Neutrino-cosmic ray connection

The Gamma-Ray Burst (GRB) case

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Contents

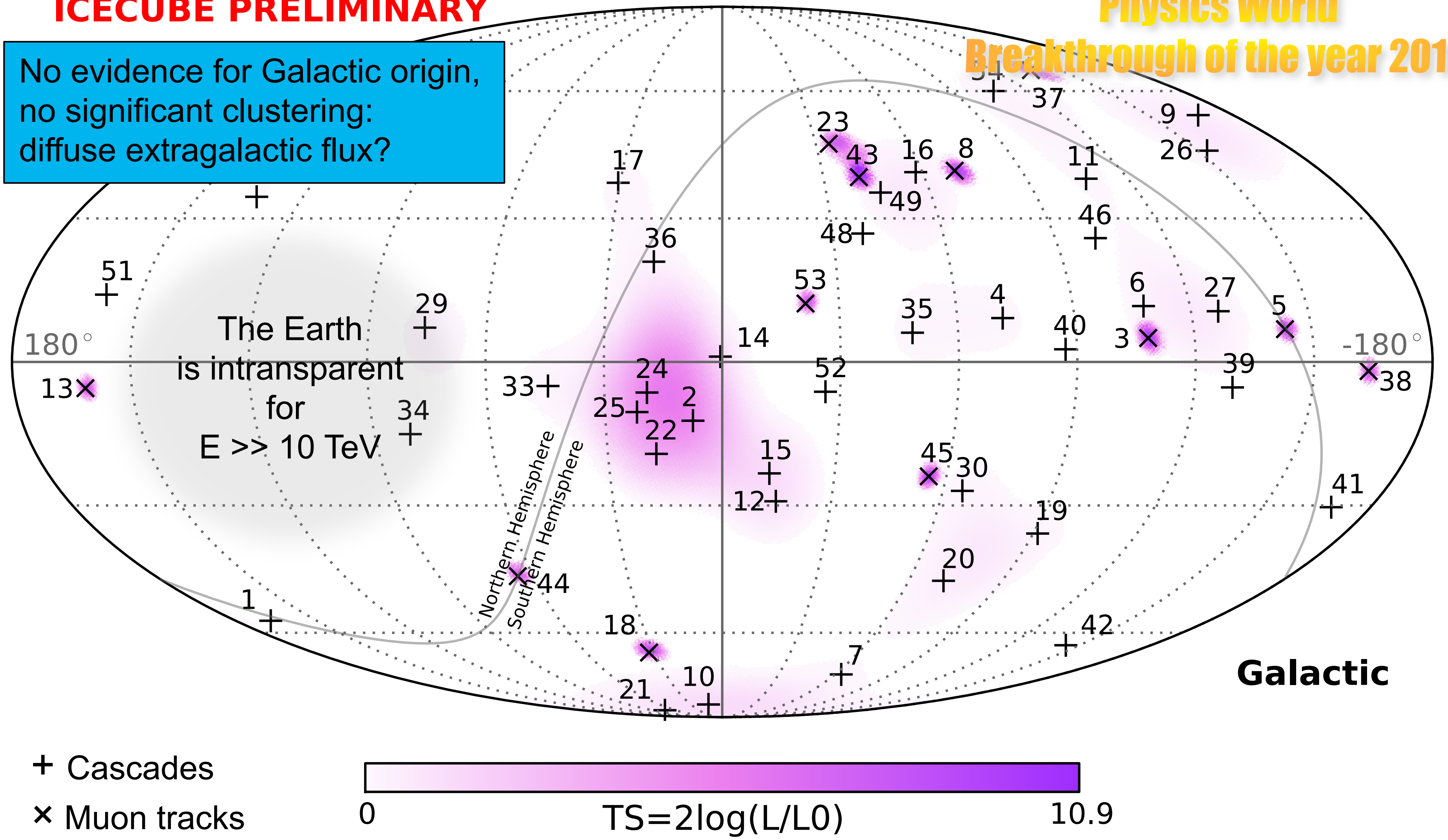
- Introduction
- The “new” TA composition paradigm, and the “old” dip model
- Role of neutrino observations
- Key challenges
  (are more universal, but GRBs used for examples …)
- What if Auger is right?
- Outlook and summary

2015: 54 high energy cosmic neutrinos

ICECUBE PRELIMINARY

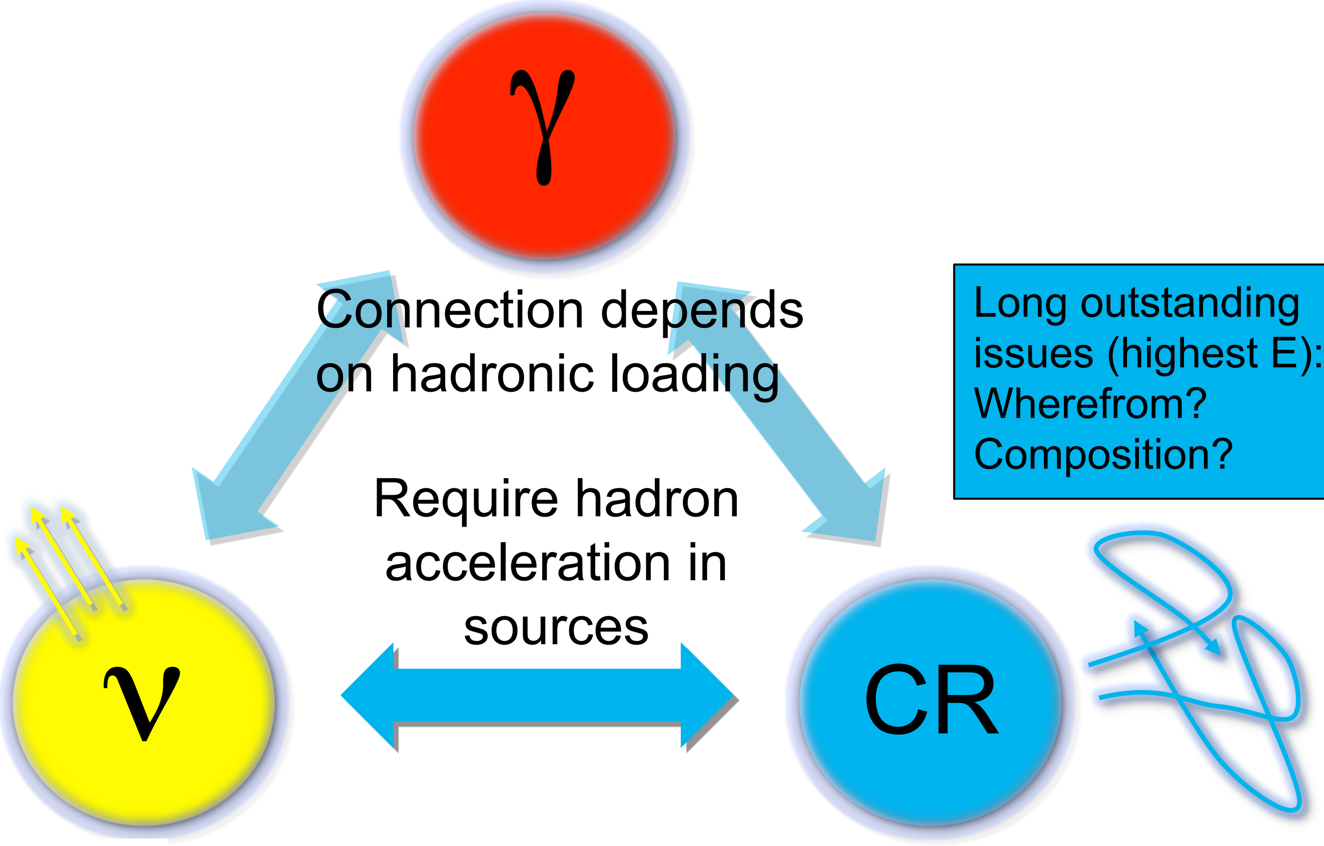
Physics World Breakthrough of the year 2013

No evidence for Galactic origin,
no significant clustering:
diffuse extragalactic flux?



IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); Halzen at WIN 2015

Neutrinos and the origin of the UHECRs (?)

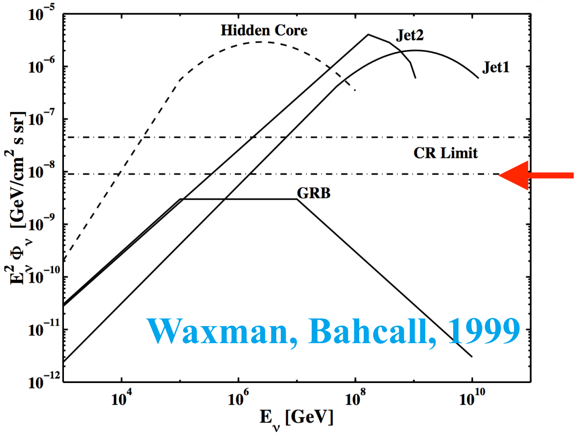


Connection depends on hadronic loading

Require hadron acceleration in sources

The new player in town: New ways to identify the sources of the cosmic rays?!

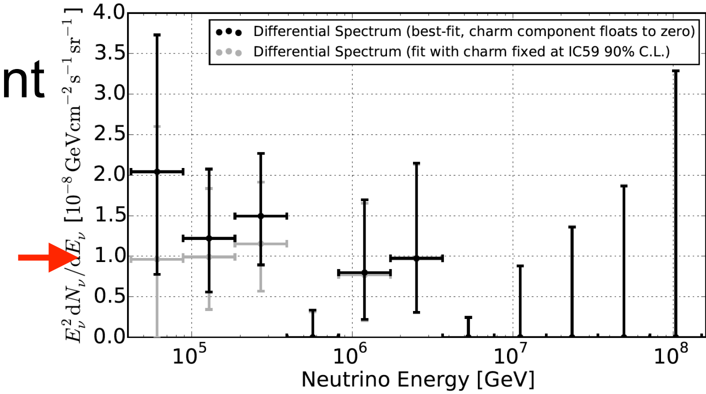
Long outstanding issues (highest E): Wherefrom? Composition?



Waxman, Bahcall, 1999

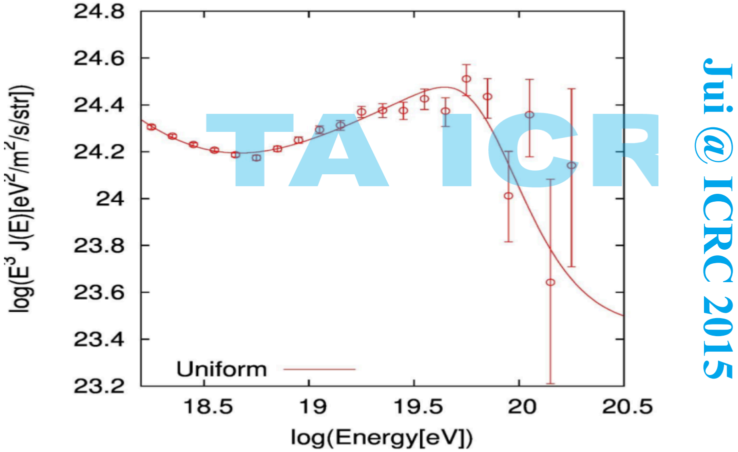
Energy input required to power UHECRs + efficient neutrino production

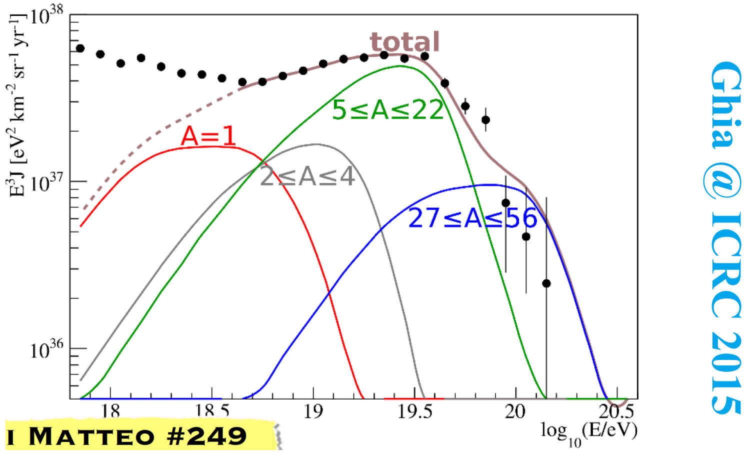
➔ **Waxman-Bahcall bound.** Matches obs.: Coincidence???

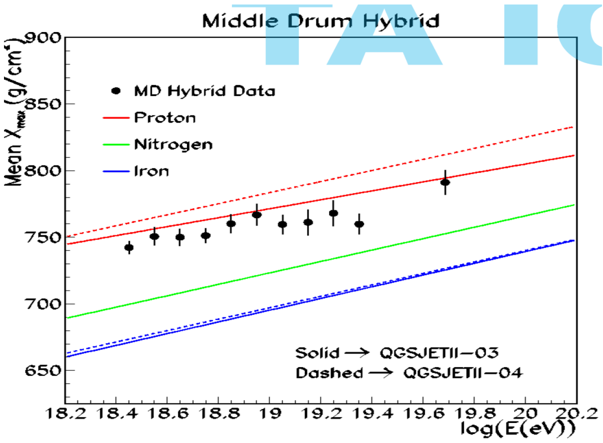


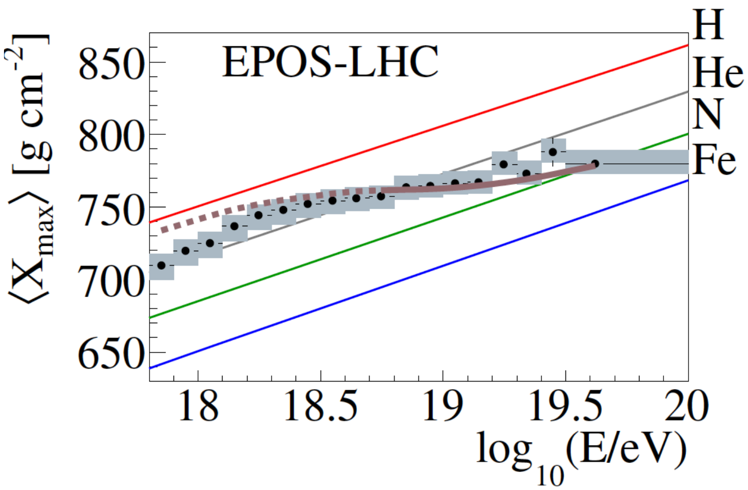
Dip versus "mixed ankle" model:
New theoretical paradigms from ICRC 2015?

TA vs. **Auger**







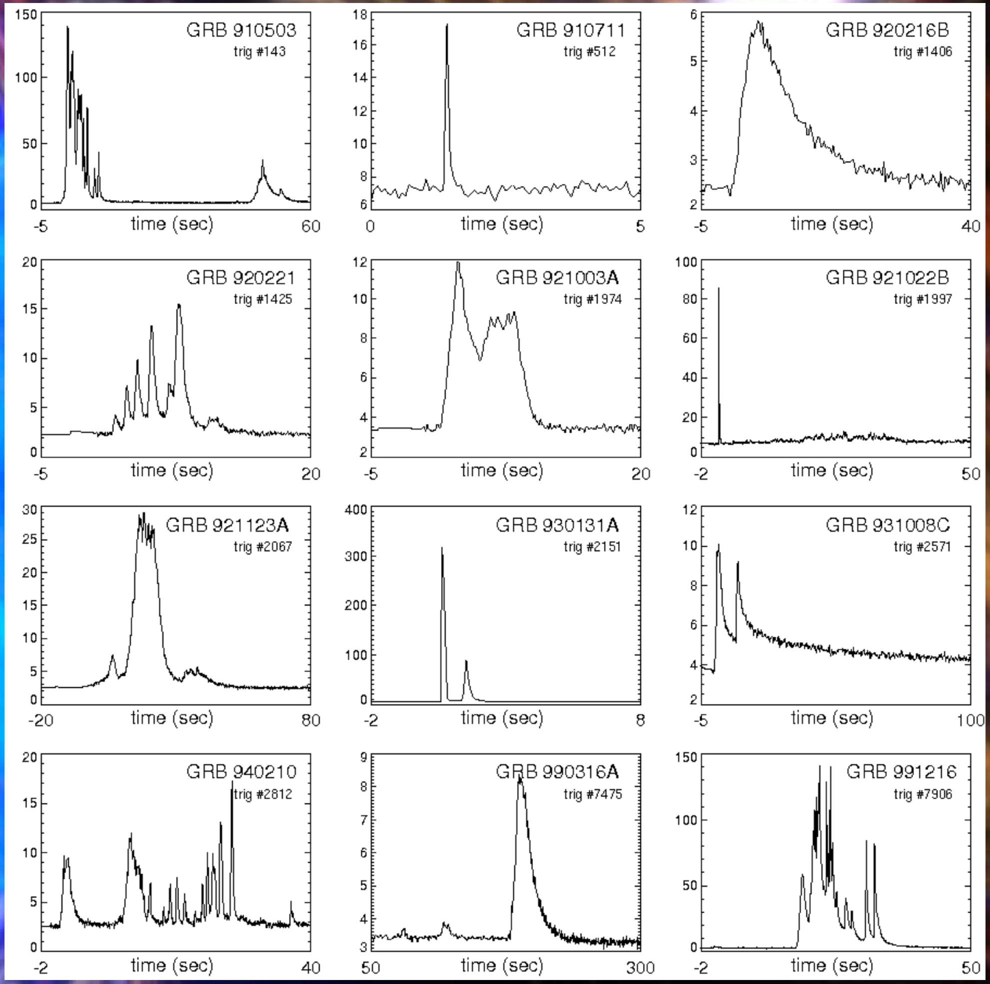


Is this a plausible scenario?
What can neutrinos tell us?
GRBs as a test case

Gamma-ray bursts (GRBs)

- Most energeric electromagnetic (gamma-ray) outburst class
- Several populations, such as
  - Long-duration bursts (~10 – 100s), from collapses of massive stars?
  - Short-duration bursts (~ 0.1 – 1 s), from neutron star mergers?
- Observed in light curves come in large variety →

Daniel Perley

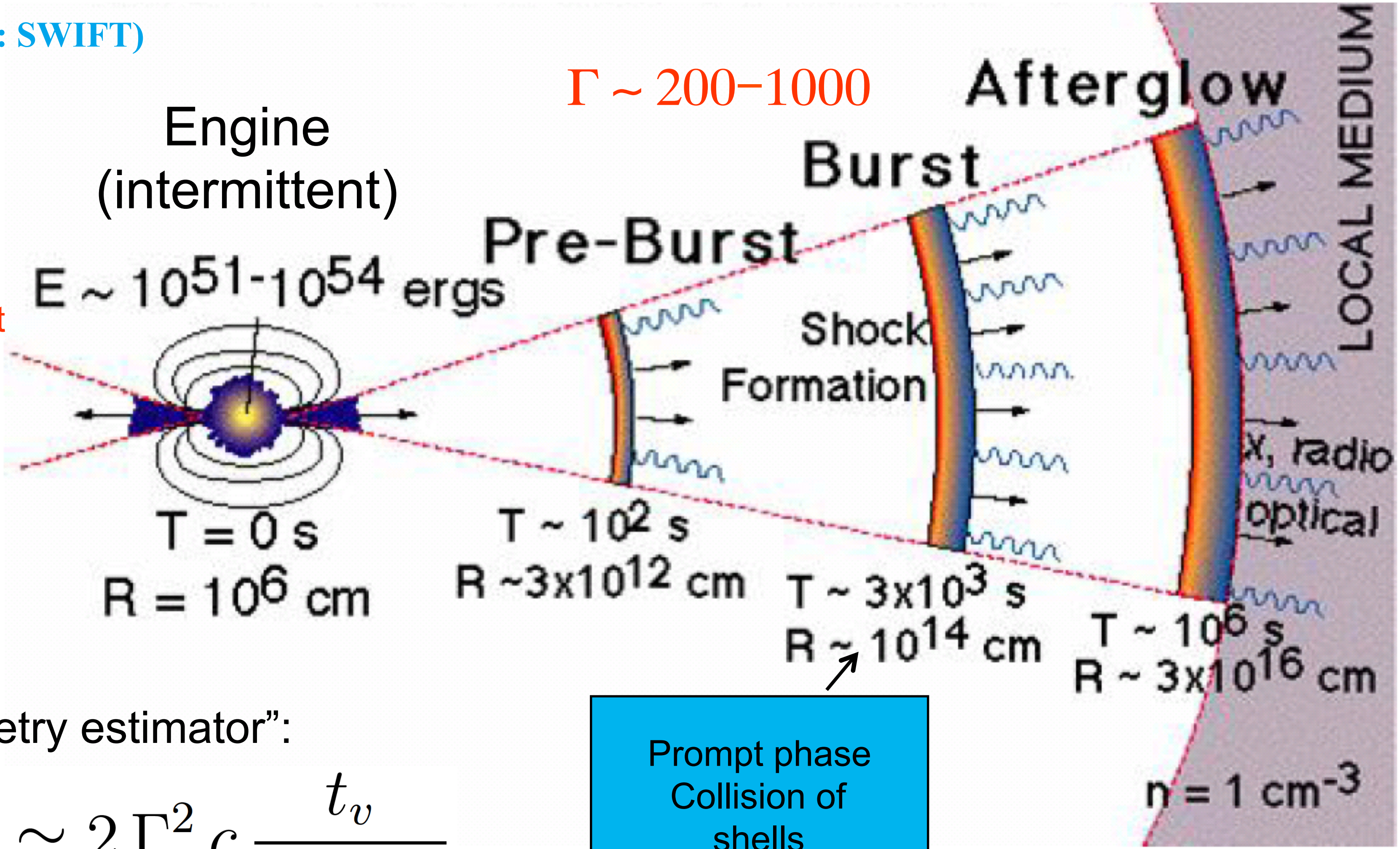


Source: NASA

GRB - Internal shock model

(Source: SWIFT)

$\Gamma \sim 200\text{–}1000$



“Isotropic equivalent energy“

“Geometry estimator”:

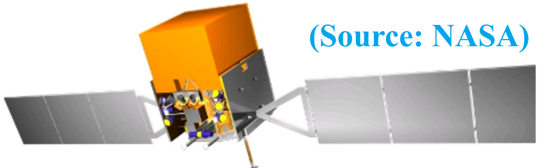
$$R_C \simeq 2\,\Gamma^2\,c\,\frac{t_v}{(1+z)}$$

t_v: variability timescale
Γ: Lorentz boost

Prompt phase
Collision of
shells
⇨ Shocks
⇨ Particle acc.

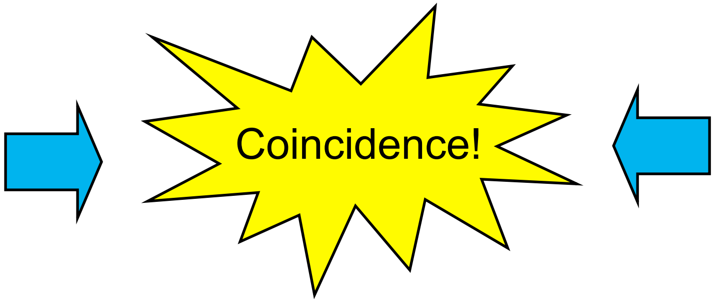
How about neutrinos from long gamma-ray bursts?

- Idea: Use timing and directional information to suppress atm. BGs

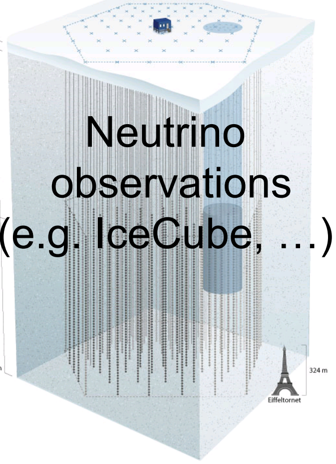


(Source: NASA)

GRB gamma-ray observations
(e.g. Fermi, Swift, etc)



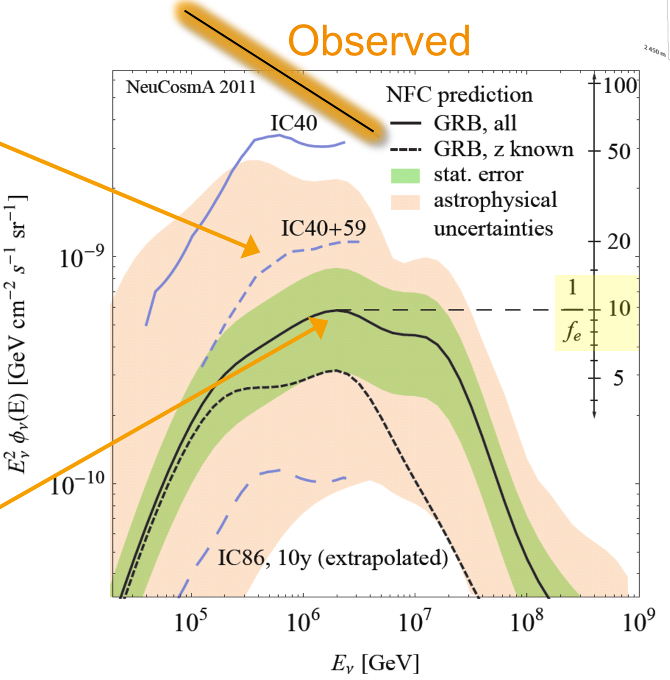
Coincidence!



Neutrino
observations
(e.g. IceCube, …)

(Source: IceCube)

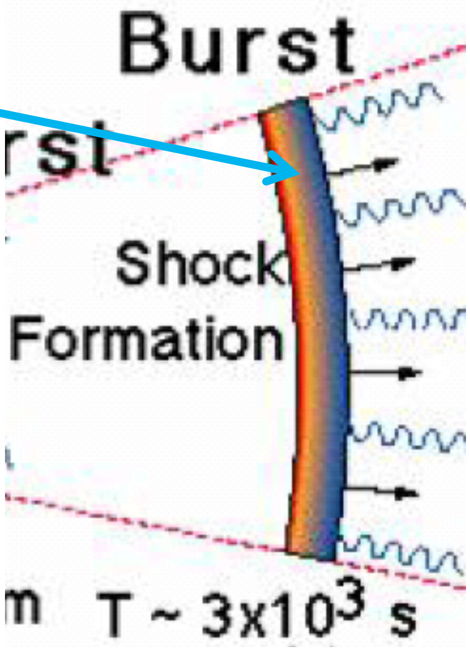
- Strong constraints from GRB stacking
  IceCube, Nature 484 (2012) 351;
  see arXiv:1412.6510 for update
- Not the dominant source of observed diffuse ν flux!
- Current limit close to prediction **from gamma-rays**; however: many assumptions
  (e.g. **baryonic loading f_e^{-1}**, Γ, z)



(Hümmer, Baerwald, Winter, PRL 108 (2012) 231101)

From gamma-ray to the neutrino flux (logic)

- Need particle densities in source
- Logic (crudely):
  - z ➔ distance
  - F_γ ➔ $L_{\gamma,\mathrm{iso}}$ (erg/s) in gamma-rays
  - Γ, t_v ➔ Volume of region
  - Ratio energy/volume: photon (energy) density
  - Proton energy density ~ photon energy density x **baryonic loading f_e^{-1}**



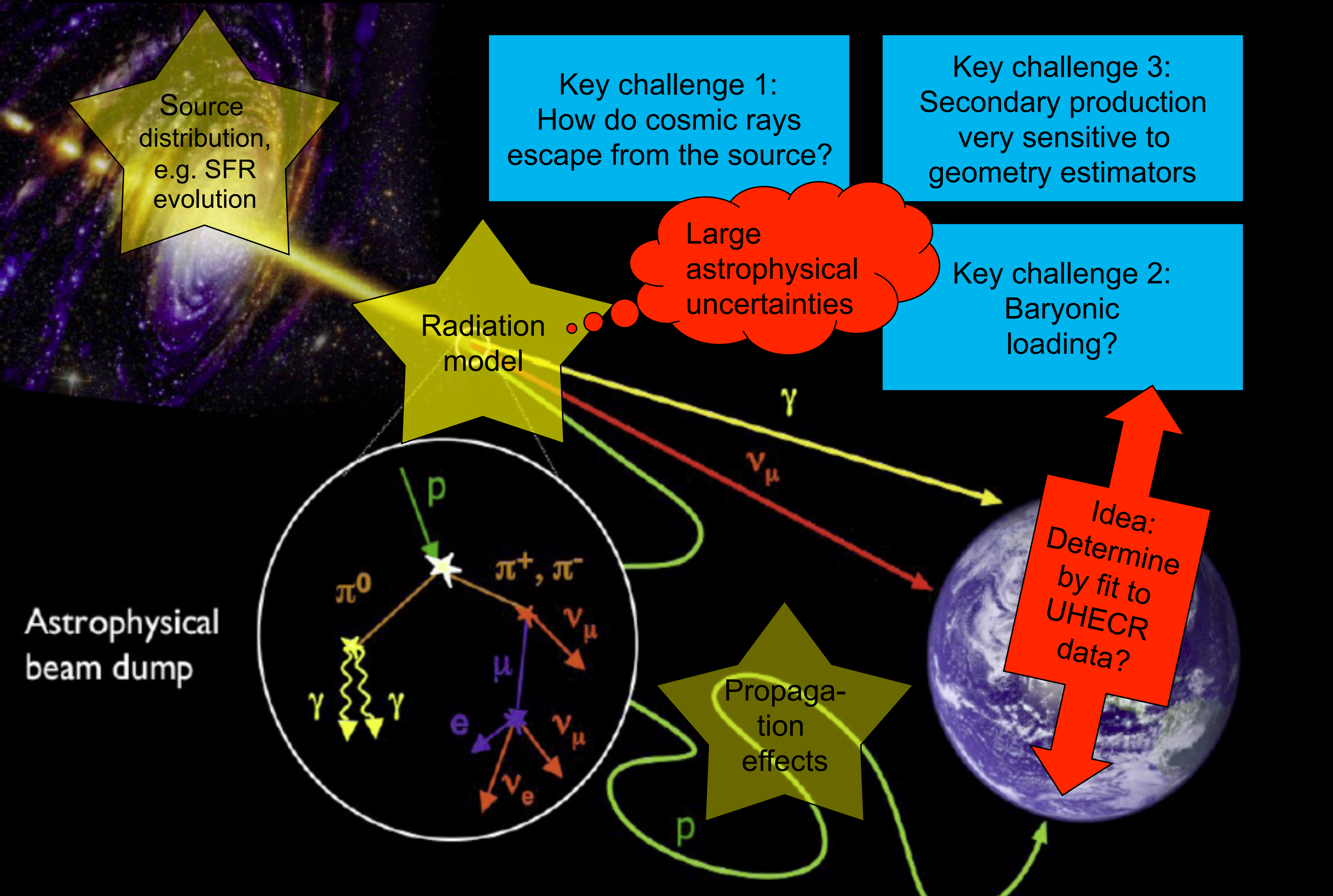
- Pion production efficiency (fraction of energy, a proton loses into pions) strongly depends on Γ because of geometry estimate

$$f_\pi(\varepsilon_p) \sim 0.2 \frac{L_{\gamma,52}}{\Gamma_{2.5}^4 t_{v,-2} \varepsilon_{\gamma,\mathrm{MeV}}^b}$$

Guetta et al, Astropart. Phys. 20 (2004) 429

- Number of protons scales directly with f_e^{-1}

Combined source-propagation models: ν-γ-UHECRs



Source distribution, e.g. SFR evolution

Key challenge 1:
How do cosmic rays escape from the source?

Key challenge 3:
Secondary production very sensitive to geometry estimators

Large astrophysical uncertainties

Radiation model

Key challenge 2:
Baryonic loading?

Idea: Determine by fit to UHECR data?

Propaga-tion effects

Key issue 1: How do cosmic rays escape from the source?

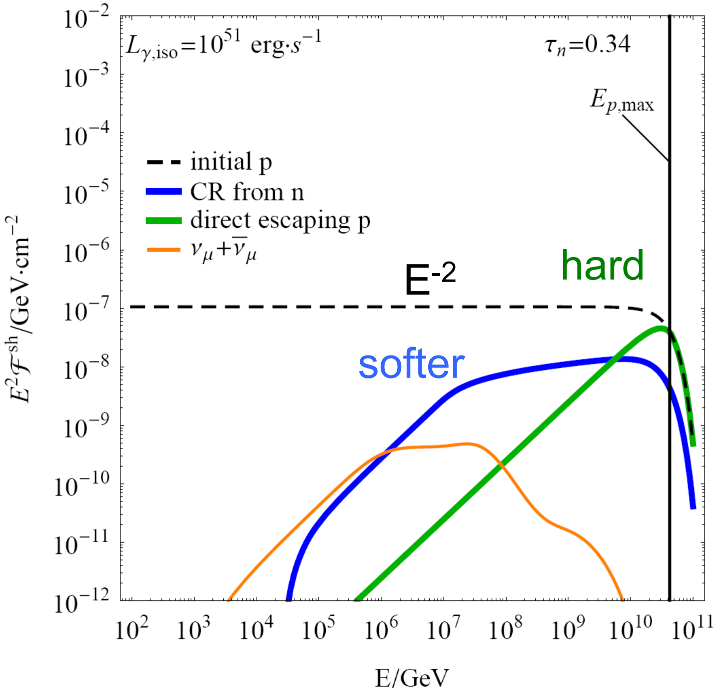
Three extreme cases:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \left\{ \begin{array}{l} n + \pi^+ \\ p + \pi^0 \end{array} \right.$$

- **Neutron model**
  Neutrinos and cosmic rays (from neutrons) produced together
  (depends on pion prod. efficiency, blue curve, softer)
  (pure neutron model excluded in IceCube, Nature 484 (2012) 351)

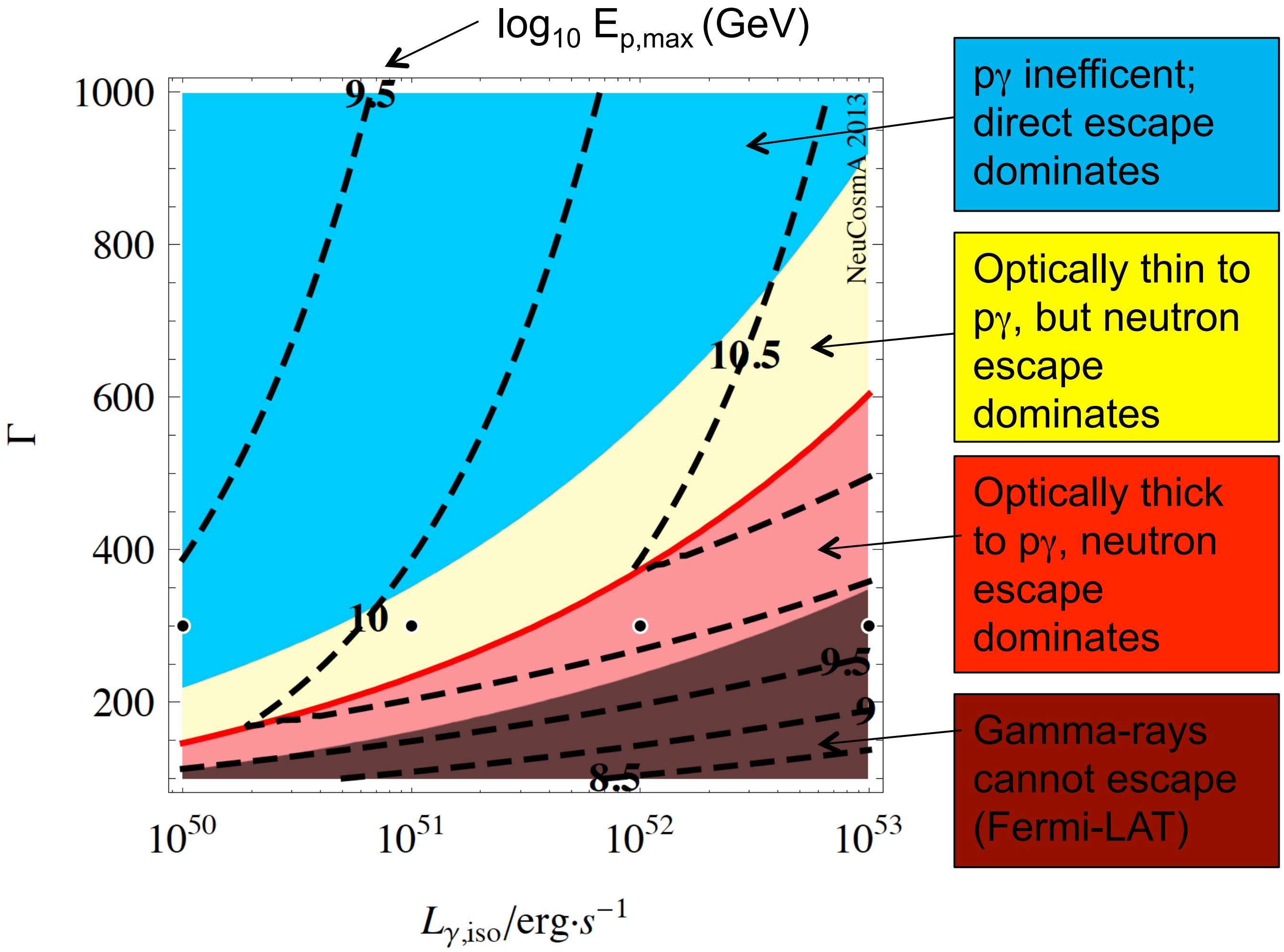
- **Direct escape** (aka "high pass filter", "leakage")
  Cosmic rays can efficiently escape if Larmor radius reaches size of shell width
  (conservative scenario, green curve, hard)
  (from:Baerwald, Bustamante, Winter, ApJ 768 (2013) 186; same argument used for nuclei in Globus et al, 2014)

- **"All escape"**: magnetic fields decay quickly enough that charged cosmic rays can escape
  (most aggressive scenario, dashed curve, ~ E^{-2})



Dependence of escape mechanism on shell parameters

- Escape mechanism depends on shell parameters
- Direct escape dominates if neutrino production is inefficient
- In fact, same model, only different parameters!



$\log_{10} E_{p,\max}$ (GeV)

pγ inefficent; direct escape dominates

Optically thin to pγ, but neutron escape dominates

Optically thick to pγ, neutron escape dominates

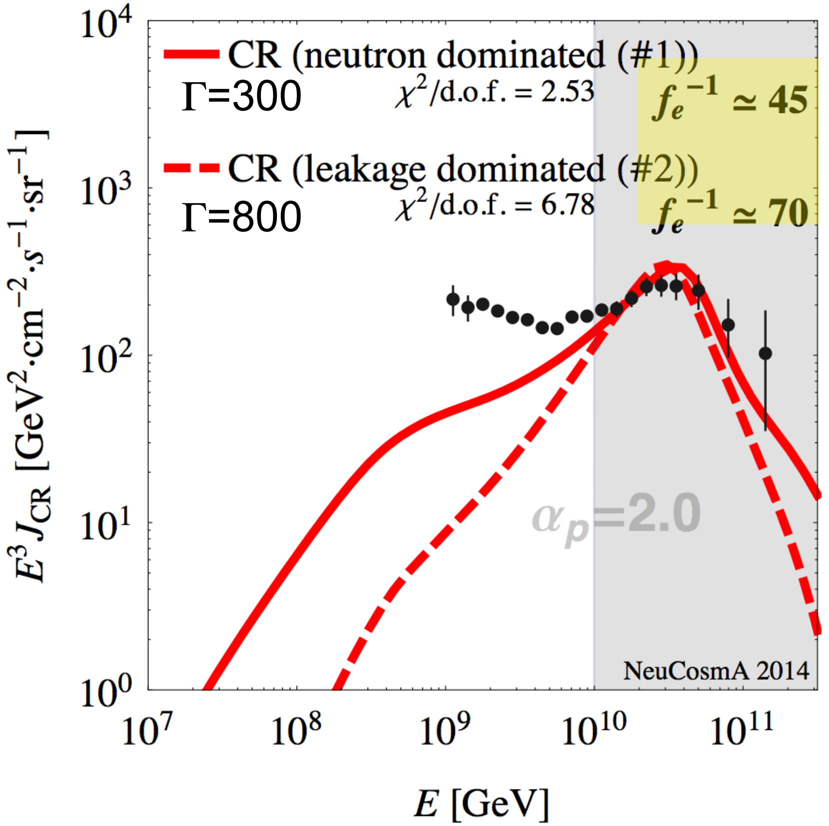
Gamma-rays cannot escape (Fermi-LAT)

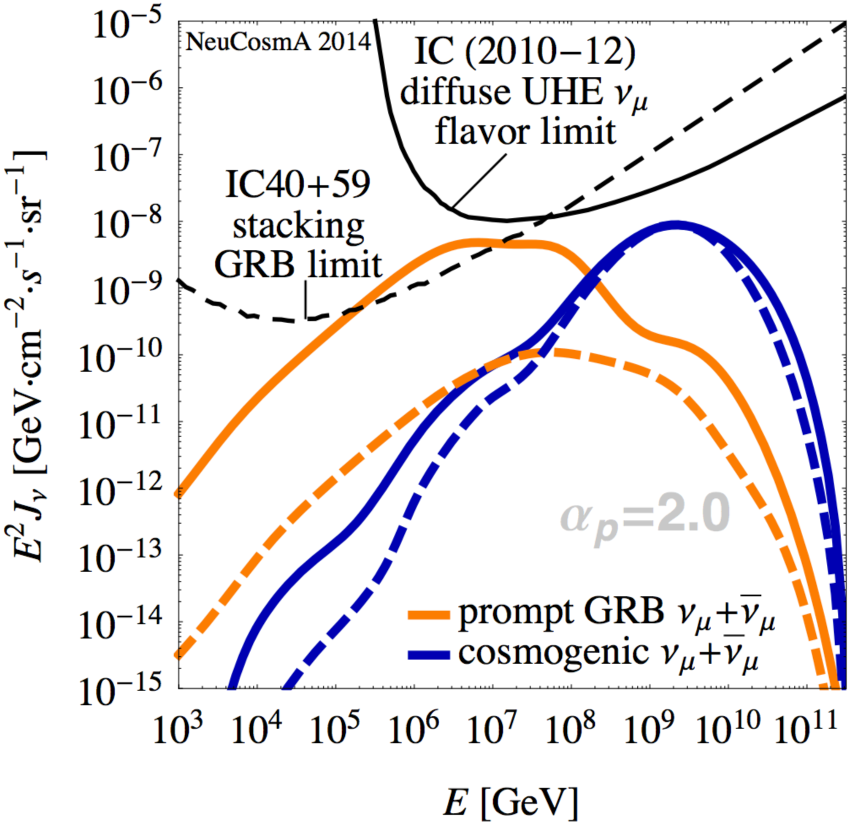
η=0.1

Baerwald, Bustamante, Winter, ApJ 768 (2013) 186

Key issue 2: Baryonic loading. Example: ankle model, TA

- Baryonic loading (f_e^{-1}) is obtained by the fit to UHECR data (no input!)
- GRBs can be the sources of the UHECRs for reasonable f_e^{-1}





Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66; here figures with TA data

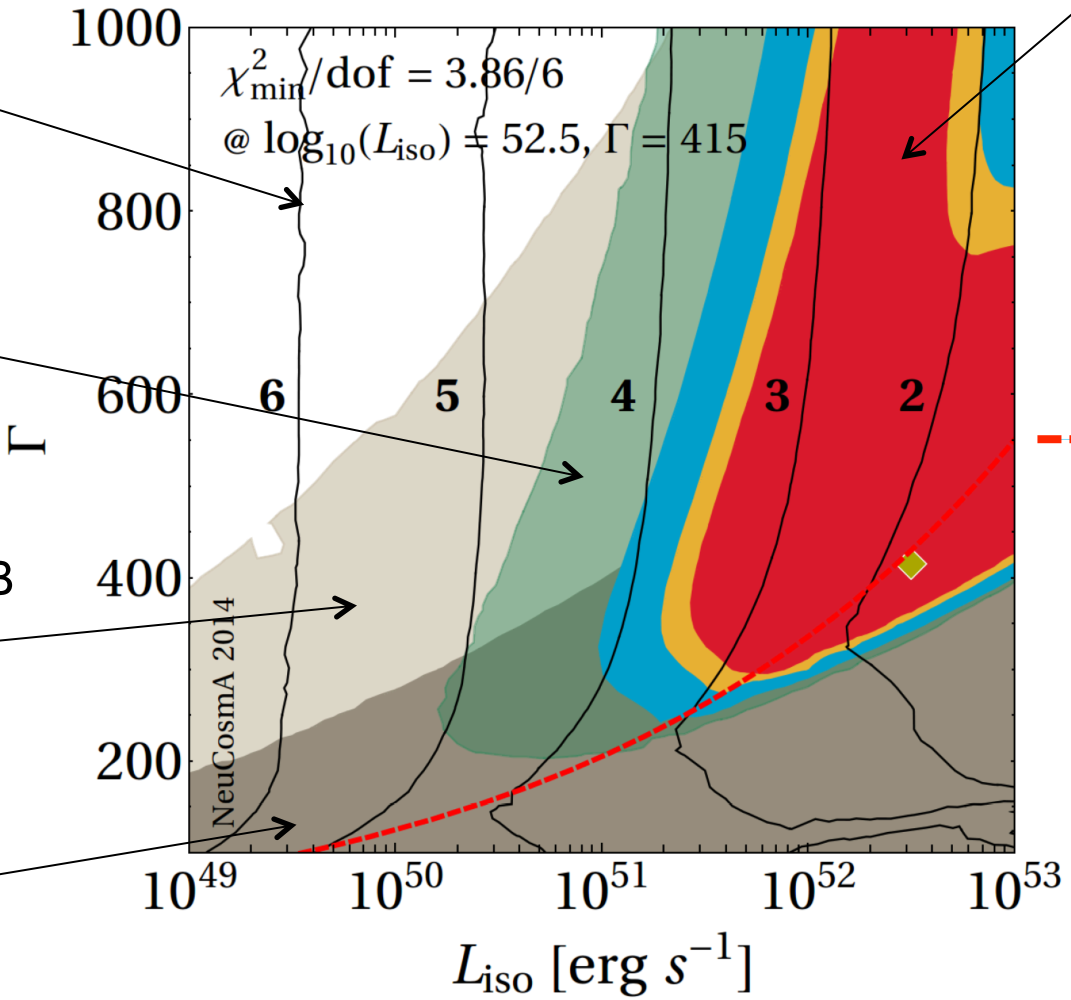
UHECR fit of ankle model: the power of (future) ν data

Baryonic loading $\log_{10} f_e^{-1}$

IceCube cosmogenic searches (15 years)

IceCube GRB stacking (15 years)

IceCube excluded (current);



UHECR fit (TA)

Direct escape significant

Neutron model dominates

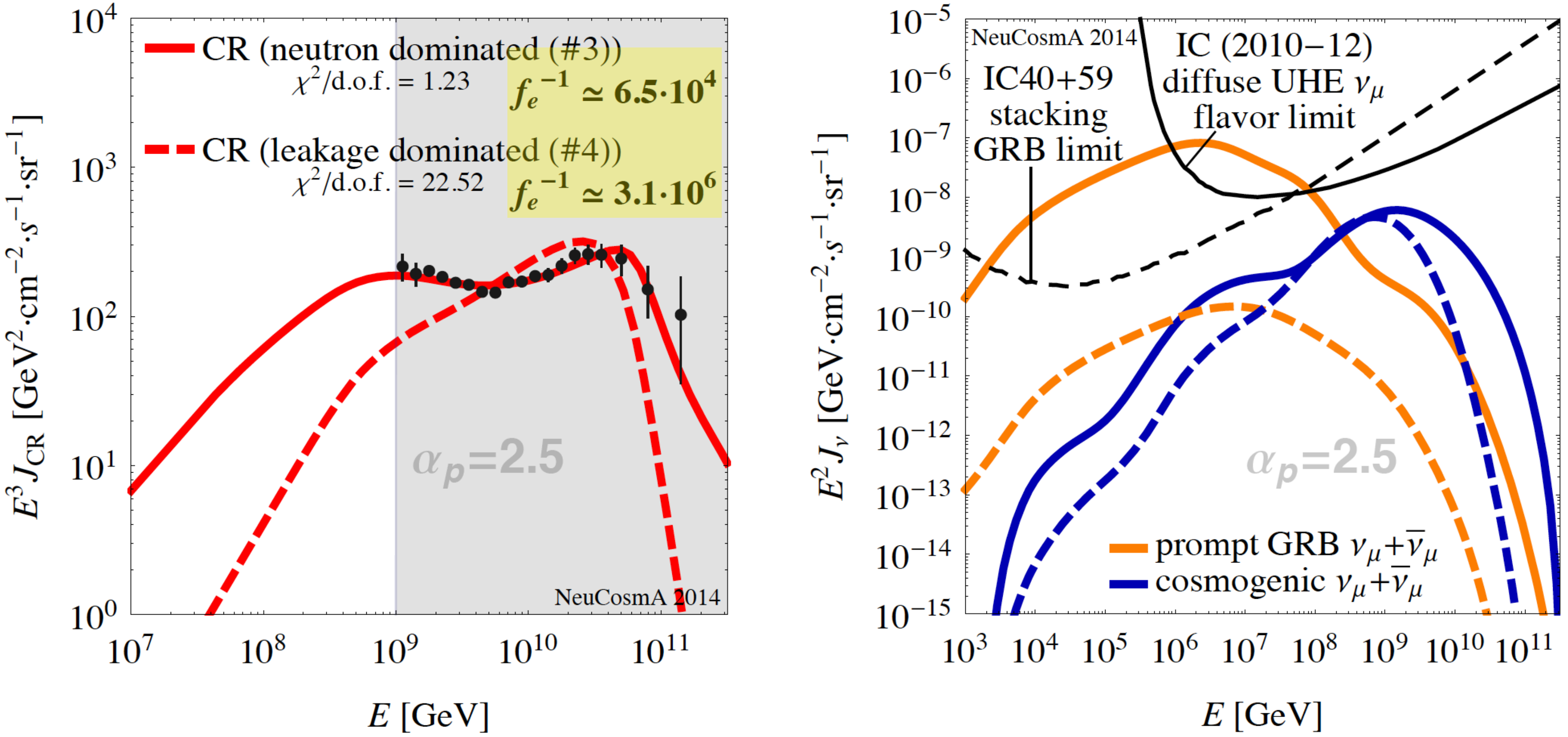
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

η=0.1

Neutron model ruled out! Neutrinos test UHECR escape mechanism!

The new TA paradigm: dip model for protons?

- Either ruled out by neutrino data, or poor UHECR fit
- Apart from that, excessive (unrealistic?) baryonic loadings

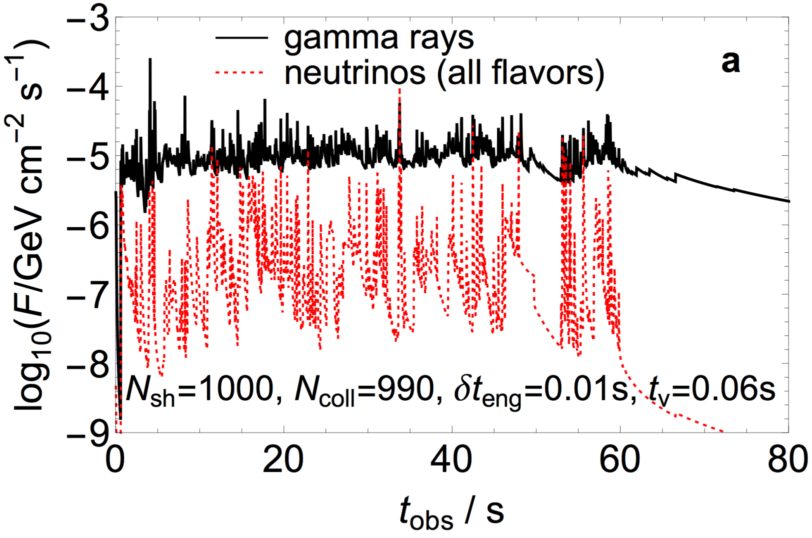


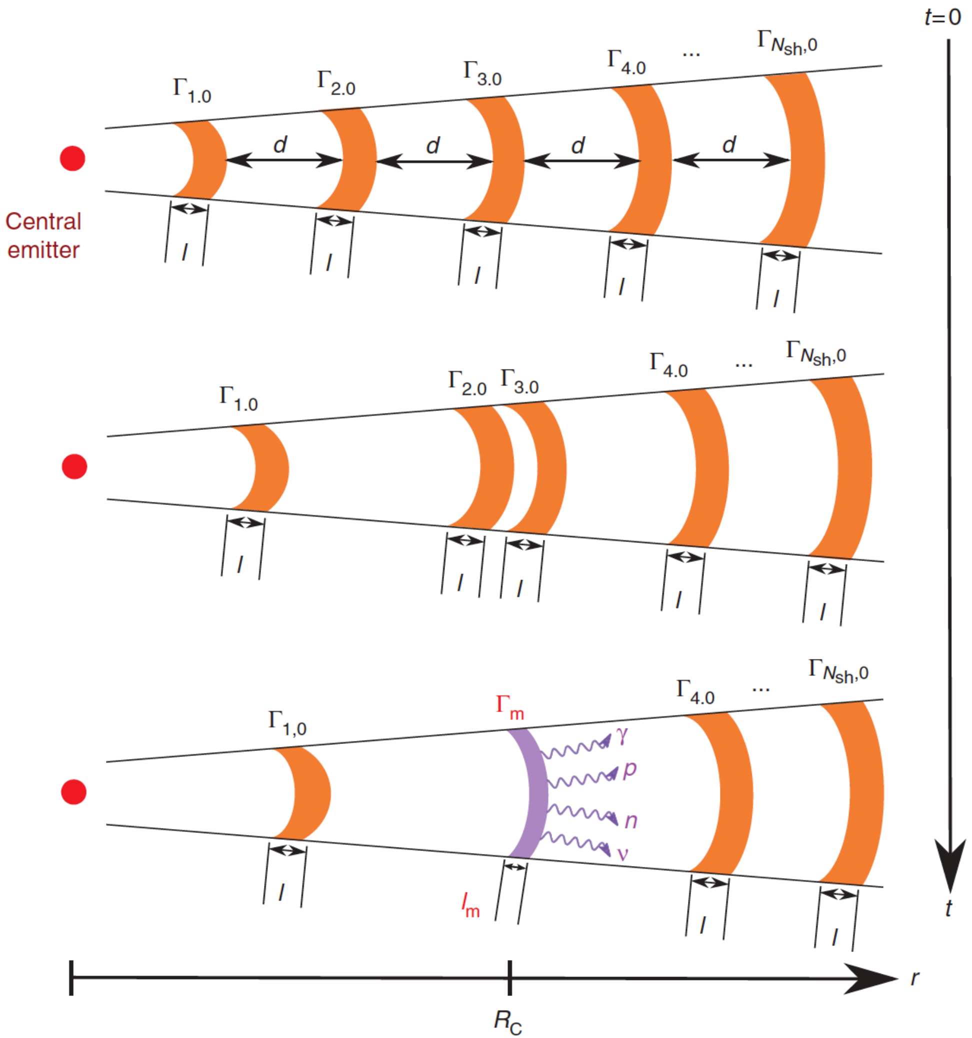
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66; here figures with TA data

Key issue 3 (sensitivity to geometry estimators)

Back to the roots: use multiple collision zones

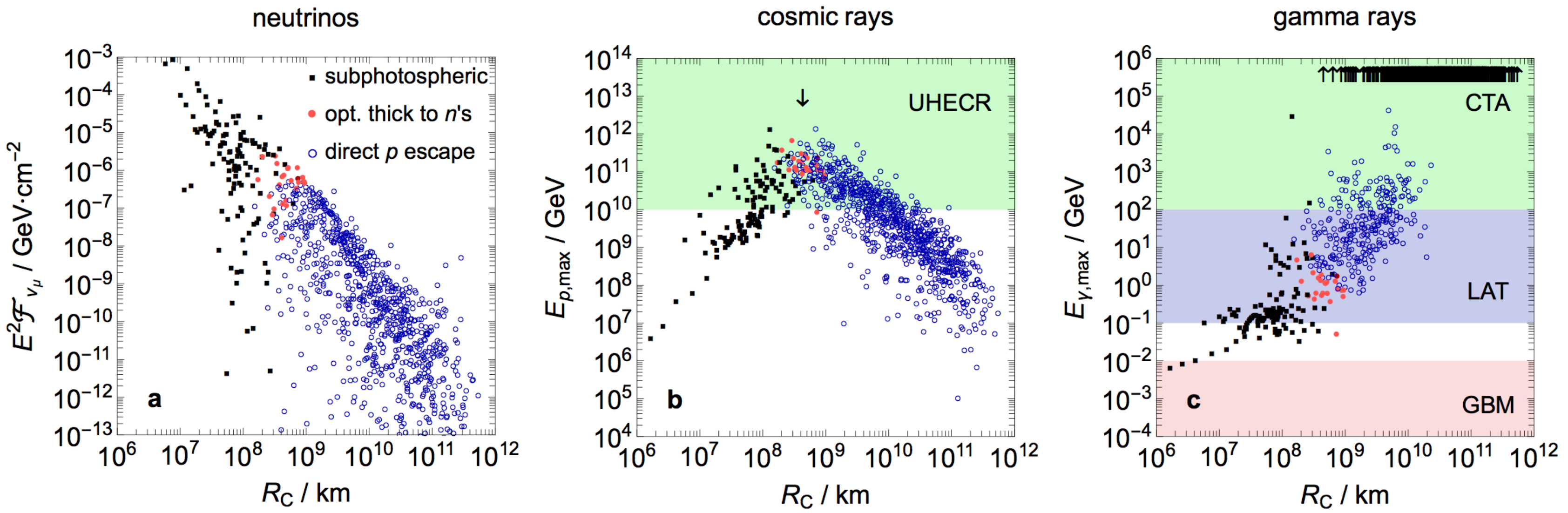
- Set our shells with Γ distribution
- The light curves can be predicted as a function of the engine parameters
- Efficient energy dissipation (conversion from kinetic to radiated E) requires broad Γ distribution
- Consequence: Collsions radii are widely distributed!



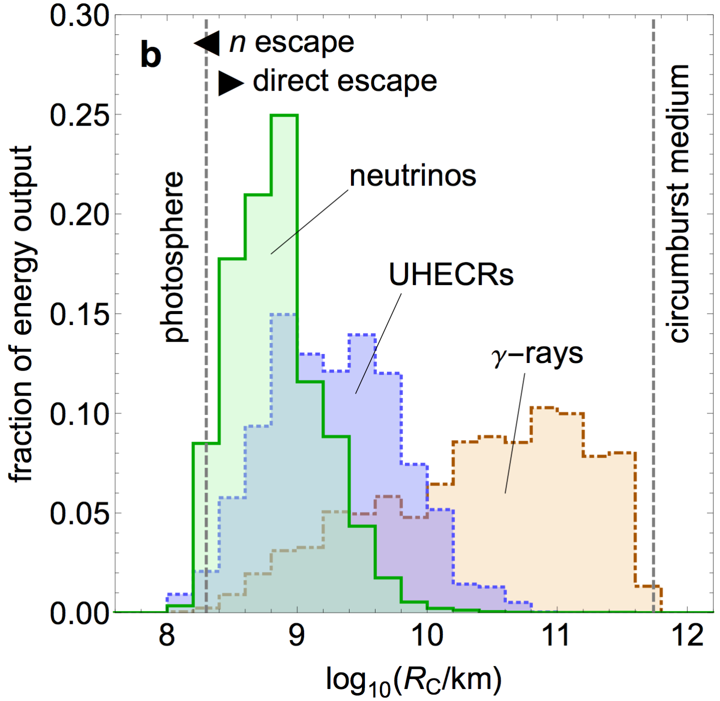


From: Bustamante, Baerwald, Murase, Winter, Nat. Commun. 6, 6783 (2015)

Consequences for multiple messengers



- The different messengers originate from → different regimes of the GRB *where the densities are very different*
- The "one zone approximation" is insufficient for multi-messenger studies



Bustamante, Baerwald, Murase, Winter,
Nat. Commun. 6, 6783 (2015)

Consequences for neutrino production

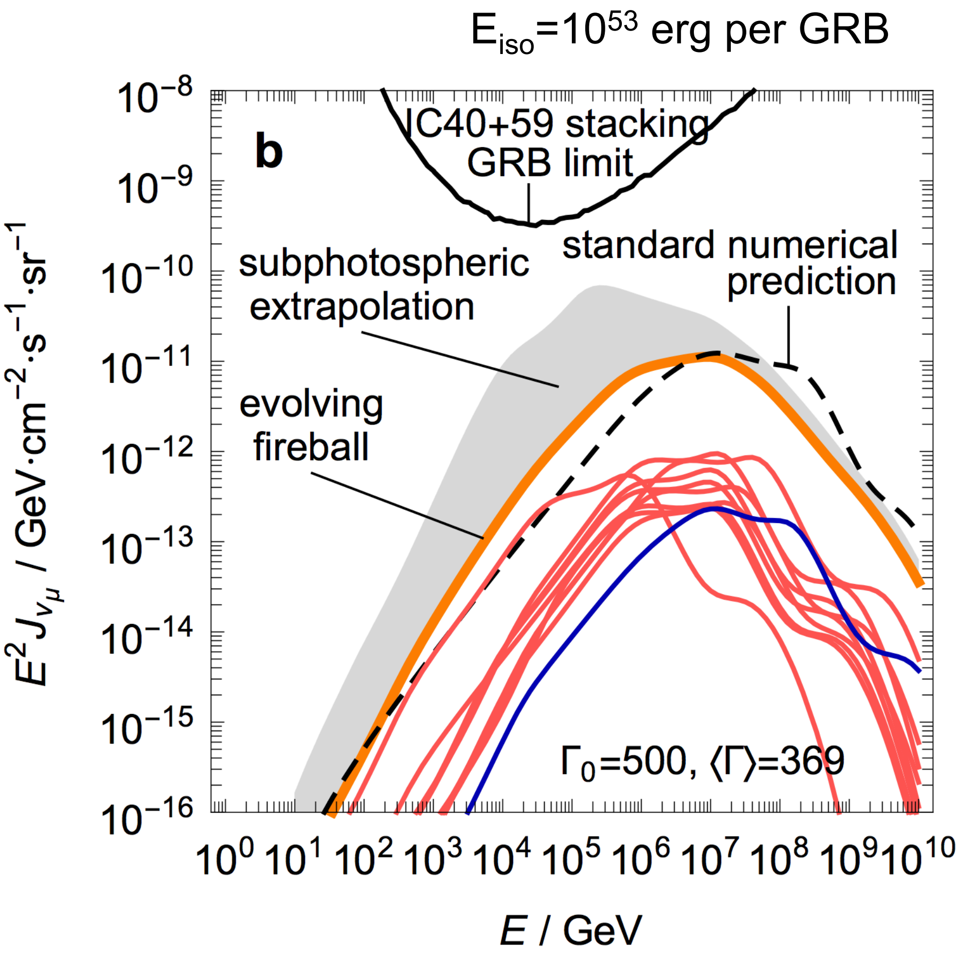
- Logic: can only use **observed** gamma-rays to predict "guaranteed" neutrino flux. These come from beyond the photosphere

  Therefore, this minimal neutrino flux is dominated by a few collisions just beyond the photosphere (red)

- **$E^2\,\phi \sim 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1}**

- This prediction is robust
  (hardly depends on Γ, baryonic loading)
  because photosphere and optical depth to pγ scale in same way with particle densities

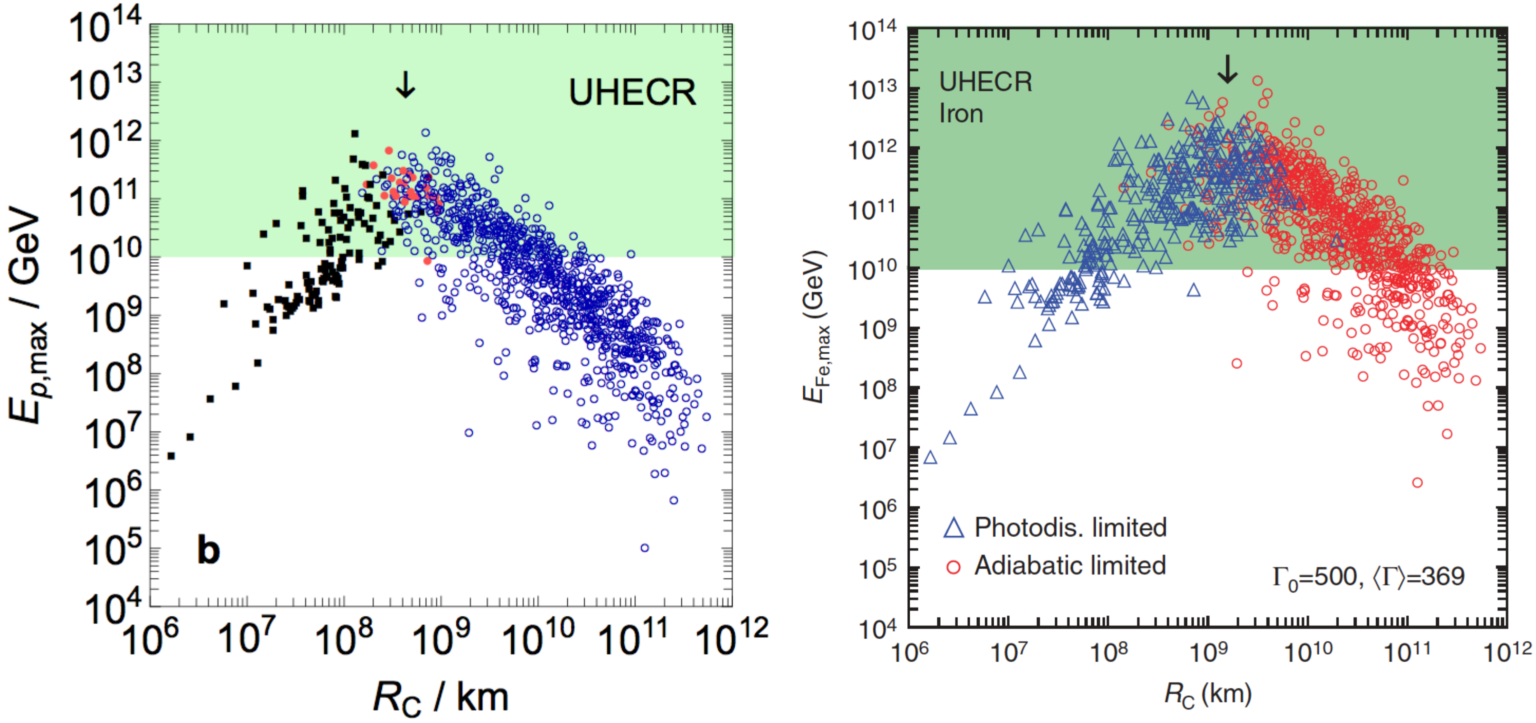
- **Moderates key challenge 3**



Bustamante, Baerwald, Murase, Winter, Nat. Commun. 6, 6783 (2015)

What if … Auger is right?

- By the same logic, UHECR nuclei can escape from regions where photon densities are lower (relavant R_C somewhat larger)



η=1

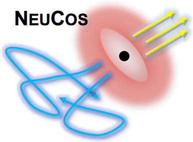
Bustamante, Baerwald, Murase, Winter, Nat. Commun. 6, 6783 (2015); arxiv:1409.2874

- Can describe Auger observations: see **Globus et al, arXiv:1409.1271, arXiv:1505.01377 (talk by Allard?)**

Outlook: current and future questions

Theory

- Dip model in multiple collision approach?
- Better understanding of UHECR escape mechanisms
  (= in practice connected with simulation of mildly relativistic shocks)
- Neutrino production in models with heavier nuclei.
  Challenges:



  - How long are specific isotopes in system? Pion production? Parameter dependencies?
  - Neutrino production may be dominated by isotopes sub-dominat for CRs
  - Role of emission near photosphere?
- Better models for individual GRBs from multi-messenger signals
  (GBM, LAT, CTA, IceCube)
- Role of cosmogenic neutrinos?

Experiment

- Role/reach of IceCube-Gen2?
- Auger versus TA composition

Summary and conclusions

- GRBs can be the sources of the UHECRs in perfect consistency with neutrino data in (proton) ankle model
- Dip model does not work in one zone approach.
  Generic problems: in conflict with neutrino data, high baryonic loadings
- Key challenges (theory):
  - *How do cosmic rays escape from the sources?*
    So far, good estimates, need better simulations
  - *Baryonic loading?*
    Can be determined from UHECR fits. What are realistic values?
  - *Strong sensitivity on geometry estimators ➔ astrophysical uncertainties*
    Can be moderated if multi-zone collision models, more careful comparison to/modeling of individual objects etc
- However: although qualitatively applicable to other object classes+heavier nuclei, detailed physics depends on astrophysical object class and chosen parameters

BACKUP

Why is the new GRB prediction robust?

- Neutrino flux comes from a few collisions at photosphere
- Photospheric radius (➔Thomson optical depth) and photohadronic interactions both depend on particle densities (scale in same way)
- Consequence: Pion production efficiency **at photosphere** does not depend on Γ:

$$f_{p\gamma}^{\mathrm{ph}} \sim 5 \times \frac{\varepsilon}{0.25} \times \frac{\epsilon_e}{0.1} \times \frac{1\,\mathrm{keV}}{\epsilon'_{\gamma,\mathrm{break}}}$$

(ε: overall dissipation efficiency: dissipated/initial kinetic energy)

- Changing the ener ts results (if baryons domina

$$\mathcal{F}_\nu \propto \frac{N_c}{\quad} \times E_{\mathrm{iso}}$$

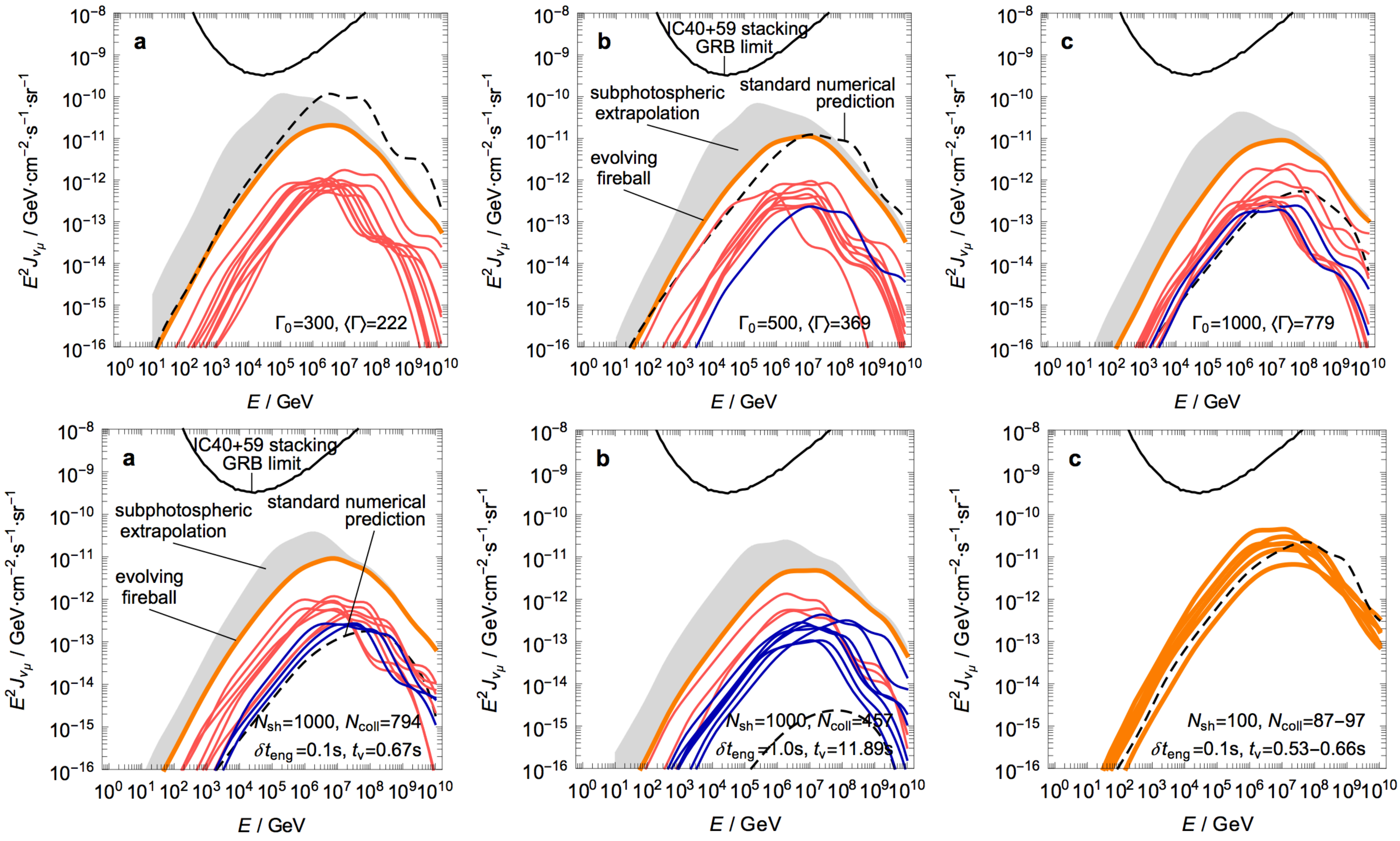
Compare to

$$f_\pi(\varepsilon_p) \sim 0.2 \frac{L_{\gamma,52}}{\Gamma_{2.5}^4 t_{v,-2} \varepsilon_{\gamma,\mathrm{MeV}}^b}$$

Guetta et al, Astropart. Phys. 20 (2004) 429

Bustamante, Baerwald, Murase, Winter,
Nat. Commun. 6, 6783 (2015)

Parameter space dependence: Numerical cross-check!



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