SORBONNE UNIVERSITÉ

Patrick Peter

INSTITUT D'ASTROPHYSIQUE DE PARIS

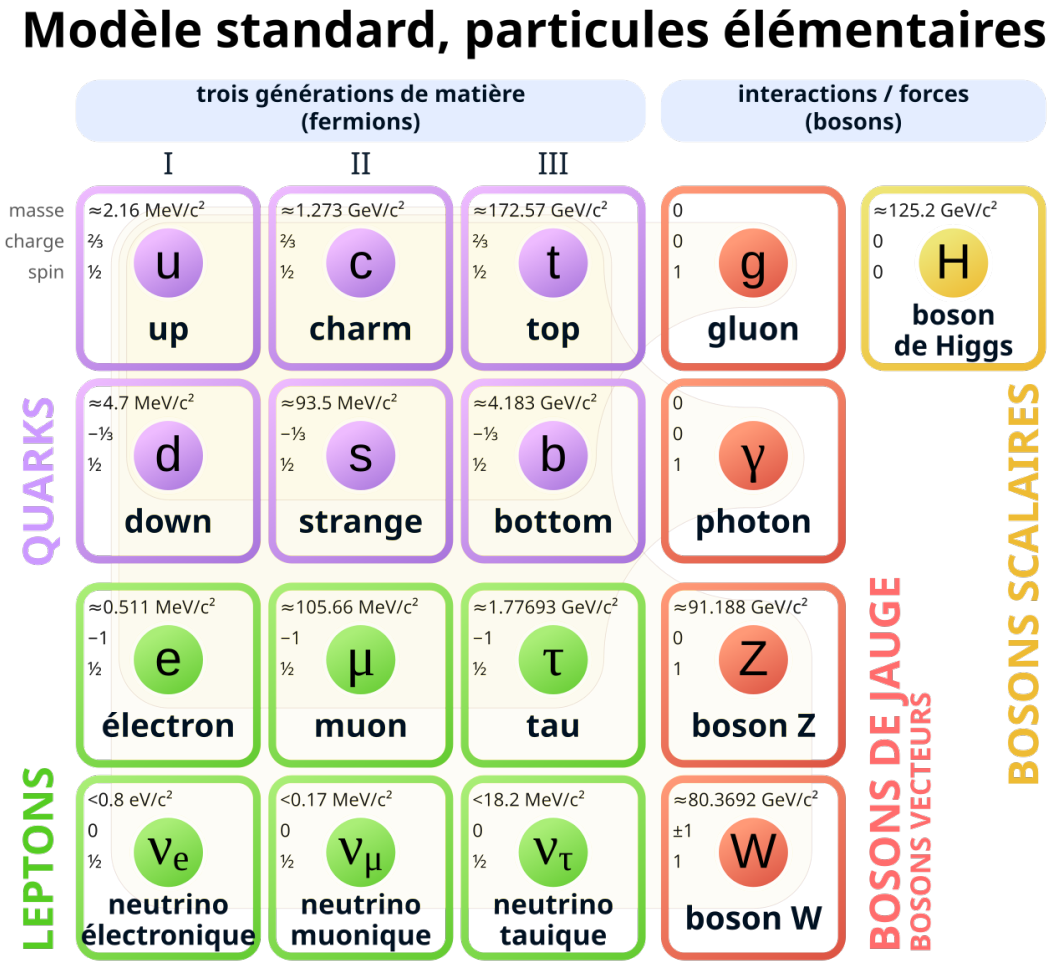
cnrs



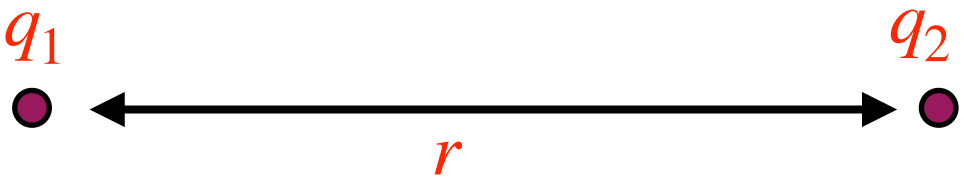
Théorie quantique des champs et cosmologie.

interactions « quantiques »: em, faible, forte

$$SU(3) \otimes SU(2) \otimes U(1)$$

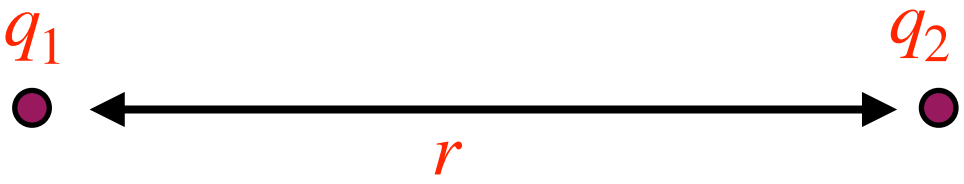


$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - g\alpha_h M (H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) - \tfrac{1}{8}g^2\alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2) - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + M(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu(H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-) - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + (\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa - \tfrac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).$$



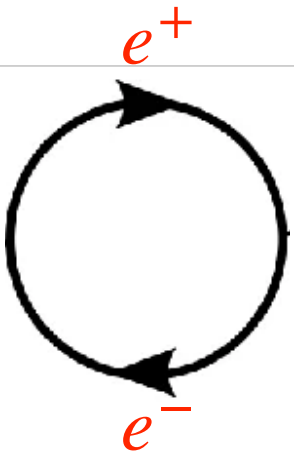
$$E_{\text{em}} = \alpha_{\text{em}} \frac{q_1 q_2}{r}$$

classique



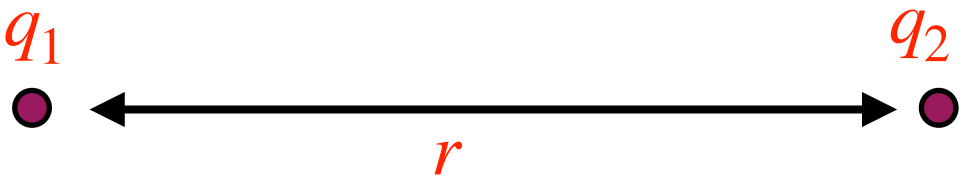
$$E_{\text{em}} = \alpha_{\text{em}} \frac{q_1 q_2}{r}$$

classique

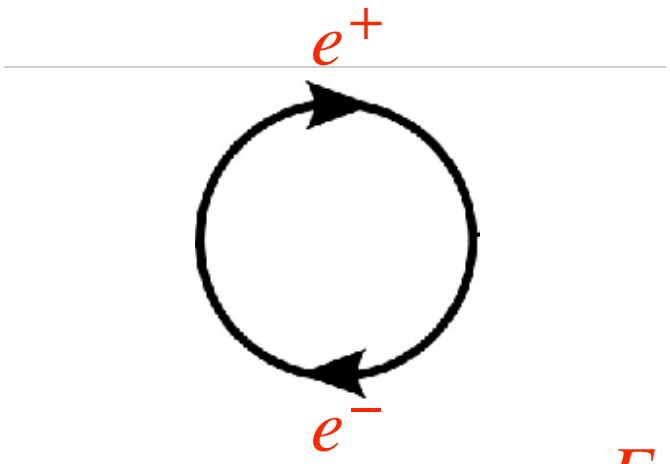


$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

quantique



$$E_{\text{em}} = \alpha_{\text{em}} \frac{q_1 q_2}{r}$$ classique

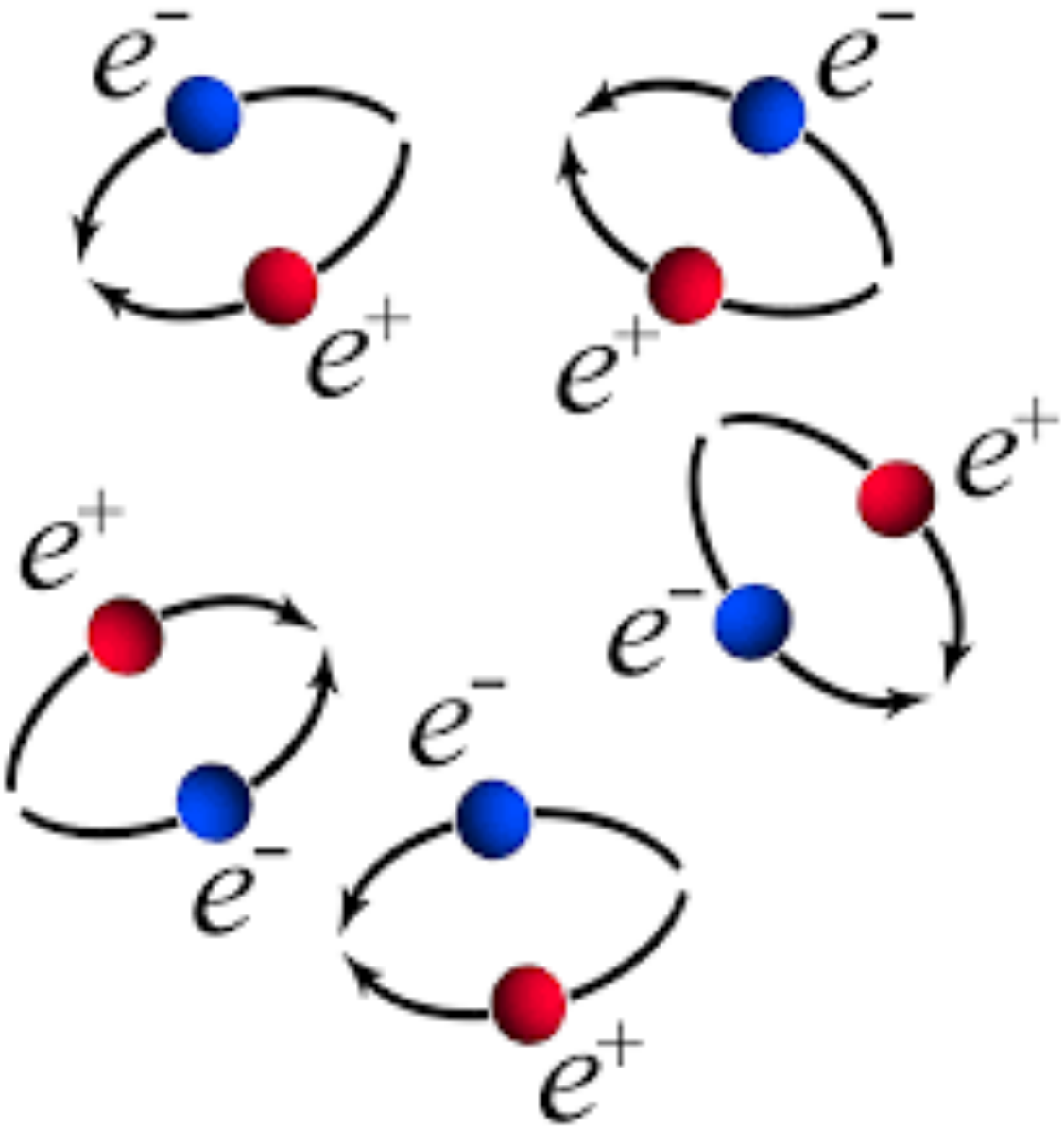


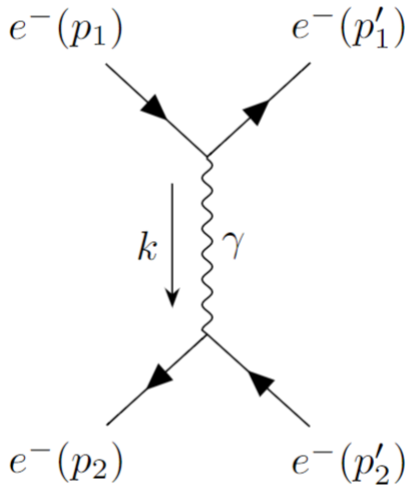
$$\Delta E \Delta t \geq \frac{\hbar}{2}$$ quantique

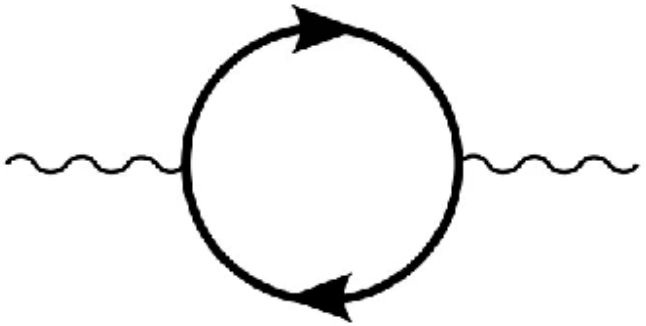
$$\downarrow$$

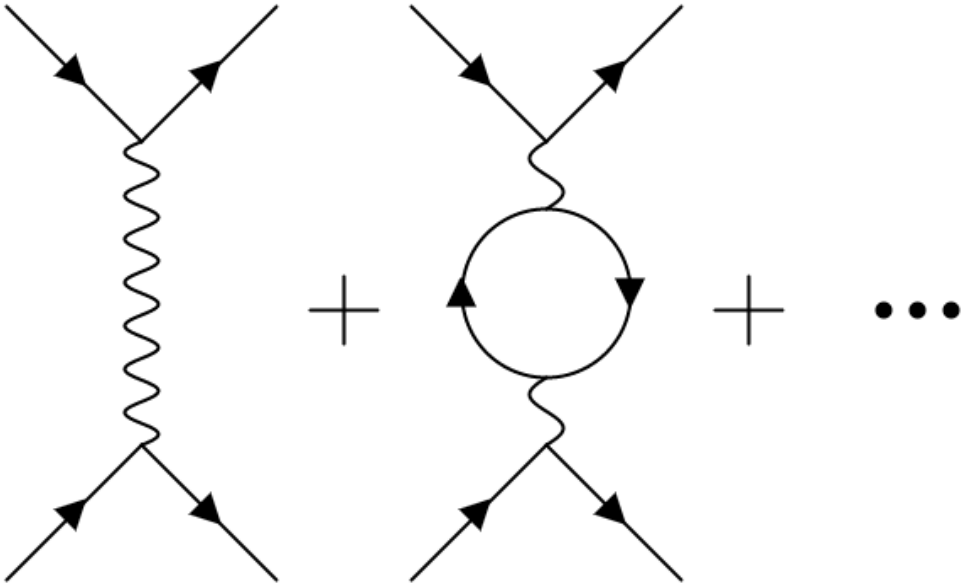
$$E_{\text{rel}} = 2\ mc^2$$ relativiste

structure du vide quantique relativiste



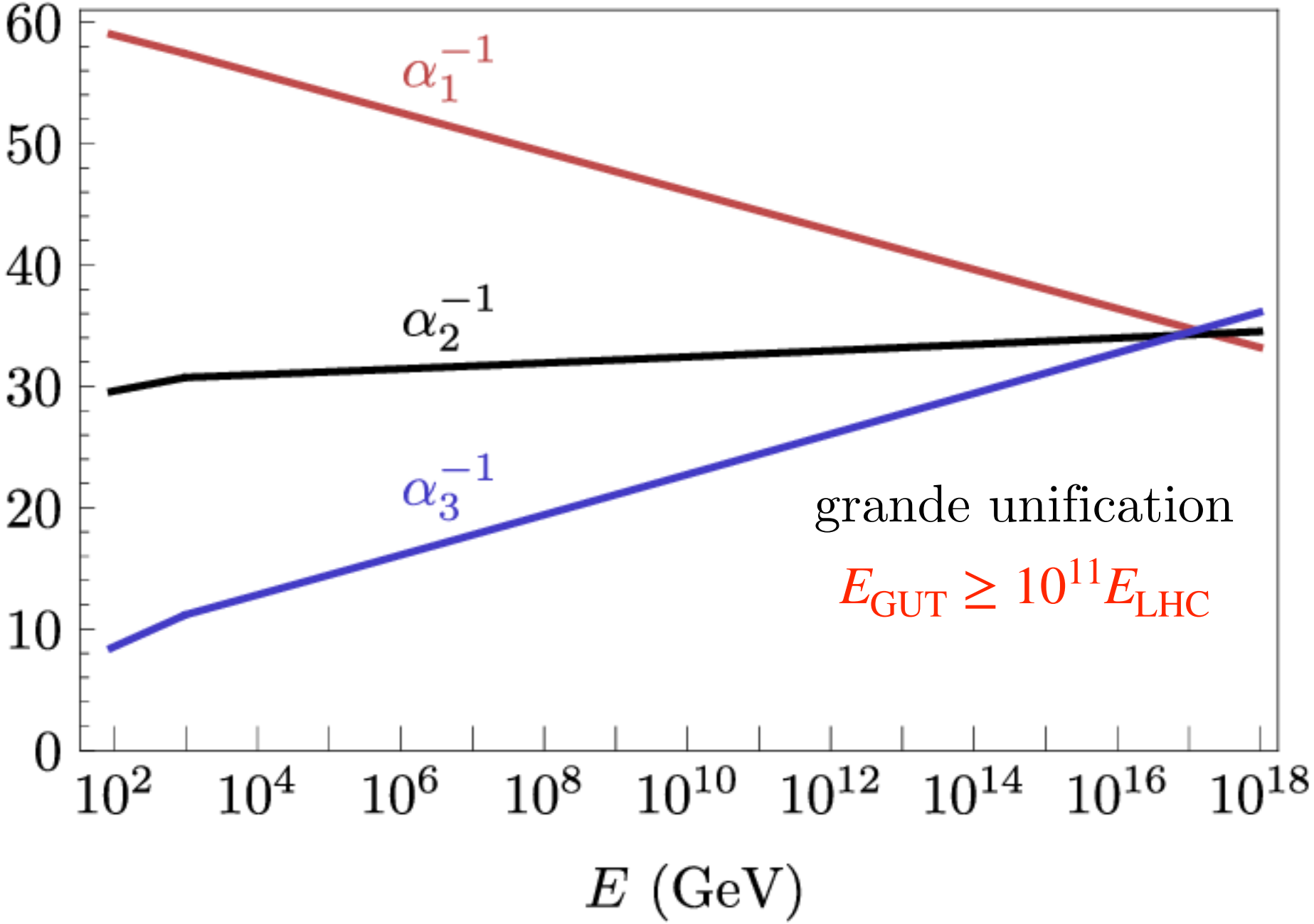






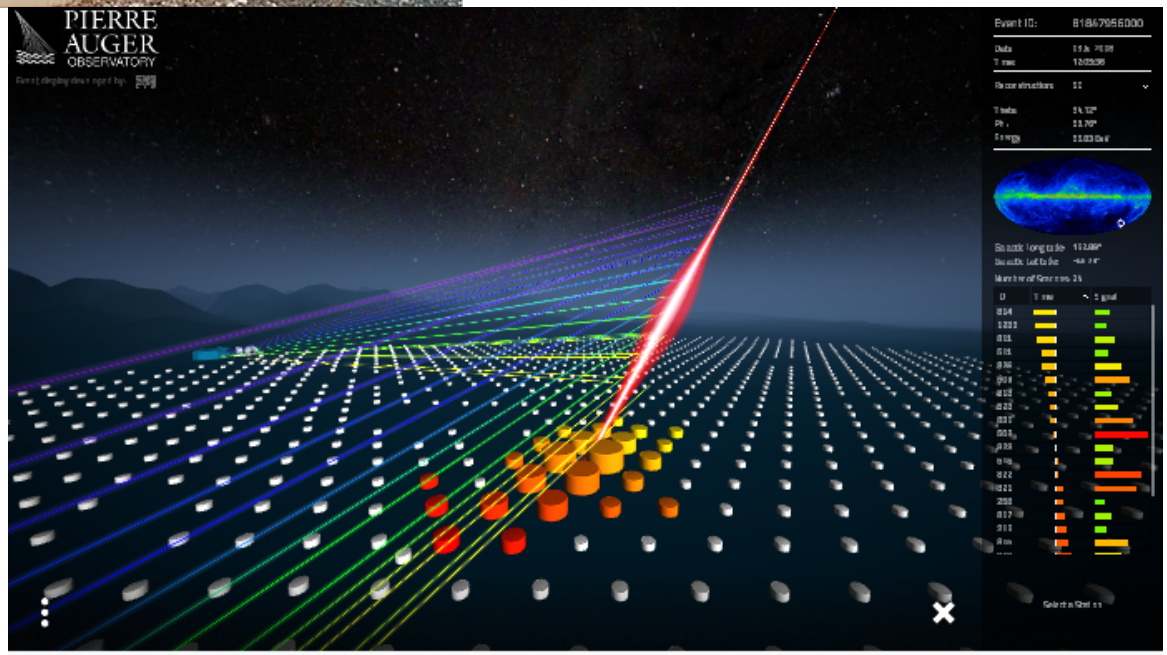
$\alpha_{\mathrm{em}}(E)$

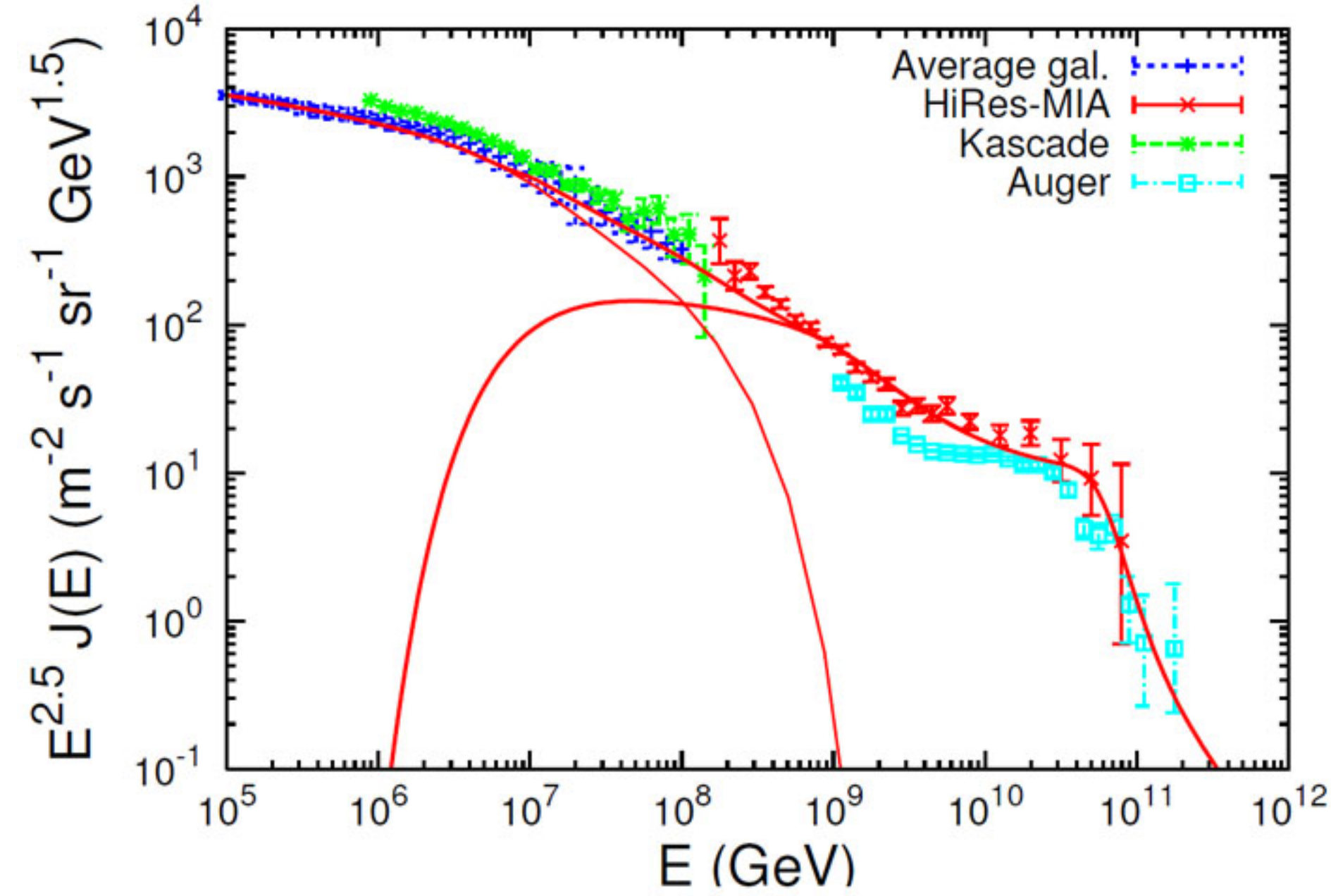
$\alpha_{\text{em}}(E)$, $\alpha_{\text{faible}}(E)$, $\alpha_{\text{forte}}(E)$



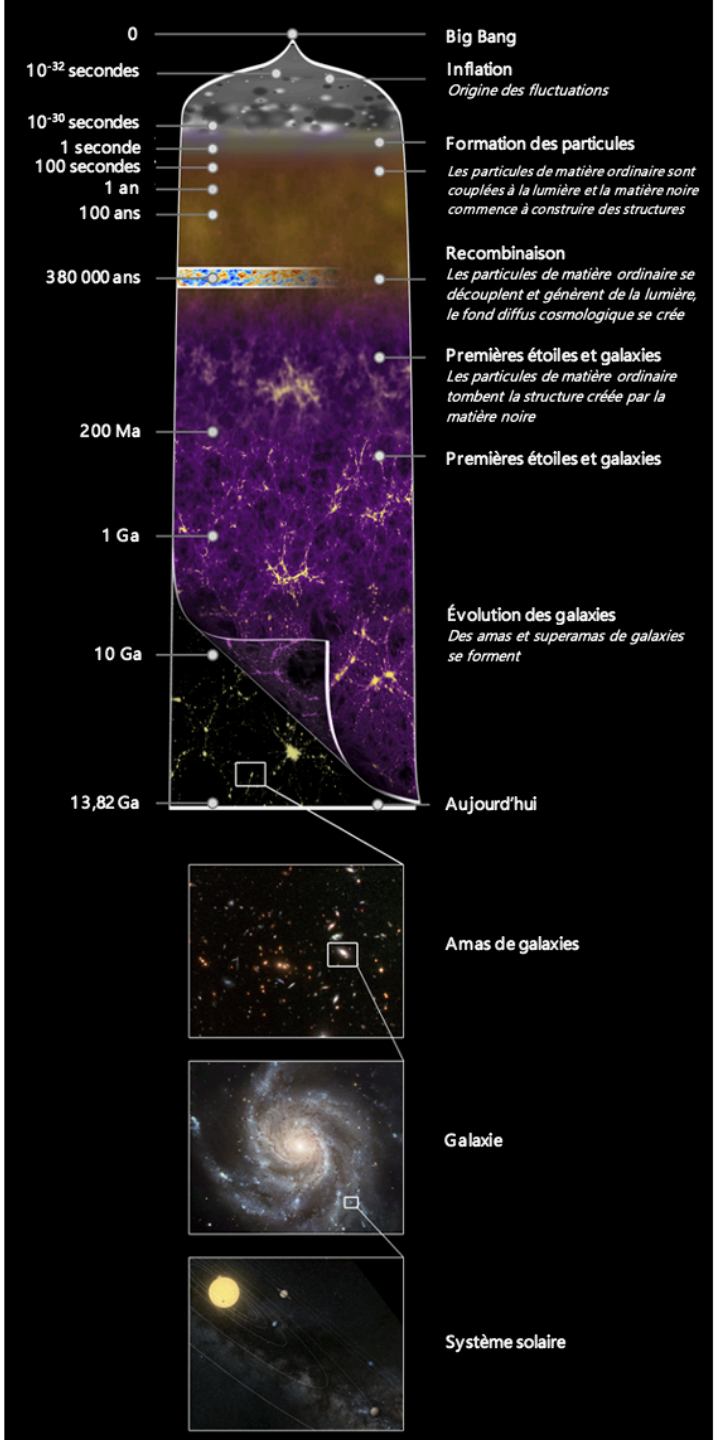
Observatoire Pierre Auger (Argentine)

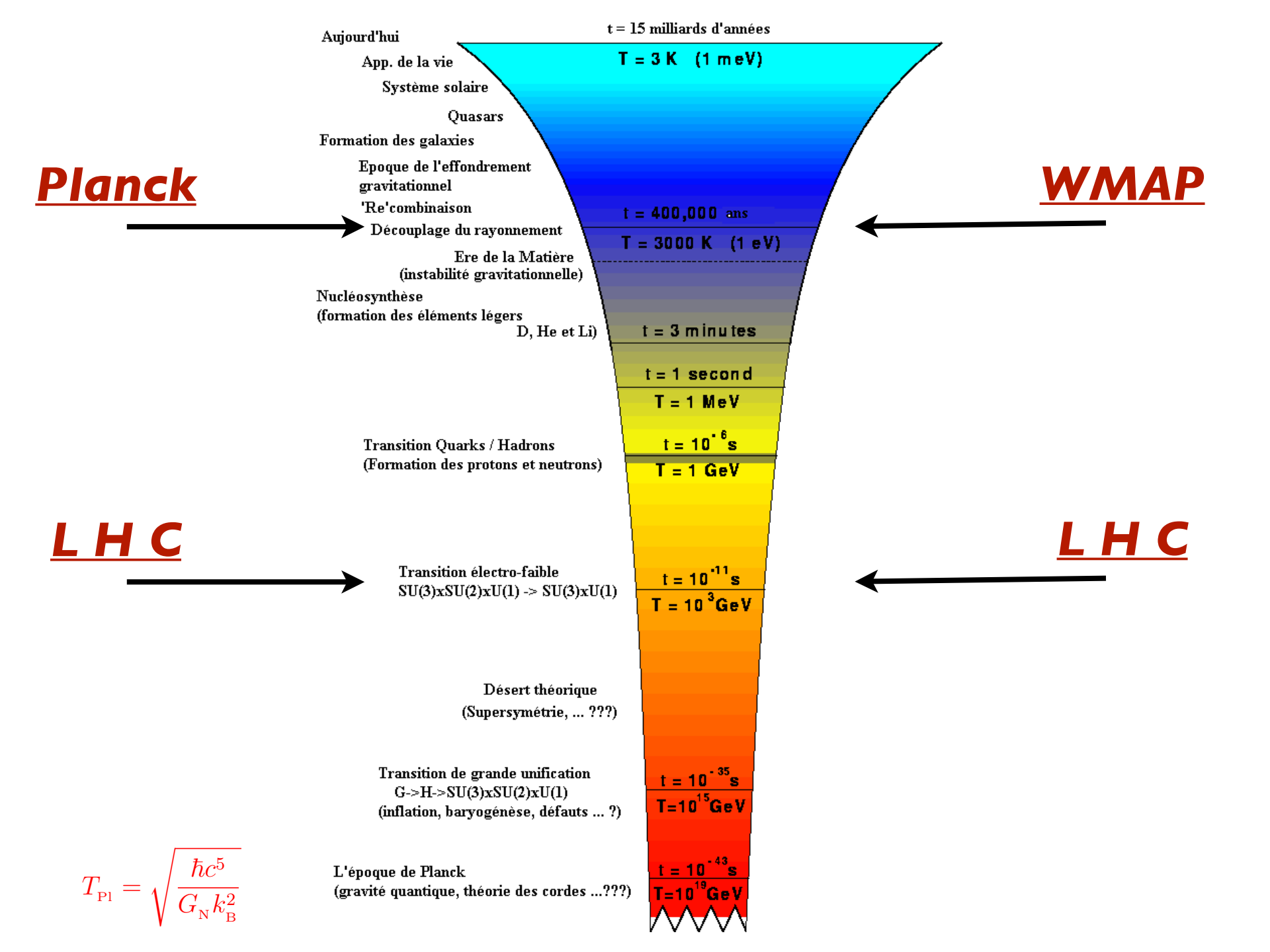




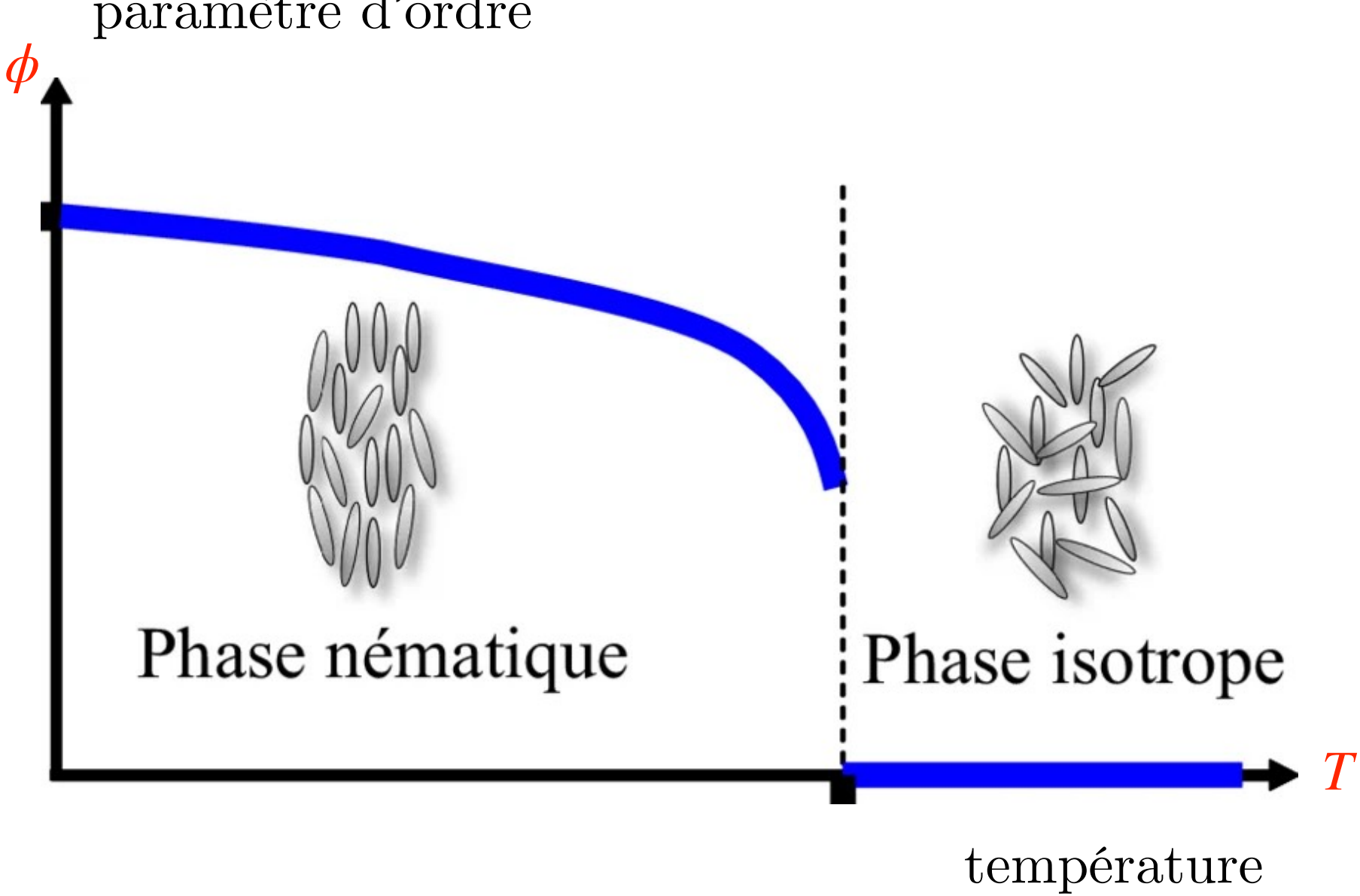


$E_{\mathrm{GUT}} \geq 10^{5} E_{\mathrm{UHECR}}$


0
Big Bang
10-32 secondes
Inflation
Origine des fluctuations
10-30 secondes
1 seconde
100 secondes
1 an
100 ans
Formation des particules
Les particules de matière ordinaire sont couplées à la lumière et la matière noire commence à construire des structures
380 000 ans
Recombinaison
Les particules de matière ordinaire se découplent et génèrent de la lumière, le fond diffus cosmologique se crée
Premières étoiles et galaxies
Les particules de matière ordinaire tombent la structure créée par la matière noire
200 Ma
Premières étoiles et galaxies
1 Ga
Évolution des galaxies
Des amas et superamas de galaxies se forment
10 Ga
13,82 Ga
Aujourd'hui
Amas de galaxies
Galaxie
Système solaire

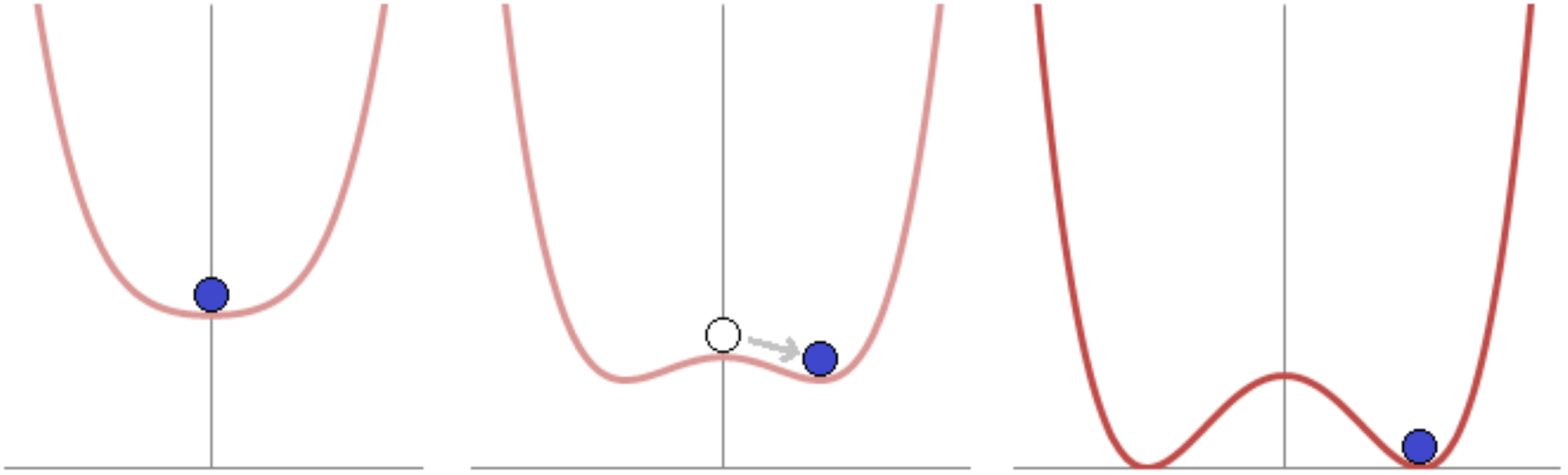


$$T_{\mathrm{Pl}} = \sqrt{\frac{\hbar c^5}{G_{\mathrm{N}} k_{\mathrm{B}}^2}}$$

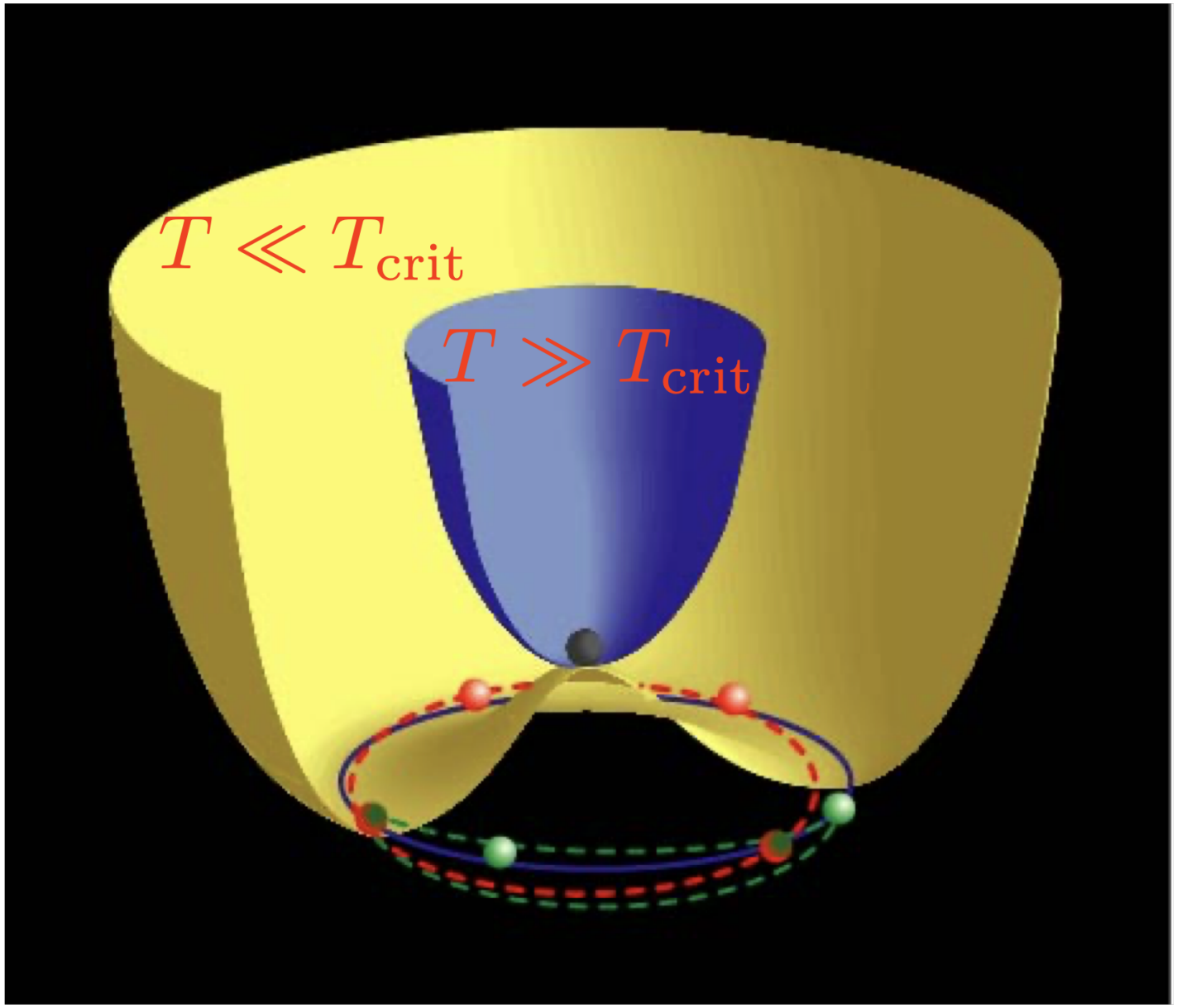

paramètre d'ordre
ϕ
Phase nématique
Phase isotrope
T
température

$T > T_c$

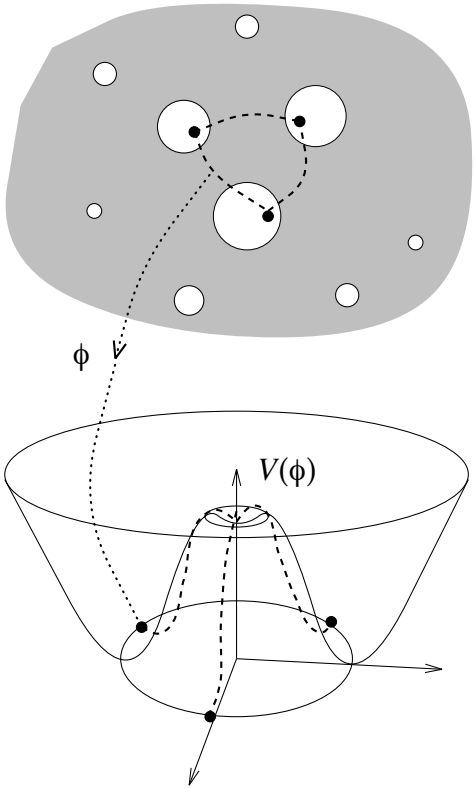
$T < T_c$

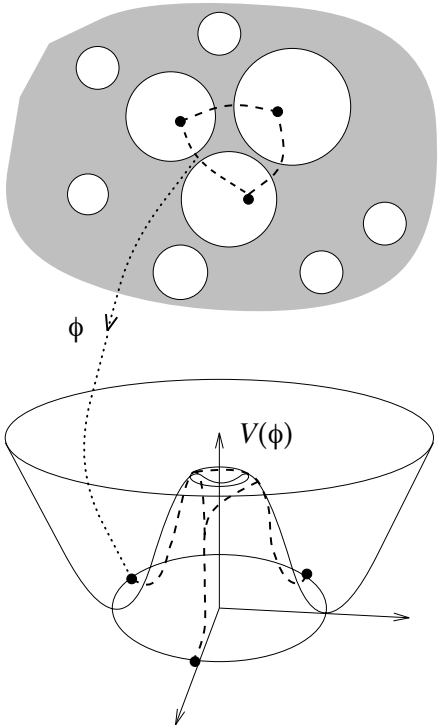


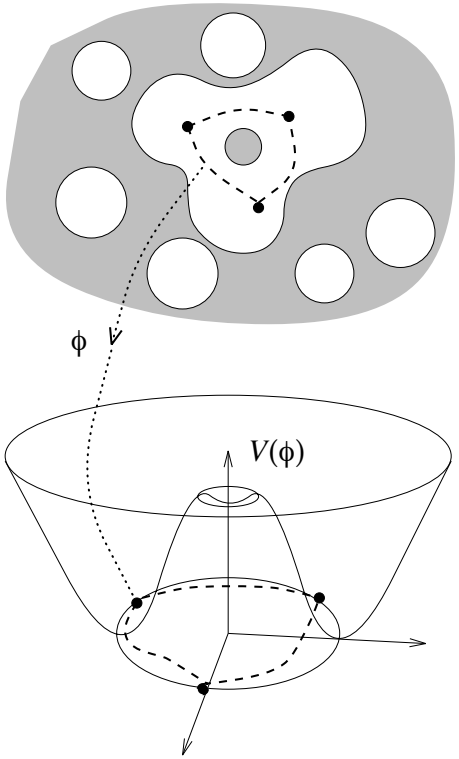
$V(\phi)$

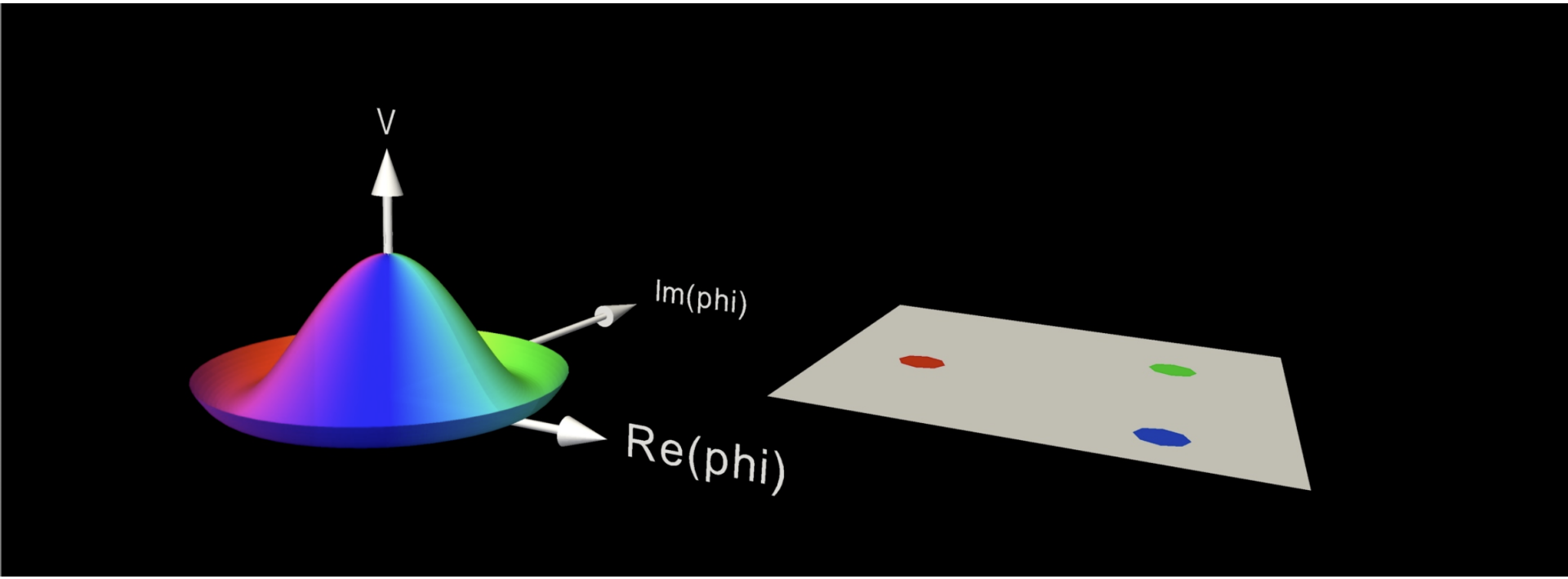


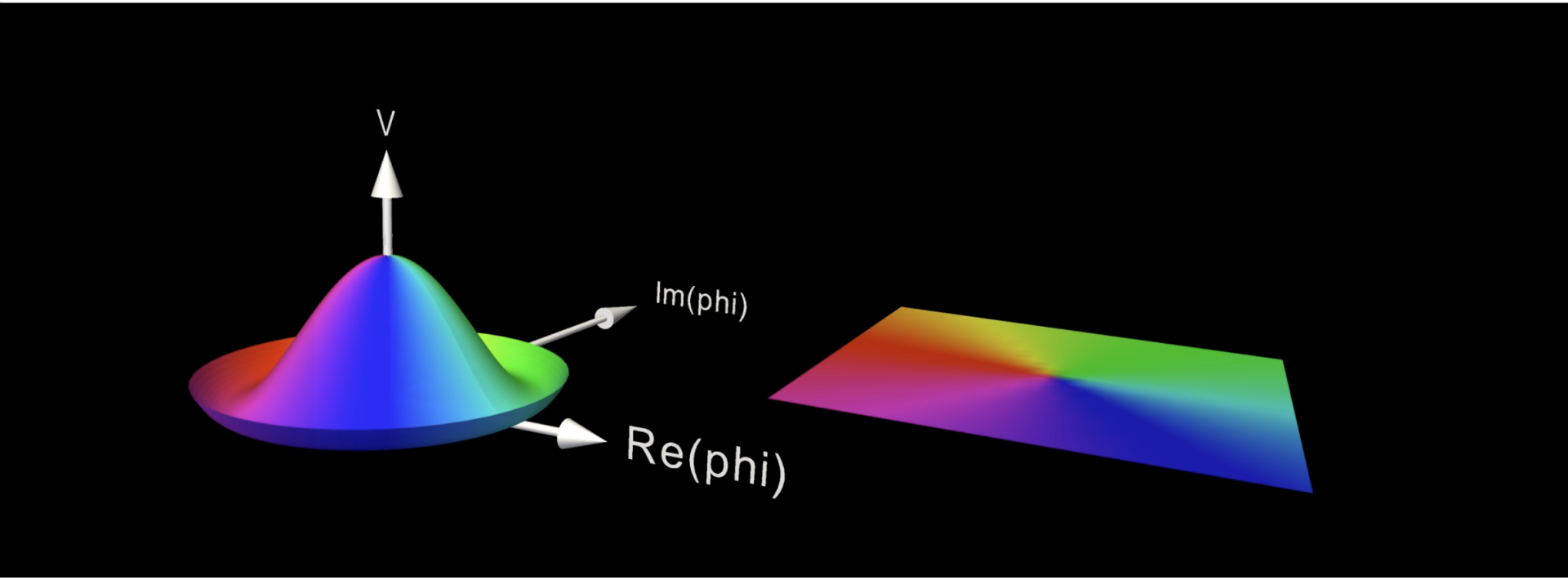
ϕ

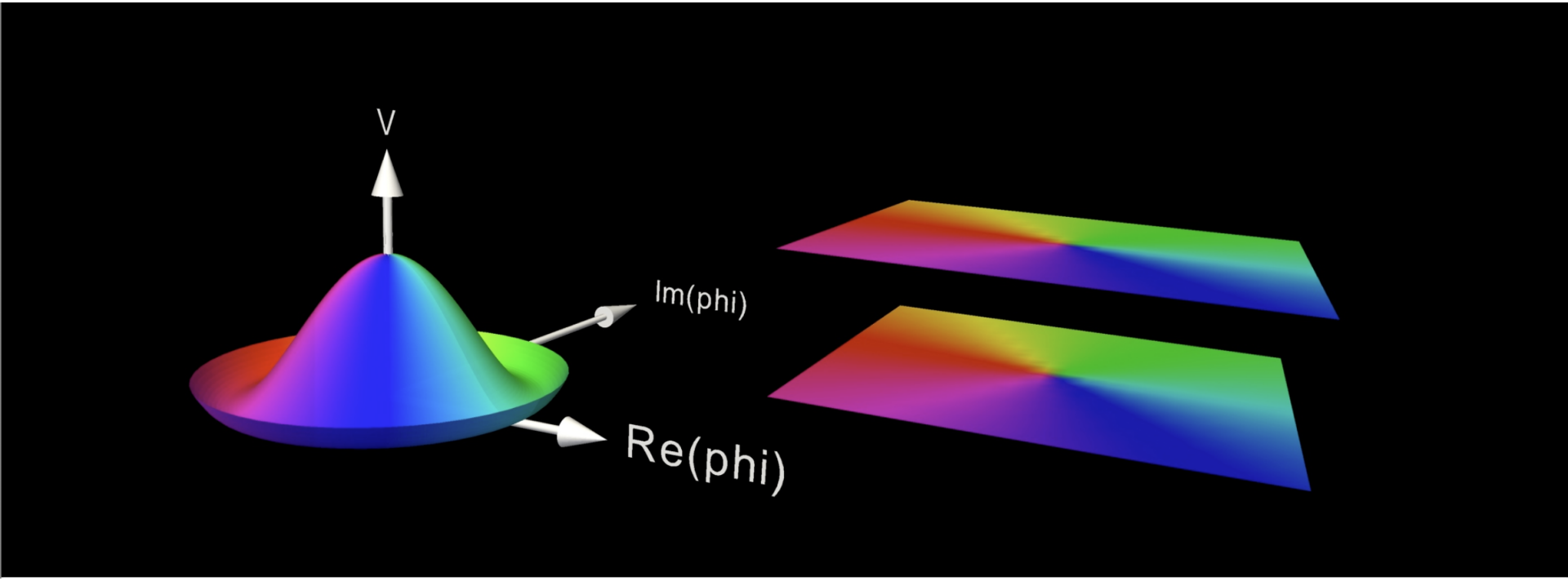

ϕ
V(ϕ)

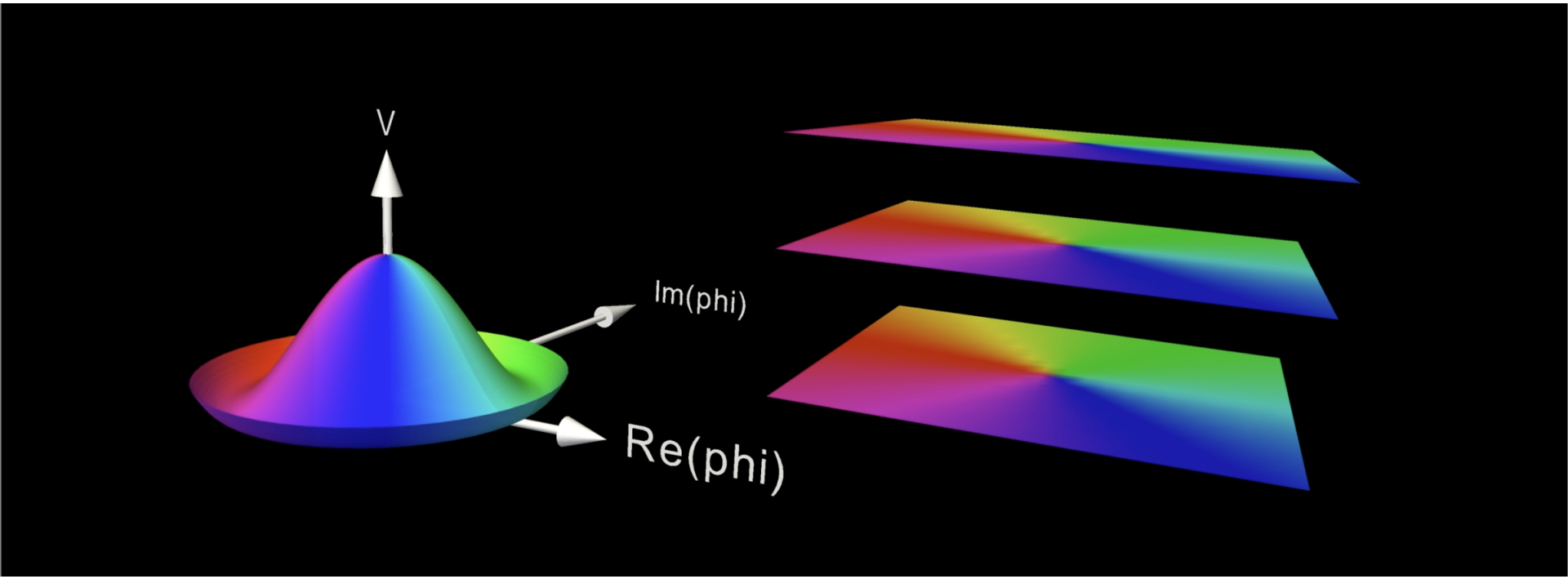

ϕ
V(ϕ)

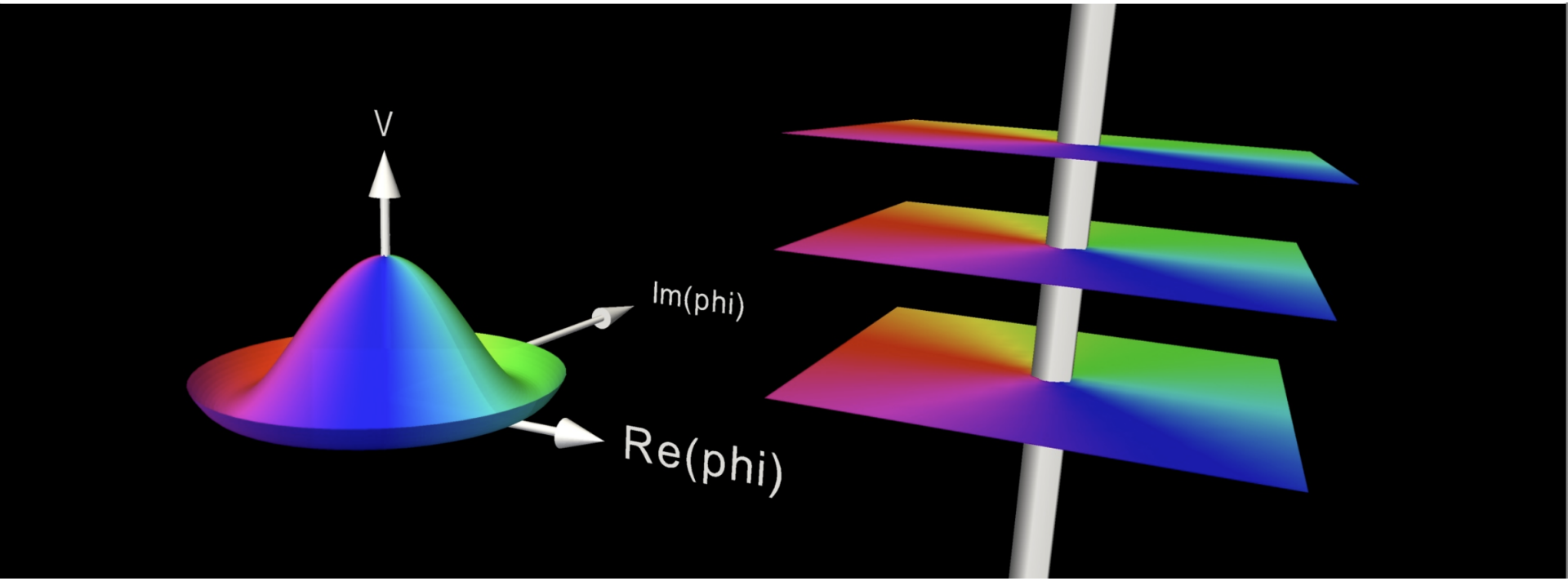

ϕ
V(ϕ)

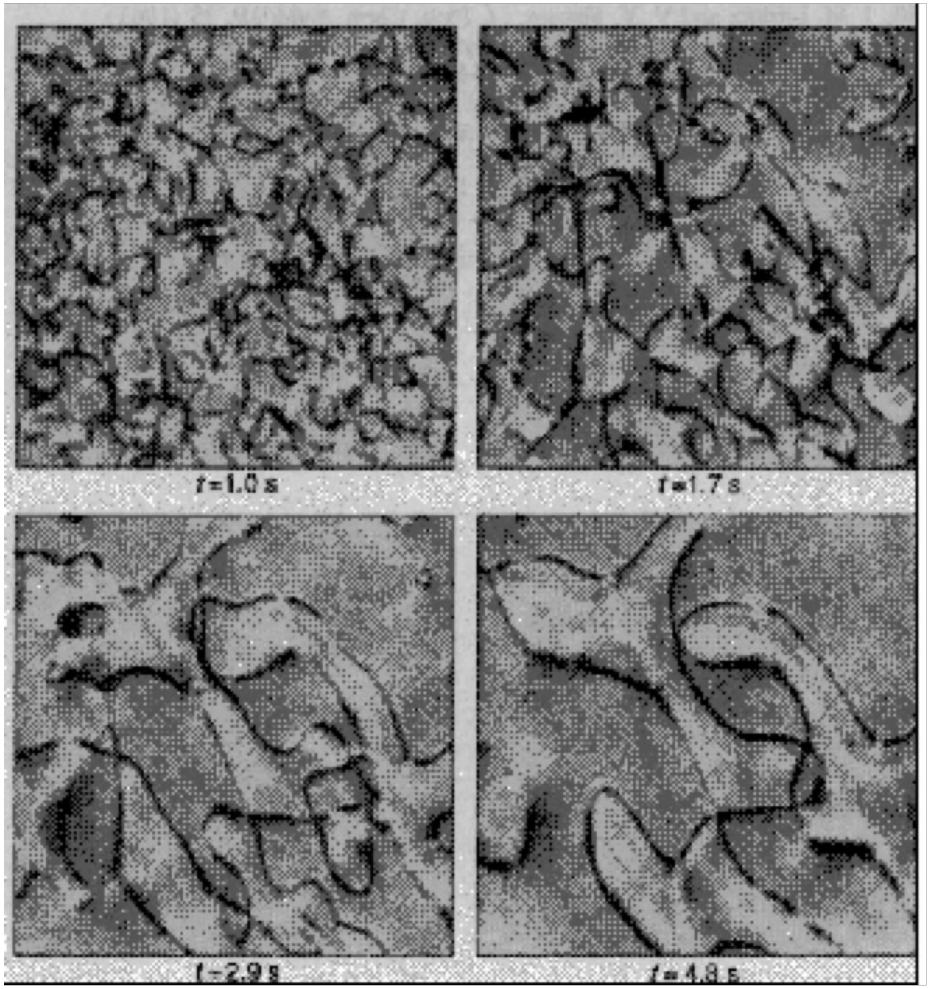

V
Im(phi)
Re(phi)

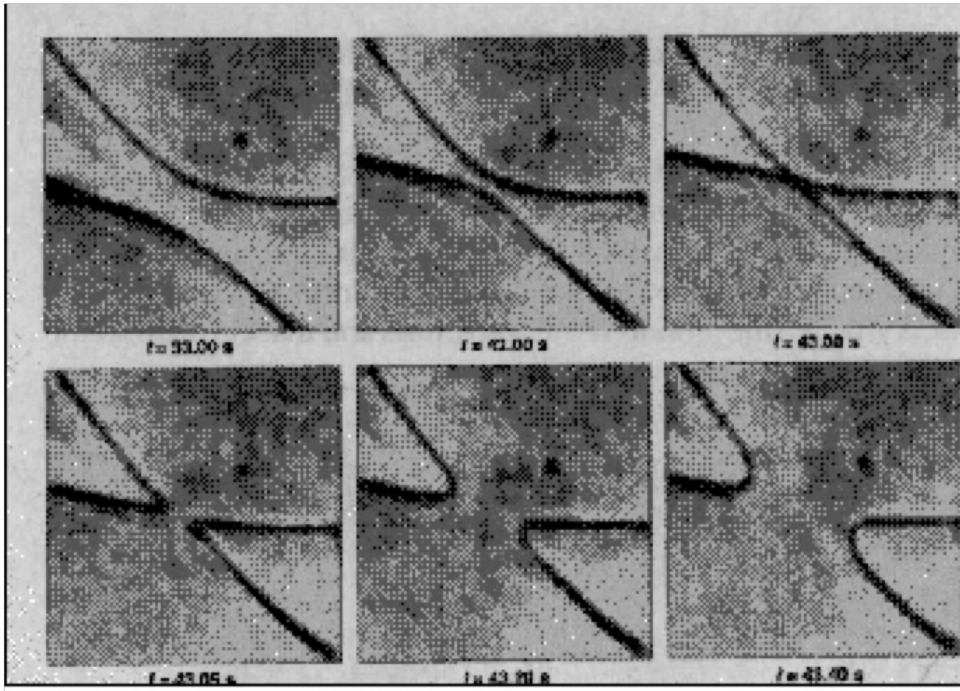

V
Im(phi)
Re(phi)

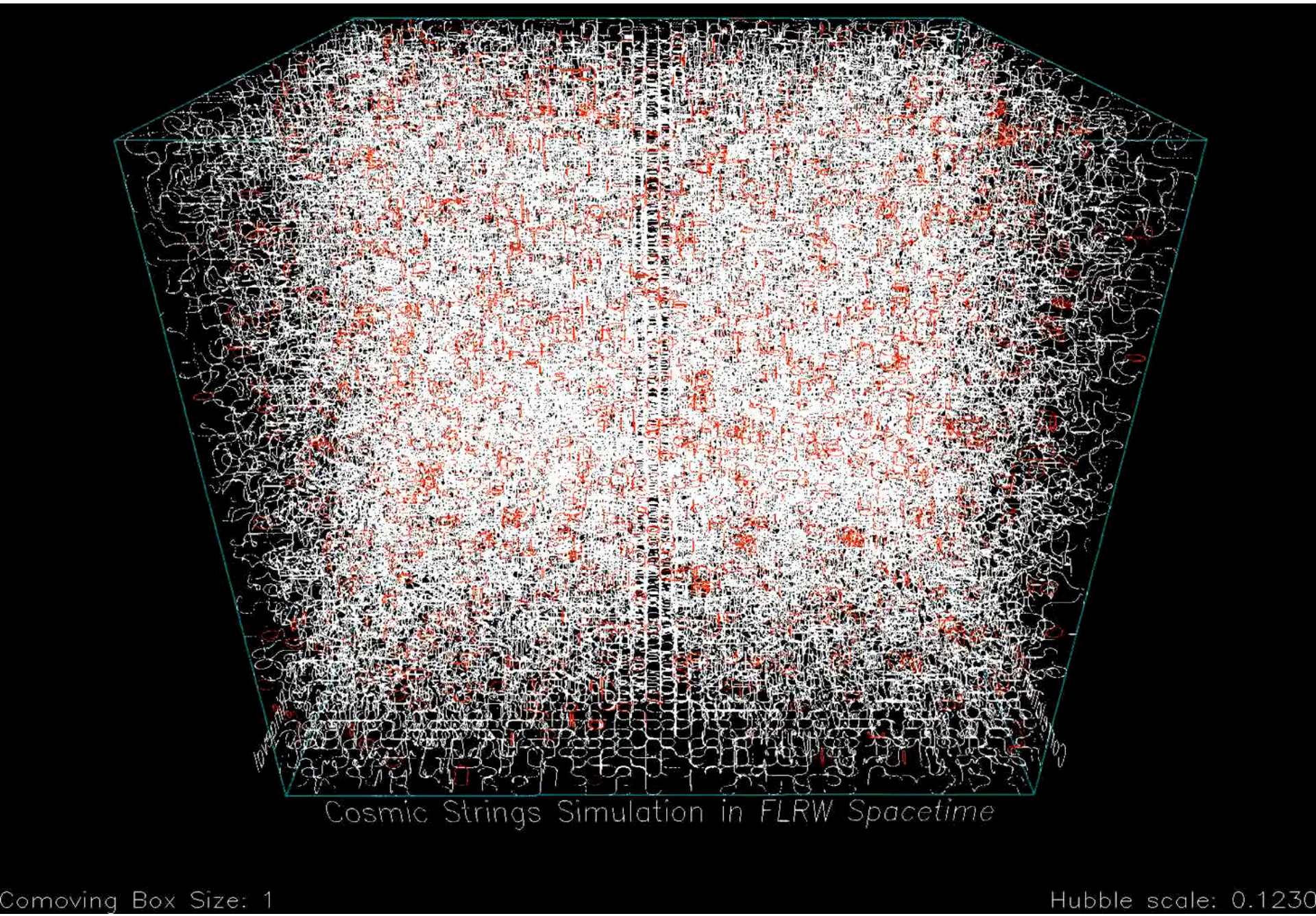

V
Im(phi)
Re(phi)

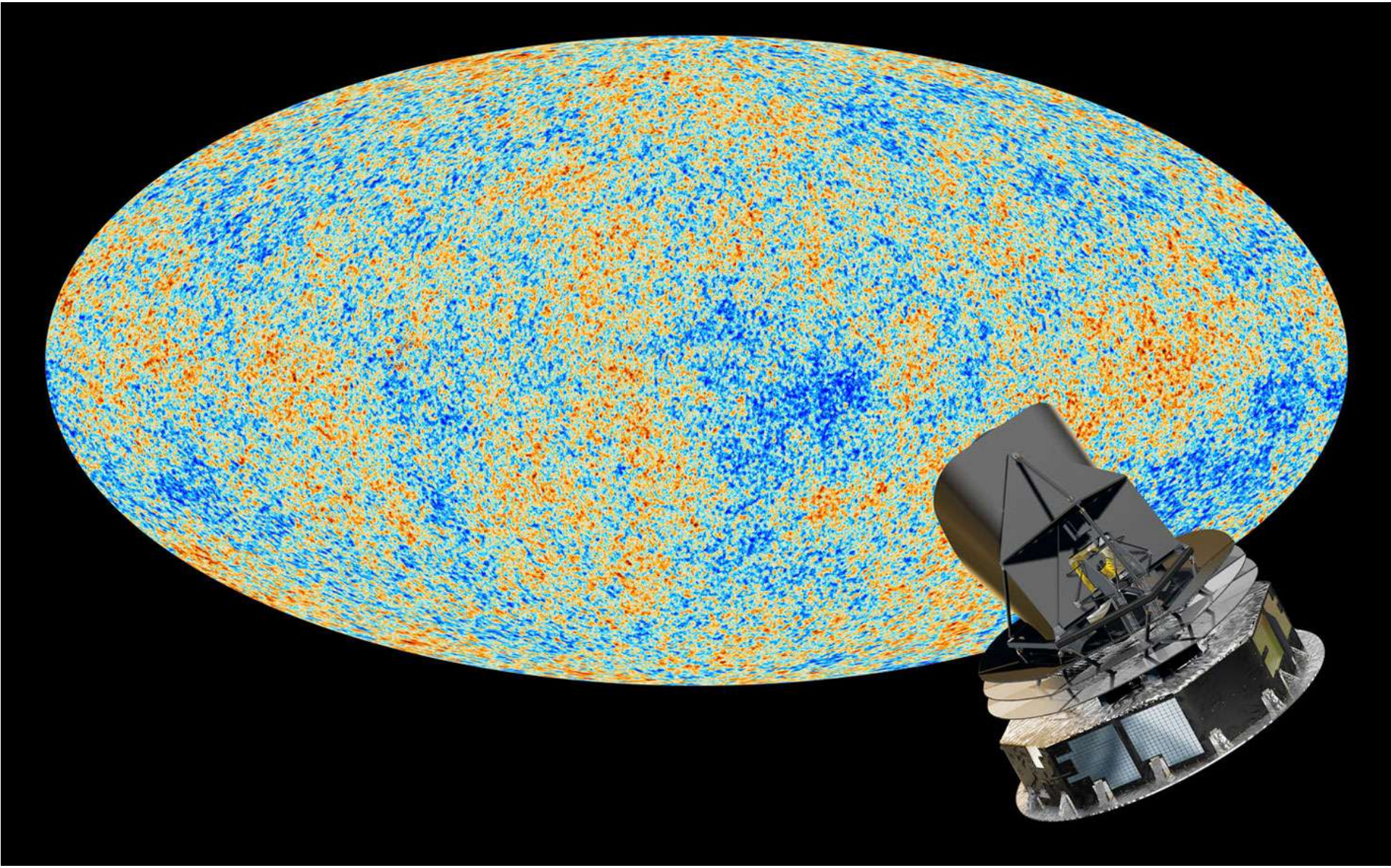

V
Im(phi)
Re(phi)

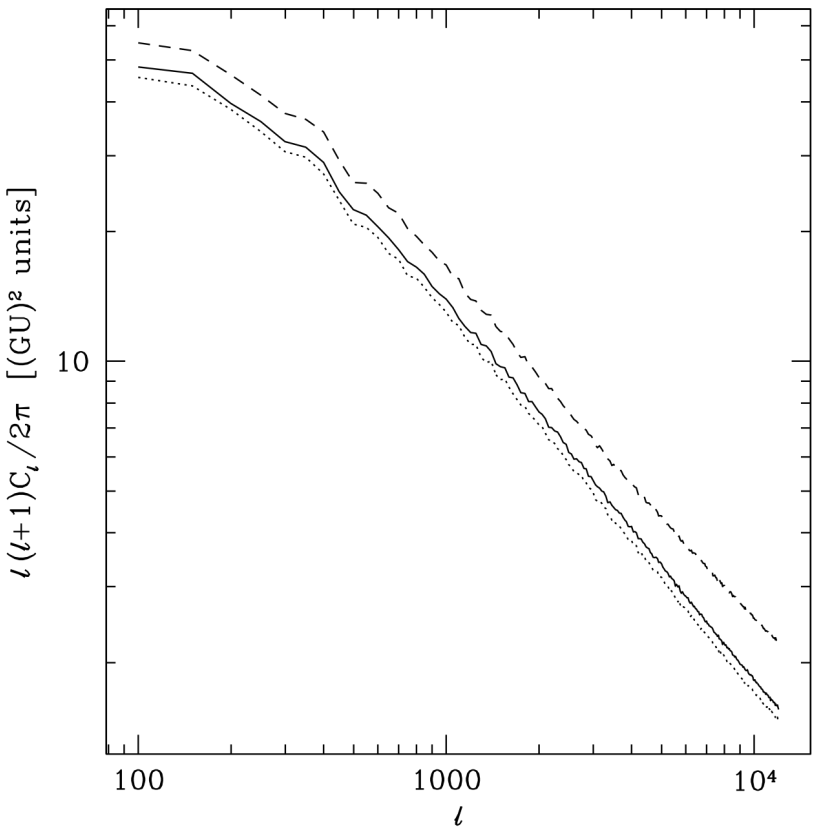

V
Im(phi)
Re(phi)

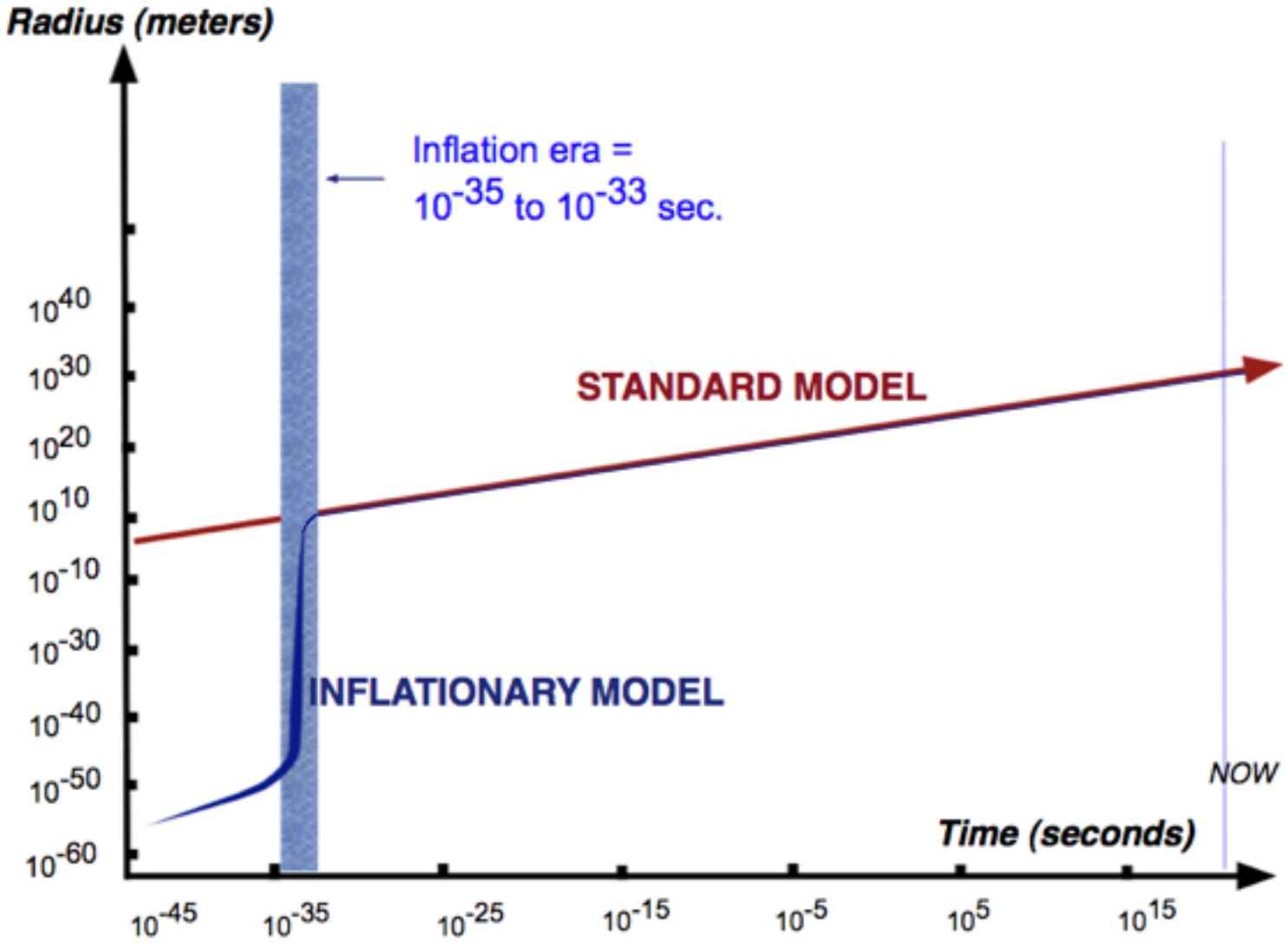

t=1.0 s
t=1.7 s
t=2.9 s
t=4.8 s




Cosmic Strings Simulation in FLRW Spacetime
Comoving Box Size: 1
Hubble scale: 0.1230

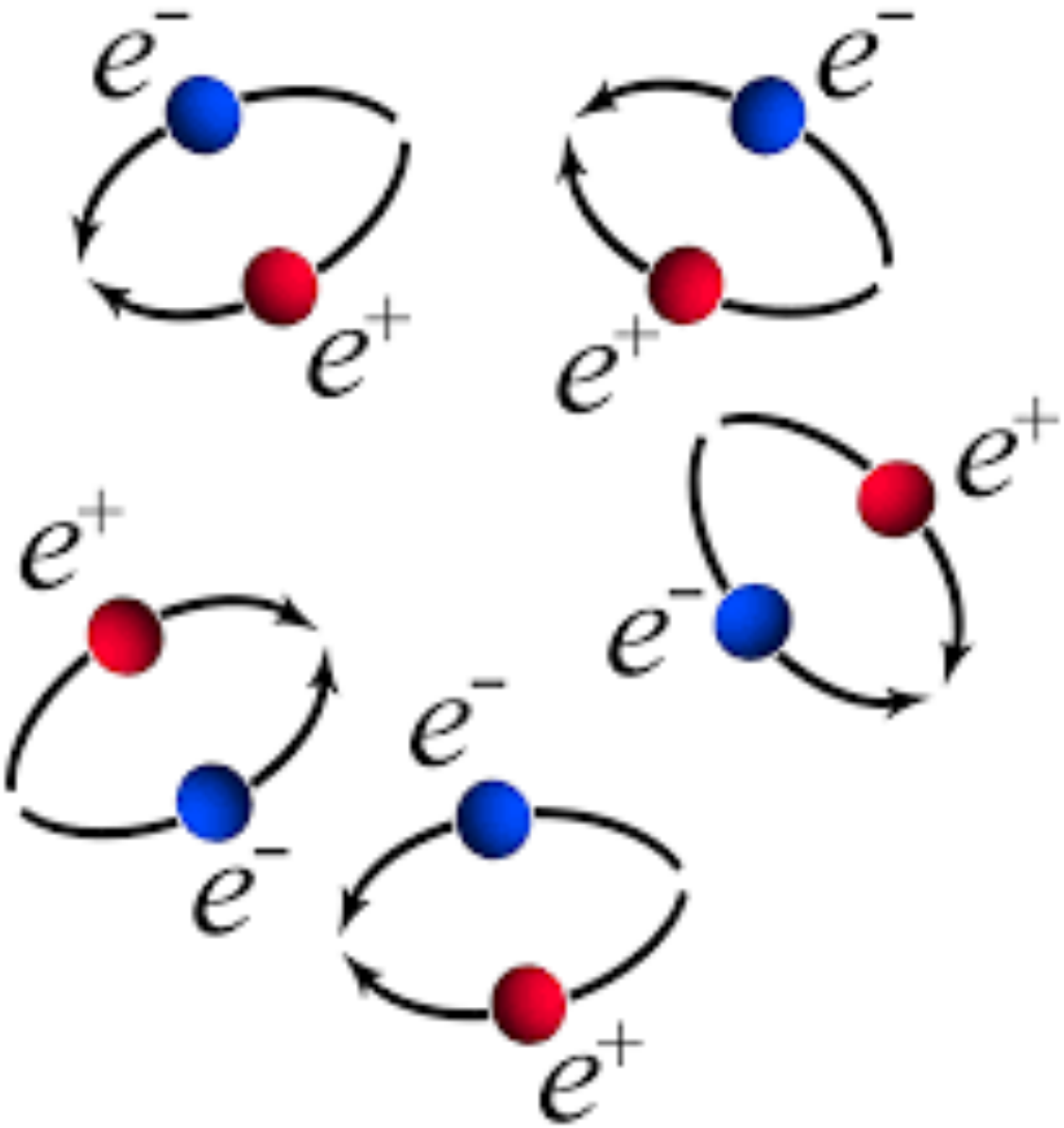



$l(l+1)C_l/2\pi$ [(GU)² units]
10
100
1000
10^4
l

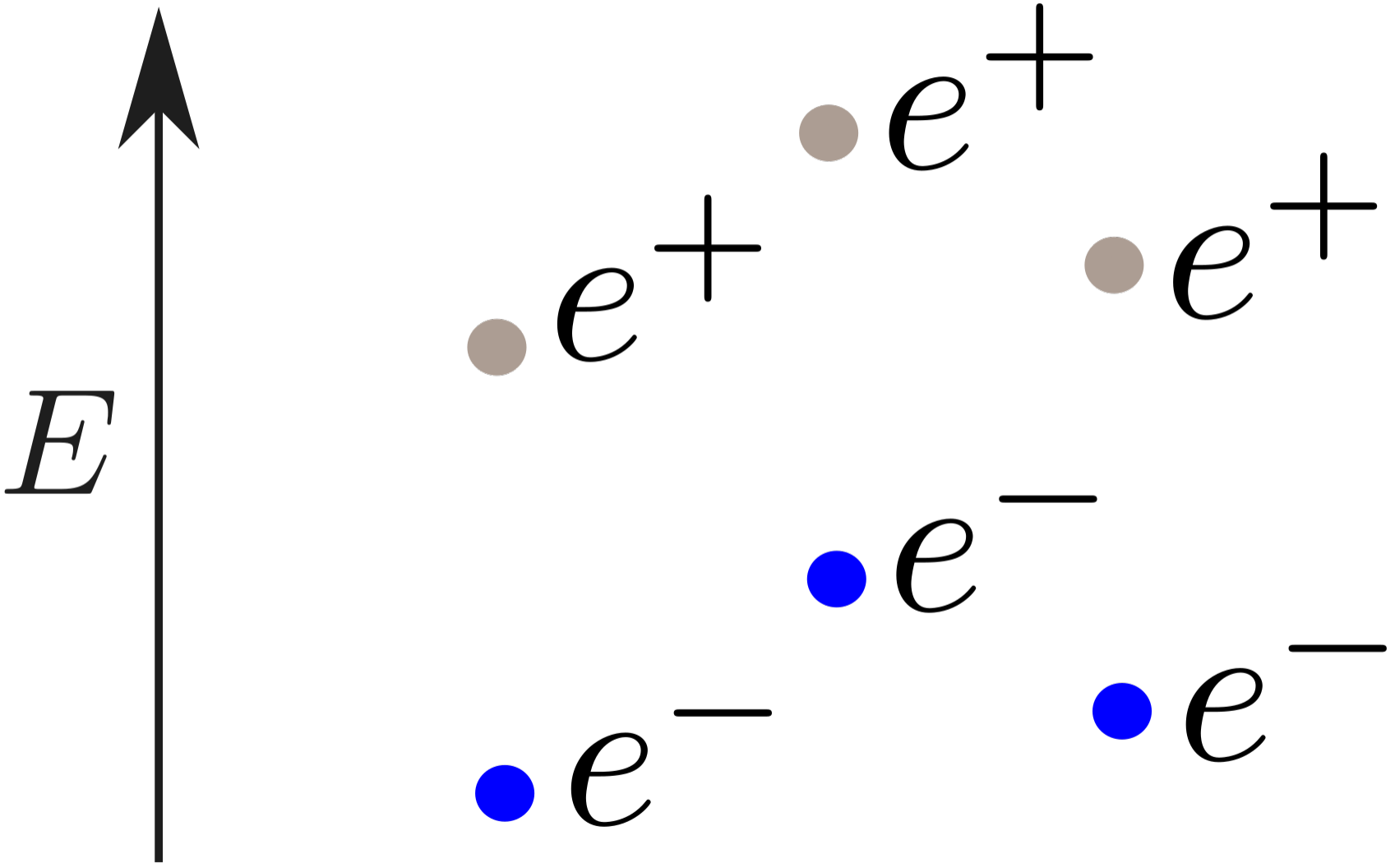


EXPANSION OF THE OBSERVABLE UNIVERSE

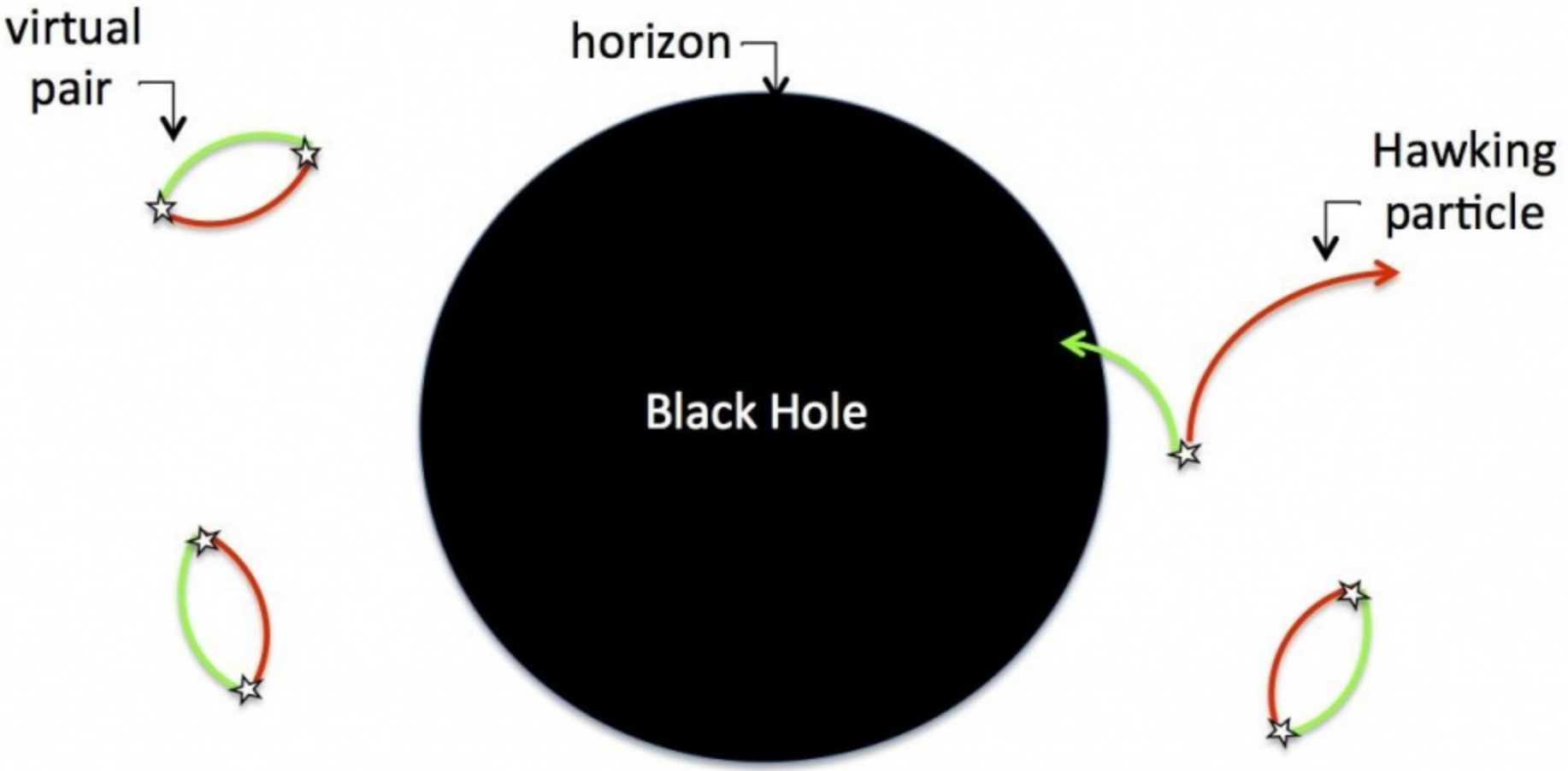
structure du vide quantique relativiste

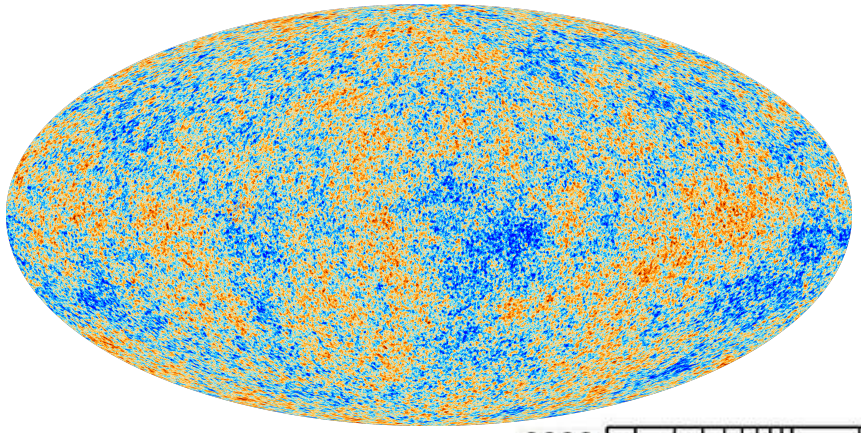


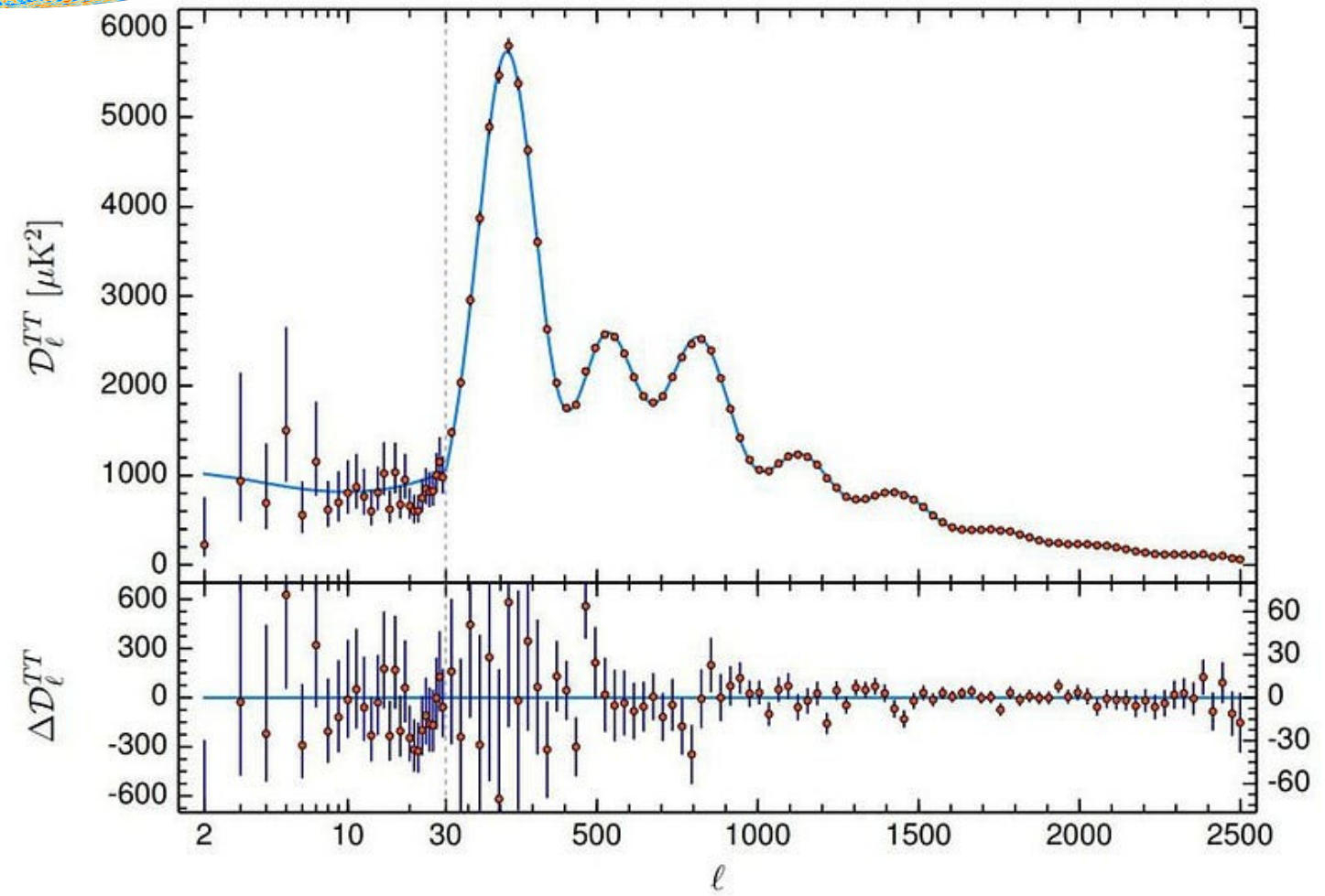
Effet Schwinger

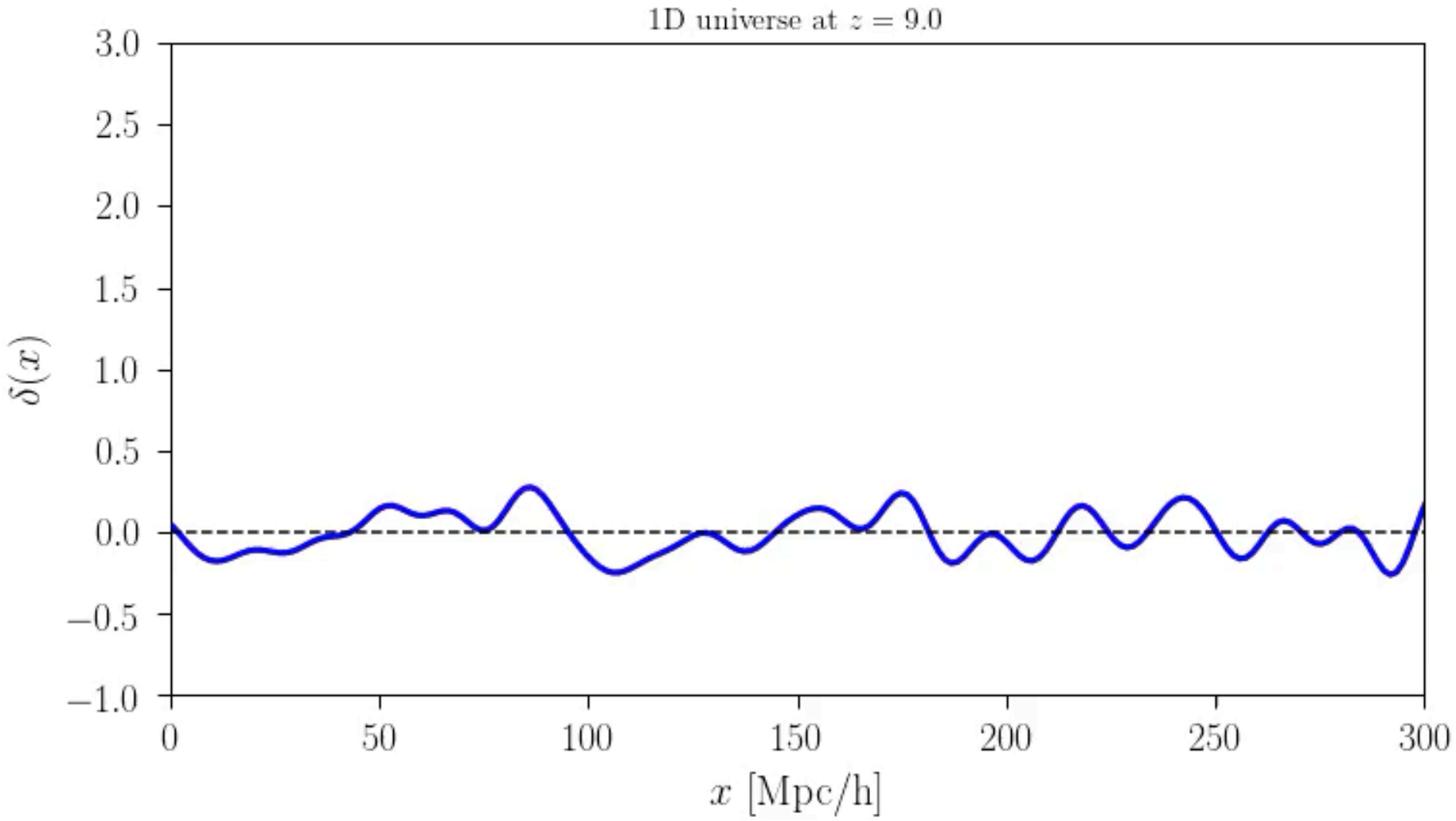


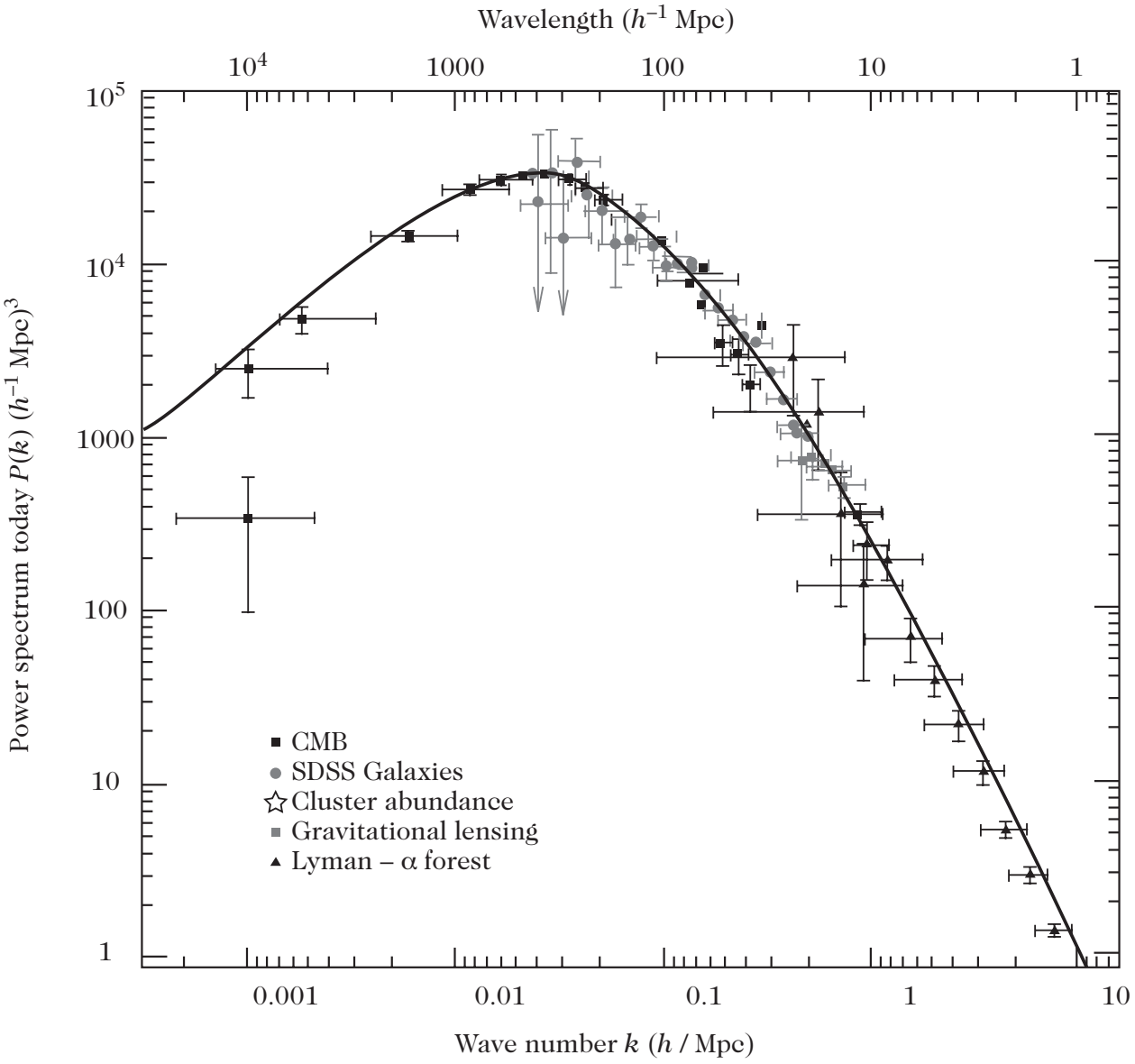
Rayonnement de Hawking



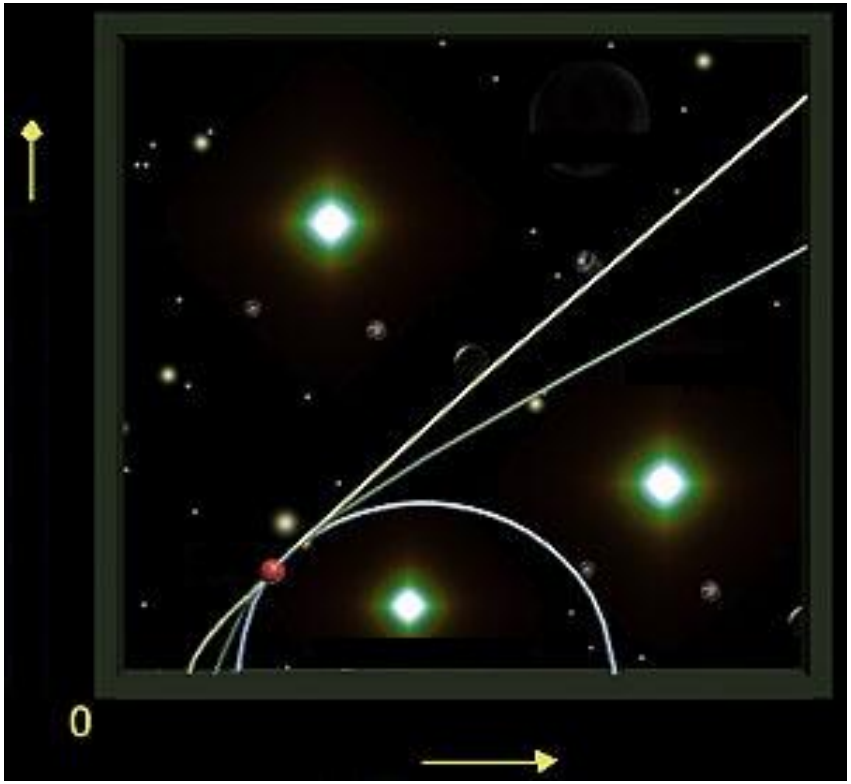


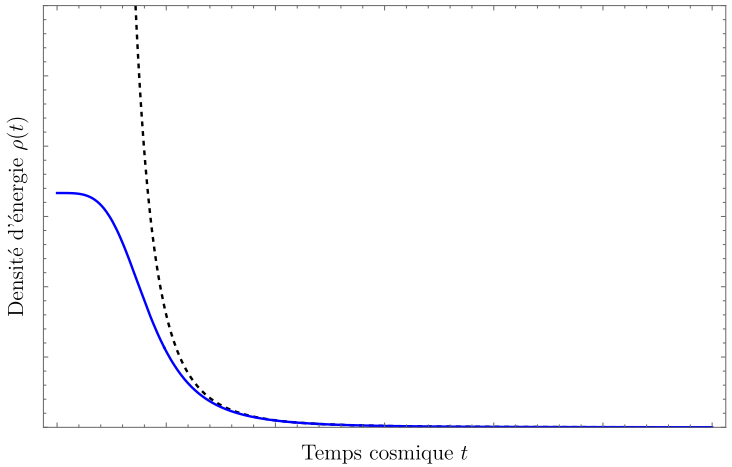

6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

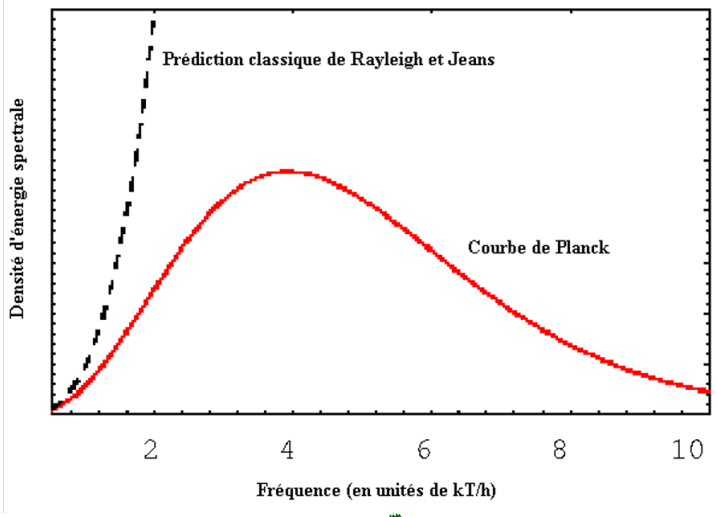

1D universe at $z = 9.0$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
$\delta(x)$
0
50
100
150
200
250
300
x [Mpc/h]

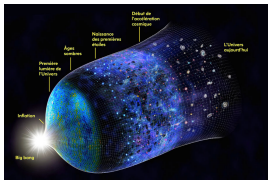

Wavelength (h^{-1} Mpc)
10^4
1000
100
10
1
10^5
10^4
1000
100
10
1
Power spectrum today $P(k)$ $(h^{-1}\,\mathrm{Mpc})^3$
CMB
SDSS Galaxies
Cluster abundance
Gravitational lensing
Lyman – α forest
0.001
0.01
0.1
1
10
Wave number k (h / Mpc)

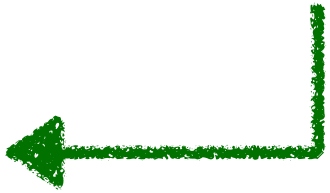
Problème de la singularité



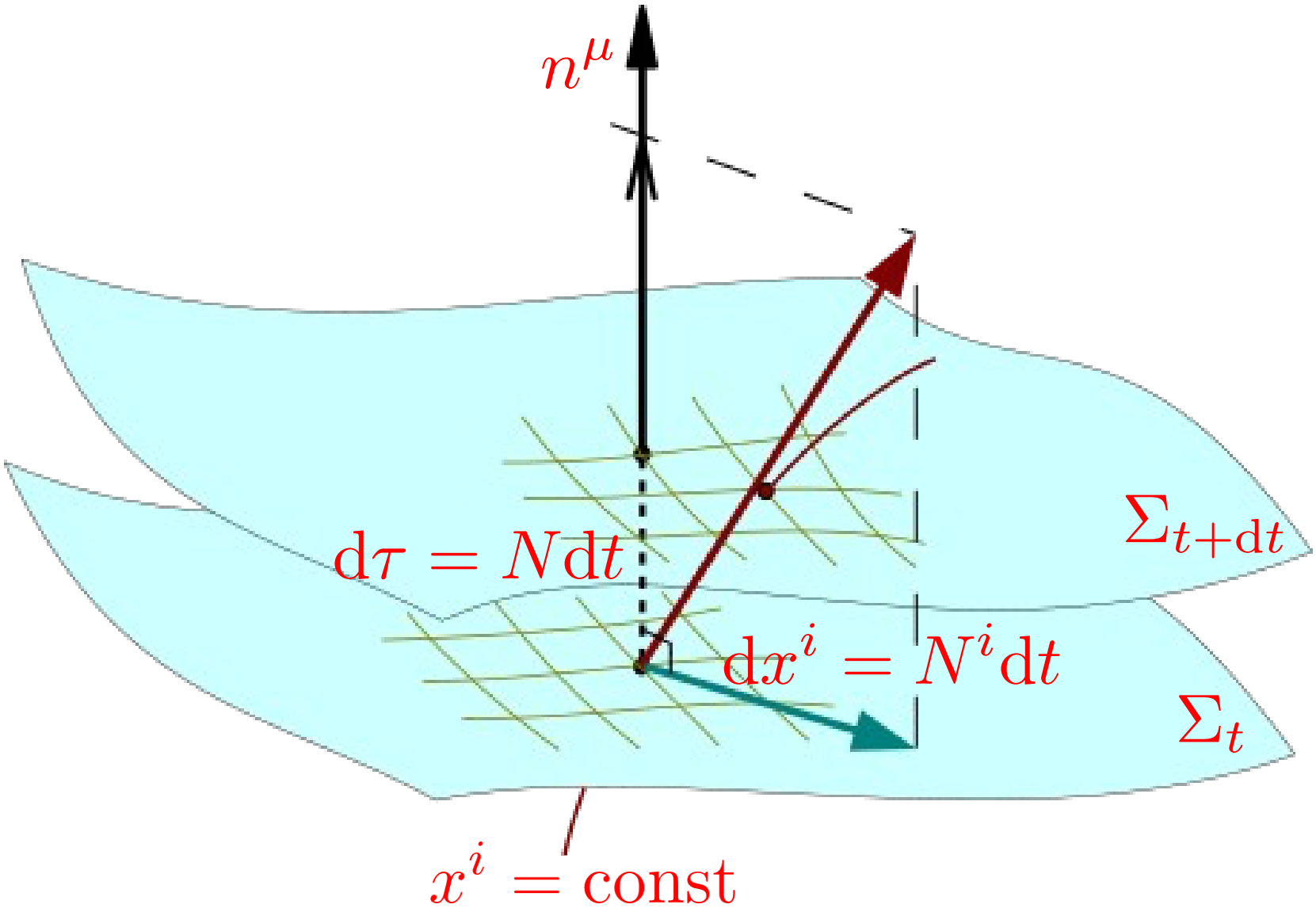




$$|\xi\rangle = |$$  $$\rangle$$



espace-temps d'Einstein $3 + 1 = 4$



Prédictions d'une théorie quantique

valeur moyenne quantique d'une « observable »

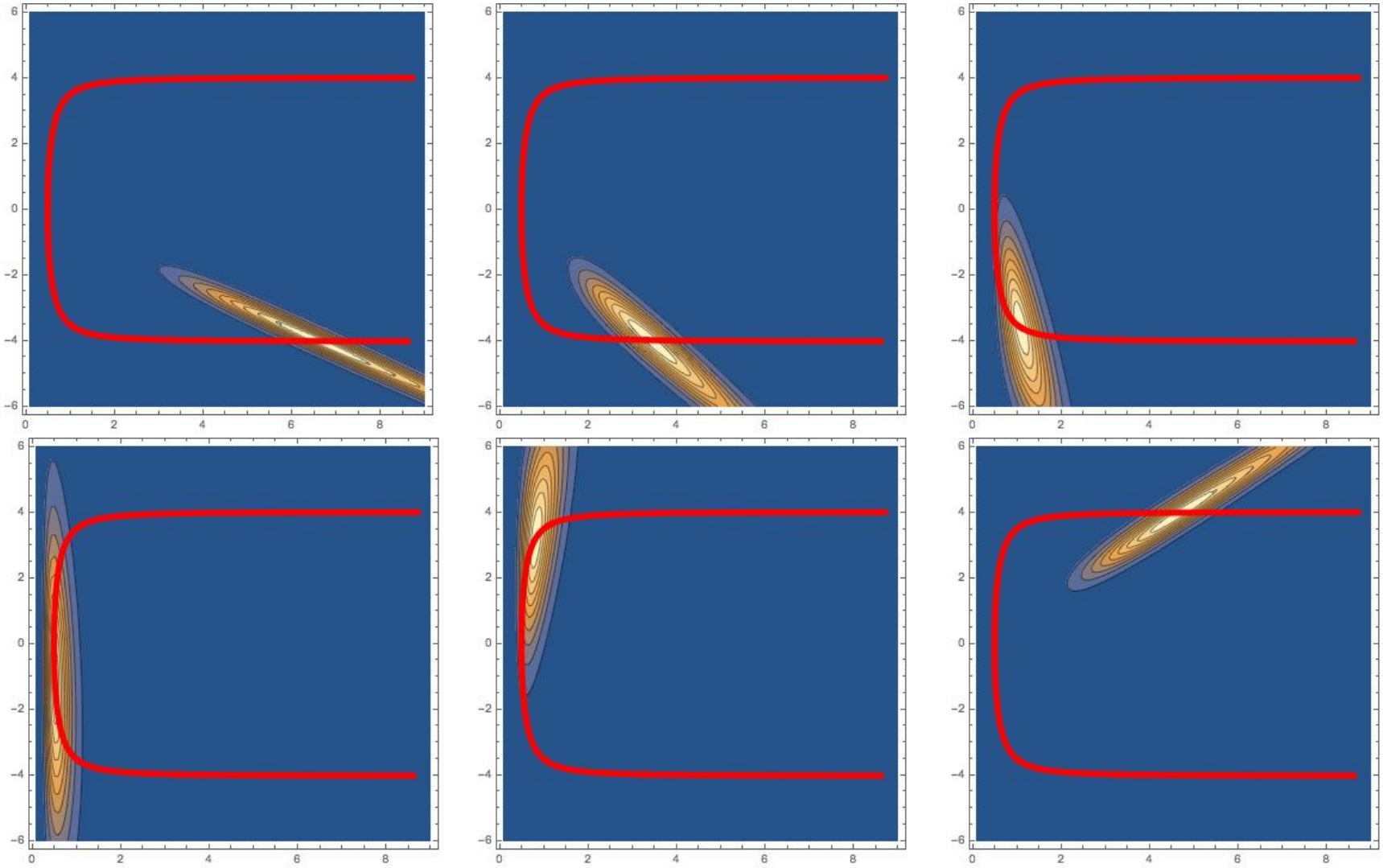
$$\langle \xi | \hat{\mathcal{O}} | \xi \rangle$$

labo :
expérience répétée

moyenne d'ensemble ⟺ moyenne quantique

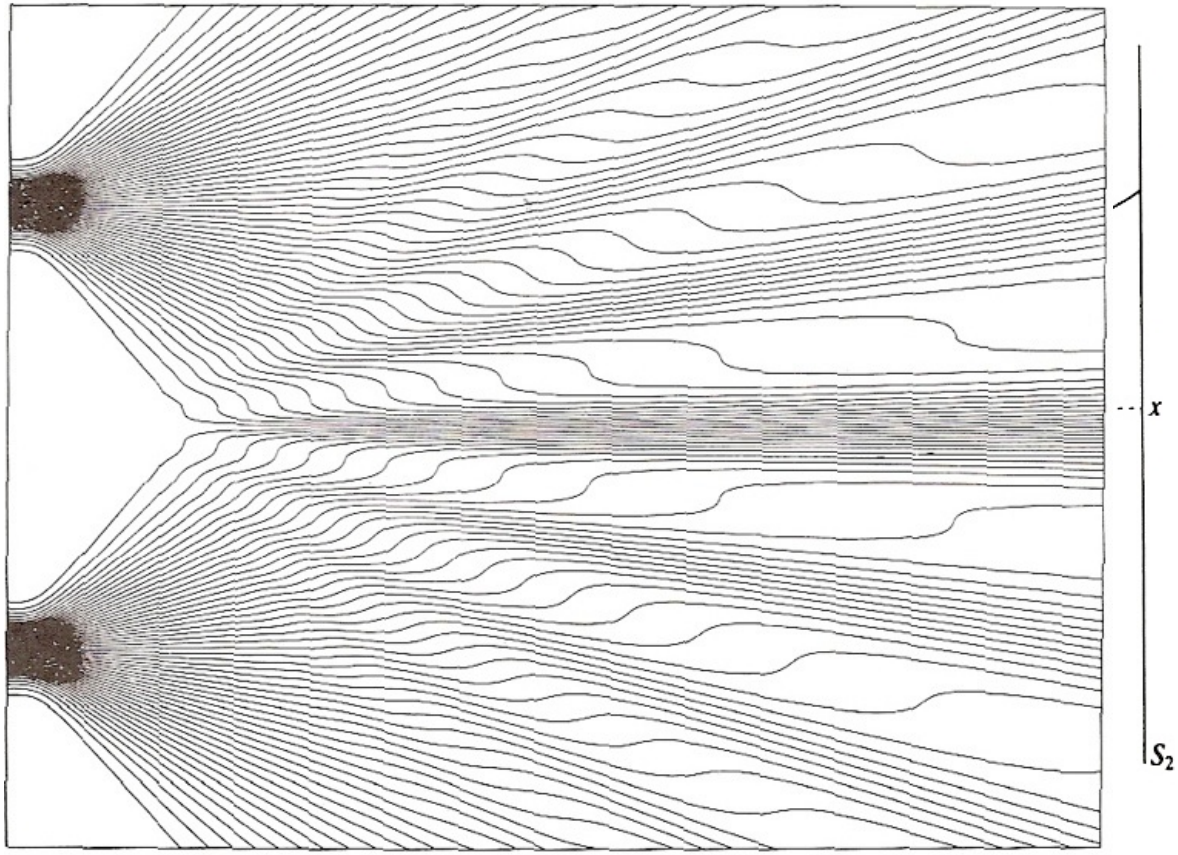


Solutions « exactes »



2024

Trajectoires quantiques

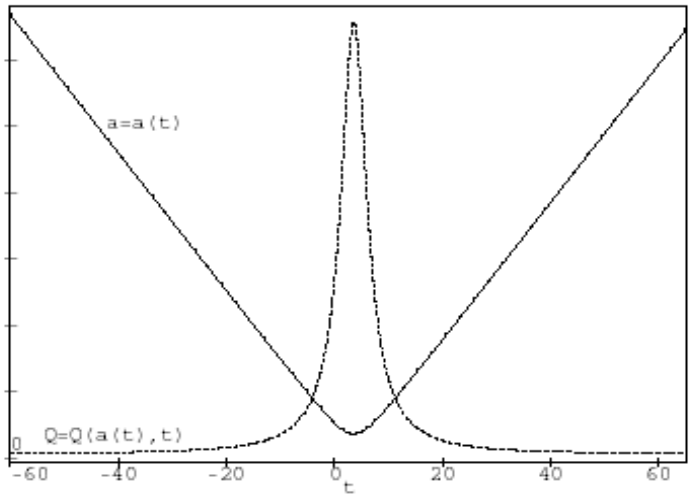


$$m\frac{\mathrm{d}^2x(t)}{\mathrm{d}t^2} = -\nabla\left(V+Q\right)$$

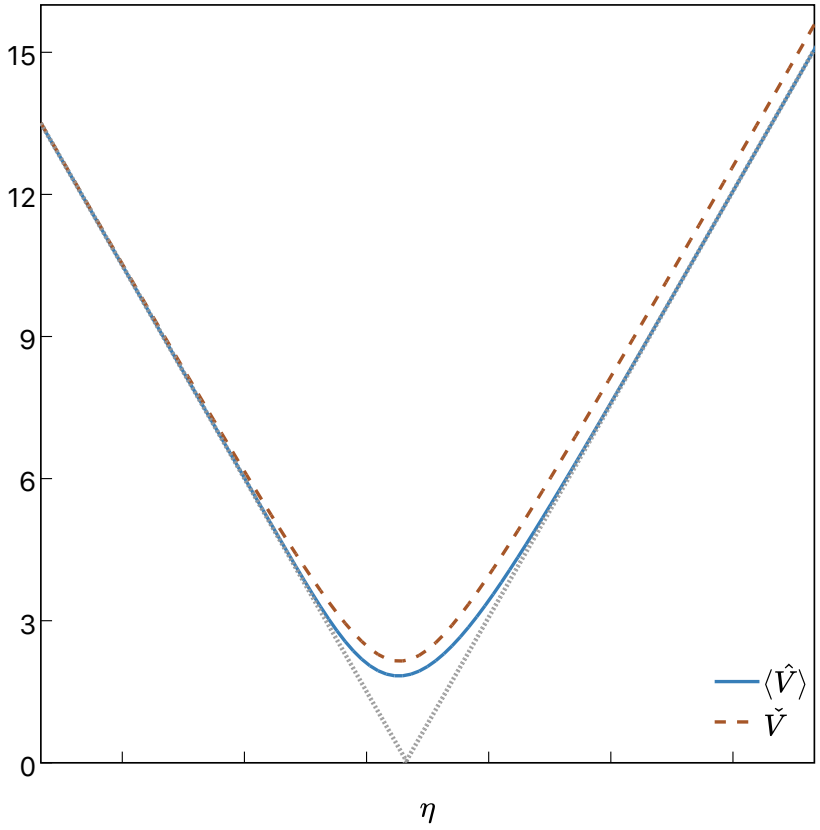
configurations (états possibles) :

$|\xi\rangle =$ *géométrie de l'espace*

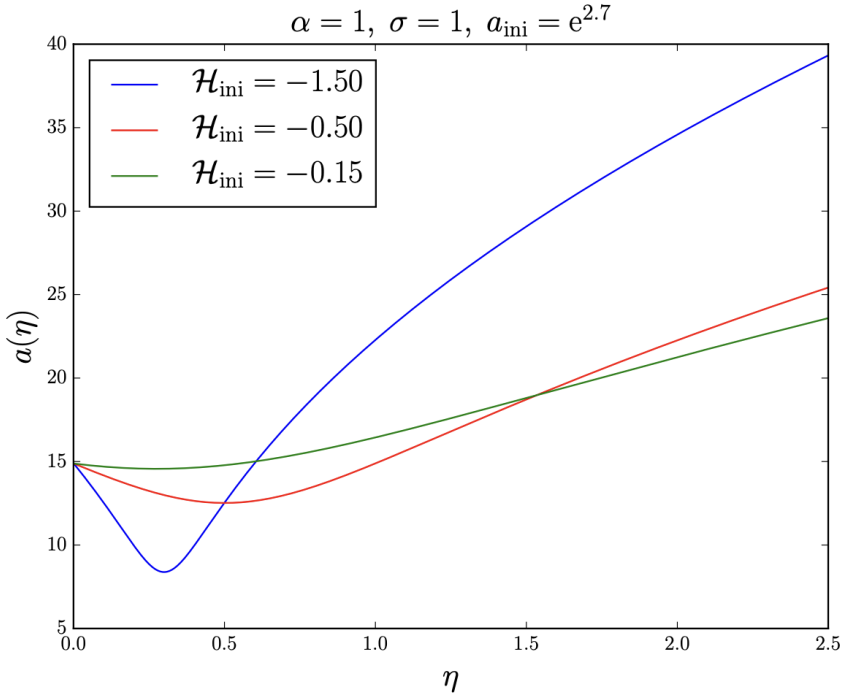
une solution au problème de la singularité ?

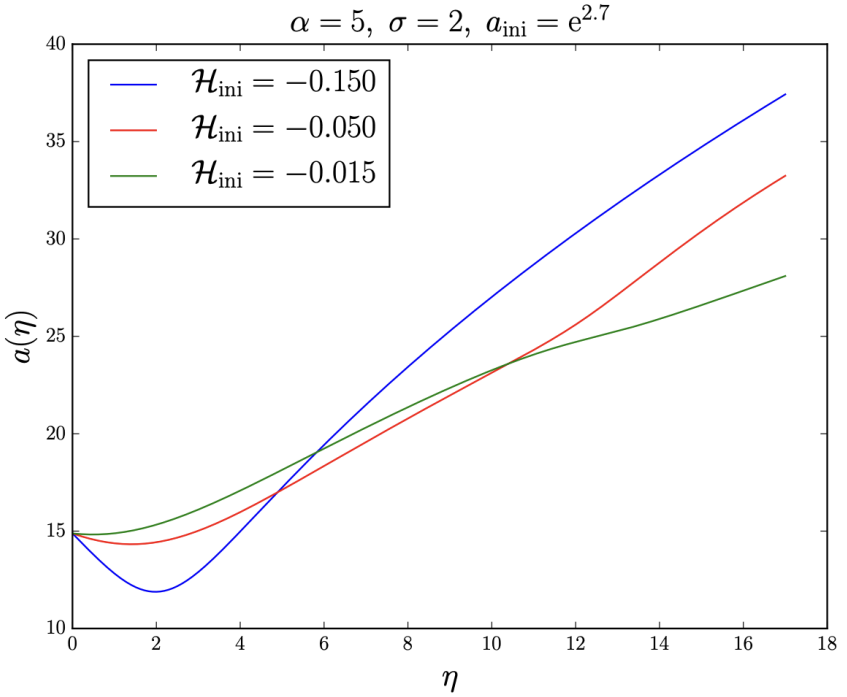


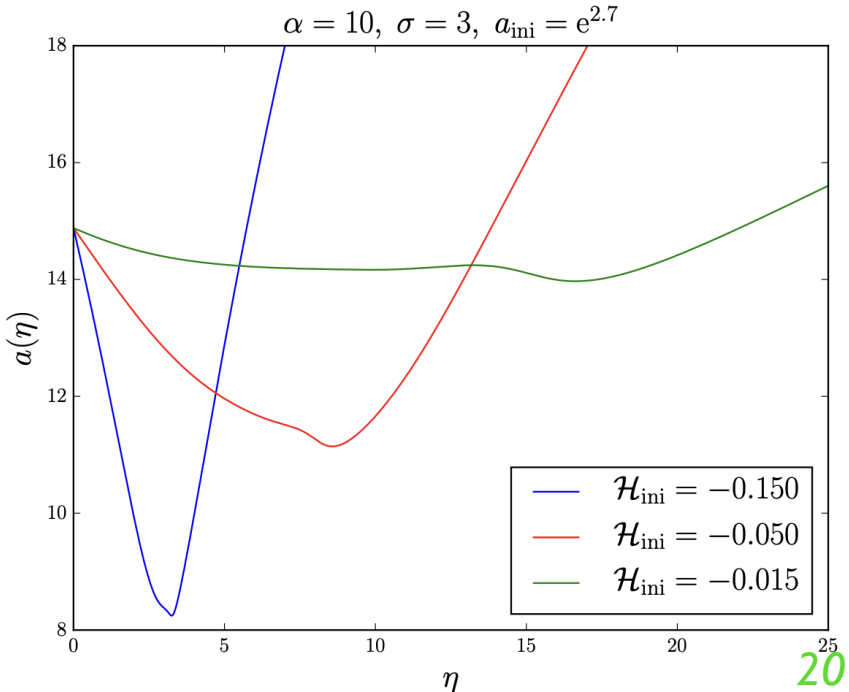
1997

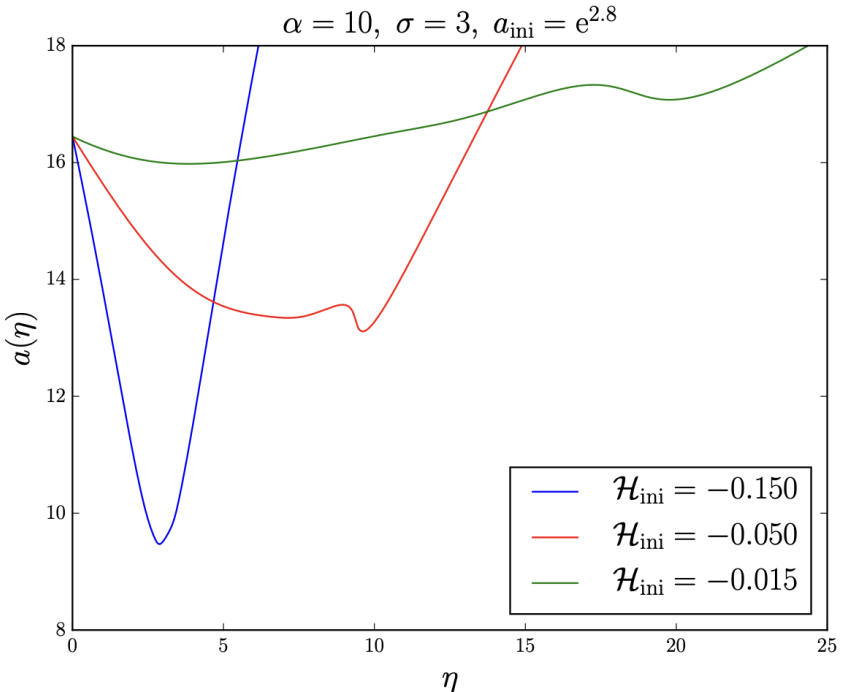


2020


$\alpha = 1,\ \sigma = 1,\ a_{\rm ini} = {\rm e}^{2.7}$
$\mathcal{H}_{\rm ini} = -1.50$
$\mathcal{H}_{\rm ini} = -0.50$
$\mathcal{H}_{\rm ini} = -0.15$
$a(\eta)$
η


$\alpha = 5,\ \sigma = 2,\ a_{\rm ini} = {\rm e}^{2.7}$
$\mathcal{H}_{\rm ini} = -0.150$
$\mathcal{H}_{\rm ini} = -0.050$
$\mathcal{H}_{\rm ini} = -0.015$
$a(\eta)$
η


$\alpha = 10,\ \sigma = 3,\ a_{\rm ini} = {\rm e}^{2.7}$
$\mathcal{H}_{\rm ini} = -0.150$
$\mathcal{H}_{\rm ini} = -0.050$
$\mathcal{H}_{\rm ini} = -0.015$
$a(\eta)$
η


$\alpha = 10,\ \sigma = 3,\ a_{\rm ini} = {\rm e}^{2.8}$
$\mathcal{H}_{\rm ini} = -0.150$
$\mathcal{H}_{\rm ini} = -0.050$
$\mathcal{H}_{\rm ini} = -0.015$
$a(\eta)$
η

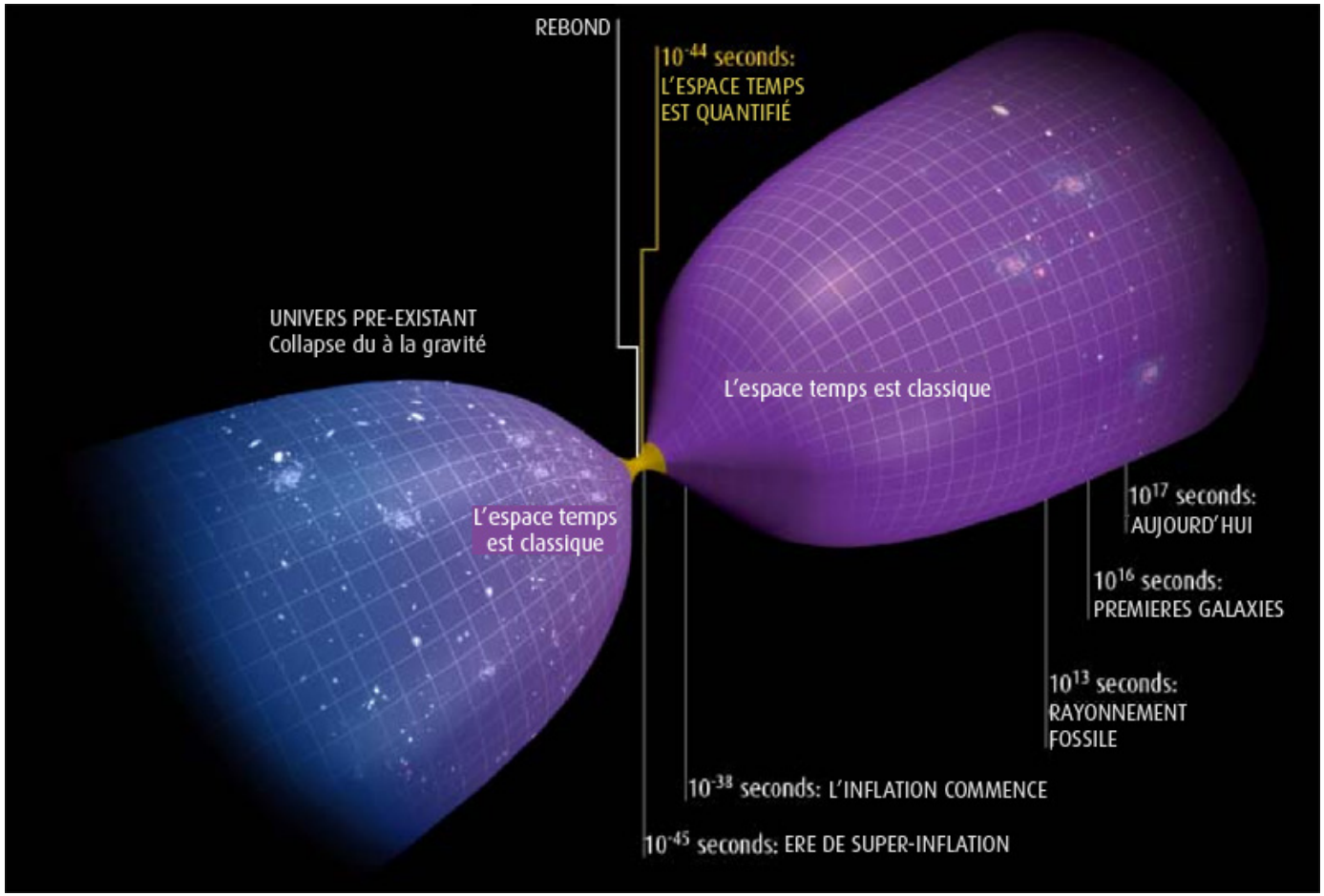
2016

configurations (états possibles) :

$|\xi\rangle =$ *géométrie de l'espace*

une solution au problème de la singularité

rebond primordial - cosmologie quantique

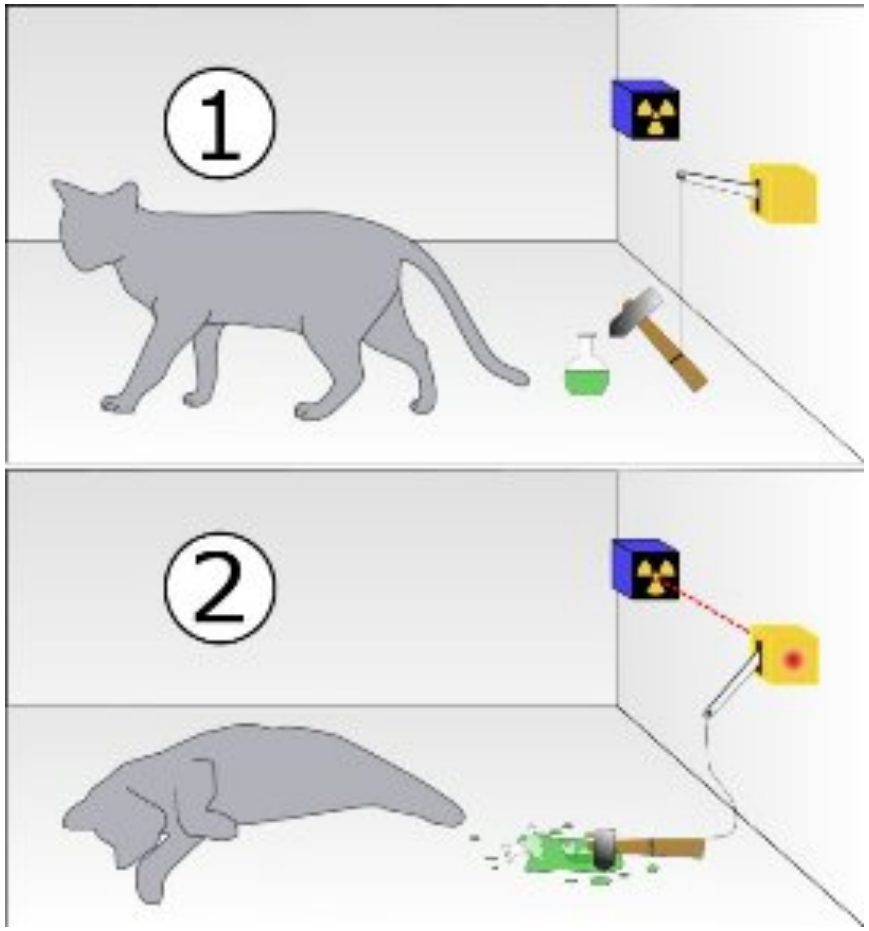


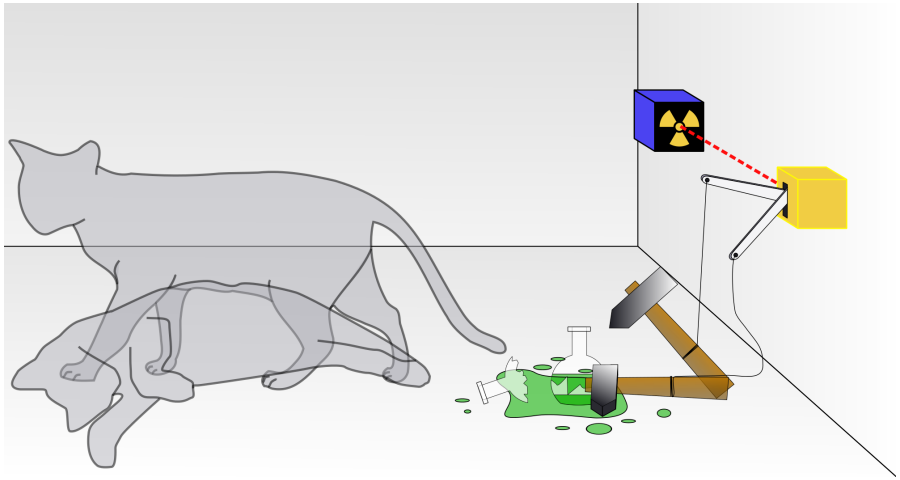
Autre option = *autre géométrie de l'espace temps*



principe de superposition :

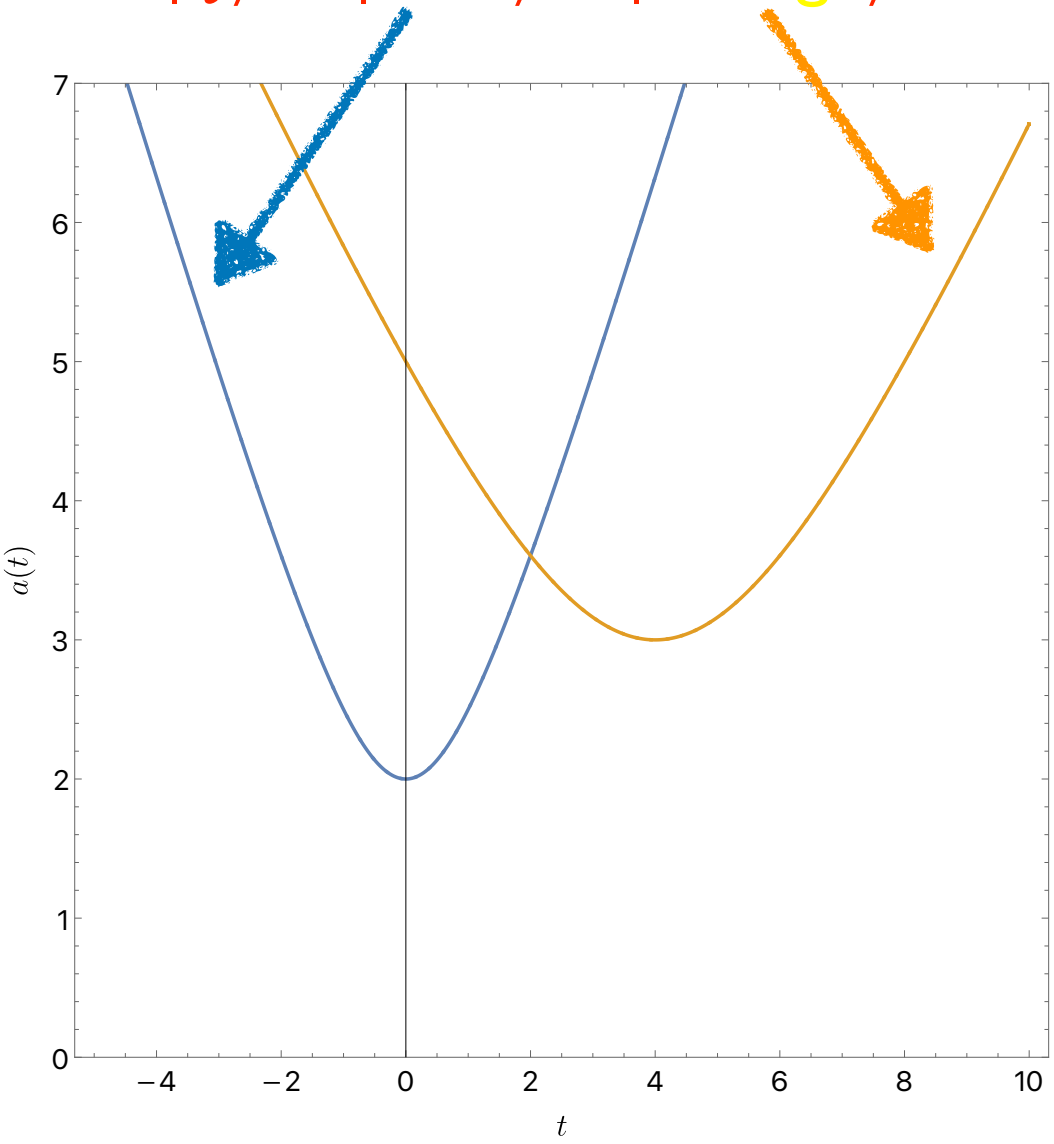
le chat de Schrödinger…



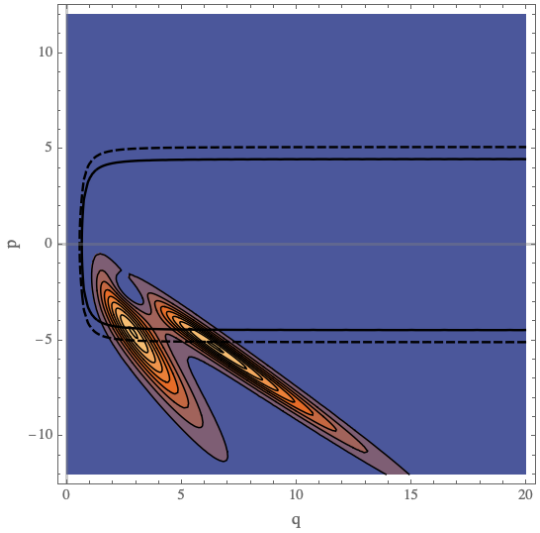


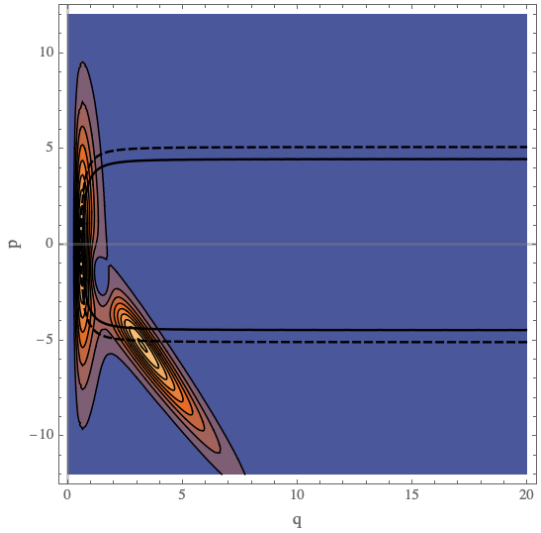
superposition cosmologique ?

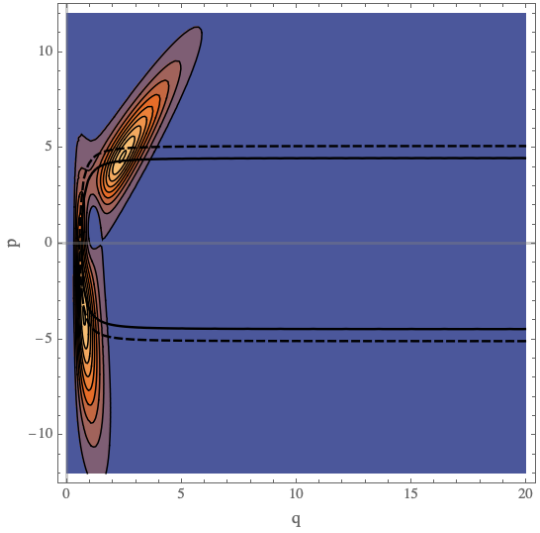
$|\xi\rangle = |\text{bleu}\rangle + |\text{orange}\rangle + \cdots$

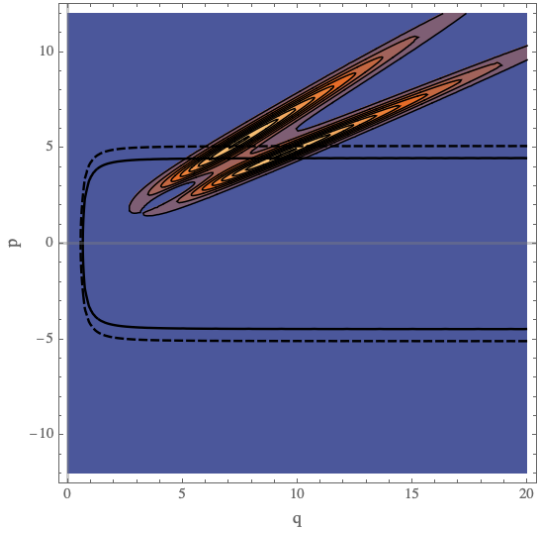


Interférences entre deux univers !

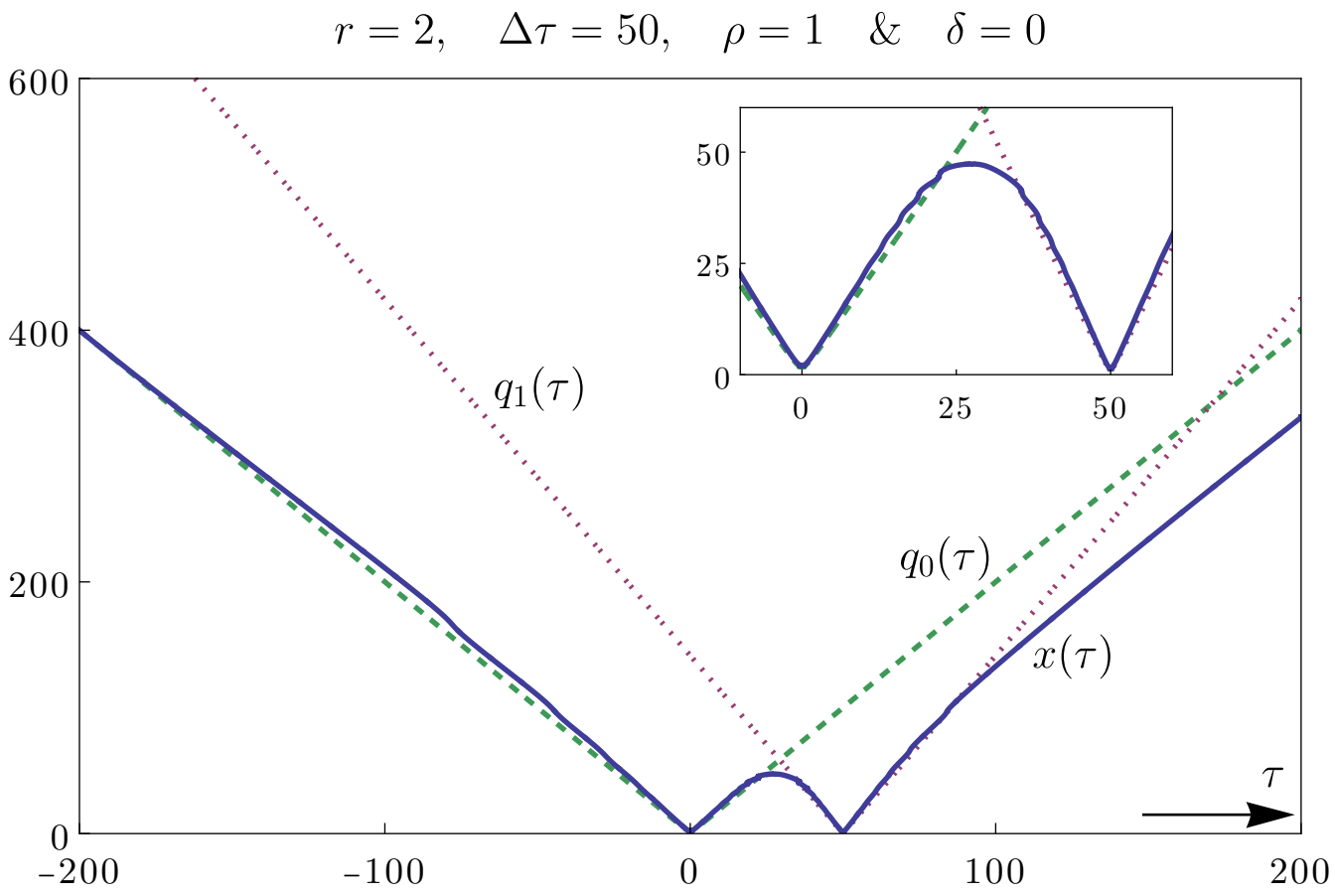






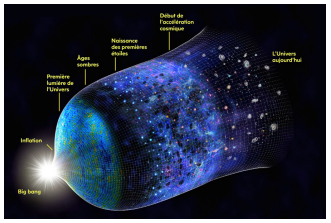
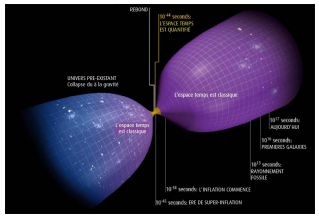


2024


$r = 2, \quad \Delta\tau = 50, \quad \rho = 1 \quad \& \quad \delta = 0$
600
400
200
0
−200
−100
0
100
200
$q_1(\tau)$
$q_0(\tau)$
$x(\tau)$
τ
50
25
0
0
25
50

principe de superposition :

avec des univers ?

$$|\xi\rangle = |$$  $$\rangle + |$$  $$\rangle$$

$$+ |$$  $$\rangle + \cdots$$

conséquences ???

