Gamma, Neutrino, and Gravitational Wave from Cosmic Ray Origin

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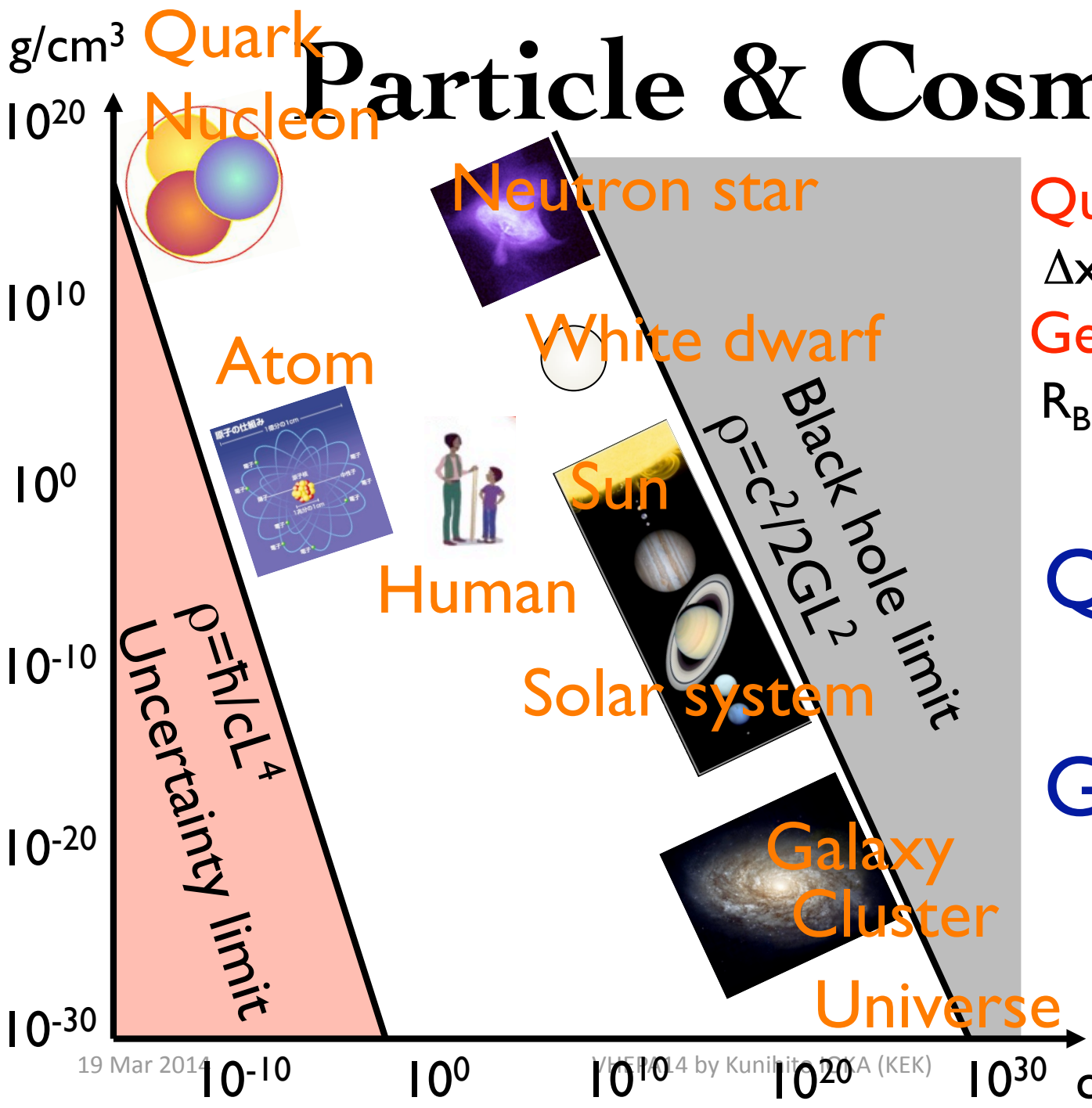
KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

The Graduate University for Advanced Studies
Sokendai

Particle & Cosmos



Quantum mechanics

$\Delta x \, \Delta p \geq \hbar$

General relativity

$R_{BH}=2GM/c^2$

Quantum "ħ"

⇒ Particle

Gravity "G"

⇒ Universe

Evolution to Black Hole

$2M_\odot$ Neutron Star
Dark Matter
LIV
Axion

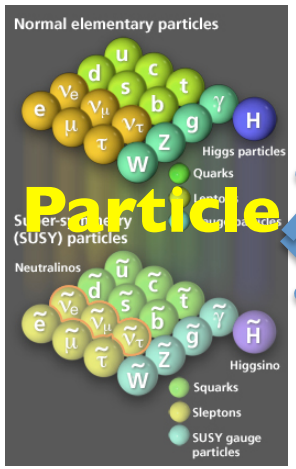
Star
Planet

Supernova
GRB

Unification/Diversity
GeV GRB
Jet Mechanism

Supernova
Remnant

GeV-TeV SNR
CR Origin
PeVatron



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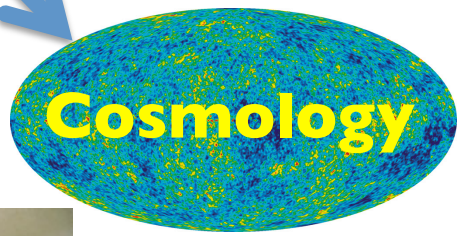
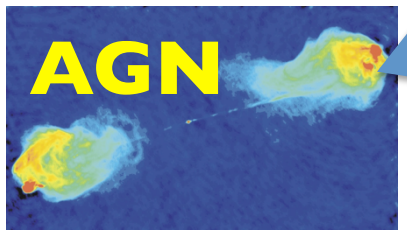


Cosmology

Dark Energy
Inflation
Dark Age
Pop III, First GRB

Computar

Supernova
Rela, Turbulence
PIC particle acc.
GR MHD

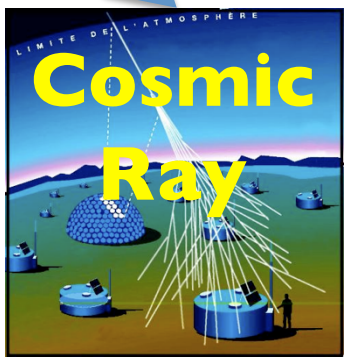


AGN

GeV-TeV AGN
Tidal Disruption Jet
Fermi Bubble

Compact
Star

GeV-TeV Pulsar
Magnetosphere
Crab Pulsar
TeV PWN

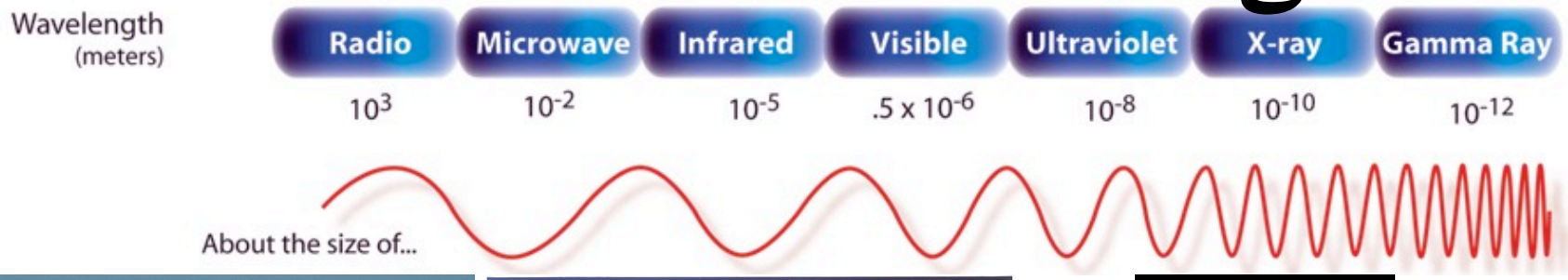


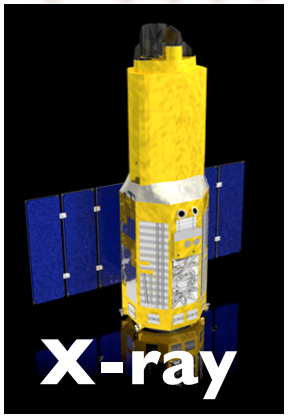
Cosmic
Ray

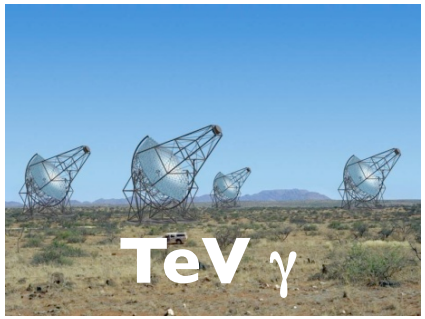
e^+ Excess
GZK cutoff
UHECR Fe

High Energy Universe

Multi-Wavelength

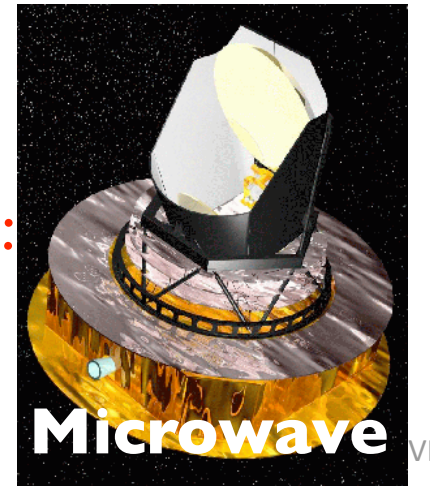




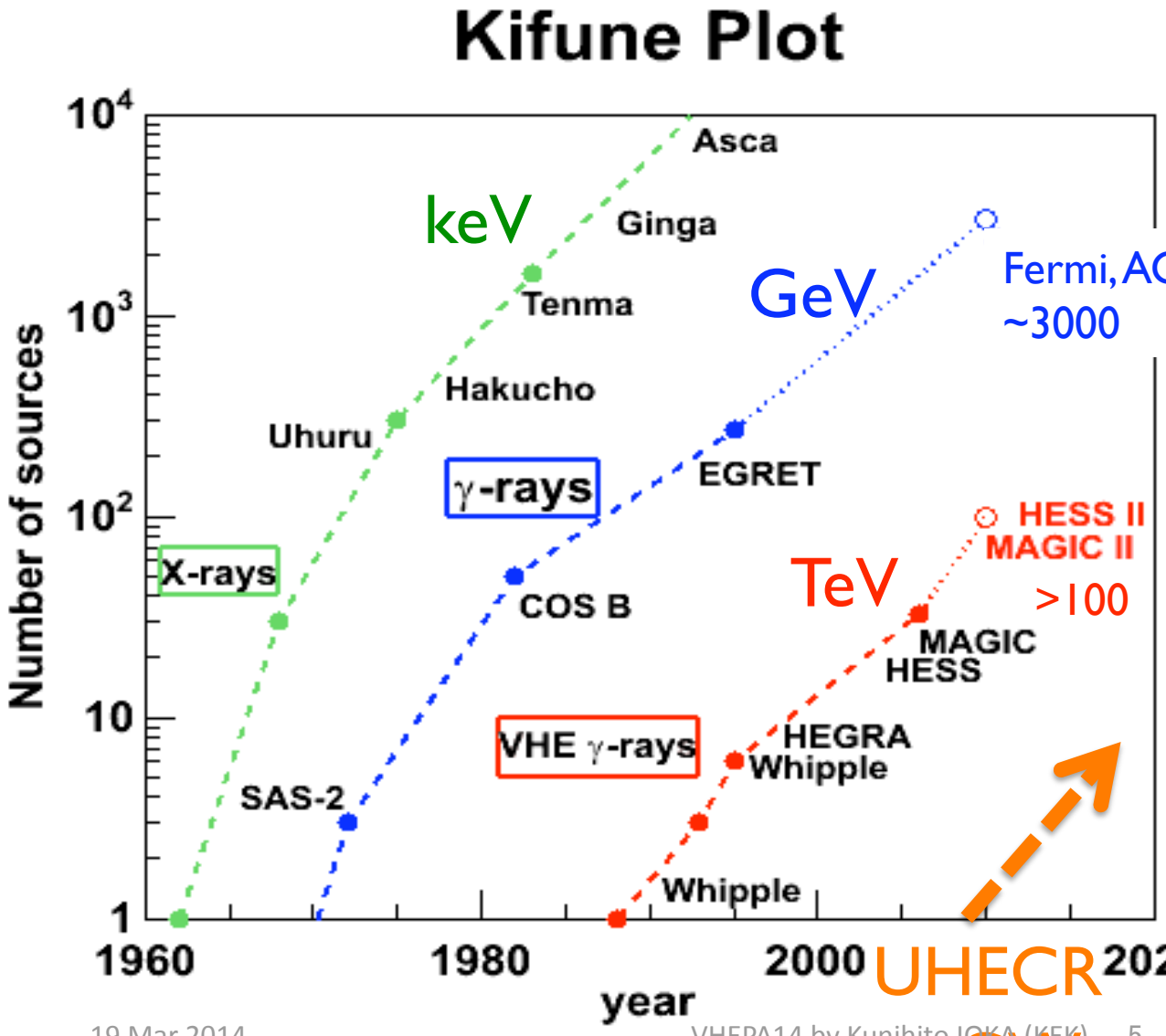


TeV=
10^{12}eV
GeV=
10^{9}eV

20th century observations:
In particular,
X-γ-VHE γ



Explosive Discoveries



- # of sources are increasing exponentially

- ***High Energy Universe***

1. Origin & Evolution (CR, Jet, …)
2. ⇔ Cosmology
3. ⇔ Fund. Physics

Evolution to Black Hole

$2M_\odot$ Neutron Star
Dark Matter
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Axion

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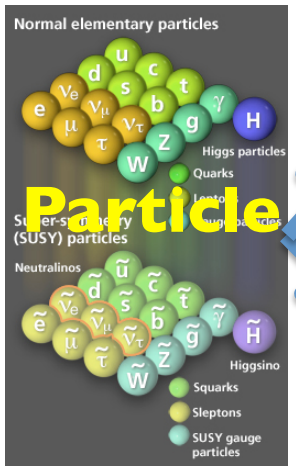

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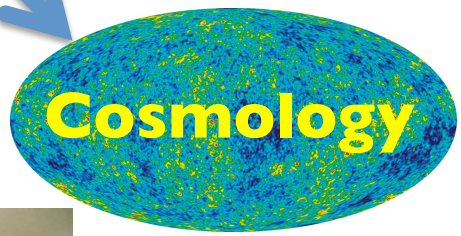

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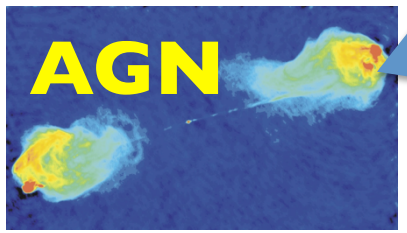

AGN

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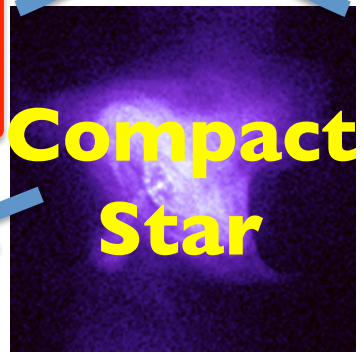

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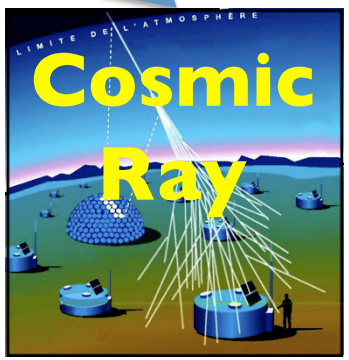


Cosmic
Ray

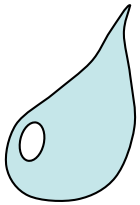
e^+ Excess
GZK cutoff
UHECR Fe

High Energy Universe

Gamma-Ray Burst

$E=mc^2$ (by Einstein)

=



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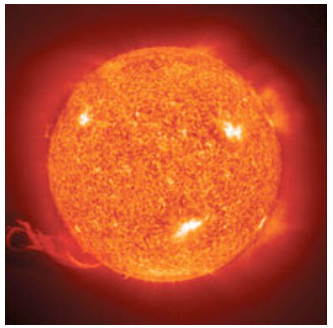


Atomic bomb ~1kg

GRB
~10^{52}erg

Sun
~10^{33}g

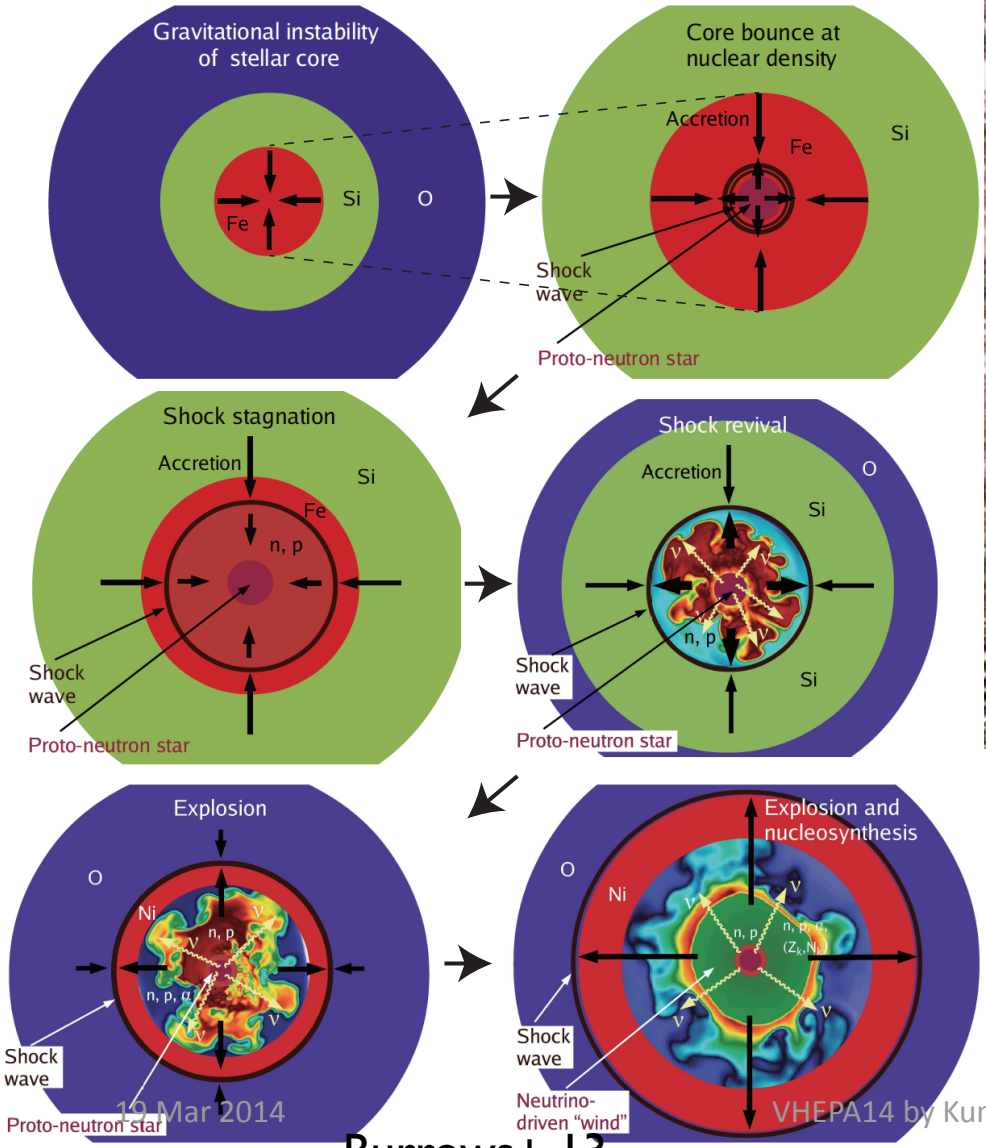
In ~sec, GRB release energy Sun emit over lifetime

GRB is the most luminous object

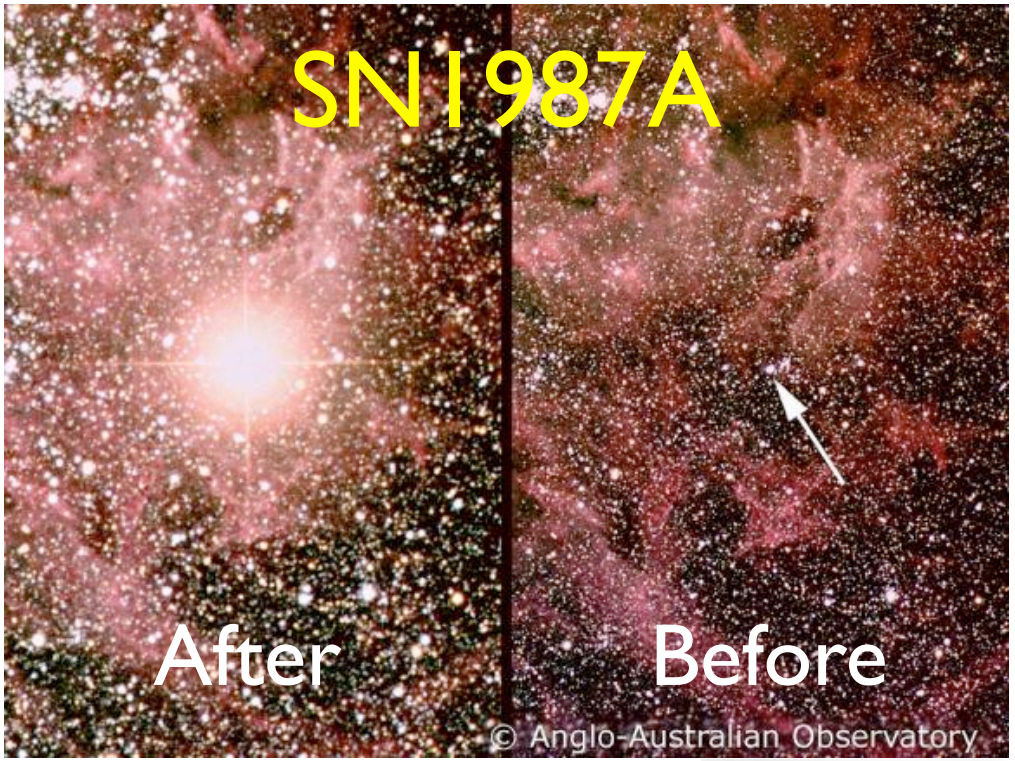
Supernova

$$^{56}_{26}\mathrm{Fe} + \gamma \leftrightarrow 13\alpha + 4n$$

$$(Z+1, A) + e^- \rightarrow (Z, A) + \nu_e$$



Burrows+ 13

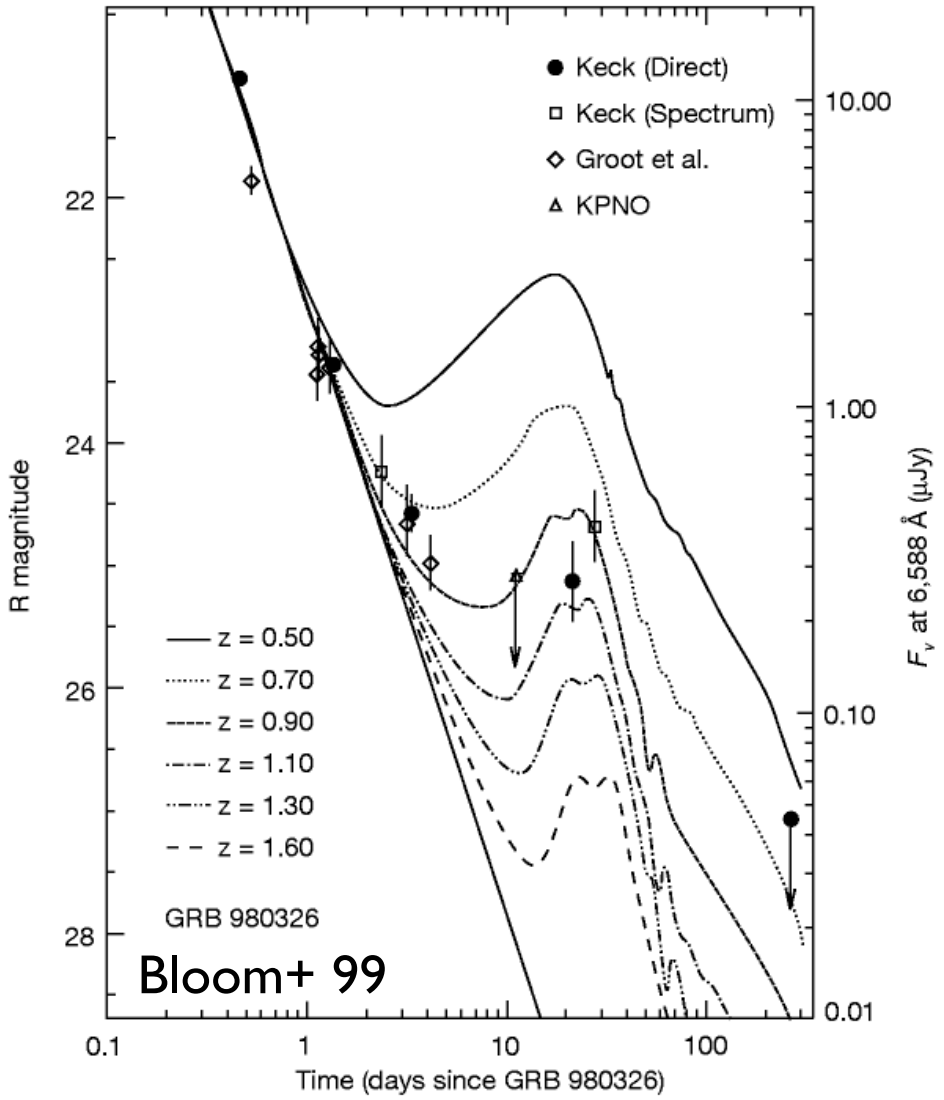


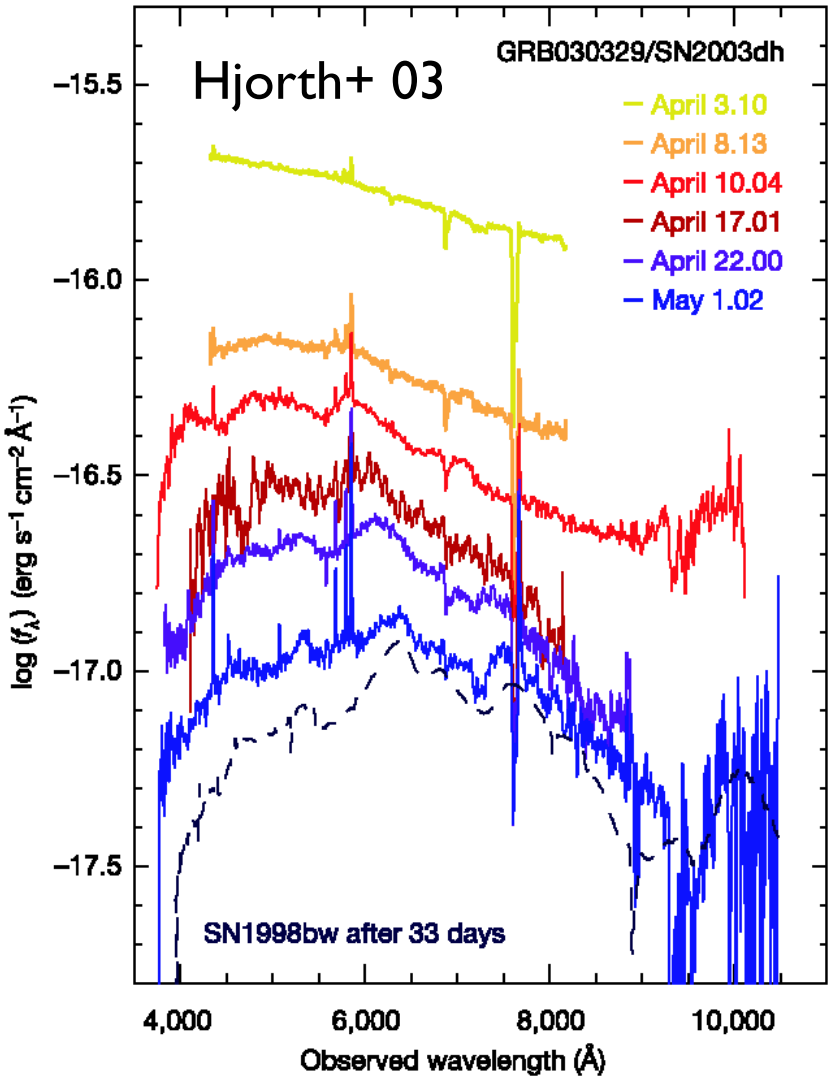
$M > \sim 8\text{-}10 M_\odot$

$E_\nu \sim 10^{53}$ erg

$E_{kin} \sim 10^{51}$ erg

Supernova-GRB Connection

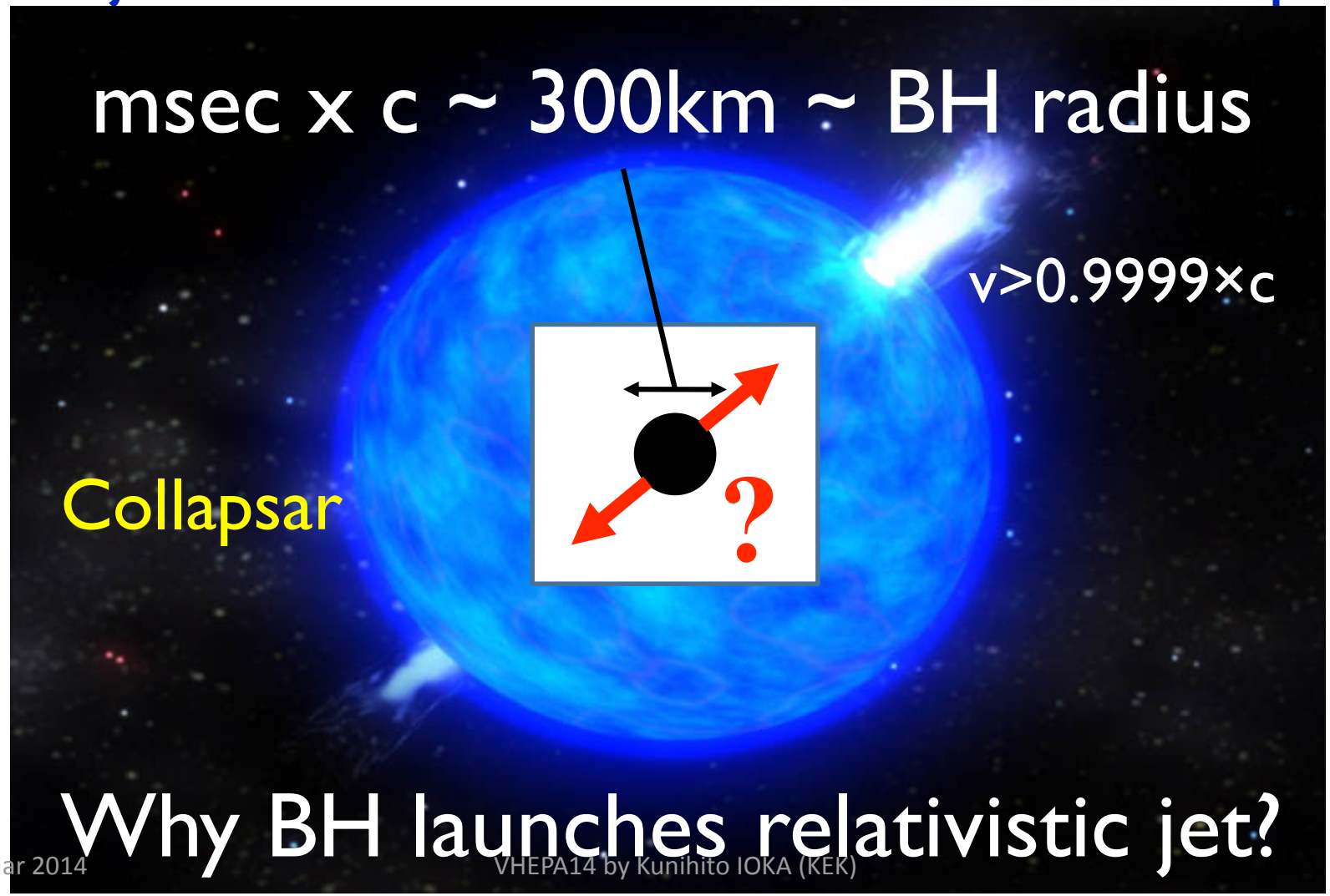




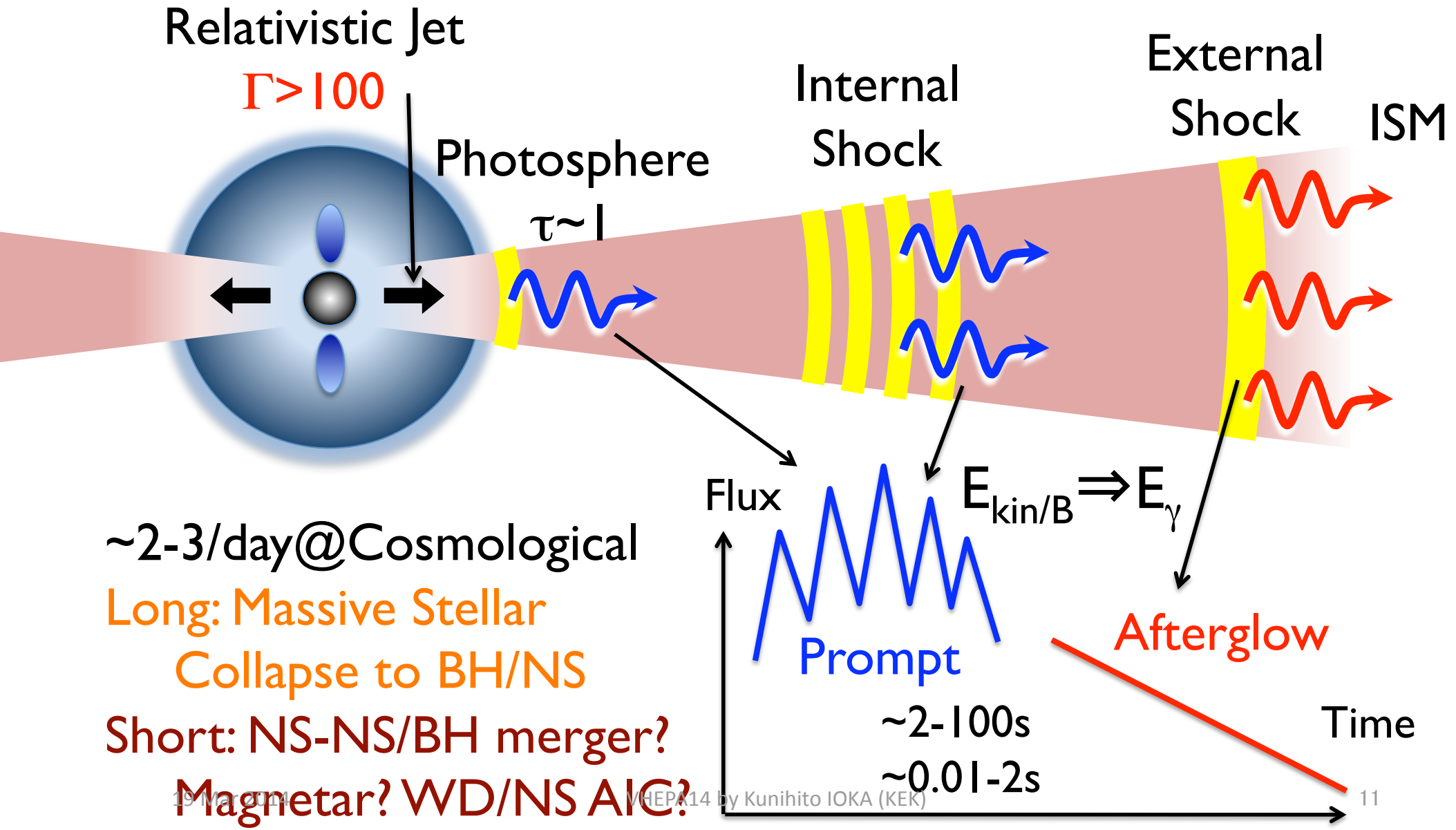
Woosley 93 "Gamma-ray bursts from stellar mass accretion disks around black holes"

GRB ≈ Black Hole Formation?

GRB jet breaks out of massive stellar envelope



Emission from Jet

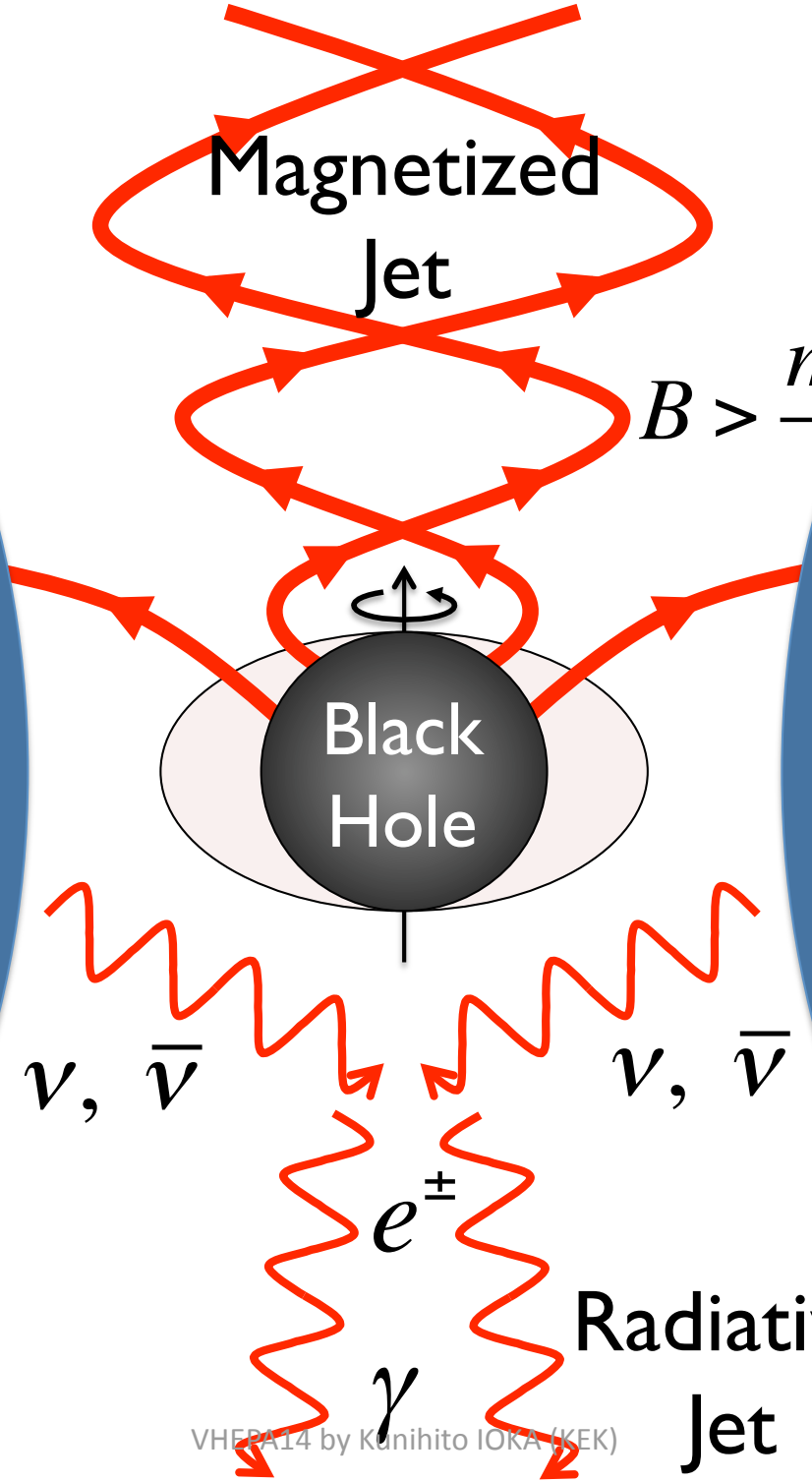


~2-3/day@Cosmological

Long: Massive Stellar Collapse to BH/NS

Short: NS-NS/BH merger? Magnetar? WD/NS AIC?

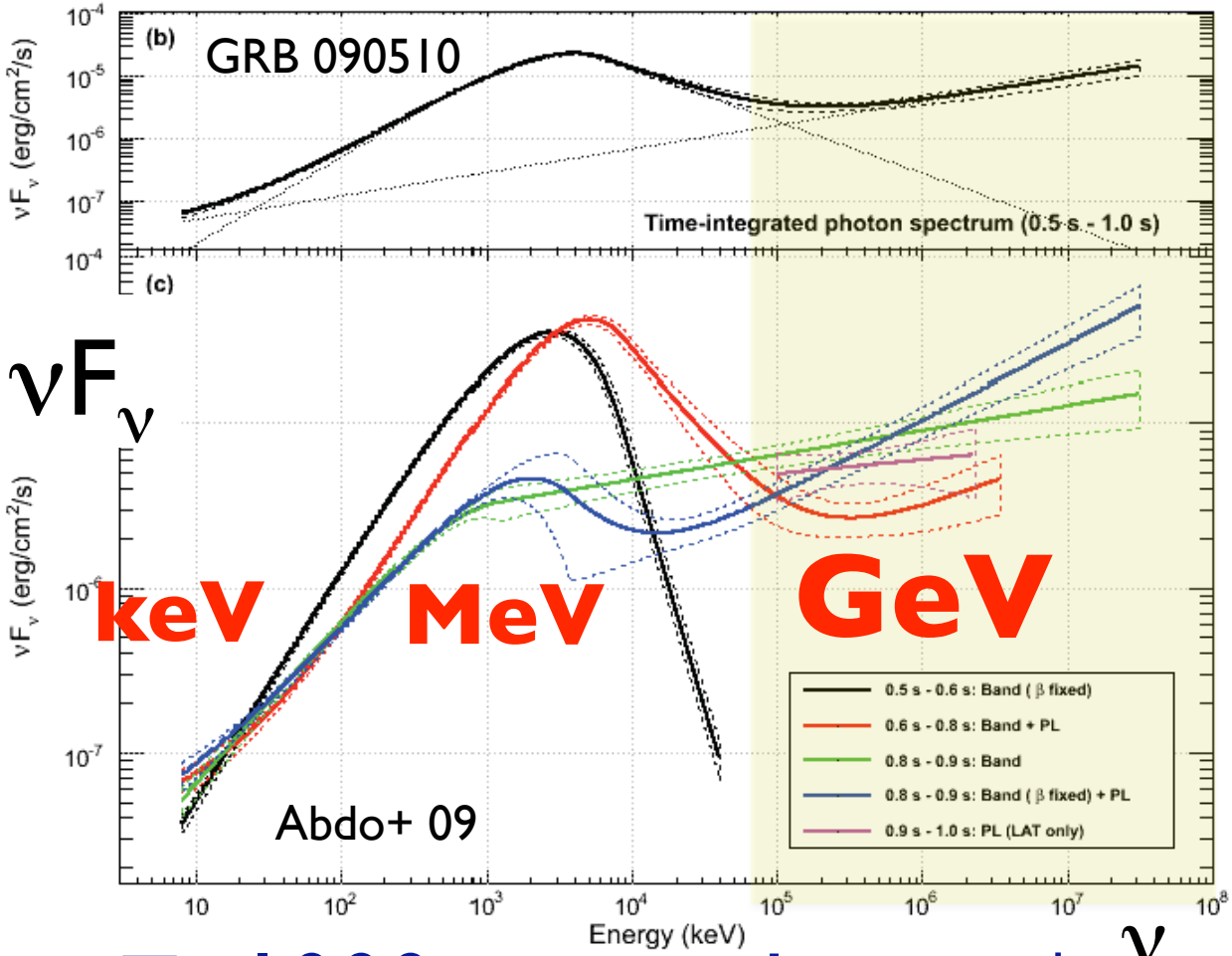
?



$$B > \frac{m_e^2 e^3}{e\hbar} \approx 4\times10^{13}\,\mathrm{G}$$

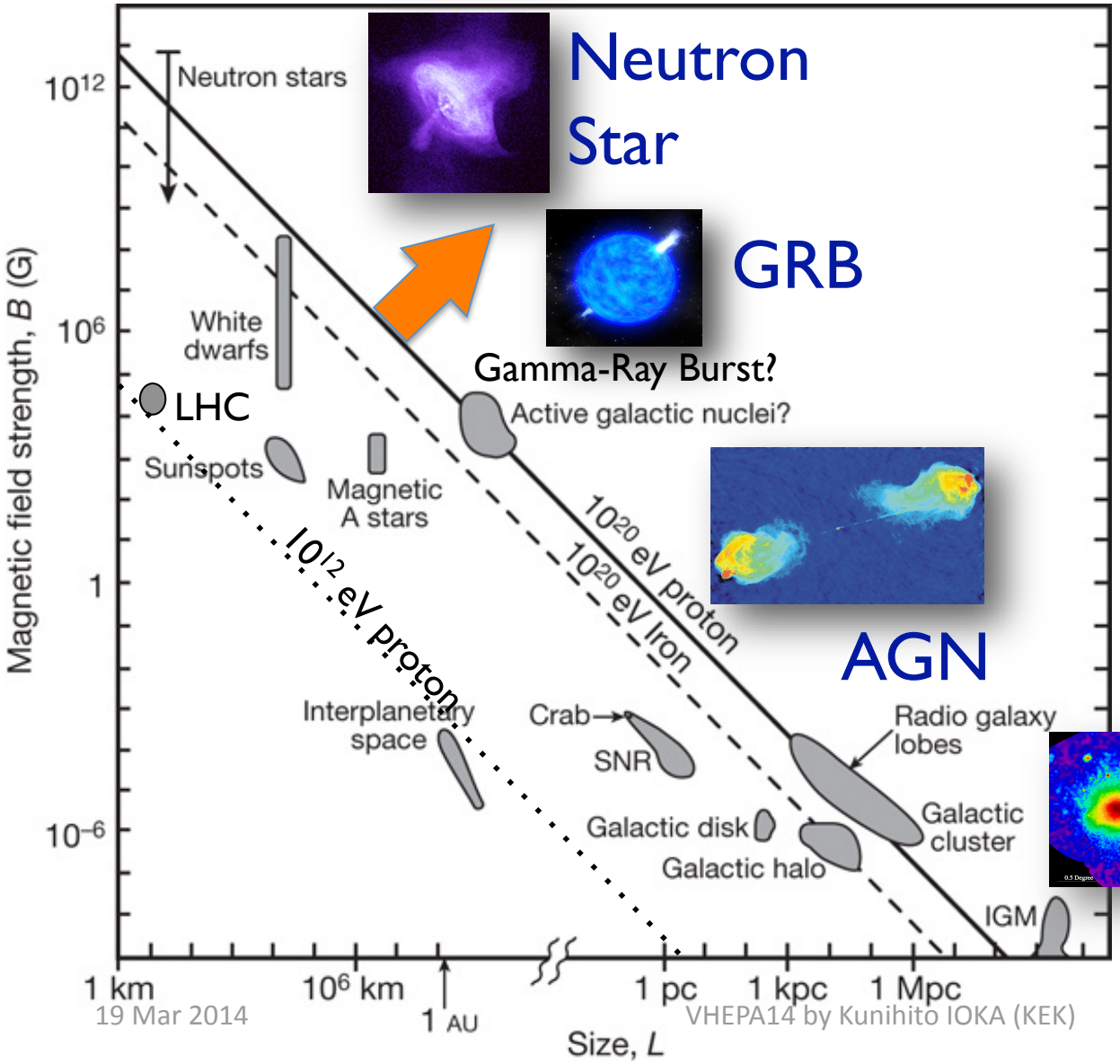
Accretion Disk
(Baryon)

>GeV γ-ray from GRBs

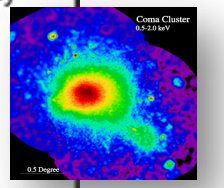


- Γ>1000 to avoid $\gamma\gamma \rightarrow e^+e^-$
- ν
- ***$>10^{17}$eV $p+\gamma \rightarrow \pi \rightarrow \gamma, e$?*** Asano+

Ultra-High Energy Cosmic-Ray

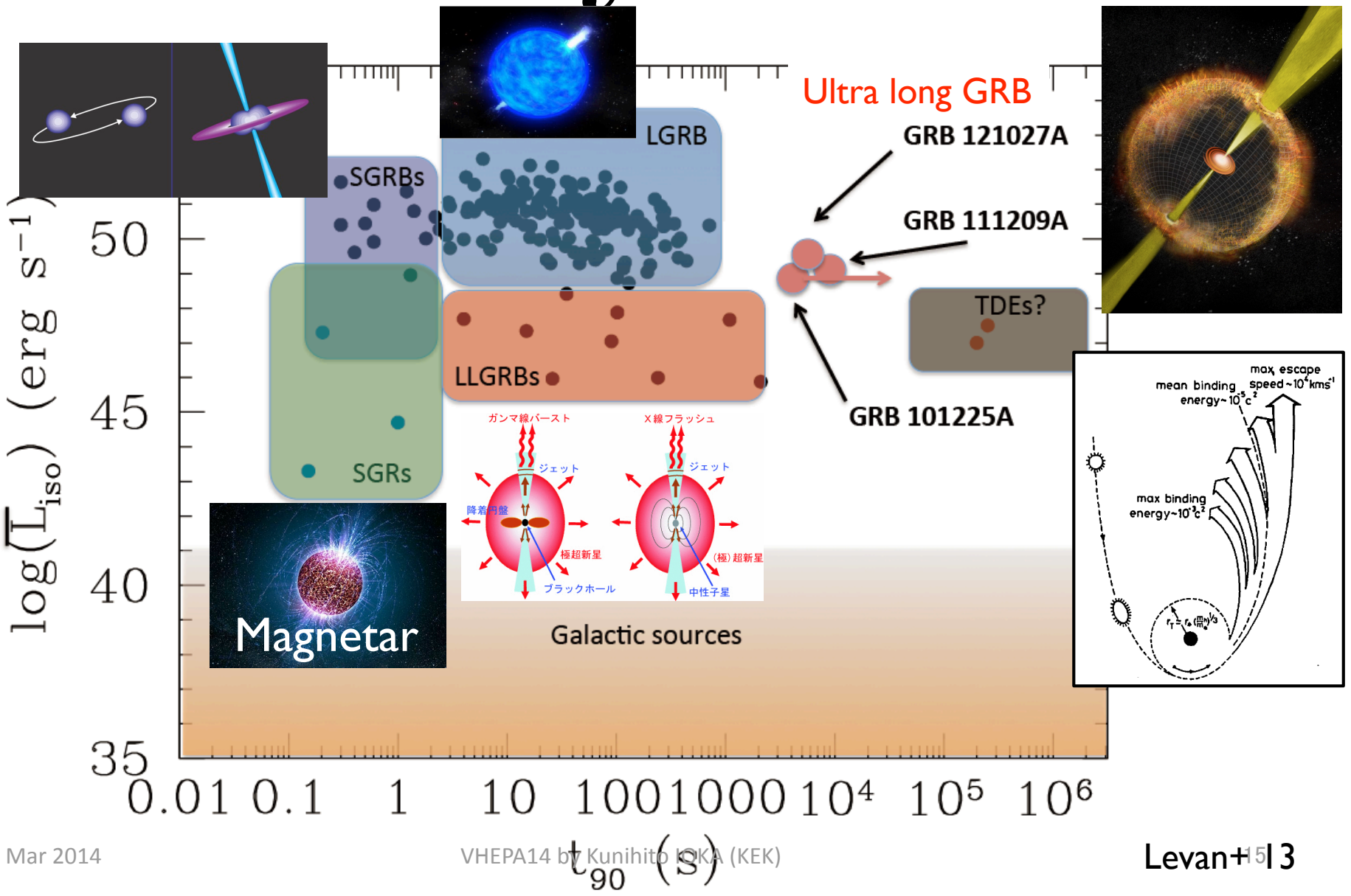


- E~10^{20}eV
- R_{Larmor}>R_{Galaxy}
  ⇒ Extragalactic
- Hillas condition
  E<ZeBR (v/c)
- Energy/Vol./Time
  ~10^{44}erg/Mpc^3/yr
  UHECR~GRB<<AGN

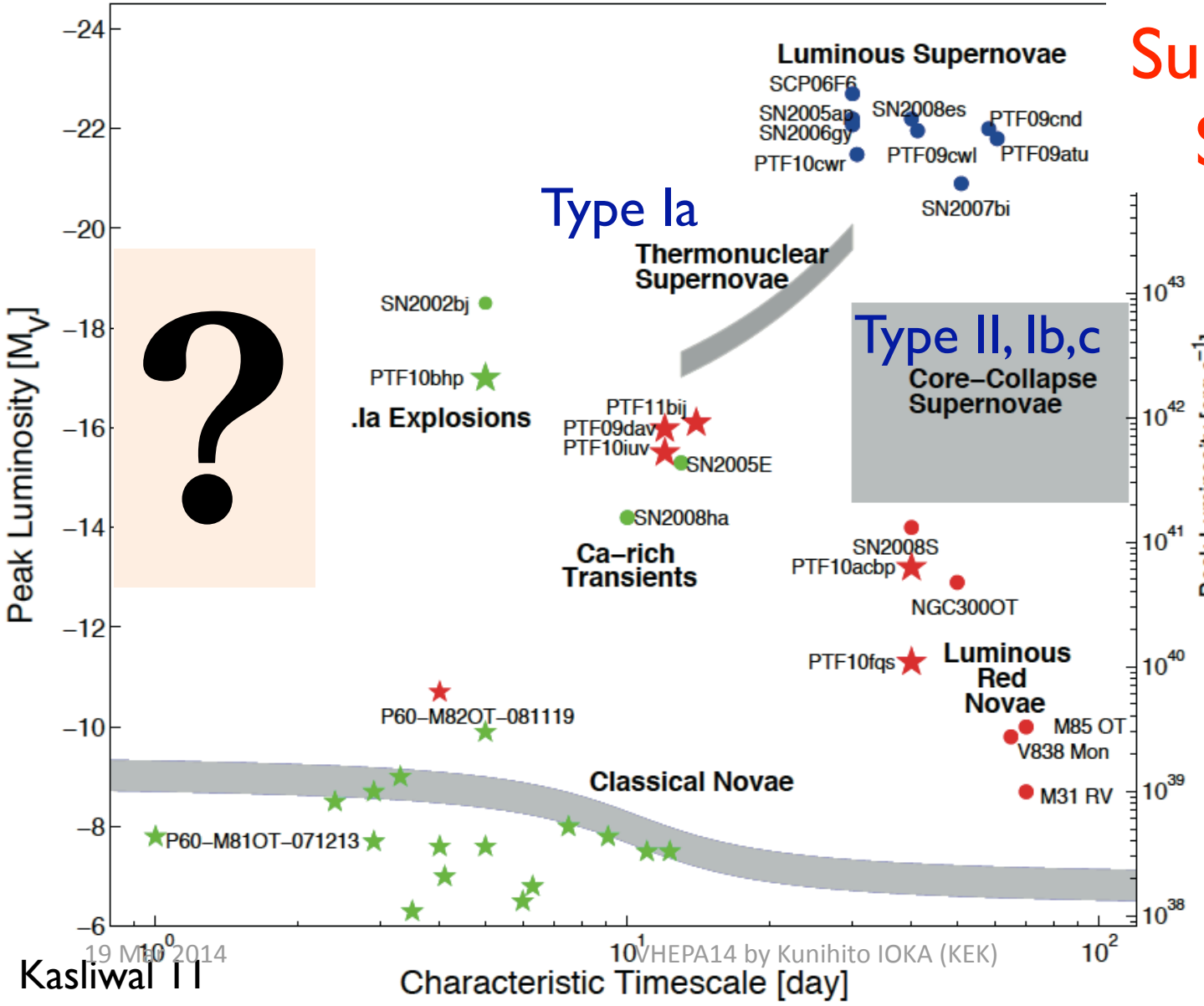


Galaxy cluster

Diversity of GRB



Diversity of Supernova



Superluminous Supernova

1. Pair-inst.
2. CSM-Ejecta
3. Magnetar

Still unknown

Evolution to Black Hole

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Dark Matter
LIV
Axion

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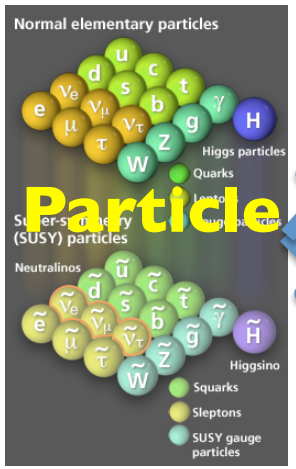

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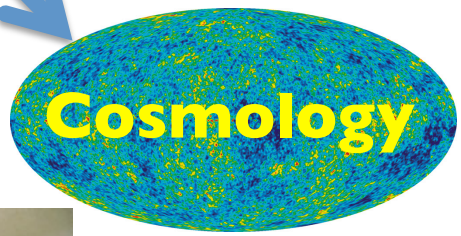

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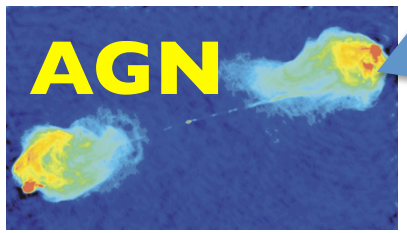

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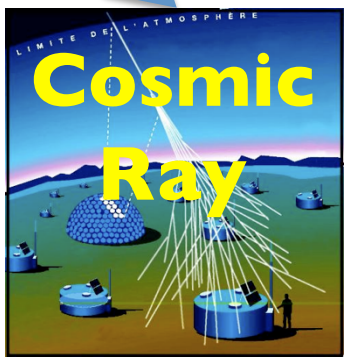
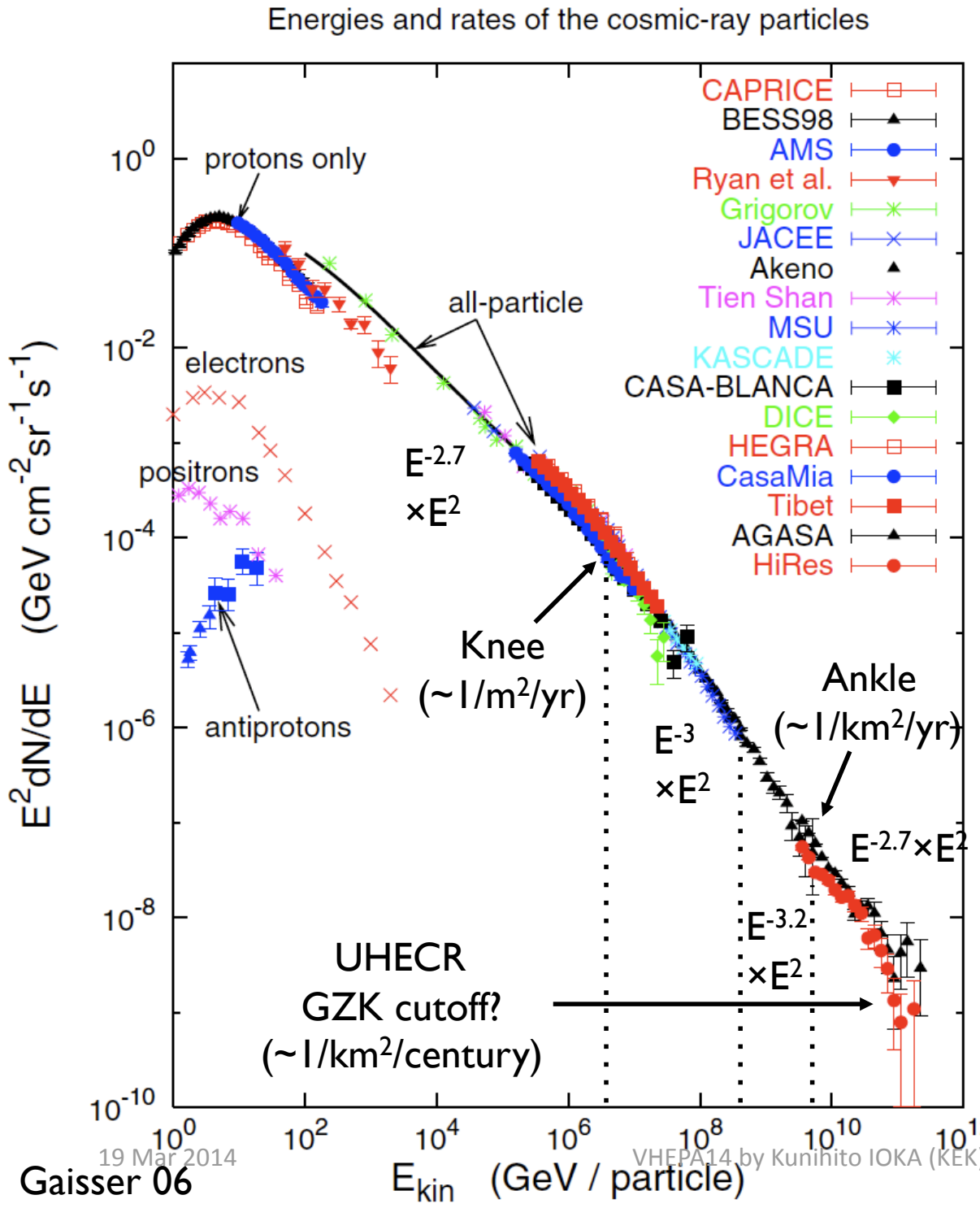


Cosmic
Ray

e^+ Excess
GZK cutoff
UHECR Fe

High Energy Universe



Cosmic Ray

$E<10^{15\text{-}16}$eV (Knee)

$F \propto E^{-2.7}$

Supernova remnant(?)

$L_{CR} \sim 10^{41}$erg/s

$\sim 0.1 E_{SN}/t_{SN}$

$10^{15\text{-}16}<E$

$<10^{18}$eV (Ankle)

$F \propto E^{-3\text{-}3.2}$

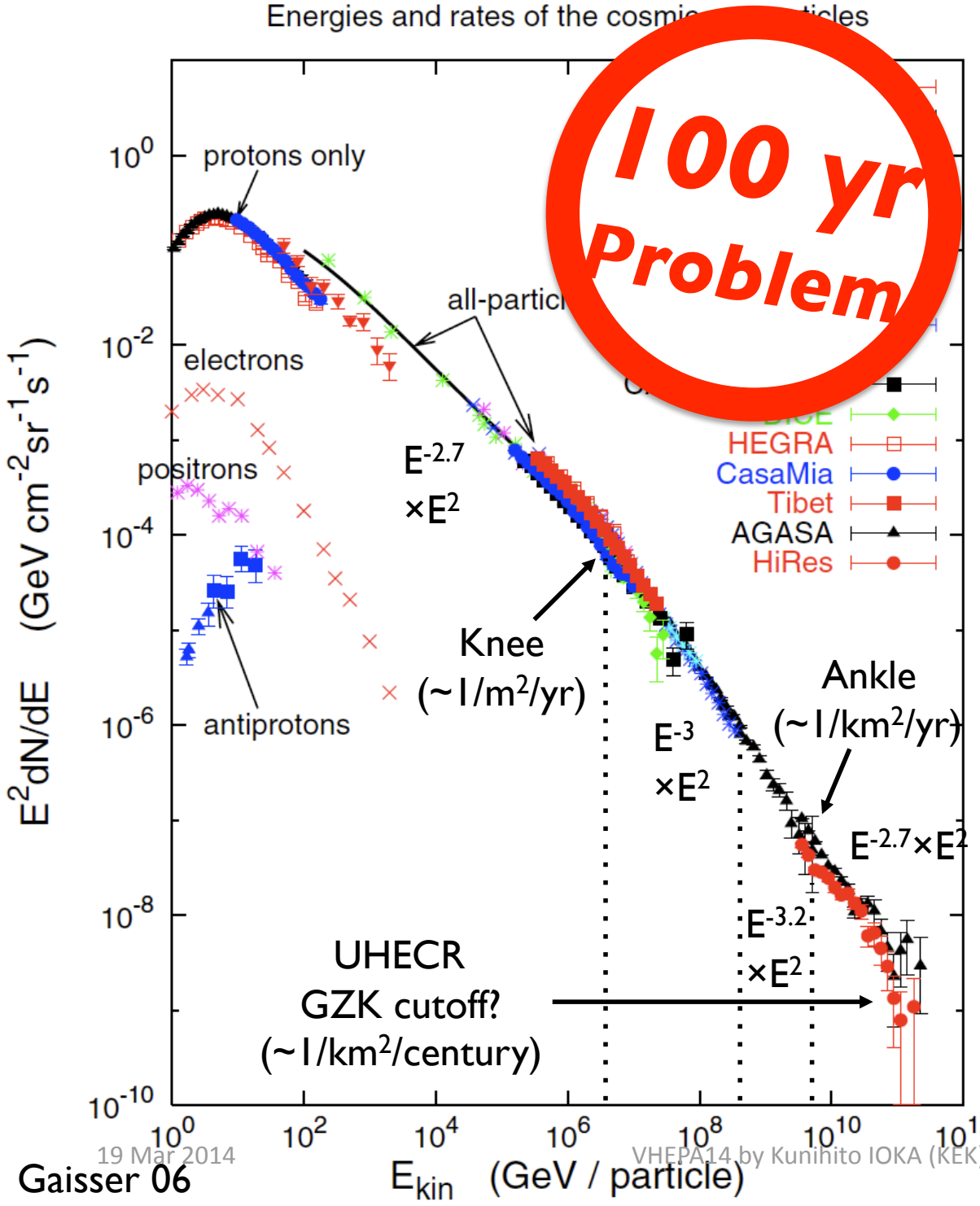
Galactic origin?

$<10^{14\text{-}15}$eV by SNR

10^{18}eV$<E$

$F \propto E^{-2.7}$

Extra-Gal. AGN? GRB?



100 yr Problem

Gaisser 06

Cosmic Ray

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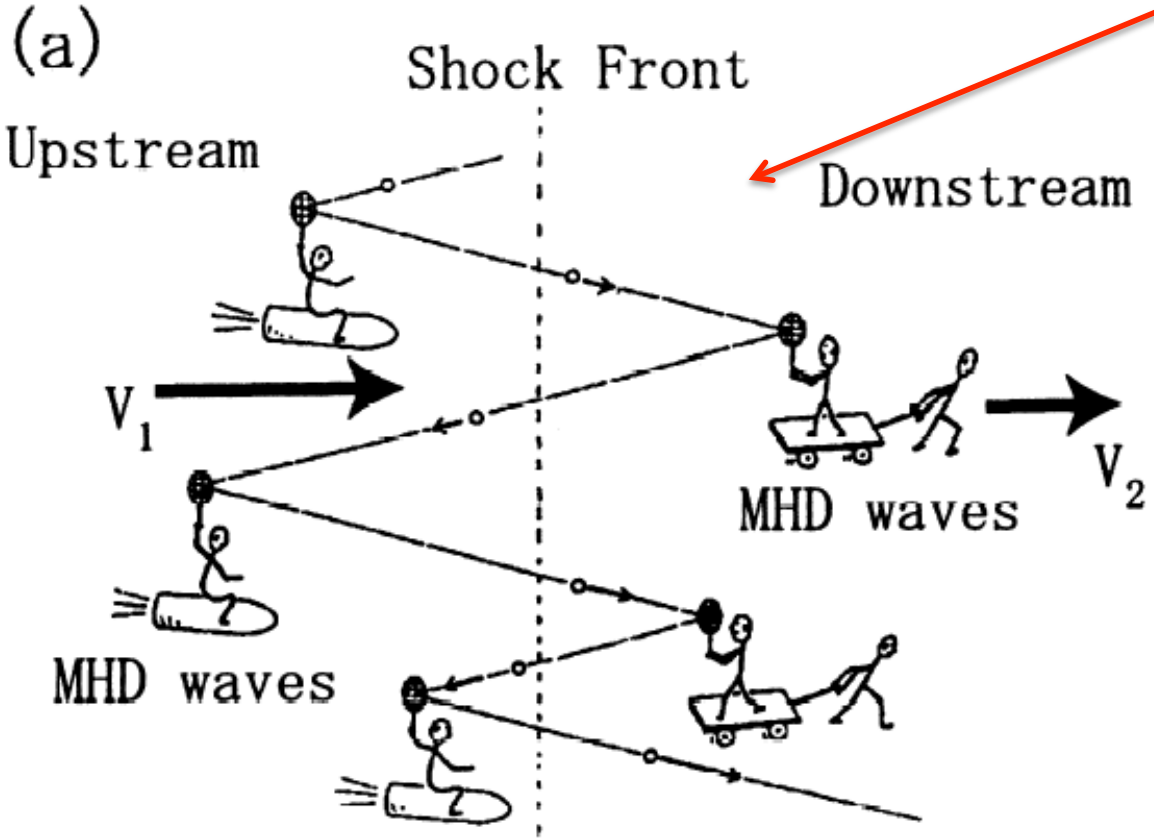
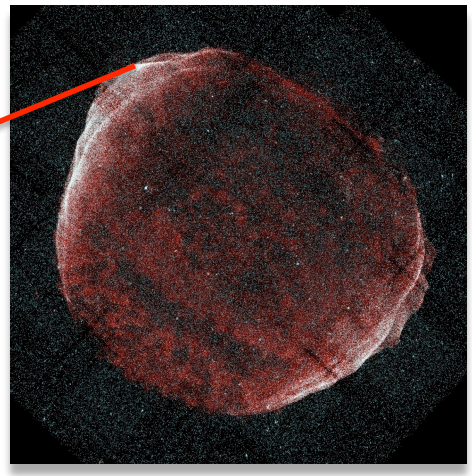
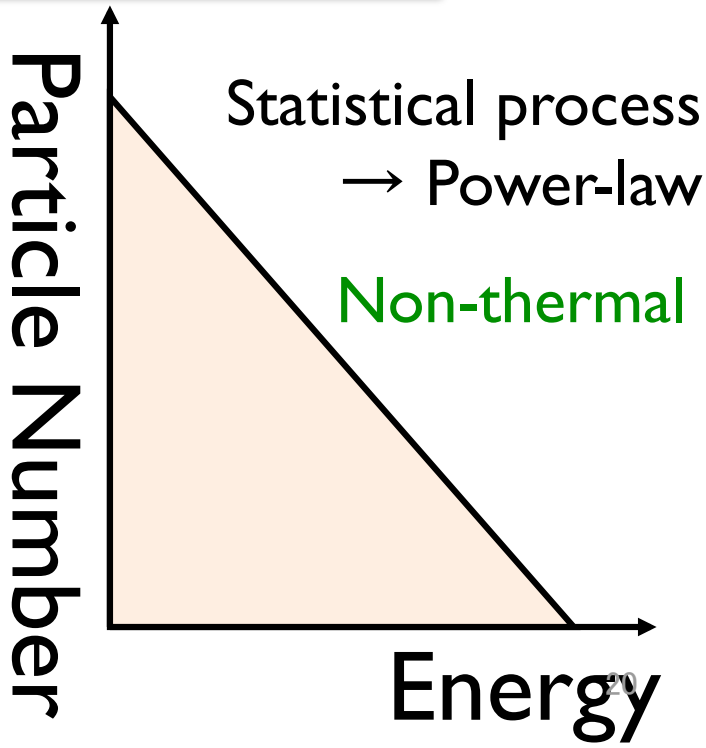
Extra-Gal. AGN? GRB?

Supernova Remnant

Collisionless shock





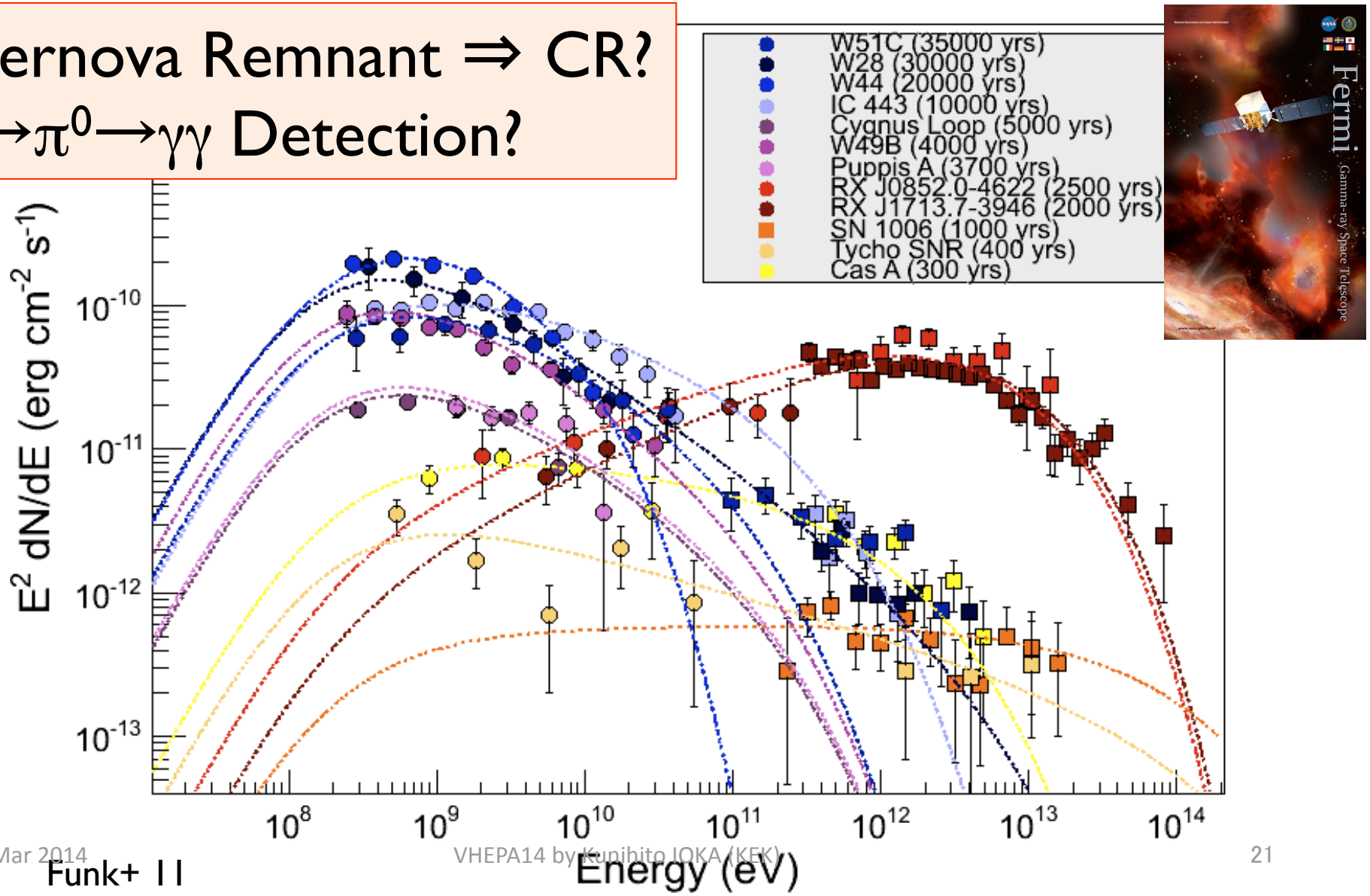


Diffusive shock acceleration
(Fermi acceleration)

Cosmic-Ray Origin?

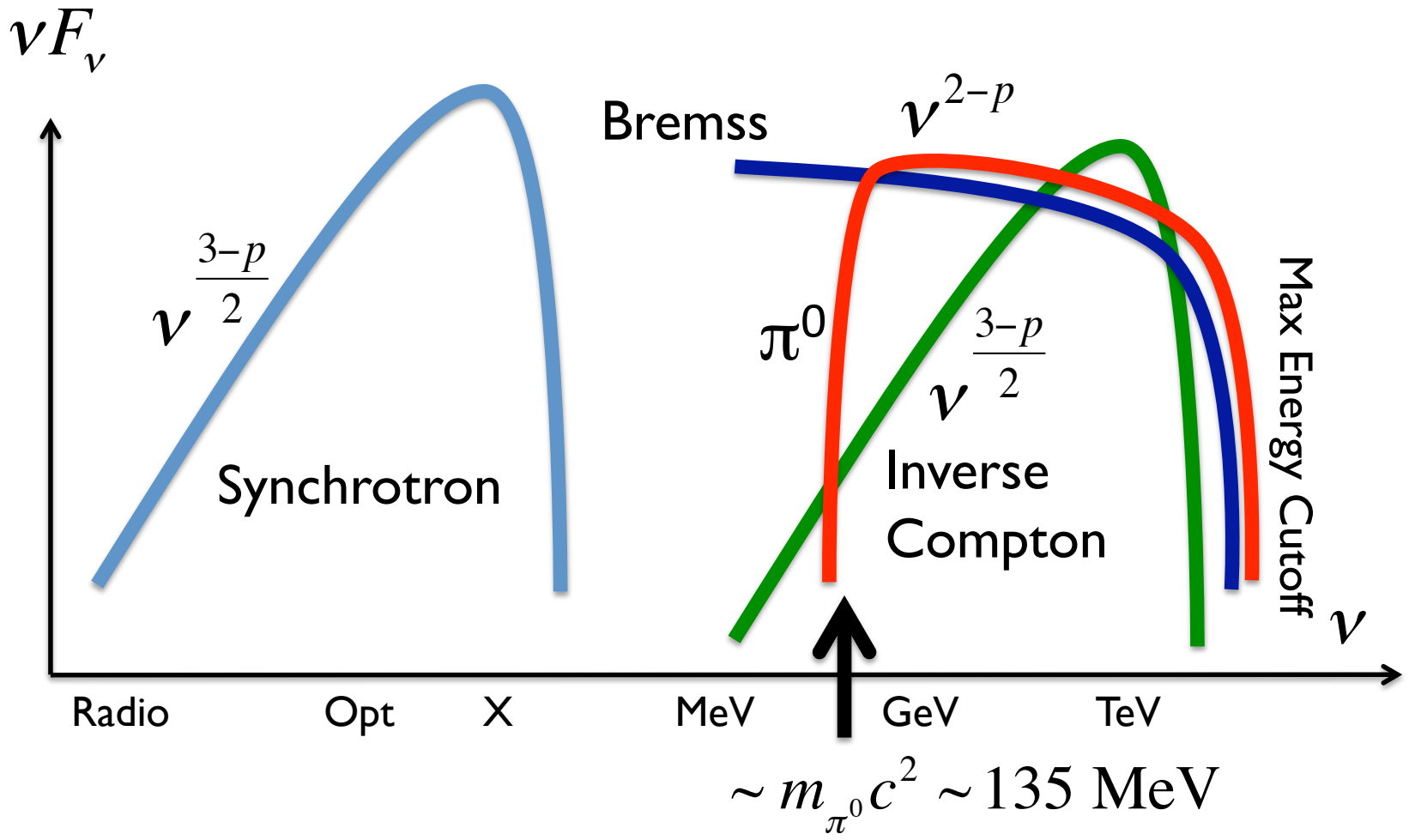
Supernova Remnant ⇒ CR?

$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$ Detection?



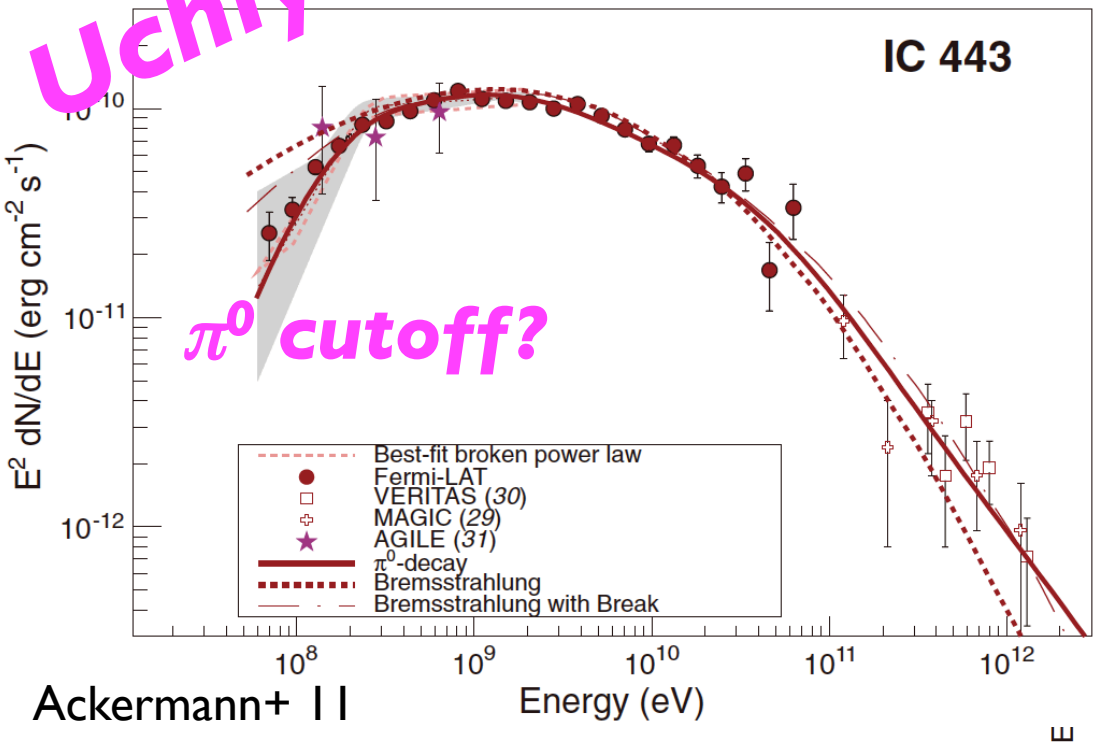
Funk+ 11

SNR Spectrum



Hadronic or Leptonic?

Uchiyama's talk



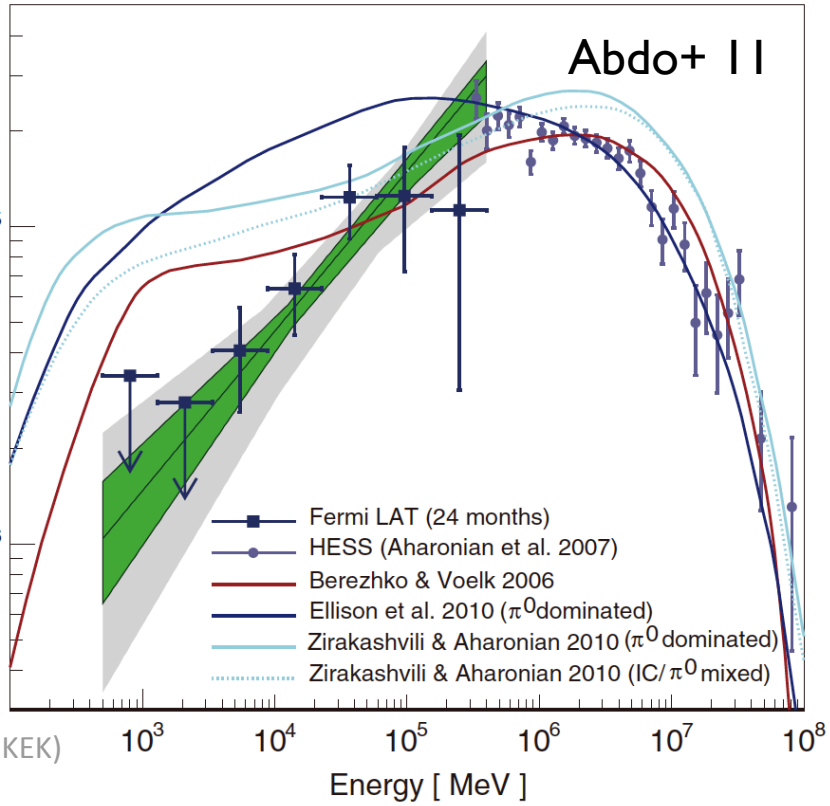
Ackermann+ 11

π^0 cutoff?

$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$

$e\gamma \rightarrow e\gamma$

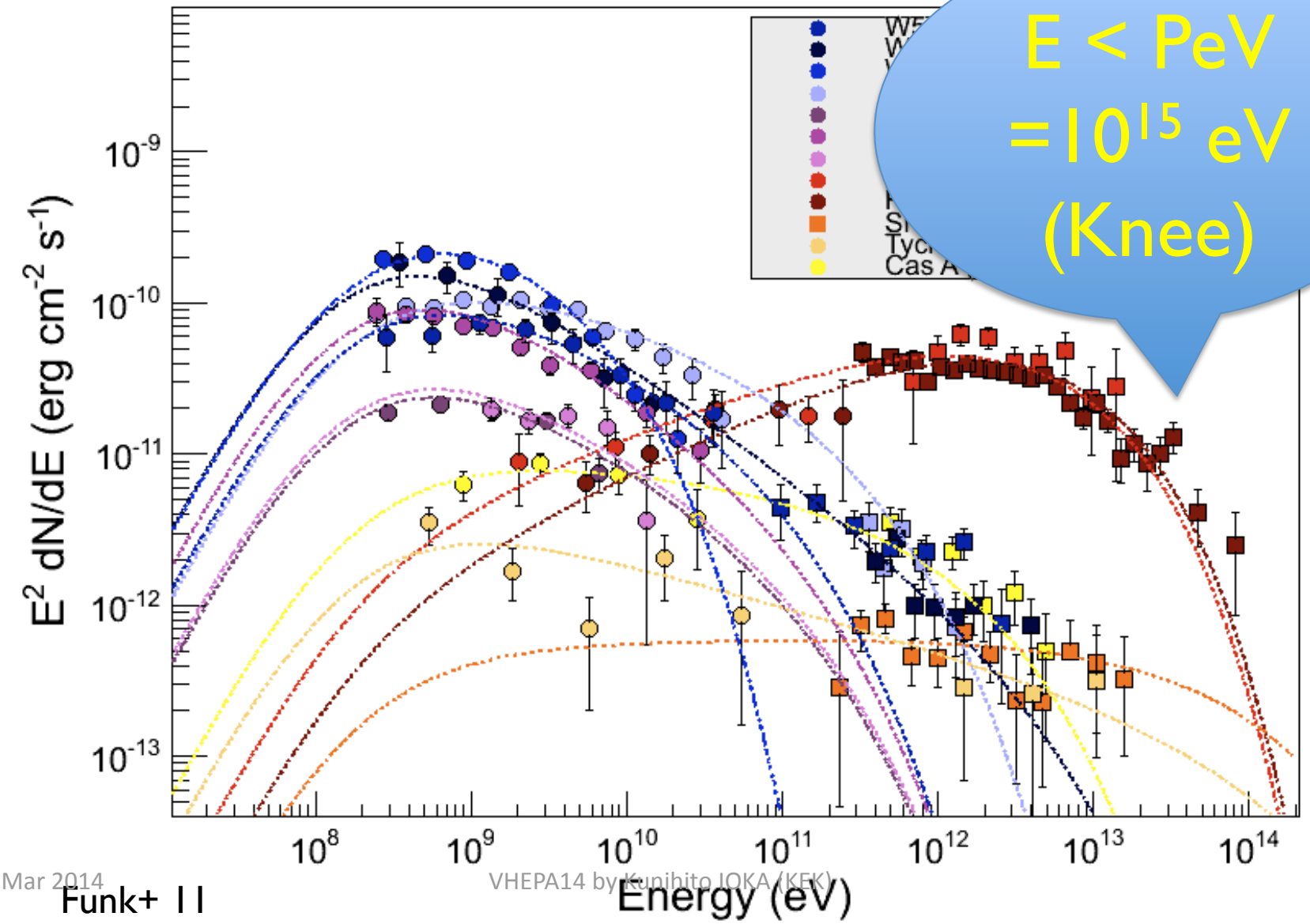
inverse Compton



First Evidence of CR Origin

Still under discussions

Where is PeVatron?



Funk+ 11

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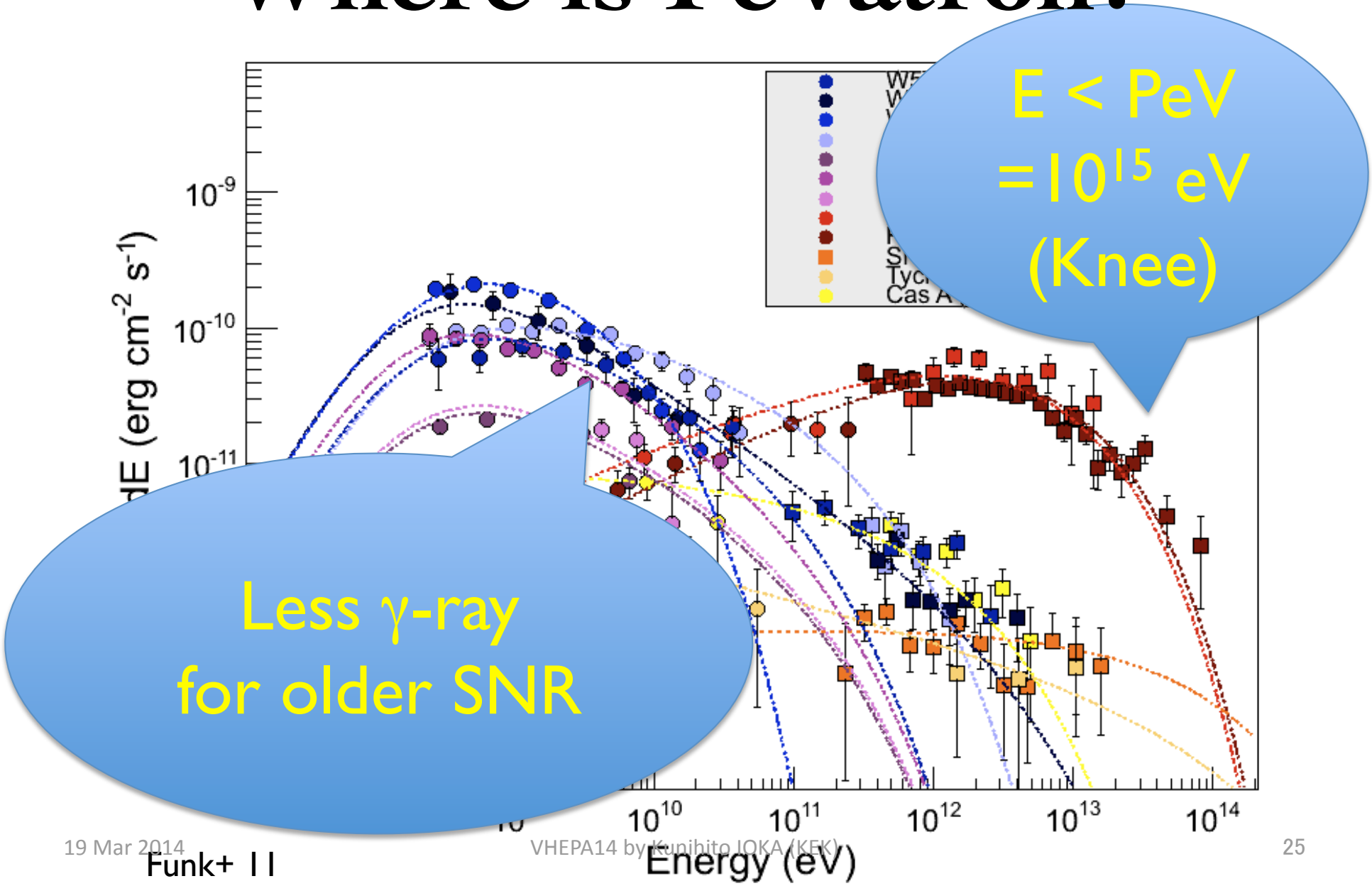
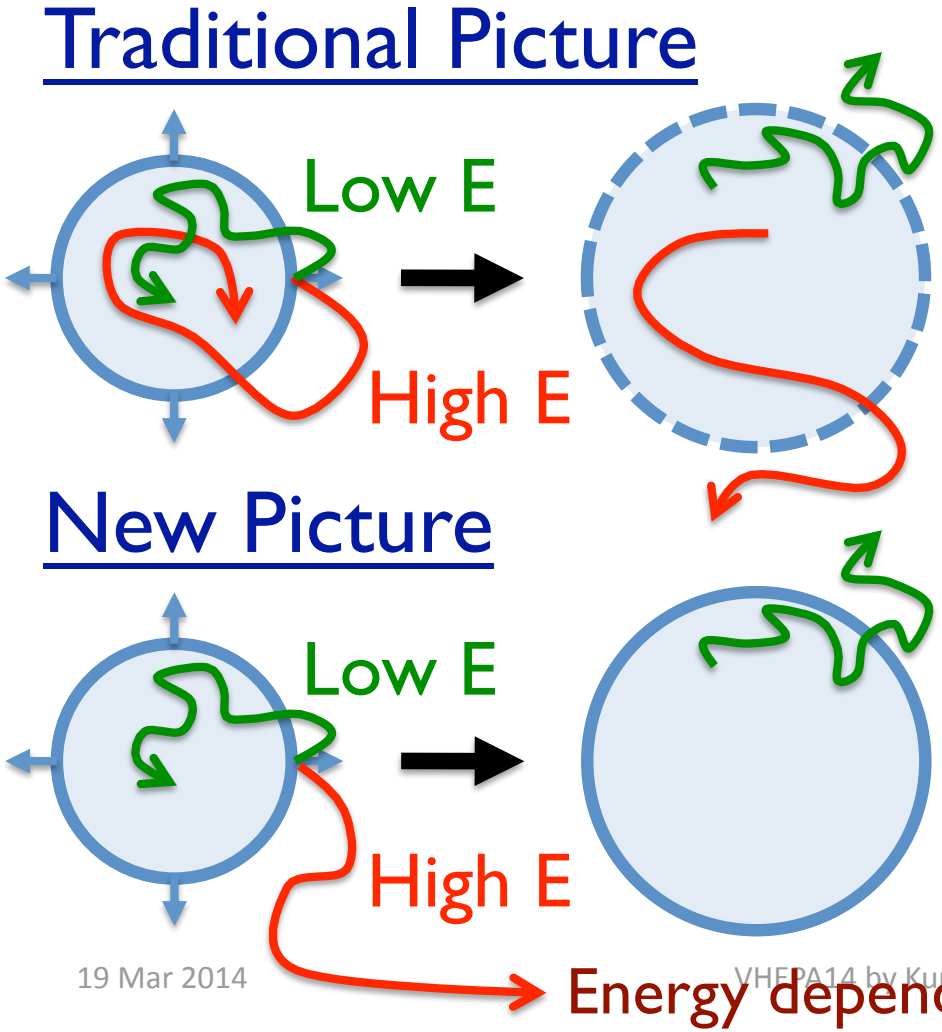
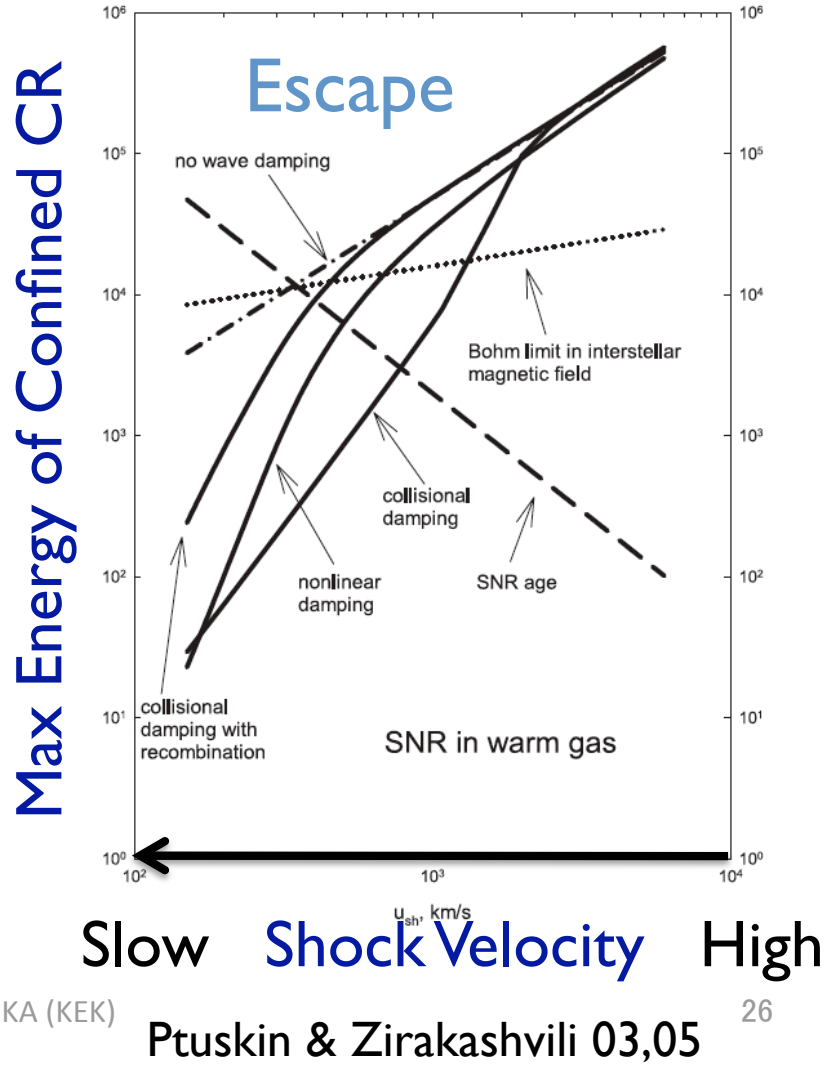


Funk+ 11

Cosmic Ray Escape

CR should run away from SNR to be observed

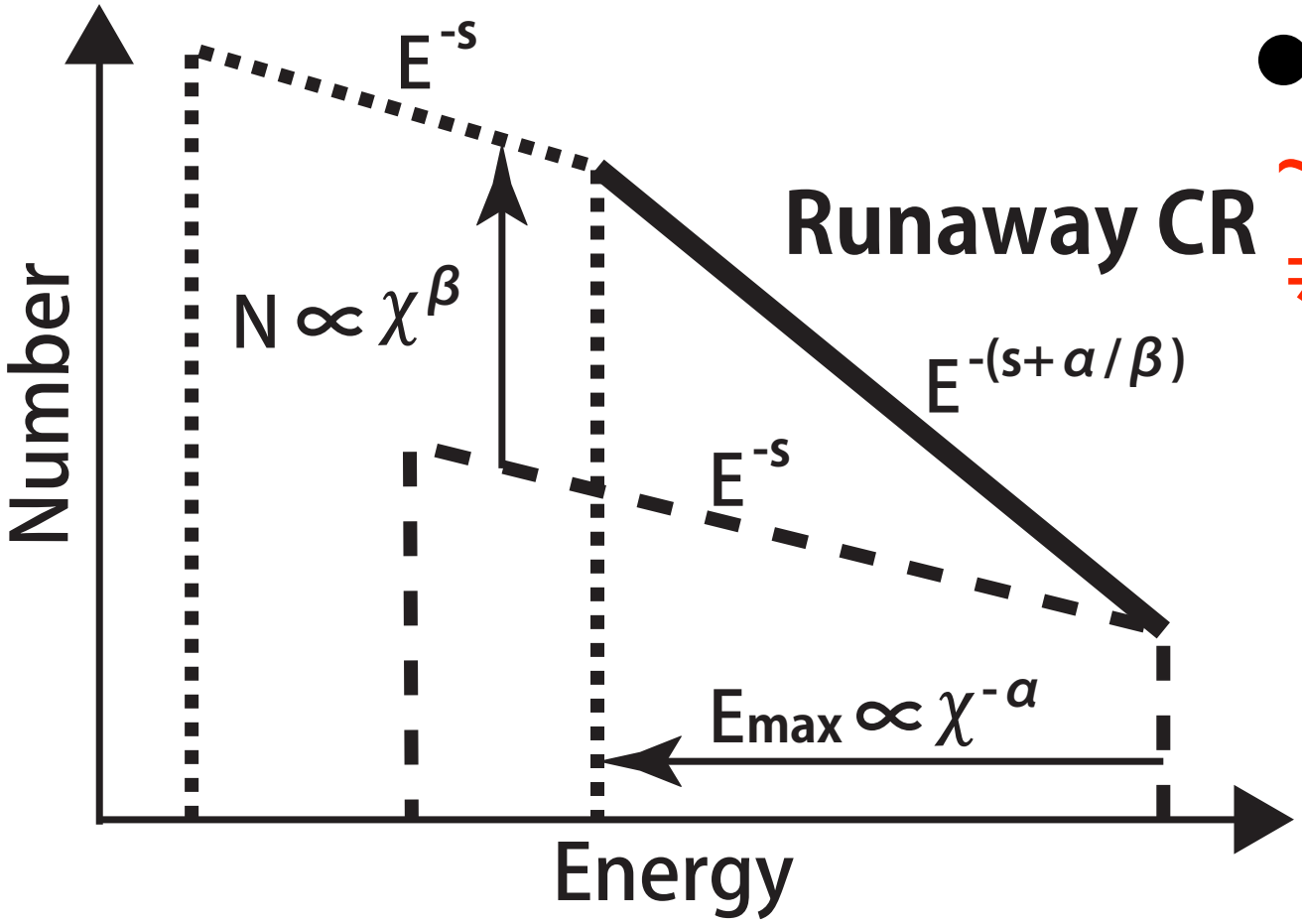




Ptuskin & Zirakashvili 03,05

Ohira's talk

Runaway CR Spectrum



- Spectrum

$\sim E^{-s}$ at SNR shock

$\neq \sim E^{-(s+\alpha/\beta)}$ escape

Also affect

- γ-ray outside SNR
  Gabici+ 07
- PeVatron is rare
- CR Helium
  Ohira & KI 11
- CR $e^{\pm}$
  Kawanaka+ 11

Ptuskin & Zirakashvili 03,05, Gabici+ 07, Caprioli+ 09,10, Ohira, Murase, Yamazaki 10, Fujita+ 10, Ohira & KI 11, Kawanaka+ 11

Evolution to Black Hole

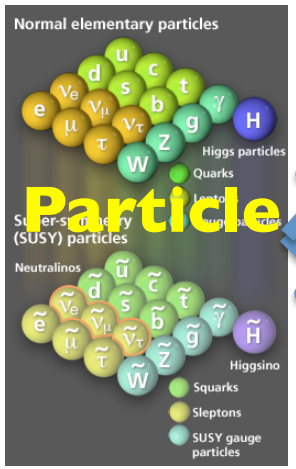
$2M_\odot$ Neutron Star
Dark Matter
LIV
Axion

Star Planet

Supernova GRB

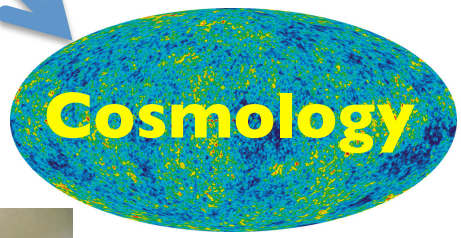
Supernova Remnant

GeV-TeV SNR
CR Origin
PeVatron



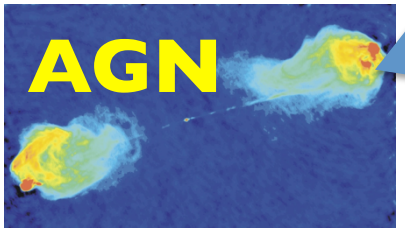
Particle

Unification/Diversity
GeV GRB
Jet Mechanism



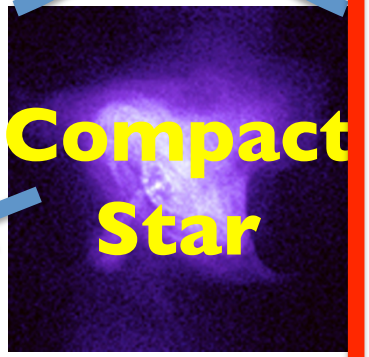
Cosmology

Dark Energy
Inflation
Dark Age
Pop III, First GRB



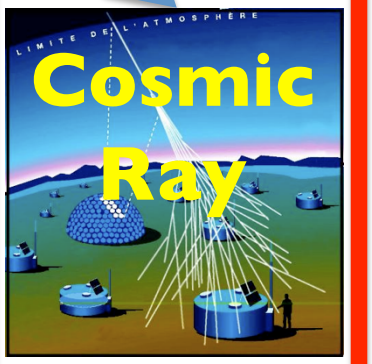
AGN

GeV-TeV AGN
Tidal Disruption Jet
Fermi Bubble



Compact Star

GeV-TeV Pulsar
Magnetosphere
Crab Pulsar
TeV PWN



Cosmic Ray

e^+ Excess
GZK cutoff
UHECR Fe

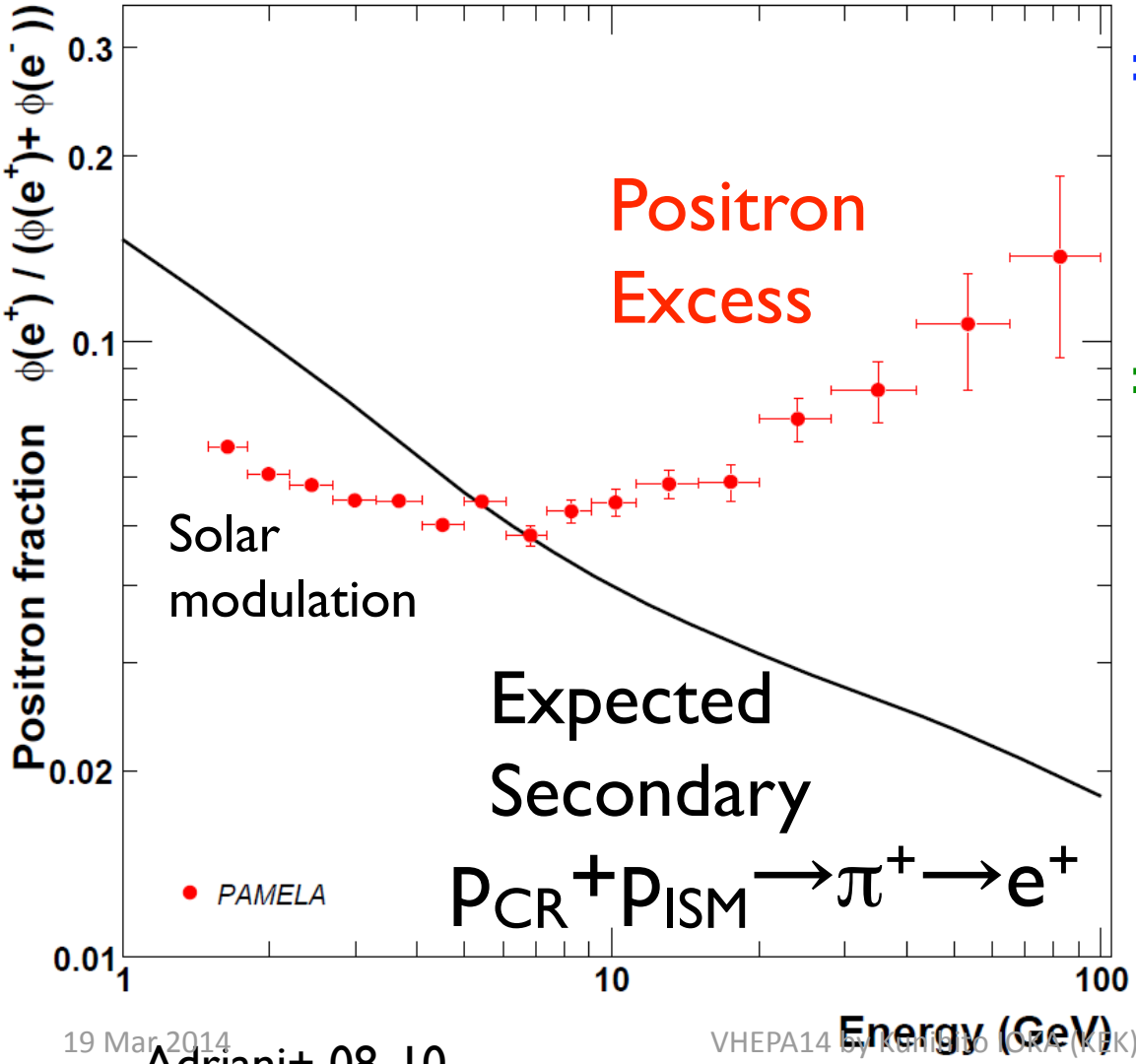
Computar

Supernova
Rela, Turbulence
PIC particle acc.
GR MHD

High Energy Universe

PAMELA

Positron excess above the predicted secondary



Adriani+ 08, 10

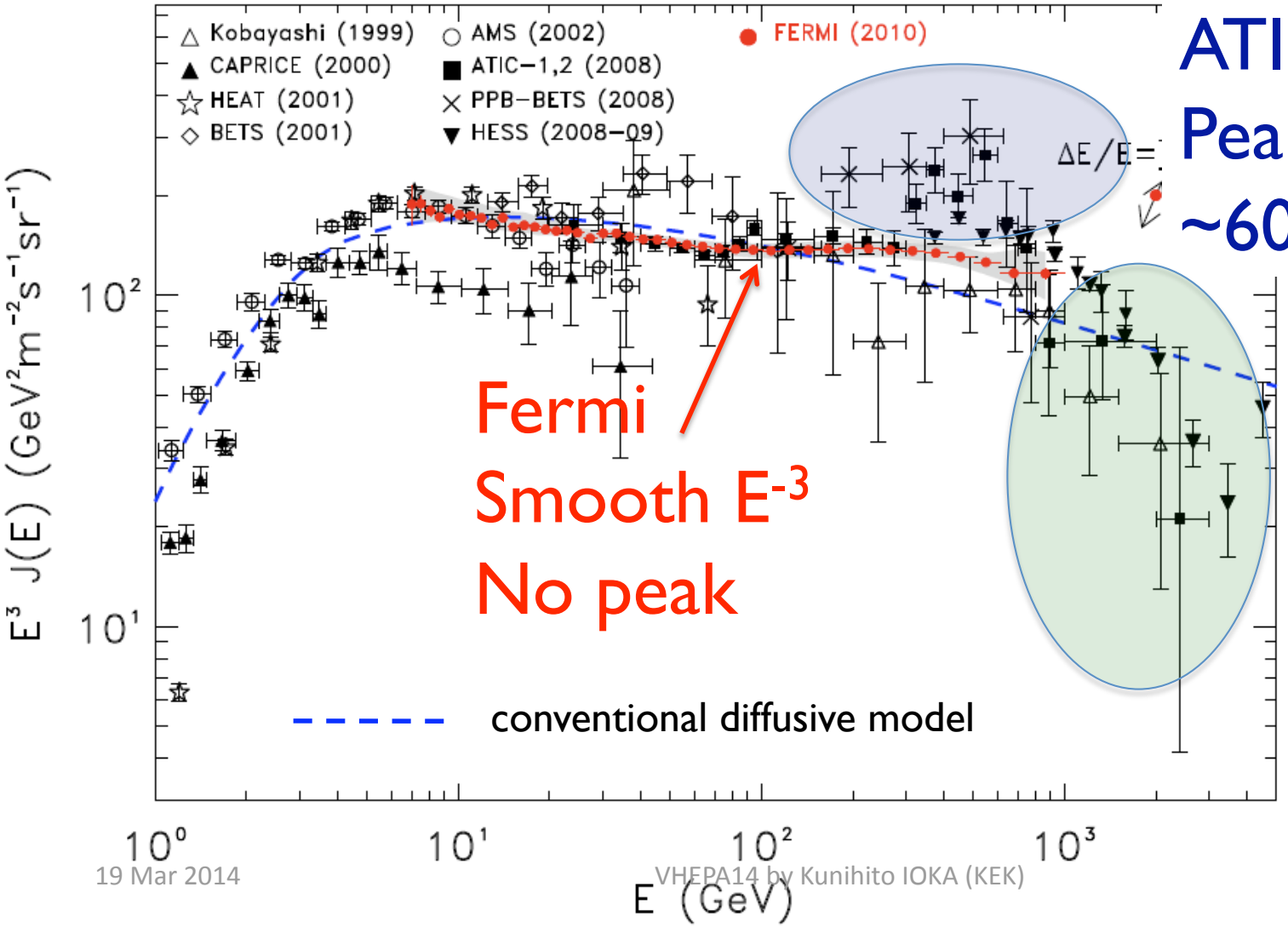
⇒ New sources
- Dark Matter?
- Astrophysical?

⇒ Many papers >10^3

Jul 06 - Feb 08
151672 e-, 9430 e+

Cosmic Ray Electron

An Excess also in (e^++e^-) Spectrum



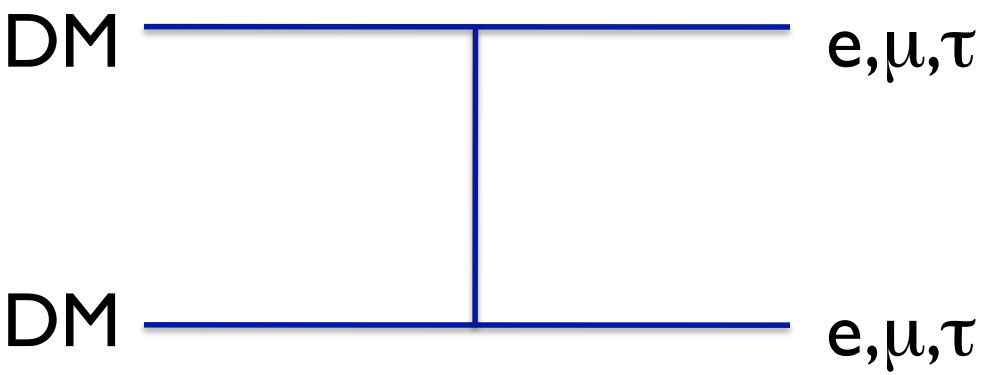
ATIC/PPB-BETS
Peak + Cutoff
~600GeV DM?

HESS
~TeV cutoff

Abdo+ 09
Ackermann+ 10
Chang+ 08, Torii+ 08
Aharonian+ 08, 09
Adriani+ 11

Dark Matter?

Annihilation



$Q \sim n^2$

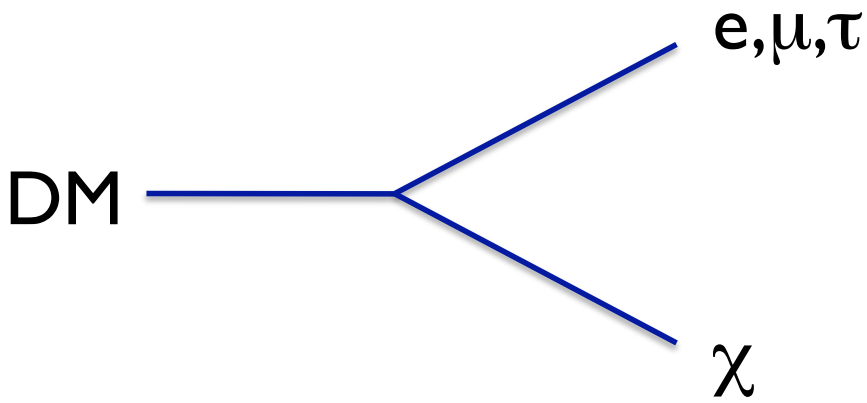
$E_{cut} \sim m_{DM} \sim$ TeV

$\langle \sigma v \rangle \sim 3 \times 10^{-24} cm^3/s$

$> 3 \times 10^{-26} cm^3/s$ (thermal)

boost factor ~100

Decay



$Q \sim n$

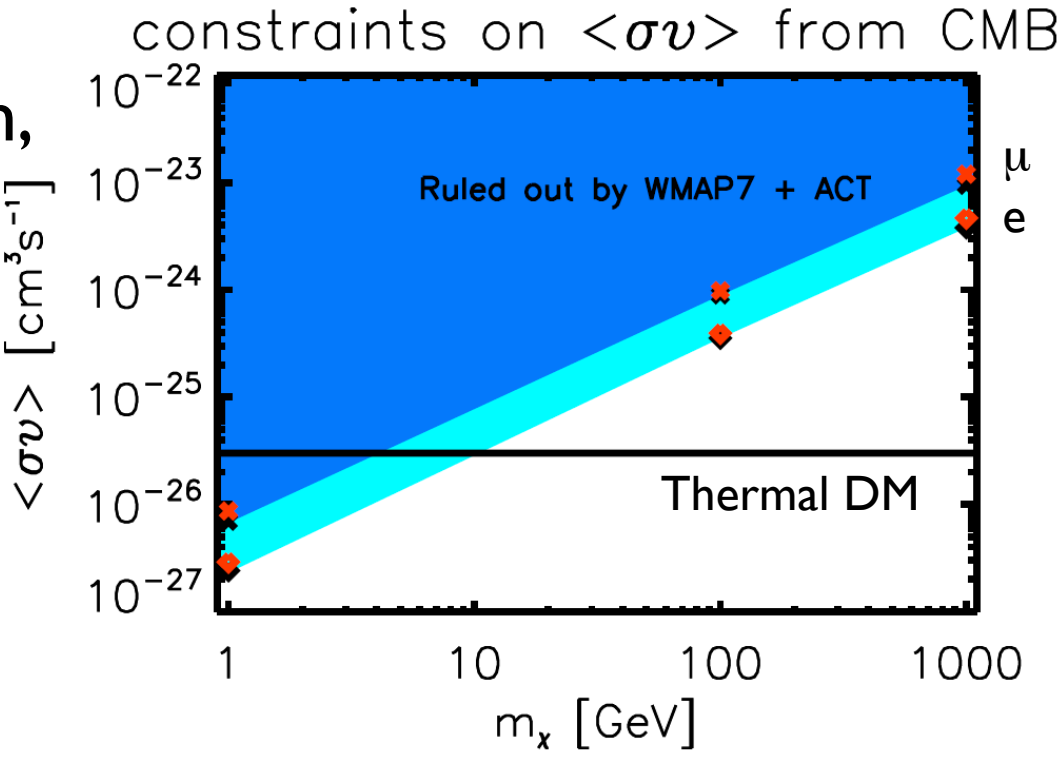
$E_{cut} \sim m_{DM}/2$

$t_{decay} \sim 6 \times 10^{26}$sec ($>H^{-1}$)

Assuming $m_{DM} \sim O(TeV)$, $n_{DM} = 0.3 GeV/cm^3$

Constraints on DM

- ***DM(+DM) → qq,WW,ee,μμ,ττ → e, pbar, γ, ν***
- ***pbar*** ⇒ ~~hadron modes~~
- ***γ-ray***
  - Line, $\pi^0 2\gamma$, Compton, Final state radiation
  - GC, Dwarf, Cluster, Background
  - ~~Cuspy DM profile~~
  - Decay is OK
- Radio, ν, CMB, BBN, X



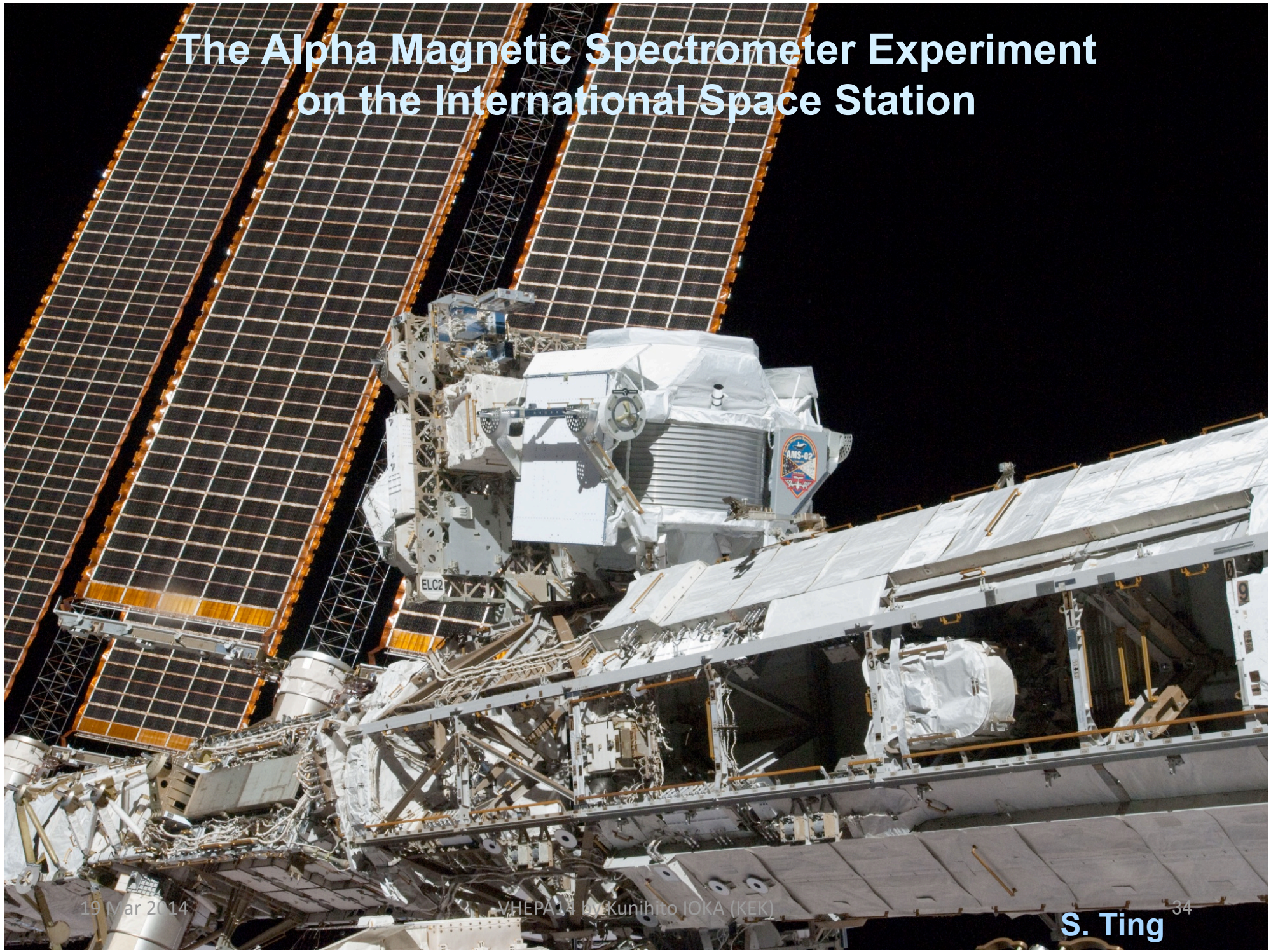
e.g., Galli+ 11, Hisano+ 11

Astrophysical Models

$U_e \ll U_p \Rightarrow$

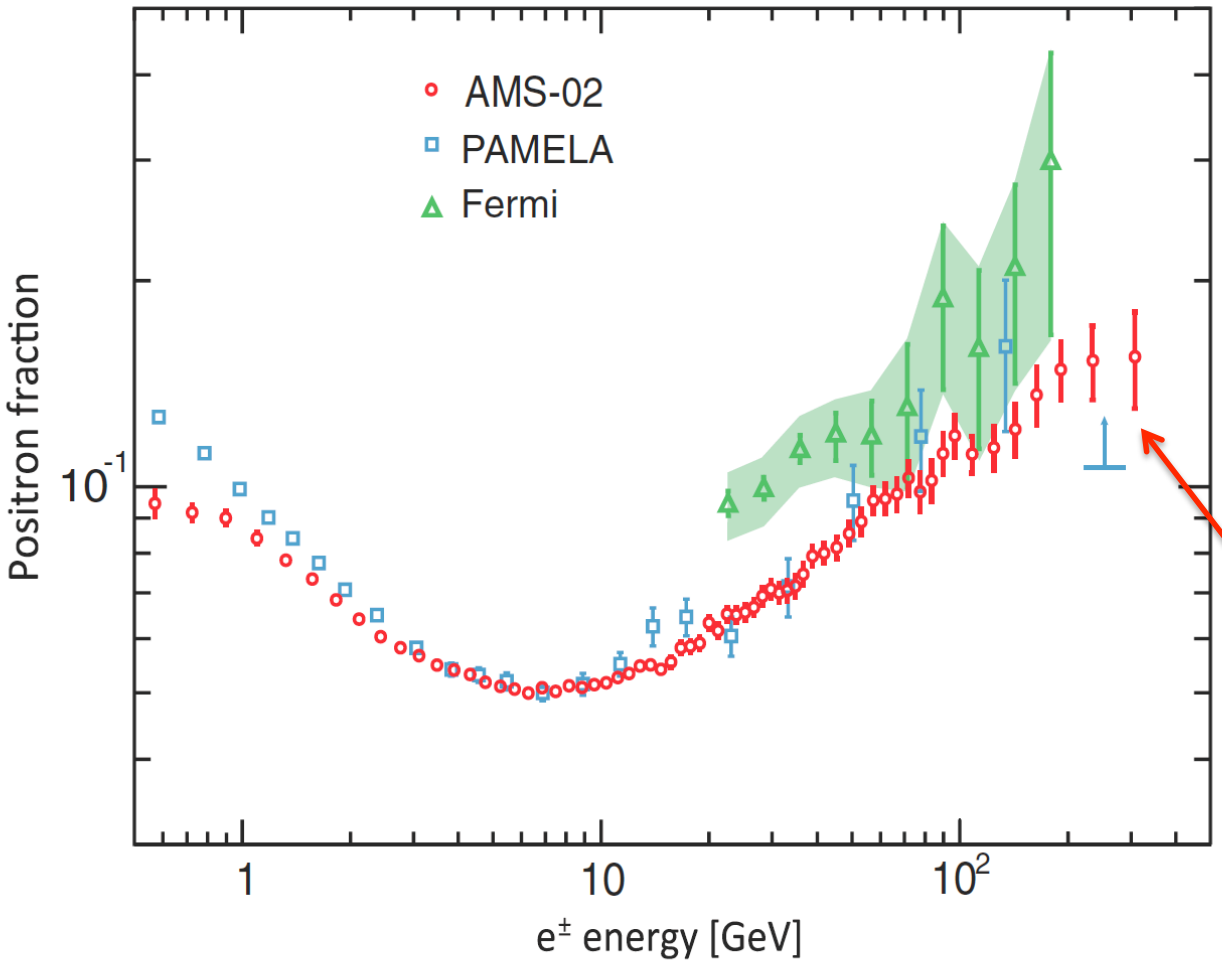
E($e^\pm$ origin) << E(Supernova)

$$\frac{E_e}{\text{Supernova}} \sim \frac{U_e}{U_p}\frac{t_{esc}}{t_{cool}} E_{SN} \sim \frac{10^{47}\,\text{erg}}{\text{Supernova}}$$


The Alpha Magnetic Spectrometer Experiment
on the International Space Station
AMS-02
ELC2

S. Ting

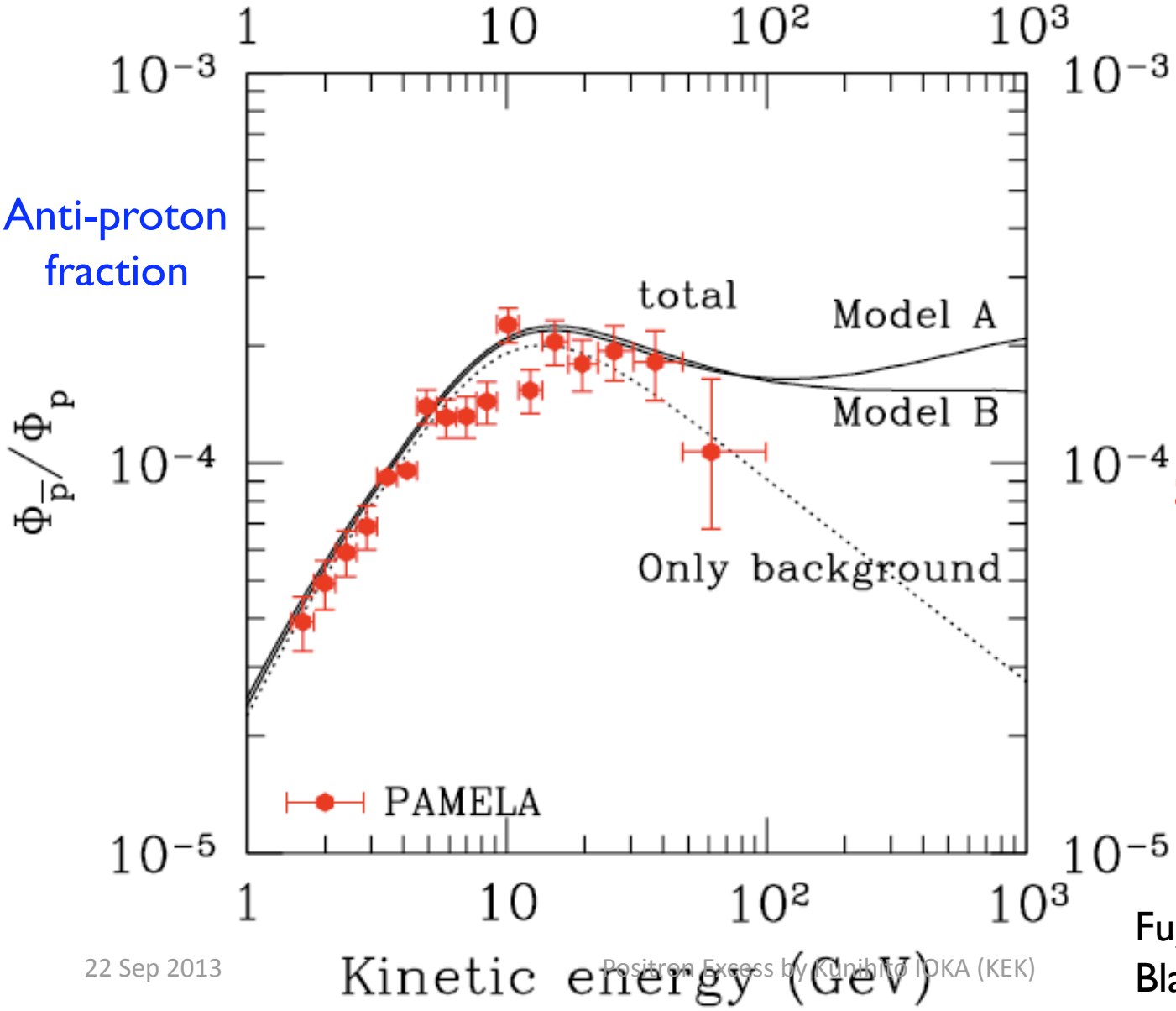
AMS-02 New Points



1. High precision
2. Up to ~350 GeV
3. No fine structure
4. Slope declines
5. No anisotropy
   δ<0.036 (95%CL)

Aguilar+ 13, ICRC13

Anti-Proton



SNR model:

$pp \rightarrow \pi^+ \rightarrow e^+e^-$

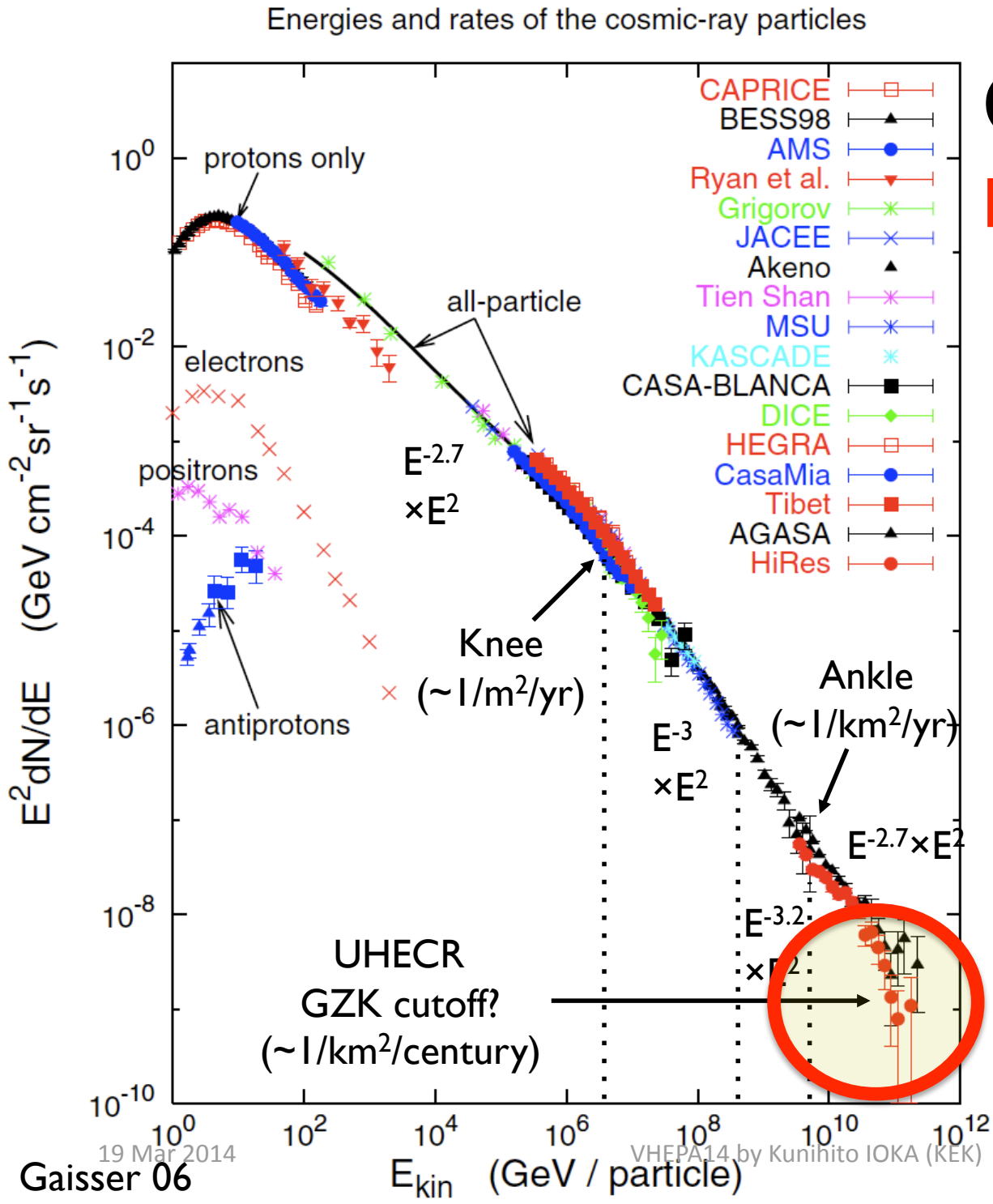
(w/ surrounding)

⇒ Inevitably anti-proton excess above ~100 GeV

⇒ AMS-02

Fujita, Kohri, Yamazaki, KI 09

Blasi & Serpico 09



Cosmic Ray

$E<10^{15\text{-}16}$eV (Knee)

$F \propto E^{-2.7}$

Supernova remnant(?)

$L_{CR} \sim 10^{41}$erg/s

$\sim 0.1 E_{SN}/t_{SN}$

$10^{15\text{-}16}<E$

$<10^{18}$eV (Ankle)

$F \propto E^{-3\text{-}3.2}$

Galactic origin?

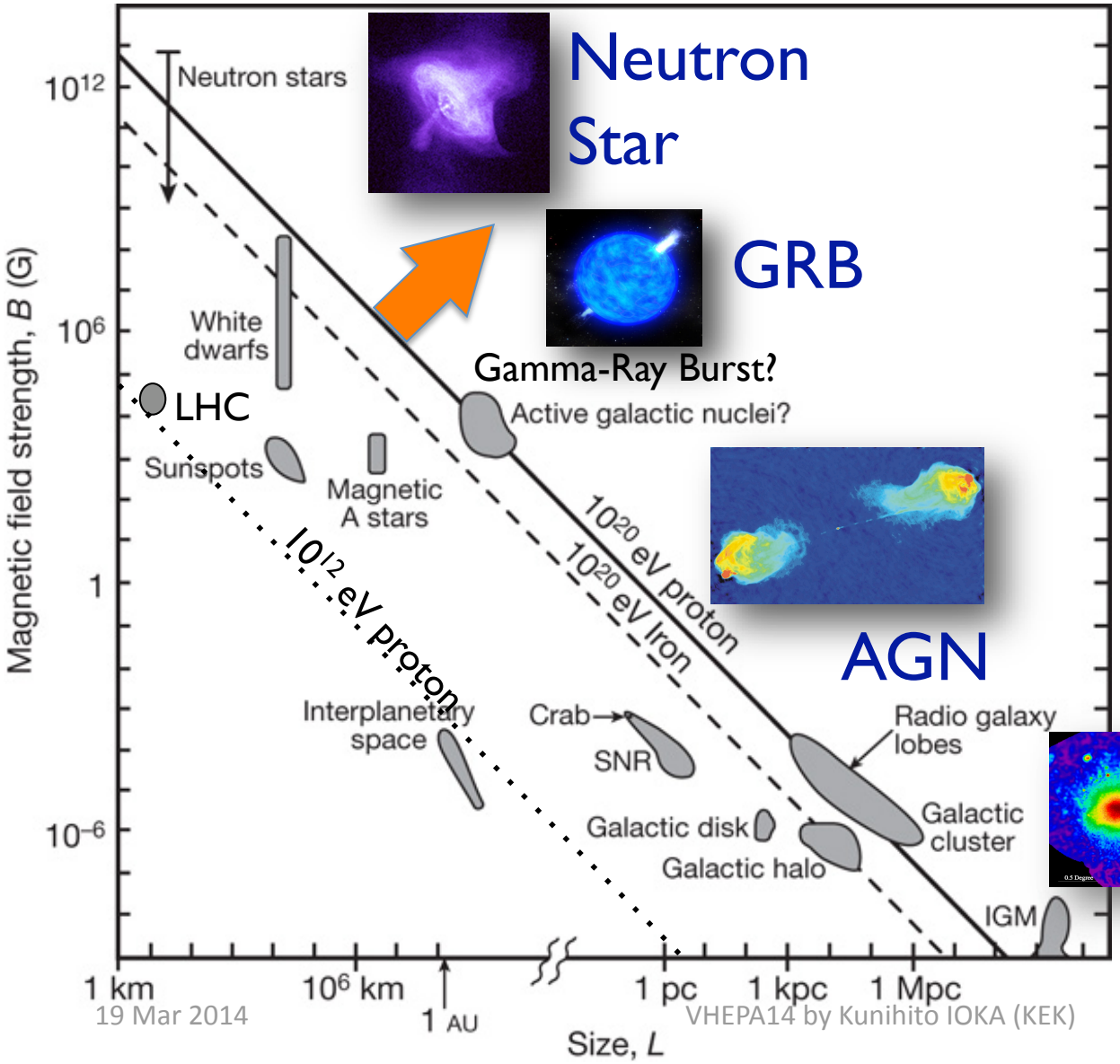
$<10^{14\text{-}15}$eV by SNR

10^{18}eV$<E$

$F \propto E^{-2.7}$

Extra-Gal. AGN? GRB?

Ultra-High Energy Cosmic-Ray



Neutron Star

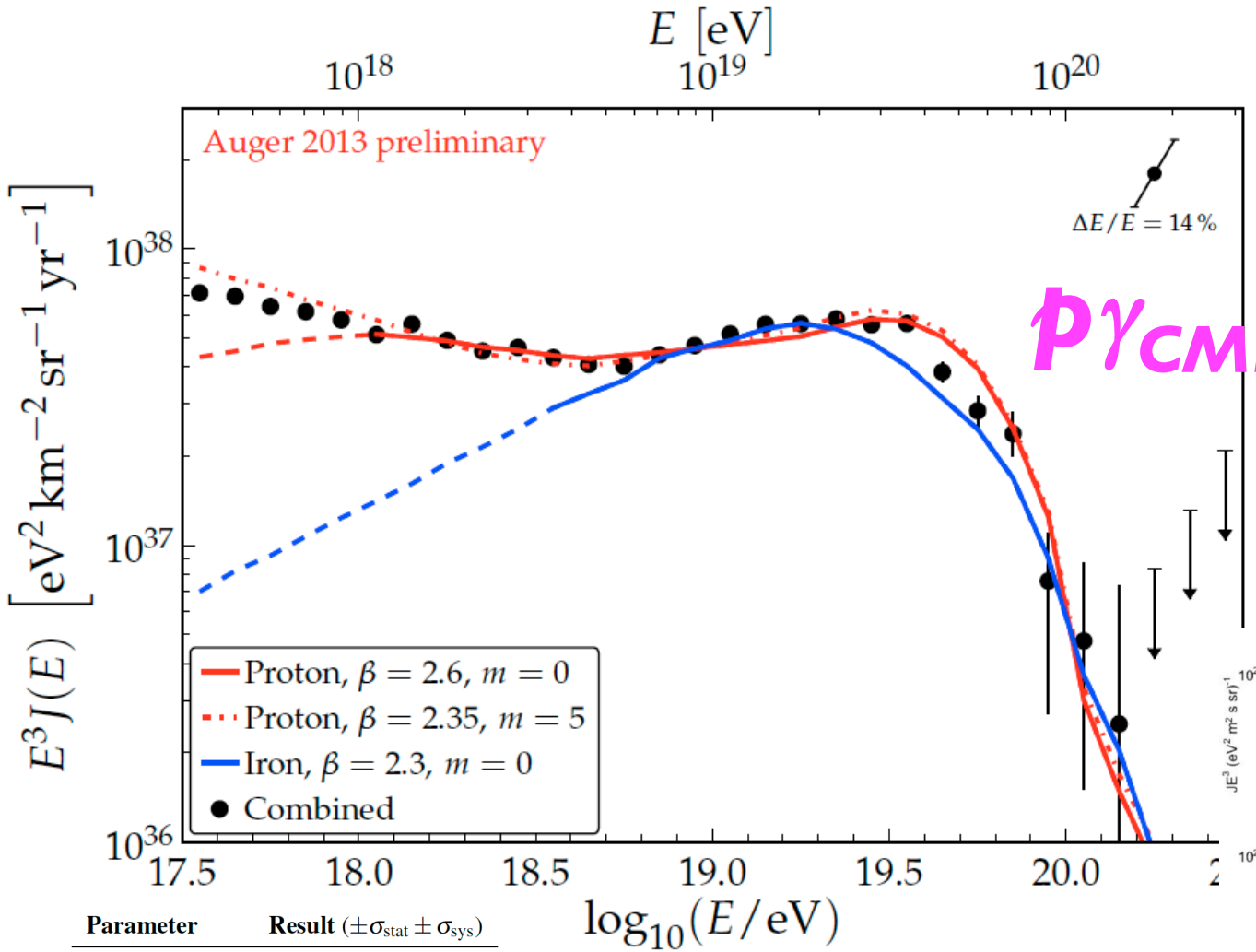
GRB

AGN

Galaxy cluster

- E~10^{20}eV
- R_{Larmor}>R_{Galaxy}
  ⇒ Extragalactic
- Hillas condition
  E<ZeBR (v/c)
- Energy/Vol./Time
  ~10^{44}erg/Mpc^3/yr
  UHECR~GRB<<AGN

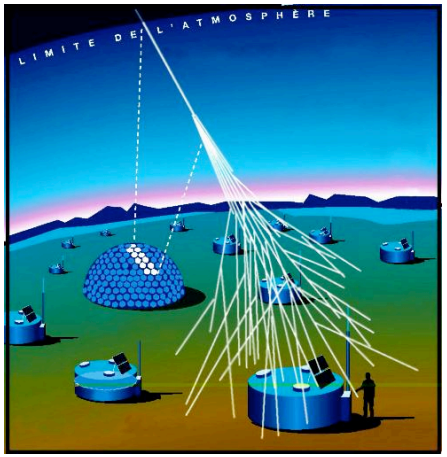
GZK-like Cutoff



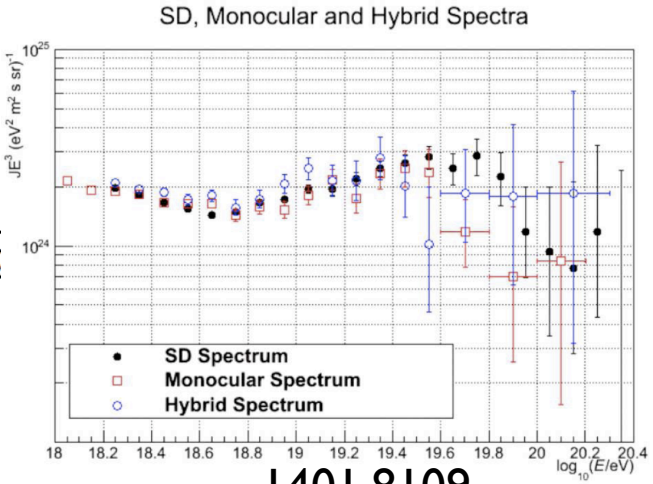
$p\gamma_{CMB}$?

Parameter	Result ($\pm\sigma_{stat} \pm \sigma_{sys}$)
$\log_{10}(E_a/\mathrm{eV})$	$18.72 \pm 0.01 \pm 0.02$
γ_1	$3.23 \pm 0.01 \pm 0.07$
γ_2	$2.63 \pm 0.02 \pm 0.04$
$\log_{10}(E_{1/2}/\mathrm{eV})$	$19.63 \pm 0.01 \pm 0.01$
$\log_{10} W_c$	$0.15 \pm 0.01 \pm 0.02$

Auger 1307.5059, TA 2013



Telescope Array also observes



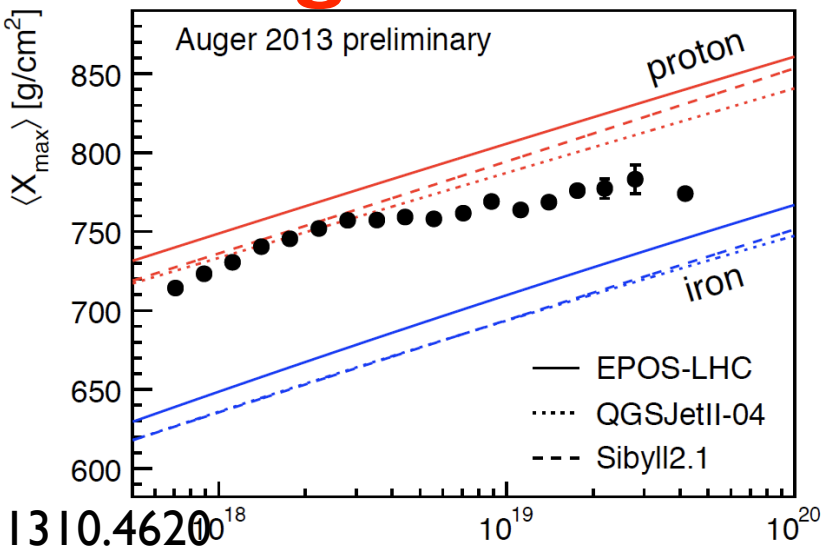
1401.8109

Proton or Iron?

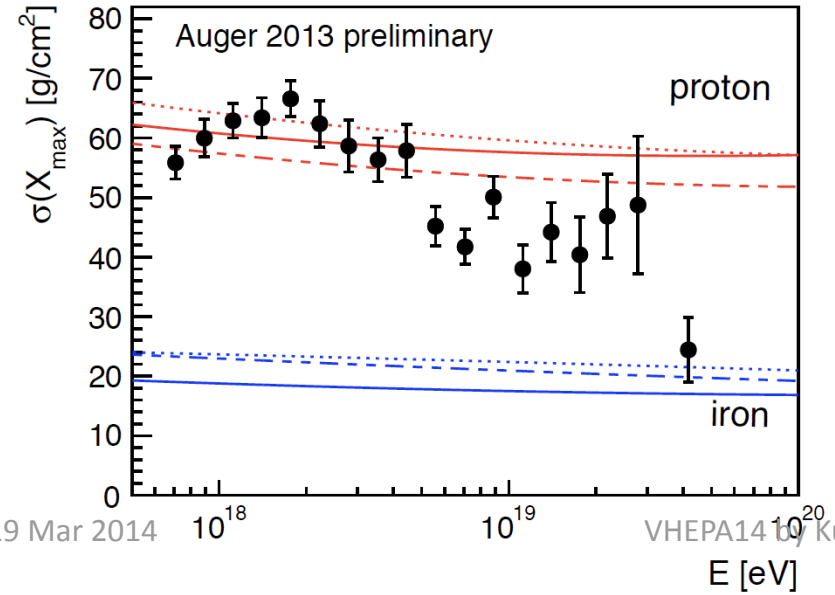
Max depth of air shower

Dispersion

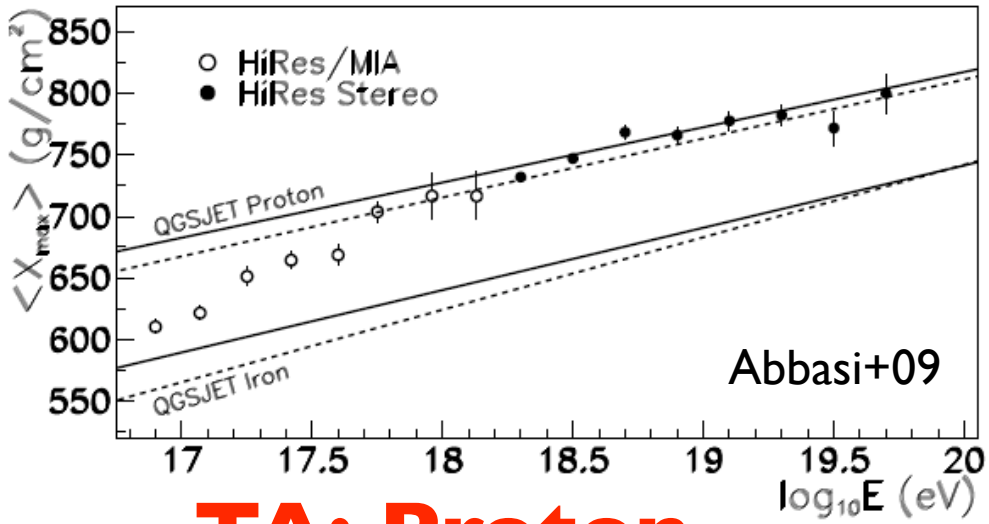
Auger: Fe



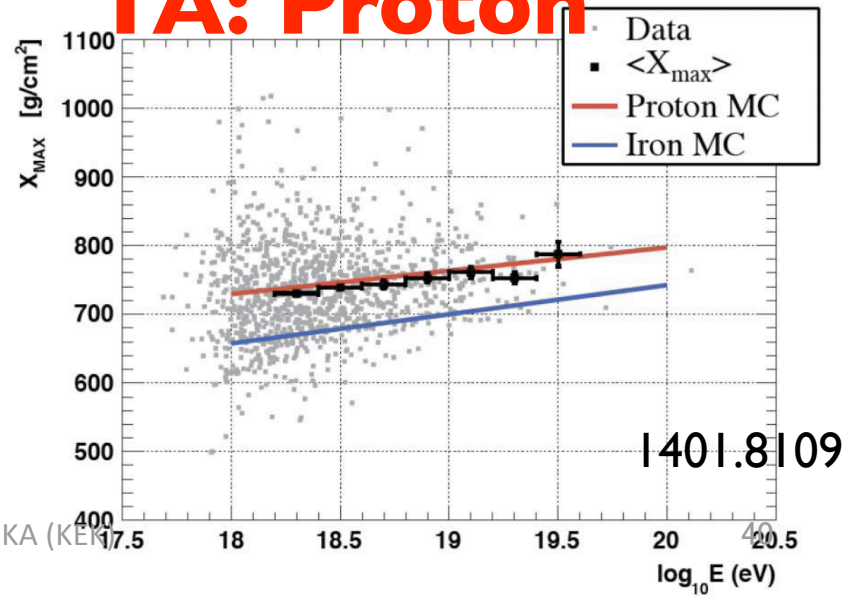
1310.4620



HiRes: Proton

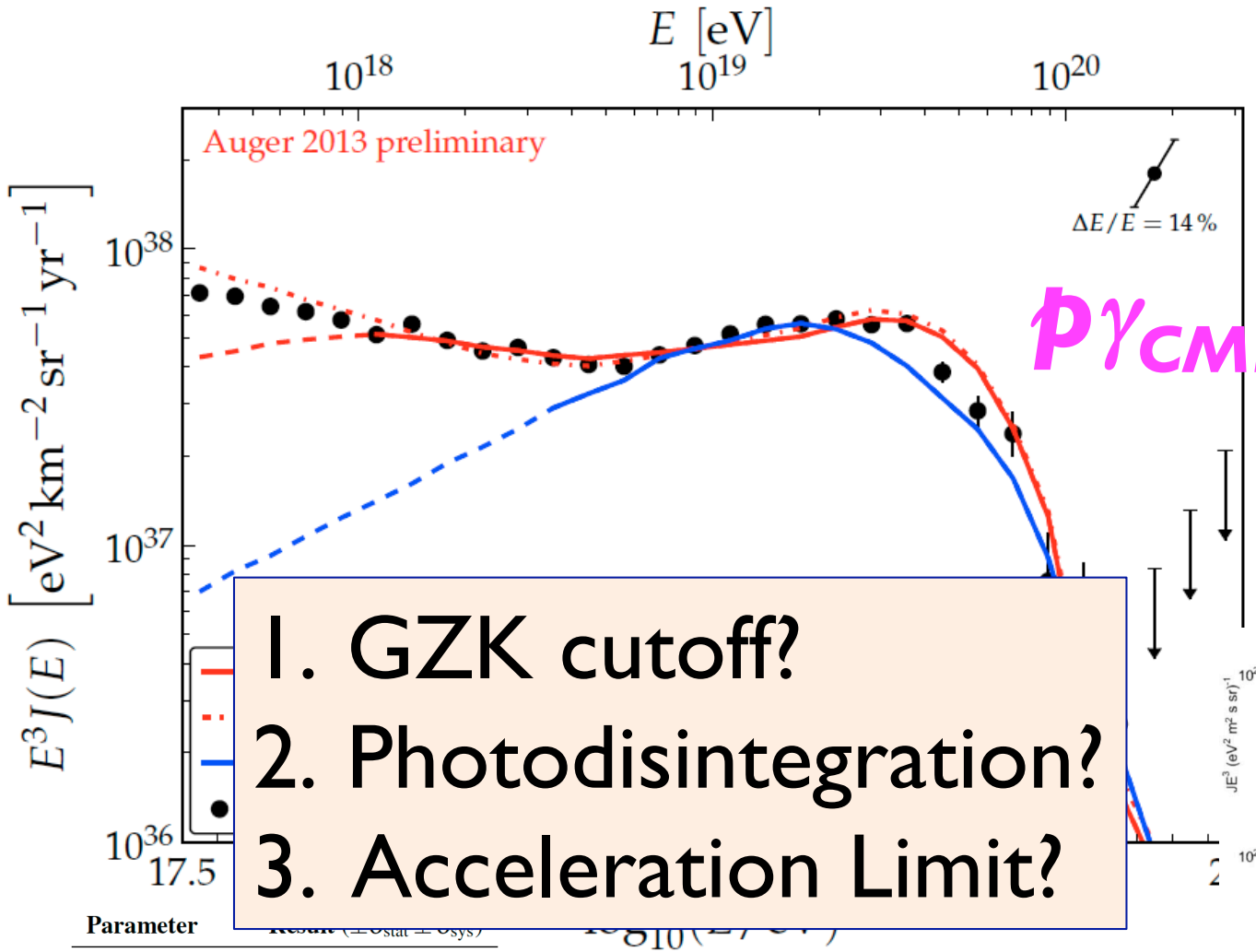


TA: Proton



1401.8109

GZK-like Cutoff



$p\gamma_{CMB}$?

1. GZK cutoff?
2. Photodisintegration?
3. Acceleration Limit?

Parameter	Result ($\pm\sigma_{stat} \pm \sigma_{sys}$)
$\log_{10}(E_a/\text{eV})$	$18.72 \pm 0.01 \pm 0.02$
γ_1	$3.23 \pm 0.01 \pm 0.07$
γ_2	$2.63 \pm 0.02 \pm 0.04$
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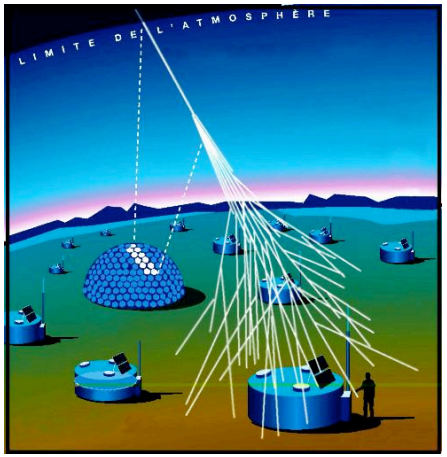

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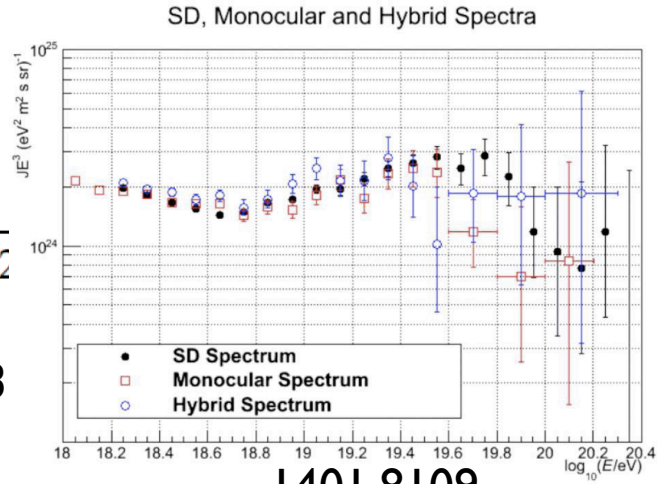


1401.8109

Evolution to Black Hole

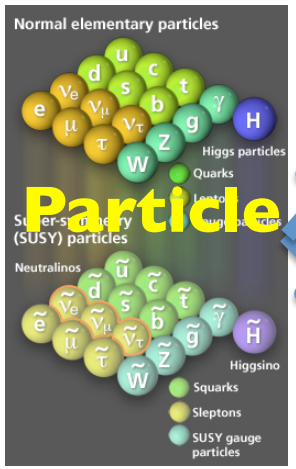
$2M_\odot$ Neutron Star
Dark Matter
LIV
Axion

Star
Planet

Supernova
GRB

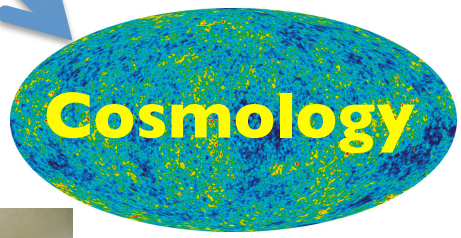
Supernova
Remnant

GeV-TeV SNR
CR Origin
PeVatron



Particle

Unification/Diversity
GeV GRB
Jet Mechanism

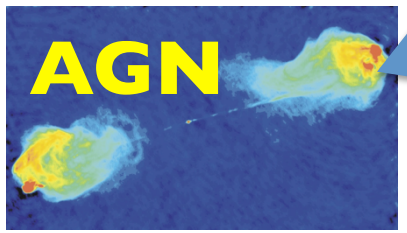


Cosmology

Dark Energy
Inflation
Dark Age
Pop III, First GRB

Computar

Supernova
Rela, Turbulence
PIC particle acc.
GR MHD

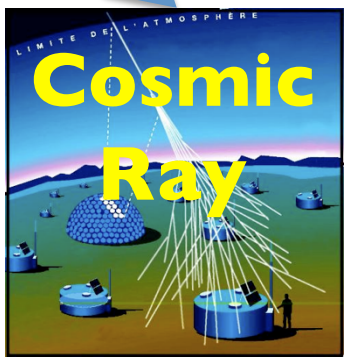


AGN

GeV-TeV AGN
Tidal Disruption Jet
Fermi Bubble

Compact
Star

GeV-TeV Pulsar
Magnetosphere
Crab Pulsar
TeV PWN

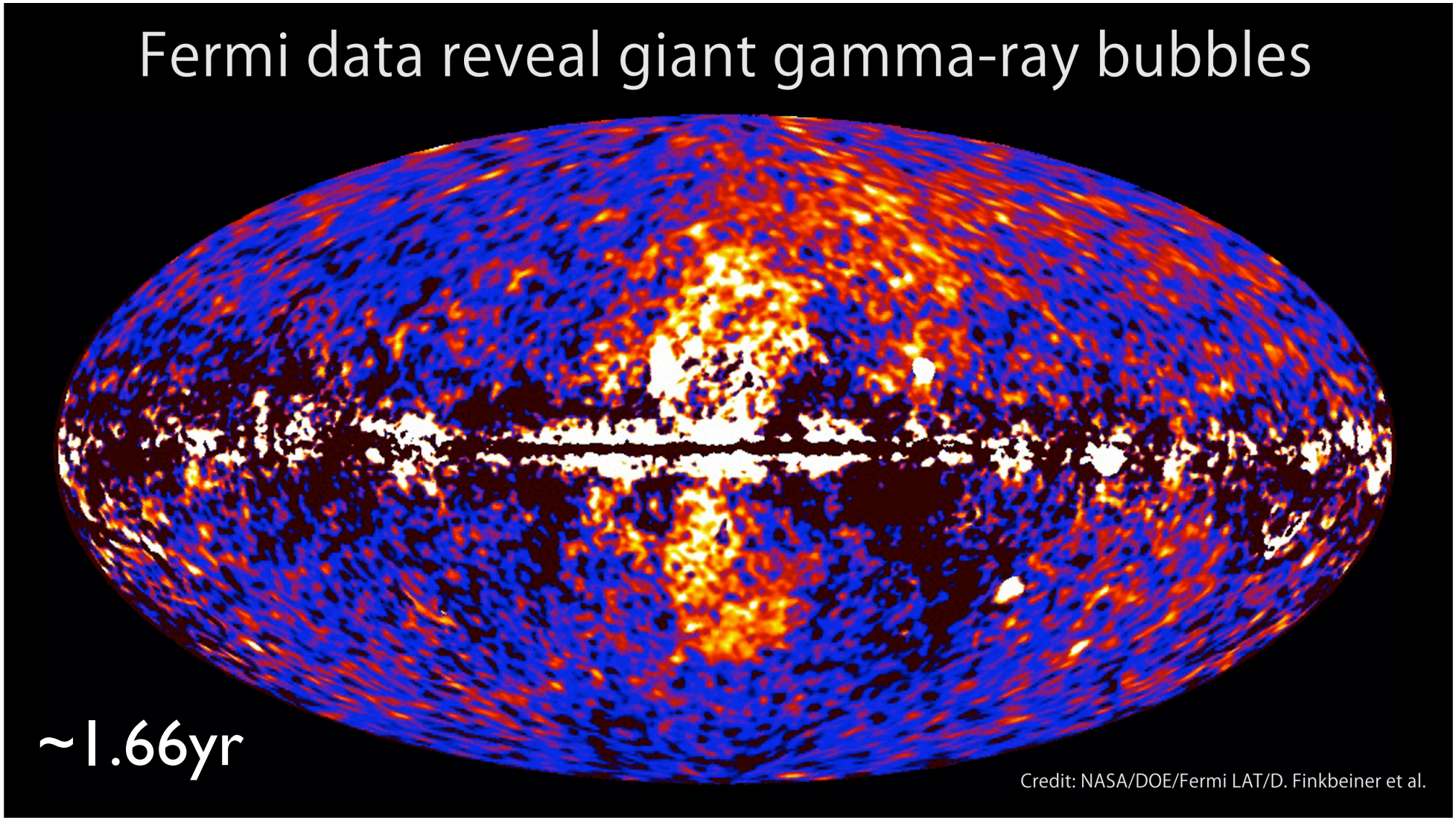


Cosmic
Ray

e^+ Excess
GZK cutoff
UHECR Fe

High Energy Universe

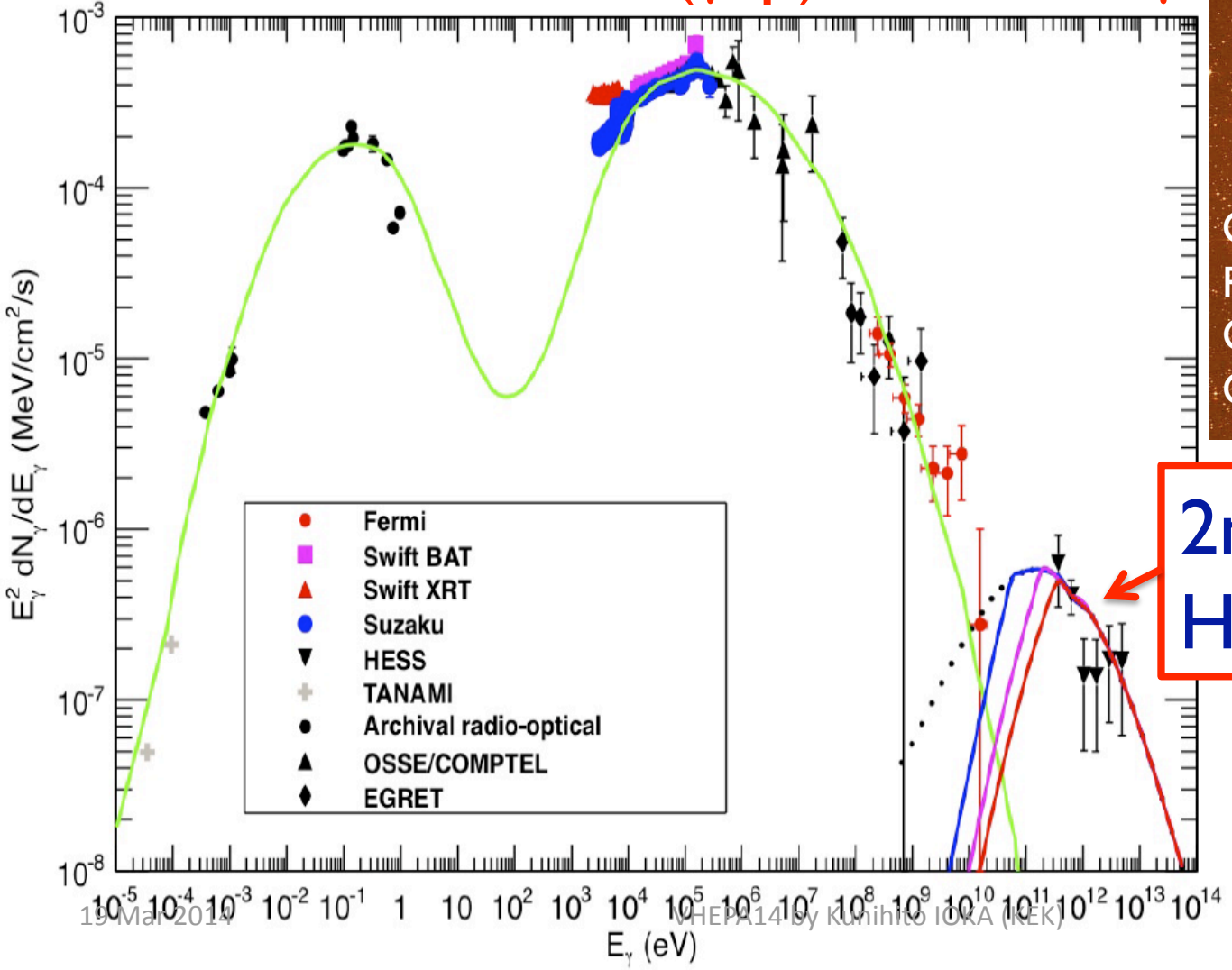
γ-ray Bubble Sky Image

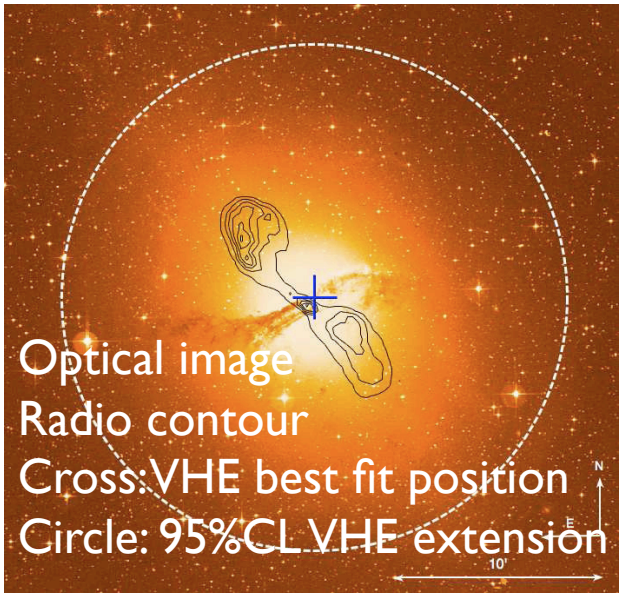


Data subtraction reveals the gamma-ray bubbles

γ-ray from Cen A

UHECR+(γ, p)→π→HE γ





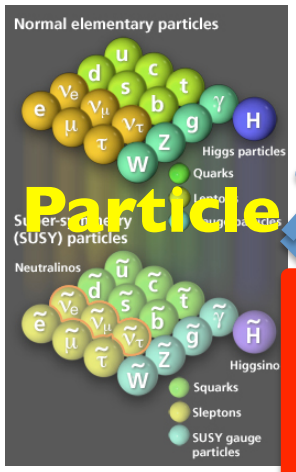
2nd Component
Hadronic origin?

Aharonian+ 09
Abdo+ 10
Kachelrieβ+ 09
Sahu+ 12

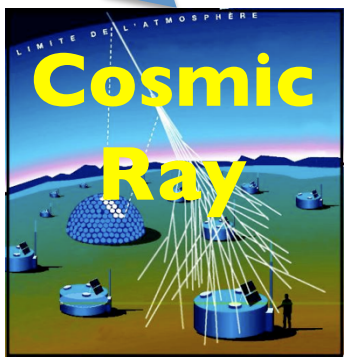
Evolution to Black Hole

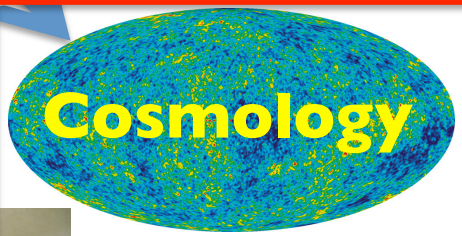
$2M_\odot$ Neutron Star
Dark Matter
LIV
Axion

GeV-TeV SNR
CR Origin
PeVatron

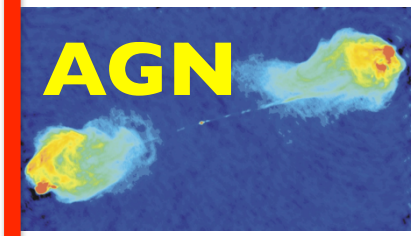


Unification/Diversity
GeV GRB
Jet Mechanism





Dark Energy
Inflation
Dark Age
Pop III, First GRB



GeV-TeV AGN
Tidal Disruption Jet
Fermi Bubble

GeV-TeV Pulsar
Magnetosphere
Crab Pulsar
TeV PWN

e^+ Excess
GZK cutoff
UHECR Fe

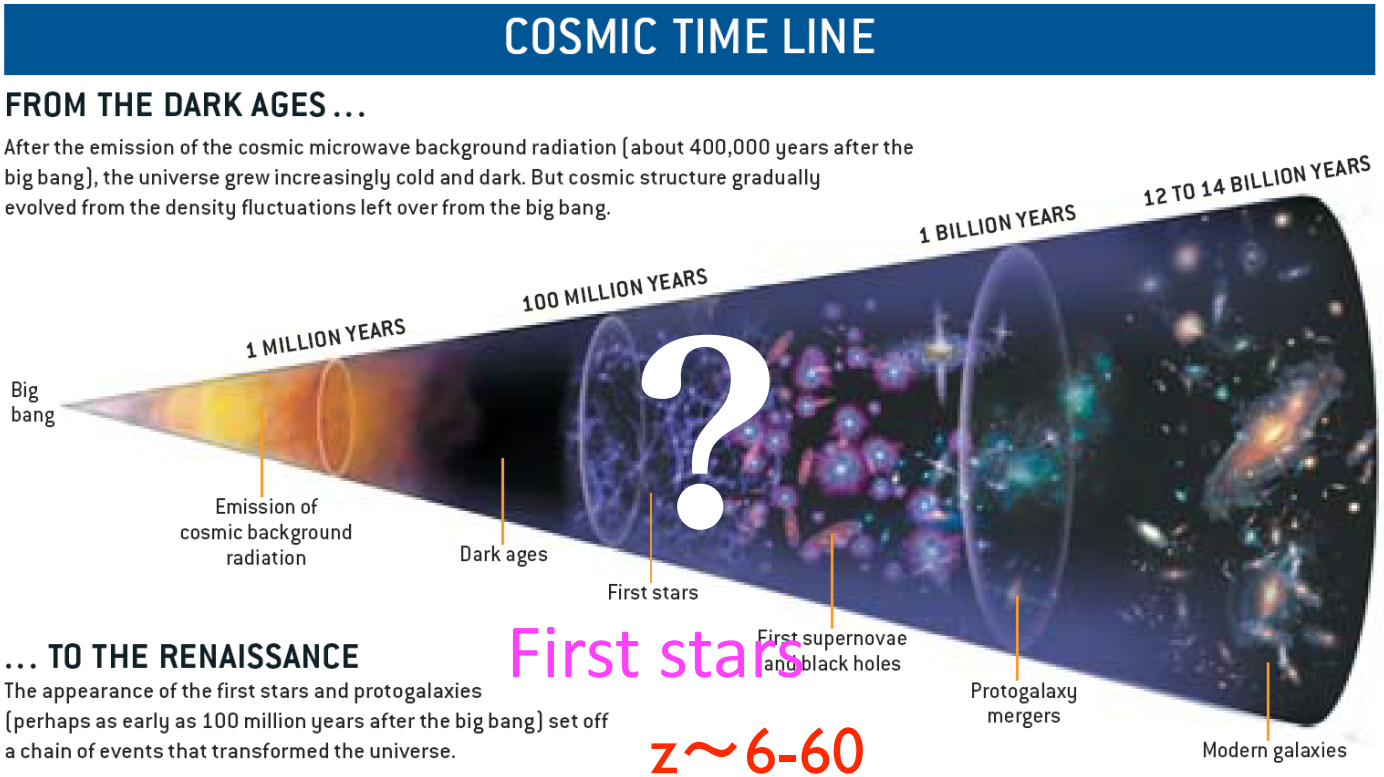
Supernova
Rela, Turbulence
PIC particle acc.
GR MHD

High Energy Universe

Dark Age

CMB z~1000 ⇔ Astronomical observations z~6

Like QSO
Like supernova
Star formation
Reionization
Metal
Dark energy
…



First stars

Larson & Bromm 02

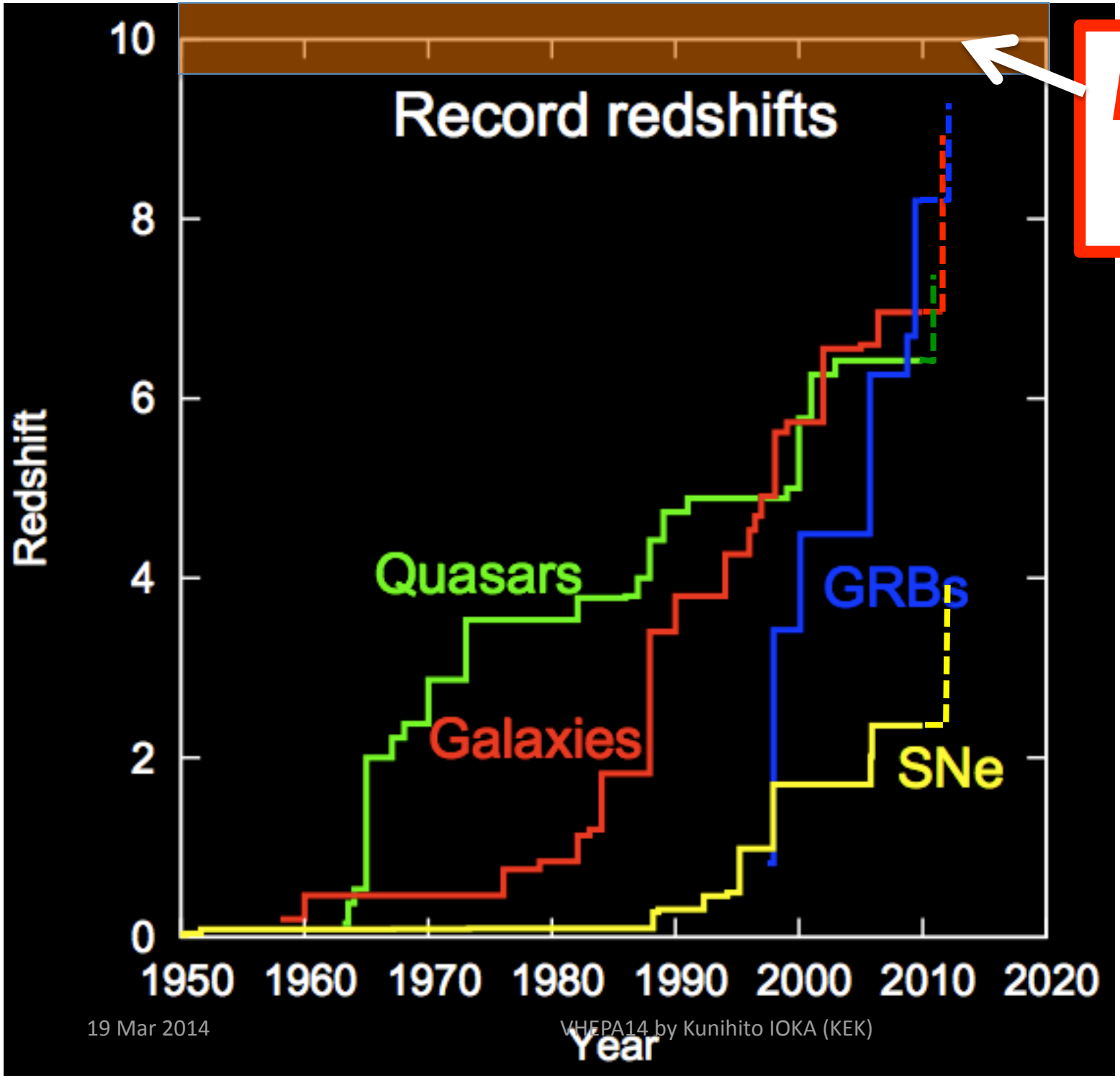
z~6-60

GRB ⟷

z~7

QSO, galaxy ⟷

GRBs are useful for probing high z

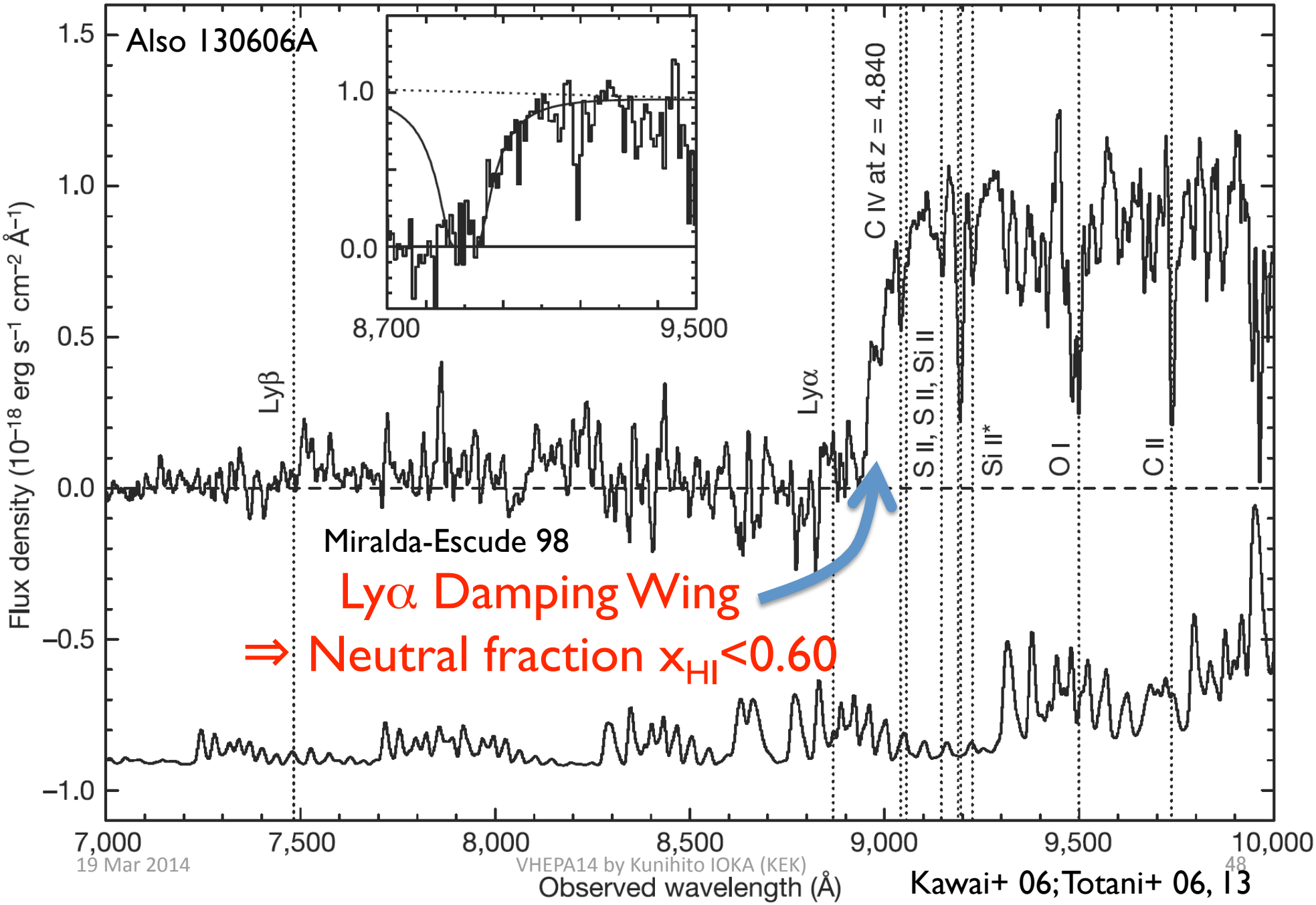


1st Star Era!!

z=6.3: GRB050904
z=6.41: Quasar
z=6.7: GRB080913
z=7.085: Quasar
z=8.26: GRB090423
z=8.6: Galaxy
z=9.4: GRB090429B

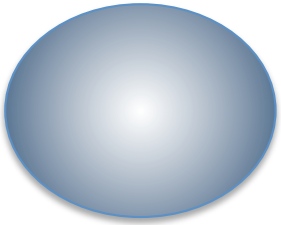
©Takana

z=6.295, GRB050904 at t=3.4d, Subaru FOCAS 4.0 hrs



Super-Massive Pop III Star?

Present Day Massive Star ~20$M_\odot$



Omukai & Nishi 98;
Abel+ 02; Bromm+ 02;
Omukai+ 03; Yoshida+ 08;

Pop III (Zero Metal) ~1000$M_\odot$(!?)

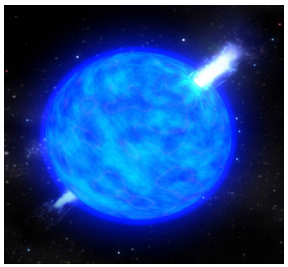
Mini halo (first object): ~1000$M_\odot$

If all the mass is accreted to a proto-star,

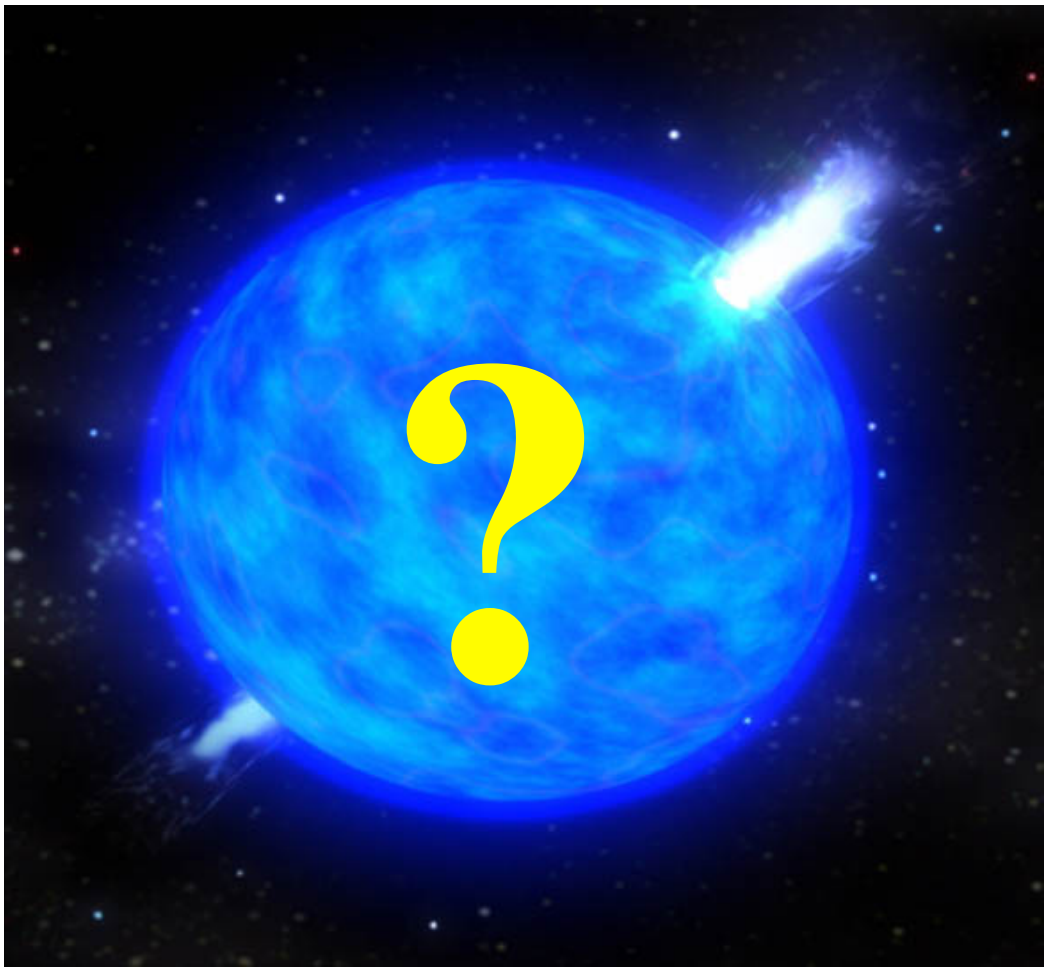
First stars are very MASSIVE?

Pop III GRB?

Present Day GRB

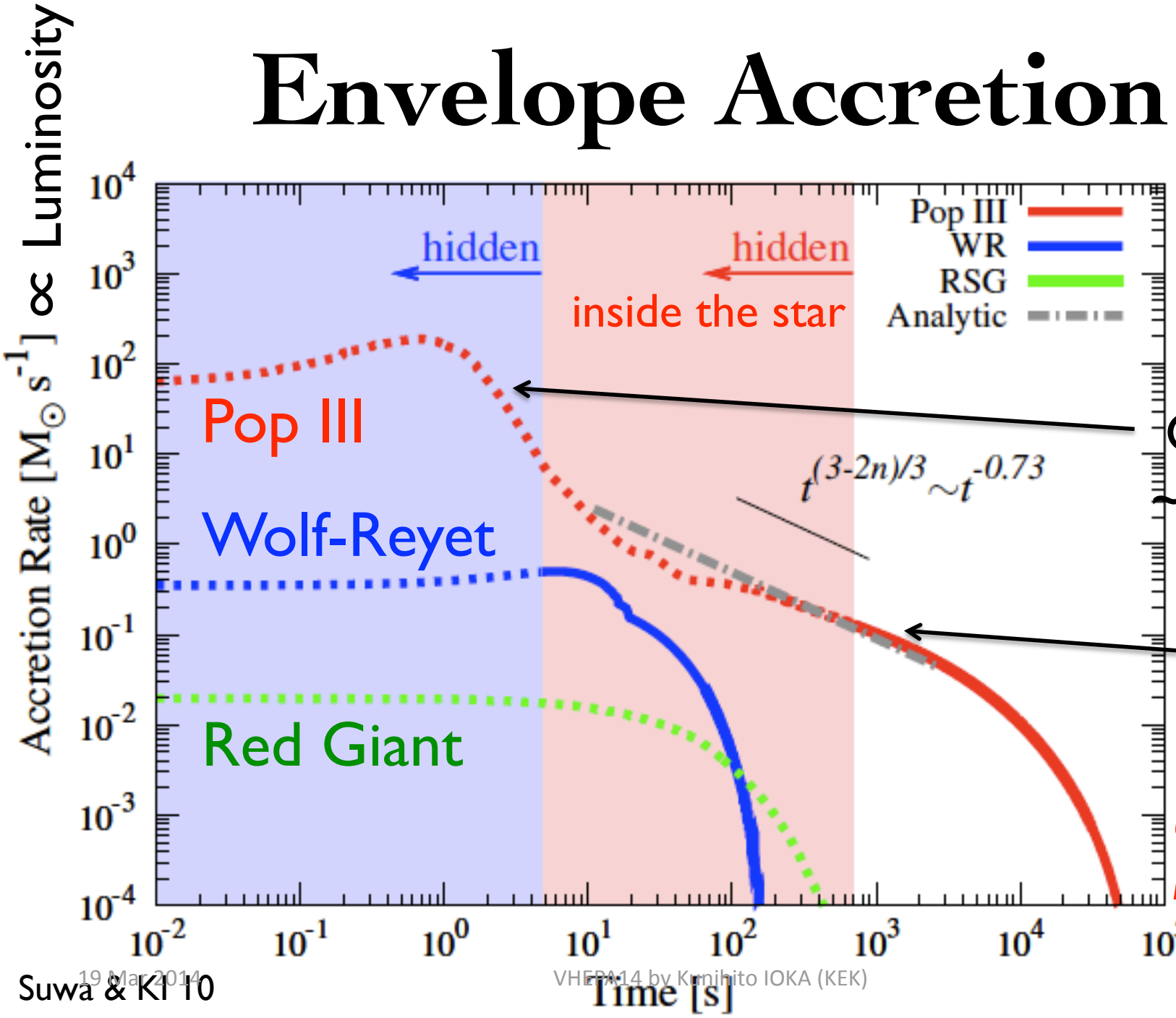


Komissarov & Barkov 10
Meszaros & Rees 10
Suwa & KI 11
Nagakura+ 11
de Souza, Yoshida & KI 11



Gigantic (x100) GRB @ z~10-30???

Envelope Accretion



$L \propto \dot{M}$

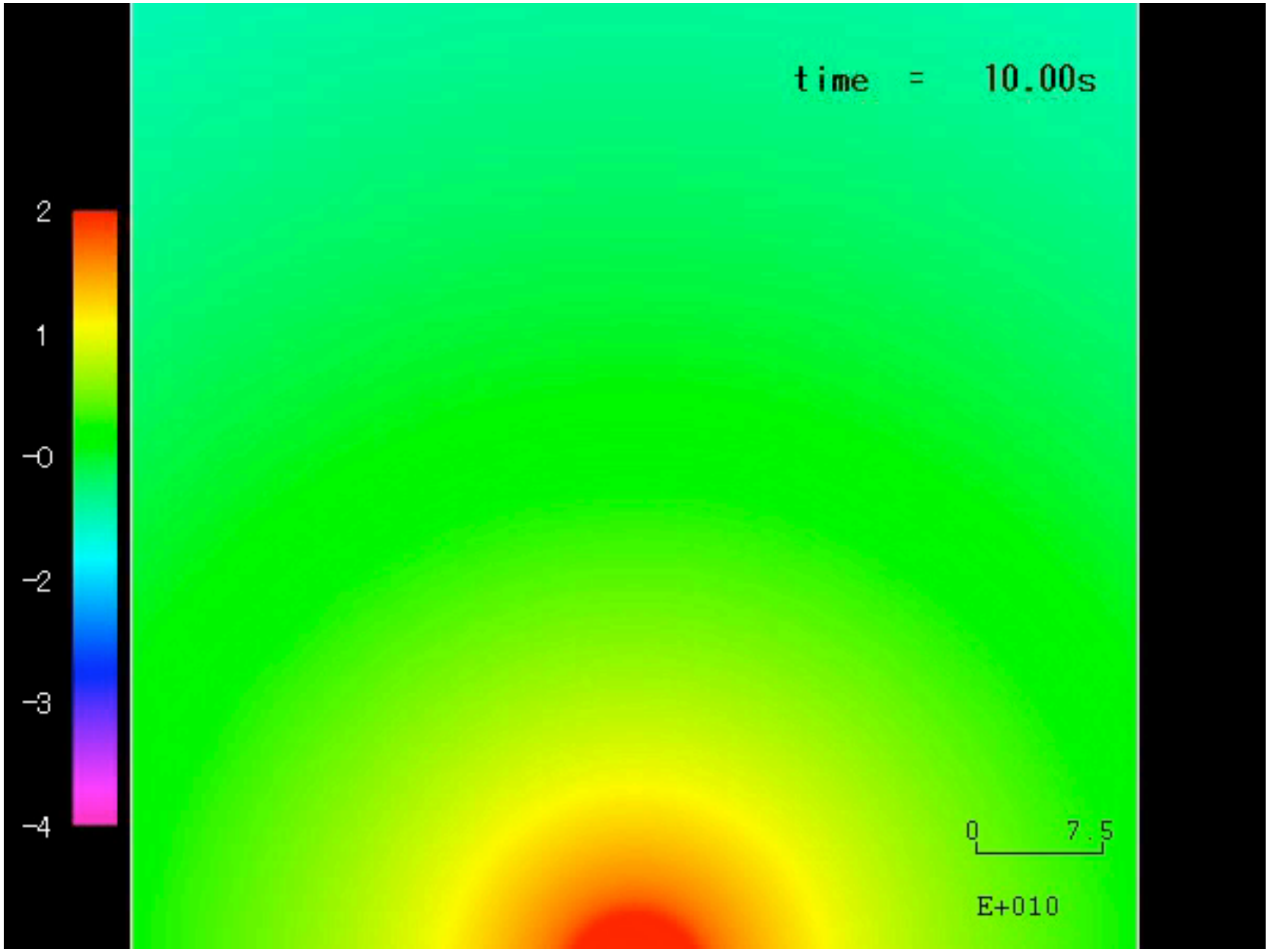
$\Rightarrow v_{\text{Jet head}}$

Core Acc.
~ a few sec

Envelope Accretion

Ultra-long
Not bright

Suwa & KI 10



Nagakura+ 11 2D, rela-hydro, Mass accretion from inner boundary ⇒ Jet

Evolution to Black Hole

$2M_\odot$ Neutron Star
Dark Matter
LIV
Axion

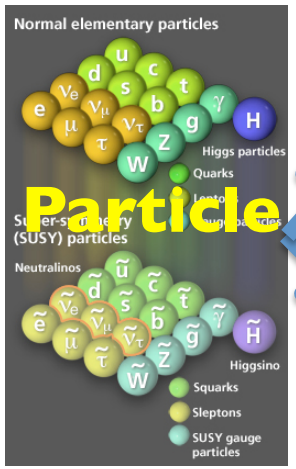
Star
Planet

Supernova
GRB

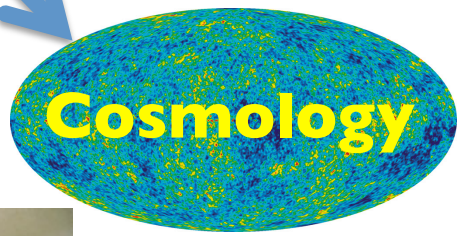
Unification/Diversity
GeV GRB
Jet Mechanism

Supernova
Remnant

GeV-TeV SNR
CR Origin
PeVatron



Particle

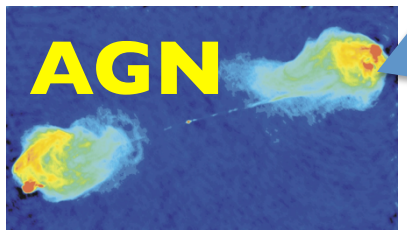


Cosmology

Dark Energy
Inflation
Dark Age
Pop III, First GRB

Computar

Supernova
Rela, Turbulence
PIC particle acc.
GR MHD

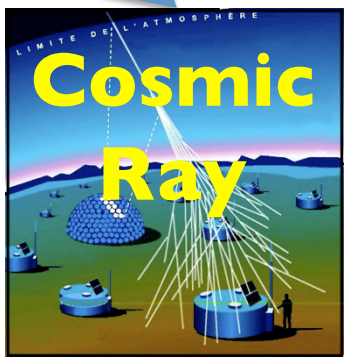


AGN

GeV-TeV AGN
Tidal Disruption Jet
Fermi Bubble

Compact
Star

GeV-TeV Pulsar
Magnetosphere
Crab Pulsar
TeV PWN

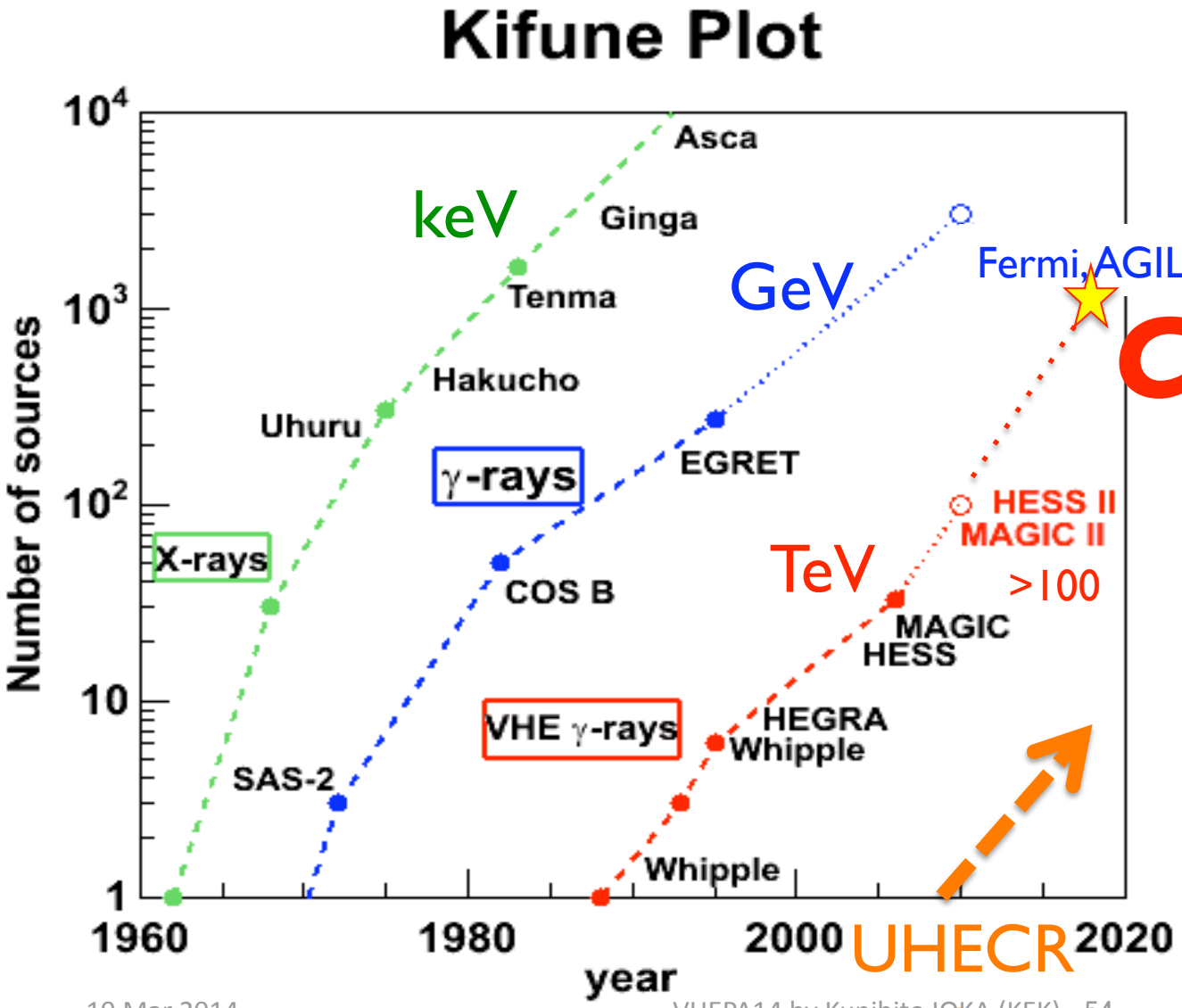


Cosmic
Ray

e^+ Excess
GZK cutoff
UHECR Fe

High Energy Universe

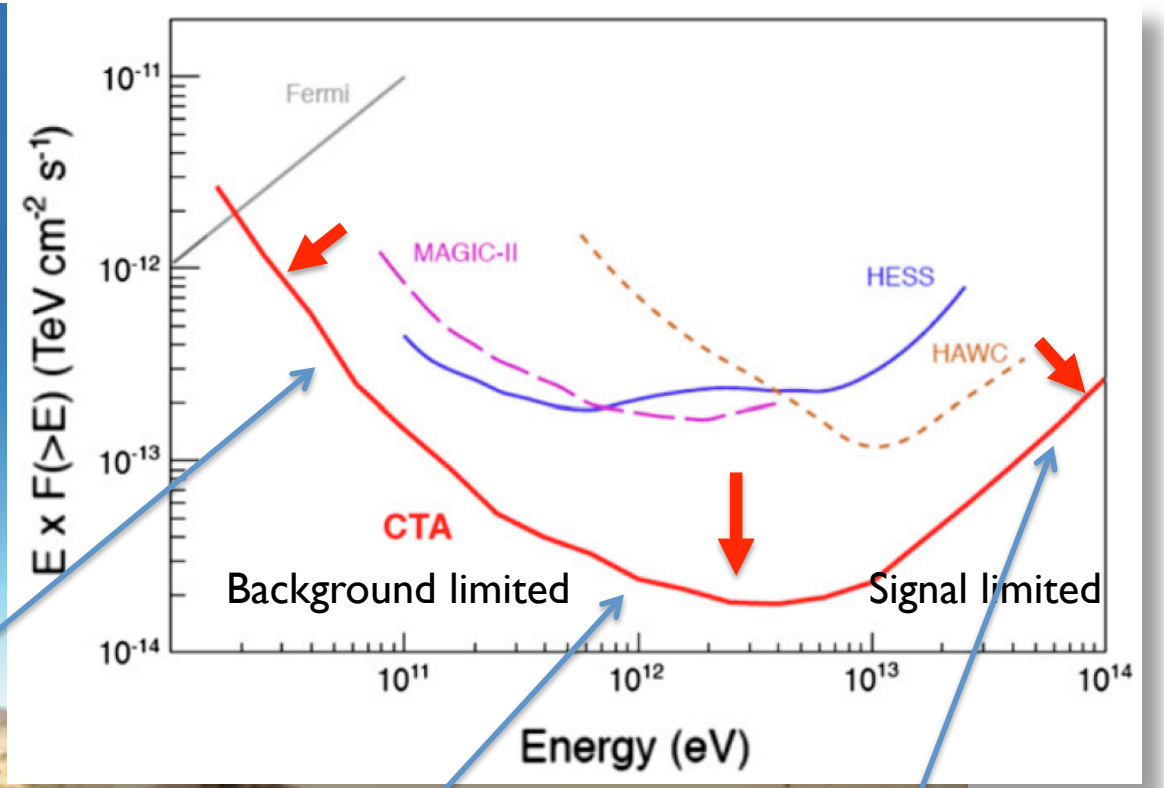
Explosive Development



# of sources are increasing exponentially

CTA

- ~20GeV-100TeV
- x10 Sensitivity
- $\Delta\theta$~1-2 min
- FOV~5-10 deg
- ~20 s slew (LST)
- ~2015-
- ~150€



AGN
Pulsar
GRB

LSTs

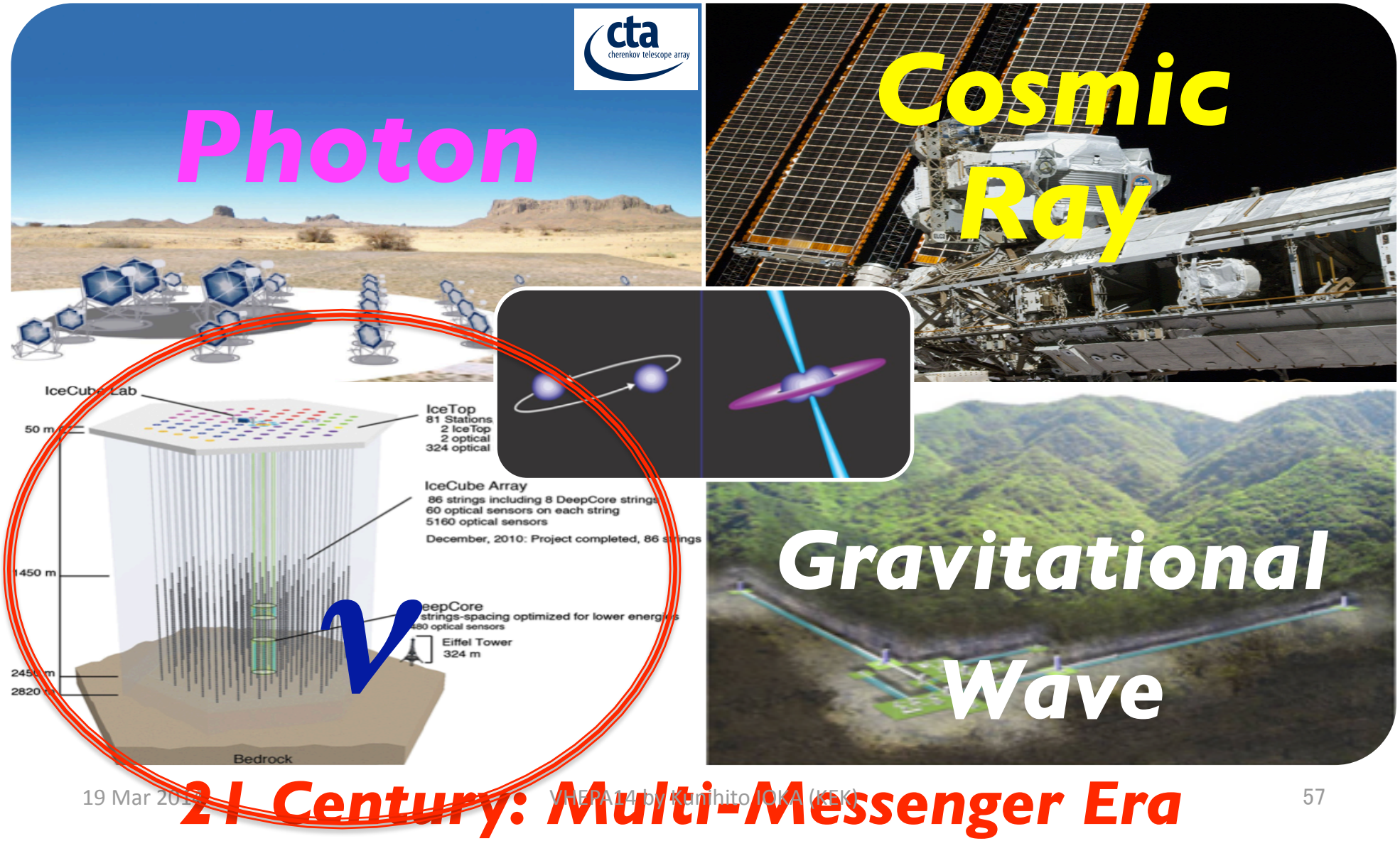
MSTs
~1 mCrab
Deep Survey

SSTs
~10km^2
Cosmic Ray
Knee

Multi-Messenger Era

21 Century: Multi-Messenger Era

Multi-Messenger Era

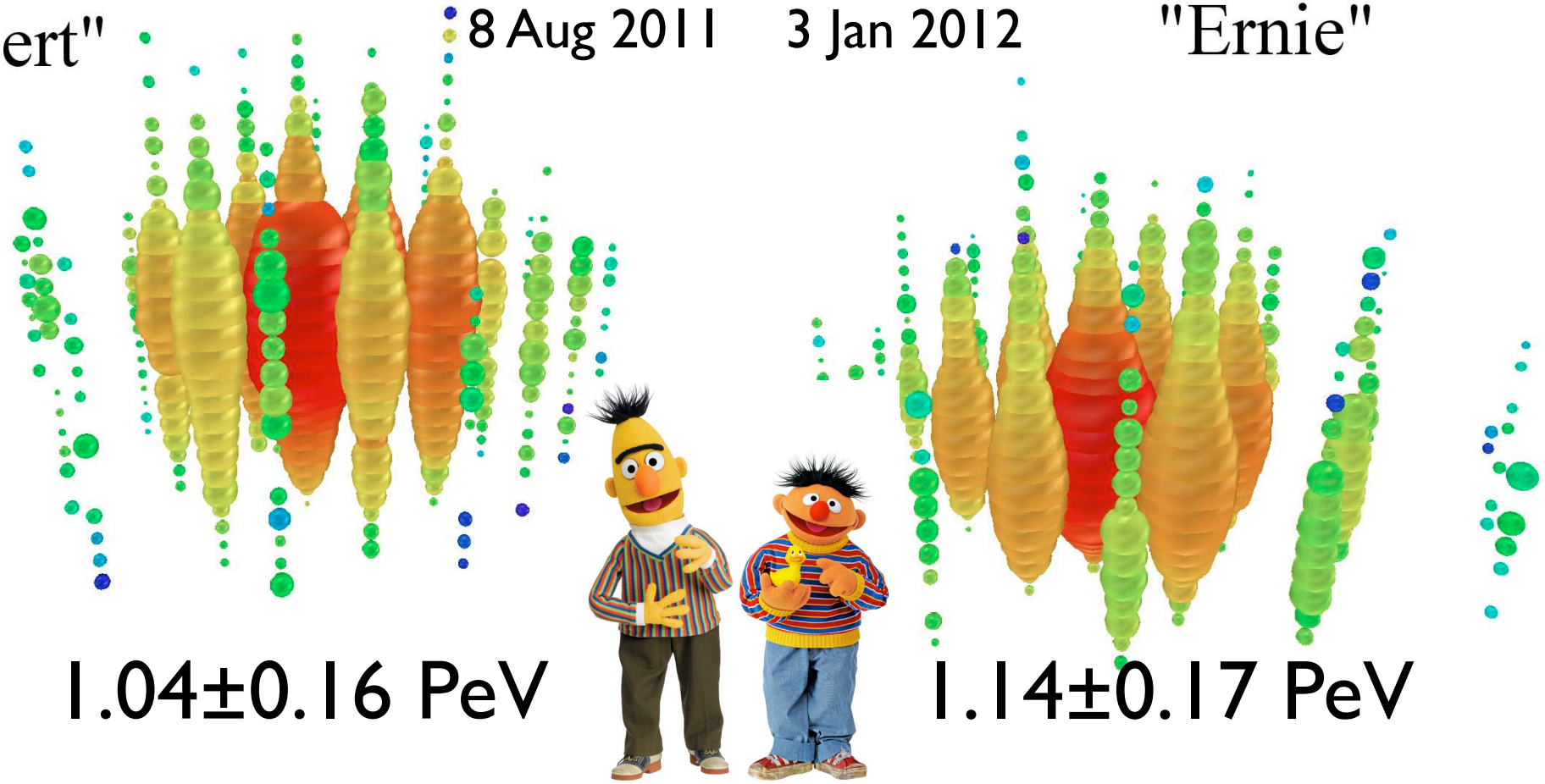


21 Century: Multi-Messenger Era

2 PeV νs

PeV=10^{15}eV

"Bert" 8 Aug 2011 3 Jan 2012 "Ernie"



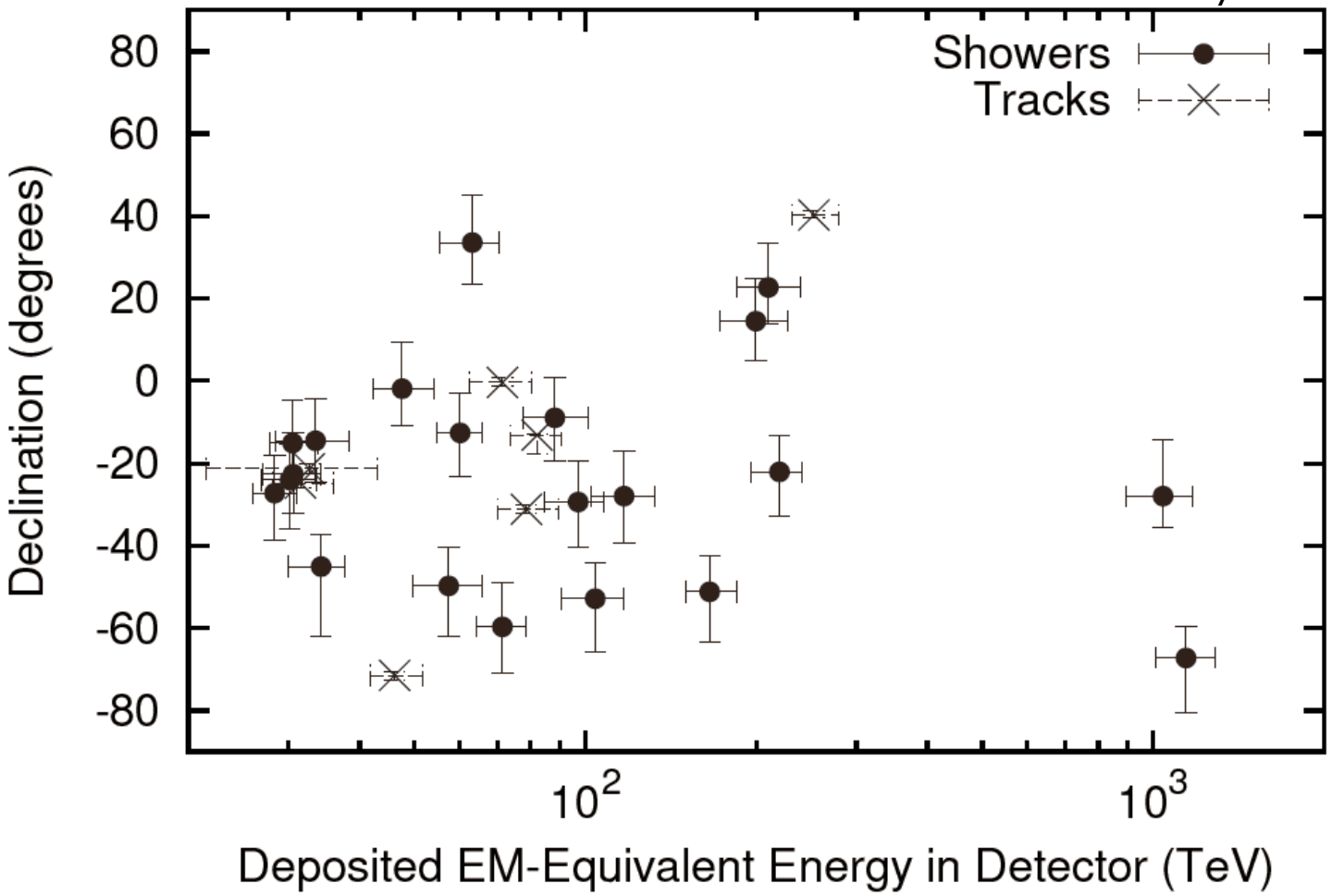
1.04±0.16 PeV 1.14±0.17 PeV

Aartsen+(IceCube), arXiv:1304.5356

Dawn of High-Energy ν Astronomy!!!

More νs

May 2010-May 2011 (79 strings)
May 2011-May 2012 (86 strings)



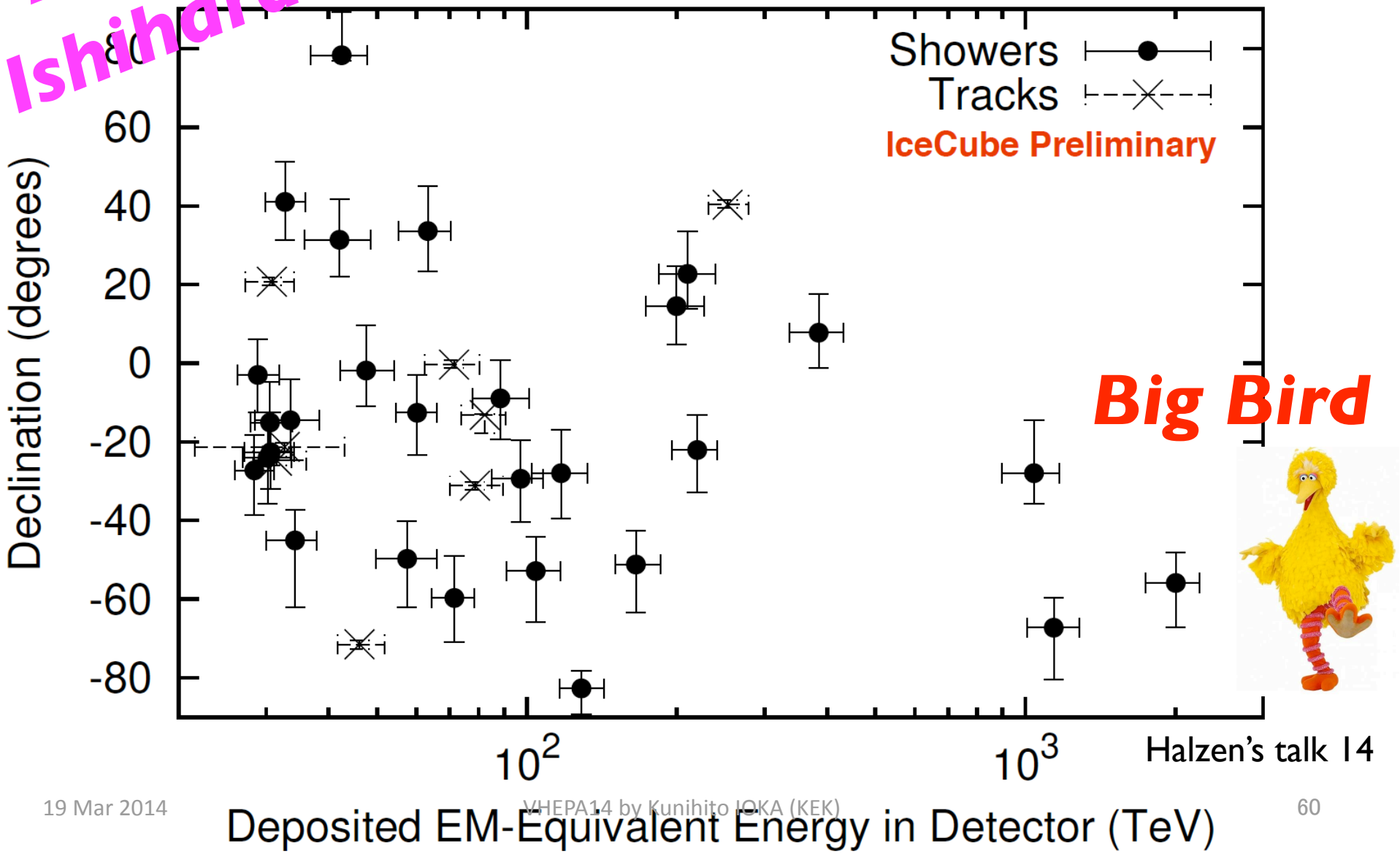
Aartsen+ 14

Contained event 2+26 (7 μ+21 shower) 4.1σ

Background $10.6^{+5.0}_{-3.6}$ (6.0±3.4 μ+4.6 ν) + 1.5 charm

Mase's talk
Ishihara's talk

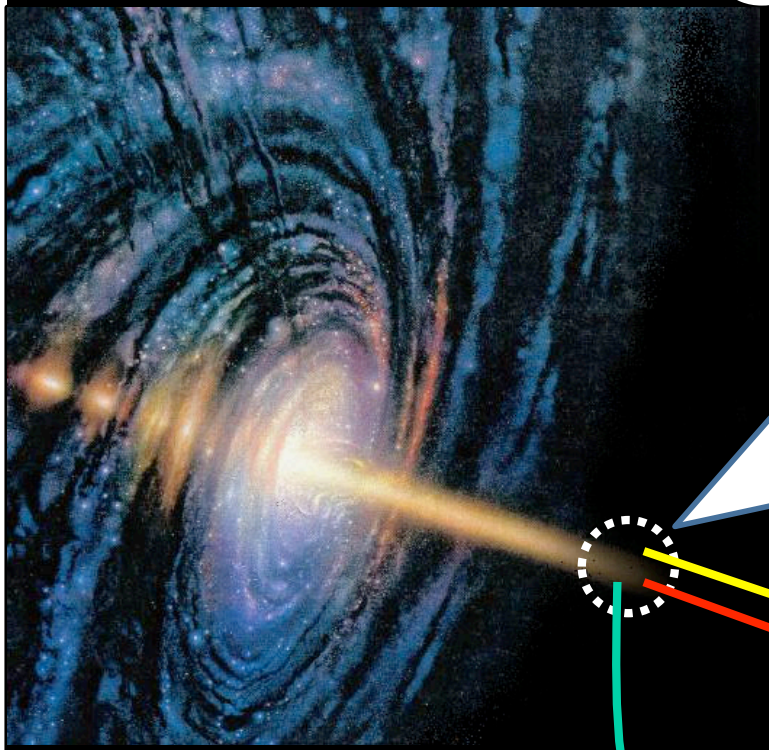
One More PeV ν

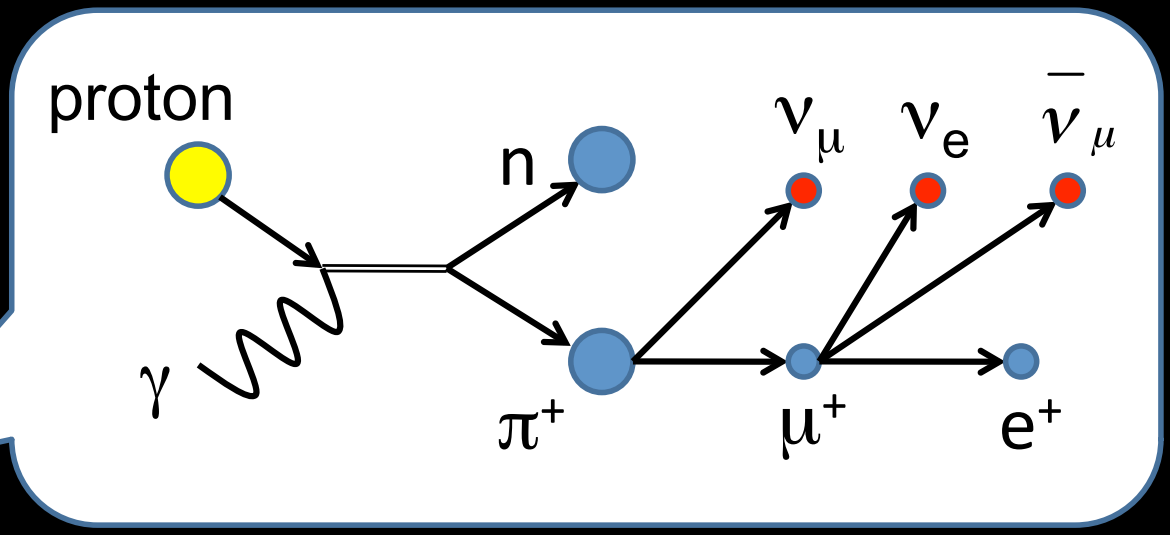


Big Bird

Halzen's talk 14

Cosmic ν





ν

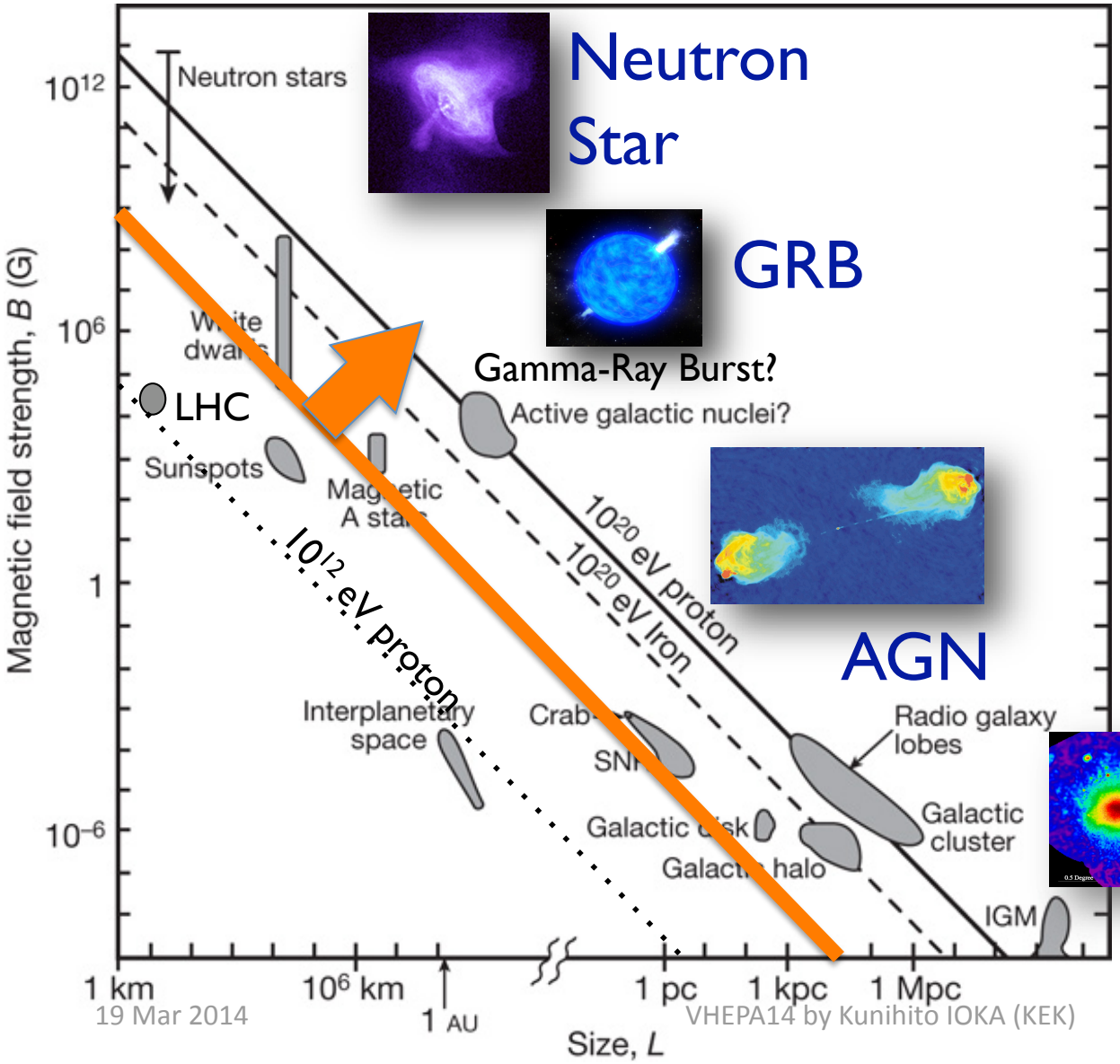
γ

p

Strong penetration
Not delayed

CR origin
ν interaction@>TeV
τ appearance
Limiting ν speed
Equivalence principle

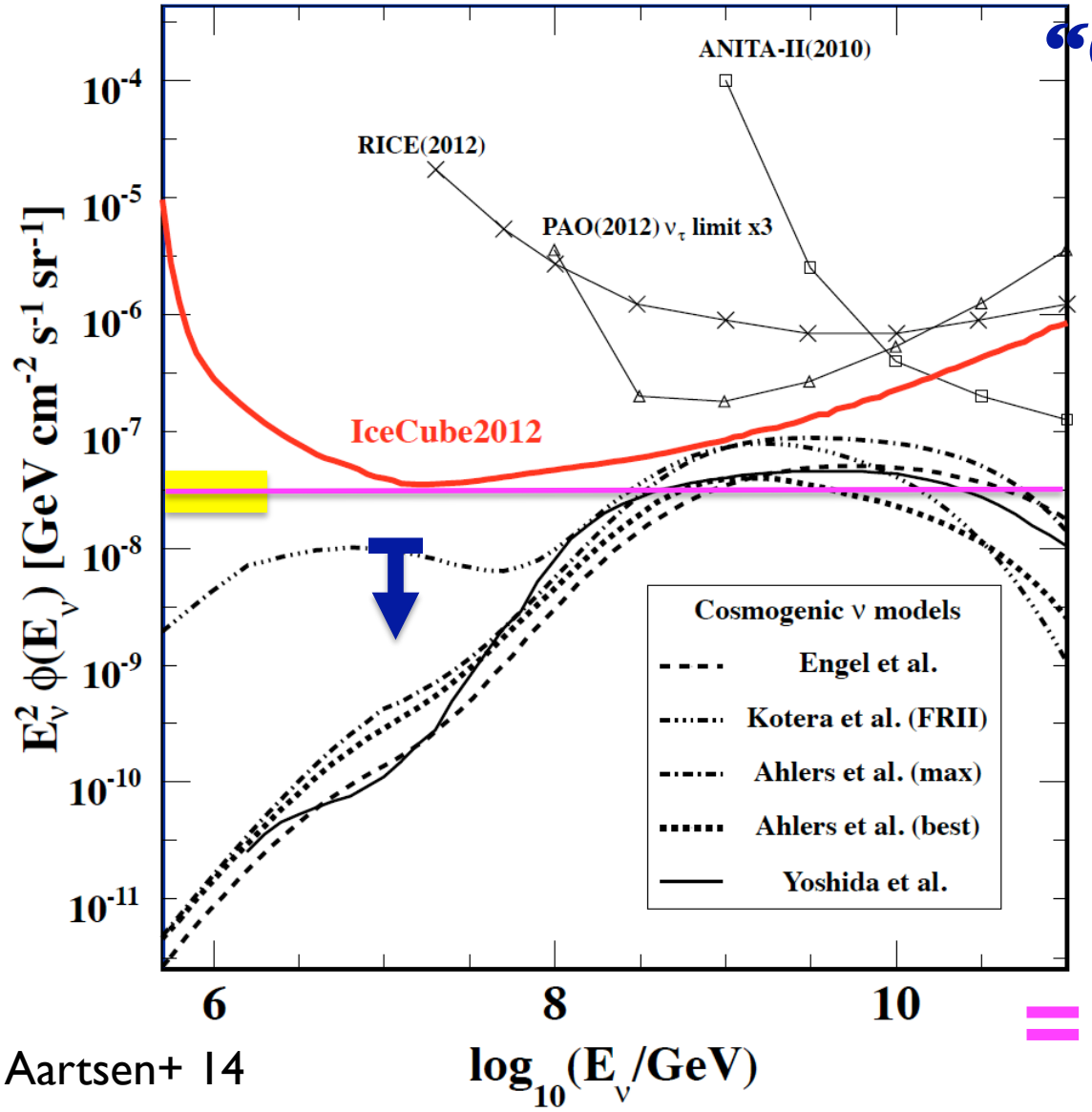
Origin of PeV ν



- E~10^{20}eV
- R_{Larmor}>R_{Galaxy}
  ⇒ Extragalactic
- Hillas condition
  E<ZeBR (v/c)
- Energy/Vol./Time
  ~10^{44}erg/Mpc^3/yr
  UHECR~GRB<<AGN

PeV Dark Matter?

Cosmogenic ν



Aartsen+ 14

"Coincidence Problem"

$F_{PeV} \sim F_{WB}$

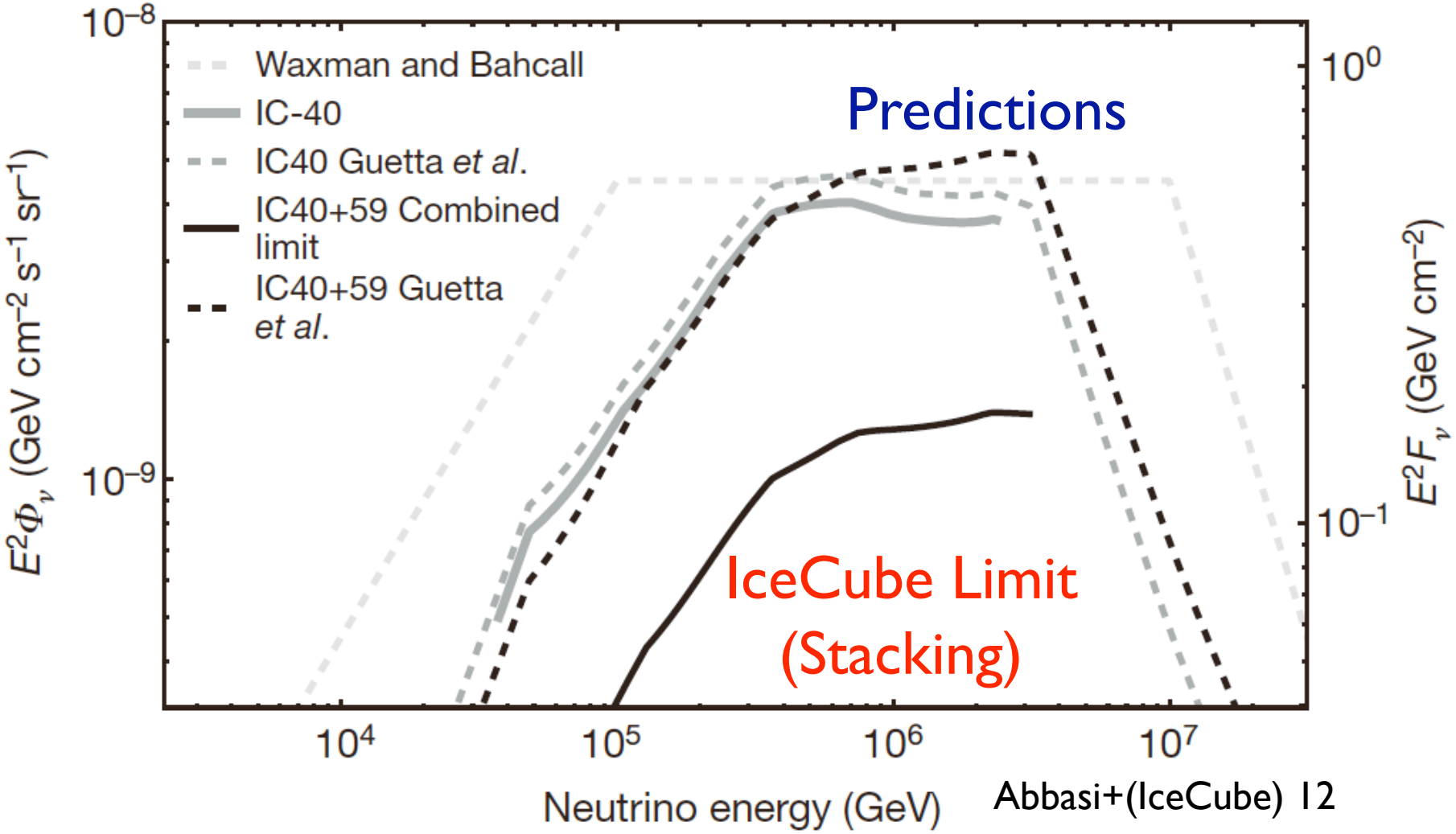
$F_{GZK} \sim F_{WB}$

$F_{10PeV} < F_{WB}$

PeV ν Source

= UHECR Source?

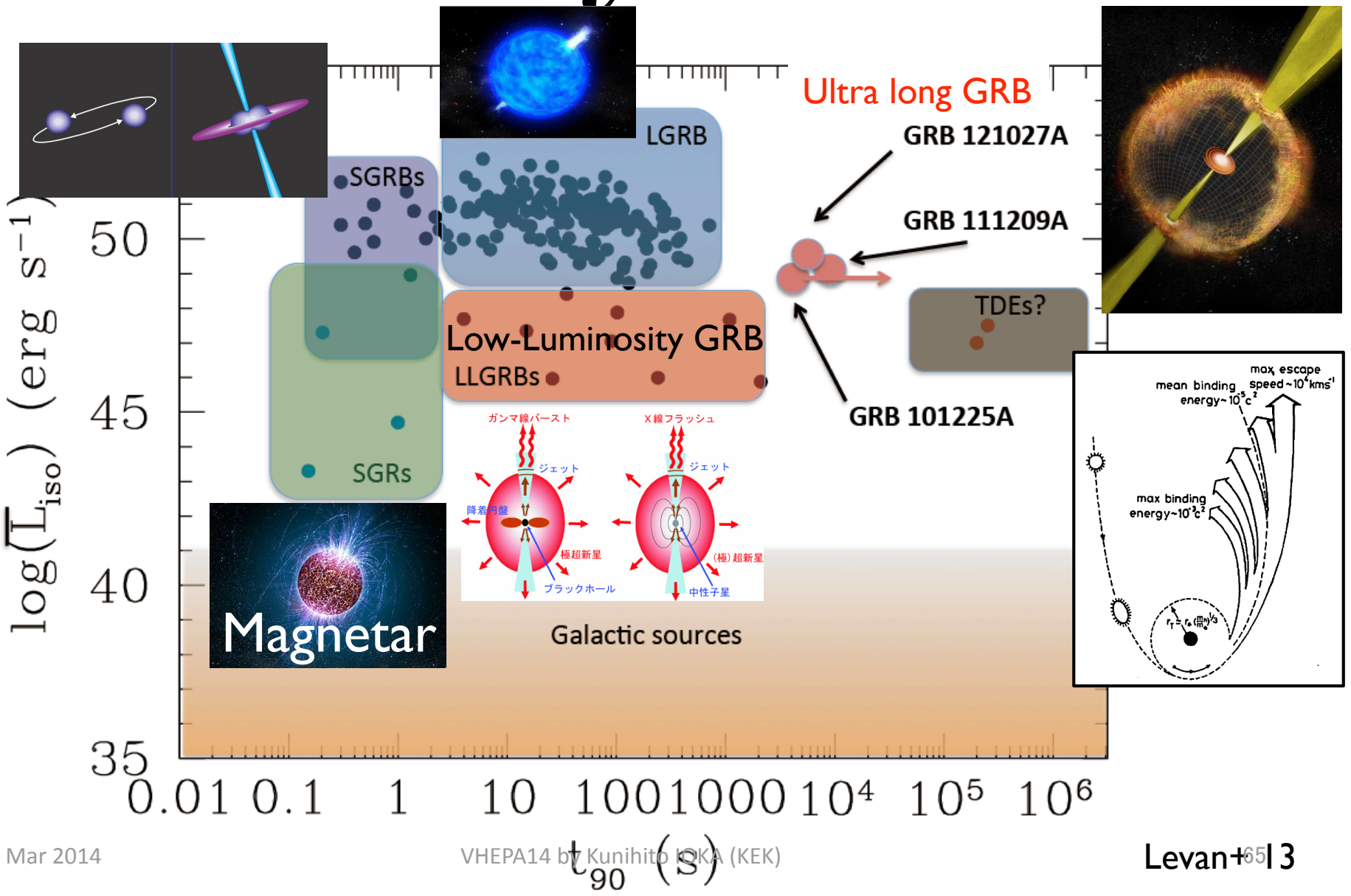
Limits on ν from GRBs



Abbasi+(IceCube) 12

GRBs ≠ PeV ν Sources? ~10^{-8}GeV cm^{-2} s^{-1} sr^{-1}

Diversity of GRB



Levan+13

Low-Power GRB = ν Source?

Murase & KI 13

- ***Classical Long GRBs***
  - $E_\gamma \sim 10^{53}$ erg, ~1 Gpc^{-3} yr^{-1}

} No ν?

- ***Low-Luminosity GRBs***
  - $E_\gamma \sim 10^{50}$ erg, $\sim 10^2$-10^3 Gpc^{-3} yr^{-1}
- ***Ultra-long GRBs***
  - $E_\gamma \sim 10^{53}$ erg, ~1 Gpc^{-3} yr^{-1}

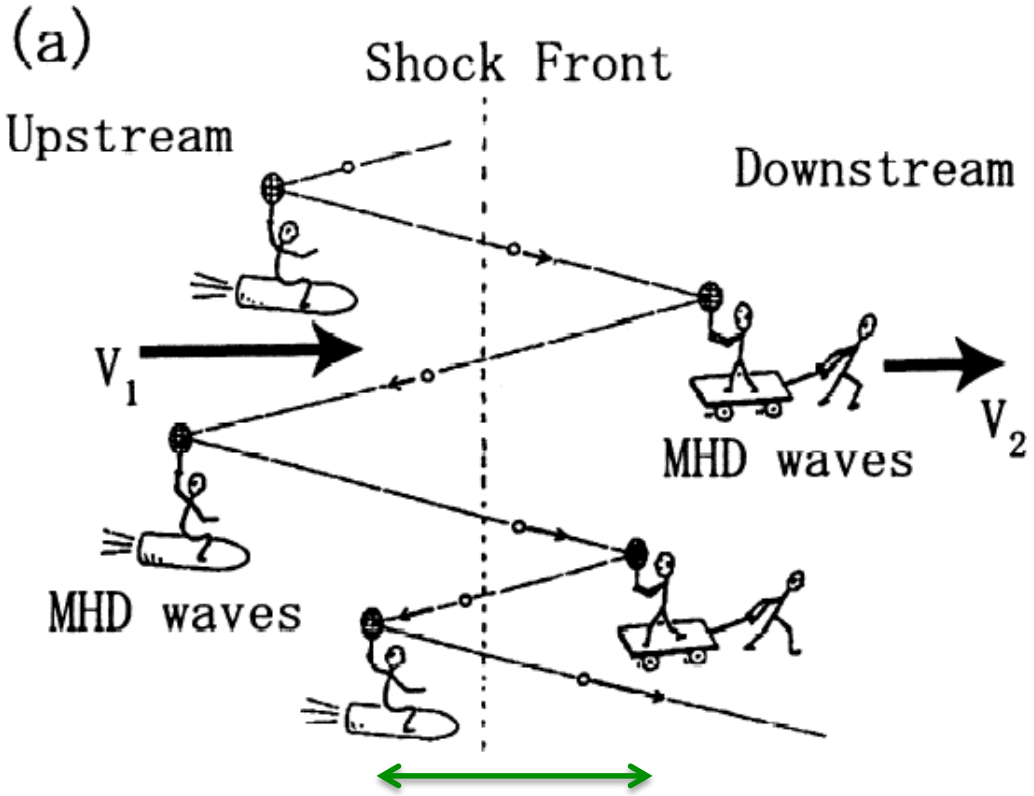
} PeV ν?

LLGRB & ULGRB are too dim to be detected so far

But the energy budget is comparable

Chocked events would be more numerous

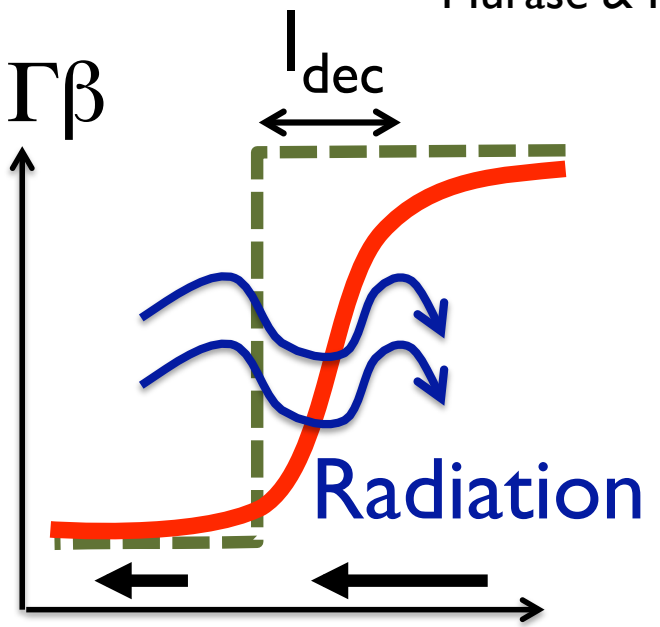
Radiation-mediated Shock



~Larmor radius

Velocity Difference is necessary

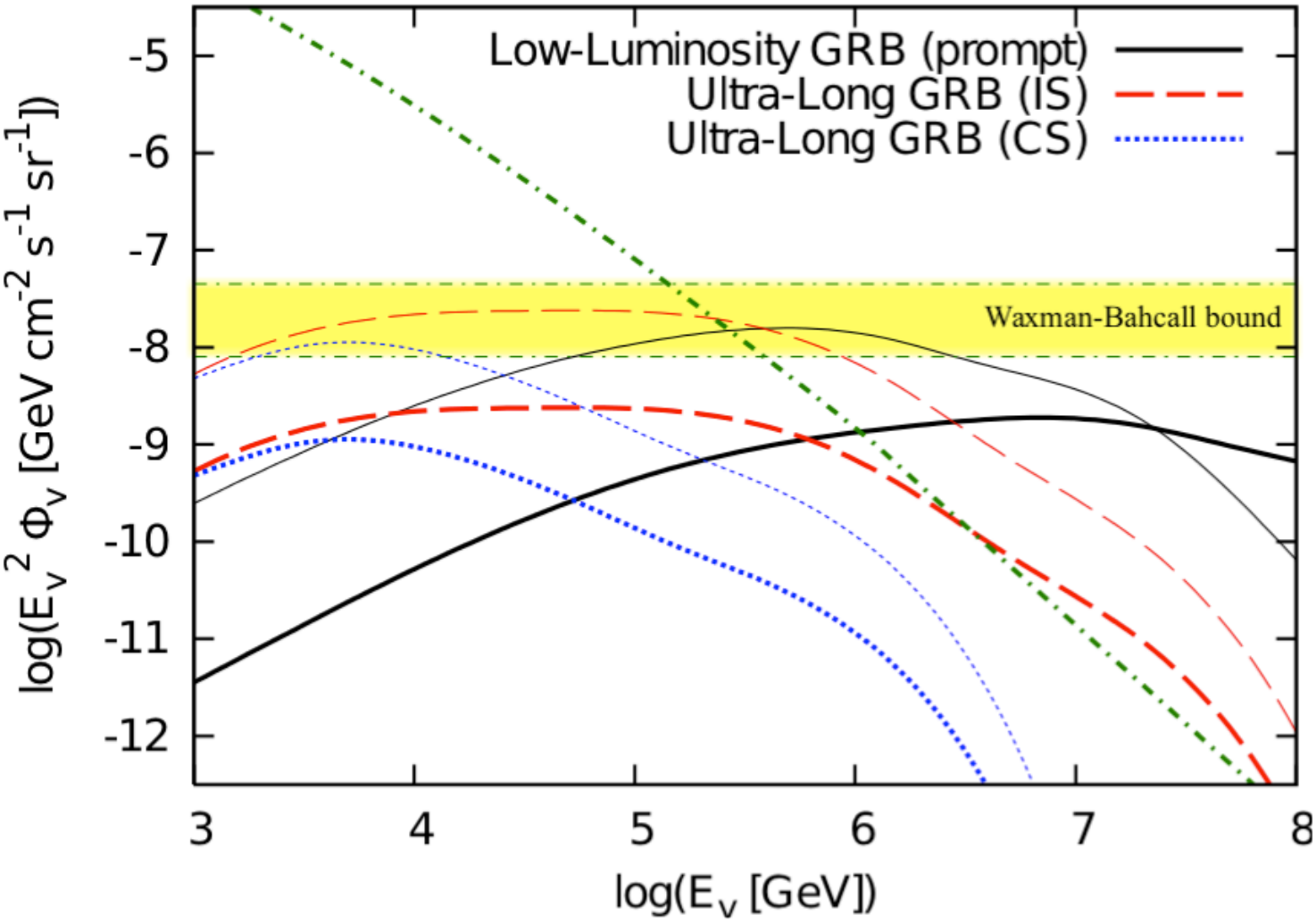
Murase & KI 13



Radiation Pressure smoothens the shock

If $r_{Larmor} << l_{dec}$, acceleration fails

ν Spectrum



Ultra-long GRB

f_{cho}=1 (thick)

f_{cho}=10 (thin)

Low-Luminosity GRB

Γ=5 (thin)

Γ=10 (thick)

Murase & KI 13

Beyond the Standard Model?

- New νν interaction remains less constrained
- Possible mediators
  - Light scalar boson, e.g., Majoron

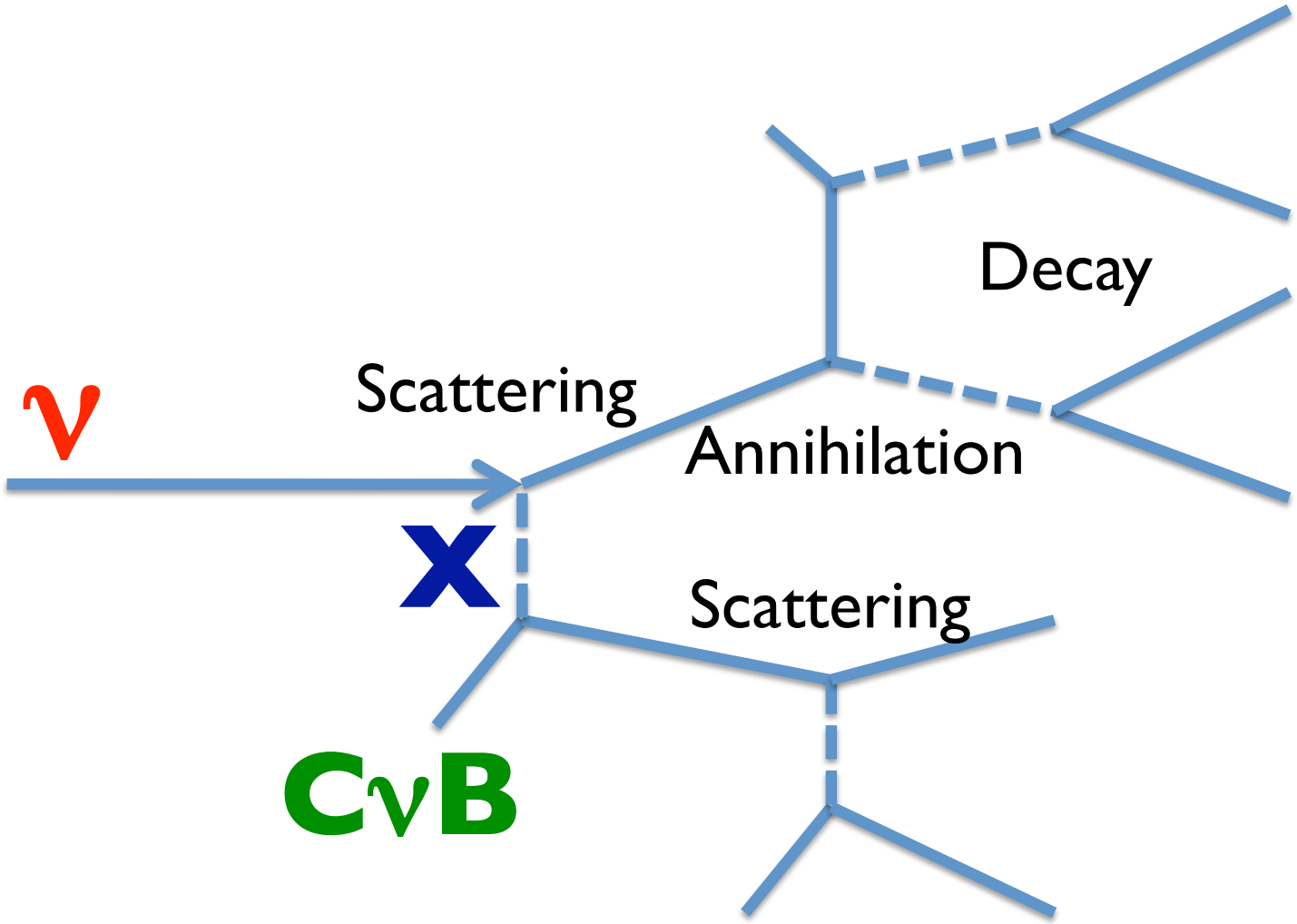
$$\mathcal{L}_{\rm int} = h_{ij}\bar{\nu}_i\nu_j\phi + g_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + h.c.$$

  - Light vector boson

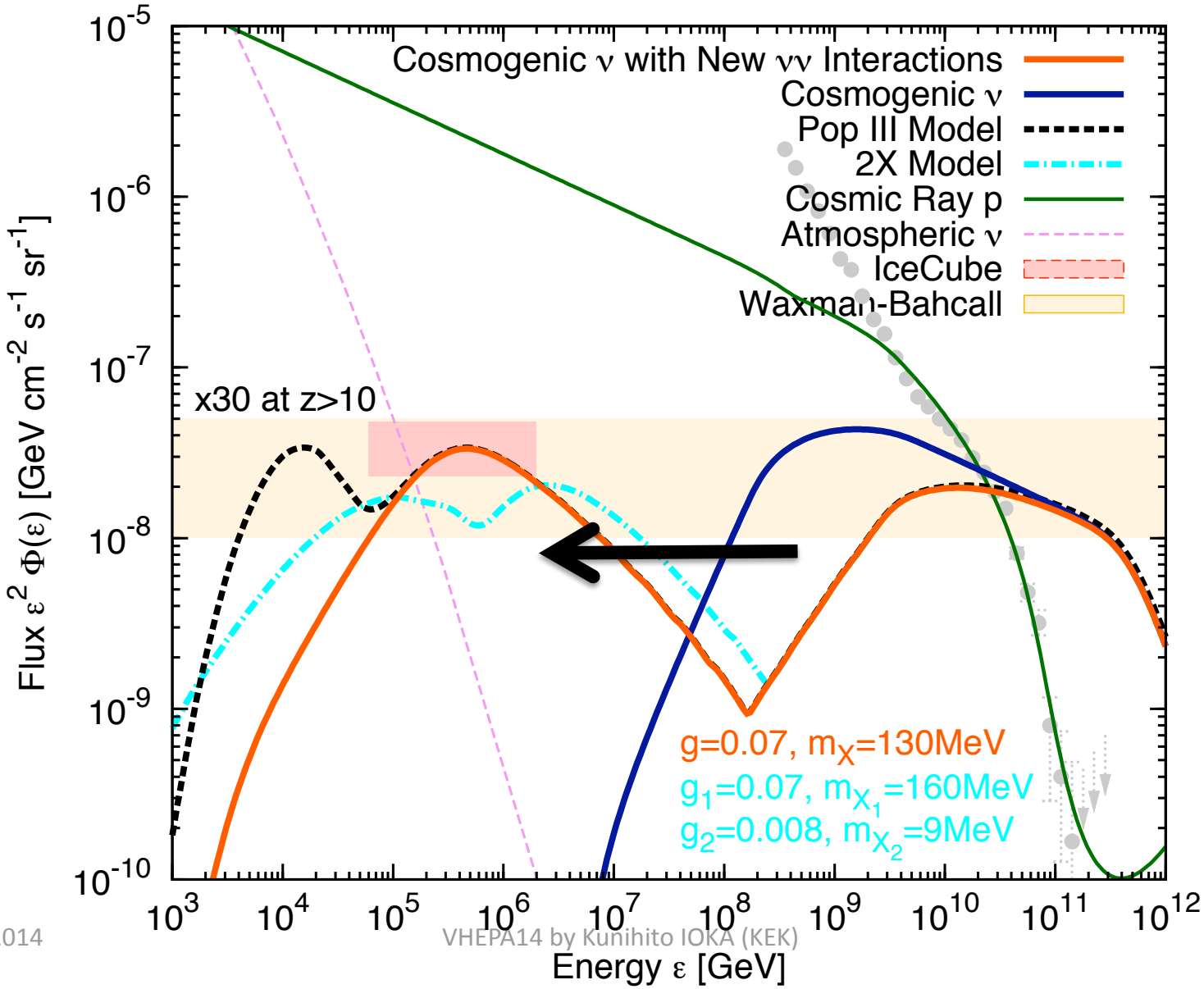
$$\mathcal{L}_{\rm int} = g_{ij}\bar{\nu}_i\gamma_\mu\nu_i V^\mu$$

- Assume $m_\phi > m_\nu$ & only νν (no νe)

ν Cascade

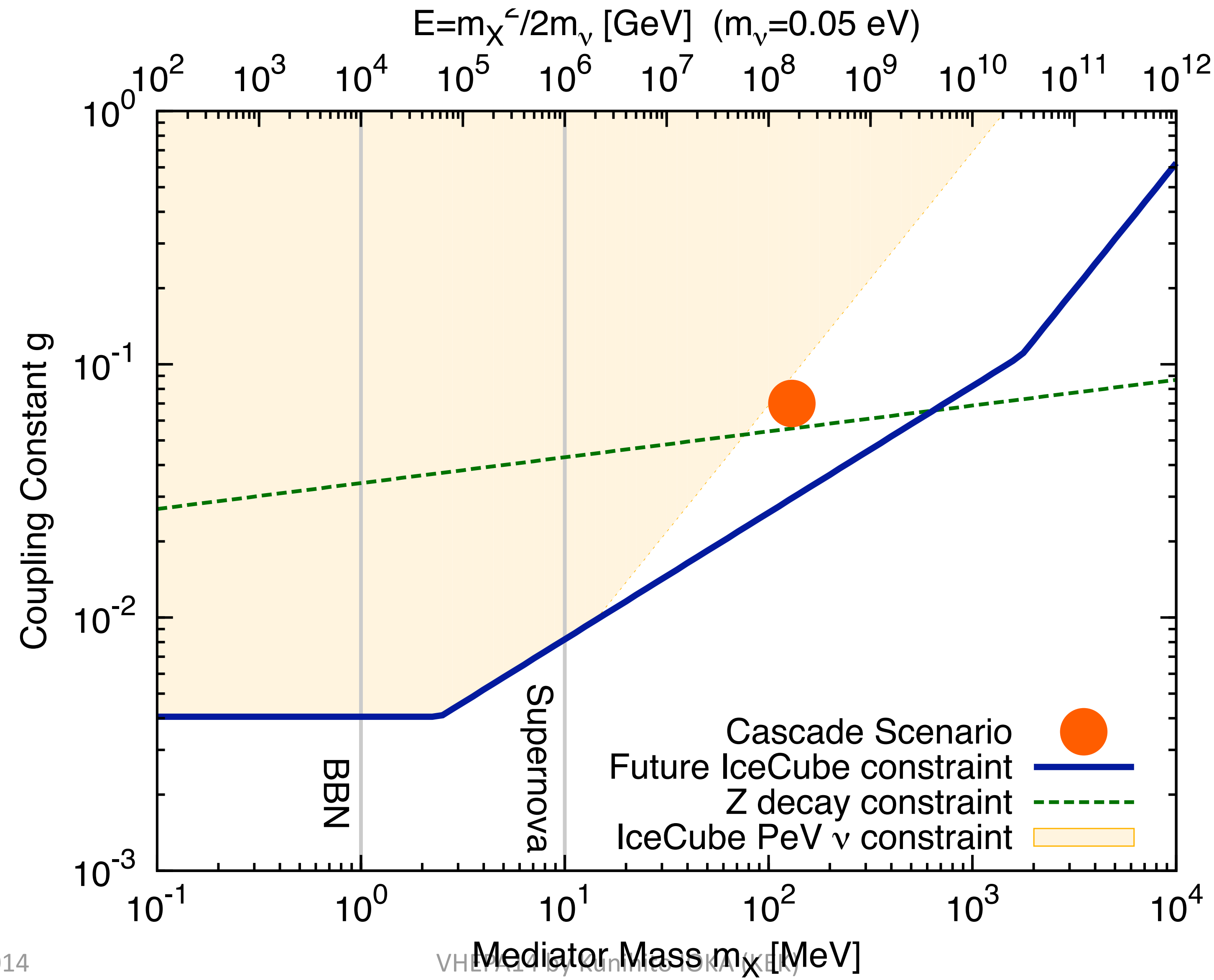


Cascade Scenario



KI in prep.

Constraint on New Boson



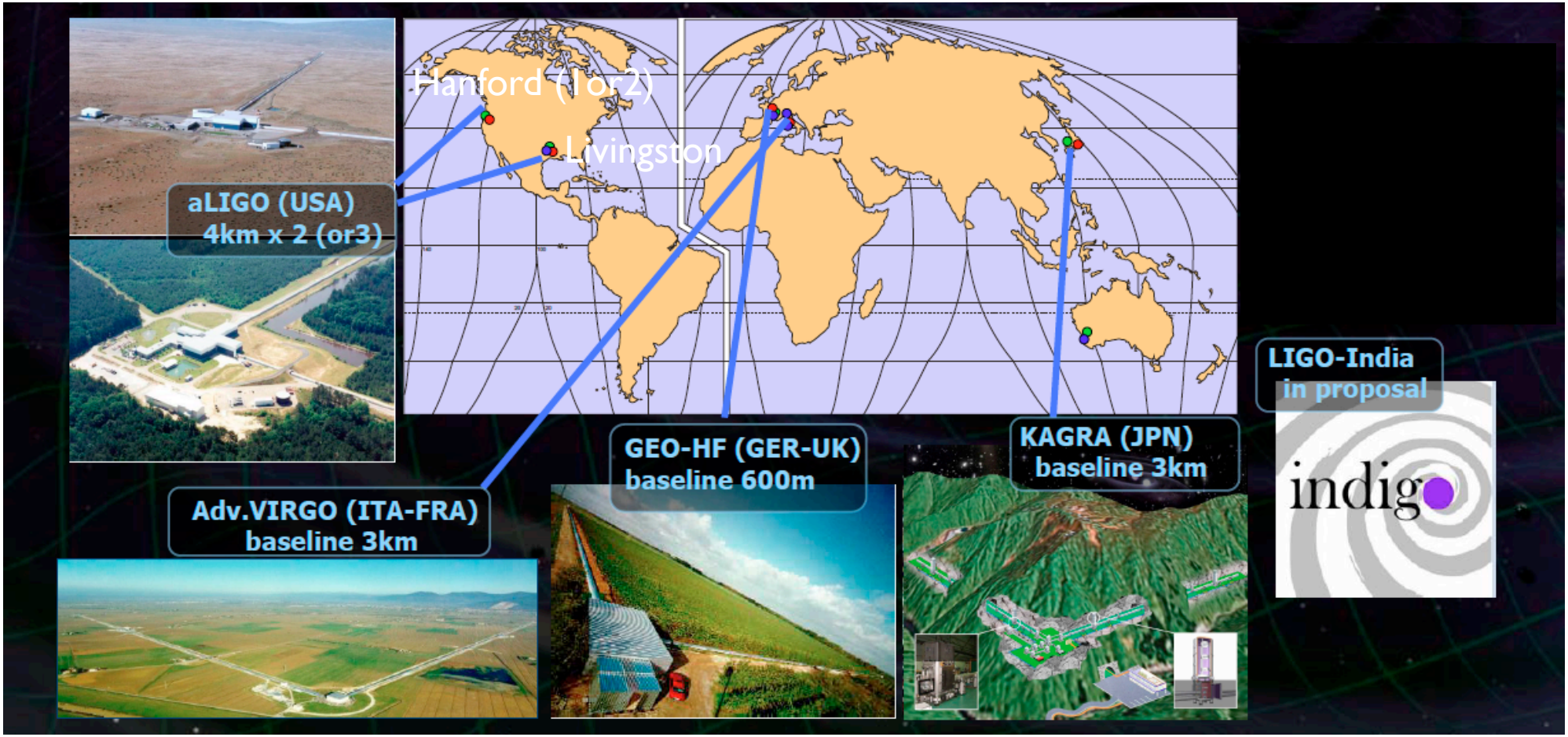
KI in prep.

Multi-Messenger Era

21 Century: Multi-Messenger Era

2nd Generation of GW Observatories

©Ando



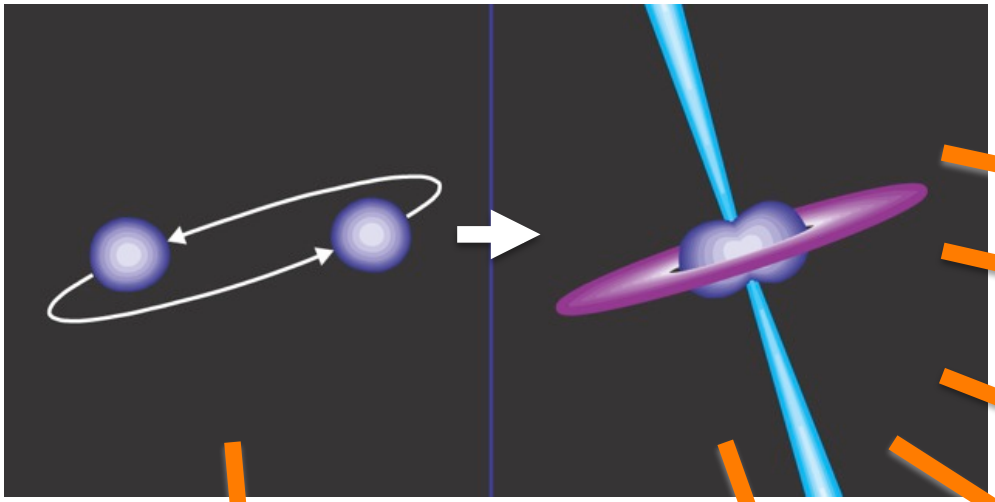
GW will be directly detected within ~5 yr

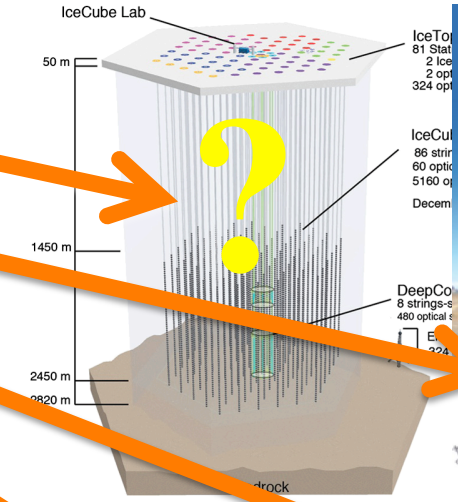
Counterparts to GW

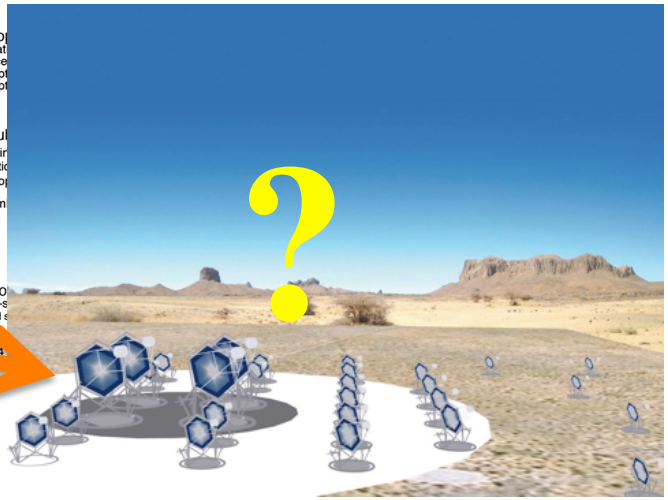
Gravitational Wave Sources

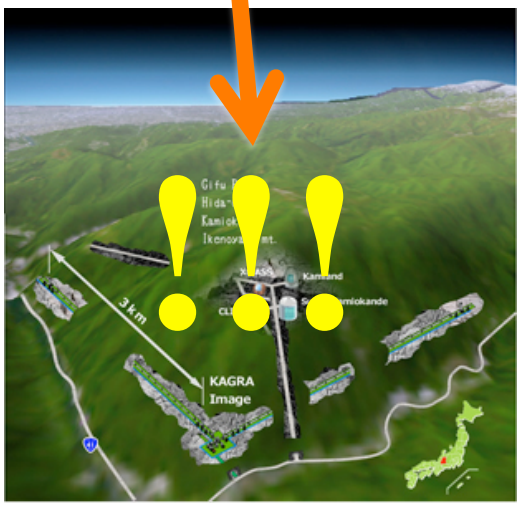
Neutrino

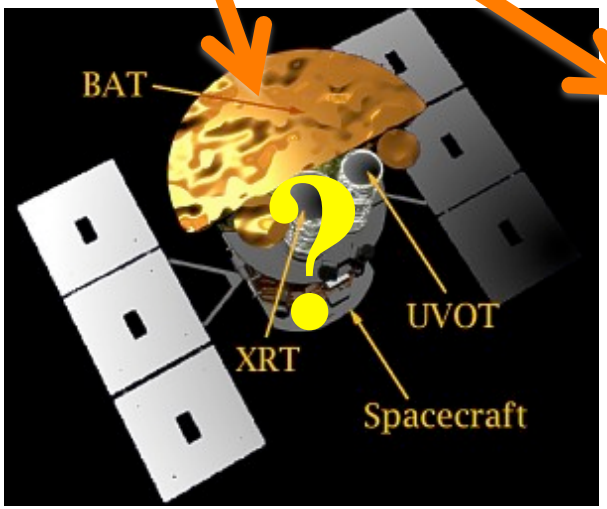
Gamma-ray











Gravitational wave

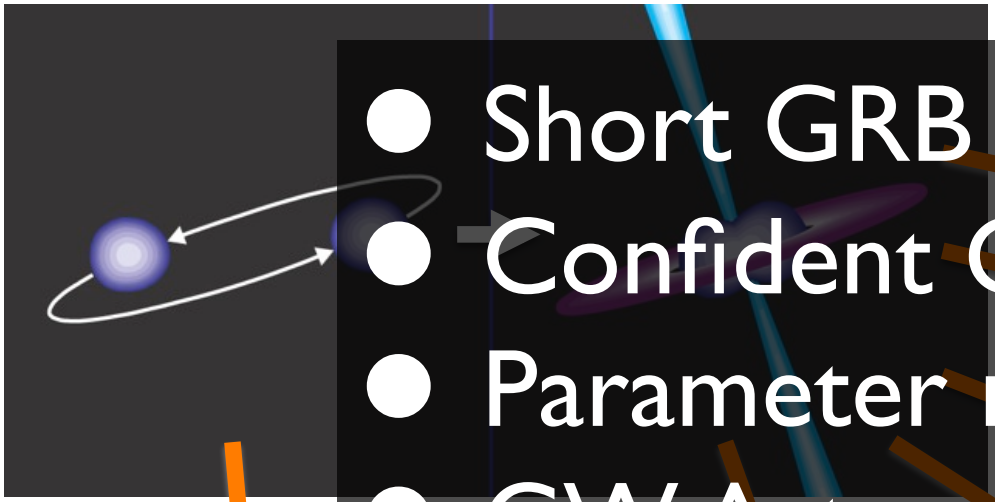
X-ray

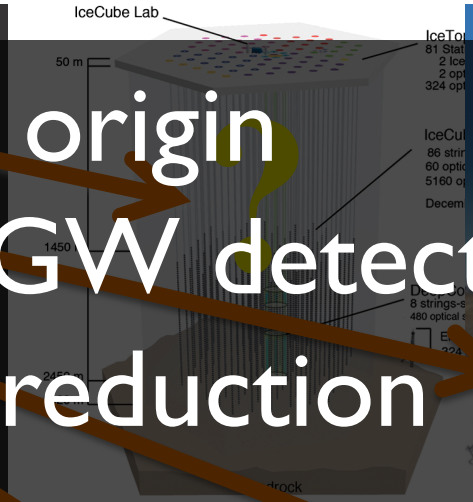
IR-Opt

Radio

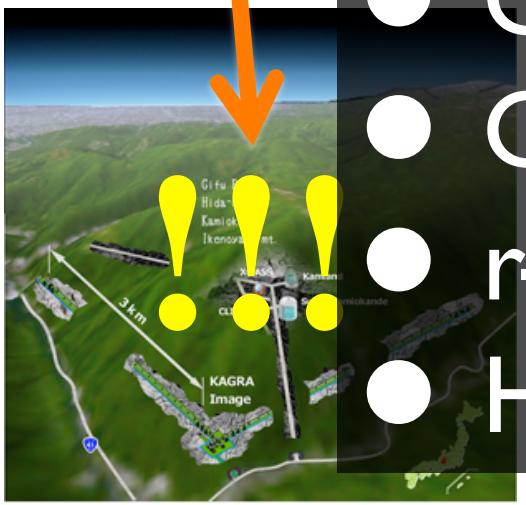
Counterparts to GW

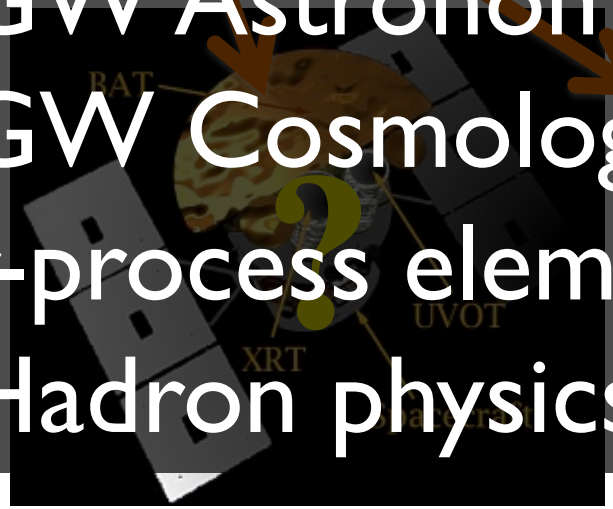
Gravitational Wave Sources | Neutrino | Gamma-ray





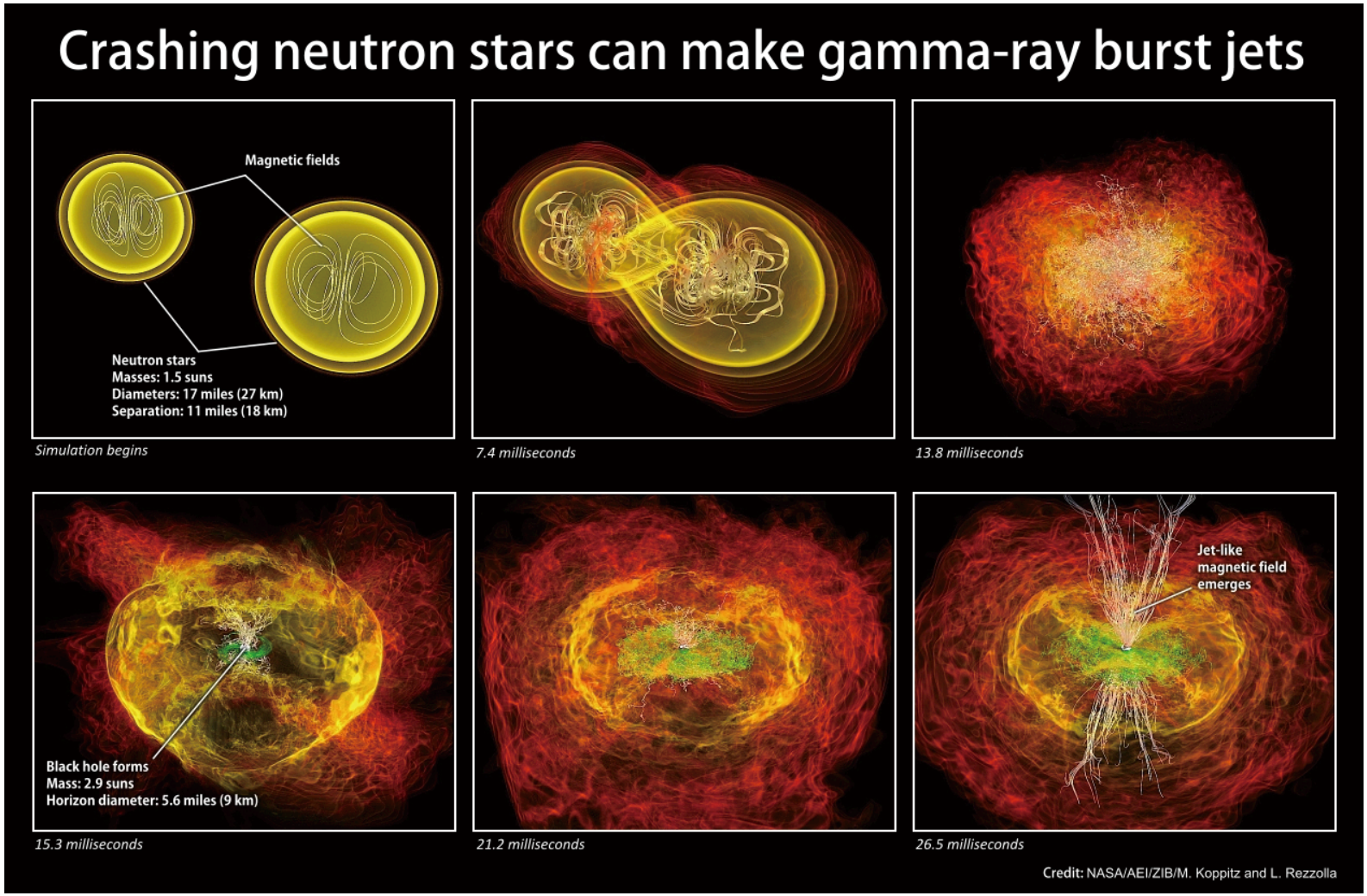
- Short GRB origin
- Confident GW detection
- Parameter reduction
- GW Astronomy
- GW Cosmology
- r-process elements
- Hadron physics





Gravitational wave | X-ray | IR-Opt | Radio

Short GRB = NS Merger?



Eichler+ 89
Rezzolla+ 11

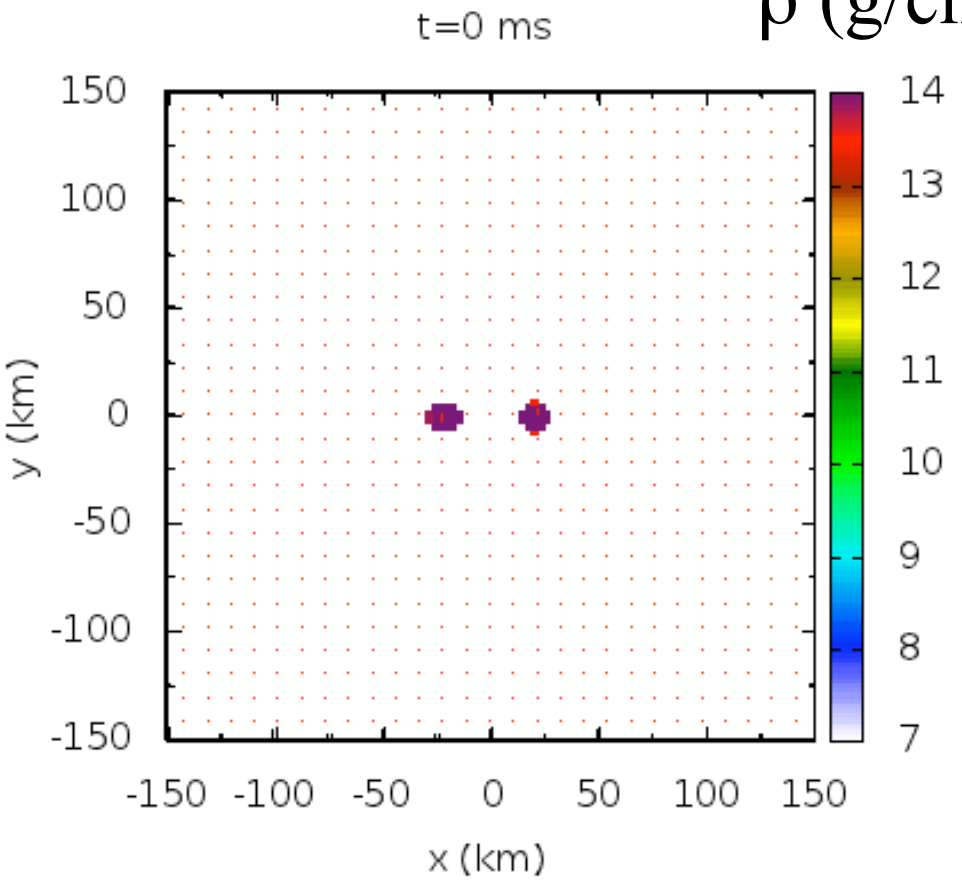
Most GRB Jets are Off-Axis ⇒ Faint

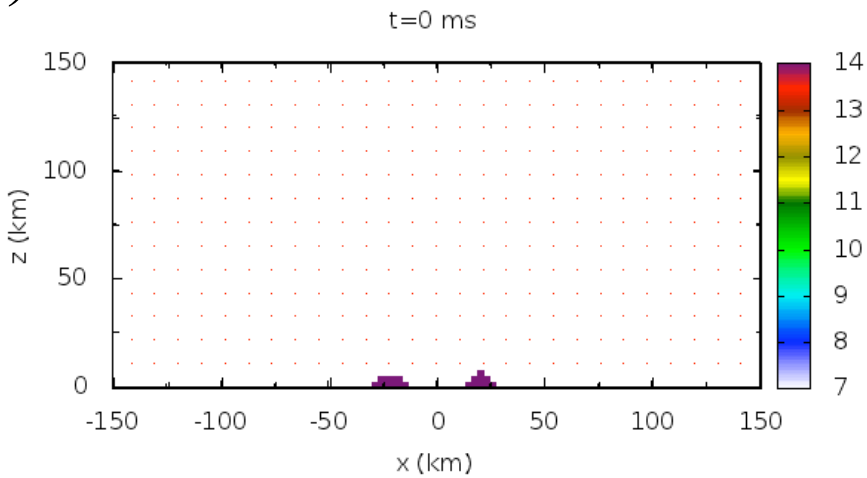
©Shibata, Hotokezaka

Merger of 1.3-1.4 M_{sun} NS:

EOS=APR4: stiff but relatively soft

ρ (g/cm^3)





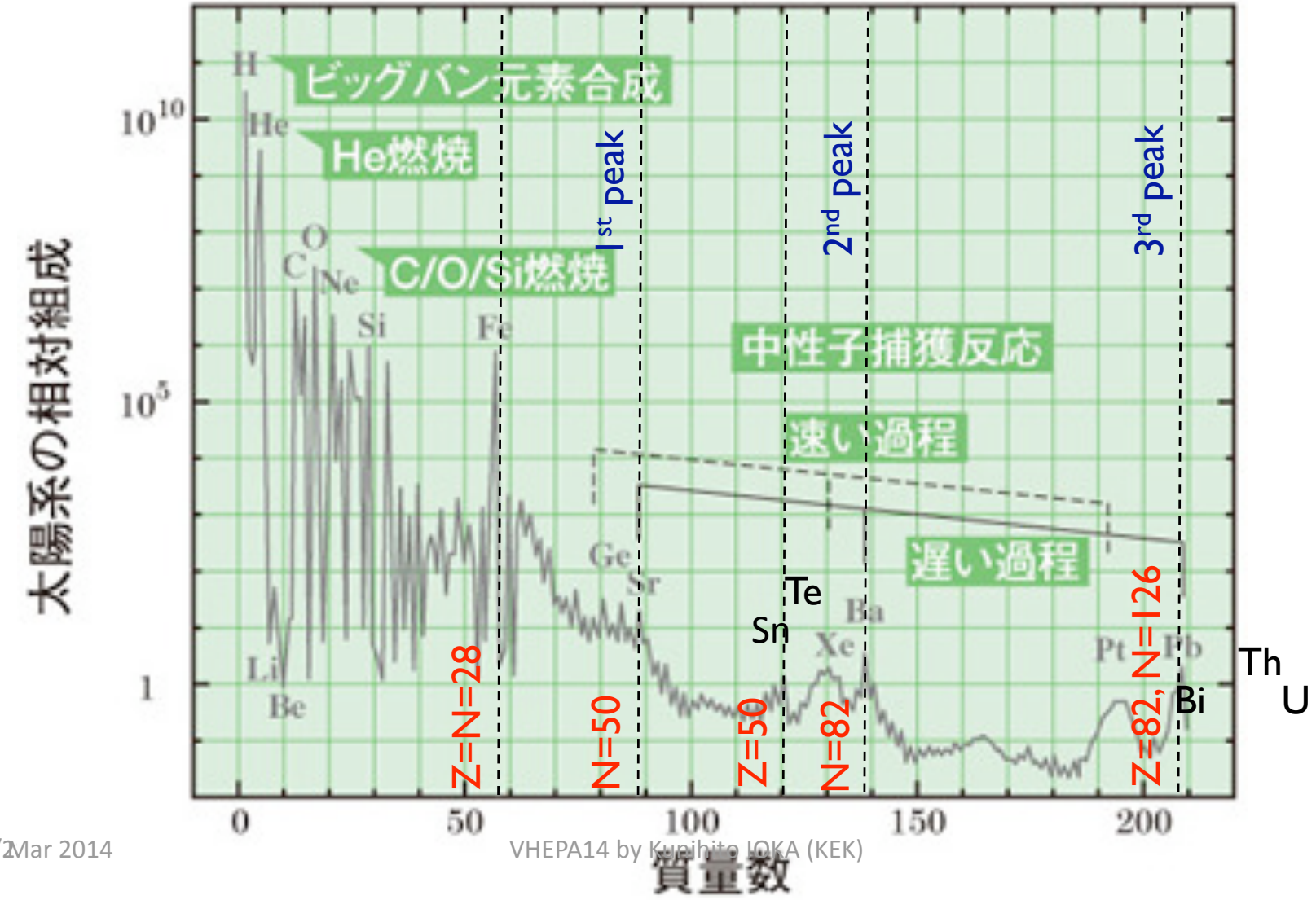
Relatively wider view

Orbital plane

***X-Z* plane**

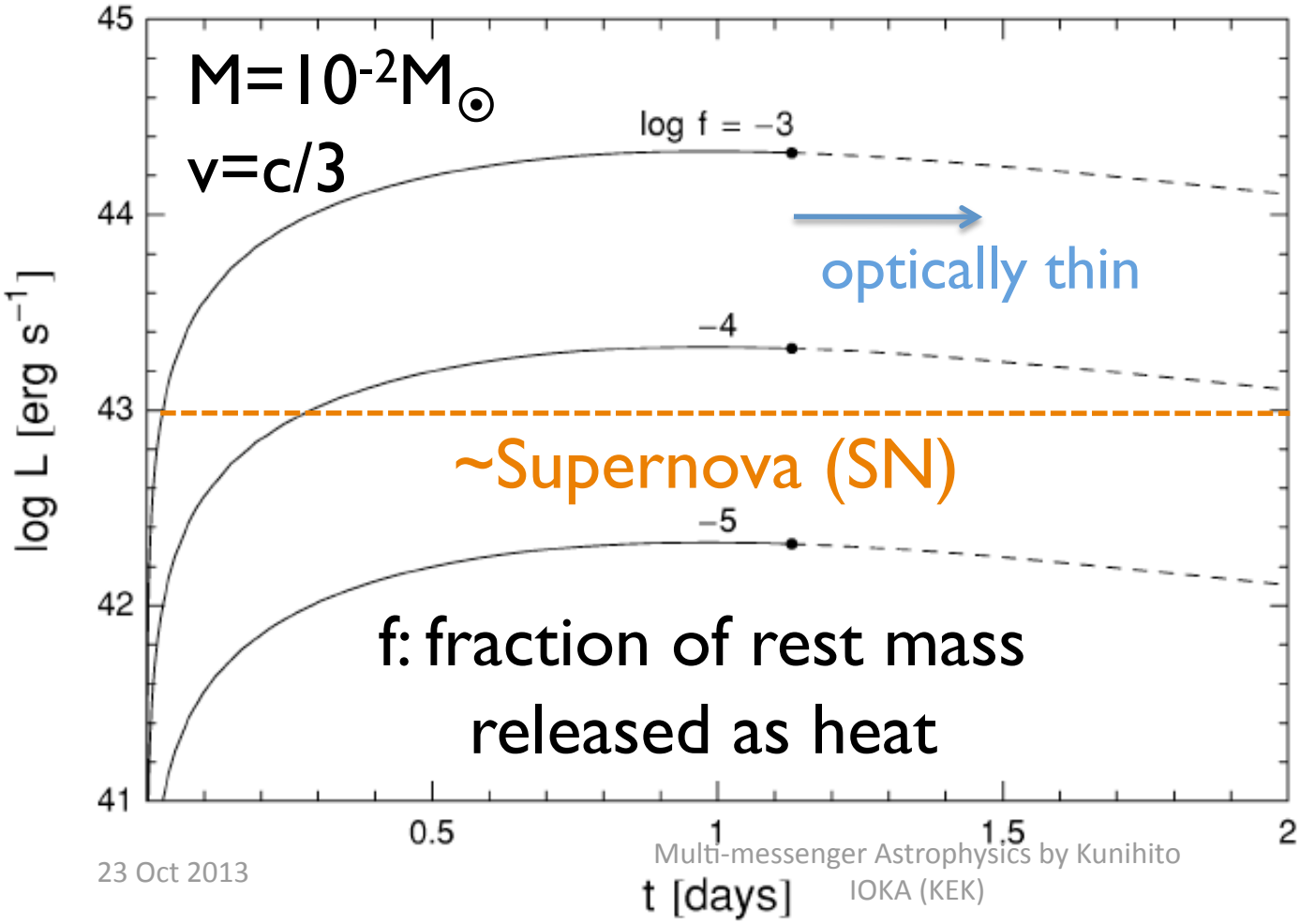
r-Process

Neutron-rich Ejecta ⇒ n-capture>β decay



Macro/Kilo-nova

Radioactivity (r-process → β-decay, fission, neutron)



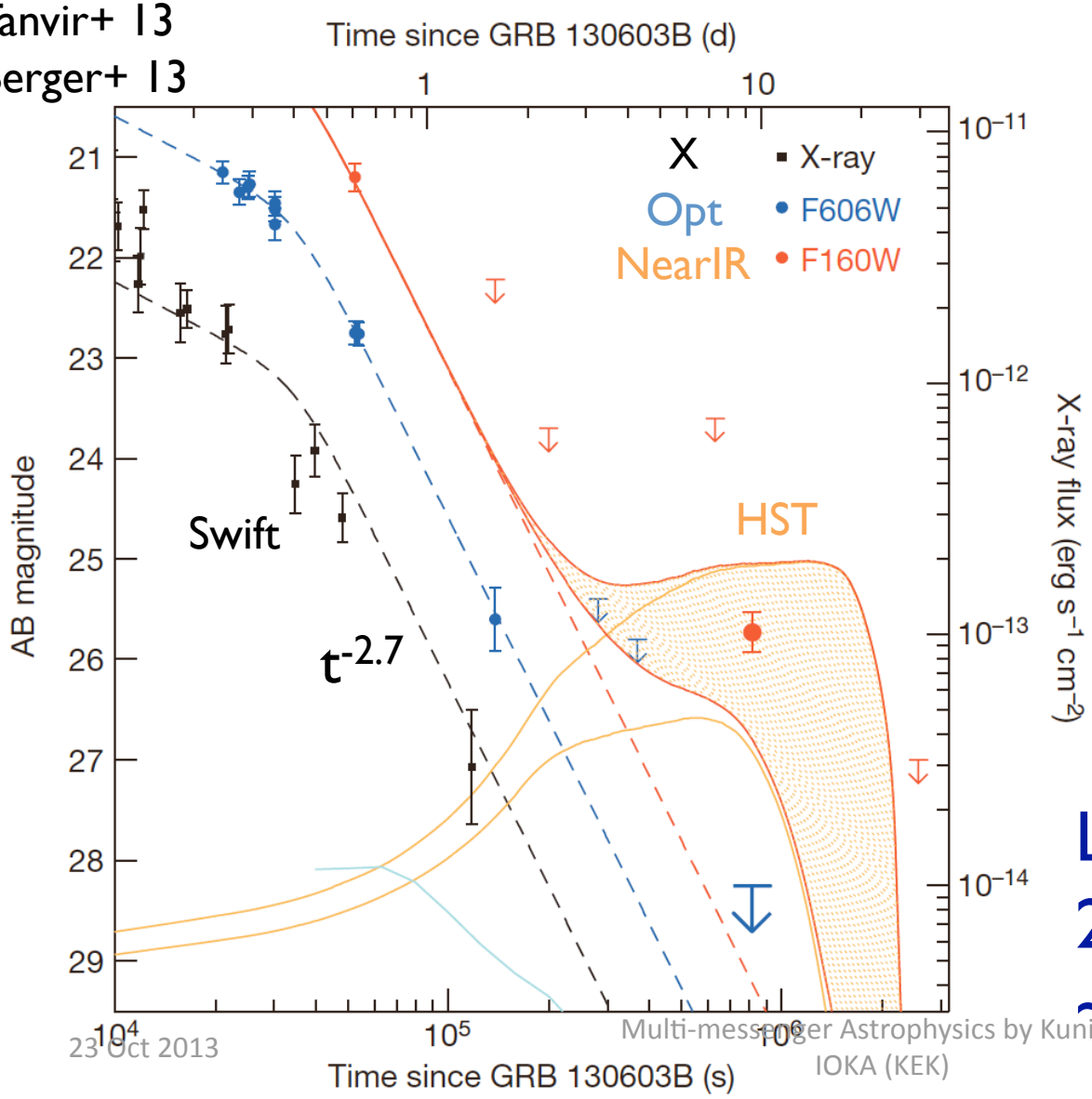
- ≈Supernova
- Duration
  $\propto (M/v)^{1/2}$
- $T \propto (f^2/Mv)^{1/8}$
  ~ IR-Opt
- $f \sim 3 \times 10^{-6}$

⇒ Faint SN

Li & Paczynski 98
Kulkarni 05

Discovery of Macro/Kilo-nova?

Tanvir+ 13
Berger+ 13

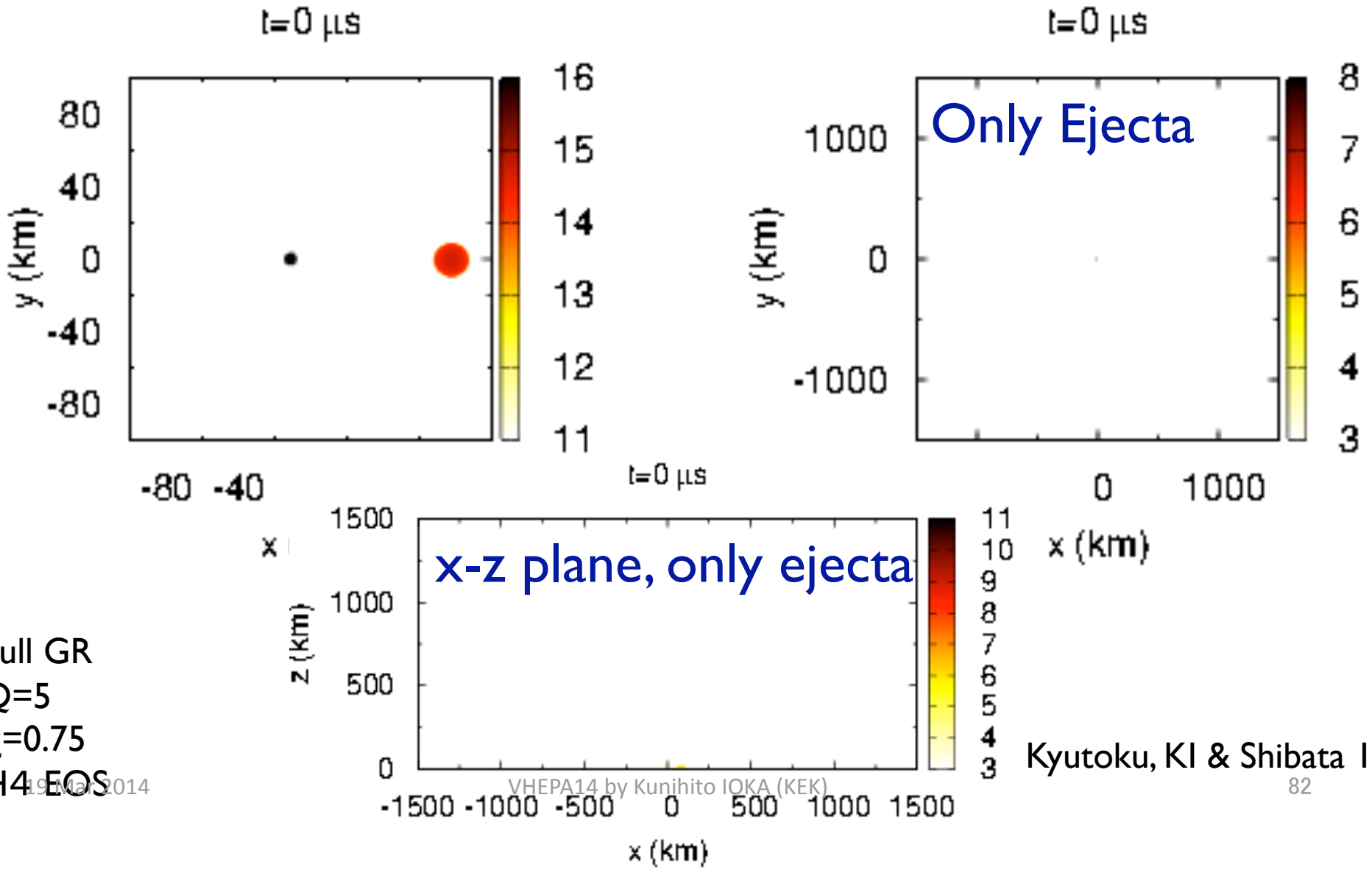


Ejecta with
~0.01-0.1$M_\odot$
~0.1-0.3c
~10^{50}-10^{52}erg
Radioactivity
$f \sim \varepsilon_r/mc^2 \sim 3e\text{-}6$

L~10^{41}erg/s @z~0.356
22-23 mag if @200Mpc
~10 days

BH-NS Merger

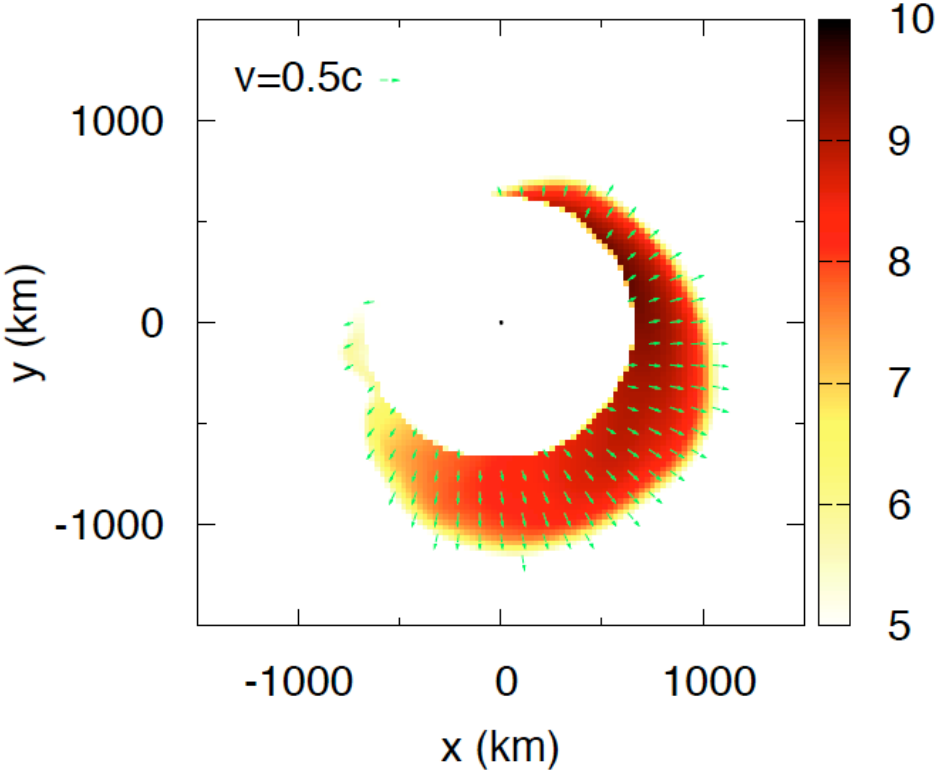
©Kyutoku

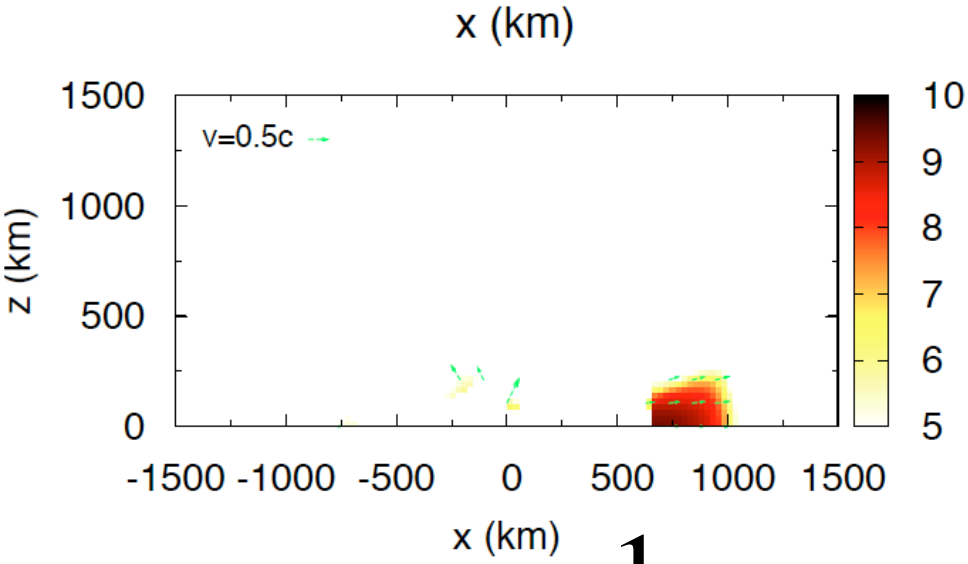


Full GR
Q=5
χ=0.75
H4 EOS

Kyutoku, KI & Shibata 13

Anisotropic Mass Ejection





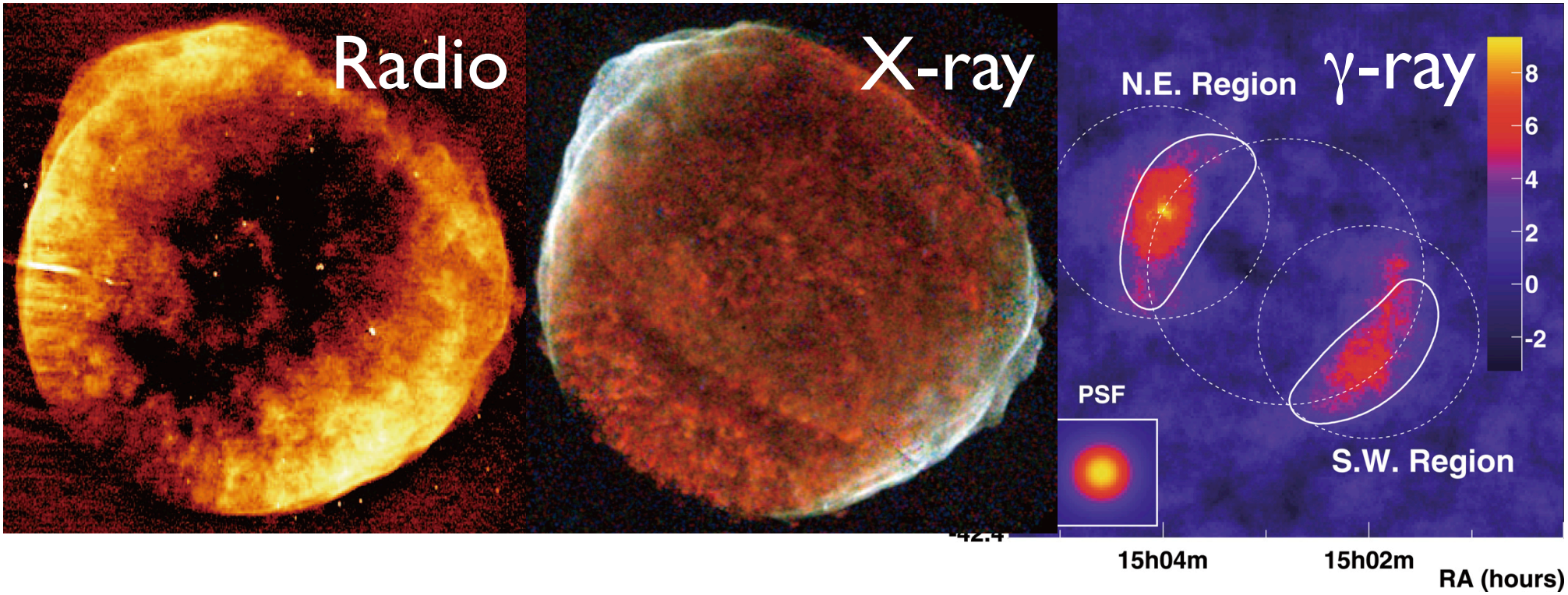
$$\theta_{ej} \approx \frac{1}{5}$$

$$\varphi_{ej} \approx \pi$$

Kyutoku, KI & Shibata 13

Viewing angle diversity
Polarization
Proper motion

Like Supernova Remnant?



NS merger remnant ~ Supernova remnant

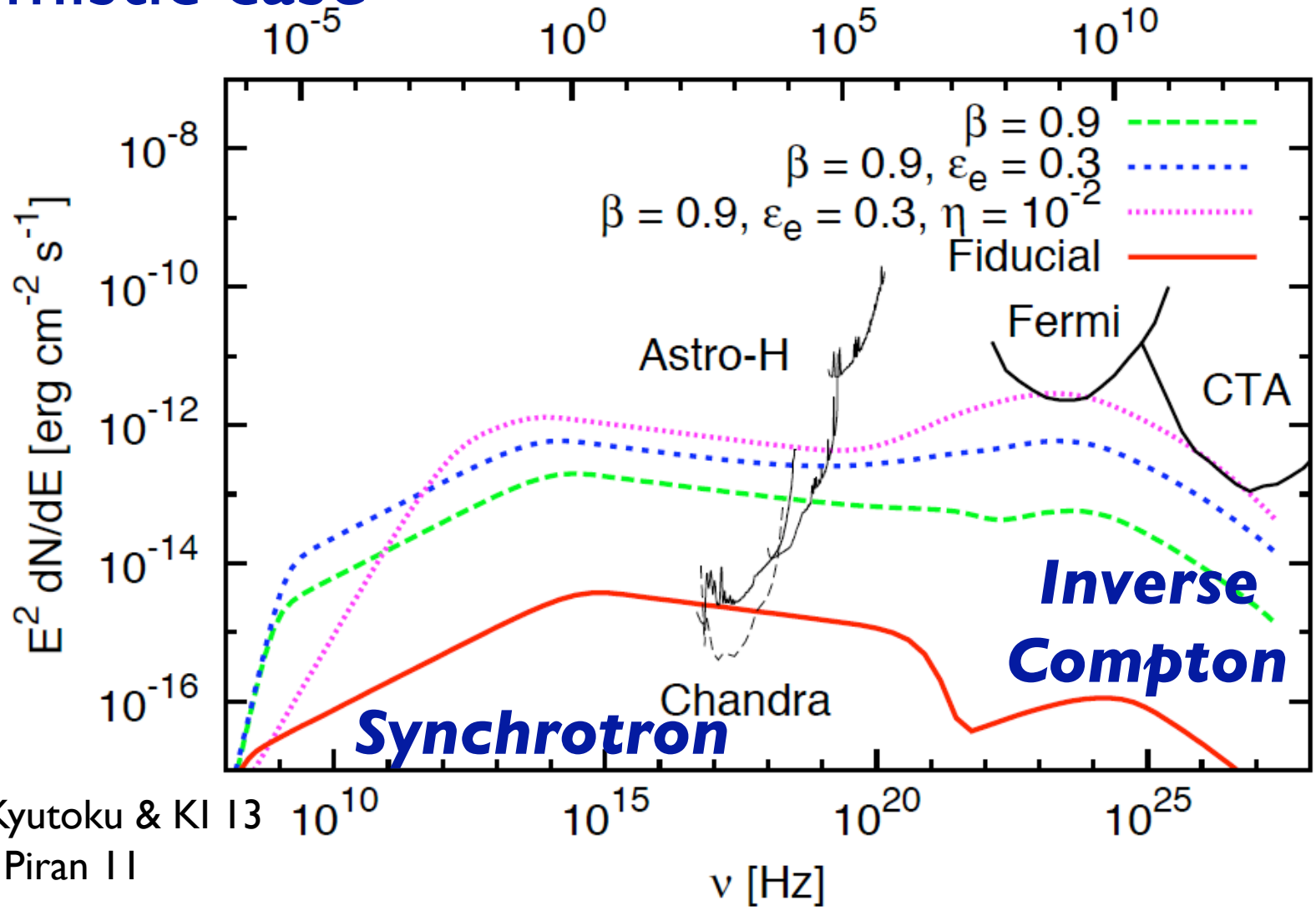
⇒ ***High energy remnant for NS merger?***

Only @t_{Sedov}~5yr

Merger Remnant

Optimistic case

$@t_{Sedov}$~5yr



Takami, Kyutoku & KI 13
Nakar & Piran 11

Cosmic Ray?

Similar to Supernova Remnant ⇒ Cosmic Ray

Maximum Energy

$$\varepsilon_{\rm max} = 2\times10^{18}\ {\rm eV}\ Z M_{ej,-2}^{1/3} v_{ave,0.3}^{2} \varepsilon_{B,-1}^{1/2} n_0^{1/6} \theta_{ej,1/5}^{2/3} \varphi_{ej,\pi}^{-1/3}$$

Larger than SNR due to large velocity

Energy Budget

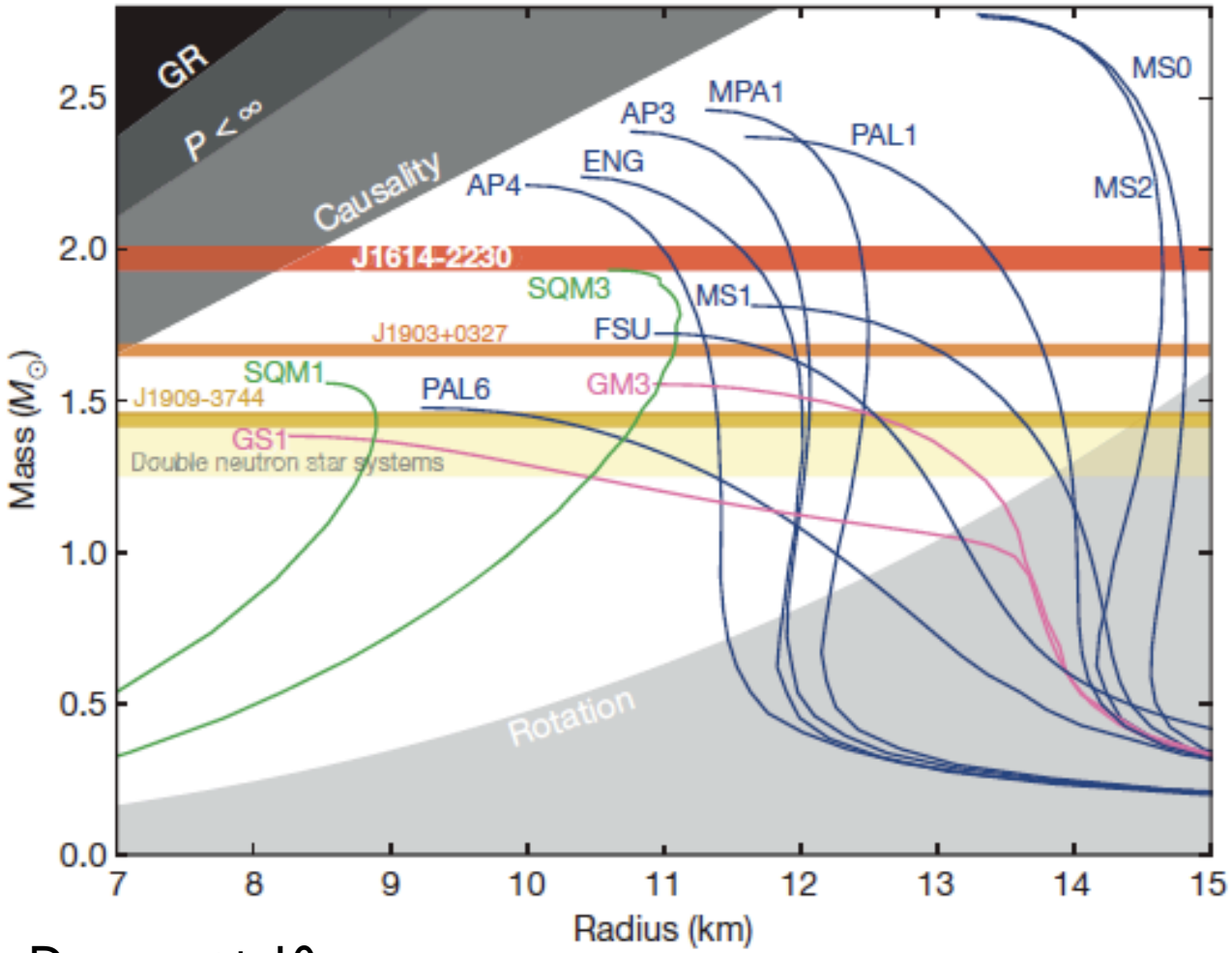
Kyutoku, KI & Shibata 13
Takami, Kyutoku & KI 13

10^{-4} NS^2/yr/galaxy ~ SN/100: Not small

Beyond knee CRs?

Ultra-high energy CRs of r-process elements?

Massive Neutron Star?



1.3+1.3Msun may survive

⇒ Massive NS msec rotation

$E_{rot} \sim 10^{52}$erg

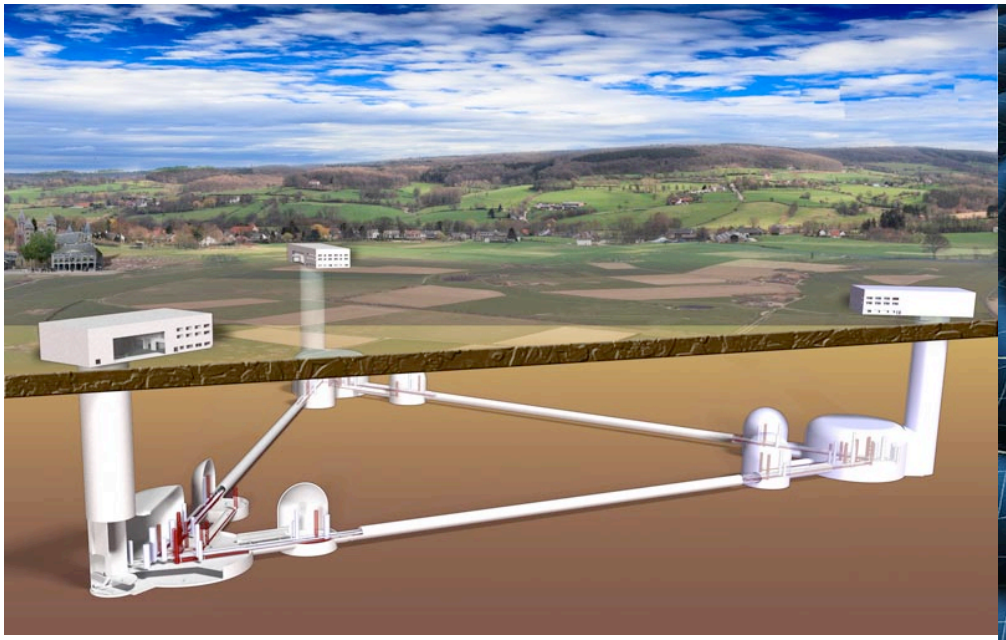
⇒ inject energy to the ejecta

Demorest+ 10
Antoniadis+ 13

Zhang 13
Gao+ 13

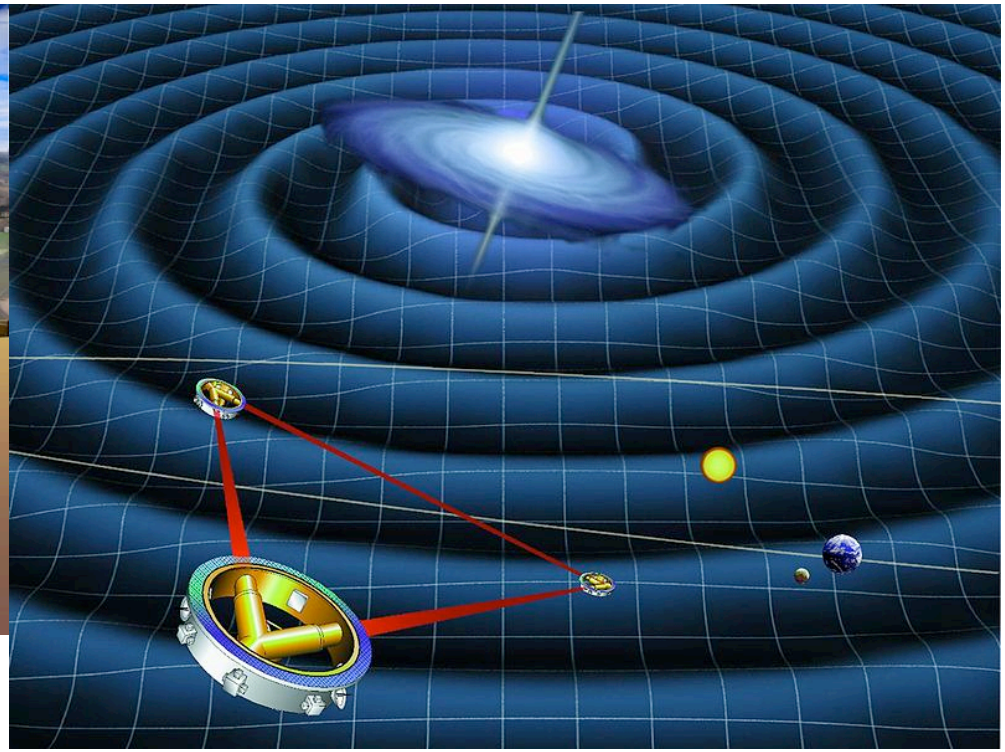
Future Projects

Einstein Telescope



10× KAGRA
~1000 NS-NS/yr

LISA (eLISA)
DECIGO

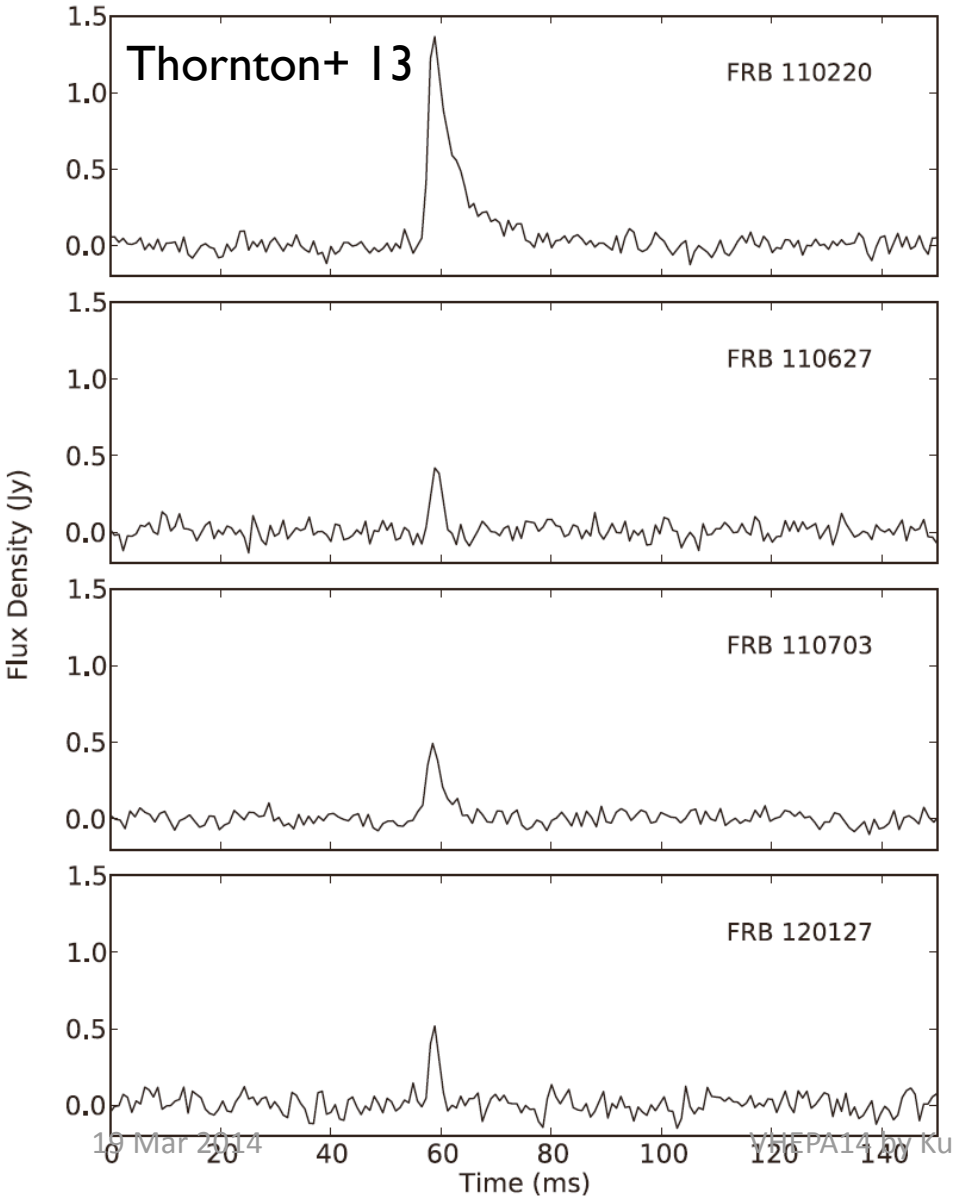


Massive black hole
Inflation, Dark energy

Multi-Messenger Era

21 Century: Multi-Messenger Era

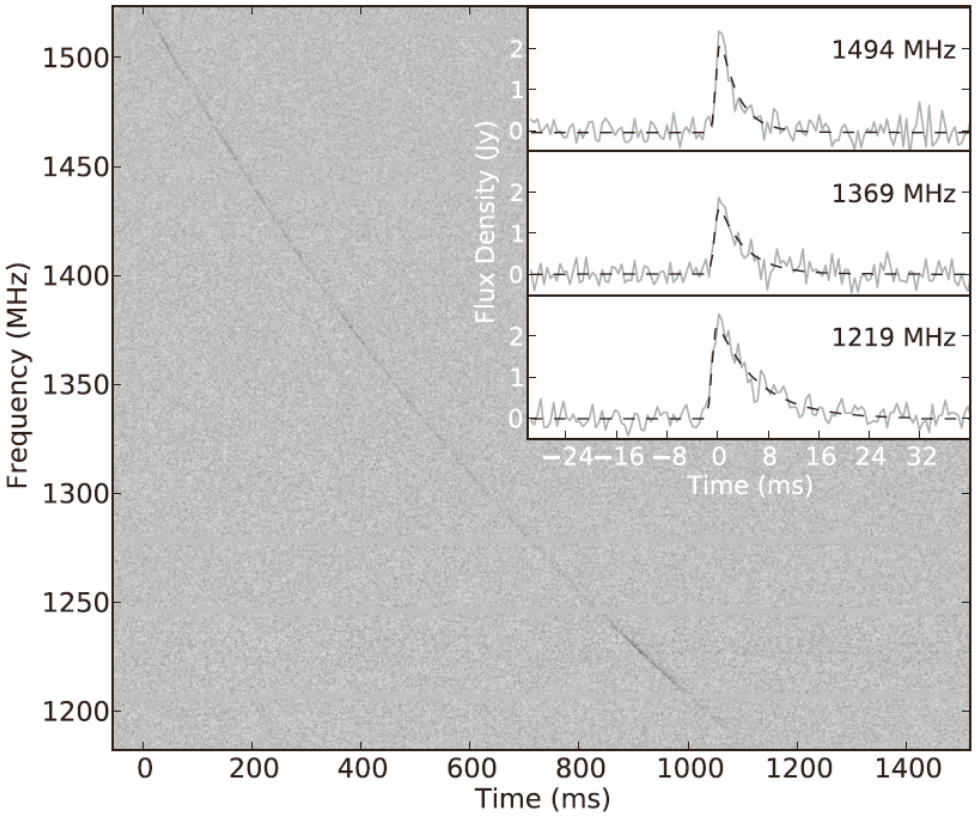
Fast Radio Bursts



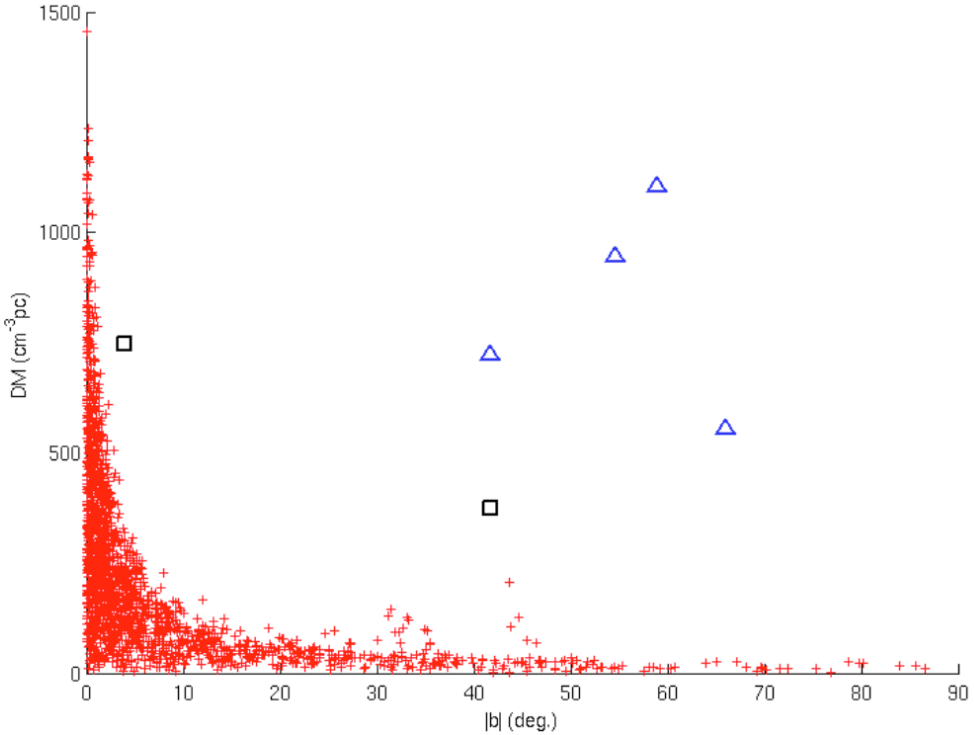
F=0.6-8.0 Jy ms !!!

Most luminous radio transients if cosmological

Dispersion Measure



Thornton+ 13

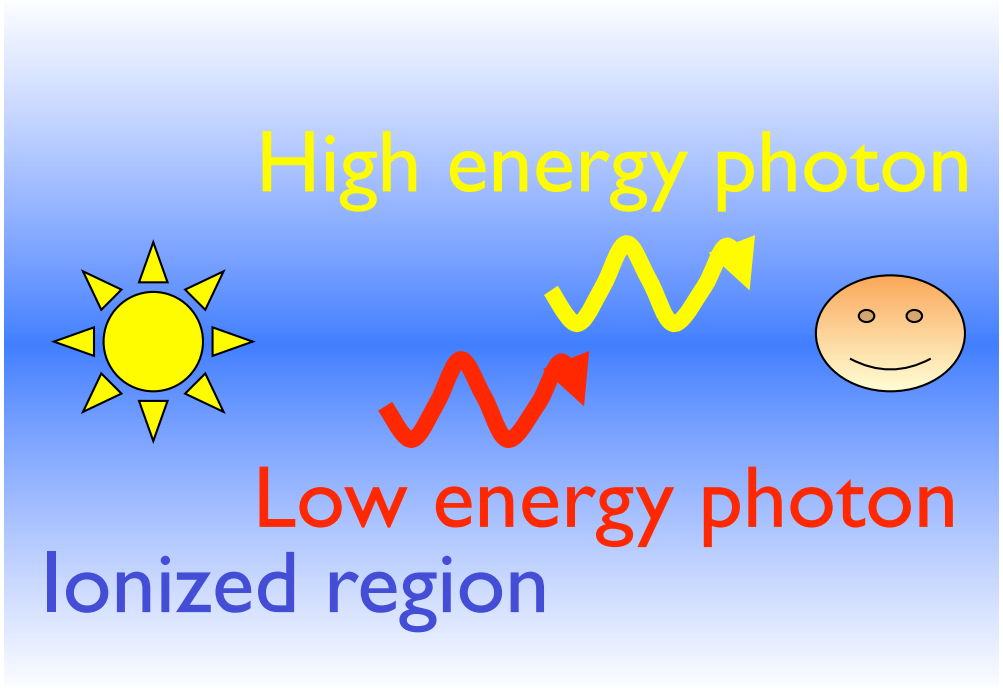


Galactic latitude

$\delta t \propto DM \cdot \nu^{-2}$

DM=500-1000 cm^{-3} pc

Photon Delay



In a plasma, a light signal is delayed

$$\omega^2 = k^2 c^2 + \omega_p^2$$

plasma frequency

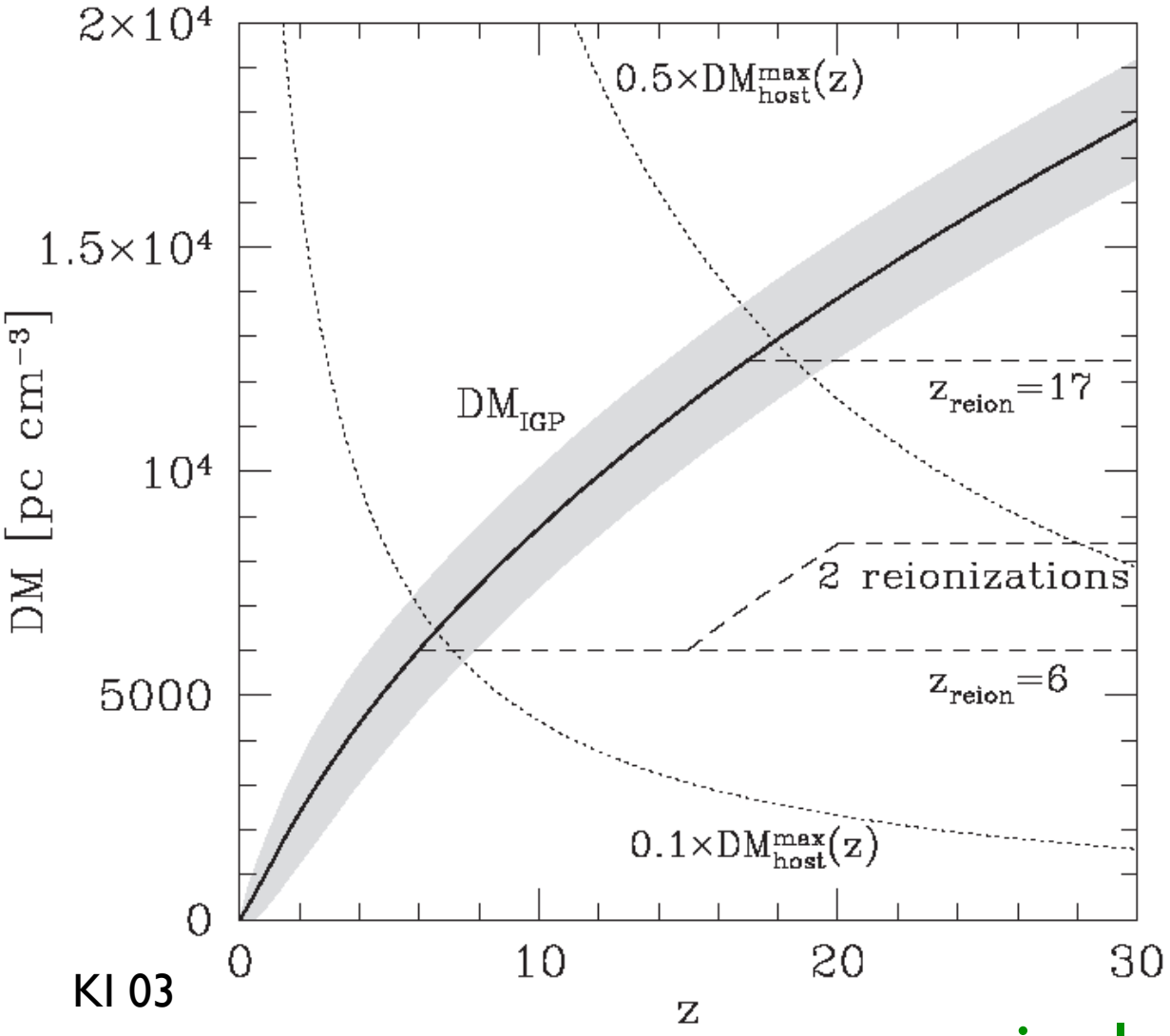
$$\omega_p = \sqrt{\frac{4\pi n e^2}{m}} = 5.63 \times 10^4 n^{1/2} \ \mathrm{s}^{-1}$$

$$\Delta t = 4.15 \ \mathrm{s} \left(\frac{\nu}{1 \ \mathrm{GHz}} \right)^{-2} \left(\frac{\mathrm{DM}}{10^3 \ \mathrm{pc \ cm}^{-3}} \right)$$

DM = Column density of free electrons

DM ⇒ Distance

Intergalactic DM



KI 03

$$\Delta t = \int_0^z dz \frac{dt}{dz} \frac{1}{2} \frac{(1+z)\nu_p^2}{\left[(1+z)\nu\right]^2}$$

$$= \frac{e^2}{2\pi m_e c} \frac{1}{\nu^2} \times$$

$$\frac{cn_0}{H_0} \int_0^z \frac{(1+z)dz}{\left[\Omega_m (1+z)^3 + \Omega_\Lambda\right]^{1/2}}$$

$$\overline{\mathrm{DM_{IGP}}}$$

DM~500-1000 cm^{-3} pc

⇒ ***z~0.5-1***

including missing baryon

Summary of FRB Obs.

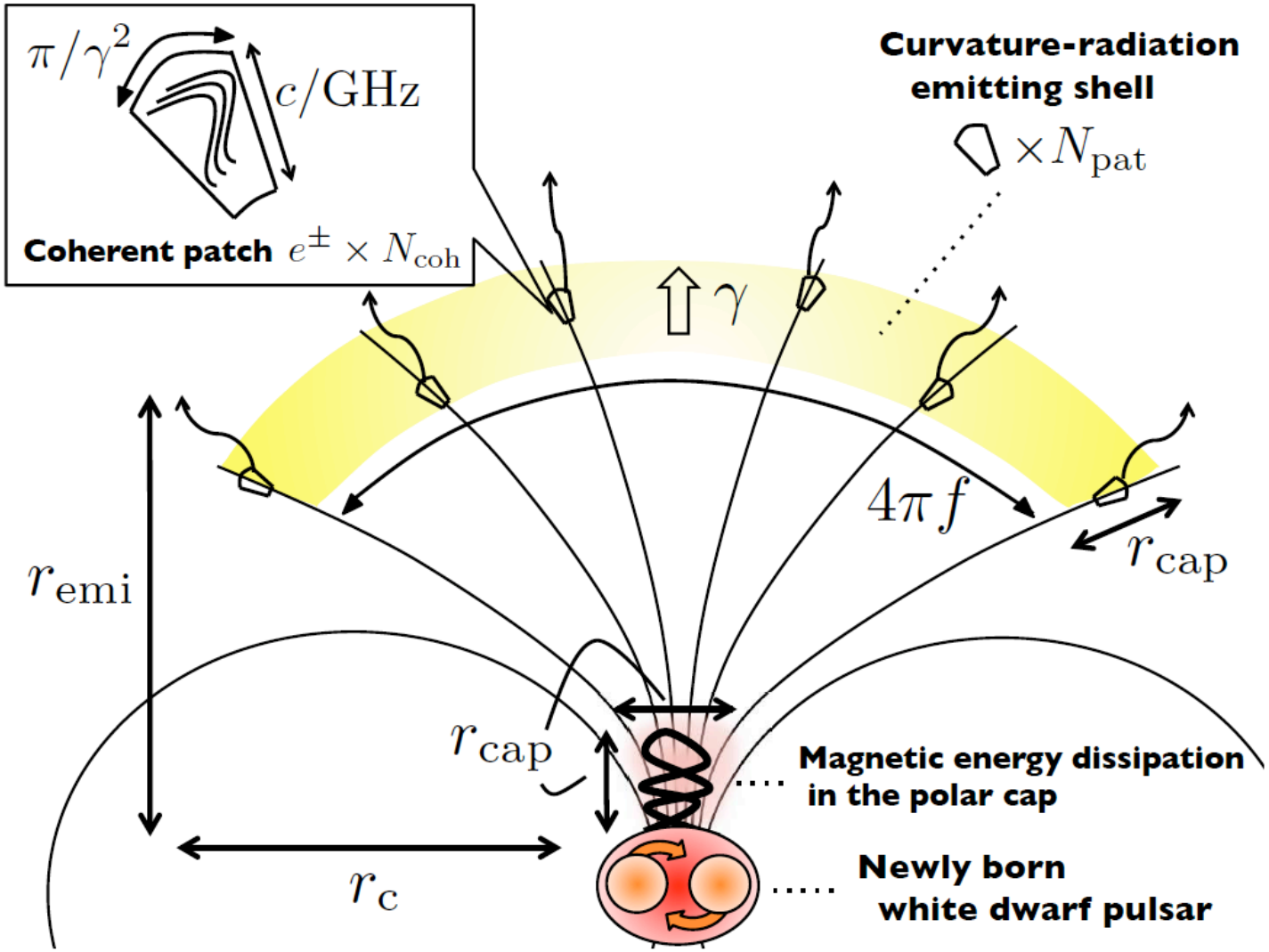
- DM=500-1000 cm^{-3} pc (z=0.5-1)
- S_ν~Jy ⇒ E_{iso}~$10^{38\text{-}40}$ erg
- δt=5.6ms,<4.3,1.4,1.1ms
  ⇒ $c\delta t(1+z)^{-1} < 1500(1+z)^{-1}$ km
- Rate~$(1\pm0.5)\times10^4$/sky/day~10^{-3}/yr/galaxy
  ⇔ Supernova rate 10^{-2}/yr/galaxy
- No repeated bursts so far
- No counterparts so far

Possible Origins

- RRAT (Rotating Radio Transient; intermittent pulsar)
- Giant pulse from a msec/young pulsar
- Evaporation of BH — Rees 77; Blandford 77; Kavic+ 08; Keane+ 12
- SN into a nearby star — Colgate+ 71,75; Egorov & Postnov 09
- Magnetar giant flare — Popov & Postnov 07; Thornton+ 13
- Collapse of hypermassive NS — Falcke & Rezzolla 13; Zhang 13
- Binary NS mergers — Hansen & Lyutikov 01; Totani 13
- Superconducting cosmic strings — Cai+ 12
- Nearby flaring stars — Loeb+ 12

Binary White Dwarf Mergers?

Kashiyama, KI & Meszaros 13



- Energetics $E_B \sim 10^{40}$erg
- Timescale $r_{cap}/c \sim$ms
- Event rate ~SN Ia
- SN Ia as a counterpart?

Brightness Temperature

$$F_\nu = \frac{\pi r_\perp^2}{d^2}\frac{2\nu^2}{c^2}kT$$

$$T \sim 3\times10^{41}\mathrm{K}\, L_{43} r_{emi,10}^{-2}$$

⇒ Coherent emission

$P \sim |E|^2 \sim |E_1+E_2+E_3+\ldots+E_N|^2$
$\sim N|E_1|^2$ (incoherent)
$\sim N^2|E_1|^2$ (coherent)

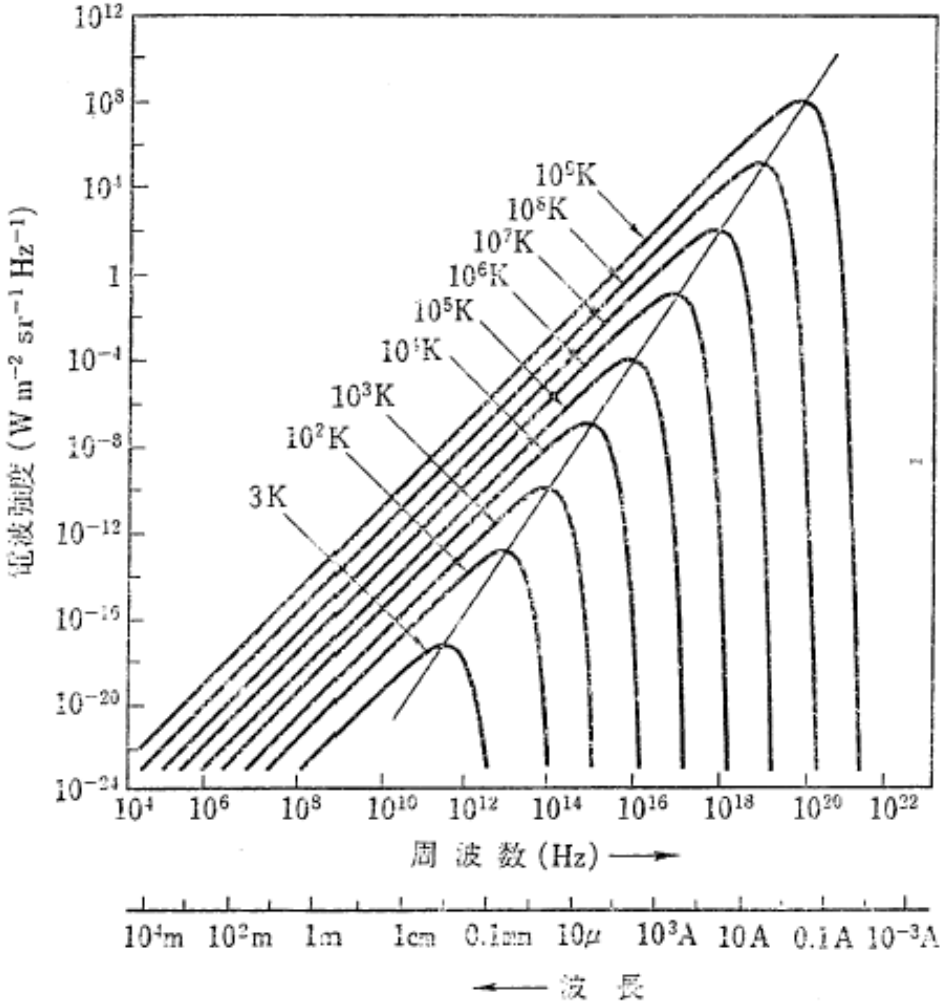
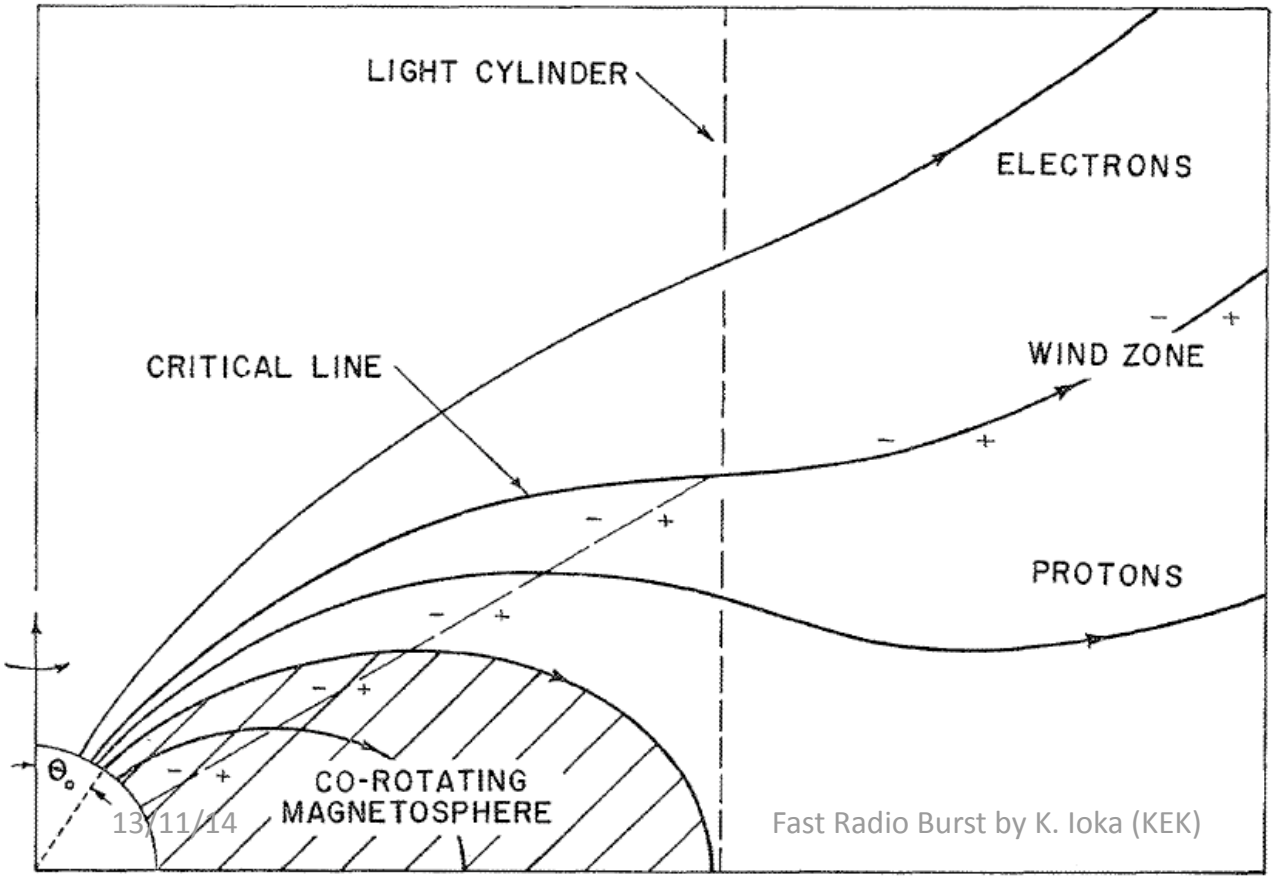


図 2·6 熱放射（プランク放射）の強度スペクトル

FRB = PeV Accelerator?

$$\Phi_{\max} \approx \frac{B\Omega^2 r^3}{2c^2} \sim 2.5\times10^{16}\ \text{Volt}\ B_9\Omega_0^2 r_{8.7}^3$$

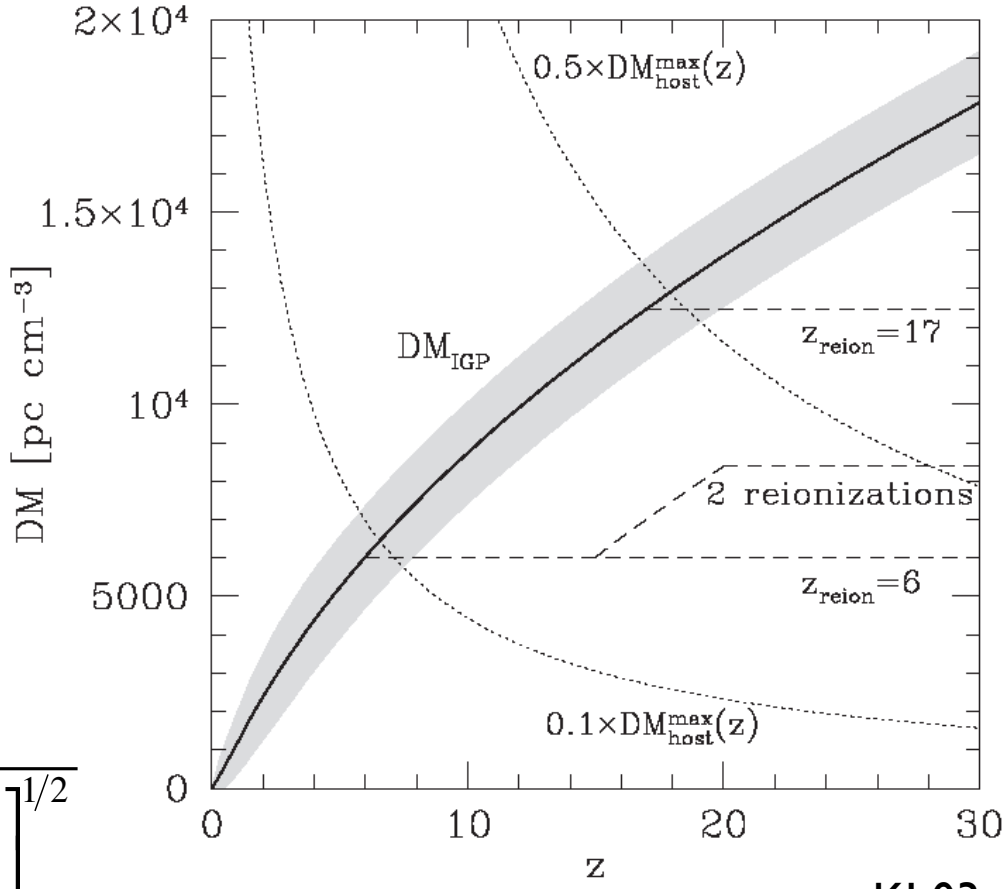


⇒ $e^{\pm}$ production

⇒ Coherent radio emission

FRB Cosmology

- Reionization
- Missing baryon
- Dark energy, cosmological parameters



KI 03

$$\mathrm{DM_{IGP}} = \frac{3cH_0\Omega_b}{8\pi G m_p}\int_0^z \frac{(1+z)\,dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}$$

$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}$$

Fast radio bursts as cosmological tools

New frontier?

Summary

- ***Multi-wavelength up to Gamma-ray***
  - SN-GRB, Supernova remnant, Fermi bubble, …
  - CTA is coming soon
- ***Cosmic-ray***: $e^{\pm}$, He/p, UHECR GZK cutoff, …
- ***Neutrino***: PeV ν sources = UHECR sources?
- ***Gravitational wave***: Macronova, NS-NS/BH?
- ***Radio***: Fast radio bursts are PeV accelerators?

21 Century: Multi-Messenger Era

Thank You