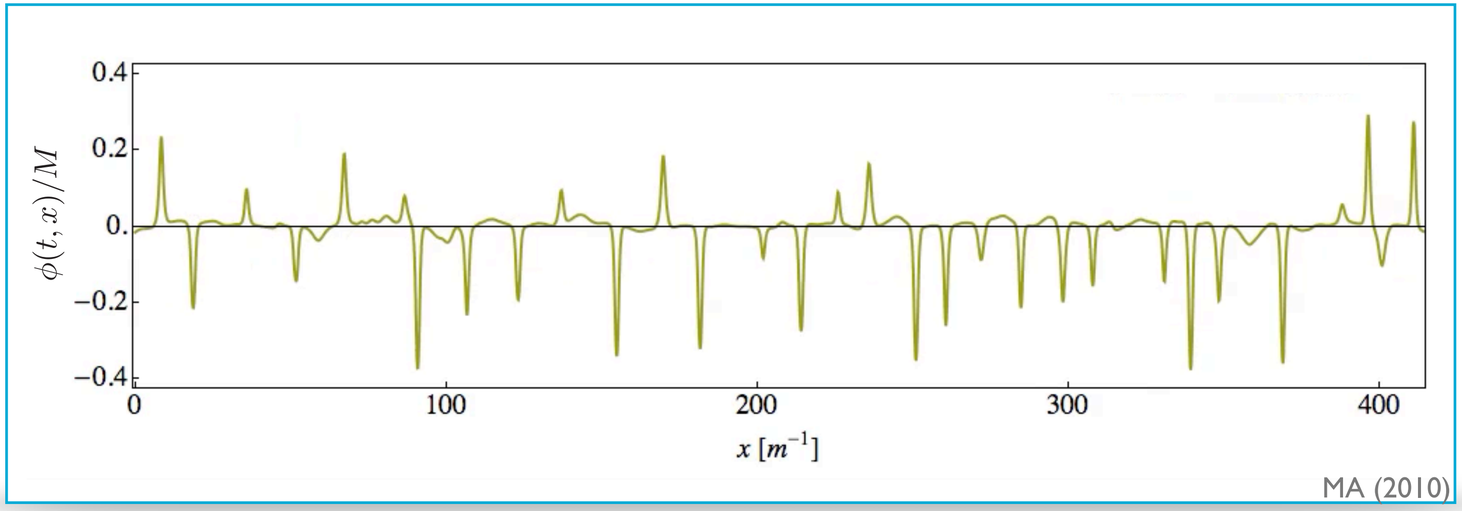
expansion ✓

self-interactions ✓

gravitational int. ✗



$$\Box\phi = V'(\phi)$$



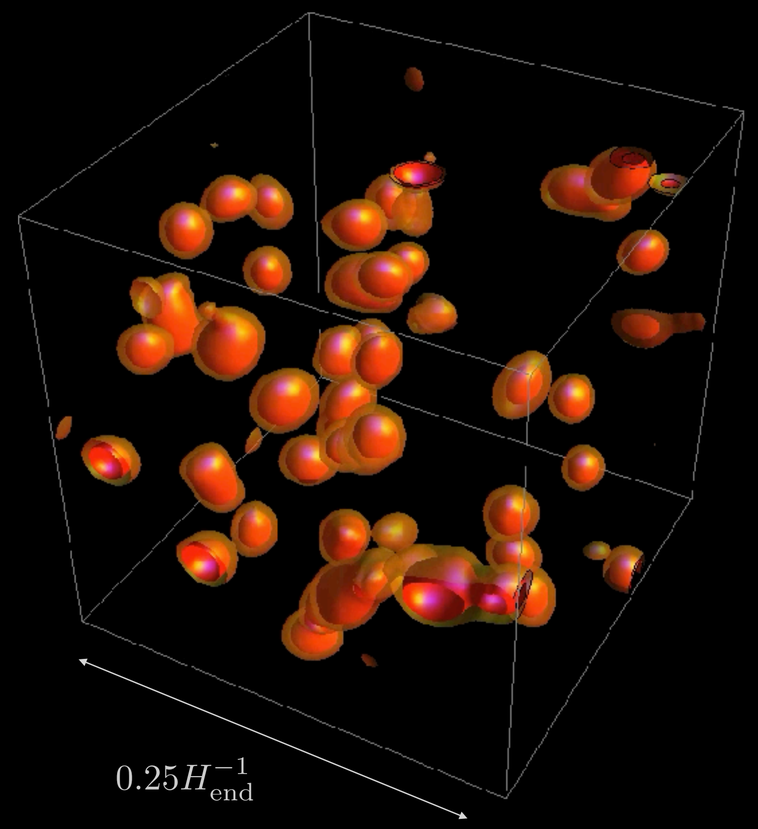
MA (2010)

$$\frac{\text{growth-rate of fluctuations}}{\text{expansion rate}} \sim \frac{m_{\rm pl}}{M} \gg 1$$

*without oscillons, but relevant for instabilities, see related (much) earlier work: Khlopov, Malomed & Zeldovich (1985)

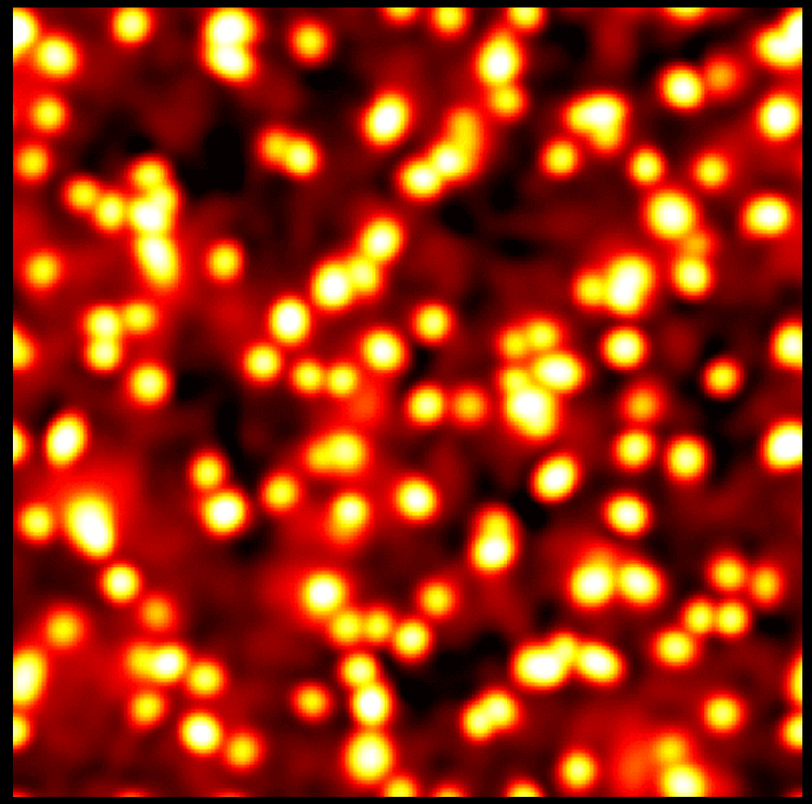
self-interaction driven fast instability & “oscillon” formation + gravitational clustering

expansion ✓
self-interactions ✓
gravitational int. ✗



MA, Easther, Finkel, Flauger & Hertzberg (2011)

expansion ✓
self-interactions ✓
gravitational int. ✓

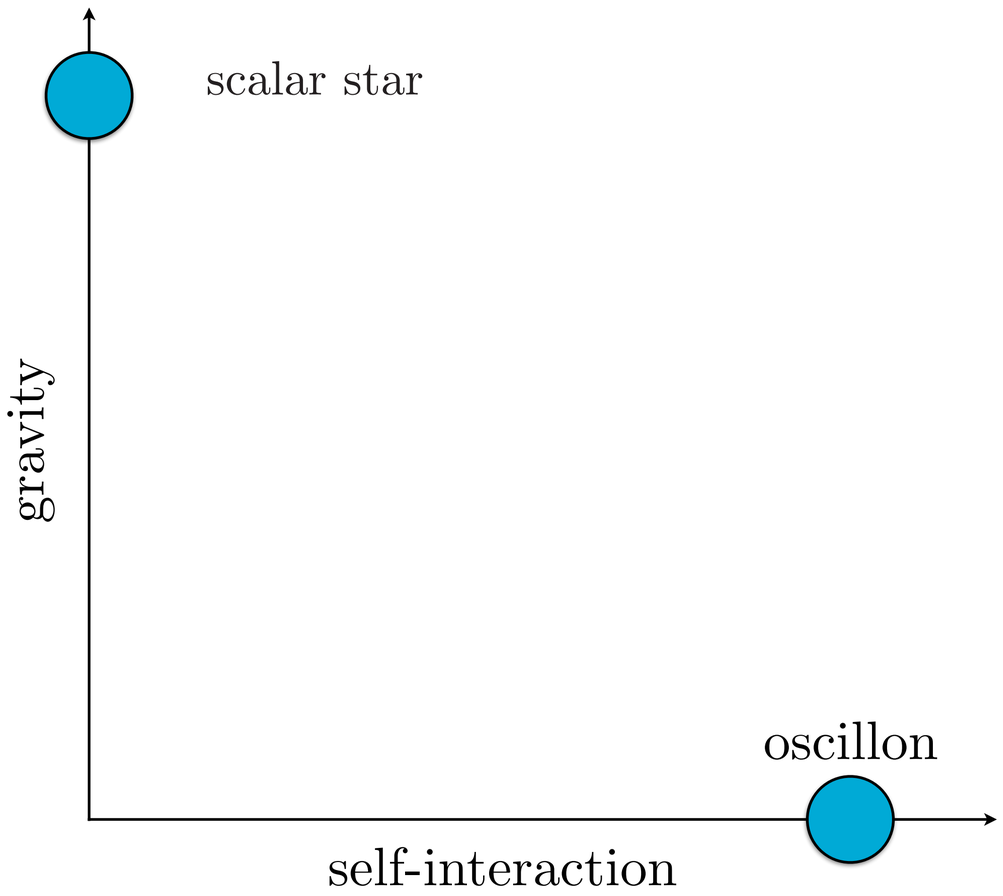


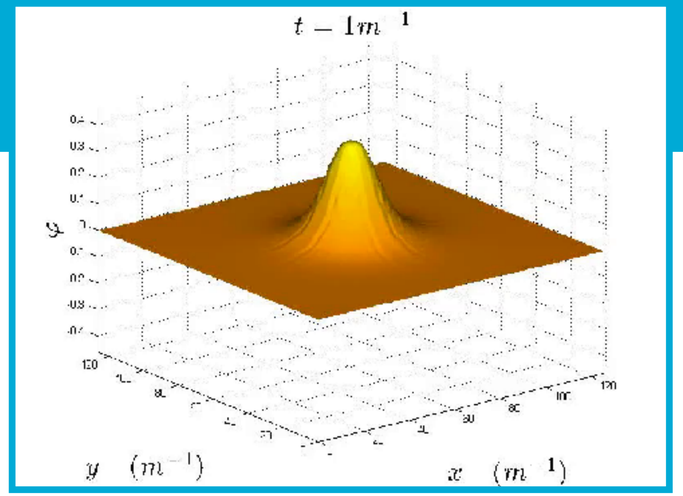
MA & Mocz (2019)

* non-relativistic, Schrodinger-Poisson

solitons : oscillons, scalar stars …

spatially localized, coherently oscillating, long-lived





spatially localized

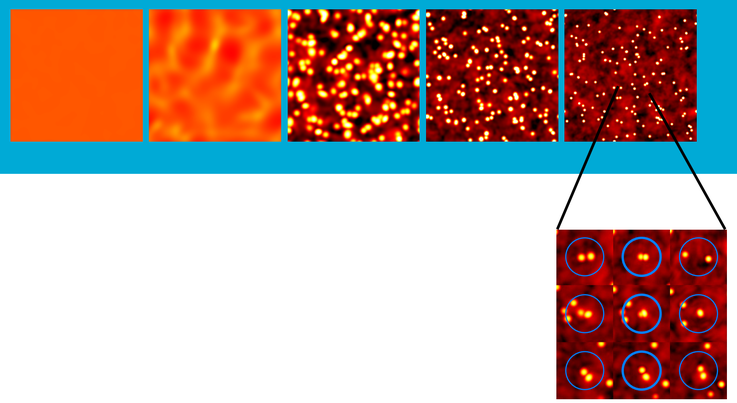
coherently oscillating

exceptionally long-lived

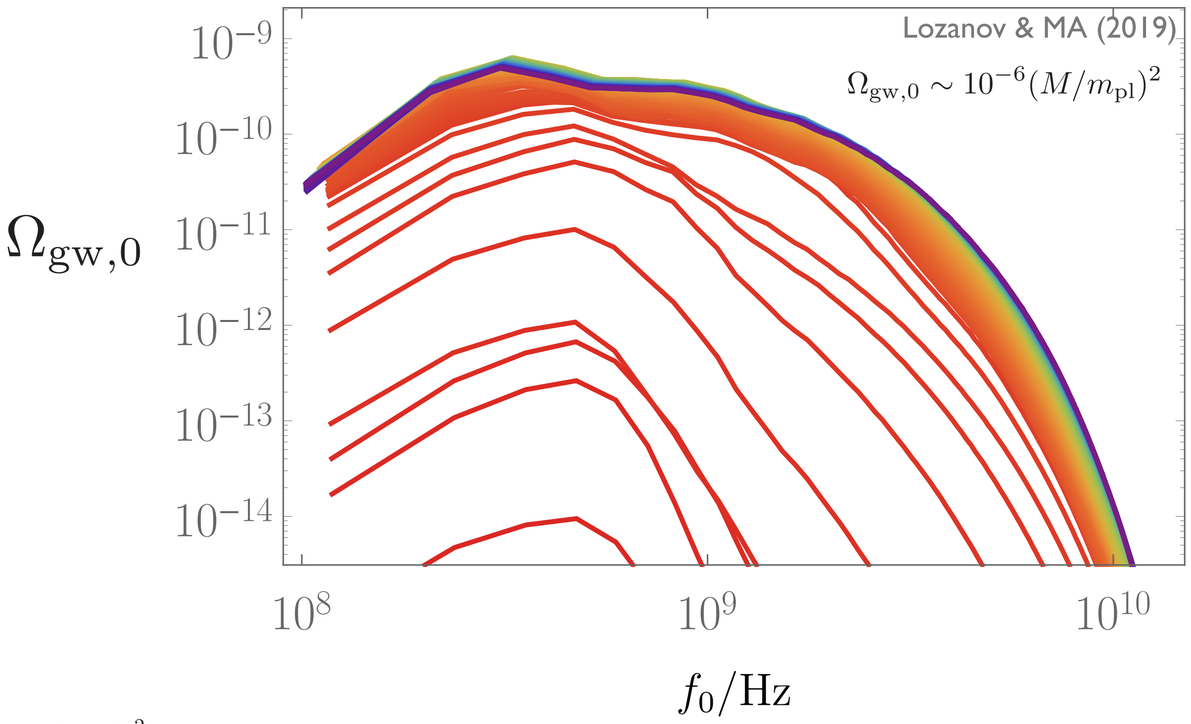
Bogolubsky & Makhankov (1976)
Seidel & Sun (1991)
Gleiser (1994)
Copeland et al. (1995)
… Zhang et. al (2020)

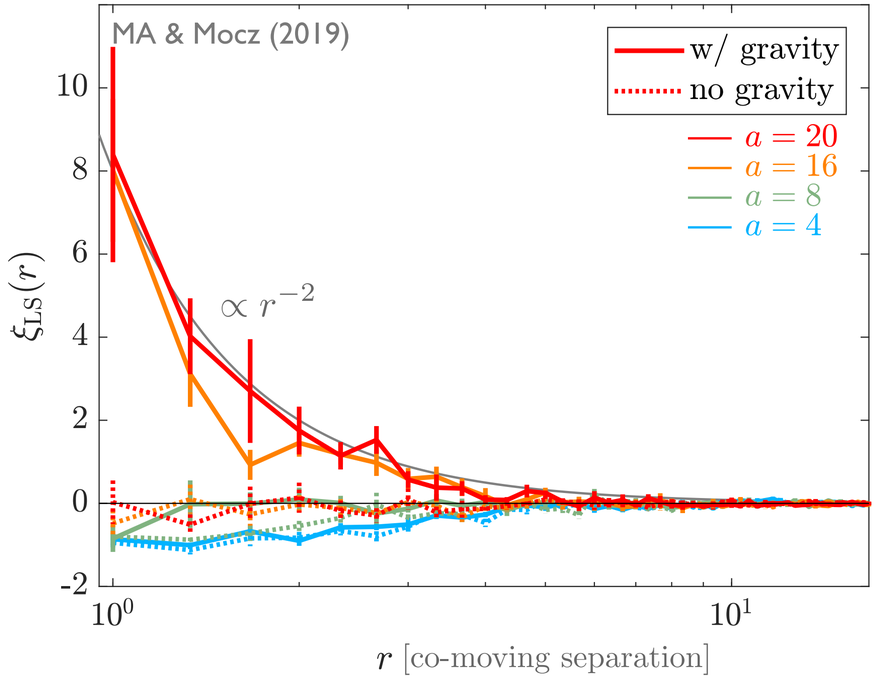
*lifetimes can be much, much larger than the Hubble time scale at the end of inflation

gravitational implications?



- stochastic gravitational wave-generation (example: Zhou et. al 2013, Kitajima et. al 2018)
- gravitational clustering — early structure formation (Erickcek & Sigurdson 2011)
- primordial black hole (PBH) formation ? (Cotner et. al 2019, full GR simulations: Giblin & Tishue 2019, Kou et. al 2021)

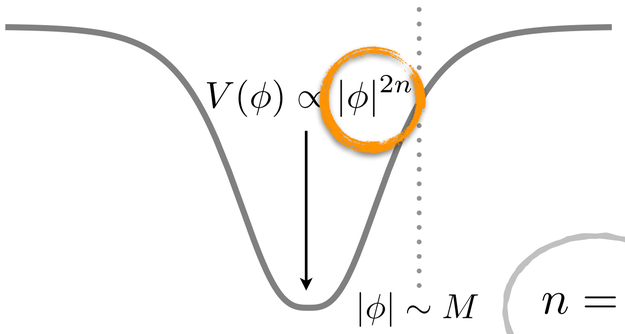




$$|\Phi|_{\rm sol} \lesssim 10 \times \left(\frac{M}{m_{\rm pl}}\right)^2$$

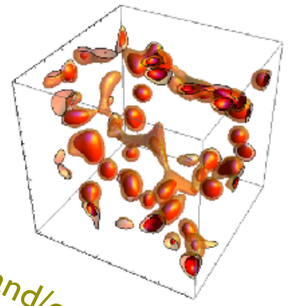
dynamics in quadratic power law minima + wings

inflaton potential



$n = 1$

field fragments into solitons and/or just gravitationally clusters



eq. of state

$w \to 0$

matter domination

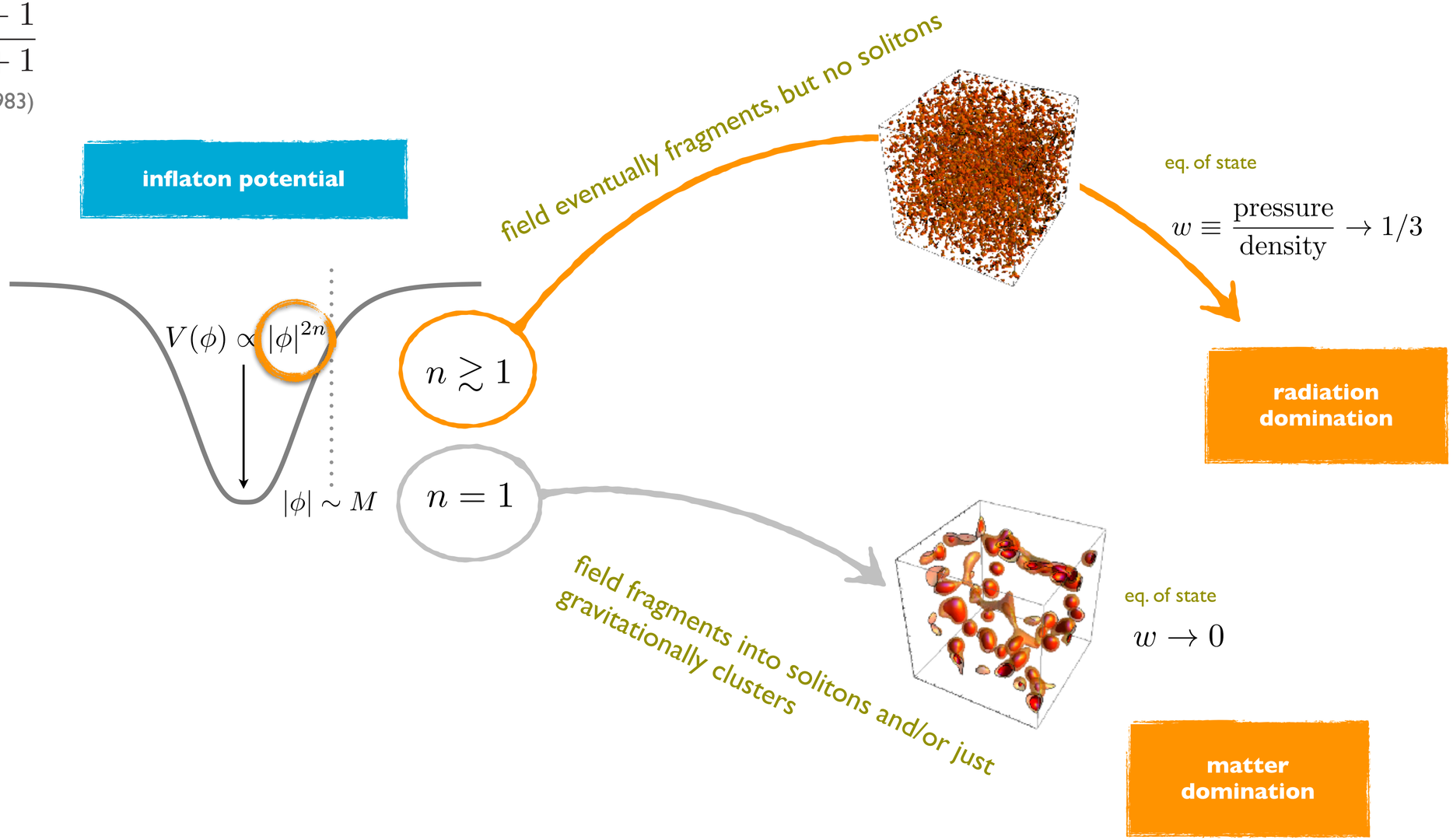
dynamics in different power law minima + wings

with Lozanov

Homogeneous oscillations

$$w = \frac{n-1}{n+1}$$

Turner (1983)



dynamics in different power law minima + wings

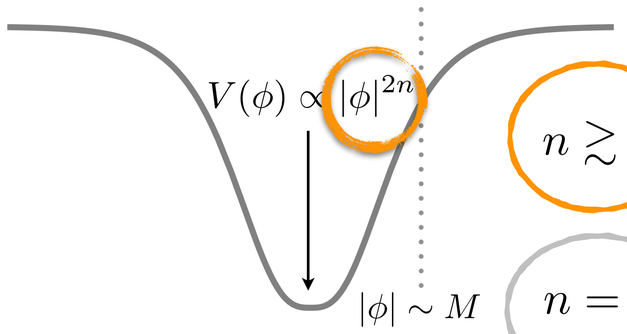
Lozanov & MA (2017)

Homogeneous oscillations

$$w = \frac{n-1}{n+1}$$

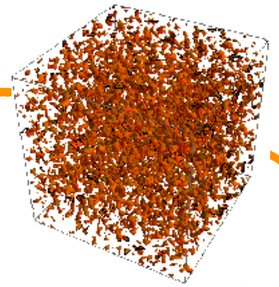
Turner (1983)

inflaton potential



$n \gtrsim 1$

field eventually fragments, but no solitons



$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \frac{n+1}{3} \ln\left(\frac{\kappa}{\Delta\kappa}\frac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

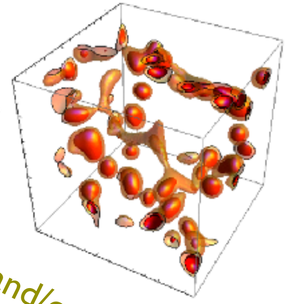
eq. of state

$$w \equiv \frac{\text{pressure}}{\text{density}} \to 1/3$$

radiation domination

$n = 1$

field fragments into solitons and/or just gravitationally clusters

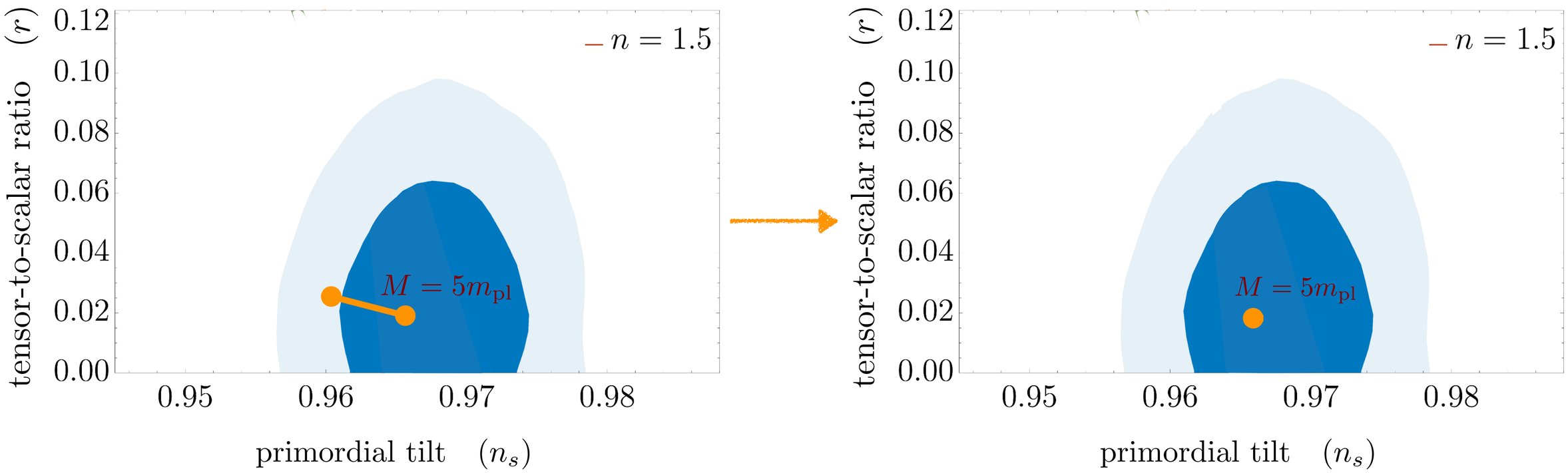


eq. of state

$$w \to 0$$

matter domination

upper bound on duration to radiation domination



* addition of other light fields, see Antusch, Figueroa, Marschall, Torrenti (2020)

* can be relevant for DM production, see recent summary of expansion history/non-thermal effects in M.A. G. Garcia (2021)

* implications of CMB observations for/on reheating (Martin & Ringeval 2010, Cook et. al 2015, Munoz and Kamionkowski 2015)

Lozanov & MA (2017)

$n \neq 1$

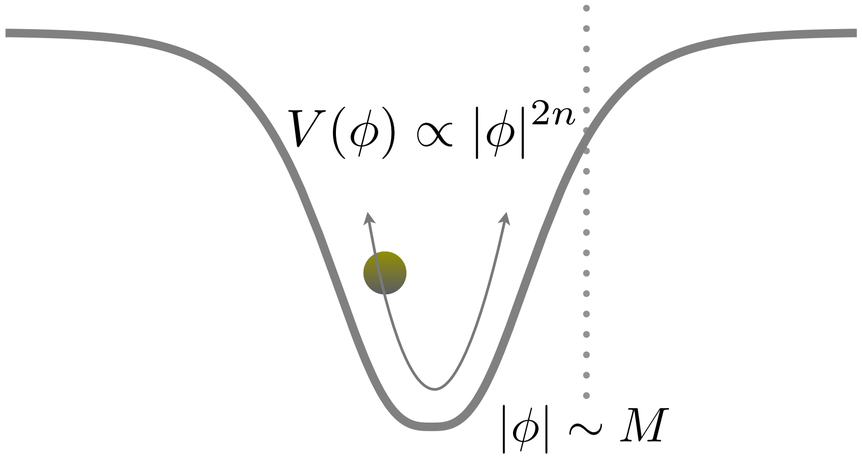
* non-quadratic minimum

* no oscillons or matter domination

so far, we have ignored couplings to other fields …

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

- shape of the potential (self couplings)
- ~~couplings to other fields~~  $\chi\ ,\psi\ A_\mu$



*there can still be gravitational particle production of other fields (like DM), see for example Ling & Long (2021)

couplings to other fields

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\right.$$

$$-\frac{1}{2}(\partial\chi)^2 - m_\chi^2\chi^2 + g_{\phi\chi}\phi\chi^2 + \ldots$$

$$\left.-\bar{\psi}(i\gamma\cdot\partial - m)\psi - g_{\phi\psi}\phi\bar{\psi}\psi + \ldots \;\supset SM\right]$$

rich history of non-perturbative dynamics after inflation from ~1990s onwards

… + recent works (examples - NOT a complete inventory)

with Higgs: Figueroa, Garcia-Bellido & Torrenti + Hertzberg & Jain (2020)

multi-field inflation + non-canonical kinetic terms: van de Vis, Nguyen, Sfakianakis, Giblin & Kaiser (2019/20)

Abelian and non-Abelian gauge fields: Adshead, Giblin, Pieroni & Weiner (2017/20)

how to efficiently drain the inflation: Fan, Lozanov & Liu (2021)

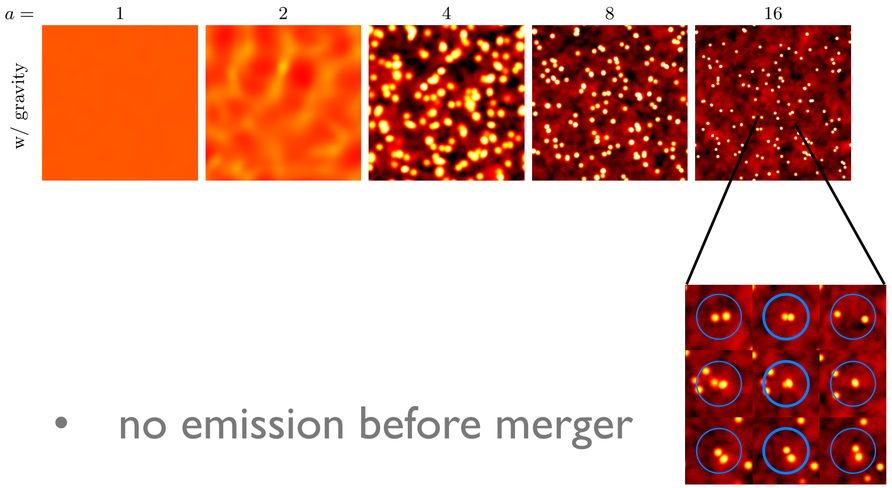
coupling to “photons” and transfer of energy

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\right.$$

$$-\frac{1}{2}(\partial\chi)^2 - m_\chi^2\chi^2 + g_{\phi\chi}\phi\chi^2 + \ldots$$

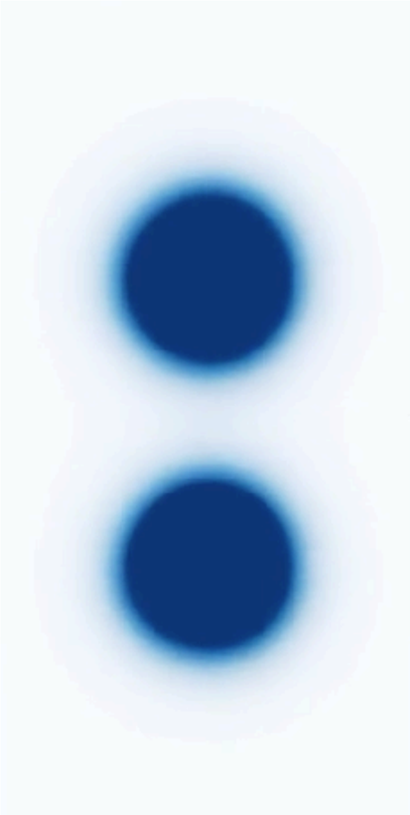
$$\left.-\bar{\psi}(i\gamma\cdot\partial - m)\psi - g_{\phi\psi}\phi\bar{\psi}\psi + \ldots\right]$$

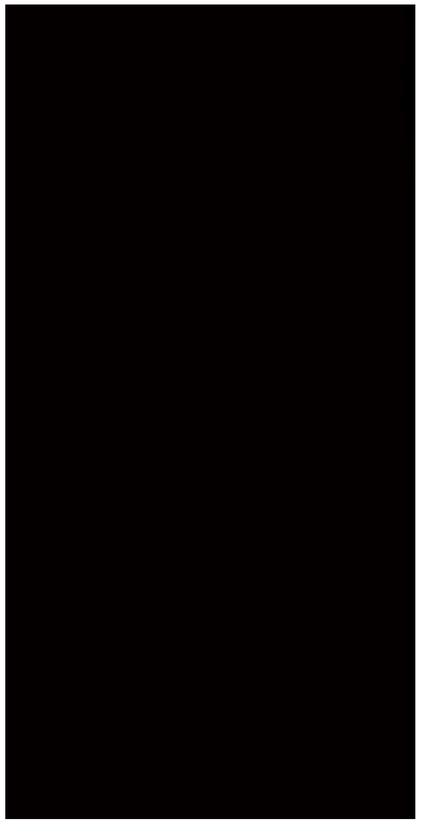
photons from oscillons



with Mou

- no emission before merger
- explosive after merger
- a threshold & resonant effect

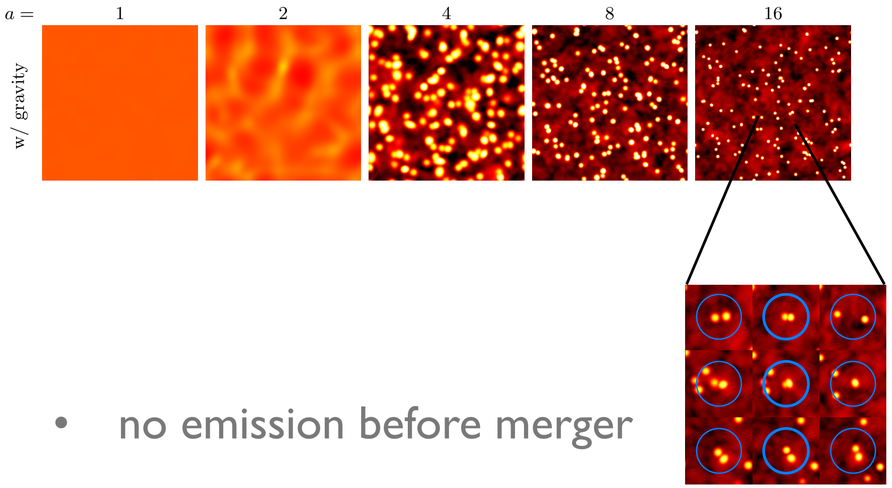




MA & Mou (2020)
also: MA, Long, Mou & Saffin (2021)

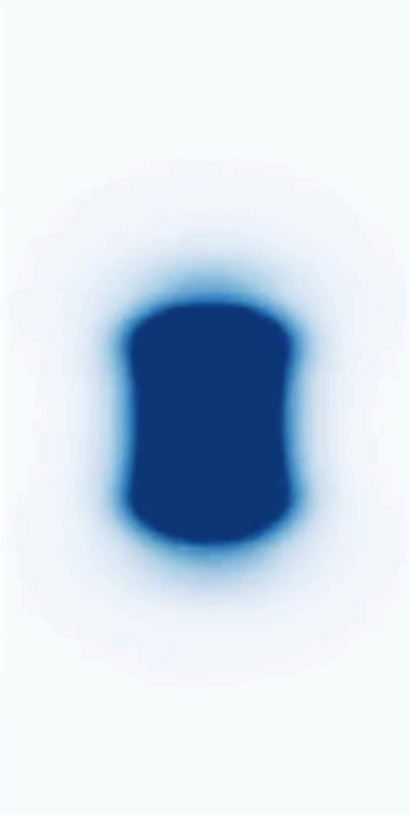
*might not be easy to achieve because the amplitude is highest at the end of inflation, so most photons produced then before (if) soliton formation. Also, likely not enough for reheating

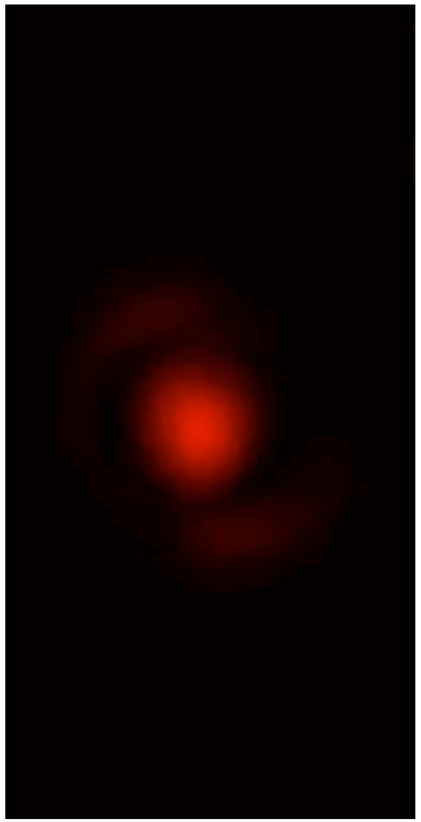
photons from oscillons



with Mou

- no emission before merger
- explosive after merger
- a threshold & resonant effect

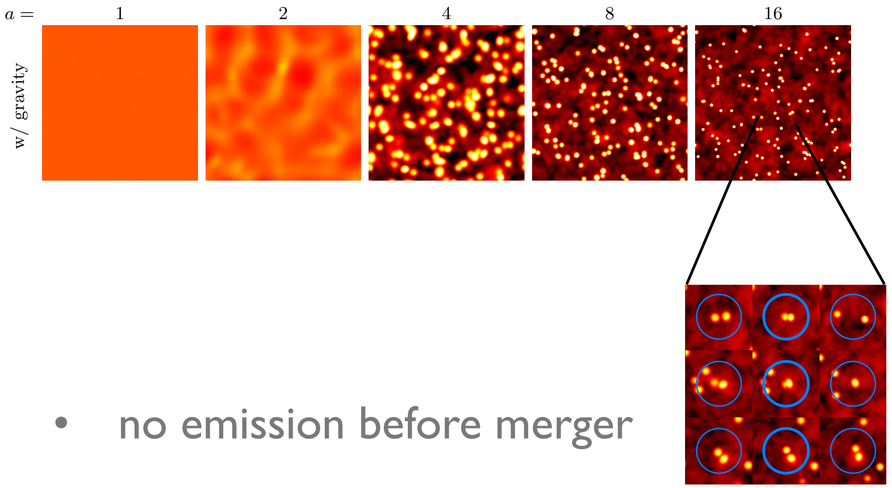




MA & Mou (2020)
also: MA, Long, Mou & Saffin (2021)

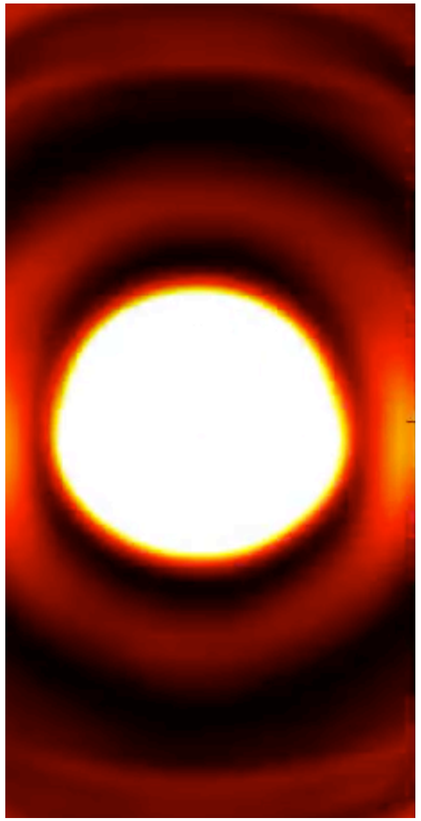
*might not be easy to achieve because the amplitude is highest at the end of inflation, so most photons produced then before (if) soliton formation. Also, likely not enough for reheating

photons from oscillons



with Mou

- no emission before merger
- explosive after merger
- a threshold & resonant effect



MA & Mou (2020)
also: MA, Long, Mou & Saffin (2021)

*might not be easy to achieve because the amplitude is highest at the end of inflation, so most photons produced then before (if) soliton formation. Also, likely not enough for reheating

coupling to massive "photons"

$$S = \int d^4x\sqrt{-g}\left[\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}m_\gamma^2 A^2 + V_{\rm nl}(A^2)\right.$$

$$-\frac{1}{2}(\partial\chi)^2 + m_\chi^2\chi^2 + g_{\phi\chi}\phi\chi^2 + \ldots$$

$$\left.-\bar{\psi}(i\gamma\cdot\partial - m)\psi - g_{\phi\psi}\phi\bar{\psi}\psi + \ldots\right]$$

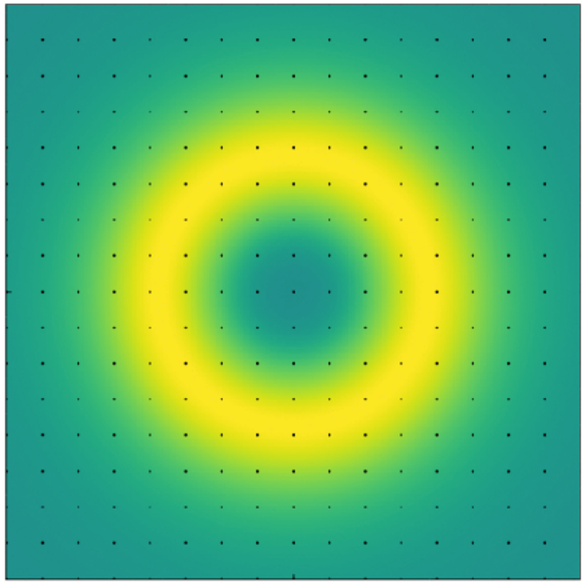
* production could be via "misalignment" of inflaton, for example: Co et. al (2018), Agrawal et. al (2018) in context of vector dark matter

Vector oscillons

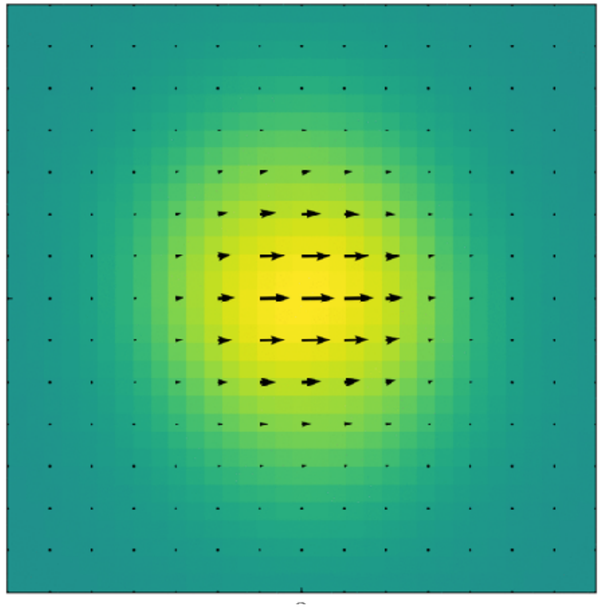

with Zhang and Jain

self-interaction supported vector field solitons

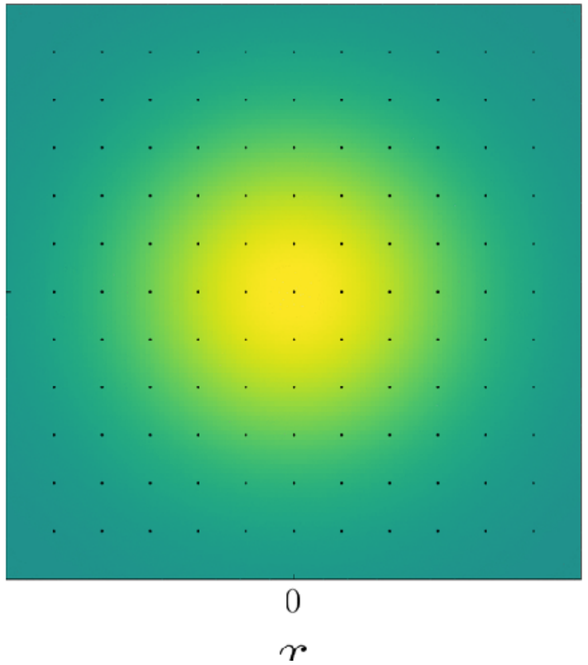
hedgehog oscillon



spin-1 oscillon



spin-0 oscillon



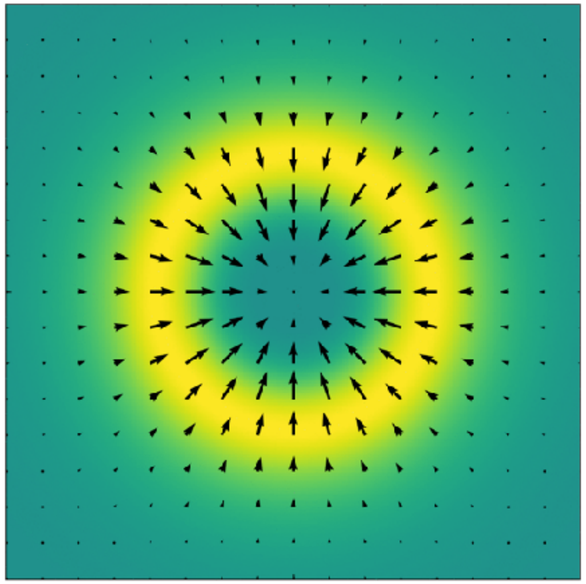
*gravitationally supported hedgehog & longitudinal solitons — Adshead & Lozanov (2021)

Vector oscillons

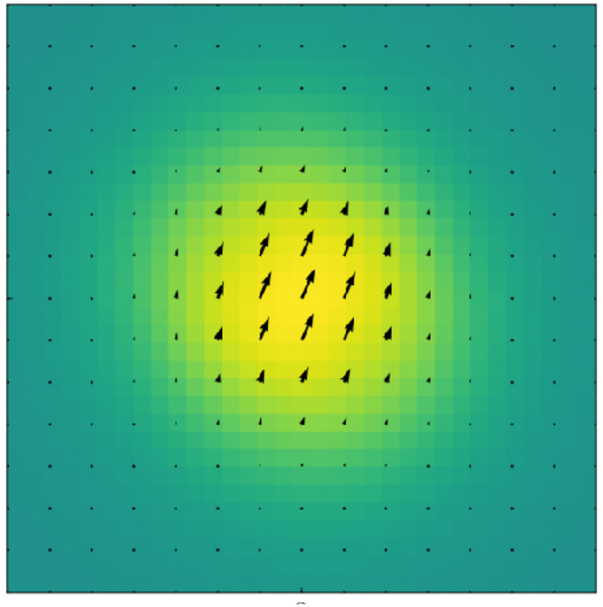

with Zhang and Jain

self-interaction supported vector field solitons

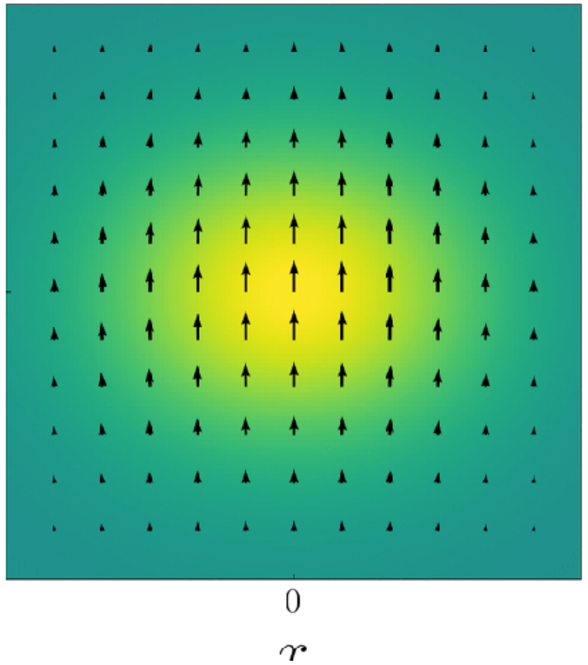
hedgehog oscillon



spin-1 oscillon



spin-0 oscillon



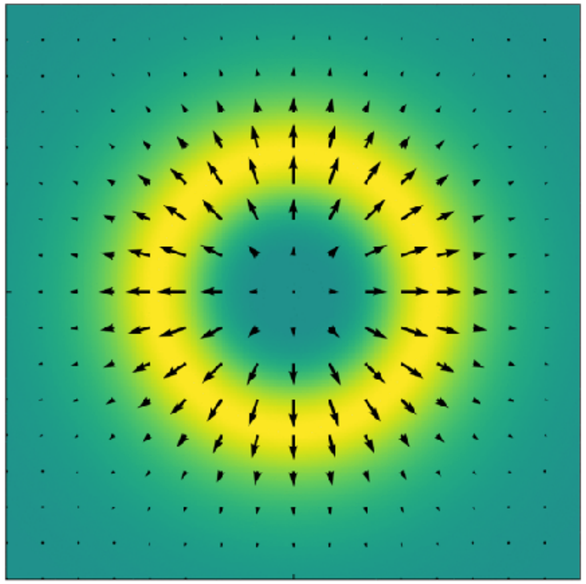
*gravitationally supported hedgehog & longitudinal solitons — Adshead & Lozanov (2021)

Vector oscillons

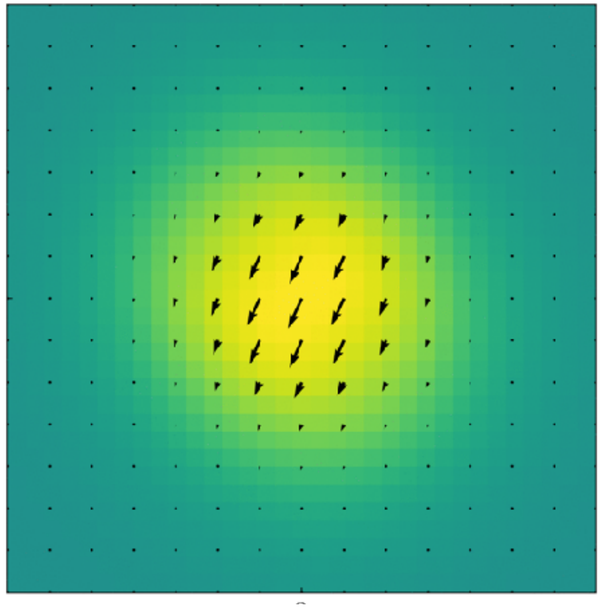

with Zhang and Jain

self-interaction supported vector field solitons

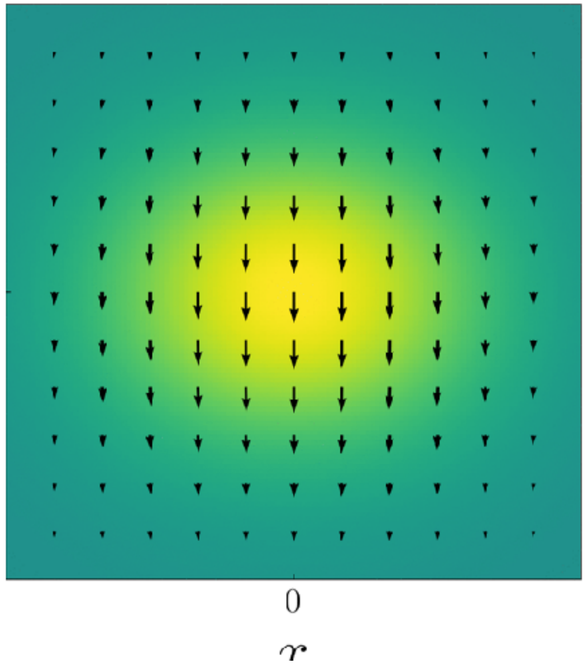
hedgehog oscillon



spin-1 oscillon



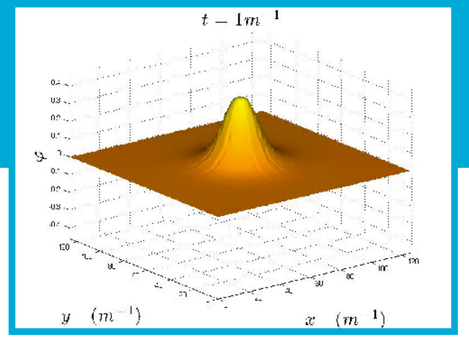
spin-0 oscillon

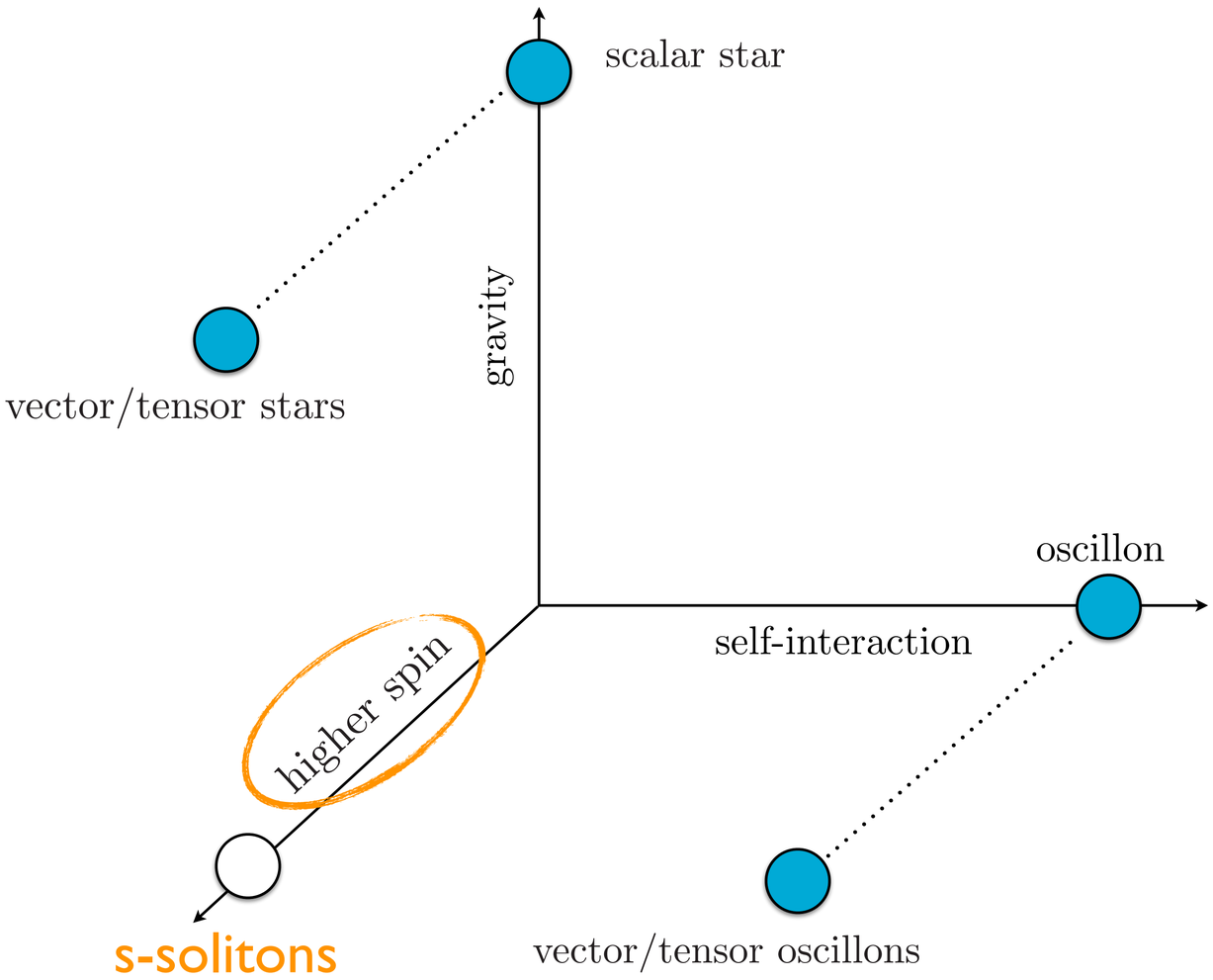


*gravitationally supported hedgehog & longitudinal solitons — Adshead & Lozanov (2021)

s-solitons: oscillons/stars in higher spin fields

spatially localized, coherently oscillating, long-lived





spatially localized

coherently oscillating (components)

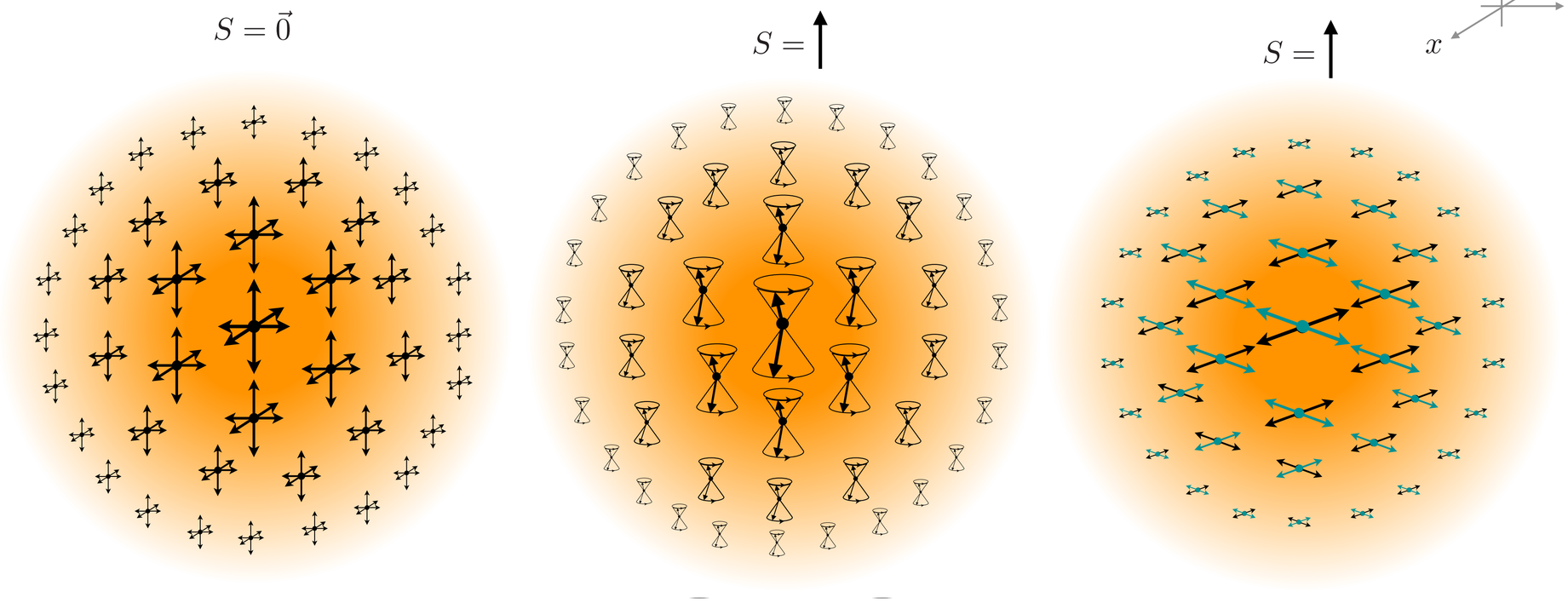
exceptionally long-lived

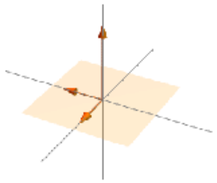
tensor solitons (more generally s-solitons)

WORK IN PROGRESS

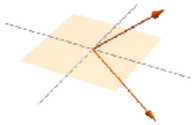
gravitationally supported solitons in massive spin-2 fields

with M. Jain

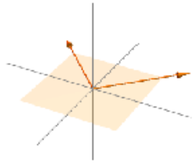




spin-0



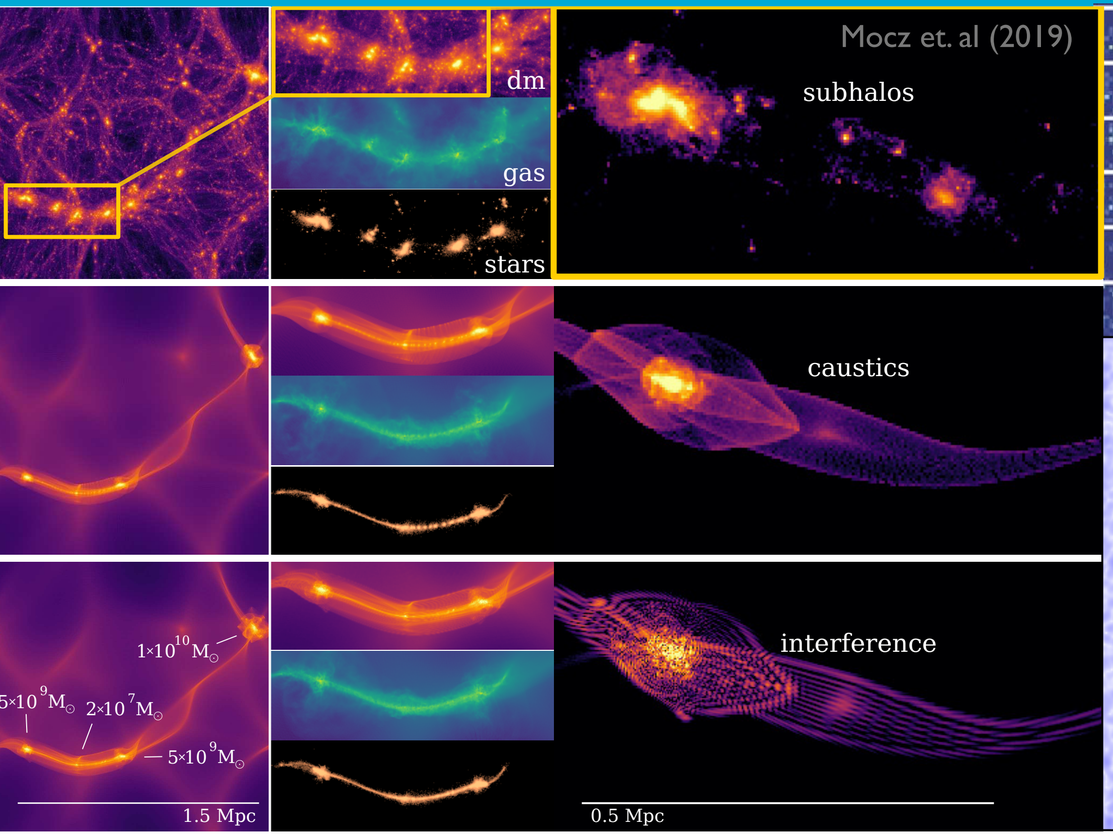
spin-1

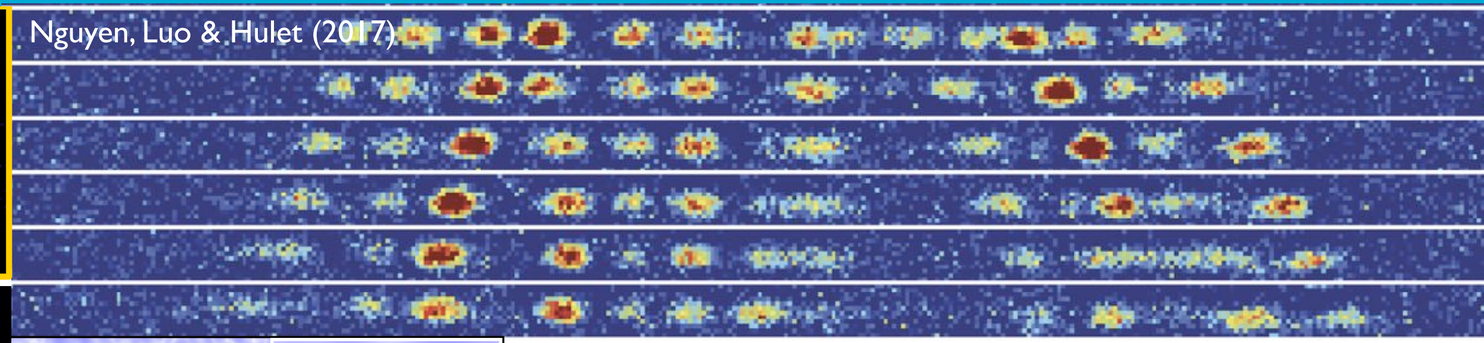


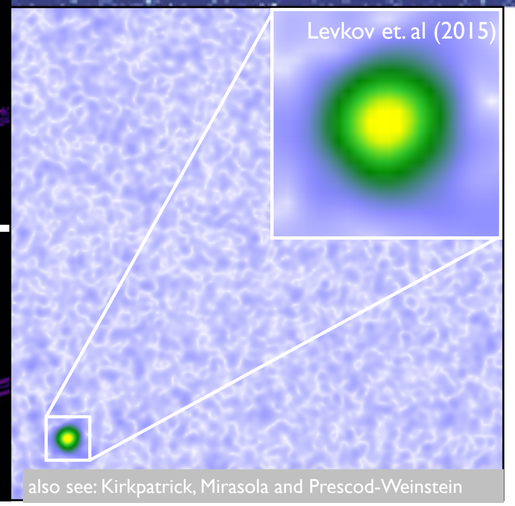
spin-2

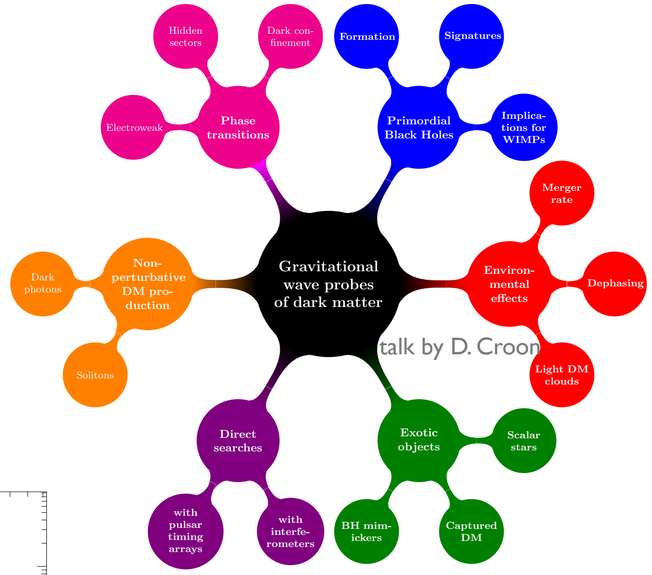
*in the non-relativistic limit of bi-gravity

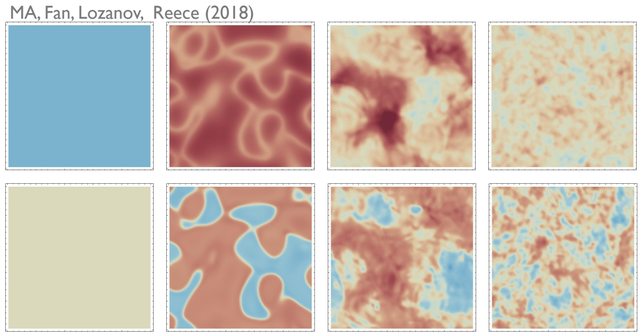
related phenomenology for moduli, axions, early dark energy etc. and BECs

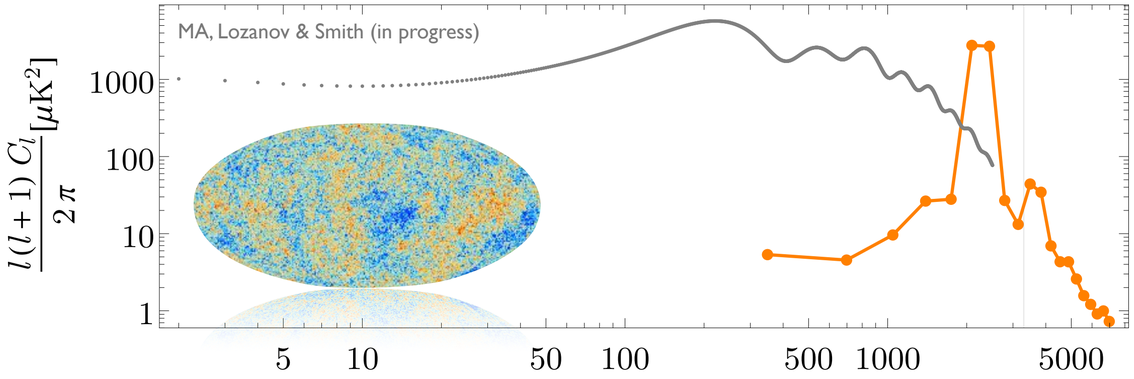


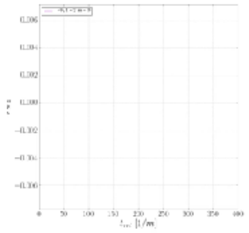


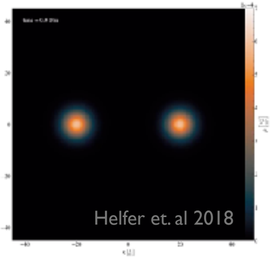












For a general moduli review, see Kane Watson and Sinha (2015)

summary & looking ahead

theory :

model dependent vs. relatively universal predictions from model-building perspective and those resulting from nonlinear phenomena

+ detailed history of the Standard Model + Dark Matter + …

simulations: LatticeEasy (2000), Defrost (2008), PSpectre (2010), HLattice (2011), GABE/Rel (2013/19), GFiRe (2019), CosmoLattice (2021)

numerical simulations with increasingly realistic field content including Abelian and non-Abelian fields, fermions etc. and non-trivial field configurations + thermalization

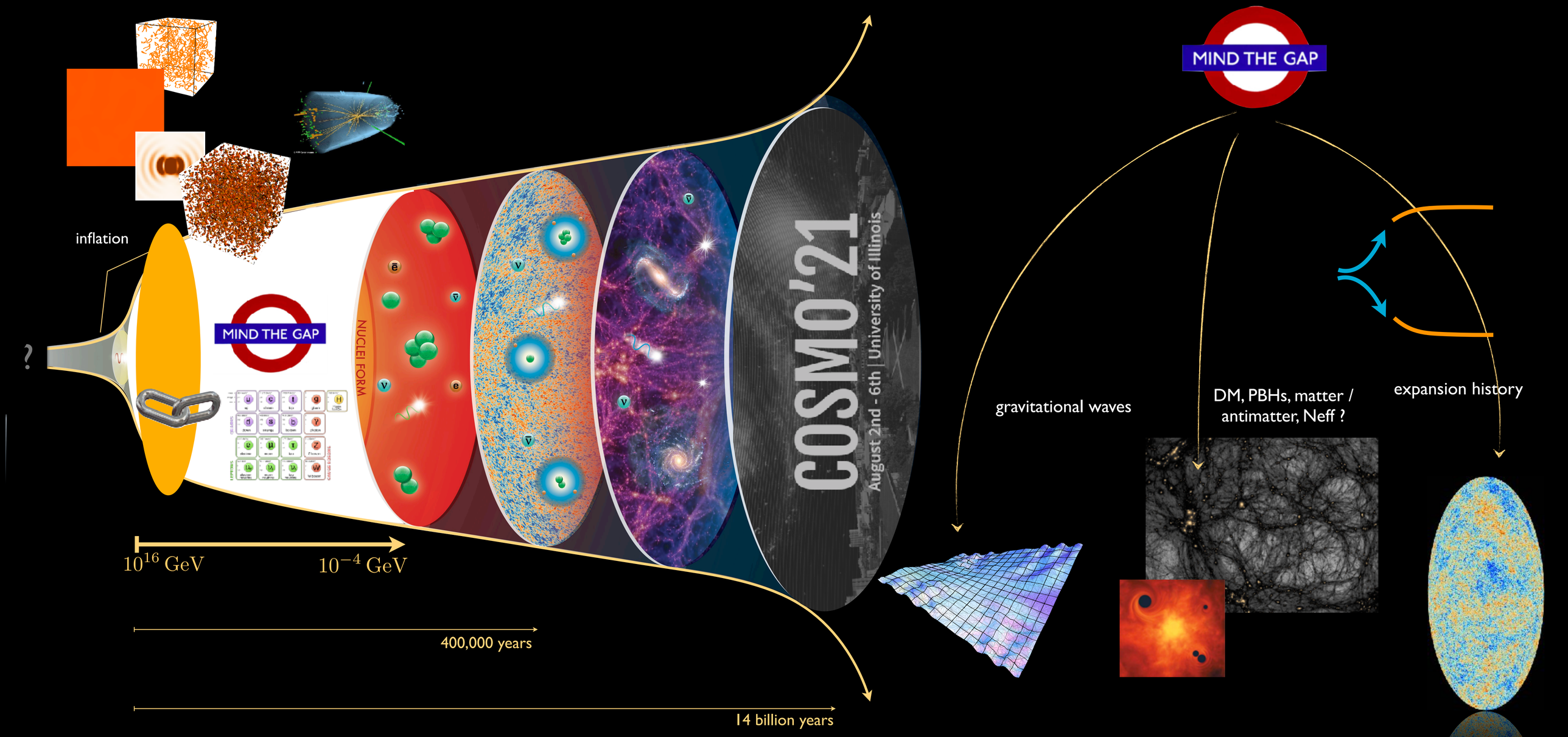
observations:

what observations do we need to figure out self-couplings and couplings of the inflation to SM (or intermediaries)

[eg. high frequency gravitational waves? thermal and non-thermal relics ? (CMB/LSS)]

2011.12414 (Challenges & Opportunities …)

1610.02743 (CMB-S4 science book)


inflation
?
MIND THE GAP
NUCLEI FORM
COSMO'21
August 2nd - 6th | University of Illinois
10^{16} GeV
10^{-4} GeV
400,000 years
14 billion years
MIND THE GAP
gravitational waves
DM, PBHs, matter / antimatter, Neff ?
expansion history

MIND THE GAP