Multimessenger astrophysics

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Astroteilchenschule 2016
Obertrubach-Bärnfels

October 2016

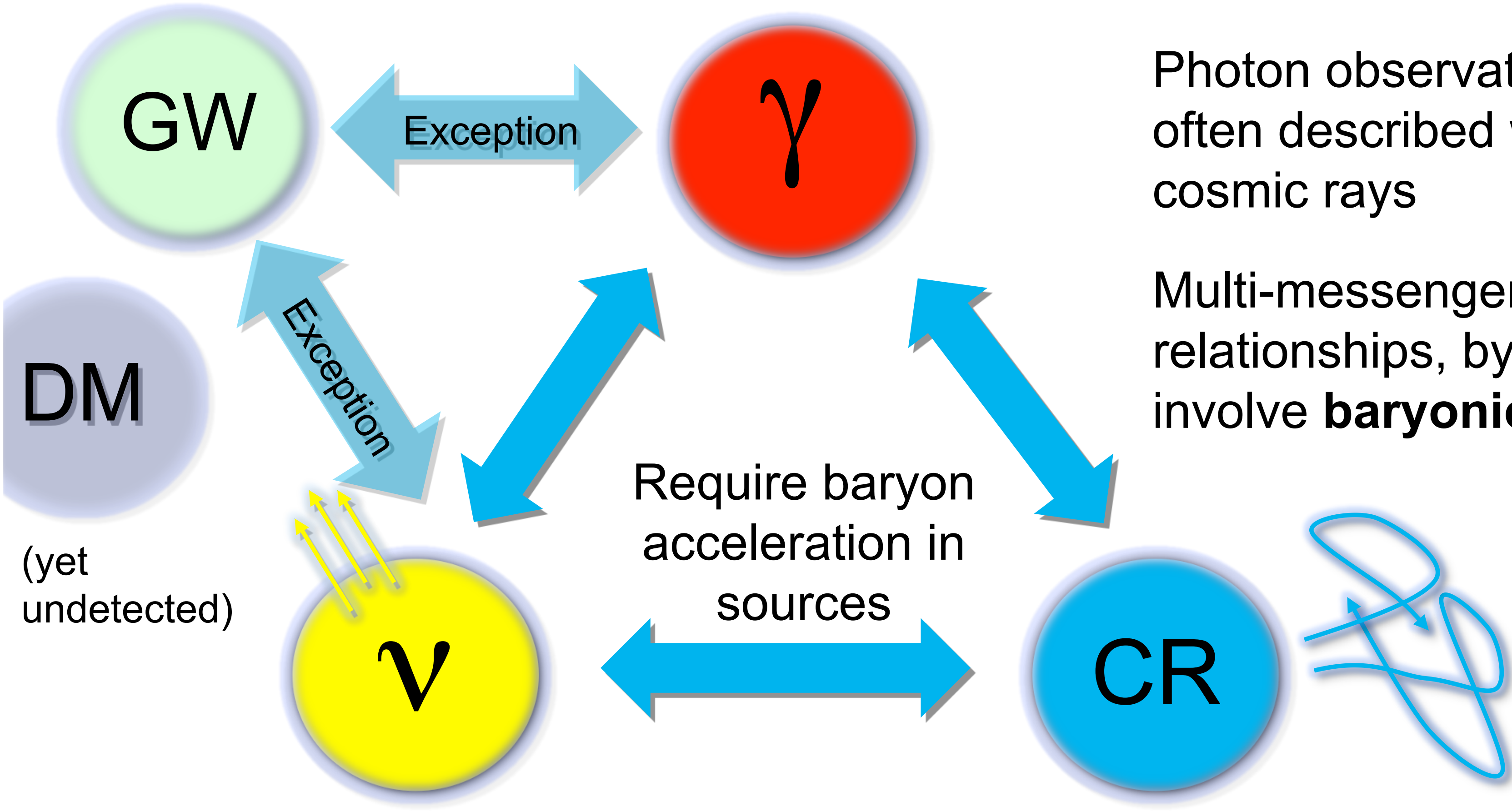
What is “multimessenger” astrophysics?

- A buzzword describing any kind of analysis including more than one messenger?
- A fashion concept, or a truly fundamental philosophy?

- Typically used in approaches involving at least two of the three messengers cosmic rays, neutrinos, gamma-rays
- But: lately also used in the context of follow-up analyses on gravitational waves for different messengers
- Sometimes mis-used instead of the word “multi-wavelength”?

- Multi-messenger astronomy = correlate signals from multiple-messengers?
- Multi-messenger astrophysics = What are the fundamental concepts describing the emitters of multiple messengers?

"Multimessenger astrophysics", definition for these lectures



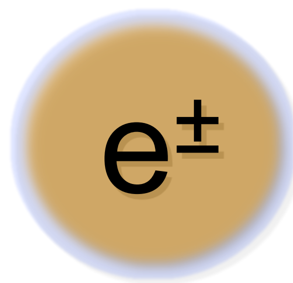
Photon observations can be often described without cosmic rays

Multi-messenger relationships, by definition, involve **baryonic loading**

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

Focus on extreme (highest) energies, extragalactic

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



Contents

Lecture 1

- Particle astrophysics of hadronic sources (basic concepts)
- Radiation models (blackboard) 

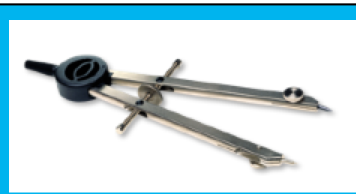
Lecture 2

- Meet the messengers:
  - Photons
  - Cosmic rays
  - Neutrinos
  - Gravitational waves
- Examples for generic multi-messenger approaches
- Describing interactions (blackboard) 

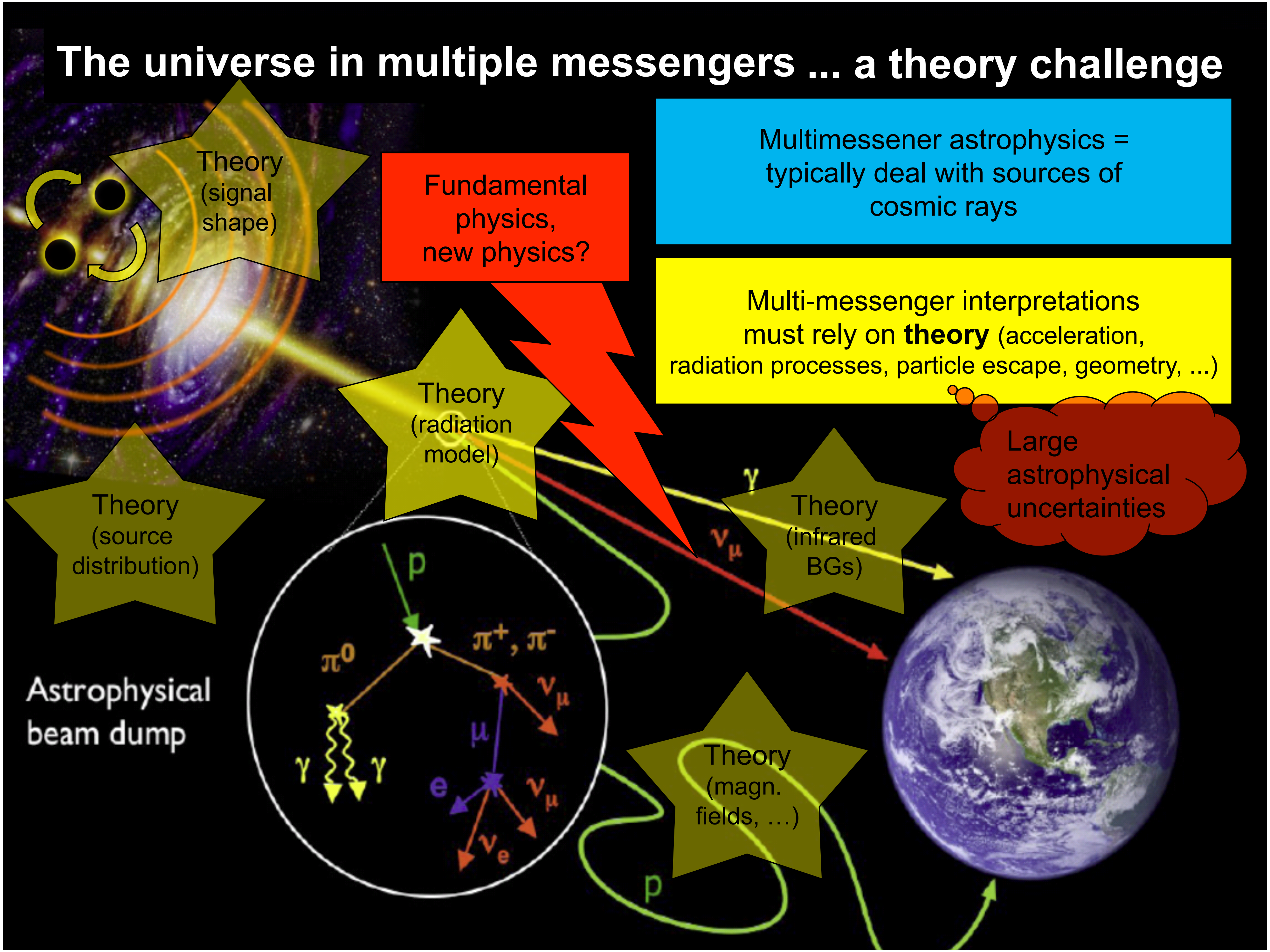
Lecture 3

- Challenges for multi-messenger approaches ← Incl. special feature: stacking analyses
- Energetics of sources (blackboard) 
- How to address the key challenges; example: GRBs

DISCLAIMER:
Apologies if specific experiments or theoretical results are not mentioned. It is impossible to review this subject completely.

Relevant for exercises 

Astroparticle physics of hadronic sources


The universe in multiple messengers ... a theory challenge
Multimessener astrophysics =
typically deal with sources of
cosmic rays
Multi-messenger interpretations
must rely on theory (acceleration,
radiation processes, particle escape, geometry, ...)
Fundamental
physics,
new physics?
Large
astrophysical
uncertainties
Theory
(signal
shape)
Theory
(radiation
model)
Theory
(source
distribution)
Theory
(infrared
BGs)
Theory
(magn.
fields, …)
Astrophysical
beam dump
p
π0
π+, π-
γ
γ
μ
e
νμ
νe
νμ
γ
νμ
p

A simple toy model for the source

If neutrons can escape:
Source of cosmic rays

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Neutrinos produced in ratio $(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \,,$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Delta resonance approximation:

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

Cosmic messengers

$$\pi^0 \longrightarrow \gamma + \gamma$$

High energetic gamma-rays;
typically cascade down to lower E
Additional constraints!

(Same process during propagation of cosmic rays in CMB: “cosmogenic neutrinos”)

Typical hadronic radiation processes

> Nucleons (protons, neutrons)

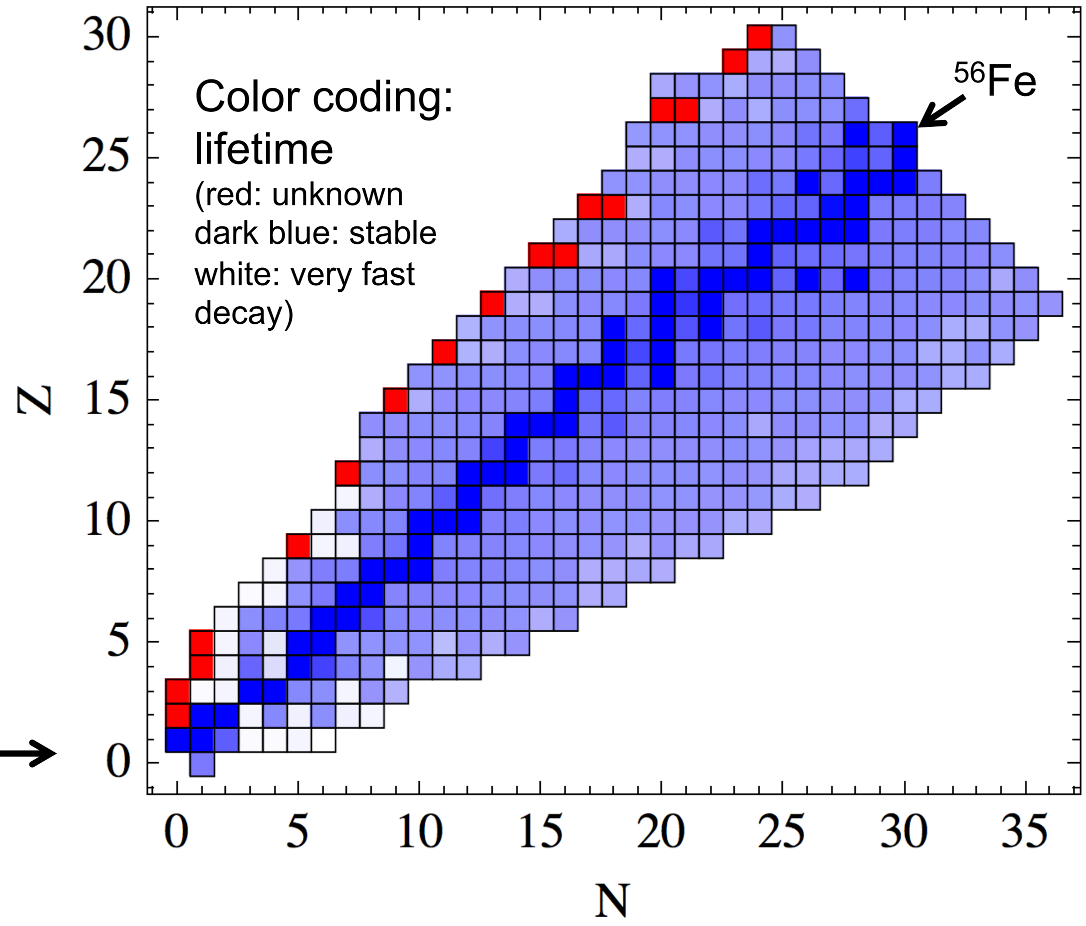
- Photo-meson production, e.g.

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

- $p\gamma \rightarrow p e^+ e^-$ pair production
- pp collisions
- Beta decay (neutrons)

> Heavy nuclei

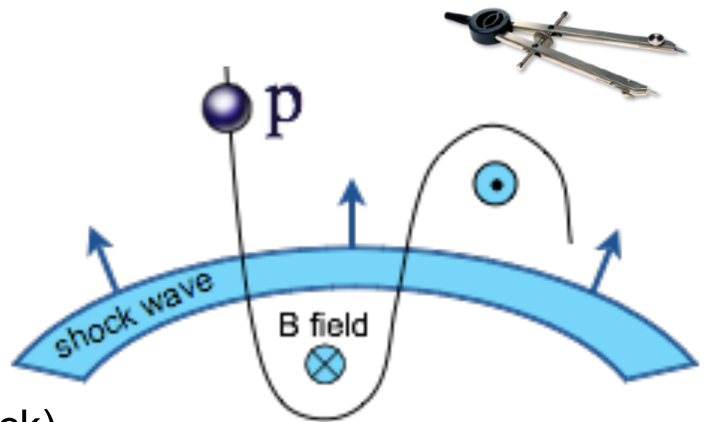
- Photo-disintegration (produces unstable isotopes)
- Photo-meson production
- Beta decay (typically blue), Spontaneous emission of nucleons (most extreme: white)
- $A\gamma \rightarrow A e^+ e^-$ pair production
- Ap collisions



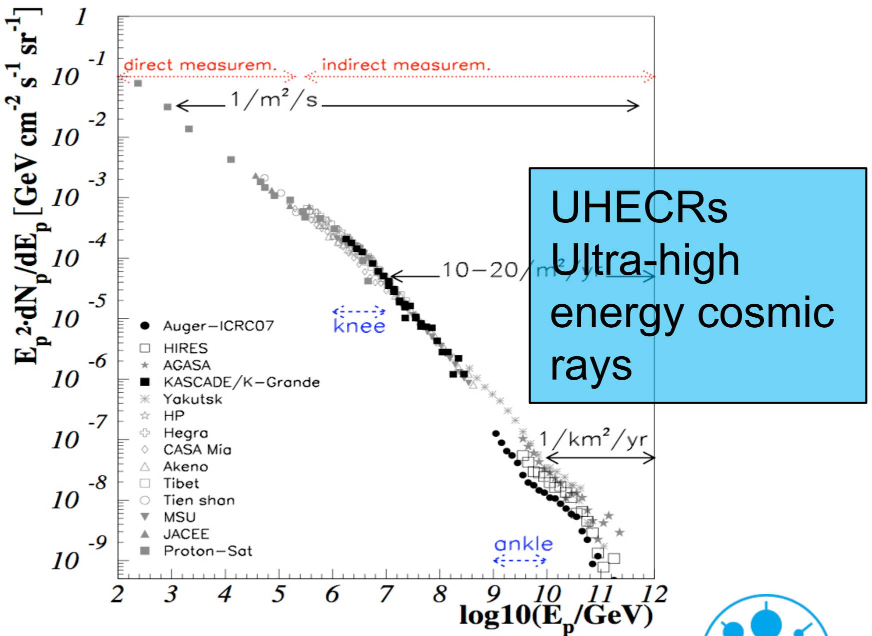
Acceleration of primaries (protons, nuclei)

Example: Fermi shock acceleration

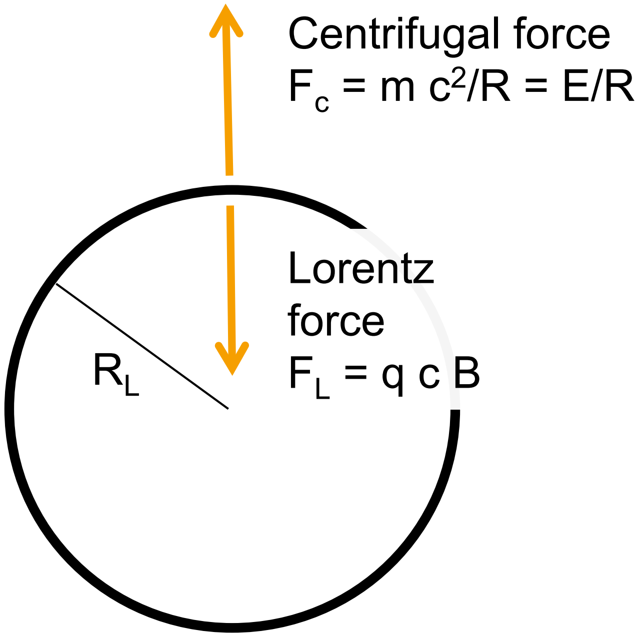
- Energy gain per cycle: E ➔ η E
- Escape probability per cycle: P_{esc}
- Yields a **power law** spectrum ~ $E^{\frac{\ln P_{\rm esc}}{\ln \eta}-1}$
- ln P_{esc}/ln η ~ -1 (from compression ratio of a strong shock), and $\mathbf{E^{-2}}$ is the typical “textbook“ spectrum



- Although theory of acceleration at relativistic shocks challenging, we **do observe** power law spectra in Nature →
- For multimessenger perspective: adopt pragmatic point of view! *(we know that it works, somehow ...)*

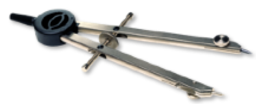


Maximal primary energy (generic concepts)



- Confinement condition in accelerator (R: size):
  $F_L = F_C$ ➔ $E_{max} = q\,c\,B\,R$ (v=c)
- Larmor-Radius of a particle $R_L = E/(q\,c\,B)$
- Rigidity (stiffness to resist magnetic field) is defined as $R_L\,B \sim E/(q\,c)$
- For nuclei at same E: $q \sim Z$ ➔ Rigidity ~ 1/Z
- Cycle time $T_{cycle} = 2\,\pi\,R_L/c \sim E/(c^2\,q\,B)$
- Acceleration rate with η = (here) fractional energy gain/cycle ~ acceleration efficiency:

$$t_{\rm acc}^{-1} \equiv \frac{1}{E}\frac{dE}{dt} \sim \frac{dE}{E}\frac{1}{T_{\rm cycle}} = \hat{\eta}\frac{1}{T_{\rm cycle}} = \eta\frac{c^2 q B}{E}$$



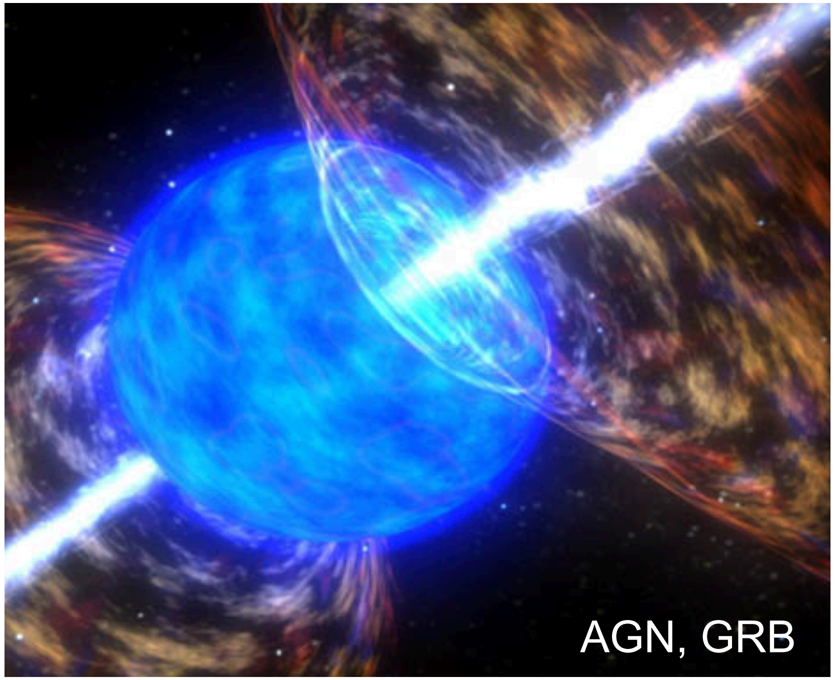
- Maximal energy *including acceleration efficiency* from $t_{acc} = t_{esc} \sim R/c$ (free streaming escape) ➔ $E_{max} \sim \eta\,q\,c\,B\,R$

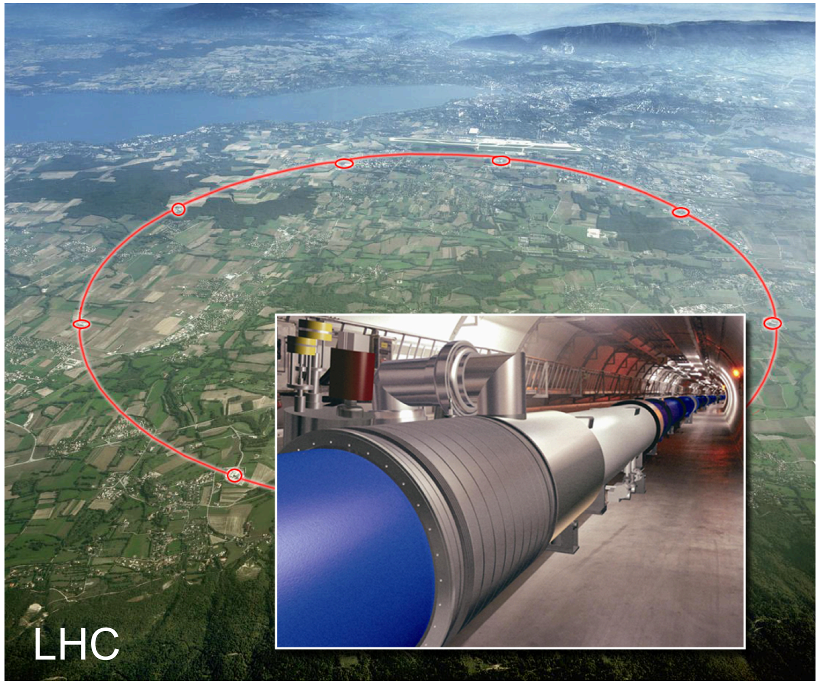
Cosmic vs. terrestrial particle accelerators

Lorentz force = centrifugal force ➔ $E_{max} \sim q\,c\,B\,R$

- E_{max} ~ **300,000,000 TeV**
- B ~ 1 mT – 1 T
- R ~ 100,000 – 10,000,000,000 km

- E_{max} ~ 7 TeV
- B ~ 8 T
- R ~ 4.3 km



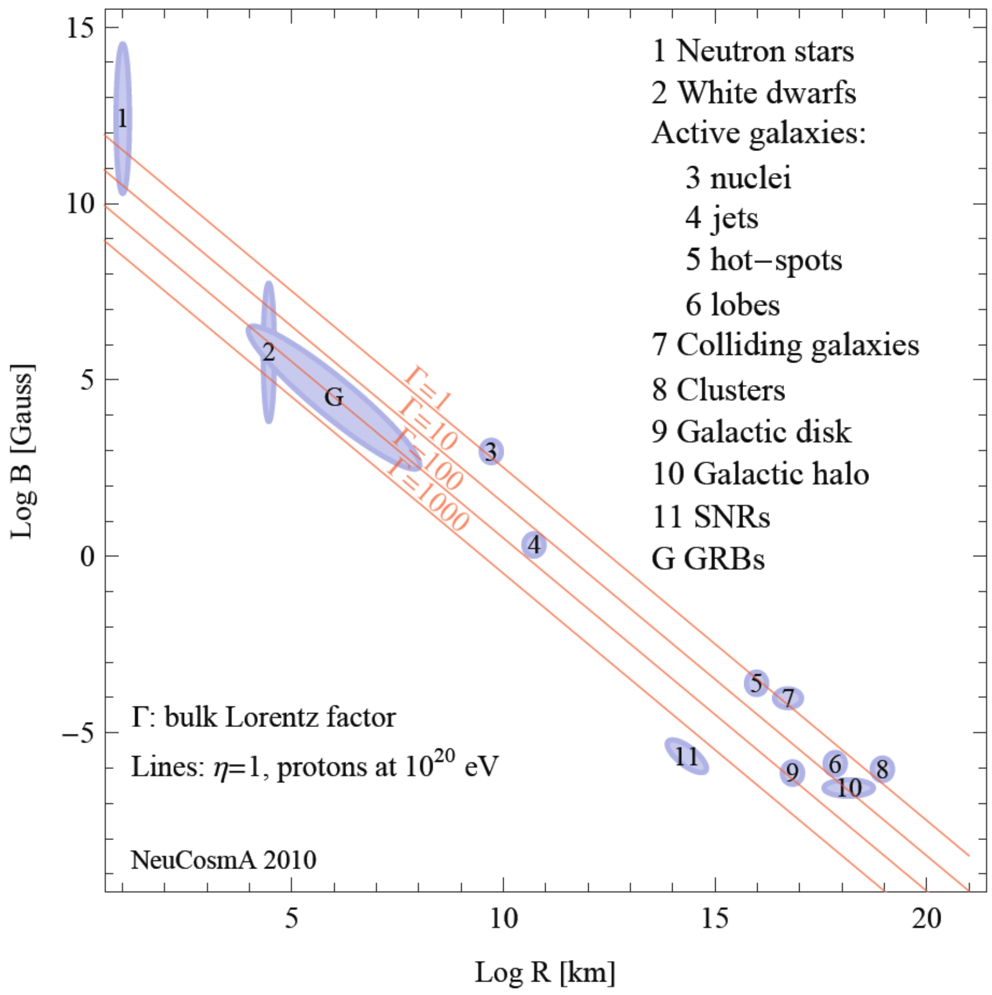


UHECR sources on Hillas plot

- Sources which can reach the maximal energy (necessary condition)
  $E_{max} \sim \eta\ q\ c\ B\ R$
  [right of lines]

- Complication: Lorentz-boosted sources, such as Gamma-Ray Bursts
  $\Gamma \sim 100 - 1000$
  relax this condition
  (interpret R and B in
  shock rest frame; primed quantities!)
  $E_{max} \sim \eta\ q\ c\ B'\ R'\ \Gamma$

- Consequence for heavy nuclei:
  $E_{max} \sim Z$ ("Peters cycle")
  Peters, 1961



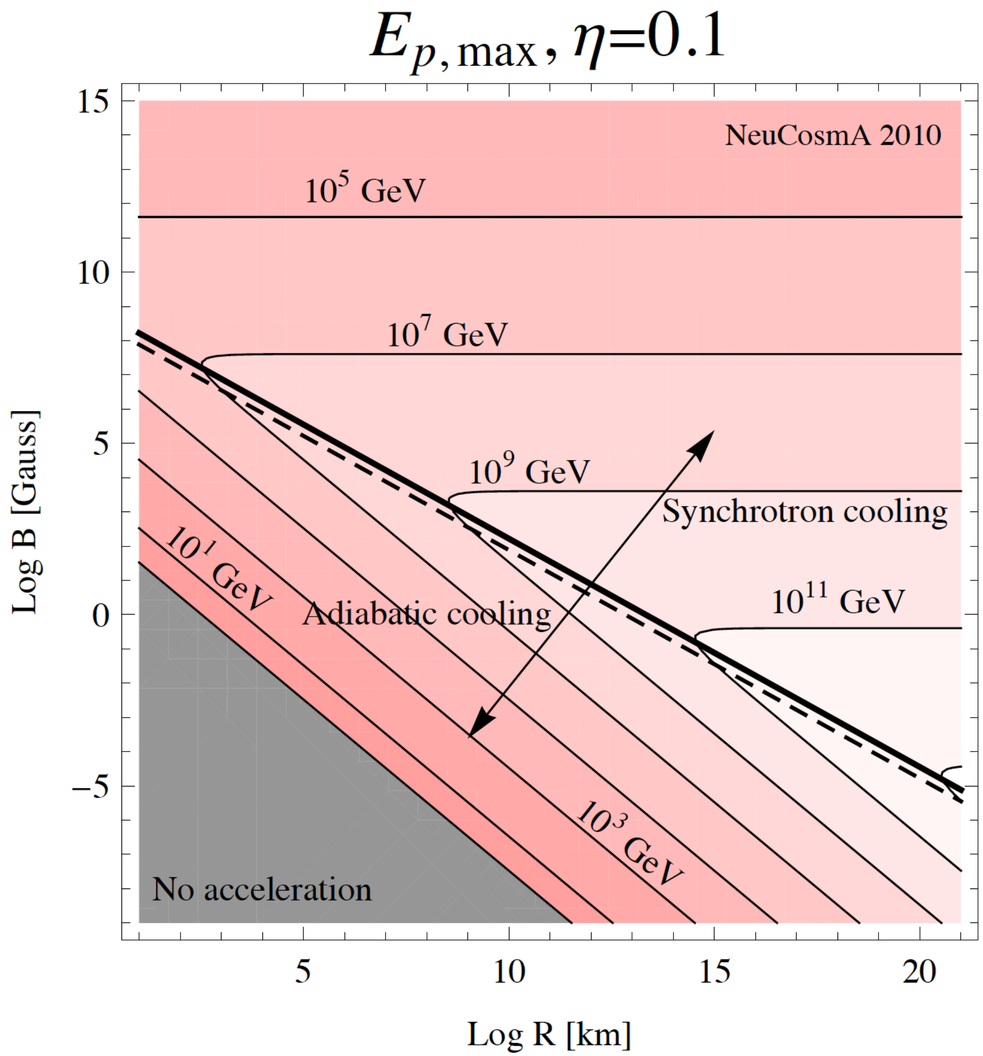
(from Astropart. Phys. 34 (2010) 205)

Other necessary conditions

- The confinement condition is necessary, but not sufficient
- Example: Protons lose energy by synchrotron losses. Loss rate

$$t_{\rm synchr}^{-1} = \frac{q^4 \, B^2 \, E}{9 \, \pi \, \epsilon_0 \, m^4 \, c^7}$$

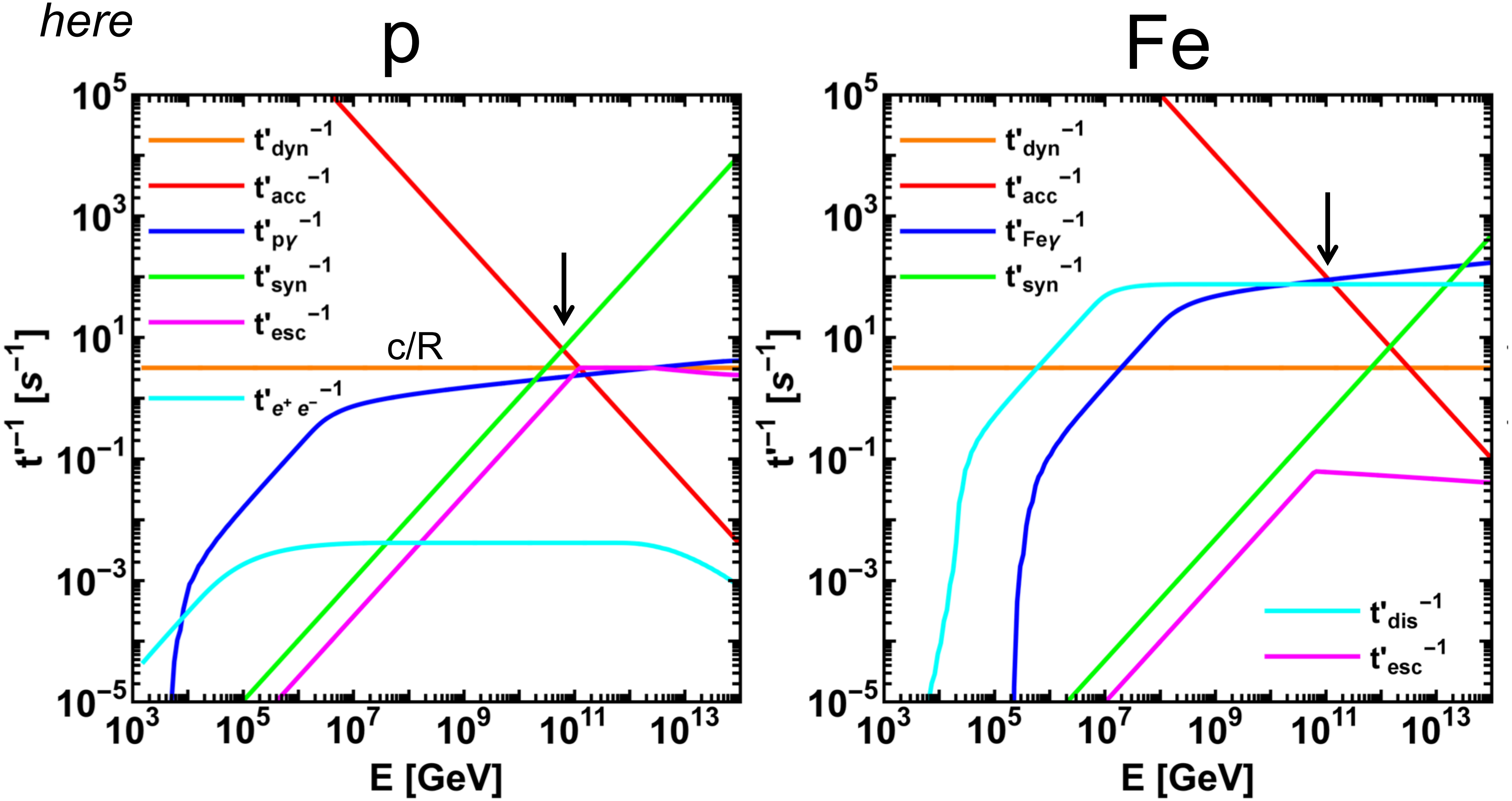
- Limits the maximal energy for large B + can affect Peters cycle for nuclei



(from Astropart. Phys. 34 (2010) 205)

Less trivial examples: Maximal energy from rate plots

- A more realistic example (Gamma-Ray Burst):
  Exercise: *1) Find the dominant process limiting the acceleration, 2) read off the maximal primary energy, 3) check if Peters' cycle is satisfied here*



(Courtesy Daniel Biehl)

Secondary production: Particle physics 101

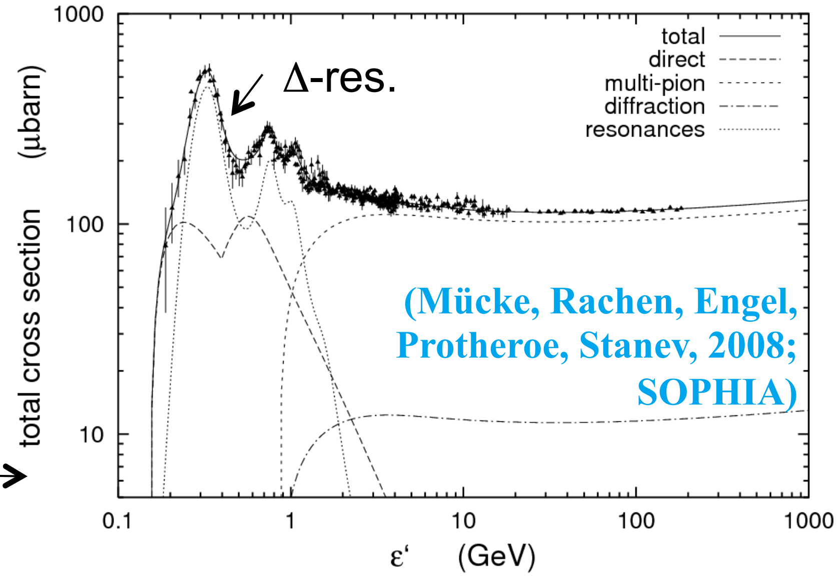
- Beam dump picture (particle physics)

Beam of p, A, …

Target
(p, γ, A, …)

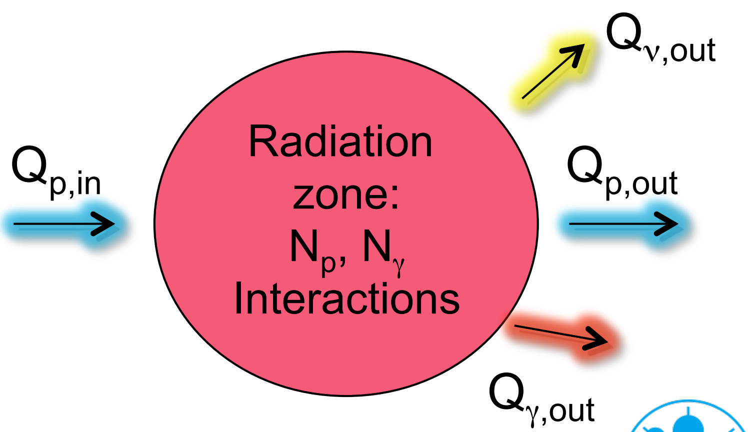
- Interaction rate $\Gamma \sim c\ N\ [cm^{-3}]\ \sigma\ [cm^2]$

Target density (e.g. N_γ) critical for secondary production!



(Photon energy in nucleon rest frame)

- Astrophysical challenges:
  - Feedback between beam and target (e.g. photons from π^0 decays); need self-consistent description called **radiation model**
  - *What you see is*, in general, **not** *what you get* in the source



Radiation models: one spatial zone

> Time-dependent PDE system, one PDE per particle species *i*

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(-b(E) N_i(E)\right) - \frac{N_i(E)}{t_{\mathrm{esc}}} + Q(E)$$

Cooling/acceleration | Escape | Injection

$b(E) = -E\, t^{-1}_{\mathrm{loss}}$

$Q(E,t)$ [GeV^{-1} cm^{-3} s^{-1}]

$N(E,t)$ [GeV^{-1} cm^{-3}] particle spectrum including spectral effects

> Injection: species *i* from acceleration zone, and from other species *j*:

$$Q(E) = Q_i(E) + Q_{ji}(E)$$

$$Q_{ji}(E_i) = \int dE_j\, N_j(E_j)\, \Gamma_j^{\mathrm{IT}}(E_j)\, \frac{dn^{\mathrm{IT}}_{j \to i}}{dE_i}(E_j, E_i)$$

Density other species | Inter-action rate | Re-distribution function +secondary multiplicity

Steady state solution: dN/dt ~ 0

- System typically reaches steady state very quickly:

$$Q(E) = \frac{\partial}{\partial E} \left(b(E) \, N(E) \right) + \frac{N(E)}{t_{\mathrm{esc}}}$$

Injection | Energy losses | Escape

One equation for each particle species!

- Typical "escape" processes: Escape from region, decay, disintegration, photomeson production (if species changed), ...
- Typical "cooling" processes: Synchrotron cooling, pair production, adiabatic cooling (by expansion of region)
- Simple case: No energy losses b=0: $N(E) = Q(E) \, t_{\mathrm{esc}}$
- Special case: t_{esc} ~ R/c (free-streaming, aka "leaky box")

… can be also more sophisticated: spatially resolved models

(synchrotron radiation, ionization loss, reacceleration, ...)

diffusion with diffusion coefficient D_i — energy losses and gains — convection with velocity $\vec{u}$

$$\frac{\partial N}{\partial t} = \nabla \cdot (D_i \nabla N_i) - \frac{\partial}{\partial E}(dE/dt N_i(E)) - \nabla \cdot \vec{u} N_i(E)$$
$$+ Q_i(E,t) - p_i N_i + \frac{v\rho}{m} \sum_{k \geq i} \frac{d\sigma_{i,k}(E,E')}{dE} N_k(E') dE'$$

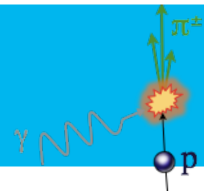
source term — loss term — cascade term: feed-down from higher energies and nuclear fragmentation processes

$$\text{loss term } p_i = \frac{v\rho}{\lambda_i} + \frac{1}{\gamma \tau_i}$$

G. Maier

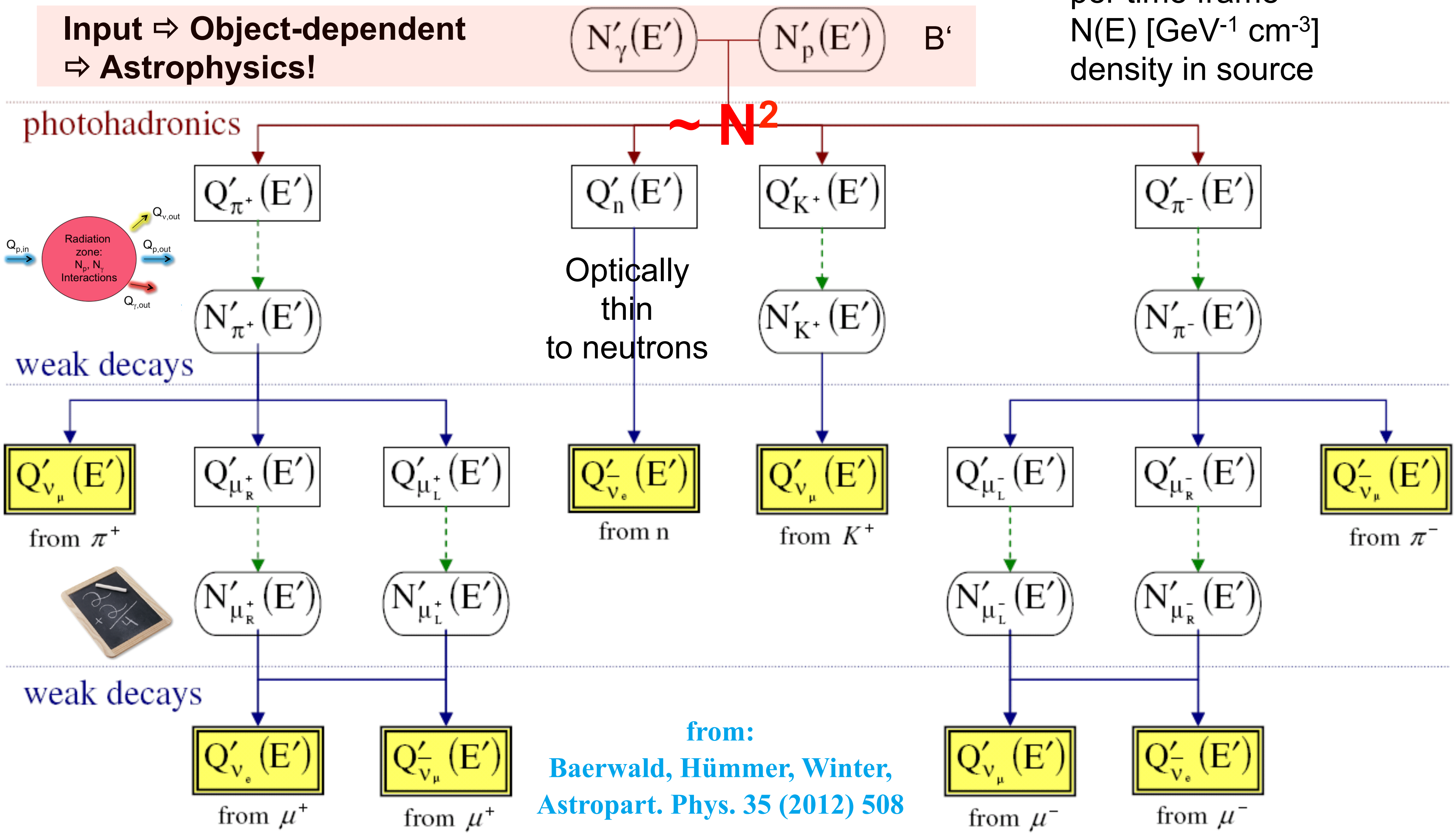
Exercise:
What are the new terms you haven't seen before?

Example: Neutrino production from pγ interactions



Dashed arrows: kinetic equations include cooling and escape

Q(E) [GeV^{-1} cm^{-3} s^{-1}] per time frame
N(E) [GeV^{-1} cm^{-3}] density in source



from:
Baerwald, Hümmer, Winter,
Astropart. Phys. 35 (2012) 508

Secondary (muon, pion, kaon) cooling

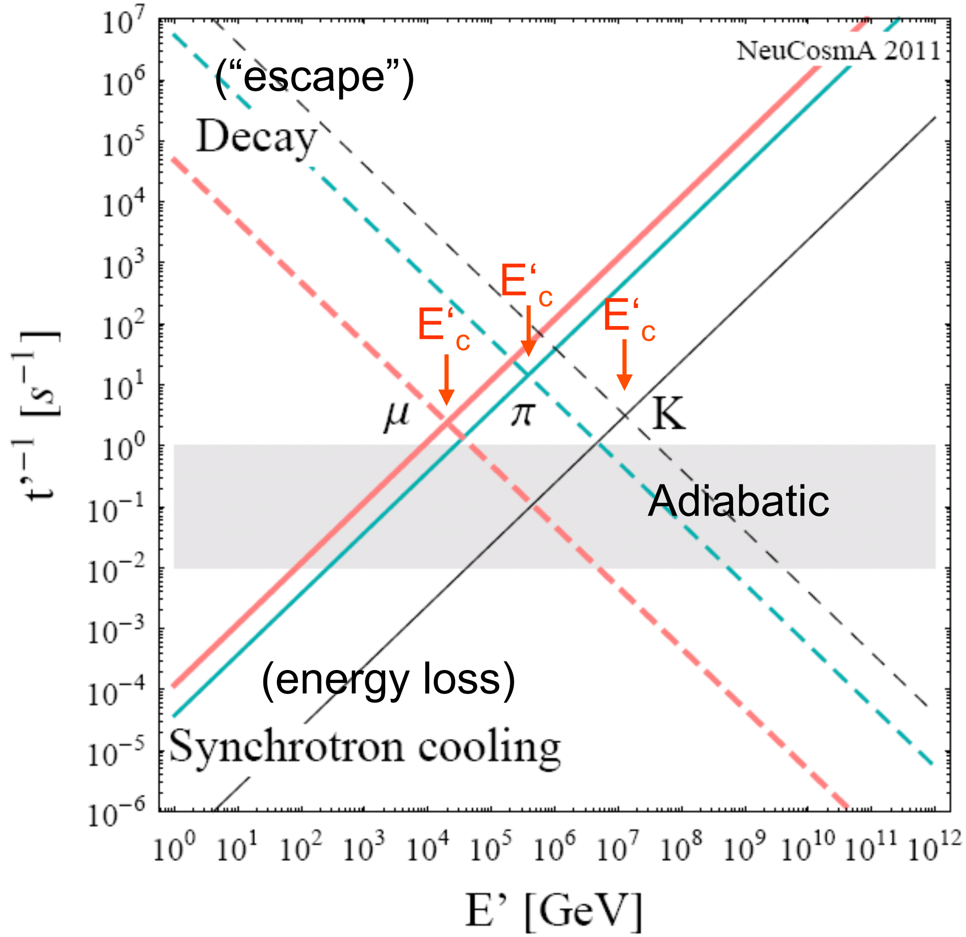
Example: GRB

Secondary spectra (μ, π, K) loss-steepend above critical energy

$$E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}}$$

- E'$_c$ depends on particle physics only (m, τ_0), and **B'**

Decay/cooling: charged μ, π, K



Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508; also: Kashti, Waxman, 2005; Lipari et al, 2007; ...

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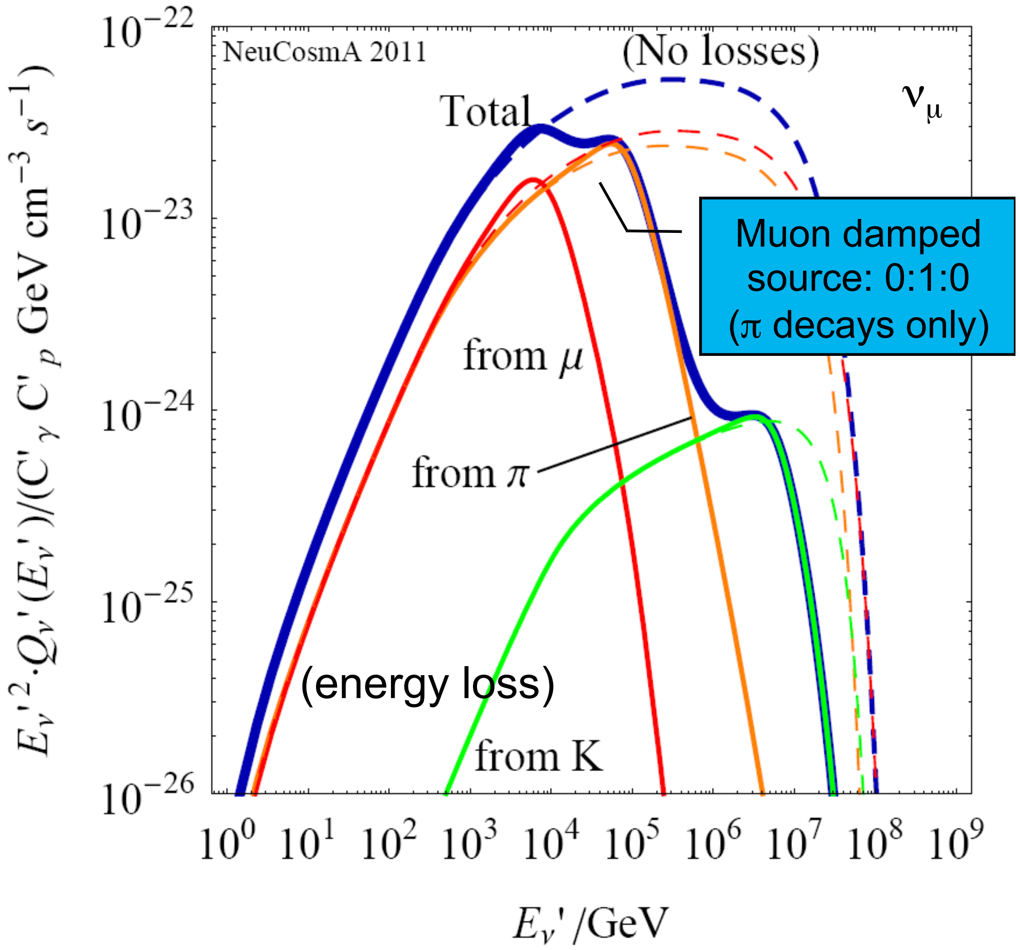
$$E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}}$$

- E'_c depends on particle physics only (m, τ_0), and **B'**
- Leads to characteristic flavor composition and shape

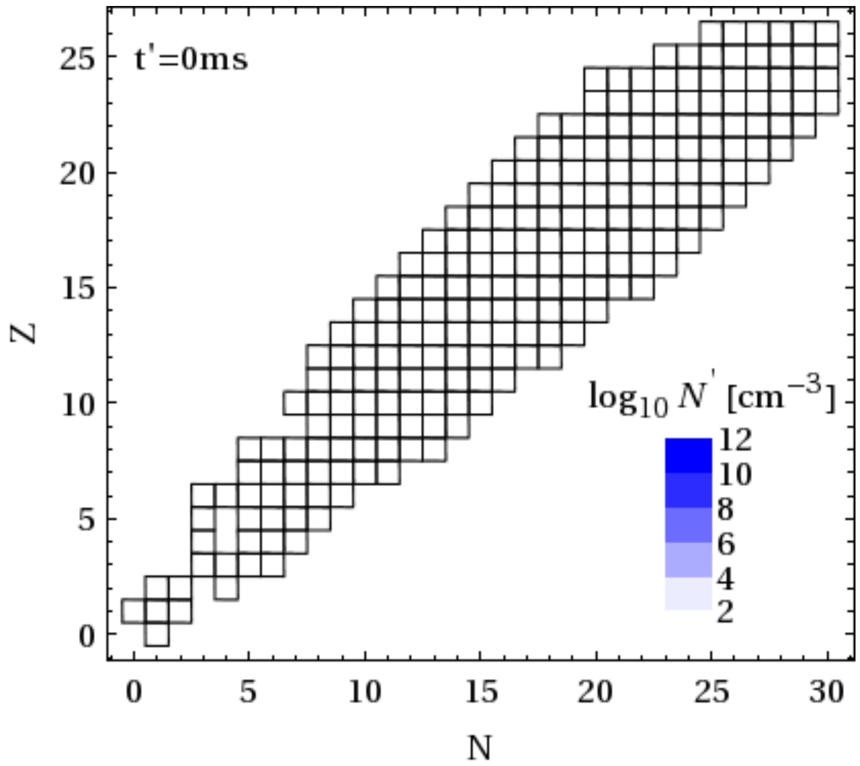
Decay/cooling: charged μ, π, K



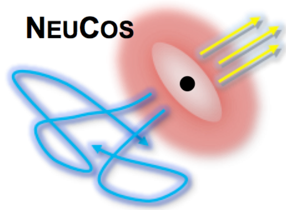
Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508;
also: Kashti, Waxman, 2005; Lipari et al, 2007; ...

Example: photo-disintegration of ^{56}Fe in a Gamma-Ray Burst

- Challenges:
  - *Arbitrary* target photon spectra
  - 481 isotopes, 41000 disintegration channels; automatic reduction
  - Efficient deterministic computation: one PDE per isotope →
  - Radiation processes: photo-disintegration, photomeson production, beta decays, spontaneous emissions, synchrotron cooling, adiabatic cooling



Boncioli, Fedynitch, Winter, 2016;
Biehl/Rodrigues+ 2016+ (to appear)



- Current questions, e.g.
  - Dependence on target spectrum? Results for different object classes?
  - Does the neutrino production depend on the cosmic ray composition?
  - How are cosmic rays ejected?

Talks by Xavier+Daniel this afternoon

Radiation models (blackboard)

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- Radiation models (blackboard)

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  - Cosmic rays
  - Neutrinos
  - Gravitational waves
- Examples for generic multi-messenger approaches
- Describing interactions (blackboard)

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- Challenges for multi-messenger approaches ← Incl. special feature: stacking analyses
- Energetics of sources (blackboard)

- How to address the key challenges; example: GRBs

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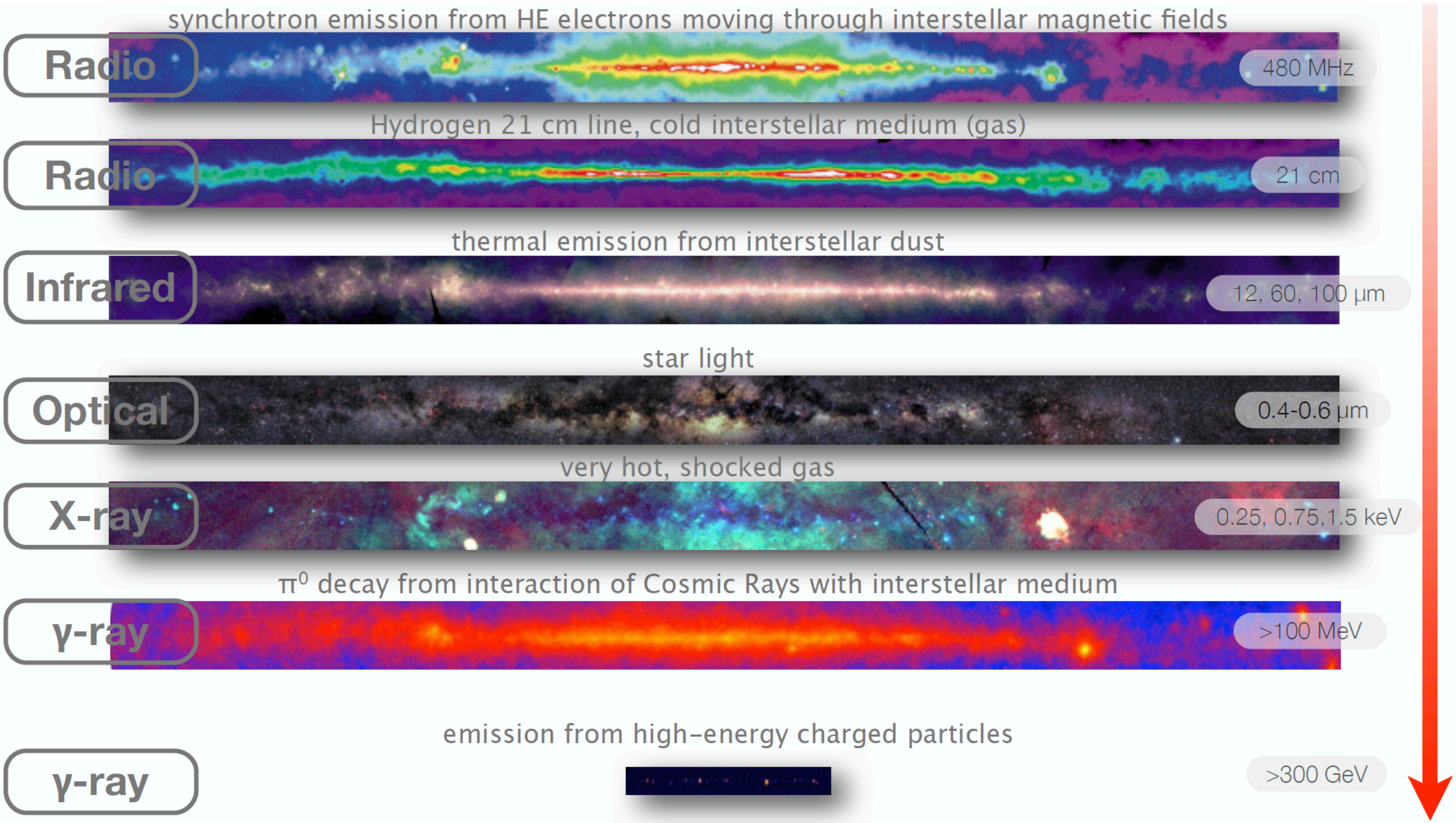
Relevant for exercises

Meet the messengers

Meet the messengers: Photons at multiple wavelengths



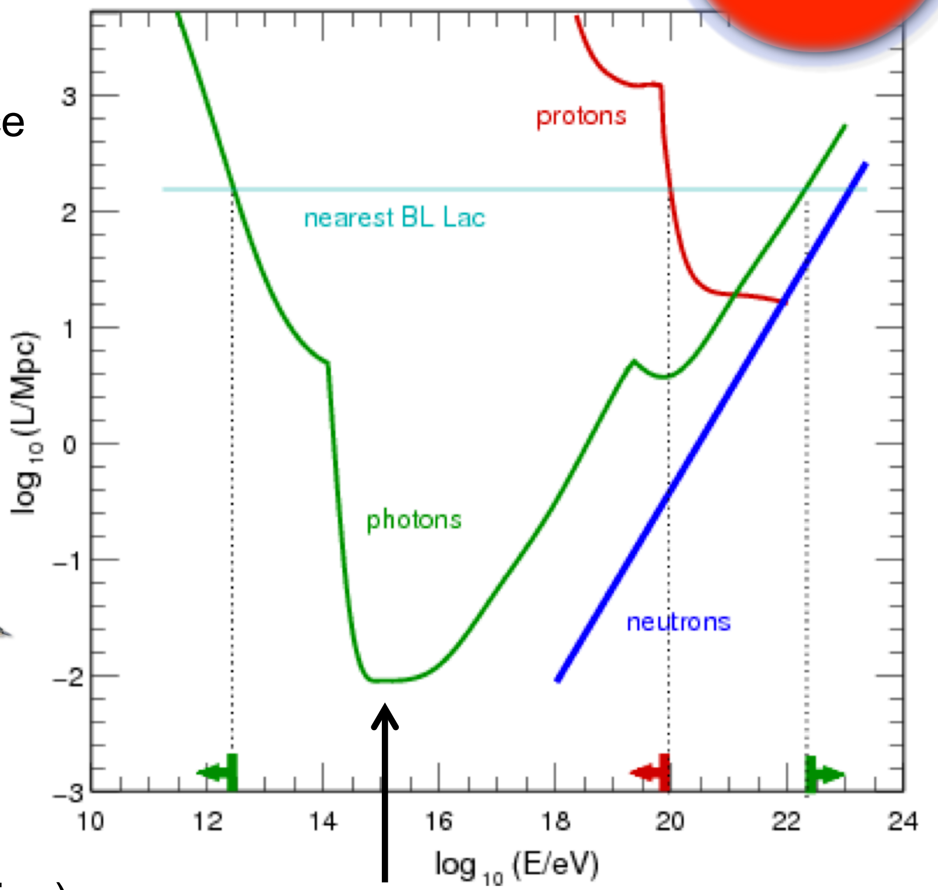
… targeted by a variety of instruments
(not possible to review all of them here)

G. Maier

High-energy photon propagation/attenuation

γ

- Attenuated by
  - Thomson scattering (γe → γe), often in source
    Density of electrons matters!
    Concept of **photosphere**
  - Pair production (γγ → ee), e.g. on cosmic backgrounds
    Distance and energy matters →



CMB attenuation

arXiv:0901.4085

- Pair production on CMB (~0.2 meV):

$$s=(P_1+P_2)^2=P_1^2+2\,P_1\,P_2+P_2^2$$

$$= 2\,P_1\,P_2 = 2\,E_1\,E_2 - 2\,p_1\,p_2\cos\theta = 4\,E_1\,E_2$$

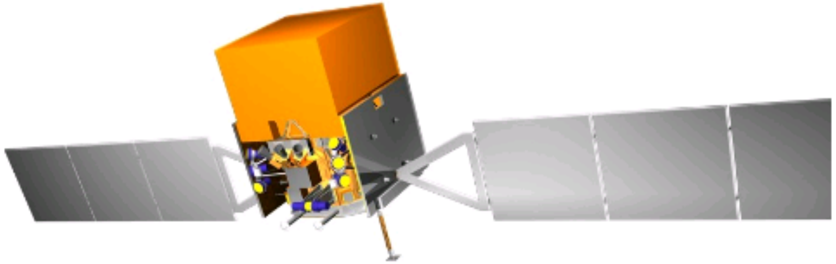
(photons, center-of-mass frame, heads-on collision)

$$= m_e^2 + 2\,m_e\,m_e + m_e^2 = 4\,m_e^2 \text{ (electrons at rest)}$$

$$\rightarrow E_1\,E_2 > m_e^2 \rightarrow E_1 > 10^{15}\text{ eV}$$

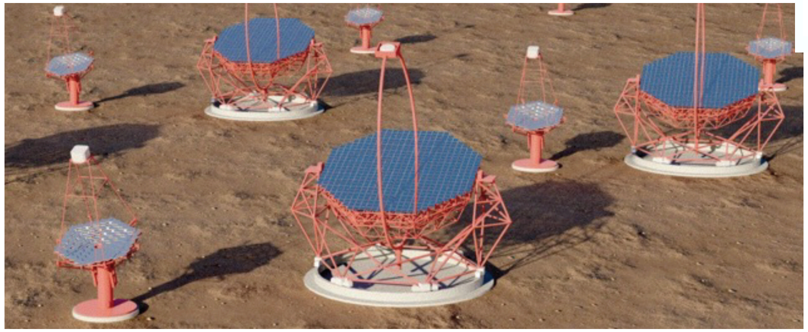
DESY

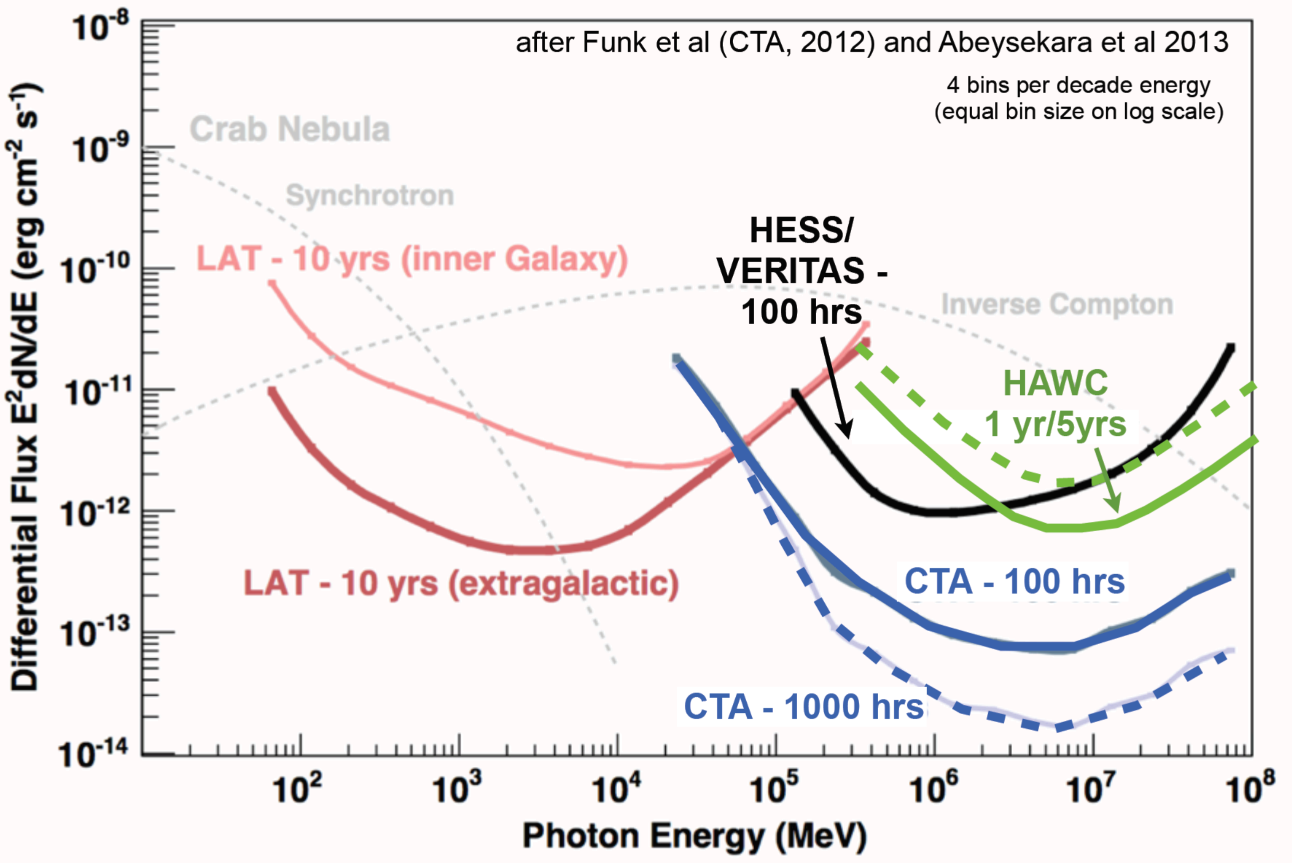
Gamma-rays: Key experiments



Fermi-LAT

CTA; MAGIC, VERITAS, H.E.S.S.

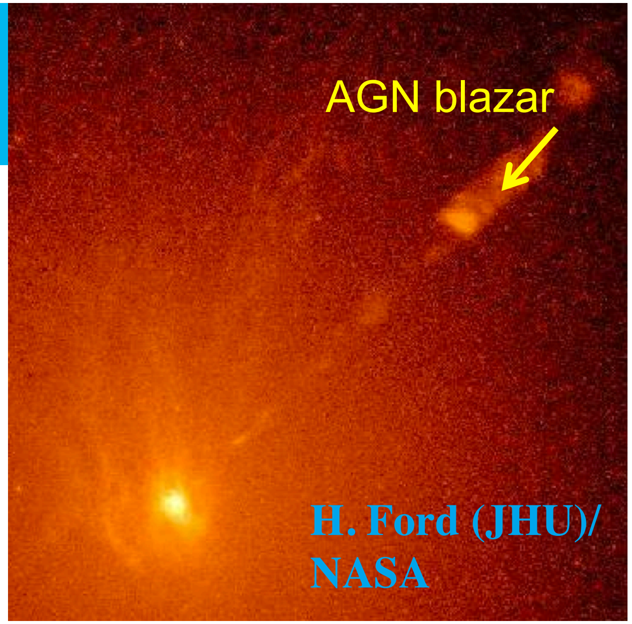


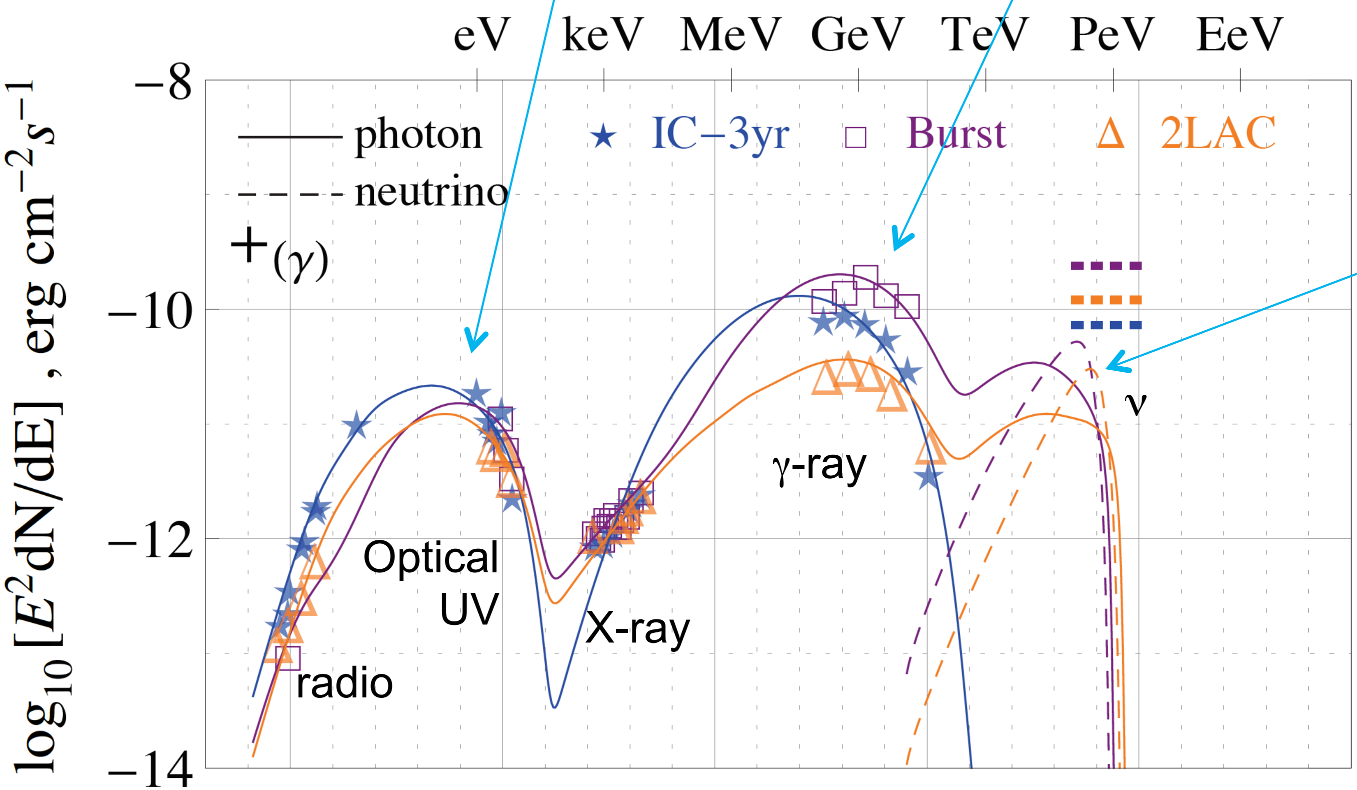


Current theoretical paradigms

Example: Multi-wavelength campaigns for AGN blazars

Model	1st hump	2nd hump
Leptonic	e synchrotron	Inverse Compton (eγ) on synchr. or ext. γ
Hadronic	Proton synchrotron	**Hadronic process** (e.g. π^0 decays)
Lepto-hadronic	e synchrotron	**Mixed processes**





Photon observations alone in most cases inconclusive.

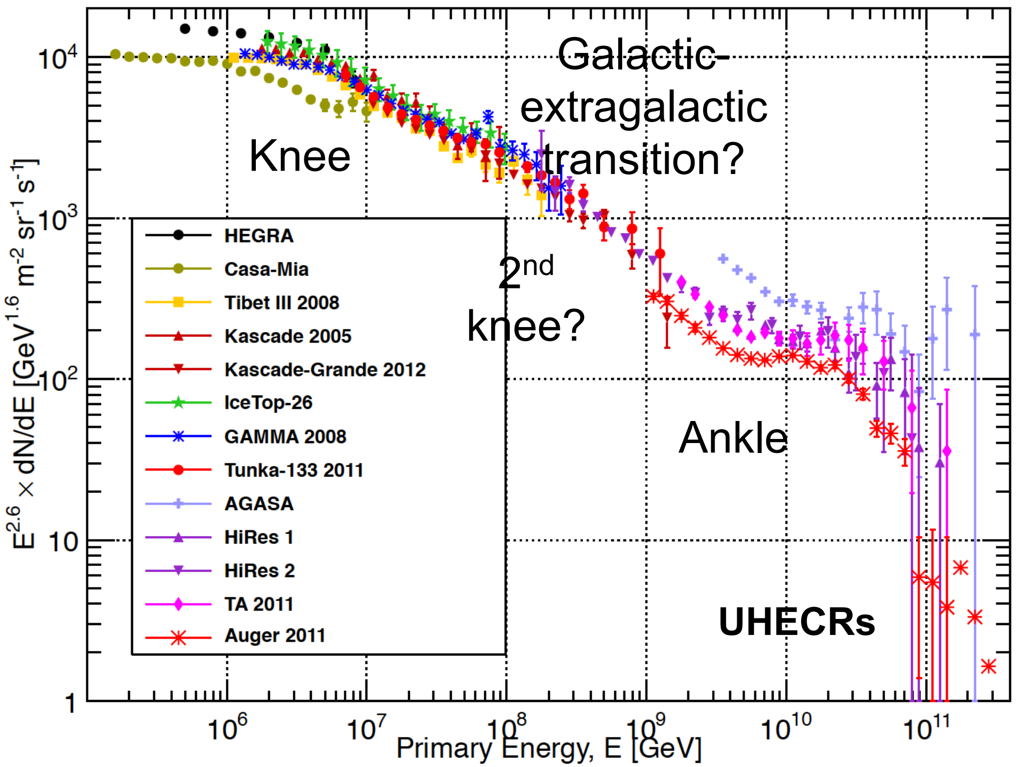
Multi-messenger astronomy may tell us if there are hadrons

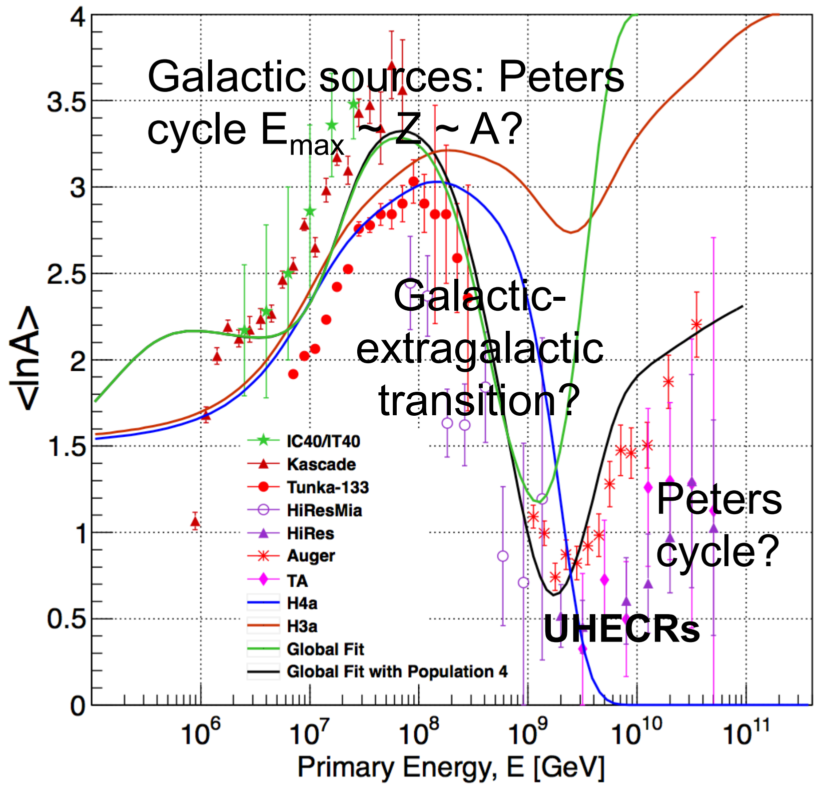
(from Gao, Pohl, Winter, 2016)

Meet the messengers: Cosmic rays

- Charged particles, proton or heavier nuclei
- Spectrum with breaks (knee, 2nd knee, ankle)
- Composition non-trivial function of energy

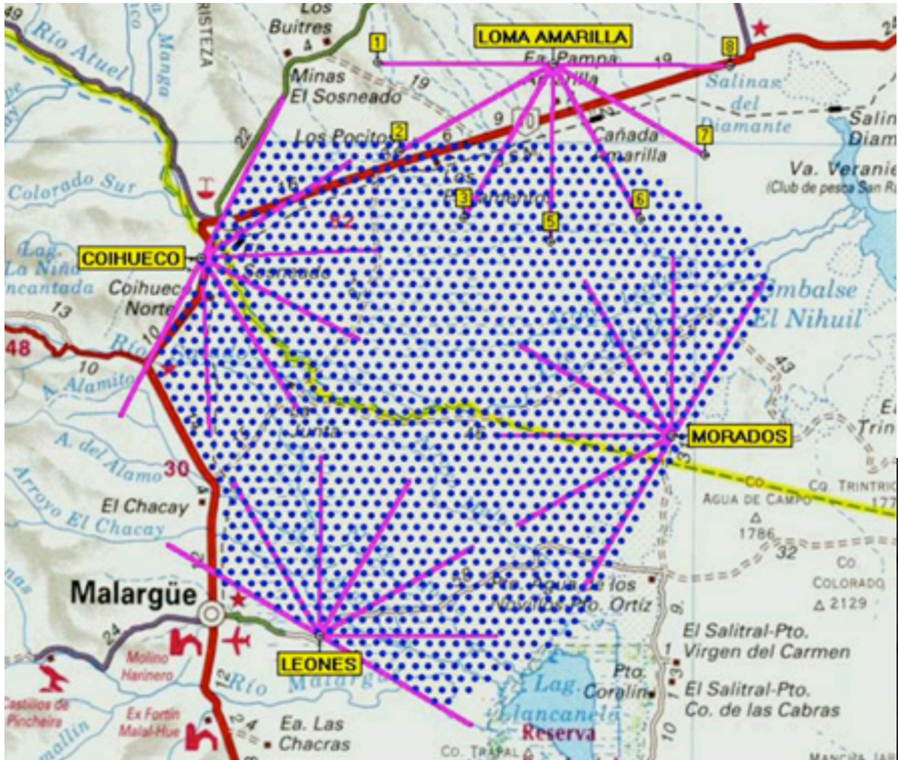
CR





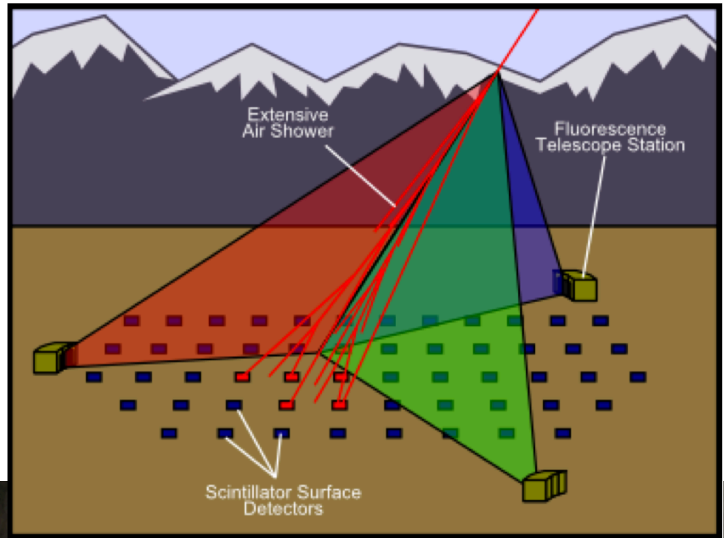
Gaisser, Stanev, Tilav, 2013

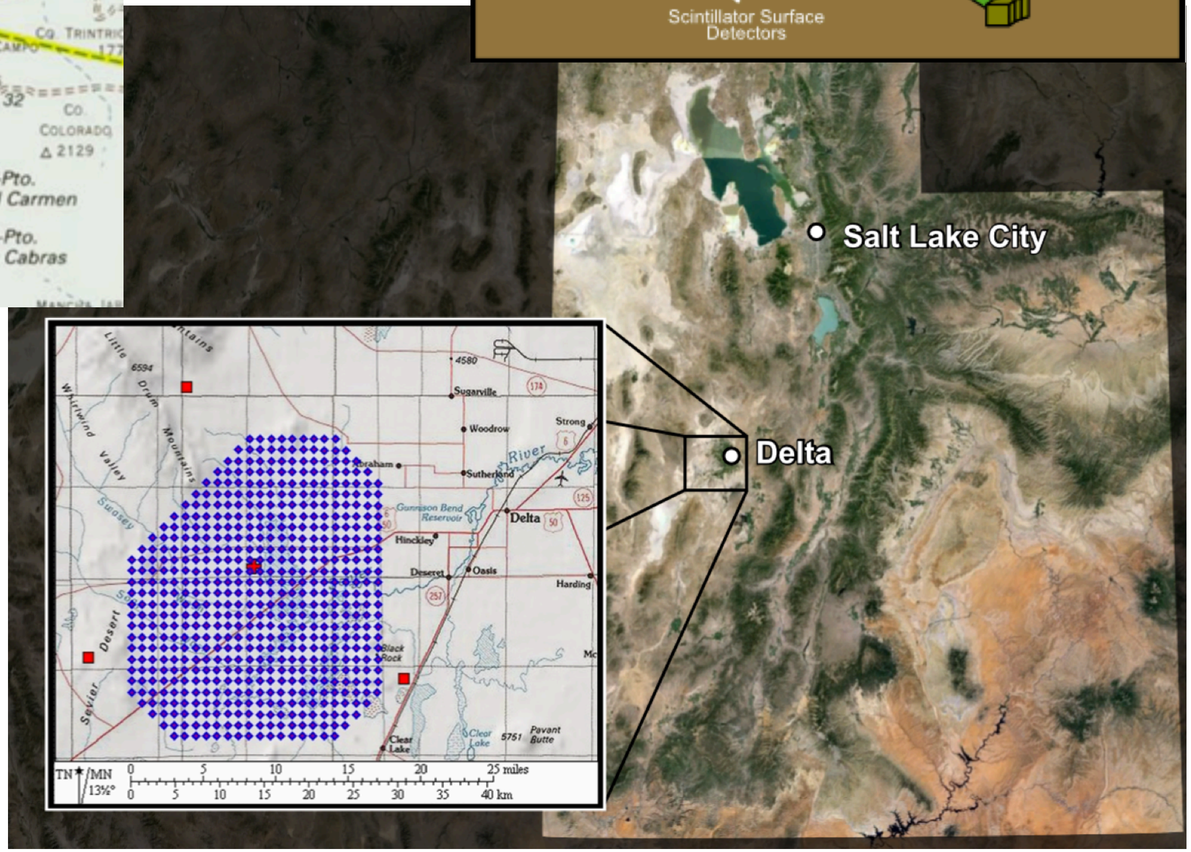
Ultra-high energy cosmic ray (UHECR) experiments



Auger

Telescope Array (TA)





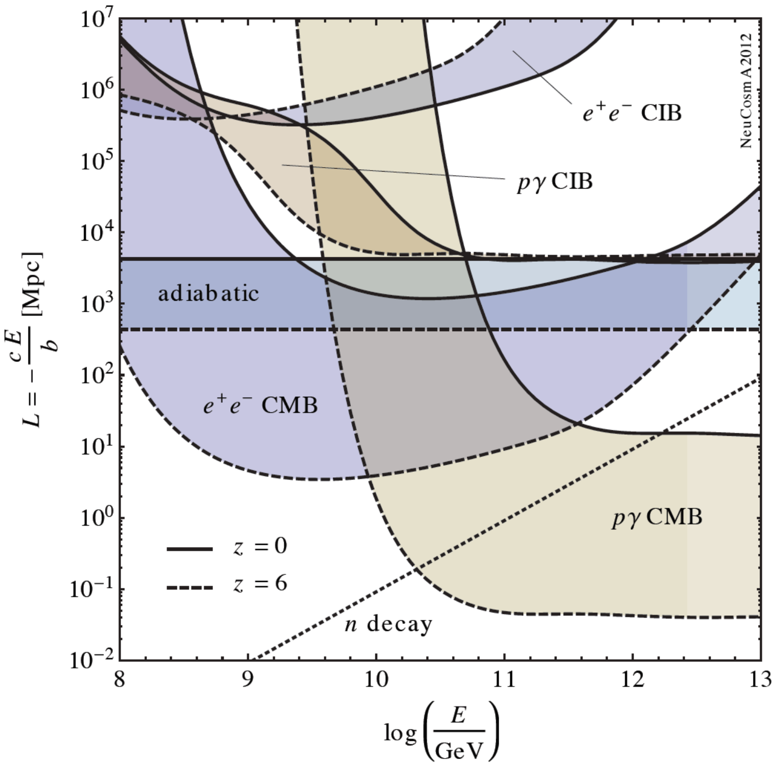
Key issue: Cosmic ray transport. Example: UHECR, protons

- Kinetic equation for co-moving number density: [here $b=-dE/dt=-E\, t^{-1}_{loss}$]

$$\dot{Y}_p = \partial_E \left(H E Y_p \right) + \partial_E \left(b_{e^+e^-} Y_p \right) + \partial_E \left(b_{p\gamma} Y_p \right) + \mathcal{L}_{\rm CR}$$

Expansion of Universe	Pair production **Blumenthal, 1970**	Photohadronics **e.g. SOPHIA**	CR inj.

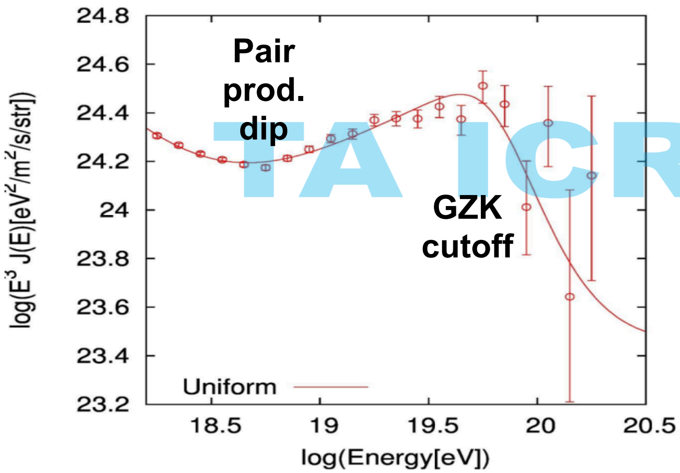
- Interactions with CMB and cosmic infrared background (CIB)
- Attenuation
  ⇨ UHECR must from from our local environment
  (~ 1 Gpc at 10^{10} GeV,
  ~ 50 Mpc at 10^{11} GeV)



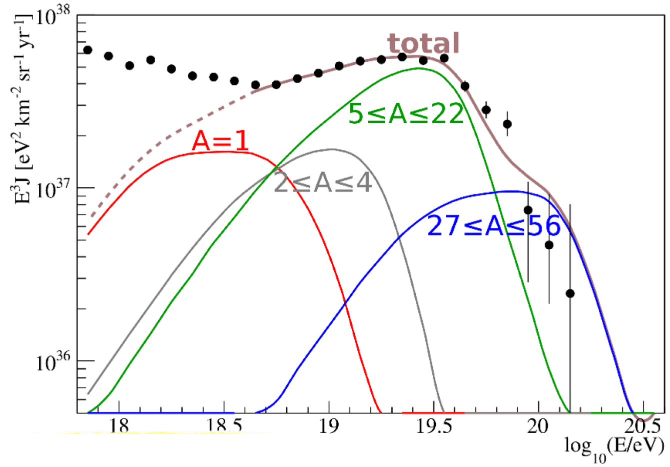
M. Bustamante

Current theoretical paradigms (UHECRs)

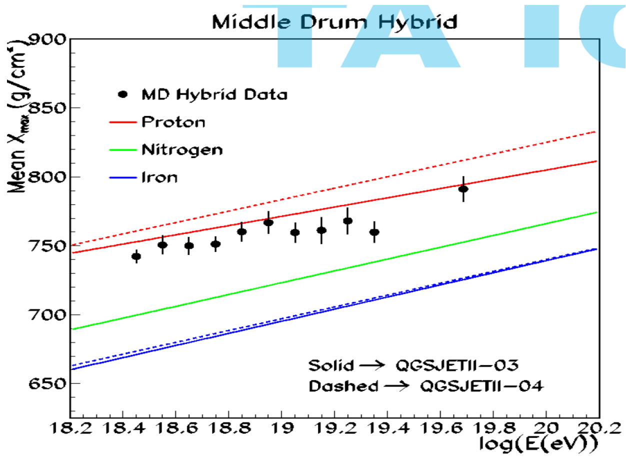
TA (Telescope Array) vs. Auger

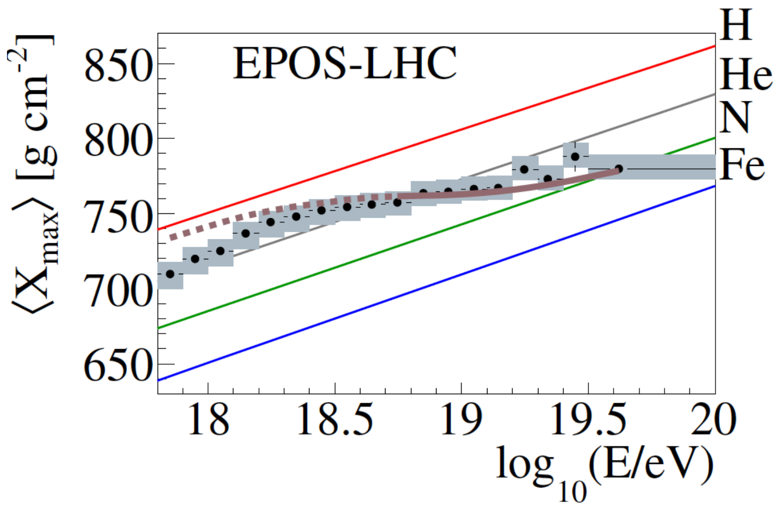


Jui @ ICRC 2015



Ghia @ ICRC 2015



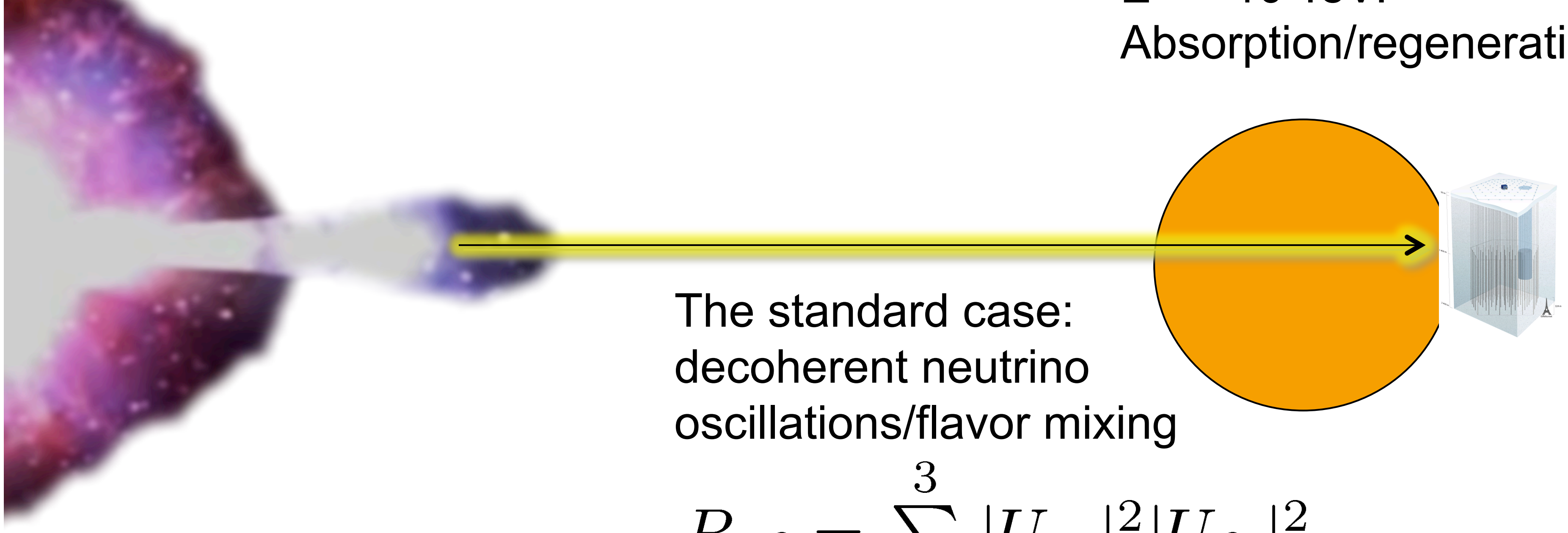


Is this a plausible scenario?
What can neutrinos tell us?

Meet the messengers: Neutrinos

- Neutral particles, extremely small mass, weak interaction
- Come in three flavors: ν_e, ν_μ, ν_τ
- Neutrino propagation:

E >> 10 TeV:
Absorption/regeneration

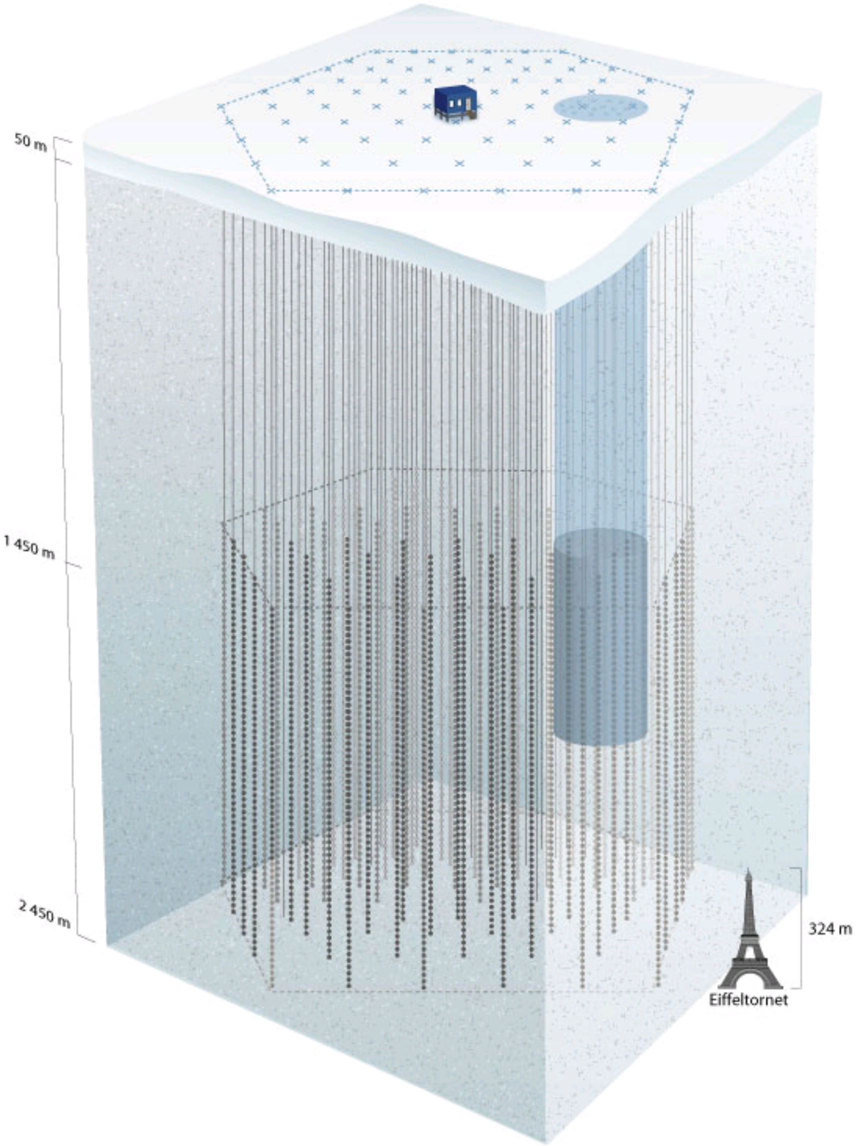


The standard case:
decoherent neutrino
oscillations/flavor mixing

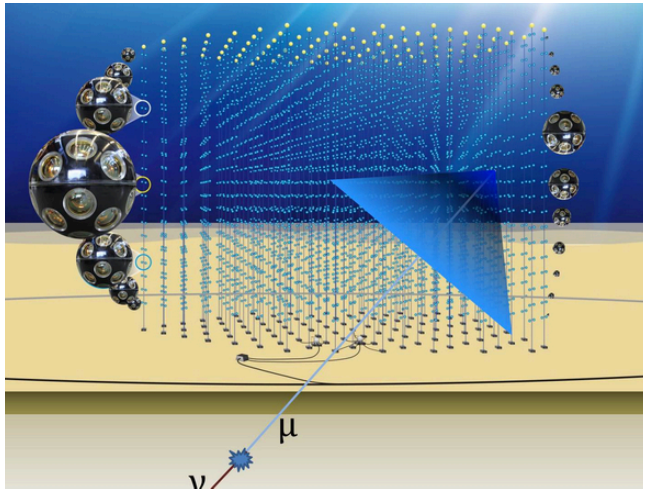
$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Source ν_e:ν_μ:ν_τ = 1:2:0 ➔ Detector 1:1:1
+ redshift of energy if cosmological distance

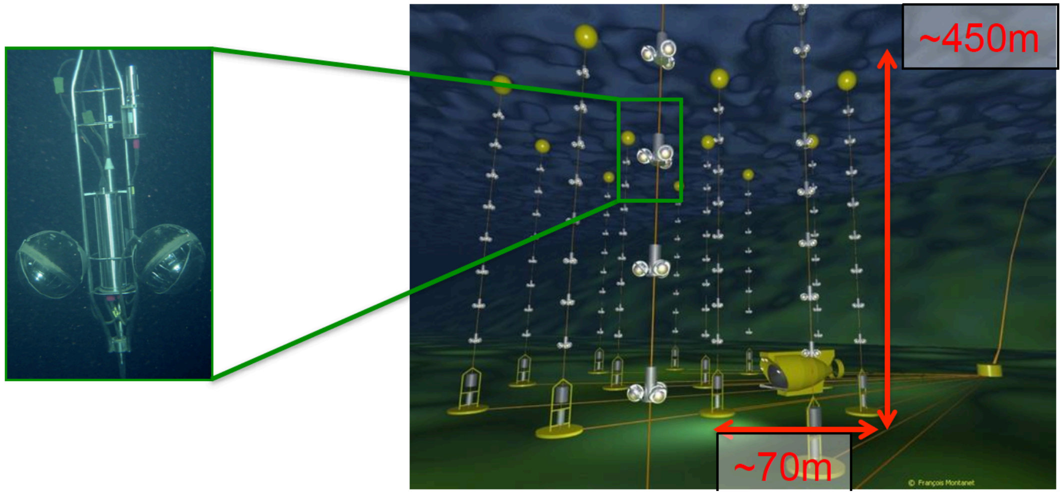
Neutrino telescopes



IceCube



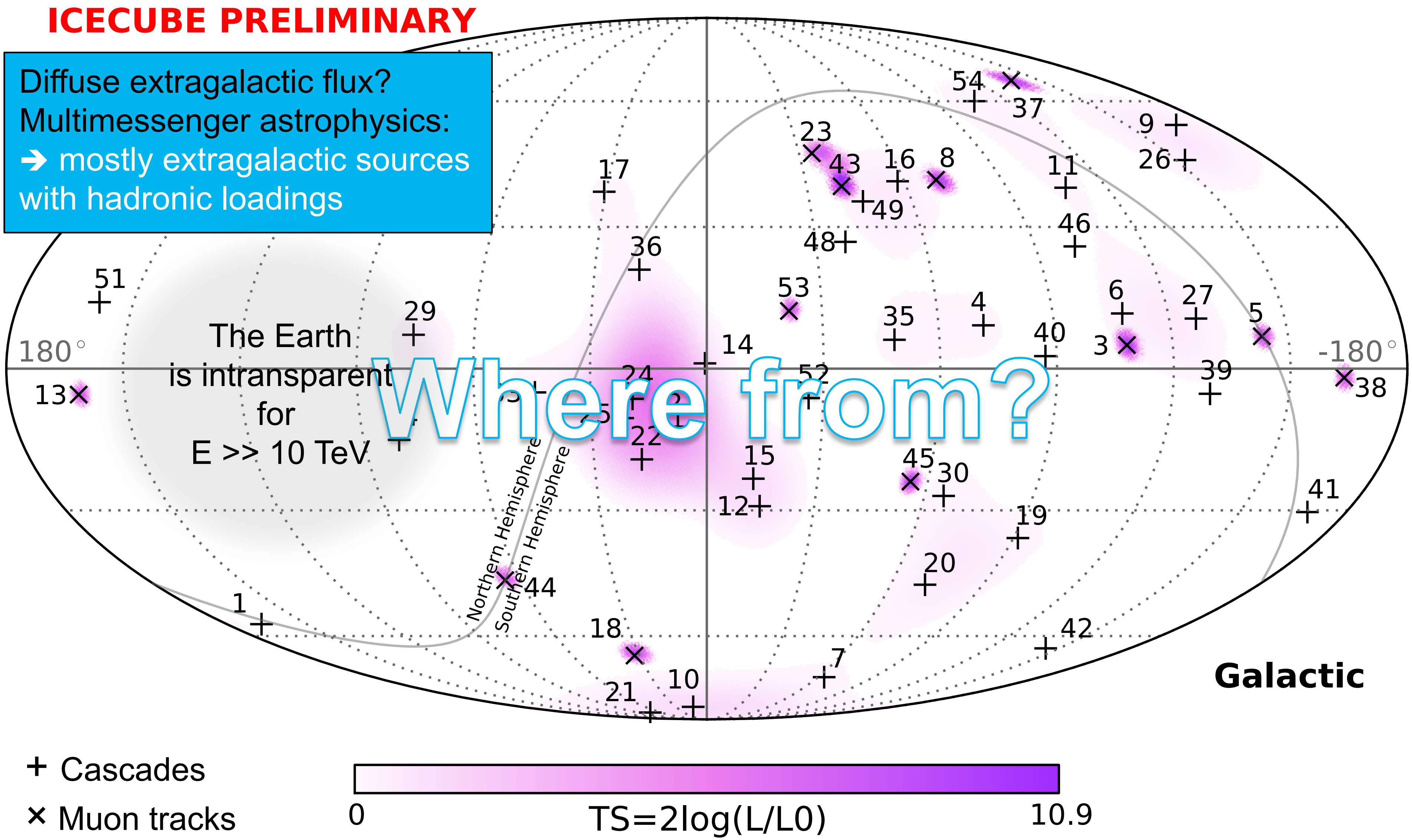
ANTARES/KM3NeT



See lectures C. Finley

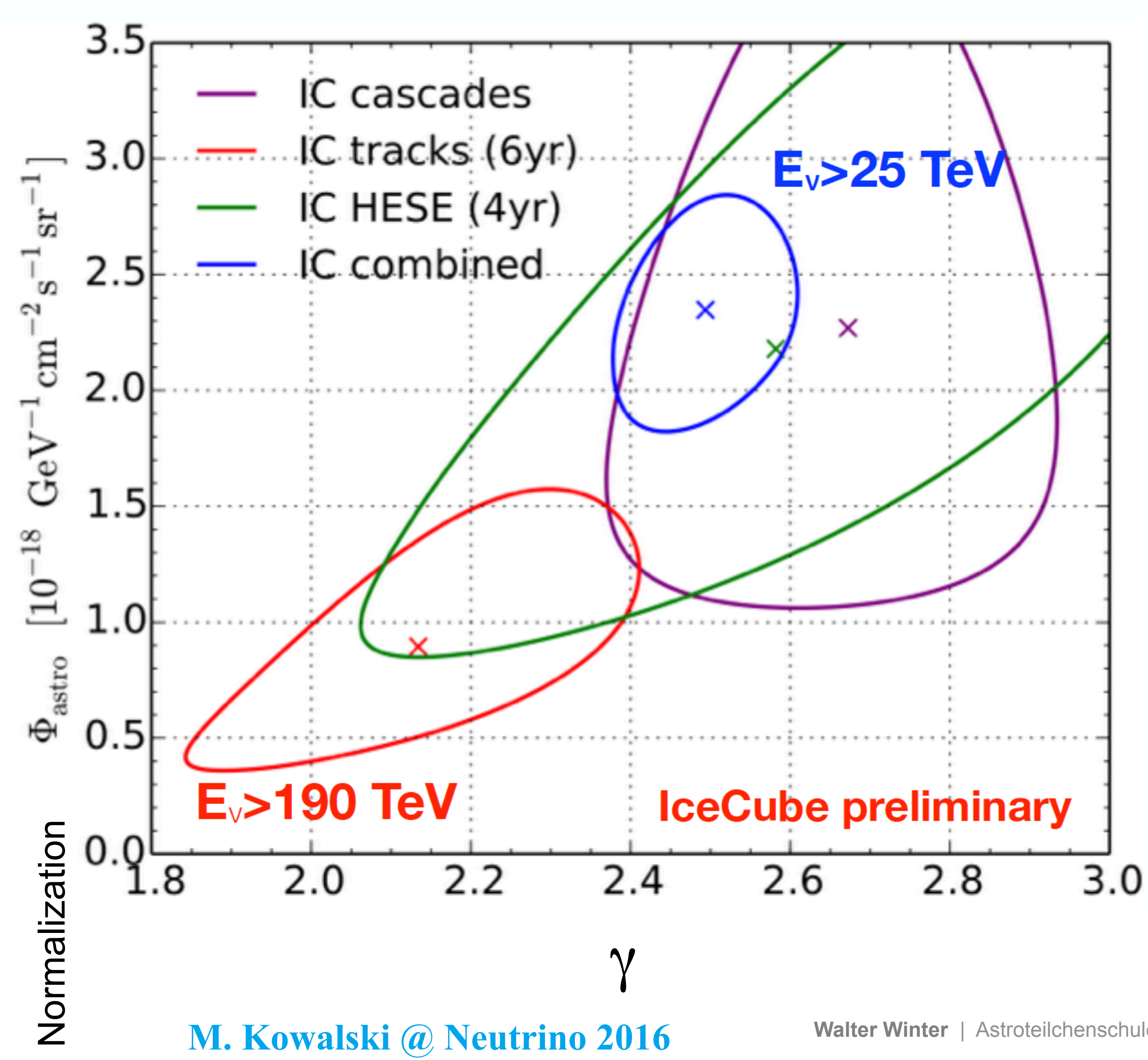
2015: 54 high energy cosmic neutrinos

Diffuse extragalactic flux?
Multimessenger astrophysics:
➔ mostly extragalactic sources with hadronic loadings



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

Neutrino spectrum: Power law fits $(E_\nu)^{-\gamma}$

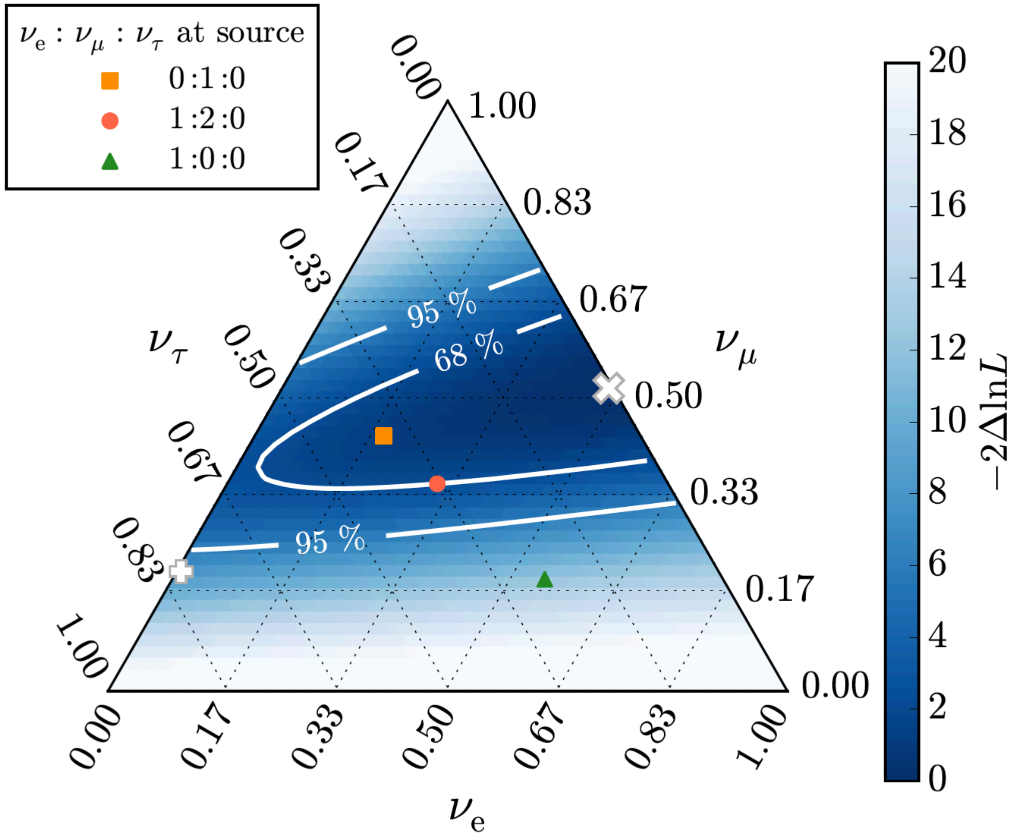


M. Kowalski @ Neutrino 2016

- Tension in different data sets?
- Flattening of spectrum? Different components?
- Softer galactic component, together with harder extragalactic one?

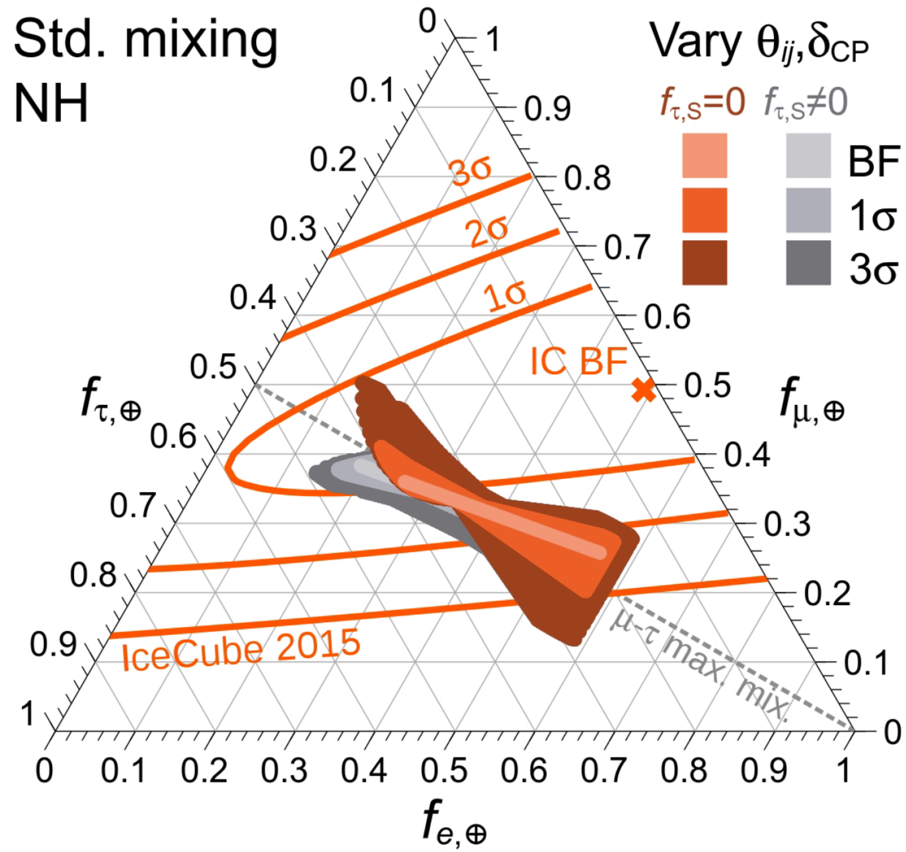
Neutrinos: Flavor composition

- **Measurement**



IceCube measurement
Astrophys. J. 809 (2015) 1, 98

- **Standard Model expectation**



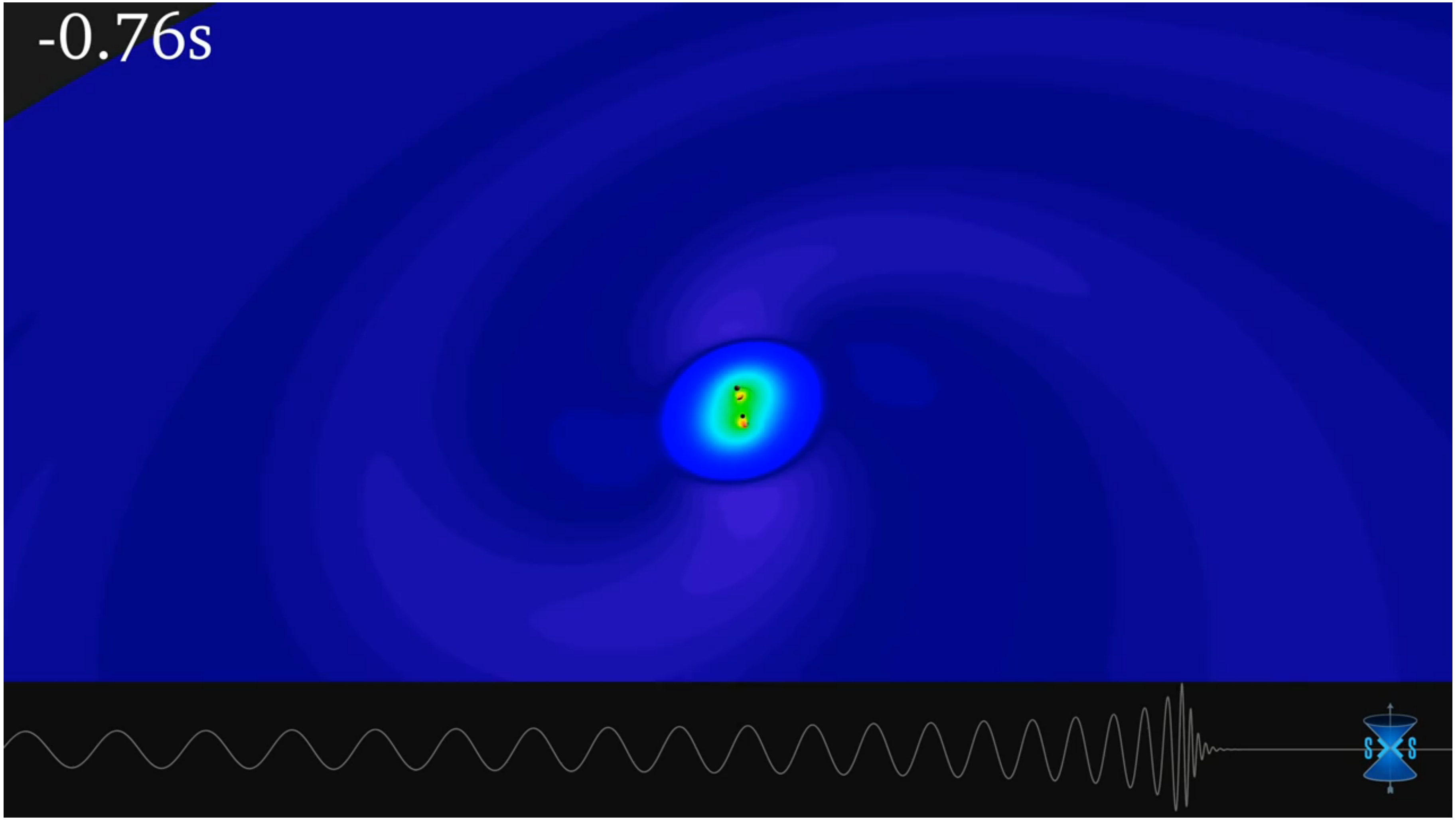
Bustamante, Beacom, Winter,
PRL 115 (2015) 16, 161302

(there is a marginal tension … hint for new physics???)

Meet the messengers: Gravitational waves

GW

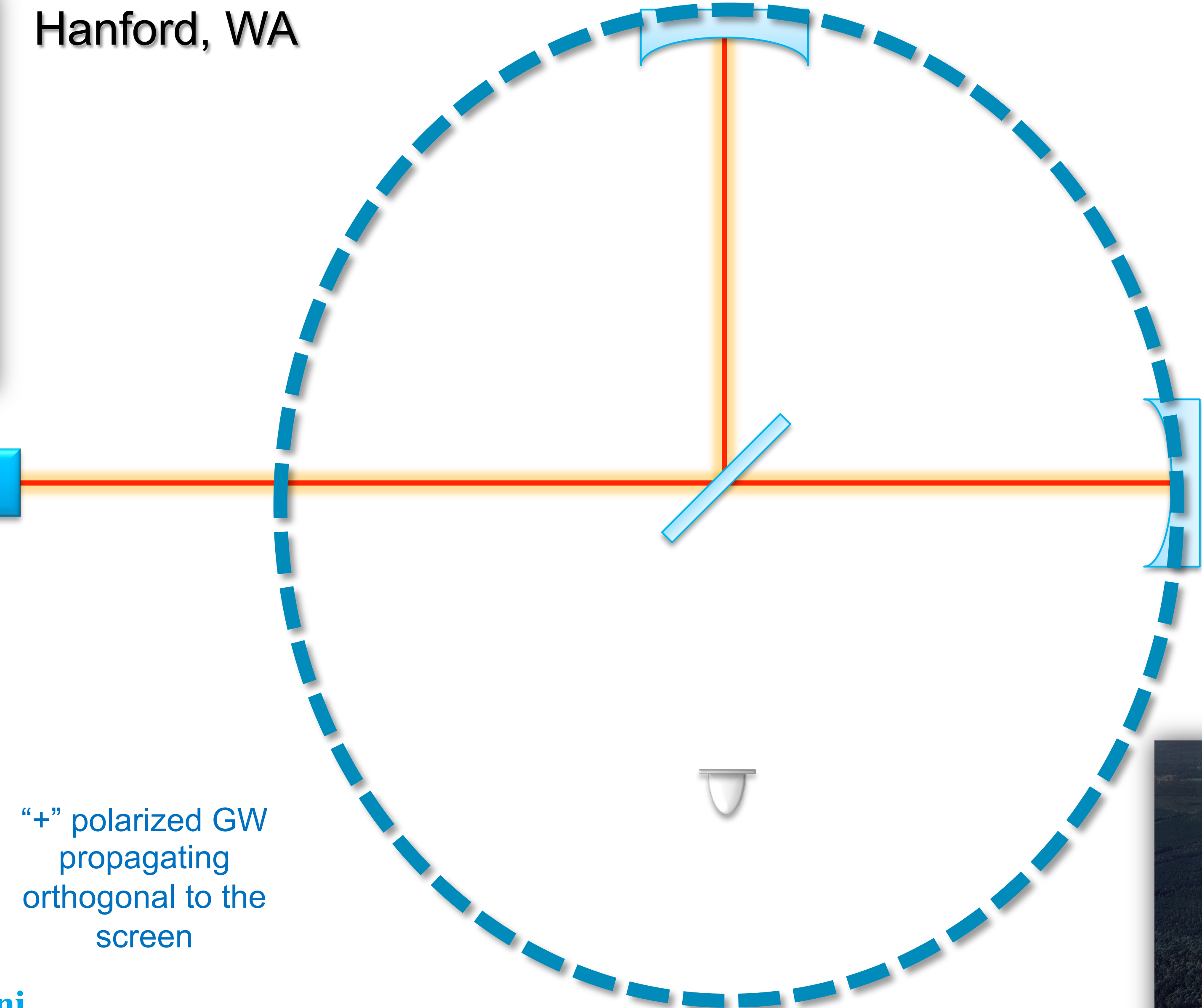
> Fluctuations of metric tensor – general relativity. Black hole merger:



SXS Collaboration/Canadian Institute for Theoretical Astrophysics/SciNet

Key experiments: Advanced LIGO

Hanford, WA

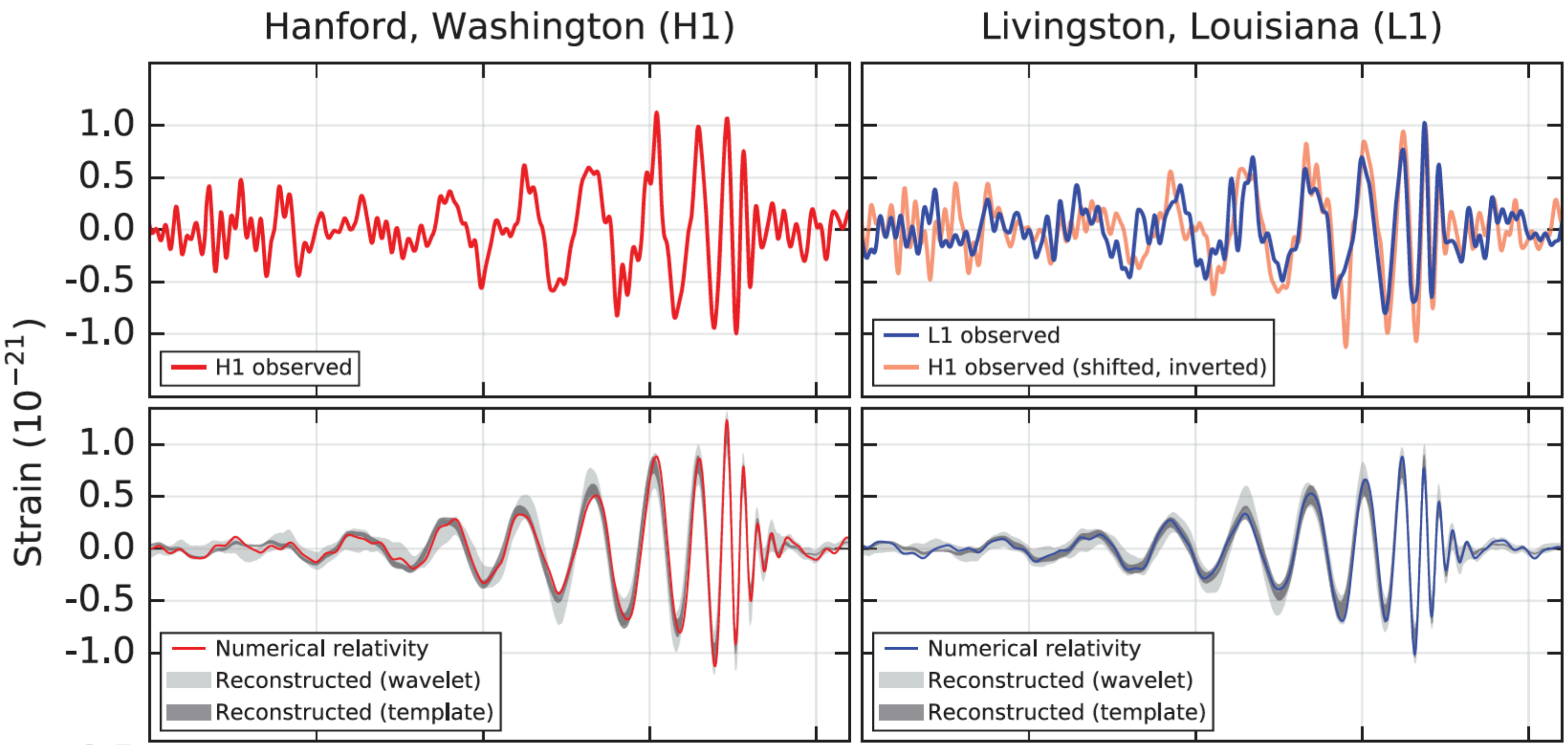


Livingston, LA

Giacomo Ciani

Experimental results

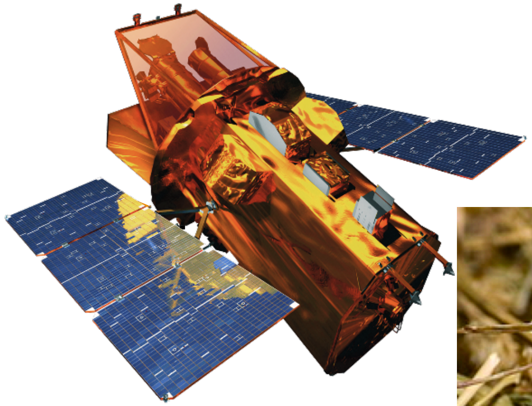
> Currently two evident events, from black hole mergers: GW150914, GW151226

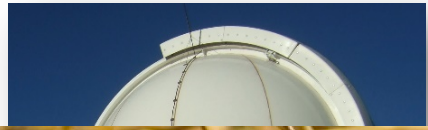


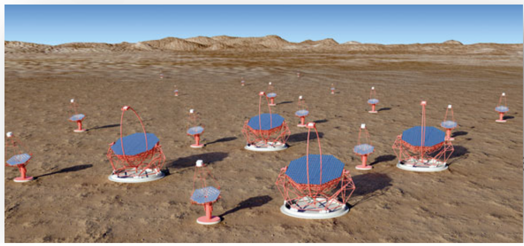
Ligo/Virgo, PRL 2016 x 2, Figure: GW 150914

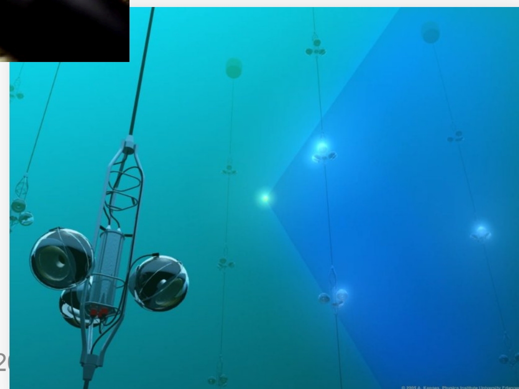
> First estimates for BH-BH merger rates ~9-240 Gpc^{-3} yr^{-1} arXiv:1606.04856

Multi-messenger follow-ups … found nothing!



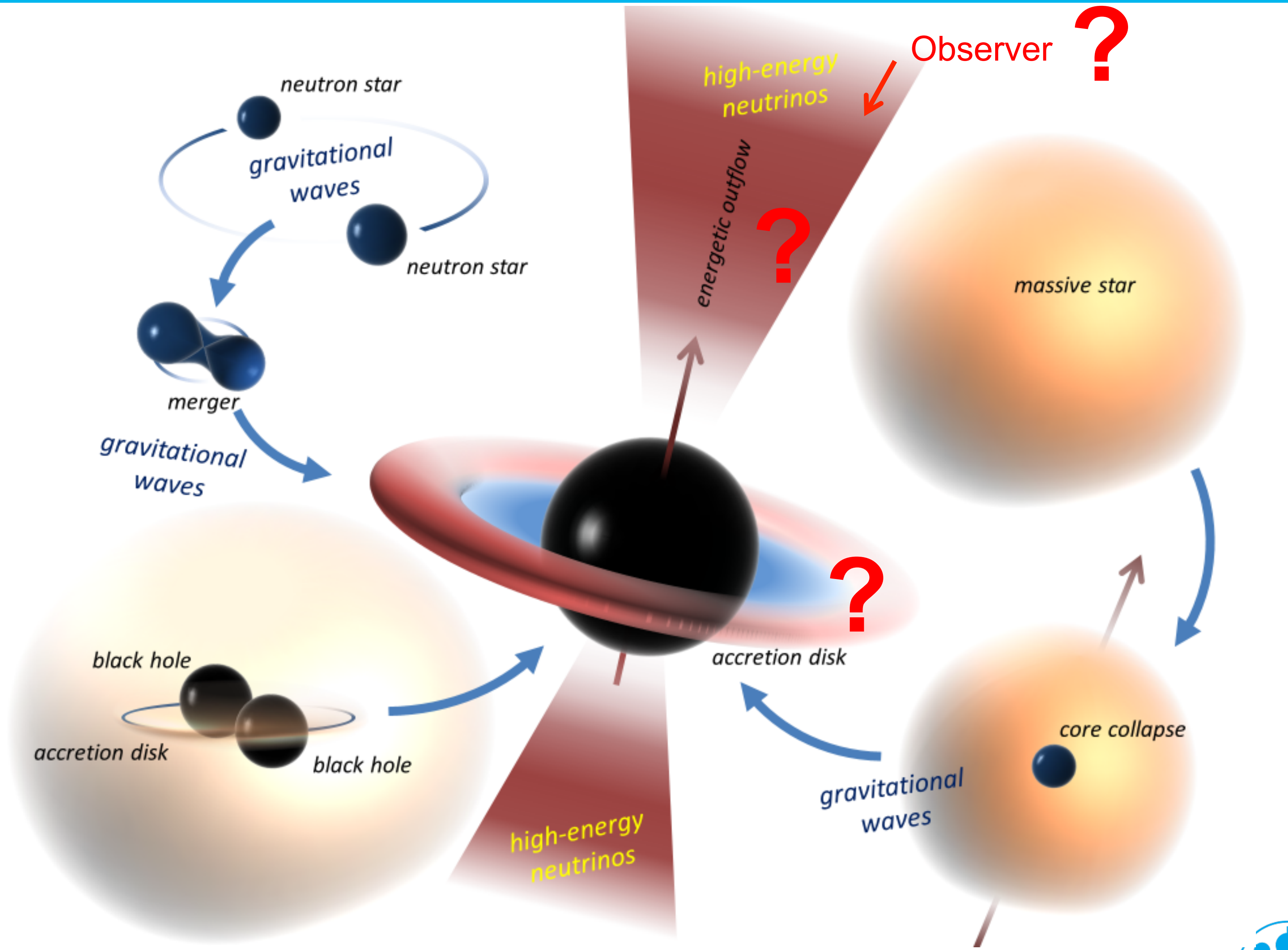






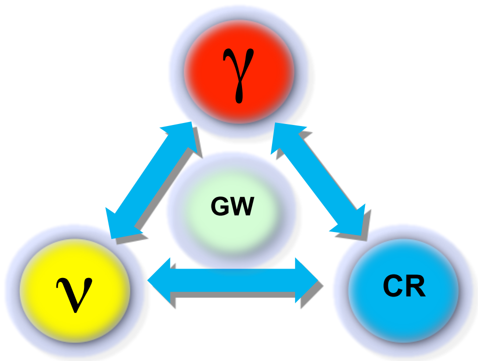
Bartos @ Neutrino 2016

Theoretical paradigms?

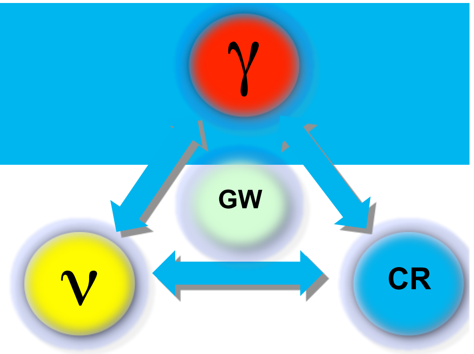


Bartos+ 2016; see e.g. arXiv:1602.06961, arXiv:1602.06938, arXiv:1609.09832 for theory papers

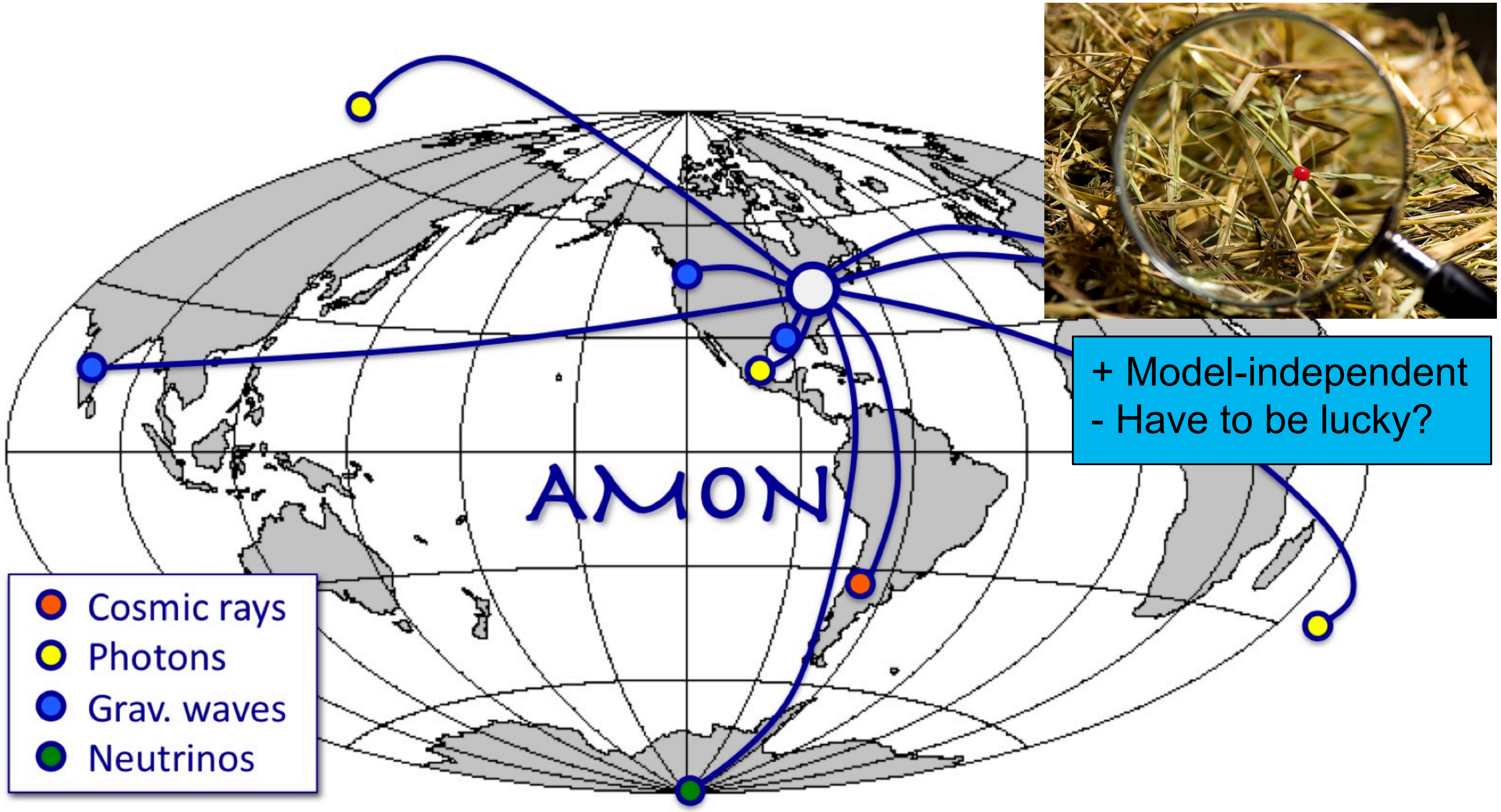
Examples for generic multi-messenger approaches



Observational strategies: Transients



- Example:
  Astrophysical Multimessenger Observatory Network
- Triggers from observatories watching large portion of sky

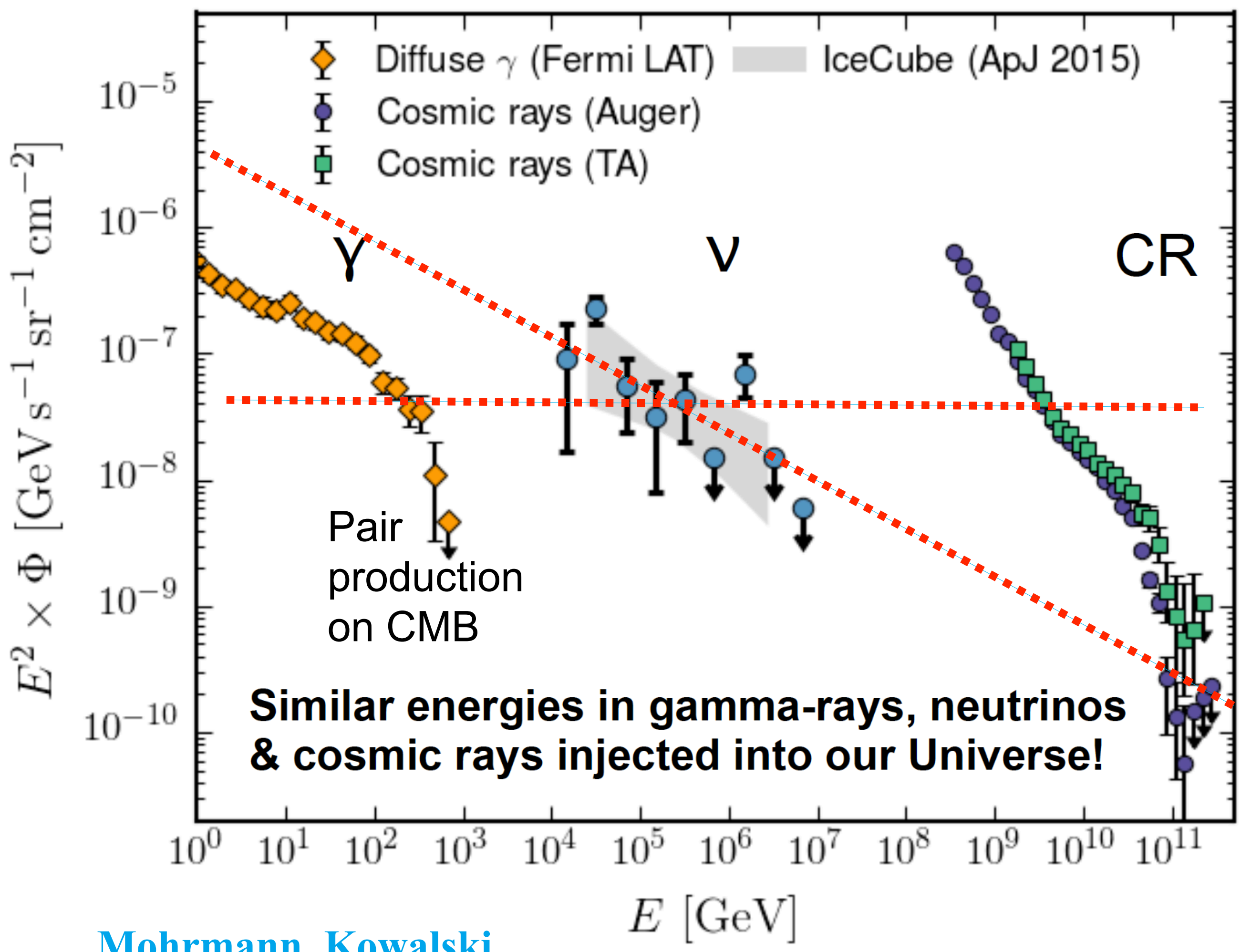


+ Model-independent
- Have to be lucky?

Waxman-Bahcall argument

- Neutrino flux compatible with expectation from UHECR injection (if efficient secondary production)
  Waxman, Bahcall, 1999

- Caveats:
  - Extrapolation over many order of E
  - If not E^{-2}, imbalance in energy

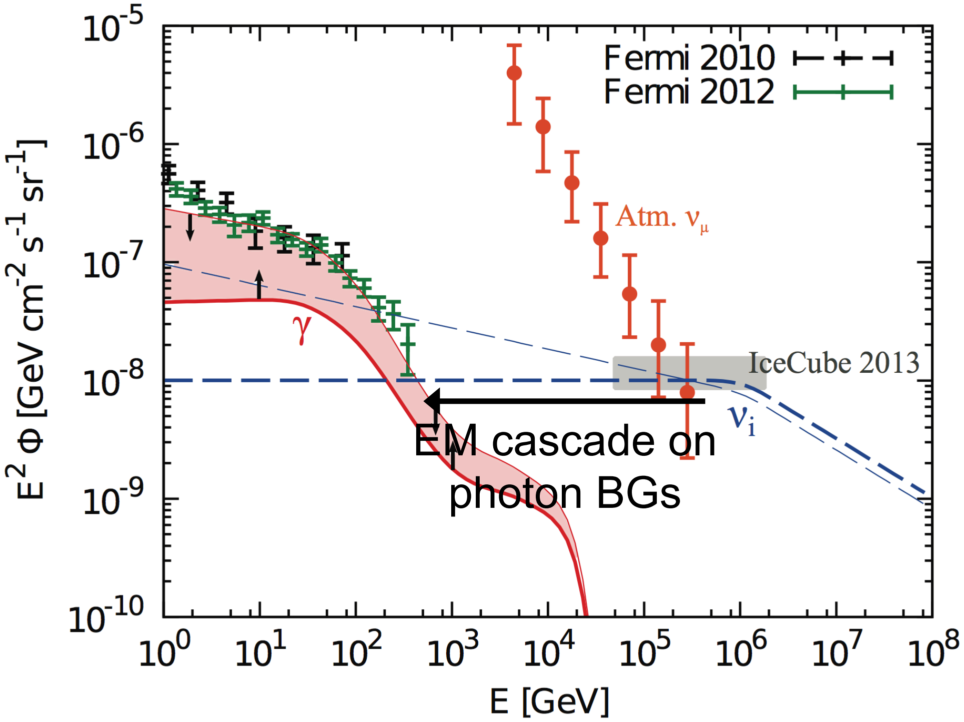


Mohrmann, Kowalski

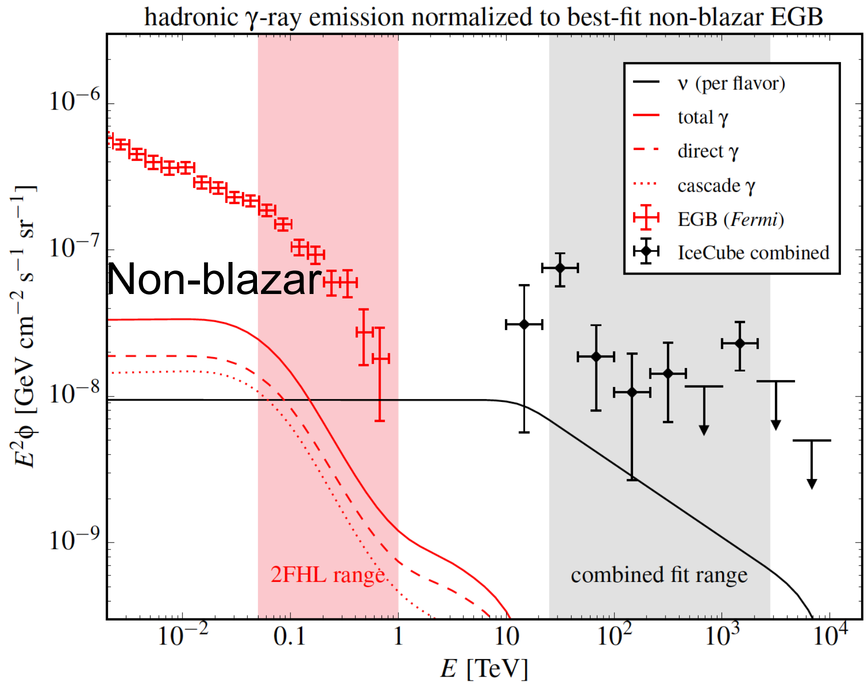
Constraints from diffuse γ-rays (Fermi)

- Recall that π^0 (→ γ) and $\pi^\pm$ (→ ν) are produced together.
  Model-independent constraints? [works well for pp sources]

- Saturate diffuse extragalactic γ-ray background:



Murase, Ahlers, Lacki, 2013



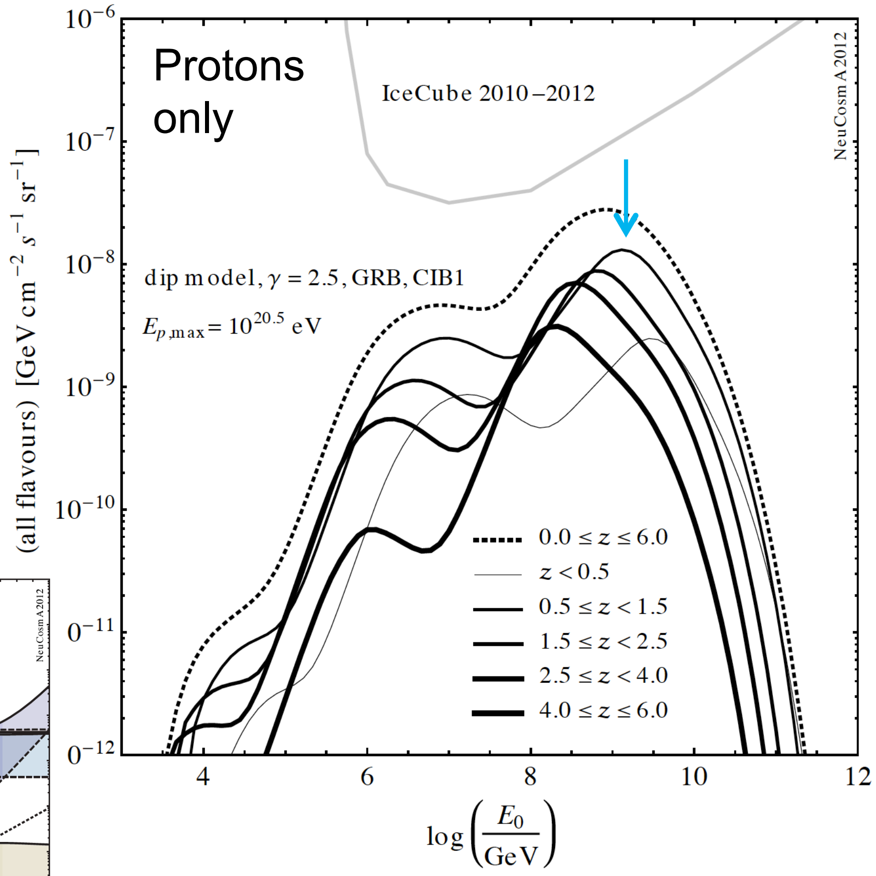
Bechtol et al, arXiv:1511.00688

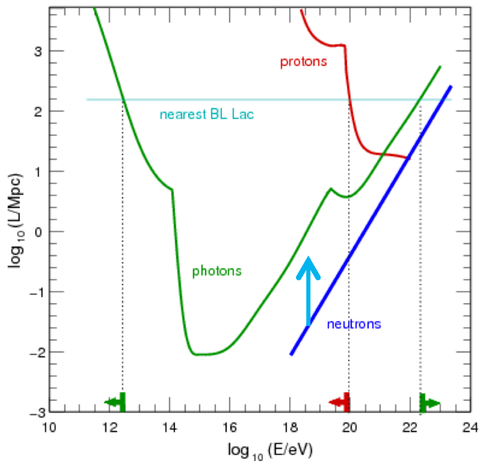
- The problem is actually more severe: the non-blazar contribution to the extragalatic γ-ray background is small (e.g. from starburst galaxies)

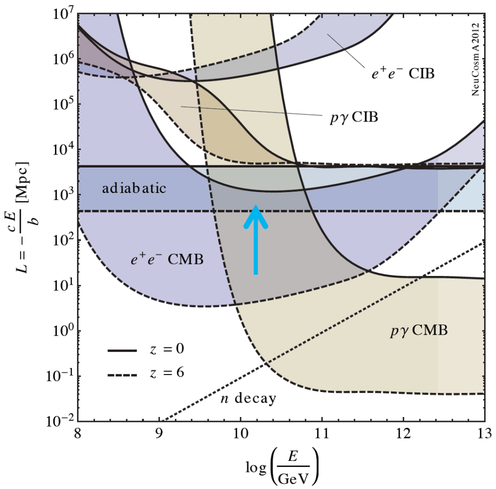
Cosmogenic neutrinos

$$p + \gamma_{\text{CMB}} \to \Delta^+ \to \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

- Neutrinos probe the Universe beyond the local environment →
- Example:
  E_ν ~ ¼ 0.2 E_p ~ 0.05 E_p
  E_γ ~ ½ 0.2 E_p ~ 0.10 E_p
  Attenuation length (z=0):
  γ ~1 Mpc, Proton ~1 Gpc (z ~0.3)



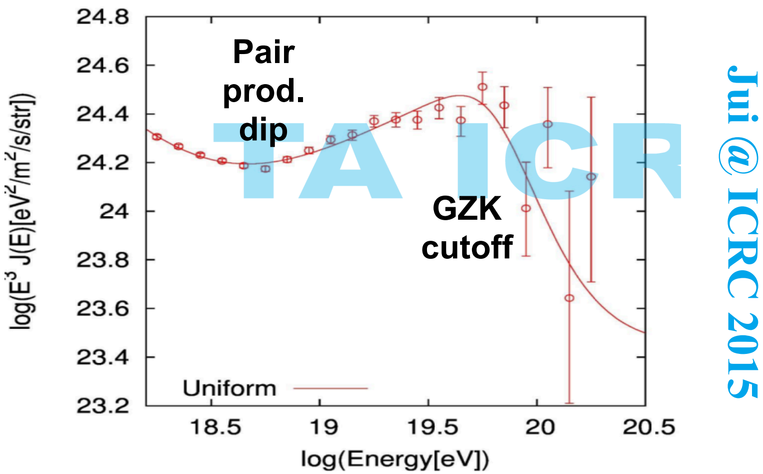




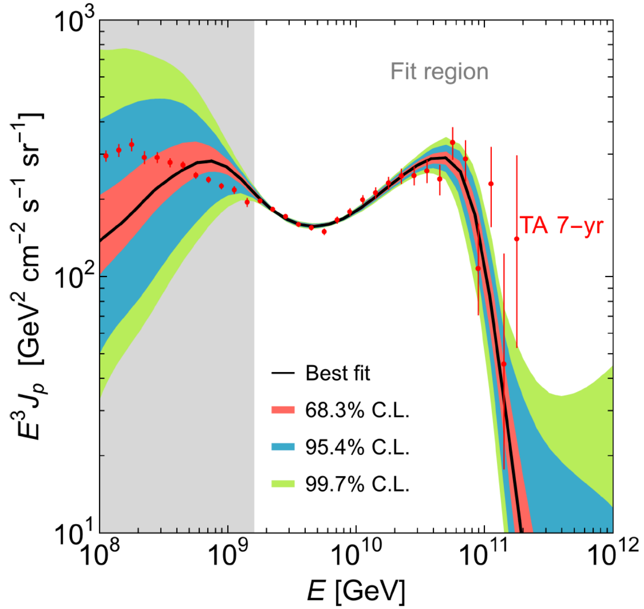
M. Bustamante

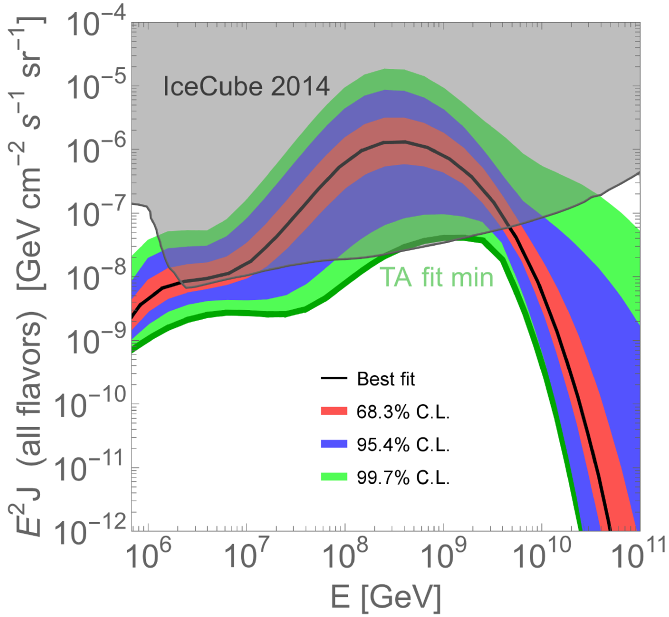
Neutrino bound on proton dip model

- Re-call proton dip model paradigm
  Berezinsky, Gazizov, Grigorieva, ~2005



- 3D fit of 7-year TA data in tension cosmogenic neutrinos
  Heinze, Boncioli, Bustamante, Winter, Astrophysical Journal 825 (2016) 122





What does it mean?

Heavier composition?

Transition at ankle?

- Similar arguments from γ-ray BG e. g. Supanitsky, 2016

Describing interactions (blackboard)

Contents

Lecture 1

> Particle astrophysics of hadronic sources (basic concepts)

> Radiation models (blackboard)

Lecture 2

> Meet the messengers:
  - Photons
  - Cosmic rays
  - Neutrinos
  - Gravitational waves

> Examples for generic multi-messenger approaches

> Describing interactions (blackboard)

Lecture 3

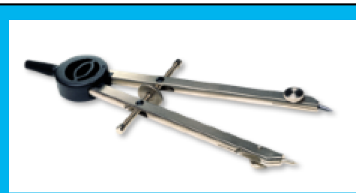
> Challenges for multi-messenger approaches ← Incl. special feature: stacking analyses

> Energetics of sources (blackboard)

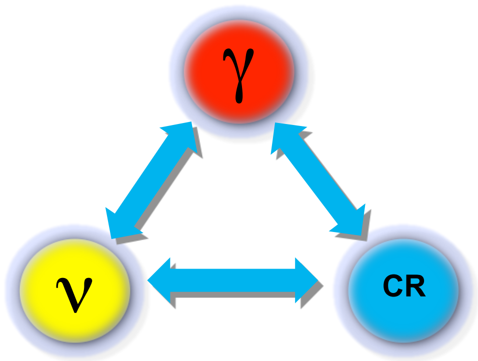
> How to address the key challenges; example: GRBs

DISCLAIMER:
Apologies if specific experiments or theoretical results are not mentioned. It is impossible to review this subject completely.

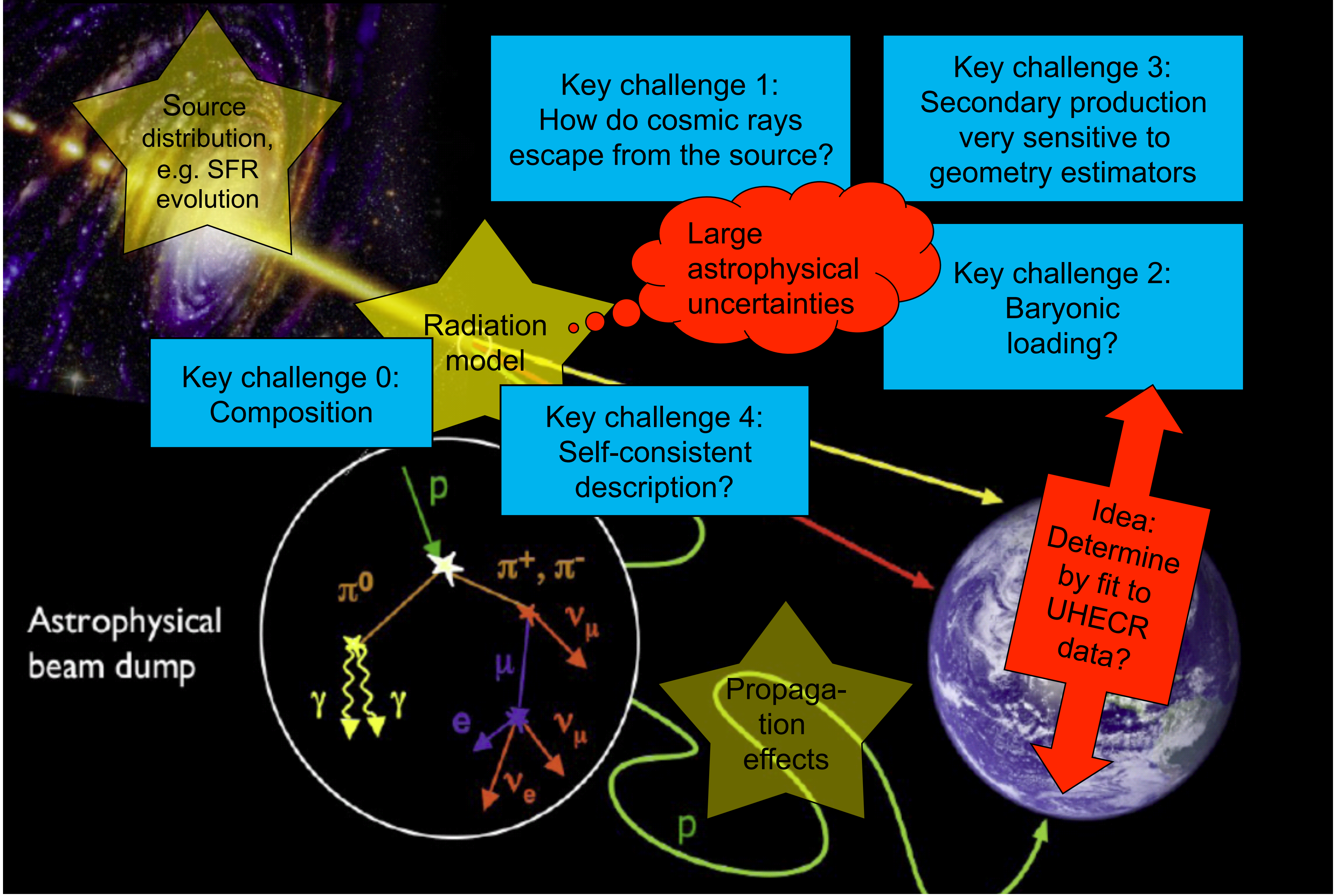
Relevant for exercises



Challenges for
multi-messenger approaches
(including special feature on stacking analyses)



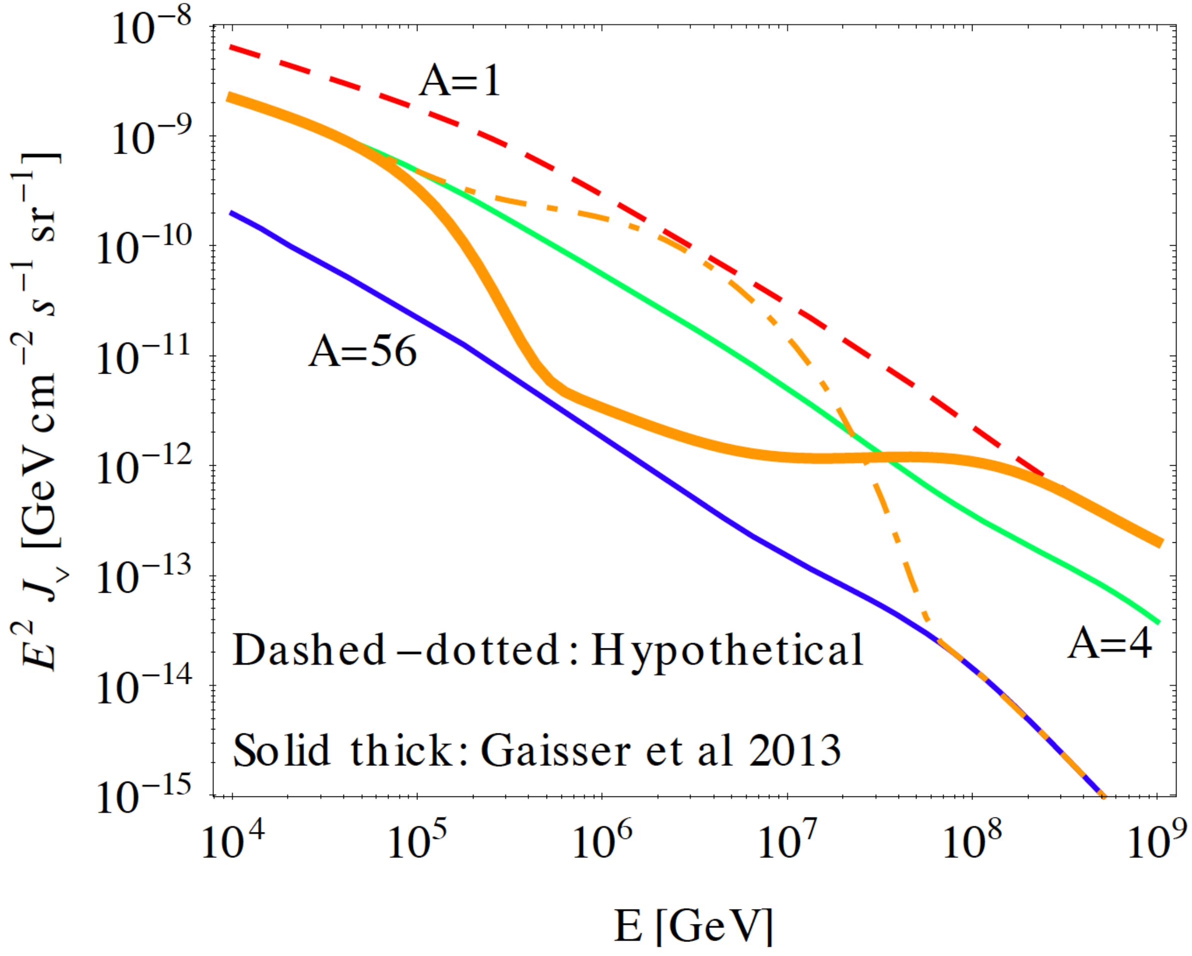
Challenges for multi-messenger analyses and models

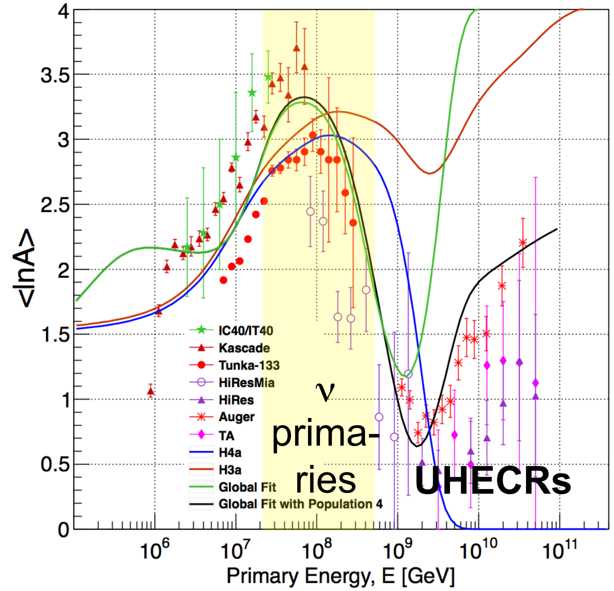


Neutrinos from CR interactions in our galaxy

ν ↔ CR

- If the protons deviate from E^{-2} (as we observe), the neutrino spectrum strongly depends on composition





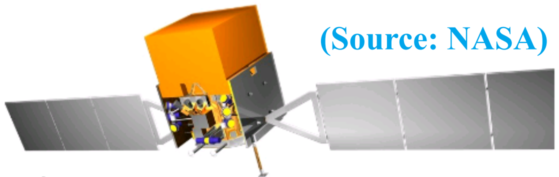
Gaisser, Stanev, Tilav, 2013

Key challenge 0: Composition

Joshi, Gupta, Winter, MNRAS 439 (2014) 3414

Multimessenger stacking analyses

ν ⟷ γ



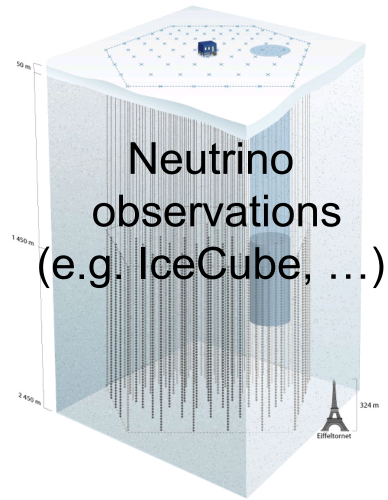
(Source: NASA)

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

A)

Coincidence!

B)



Neutrino observations
(e.g. IceCube, …)

(Source: IceCube)

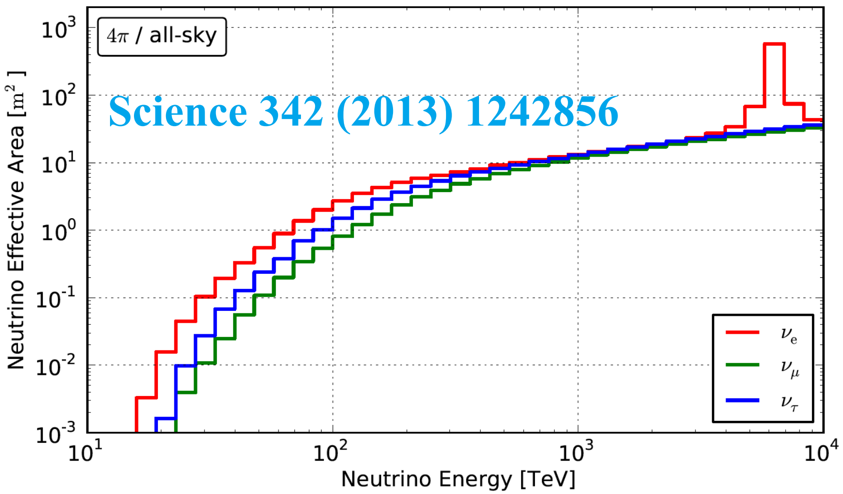
- Constrain the flux in messenger B) for individual similar-type objects observed in messenger A) (typically photons in different energy bands, such as X-rays, γ-rays)
- Use timing (transients, flares), directional or energy information to reduce backgrounds and filter out the relevant information from messenger B)
- Effective background reduction techniques e.g. for neutrinos (Atmospheric backgrounds are suppressed by “duty cycle” of observation, energy cuts or directional cuts)

Stacking analysis, illustrated (e.g. neutrinos, transients)

- Expected number of events from one transient:

$$N_i = \int dE \mathcal{F}_i(E) A_{\rm eff}(E)$$

Effective area $A_{\rm eff}$ typically includes analysis cuts; *fluence* (time-integrated flux from a transient) F_i in units cm^{-2} GeV^{-1}



- The fluence F_i typically has a specified shape and a free normalization, e.g. $\mathcal{F}_i = K \cdot E^{-2}$ (if all sources are alike)

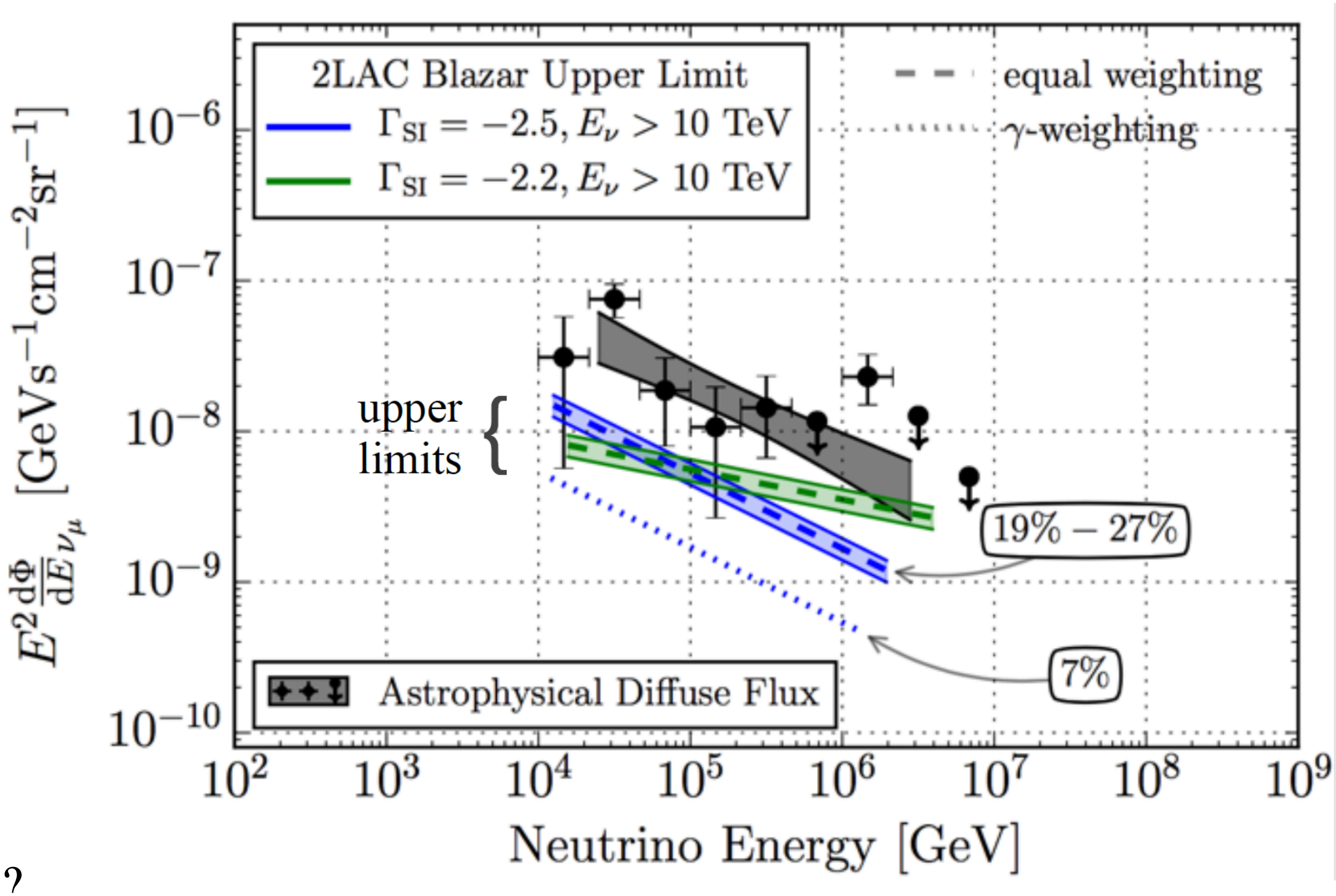
- Expected total number of events $N = \sum_i N_i$ can be translated into a limit on K (e.g. N=2.44 for 90% CL with 0 BG) (Feldman, Cousins, 1998)

- If a prediction or limit for F_i exists, one can convert that into a quasi-diffuse flux $\phi_{\rm QD} \equiv (4\pi)^{-1} \mathcal{F}_i \, \dot{n}$, where $\dot{n}$ is the expected number of transient events (observable in messenger A) per time frame (year)

- *Exercise: How do prediction and limit scale with observation time?*

Real-life example: AGN blazars

- AGN blazar search with 2nd Fermi-LAT catalogue
- Power law shape
- Different assumptions:
  - All F_i alike
  - $F_i^\nu \sim F_i^\gamma$
- However: wouldn't one expect $F_i^\nu \sim (F_i^\gamma)^2$? (Secondary production ~Density^2)



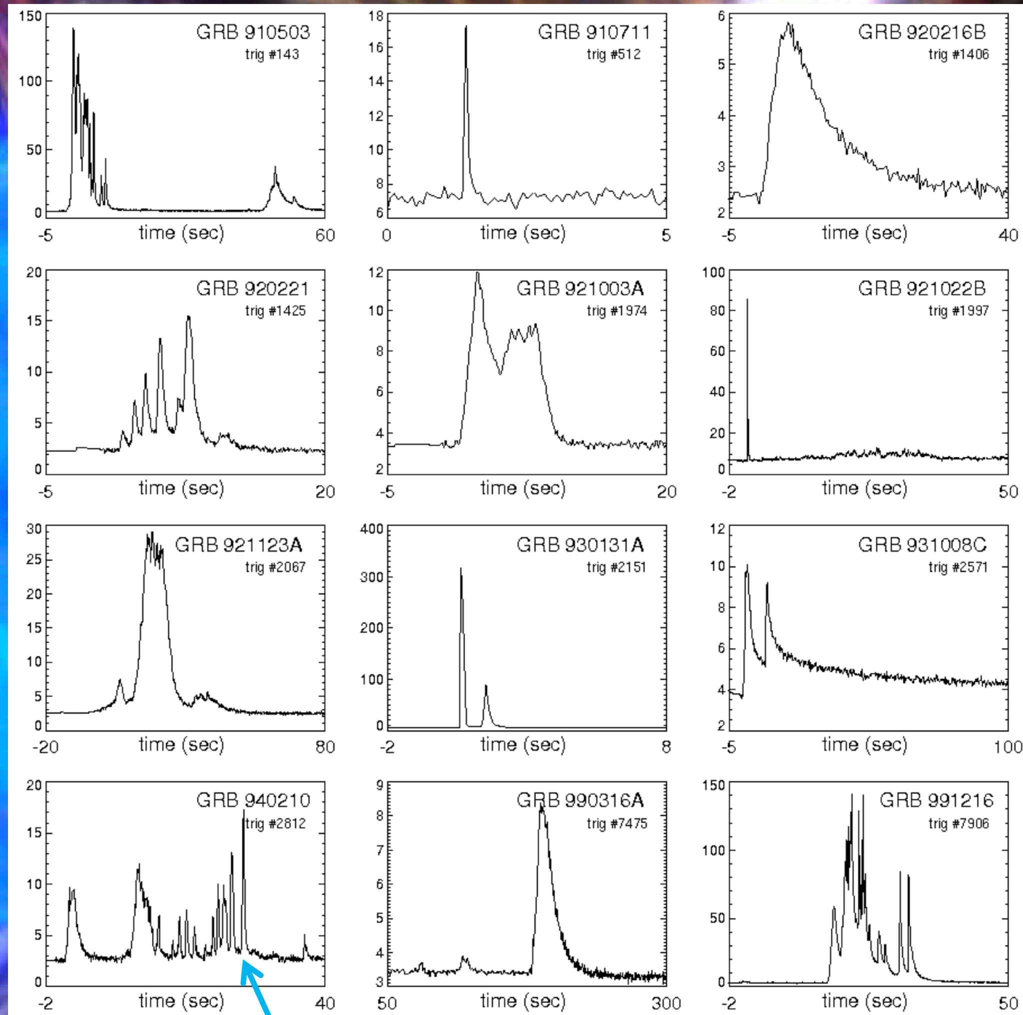
Key challenge 3: Secondary production very sensitive to geometry estimators

(Thorsten Glüsenkamp, arXiv:1502.03104; Kowalski@Neutrino 2016; IceCube to appear; for the experts: see also talk by M. Peptropoulou at TeVPA 2016)

Gamma-ray bursts (GRBs)

- Most energetic 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?
- Typical redshift ~ 1-3 (cosmological distances) Useful as “standard candles”?
- Observed light curves come in large variety →

Daniel Perley

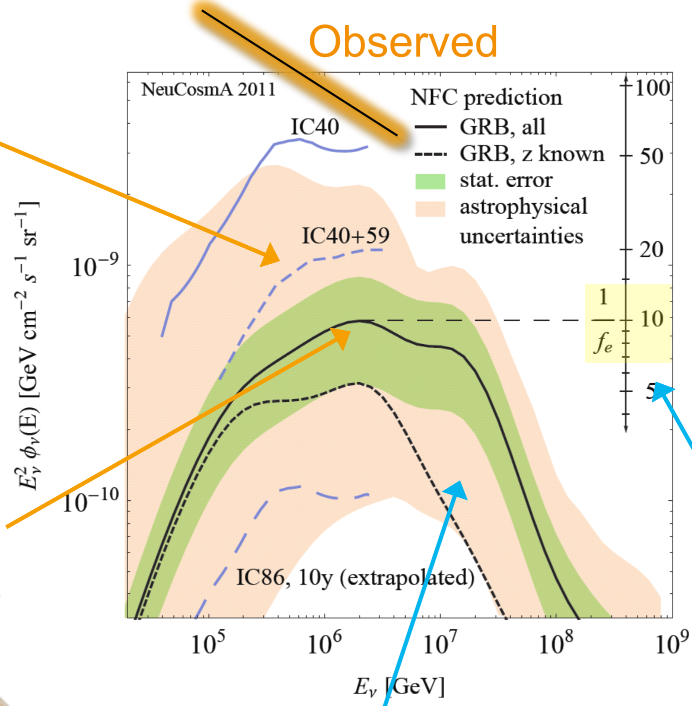


t_V: variability timescale

Source: NASA

GRB stacking analysis

- More sophisticated stacking: Use spectral information and measured properties of GRBs to predict individual GRB expectation
- Need Density ~ Energy / Volume in source
  Geometry estimators (from time variability, Γ) used to compute volume
- Strong limit,
  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, t_v)



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

Key challenge 2: Baryonic loading?

Are the properties inferred from γ-ray observations representative for CR and ν emission?

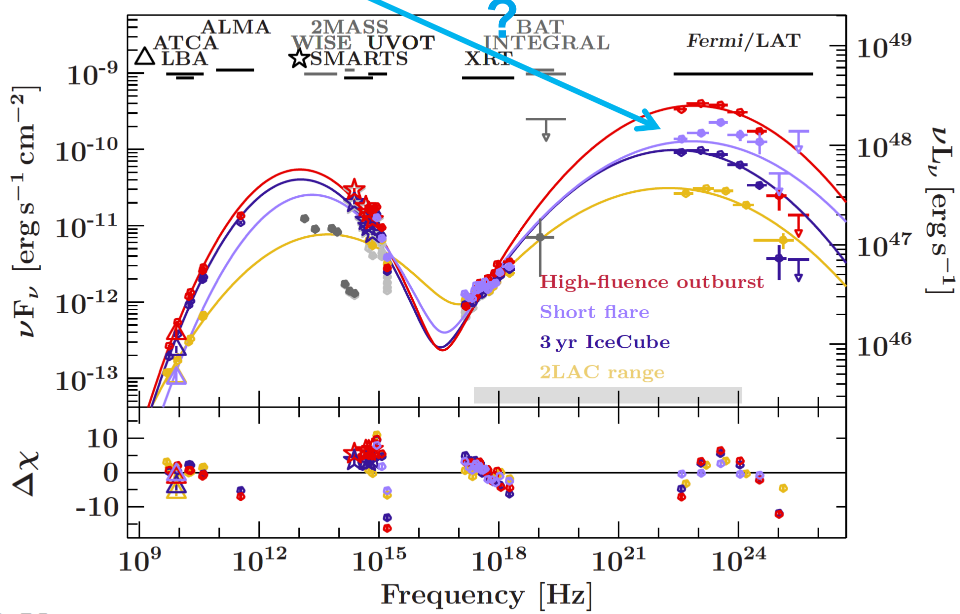
Key challenge 3: Secondary production very sensitive to geometry estimators (pink region)

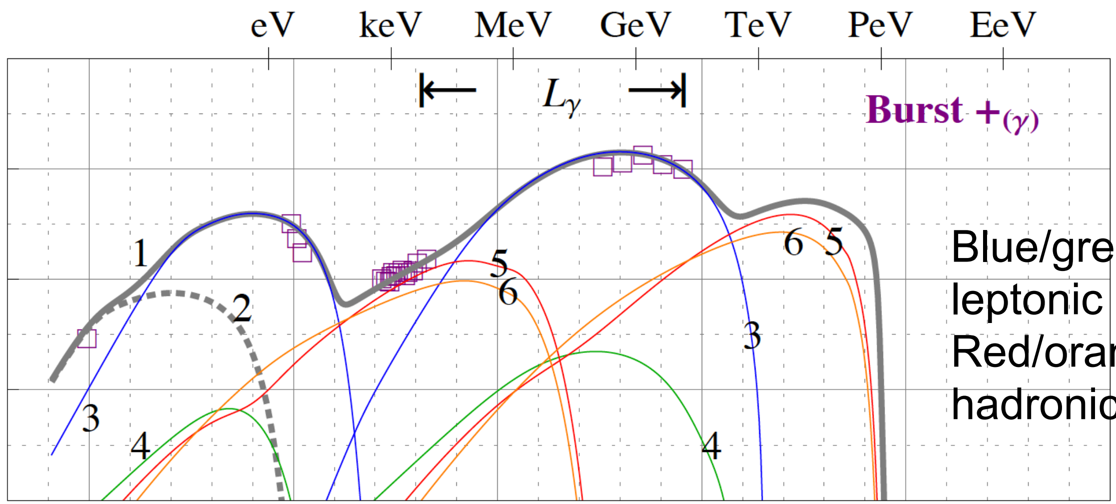
Neutrino production in AGN

ν ⟷ γ

- Re-call connection: $p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$
- Assume that 2nd peak from hadronic γ-rays (from π^0 produced with π^+)
- One neutrino event from blazar PKS B1424-418?

Probem: cannot describe 2nd peak by hadronic processes only in self-consistent model





Key challenge 4: Self-consistent description?

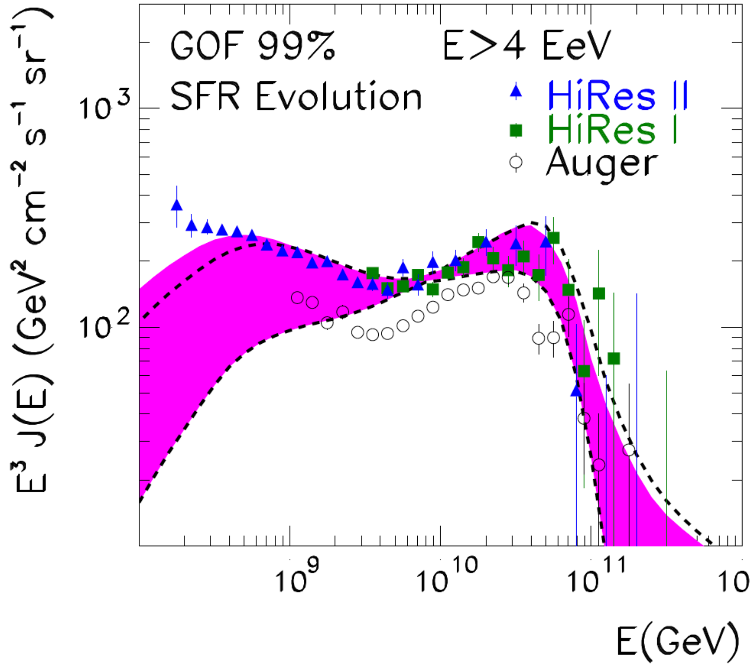
Kadler et al, arXiv:1602.02012, Nature Physics

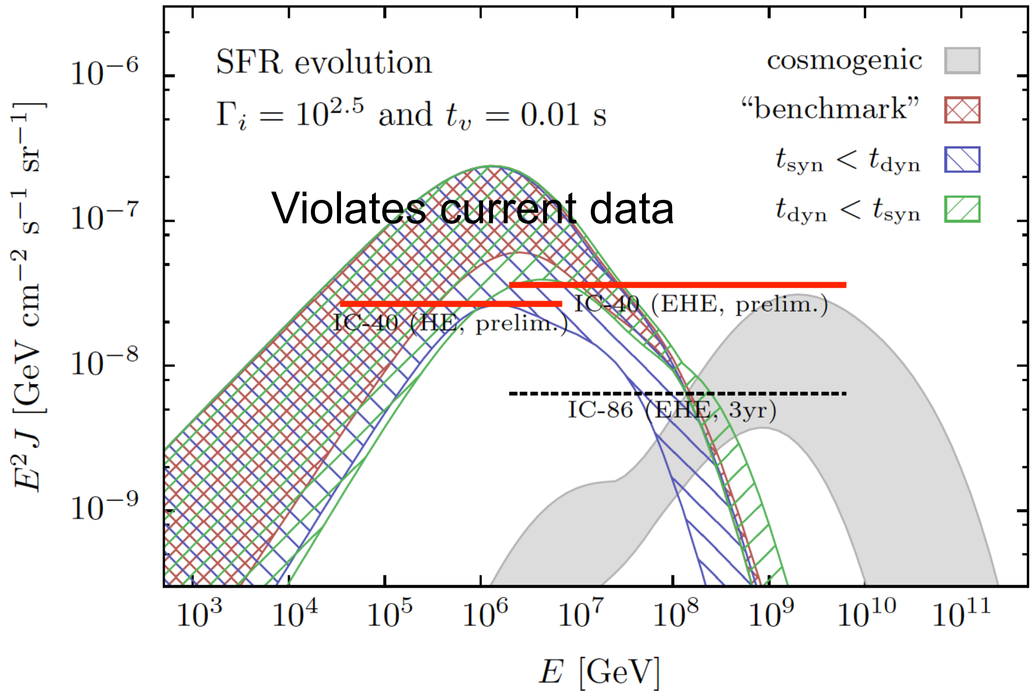
Blue/green: leptonic origin
Red/orange: hadronic origin

Gao, Pohl, Winter, 2016; for working examples: see Petropoulou et al, 2015+

Similar arguments: ν production in GRBs?

- Re-call connection: $p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$





Ahlers, Gonzalez-Garcia, Halzen, Astropart. Phys. 35 (2011) 87

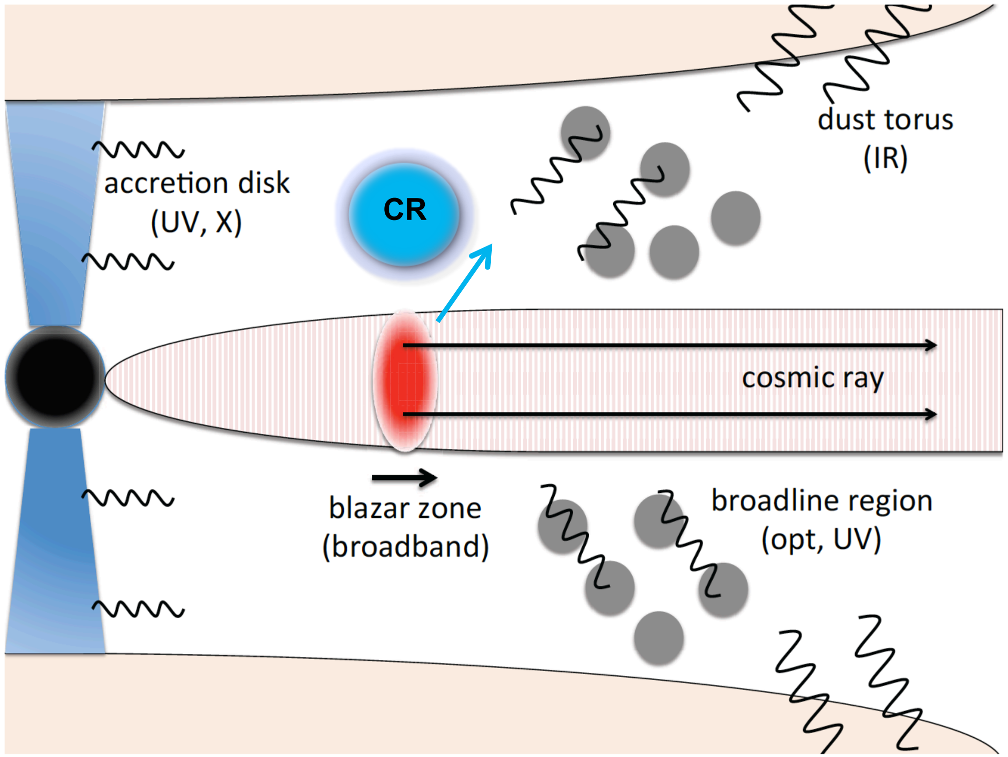
Key challenge 1: How do cosmic rays escape from the source?

Key challenge 2: Baryonic loading?

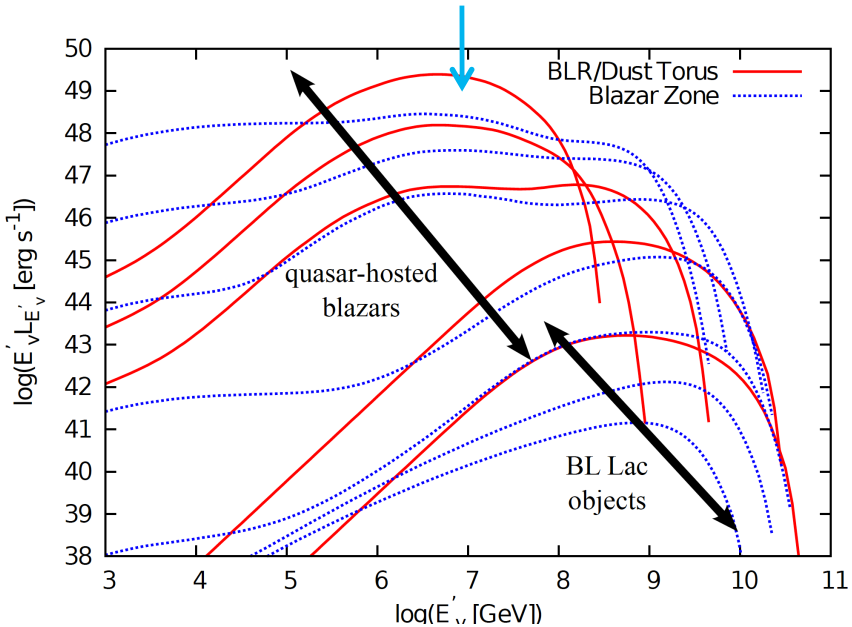
e.g. Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

Neutrinos from protons escaping AGN blazars

- Neutrinos from pion production on external photons may dominate over neutrinos from blazar zone *if the cosmic rays can efficiently escape*



Can the primaries efficiently escape from the blazar zone at 10^8 GeV (here: black hole frame)?



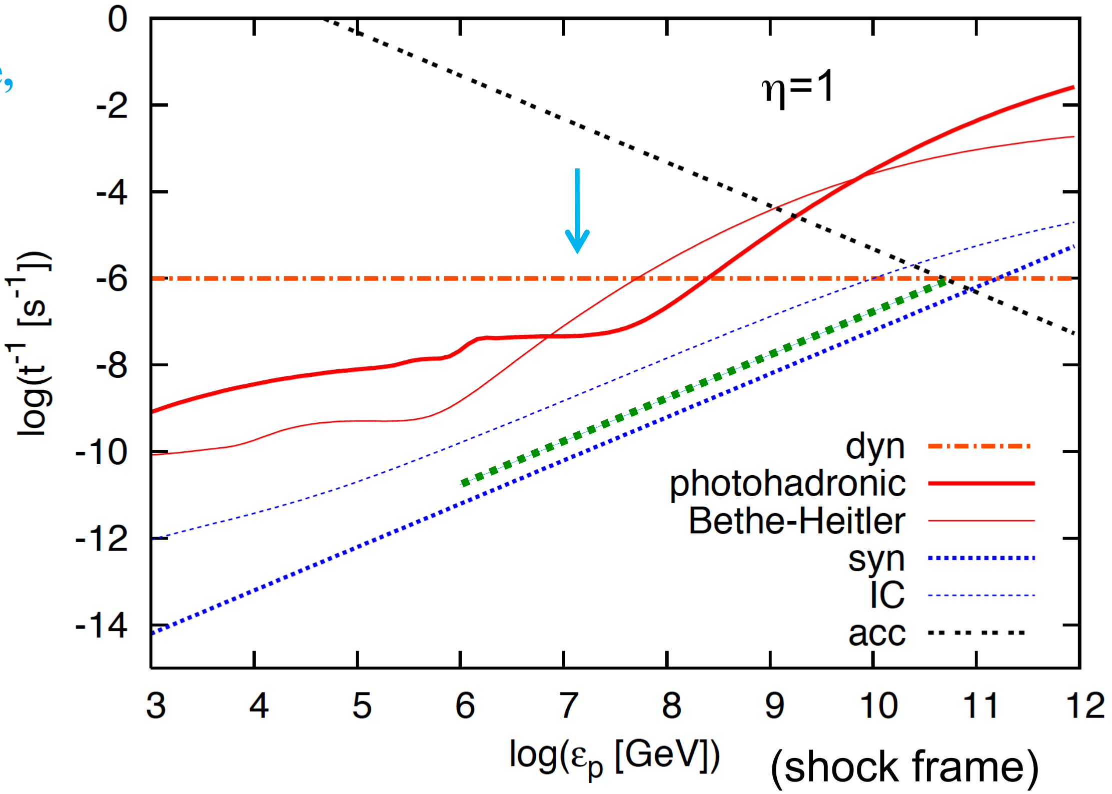
Key challenge 1:
How do cosmic rays escape from the source?

Murase, Inoue, Dermer, 2014

Impact of assumptions on cosmic ray escape

- The authors assume escape fraction $f_{esc}=(1-\min(1,t_{dyn}/t_{cool}))$
  What fraction of cosmic rays can escape at 10^7 GeV (shock frame)?

Murase, Inoue, Dermer, 2014

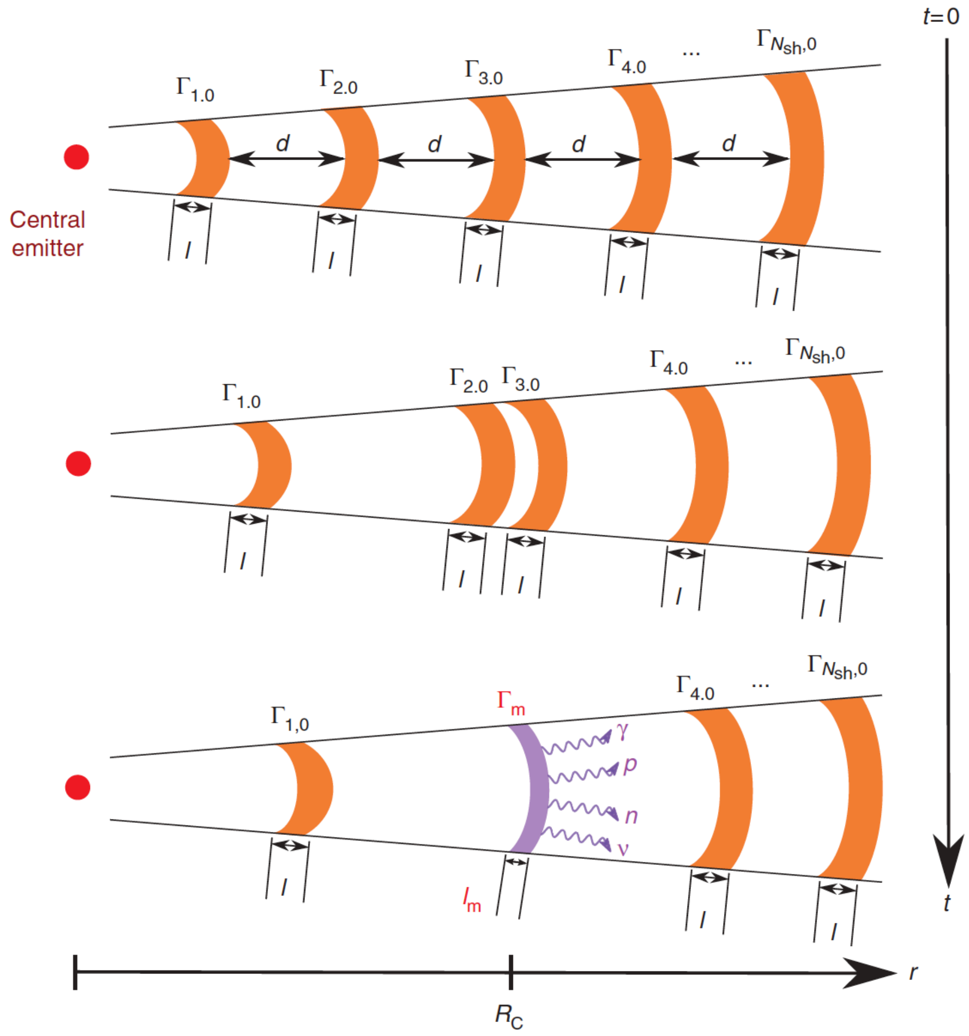


Effective direct escape rate

- Assume that the protons are magnetically confined and only the fraction $f_{esc}=\min(1,c\,R_L/t_{dyn})$ can escape (escape from edge of region within R_L)
  What fraction of cosmic rays can escape now at 10^7 GeV? Consequence?

Energetics of sources, geometry estimators (blackboard)

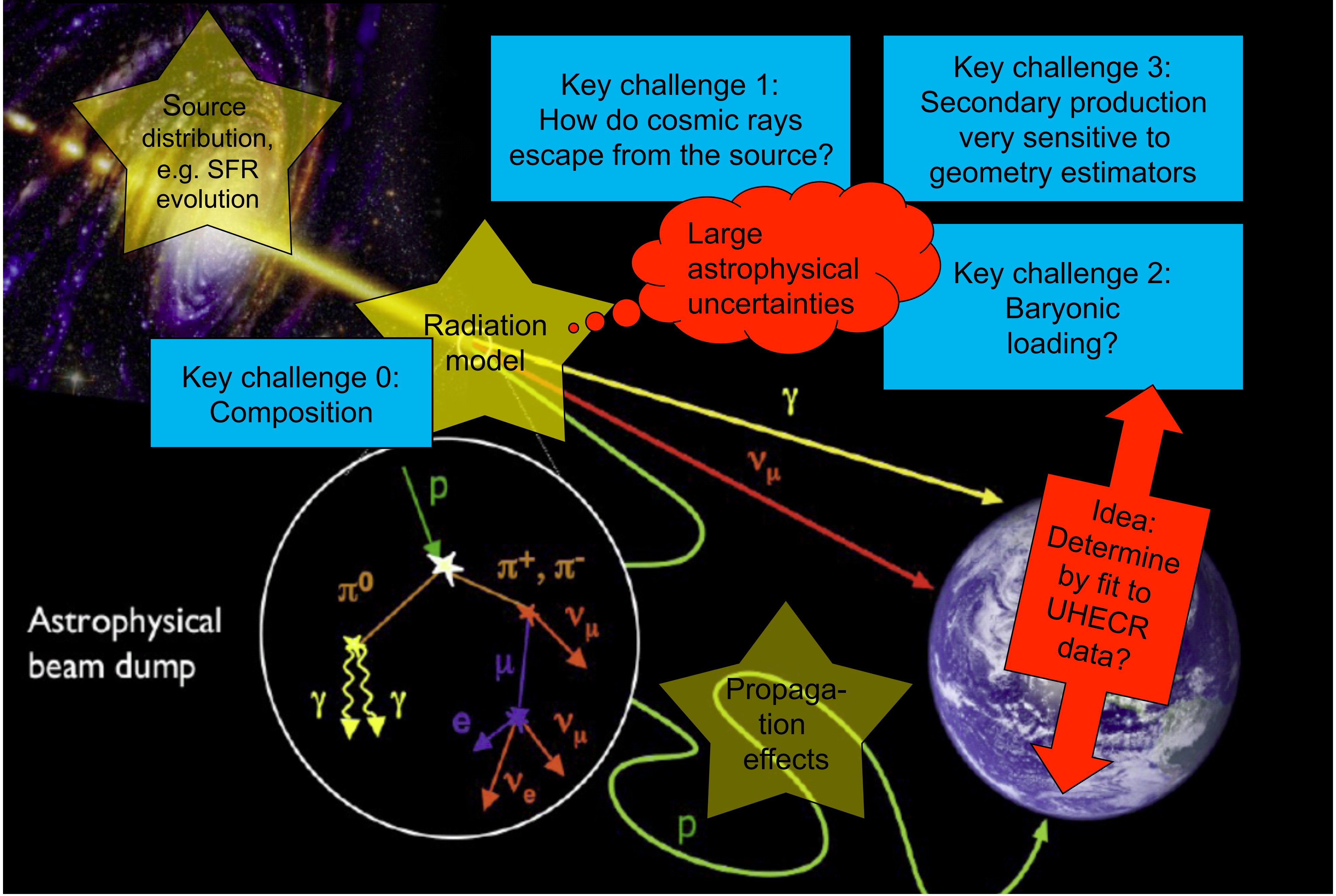
Example: GRBs



Towards addressing the key challenges in multi-messenger models

Example: GRBs

Challenges for multi-messenger models



GRB - Internal shock model

- **One zone model**: All collisions assumed to occur at same radius: $R_C \sim 2\,\Gamma^2\, c\, t_v/(1+z)$ (requires "machine-gun" precision)

  Volume ~ $R_C^2\, t_v$ estimated from Γ, t_v; therefore strong dependence of pion production efficiency on geometry estimator (key challenge 3)

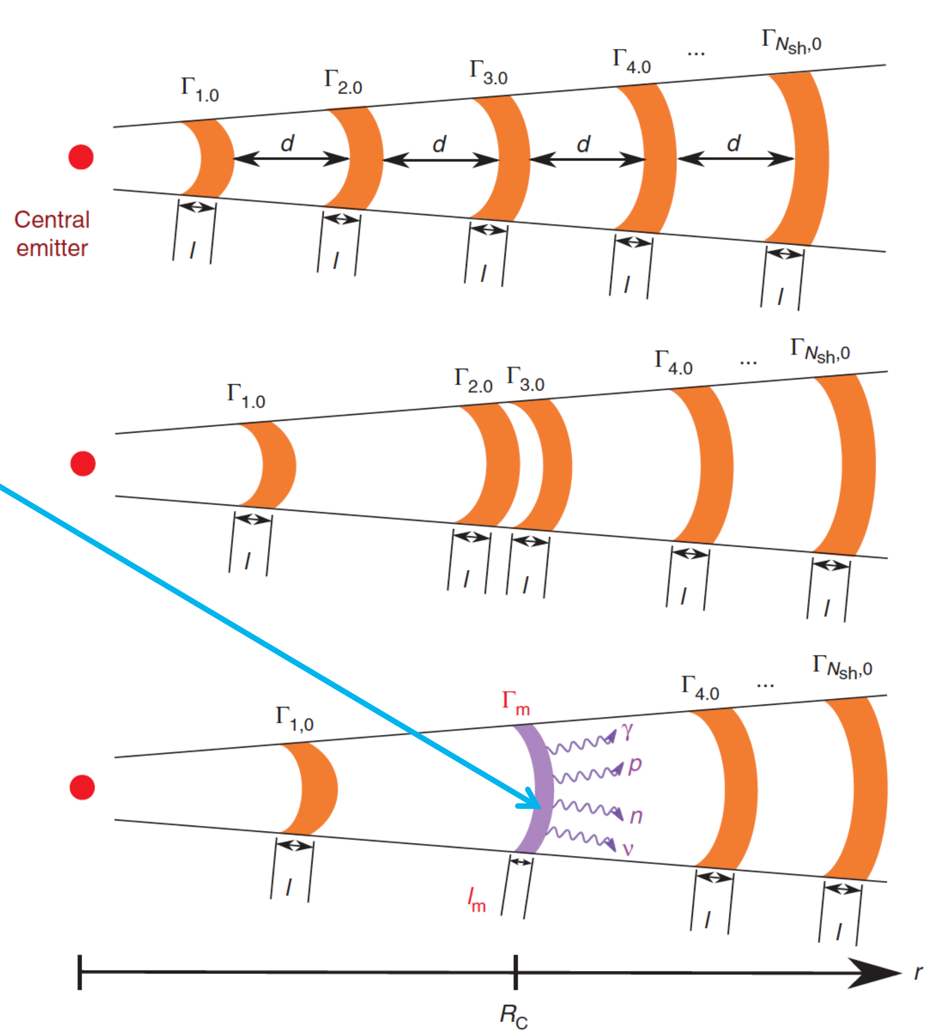
  

  Guetta et al, Astropart. Phys. 20 (2004) 429

- **Multi-zone model**: Distribution of collisions depending on properties of the central engine

  (needed to dissipate initial kinetic energy efficiently)

$\langle\Gamma\rangle \sim 100-500$



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

Three extreme cases:

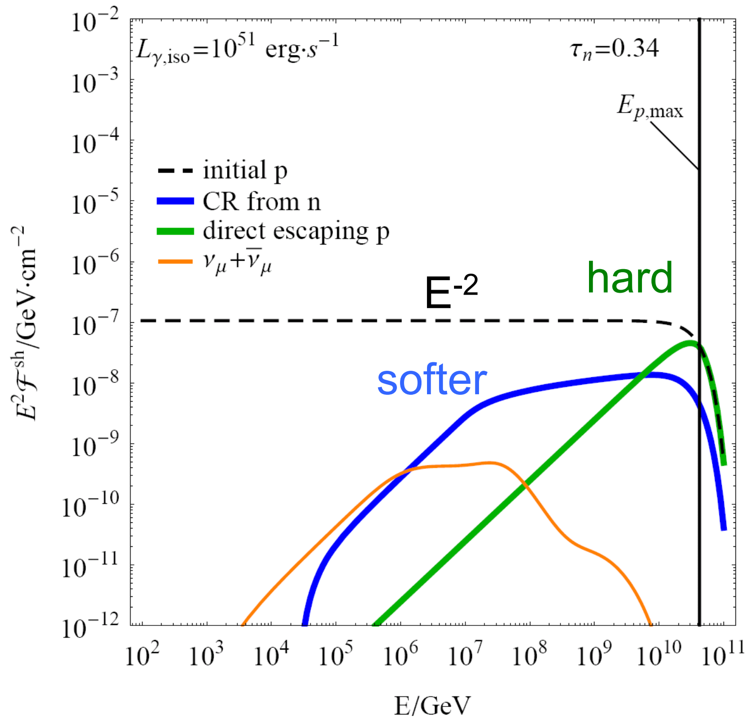
$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

- **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})

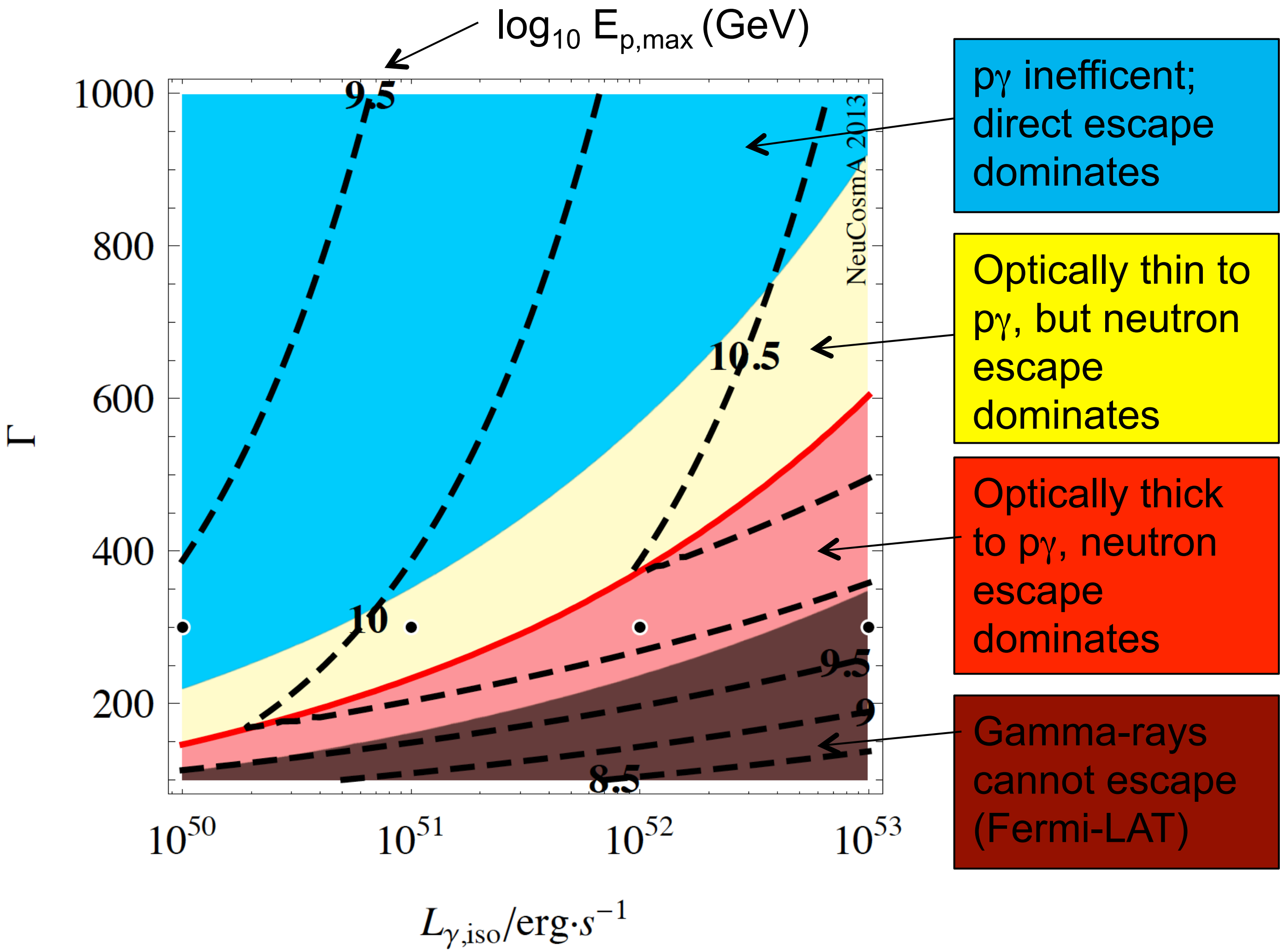
- Diffusion (need spatially resolved models …)



(without prop. effects)

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!

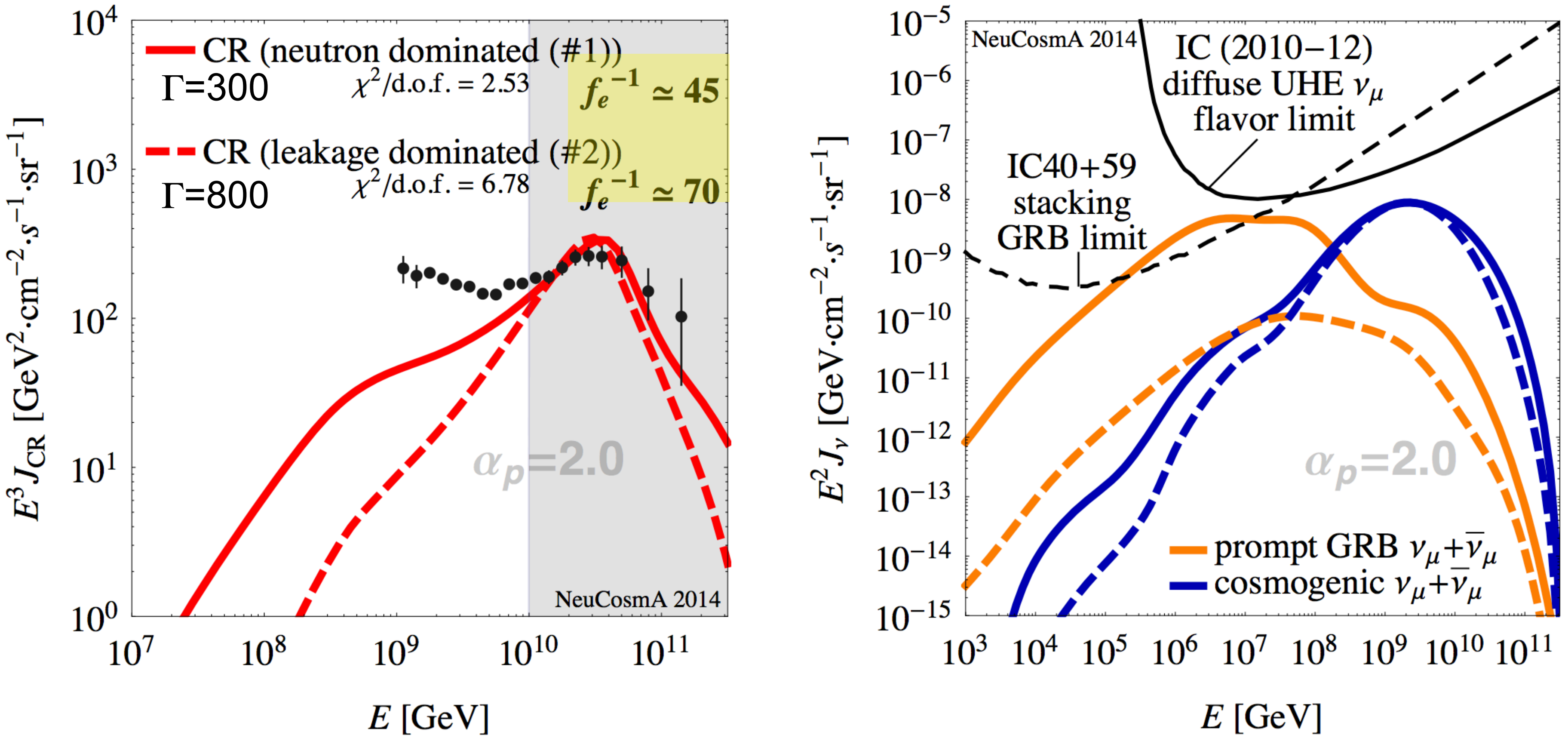


η=0.1

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

Key issue 2: Baryonic loading. UHECR fit to TA data

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

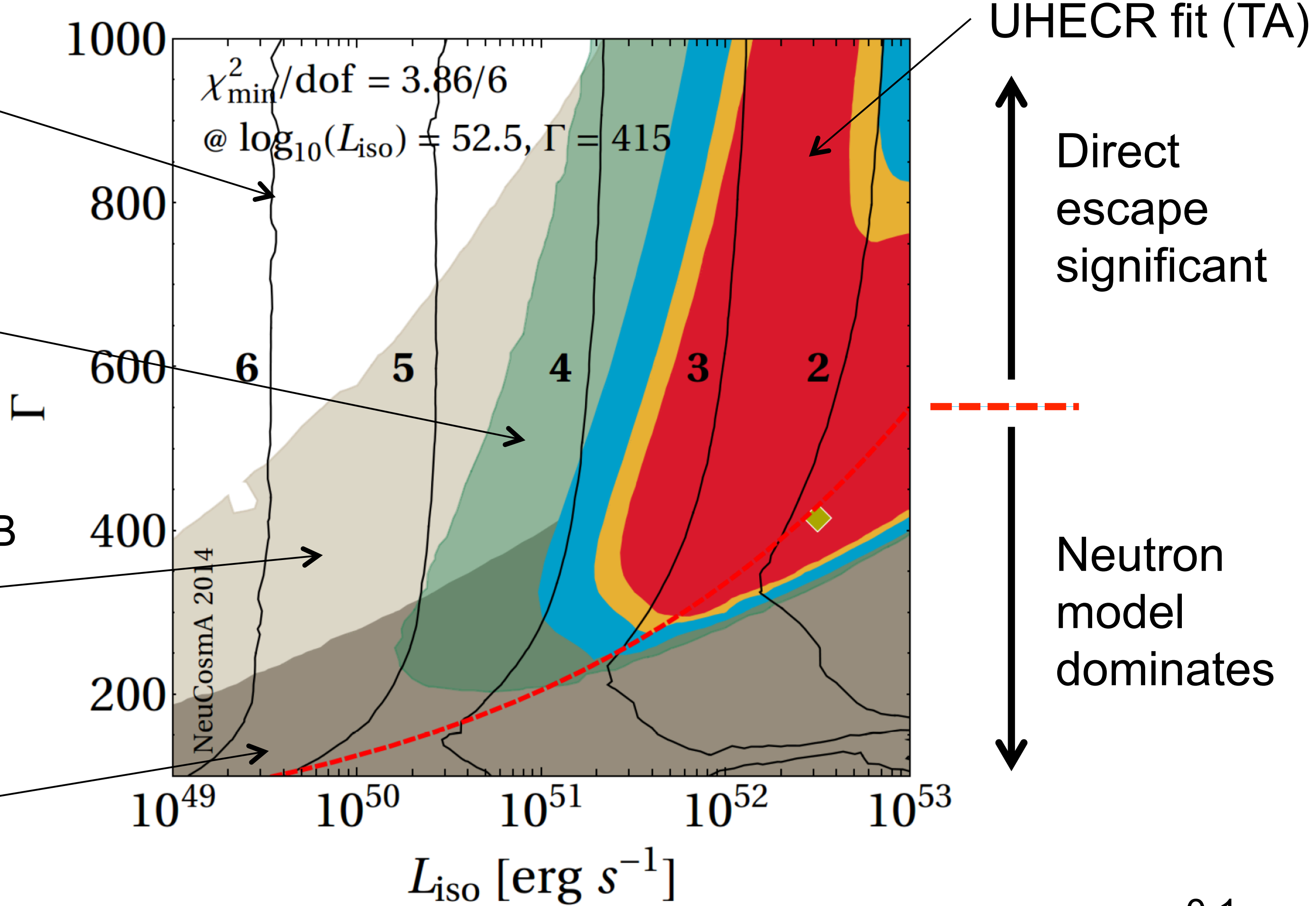
IceCube cosmogenic searches (15 years)

IceCube GRB stacking (15 years)

IceCube excluded (current);

Neutron model ruled out! Neutrinos test UHECR escape mechanism!

Key challenge 1

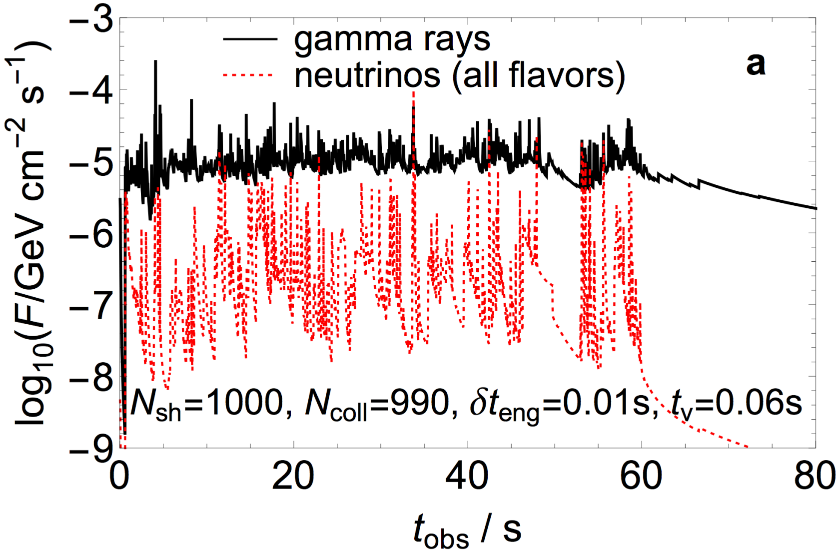


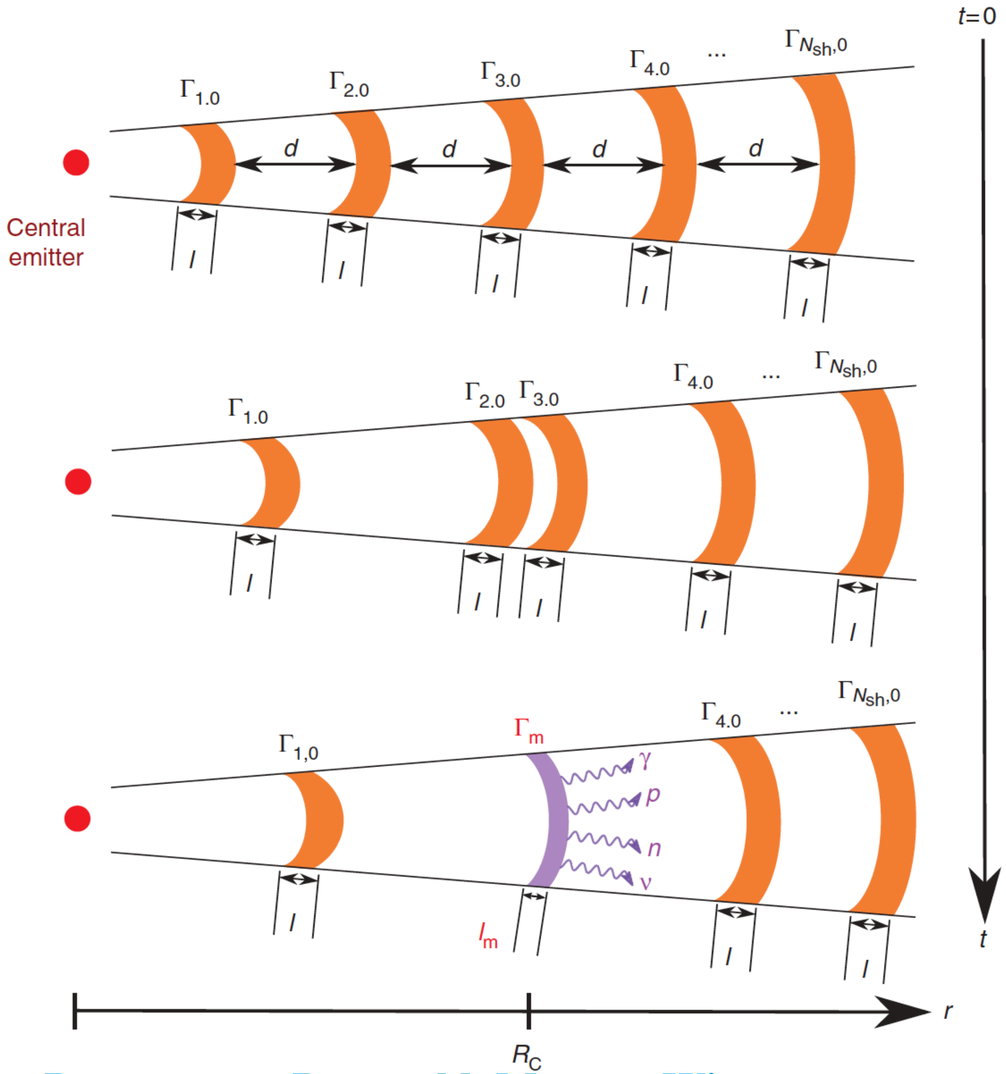
Baerwald, Bustamante, Winter, Astropart. Phys. 62 (2015) 66

η=0.1

Key issue 3 (sensitivity to geometry estimators)
Back to the roots: use multiple collision zones

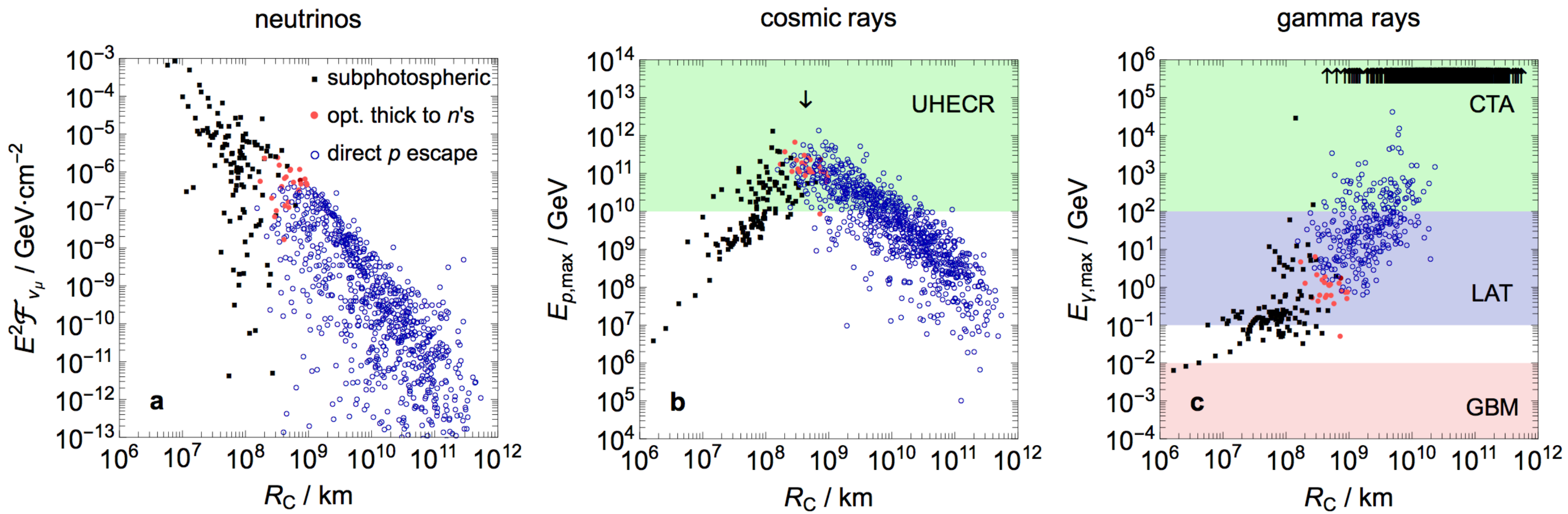
- Set our shells with Γ distribution
- The light curves can be predicted as a function of the engine parameters
- Consequence: Collsions radii are widely distributed!
- Neutrino flux not directly proportional to gamma-ray flux!



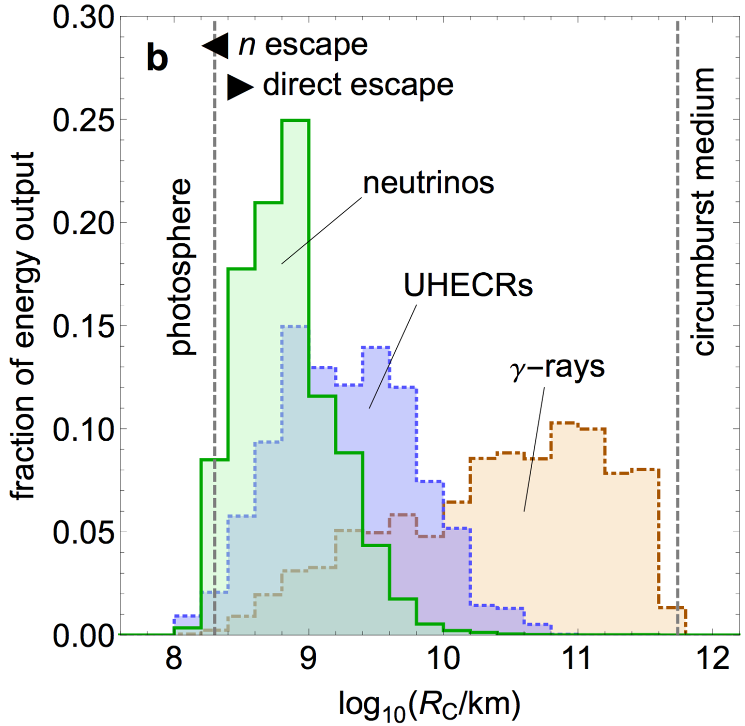


Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015)

Consequences for multiple messengers from one GRB



- The different messengers originate from different regimes of the GRB *where the densities are very different* →
- Observables from γ-ray observations may not be representative for the other messengers

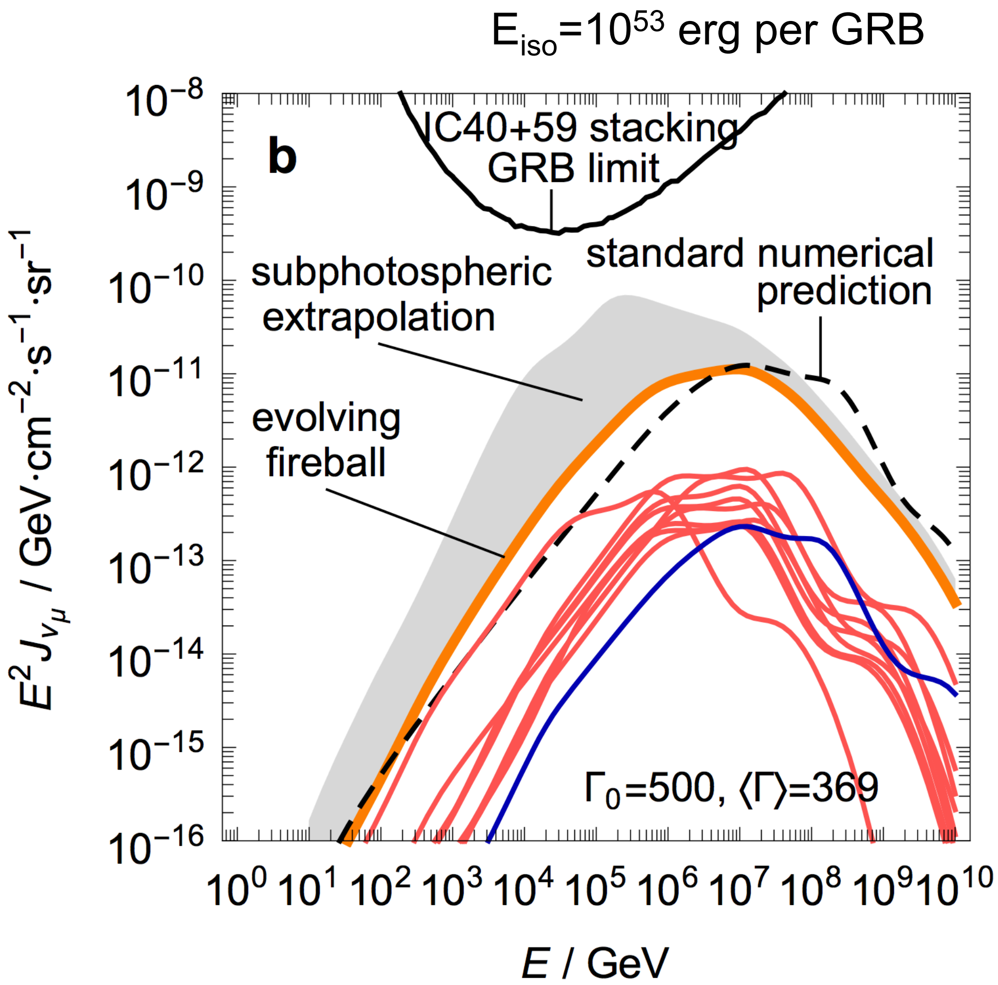


Bustamante, Baerwald, Murase, Winter, Nature Commun. 6, 6783 (2015)

Consequences for neutrino production

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

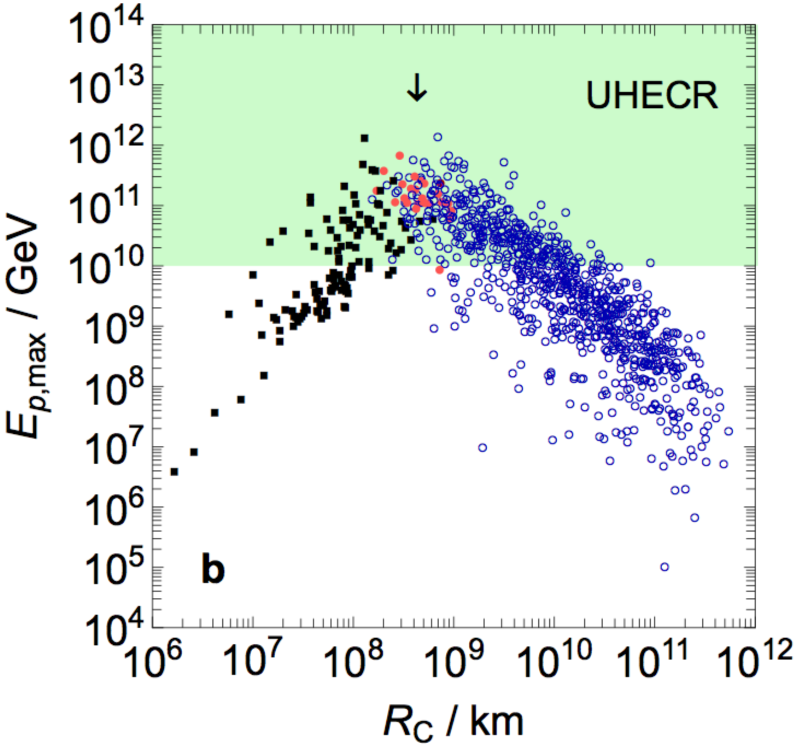
  Therefore, this minimal neutrino flux is dominated by a few collisions just beyond the photosphere (red)
- **$E^2 \phi \sim 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1}**
- This prediction is robust
  (hardly depends on Γ, baryonic loading)
  because Thomson scattering (→photosphere) and pγ scale in same way with particle density (for fixed E_{iso})
- **Moderates key challenge 3**

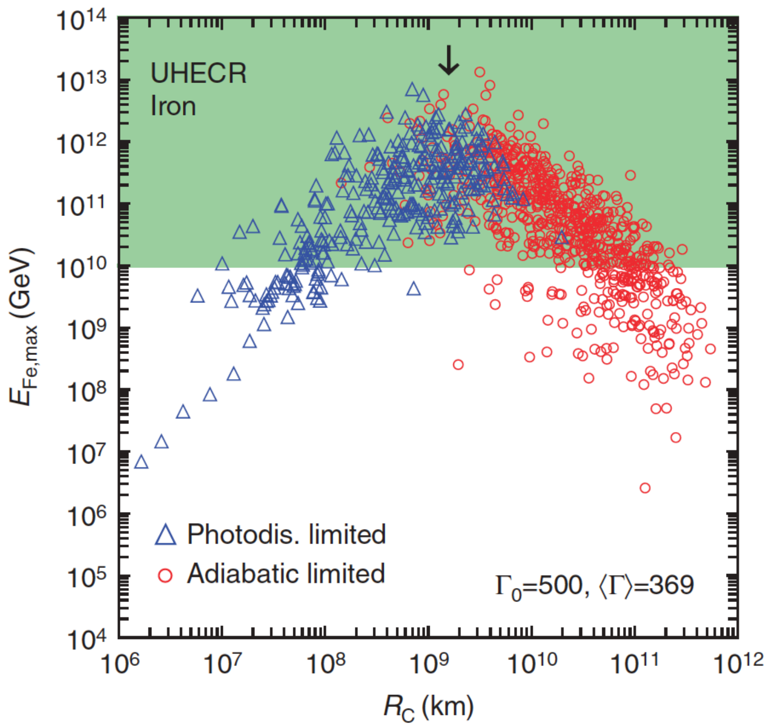


Bustamante, Baerwald, Murase, Winter,
Nat. Commun. 6, 6783 (2015)

Key challenge 0: What if … Auger is right?

- By the same logic, UHECR nuclei can escape from regions where photon densities are lower (relevant 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

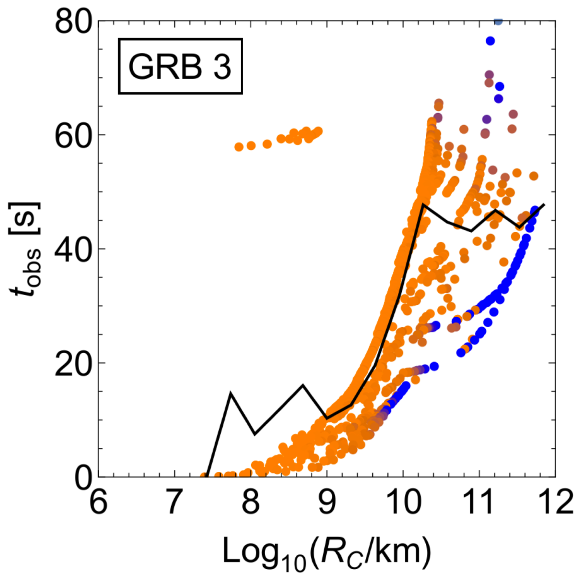
GRBs with central engine Γ ramp-up and slowdown

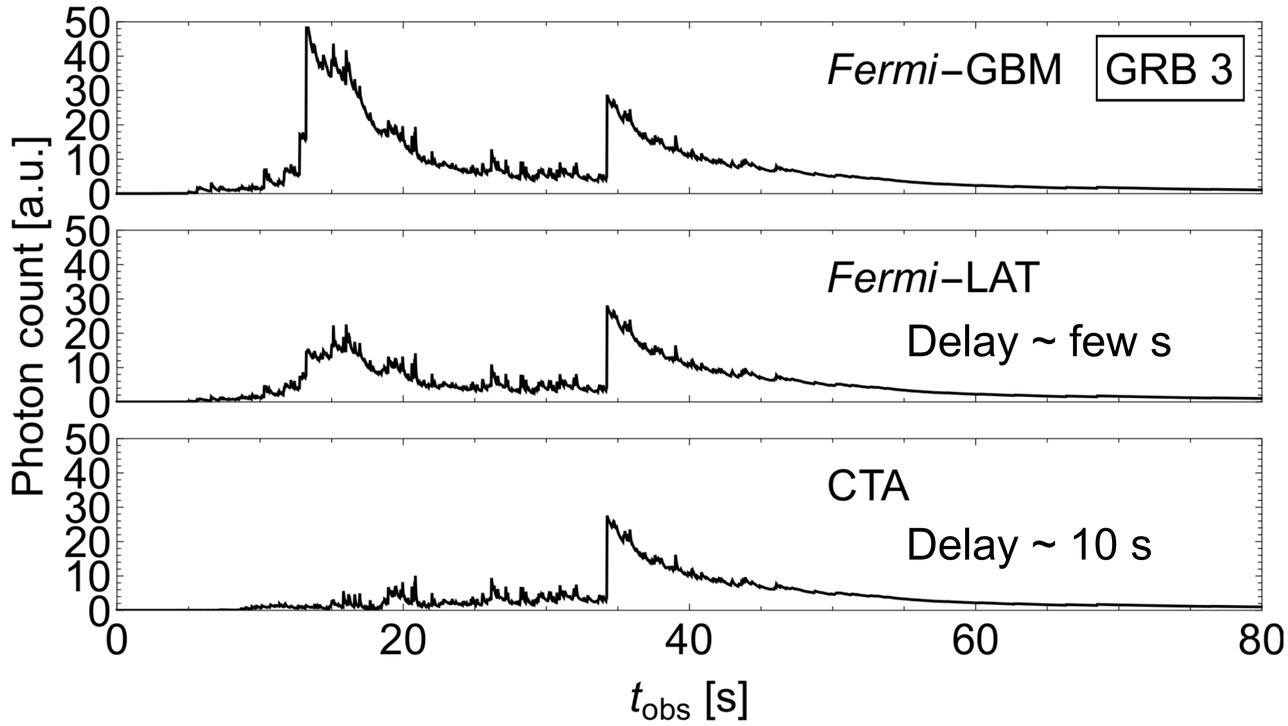
… first steps towards multi-messenger – multi-wavelength approaches

- Fast variability + pulse structure

  Bustamante, Murase, Winter, arXiv:1606.02325, ApJ (to appear)

- Time-delays in high-E bands expected if there is a correlation between R_C and t_{obs}:





- Time delay from suppression of high-E signal by γγ interactions from early collisions at low R_C

Summary and conclusions

- Multi-messenger *astronomy*: use observational arguments (timing, direction, energy, anisotropies, multiplets, …)
- Beyond that: analyses typically rely on a theory for the source, which may be sometimes hidden; assumptions have to critically reviewed, and may be over-simplified
- Bottom-up models predict different production regions for neutrinos, gamma-rays, cosmic rays; consequence: difficult to relate messengers to each other in model-independent way.
  Advantage: clues how to search the haystack →

- Discussed key challenges: Cosmic ray composition, cosmic ray escape, baryonic loading, geometry estimators, self-consistent description of emissions
- Multi-messenger *astrophysics* can address these questions!
  [but we are not yet there …]