DIAS
Danish Institute for Advanced Study

University of Southern Denmark

Beyond QCD

Francesco Sannino

CP^3 - Origins
Particle Physics & Cosmology

QCD @ Work 2012

Riddles

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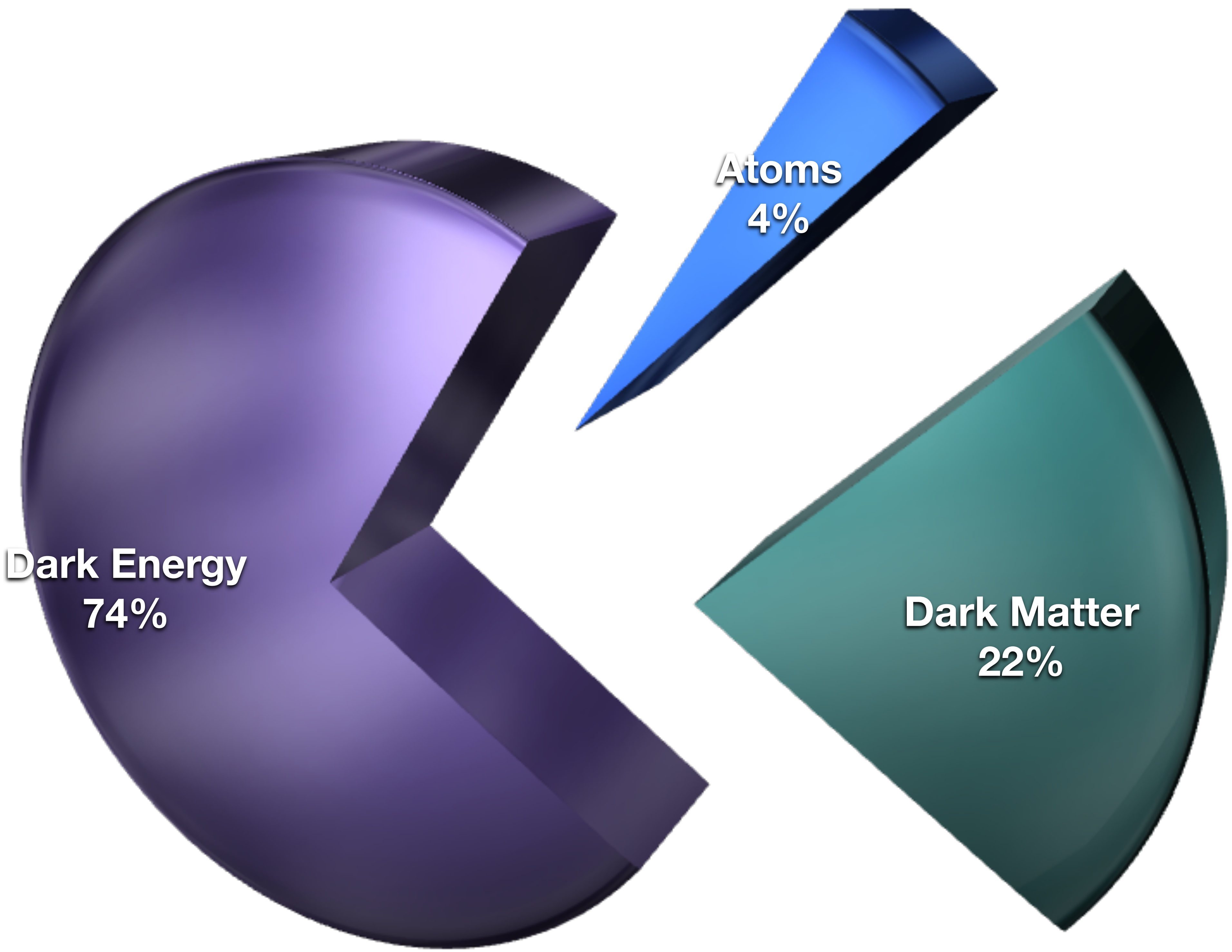

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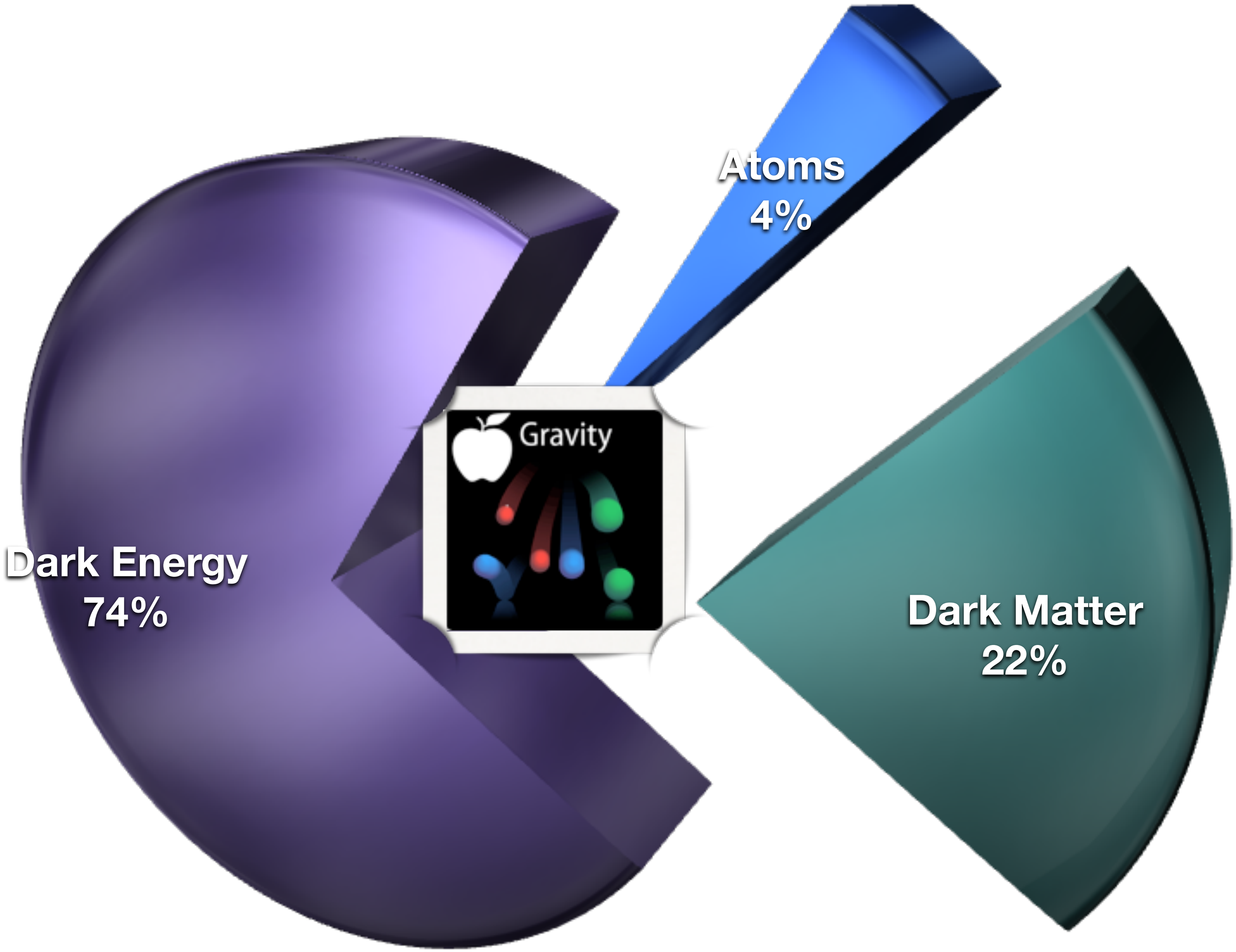

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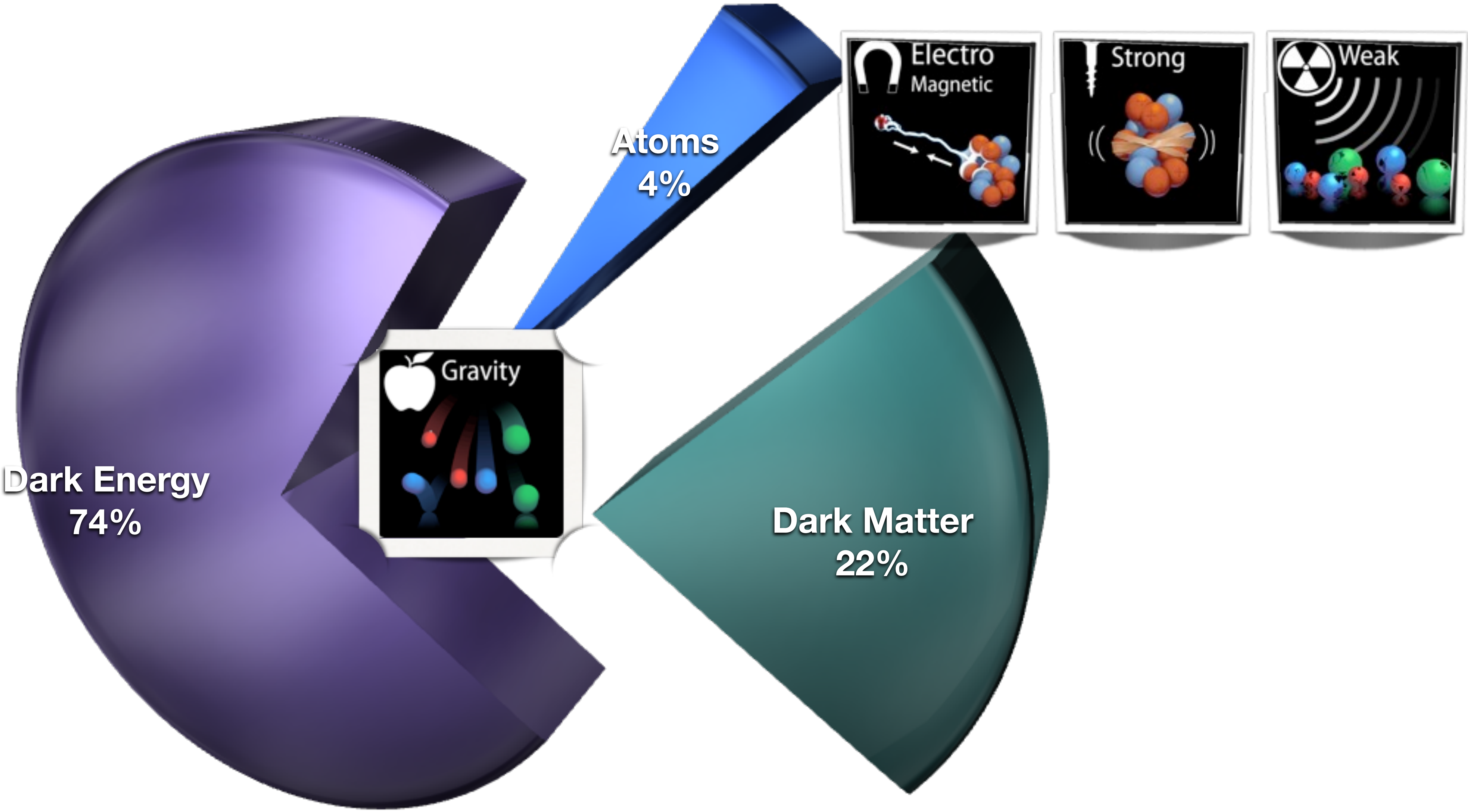
Atoms
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Electro
Magnetic
Strong
Weak
Gravity
Dark Energy
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Dark Matter
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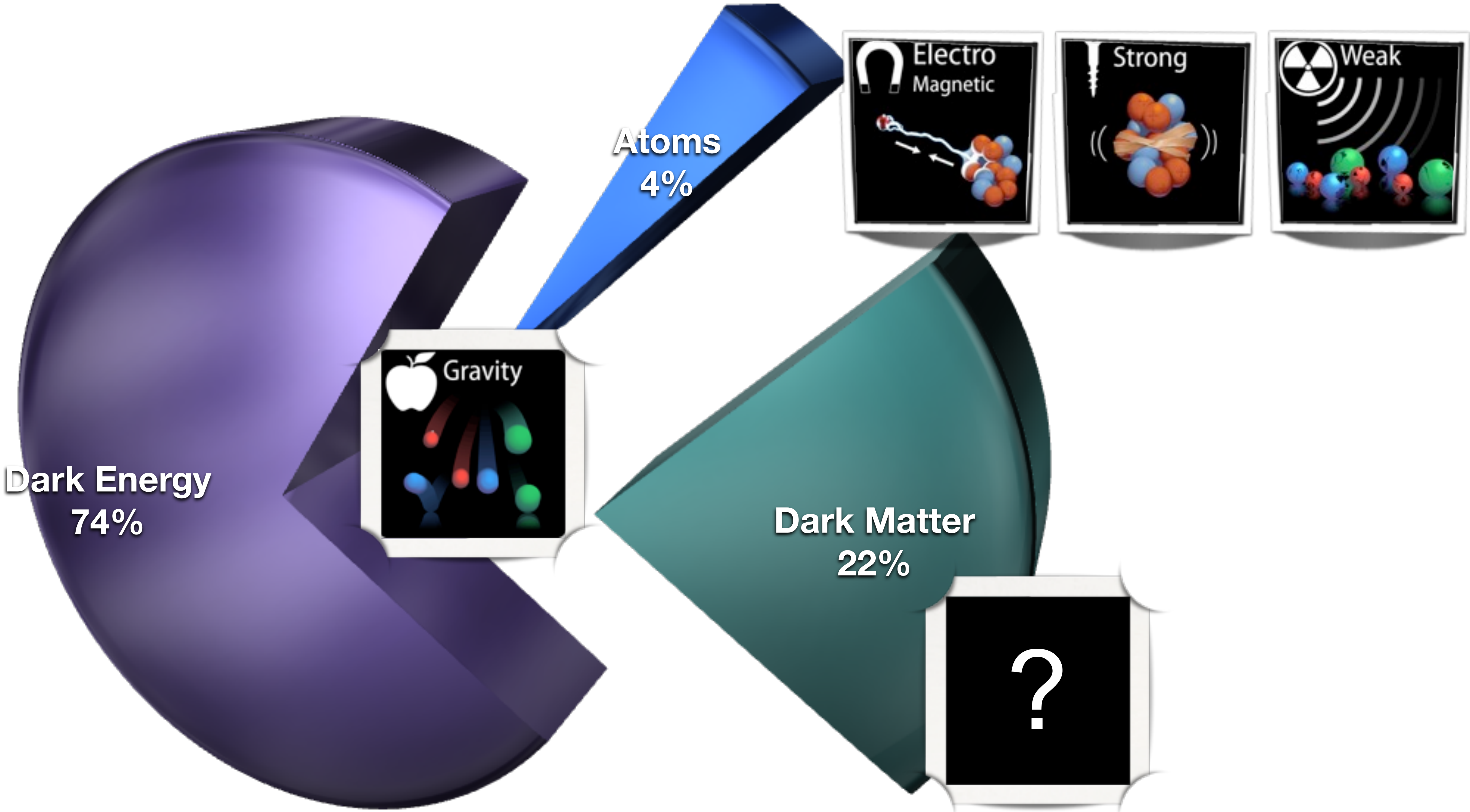

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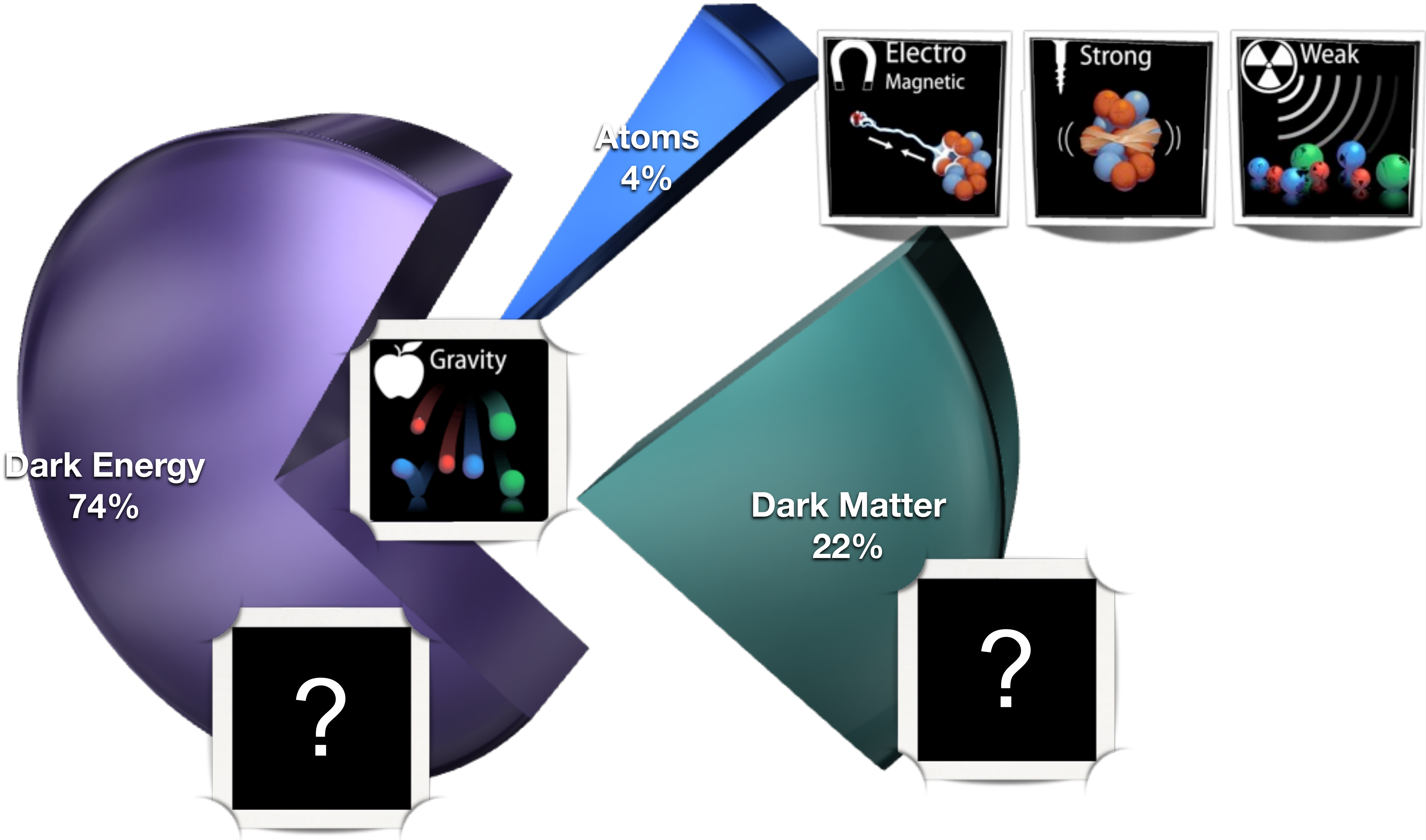
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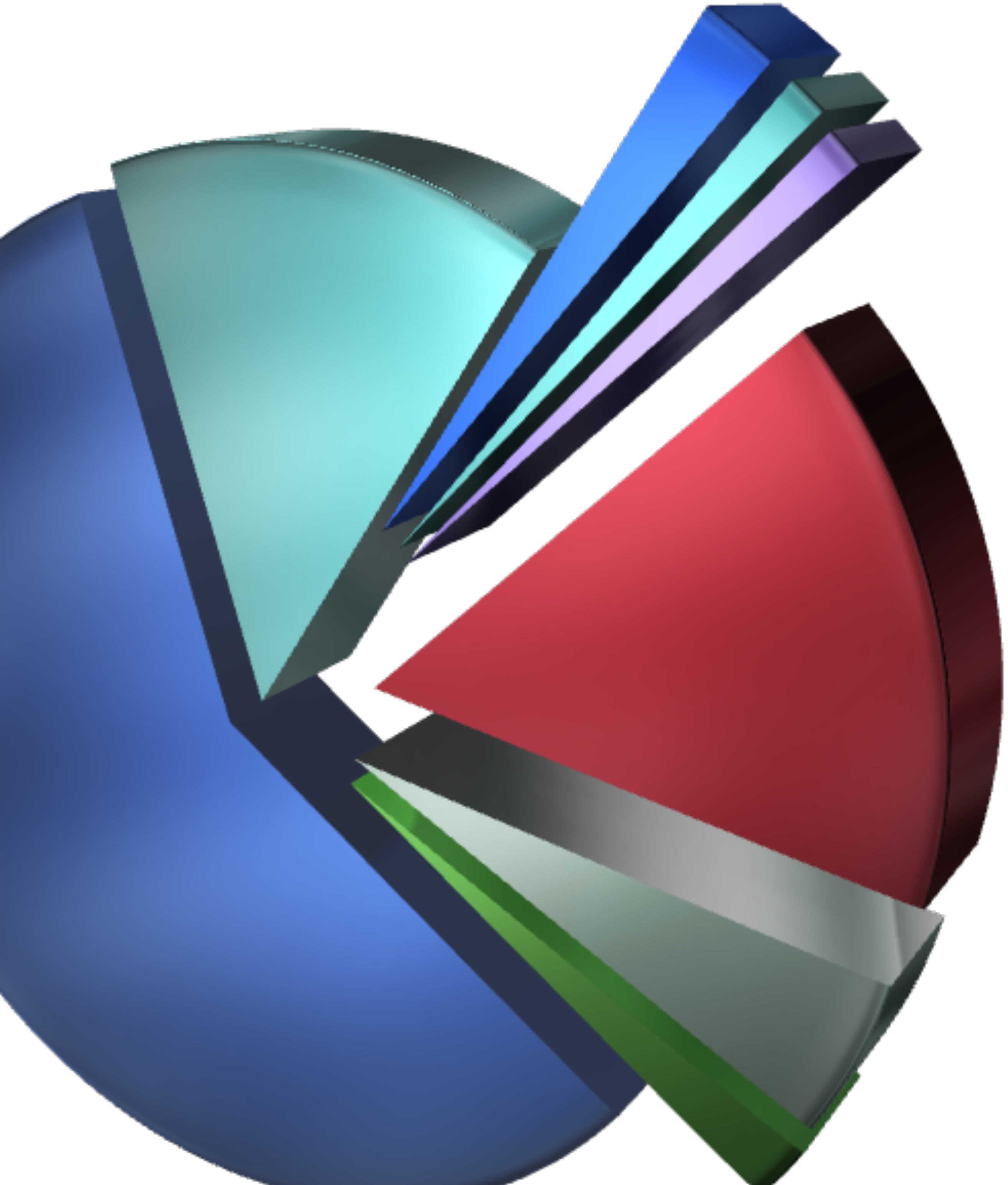

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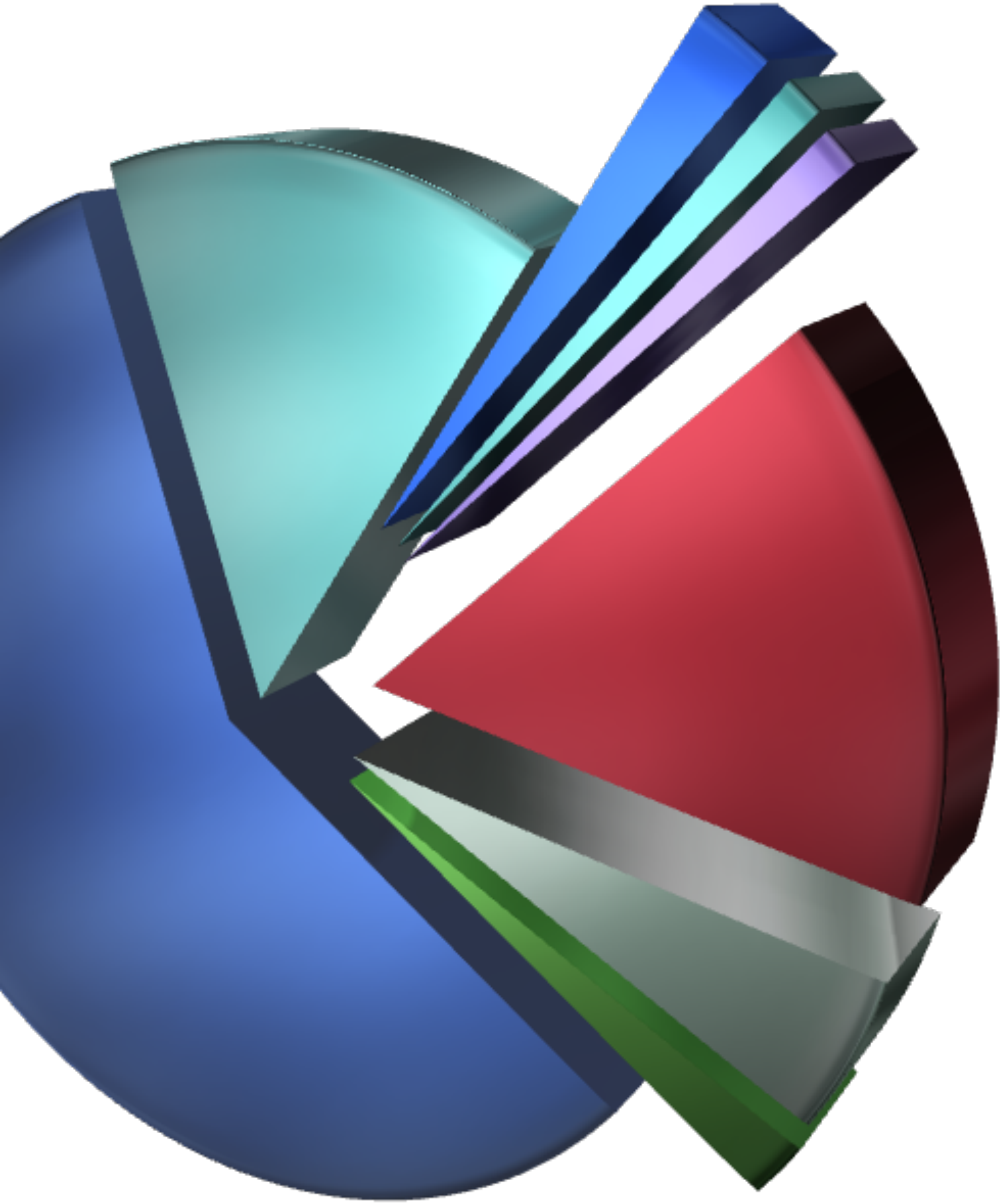

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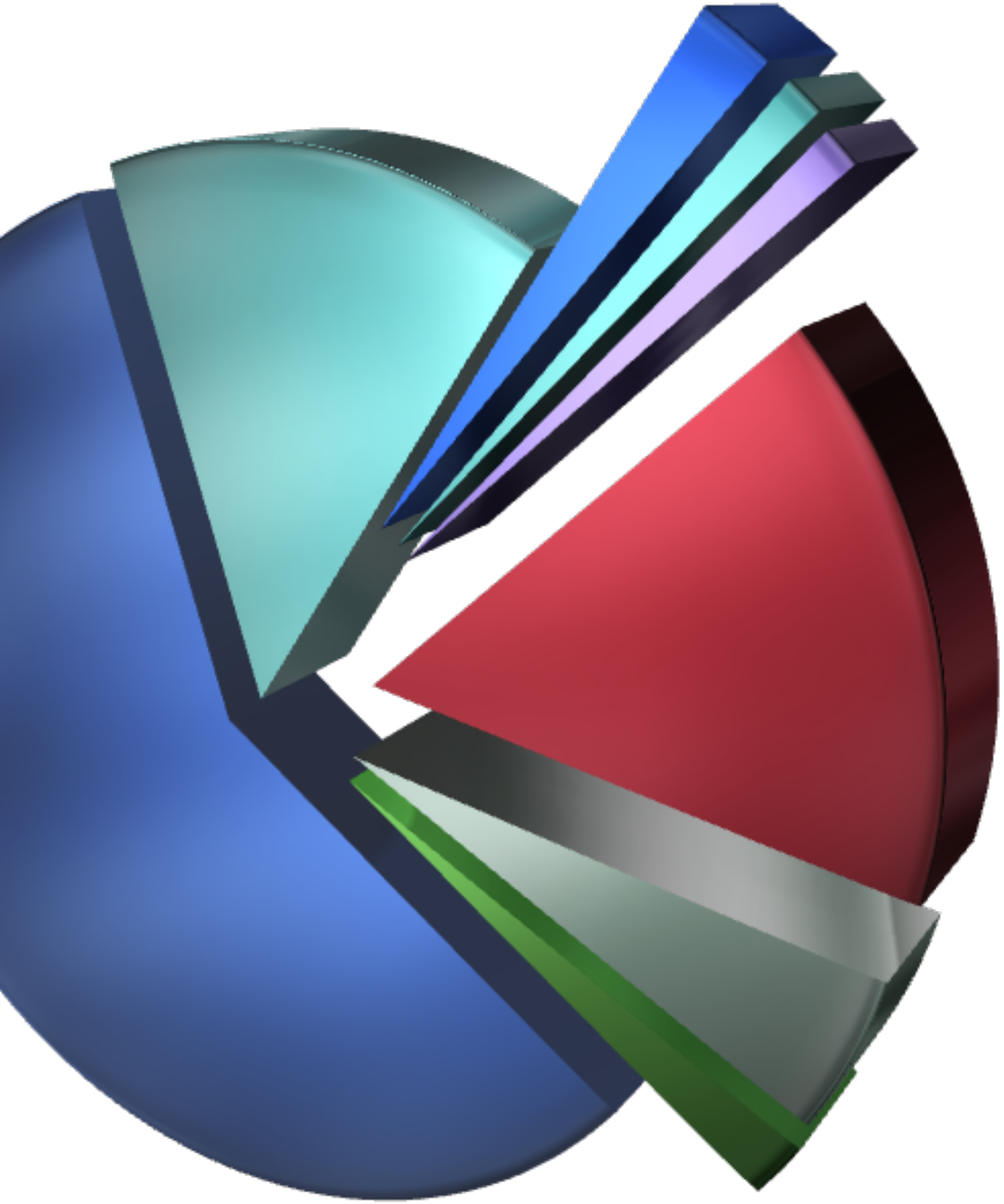
Beyond QCD @ Work



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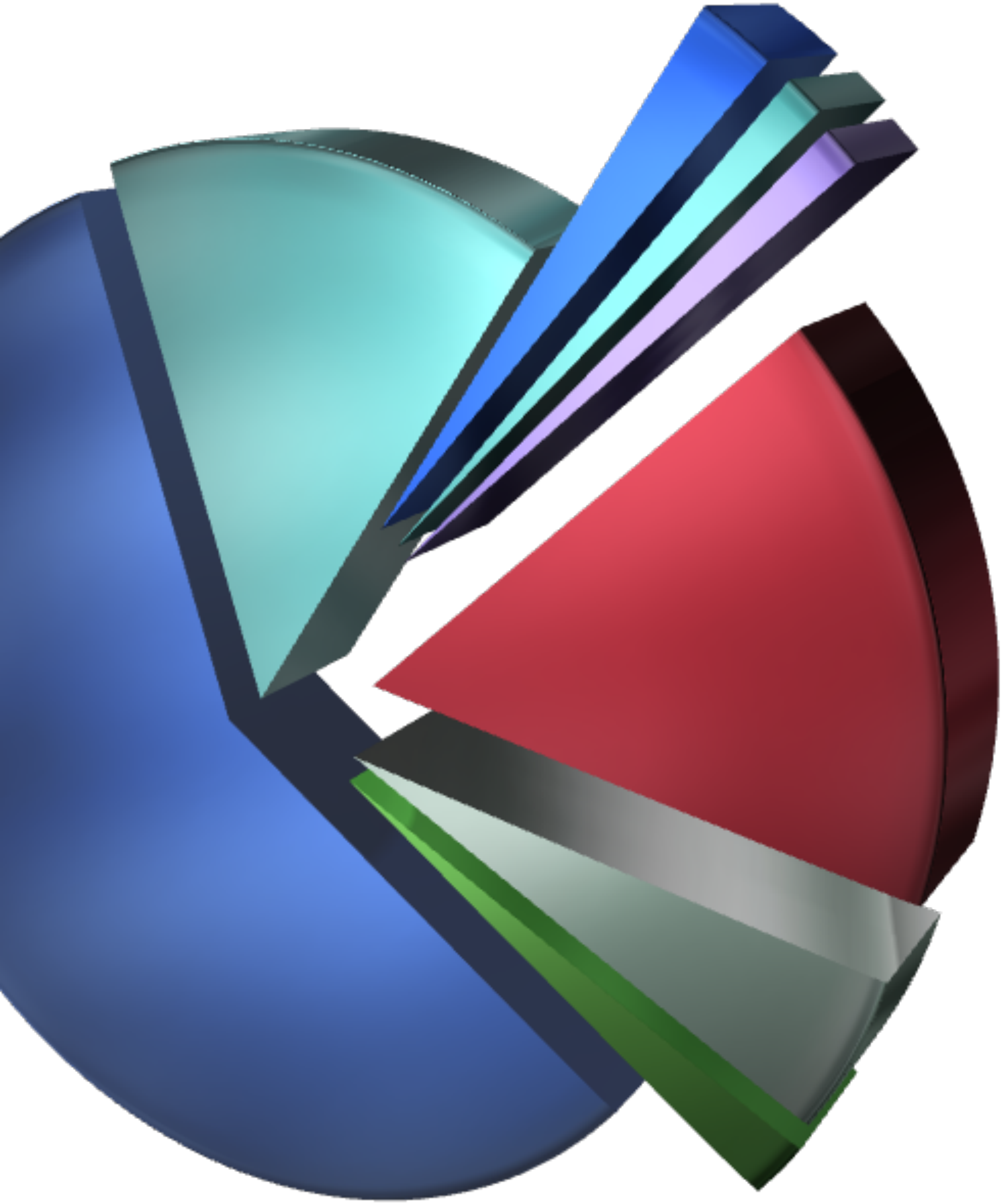

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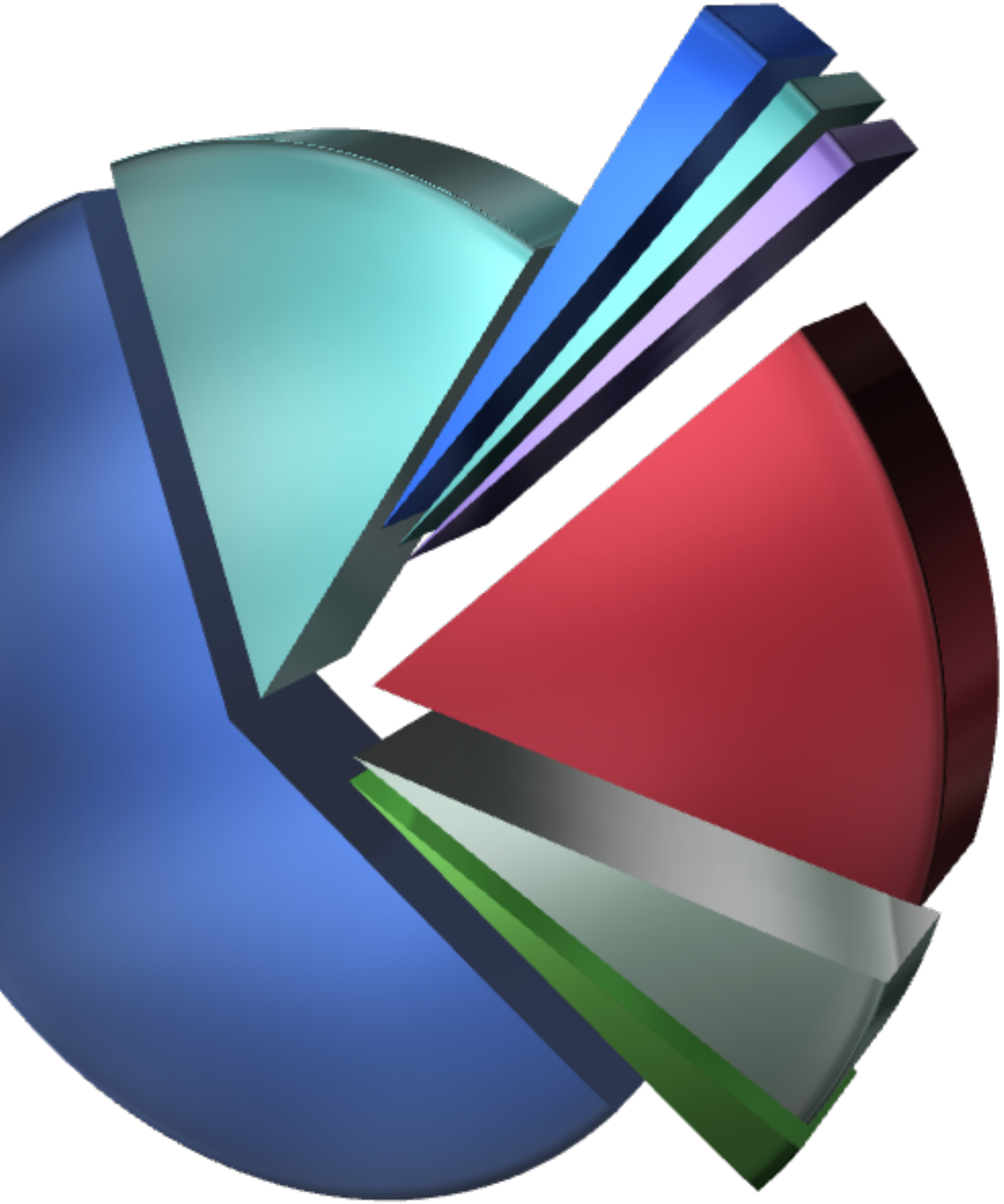

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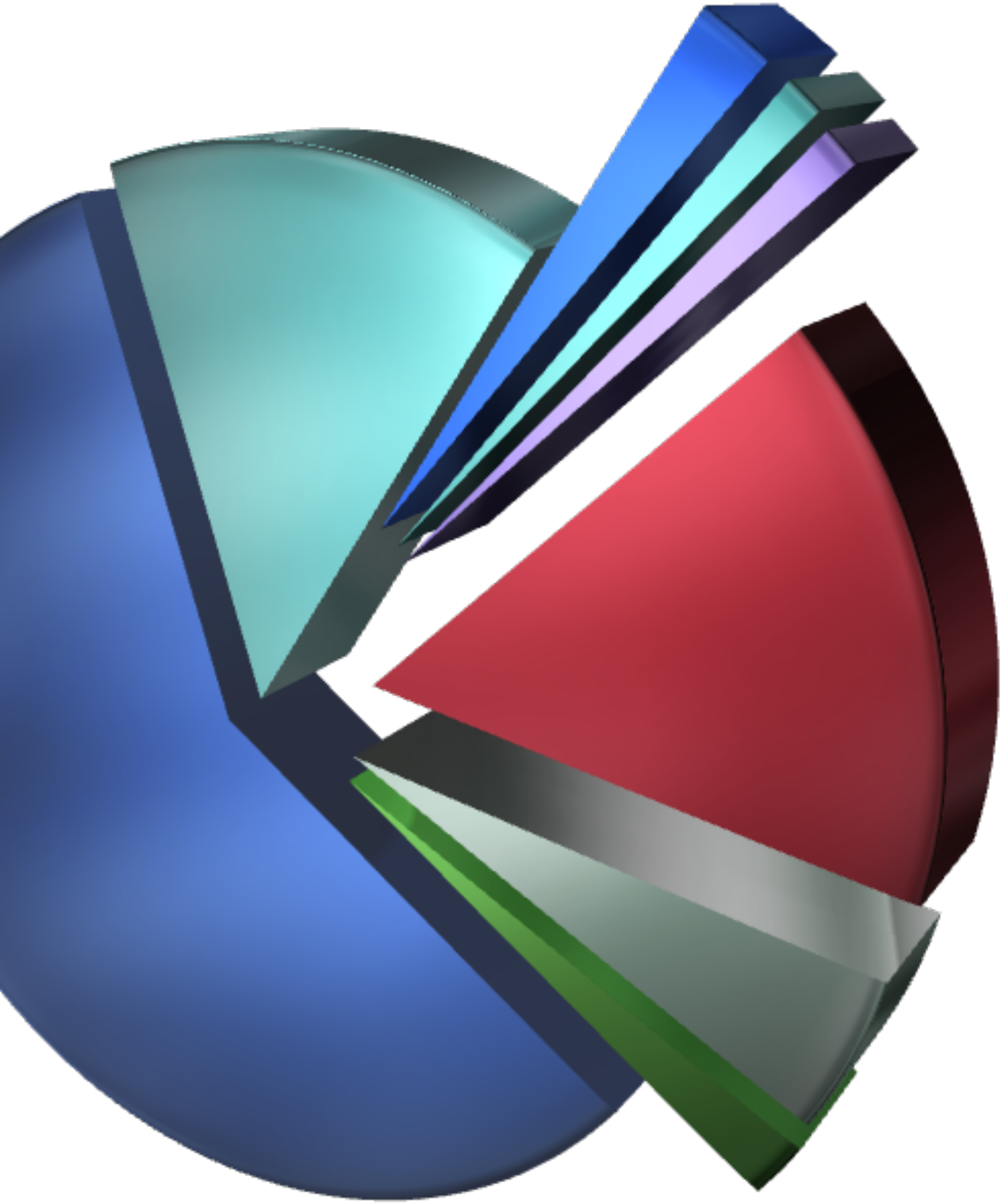

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$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246 \text{ GeV}$$

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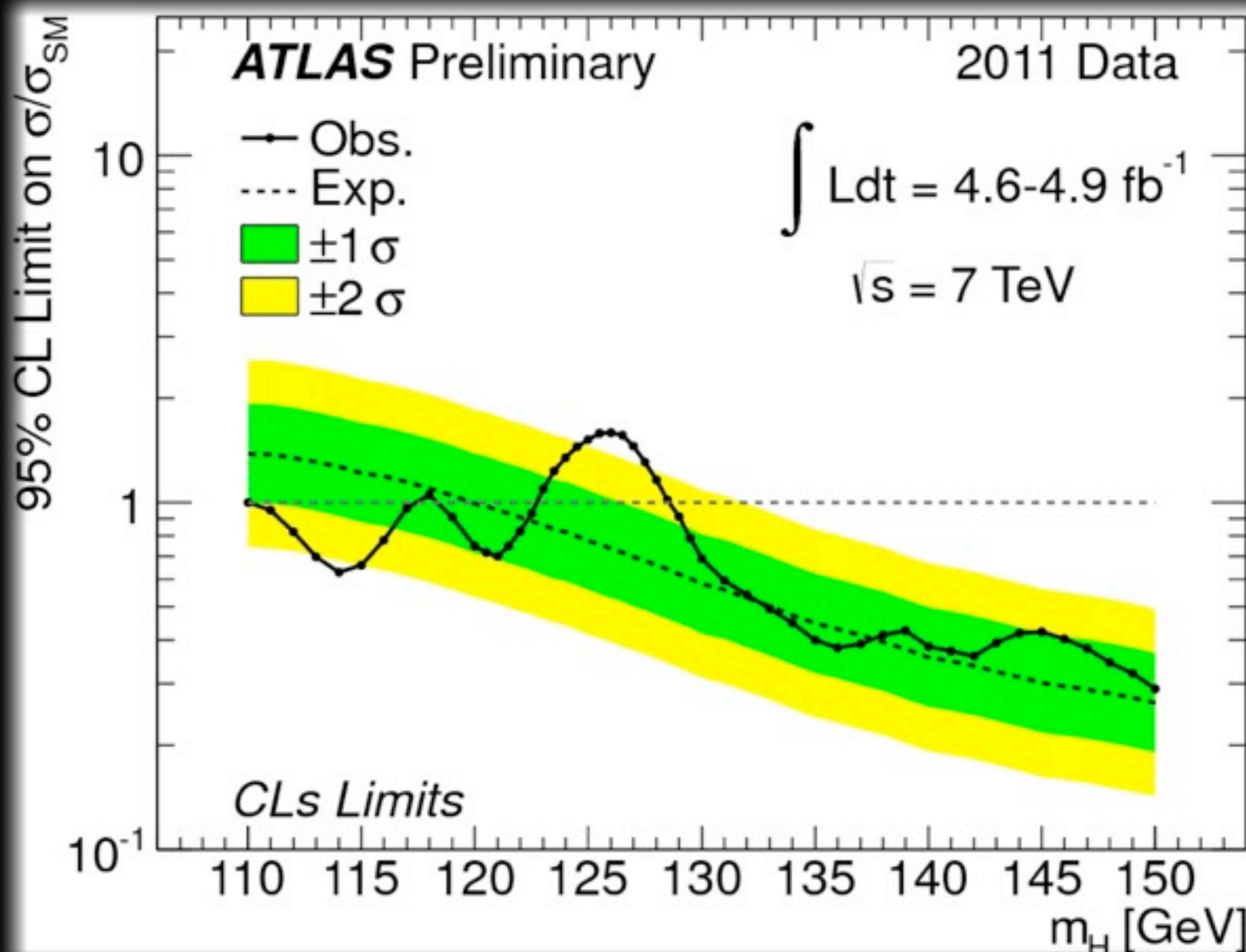
Light quarks and leptons are also natural!

O' Higgs, where art thou!



Excluded @ 95% CL

$$112.7 < M_H < 115.5 \text{ GeV}$$

$$131 < M_H < 453 \text{ GeV}$$ except $$237 - 251 \text{ GeV}$$

What if Higgs-like state is there?

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$$\frac{M_H}{1.2\ \mathrm{TeV}} \simeq 0.1$$

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Dietrich, Sannino, Tuominen hep-ph/0510217

Dietrich, Sannino hep-ph/0611341

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Grinstein, Uttayarat 1105.2370
Antipin, Mojaza, Sannino 1107.2932

A new particle?

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- Maybe yes

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✴ In line with Technicolor ?

Technicolor

Dynamical EW Breaking

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$$\cdots \qquad \rightarrow \qquad L(\text{New SM Fermions})$$

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New Strong Interactions at ~ 250 GeV

[Weinberg, Susskind]

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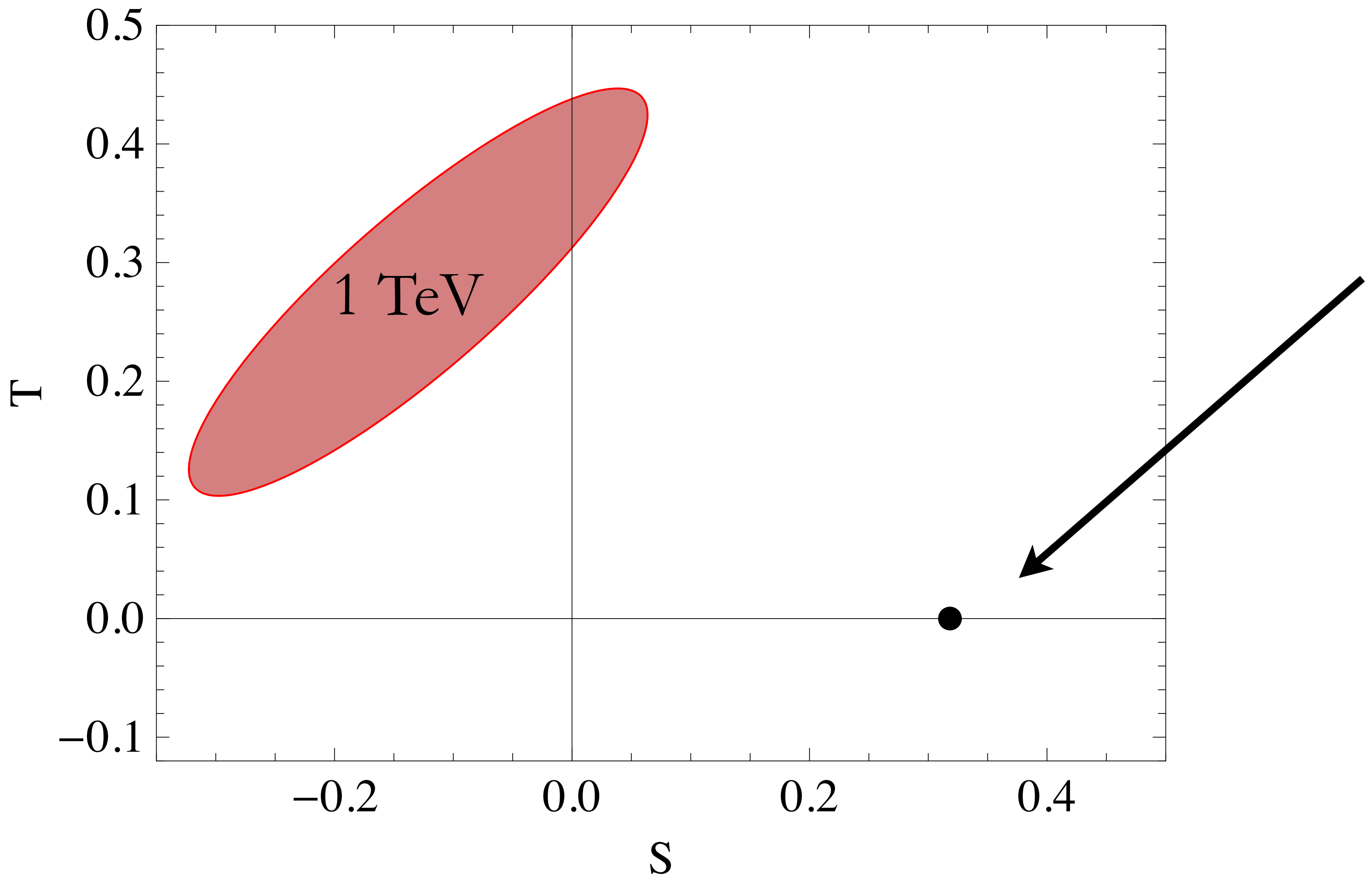
$$\langle Q^f \widetilde{Q}_{f'} \rangle = \Lambda_{TC}^3 \qquad \Lambda_{TC} \simeq 1 \text{ TeV}$$

Need novel dynamics



SU(3) + 1 Fund. Doublet

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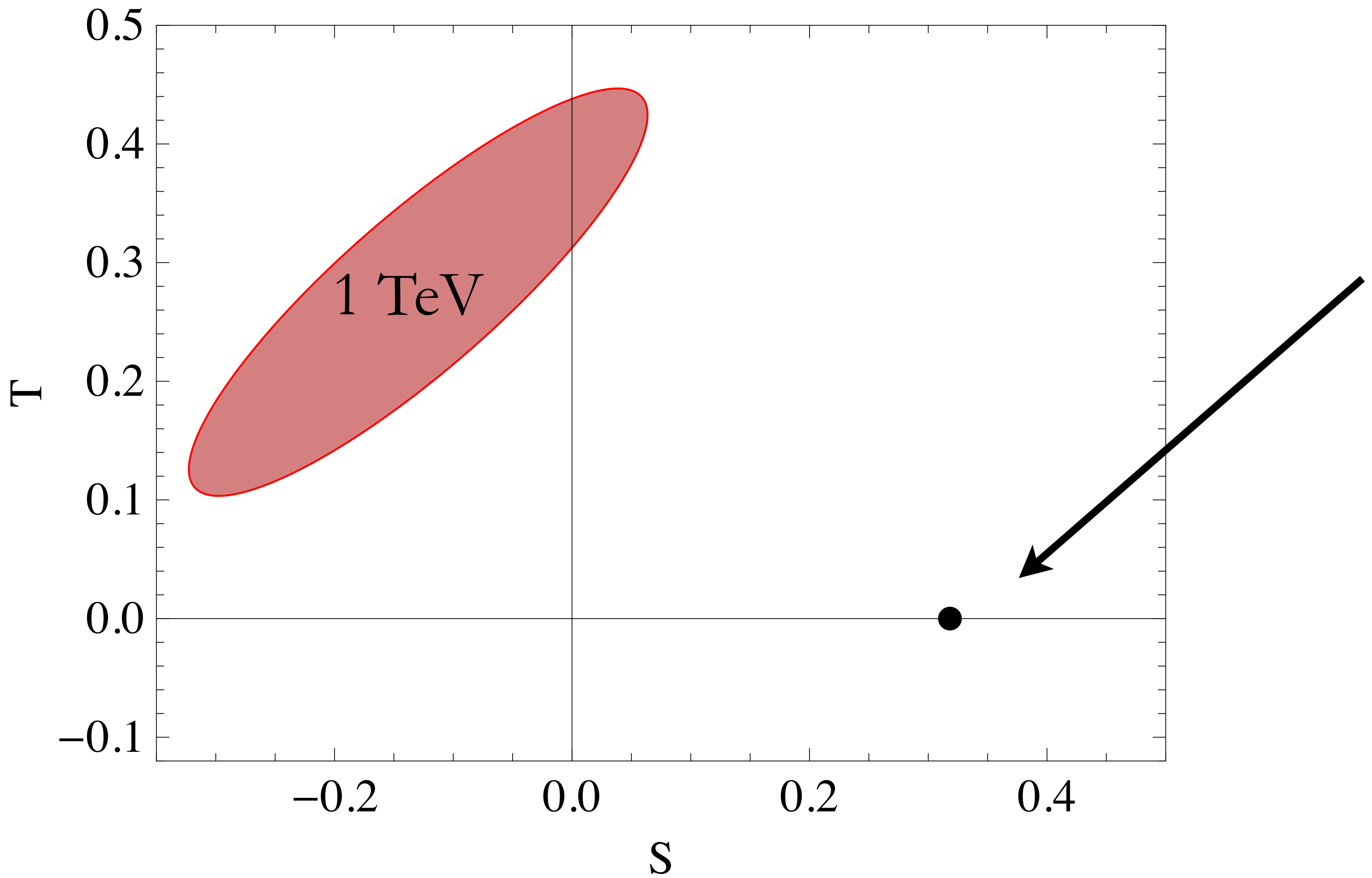

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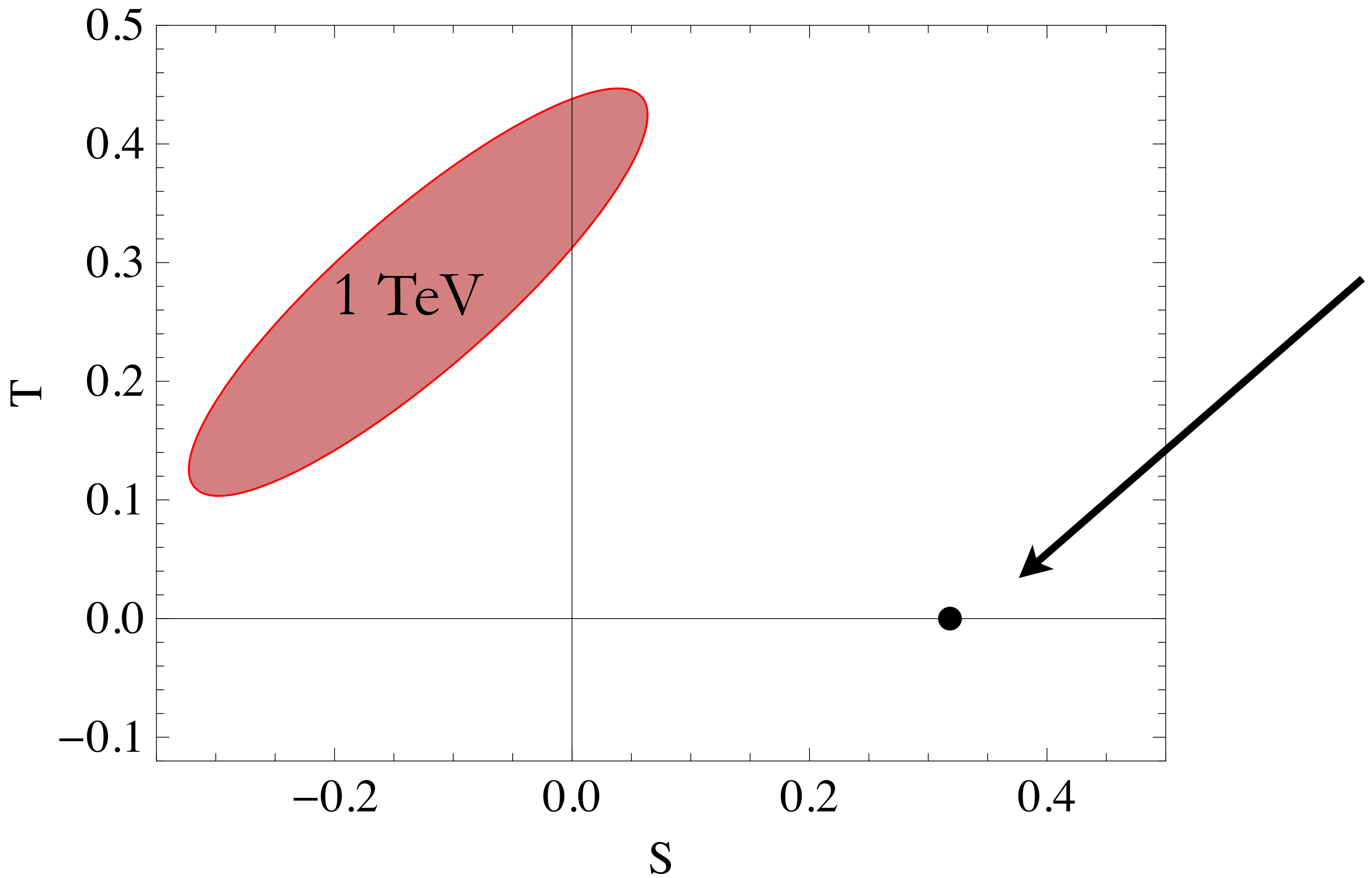

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- Extend TC works if flavor decouples from the EW scale

Walking

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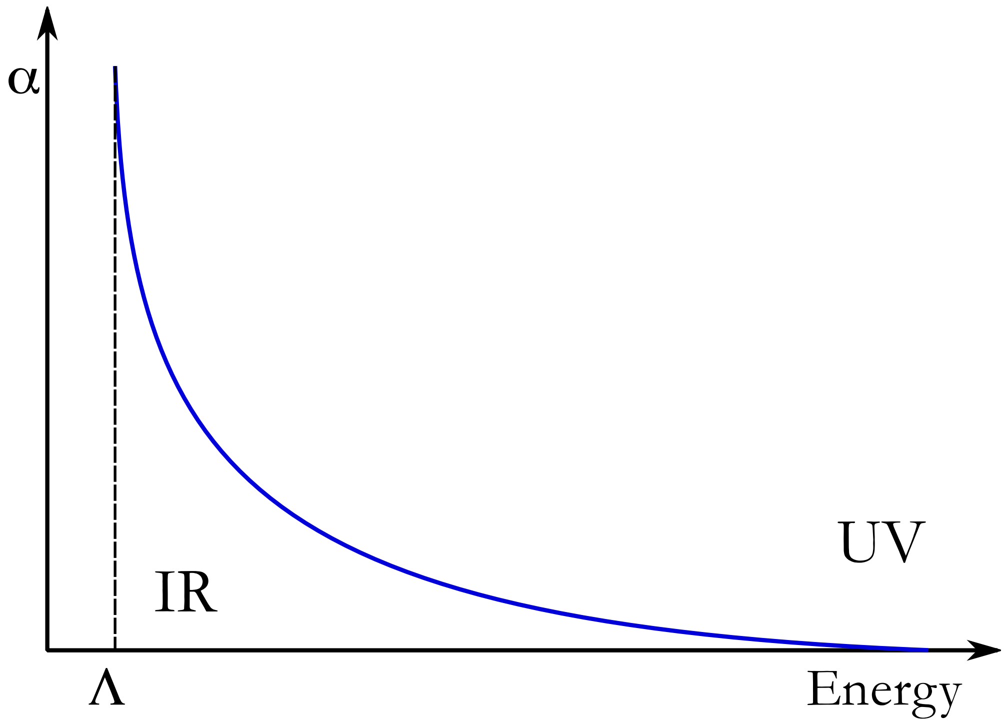

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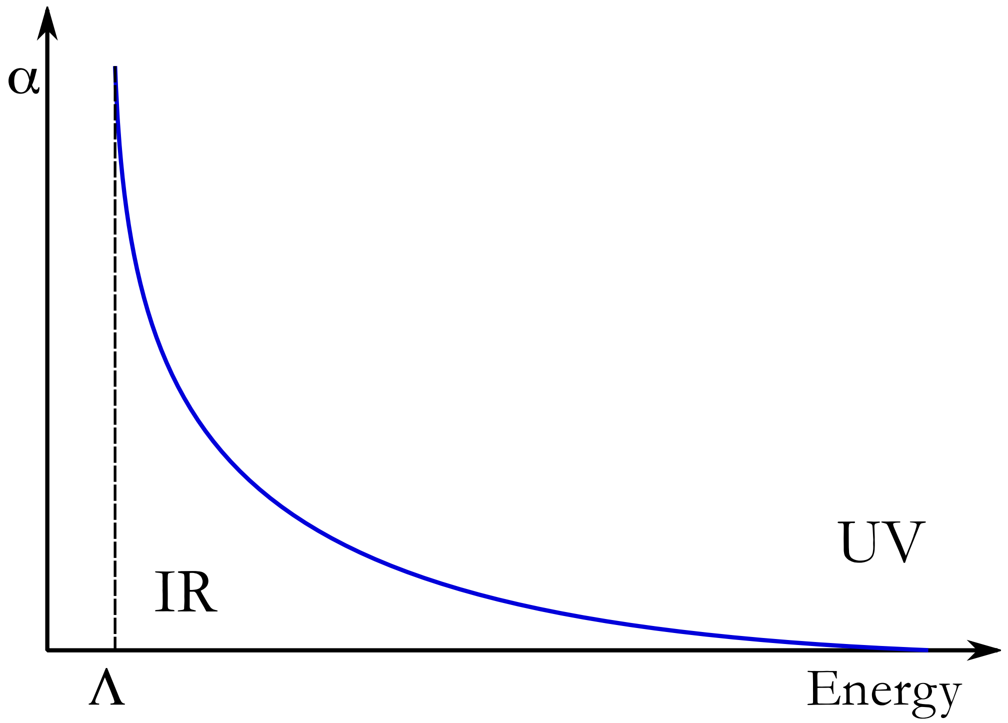

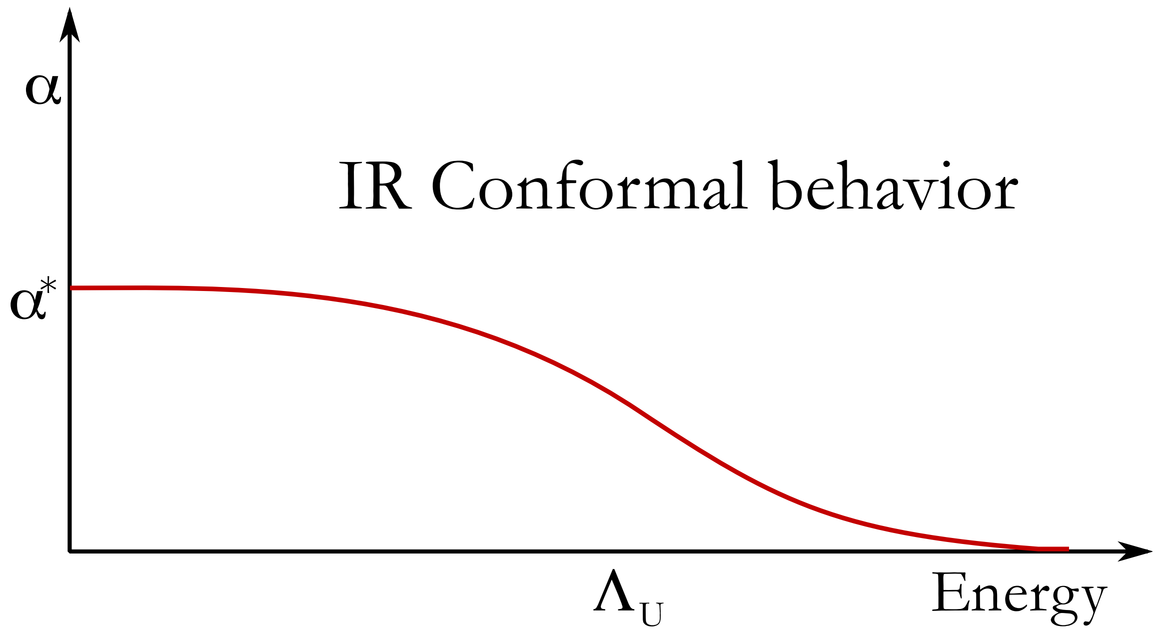

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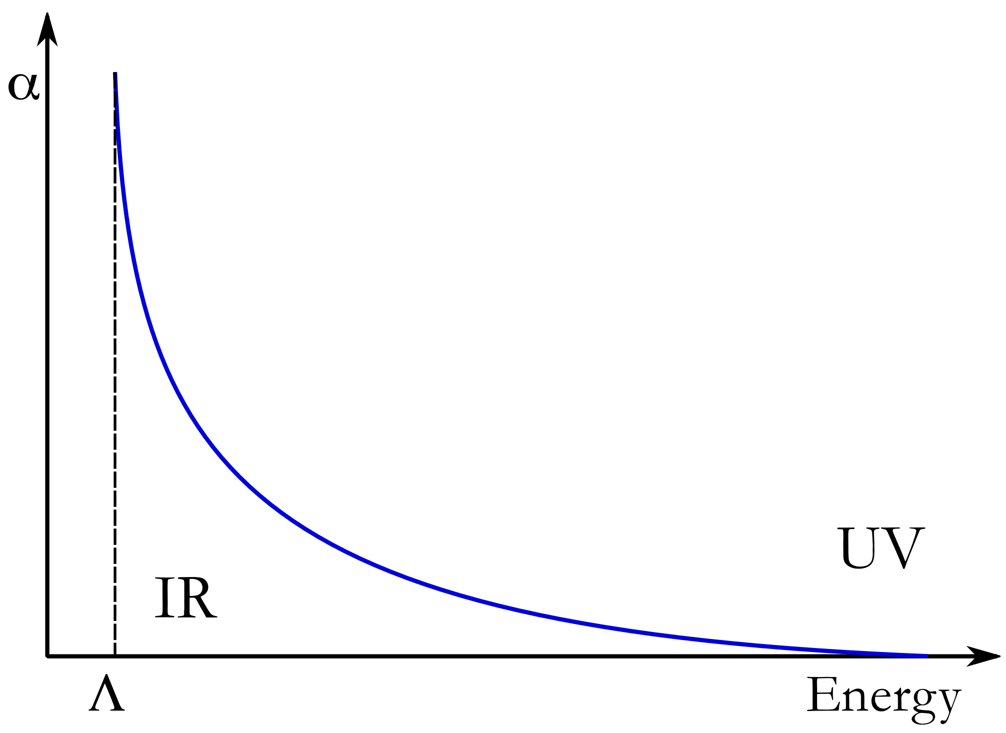

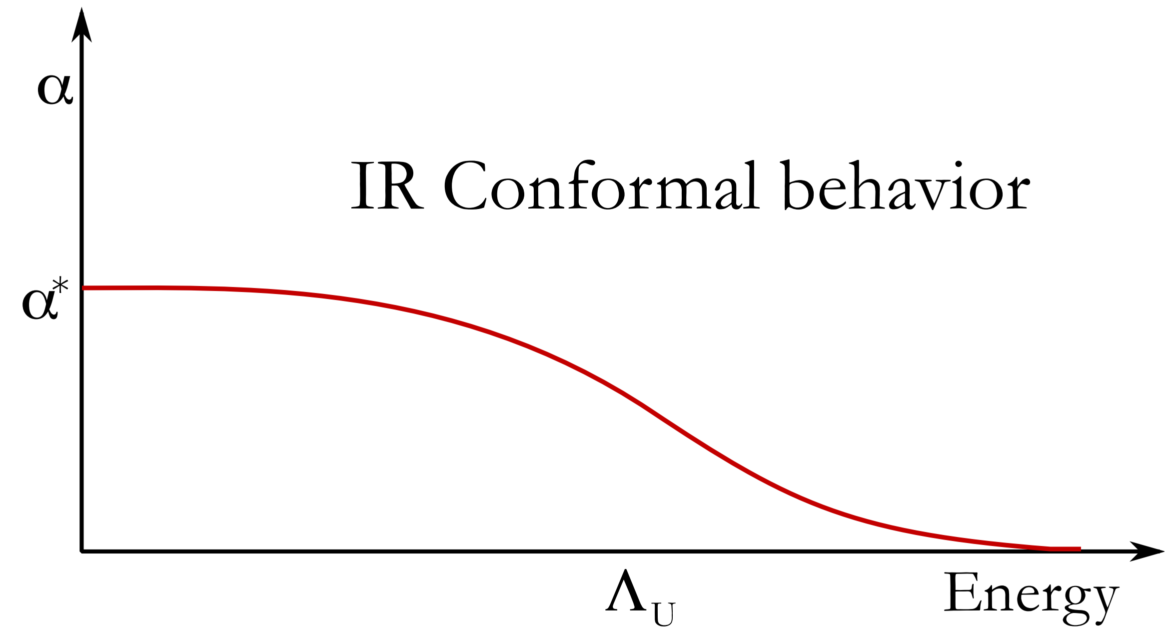

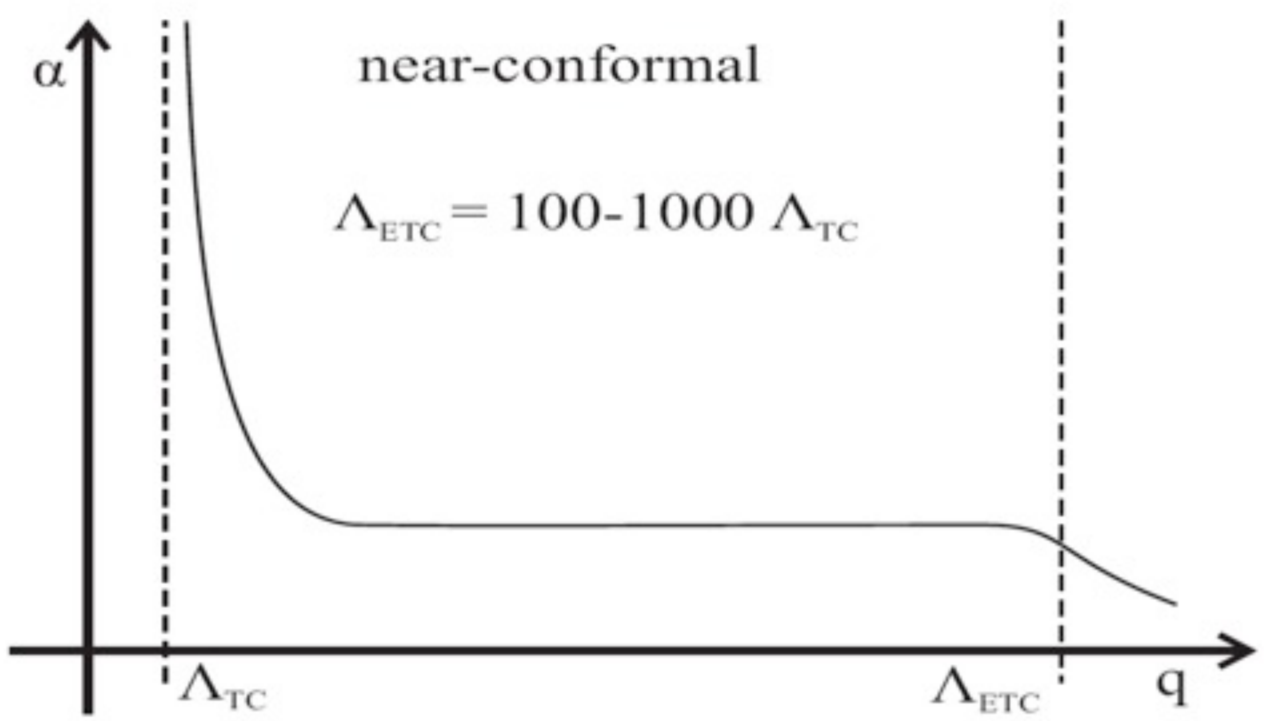

Holdom,

Appelquist, Miranski, Yamawaki, Wijewardhana...

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Matter Representation

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# of Flavors per Representation

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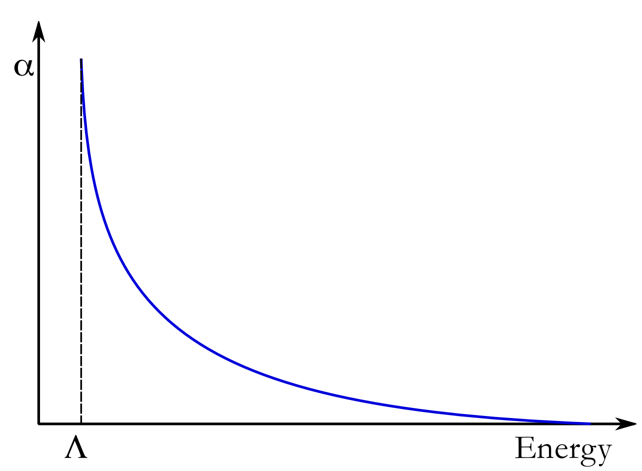

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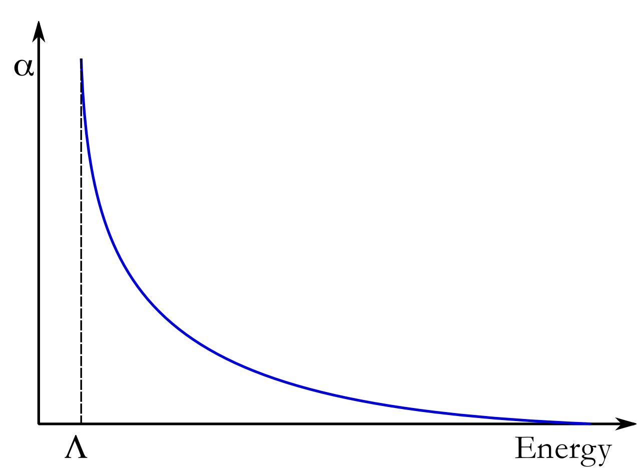

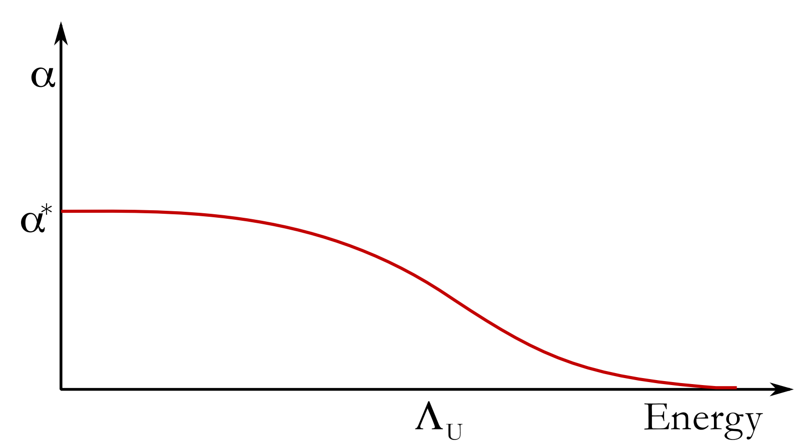

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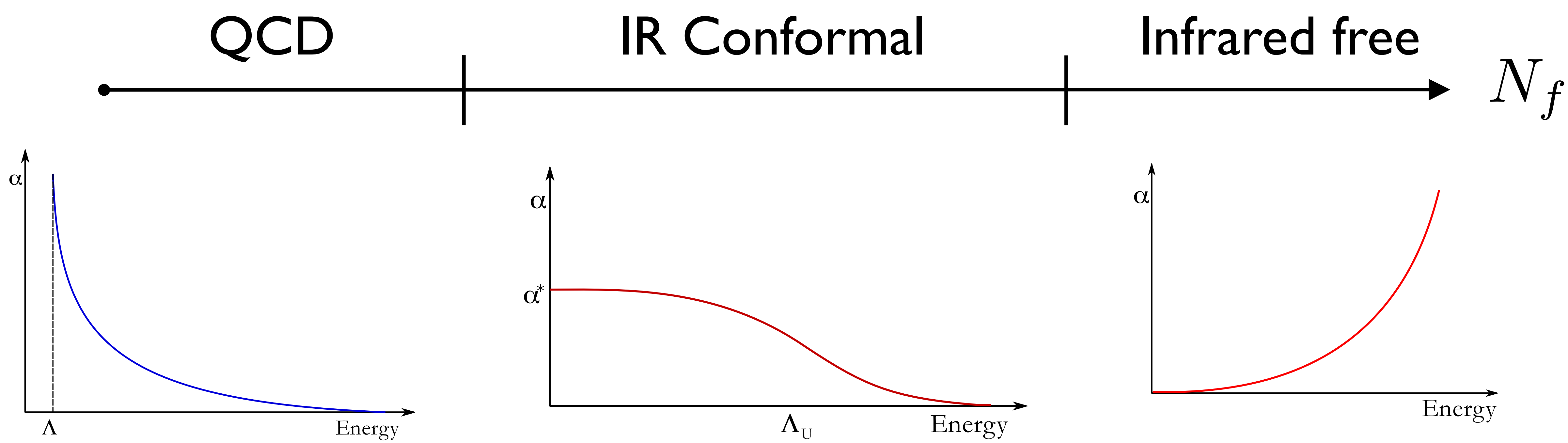

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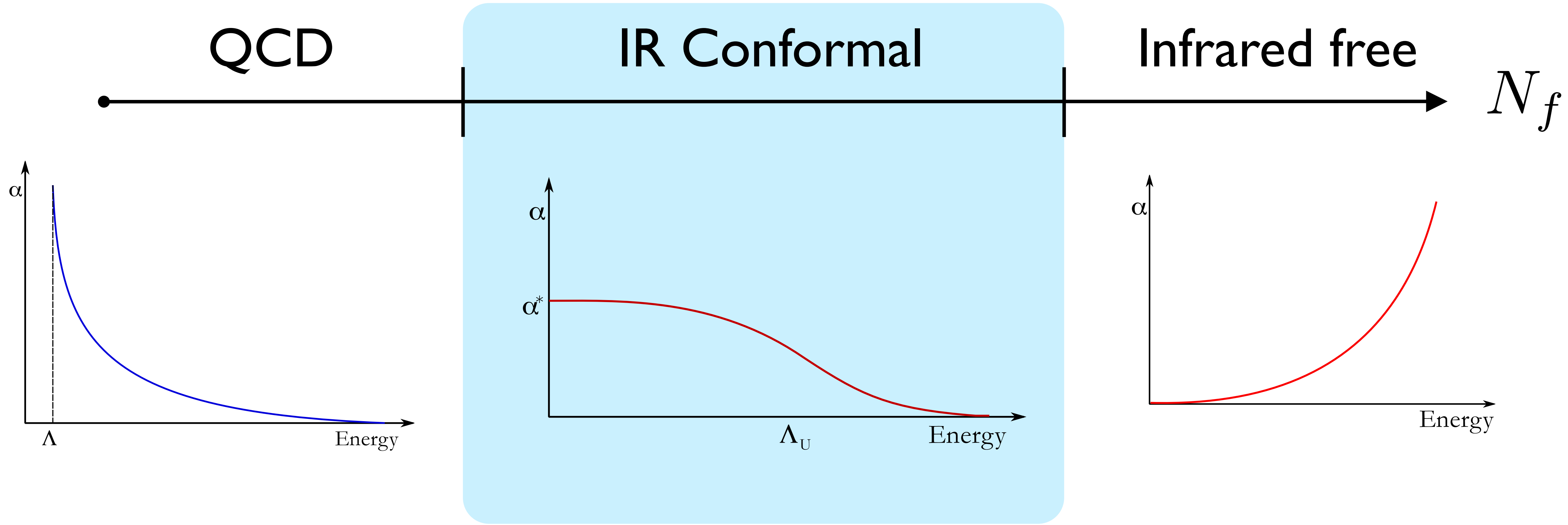

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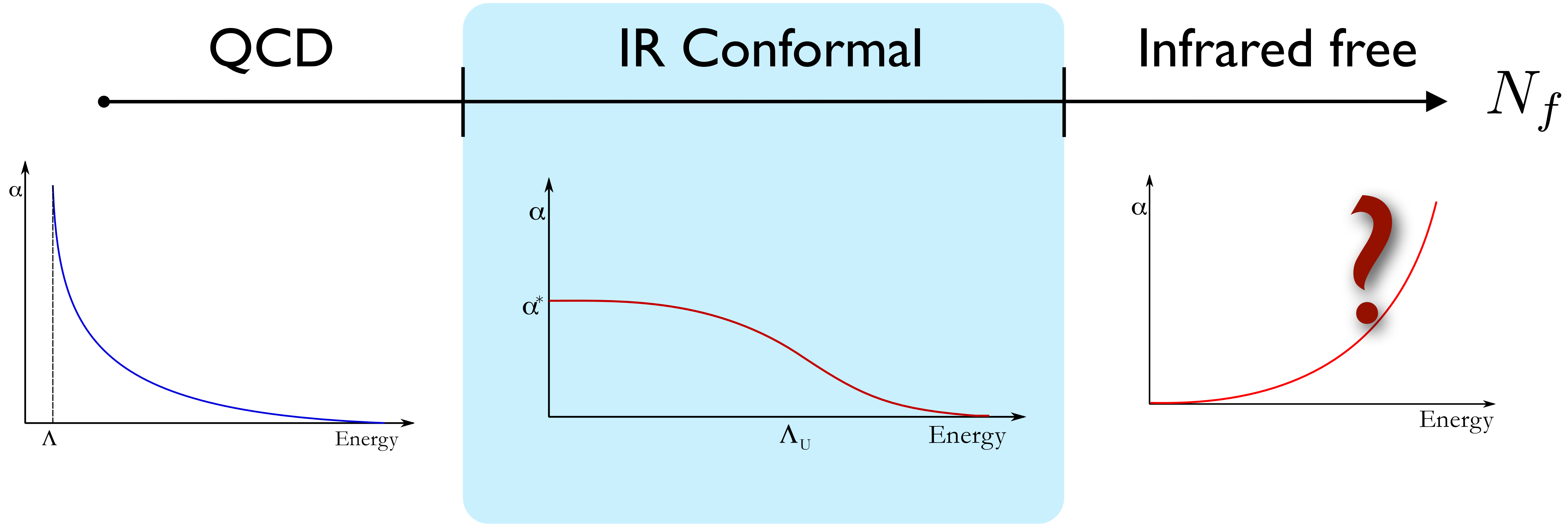
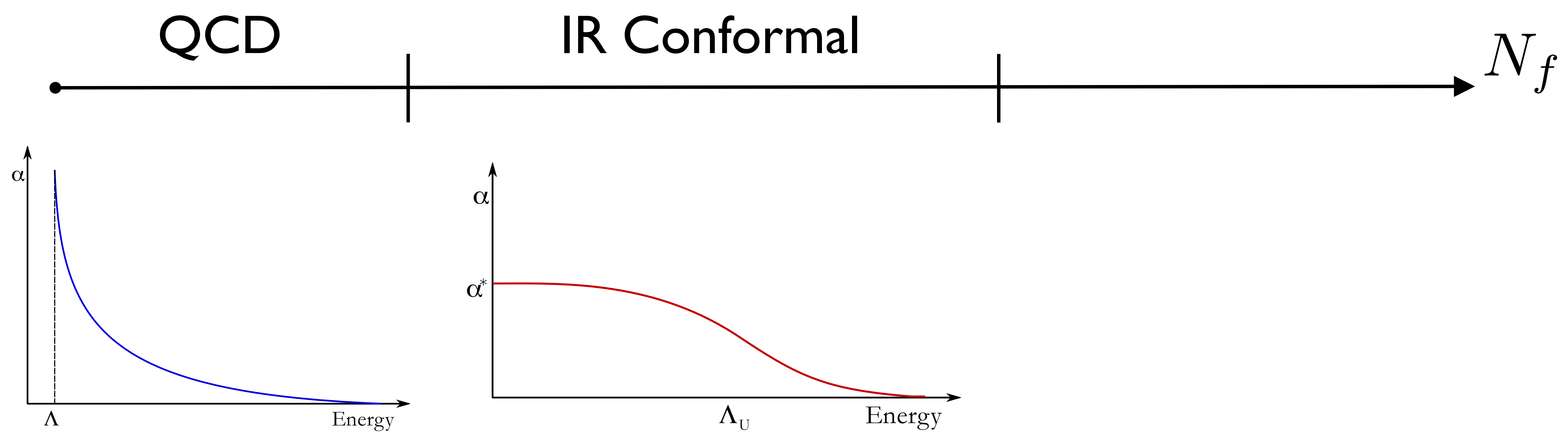


A novel phase @ large Nf

Pica & Sannino 10



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Interesting structure at large Nf

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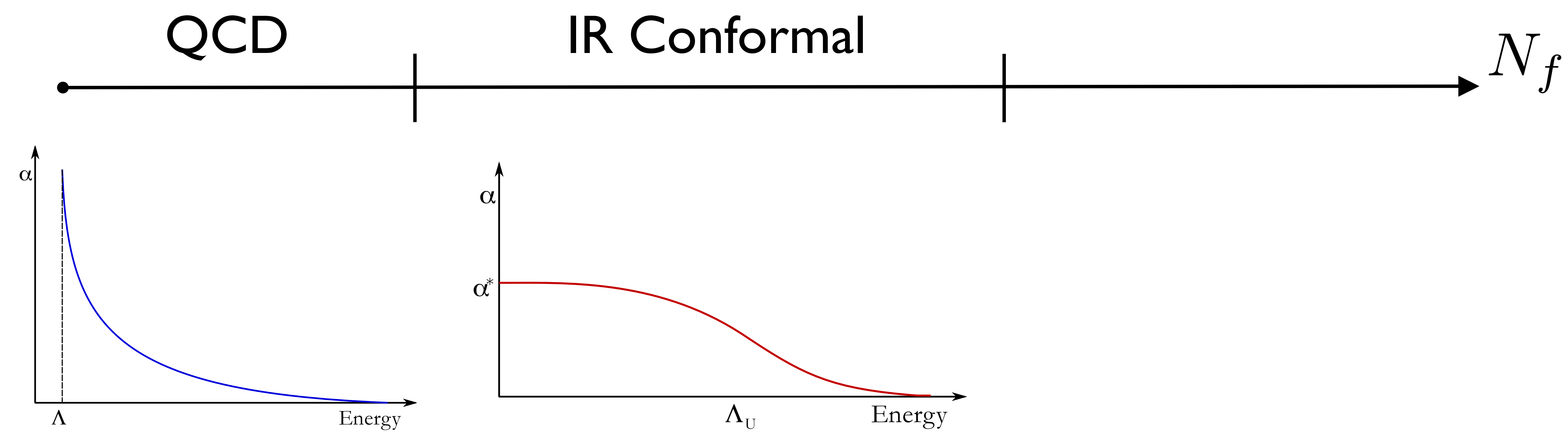

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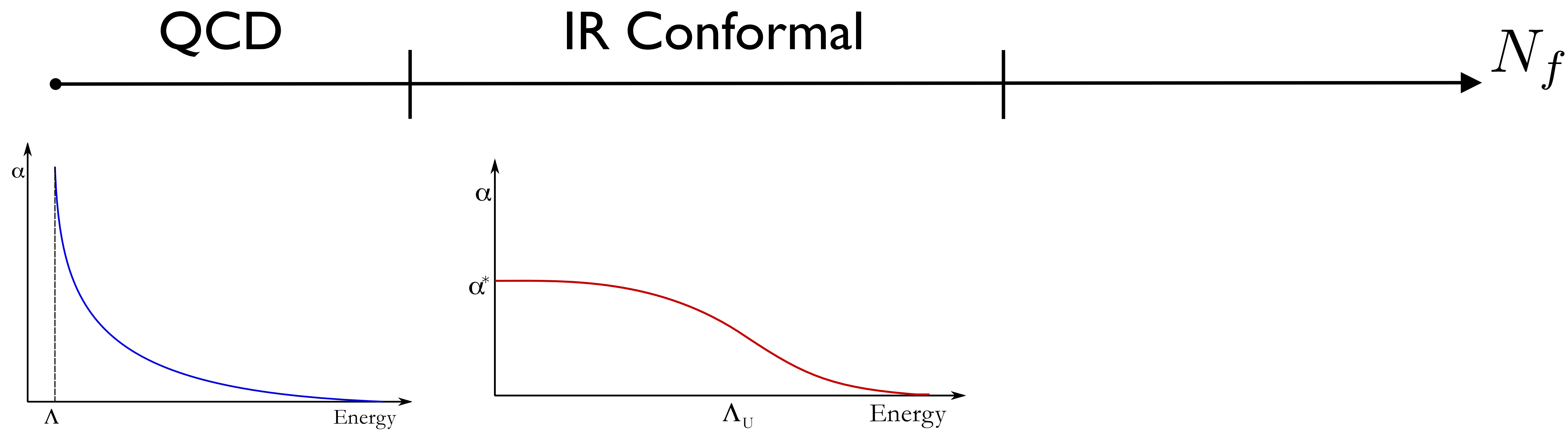
First coefficients at large Nf are known

Ciuchini, Derkachov, Gracey, Manashov '99



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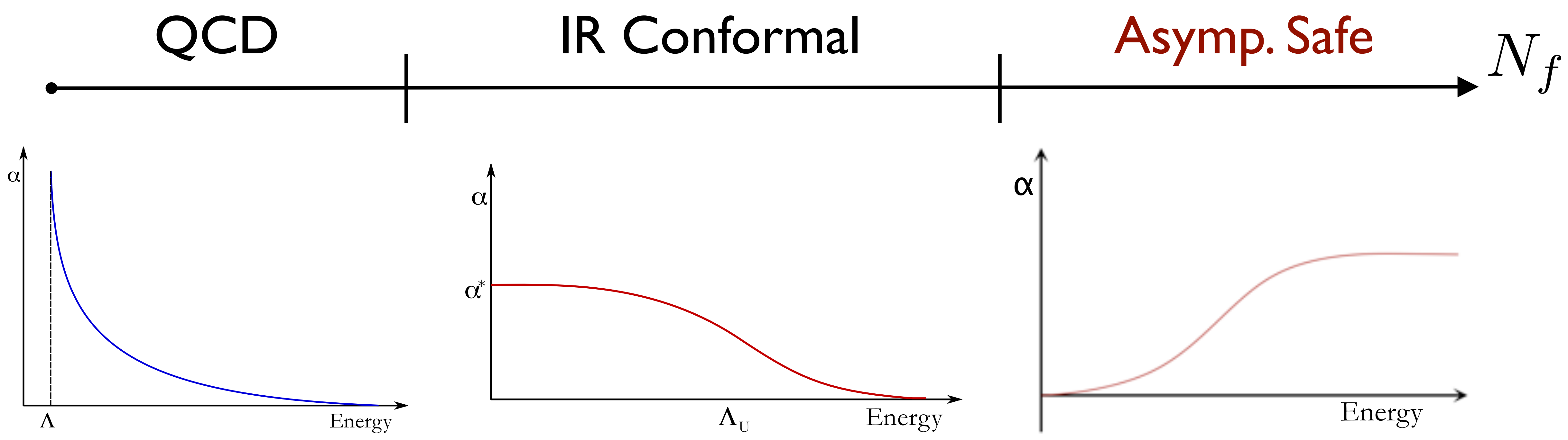

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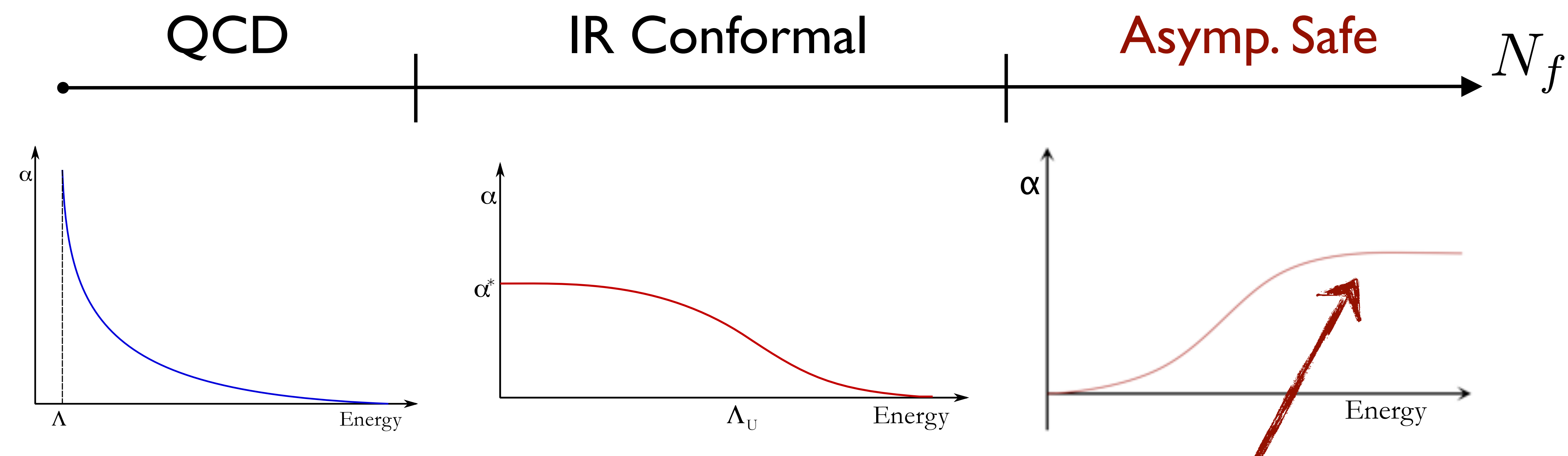

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$$\frac{3}{4N_f T_f} \frac{\beta(a)}{a^2} = 1 + \frac{H\left(4aN_f T_f\right)}{N_f} + \ldots$$

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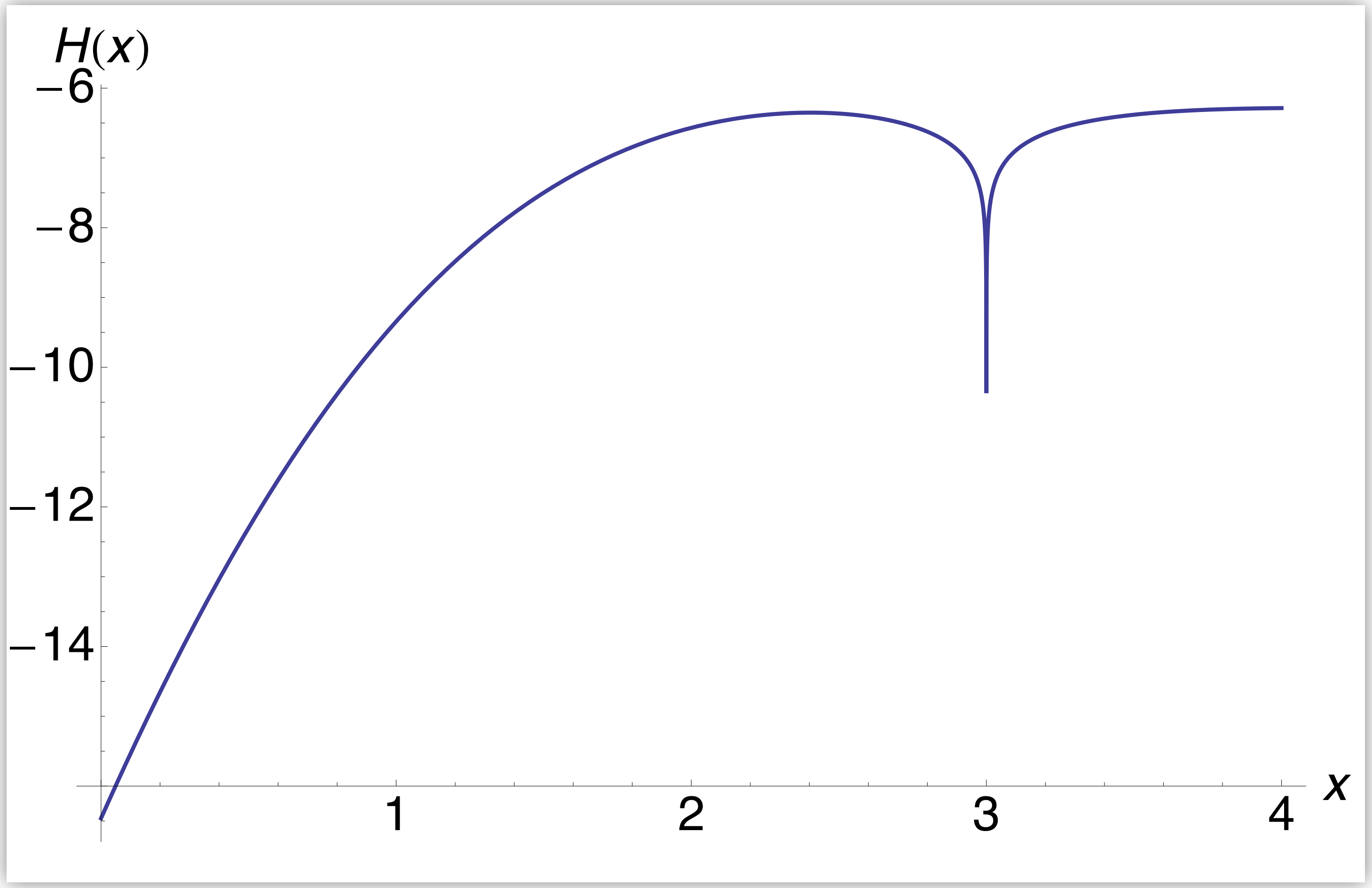

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B. Holdom, 2010

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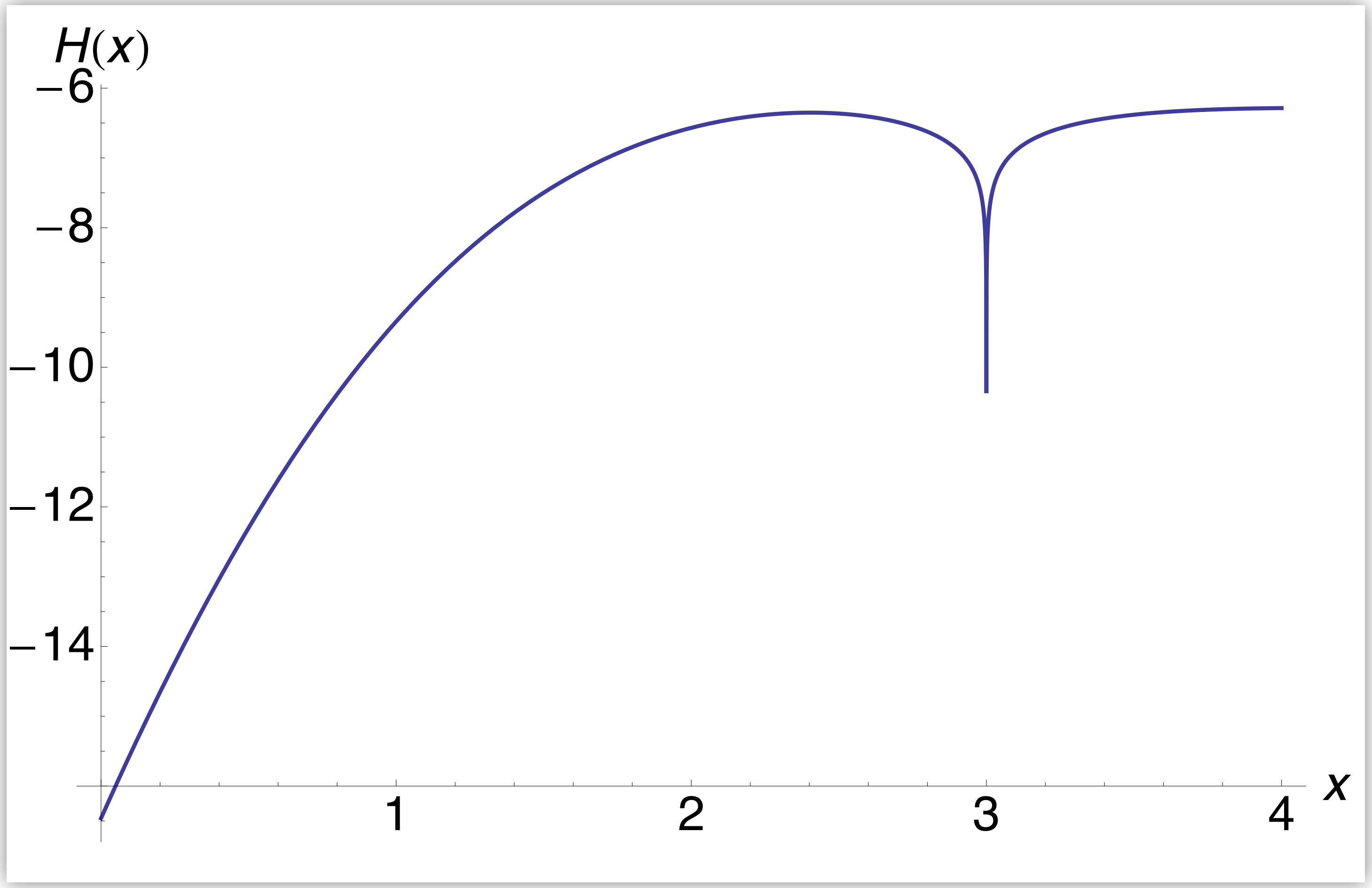
$$\alpha_{UV} = \frac{3\pi}{T_F N_f}$$

Pica & Sannino 10

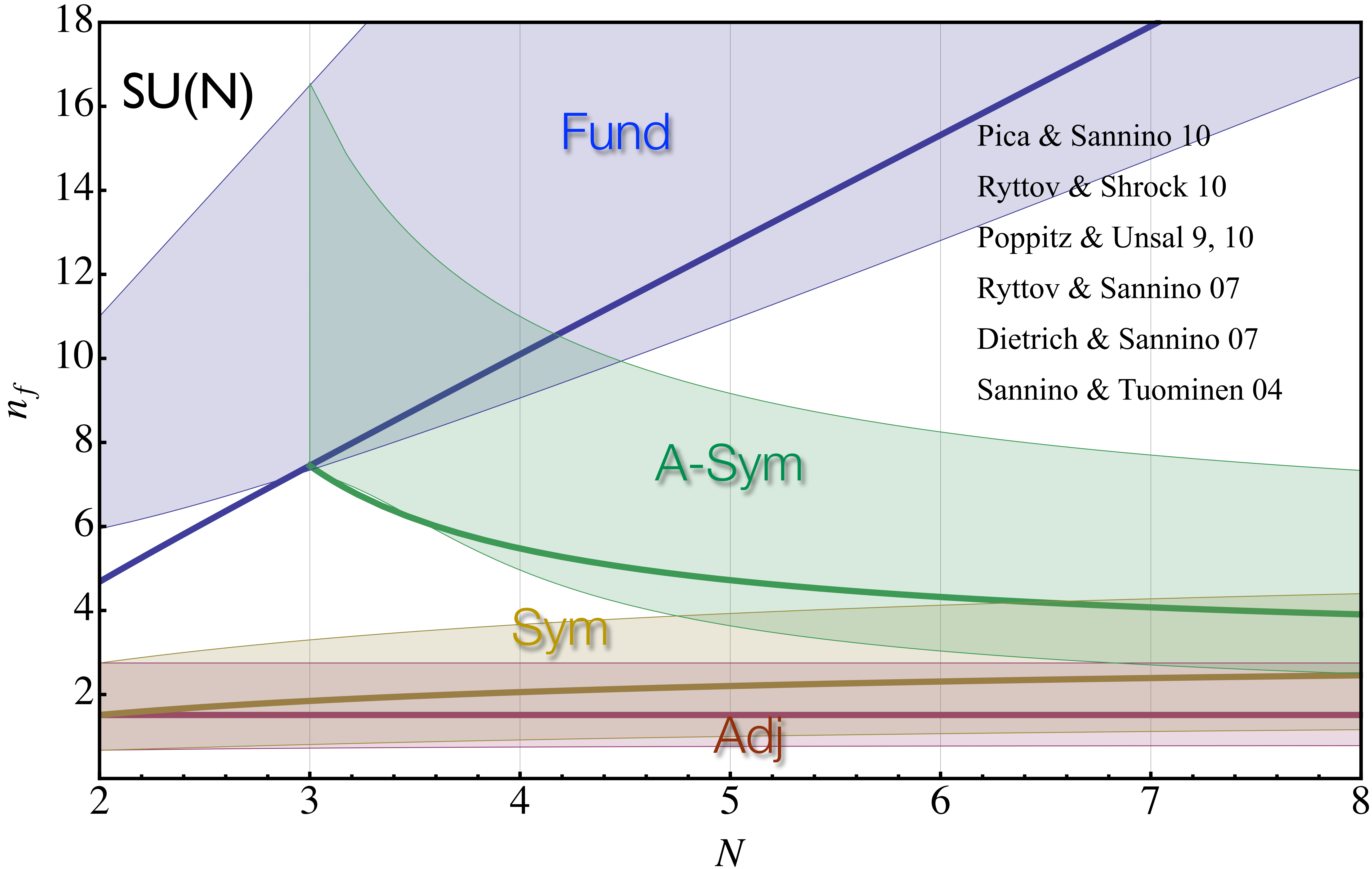


Ciuchini, Derkachov, Gracey, Manashov ‘99

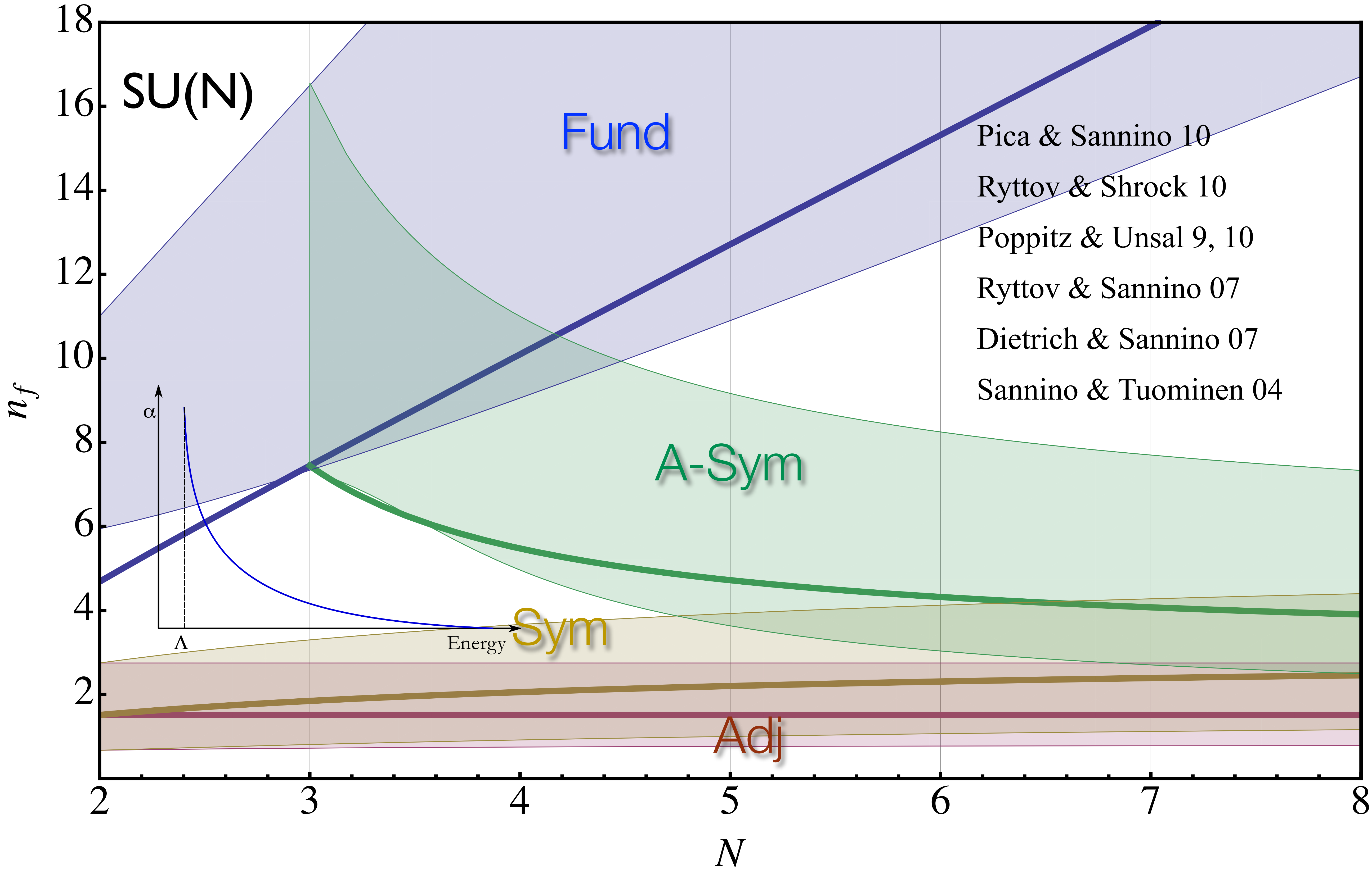
B. Holdom, 2010

Universal Picture

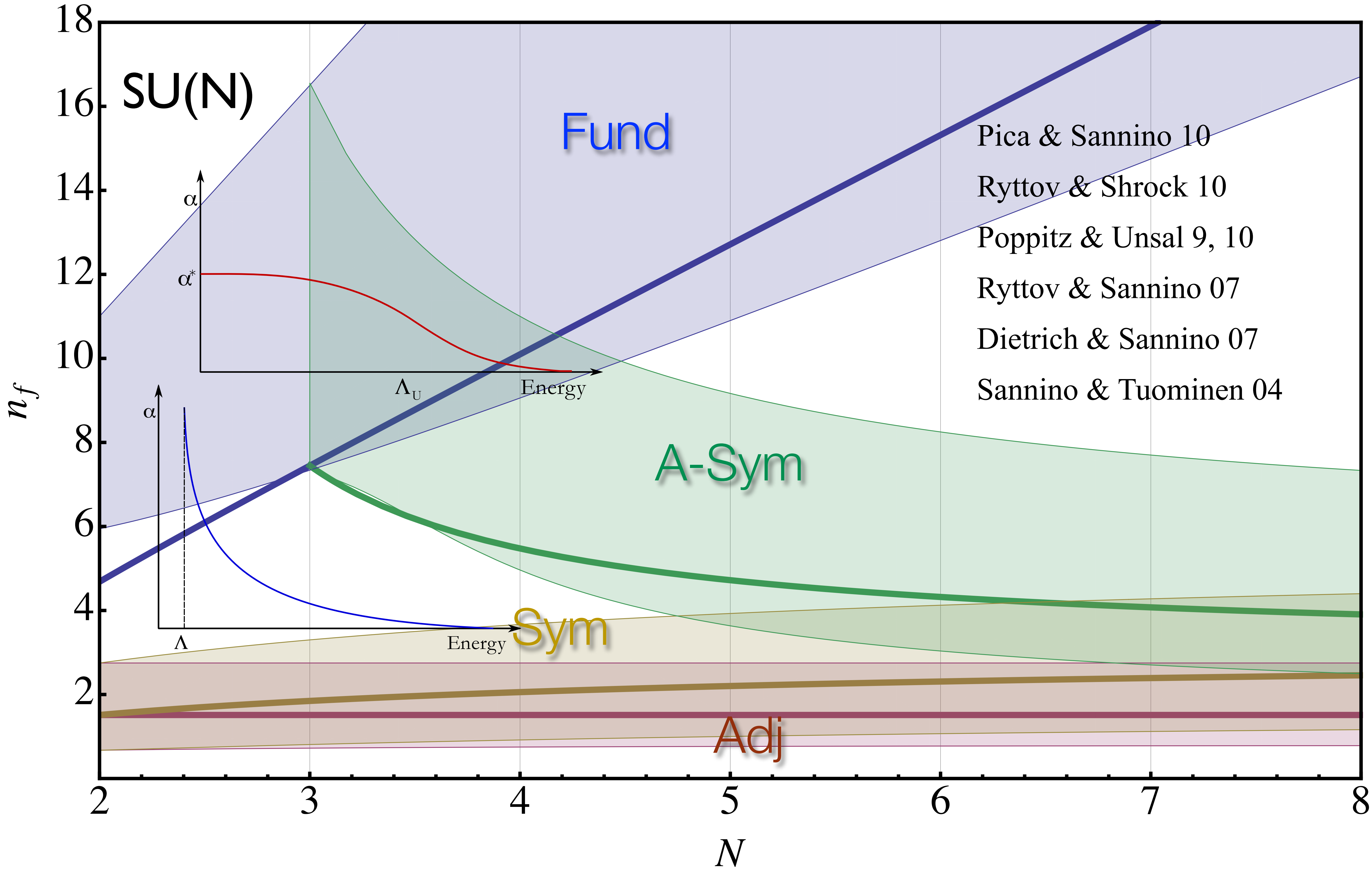
SU(N) Phase Diagram



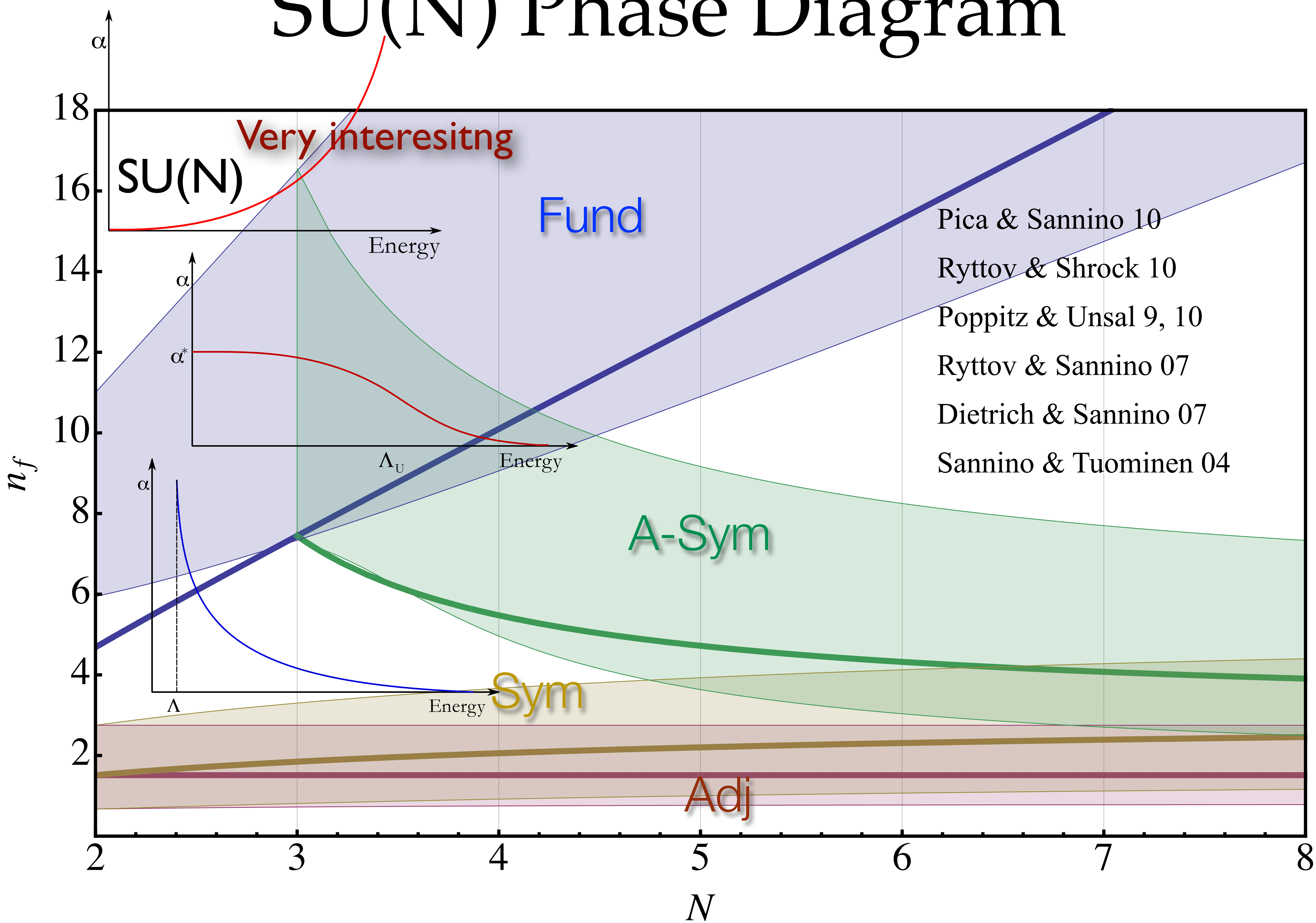
SU(N) Phase Diagram



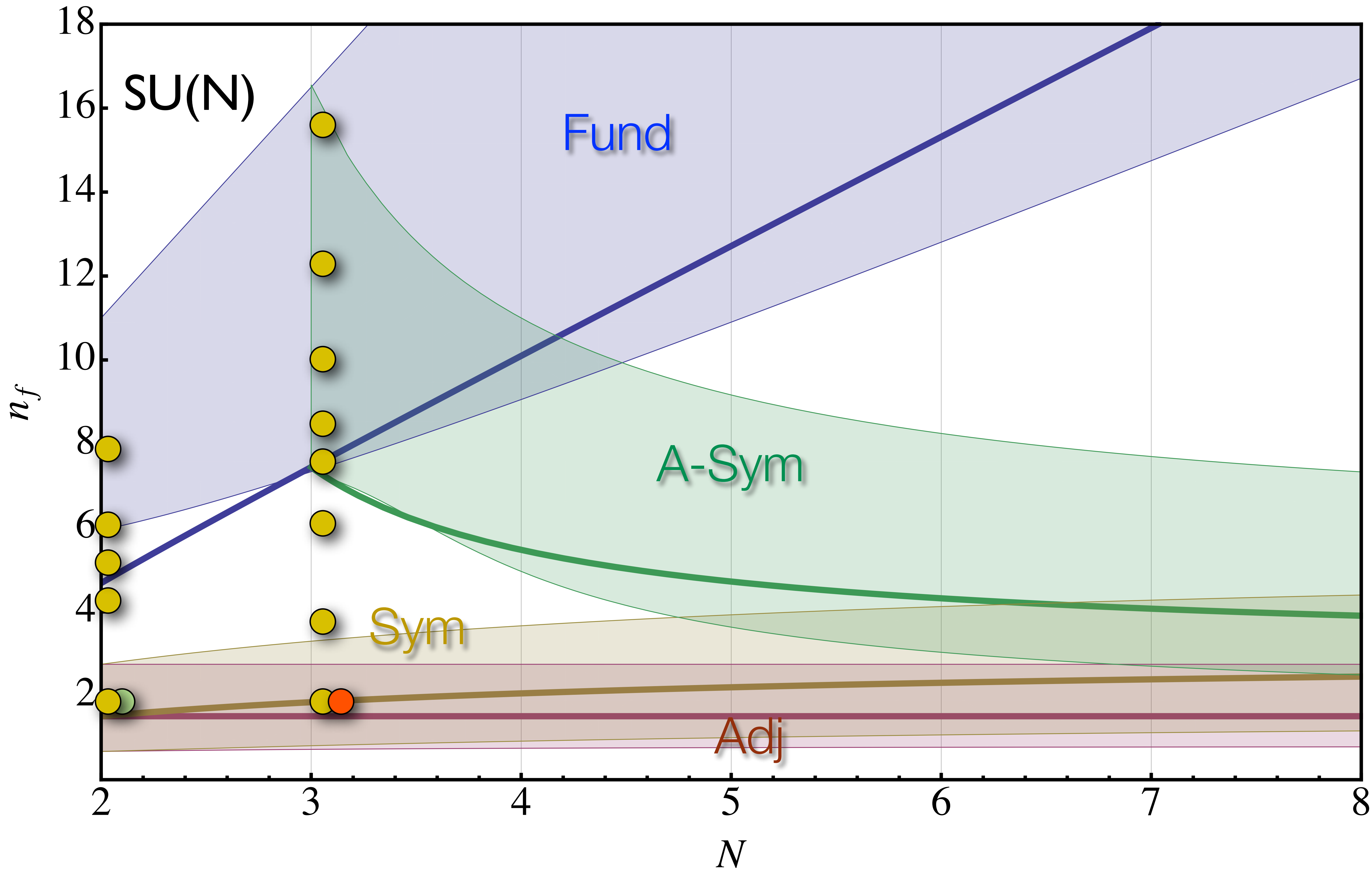
SU(N) Phase Diagram

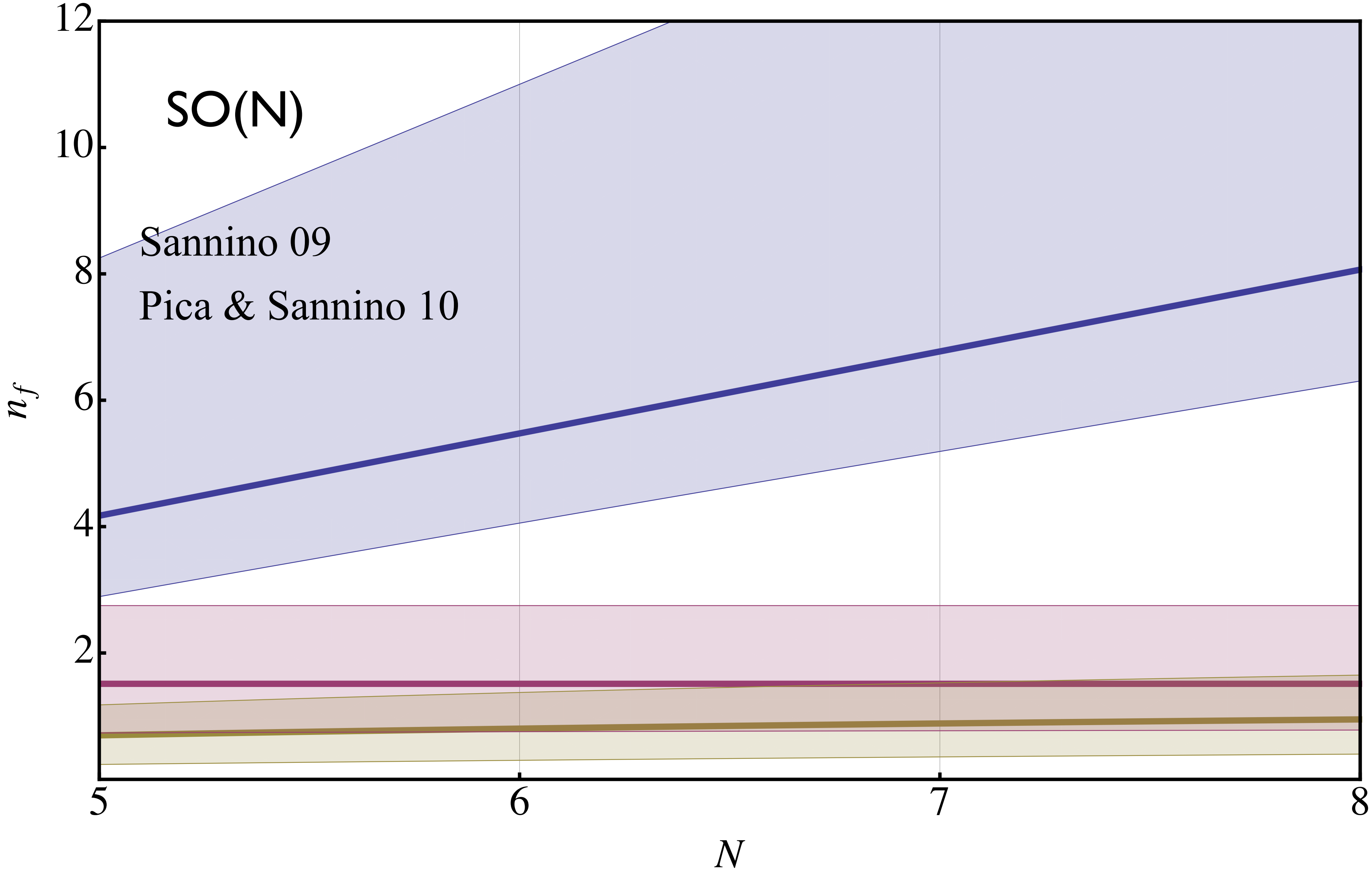


SU(N) Phase Diagram

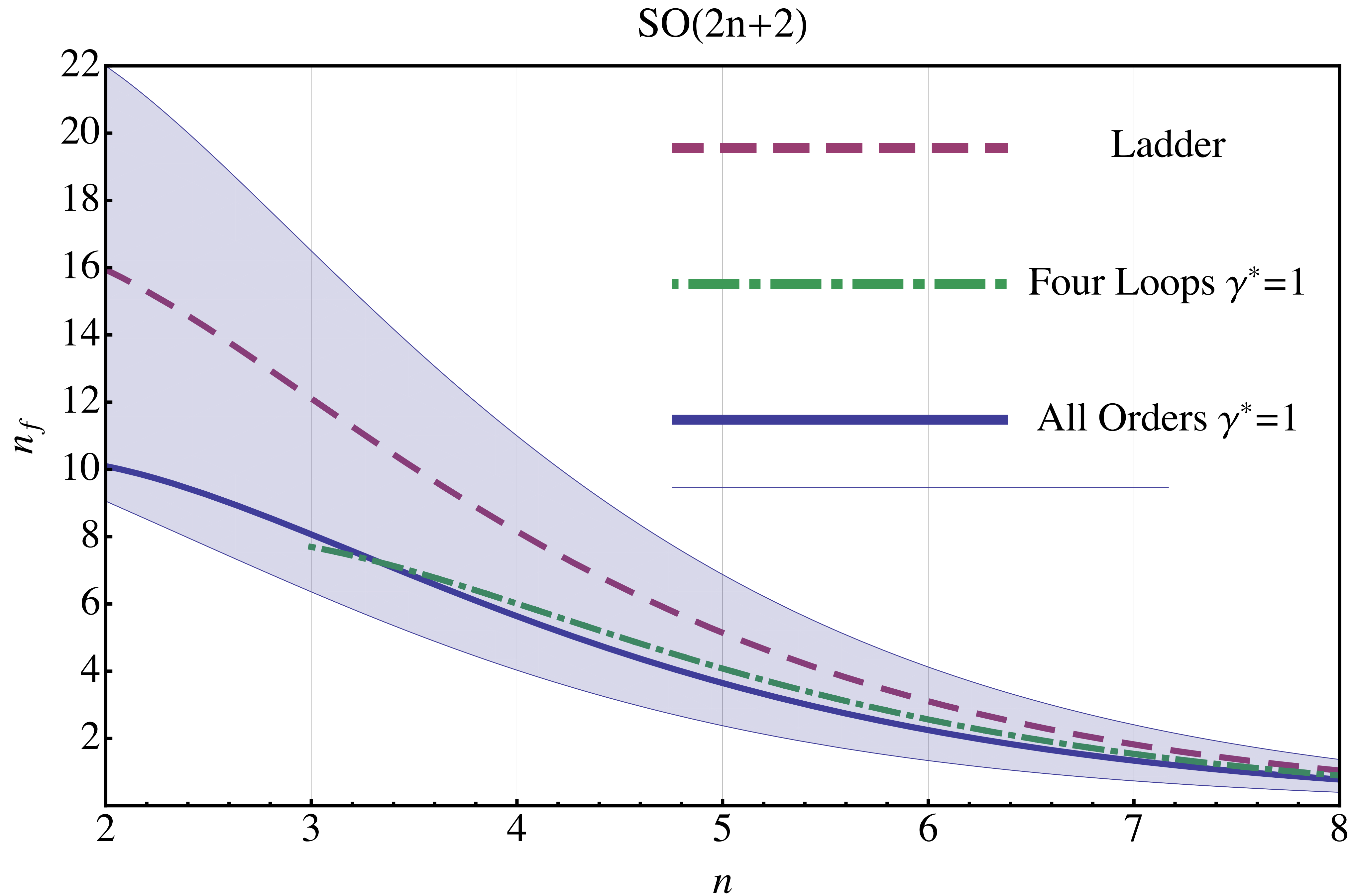


Lattice SU(N) Phase Diagram

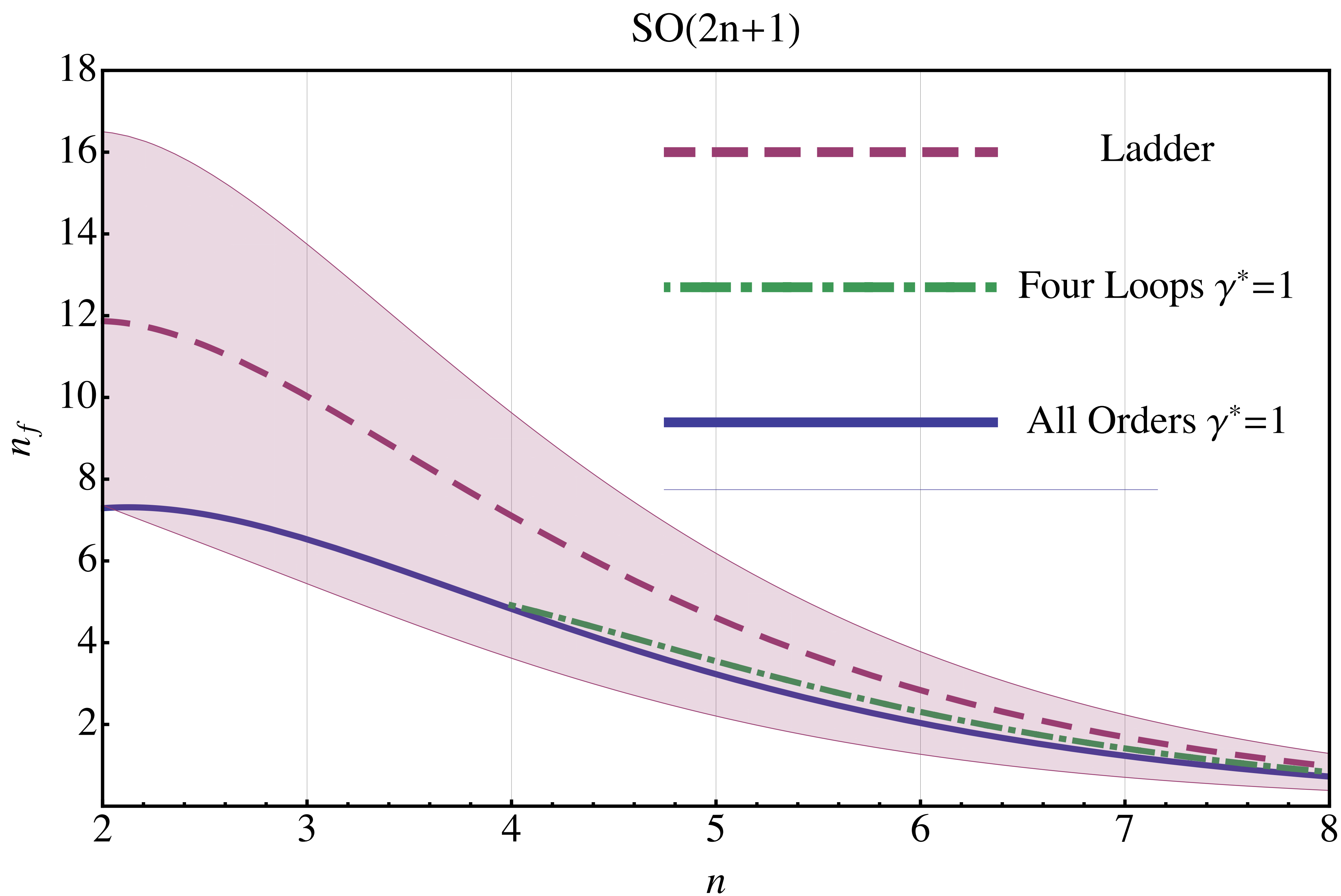




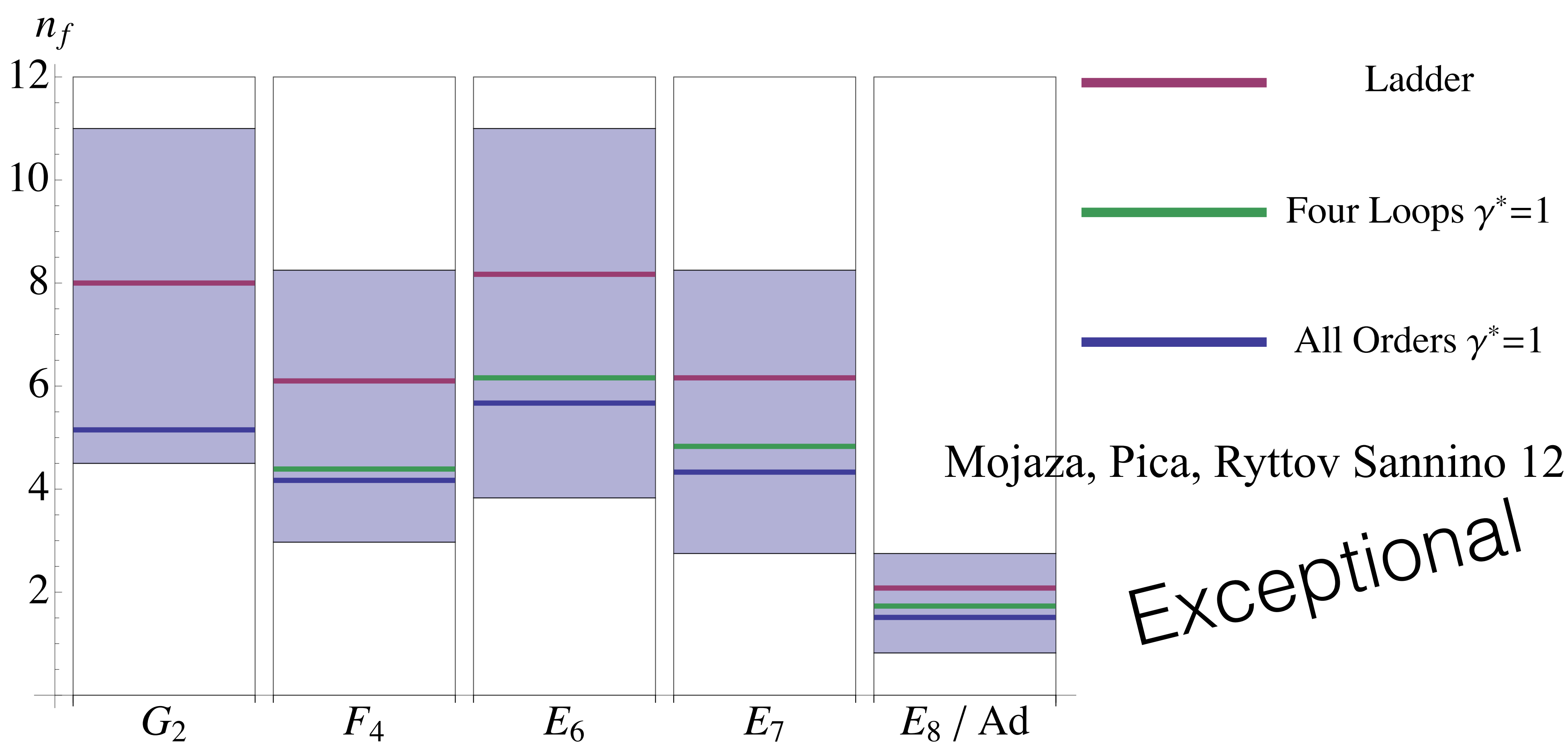
SO(N)
Sannino 09
Pica & Sannino 10
n_f
N
12
10
8
6
4
2
5
6
7
8



SO(2n+2)
Ladder
Four Loops γ*=1
All Orders γ*=1
n_f
n
2
3
4
5
6
7
8
22
20
18
16
14
12
10
8
6
4
2



SO(2n+1)
Ladder
Four Loops γ^*=1
All Orders γ^*=1
n_f
n
18
16
14
12
10
8
6
4
2
2
3
4
5
6
7
8



Mojaza, Pica, Ryttov Sannino 12

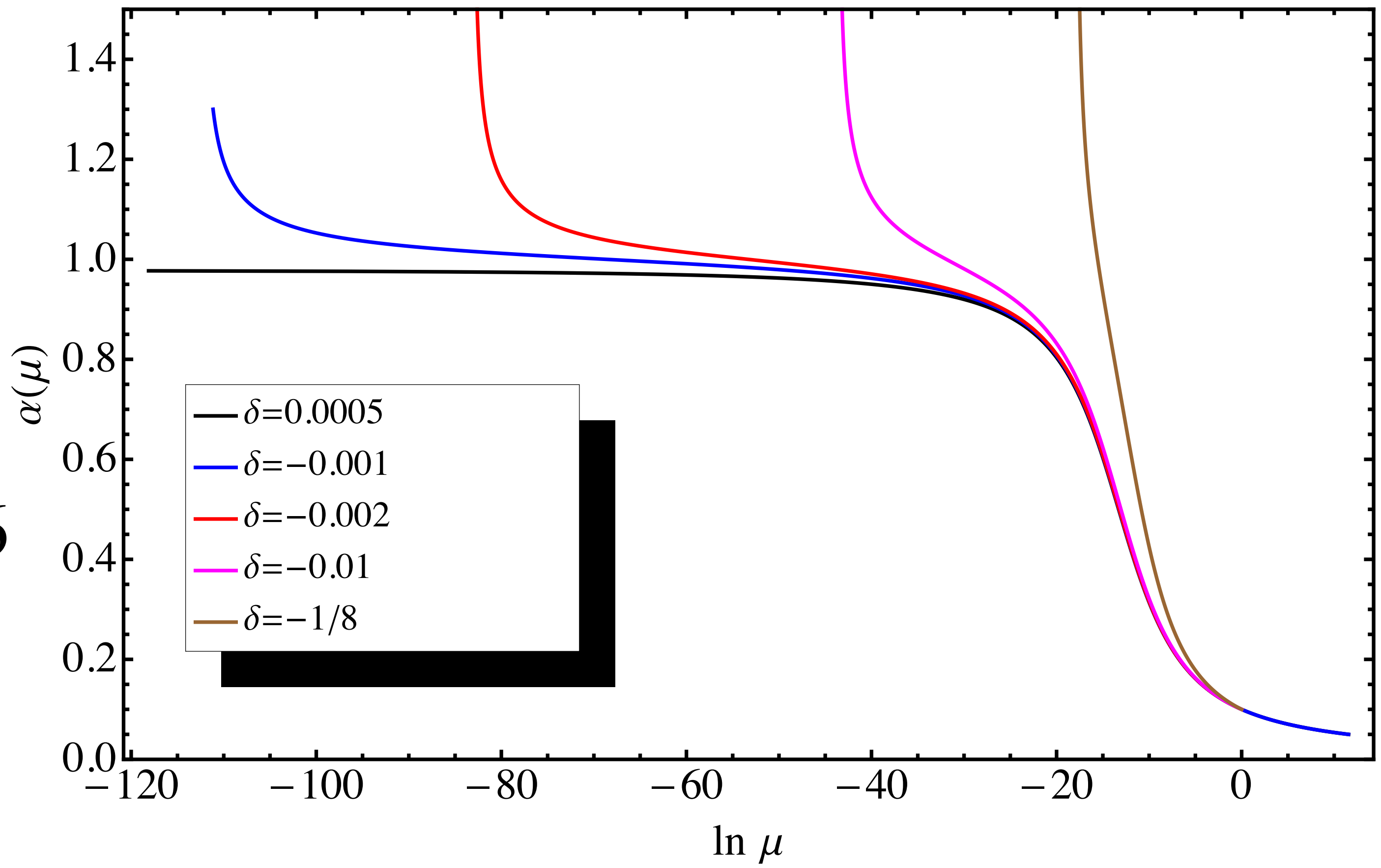
Exceptional

Walk or Jump ?

Walking

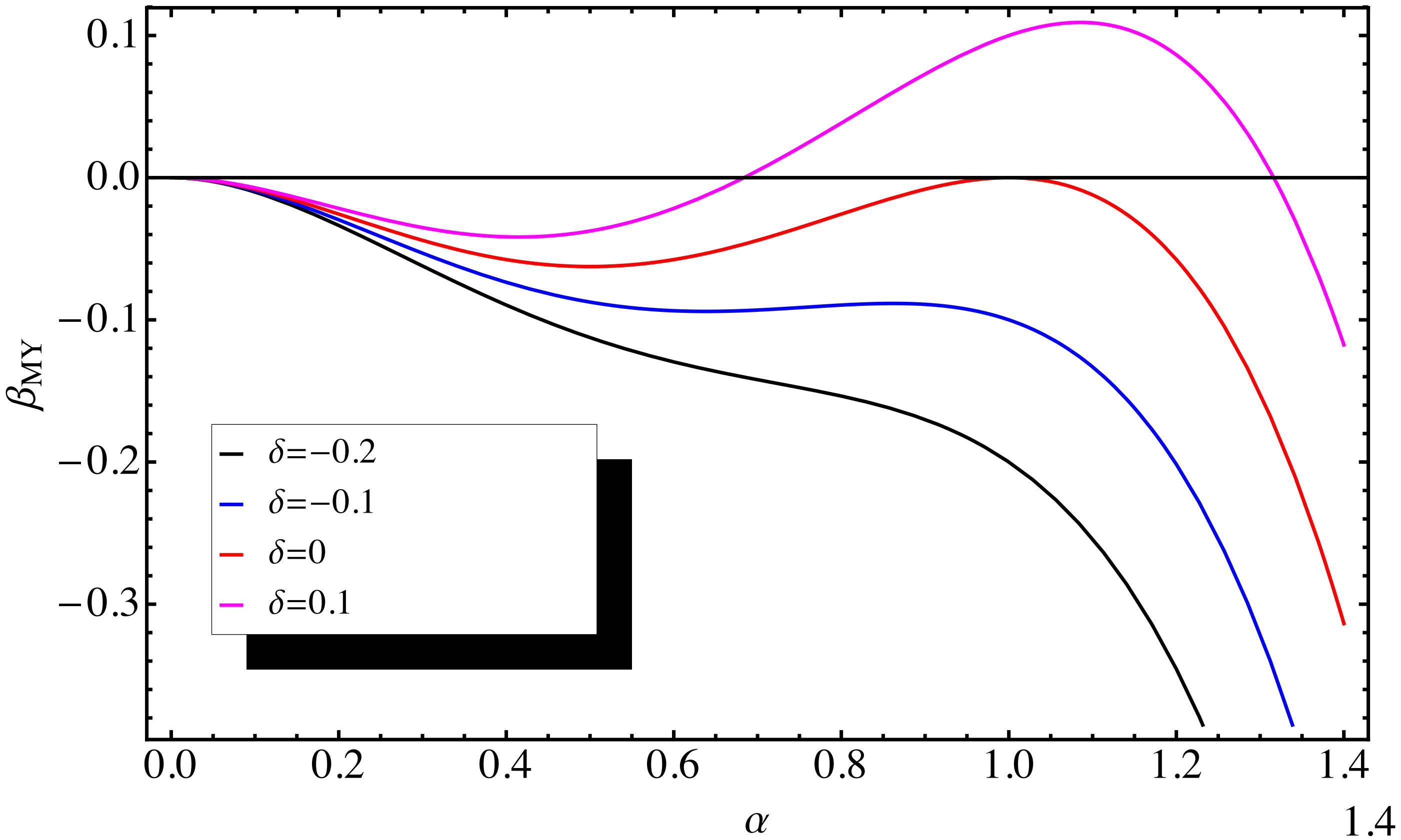
$$\delta = n_f - n_f^c$$

Miransky 85
Miransky & Yamawaki 89
Miransky & Yamawaki 97
Yamawaki, Bando, Matumoto 86
Appelquist, Karabali, Wijewardhana 86



© Francesco Sannino

Walking



$$\beta_{MY} = -\alpha^2 \left((\alpha - 1)^2 - \delta \right)$$

$$\delta = n_f - n_f^c$$

Sannino 2012

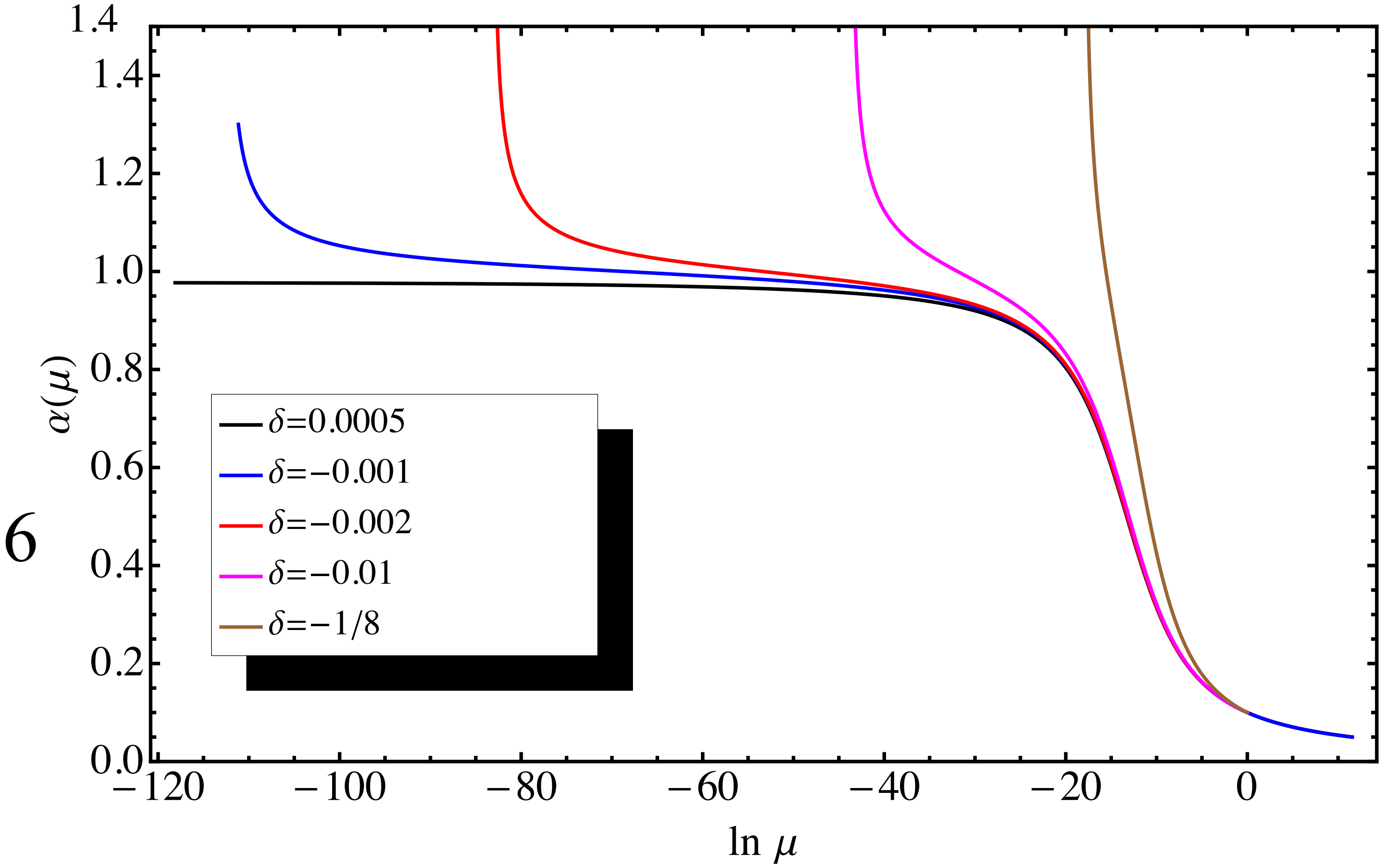
Miransky 85

Miransky & Yamawaki 89

Miransky & Yamawaki 97

Yamawaki, Bando, Matumoto 86

Appelquist, Karabali, Wijewardhana 86



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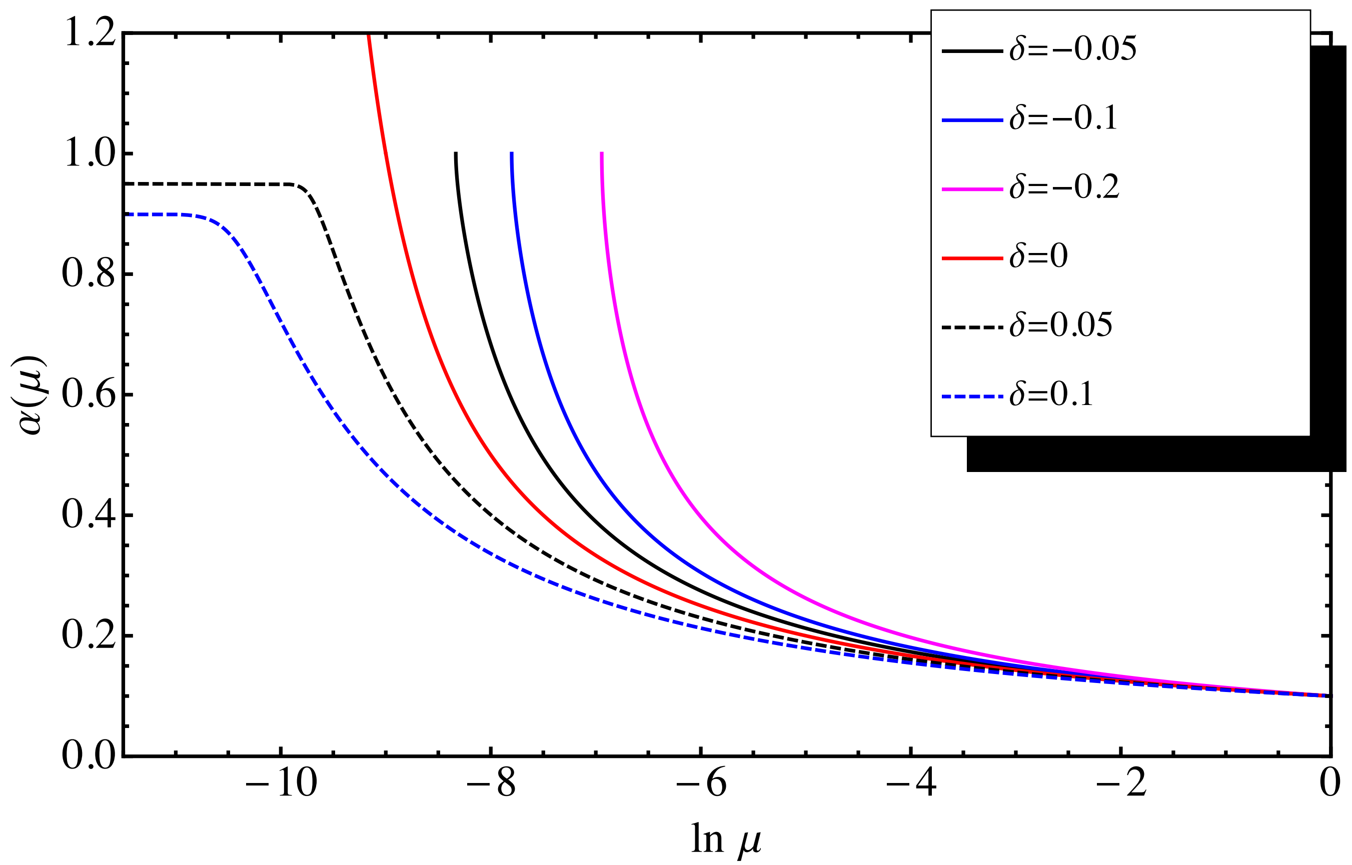
Condensate Enhancement

$$\langle \bar{Q}Q \rangle_\mu = \exp\left(\int_{\alpha(\Lambda)}^{\alpha(\mu)} \mathrm{d}\alpha \frac{\gamma(\alpha)}{-\alpha^2((\alpha-1)^2 + |\delta|)} \right) \langle \bar{Q}Q \rangle_\Lambda$$

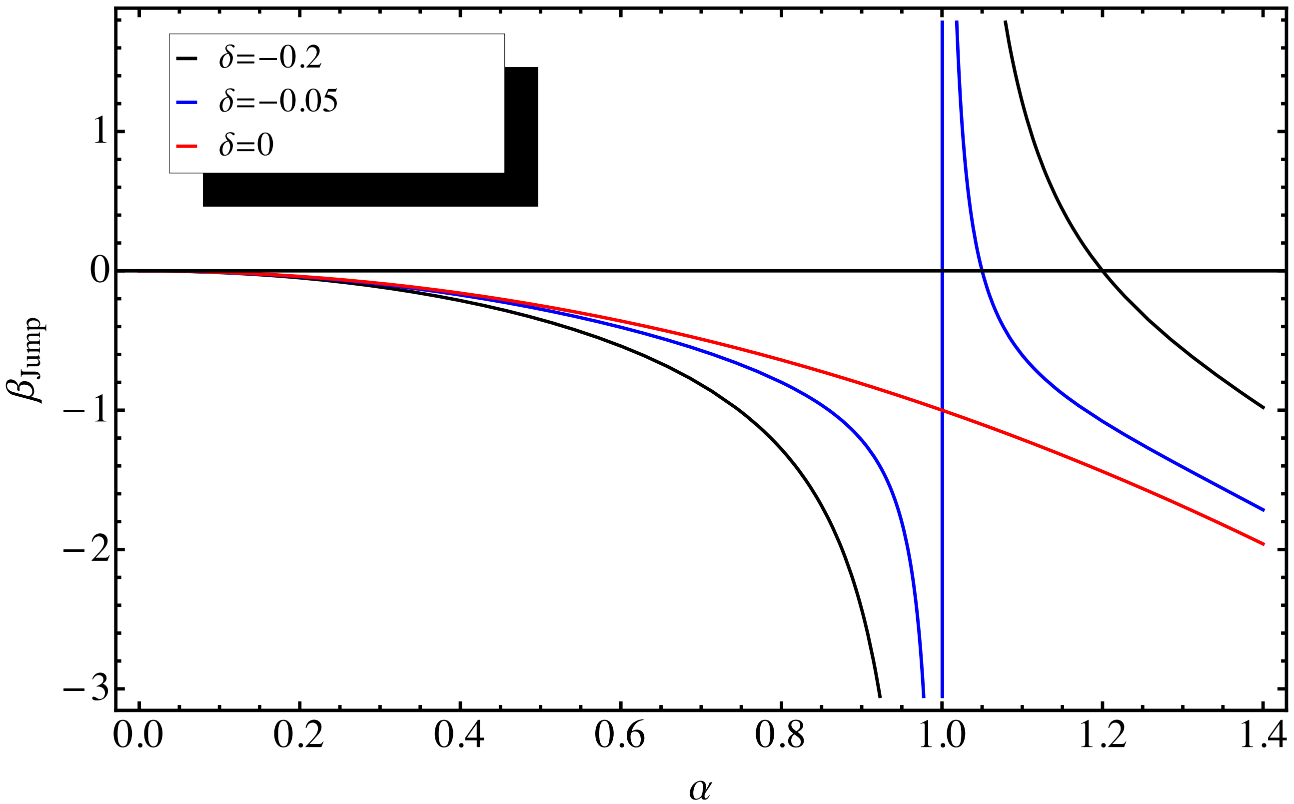
$$\simeq \exp\left(\gamma(1) \int_{\alpha(\Lambda)}^{\alpha(\mu)} \mathrm{d}\alpha \frac{1}{\beta_{MY}} \right) \langle \bar{Q}Q \rangle_\Lambda \;\; = \left(\frac{\mu}{\Lambda} \right)^{\gamma(1)} \langle \bar{Q}Q \rangle_\Lambda$$

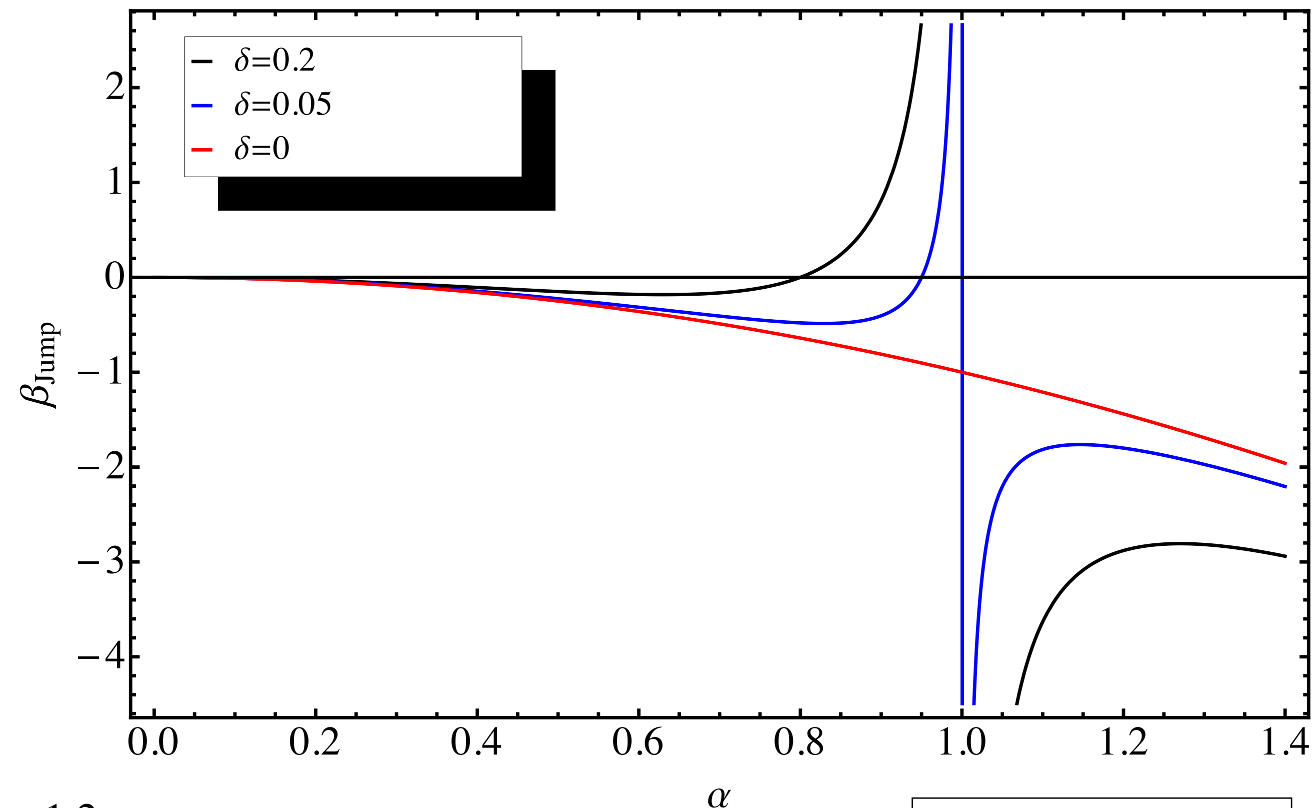
Jumping



Sannino 2012

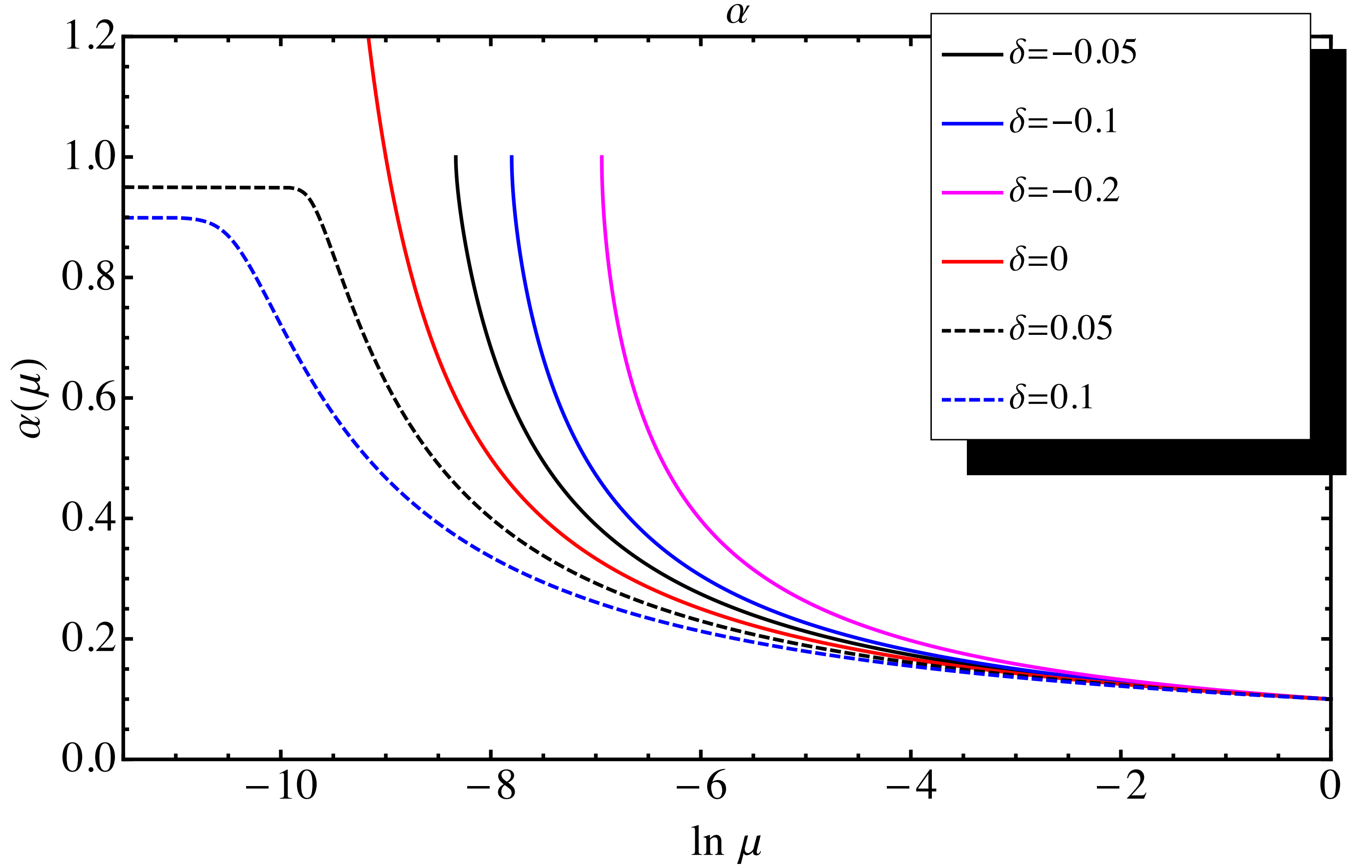
Jumping





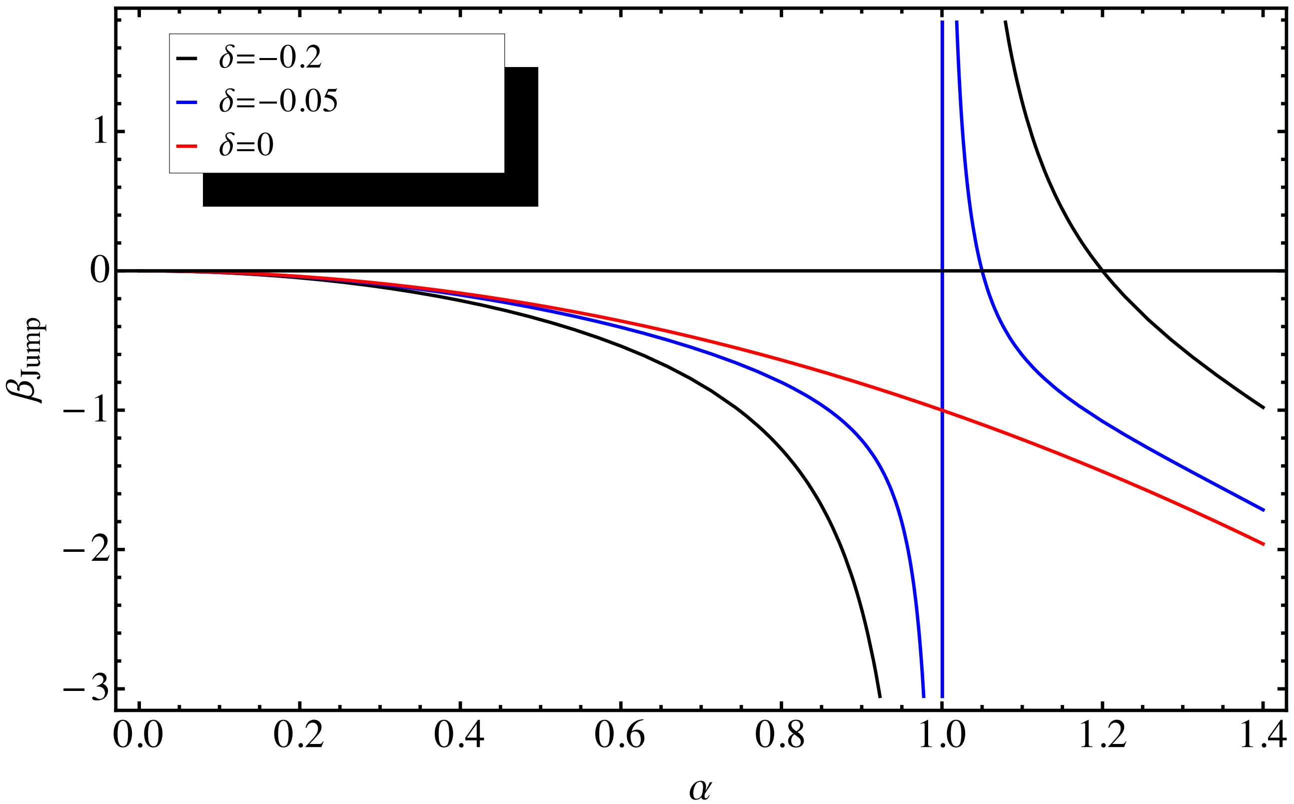
$$\beta_{Jump} = -\alpha^2 \frac{1 - \delta - \alpha}{1 - \alpha}$$

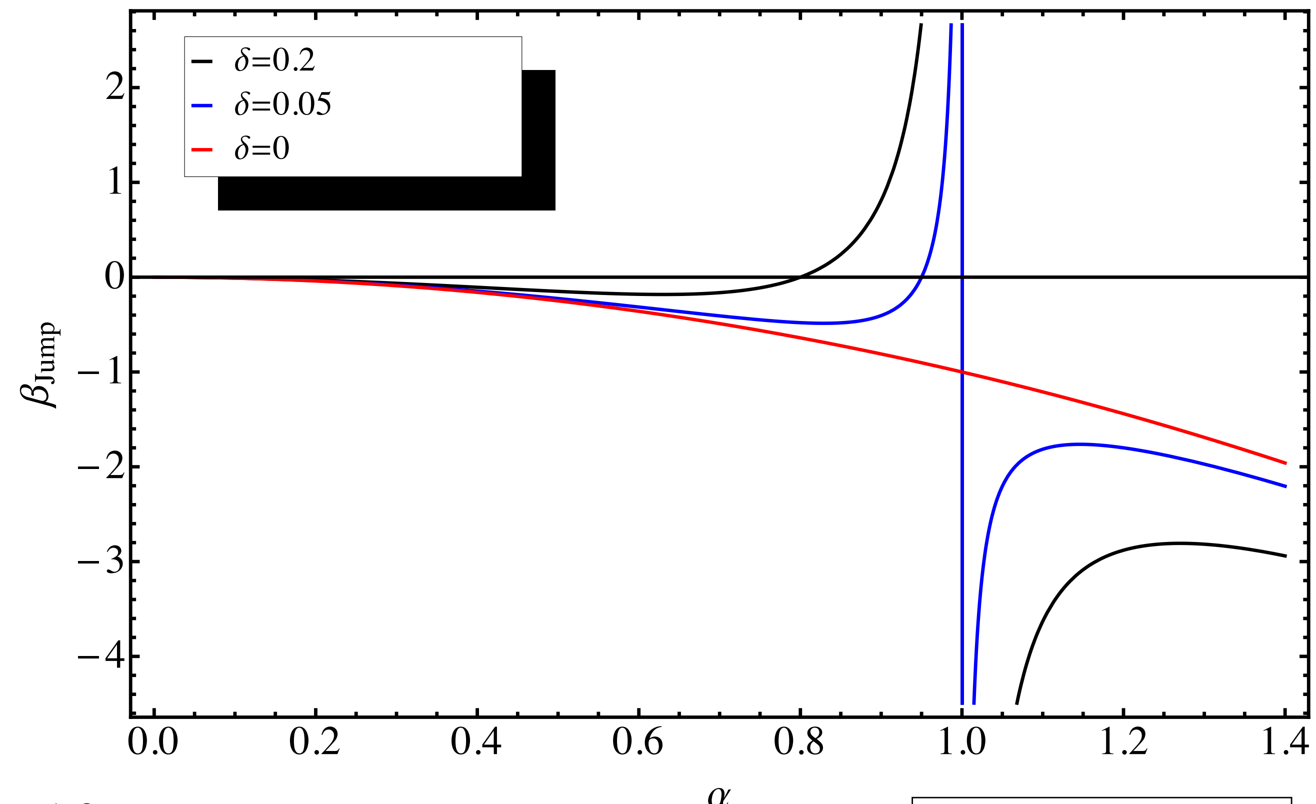
$$\delta = n_f - n_f^c$$



Sannino 2012

Jumping

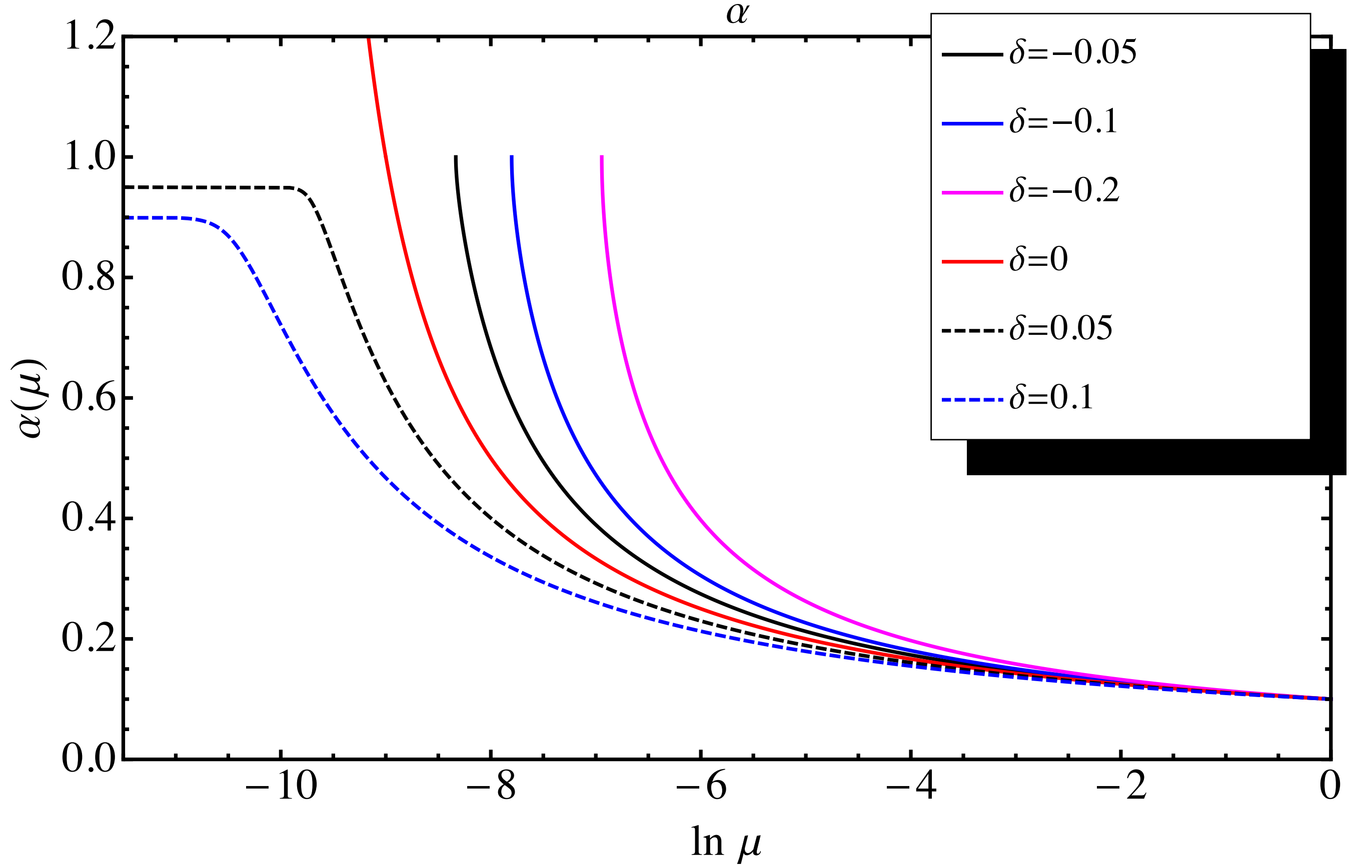




$$\beta_{Jump} = -\alpha^2 \frac{1-\delta-\alpha}{1-\alpha}$$

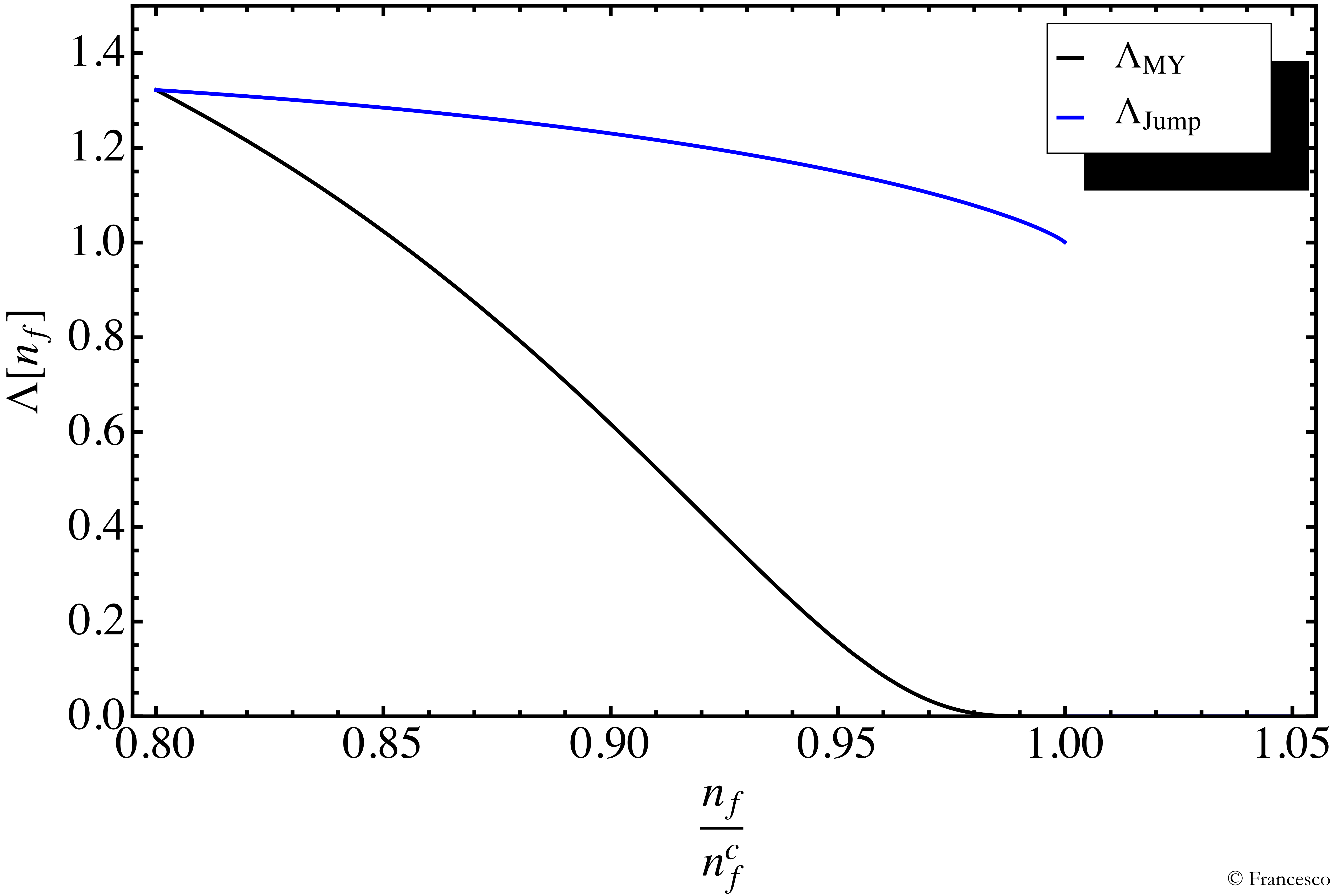
$$\delta = n_f - n_f^c$$

$$\langle \bar{Q} Q \rangle_\mu \simeq \gamma(1) \ \ln\left(\frac{\mu}{\Lambda}\right) \langle \ \bar{Q} Q \rangle_\Lambda$$



Sannino 2012

Walking or Jumping?



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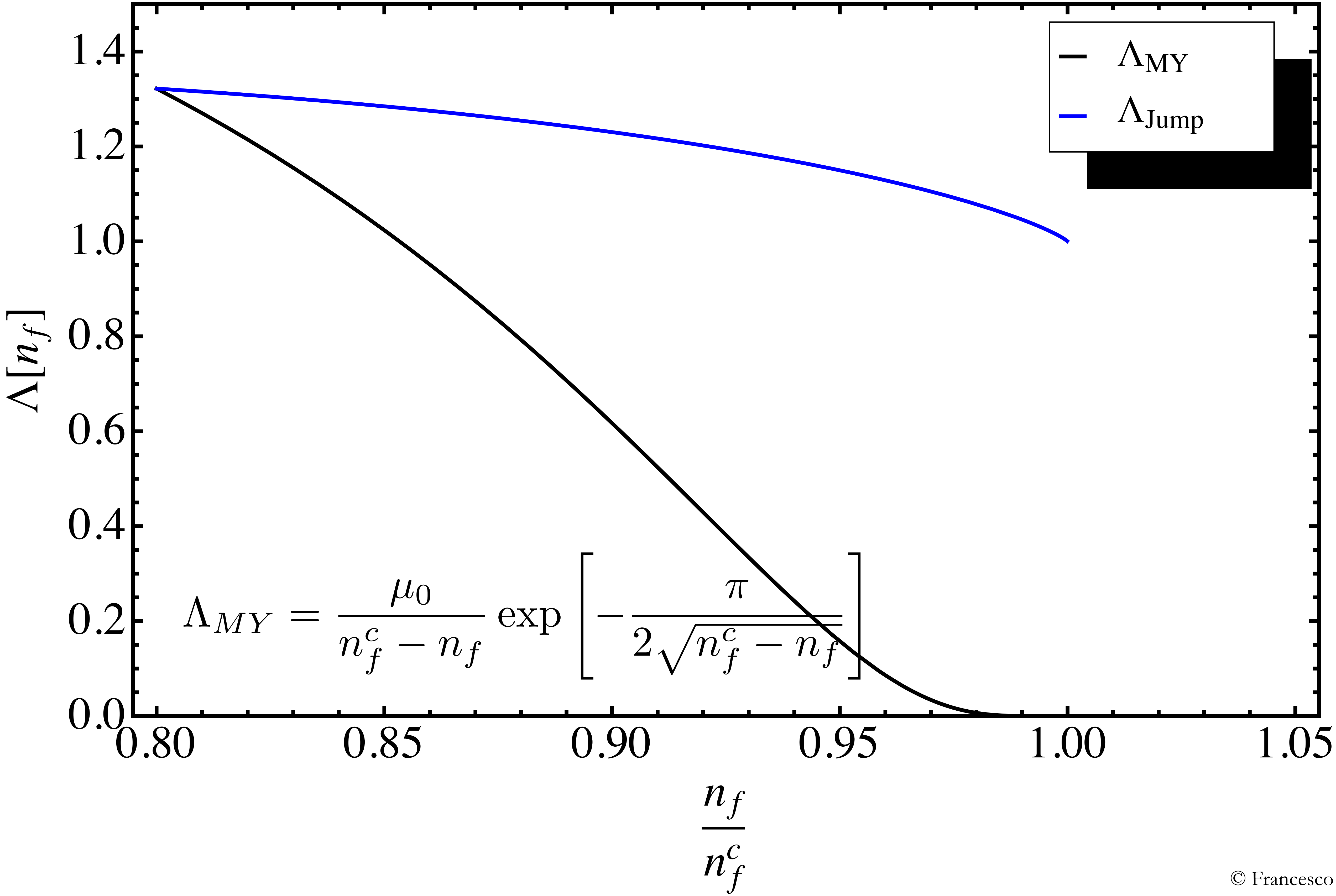
Walking or Jumping?



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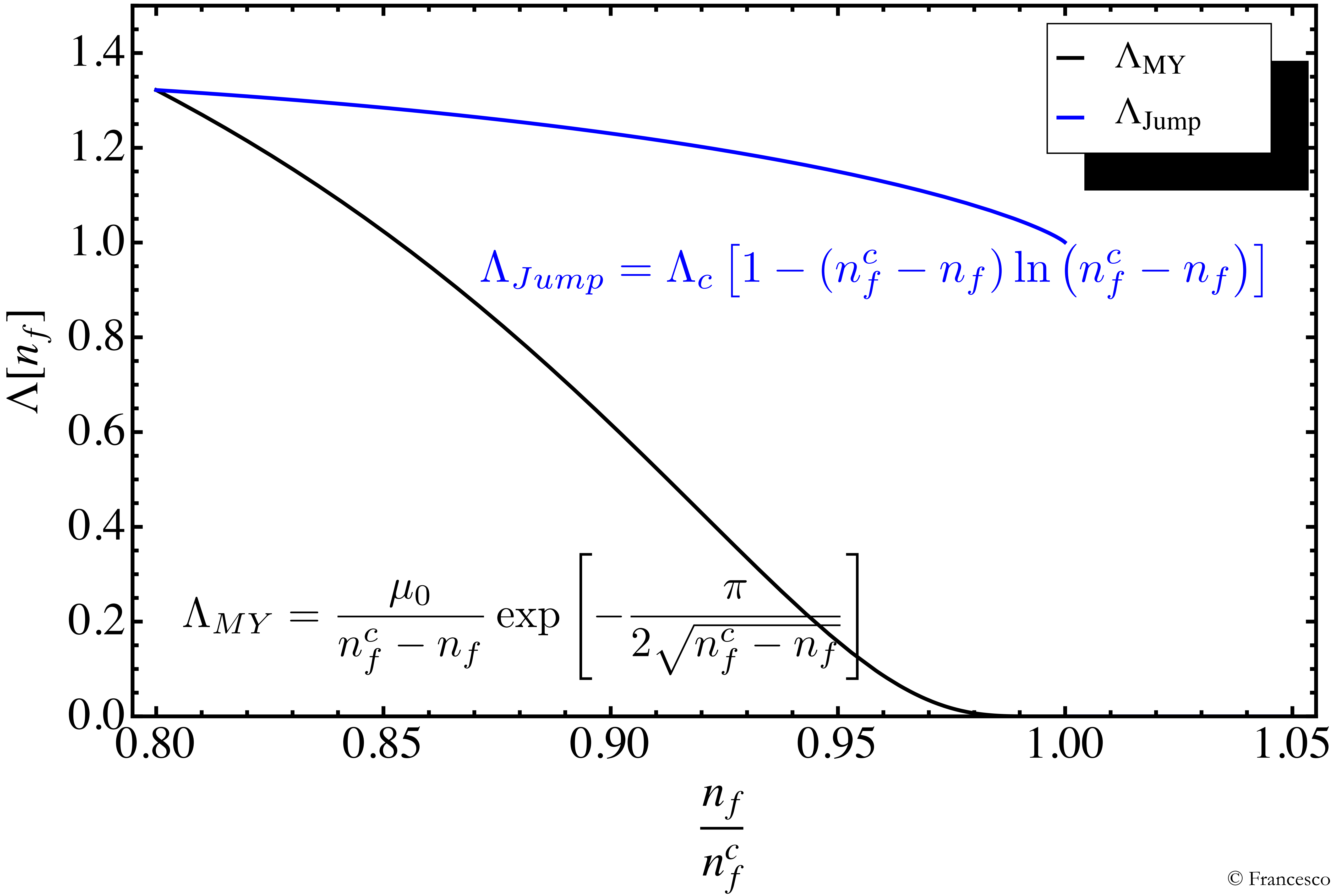
Walking or Jumping?



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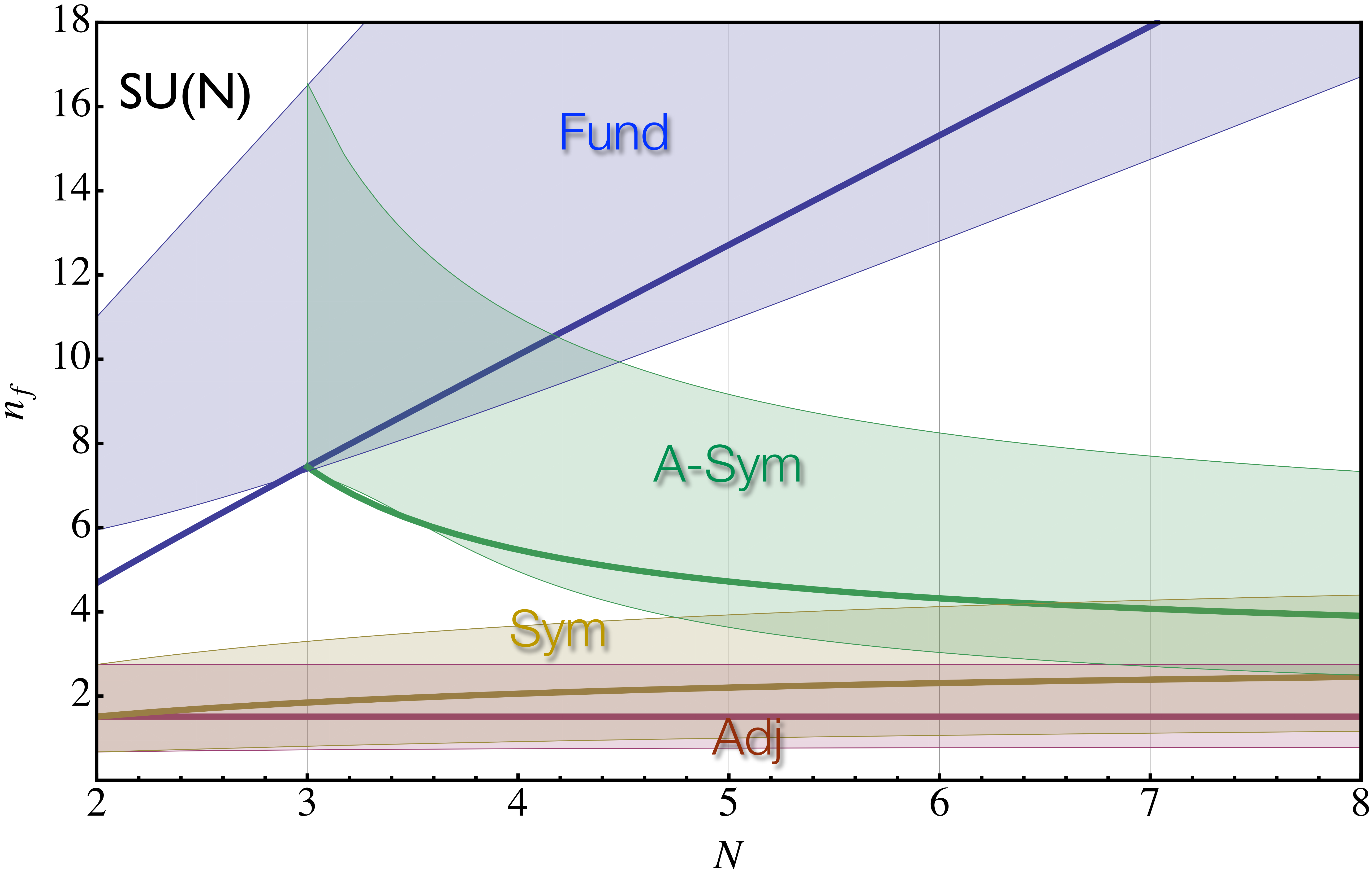
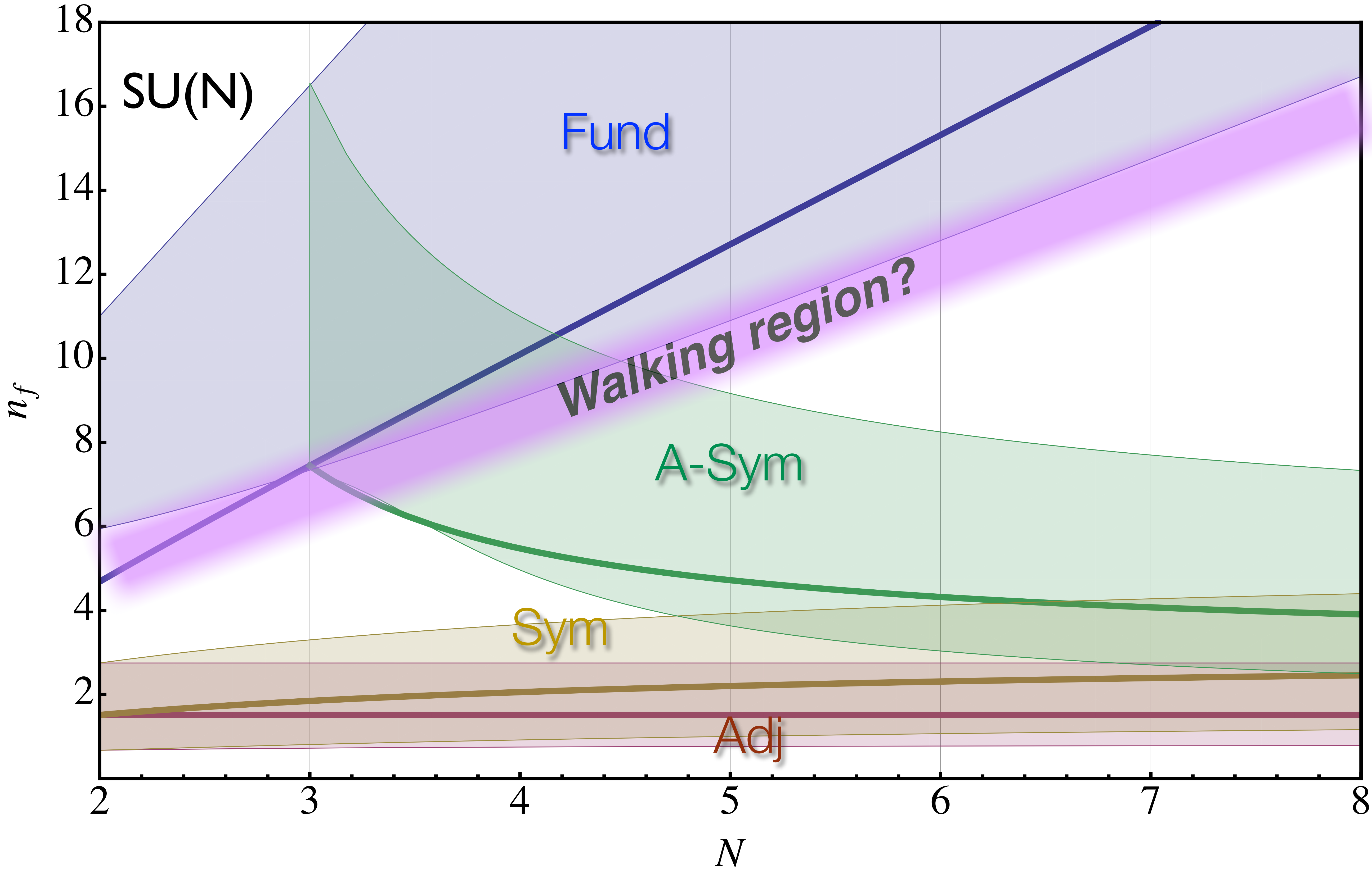
SU(N) Phase Diagram



SU(N) Phase Diagram



Still

Still

- Do we know any 4D walking gauge theory?

Still

- Do we know any 4D walking gauge theory?
- What is the size of the walking window?

Still

- Do we know any 4D walking gauge theory?
- What is the size of the walking window?
- What is the anomalous dimension?

Walking 4D Gauge theory

$$Tr\left[-\frac{1}{2}F^{\mu\nu}F_{\mu\nu} + i\bar{\lambda}\not{D}\lambda + \overline{Q}i\not{D}Q + \partial_\mu H^\dagger\partial^\mu H + y_H\overline{Q}HQ\right]$$

$$-u_1(Tr[H^\dagger H])^2 - u_2 Tr(H^\dagger H)^2 \ .$$

Fields	$[SU(N_c)]$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_V$	$U(1)_{AF}$
λ	Adj	1	1	0	1
q	$\square$	$\overline{\square}$	1	$\frac{N_f - N_c}{N_c}$	$-\frac{N_c}{N_f}$
$\widetilde{q}$	$\overline{\square}$	1	$\square$	$-\frac{N_f - N_c}{N_c}$	$-\frac{N_c}{N_f}$
H	1	$\square$	$\overline{\square}$	0	$\frac{2N_c}{N_f}$
G_μ	Adj	1	1	0	0

Antipin, Mojaza, Sannino 2011

Walking 4D Gauge theory

$$Tr\left[-\frac{1}{2}F^{\mu\nu}F_{\mu\nu} + i\bar{\lambda}\not{D}\lambda + \overline{Q}i\not{D}Q + \partial_\mu H^\dagger\partial^\mu H + y_H\overline{Q}HQ\right]$$

$$-u_1(Tr[H^\dagger H])^2 - u_2 Tr(H^\dagger H)^2\ .$$

Fields	$[SU(N_c)]$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_V$	$U(1)_{AF}$
λ	Adj	1	1	0	1
q	$\square$	$\overline{\square}$	1	$\frac{N_f-N_c}{N_c}$	$-\frac{N_c}{N_f}$
$\widetilde{q}$	$\overline{\square}$	1	$\square$	$-\frac{N_f-N_c}{N_c}$	$-\frac{N_c}{N_f}$
H	1	$\square$	$\overline{\square}$	0	$\frac{2N_c}{N_f}$
G_μ	Adj	1	1	0	0

Antipin, Mojaza, Sannino 2011

Walking 4D Gauge theory

$$Tr\left[-\frac{1}{2}F^{\mu\nu}F_{\mu\nu}+i\bar{\lambda}\not{D}\lambda+\overline{Q}i\not{D}Q+\partial_\mu H^\dagger\partial^\mu H+y_H\overline{Q}HQ\right]$$

$$-u_1(Tr[H^\dagger H])^2-u_2 Tr(H^\dagger H)^2 \ .$$

Fields	$[SU(N_c)]$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_V$	$U(1)_{AF}$
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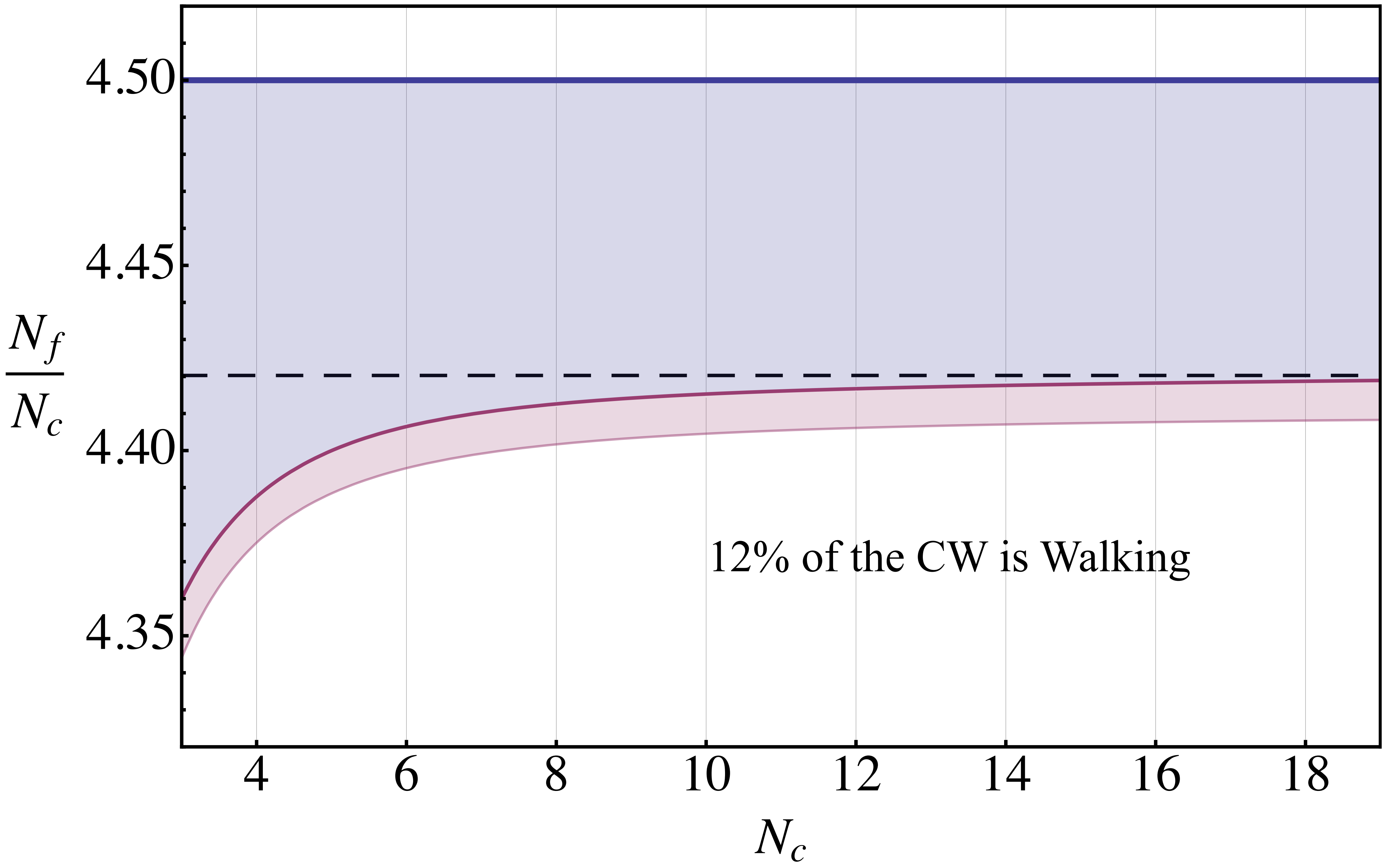
q	$\square$	$\overline{\square}$	1	$\frac{N_f-N_c}{N_c}$	$-\frac{N_c}{N_f}$
$\widetilde{q}$	$\overline{\square}$	1	$\square$	$-\frac{N_f-N_c}{N_c}$	$-\frac{N_c}{N_f}$
H	1	$\square$	$\overline{\square}$	0	$\frac{2N_c}{N_f}$
G_μ	Adj	1	1	0	0

Antipin, Mojaza, Sannino 2011

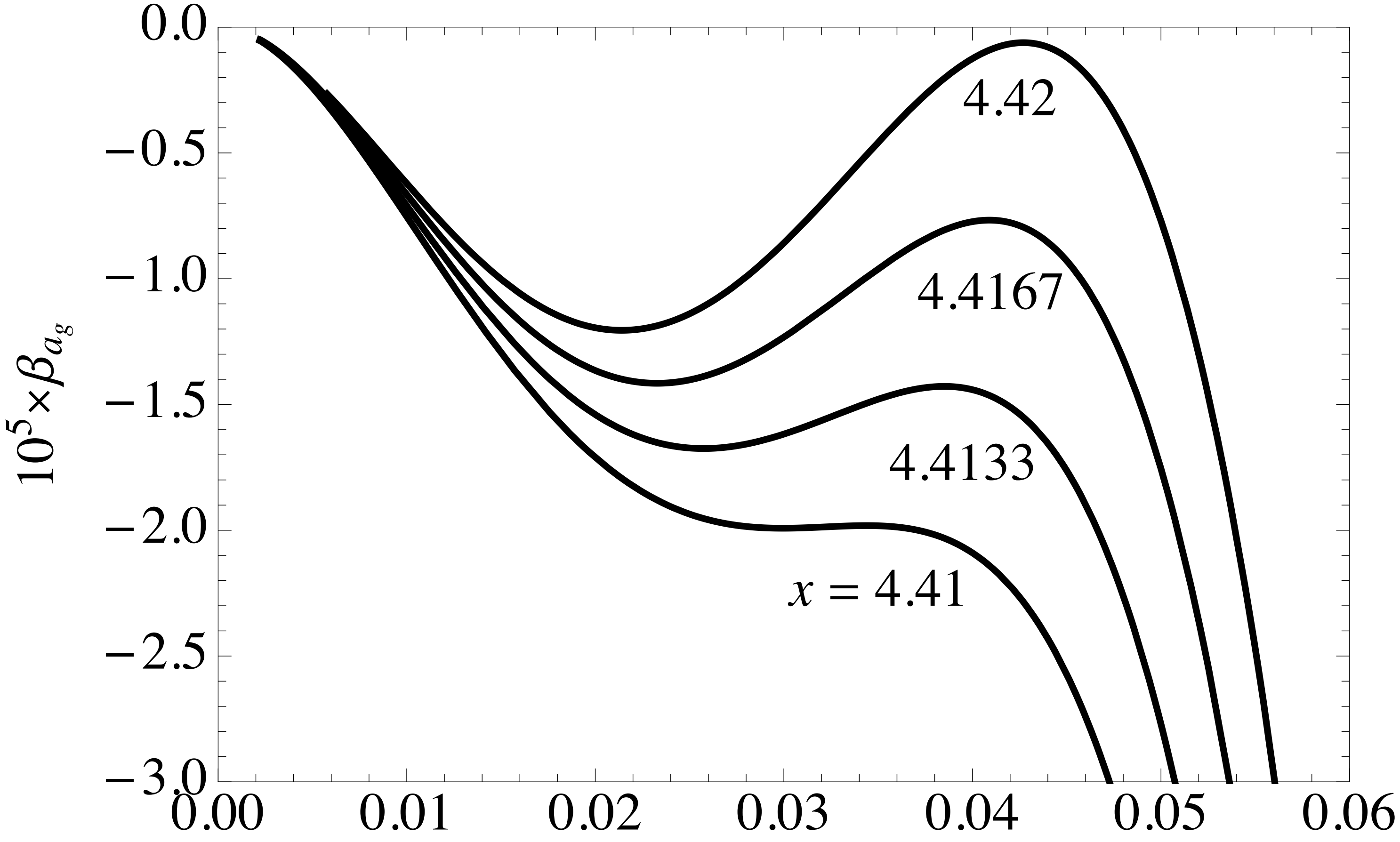
Conformal Window and Walking



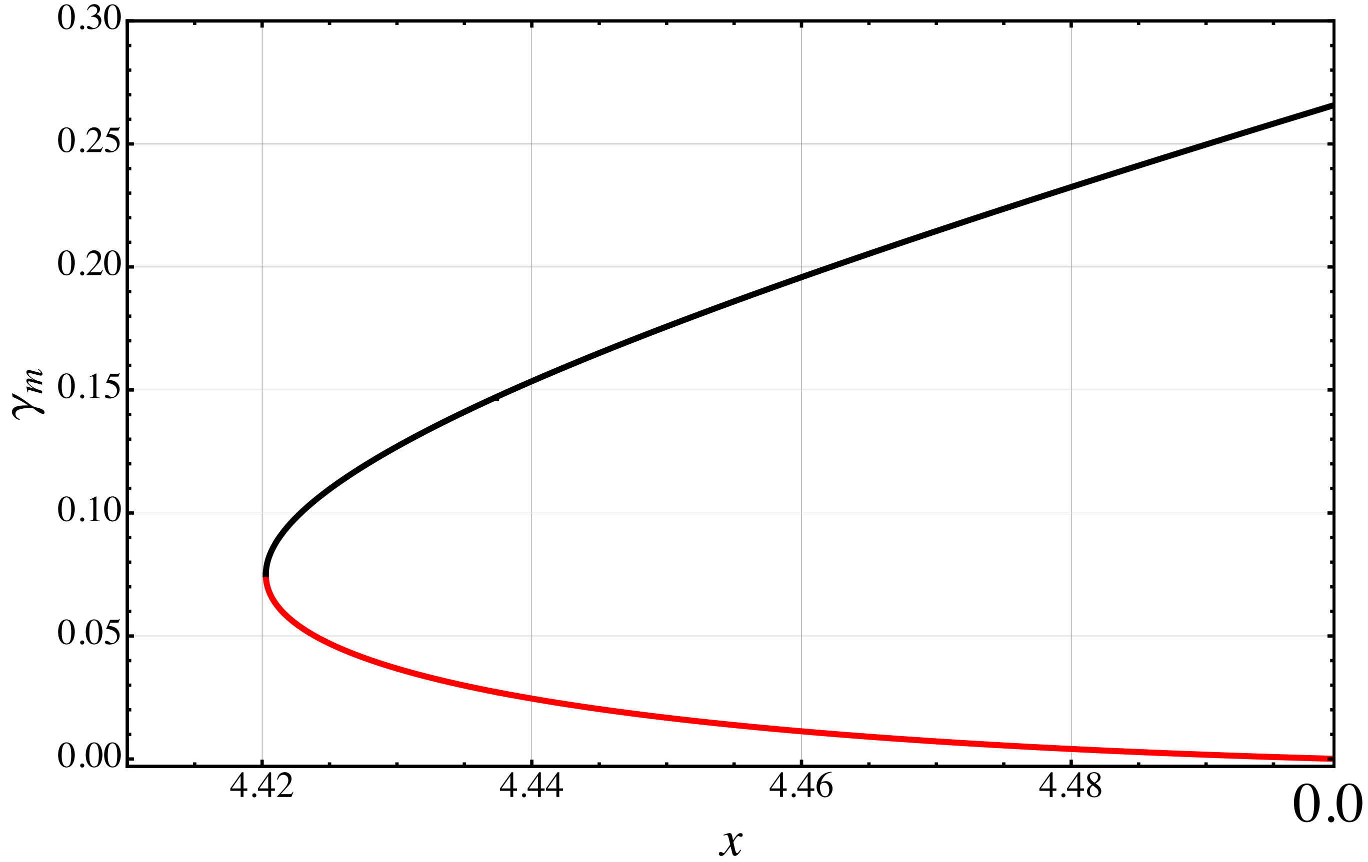
Antipin, Di Chiara, Mojaza, Mølgaard, Sannino 2012

Perturbative Walking

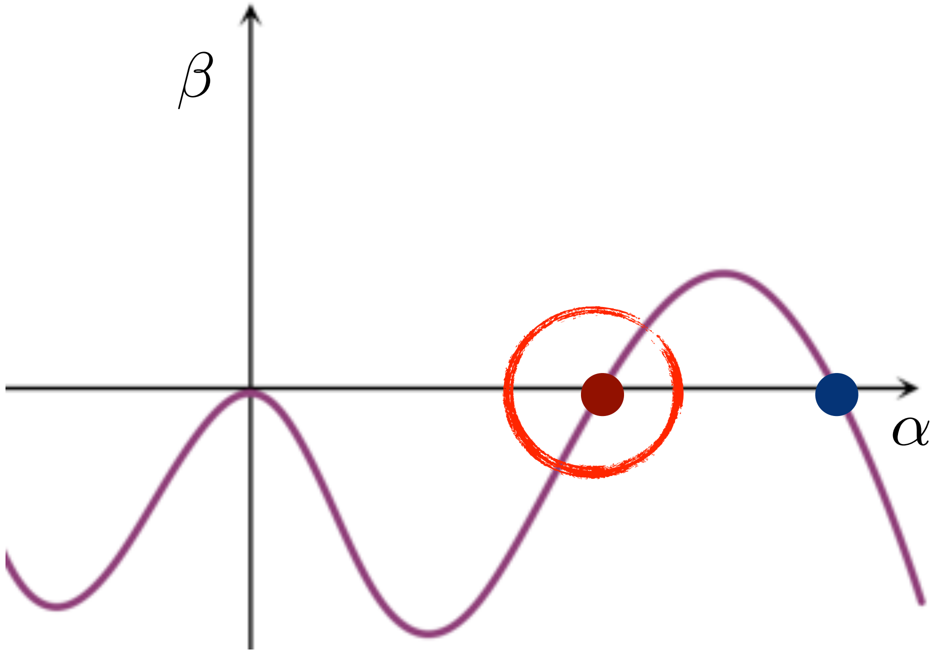
$$x = \frac{N_f}{N_c}$$

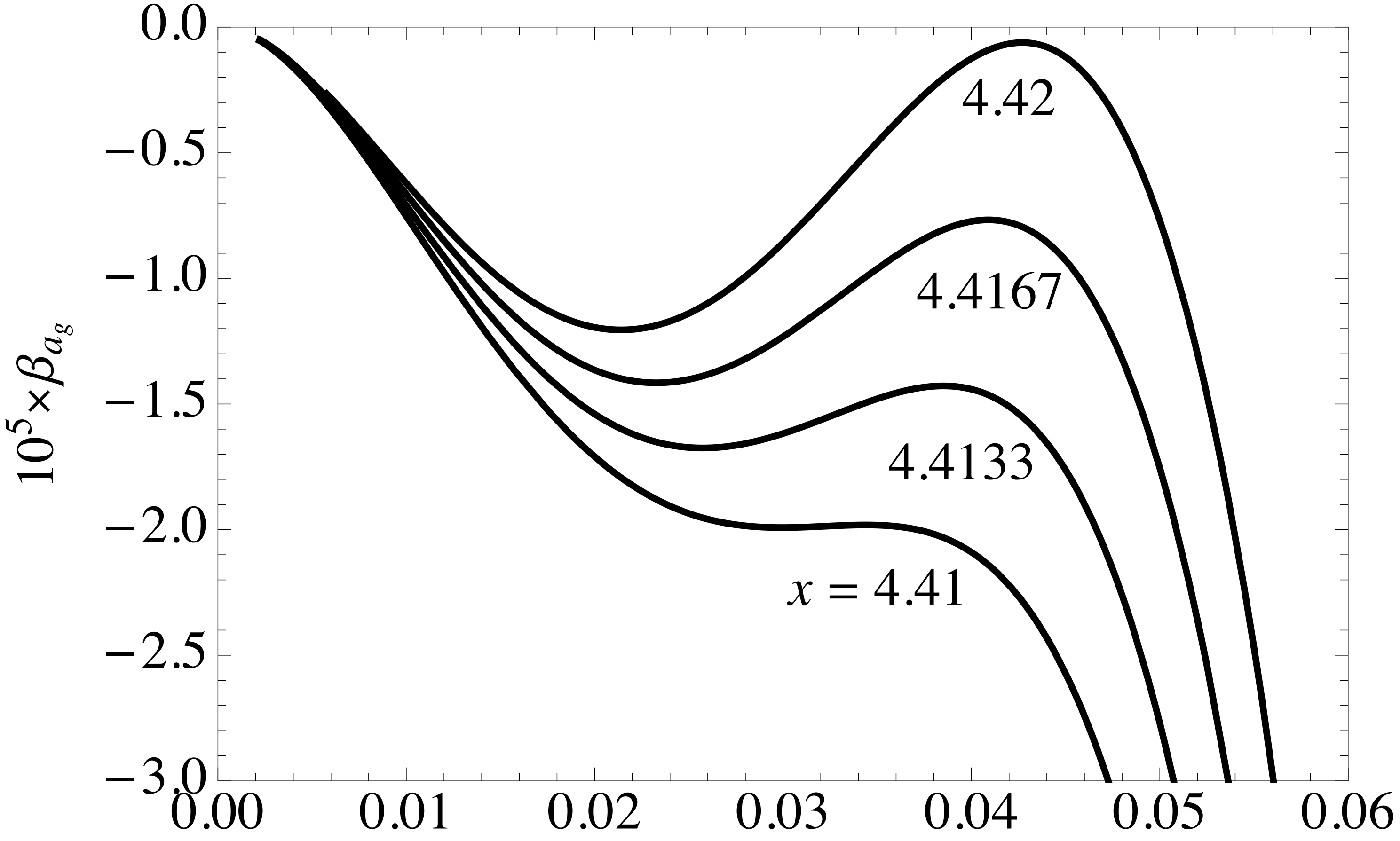


Perturbative Walking



$$x = \frac{N_f}{N_c}$$





Minimal TC

U

D

Minimal TC

- Minimal WT

$SU(2)_{TC}$ $\square\!\square$ **U** **N**
D **E**

Sannino & Tuominen 04

Dietrich, Sannino, Tuominen 05

Frandsen, Masina, Sannino 09

Minimal TC

- Minimal WT

$SU(2)_{TC}$ $\square\square$ **U** **N** **D** **E**

Sannino & Tuominen 04

Dietrich, Sannino, Tuominen 05

Frandsen, Masina, Sannino 09

- Next to MWT

$SU(3)_{TC}$ $\square\square$ **U** **D**

Sannino, Tuominen 04

Dietrich, Sannino, Tuominen 05

Minimal TC

- Minimal WT

$SU(2)_{TC}$ $\square\square$ **U** **D** **N** **E**

Sannino & Tuominen 04

Dietrich, Sannino, Tuominen 05

Frandsen, Masina, Sannino 09

- Next to MWT

$SU(3)_{TC}$ $\square\square$ **U** **D**

Sannino, Tuominen 04

Dietrich, Sannino, Tuominen 05

- Orthogonal

$SO(4)_{TC}$ $\square$ **U** **D**

Frandsen, Sannino 09

Minimal TC

- Minimal WT

$SU(2)_{TC}$ $\square\!\square$ **U** **D** **N** **E**

Sannino & Tuominen 04

Dietrich, Sannino, Tuominen 05

Frandsen, Masina, Sannino 09

- Next to MWT

$SU(3)_{TC}$ $\square\!\square$ **U** **D**

Sannino, Tuominen 04

Dietrich, Sannino, Tuominen 05

- Orthogonal

Vanilla TC

$SO(4)_{TC}$ $\square$ **U** **D**

Frandsen, Sannino 09

- Ultra MT

$SU(2)_{TC}$ $\square$ **U** **D**

Ryttov & Sannino 08

(Next) Minimal Walking Technicolor

(Next) Minimal Walking Technicolor

- Next to minimal is just outside the conformal window

  Fodor, Holland, Kuti, Nogradi, Schroeder, Wong

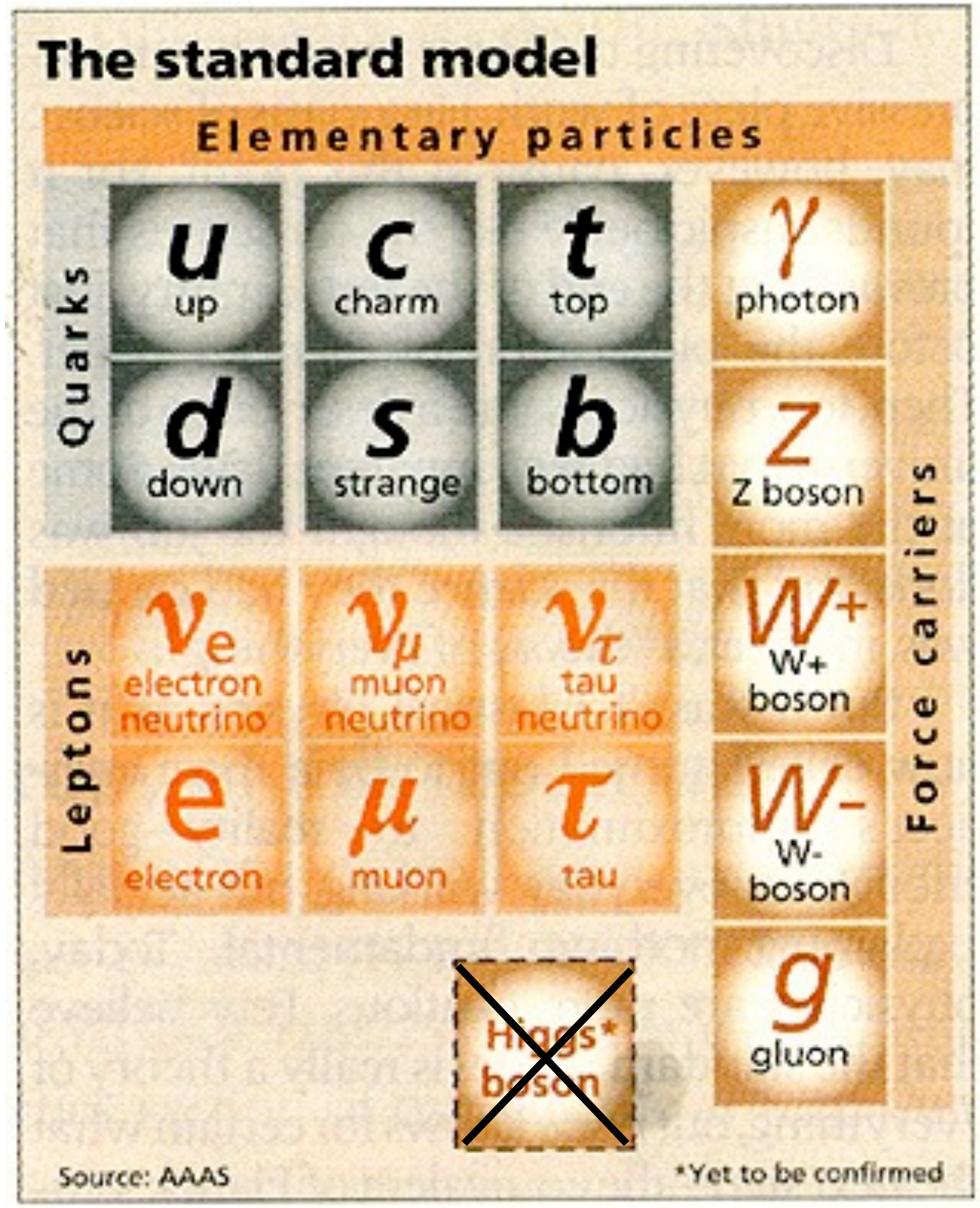
(Next) Minimal Walking Technicolor

- Minimal Walking TC is ideal for iWalk

  Catterall & Sannino;
  Del Debbio, Lucini Patella, Pica, Rago
  Hietanen, Rummukainen, Tuominen
  Catterall, Giedt, Sannino

- Next to minimal is just outside the conformal window

  Fodor, Holland, Kuti, Nogradi, Schroeder, Wong



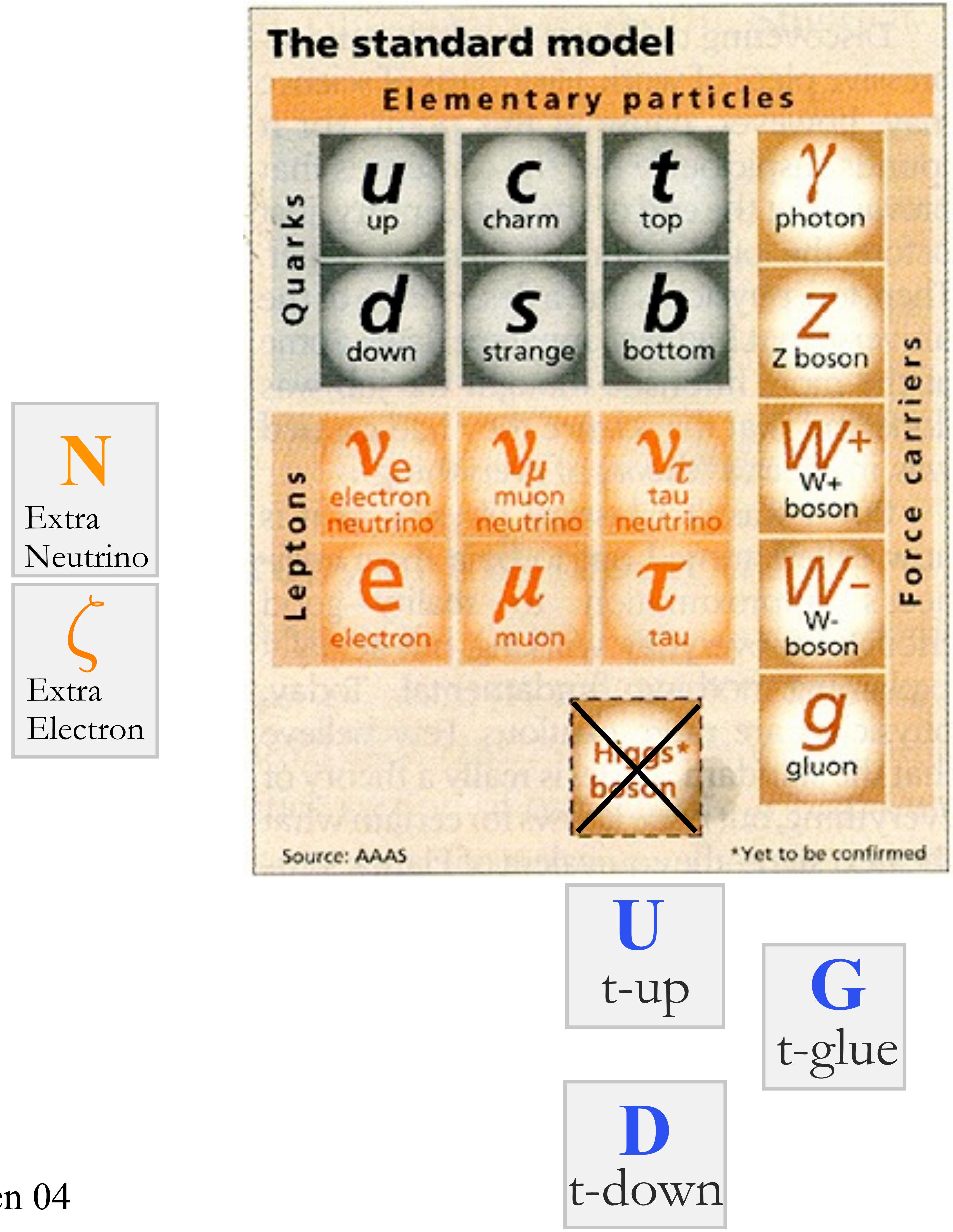
U(1)

SU(2)

SU(3)

F.S. + Tuominen 04

Dietrich, F.S., Tuominen 05



U(1)

SU(2)

SU(3)

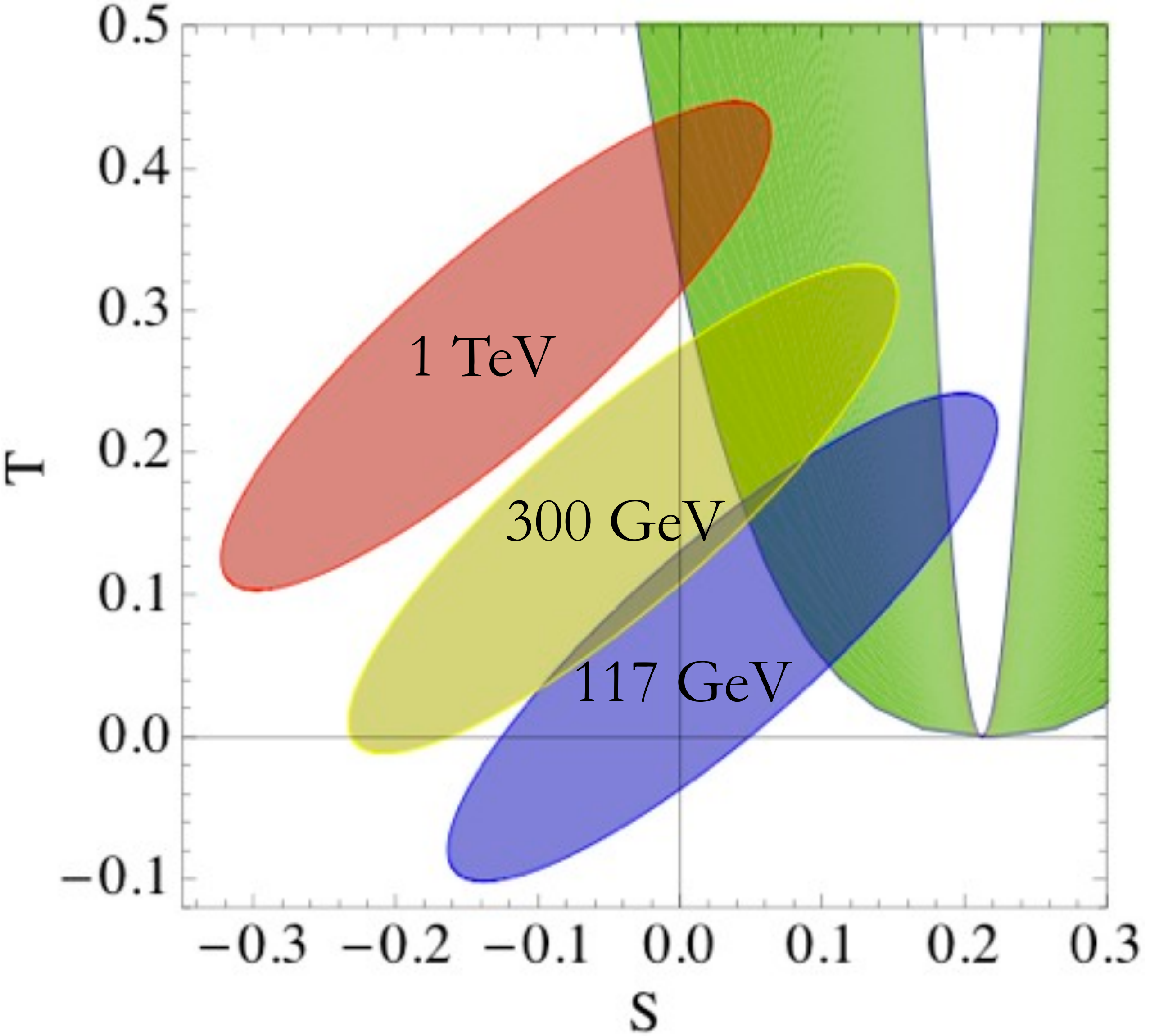
SU(2)

F.S. + Tuominen 04

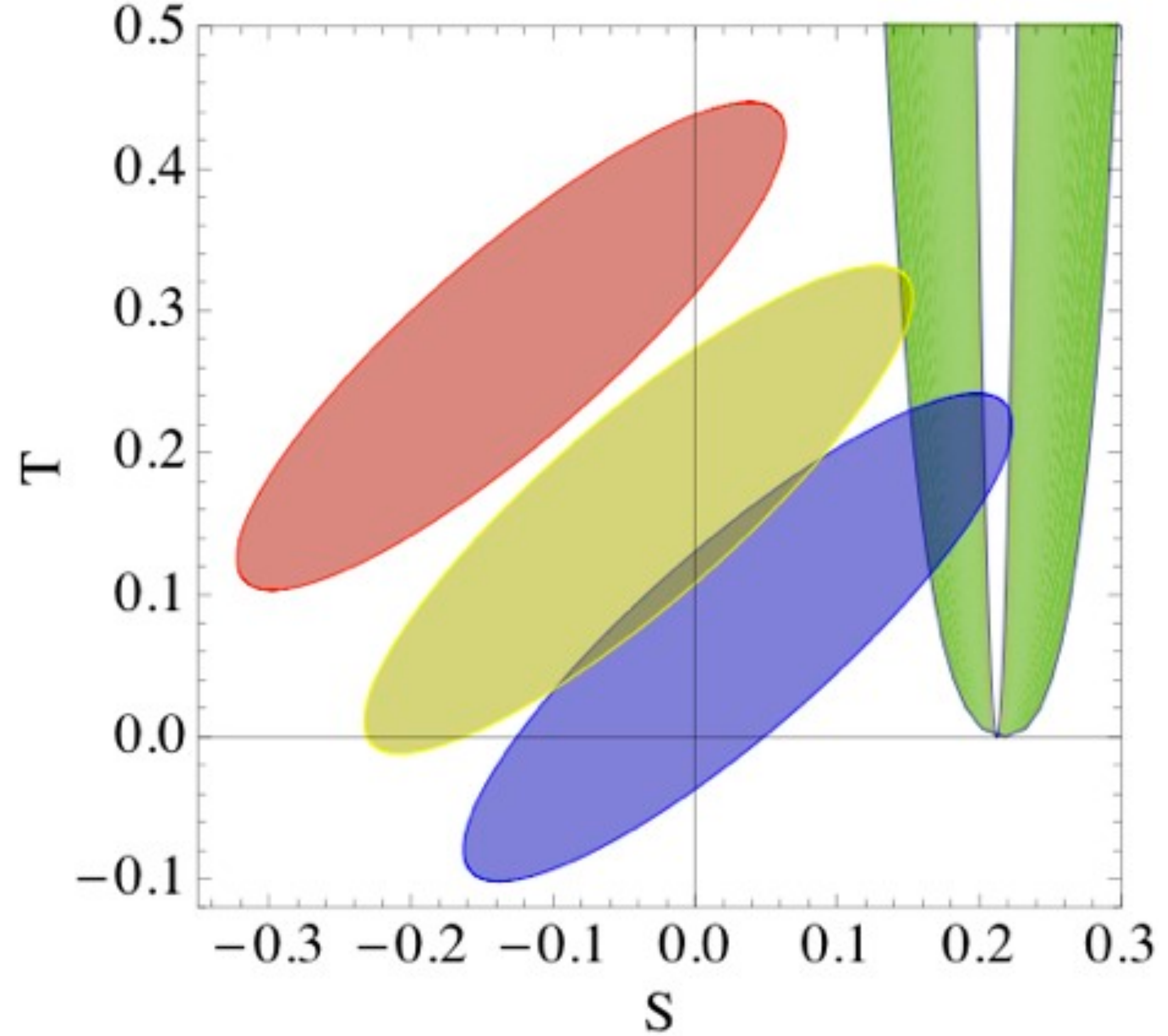
Dietrich, F.S., Tuominen 05

U and D: Adj of SU(2)

New Leptons & Precision Data



Exotic Leptonic hypercharge Y=-3/2



Standard Model Leptonic hypercharge

MWT Lagrangian

$$\mathcal{L}_H \rightarrow -\frac{1}{4}\mathcal{F}^a_{\mu\nu}\mathcal{F}^{a\mu\nu} + i\bar{Q}_L\gamma^\mu D_\mu Q_L + i\bar{U}_R\gamma^\mu D_\mu U_R + i\bar{D}_R\gamma^\mu D_\mu D_R$$
$$+ i\bar{L}_L\gamma^\mu D_\mu L_L + i\bar{N}_R\gamma^\mu D_\mu N_R + i\bar{E}_R\gamma^\mu D_\mu E_R$$

$$\mathcal{F}^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g_{TC}\epsilon^{abc}\mathcal{A}^b_\mu \mathcal{A}^c_\nu \qquad a, b, c = 1, \ldots, 3$$

$$D_\mu Q^a_L = \left(\delta^{ac}\partial_\mu + g_{TC}\mathcal{A}^b_\mu \epsilon^{abc} - i\frac{g}{2}\vec{W}_\mu \cdot \vec{\tau}\delta^{ac} - ig'\frac{y}{2}B_\mu \delta^{ac}\right) Q^c_L$$

MWT Lagrangian

$$\mathcal{L}_H \rightarrow -\frac{1}{4}\mathcal{F}^a_{\mu\nu}\mathcal{F}^{a\mu\nu} + i\bar{Q}_L\gamma^\mu D_\mu Q_L + i\bar{U}_R\gamma^\mu D_\mu U_R + i\bar{D}_R\gamma^\mu D_\mu D_R$$

$$+i\bar{L}_L\gamma^\mu D_\mu L_L + i\bar{N}_R\gamma^\mu D_\mu N_R + i\bar{E}_R\gamma^\mu D_\mu E_R$$

$$\mathcal{F}^a_{\mu\nu} = \partial_\mu\mathcal{A}^a_\nu - \partial_\nu\mathcal{A}^a_\mu + g_{TC}\epsilon^{abc}\mathcal{A}^b_\mu\mathcal{A}^c_\nu \qquad a, b, c = 1, \ldots, 3$$

$$D_\mu Q^a_L = \left(\delta^{ac}\partial_\mu + g_{TC}\mathcal{A}^b_\mu\epsilon^{abc} - i\frac{g}{2}\vec{W}_\mu\cdot\vec{\tau}\delta^{ac} - ig'\frac{y}{2}B_\mu\delta^{ac}\right)Q^c_L$$

MWT Lagrangian

$$\mathcal{L}_H \rightarrow -\frac{1}{4}\mathcal{F}^a_{\mu\nu}\mathcal{F}^{a\mu\nu} + i\bar{Q}_L\gamma^\mu D_\mu Q_L + i\bar{U}_R\gamma^\mu D_\mu U_R + i\bar{D}_R\gamma^\mu D_\mu D_R$$

$$+i\bar{L}_L\gamma^\mu D_\mu L_L + i\bar{N}_R\gamma^\mu D_\mu N_R + i\bar{E}_R\gamma^\mu D_\mu E_R$$

$$\mathcal{F}^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g_{TC}\epsilon^{abc}\mathcal{A}^b_\mu \mathcal{A}^c_\nu \qquad a, b, c = 1, \ldots, 3$$

$$D_\mu Q^a_L = \left(\delta^{ac}\partial_\mu + g_{TC}\mathcal{A}^b_\mu \epsilon^{abc} - i\frac{g}{2}\vec{W}_\mu \cdot \vec{\tau}\delta^{ac} - ig'\frac{y}{2}B_\mu \delta^{ac}\right) Q^c_L$$

What you see is “not” what LHC will see

MWT Effective Lagrangian

$$\mathcal{L}(\text{Composites}) + \mathcal{L}(\text{Mixing with SM}) + \mathcal{L}(\text{New Leptons}) + \mathcal{L}(\text{SM} - \text{Higgs})$$

Foadi, Frandsen, Ryttov & F.S. 07

MWT Effective Lagrangian

$$\mathcal{L}(\text{Composites}) + \mathcal{L}(\text{Mixing with SM}) + \mathcal{L}(\text{New Leptons}) + \mathcal{L}(\text{SM} - \text{Higgs})$$

Composite Higgs	H
Composite Axial - Vector States	$R_{1,2}$

Foadi, Frandsen, Ryttov & F.S. 07

MWT Effective Lagrangian

$$\mathcal{L}(\text{Composites}) + \mathcal{L}(\text{Mixing with SM}) + \mathcal{L}(\text{New Leptons}) + \mathcal{L}(\text{SM} - \text{Higgs})$$

Composite Higgs — H

Composite Axial - Vector States — $R_{1,2}$

Heavy Electron — ζ

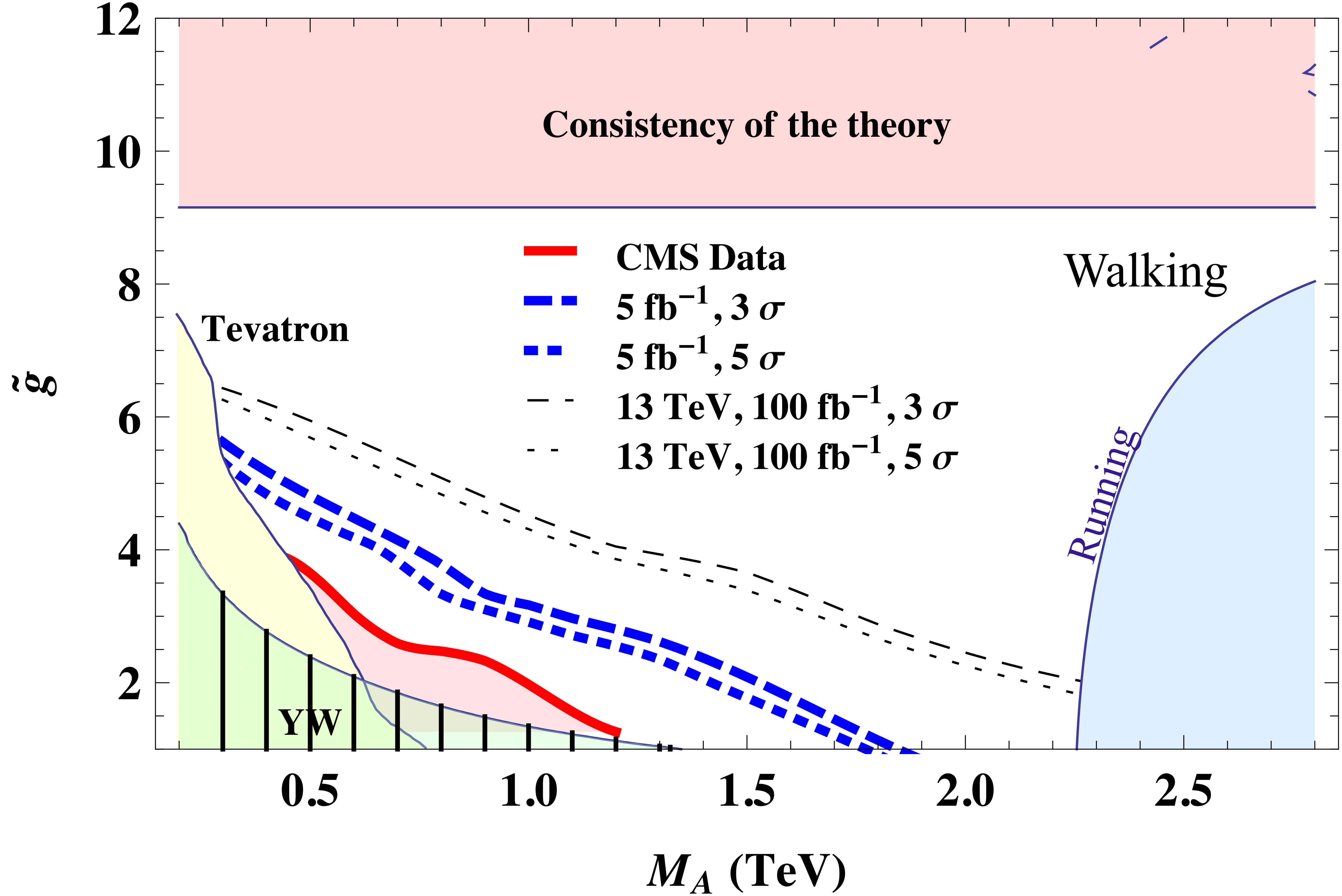
2 Heavy Majoranas — $N_1 \quad N_2$

Frandsen, Masina, Sannino 09

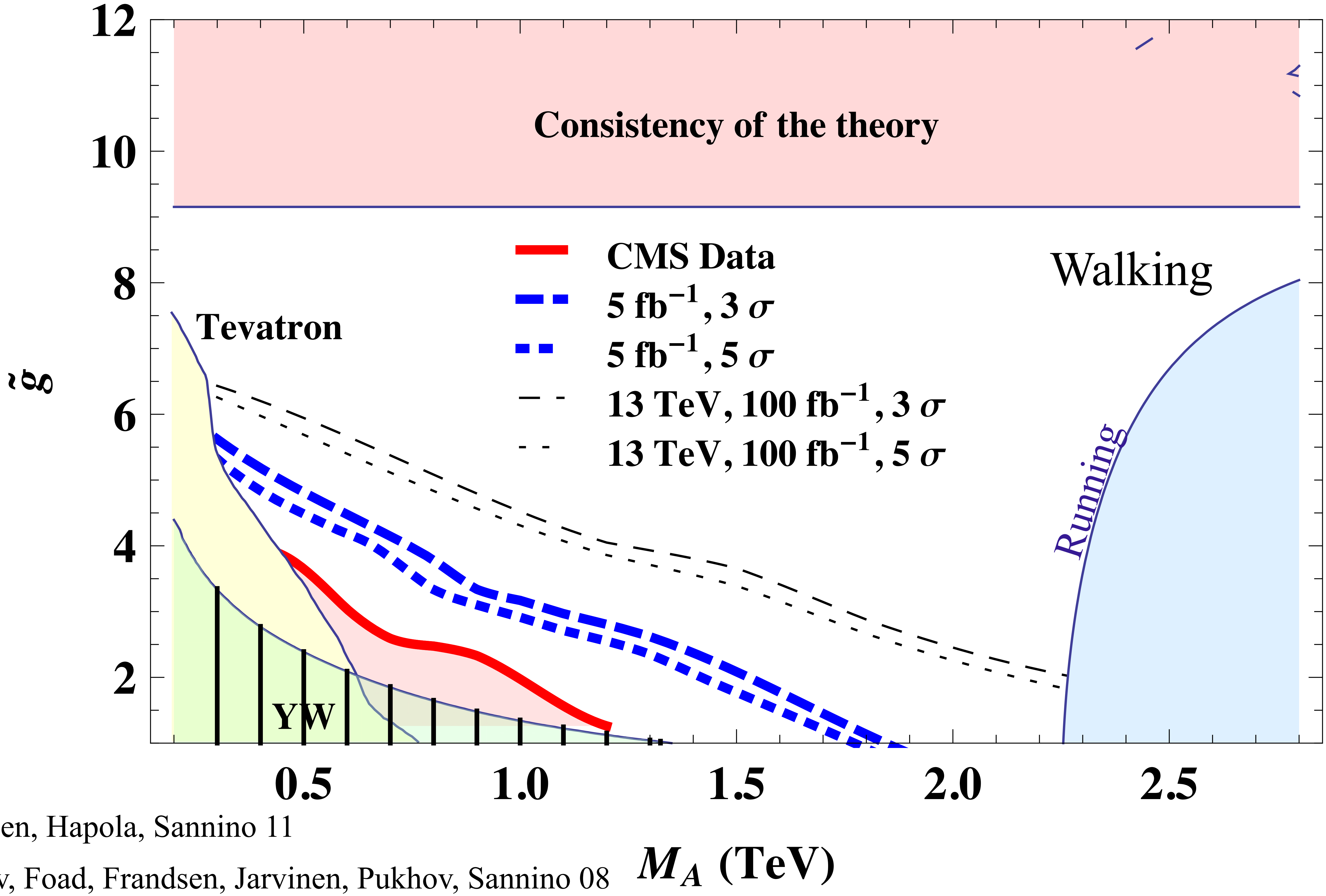
Hapola, Masina, Sannino 11

Foadi, Frandsen, Ryttov & F.S. 07

Constraining MWT



Constraining MWT



Andersen, Hapola, Sannino 11

Belyaev, Foad, Frandsen, Jarvinen, Pukhov, Sannino 08

Conclusions

Conclusions

- New interactions ready to be discovered

Conclusions

- New interactions ready to be discovered
- Example: Technicolor

Conclusions

- New interactions ready to be discovered
- Example: Technicolor
- New phase diagrams

Conclusions

- New interactions ready to be discovered
- Example: Technicolor
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