A CARDY FORMULA FOR OFF-DIAGONAL 3-PT COEFFICIENTS;

or,

HOW THE GEOMETRY BEHIND THE HORIZON GETS DISENTANGLED

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with Philippe Sabella Garnier & Koenraad Schalm

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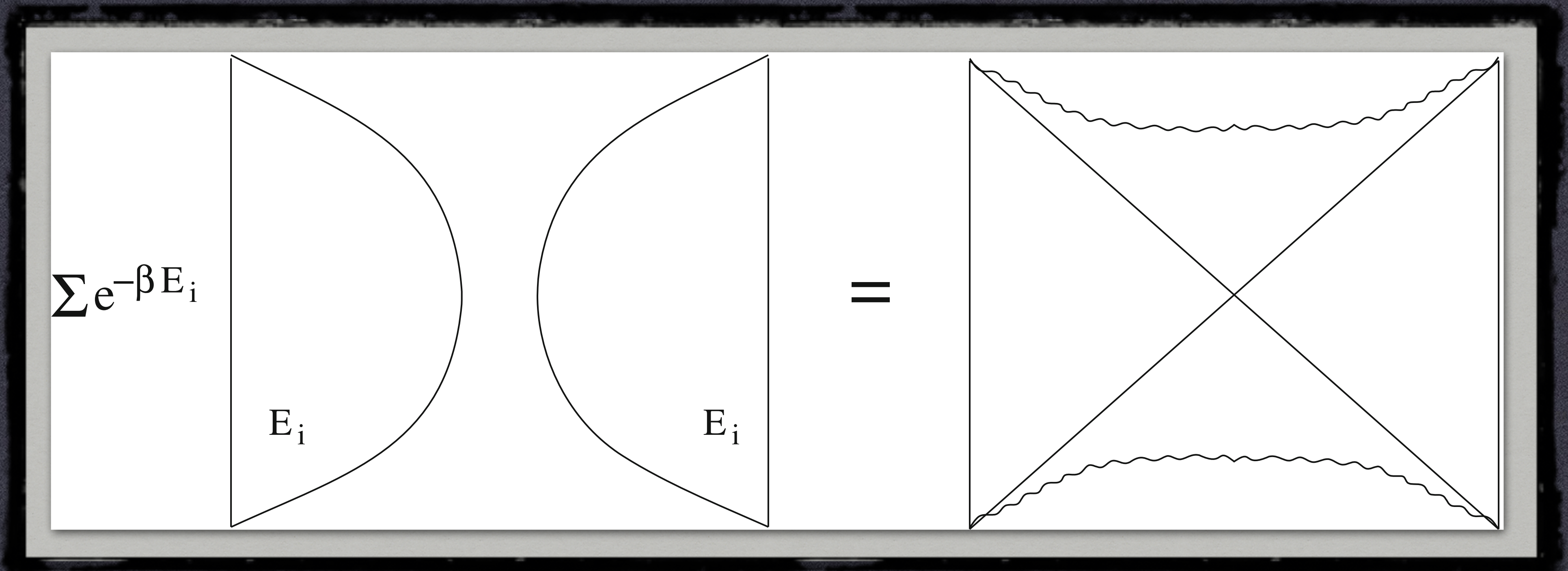
INTRO I: TFD AND GEOMETRY

$$\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$$

$$|\Psi(\beta)\rangle = \sum_i e^{-\frac{\beta E_i}{2}} |E_i\rangle \otimes |E_i\rangle$$

Quant. superpos. of disconnected spacetimes $\longleftrightarrow$ Eternal BH



$$\mathrm{Tr}_2(|\Psi(\beta)\rangle\langle\Psi(\beta)|) = \rho_T(\beta)$$

One-sided observer sees Schwarzschild BH

Many authors to be cited

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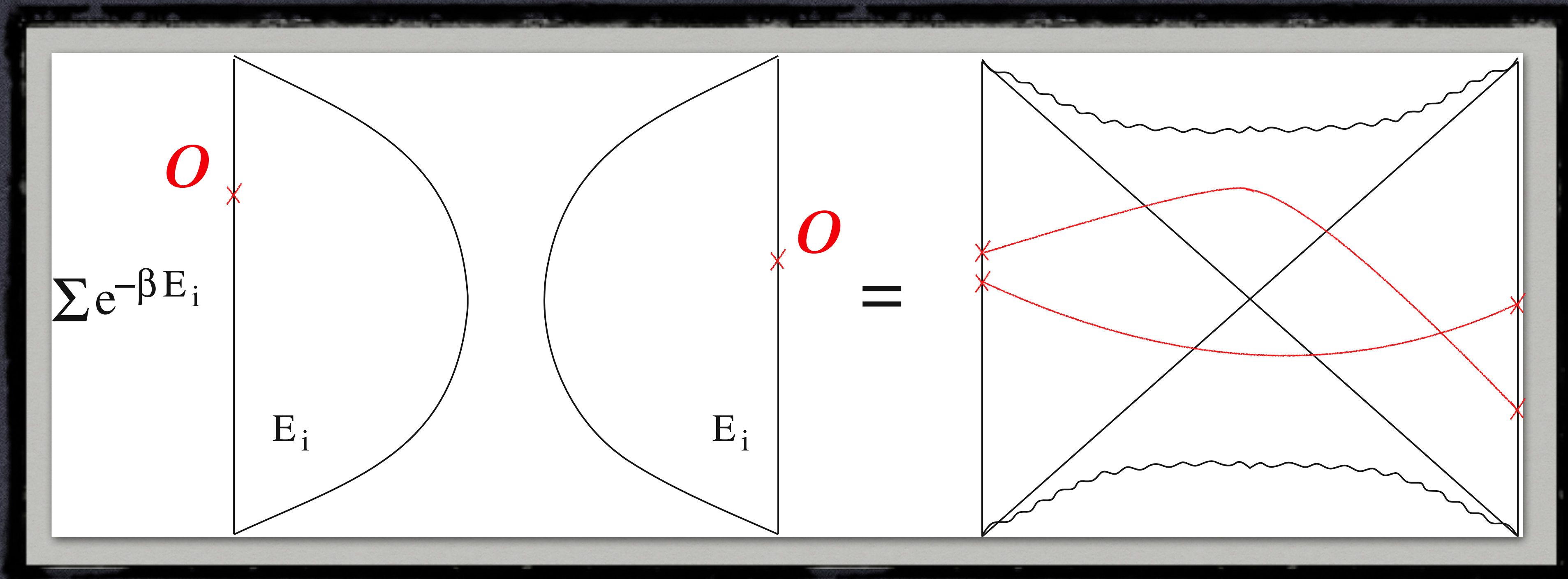

Festuccia, Liu '09

$$G^L(t_{12}, \phi_{12}) = \frac{1}{Z(\beta)} \sum_{ab} e^{-\beta\frac{E_a+E_b}{2}} e^{-it_{12}E_{ab}} |\langle a|O|b\rangle|^2$$

INTRO II: CONF. BLOCKS & THEIR DUAL INTERPRETATION

- Conformal blocks in CFTs $\longleftrightarrow$ Exchange of primaries & gravitons

  Witten diagrams

Fitzpatrick, Kaplan, Walters '14

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- Average (coarse-graining) of OPEs:

$$\overline{\langle E|O|E\rangle} \equiv \frac{\sum_i \langle i|O|i\rangle \delta(E-E_i)}{\rho(E)}$$

$$\overline{\langle E|O|E\rangle} \sim C_{O\chi\chi}\left(E-\frac{c}{12}\right)^{E_O/2} \exp\left[-\frac{\pi c}{3}\left(1-\sqrt{1-\frac{12E_\chi}{c}}\right)\sqrt{\frac{12E}{c}-1}\right]$$

in the limit of $\beta \to 0$, $E/E_O <<1$, $E>>c$

Kraus, Maloney '16

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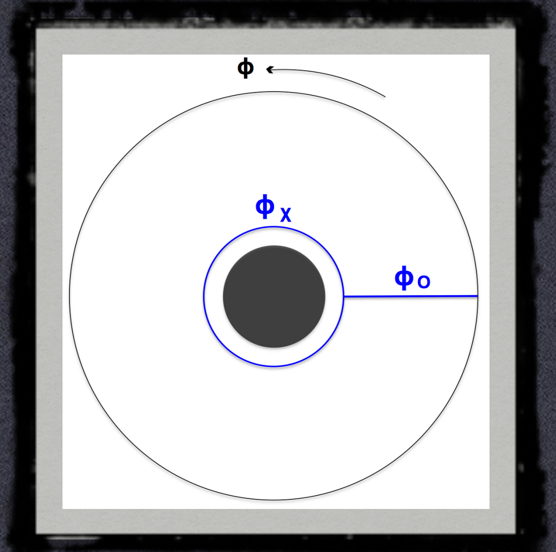
in the limit of $\beta \to 0$, $E/E_O \ll 1$, $E \gg c$



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INTRO III: ETH

$$|\psi(0)\rangle = \sum_a c_a |\Psi_a\rangle \qquad |\psi(t)\rangle = \sum_a c_a e^{-iE_a t} |\Psi_a\rangle$$

$$\langle O(t)\rangle = \langle \psi(t)|O|\psi(t)\rangle$$

$$\overline{\langle O(t)\rangle} \equiv \lim_{t\to\infty} \frac{1}{t} \int_0^t \mathrm{d}t' \langle O(t')\rangle = \sum_a |c_a|^2 O_{aa}$$

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Details of IC

ETH

$$= \frac{1}{N_{E_0,\Delta E}} \sum_{\substack{a \\ |E_a - E_0| < \Delta E}} O_{aa}$$

Initial energy $E_0 = \langle \psi(0)|H|\psi(0)\rangle$

Rigol; Srednicki; ...
late 2000s, 2010s

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O_{aa} do not fluctuate much between eigenstates close in energy:

$O_{aa} - O_{a+1,a+1} \sim e^{-N}$ for an N-body Hamiltonian

$O_{ab} \sim e^{-N}$ for a≠b

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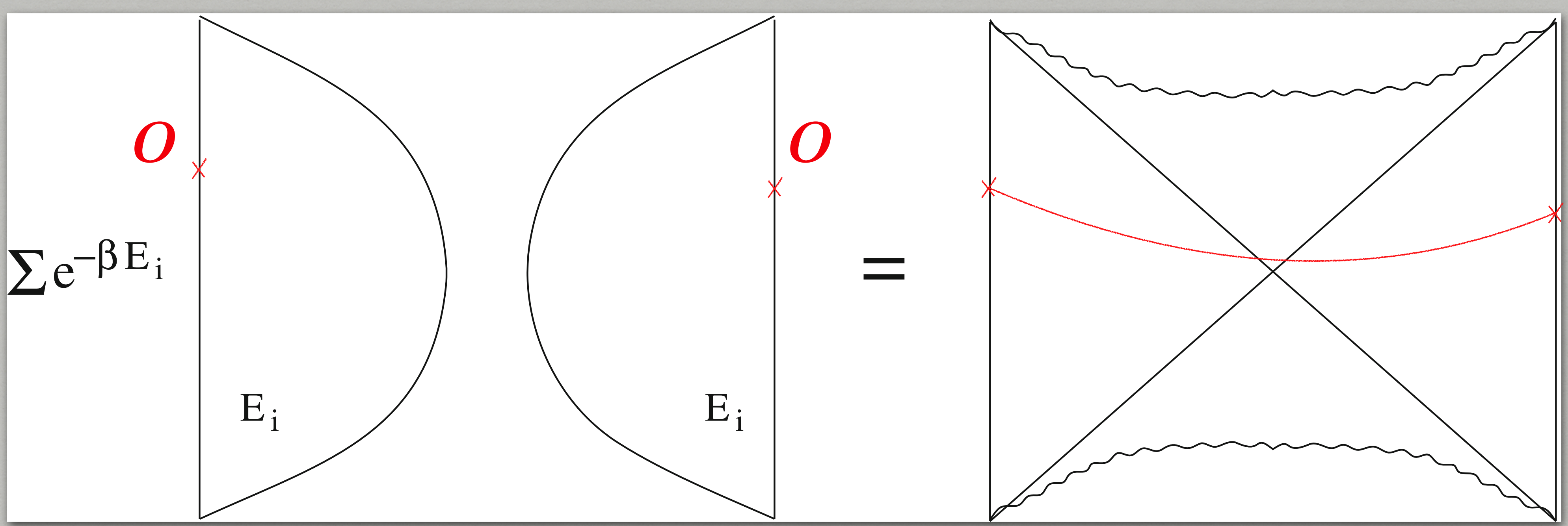
Non-Integrability is important for ETH

Goal for the day

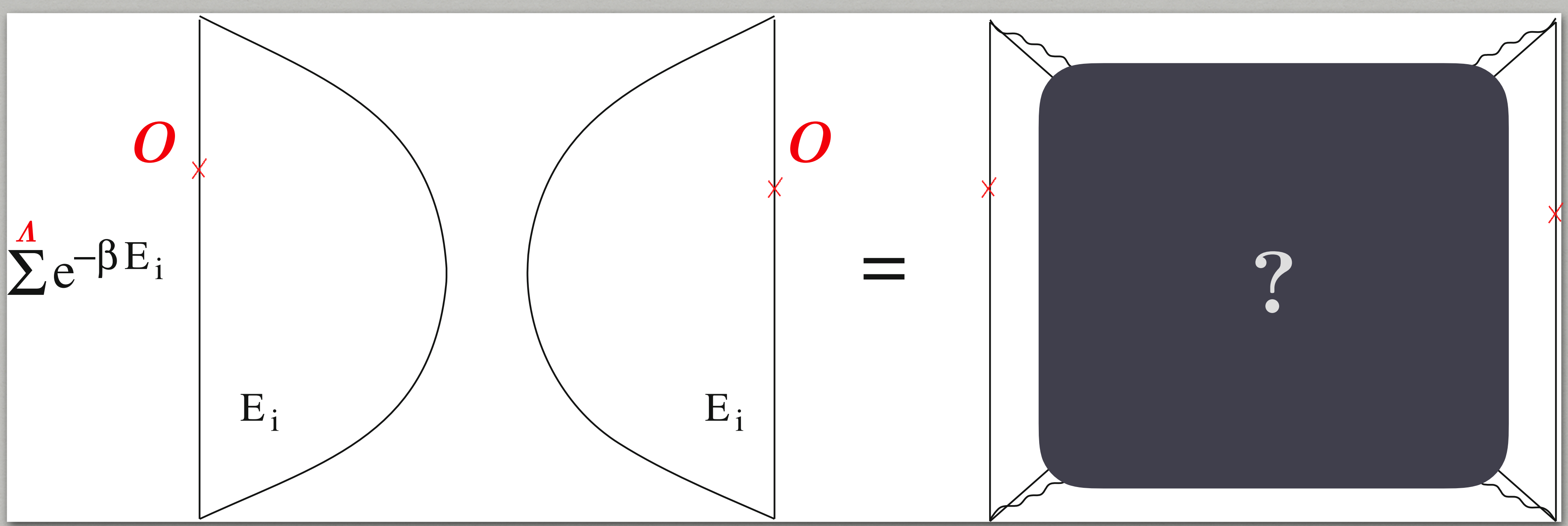
$$G^L(t_{12}, \phi_{12}) = \frac{1}{Z(\beta)} \sum_{ab} e^{-\beta \frac{E_a + E_b}{2}} e^{-it_{12}E_{ab}} |\langle a | O | b \rangle|^2$$



Goal for the day

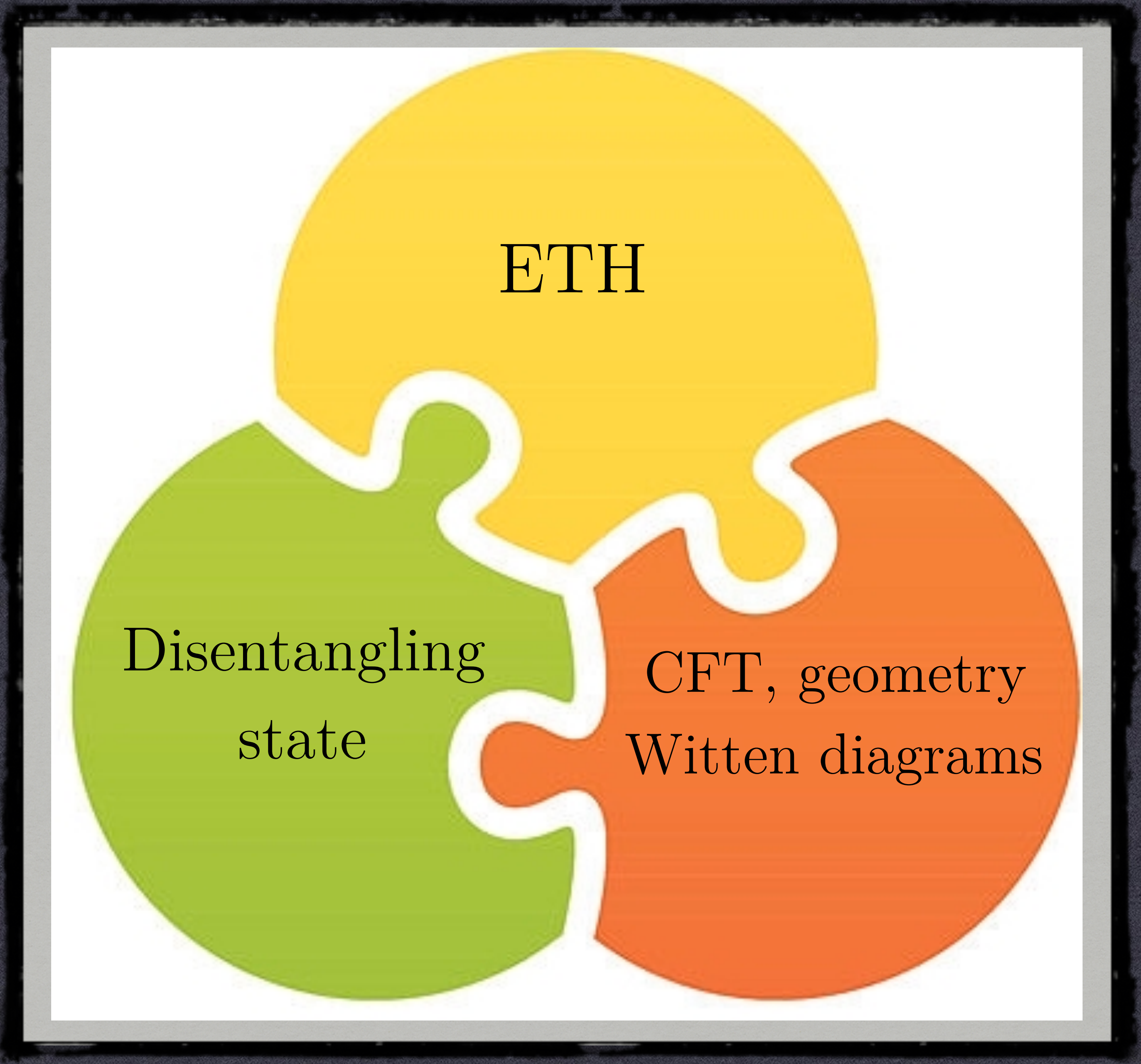
$$G^{\Lambda}(t_{12},\phi_{12}) = \frac{1}{Z^{\Lambda}(\beta)} \sum_{ab} e^{-\beta\frac{E_a+E_b}{2}} e^{-it_{12}E_{ab}} |\langle a|O|b\rangle|^2$$

$E_a, E_b < \Lambda$



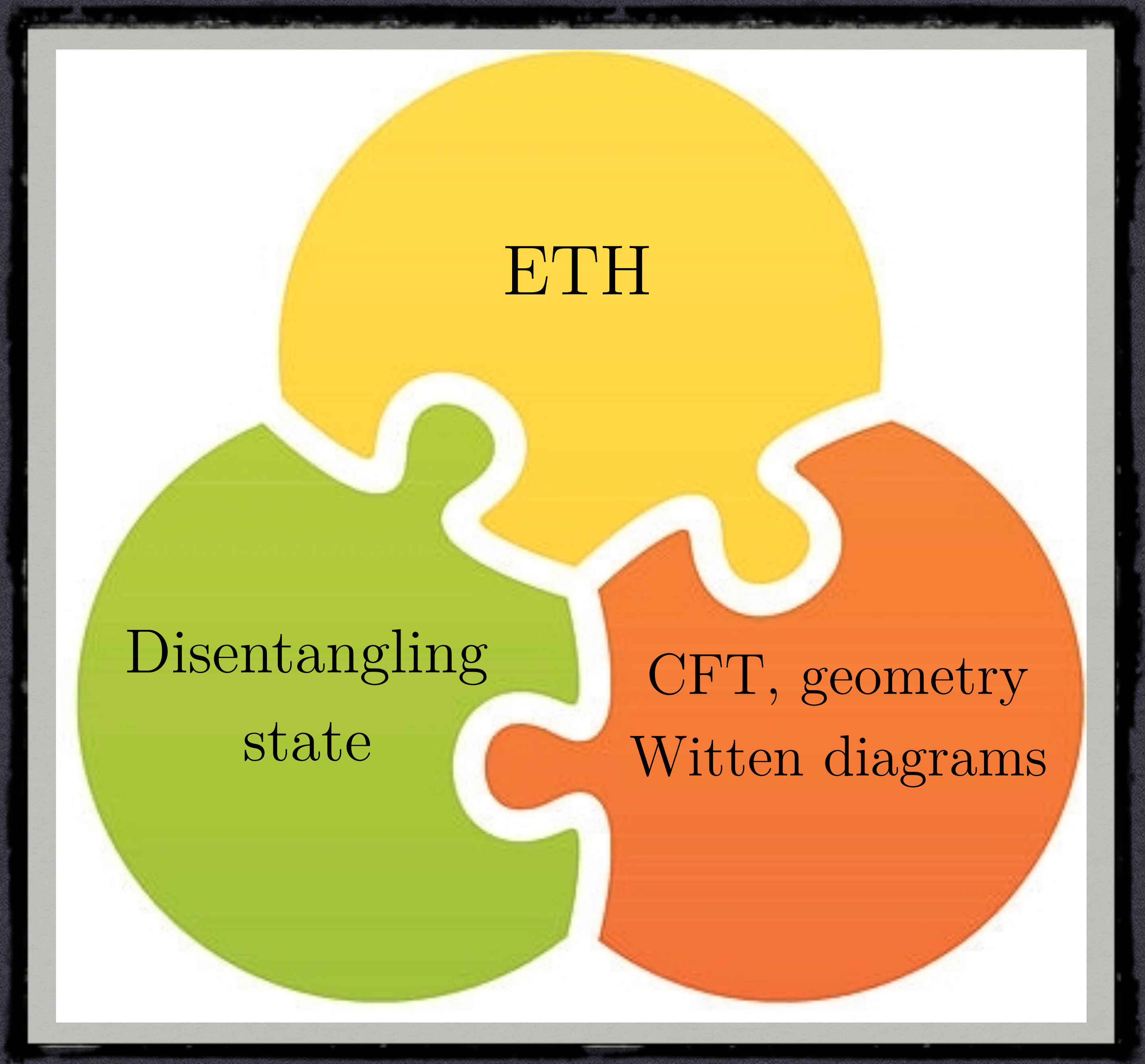
'Disentangling experiment'

PUZZLE & OUTLINE



PUZZLE & OUTLINE

1- Take Wightman function & partition fun.



CFT_2 on the circle (line)

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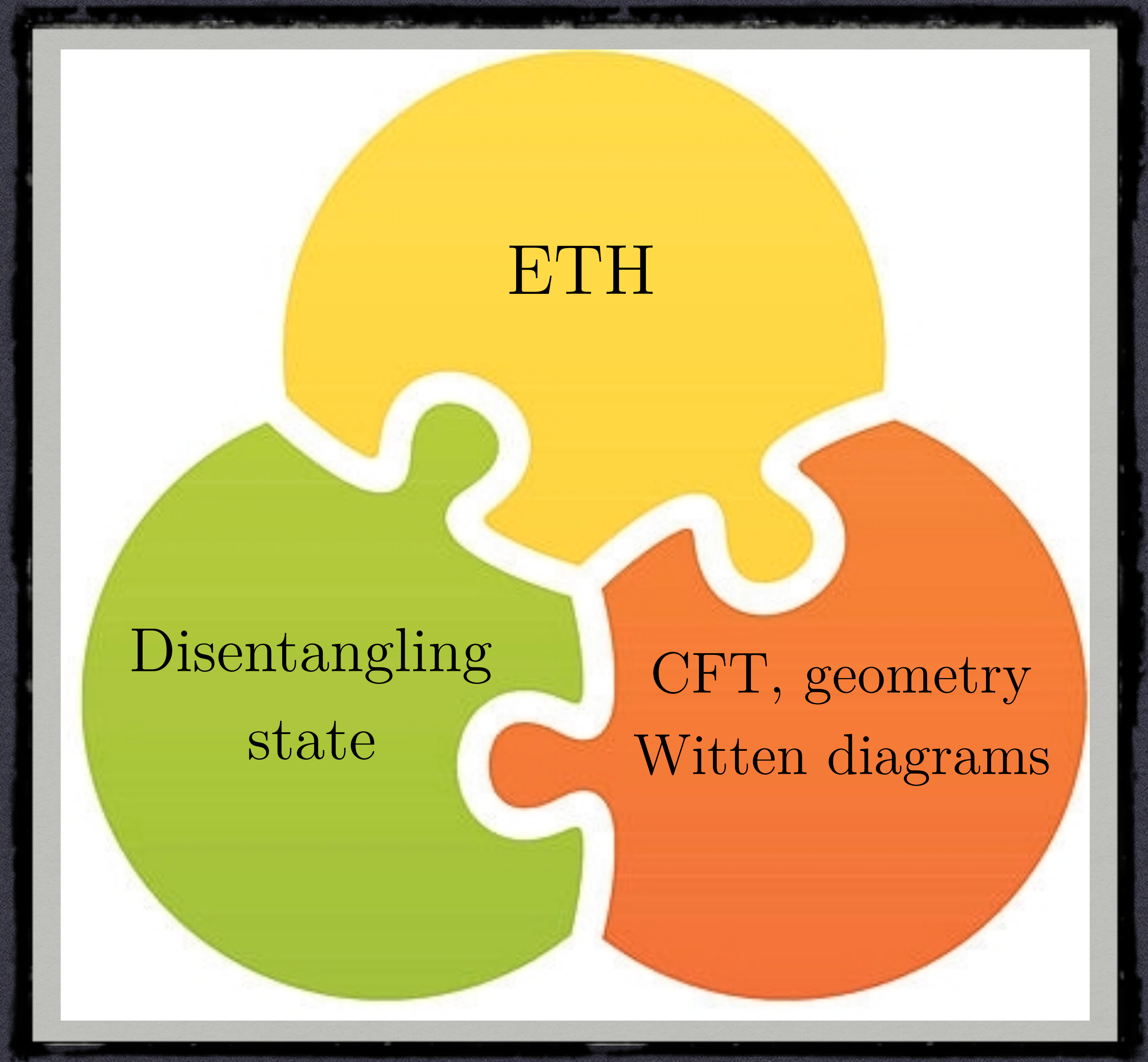

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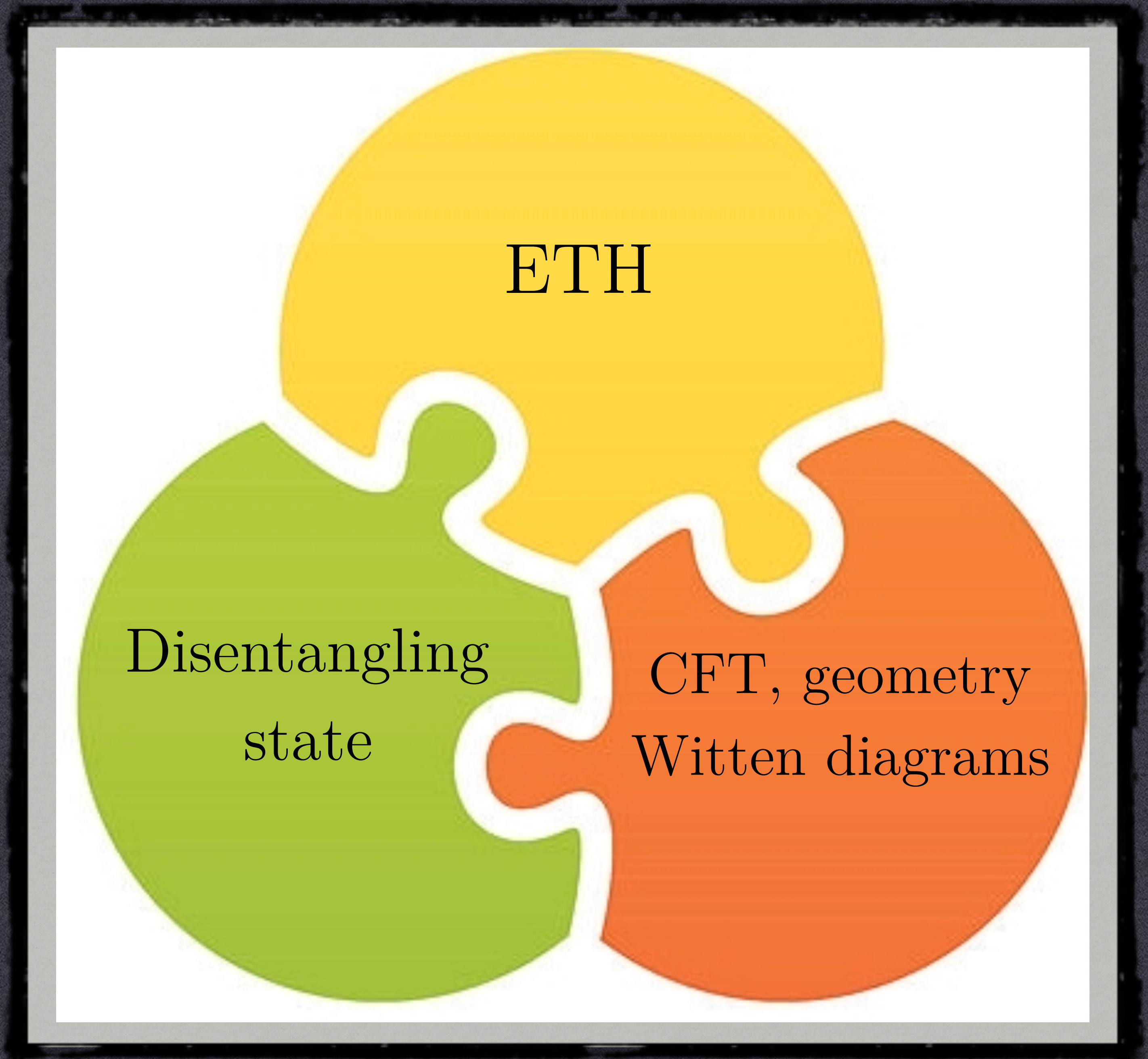
3- Invert



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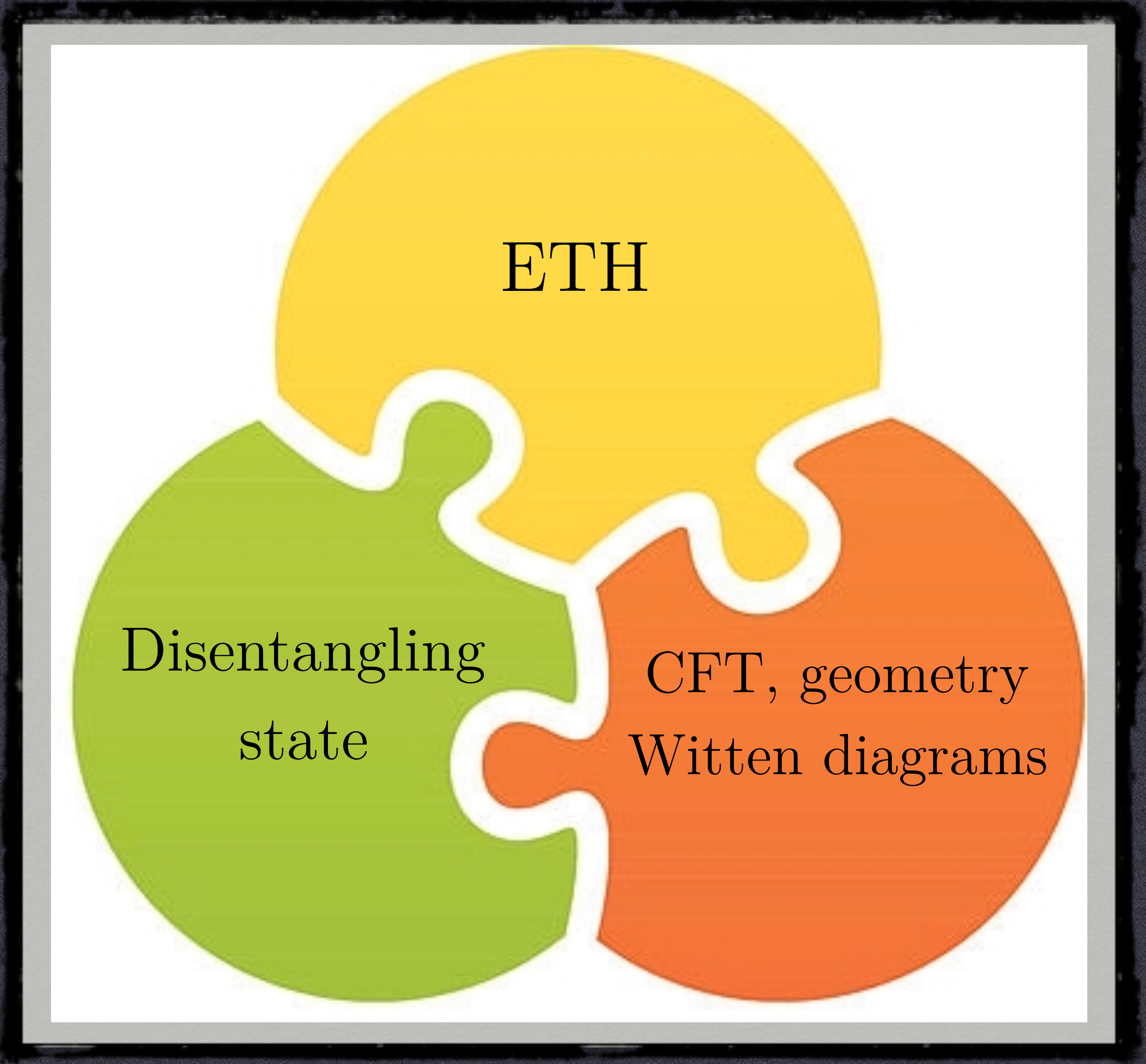
3- Invert

4- Plug back into:

$$G^\Lambda(t_{12},\phi_{12}) = \frac{1}{Z^\Lambda(\beta)}\sum_{\substack{ab \\ E_a,E_b<\Lambda}} e^{-\beta\frac{E_a+E_b}{2}} e^{-it_{12}E_{ab}} |\langle a|O|b\rangle|^2$$



CFT_2 on the circle (line)

1- Starting point and sketch of derivation

Known from CFT:

$$Z(\beta) = e^{\frac{\pi^2 c}{3\beta}} + O(c^0)$$

$$G^L(t_{12}, \phi_{12}) = \sum_{n\in\mathbb{Z}} \frac{(2\pi T)^{2\Delta}}{\left[\cosh(2\pi T(\phi_{12} + 2\pi n)) + \cosh(2\pi T t_{12}) + i\epsilon\right]^{\Delta}}$$

$$G^L(t_{12}, \phi_{12} = 0) = \frac{1}{Z(\beta)} \sum_{ab} e^{-\beta\frac{E_a + E_b}{2}} e^{-it_{12}E_{ab}} |\langle a|O|b\rangle|^2$$

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$$= \frac{1}{Z(\beta)} \sum_{E_a,E_b} e^{-\beta\frac{E_a+E_b}{2} - iE_{ab}t_{12}} \sum_{\substack{a|E(a)=E_a \\ b|E(b)=E_b}} |\langle a|\mathcal{O}|b\rangle|^2$$

$$= \frac{1}{Z(\beta)} \sum_{E_a,E_b} e^{-\frac{E_a+E_b}{2} - it_{12}E_{ab}} e^{S(E_a)} e^{S(E_b)} \mathscr{F}(E_a, E_b, \Delta)$$

$$\overline{\langle a|O|b\rangle^2}$$

2- Derivation: key assumption

$$G^L(t_{12}) = \frac{1}{Z(\beta)} \sum_{E_a, E_b} e^{-\frac{E_a+E_b}{2} - it_{12}E_{ab}} \, e^{S(E_a)} e^{S(E_b)} \mathcal{F}(E_a, E_b, \Delta)$$

$$\sum_{E_a, E_b} e^{S(E_a)} e^{S(E_b)} \to \int dE_a dE_b \rho(E_a)\rho(E_b)$$

$\overline{\langle a|O|b\rangle^2}$ smooth function of energies

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c.f. ETH: $\langle a|O|b\rangle = O(E)\delta_{\hat{\delta}}(\chi) + e^{-\frac{S(E)}{2}} f(E,\chi) R_{ab}$

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c.f. **ETH:** $\langle a | O | b \rangle = O(E)\delta_{\hat{\delta}}(\chi) + e^{-\frac{S(E)}{2}} f(E, \chi) R_{ab}$

$$E = \frac{E_a + E_b}{2}, \quad \chi = E_a - E_b$$

$$G^L(t_{12}) = \frac{1}{Z(\beta)} \int_{-\infty}^{\infty} \mathrm{d}\chi \int_{-c/12}^{\infty} \mathrm{d}E \;\; e^{i\chi t_{12}} e^{-\beta E} \rho\left(E + \frac{\chi}{2}\right) \rho\left(E - \frac{\chi}{2}\right) \mathcal{F}(E, \chi, \Delta)$$

3- Derivation: inversion

$$G^L(t_{12}) = \frac{1}{Z(\beta)} \int_{-\infty}^{\infty} \mathrm{d}\chi \int_{-c/12}^{\infty} \mathrm{d}E \;\; e^{i\chi t_{12}} e^{-\beta E} \rho\left(E + \frac{\chi}{2}\right) \rho\left(E - \frac{\chi}{2}\right) \mathscr{F}(E, \chi, \Delta)$$

(3.1) Inversion of Fourier Transform

$$\int_{-c/12}^{\infty} \mathrm{d}E \; e^{-\beta E} \rho\left(E + \frac{\chi}{2}\right) \rho\left(E - \frac{\chi}{2}\right) \mathscr{F}(E, \chi, \Delta) = Z(\beta) \left(\frac{2\pi}{\beta}\right)^{2\Delta} \sum_{n \in \mathbb{Z}} F_n(\Delta, \chi, \beta)$$

(3.2) Inversion of Laplace Transform: Mellin inversion formula

Result: $\overline{\langle a|O|b\rangle^2}$ and Wightman

- $\overline{\langle a|O|b\rangle^2} \equiv \mathcal{F}(E,\chi,\Delta)$

$$\mathcal{F}(E,\chi,\Delta)\rho\left(E+\frac{\chi}{2}\right)\rho\left(E-\frac{\chi}{2}\right) = \sum_{n\in\mathbb{N}}\int_0^E \mathrm{d}x\ \rho(x,\chi,\Delta)\ \hat{F}_n(E-x,\chi,\Delta)$$

known

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- ***Disentangling experiment:***

$$G_L^\Lambda(t_{12}) \equiv \frac{1}{Z^\Lambda(\beta)}\int_{-\Lambda}^{\Lambda}\mathrm{d}\chi \int_{\chi/2}^{\Lambda-\chi/2}\mathrm{d}E\ e^{i\chi t_{12}}\ e^{-\beta E}\ \mathscr{F}(E,\chi,\Delta)$$

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Problem:

- Two sums we cannot do

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Circle → Line

$\overline{\langle a|O|b\rangle^2}$ on the Line

- Drop the sum over images, n=0
- Set $b_n(\phi) \equiv \cosh(2\pi T\phi_{12}) = 1$

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- Drop the sum over images, n=0
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We can perform the sum corresponding to simple poles in

$$\rho\left(E+\frac{\chi}{2}\right)\rho\left(E-\frac{\chi}{2}\right)\mathcal{F}(E,\chi,\Delta) = \frac{1}{2\pi}\int_0^E \rho(E')\hat{F}_0(E'-E,\chi,\Delta)dE'$$

$$\rho(E,\Delta) = \sqrt{\frac{\pi c}{6}\frac{L}{E}}I_1\left(2\sqrt{\frac{\pi c}{6}LE}\right)$$

$$\hat{F}_0(E,\chi,\Delta) \propto \chi^{2\Delta-2}\left\{e^{-i2\pi\Delta\frac{E}{\chi}}\,{}_{2\Delta}F_{2\Delta-1}\left[\begin{array}{c} a_1,\ldots,a_{2\Delta} \\ b_1,\ldots,b_{2\Delta-1}\end{array}\middle| -e^{i2\pi\frac{E}{\chi}}\right] + cc\right\}$$

$\overline{\langle a|O|b\rangle^2}$ on the Line

Some analytical results:

- Saddle point approx. $ELc \gg 1$

$$\mathcal{F}(E,\chi,\Delta) = \frac{C_{\mathcal{O}}}{2\pi}\frac{1}{\rho\left(E+\frac{\chi}{2}\right)\rho\left(E-\frac{\chi}{2}\right)}\frac{1}{2\pi i}\oint d\beta\, e^{\beta E}Z(\beta)\left(\frac{2\pi}{\beta}\right)^{2\Delta}F_0(\beta,\chi,\Delta)$$

peaked around $\beta_0 = \sqrt{\frac{\pi c L}{6E}}$

$$\mathcal{F}(E,\chi,\Delta) \simeq \frac{2^{3\Delta-2}}{\pi\Gamma(2\Delta)}\frac{\rho(E)}{\rho(E+\chi/2)\rho(E-\chi/2)}\left(\frac{6E\pi}{cL}\right)^{\Delta-1/2}\Gamma\left(\Delta-\frac{i\chi}{2\pi}\sqrt{\frac{\pi cL}{6E}}\right)\Gamma\left(\Delta+\frac{i\chi}{2\pi}\sqrt{\frac{\pi cL}{6E}}\right)$$

c.f. Brehm, Das, Datta, '18

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- Expand F_0 in small χ:

$$\mathcal{F}(E,\chi,\Delta) \simeq \frac{C_{\mathcal{O}}(2\pi)^{2\Delta-2}}{\rho\left(E+\frac{\chi}{2}\right)\rho\left(E-\frac{\chi}{2}\right)}\frac{2^{\Delta}\Gamma(\Delta)^2}{\Gamma(2\Delta)}\left(\frac{6E}{\pi c L}\right)^{\Delta-1}\left[I_{2\Delta-2}\left(2\sqrt{\frac{EL\pi c}{6}}\right)\right.$$
$$\left. -\chi^2\left(\frac{6E}{\pi c L}\right)^{-1}\frac{\psi^{(1)}(\Delta)}{4\pi^2}I_{2\Delta-4}\left(2\sqrt{\frac{EL\pi c}{6}}\right)+O(\chi^4L^2/E^2)\right]$$

On the Line: a view to the spectrum

$$E = \frac{E_a + E_b}{2}$$
$$\chi = E_a - E_b$$

c=20

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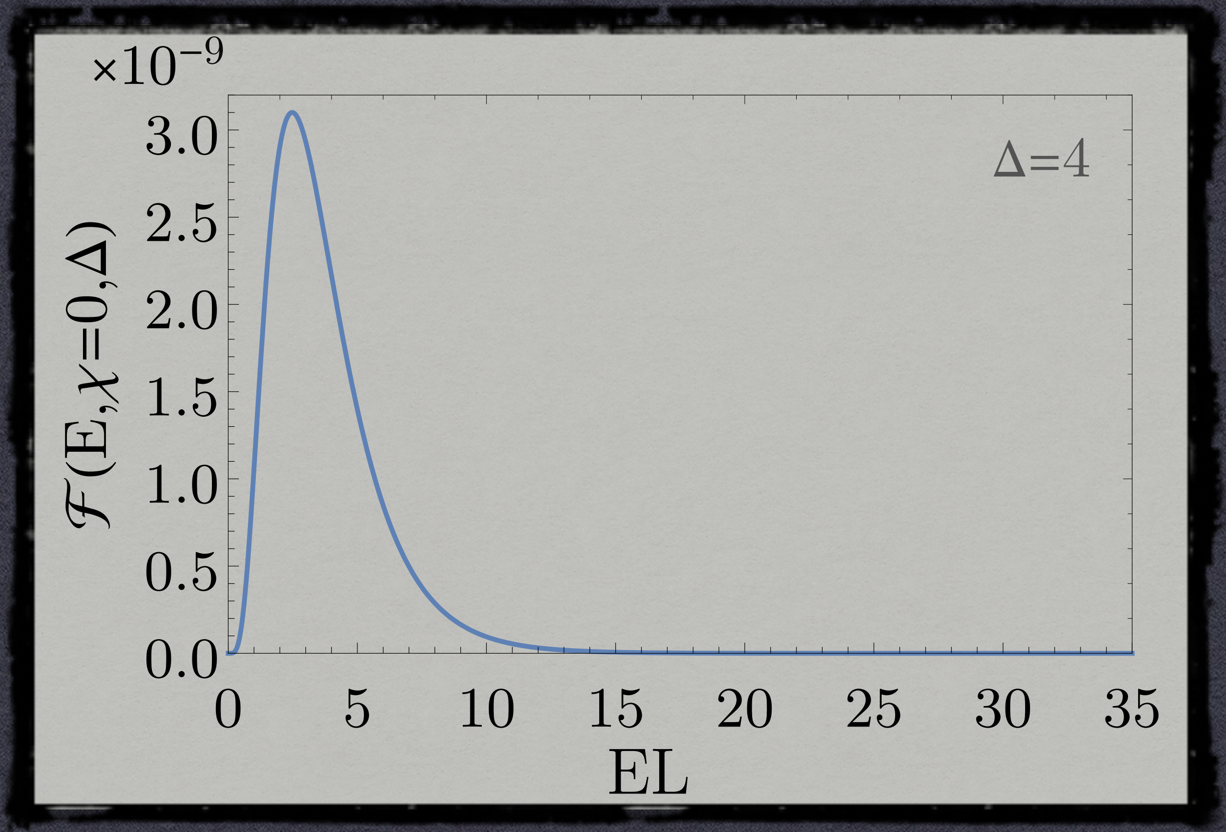

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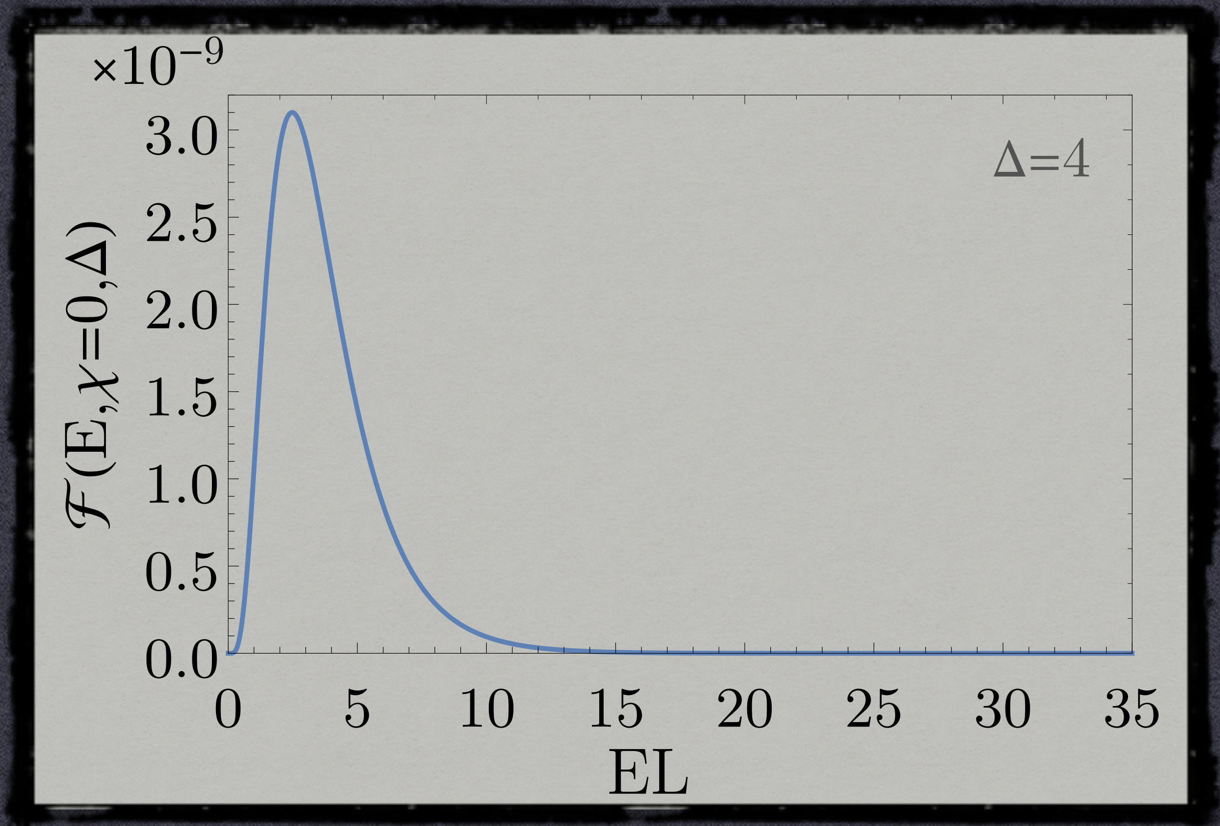

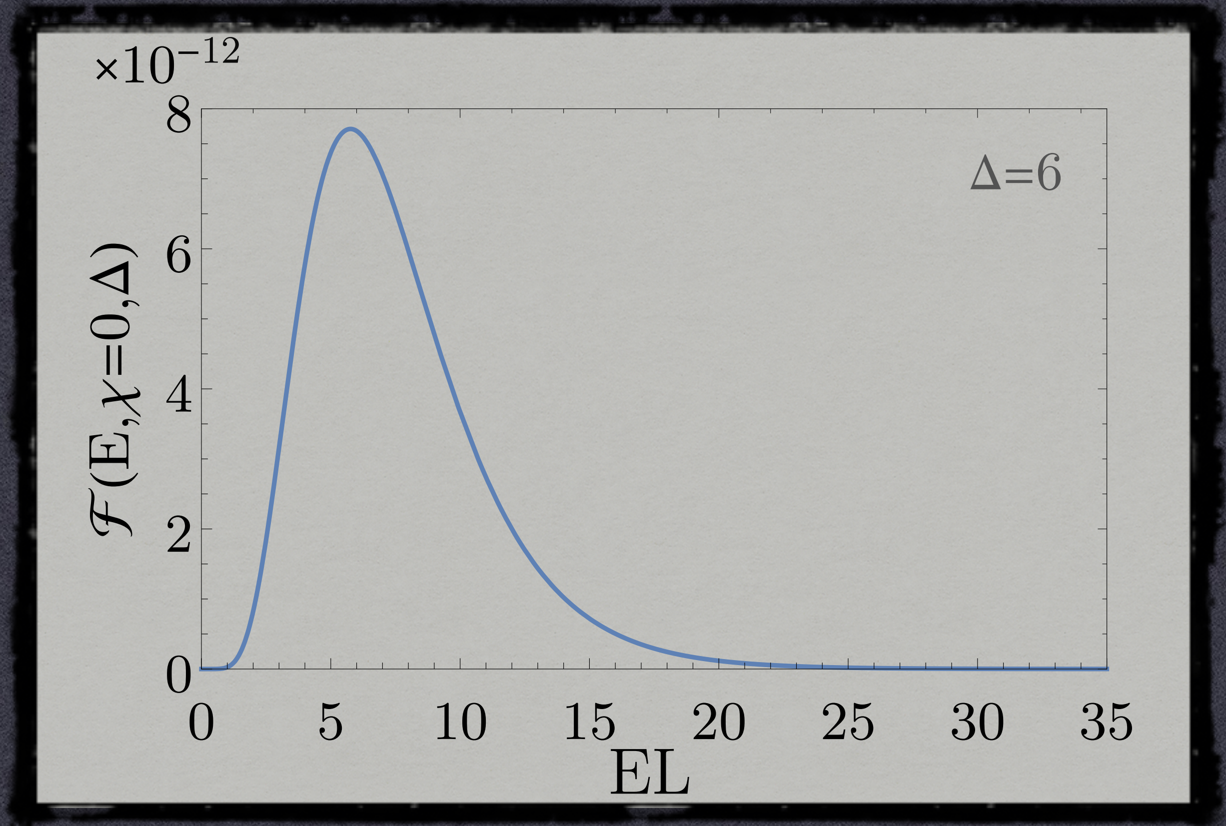

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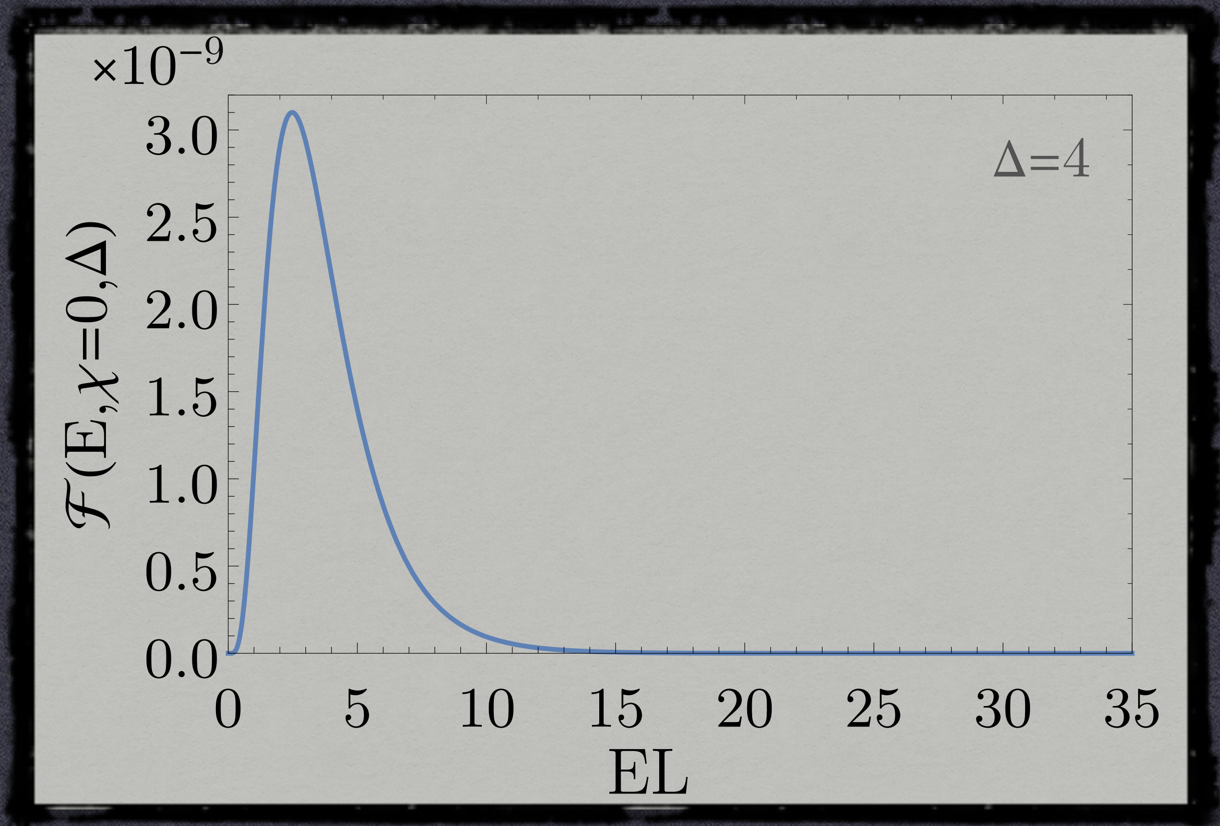
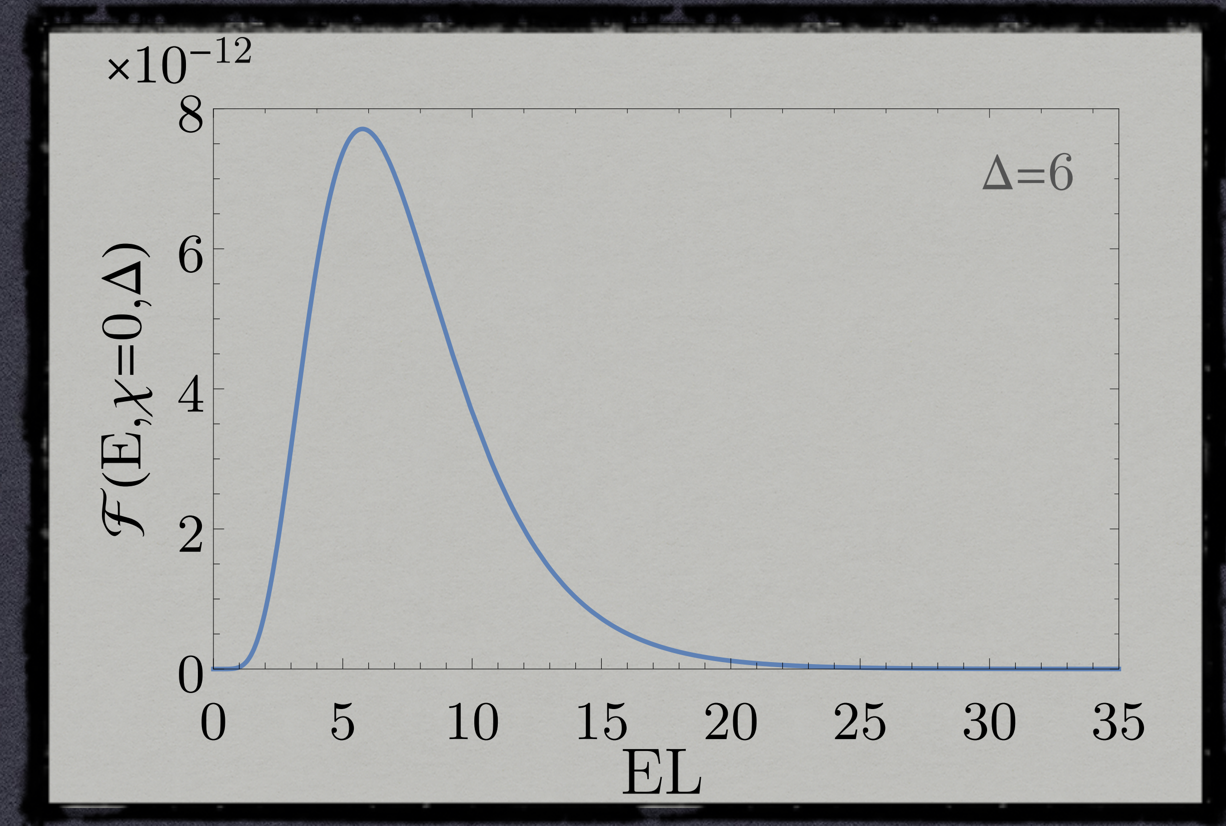
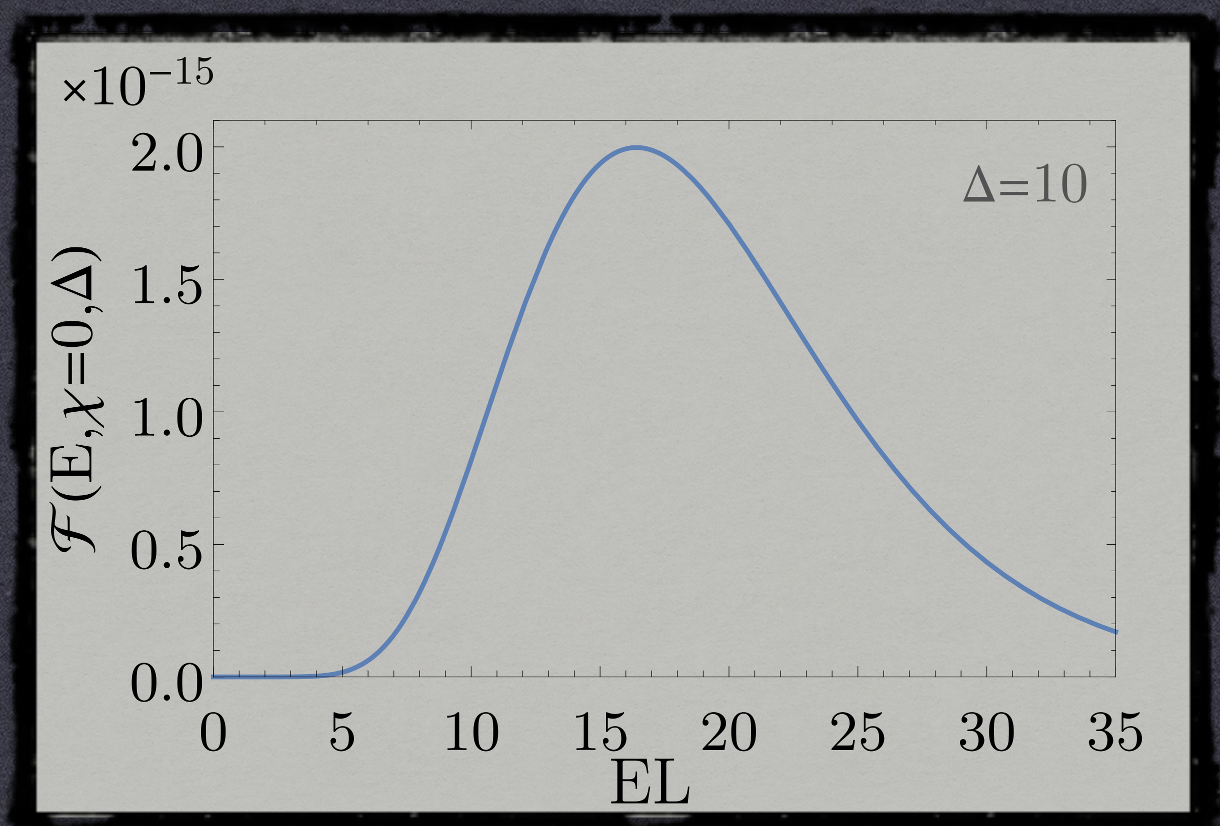


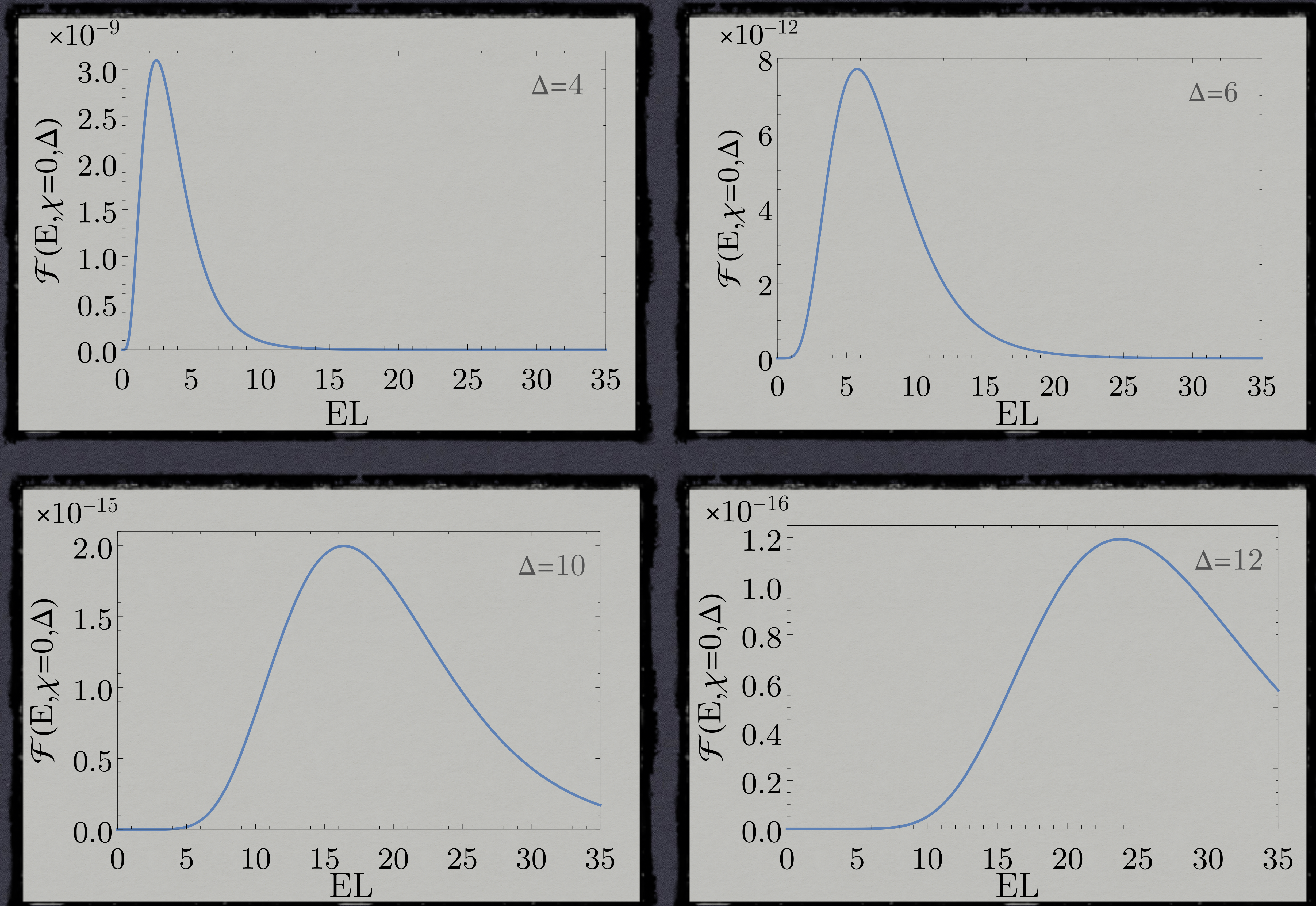




On the Line: a view to the spectrum

$$E = \frac{E_a + E_b}{2}$$
$$\chi = E_a - E_b$$

c=20



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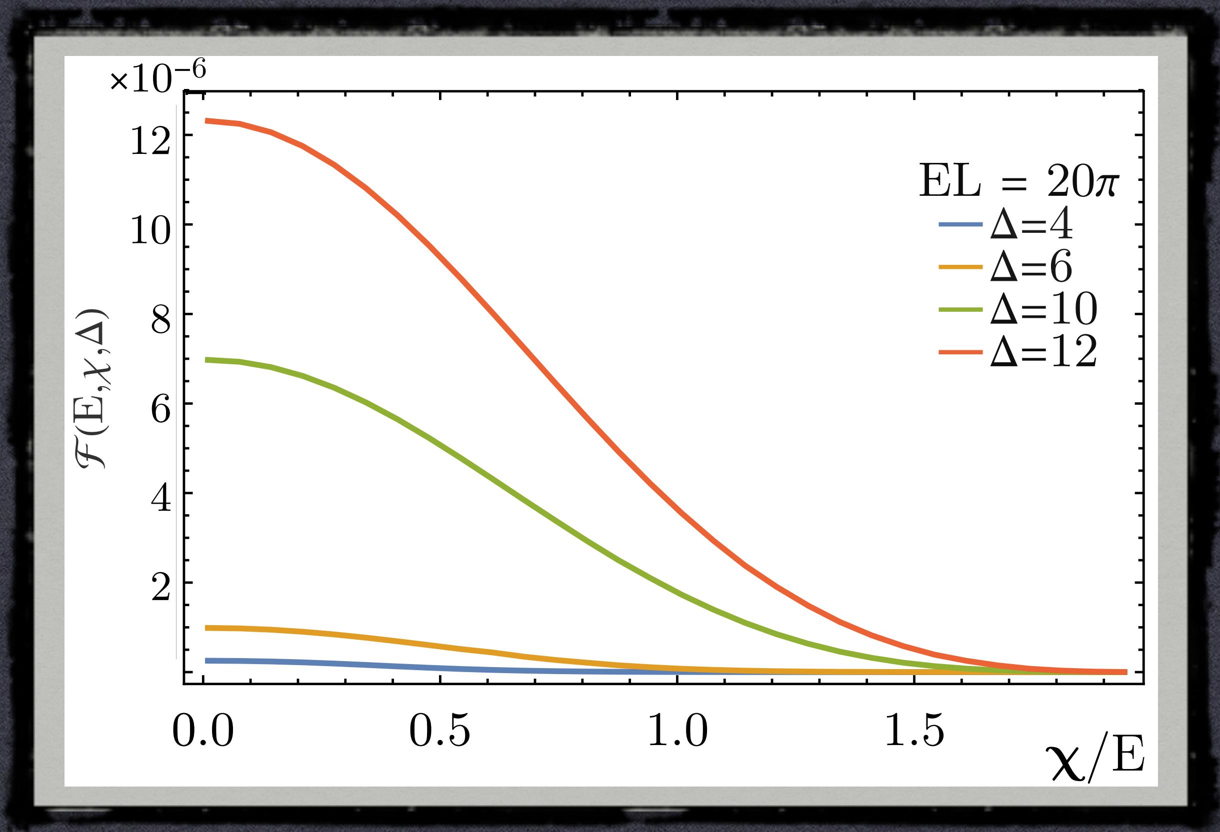
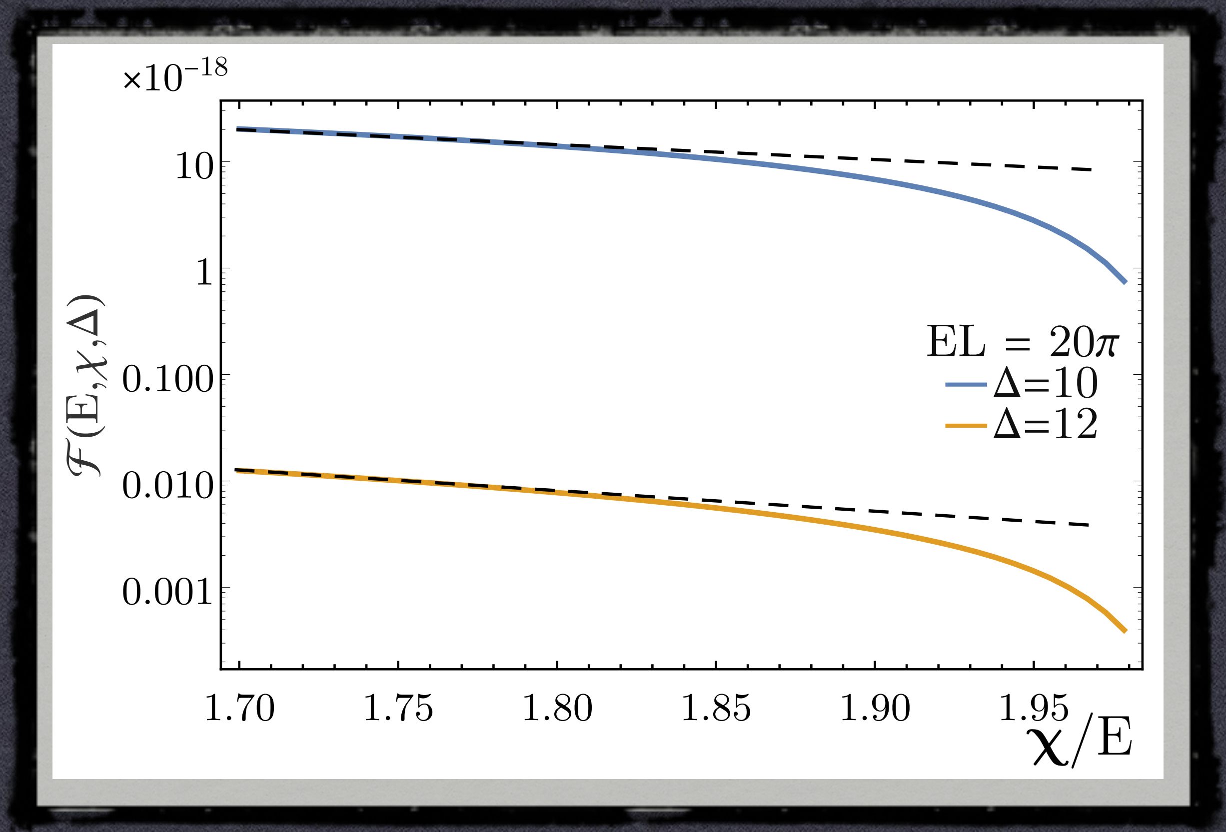




ETH?

4- Disentangling experiment

Hard cutoff in the spectrum:

$$|\Lambda\rangle \equiv \frac{1}{\sqrt{Z_\Lambda}} \sum_{a|E_a \leq \Lambda} e^{-\beta E_a/2} |a\rangle |a\rangle$$

$$Z_\Lambda \equiv \sum_{a|E_a \leq \Lambda} e^{-\beta E_a} = \int_0^\Lambda dE \rho(E) e^{-\beta E}$$

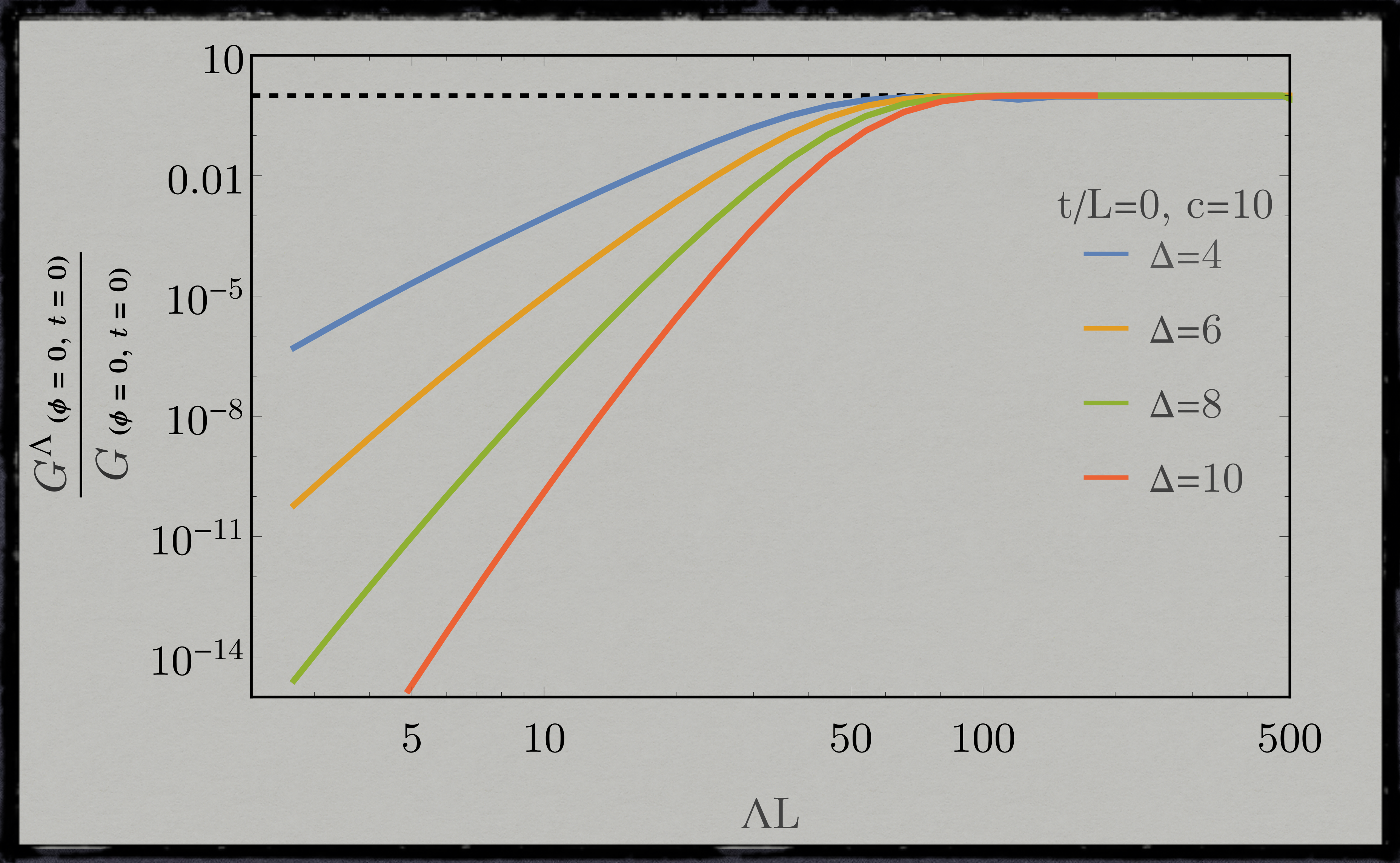
$$\langle \mathbf{TFD} | \mathcal{O}(t_1) \otimes \mathcal{O}(t_2) | \mathbf{TFD} \rangle \to \langle \Lambda | \mathcal{O}(t_1) \otimes \mathcal{O}(t_2) | \Lambda \rangle \equiv G_L^\Lambda(t_{12}, \phi_{12})$$

$$G_L^\Lambda(t_{12}, \phi_{12}) \equiv \frac{1}{Z^\Lambda(\beta)} \int_{-\Lambda}^{\Lambda} \mathrm{d}\chi \int_{\chi/2}^{\Lambda-\chi/2} \mathrm{d}E \; e^{i\chi t_{12}} \; e^{-\beta E} \; \mathcal{F}(E, \chi, \Delta)$$

4- Disentangling experiment

$$G_L^{\Lambda}(t_{12},\phi_{12}) \equiv \frac{1}{Z^{\Lambda}(\beta)} \int_{-\Lambda}^{\Lambda} \mathrm{d}\chi \int_{\chi/2}^{\Lambda-\chi/2} \mathrm{d}E \; e^{i\chi t_{12}} \; e^{-\beta E} \; \mathscr{F}(E,\chi,\Delta)$$

t=0, β fixed, cutoff dependence



4- Disentangling experiment

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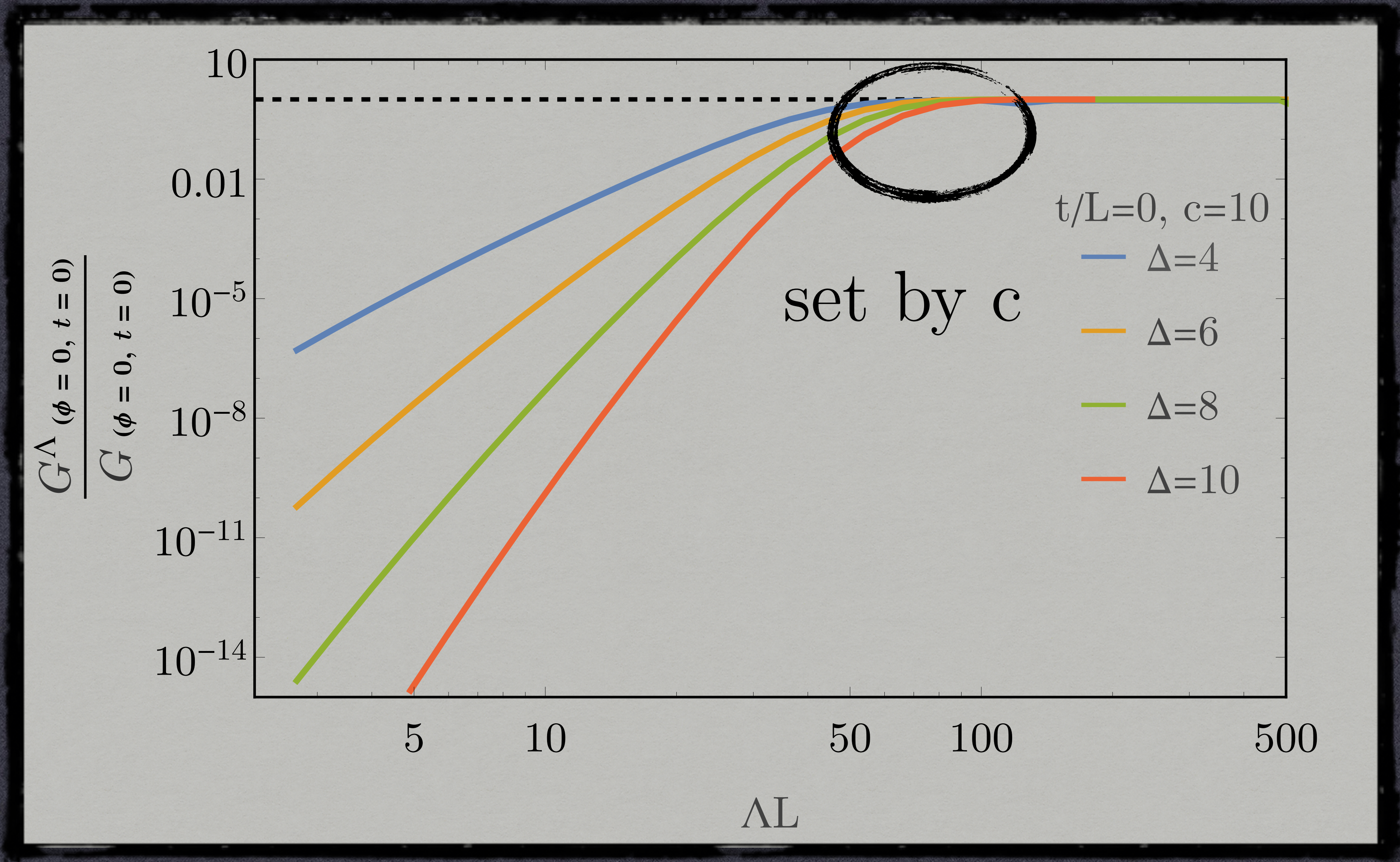
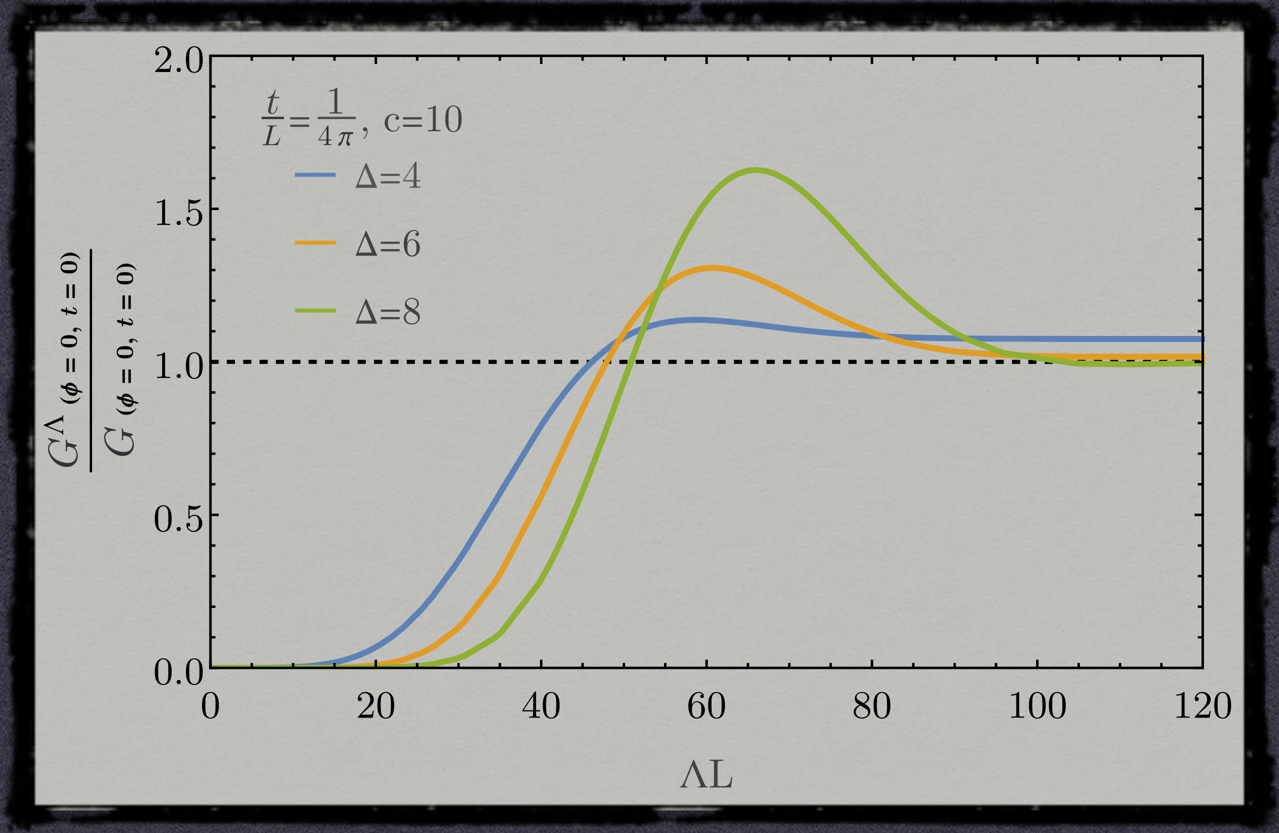
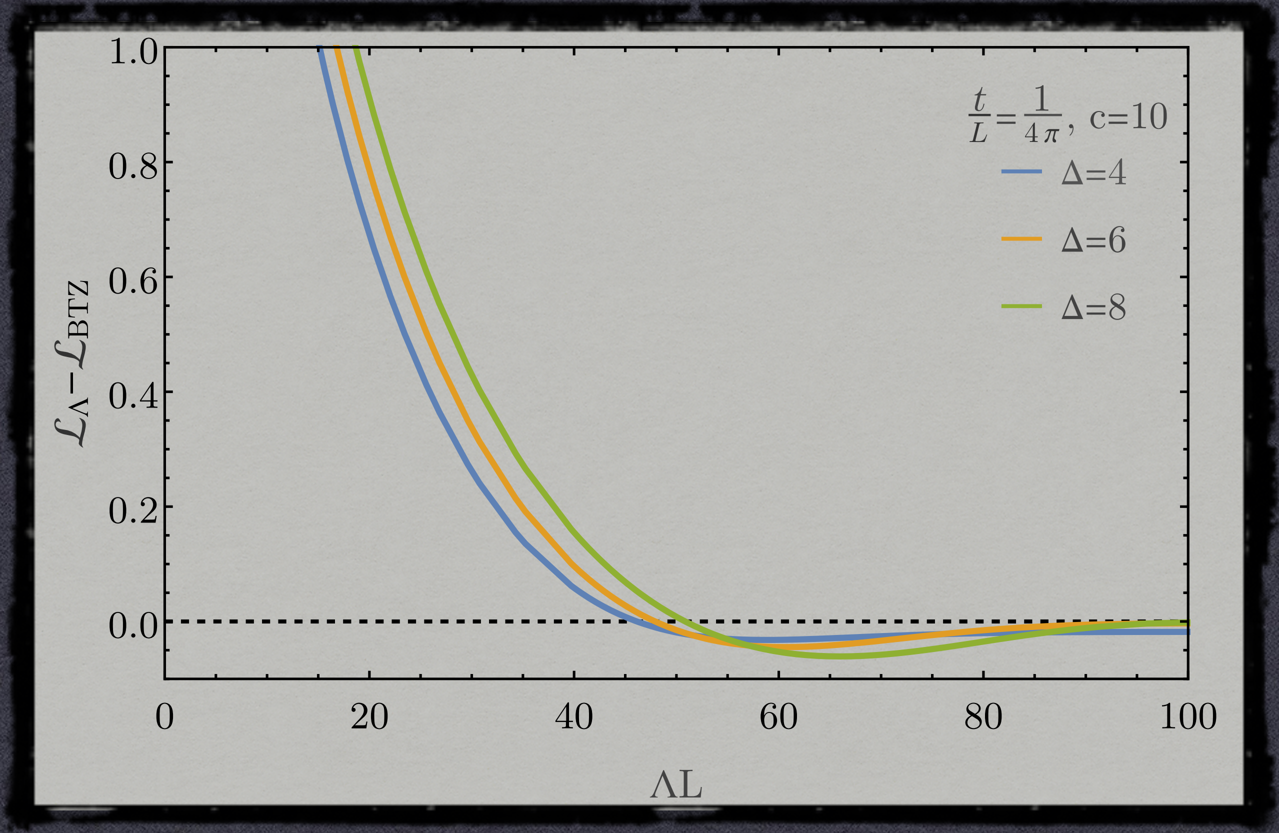


4- Disentangling experiment

t≠0, β fixed, cutoff dependence





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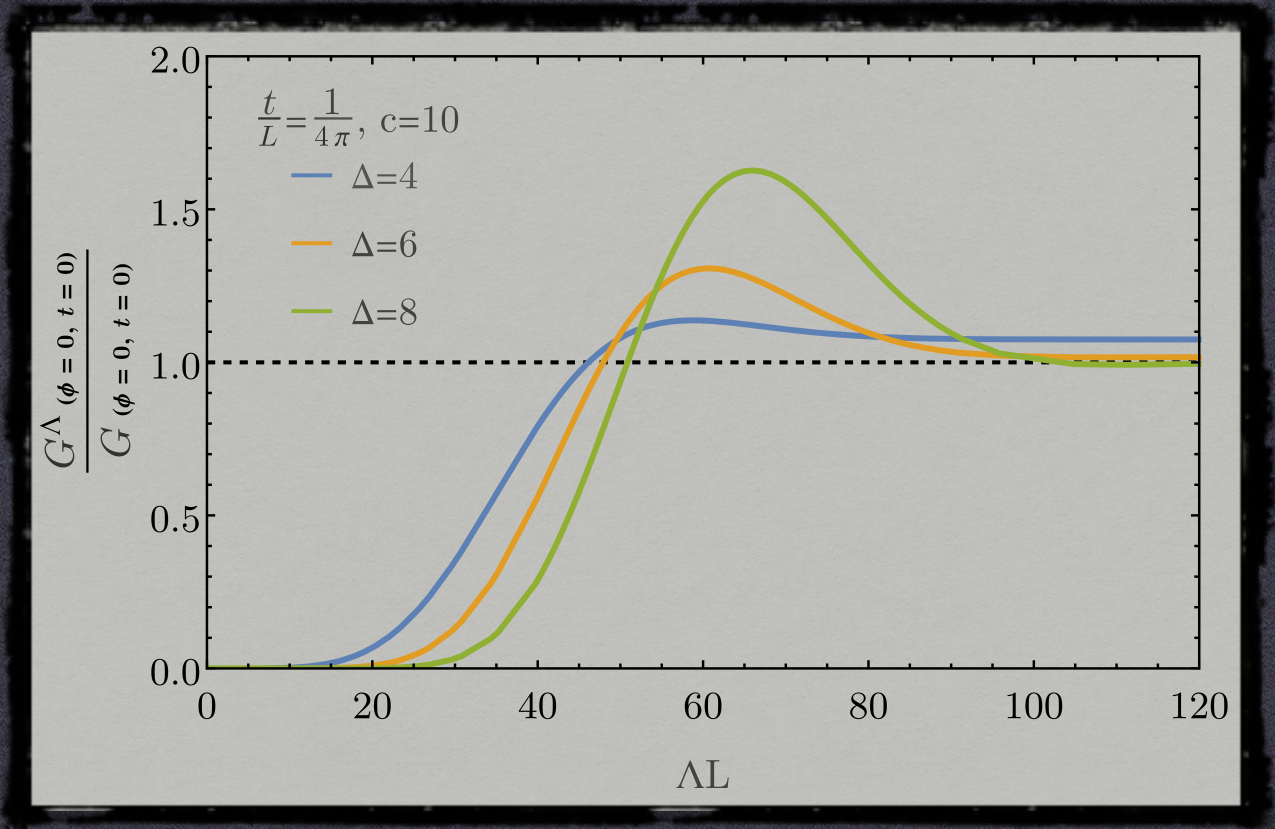
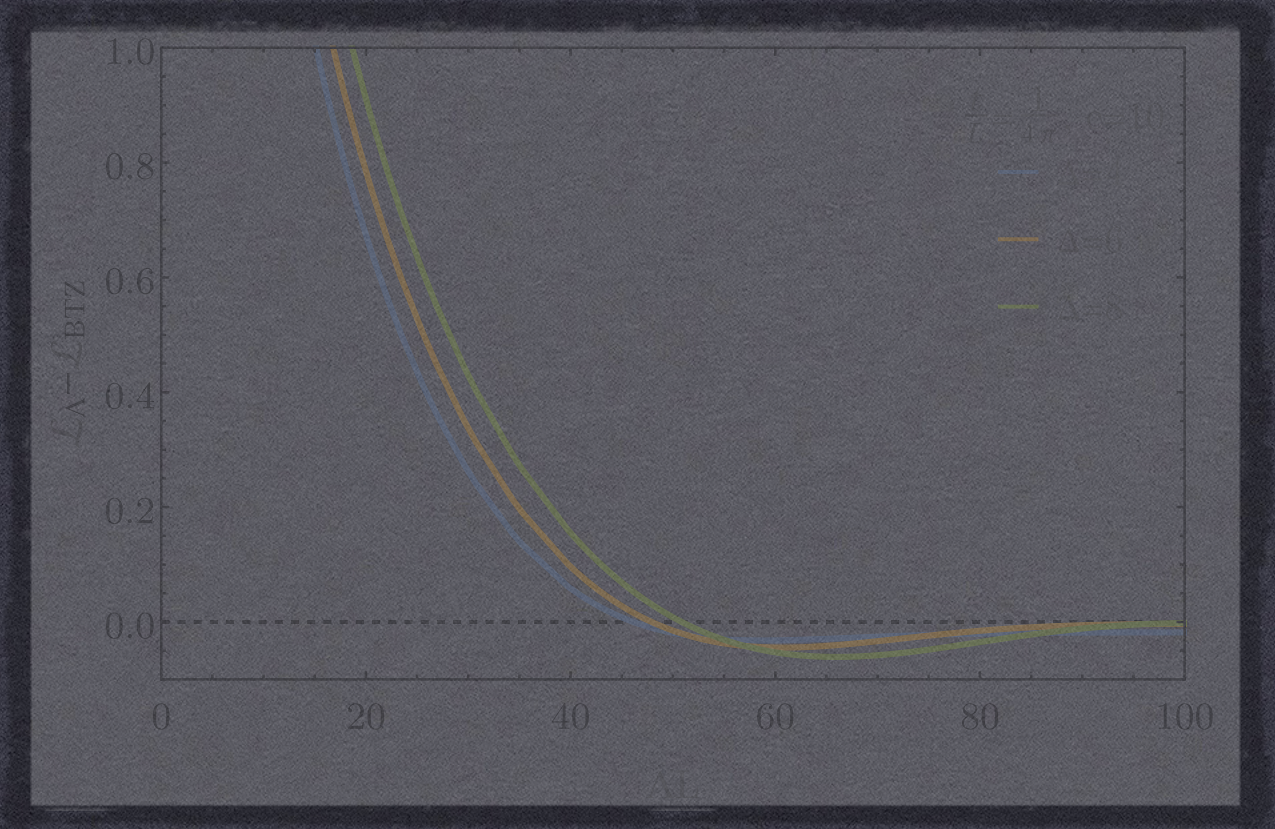
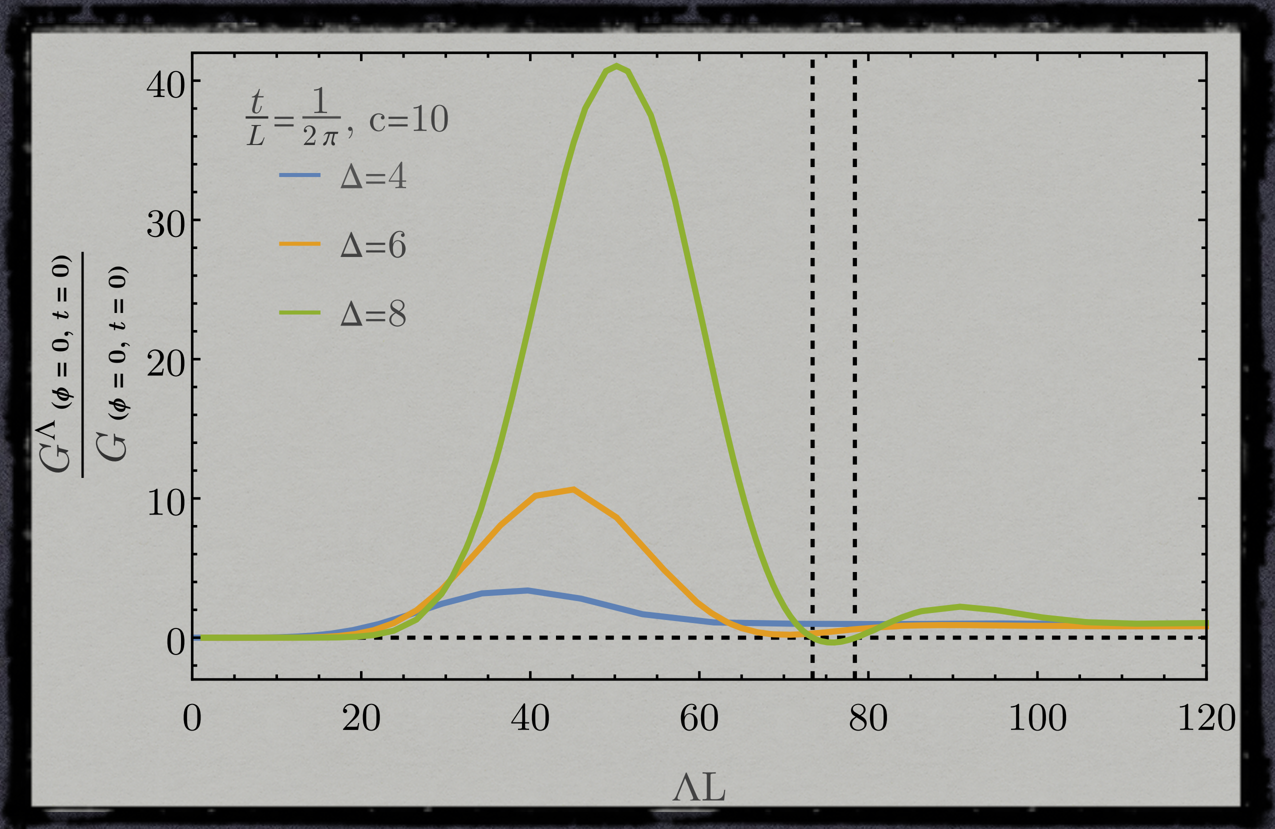
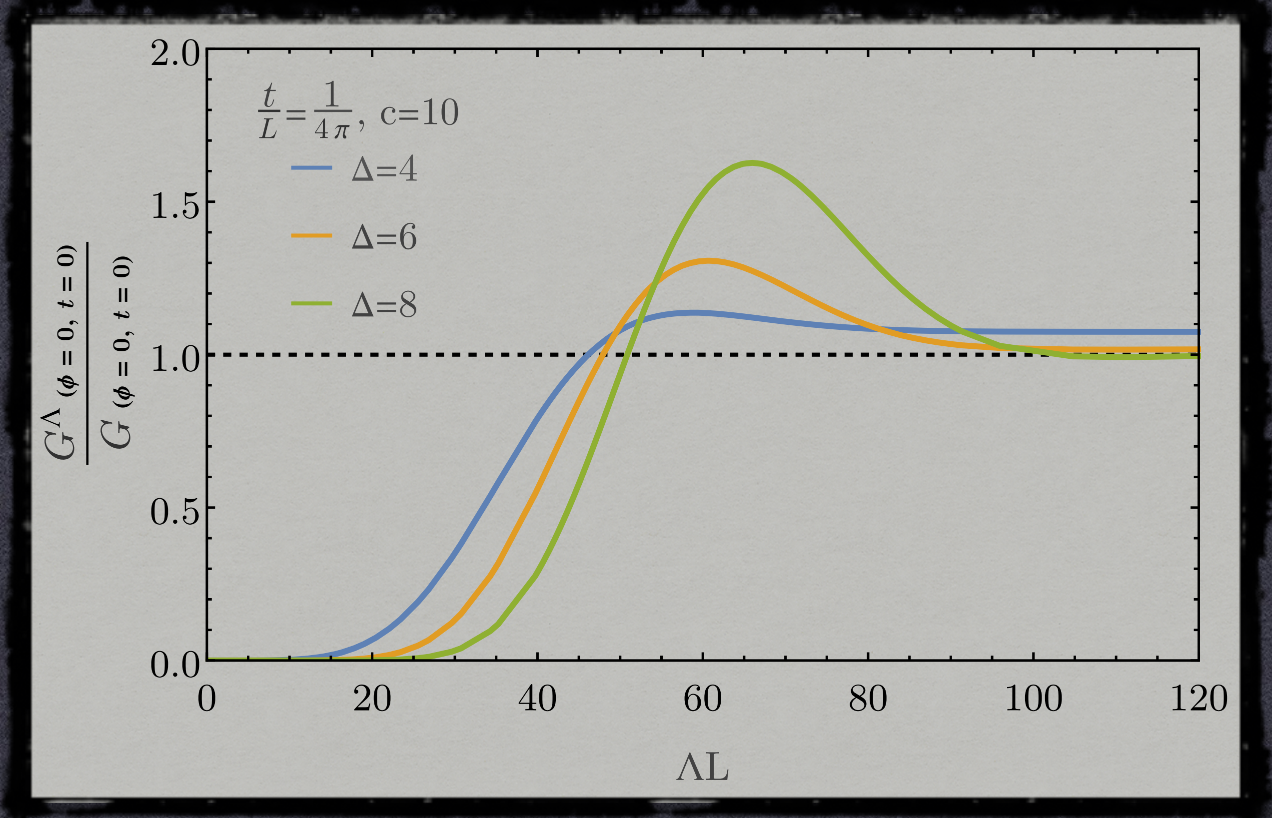


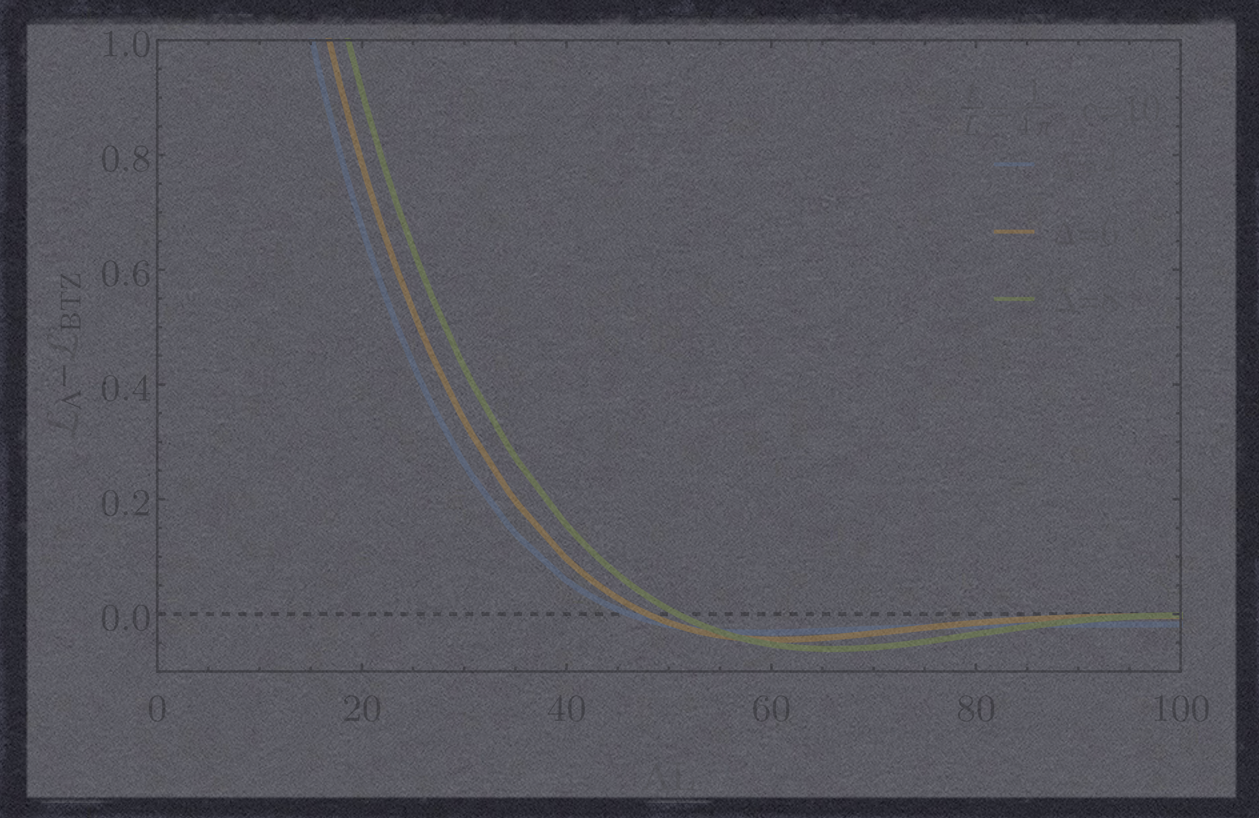


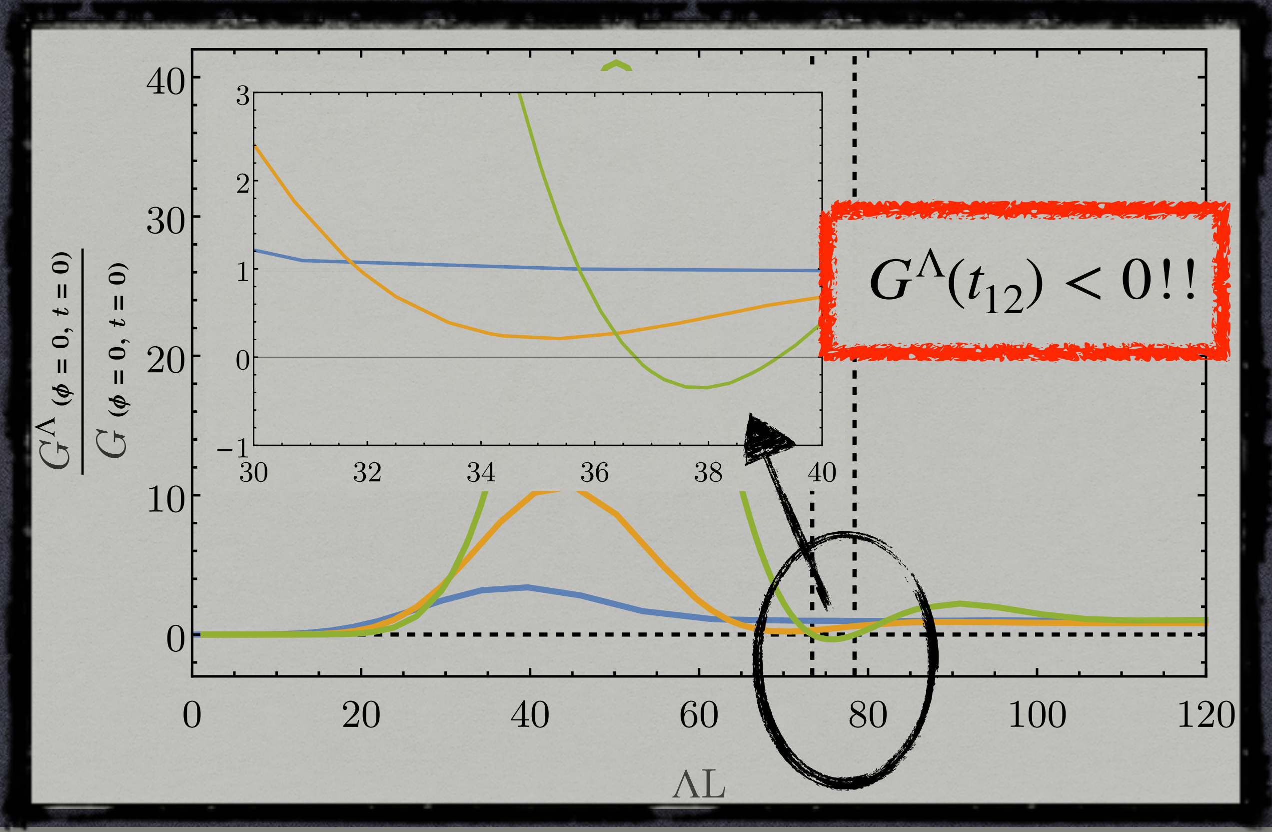


4- Disentangling experiment

t≠0, β fixed, cutoff dependence

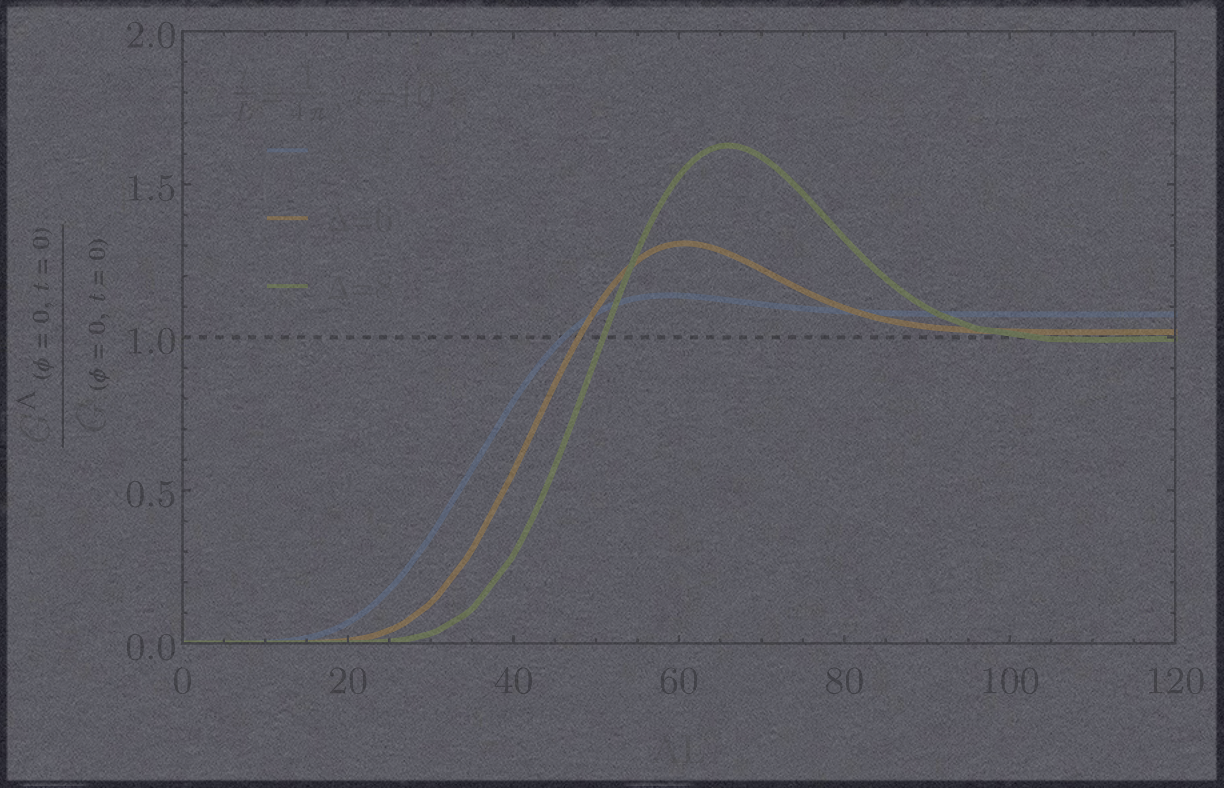


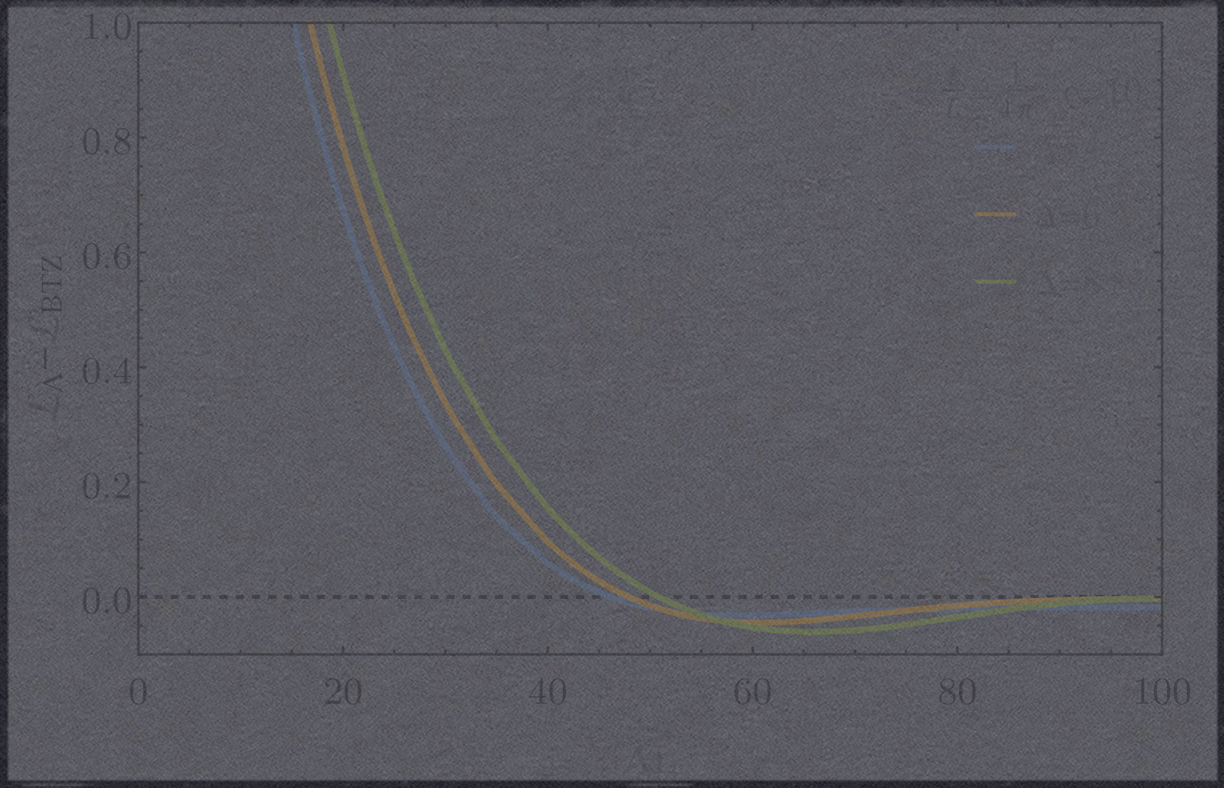


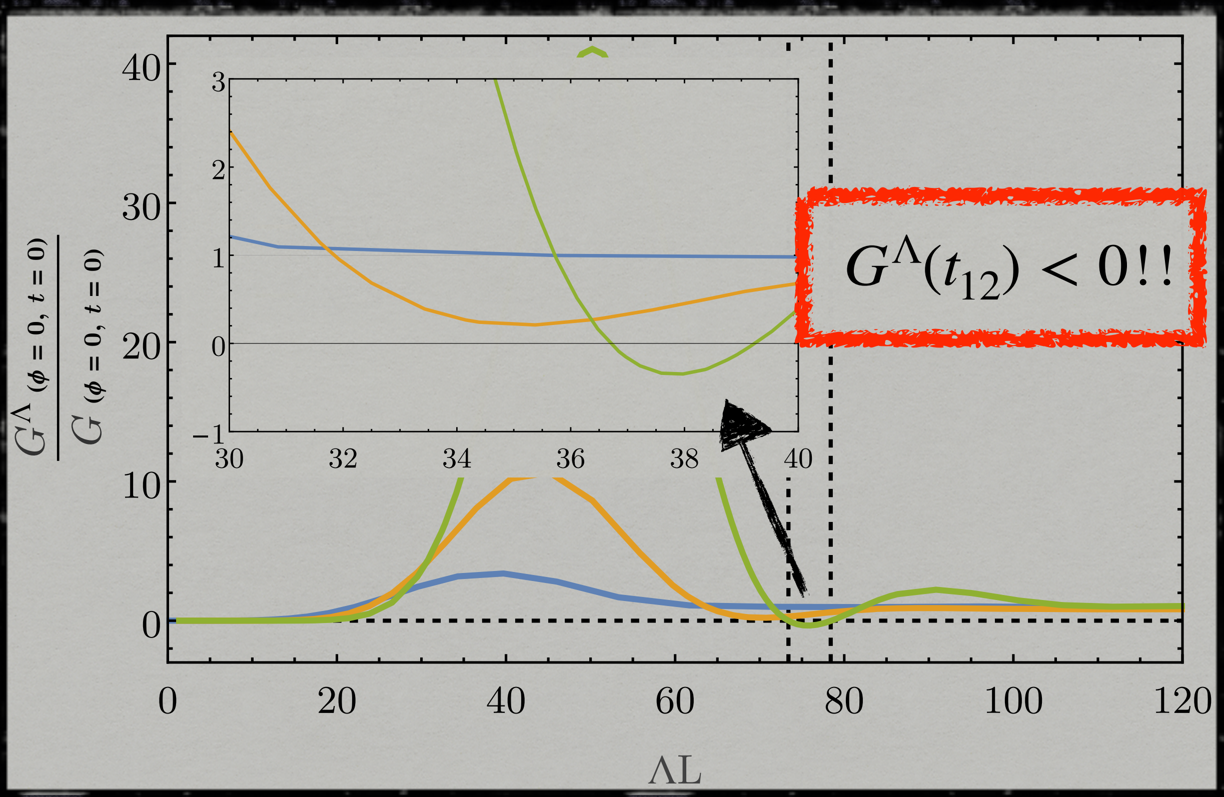


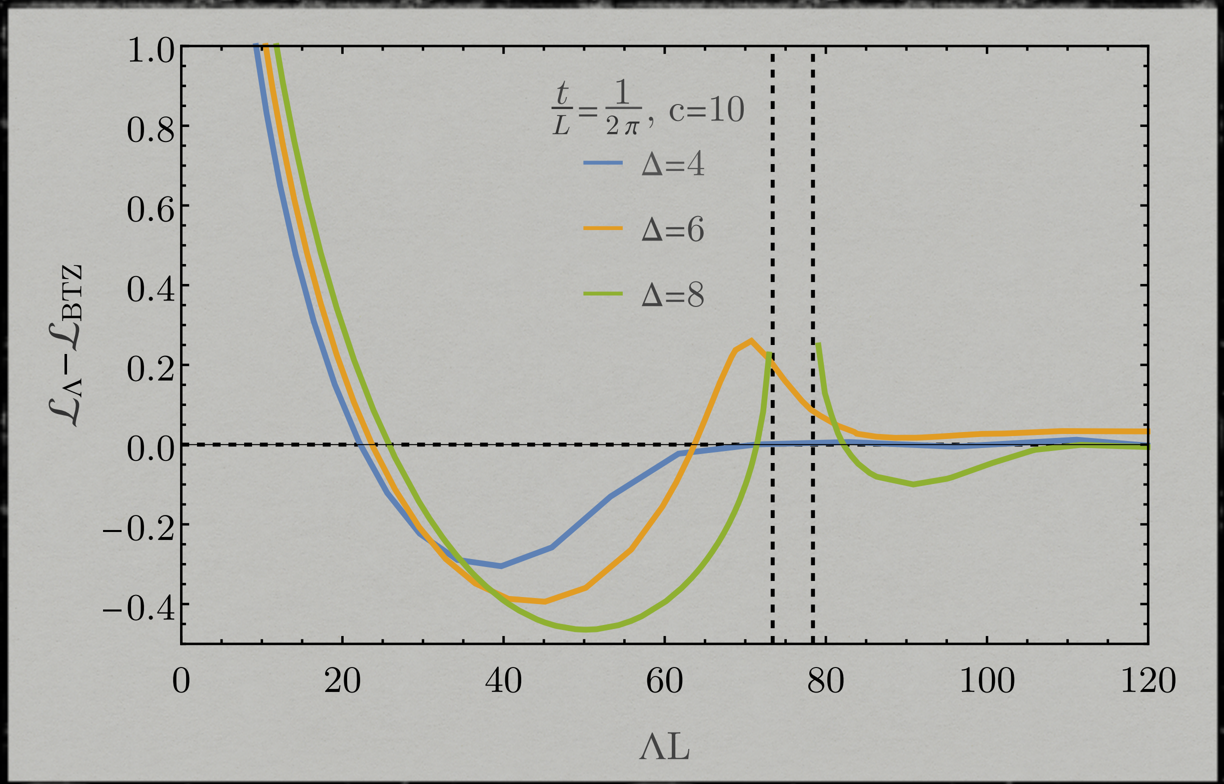
4- Disentangling experiment

t≠0, β fixed, cutoff dependence



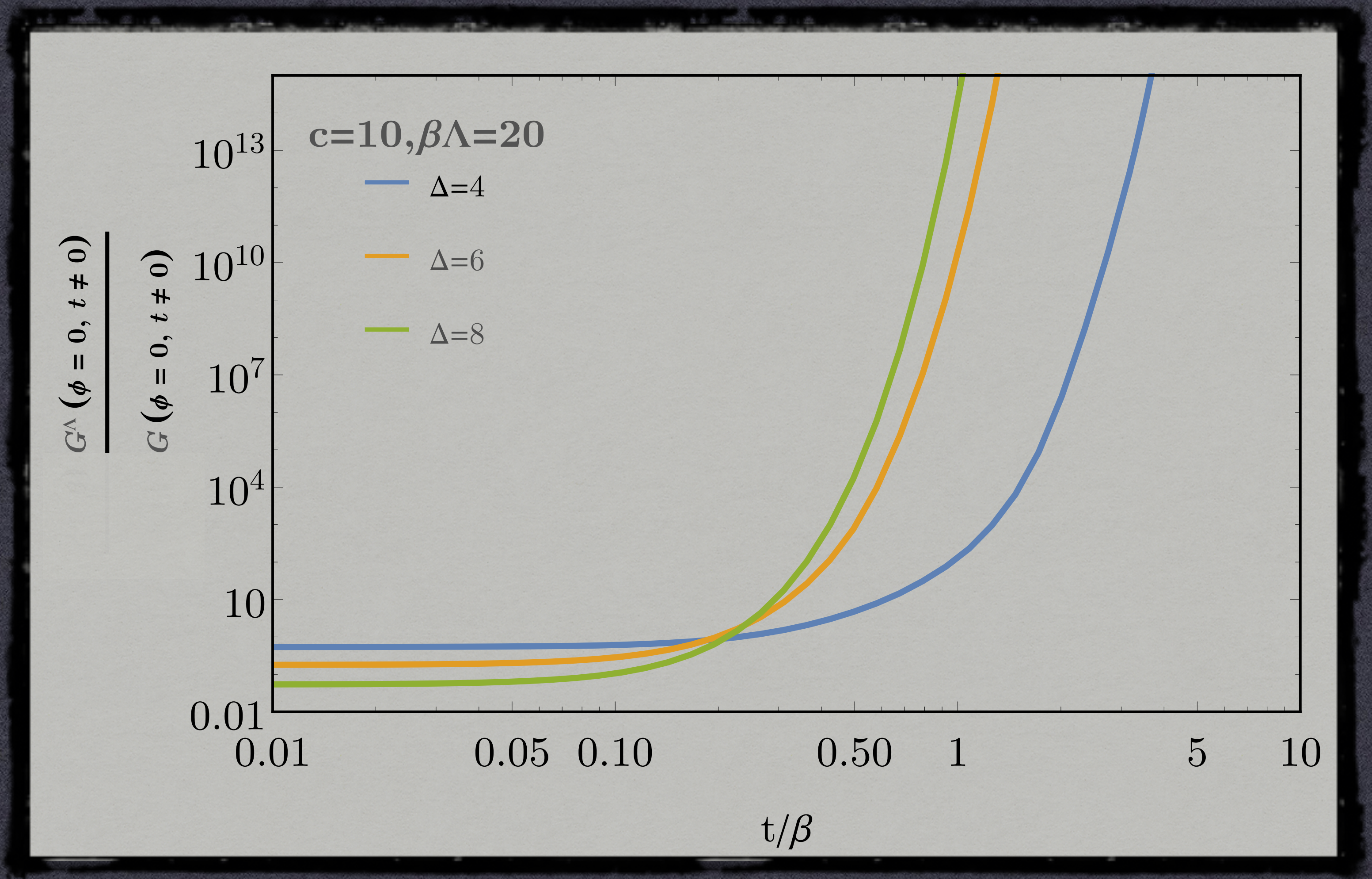






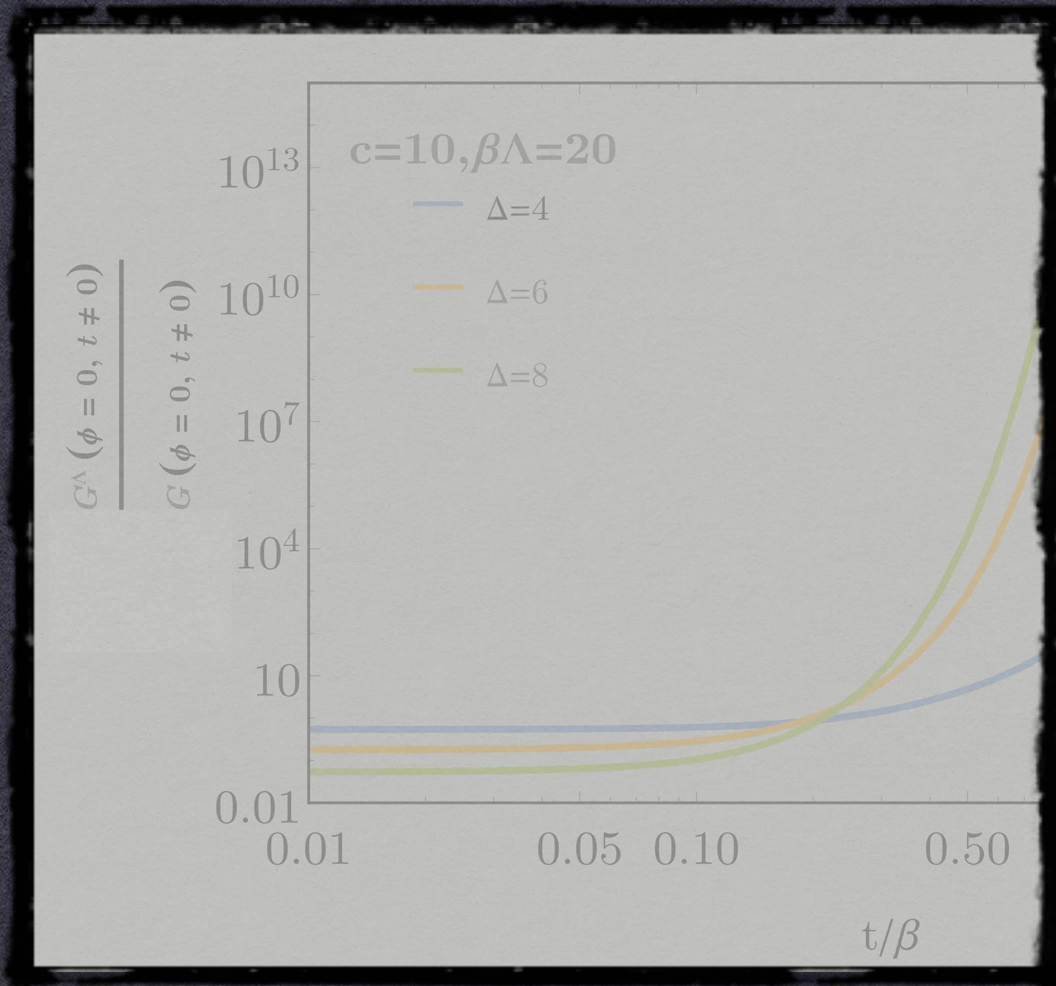
4- Disentangling experiment

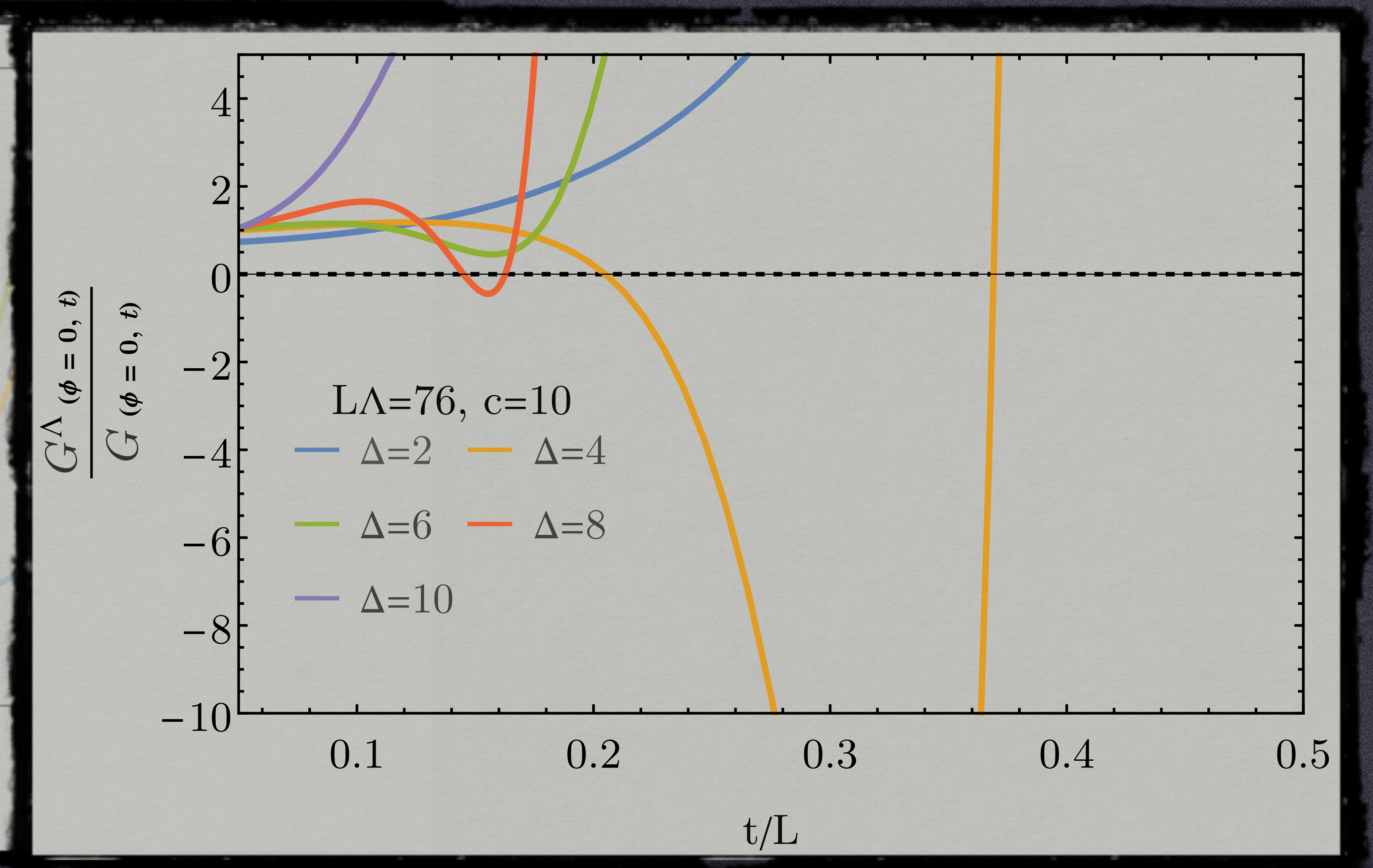
βΛ fixed, time dependence



4- Disentangling experiment

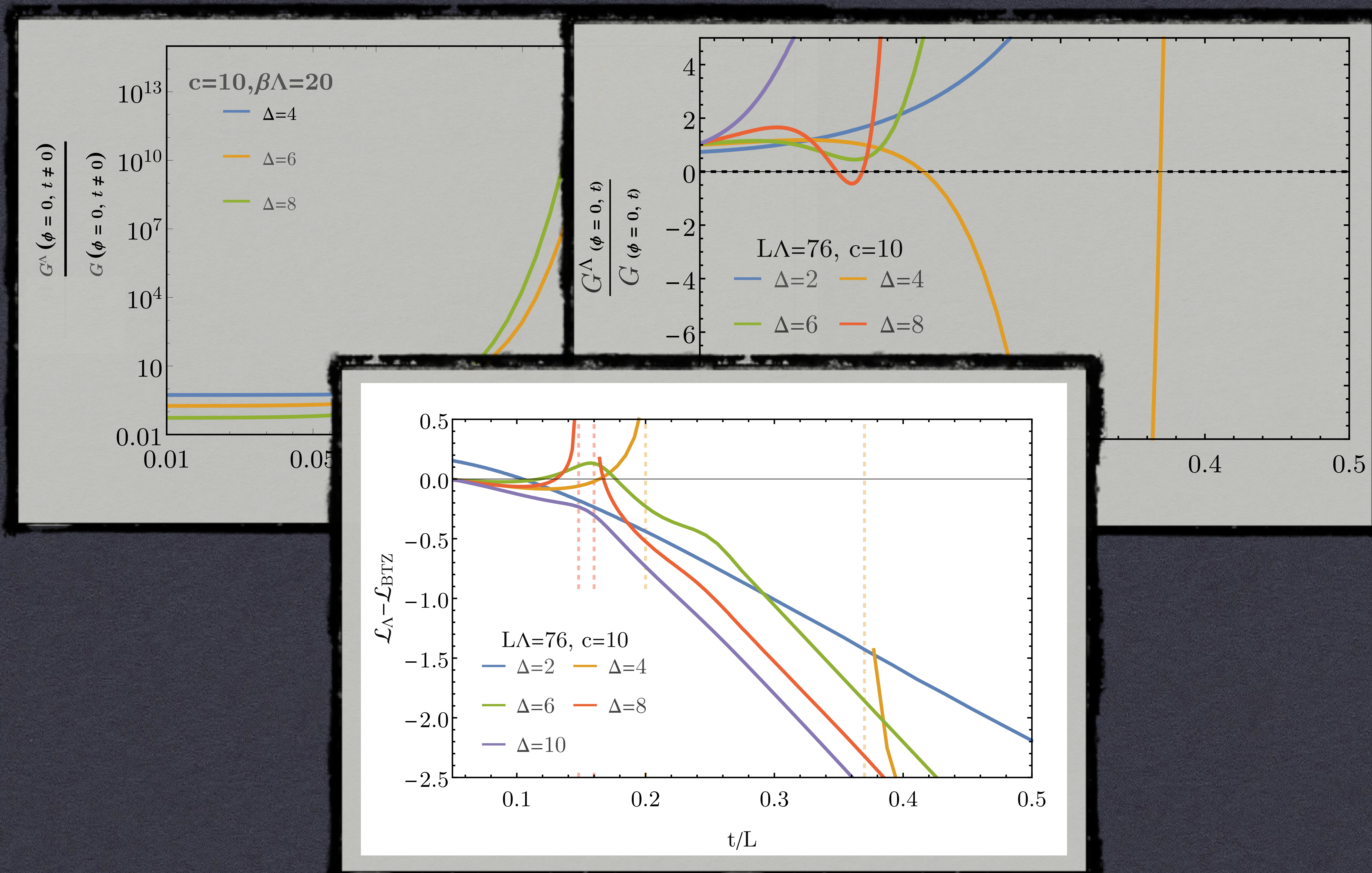
$\beta\Lambda$ fixed, time dependence





4- Disentangling experiment

βΛ fixed, time dependence



Wightman with arbitrary entanglement

$$|\Lambda\rangle \equiv \frac{1}{\sqrt{Z_\Lambda}} \sum_{a|E_a \le \Lambda} e^{-\beta E_a/2} |a\rangle |a\rangle \to \ |\Psi\rangle \equiv \frac{1}{\sqrt{Z_\Psi}} \sum_a \Psi(E_a) |a\rangle |a\rangle$$

$$Z_\Psi = \sum_a |\Psi(E_a)|^2 < \infty$$

Wightman with arbitrary entanglement

$$|\Lambda\rangle \equiv \frac{1}{\sqrt{Z_\Lambda}} \sum_{a|E_a \le \Lambda} e^{-\beta E_a/2} |a\rangle |a\rangle \rightarrow \quad |\Psi\rangle \equiv \frac{1}{\sqrt{Z_\Psi}} \sum_a \Psi(E_a) |a\rangle |a\rangle$$

$$Z_\Psi = \sum_a |\Psi(E_a)|^2 < \infty$$

$$\langle \Psi | \mathcal{O}(t) \otimes \mathcal{O}(0) | \Psi \rangle$$

$$= \frac{1}{Z_\psi} \int_{-\infty}^{\infty} \mathrm{d}\chi e^{-i\chi t} \int_{|\chi|/2}^{\infty} \mathrm{d}E \ \Psi^* \left(E + \frac{\chi}{2}\right) \Psi \left(E - \frac{\chi}{2}\right) \rho \left(E + \frac{\chi}{2}\right) \rho \left(E - \frac{\chi}{2}\right) \mathcal{F}(E, \chi, \Delta)$$

CONCLUSIONS

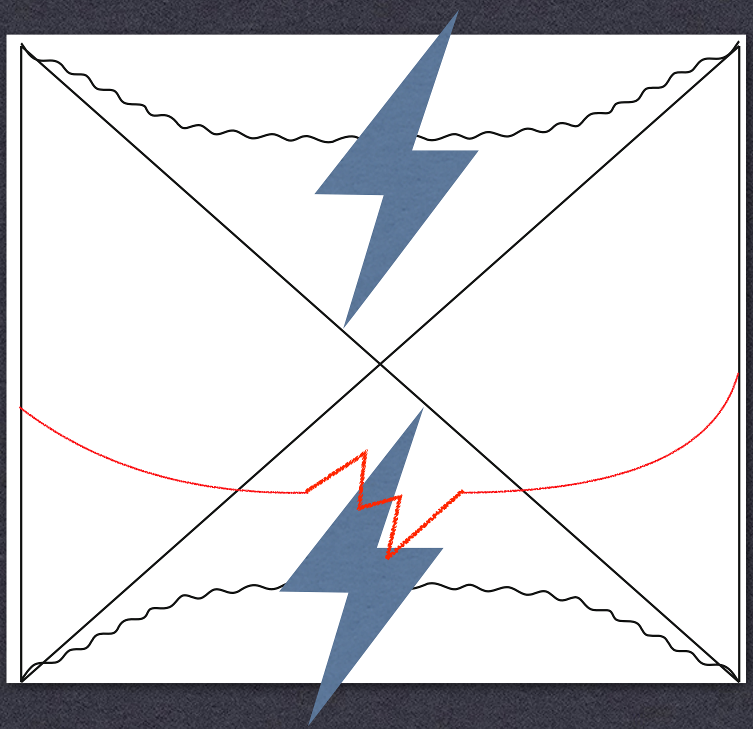
- Obtained $\overline{\langle a|O|b\rangle^2} \equiv \mathcal{F}(E,\chi,\Delta)$

If ETH is at work $\rho(E)\mathcal{F}(E,\chi,\Delta) = O(E)^2\delta_{\hat{\delta}}(\chi) + f(E,\chi)^2 R_{ab}$

- Disentangling the TFD:

$$G^{\Lambda}(t_{12},\phi_{12}) = \frac{1}{Z^{\Lambda}(\beta)} \sum_{\substack{ab \\ E_a, E_b < \Lambda}} e^{-\beta\frac{E_a+E_b}{2}} e^{-it_{12}E_{ab}} |\langle a|O|b\rangle|^2$$

Dramatic behaviour of the geometry as measured using the geodesic approximation with $G^{\Lambda}(t_{12},\phi_{12})$



- Change in the geometry must be nonlocal due to Killing symmetry

CONCLUSIONS

What else?

- Repeat on the circle?
- Use $\overline{\langle a \,|\, O \,|\, b \rangle^2} \equiv \mathscr{F}(E, \chi, \Delta)$ for some time evolution/quench?
- Interpretation of 'disentangling experiment' in terms of geometric objects?

  Perhaps recasting this with conformal blocks and use interpretation in terms of geodesic Witten diagrams