Time-dependent screening of the electric field in pulsar discharges and its implications for coherent radio emission

APS DPP
November 2021

Based on paper in preparation: "Dynamical screening of the electric field in pair discharges and its implications for pulsar radio luminosity and spectrum," E.A. Tolman, A.A. Philippov, and A.N. Timokhin. Available shortly on arXiv.

Elizabeth A. Tolman[1], A.A. Philippov[2], and A.N. Timokhin[3]

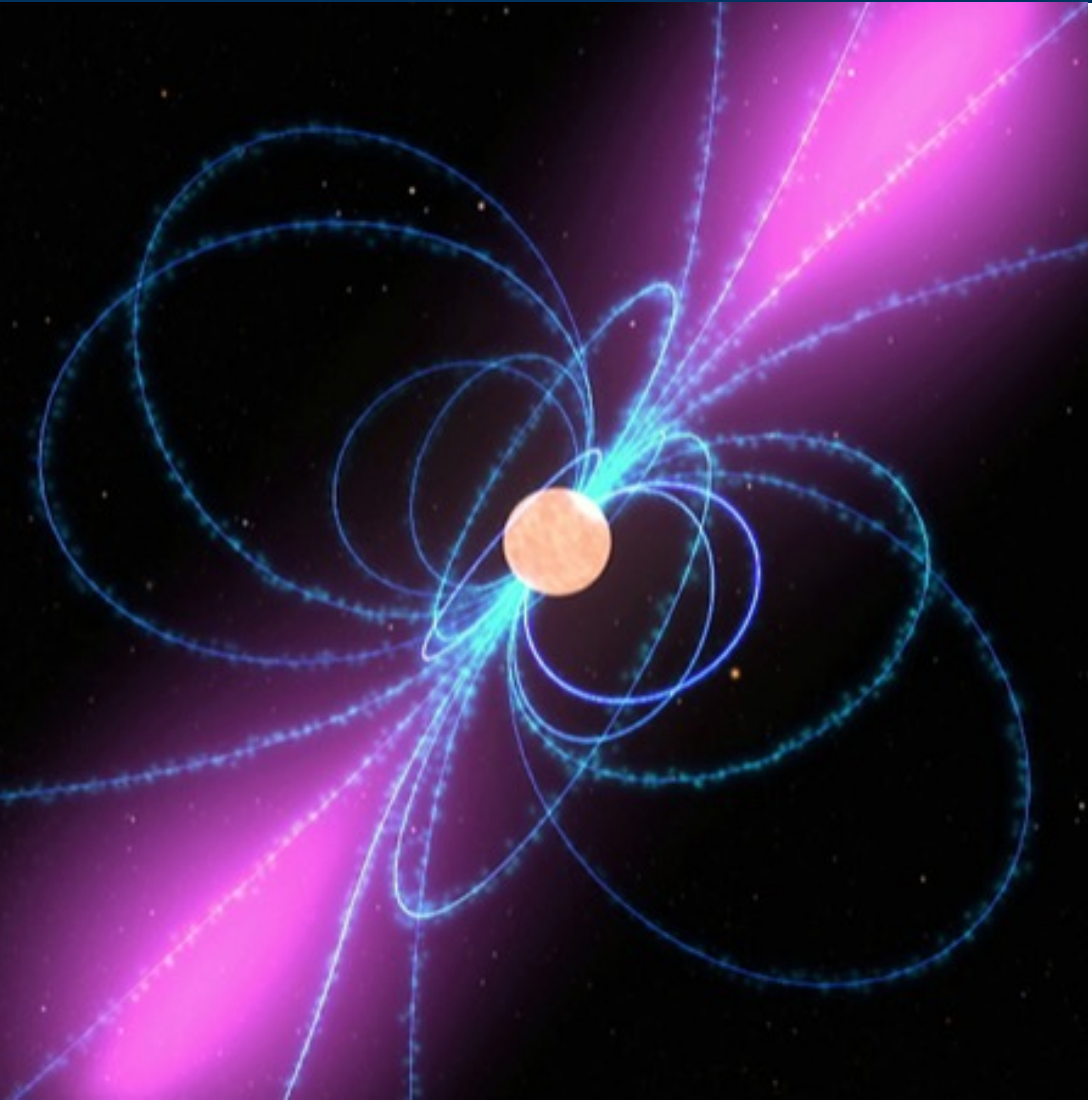
[1]School of Natural Sciences, Institute for Advanced Study, Princeton, NJ USA

[2]Center for Computational Astrophysics, Flatiron Institute, New York, NY USA

[3]Janusz Gil Institute of Astronomy, University of Zielona Góra, Zielona Góra, Poland

INSTITUTE FOR ADVANCED STUDY

Pulsars emit coherently in radio from polar cap



- Pulsars emit coherently in radio from polar cap
- Many aspects of this emission are unexplained

Image source: NASA

Radio luminosity is independent of spindown luminosity

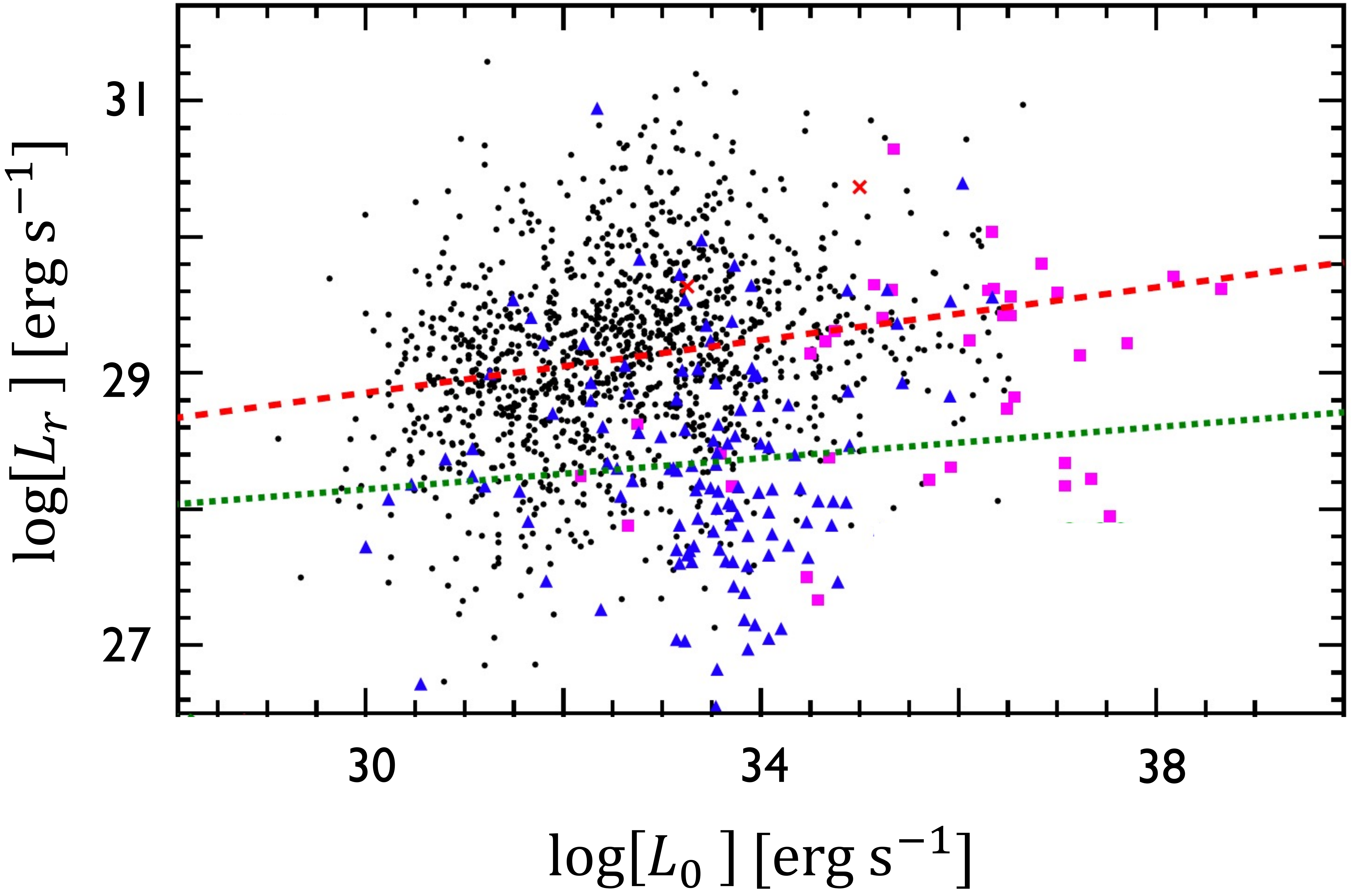


Image source: Szary et al., ApJ 2014

- Radio luminosity L_r has magnitude

$$L_r \sim 10^{27} - 10^{31} \text{ erg s}^{-1}$$

- Roughly independent of spindown luminosity L_0

Pulsar radio spectrum is $S_\omega \sim \omega^{-1.4\pm1.0}$

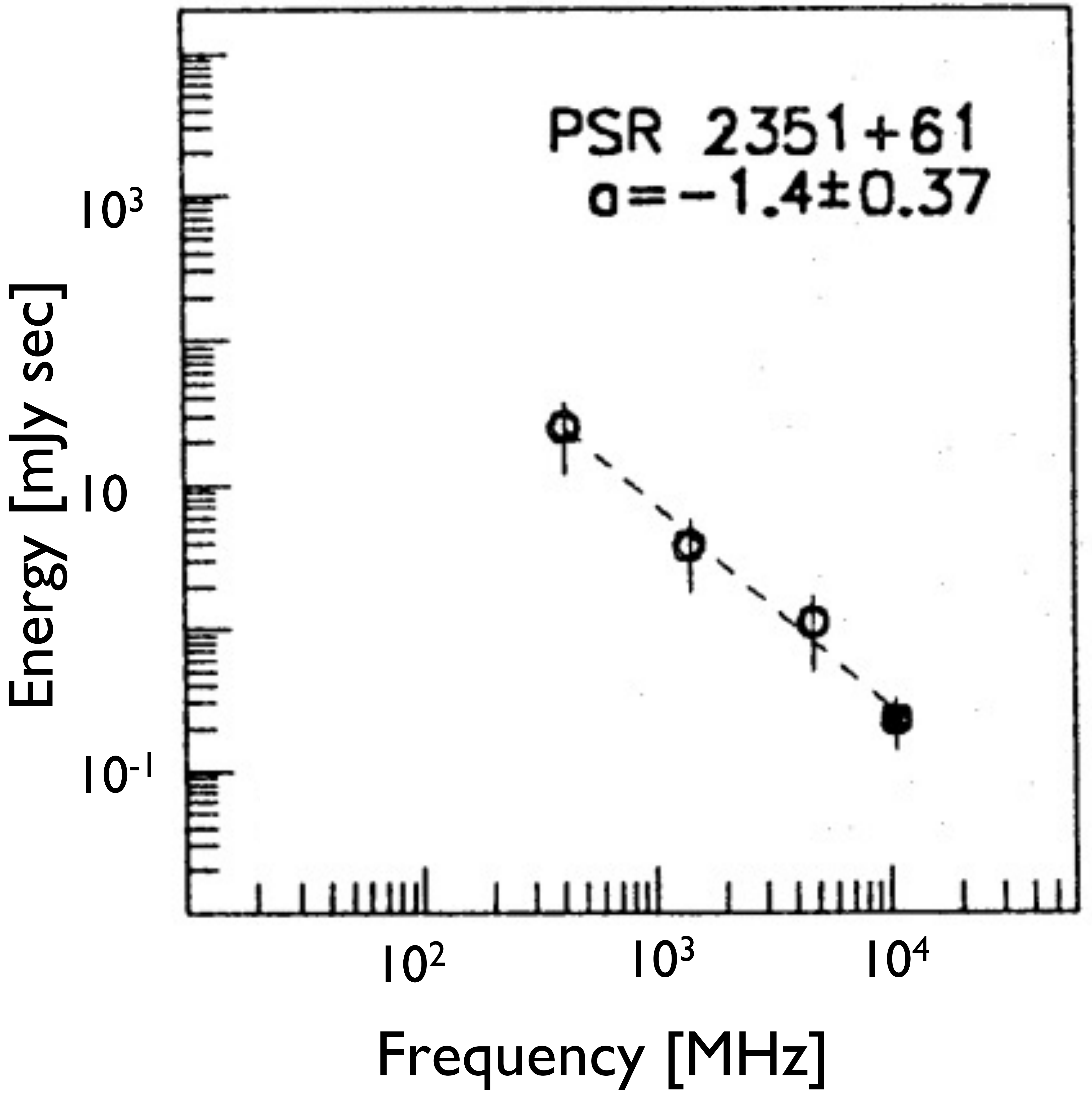
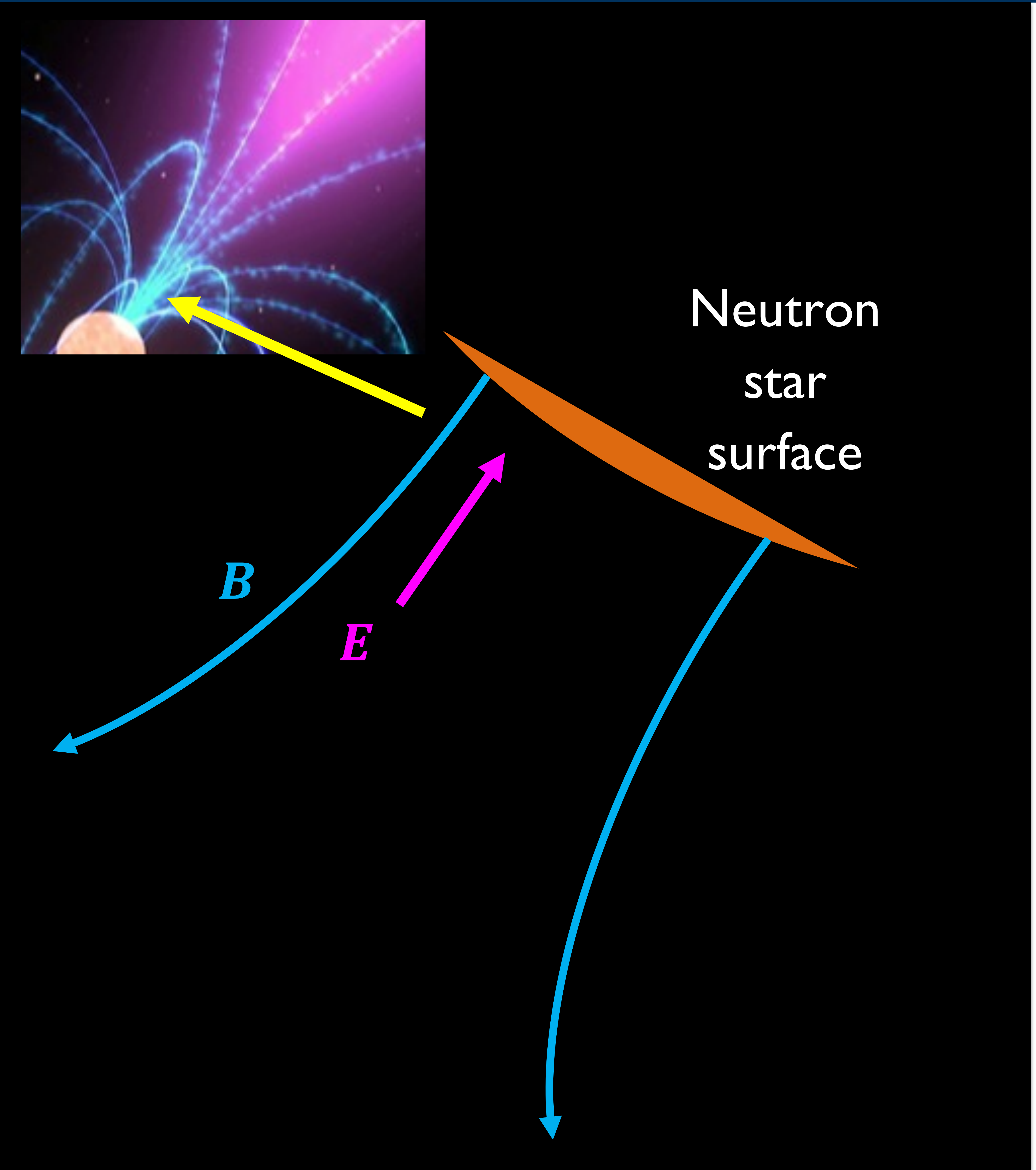


Image source: Malofeev et al., A&A 1994

- Typical radio spectrum across several pulsar observations is [Bates et al. MNRAS 2013]:

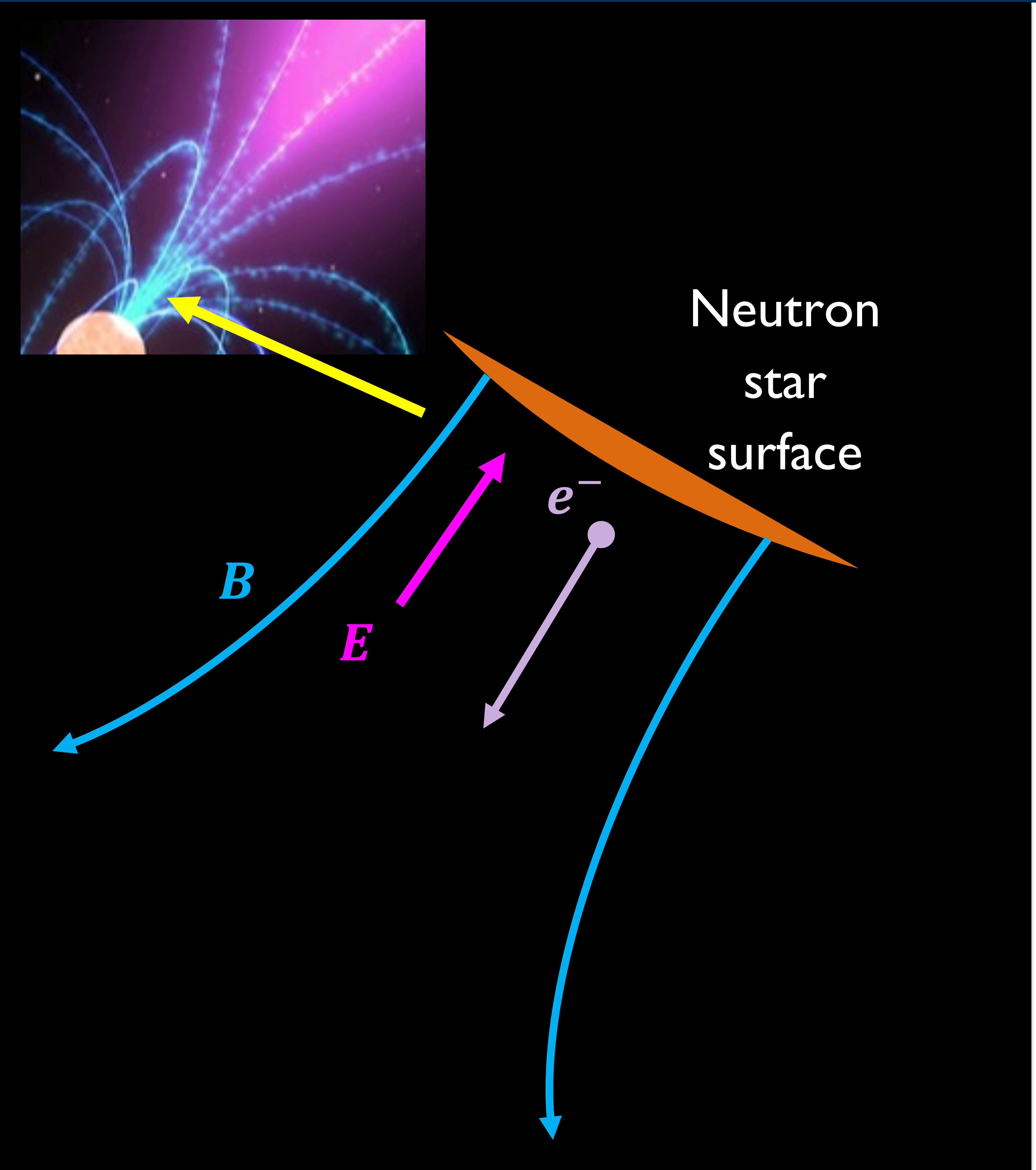
$$S_\omega \sim \omega^{-1.4\pm1.0}$$

Pair discharge in polar cap may create radio emission



- Polar cap has strong inductive E field which creates pair discharge:

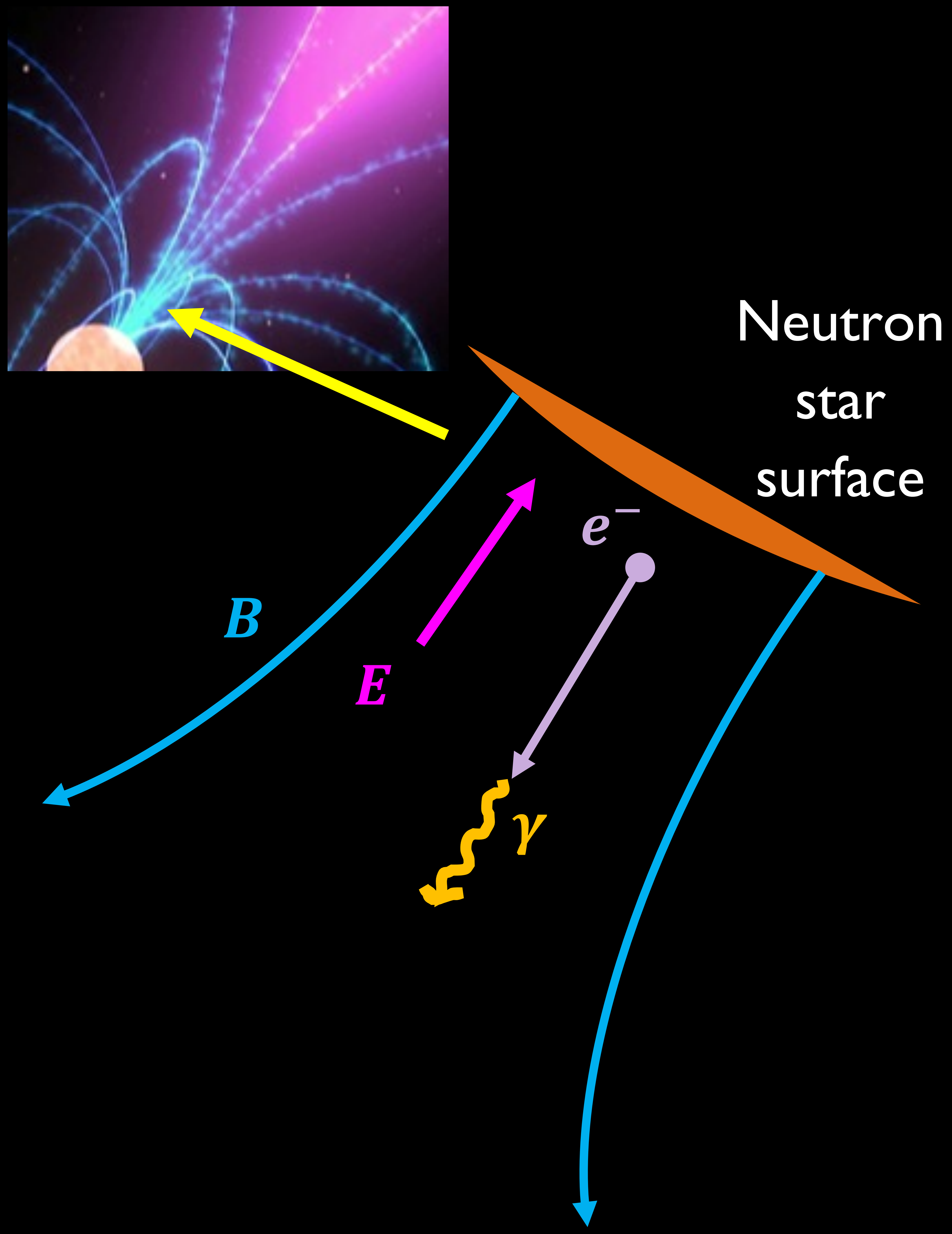
Pair discharge in polar cap may create radio emission



- Polar cap has strong inductive E field which creates pair discharge:

  1. E field accelerates e- from surface to $\gamma \sim 10^7$

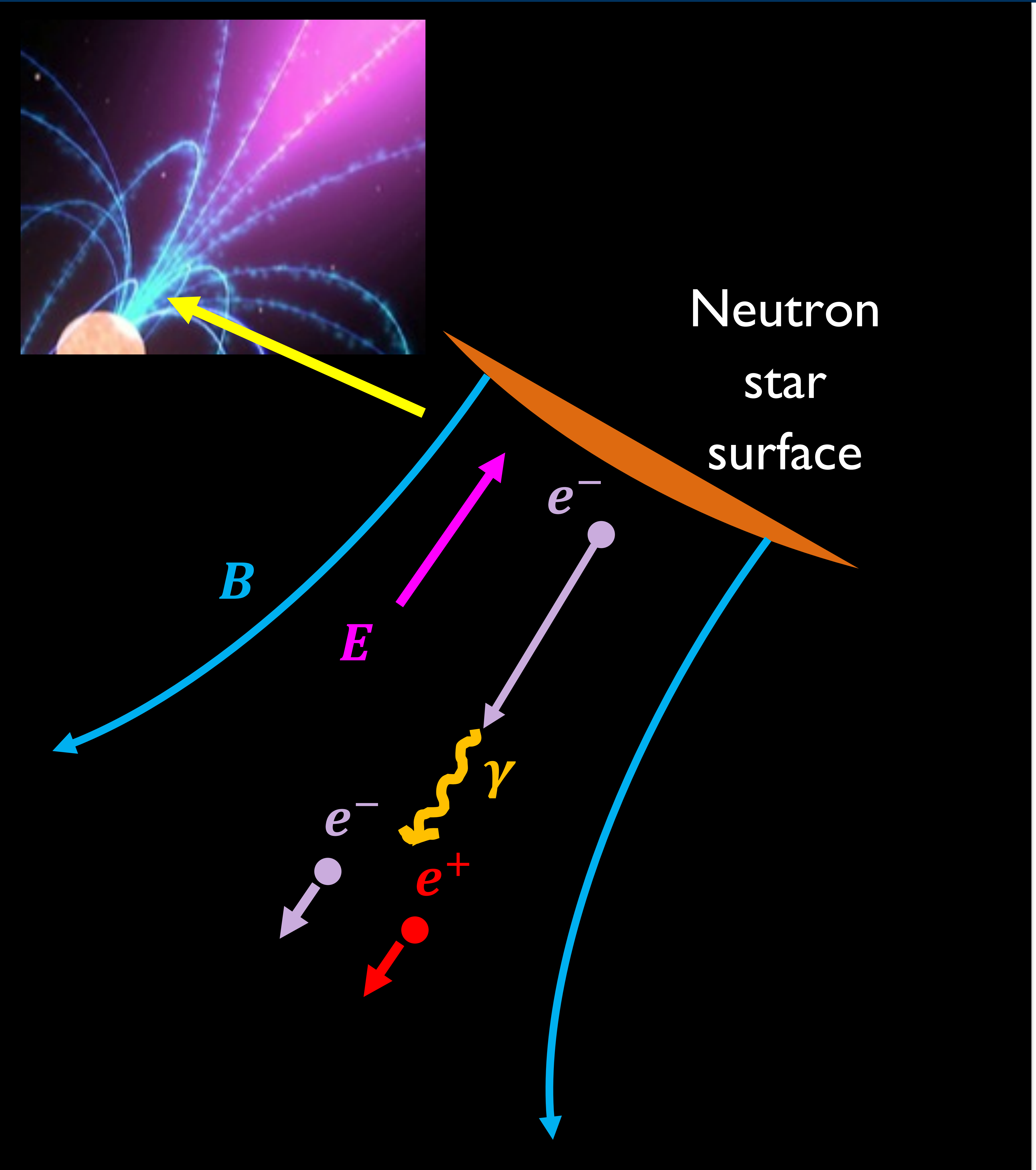
Pair discharge in polar cap may create radio emission



- Polar cap has strong inductive E field which creates pair discharge:

  1. E field accelerates e- from surface to $\gamma \sim 10^7$
  2. Primary e- continually curvature radiate gamma rays

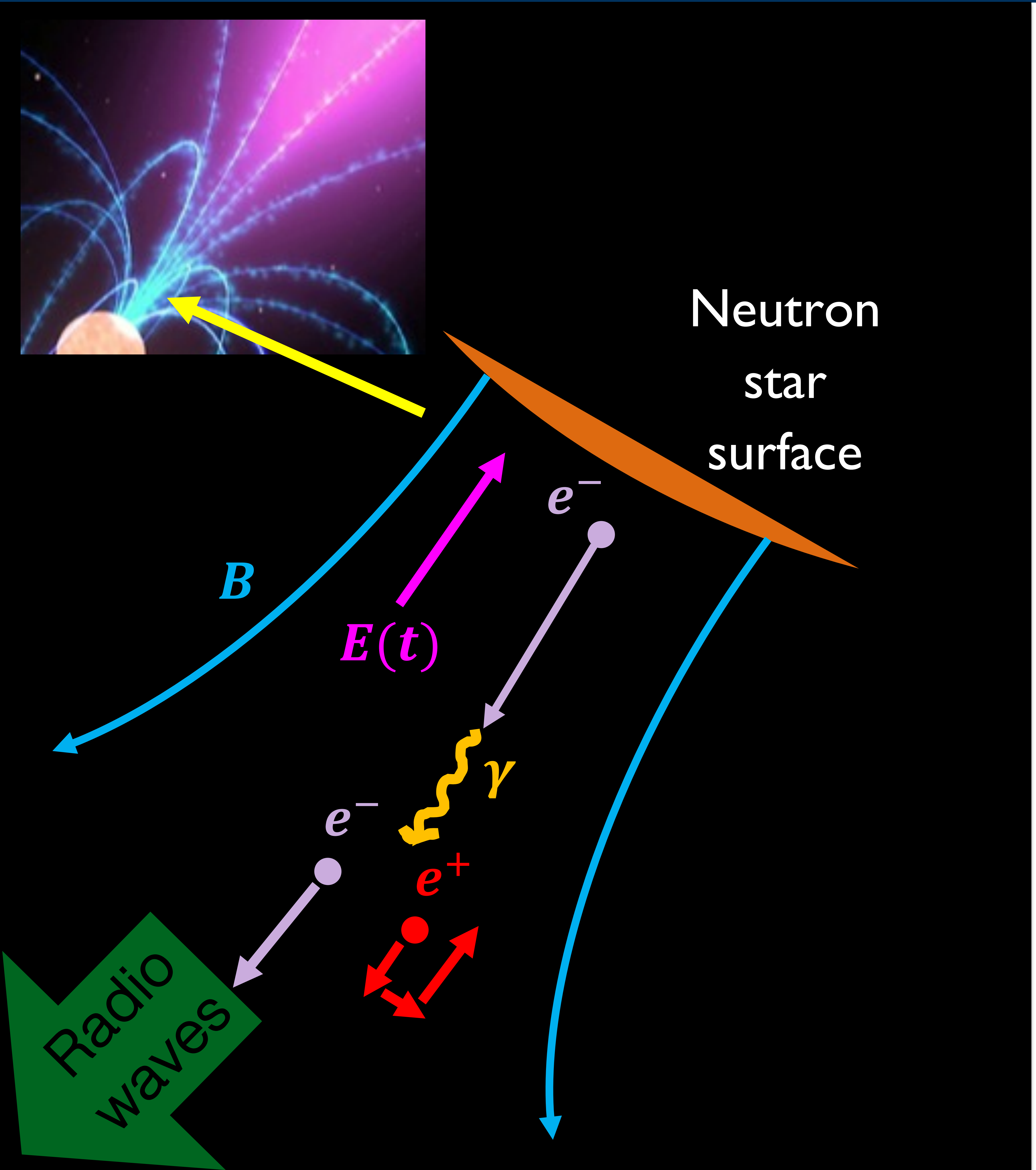
Pair discharge in polar cap may create radio emission



- Polar cap has strong inductive E field which creates pair discharge:

1. E field accelerates e- from surface to $\gamma \sim 10^7$
2. Primary e- continually curvature radiate gamma rays
3. Gamma rays are absorbed in magnetic field
4. QED process continually creates lower energy $\gamma \sim 10^2$ pairs

Pair discharge in polar cap may create radio emission



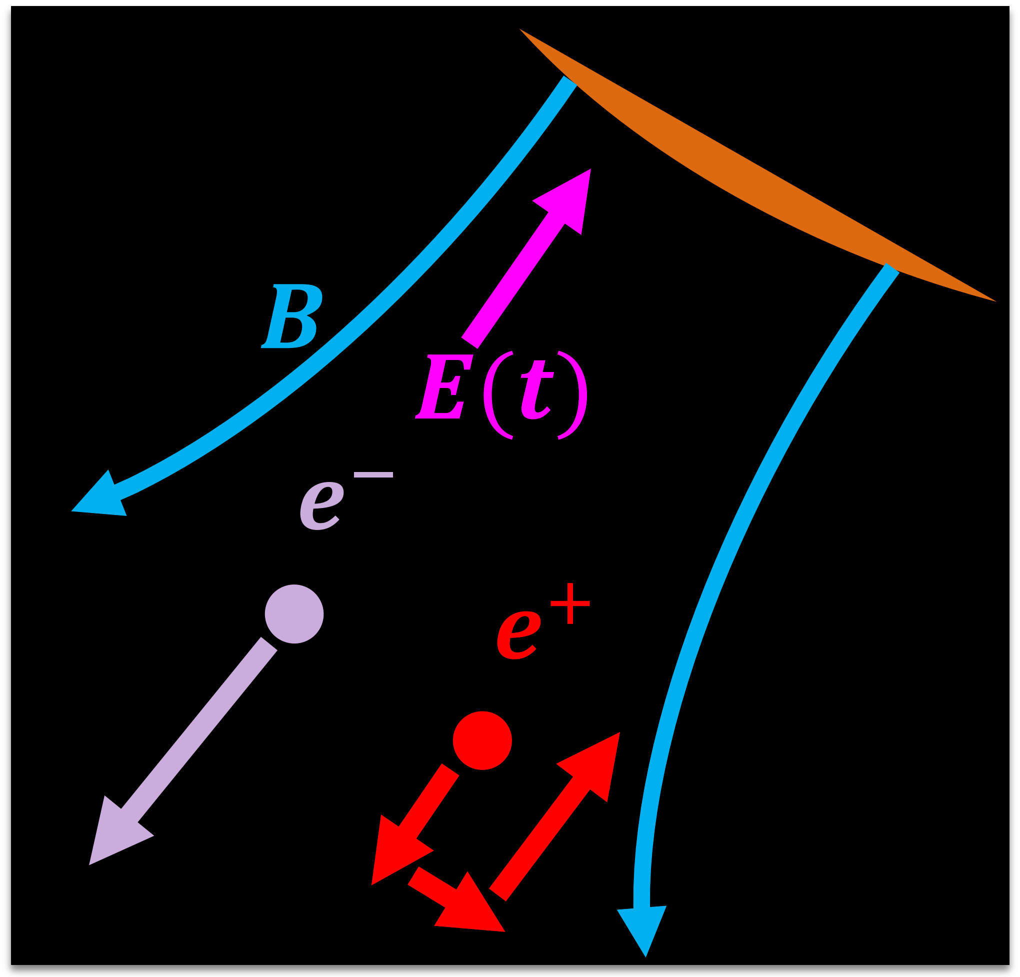
- Polar cap has strong inductive E field which creates pair discharge:

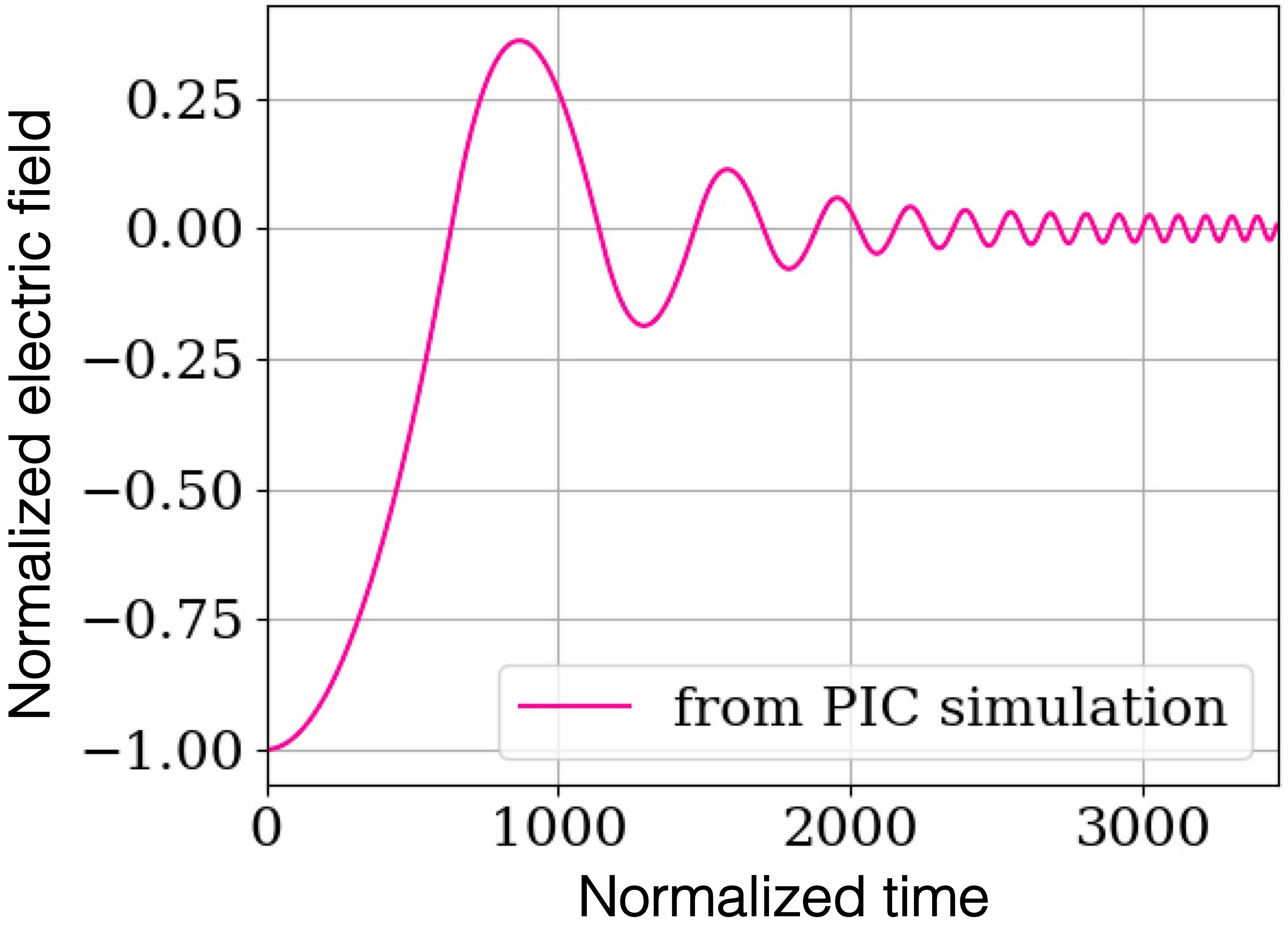
  1. E field accelerates e- from surface to $\gamma \sim 10^7$
  2. Primary e- continually curvature radiate gamma rays
  3. Gamma rays are absorbed in magnetic field
  4. QED process continually creates lower energy $\gamma \sim 10^2$ pairs

- Continuously created $\gamma \sim 10^2$ pairs screen E

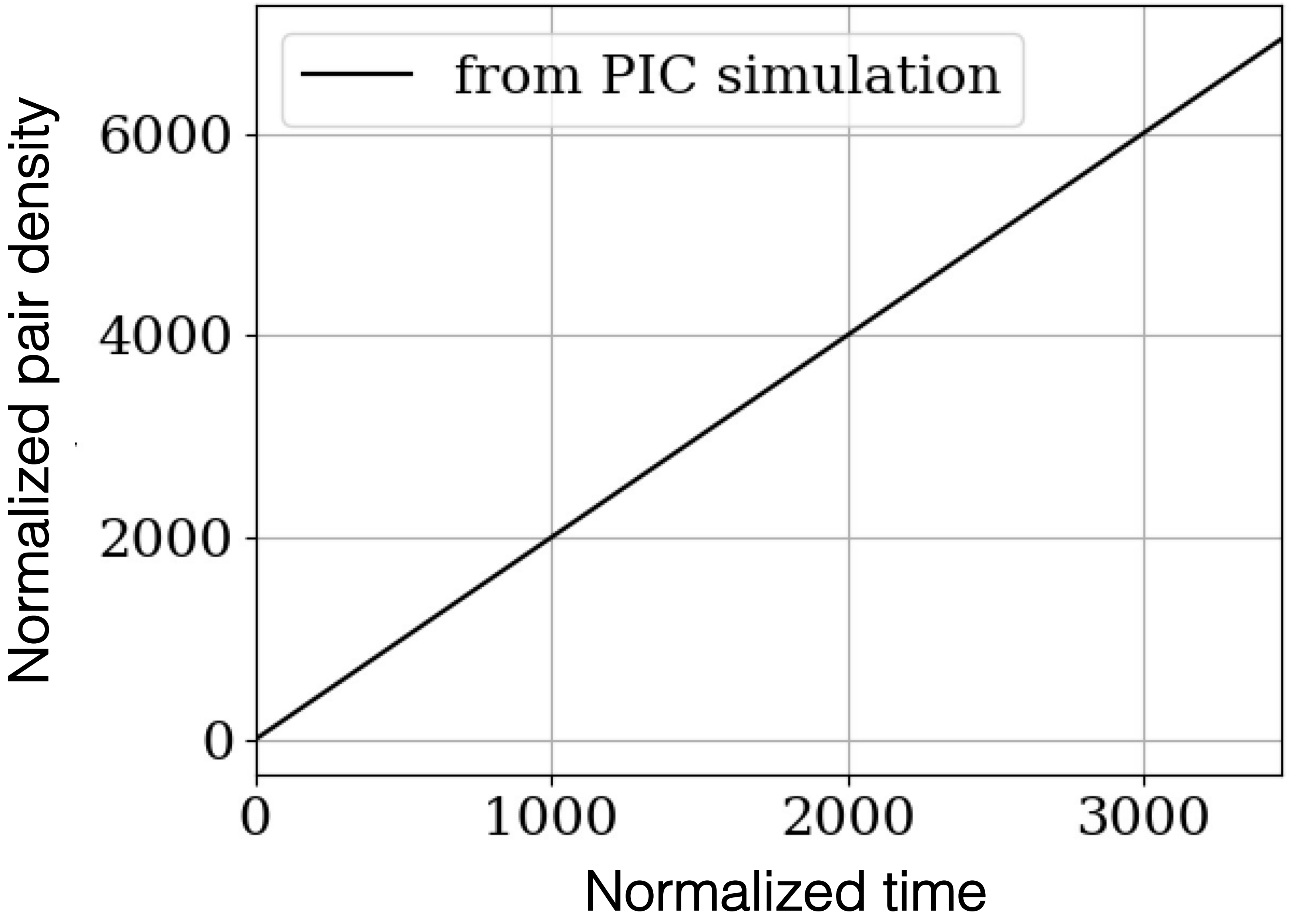
- Set up waves which become radio emission

We analytically study screening, explain L_r, S_ω



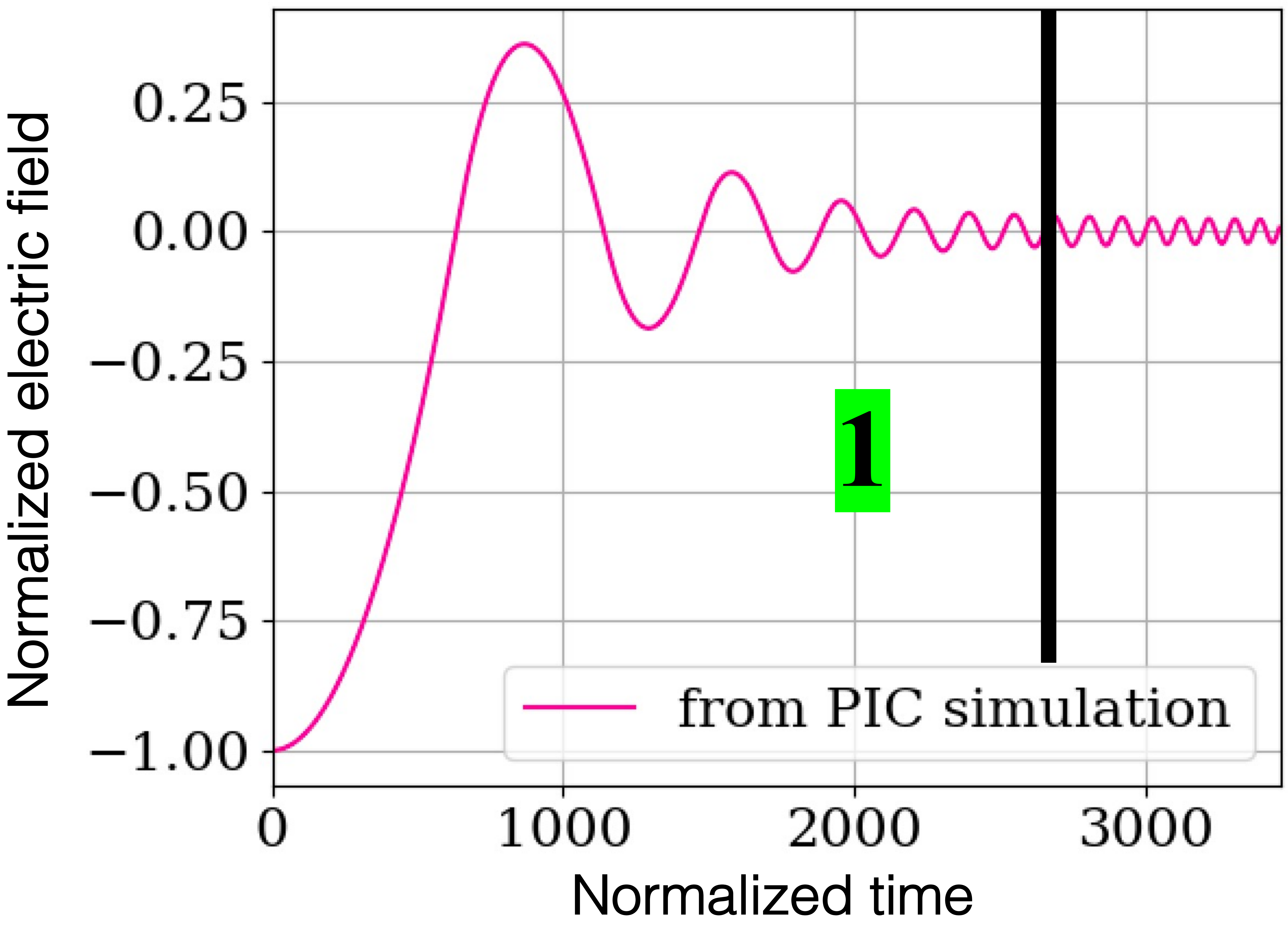


- Screening of a vacuum electric field by continuous creation of $\gamma \sim 10^2$ pairs can be seen in 1D PIC simulations at right

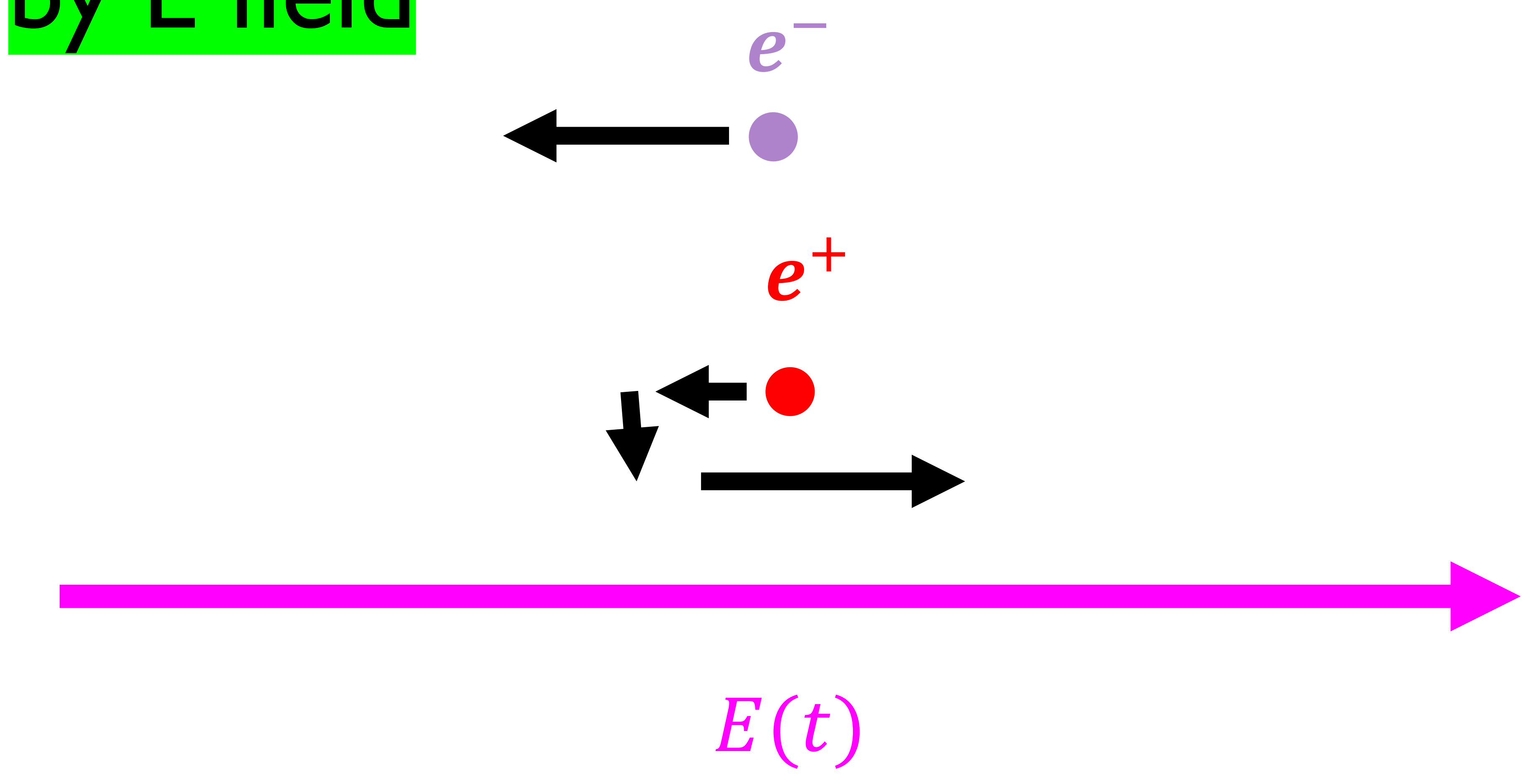


- Our work: analytical models of this screening process, used to explain luminosity + spectrum

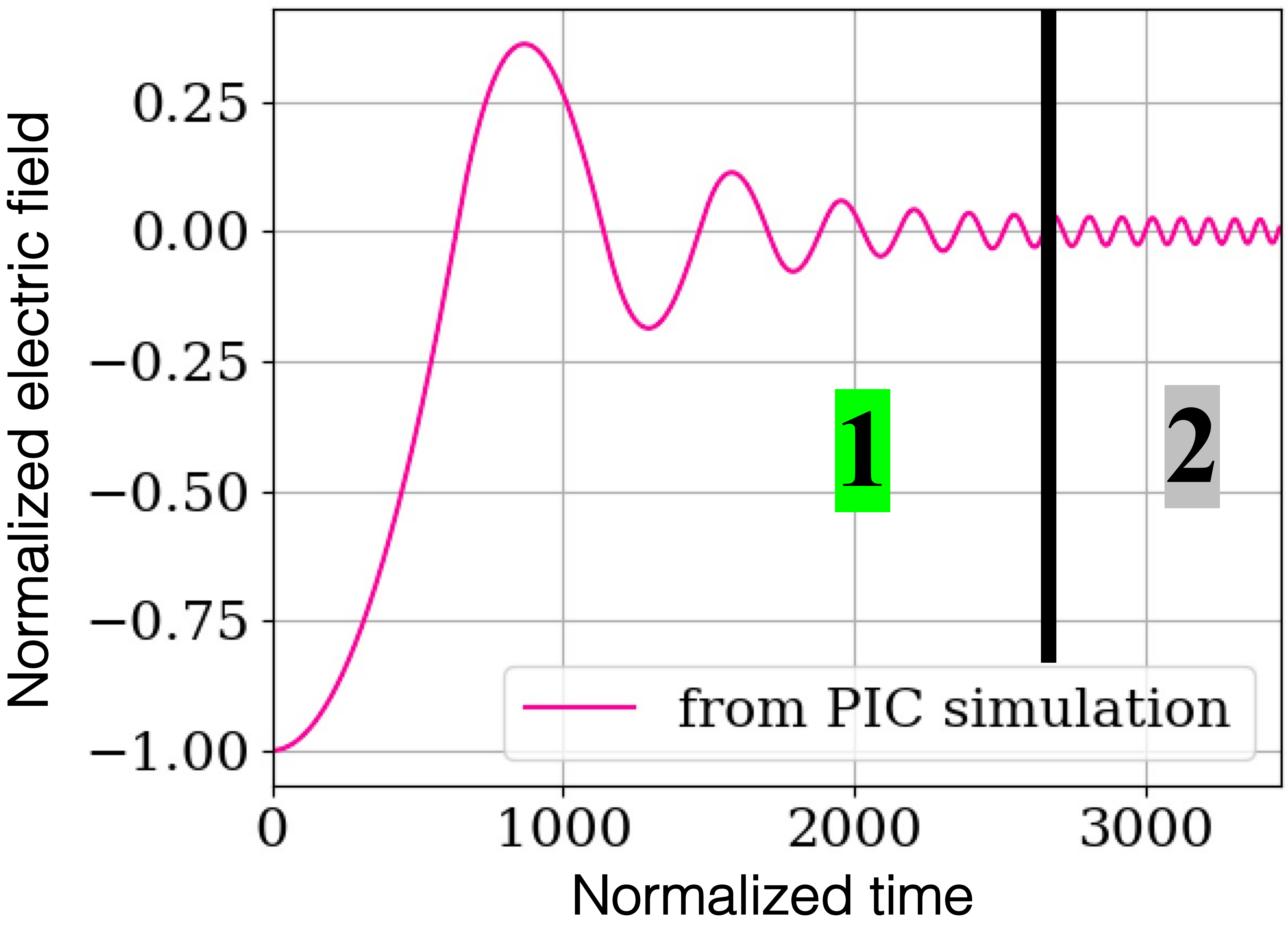
E field damping has two phases: nonlinear and linear



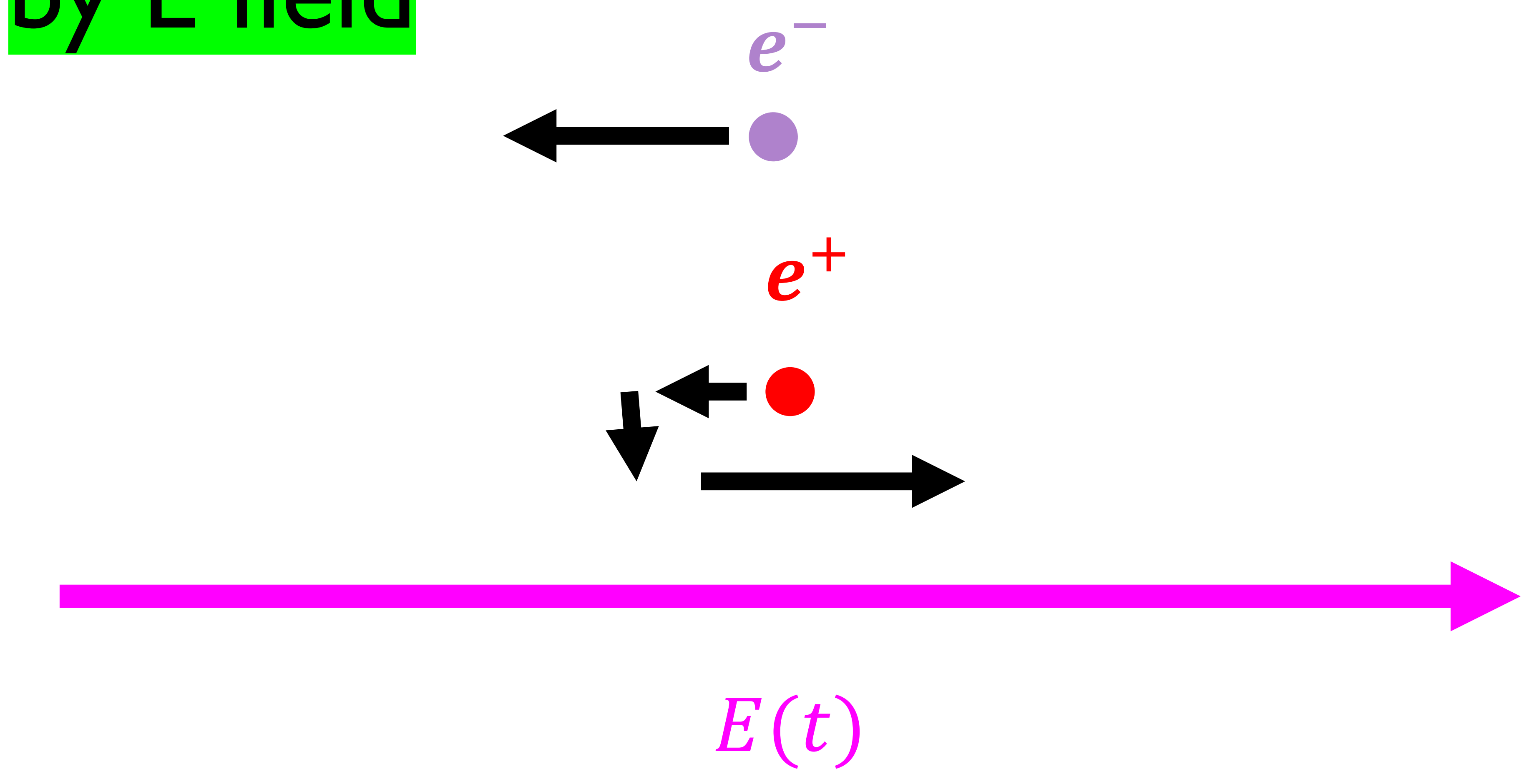
1. **Nonlinear waves, strong damping**: new pairs fully reversed by E field



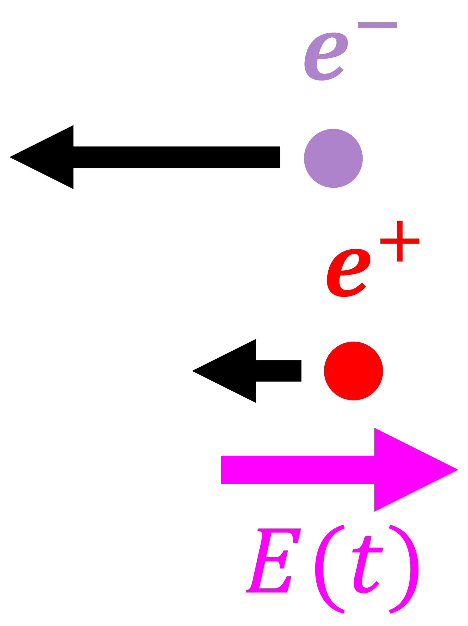
E field damping has two phases: nonlinear and linear



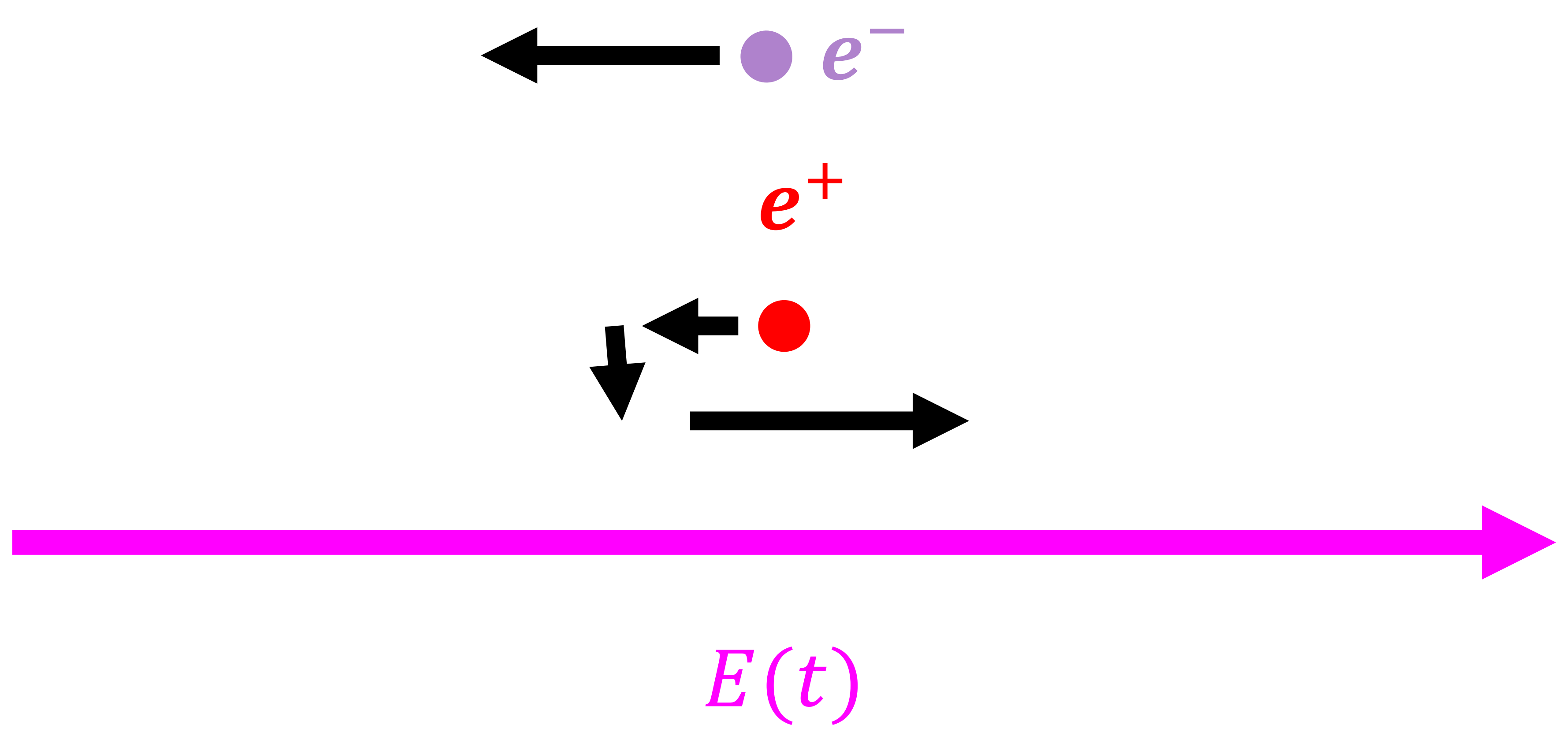
1. **Nonlinear waves, strong damping**: new pairs fully reversed by E field

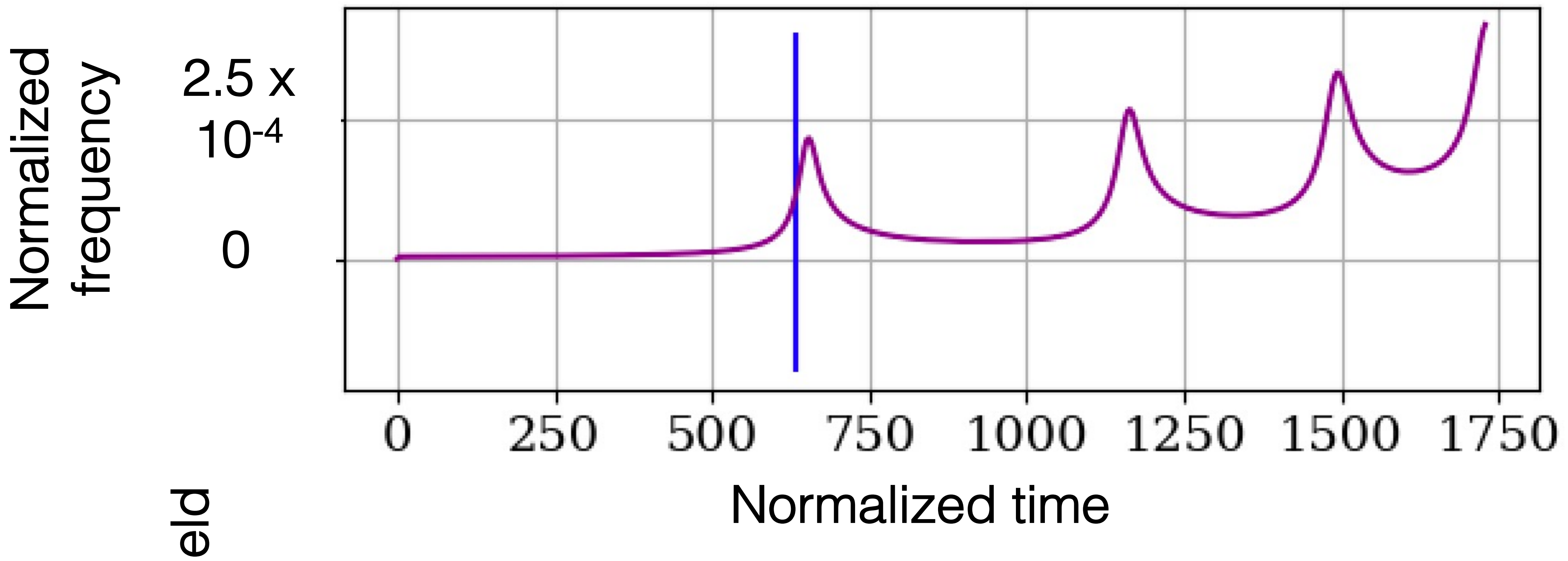


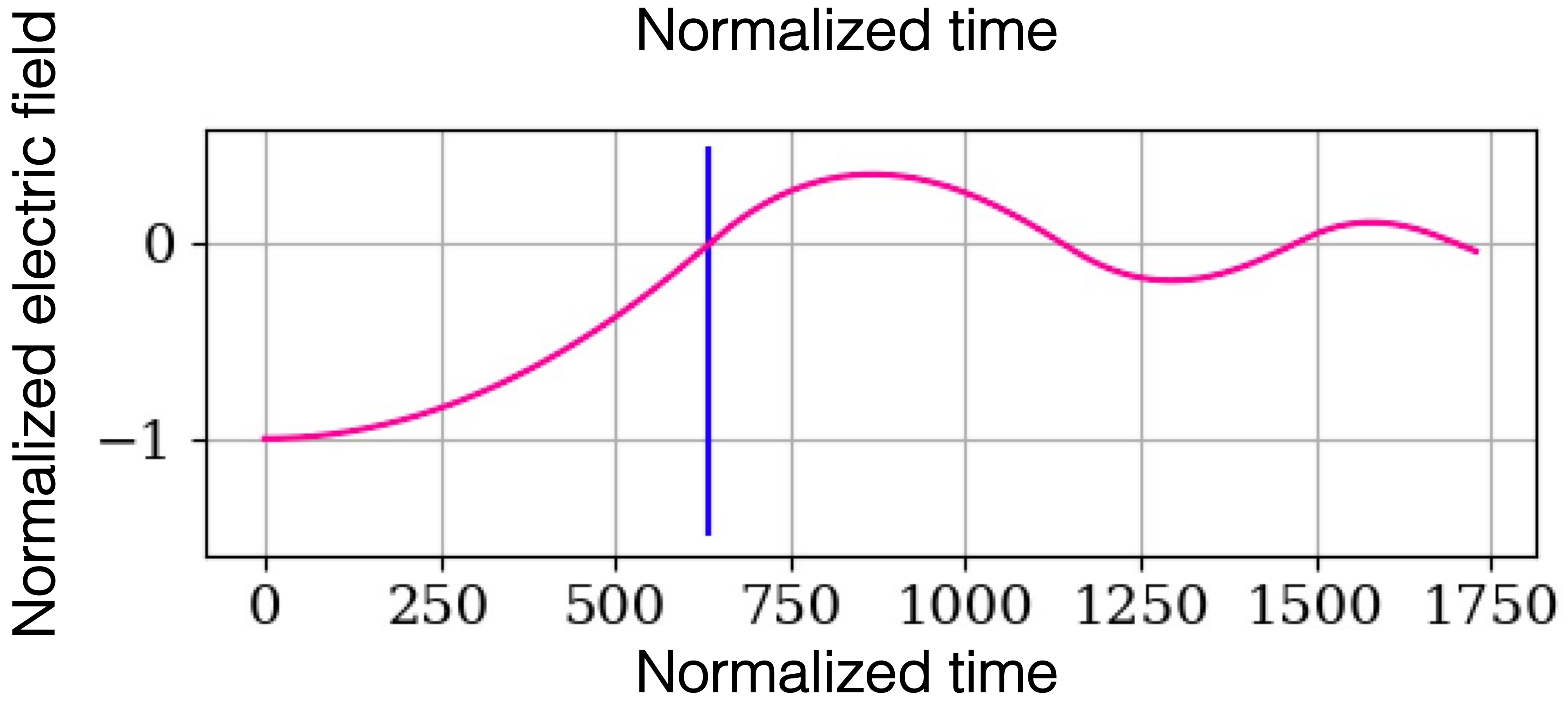
2. **Linear waves, weak damping:** new pairs not reversed by E field



Nonlinear stage marked by strong damping







- Nonlinear stage marked by strong damping, governed by:

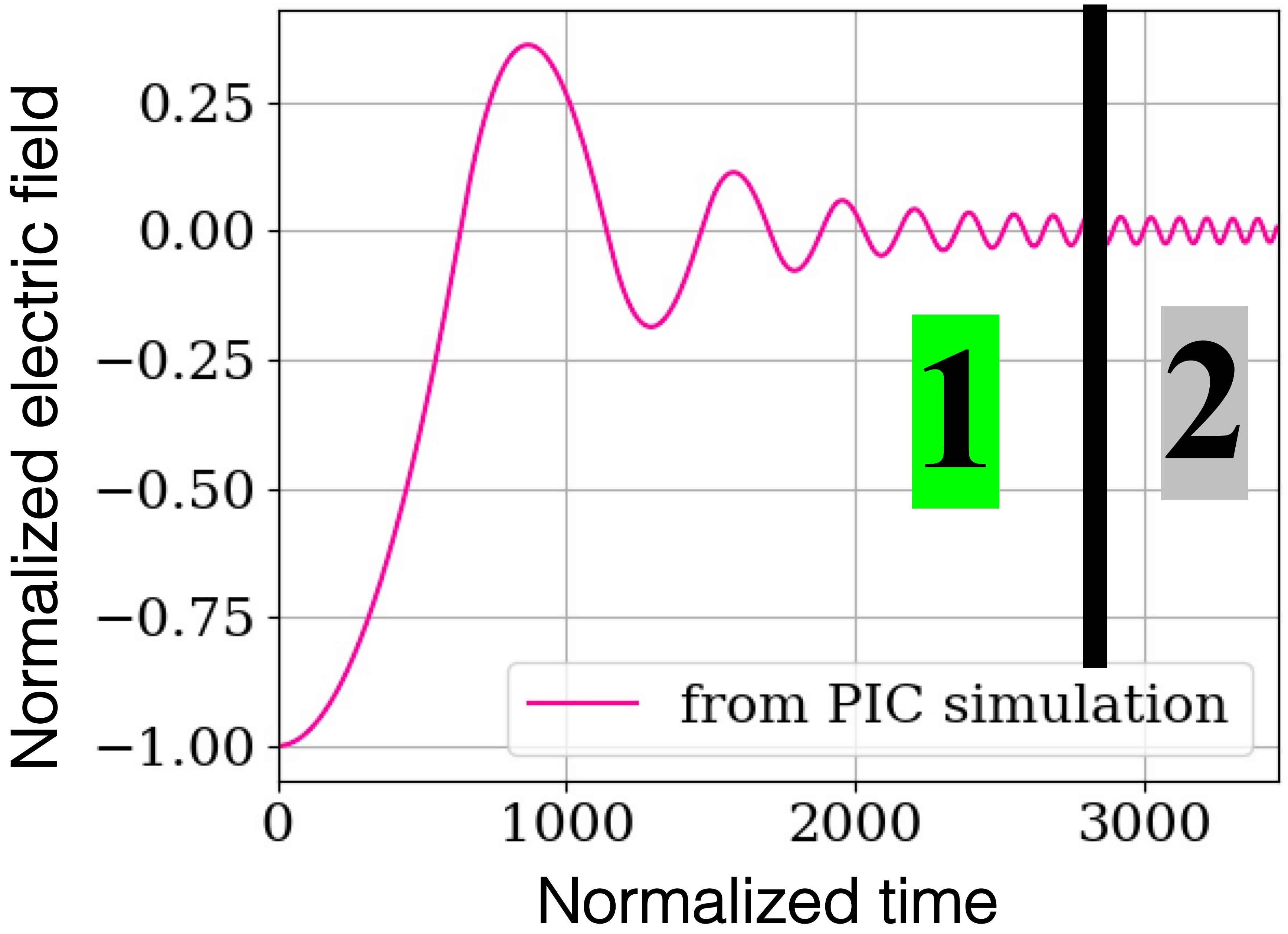
$$\partial_{\hat{t}}^2 \hat{E} + \hat{\omega}^2 \hat{E} = 0$$

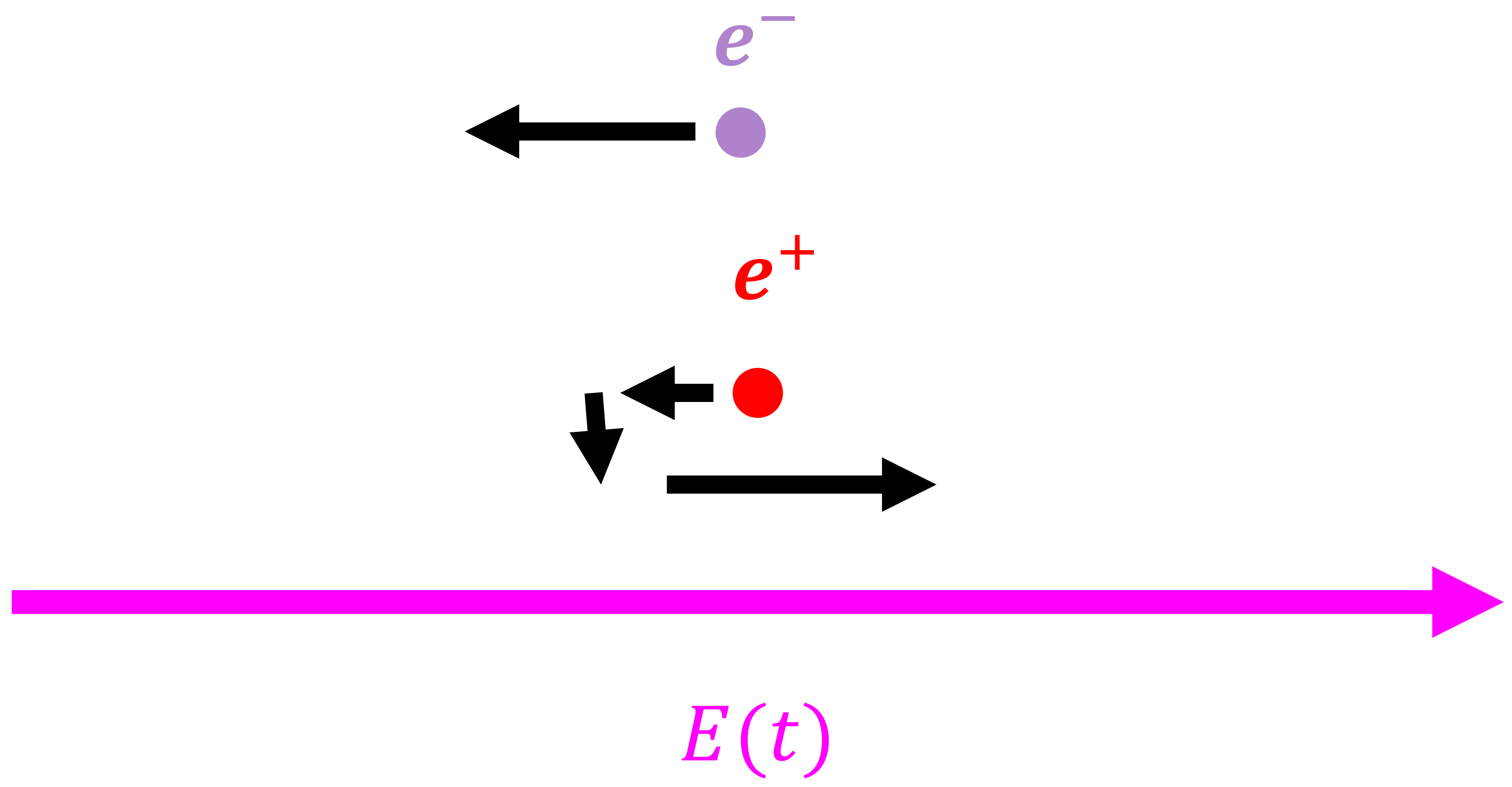
$$\hat{\omega}^2 \propto \hat{n}_+ \left\langle \frac{1}{\gamma^3} \right\rangle$$

Quantity	Definition
$\hat{t}$	normalized time
$\hat{E}$	normalized electric field
$\hat{\omega}$	normalized relativistic plasma frequency
$\hat{n}_+$	normalized positron density

- Spikes in frequency cause damping of E
- Spikes caused by acceleration of pairs added near zeros of E
- See paper for much more

Transition from strong to weak damping gives luminosity





- Strong damping stops when change in pair γ from wave cannot reverse injected pairs

change in pair γ from wave

Injected pair γ

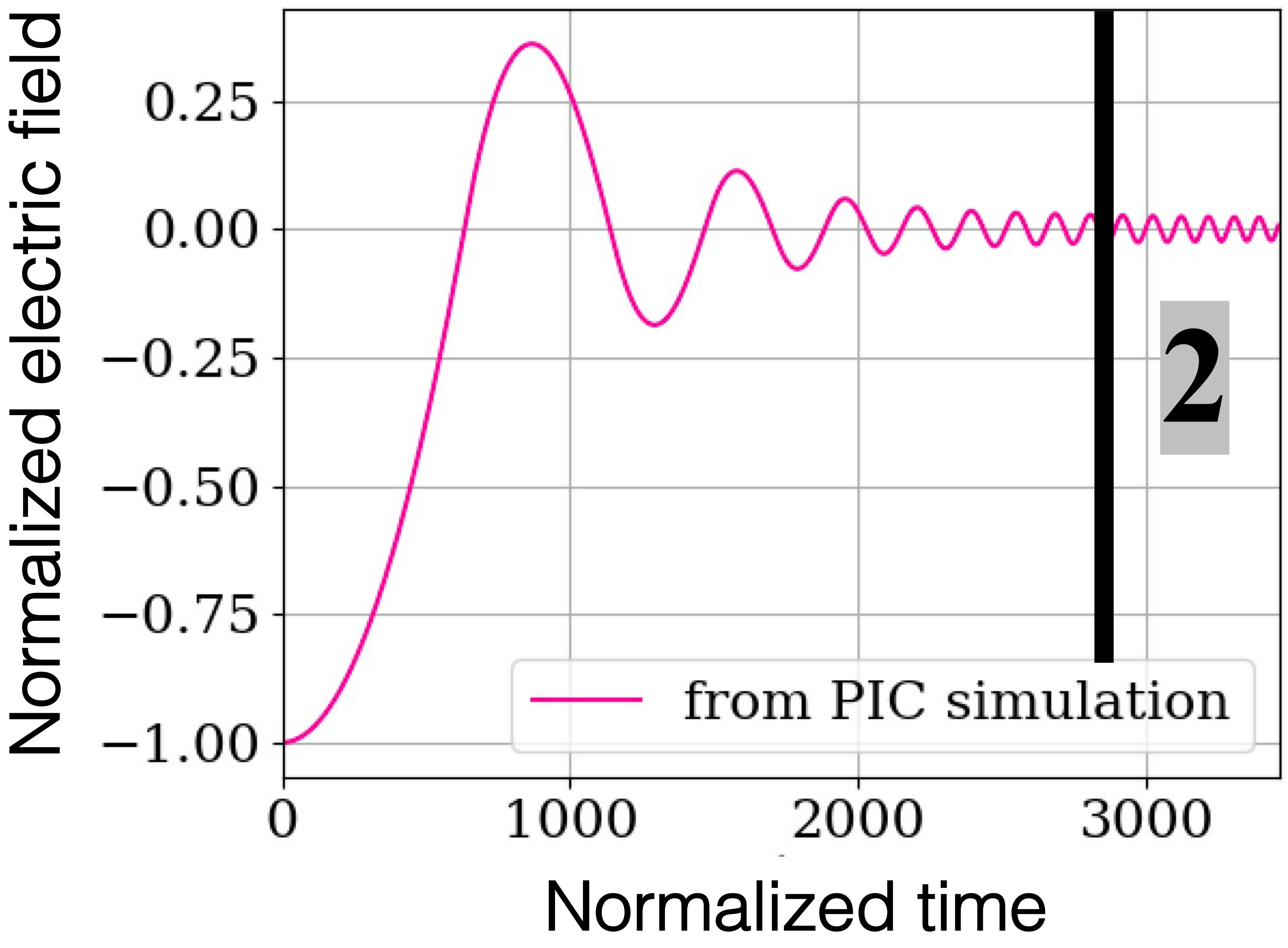
$$\frac{e\,E}{m\,\omega c} \sim 10^2$$

ω in radio

$$E \sim 10^4\ \mathrm{G}$$

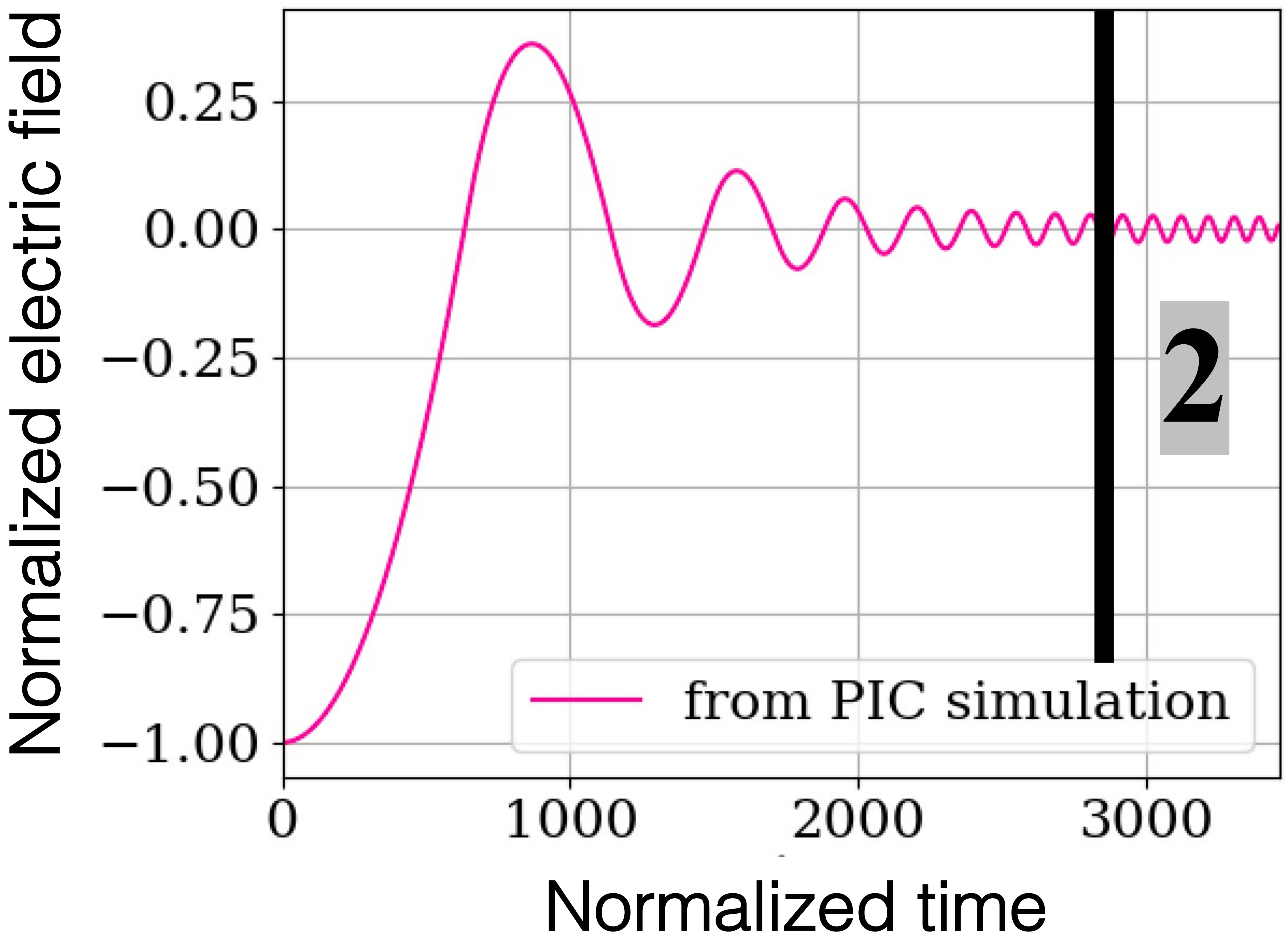
- $cE^2\pi r_{pc}^2 \approx 10^{28}\ \mathrm{erg\,s^{-1}}$: consistent with observed radio luminosity
- Independent of spindown luminosity

Weak damping in linear stage sets pulsar spectrum



- After transition, system enters linear stage during which waves escape as radio emission
- Across polar cap, emission escapes at **different** times with **different** $\hat{E}, \hat{\omega}$
- Relationship between $\hat{E}, \hat{\omega}$ gives spectrum

Weak damping in linear stage sets pulsar spectrum



- After transition, system enters linear stage during which waves escape as radio emission
- Across polar cap, emission escapes at **different** times with **different** $\hat{E}$, $\hat{\omega}$
- Relationship between $\hat{E}$, $\hat{\omega}$ gives spectrum
- $\hat{E}$, $\hat{\omega}$ governed by $\partial_{\hat{t}}^2 \hat{E} + \hat{\omega}^2 \hat{E} = 0$
- Change in $\hat{\omega}$ is slow compared to $\hat{\omega}$
- Applying WKB method gives relationship

$$\hat{E}^2 \sim \hat{\omega}^{-1}$$

- Compare to $S_\omega \sim \omega^{-1.4 \pm 1.0}$

Conclusions

- Pulsar radio emission may be created by electric field screening in polar cap
- Radio luminosity can be understood as transition from nonlinear to linear physics
- Radio spectrum can be understood from linear damping

Based on Tolman, Philippov, and Timokhin, *In preparation*, available shortly on arXiv

For more details, attend Princeton Astroplasmas seminar Dec. 3rd or 10th (date uncertain)

Slides available at elizabethtolman.com

Acknowledgements: I am indebted to an extremely helpful comment on Math StackExchange from user ``DinosaurEgg." This research made use of the ``Tristan-MP v2" particle-in-cell code. We thank Peter Catto, Lev Arzamasskiy, Carolyn Raithel, and Fabio Cruz for helpful conversations. Hayk Hakobyan provided expert advice on code usage. A.P. was supported by NSF grant no. PHY-2010145. A.T. was supported by the grant 2019/35/B/ST9/03013 of the Polish National Science Centre. E.T. was supported by the W. M. Keck Foundation Fund at the Institute for Advanced Study.