results from 2203.17197 with Strumia and Wulzer

Colliders ↔ Landscape

ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

SEP. 26 2024, TOP 2024 - ST. MALO, FRANCE

ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Roma3

results from 2203.17197 with Strumia and Wulzer

Colliders ↔ Landscape

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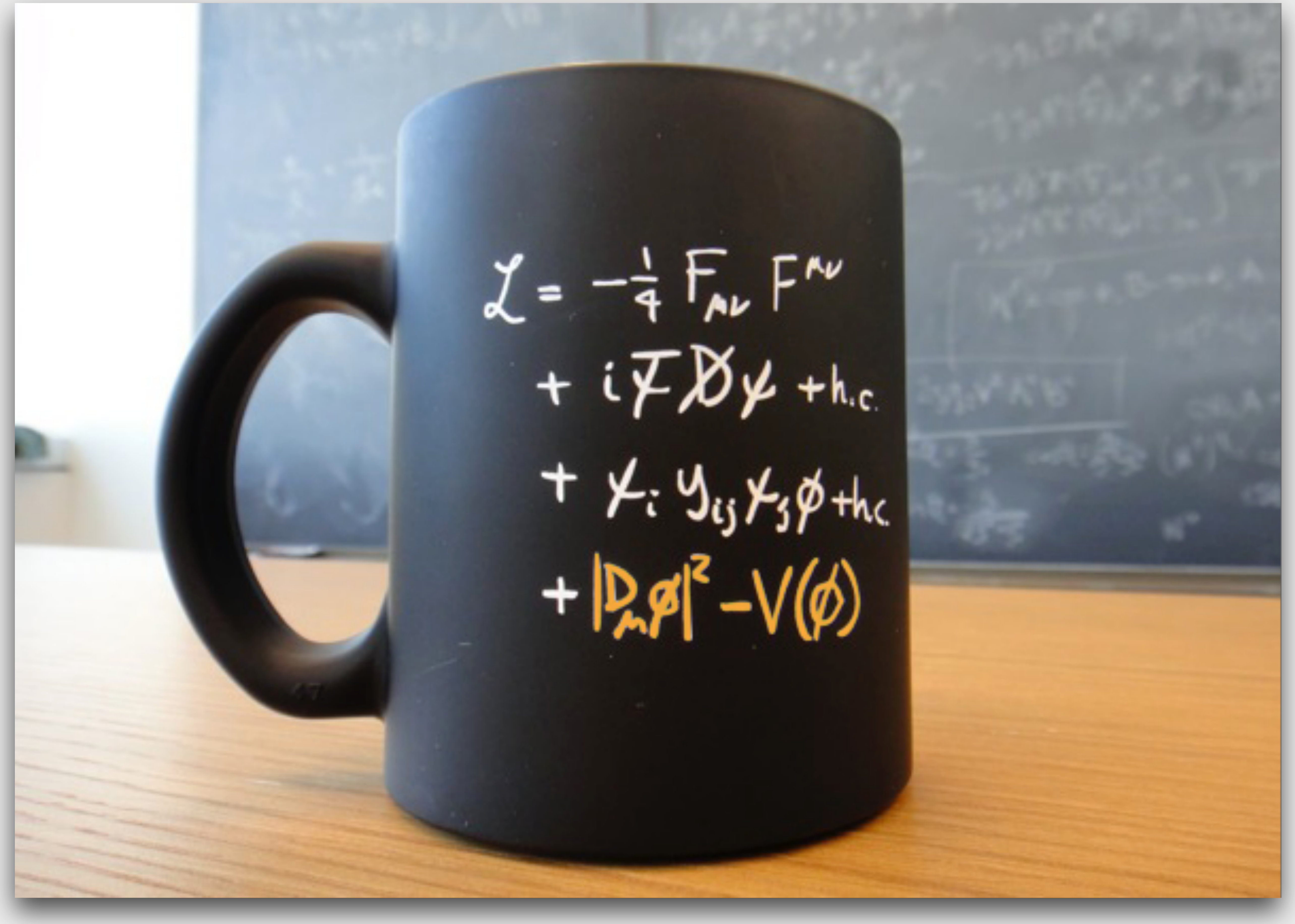
Where do we stand?



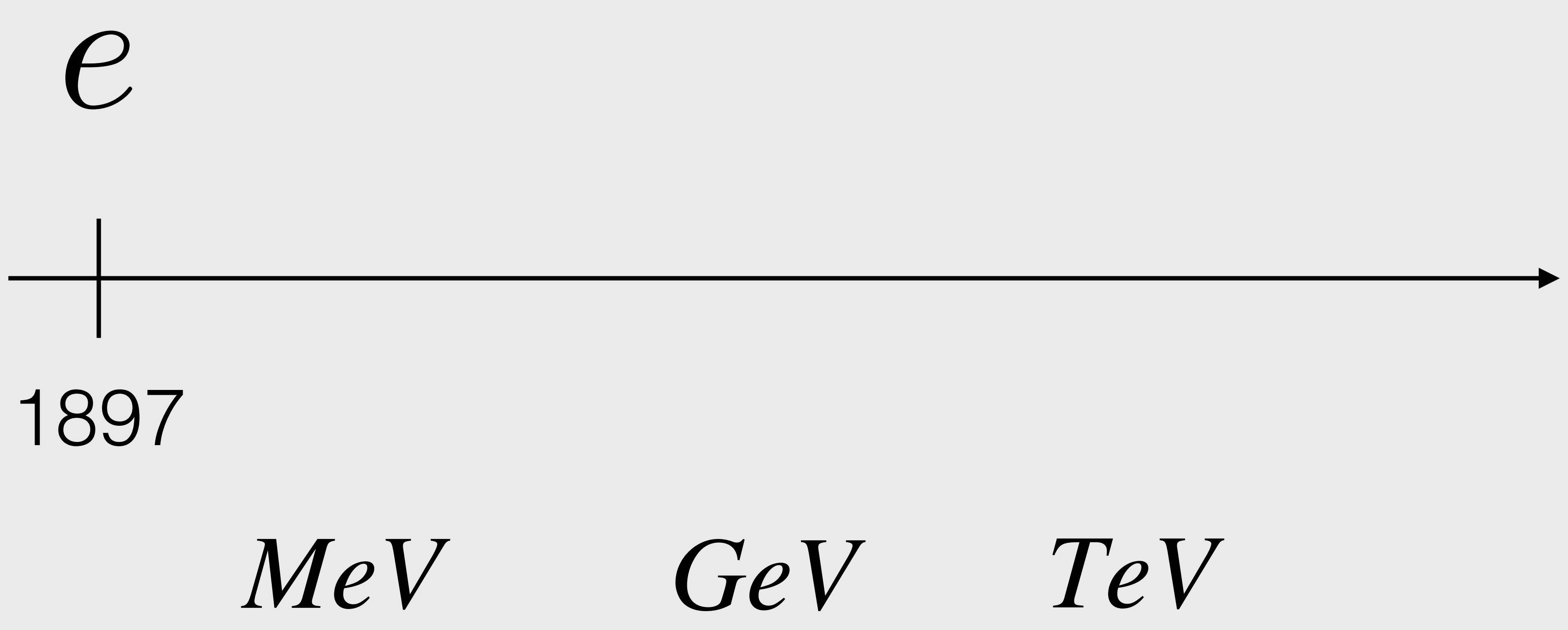
We have got “the” formula

… and it is surprisingly short!

The march of symmetry

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



e

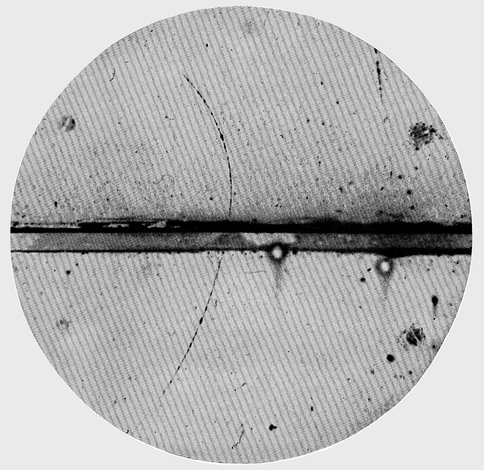
1897

MeV GeV TeV

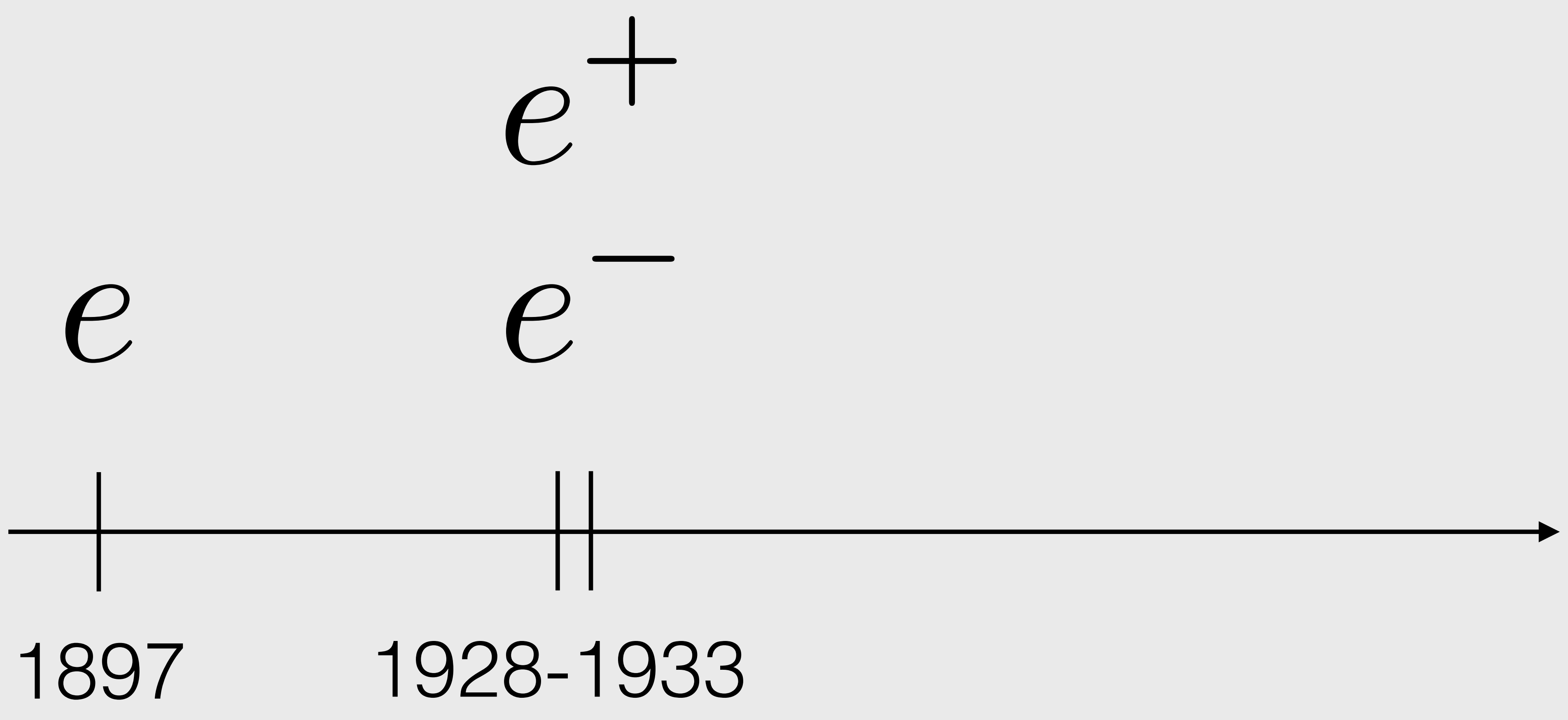
The march of symmetry

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



$B = 1.5\,\mathrm{T}$

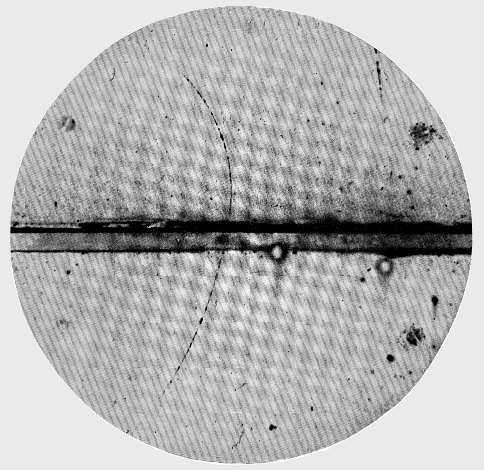


MeV *GeV* *TeV*

The march of symmetry

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



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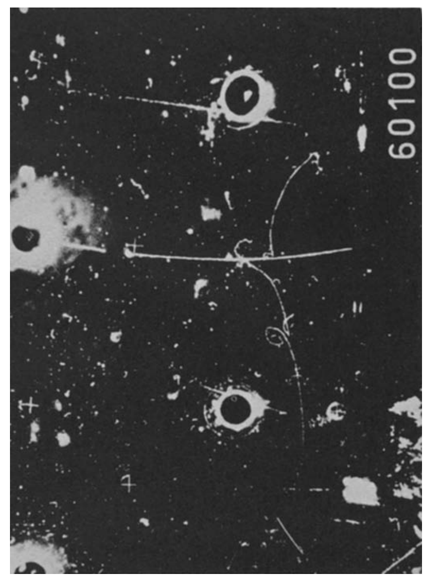
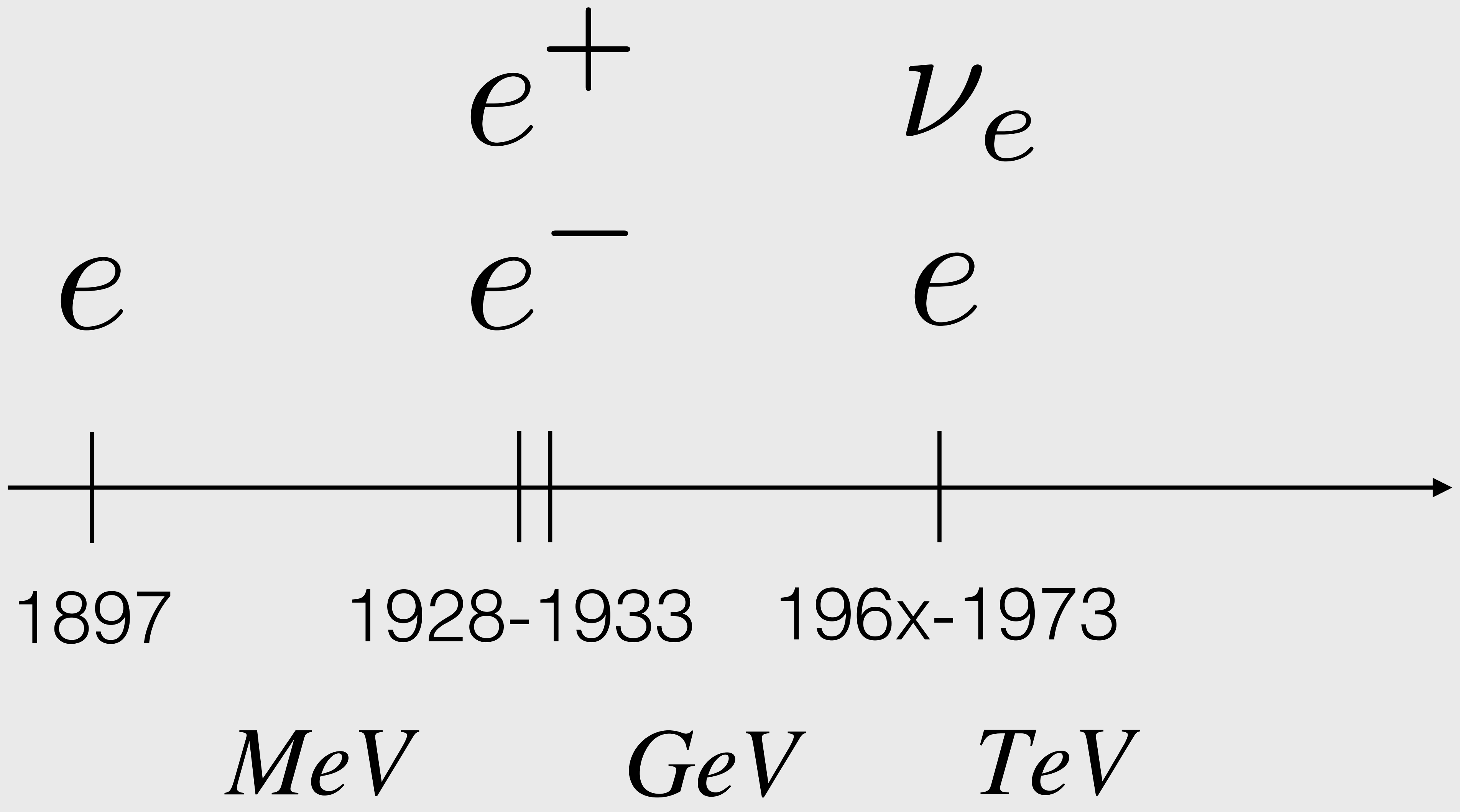


Fig. 1. Possible event of the type $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$.

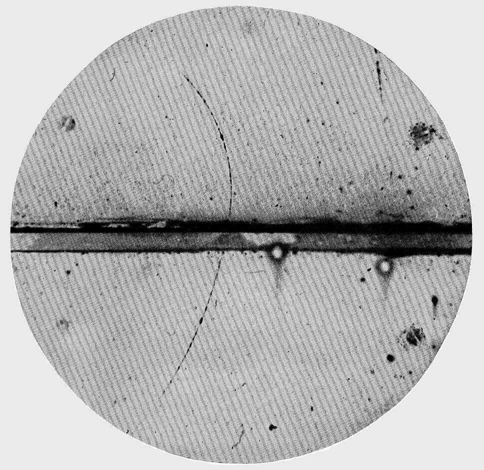
$B = 2\ \mathrm{T}$



The march of symmetry

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles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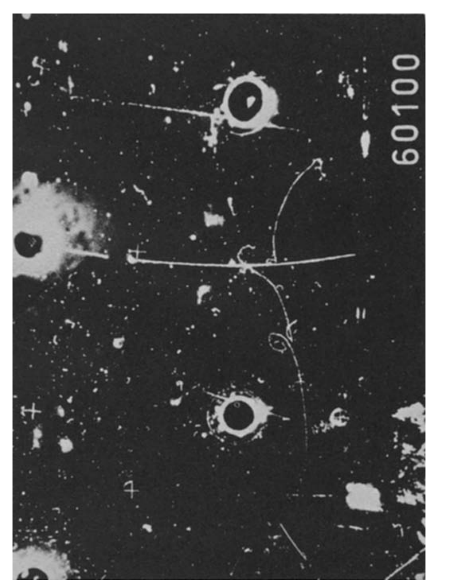

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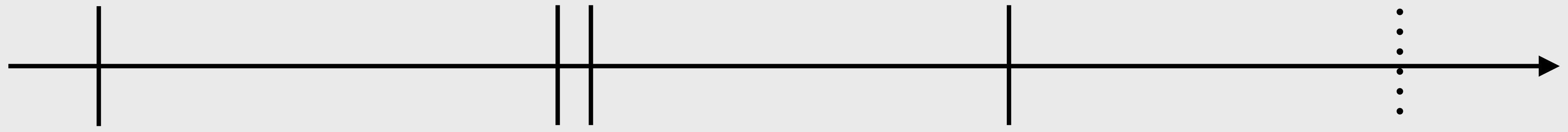
$B = 2\,\mathrm{T}$

e $\quad$ e^+, e^- $\quad$ ν_e, e


1897

1928-1933

196x-1973

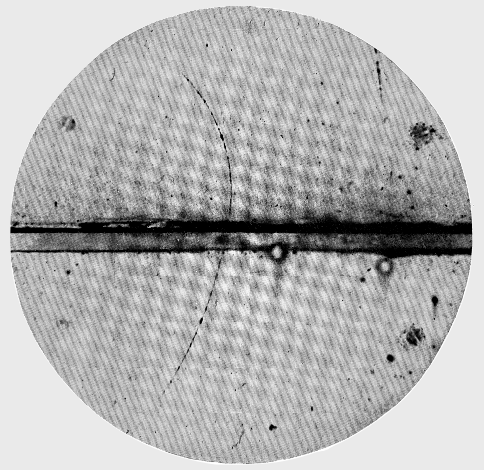
2020s

MeV *GeV* *TeV*

The march of symmetry

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE

Symmetries and particles



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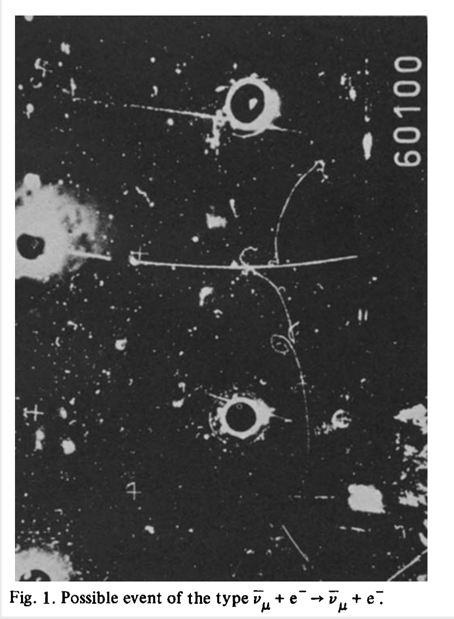
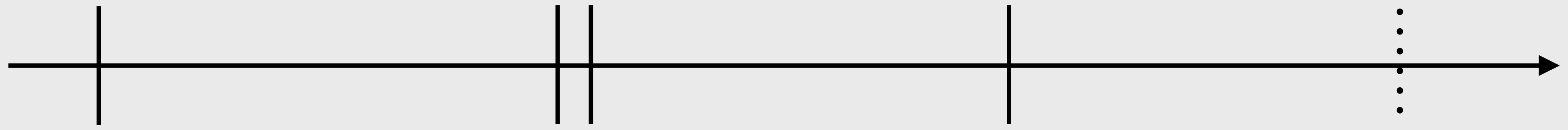


$B = 2$ T

e^+ ν_e

e e^- e

?



1897 1928-1933 196x-1973 2020s

MeV *GeV* *TeV*

Open Questions on the “big picture” on fundamental physics as of 2020s

?	Need new matter (or even bigger modifications to the SM)
●	Adjusting one SM parameter might do
⚙	Adjusting several SM parameters might do
~~EFT~~	Separation of scales as an organizing principle might fail

- ? what is the dark matter in the Universe?
- ● why QCD does not violate CP?
- ● how have baryons originated in the early Universe?
- ⚙ what originates flavor mixing and fermions masses?
- ⚙ what gives mass to neutrinos?
- ~~EFT~~ ● why gravity and weak interactions are so different?
- ~~EFT~~ ● what fixes the cosmological constant?

EACH of these issues one day will teach us a lesson

Open Questions on the "big picture" on fundamental physics as of 2020s

	?	• what is the dark matter in the Universe?	✓	
	●	• why QCD does not violate CP?	✓	✓
	●	• how have baryons originated in the early Universe?	✓	
	⚙	• what originates flavor mixing and fermions masses?	✓	
	⚙	• what gives mass to neutrinos?	✓	
~~EFT~~	●	• why gravity and weak interactions are so different?	✓	
~~EFT~~	●	• what fixes the cosmological constant?	✓	

🟧 WEAK INTERACTIONS

⬜ STRONG INTERACTIONS

🟦 NEED SOME COSMOLOGY INPUTS

- Outlook

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????

Coincidences ?

$$\mathcal{L} = c + \mu^2 H^2 + \lambda H^4$$

Cosmological Constant
(galaxy formation)

Fermi constant
(periodic table)

Higgs boson mass
(meta-)stability of the Universe

Steven Weinberg Phys. Rev. Lett. 59, 2607 - If $c > 200\, c_{\text{measured}}$ galaxies would ne be able to form (matter-domination phase too short)

arXiv:hep-ph/9707380 Agrawal et al. - If $\mu > 5 \cdot \mu_{SM}$ periodic table disappears! (neutron decay too fast)

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• Outlook

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????

Coincidences ?

$$\mathcal{L} = c + \mu^2\ H^2 + \lambda\ H^4$$

- Symmetry, the very idea at the basis of “the” formula, is challenged by a number of phenomena, which may, at best, be described in this language

Cosmological Constant
(galaxy formation)

(meta-)stability of the Universe

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SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE ?????

Coincidences ?

- What if fundamental interactions are not just the language to describe micro-physics (and supposedly be able to derive macro-physics from it) but they also have a direct link to everyday life? or simply “life”?

(galaxy formation)

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• Outlook

SYMMETRY | AS A FUNDAMENTAL CHARACTER OF NATURE | ?????

There is a special pleasure that comes from identifying symmetries in nature, from understanding that the ubiquitous and tangible electron is an immediate relative of the elusive neutrino. But the challenge of particle physics today is to understand symmetry breaking, for that is what makes the world what it is. The neutrino and the electron are really as different as they can be. How does that happen? Why do we have two very light quarks and one very light charged lepton? Why did electroweak symmetry breaking leave one symmetry unbroken, bequeathing us the photon? Why is there light, and why does matter take the form it does? These are the goals of particle physics: not to describe the collisions of highly relativistic protons, but to learn why our world has the shape and form it does. **But to answer questions about the everyday world we need to observe phenomena that occur only at very high energies.**

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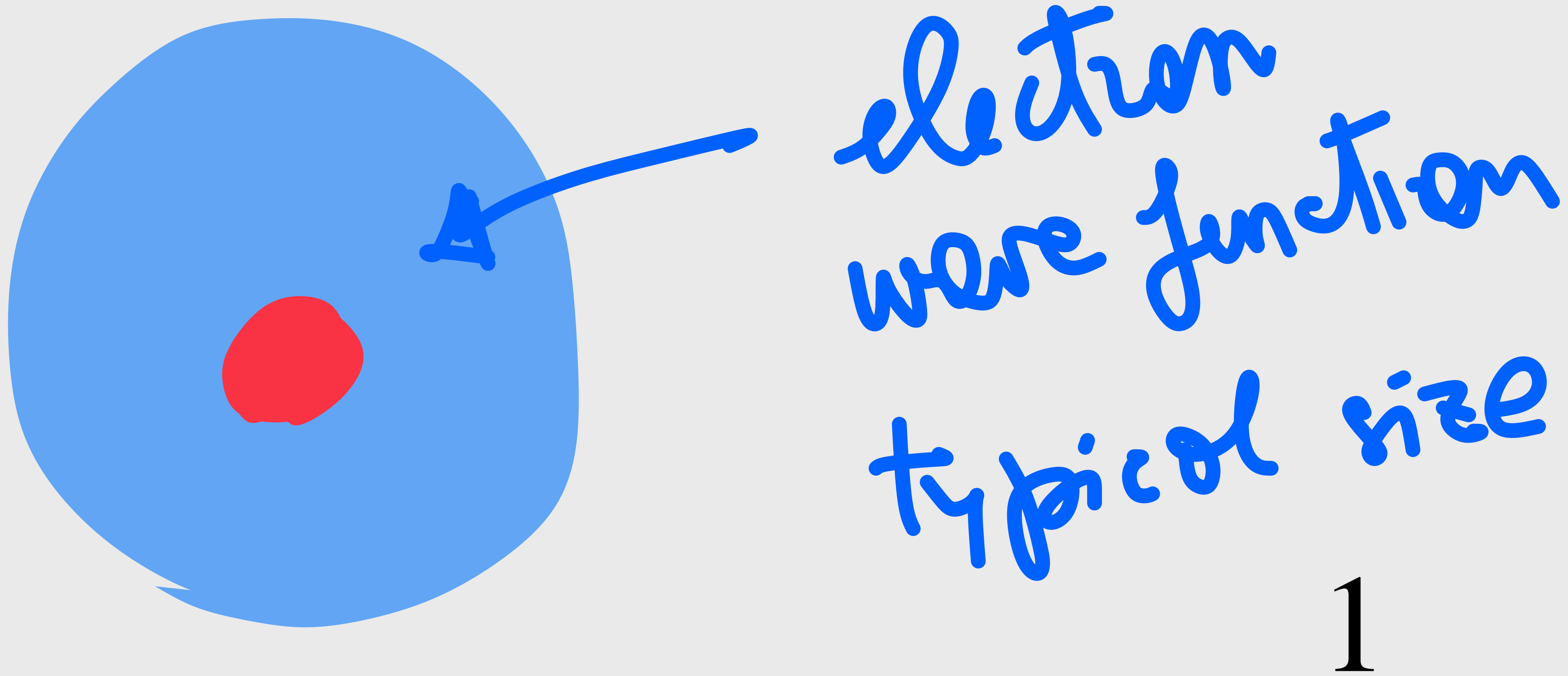
Electron mass in everyday life

Dialing m_e



$$r_0 = \frac{1}{\alpha m_e}$$

- r_0 sets the size of molecules (covalent bonds)

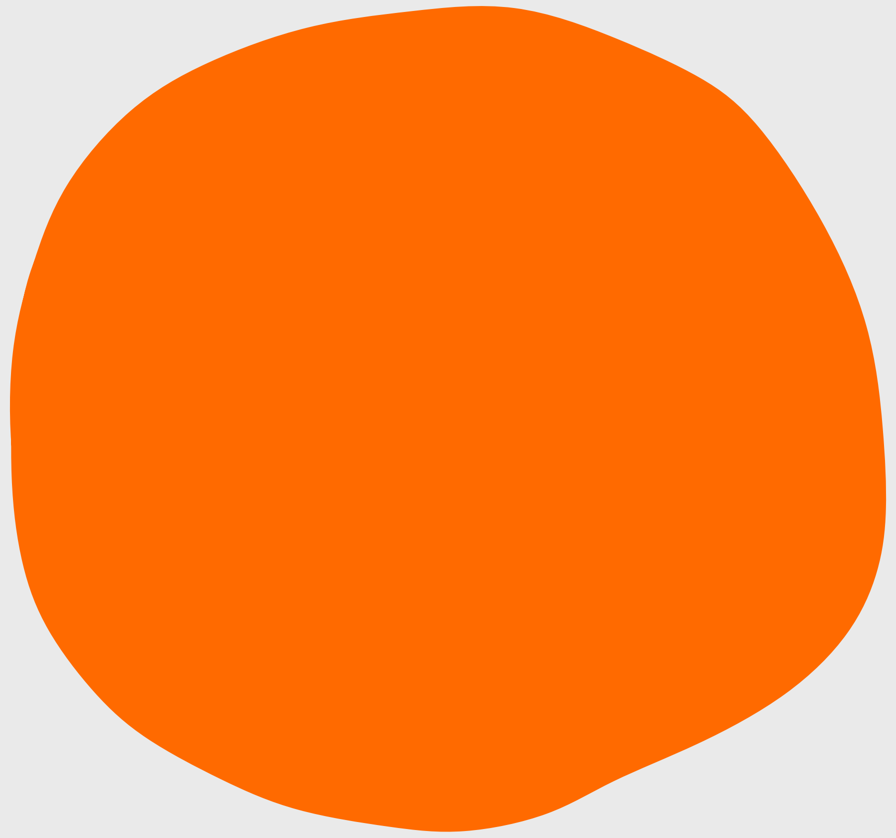
$$e^- p \to n\nu$$

- electron capture in nucleus is less an less suppressed as m_e grows
- $m_e = 0.5$ MeV → 0.6 MeV starts to make nitrogen disappear $^{14}N \to {}^{14}C$

Weak scale and mixings in everyday life

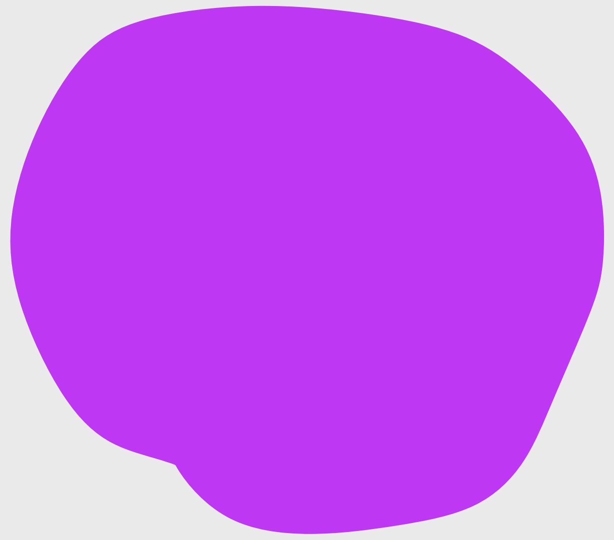
Dialing m_W or V_{ud}

$$pp \to (np)_d e^+ \nu \sim V_{ud}^2 G_F^2 \sim \frac{\lambda_c^2}{v^4}$$



- m_W increases, fusion cross-section is reduced
- star shrinks, thus gets hotter
- flux of protons increased (denser star)
- heat release can now balance pressure from gravity

your new "concentrated" purple Sun



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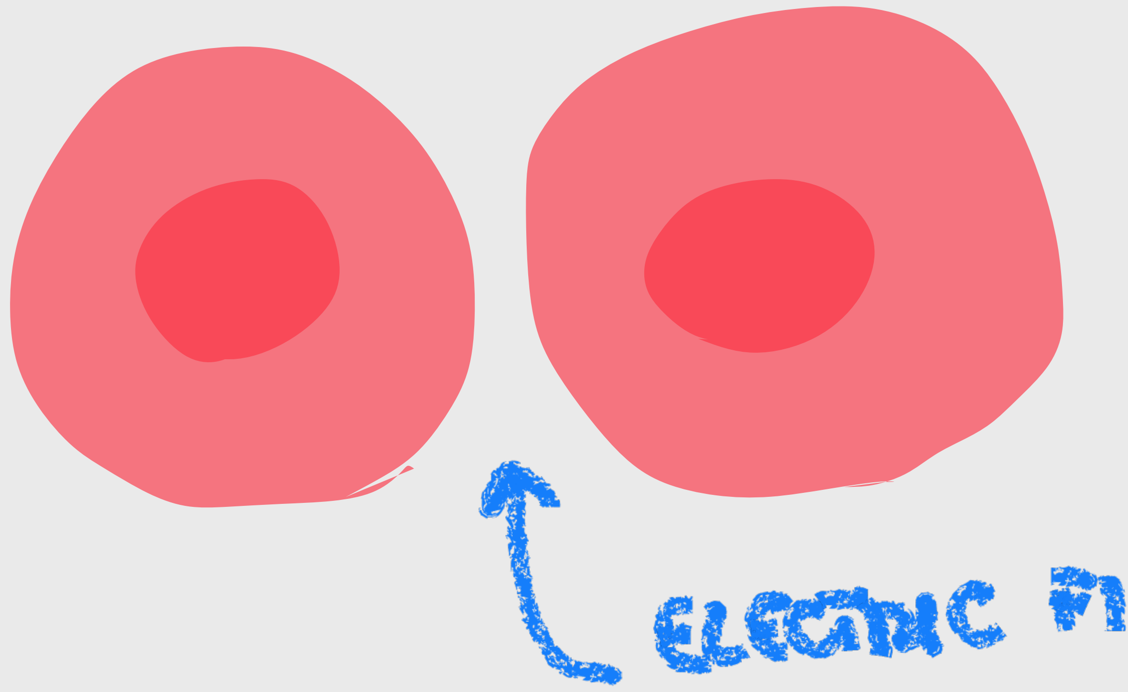
Neutron-proton mass order in everyday life

$m_n < m_p$ from a change in $m_u - m_d$ ~ few MeV (variation about 100% of the present value)

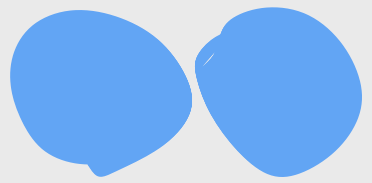
proton, aka Hydrogen, collapses to forms stars



ELECTRIC FIELD
POTENTIAL BARRIER

$$pp \to (np)_d e^+ \nu$$

Neutron would be the lightest baryon, it collapses to forms stars

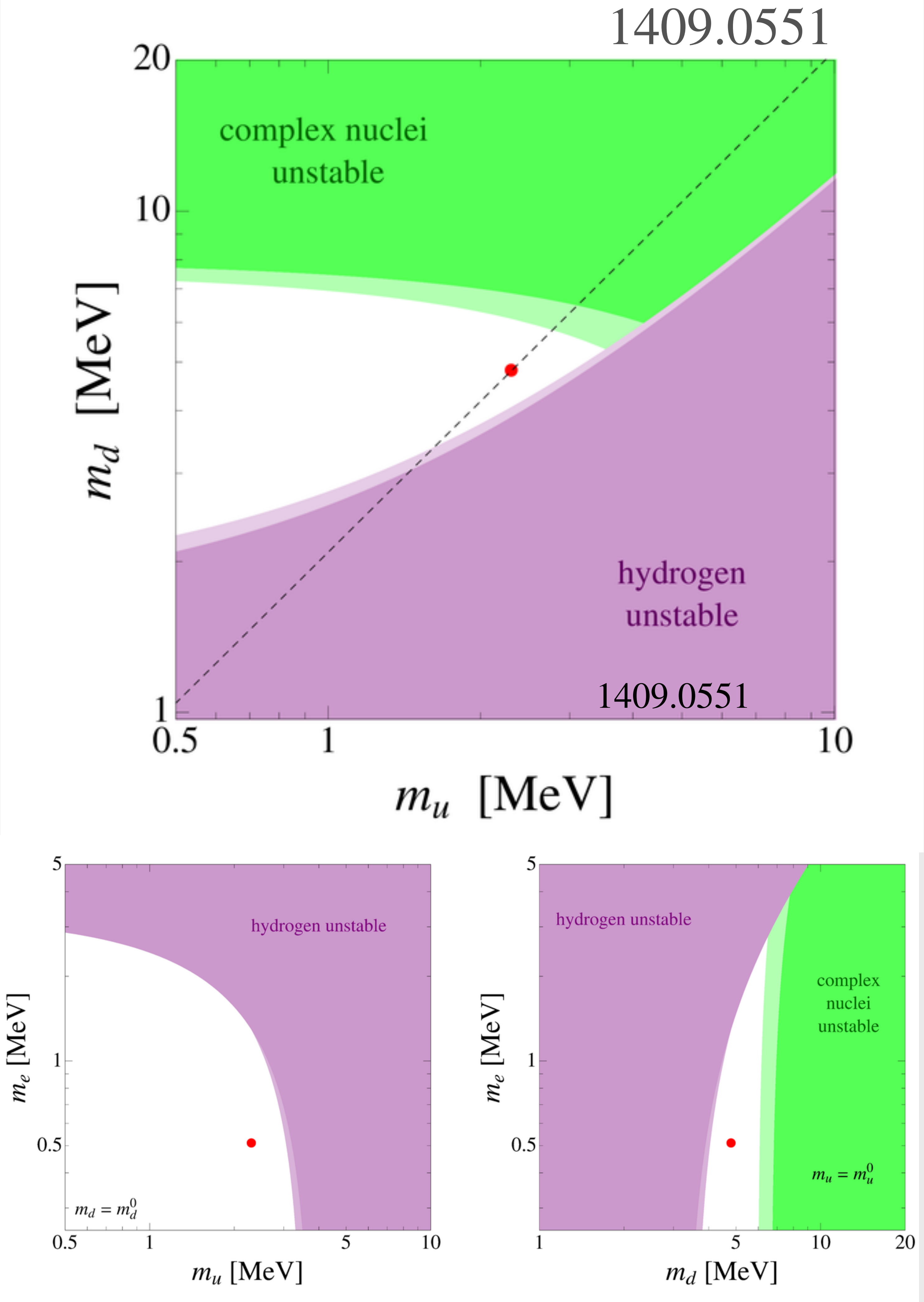


$$nn \to$$

MUCH FASTER FUSION IN STARS
IF LIGHTES BARYON IS NEUTRAL

1409.0551 - Hall, L.~J. and Pinner, D. and Ruderman, J.~T. - The Weak Scale from BBN

Scanning m_t, m_h, α_3 m_e, m_d, m_u, v



How to react to all this?

the Standard Model (after 2012) can be extrapolated to very high energies

this is very unsettling to us, first of all it is completely unprecedented, because we always "needed" something else (the famous "guaranteed" discoveries, although some in hindsight)

before Higgs discovery

one big jammed lane

embrace the SM as "the" theory and use it

insist on its flaws, looking for BSM

Invitation

Several deep open questions open for investigation

if the SM is the theory of Nature up to a very large scale far above the reach we can image with colliders

- no reason to get depressed(!)
- **we can still gain knowledge on the theory that has to supersede it.**
  - big increase of importance of measurements, most of all m_t
  - still searches are needed to confirm there is nothing new beyond the SM

Keep looking for “sharp edges”

- Outlook

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(galaxy formation)

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EFT expectations

$$\mathcal{L} = \mathrm{c} + \mu^2\ H^2 + \lambda\, H^4$$

$$[\mu^2] = 2$$

$$[\lambda] = 0$$

$$[c] = 4$$

- From dimensional analysis the constant term should be the most relevant at macroscopic scale, the others are “irrelevant”. **Universe expansion ruled by c**

- As we proceed to look at phenomena at smaller scales the “irrelevant” terms start to play a role. So it is not surprising that **“particle physics” parameters ($m_e, m_W, \ldots$) rule nuclear physics** (which rule stars, but much less the Universe on the large scale)

[1] 1409.0551 - Hall, L.~J. and Pinner, D. and Ruderman, J.~T. - The Weak Scale from BBN

[2] hep-ph/0604027 - Harnik, R. and Kribs, G.~D. and Perez, G. - A universe without weak interactions

• Outlook

SYMMETRY AS A FUNDAMENTAL CHARACTER OF NATURE ?????

Coincidences ?

$$\mathcal{L} = c + \mu^2 H^2 + \lambda H^4$$

My take: embrace the SM renormalizability and use our knowledge of fundamental interaction to identify more of these “catastrophic boundaries” [1] at all length scales, or find out whole new possibilities for a “complex” world[2].

(periodic table)

Higgs boson mass
(meta-)stability of the Universe

Cosmological Constant
(galaxy formation)

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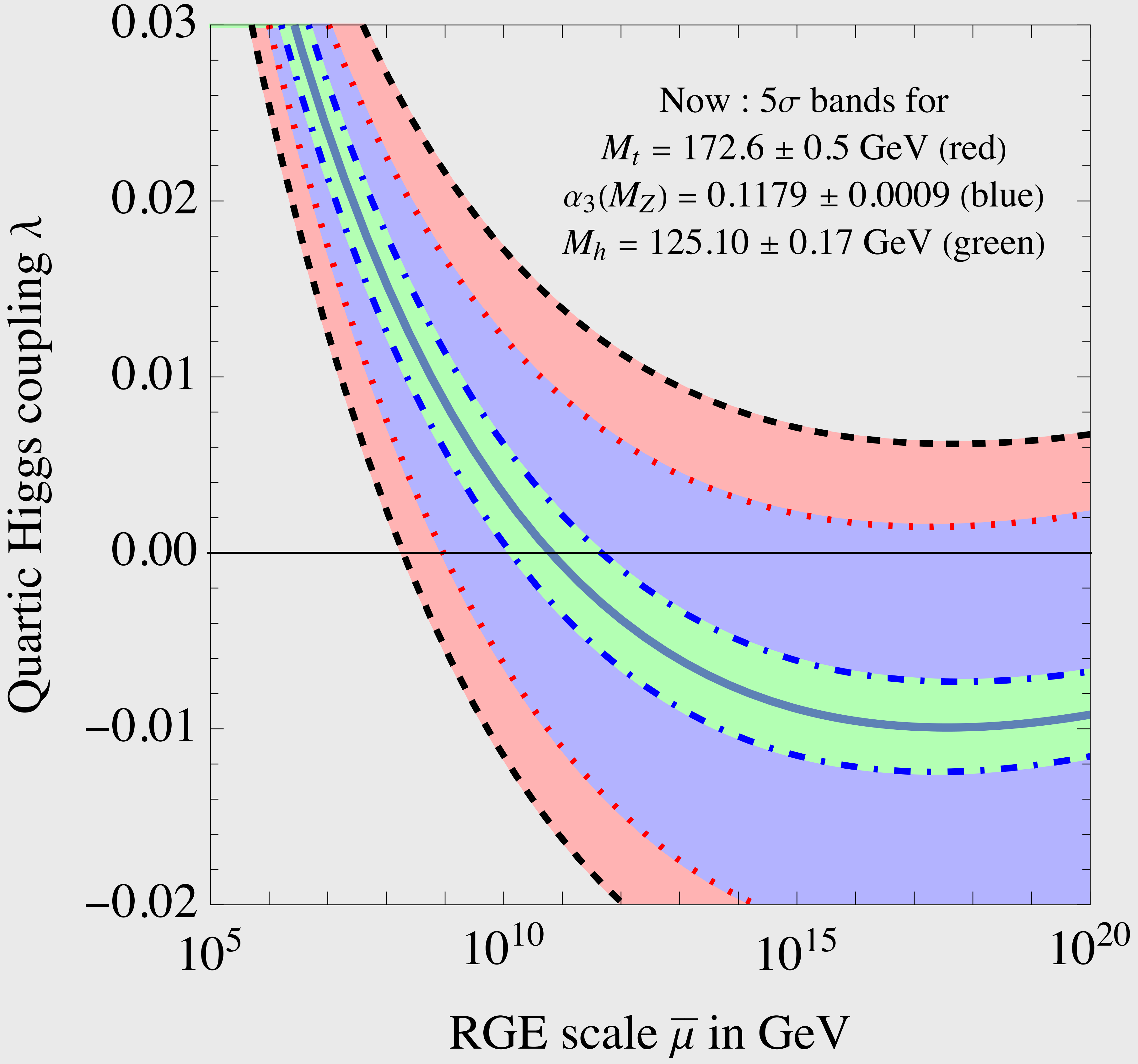
What would be needed to predict with some precision the scale of instability of the SM ? say at 10%-30% …

- such result would be the input for any “theory” that sets the values of the fundamental parameters of the SM in our Universe



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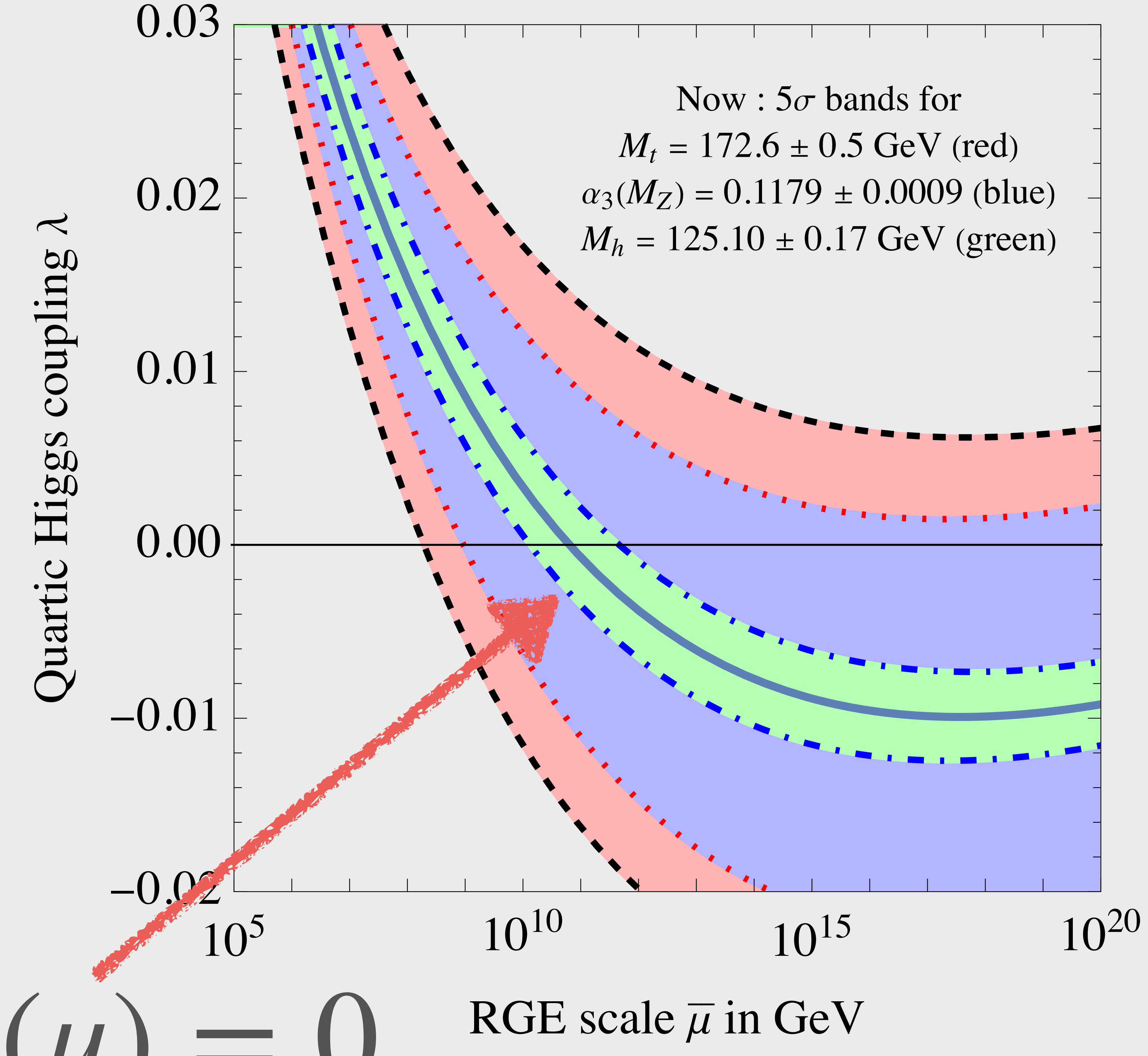


unclear at what energy $\lambda(\mu) = 0$

2203.17197

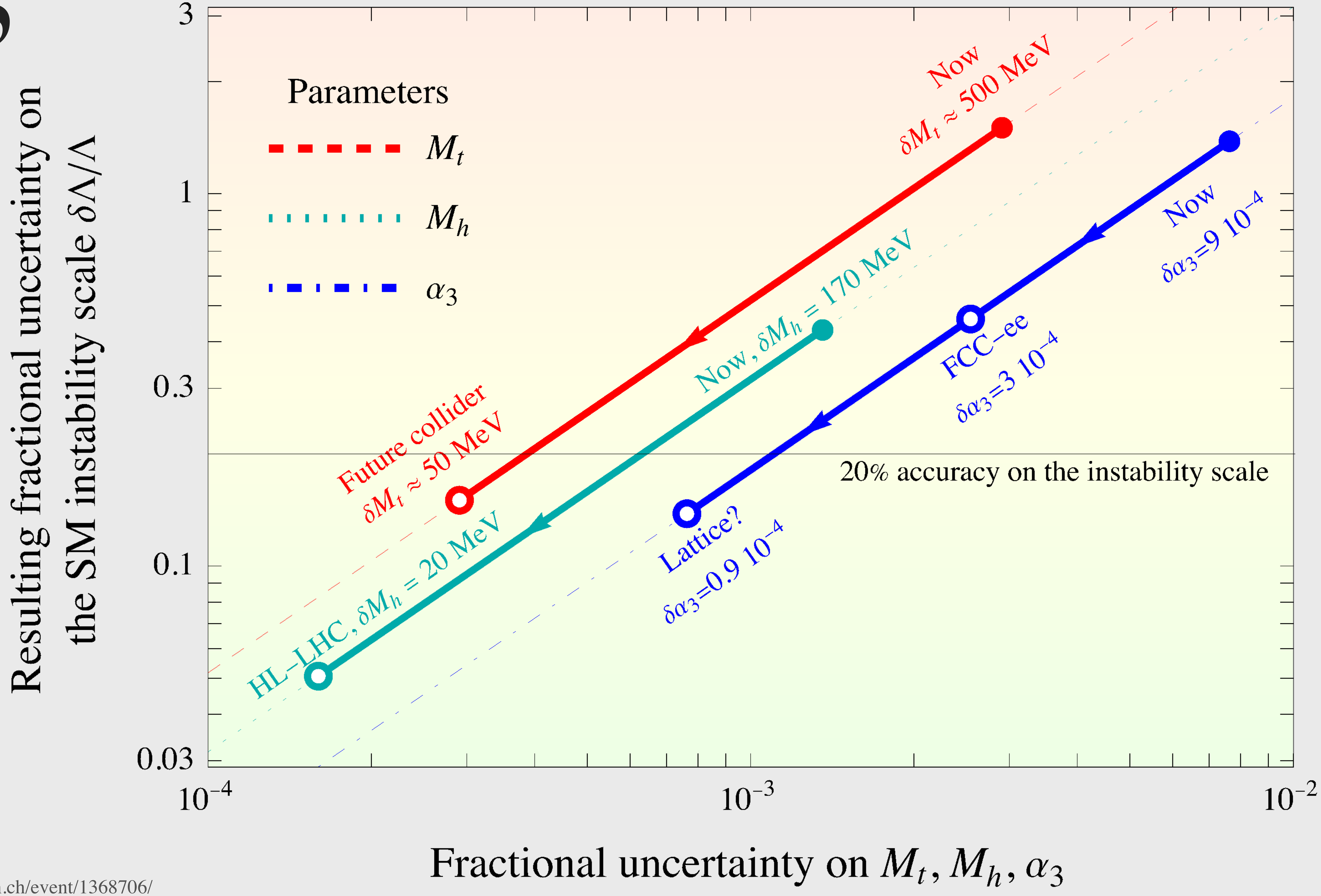
Shopping list

I am assuming the SM, so α_3 can be taken from Lattice QCD

Top and Higgs properties are fixed by the SM (e.g. $m_t = y_t \cdot v$)

Higgs mass from HL-LHC will be good enough

Top mass is the biggest player



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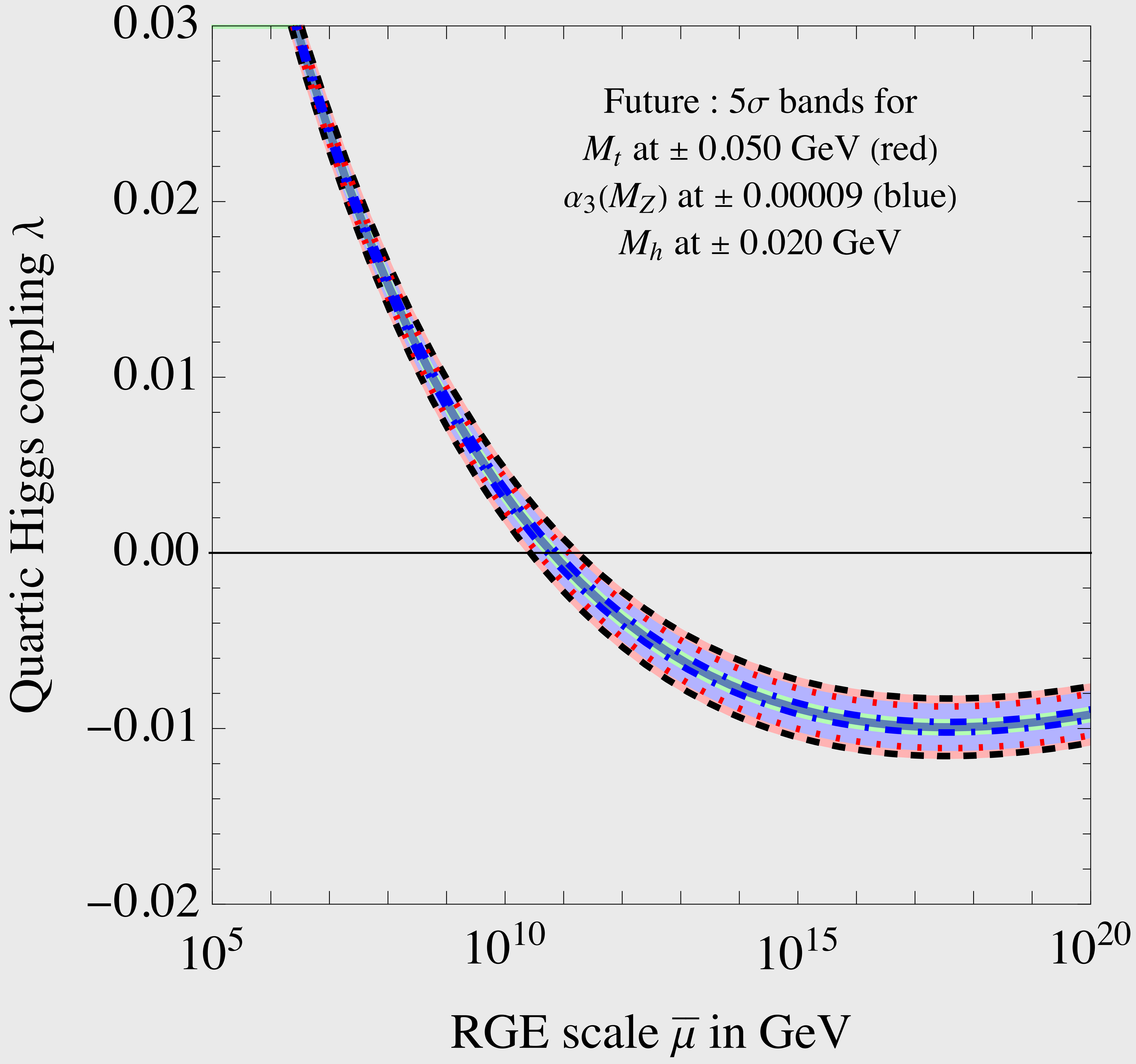

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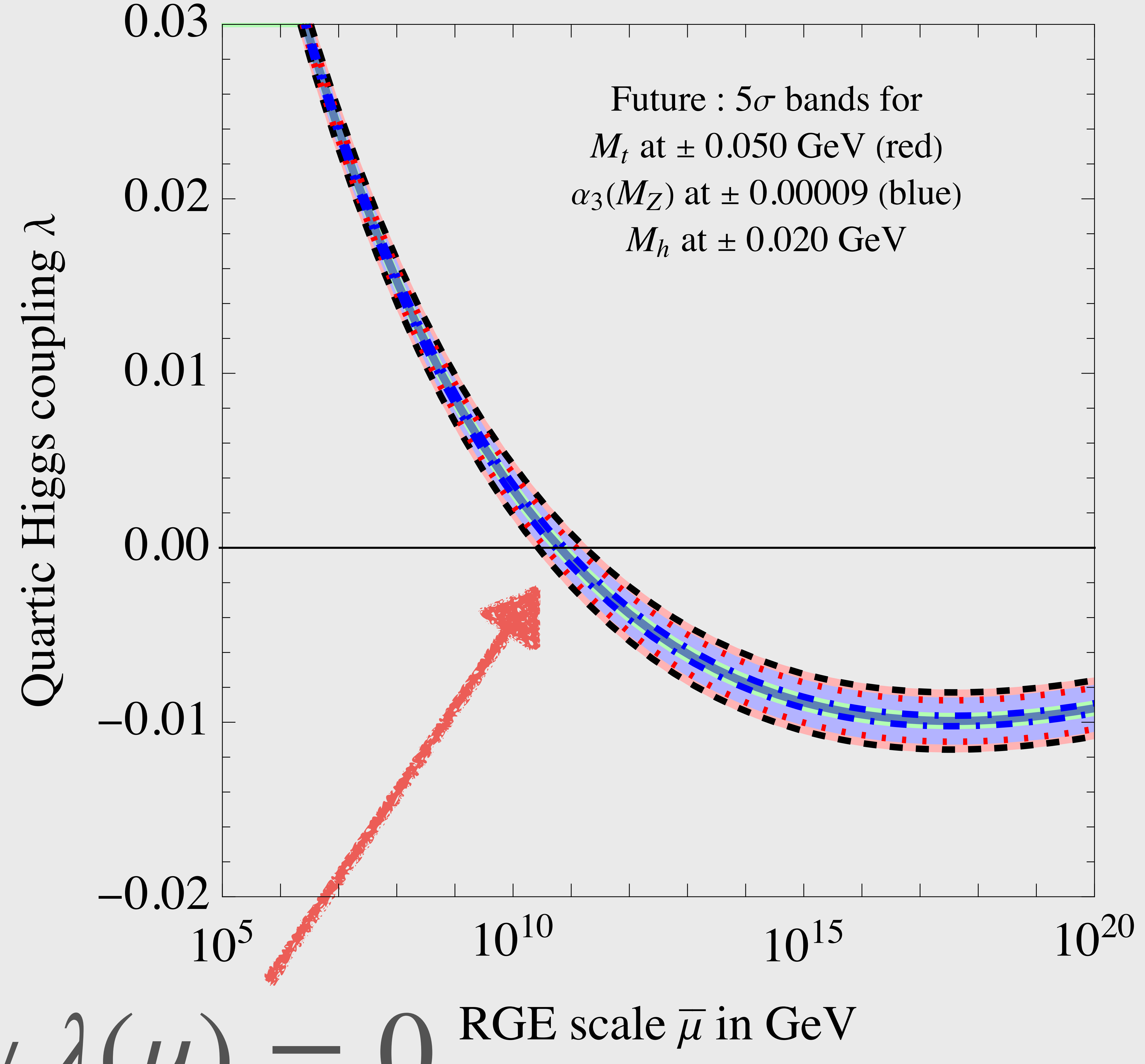
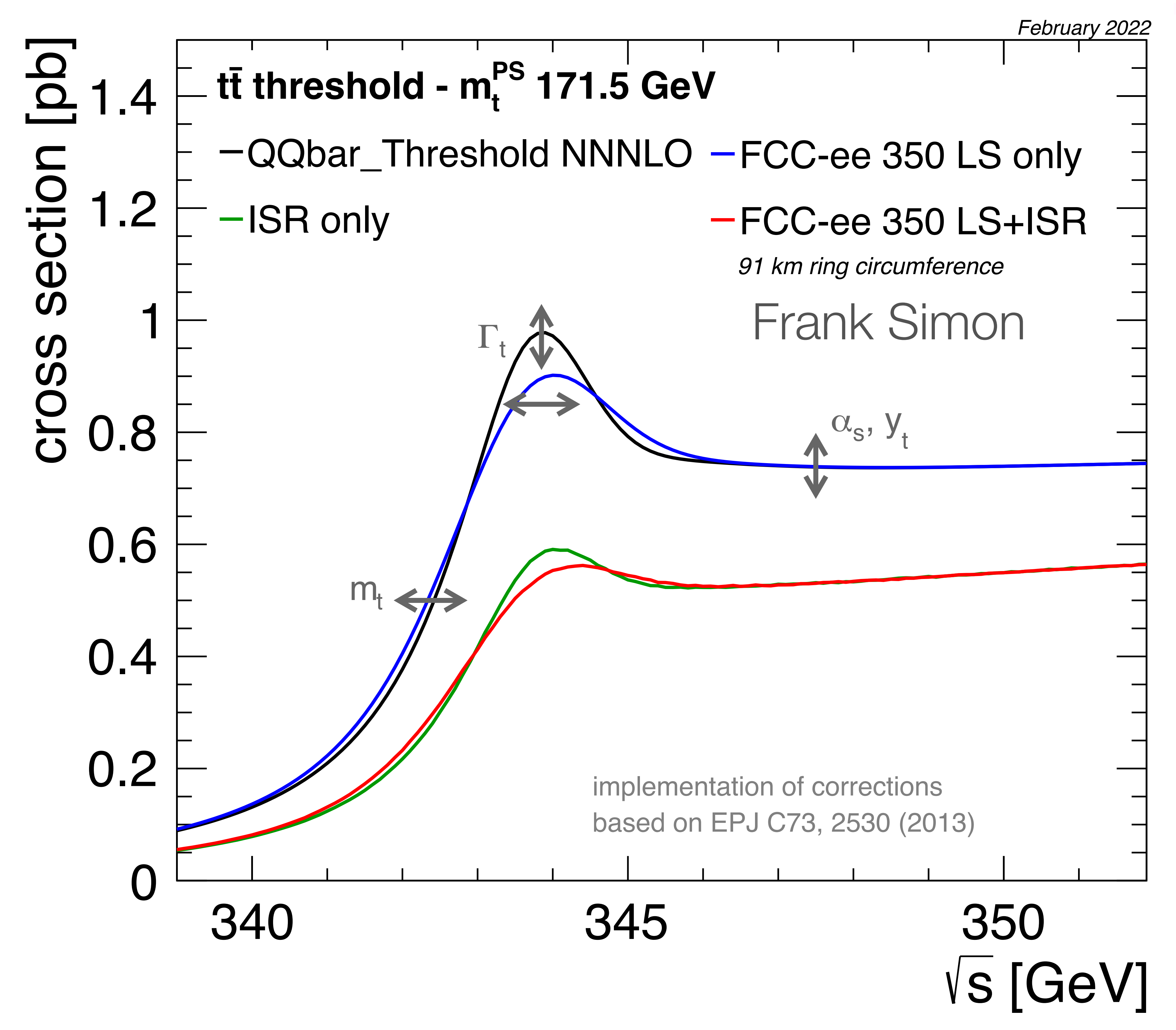
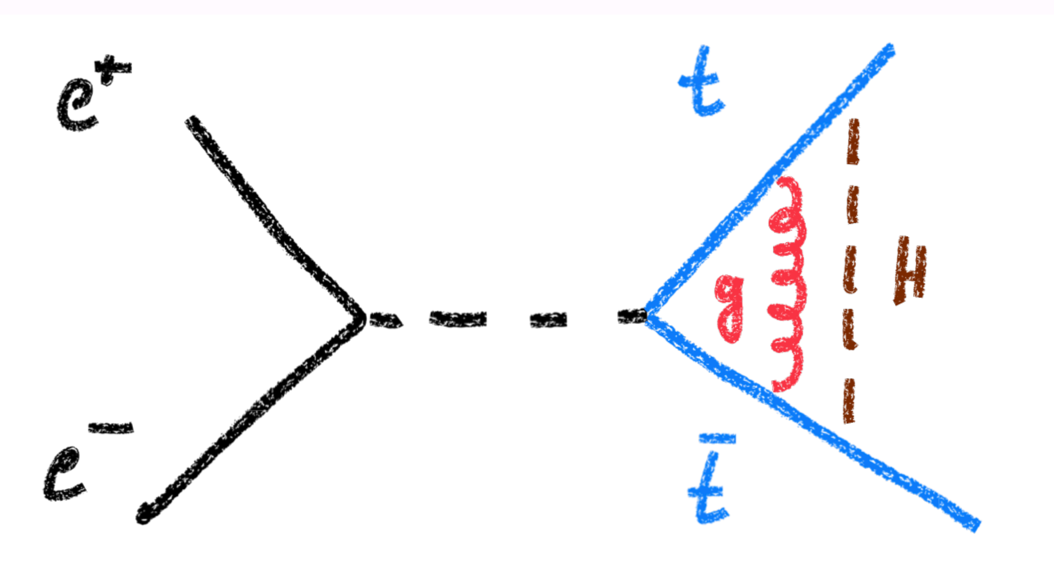


finally clear at what energy $\lambda(\mu) = 0$

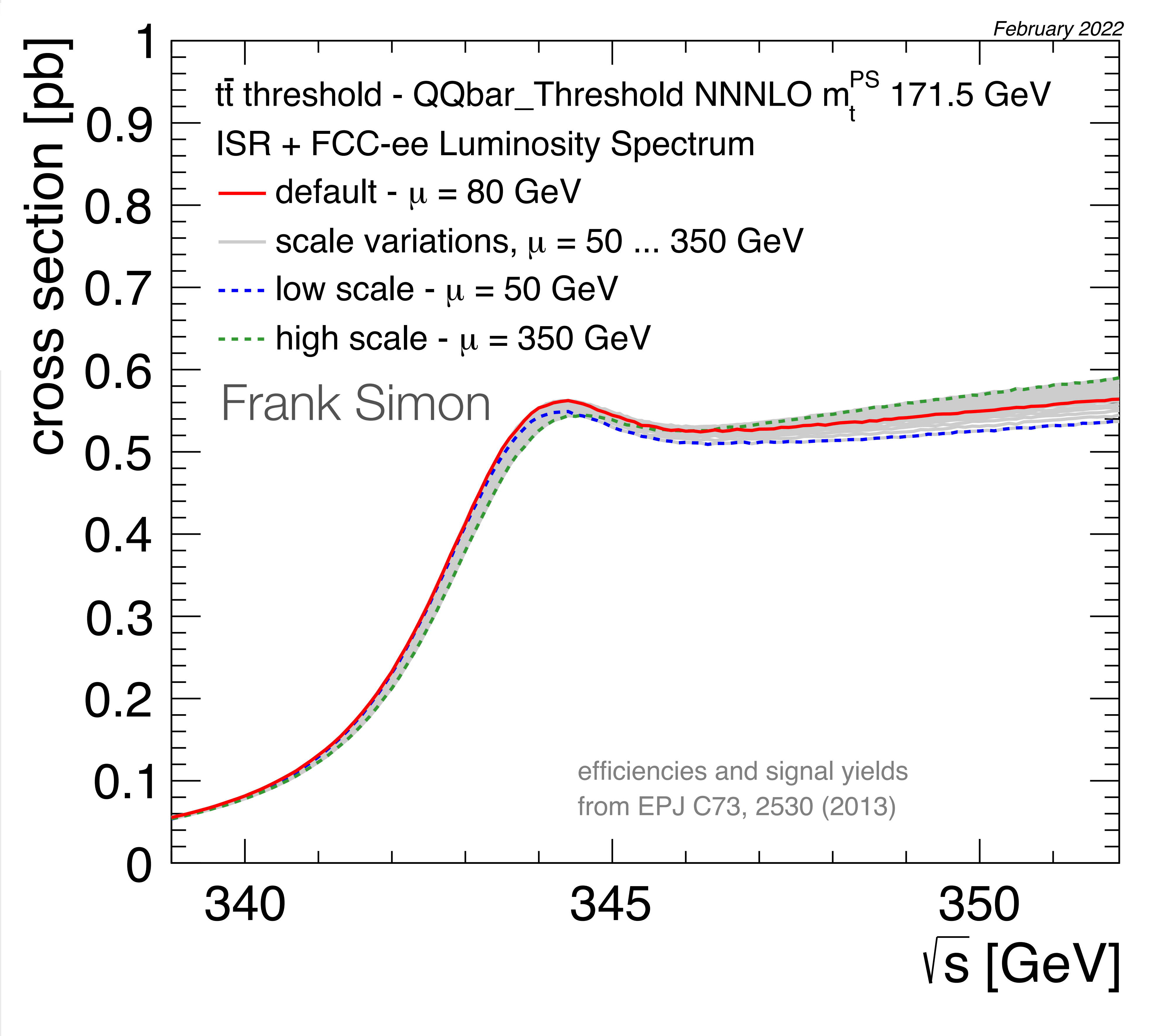
Top mass at future e^+e^- colliders





in general the threshold scan is sensitive to

- Higgs exchange (y_t)
- gluon exchange (α_3)



for our study everything is fixed at the prediction of the SM, therefore y_t and Γ_t are fixed by m_t and $\alpha_3(\mu)$ is set by the low-energy, lattice QCD and RGE

$$\delta m_t^{[theory]} \simeq 50 \text{ MeV}$$

m_t at future colliders

`QQbar_threshold`
1605.03010, 1711.10429

THRESHOLD SCAN

- study of the cross-section around the opening of the threshold is known to be a most sensitive probe to m_t

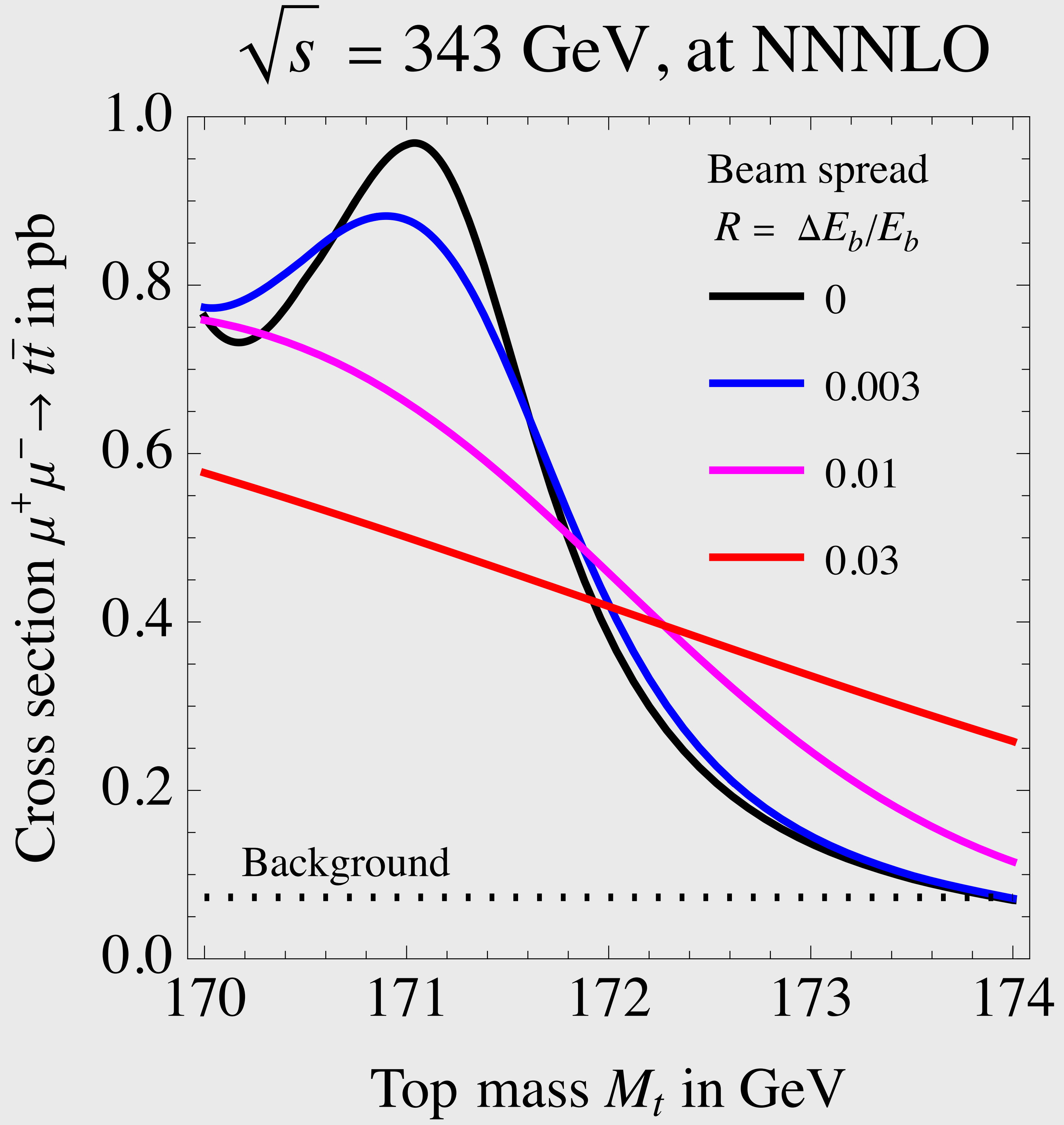
$$\frac{d\ln\sigma}{d\ln M_t} \sim 1.6\,\frac{M_t}{\Gamma_t} \approx 200$$

- meaning there is 200x magnification of the precision on the measurement of (a feature of) the cross-section

- beam quality matters a lot and spoils the measurement entirely when the uncertainty on the beam energy is comparable to $\Gamma_t/m_t \simeq 0.01$

$$\delta M_t \approx \frac{\Gamma_t}{1.6\sqrt{N_t}}\left[1+\left(\frac{M_t R}{0.5\,\Gamma_t}\right)^2\right]^p$$

$p \simeq 0.45$ from fitting



sample collaborations results:
CLIC 100fb^{-1} → 21 MeV
FCCee R=2e-3 L=200fb^{-1} → 9 MeV

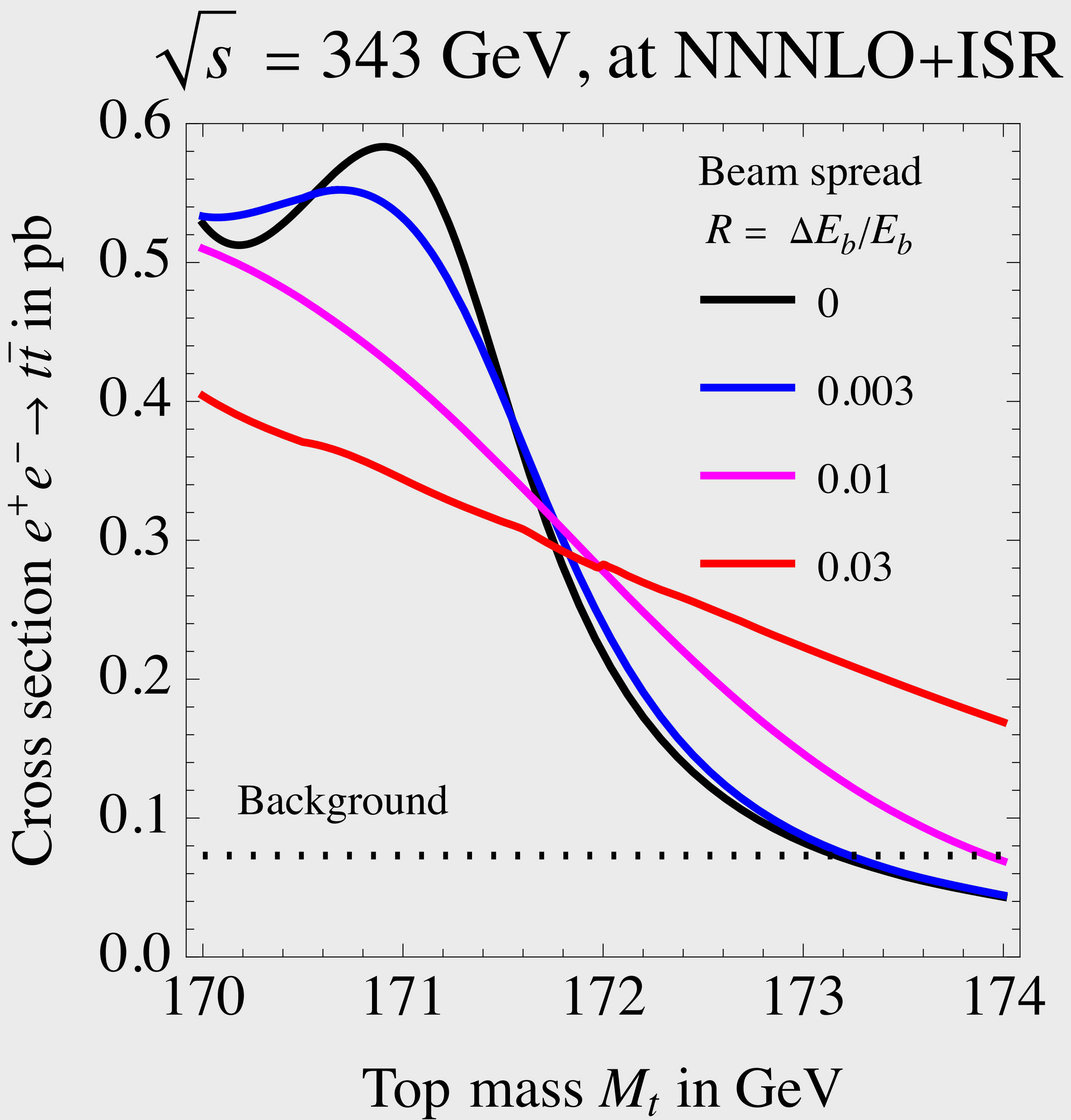
m_t at future colliders

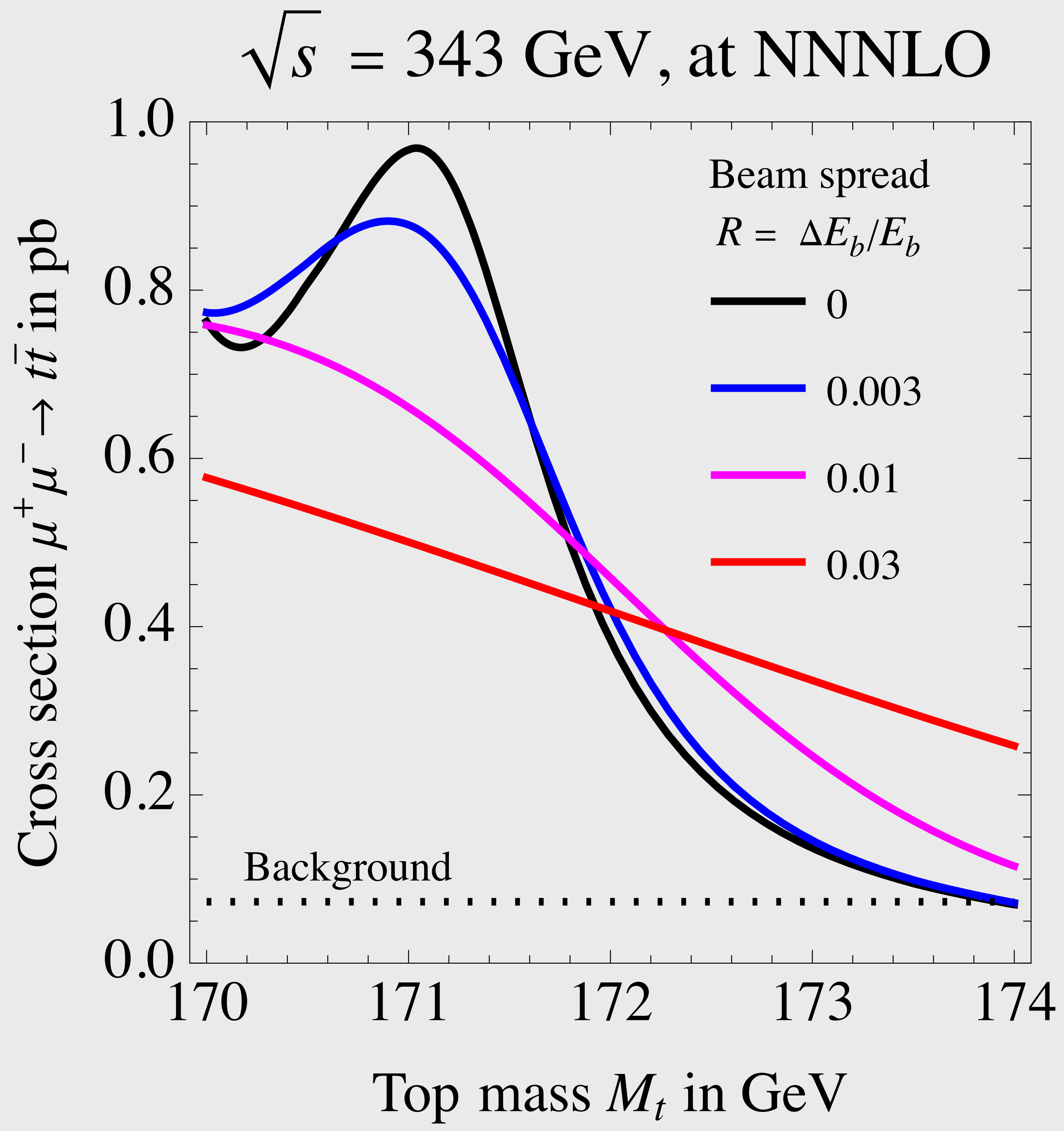
`QQbar_threshold`

1605.03010, 1711.10429

THRESHOLD **SCAN**

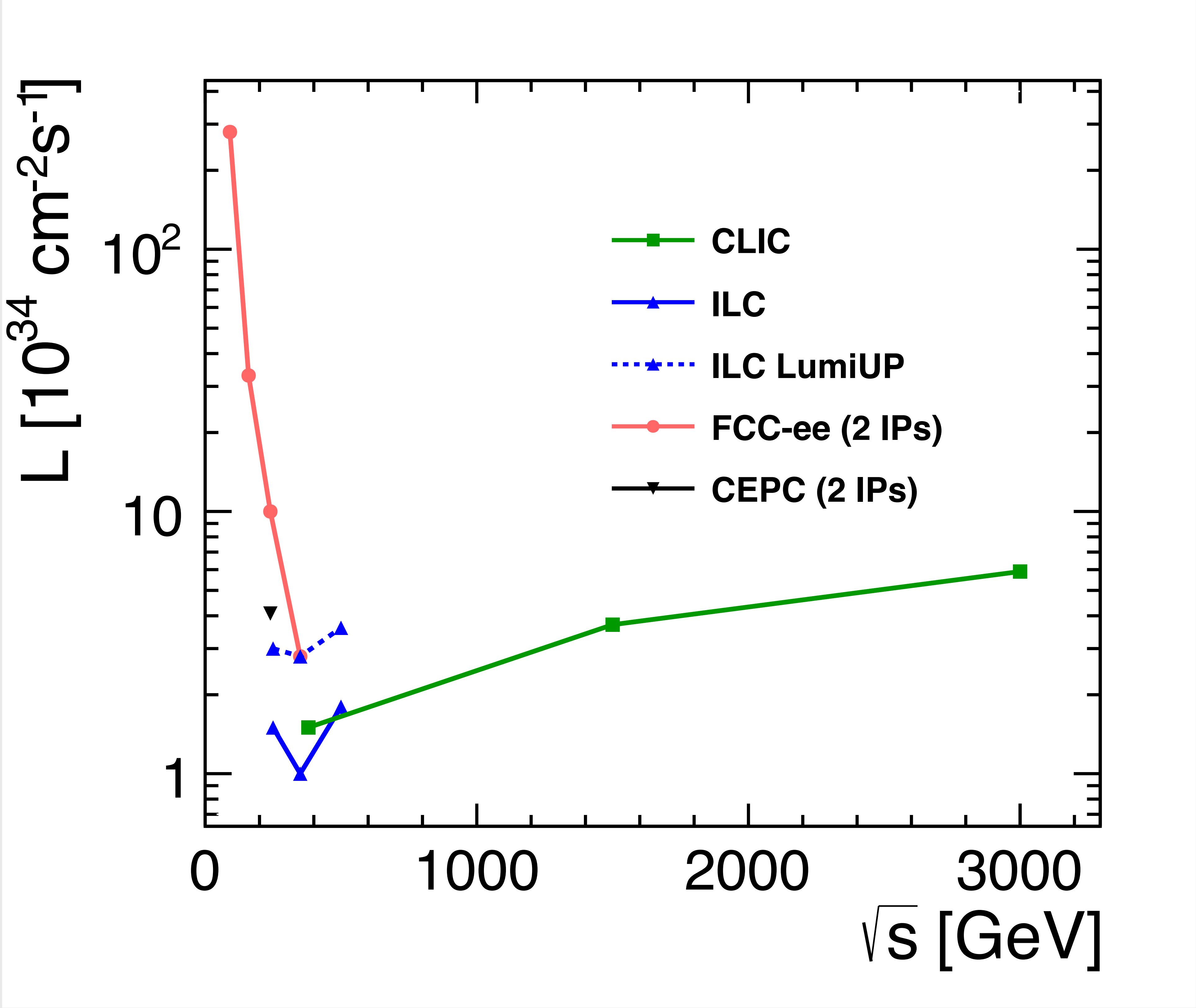
- e^+e^- is well established, but it is not even clear if it can reach 350 GeV in an affordable way. Better if you do it in a large (90 Km) tunnel, of course.
- $\mu^+\mu^-$ much less well established, but does not have ISR, because $W_{ISR} \propto (E_{beam}/m_\ell)^4$





[1] arXiv:1208.0504 - A. Blondel et al., High Luminosity e+e− Storage Ring Colliders to Study the Higgs Boson 1112.2518

The issue of luminosity

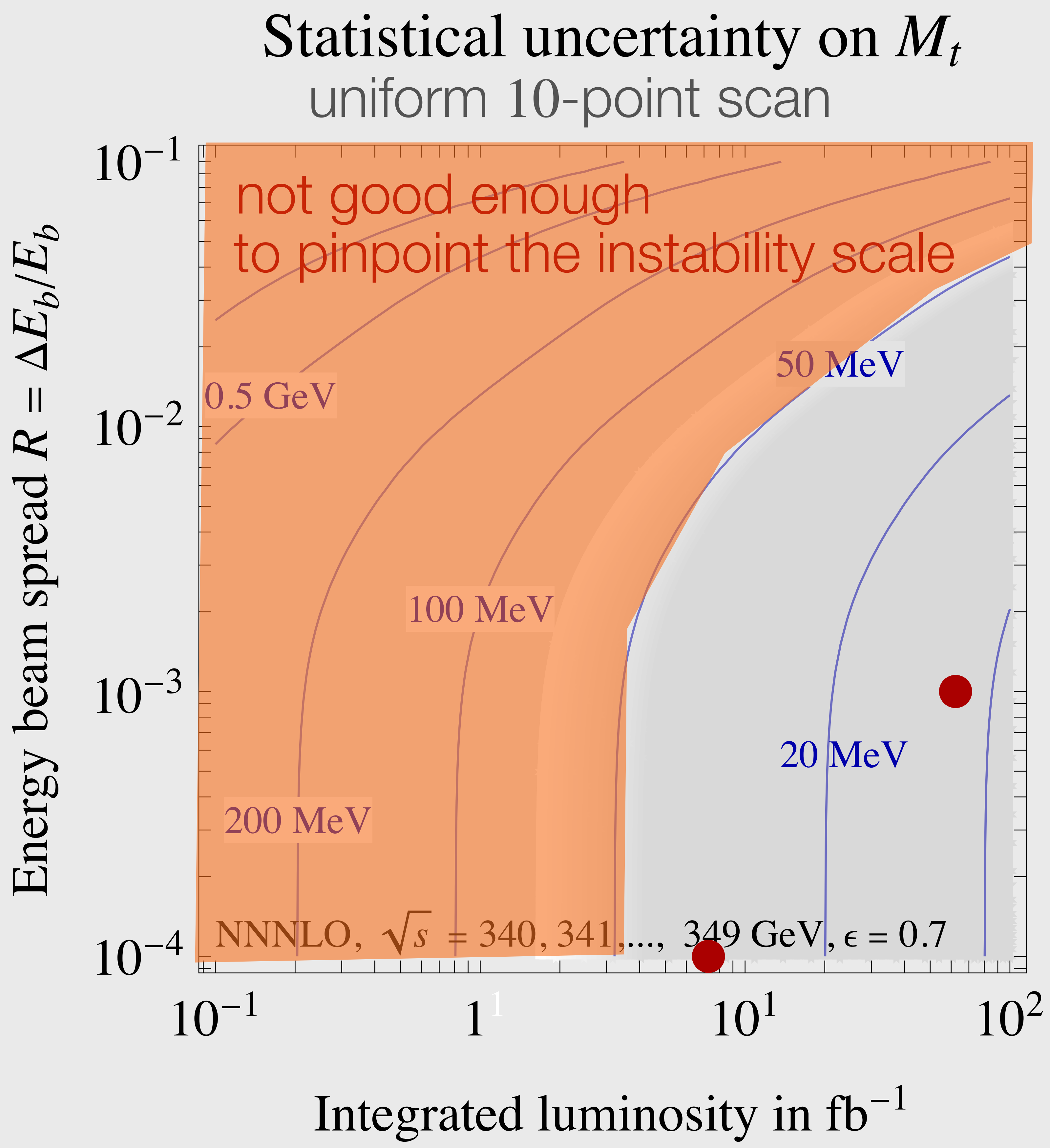


- due to large ISR in e^+e^- the luminosity that can be achieved scale as $\mathscr{L}_{ee} \propto E^{-4}$
- due to muon beam decay and general difficulty to deal with low-energy muon beams, thus $\mathscr{L}_{\mu\mu} \propto E^2$

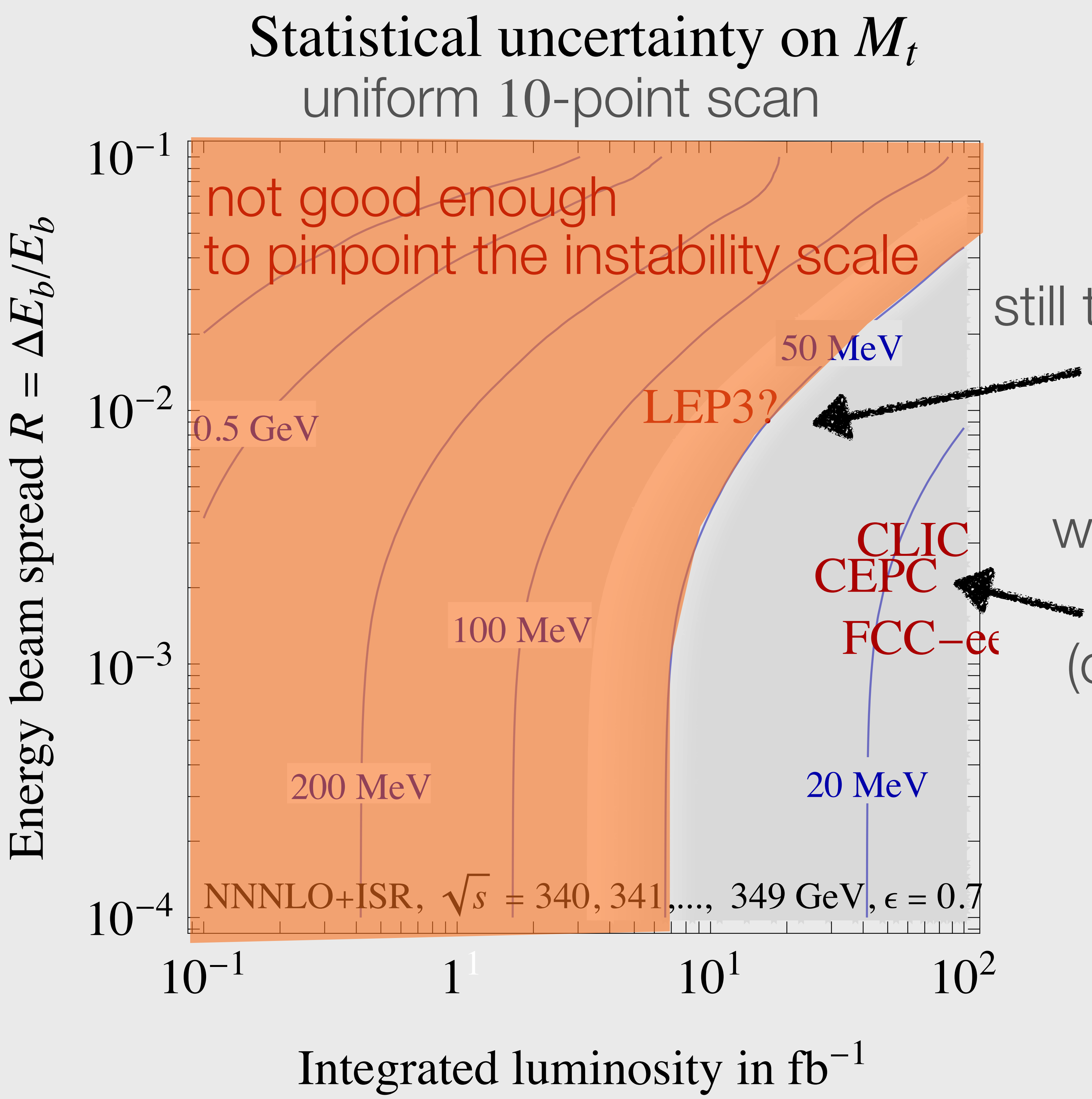
		$\mathscr{L}$ [$10^{34} cm^{-2} s^{-1}$]			
Collider		LEP	LEP3	FCC-ee [31]	CEPC [59]
Total length L		26.6 km	26.6 km	100 km	100 km
Z	$E_{\rm cm} = 91$ GeV	~ 0.004	7^*	460	115
W^+W^-	$E_{\rm cm} = 160$ GeV	~ 0.01	2^*	56	16
Zh	$E_{\rm cm} = 240$ GeV	0	1 [35]	17	5
$t\bar{t}$	$E_{\rm cm} = 350$ GeV	0	0.1^*	3.8	0.5

* estimates from general physics and [1]

Results



a muon collider with 10-100 fb^{-1} and BES 10^{-3}-10^{-4} hits the target perfectly



machine
still to be studied

well established
projects
(can do better)

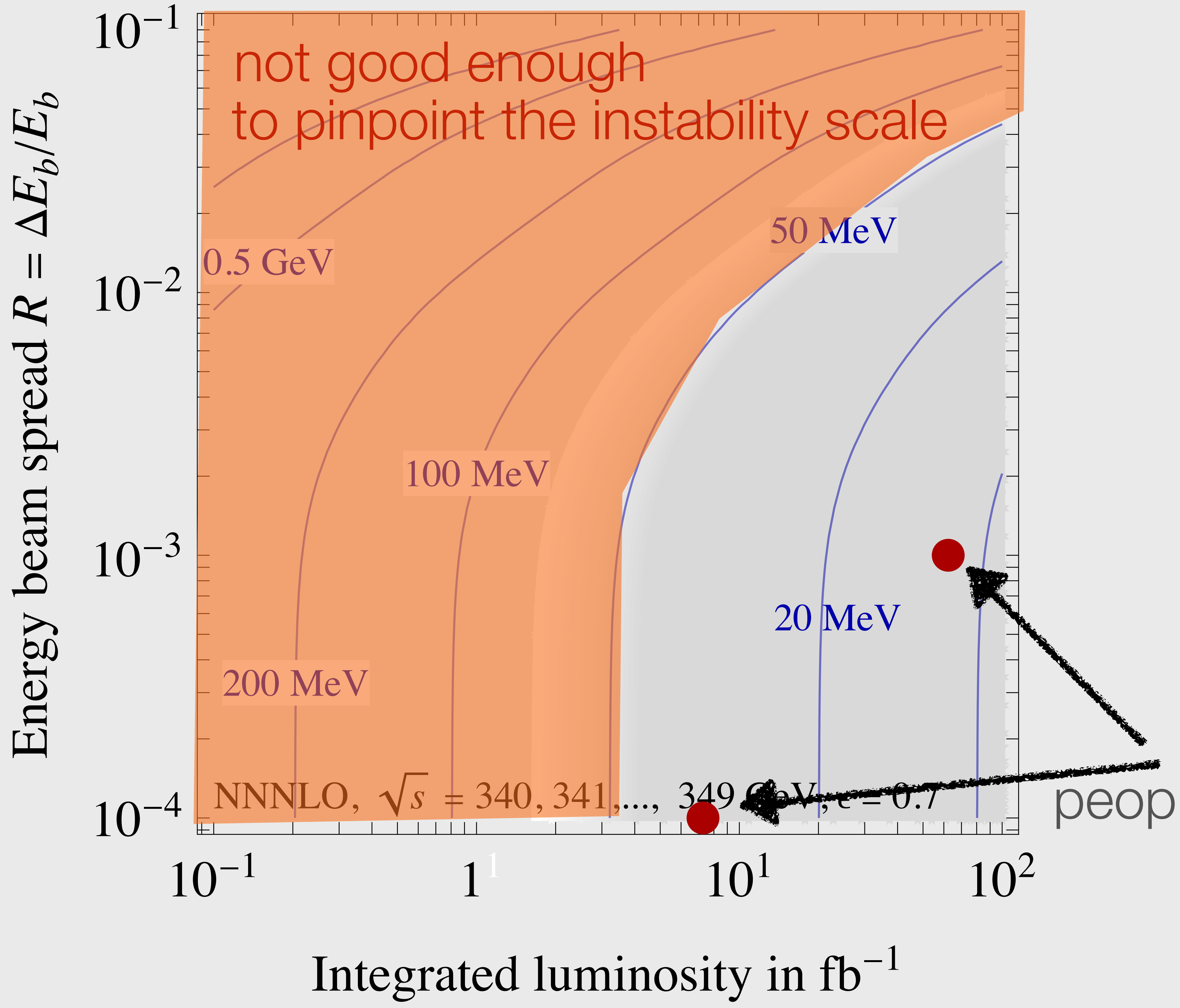
all e^+e^- projects on the table
exceed by far the target

LEP3 is borderline (and uncertain)

Results

Statistical uncertainty on M_t

uniform 10-point scan

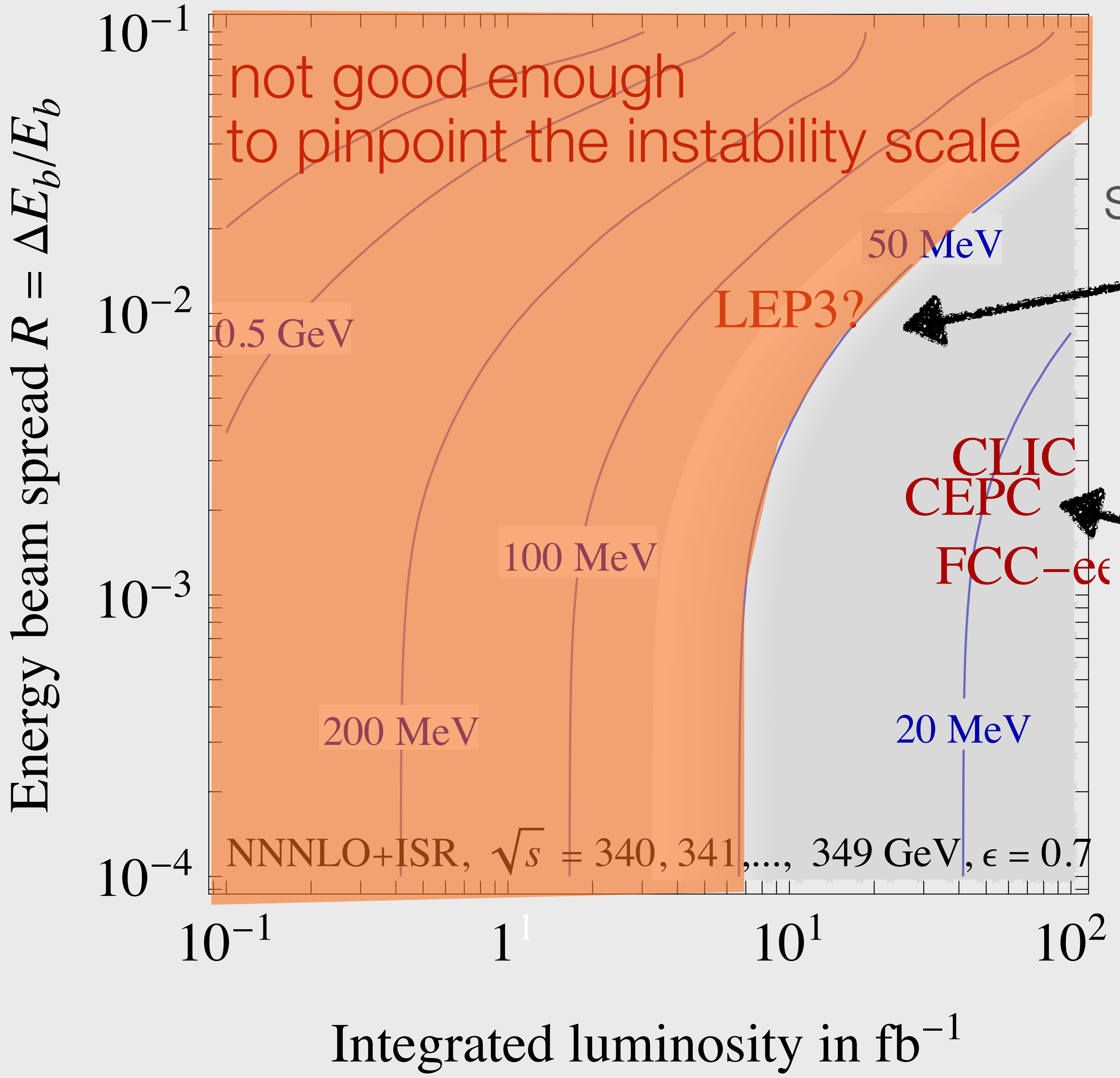


muon colliders
people think are buildable

a muon collider with 10-100 fb^{-1} and BES 10^{-3}-10^{-4}
hits the target perfectly

Statistical uncertainty on M_t

uniform 10-point scan



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LEP3 is borderline (and uncertain)

Discussion

- even in absence of direct evidence of new physics **we can learn rather precisely where the SM must give way to new physics**. Measuring m_t at 50 MeV does the job. Even a “bad” e^+e^- collider like LEP3 can make it(!)
- A **muon collider “full scale demonstrator”** at 350 GeV does not suffer too much the lack of lumi that is typical for muon colliders at low energy and can pinpoint the instability scale
- given the challenges (and costs) of making an e^+e^- at 350+ GeV, can we **strategically use the measurement of m_t** as a target for the first “low energy” muon collider? (a full scale μCol demonstrator from source to collision and experiment)
- is there room to reduce the demands of major e^+e^- projects (FCCee, CEPC) to hit lower luminosity targets at 350 GeV? (to match the 40 MeV from theory systematics)
- can we make up for the “e^+e^- **High-Lumi” 365 GeV** runs that are meant to produce 10^6 top quarks? (e.g. Ztt couplings)
- is there a physics case for **“site filler”** options such as LEP3 (or a FNAL site-filler?)

A gauge of the progress made so far

- The **depth of the questions** that can be asked based on the progress made so far witnesses the maturity of the investigation on fundamental interactions
- The Standard Model being a candidate to be a “complete” theory is not necessarily a curse, because this very fact enables the possibility to ask deeeeeep questions on the Universe. We should not miss the opportunity to use our knowledge of fundamental interactions in this direction
- The guaranteed discovery of the Higgs or its substitute at the LHC is a very enviable position under which ambitious projects could be envisioned and implemented.
- None of the future colliders currently under study enjoy this enviable position … back to regular science exploration

Conclusions

Several deep open questions open for investigation

	?	• what is the dark matter in the Universe?	✓		✓
	●	• why QCD does not violate CP?	✓	✓	
	●	• how have baryons originated in the early Universe?	✓		✓
	⚙	• what originates flavor mixing and fermions masses?	✓		
	⚙	• what gives mass to neutrinos?	✓		
~~EFT~~	●	• why gravity and weak interactions are so different?	✓		
~~EFT~~	●	• what fixes the cosmological constant?	✓		

🟧 WEAK INTERACTIONS

⬜ STRONG INTERACTIONS

🟩 ACCELERATORS

Future Colliders can provide significant advances on these issues

Conclusions

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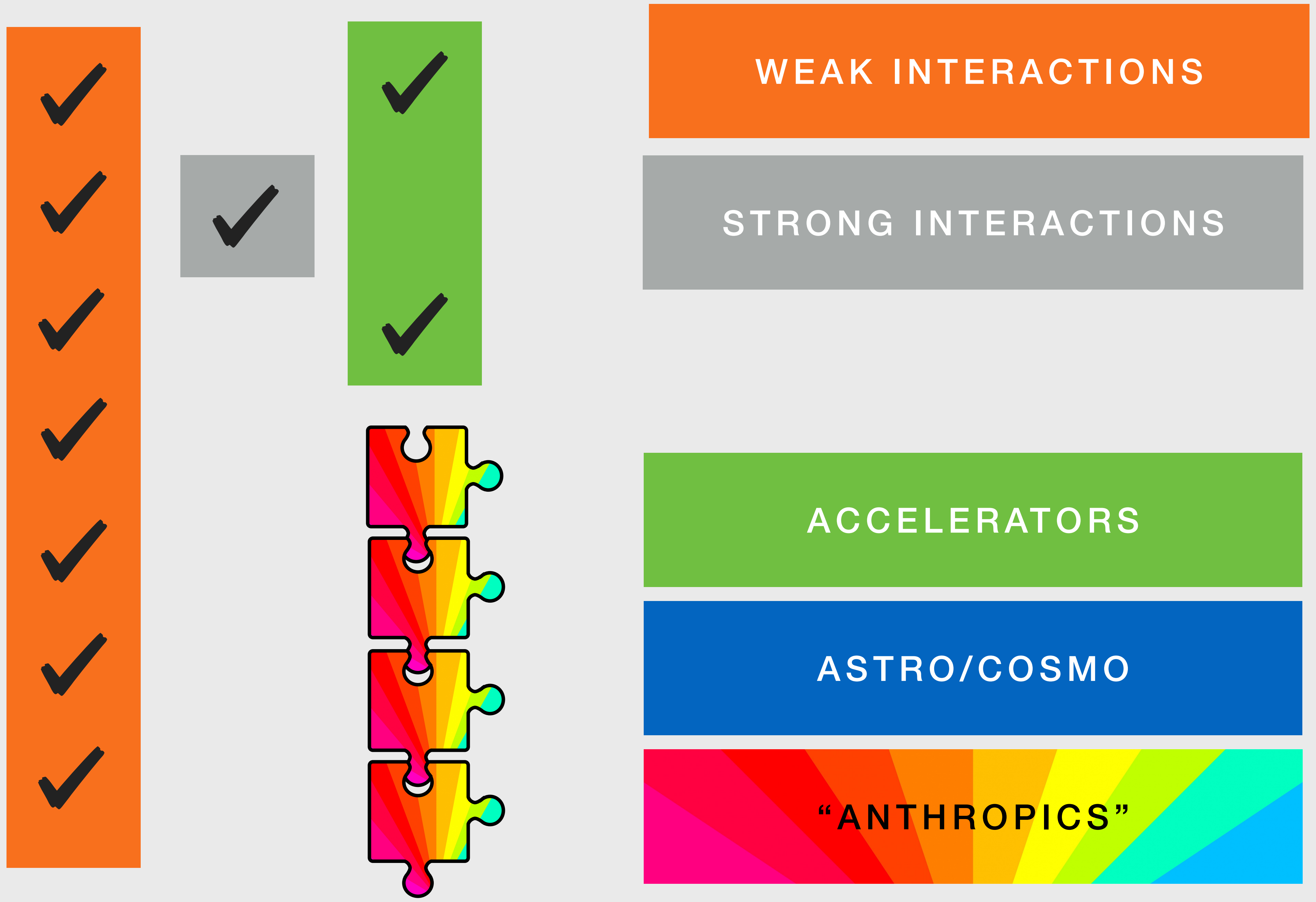


WEAK INTERACTIONS

STRONG INTERACTIONS

ACCELERATORS

ASTRO/COSMO

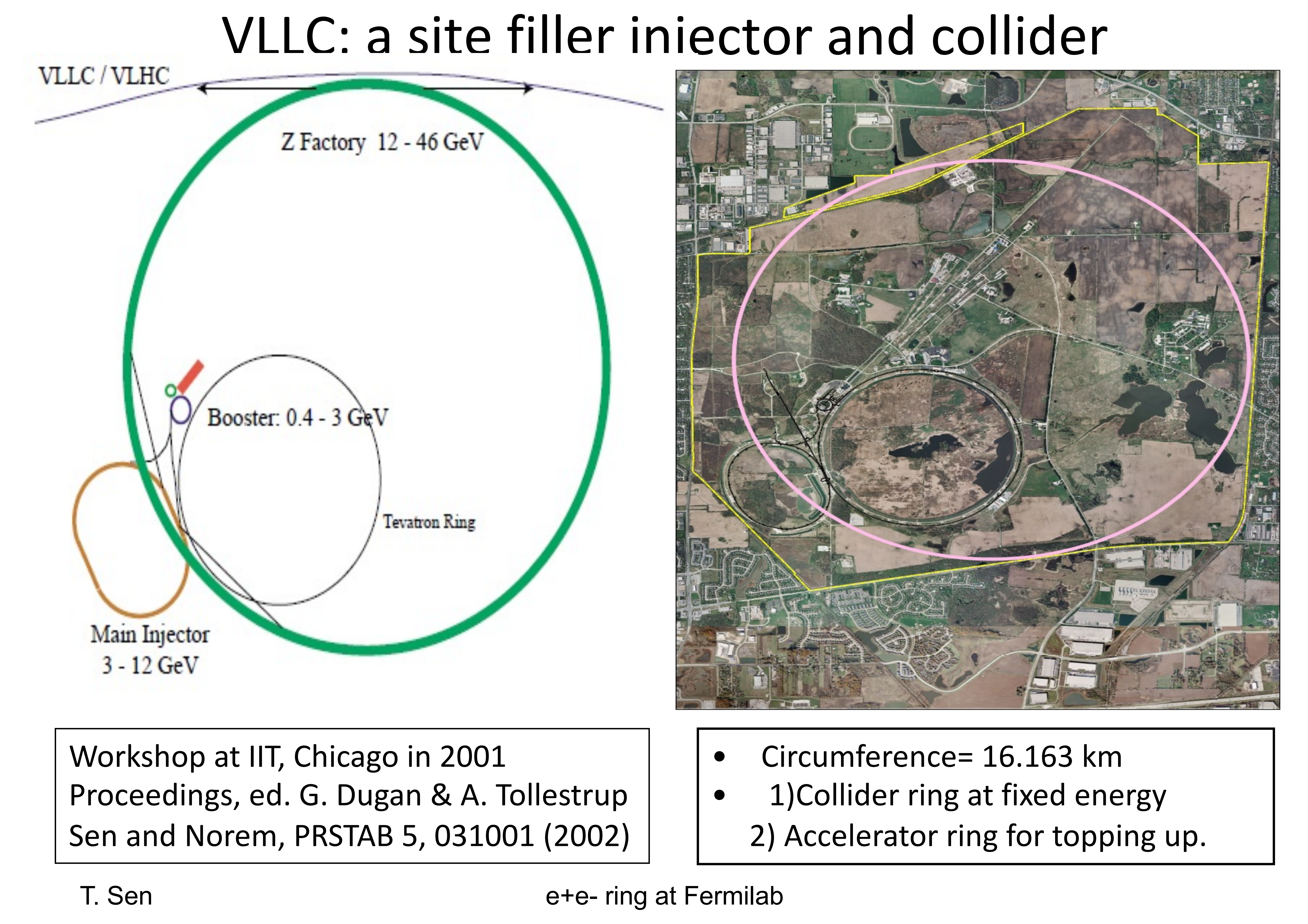
“ANTHROPICS”

Future Colliders can provide significant advances on these issues

thank you for listening!

Fermilab "Site Filer"

A reference point

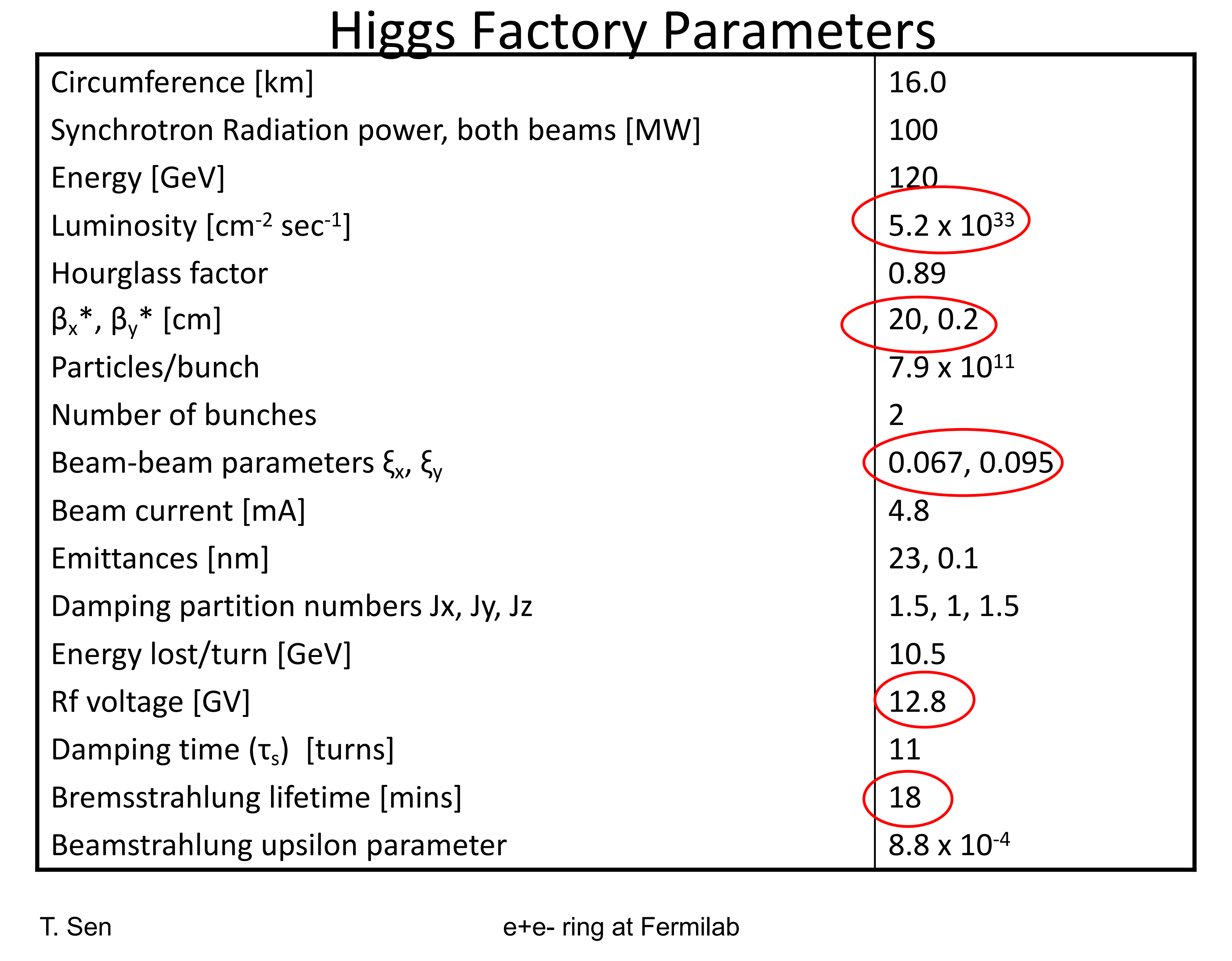


VLLC: a site filler injector and collider

Workshop at IIT, Chicago in 2001
Proceedings, ed. G. Dugan & A. Tollestrup
Sen and Norem, PRSTAB 5, 031001 (2002)

- Circumference= 16.163 km
- 1)Collider ring at fixed energy
  2) Accelerator ring for topping up.

T. Sen e+e- ring at Fermilab



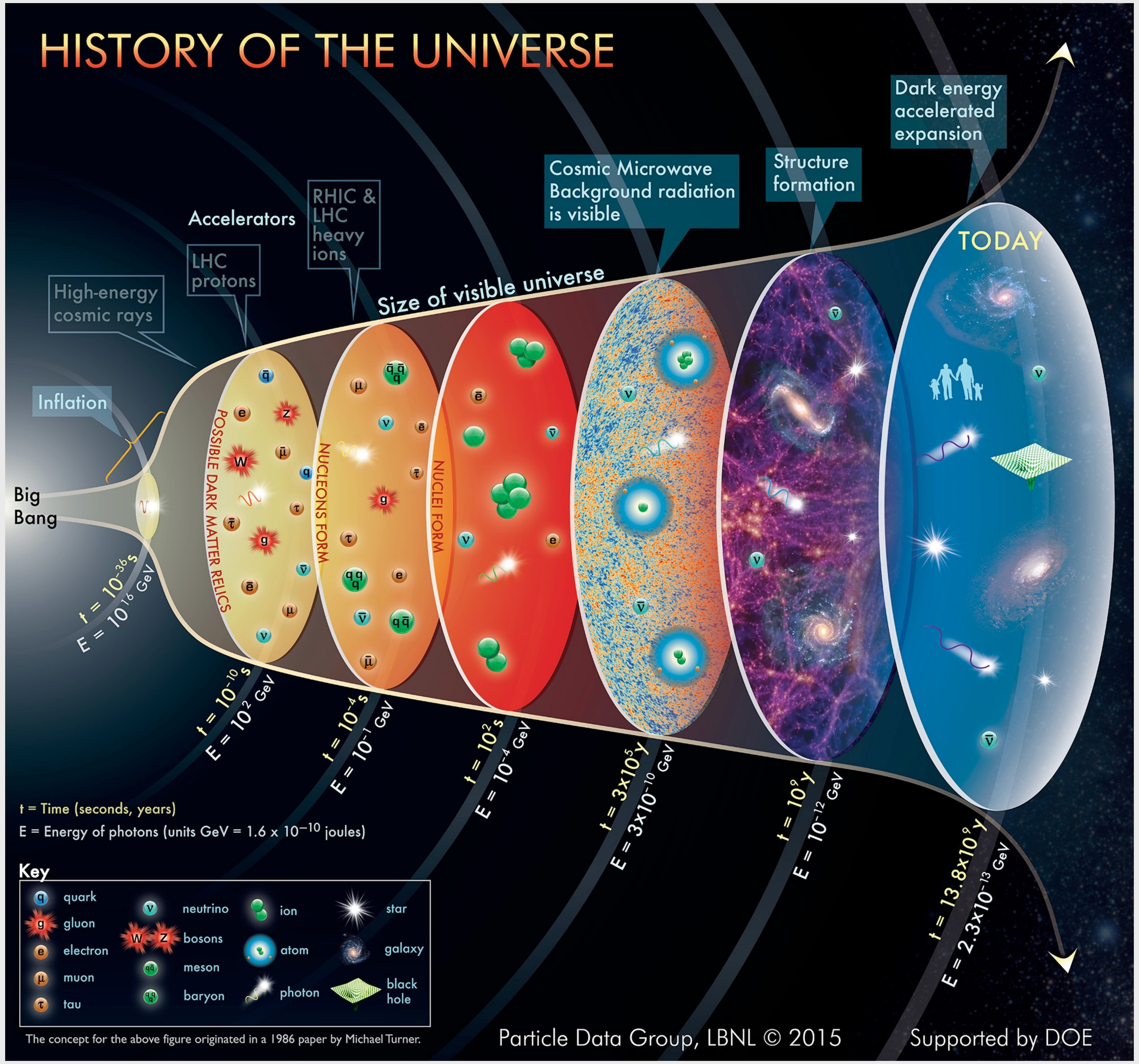
Higgs Factory Parameters

Circumference [km]	16.0
Synchrotron Radiation power, both beams [MW]	100
Energy [GeV]	120
Luminosity [cm^{-2} sec^{-1}]	5.2×10^{33}
Hourglass factor	0.89
β_x*, β_y* [cm]	20, 0.2
Particles/bunch	7.9×10^{11}
Number of bunches	2
Beam-beam parameters ξ_x, ξ_y	0.067, 0.095
Beam current [mA]	4.8
Emittances [nm]	23, 0.1
Damping partition numbers Jx, Jy, Jz	1.5, 1, 1.5
Energy lost/turn [GeV]	10.5
Rf voltage [GV]	12.8
Damping time (τ_s) [turns]	11
Bremsstrahlung lifetime [mins]	18
Beamstrahlung upsilon parameter	8.8×10^{-4}

T. Sen e+e- ring at Fermilab

open questions

Open Questions on the “big picture” on fundamental physics circa 2020



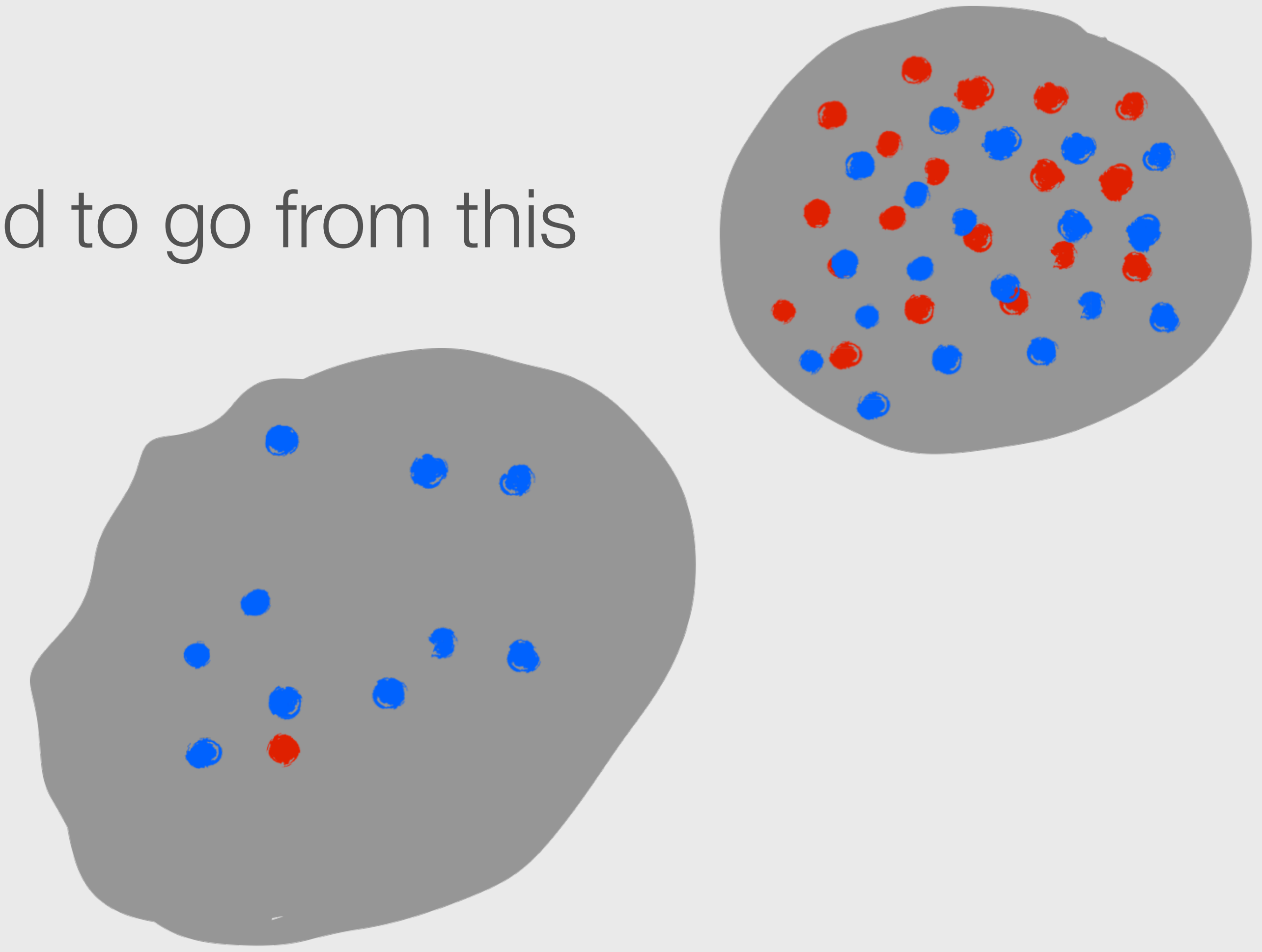
The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

Nothing we have measured in high energy physics makes so much of a distinction between particles and anti-particles.

The observable Universe is made of matter, no antimatter



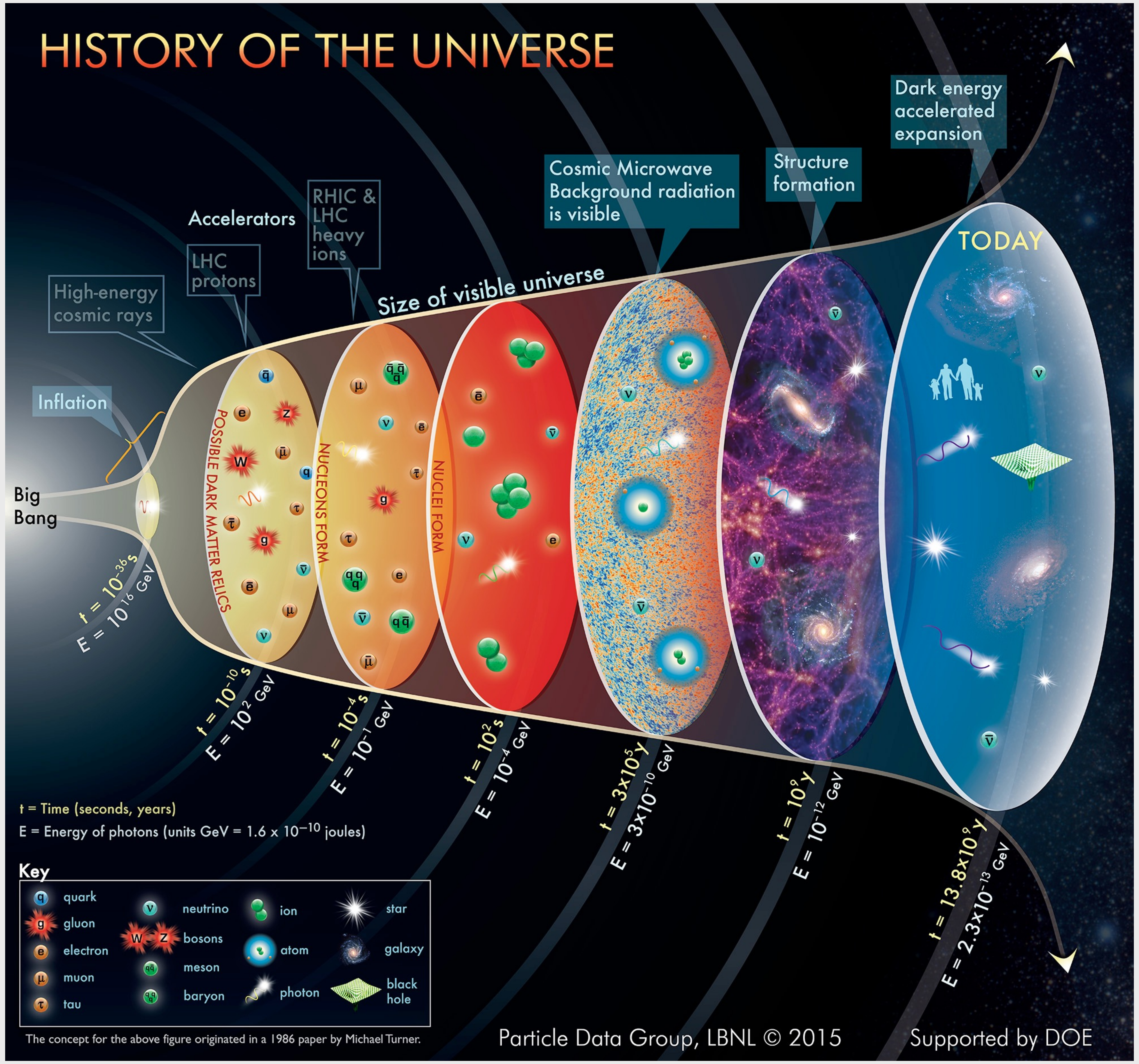
We need to go from this

to this

particles
antiparticles

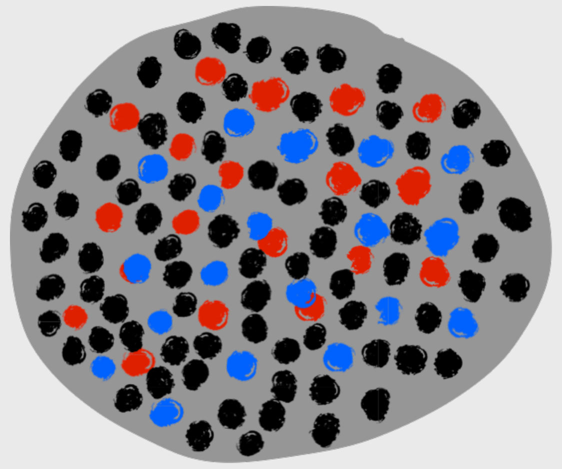
out-of-equilibrium processes are necessary

Open Questions on the "big picture" on fundamental physics circa 2020



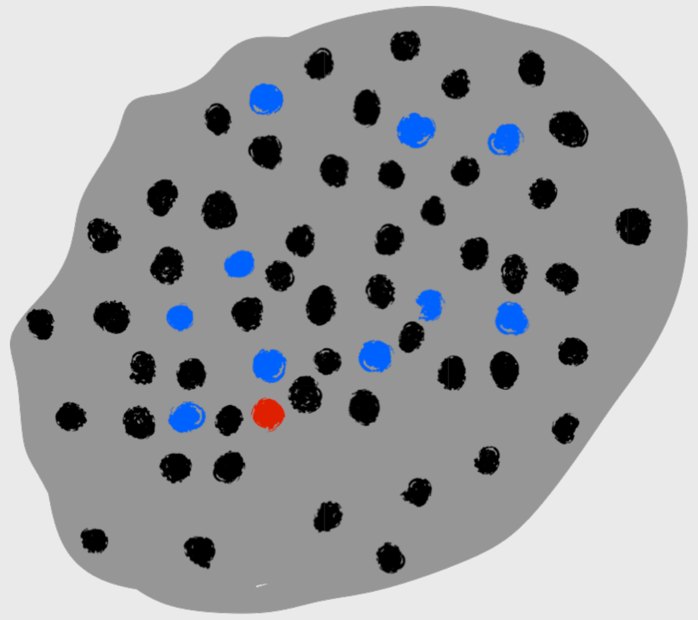
The observable Universe is made of matter, plus about 5 times as much dark matter

We need to go from this



normal particles
dark matter
antiparticles

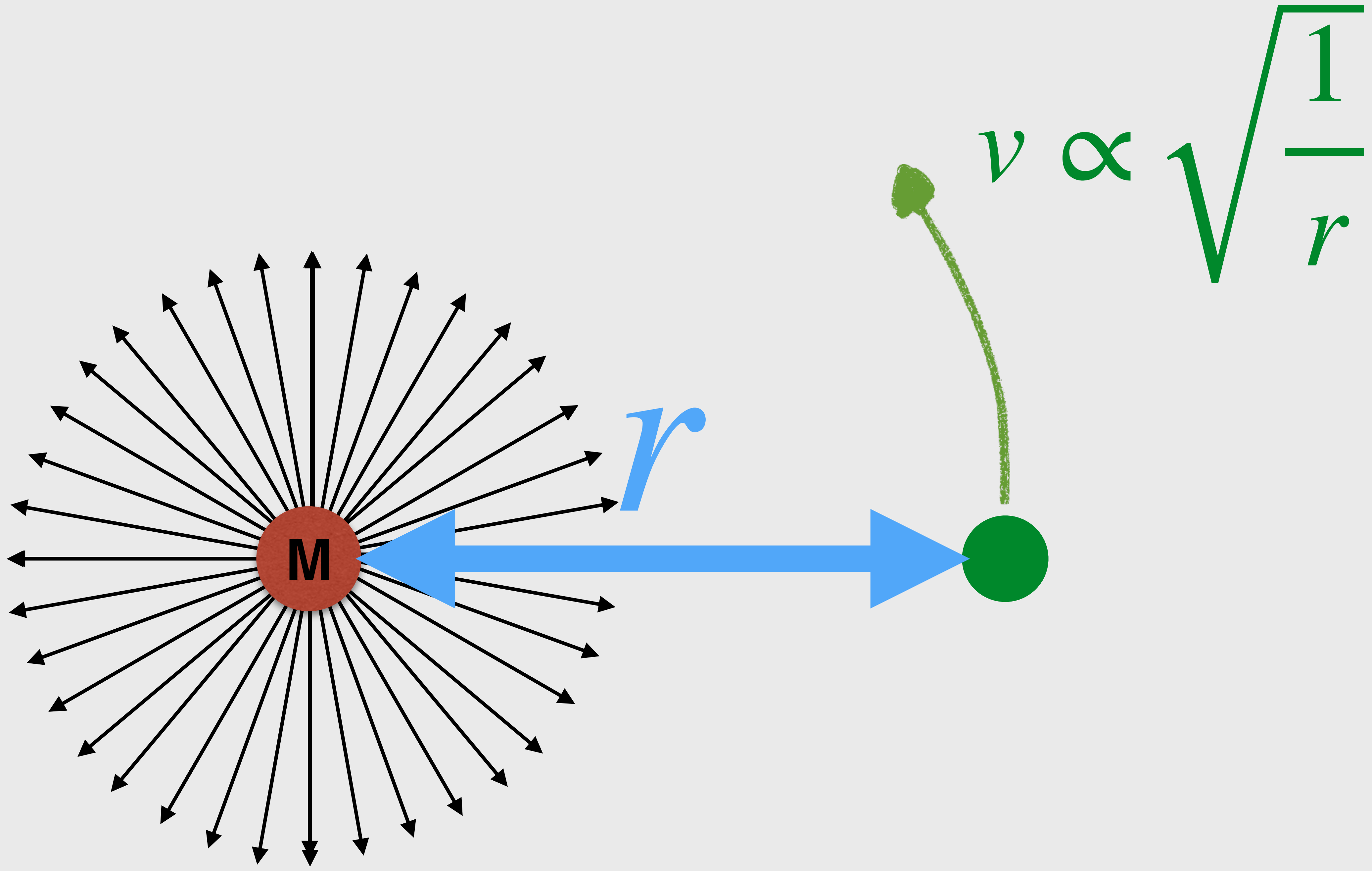
to this



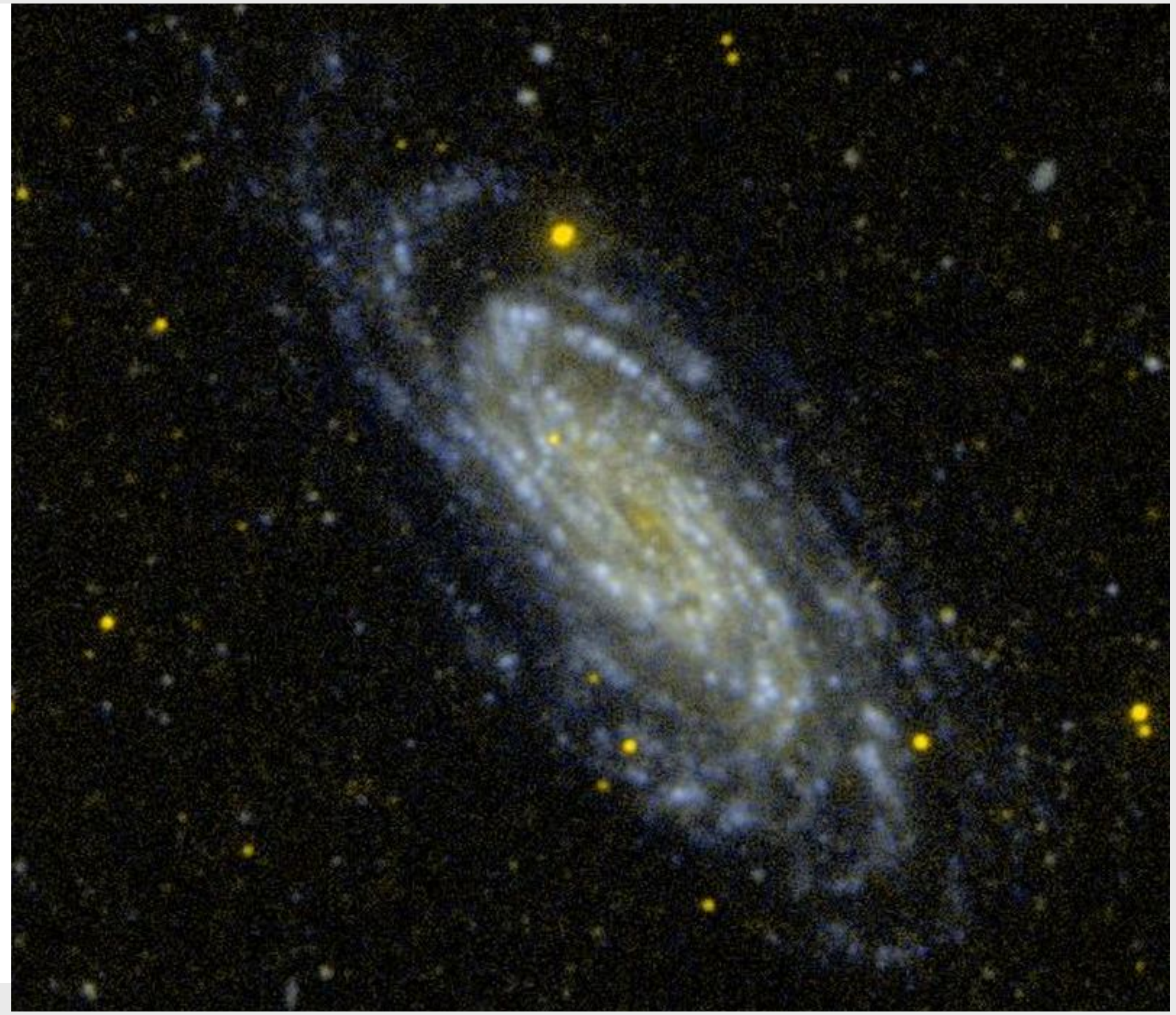
interactions rate from $\sigma = \left(\frac{g_{weak}}{M_{weak}}\right)^2$ are just about right!

A puzzle we have no idea how to solve

NEWTONIAN **MECHANICS FAILS?**



Perfect in our “neighborhood”



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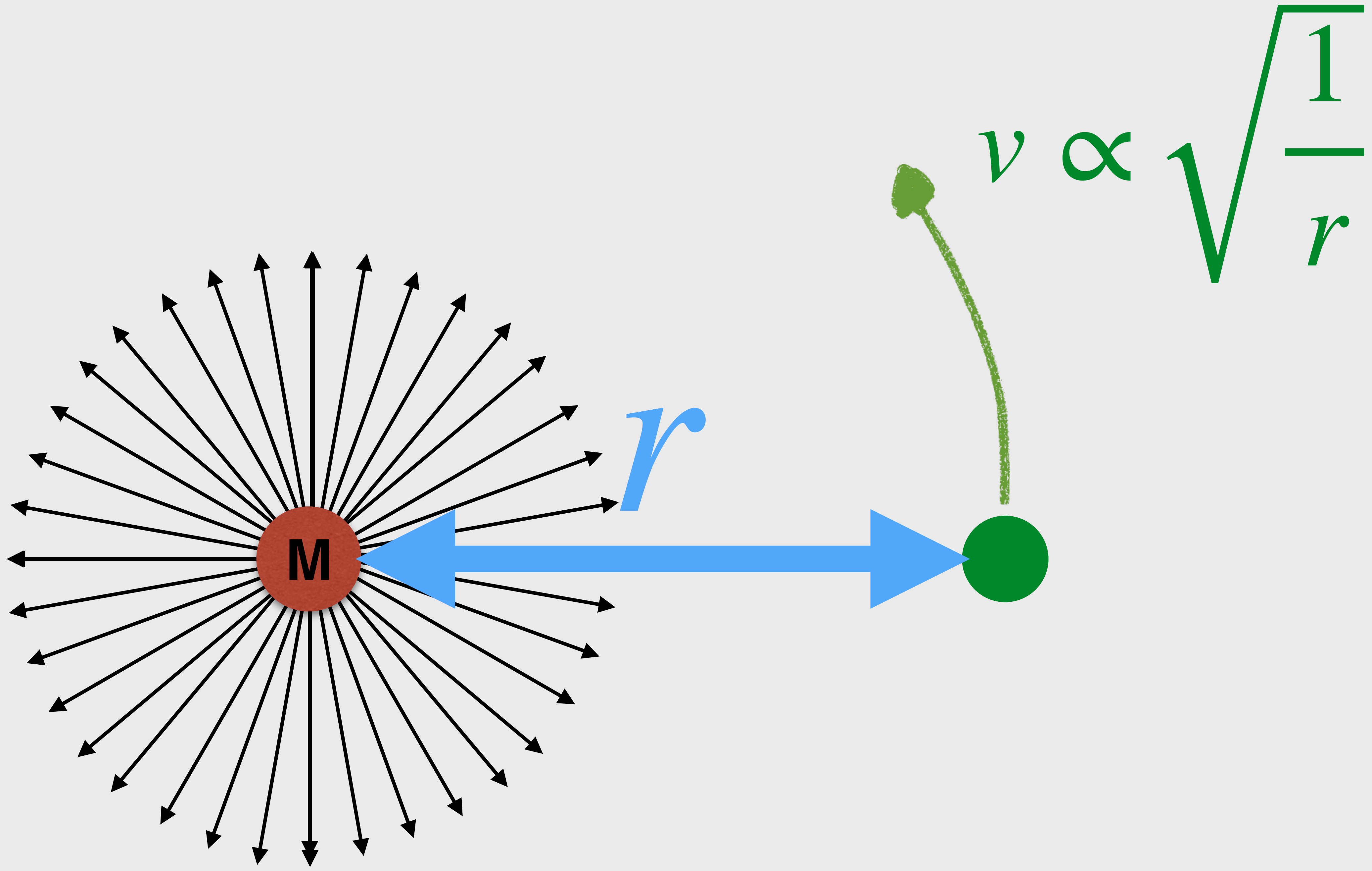

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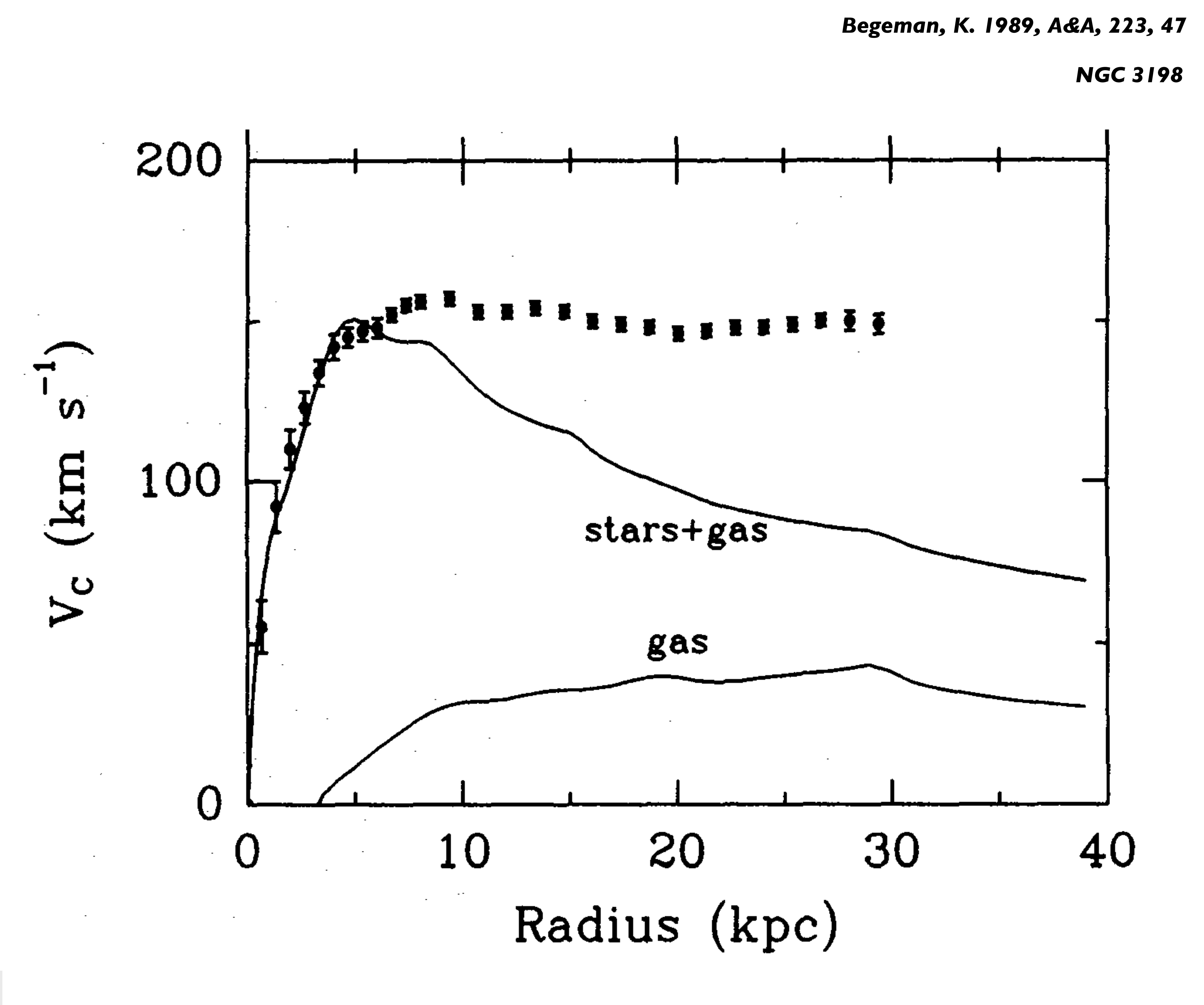

A puzzle we have no idea how to solve

A number of observations (including CMB from early Universe) suggest

a new form of matter must exist

It may well be not of the kind we are used to:

- It may have only weak interactions (even possible it feels only gravity)
- There are candidates "particles" with Compton length 1/M ranging from the size of a Galaxy down to High Energy Physics scales (GeV-TeV) and even beyond

It is not necessarily material for particle physics and accelerators

A puzzle we have no idea how to solve

A number of observations (including CMB from early Universe) suggest

- We know the scope of the search for Dark Matter is huge
- In principle, it can be very elusive (to all experiments)
- The simplest history of the early Universe suggests the “TeV” mass range
- Accelerators are the only way to go see it and study it in detail

Open Questions on the “big picture” on fundamental physics circa 2020

- ? what is the dark matter in the Universe?
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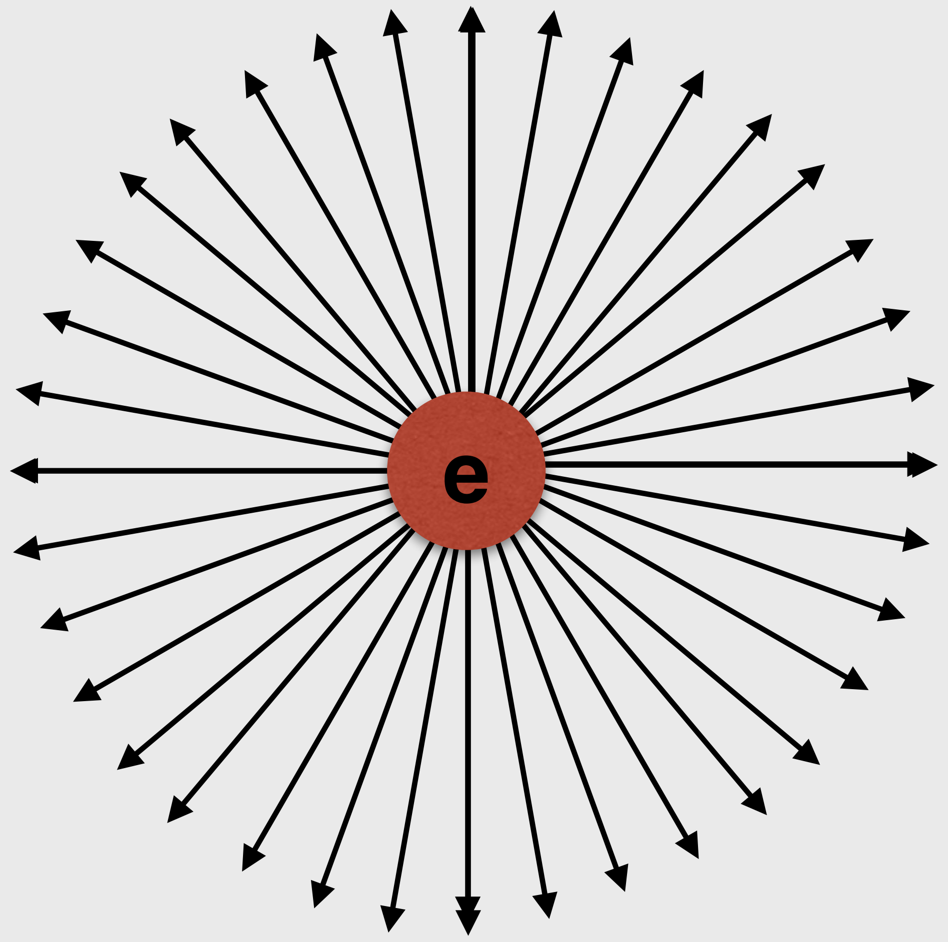
EACH of these issues one day will teach us a lesson

A puzzle (today) we know how to solve

AFTER **RELATIVITY**



$$m_e = m_e^{(0)} + \int_{r_e}^{\infty} \mathcal{E}$$

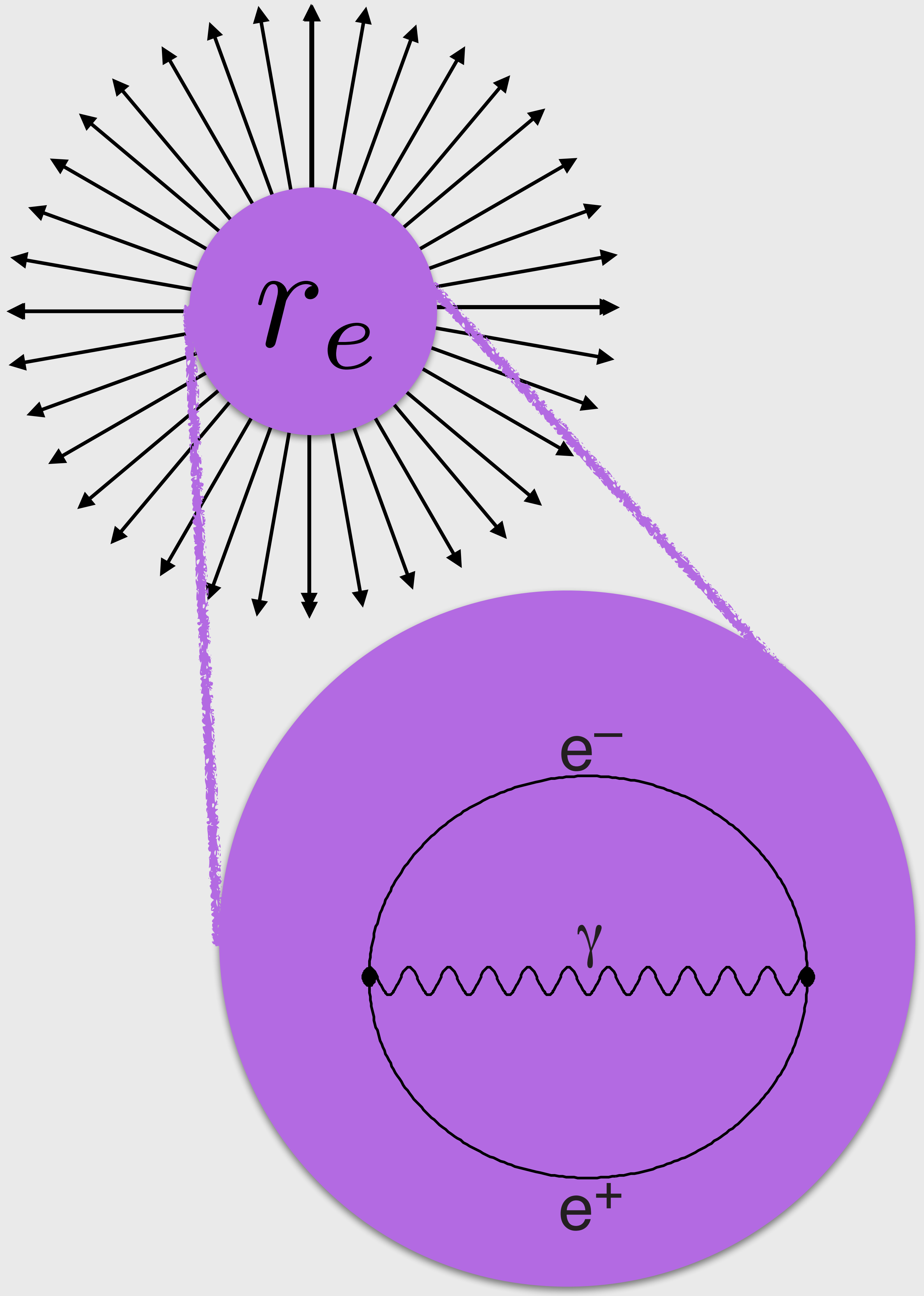
$$\int_{r_e}^{\infty} \mathcal{E} = \frac{1}{4\pi\epsilon_0} \frac{e^2}{r_e}$$

$$\delta m_e \simeq \frac{\alpha_{em}}{r_e} \xrightarrow{r_e \to 0} \infty$$

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS



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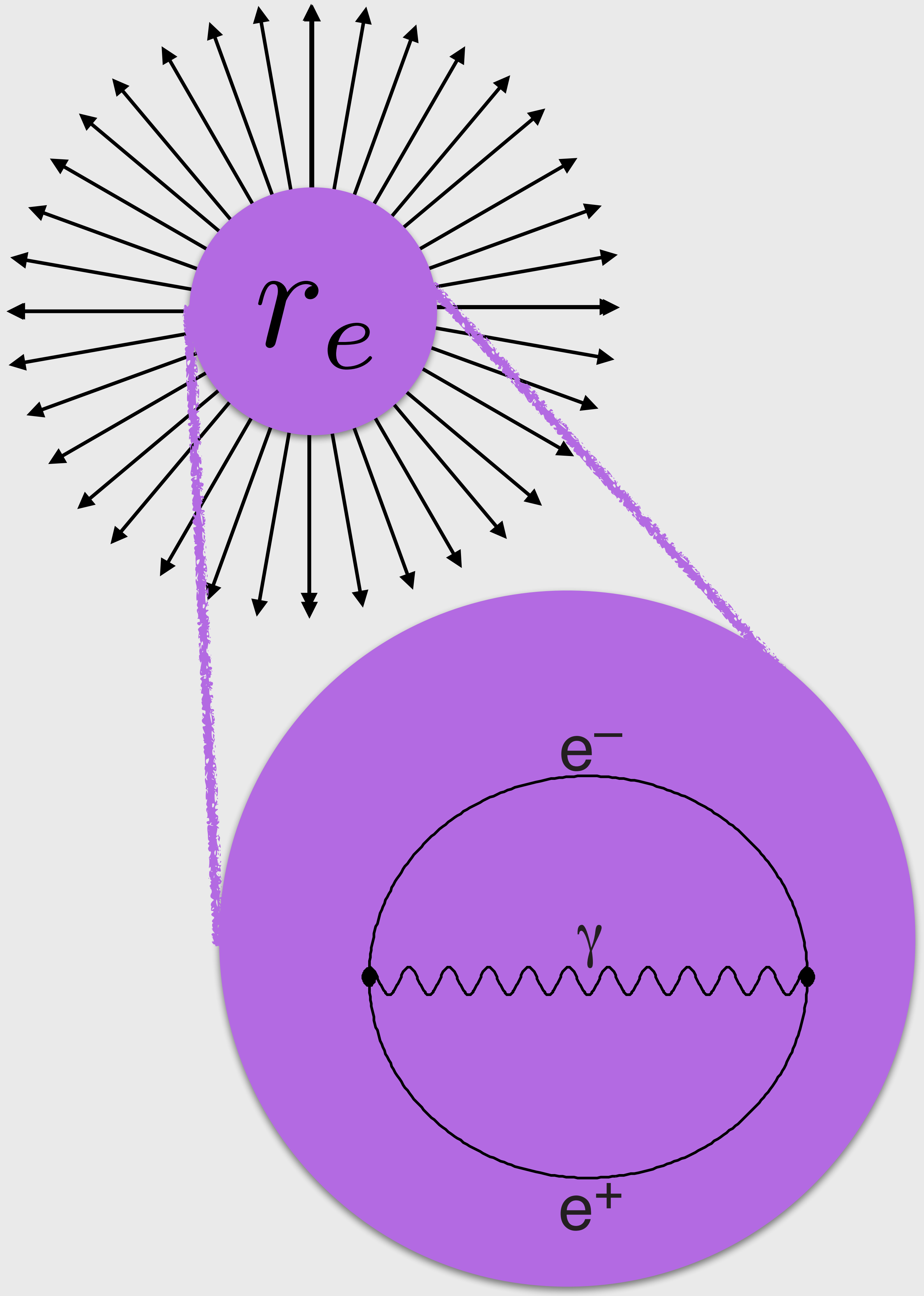


New symmetry (particle-antiparticle) which brought a new particle: the positron

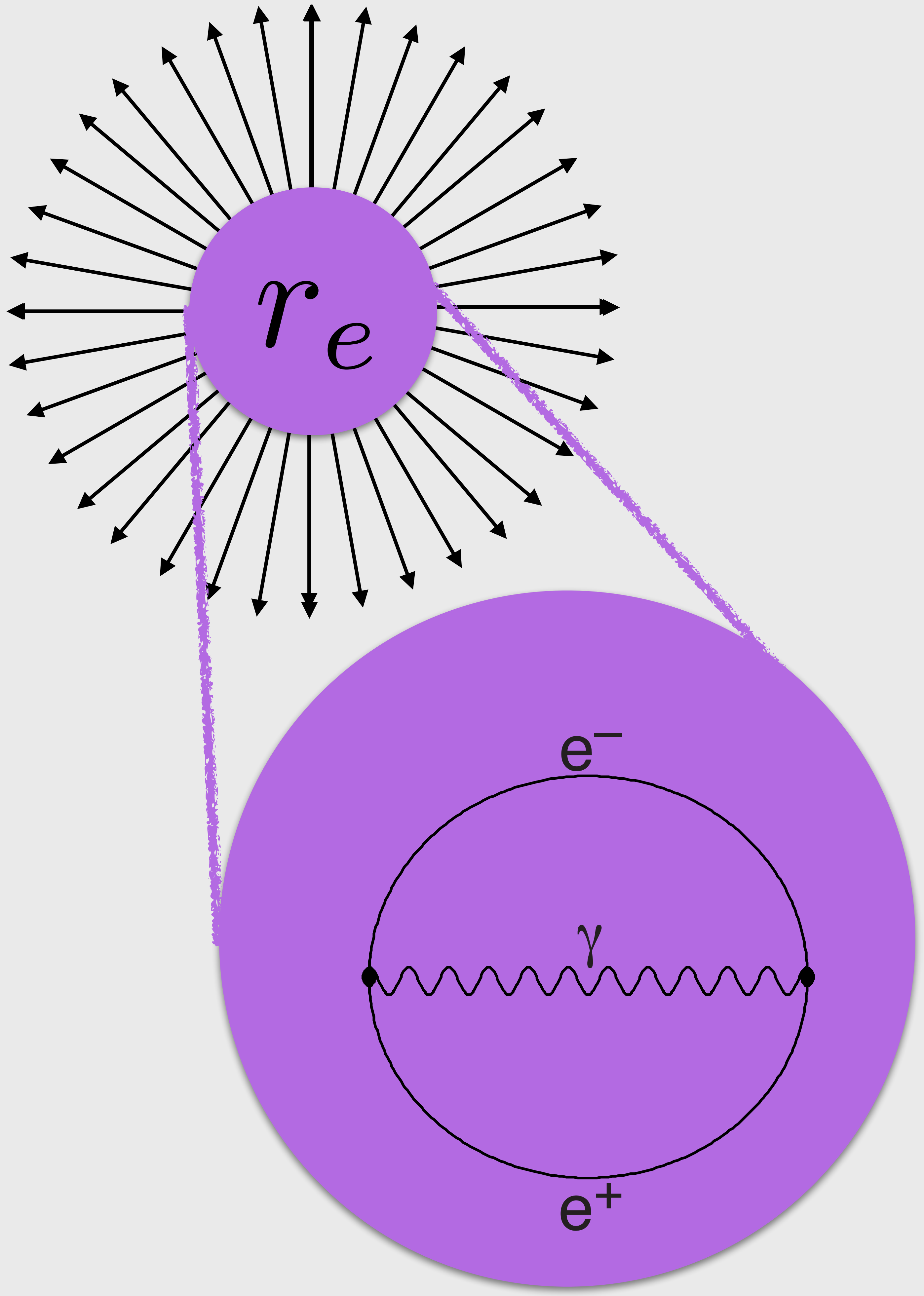
We learned a lesson on physics **at the same mass scale** as where the puzzle arises:

$$m_{positron} = m_{electron} \ll m_{electron}/\alpha_{em}$$

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS



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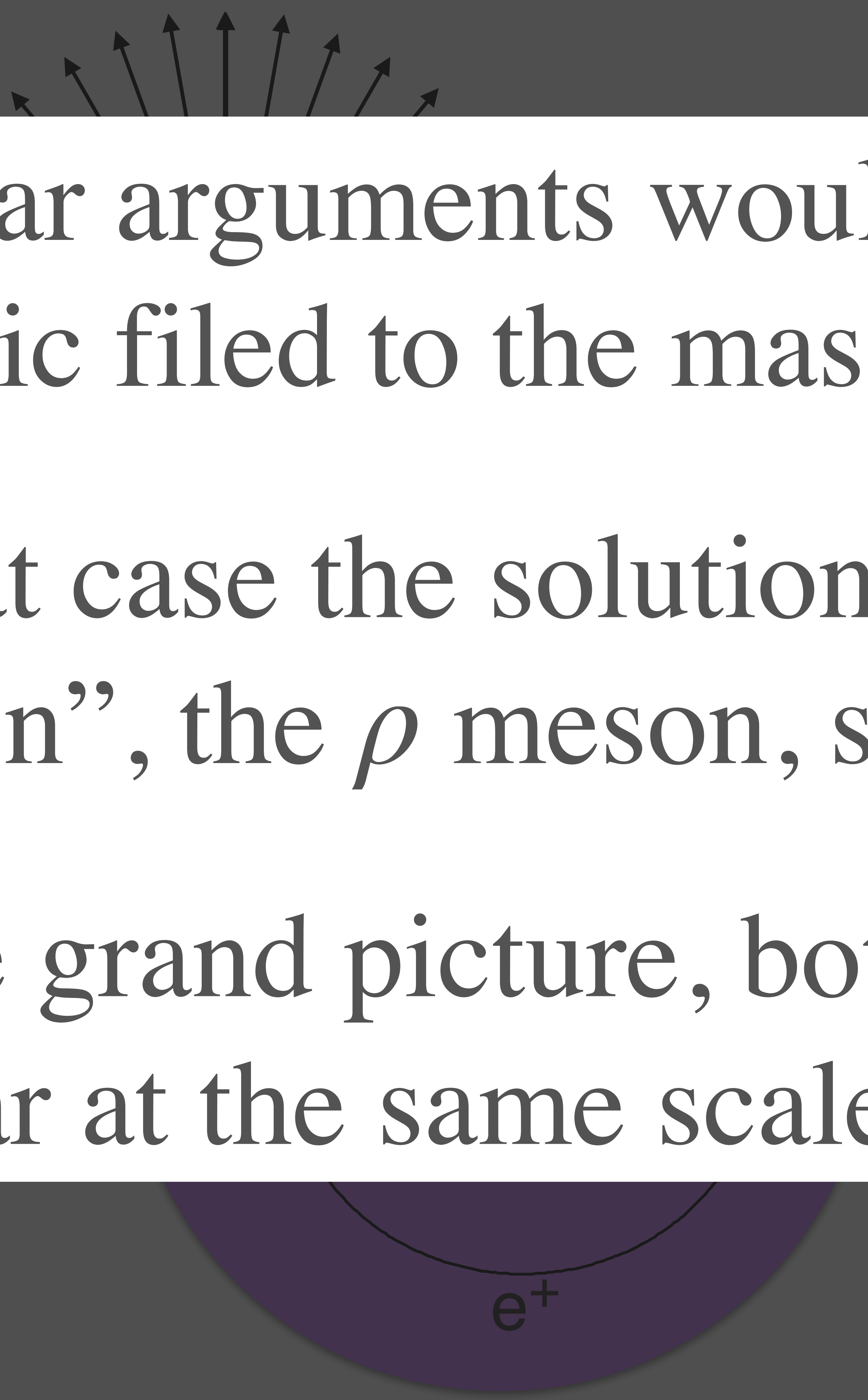

- Similar arguments would require a contribution of the electric filed to the mass of the charged pion
- In that case the solution is not an antiparticle, but a “heavy photon”, the ρ meson, somewhat heavier than the pion
- In the grand picture, both the positron and the ρ meson appear at the same scale where the problem arises.