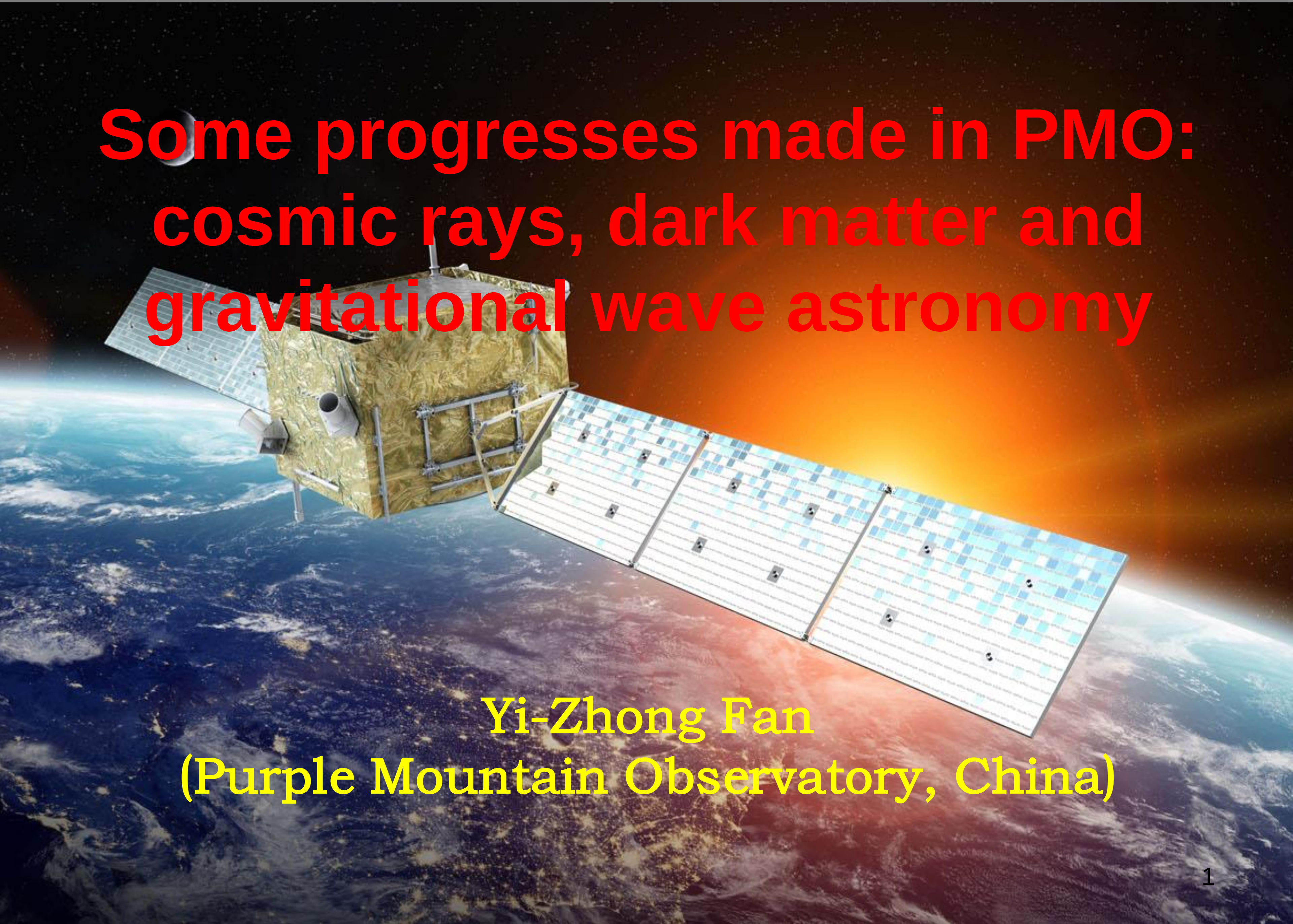


Some progresses made in PMO: cosmic rays, dark matter and gravitational wave astronomy

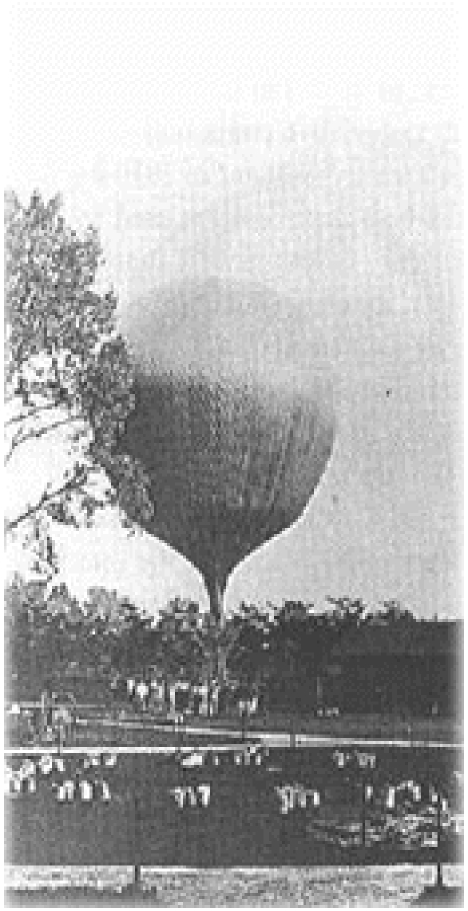
Yi-Zhong Fan
(Purple Mountain Observatory, China)

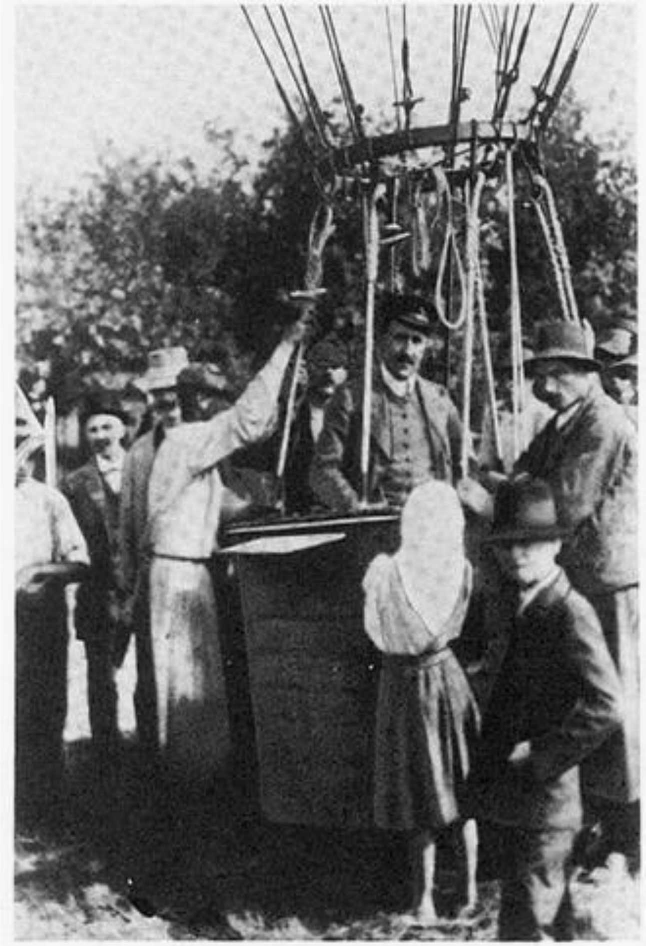
My collaborators on cosmic ray and dark matter; Other eight on GW and GRB

Outline

- Direct detection of cosmic rays by DAMPE
- Indirect detection of dark matter particles
- Signature of gravitational wave radiation in the X-ray afterglow of sGRB?
- Kilonovae associated with GRB 050709, GRB 060614 and GRB 070809

Cosmic rays and fundamental physics

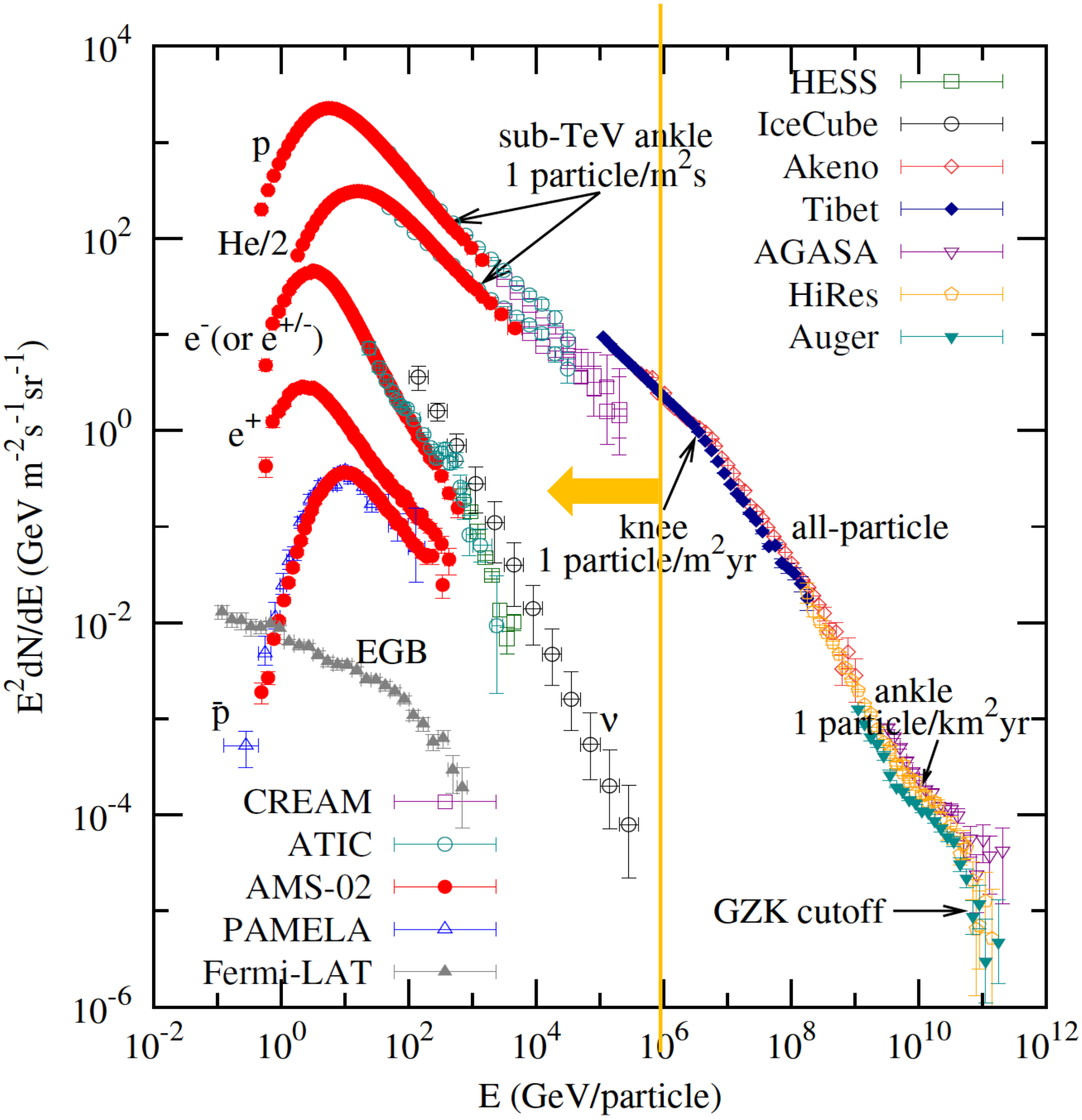




Hess bei Ballonlandung (1912).

- Cosmic ray was discovered by V. Hess and his colleagues in ~1912
- Cosmic rays played a remarkable role in studying high energy physics before 1950s (discovering positron, muon, kaon and pion)
- Cosmic rays may reveal the nature of dark matter

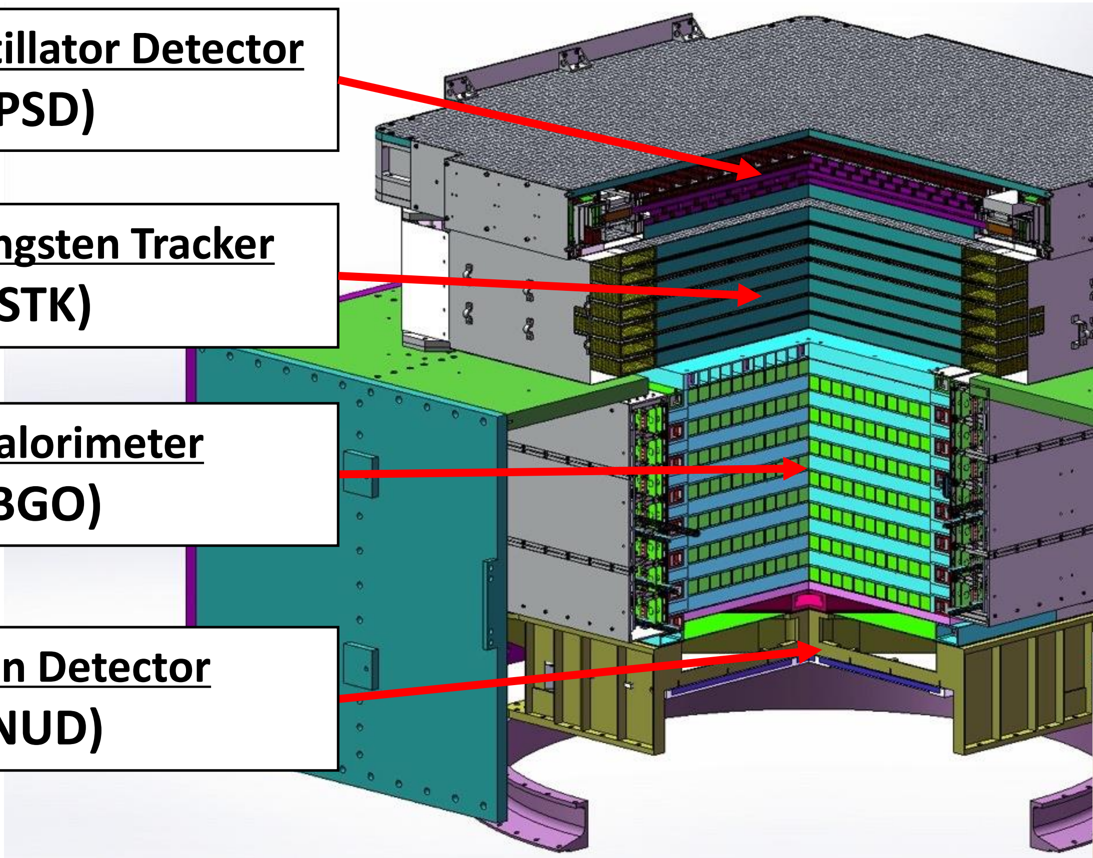
Cosmic ray detection



- Indirect detection: from a few tens of GeV up to >100EeV by ground-based large detectors

- Direct detection: up to 1 PeV by balloon-borne or satellite-borne detectors

Dark matter particle Explorer (DAMPE)



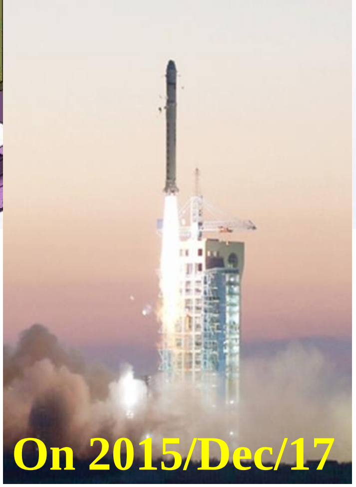
Plastic Scintillator Detector
(PSD)

Silicon-Tungsten Tracker
(STK)

BGO Calorimeter
(BGO)

Neutron Detector
(NUD)

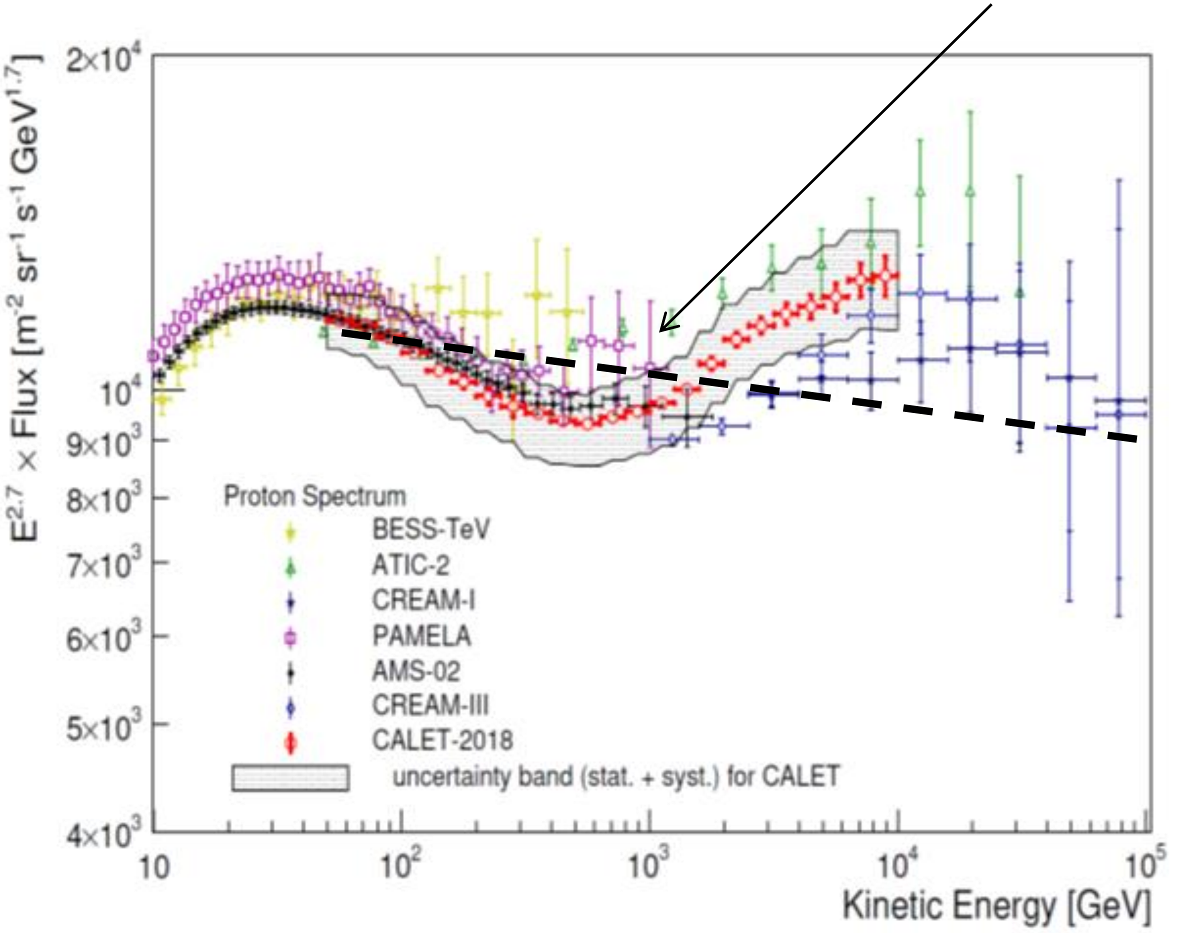
- Charge measurement (dE/dx in PSD, STK and BGO)
- Pair production and tracking (STK and BGO)
- Precise energy measurement (BGO bars)
- Hadron rejection (BGO and NUD)



On 2015/Dec/17

Spectral hardening: recent breakthrough

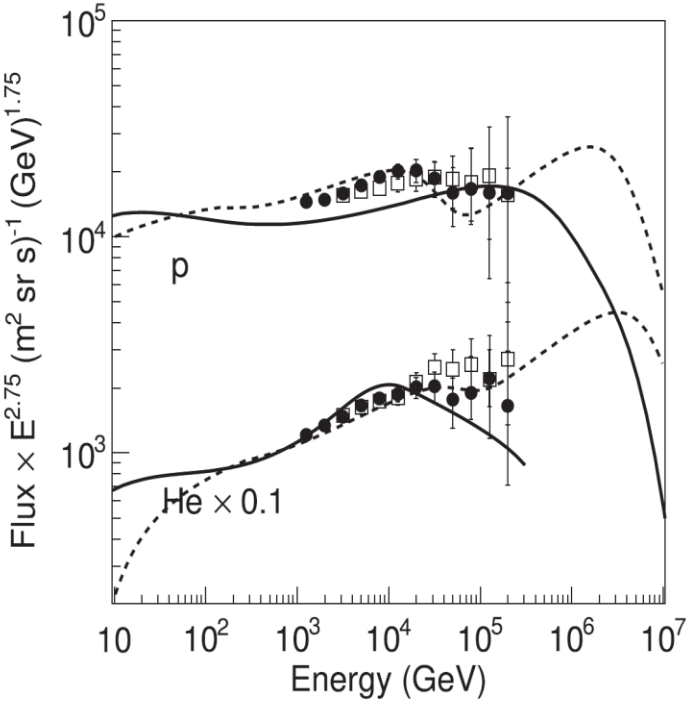
Previous standard assumption: $E^{-2.75}$

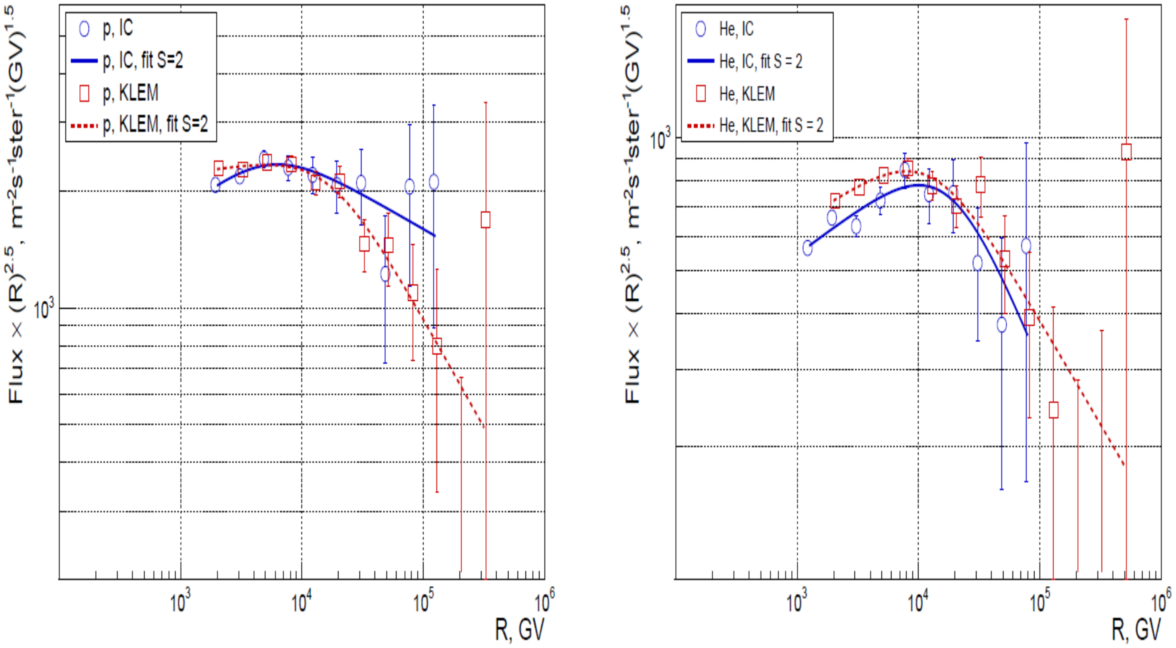


CALET collaboration (2019 PRL) and the results reported since 2008:

Spectral hardening at 300-400 GV. Implications: nearby source, or multi kinds of sources, or new acceleration model, or new diffusion model?

CREAM-I+III & NUCLEON: hints for a new structure at ~10TV

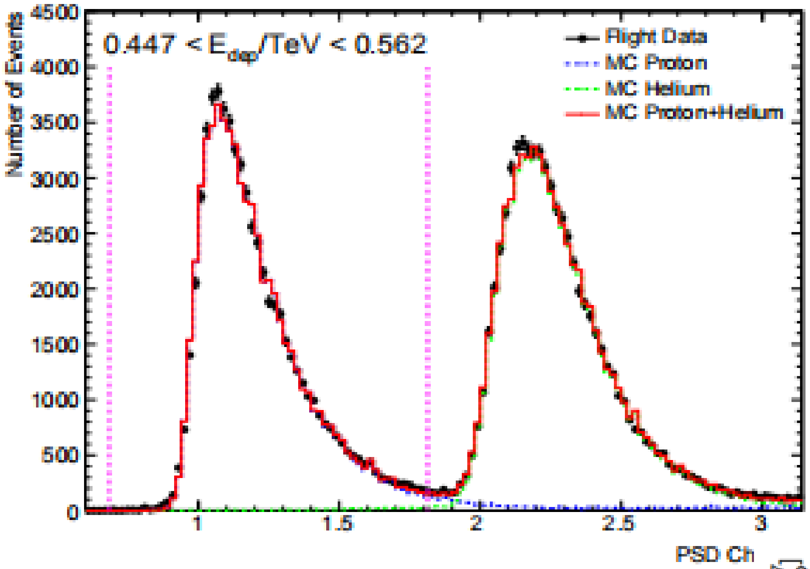


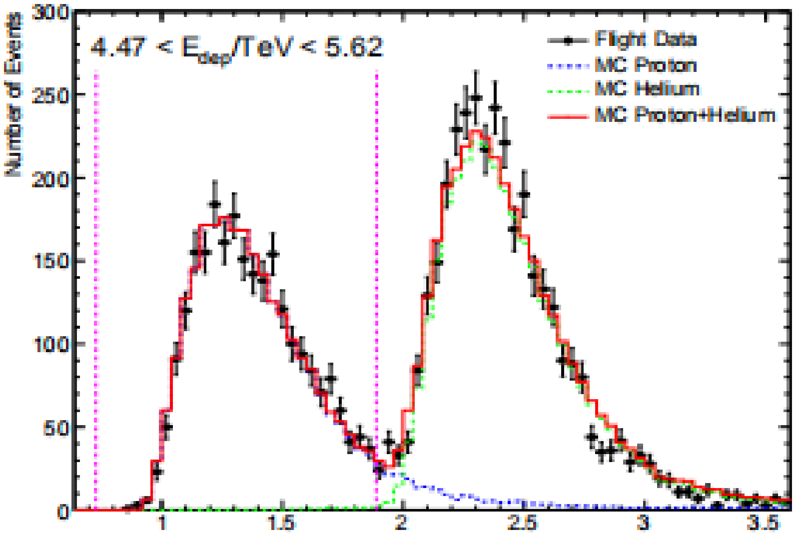


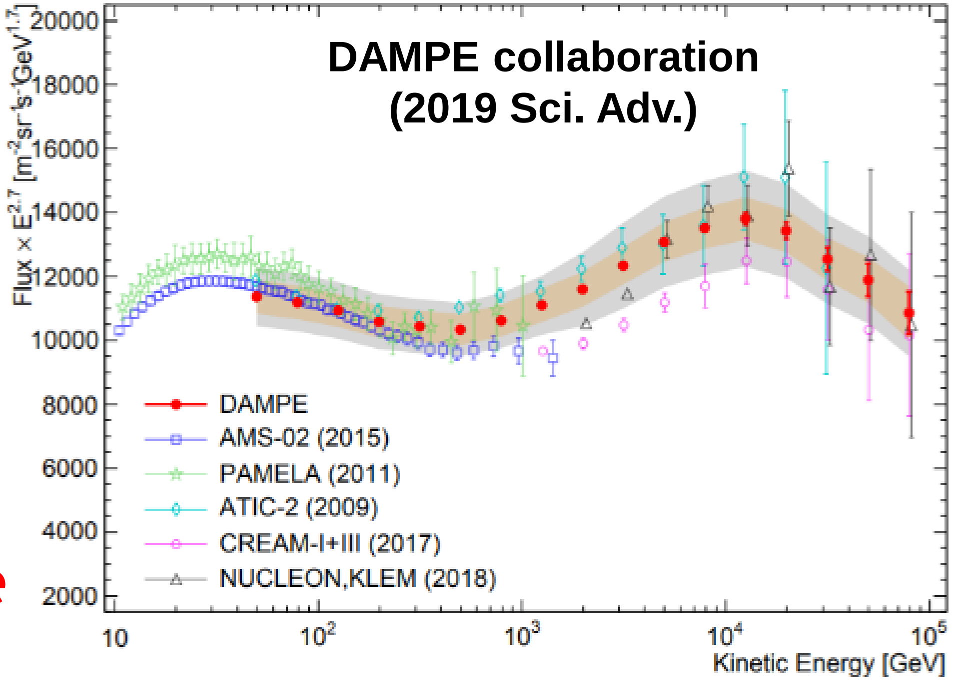
Yoon et al. (2017 ApJ) **Atkin et al. (2018 JETP Lett.)**

Some hints for a spectral softening at ~10TV. Just the statistical uncertainties of the CREAM and NUCLEON data are shown in the plots.

Proton spectrum by DAMPE

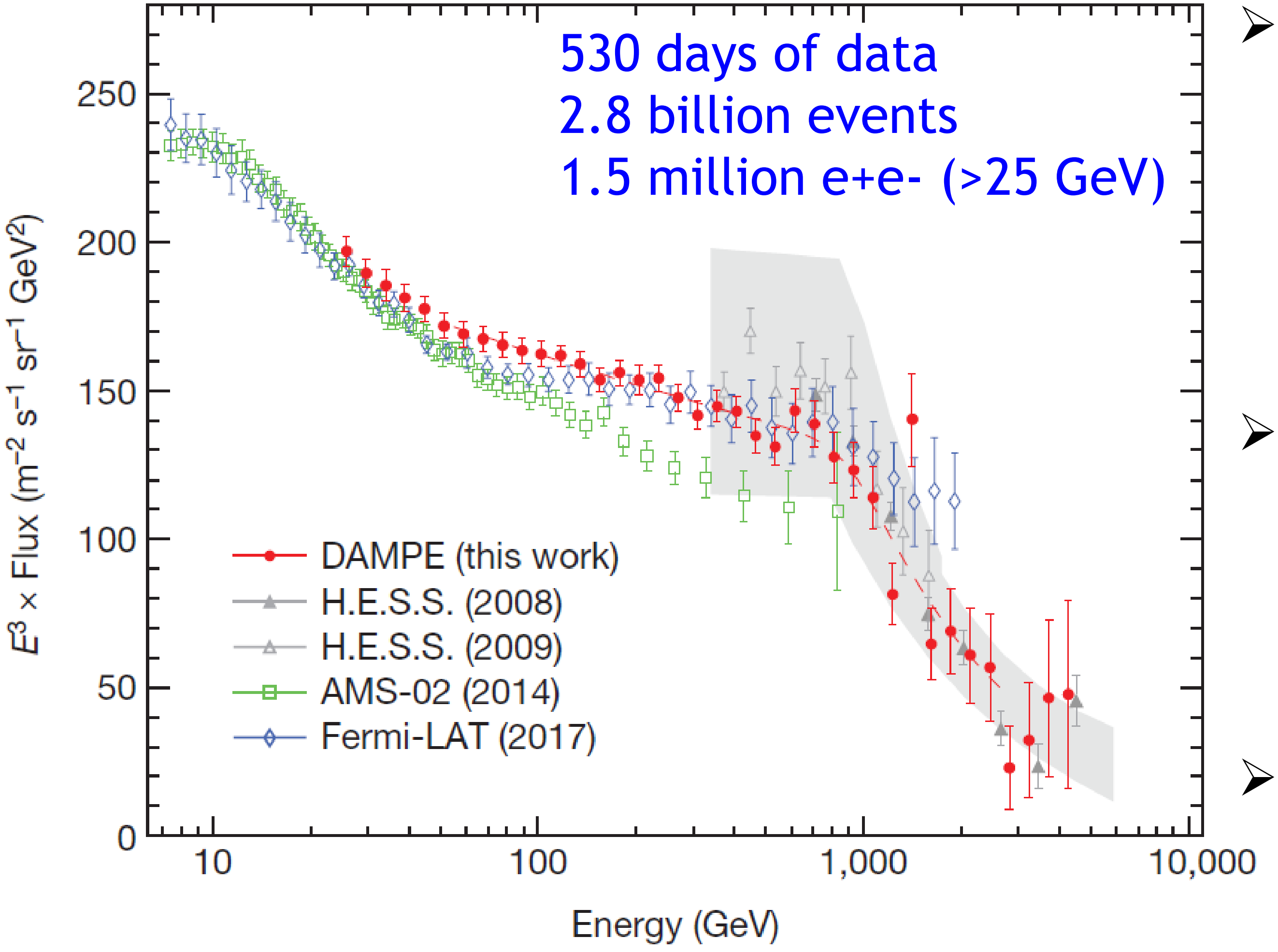






- Confirms the hundreds GeV hardening
- Detecting a softening at ~13 TeV with high significance, suggesting a new spectral structure before the so-called knee

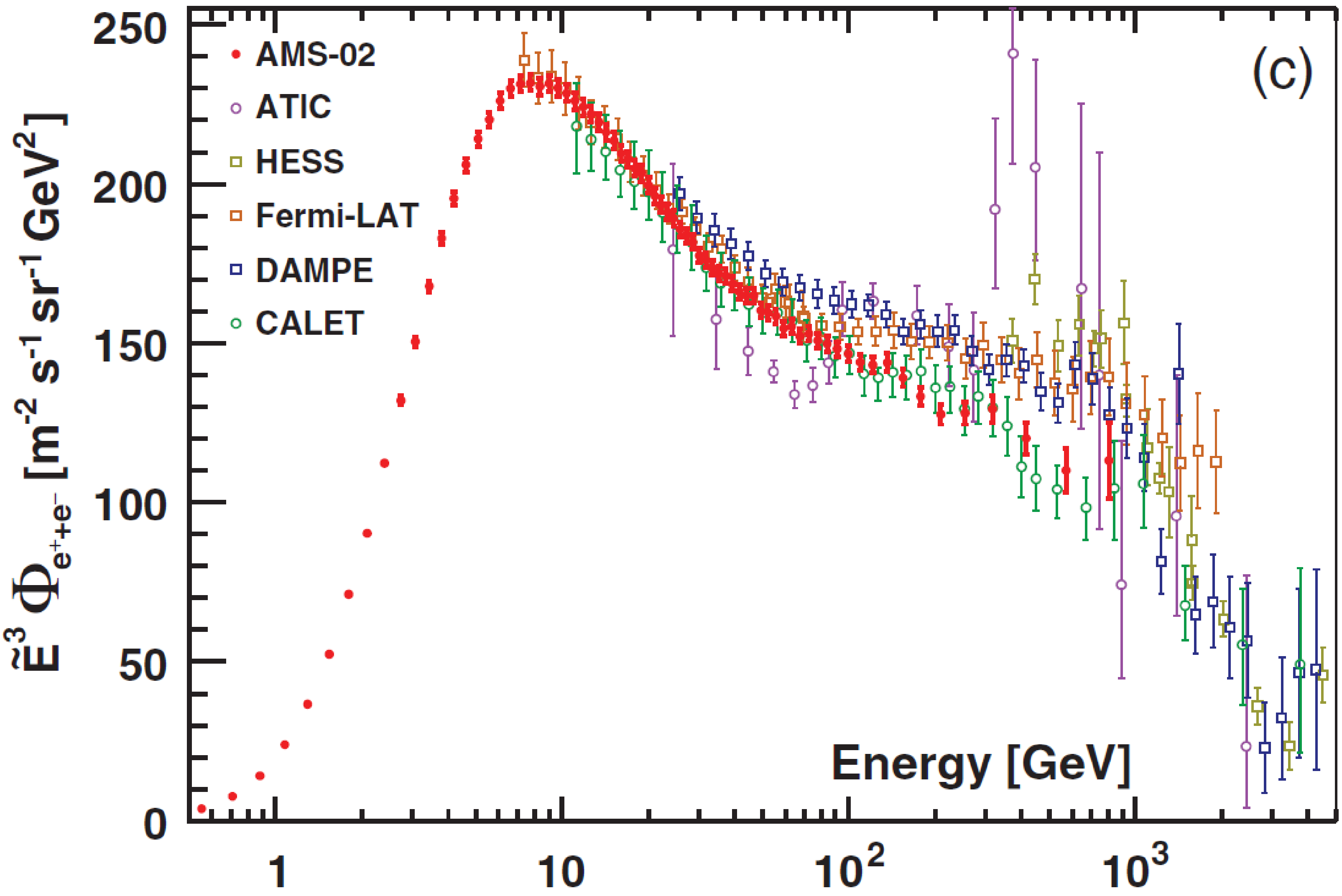
DAMPE $e^+ + e^-$ spectrum


530 days of data
2.8 billion events
1.5 million e+e- (>25 GeV)

- Three different PID methods give very consistent results on event-by-event level
- Direct detection of a spectral break at ~1 TeV with 6.6σ confidence level
- Analysis with new data is on-going

(DAMPE collaboration. 2017, Nature 552, 63-66)

AMS-02 and CALET $e^+ + e^-$ spectrum



(CALET collaboration. 2018 PRL; AMS-02 collaboration 2019 PRL)

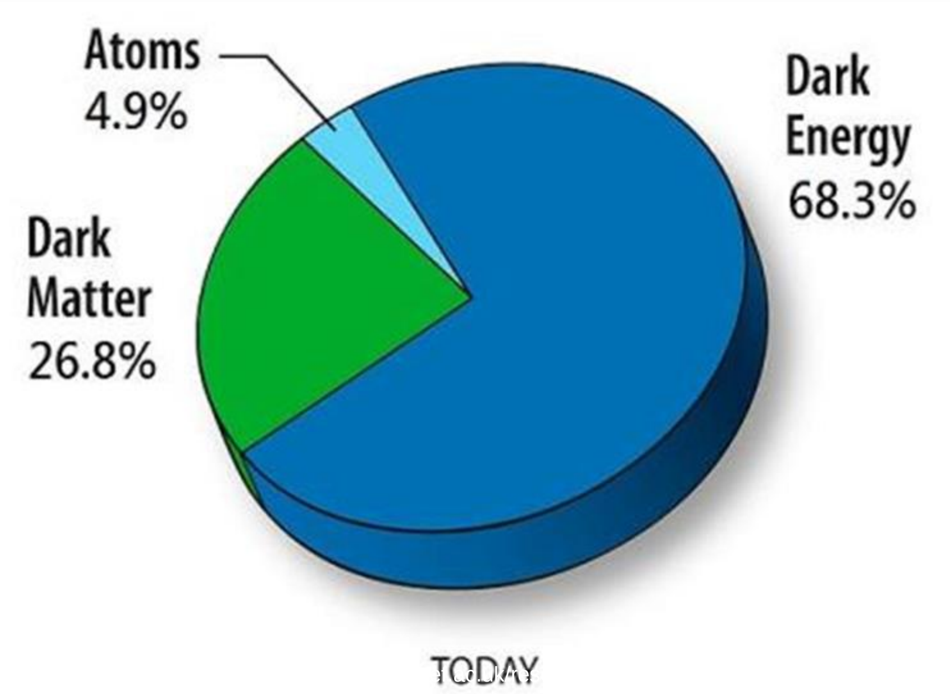
Summary: cosmic ray measurements by DAMPE

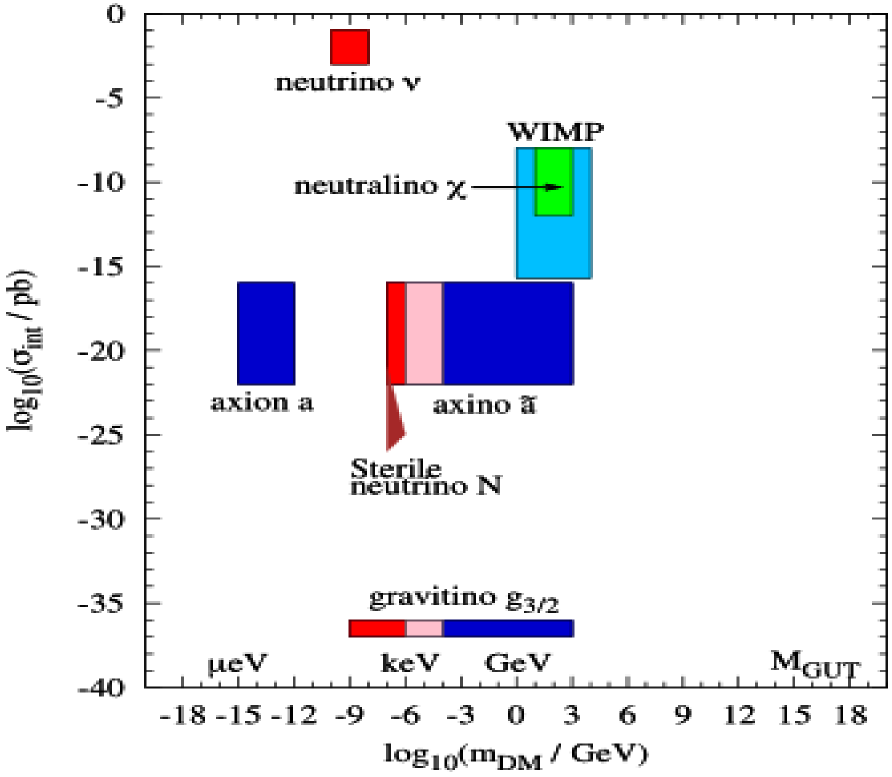
- A TeV spectral break in the e^-+e^+ spectrum has been directly measured
- The spectral hardening of protons at about 400 GeV has been confirmed
- A new spectral structure at ~10TeV displays in the proton data
- More results will be published soon

Outline

- **Direct detection of cosmic rays by DAMPE**
- **Indirect detection of dark matter particles**
- **Signature of gravitational wave radiation in the short GRB afterglow?**
- **Kilonovae associated with GRB 050709, GRB 060614 and GRB 070809**

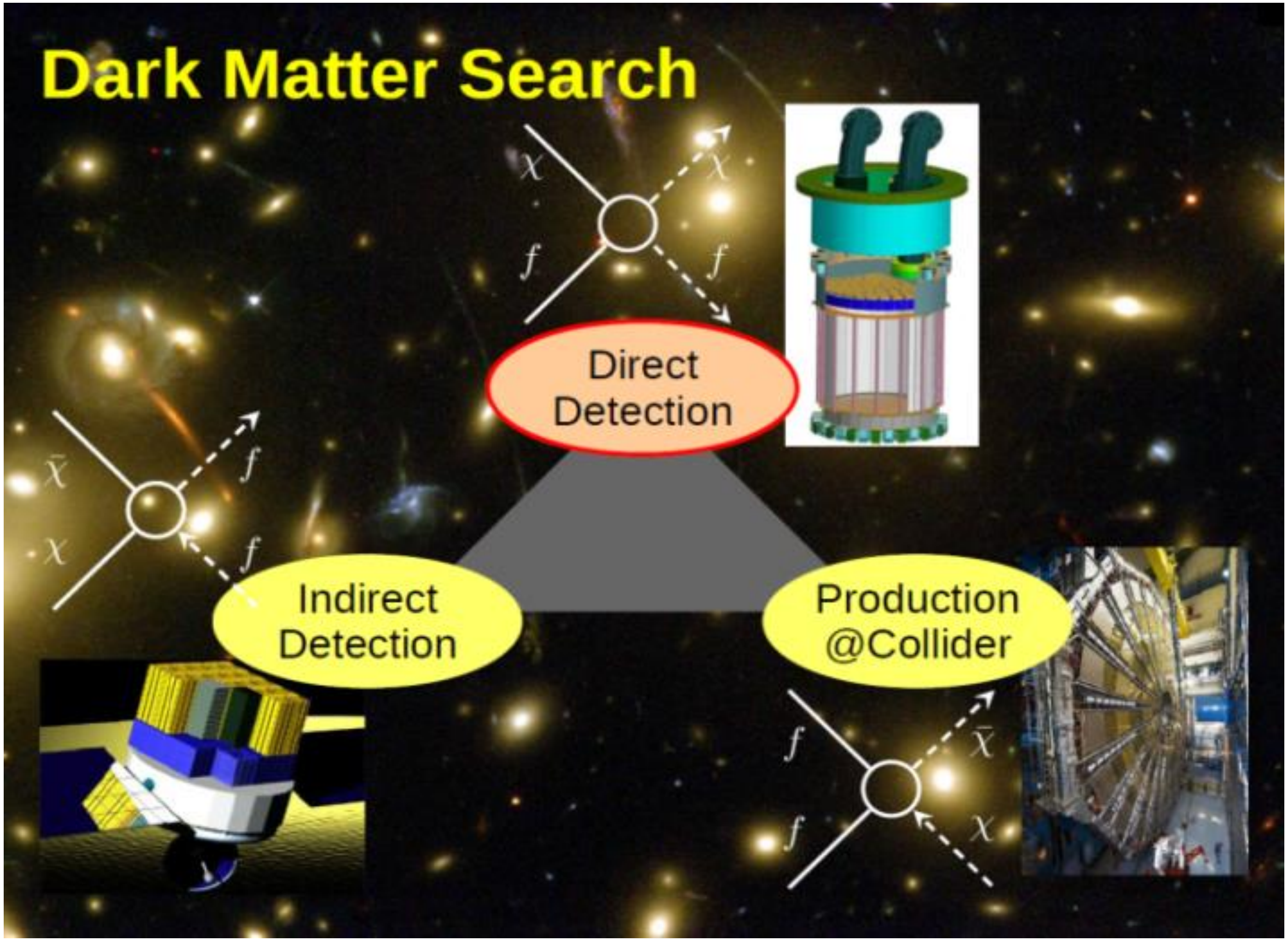
Dark matter particle candidates





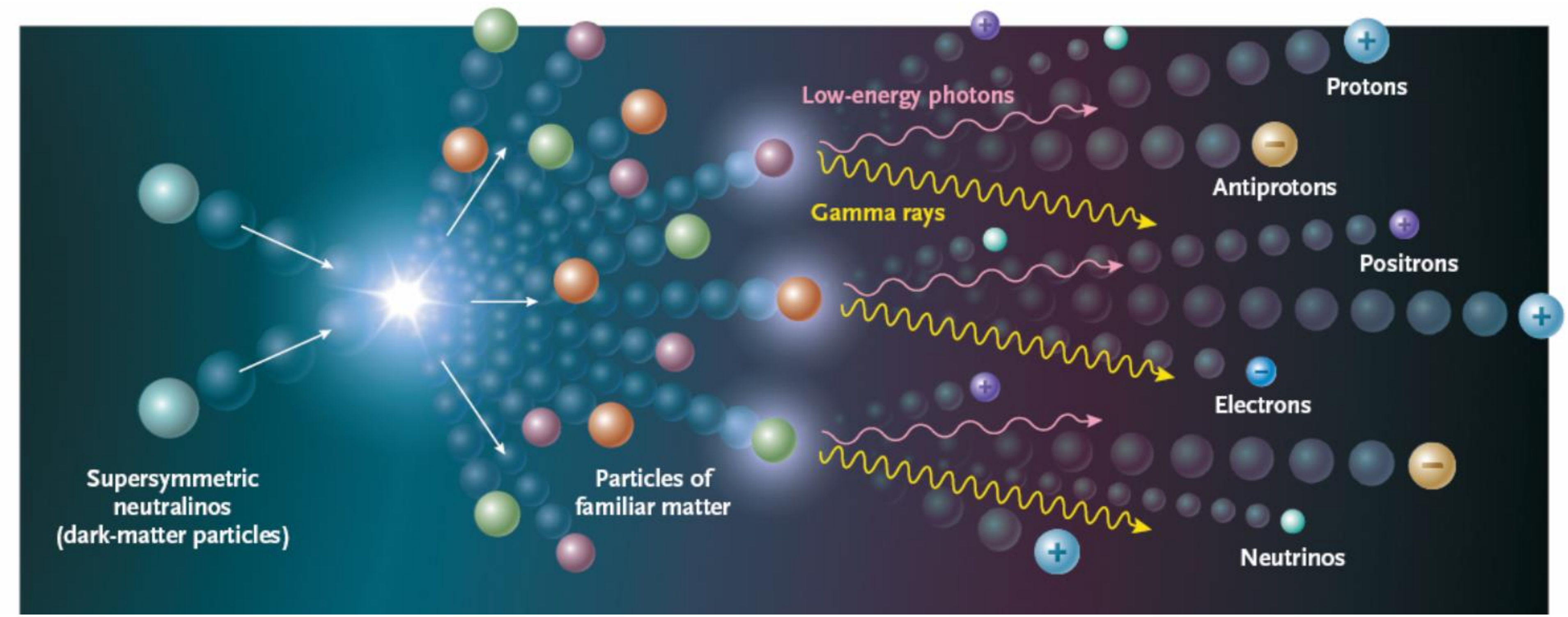
Some widely-discussed DM particle candidates: WIMPs (~100 GeV), axion (ALPs) and sterile neutrinos.

Dark matter: detection methods



Collider searches: DM mass
Direct detection: DM mass and interaction cross section with nucleus
Indirect detection: DM mass and the annihilation cross section or lifetime

Dark matter indirect detection

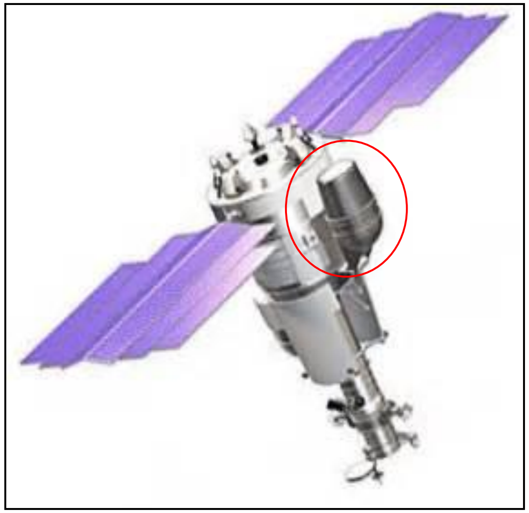


Dark matter particles may annihilate and then generate pairs of particles and anti-particles (gamma-rays, electrons/positrons, proton and antiprotons), see e.g., Bergström & Snellman (1988).

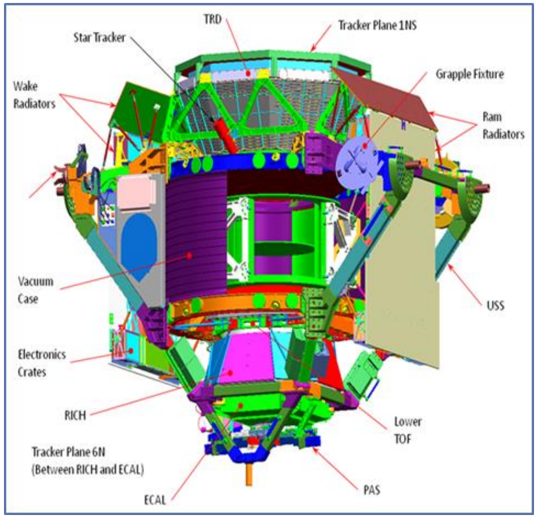
The goal of DM indirect detection: Identifying such products

Onging experiments in space

Magnetic spectrometer experiments

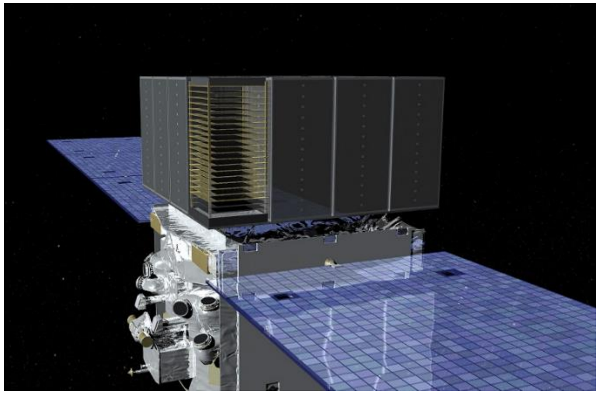


PAMELA

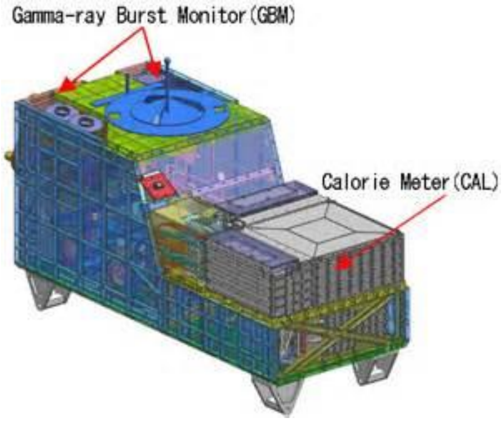


AMS-02

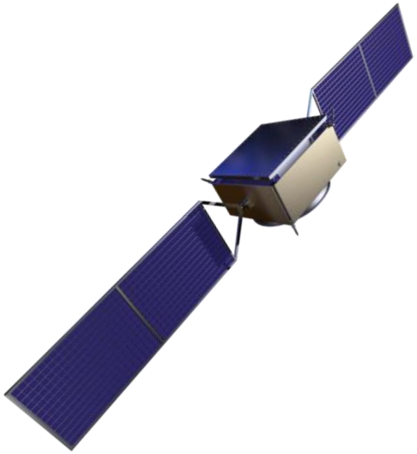
Calorimeter experiments



Fermi-LAT



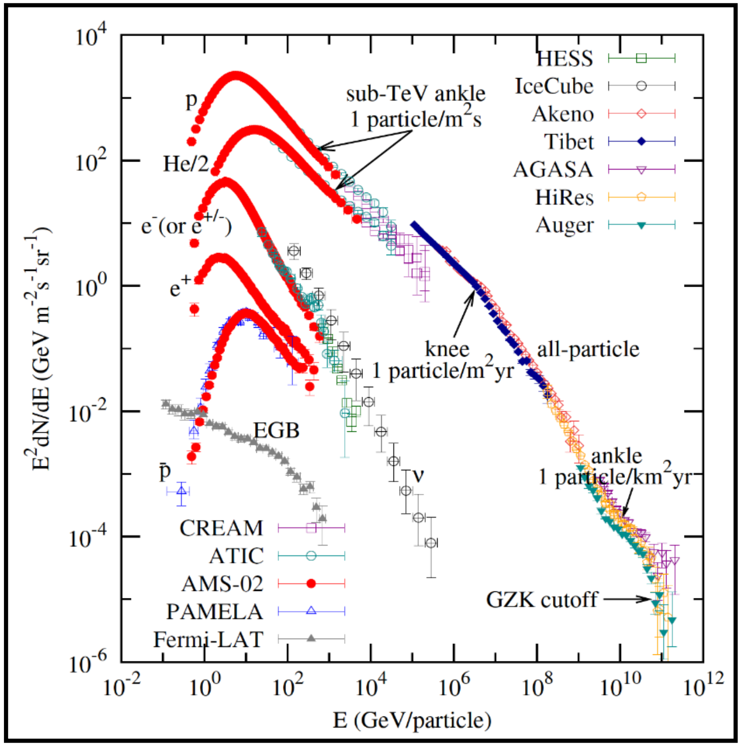
CALET



DAMPE

DM indirect Detection: objects

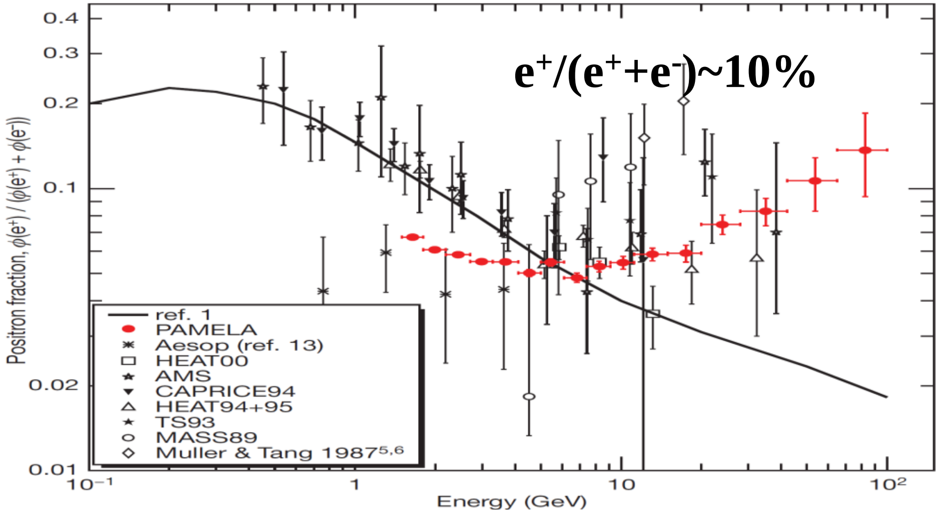
Measurement technique	objects	Notes
Magnetic spectrometer	positron antiproton electron	particle/antiparticle separation, complex detector/expensive, small acceptance, rigidities ≤ 1 TV
Calorimeter	electron+positron γ-ray	simpler detector/cheaper, much larger acceptance and wider energy range



DM signal in anti-particles: low background

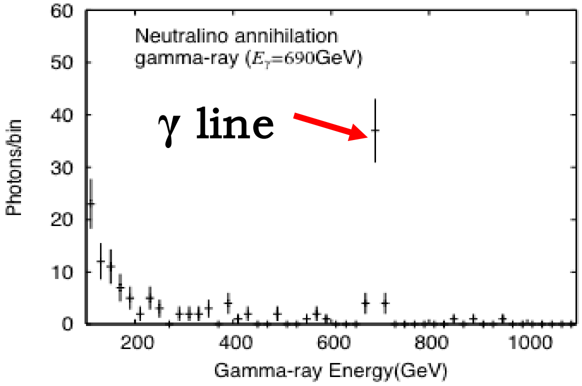
γ-rays: directly trace the source

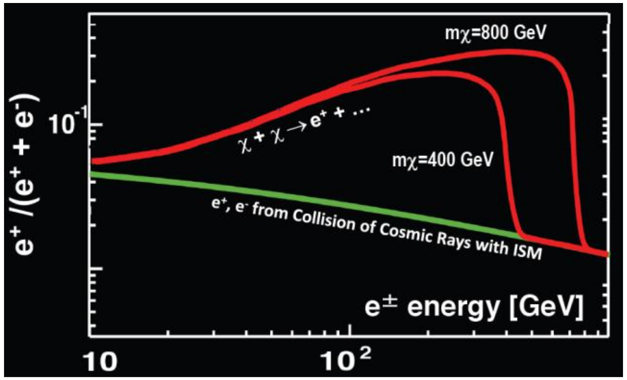
e^++e^-: high statistics

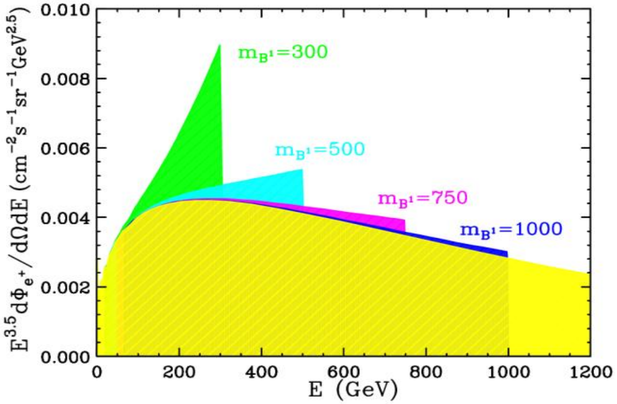


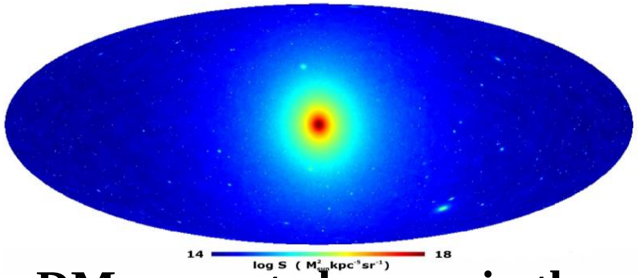
$e^+/(e^++e^-)$~10%

DM indirect detection: attractive signals

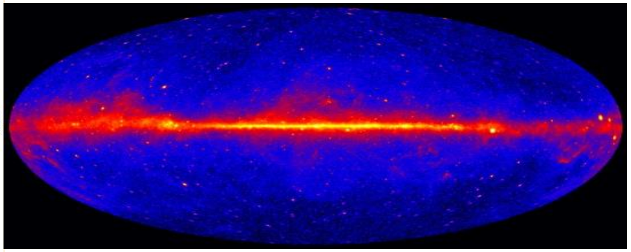




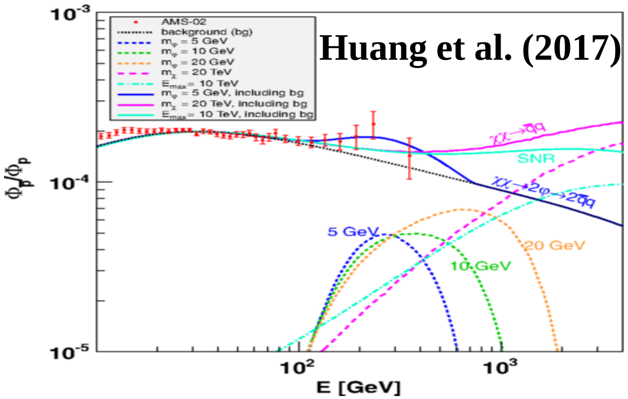




DM generated γ-rays in the Galaxy (Predicted)

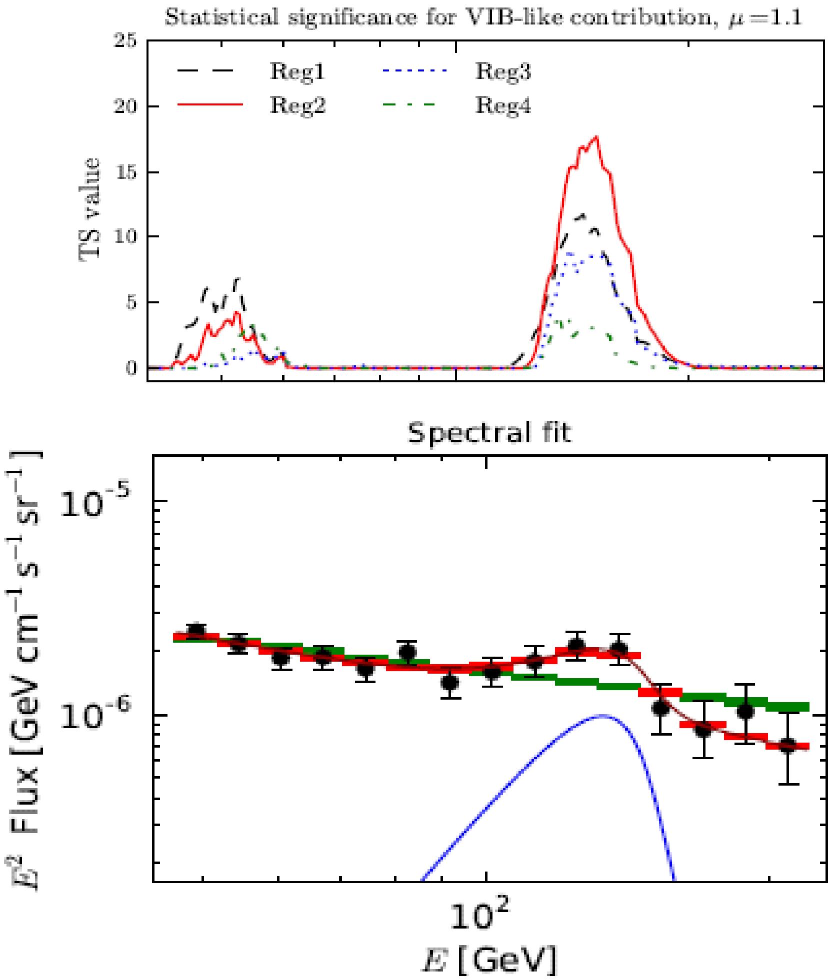


Background: disk-like (observed)

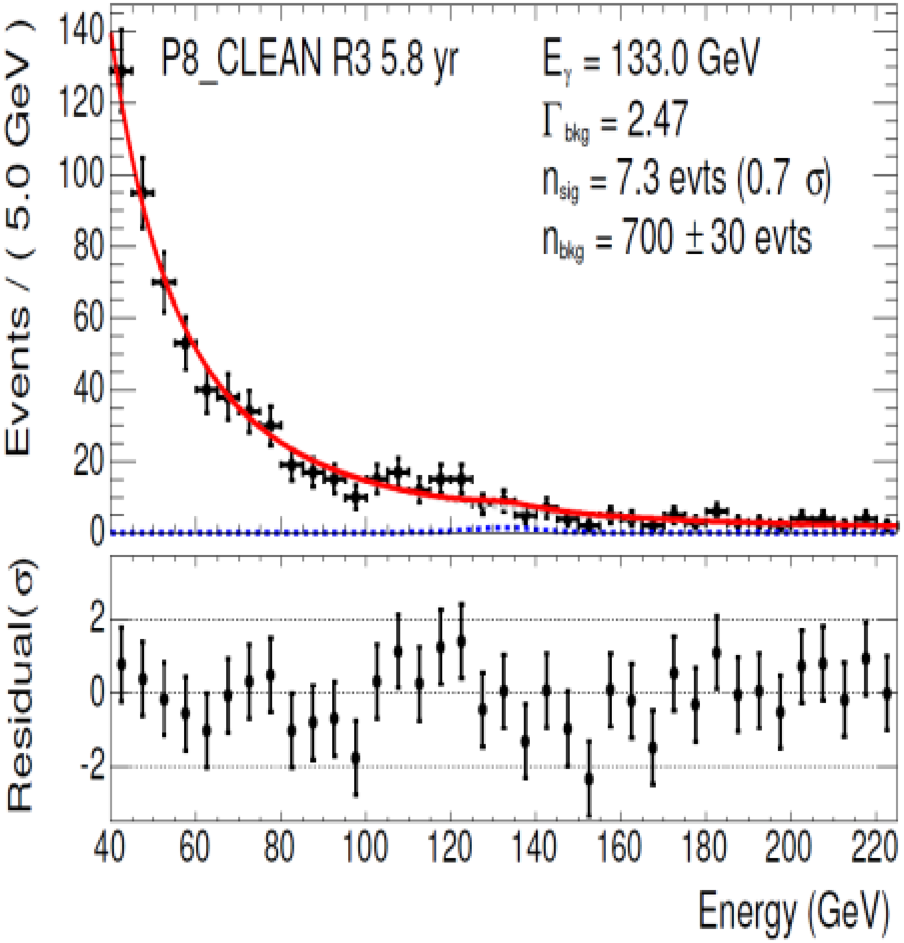

Huang et al. (2017)

- **GeV-TeV γ-ray line**
- **Continual γ-ray emission spatially correlated with the DM distribution**
- **Sharp cutoff in positron spectrum, excess in antiproton spectrum**
- **Electrons+positrons with "unusual" spectrum**

DM γ-ray signal: ~130 GeV line?

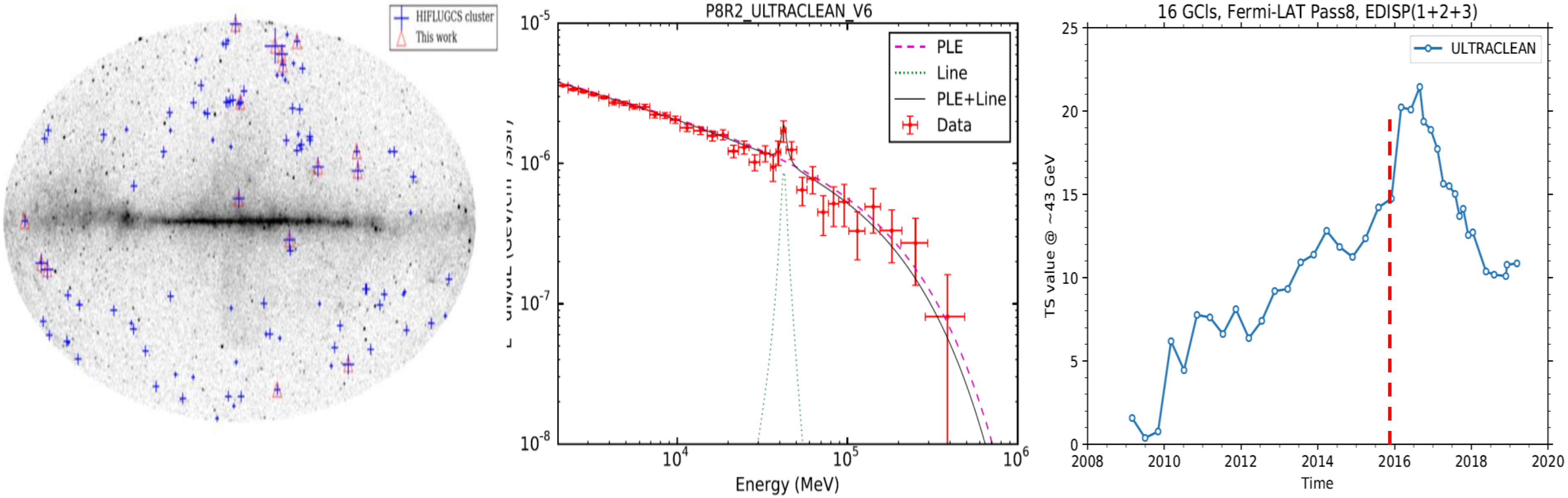


Bringmann, Huang et al. (arXiv:1203.1312)



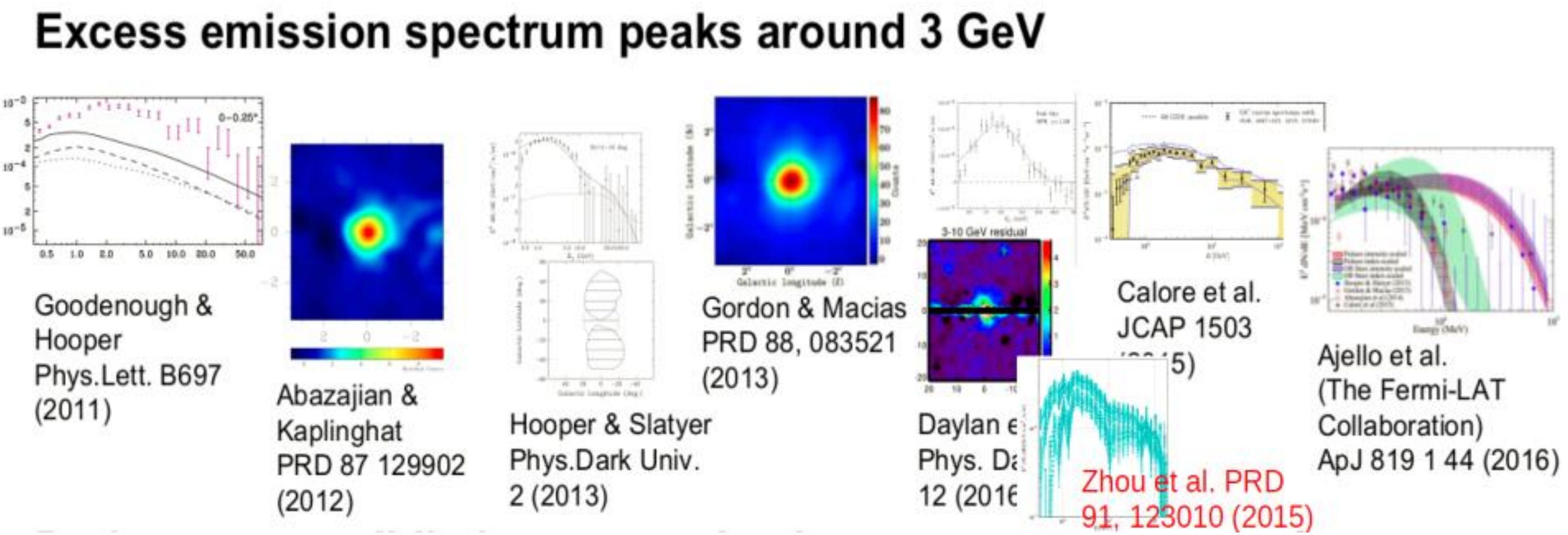
Fermi-LAT collaboration (arXiv:1506.00013)

DM γ-ray signal: ~43 GeV line?



Liang, Y. F. et al. (2016 PRD): analysis of 16 nearby galaxy clusters

DM γ-ray signal: galactic GeV excess?



Excess emission spectrum peaks around 3 GeV

Goodenough & Hooper
Phys.Lett. B697
(2011)

Abazajian & Kaplinghat
PRD 87 129902
(2012)

Hooper & Slatyer
Phys.Dark Univ.
2 (2013)

Gordon & Macias
PRD 88, 083521
(2013)

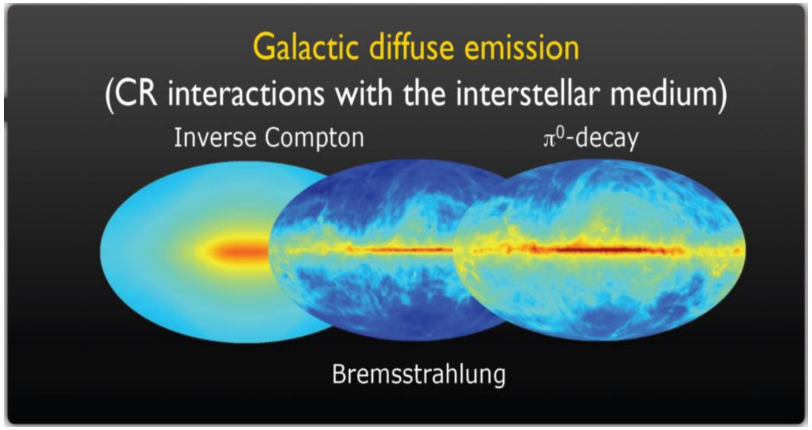
Daylan e
Phys. Da
12 (2016

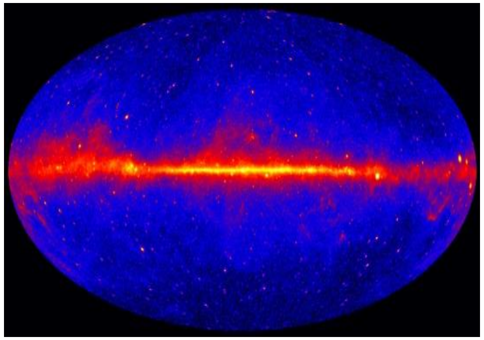
Calore et al.
JCAP 1503
5)

Ajello et al.
(The Fermi-LAT Collaboration)
ApJ 819 1 44 (2016)

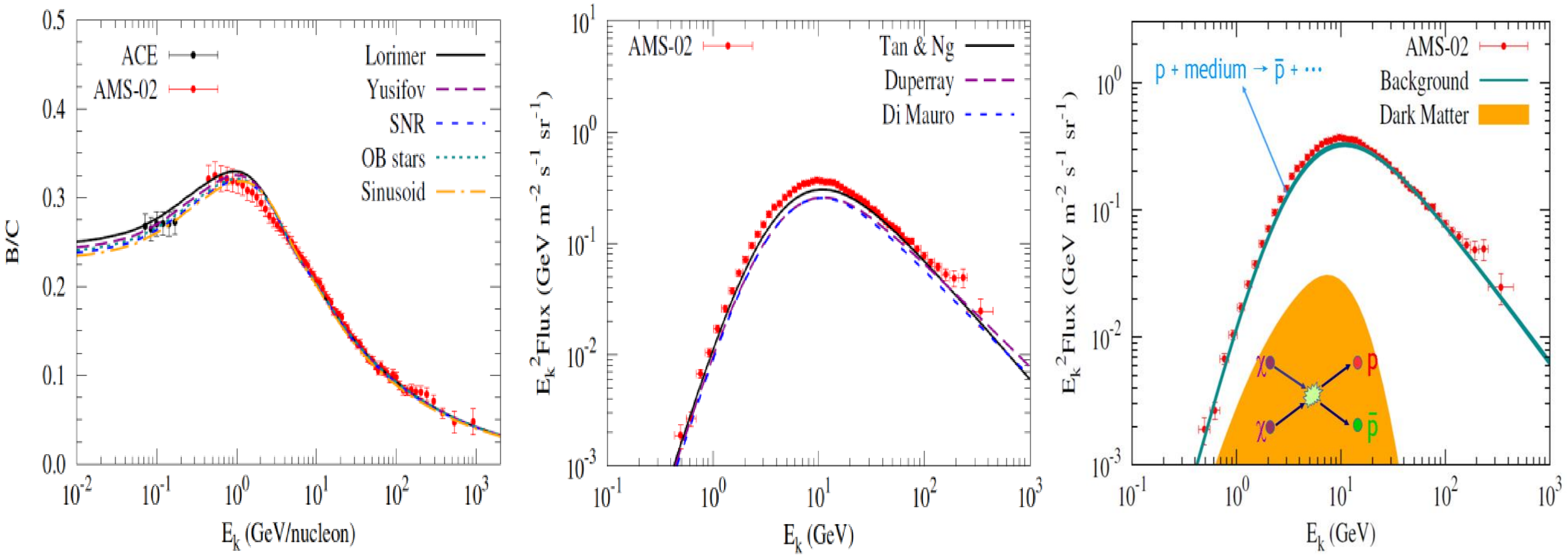
Zhou et al. PRD 91, 123010 (2015)

The Galactic GeV excess is consistent with the dark matter model both spatially and spectrally. But the GC is very complicated in γ-rays!





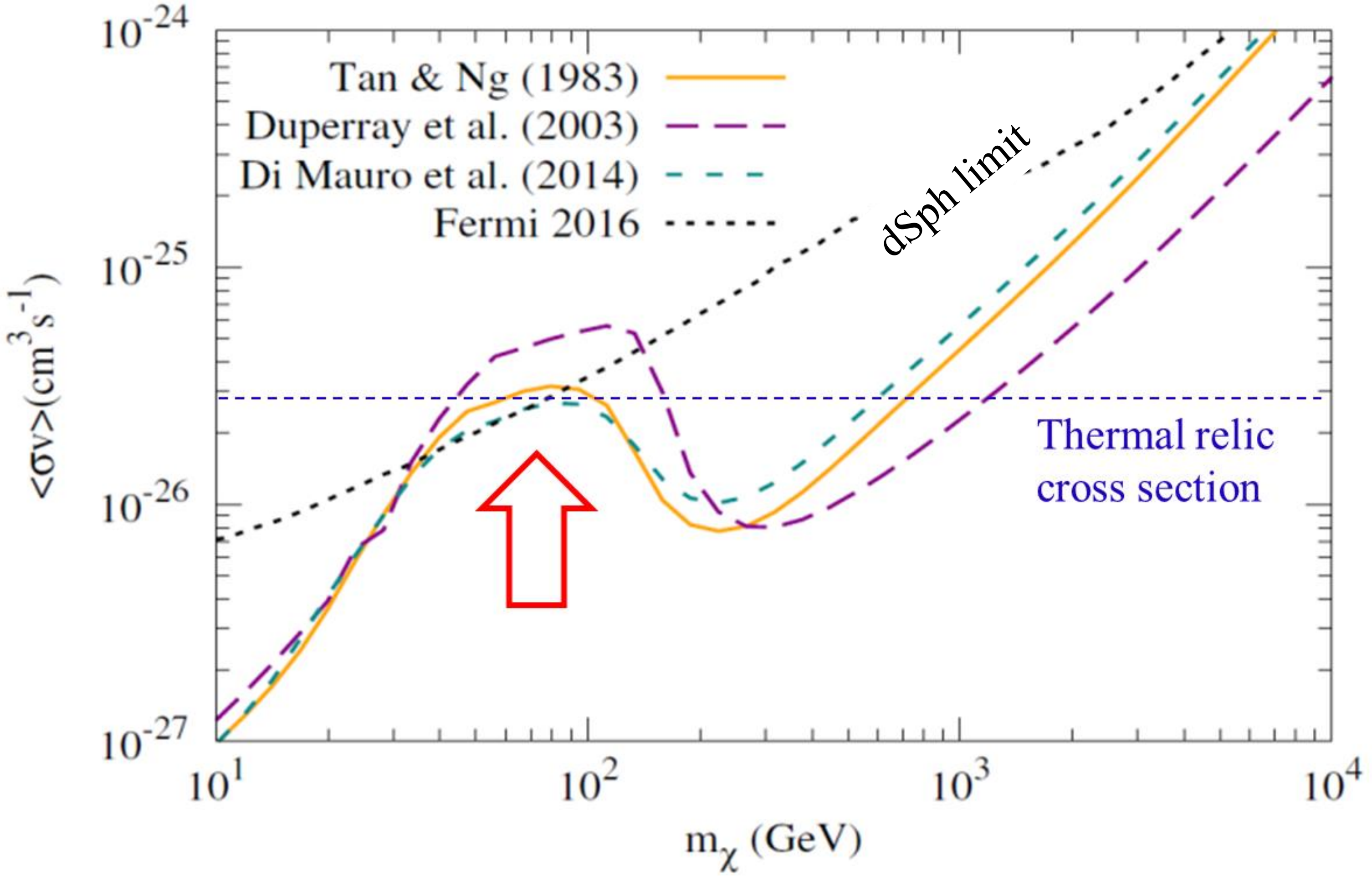
DM signal in AMS-02 antiprotons?



Cui, Yuan, Tsai & Fan (2017 PRL):

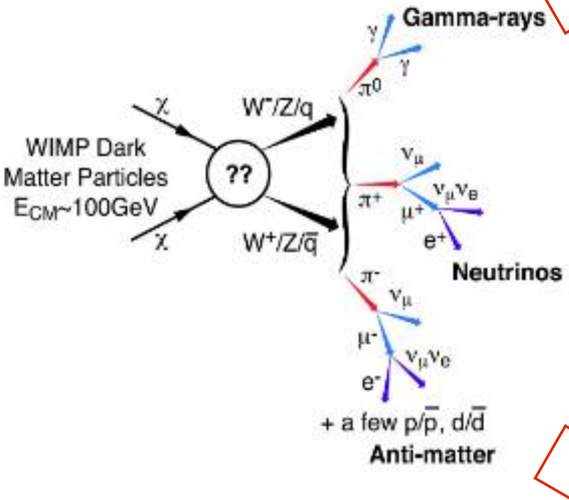
- Parameters of the propagation, source injection, and solar modulation of cosmic rays are inferred from the modeling of recent B/C ratio and proton spectrum measurements
- The antiproton data at GeV energies can not be well reproduced and the inclusion of a dark matter component significantly improves the fit

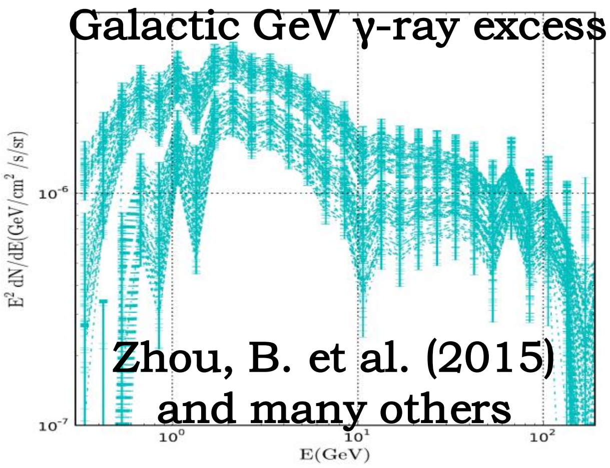
DM signal in AMS-02 antiprotons?



**Cui et al. (2017 PRL; see also Cuoco et al. 2017 PRL;
Cui et al. 2018 JCAP; Cuoco et al. 2019 PRD; Cholis, Linden & Hooper 2019 PRD):
Dark matter with a rest mass of ~50-100 GeV?**

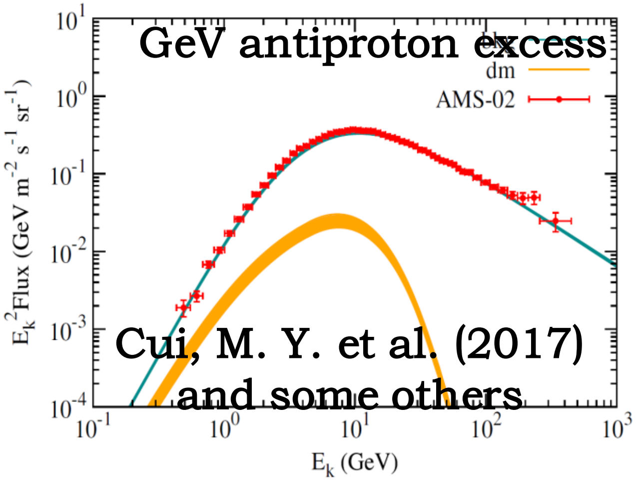
WIMP: Multi-messenger signals?





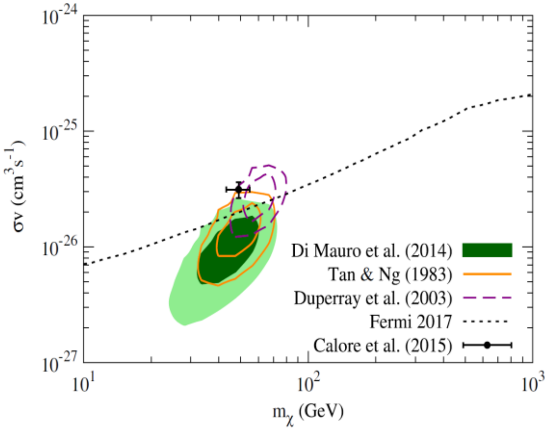
Galactic GeV γ-ray excess

Zhou, B. et al. (2015) and many others



GeV antiproton excess

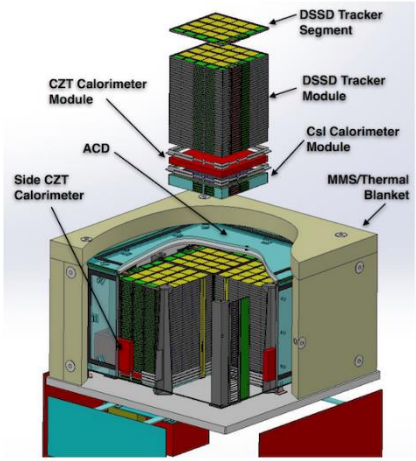
Cui, M. Y. et al. (2017) and some others



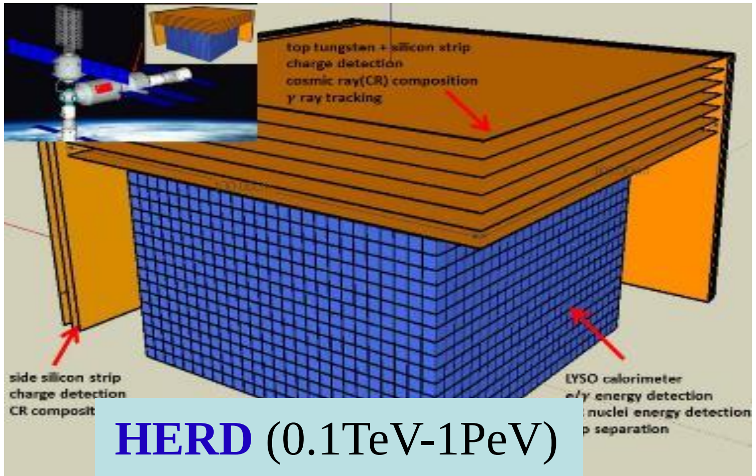
Cui et al. (2017): annihilation of ~50-100 GeV DM particles into b\bar{b}!

The future

Proposed space telescopes:



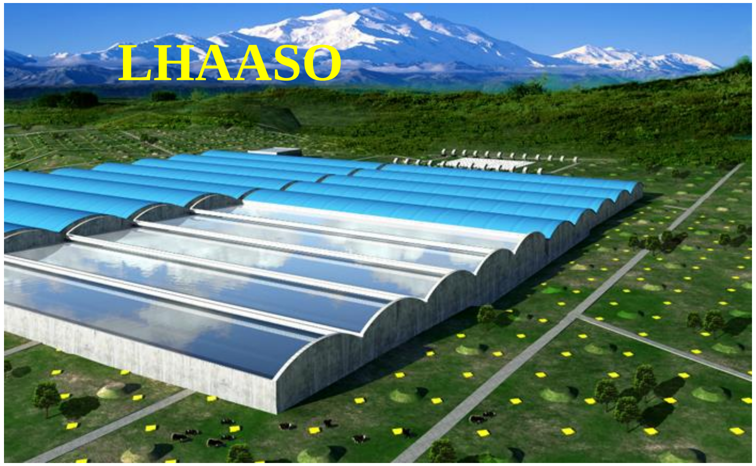
AMEGO
(MeV-GeV;
~1000 cm^2)



HERD (0.1TeV-1PeV)

Ground based telescopes (under construction):

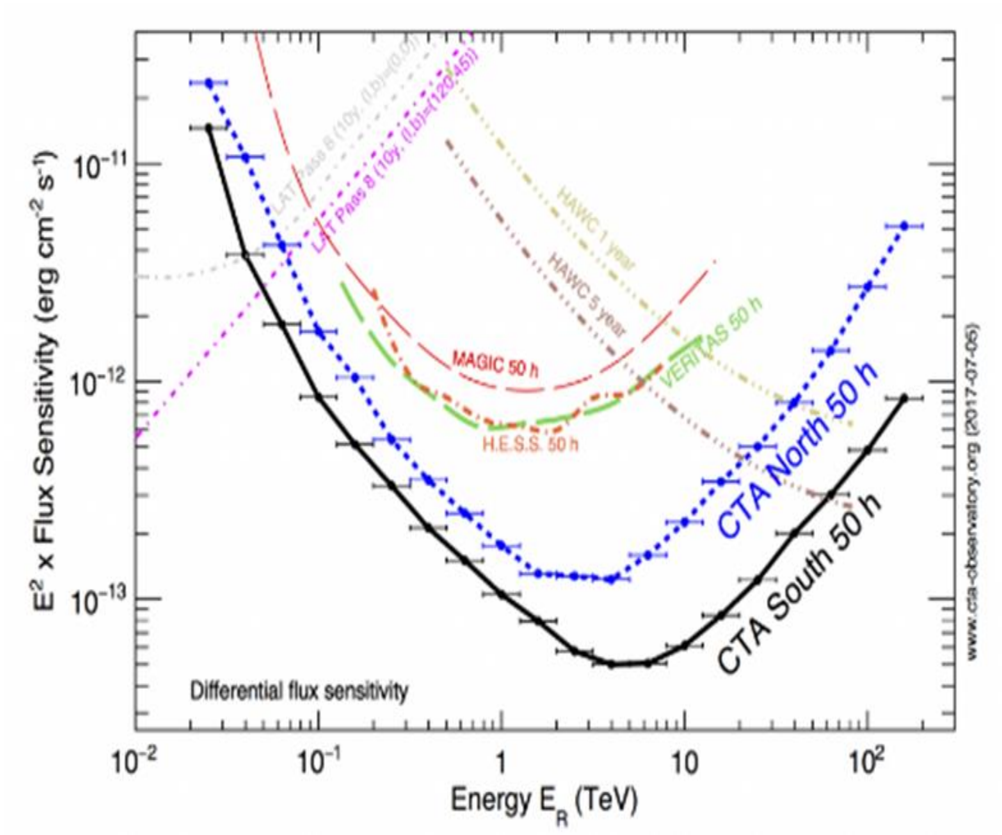
CTA

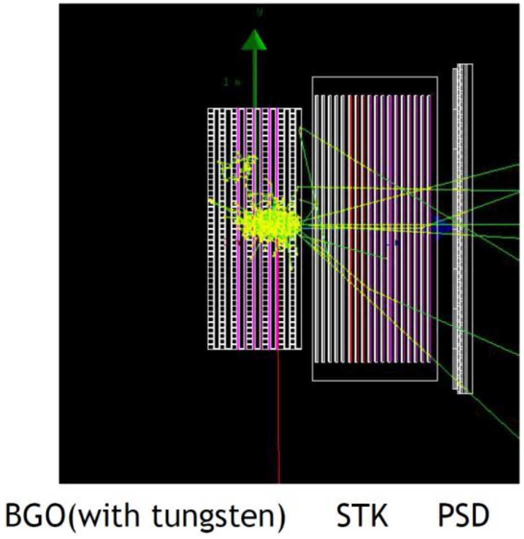


LHAASO

The future

Competition with the ground-based γ-ray telescopes: a <100 GeV "window" for space telescopes?





- Energy range: 0.2 GeV - 20 TeV
- Geometry factor: > 3 m²sr
- Energy resolution: 1% @ 100 GeV
- Spatial resolution: 0.1° @ 100 GeV

Keep excellent performance of energy resolution and e/p separation capabilities of DAMPE, enhace substantially the gamma-ray potential

Very Large Area gamma-ray Space Telescope (VLAST): the second generation of DAMPE aiming to catch DM in gamma-rays

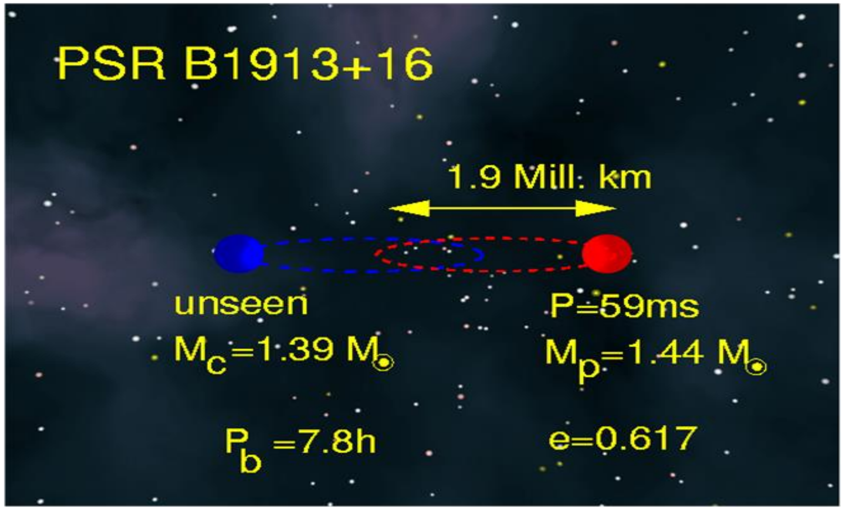
Summary: DM indirect detection

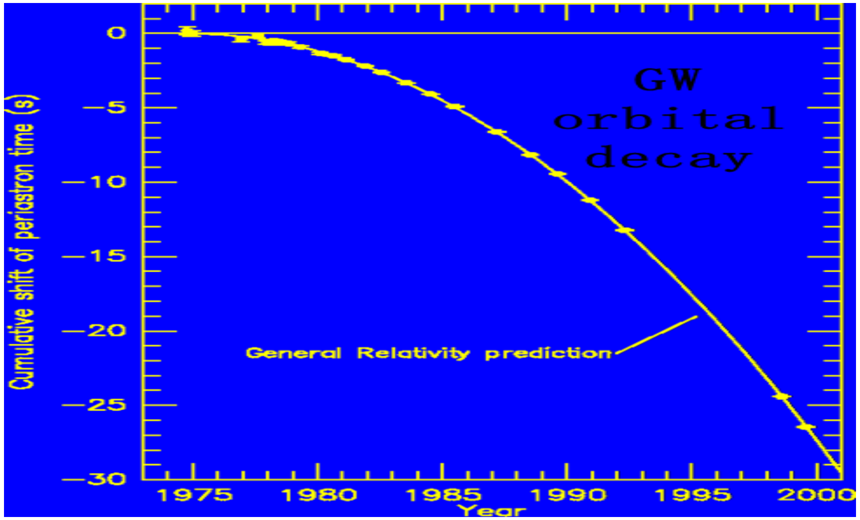
- There is no conclusive evidence yet
- Some hints in cosmic rays and γ-rays (in particular the Galactic GeV excess and possible antiproton excess)
- For sub-TeV dark matter, a space mission more powerful than Fermi-LAT may be needed and we are proposing VLAST

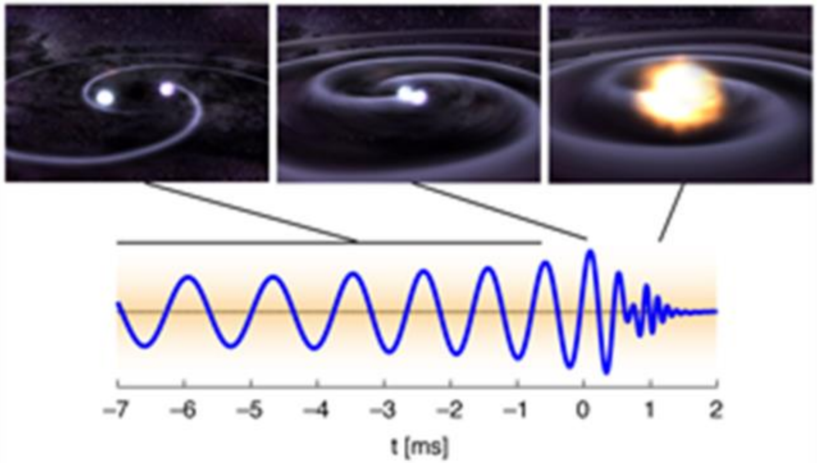
Outline

- **Direct detection of cosmic rays by DAMPE**
- **Indirect detection of dark matter particles**
- **Signature of gravitational wave radiation in the short GRB afterglow?**
- **Kilonovae associated with GRB 050709, GRB 060614 and GRB 070809**

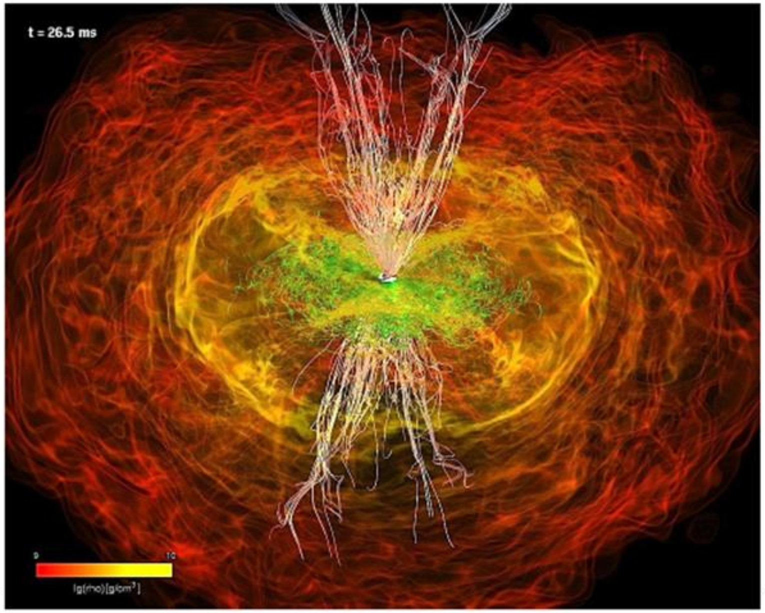
Neutron star mergers and the “prompt” signals







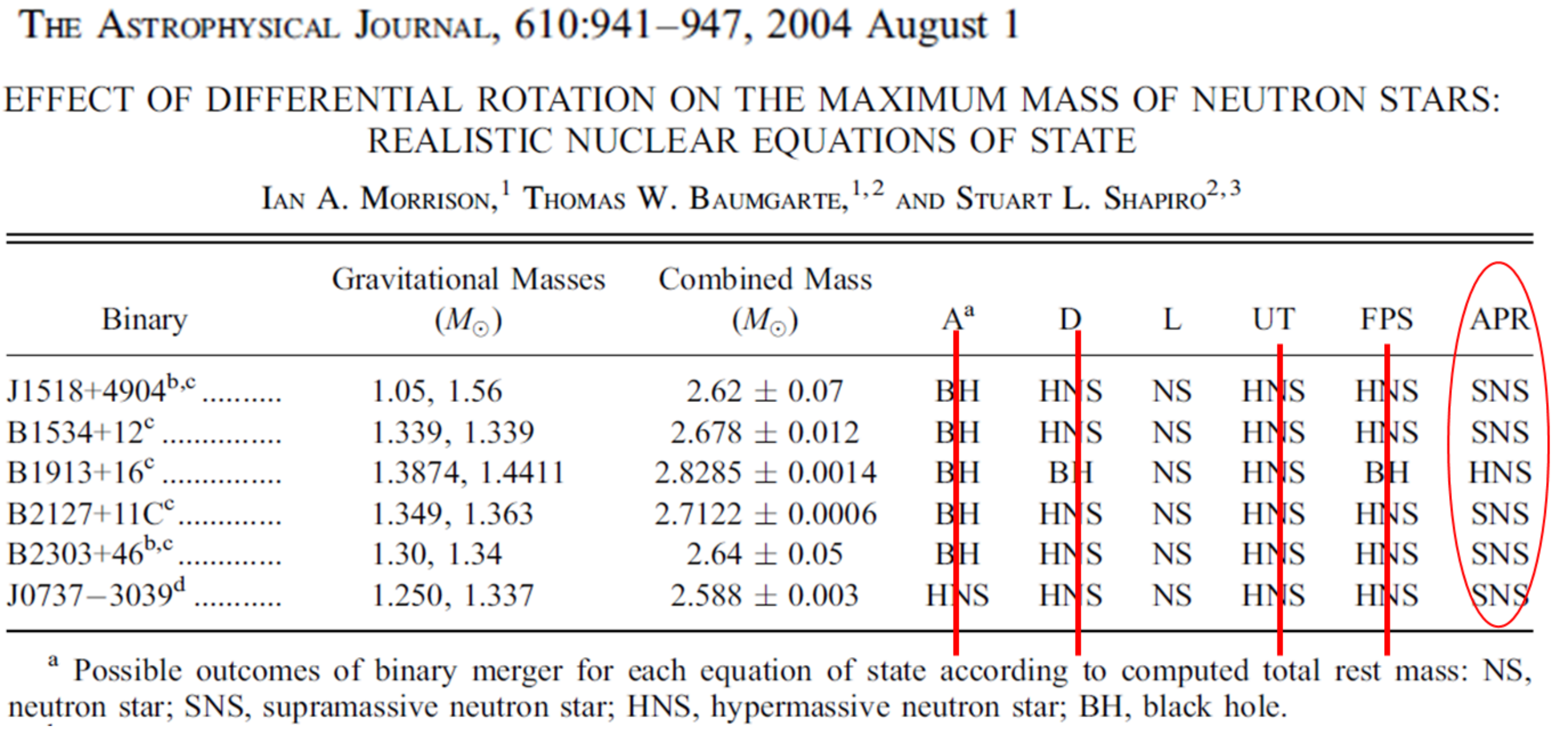
(Generate strong gravitational wave event!)



(Produce short Gamma-ray Bursts!
Eichler et al. 1989 Nature;
Abbott et al. 2017 PRL;
Goldstein et al. 2017 ApJL)

Supramassive NSs: plausible remnants of mergers of Galactic NS-NS binaries

- M_{TOV}、 M_{tot} and mass ejection、 angular momentum



THE ASTROPHYSICAL JOURNAL, 610:941–947, 2004 August 1

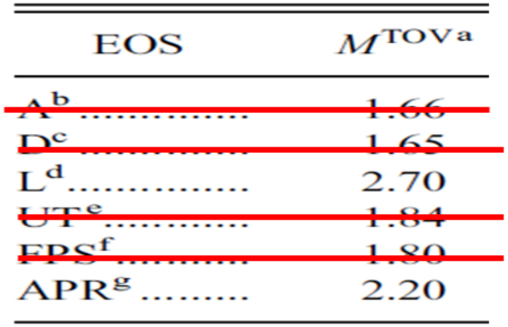
EFFECT OF DIFFERENTIAL ROTATION ON THE MAXIMUM MASS OF NEUTRON STARS: REALISTIC NUCLEAR EQUATIONS OF STATE

IAN A. MORRISON,[1] THOMAS W. BAUMGARTE,[1,2] AND STUART L. SHAPIRO[2,3]

Binary	Gravitational Masses ($M_\odot$)	Combined Mass ($M_\odot$)	A[a]	D	L	UT	FPS	APR
J1518+4904[b,c]	1.05, 1.56	2.62 ± 0.07	BH	HNS	NS	HNS	HNS	SNS
B1534+12[c]	1.339, 1.339	2.678 ± 0.012	BH	HNS	NS	HNS	HNS	SNS
B1913+16[c]	1.3874, 1.4411	2.8285 ± 0.0014	BH	BH	NS	HNS	BH	HNS
B2127+11C[c]	1.349, 1.363	2.7122 ± 0.0006	BH	HNS	NS	HNS	HNS	SNS
B2303+46[b,c]	1.30, 1.34	2.64 ± 0.05	BH	HNS	NS	HNS	HNS	SNS
J0737−3039[d]	1.250, 1.337	2.588 ± 0.003	HNS	HNS	NS	HNS	HNS	SNS

[a] Possible outcomes of binary merger for each equation of state according to computed total rest mass: NS, neutron star; SNS, supramassive neutron star; HNS, hypermassive neutron star; BH, black hole.

Mass of PSR J0740+6620:
2.14± 0.1 $M_\odot$（**2019**）



EOS	M^{TOV}[a]
~~A[b] ....~~	~~1.66~~
~~D[c] ....~~	~~1.65~~
L[d]...............	2.70
~~UT[e] ....~~	~~1.84~~
~~FPS[f] ....~~	~~1.80~~
APR[g]	2.20

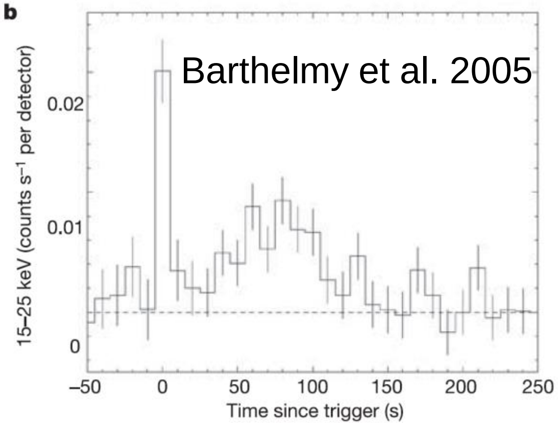
Supramassive NS: Possible evidence?

Chin. J. Astron. Astrophys. Vol. 6 (2006), No. 5, 513–516
(*http://www.chjaa.org*)

LETTERS

Short-living Supermassive Magnetar Model for Flares Following Short GRBs *

Wei-Hong Gao[1] and Yi-Zhong Fan[2,3,4]



Barthelmy et al. 2005

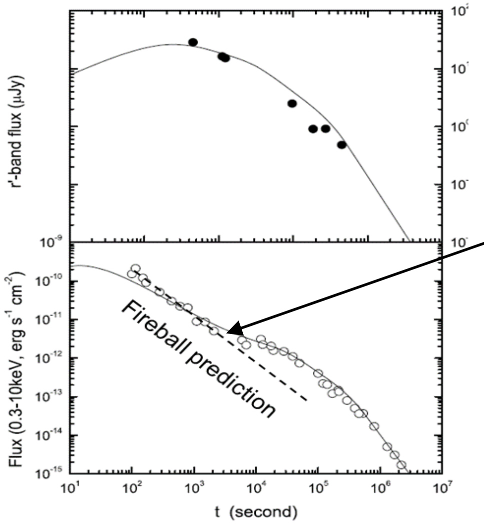
Extended X-ray emission or flares: The prompt energy dissipation of the magnetar wind?

See Metzger et al. (2008) and Zhang (2013) for further investigation

Mon. Not. R. Astron. Soc. **372,** L19–L22 (2006) doi:10.1111/j.1745-3933.2006.00217.x

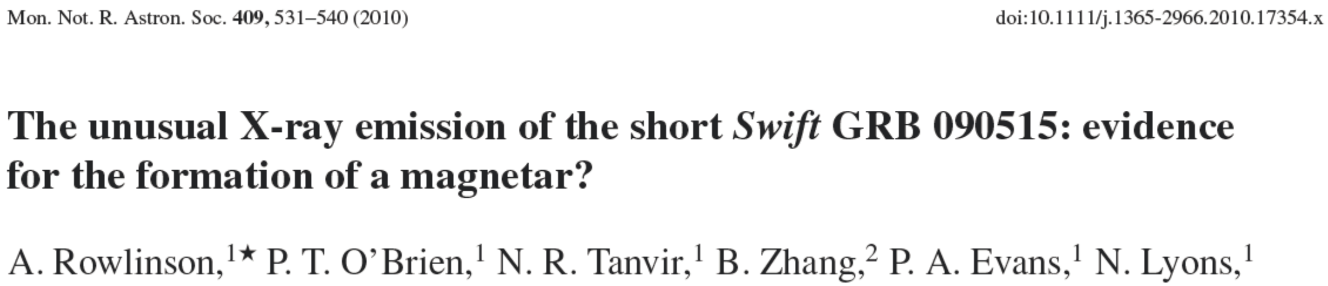
The X-ray afterglow flat segment in short GRB 051221A: Energy injection from a millisecond magnetar?

Yi-Zhong Fan[1,2,3★] and Dong Xu[4]



X-ray flat segment: Energy injection into the blast wave from a magnetar?

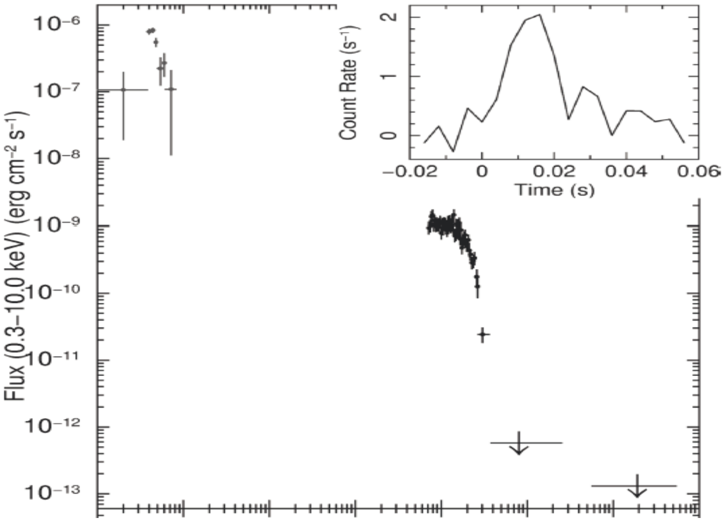
Supramassive NS: Possible evidence?



Mon. Not. R. Astron. Soc. **409,** 531–540 (2010) doi:10.1111/j.1365-2966.2010.17354.x

The unusual X-ray emission of the short *Swift* GRB 090515: evidence for the formation of a magnetar?

A. Rowlinson,[1★] P. T. O'Brien,[1] N. R. Tanvir,[1] B. Zhang,[2] P. A. Evans,[1] N. Lyons,[1]

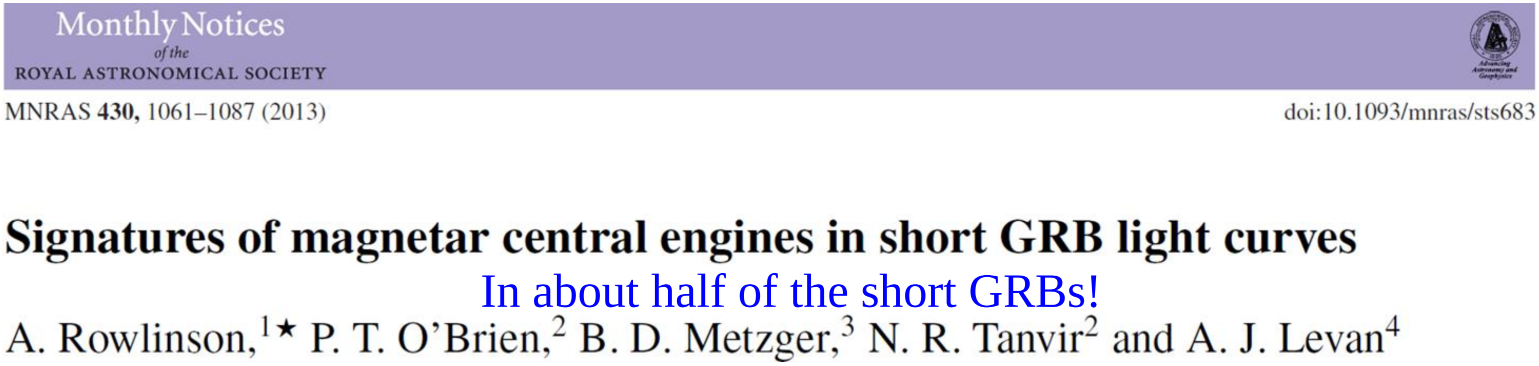


X-ray plateau followed by a sudden drop:

Prompt energy dissipation of the magnetar wind?

$$L_{\rm dip}(t_{\rm b}) \simeq 2.6 \times 10^{48}\ {\rm erg\ s^{-1}}\ B_{\perp,14}^{2} R_{{\rm s},6}^{6} \Omega_{4}^{4} (1 + t_{\rm b}/T_{\rm o})^{-2}$$

The termination of the X-ray emission because of the collapse of magnetar?



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

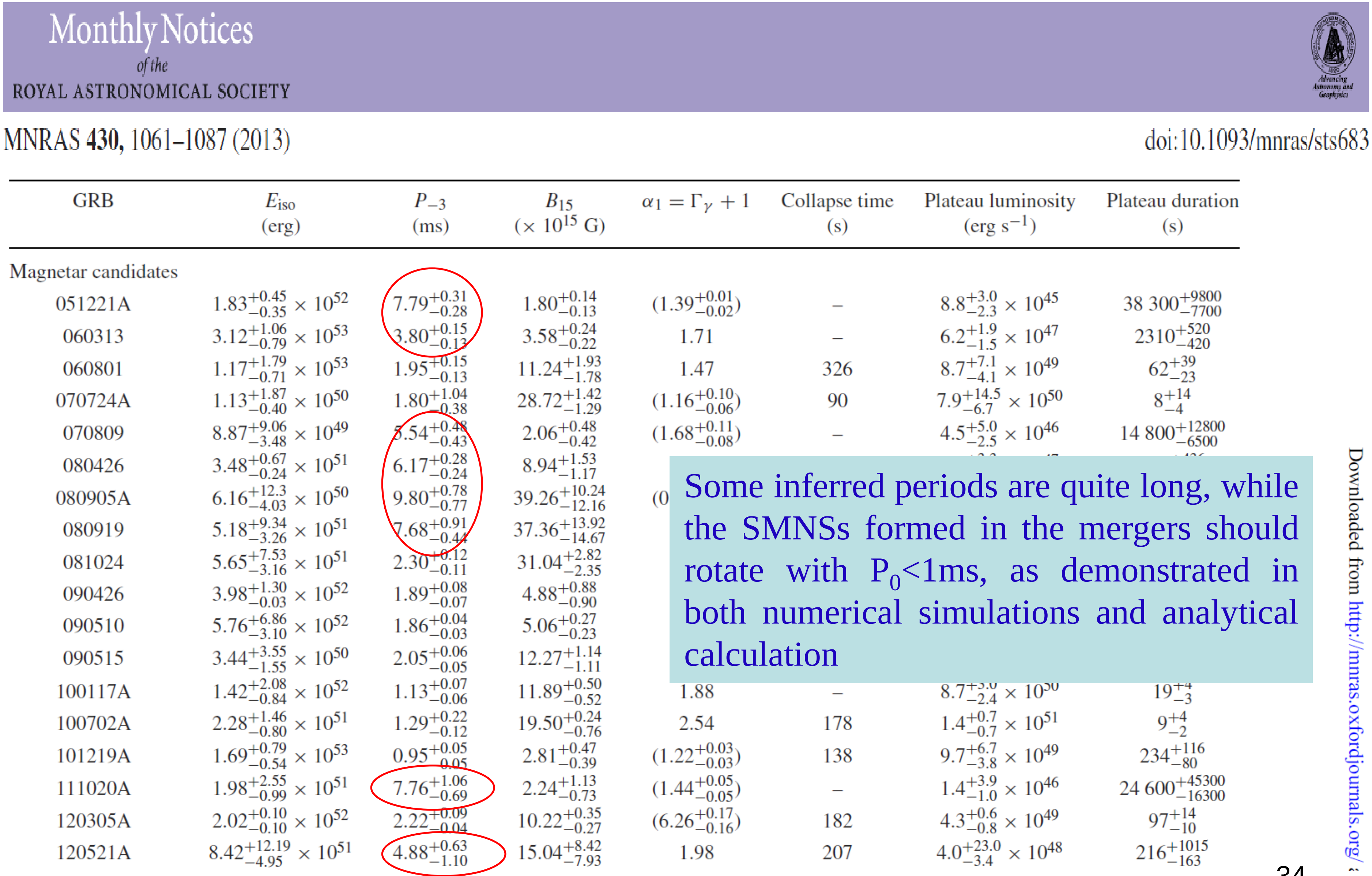
MNRAS **430,** 1061–1087 (2013) doi:10.1093/mnras/sts683

Signatures of magnetar central engines in short GRB light curves

A. Rowlinson,[1★] P. T. O'Brien,[2] B. D. Metzger,[3] N. R. Tanvir[2] and A. J. Levan[4]

In about half of the short GRBs!

The inferred initial rotation periods



Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **430,** 1061–1087 (2013)
doi:10.1093/mnras/sts683

GRB	$E_{\rm iso}$ (erg)	P_{-3} (ms)	B_{15} ($\times 10^{15}$ G)	$\alpha_1 = \Gamma_\gamma + 1$	Collapse time (s)	Plateau luminosity (erg s^{-1})	Plateau duration (s)
Magnetar candidates							
051221A	$1.83^{+0.45}_{-0.35} \times 10^{52}$	$7.79^{+0.31}_{-0.28}$	$1.80^{+0.14}_{-0.13}$	$(1.39^{+0.01}_{-0.02})$	–	$8.8^{+3.0}_{-2.3} \times 10^{45}$	$38\,300^{+9800}_{-7700}$
060313	$3.12^{+1.06}_{-0.79} \times 10^{53}$	$3.80^{+0.15}_{-0.13}$	$3.58^{+0.24}_{-0.22}$	1.71	–	$6.2^{+1.9}_{-1.5} \times 10^{47}$	2310^{+520}_{-420}
060801	$1.17^{+1.79}_{-0.71} \times 10^{53}$	$1.95^{+0.15}_{-0.13}$	$11.24^{+1.93}_{-1.78}$	1.47	326	$8.7^{+7.1}_{-4.1} \times 10^{49}$	62^{+39}_{-23}
070724A	$1.13^{+1.87}_{-0.40} \times 10^{50}$	$1.80^{+1.04}_{-0.38}$	$28.72^{+1.42}_{-1.29}$	$(1.16^{+0.10}_{-0.06})$	90	$7.9^{+14.5}_{-6.7} \times 10^{50}$	8^{+14}_{-4}
070809	$8.87^{+9.06}_{-3.48} \times 10^{49}$	$5.54^{+0.48}_{-0.43}$	$2.06^{+0.48}_{-0.42}$	$(1.68^{+0.11}_{-0.08})$	–	$4.5^{+5.0}_{-2.5} \times 10^{46}$	$14\,800^{+12800}_{-6500}$
080426	$3.48^{+0.67}_{-0.24} \times 10^{51}$	$6.17^{+0.28}_{-0.24}$	$8.94^{+1.53}_{-1.17}$				
080905A	$6.16^{+12.3}_{-4.03} \times 10^{50}$	$9.80^{+0.78}_{-0.77}$	$39.26^{+10.24}_{-12.16}$	(0			
080919	$5.18^{+9.34}_{-3.26} \times 10^{51}$	$7.68^{+0.91}_{-0.44}$	$37.36^{+13.92}_{-14.67}$				
081024	$5.65^{+7.53}_{-3.16} \times 10^{51}$	$2.30^{+0.12}_{-0.11}$	$31.04^{+2.82}_{-2.35}$				
090426	$3.98^{+1.30}_{-0.03} \times 10^{52}$	$1.89^{+0.08}_{-0.07}$	$4.88^{+0.88}_{-0.90}$				
090510	$5.76^{+6.86}_{-3.10} \times 10^{52}$	$1.86^{+0.04}_{-0.03}$	$5.06^{+0.27}_{-0.23}$				
090515	$3.44^{+3.55}_{-1.55} \times 10^{50}$	$2.05^{+0.06}_{-0.05}$	$12.27^{+1.14}_{-1.11}$				
100117A	$1.42^{+2.08}_{-0.84} \times 10^{52}$	$1.13^{+0.07}_{-0.06}$	$11.89^{+0.50}_{-0.52}$	1.88	–	$8.7^{+3.0}_{-2.4} \times 10^{50}$	19^{+4}_{-3}
100702A	$2.28^{+1.46}_{-0.80} \times 10^{51}$	$1.29^{+0.22}_{-0.12}$	$19.50^{+0.24}_{-0.76}$	2.54	178	$1.4^{+0.7}_{-0.7} \times 10^{51}$	9^{+4}_{-2}
101219A	$1.69^{+0.79}_{-0.54} \times 10^{53}$	$0.95^{+0.05}_{-0.05}$	$2.81^{+0.47}_{-0.39}$	$(1.22^{+0.03}_{-0.03})$	138	$9.7^{+6.7}_{-3.8} \times 10^{49}$	234^{+116}_{-80}
111020A	$1.98^{+2.55}_{-0.99} \times 10^{51}$	$7.76^{+1.06}_{-0.69}$	$2.24^{+1.13}_{-0.73}$	$(1.44^{+0.05}_{-0.05})$	–	$1.4^{+3.9}_{-1.0} \times 10^{46}$	$24\,600^{+45300}_{-16300}$
120305A	$2.02^{+0.10}_{-0.10} \times 10^{52}$	$2.22^{+0.09}_{-0.04}$	$10.22^{+0.35}_{-0.27}$	$(6.26^{+0.17}_{-0.16})$	182	$4.3^{+0.6}_{-0.8} \times 10^{49}$	97^{+14}_{-10}
120521A	$8.42^{+12.19}_{-4.95} \times 10^{51}$	$4.88^{+0.63}_{-1.10}$	$15.04^{+8.42}_{-7.93}$	1.98	207	$4.0^{+23.0}_{-3.4} \times 10^{48}$	216^{+1015}_{-163}

Some inferred periods are quite long, while the SMNSs formed in the mergers should rotate with P_0<1ms, as demonstrated in both numerical simulations and analytical calculation

Signature of gravitational wave radiation in the X-ray afterglow lightcurve?

If the supramassive NS model is correct:

$E_k \propto P_0^{-2}$, then there was dominant energy missing! Two possible solutions:

(a) Very low radiation efficiency of the (late prompt) X-ray emission? Disfavored by the extremely dim forward shock emission of some events!

(b) Strong gravitational wave radiation (?)

$$-dE_{\rm rot}/dt = \pi^4 R_{\rm s}^6 B_\perp^2 f^4/6c^3 + 32\pi^6 G I_{\rm zz}^2 \epsilon^2 f^6/5c^5,$$

where $\epsilon = 2(I_{\rm xx} - I_{\rm yy})/(I_{\rm xx} + I_{\rm yy})$ is the ellipticity in terms of the principal moments of inertia (i.e., I).

(Fan, Wu & Wei 2013 PRD)

Signature of gravitational wave radiation in the X-ray afterglow lightcurve?

For

$$\epsilon < 1.5\times10^{-3}\left(\frac{I_{zz}}{10^{45.3}\ \mathrm{g\ cm^2}}\right)^{-1}\left(\frac{P_0}{1\ \mathrm{ms}}\right)\left(\frac{R_s}{10^6\ \mathrm{cm}}\right)^3\left(\frac{B_\perp}{10^{15}\ \mathrm{G}}\right)$$

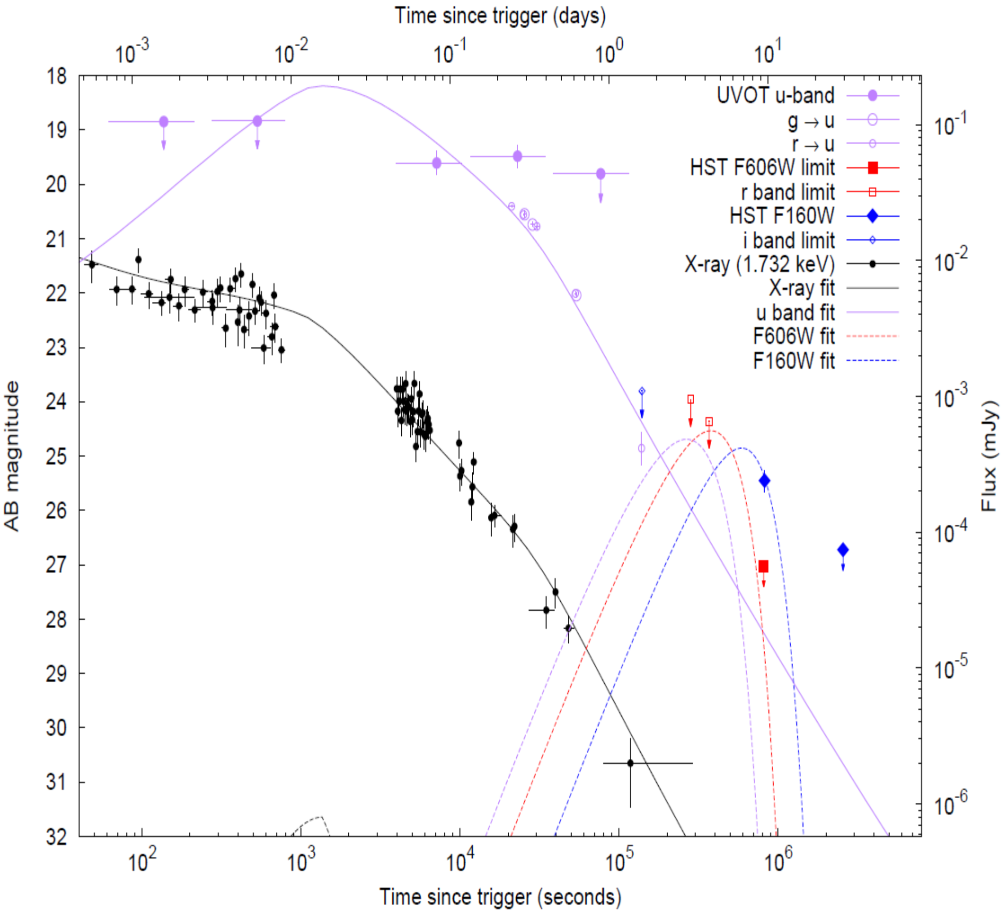
the rotational energy loses mainly through the dipole radiation and the spin down timescale is estimated by eq.(2) otherwise the rotational energy loses mainly via the gravitational wave radiation and the spin down timescale is given by

$$\tau_{\rm GW} \approx 90\ \mathrm{s}\ \left(\frac{I_{zz}}{10^{45.3}\mathrm{g\ cm^2}}\right)^{-1}\left(\frac{P_0}{1\mathrm{ms}}\right)^4\left(\frac{\epsilon}{0.01}\right)^{-2}.$$

The observed "shortened" duration of the X-ray plateau can be accounted for if the ellipticity~0.01(P_0/1ms)^2, possibly contributed by ~1E17 Gauss interior magnetic field. The GW frequency is ~2/(P_0/1s)>2000 Hz.

(Fan, Wu & Wei 2013 PRD)

Signature of gravitational wave radiation in the short GRB data?



1. The early X-ray flat segment: energy injection from a magnetar (?)

2. The afterglow modeling gives E<2E51 erg (Fong et al. 2013) and the kilonova kinetic energy is ~1E51 erg (Berger et al. 2013; Tanvir et al. 2013): << rotational energy ~1E53 erg of the magnetar formed in merger!

3. Plausibly the “missing energy” had been taken away by GW!

(Fan et al. 2013 ApJL: the case of GRB 130603B/“first” kilonova)

Prospect of forming SMNS in NS mergers: clue from GW170817/GRB170817A/AT2017gfo

We denote M_{TOV} as the maximal gravitational mass of non-rotating NSs.

We have also defined $m_{\mathrm{loss}} = m_{\mathrm{eje}} + m_{\mathrm{disk}}$ and $\zeta_{\mathrm{TOV}} = \frac{GM_{\mathrm{TOV}}{}^{2}}{R_{\mathrm{TOV}}c^{2}}$.

The threshold total gravitational mass of the pre-merger binary neutron stars, above which the formed remnant will collapse quickly, is shown to be (Shao, D. S. et al. 2019)

$$M_{\mathrm{tot,c}} \approx 0.924 M_{\mathrm{TOV}}(1 + 7.94\times10^{-2}\zeta_{\mathrm{TOV}}^{-1} j^{2} + 1.70\times10^{-2}\zeta_{\mathrm{TOV}}^{-2} j^{4})$$
$$(0.8634 + 1.051\zeta_{\mathrm{TOV}})(1 - 0.091\, M_{\odot}^{-1}\, m_{\mathrm{loss}}) + m_{\mathrm{loss}}.$$

where $j(\leq 0.73)$ is the Kerr parameter of the nascent NS.

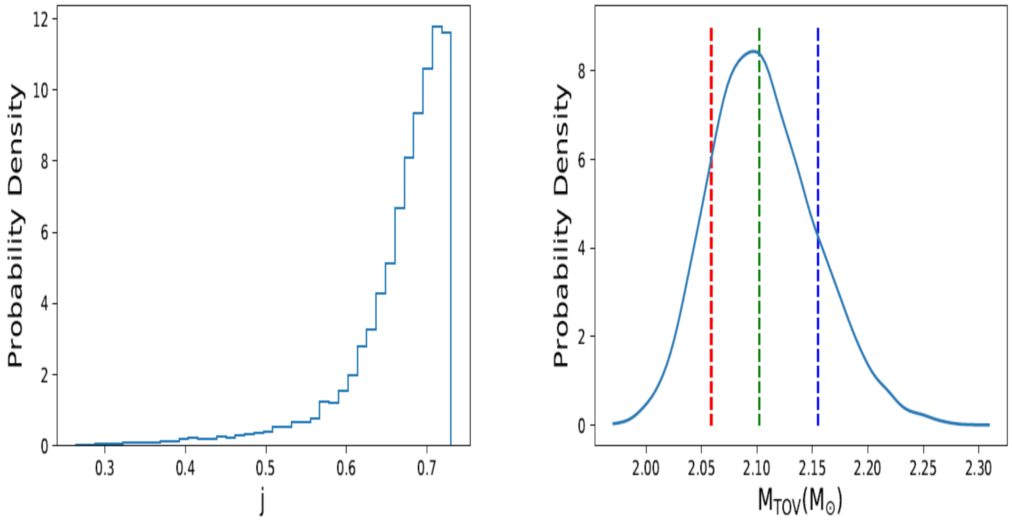
Prospect of forming SMNS in NS mergers: clue from GW170817/GRB170817A/AT2017gfo

For the double neutron star merger event of GW170817

- **M_{tot} is from the GW data (LVC 2017).**
- **m_{eje} is estimated with AT2017gfo (Pian et al. 2017).**
- **m_{disk} can be estimated with GRB170817A and afterglow (though uncertain due to the off-axis nature; Wang, Y. Z. et al. 2019).**
- **j can be estimated in the way of Shibata et al. (2019).**

Under the assumption of that the central engine of GRB 170817A was a black hole formed from a quick collapse of a SMNS, the condition of $M_{\mathrm{tot}} = M_{\mathrm{tot,c}}$ yields the value of M_{TOV}.

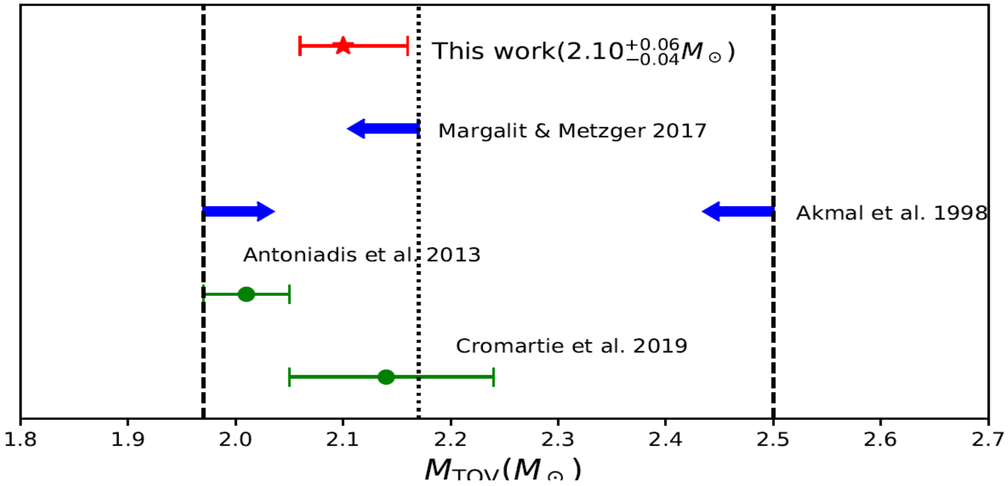
Prospect of forming SMNS in NS mergers: clue from GW170817/GRB170817A/AT2017gfo



Shao et al. 2019 submitted

The estimated M_{TOV} is already comparable with that of PSR J0740+6620!

So the mergers of DNS binary systems lighter than GW170817 likely produce SMNSs!



Cautions: Rotation prolife may be too simplified (initially the core rotated slower than the outer material); The temperature effect is not included.

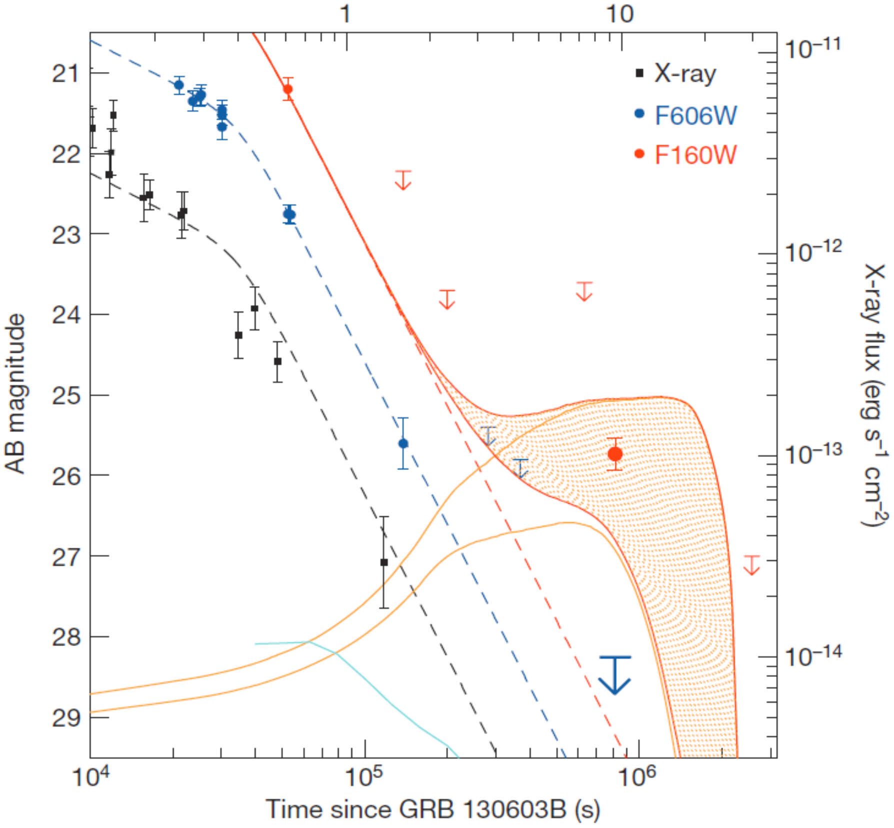
Summary: magnetar model and GW radiation

- There is the growing interest in the supramassive NS model for the peculiar X-ray afterglow of some short GRBs
- If correct, the rotational kinetic energy of the NS should be ~1E53 erg, while the observed/inferred energies are much smaller
- This could be the evidence for the dominant energy loss via gravitational wave radiation (in both prompt magnetic wind dissipation model and energy injection model)

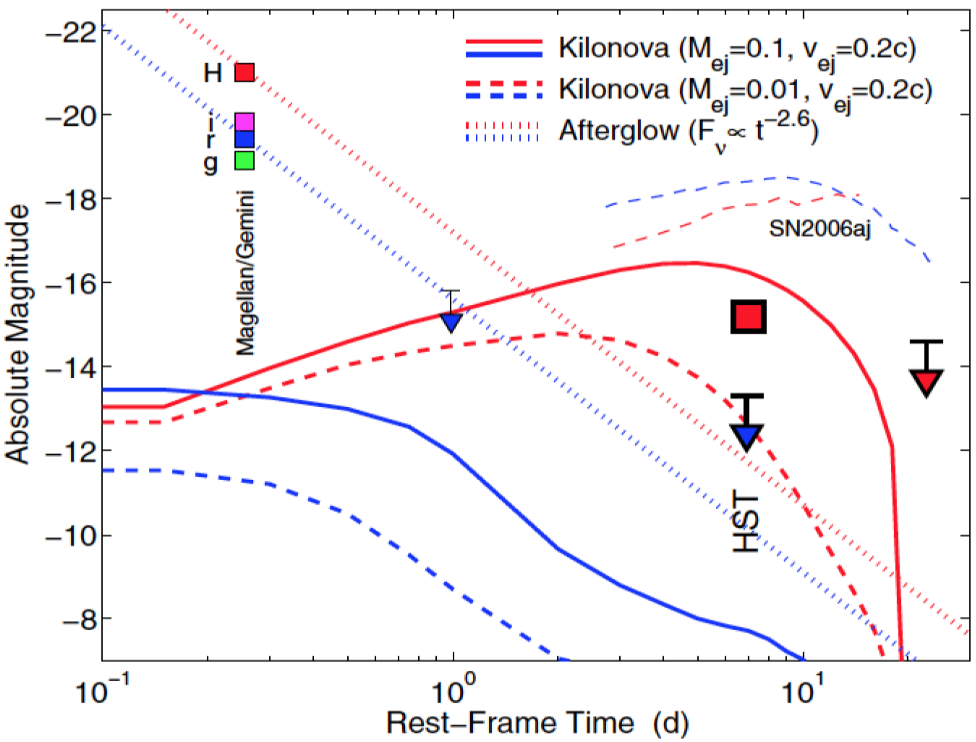
Outline

- **Direct detection of cosmic rays by DAMPE**
- **Indirect detection of dark matter particles**
- **Signature of gravitational wave radiation in the short GRB afterglow?**
- **Kilonovae/macronovae associated with GRB 050709, GRB 060614 and GRB 070809**

GRB130603B：the first credible kilonova



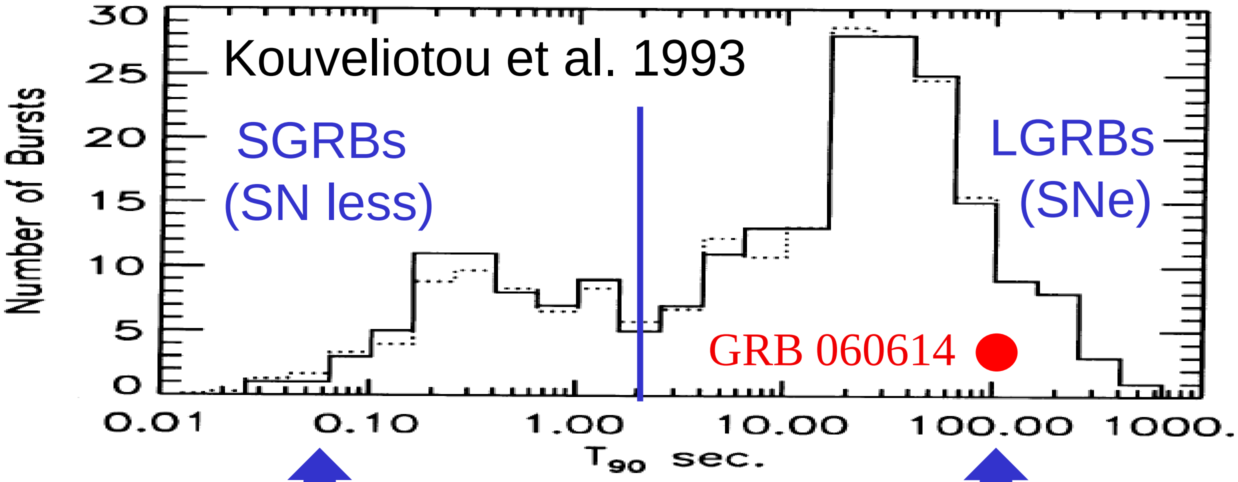
Tanvir et al. 2013 Nature

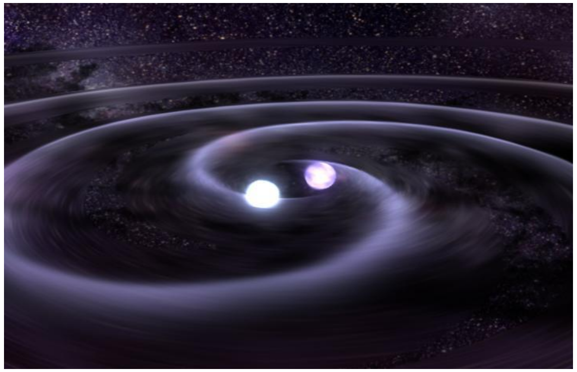


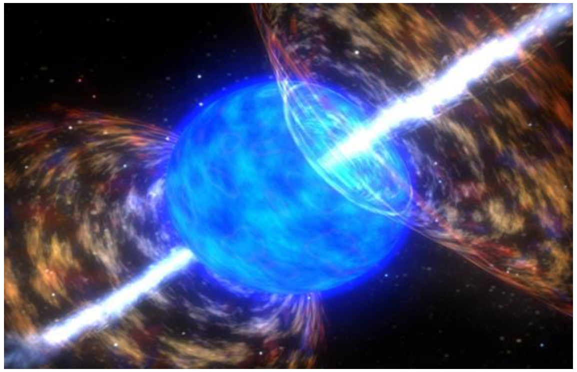
Berger et al. 2013 ApJL

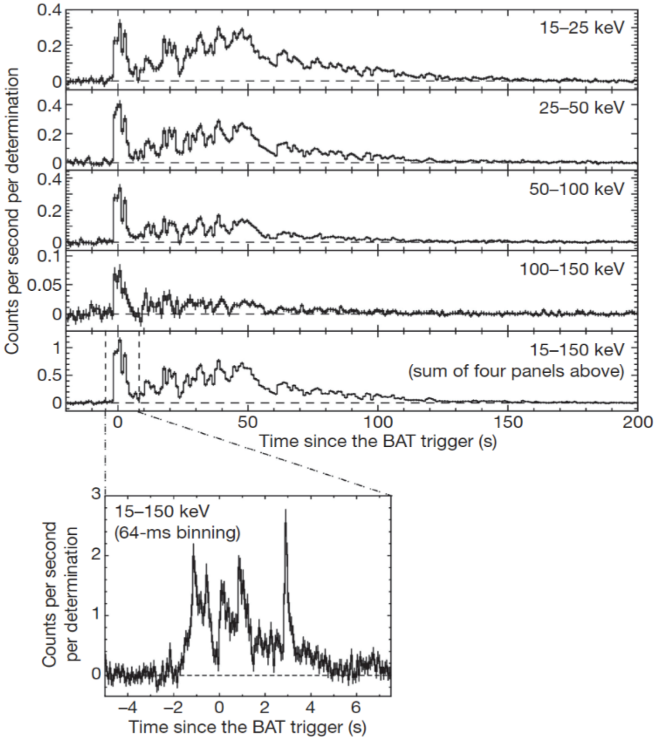
One H-band excess and 1 simultaneous r-band upper limit

GRB 060614: a long burst at z=0.125


Kouveliotou et al. 1993





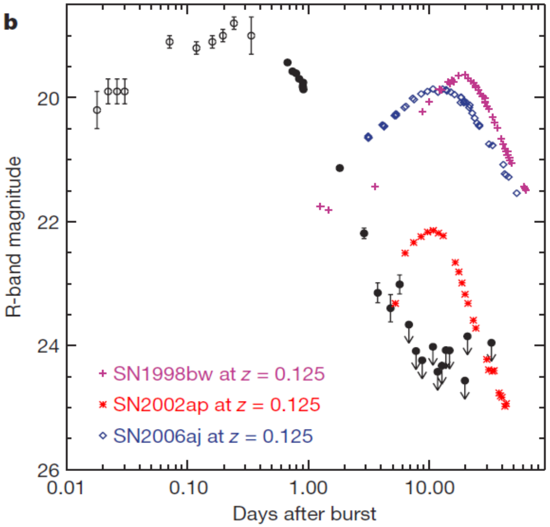


Gehrels et al. 2006 Nature

There is a second component which is weak and soft. But the first hard spike is still longer than 5 seconds.

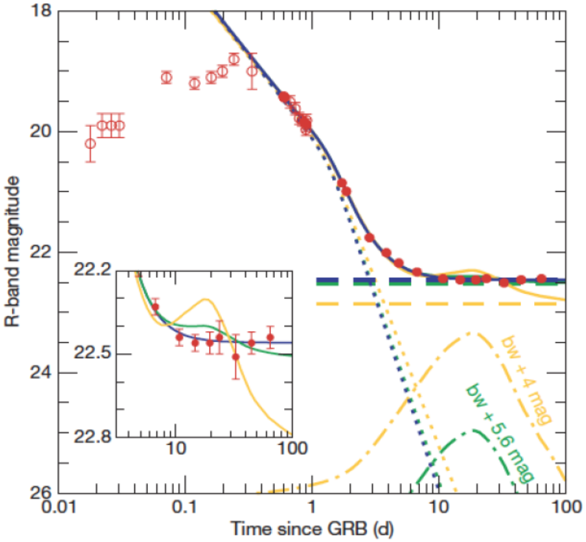
GRB 060614: plentiful data

1.5m Danish Telescope



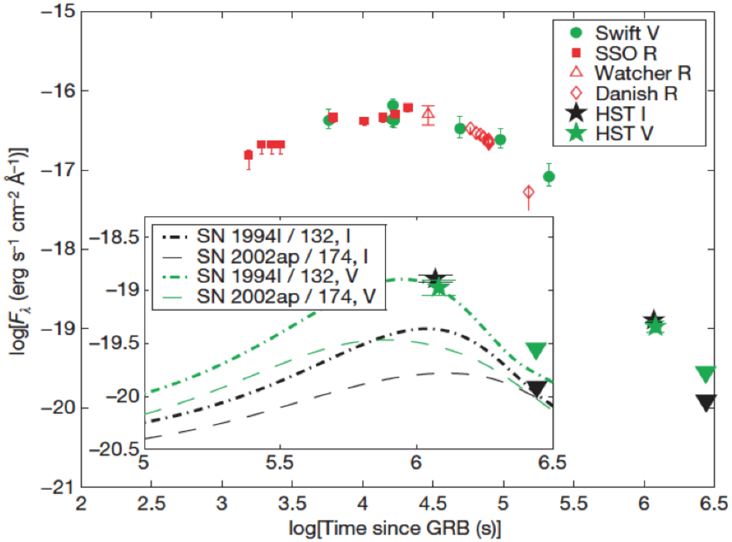
Fynbo et al. 2006 Nature

ESO VLT (8.2m 6 hours)



Della Valle et al. 2006 Nature

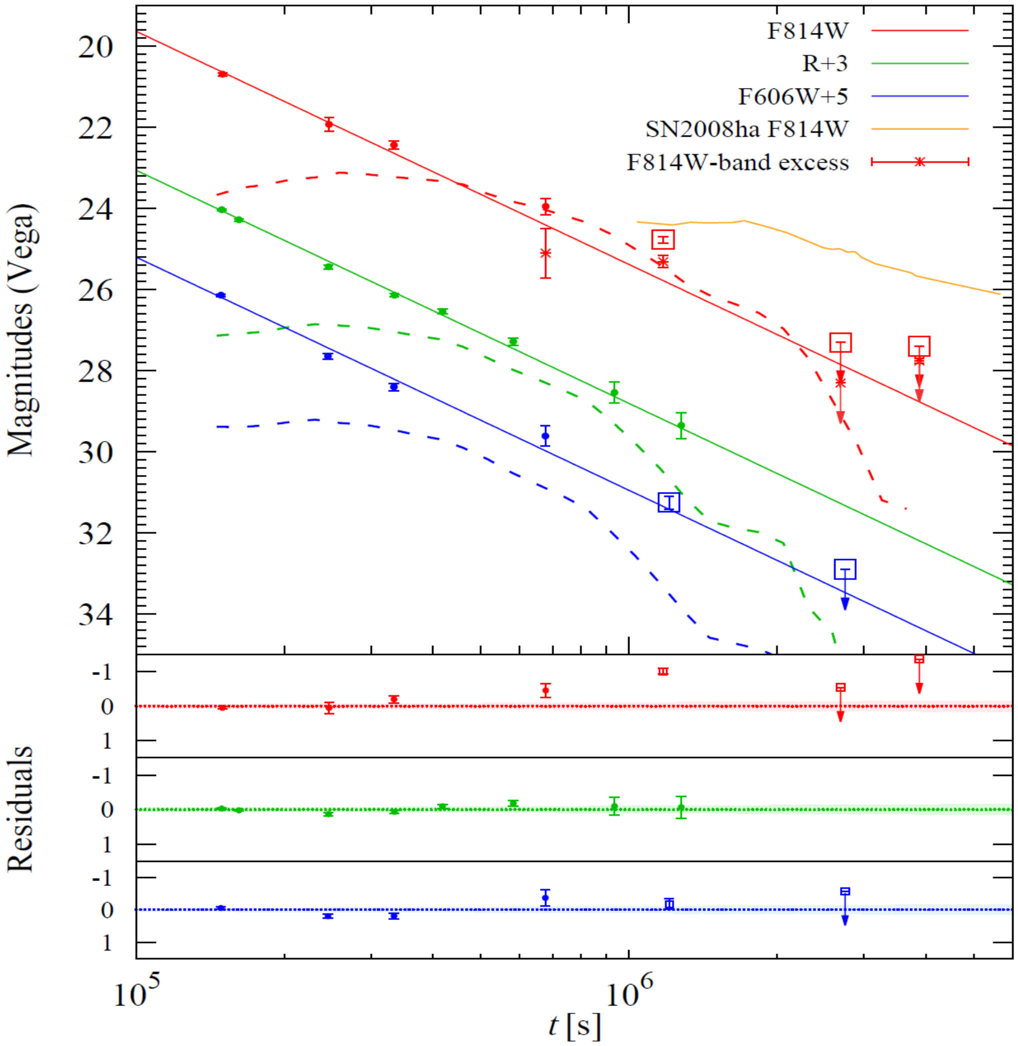
HST (10 hours)



Gal-Yam et al. 2006 Nature

Two origin models: peculiar collapsar without bright SN vs. neutron star merger! Nicknamed as a long-short GRB or a hybrid GRB.

GRB060614: kilonova signal?

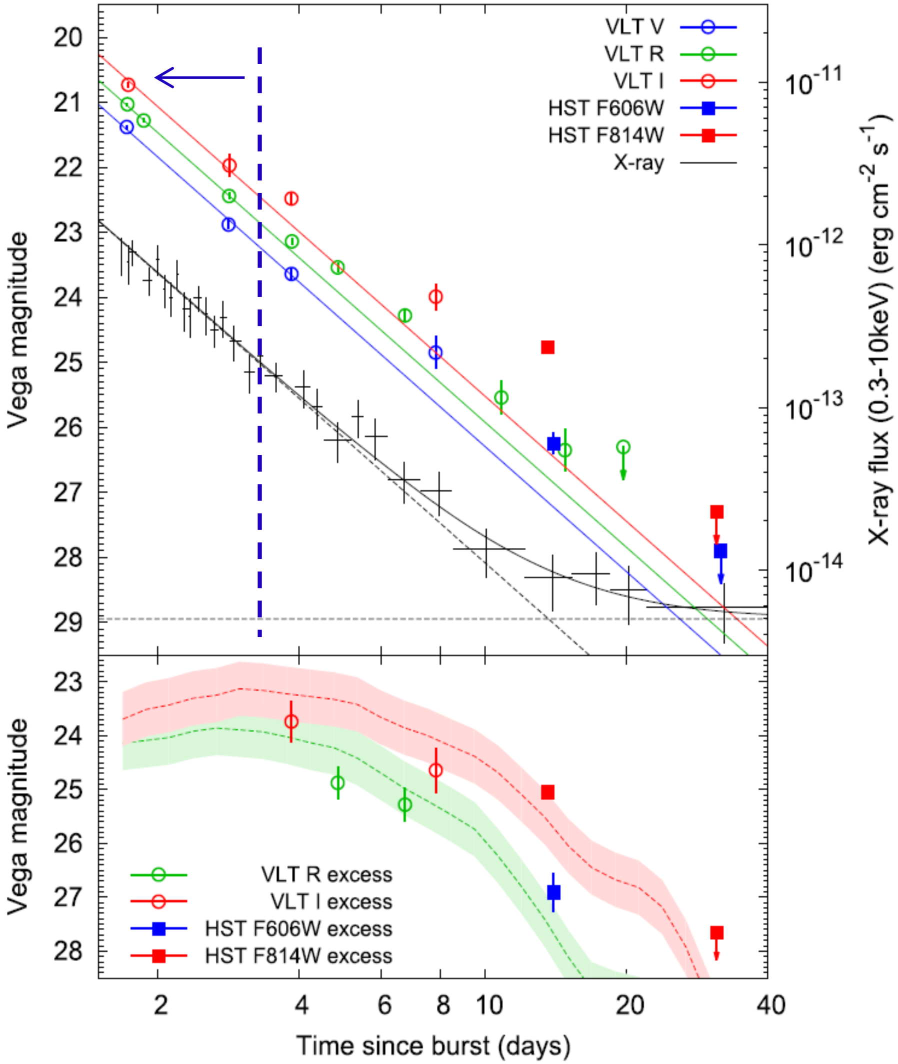


First kilonova/macronova signal from long-short/hybrid GRBs

Total ejecta mass ~ 0.1 $M_\odot$ dominated by heavy elements, may be from a NS-BH binary merger?

(Yang et al. 2015, Nat. Commun.)

GRB060614: first lightcurves of kilonova?



(Jin, Li & Cano et al. 2015 ApJL):
fit the afterglow decline with the data of t \leq 3 days

GRB 060614: first measurement of the (late time) temperature of kilonova?

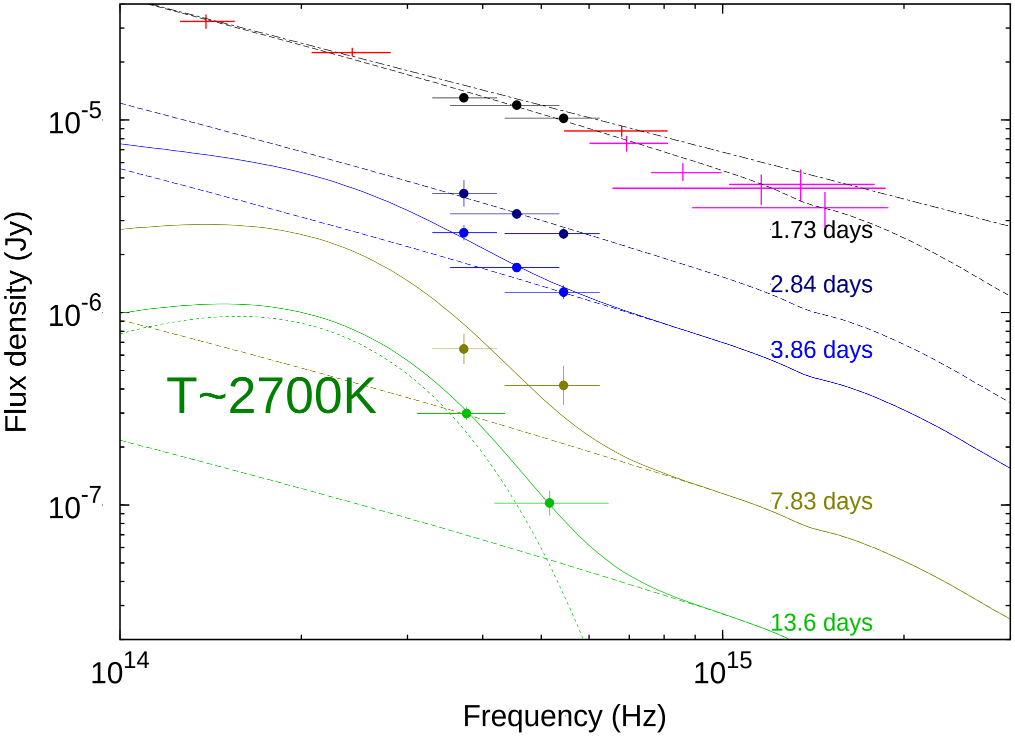
GRB 060614

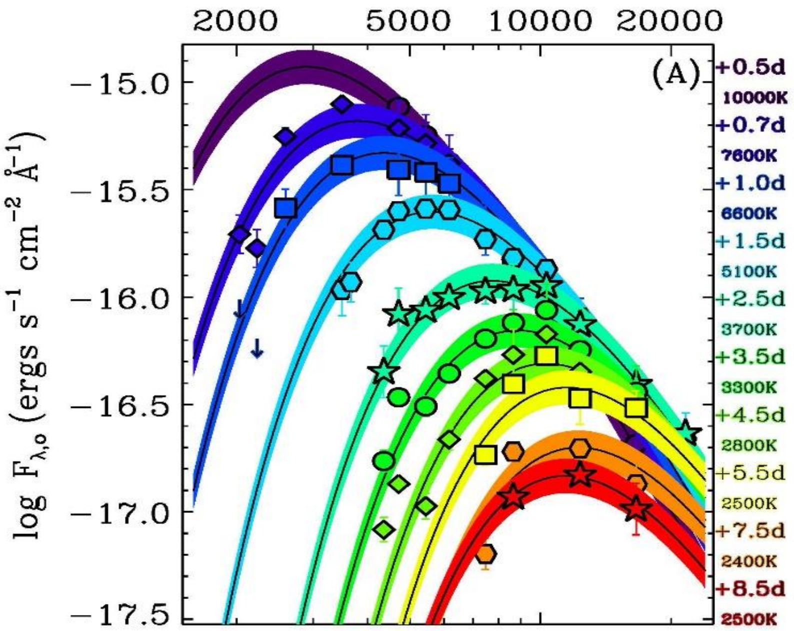
temperature ~2700K@13.6days

GW 170817

late temperature ~2500K

(Drout et al. 2017 Science)

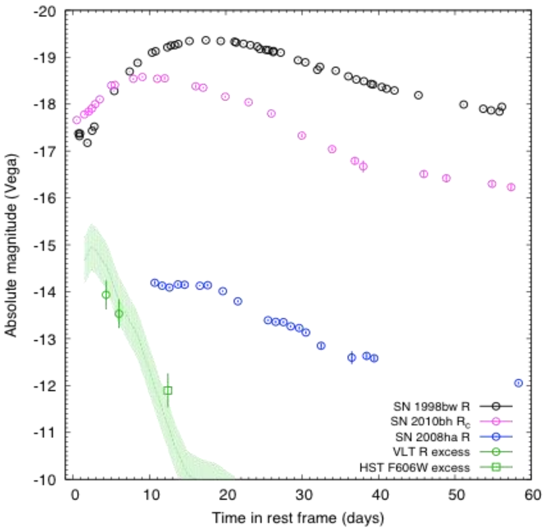




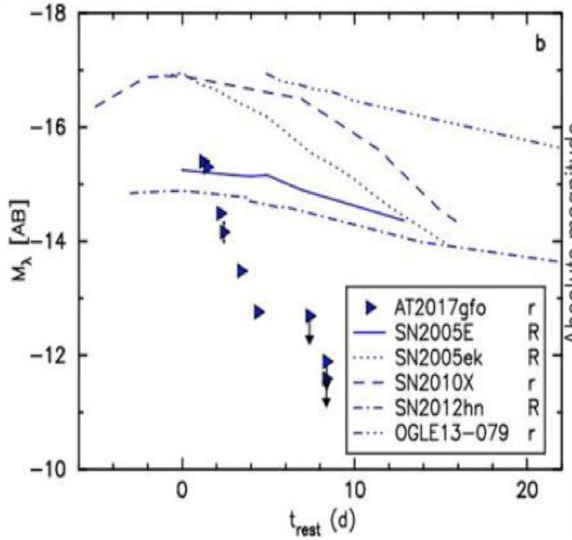
Jin et al. 2015 ApJL: at t>3.8 days the emergence of a soft component

A late time temperature of ~2500 K suggests the production of Lanthanides!

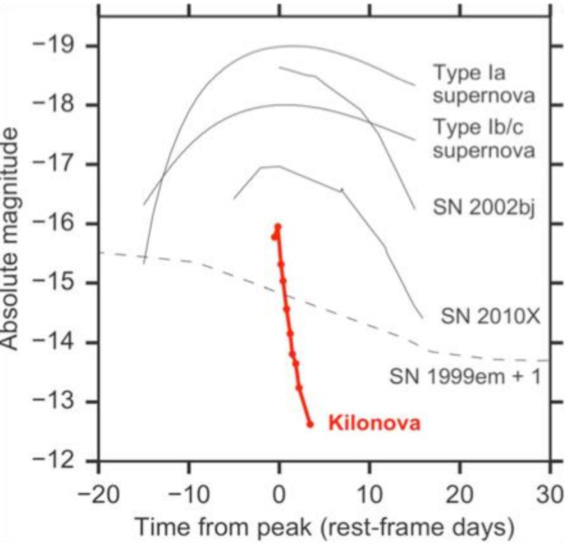
GRB 060614 & AT2017gfo vs. SNe



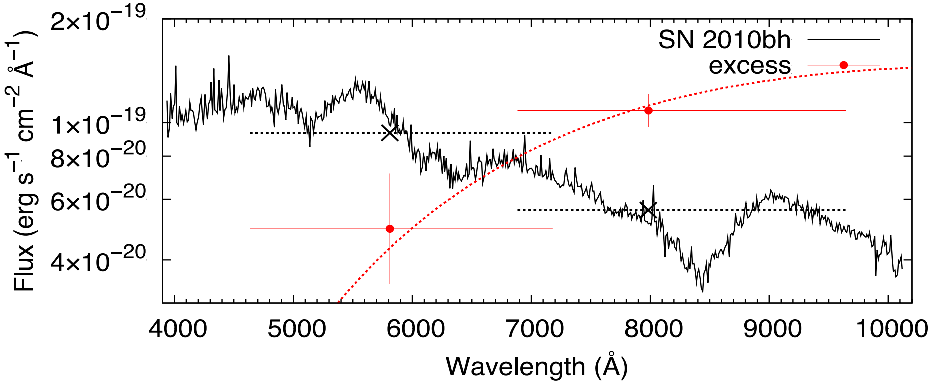
Jin et al. 2016 EPJWC



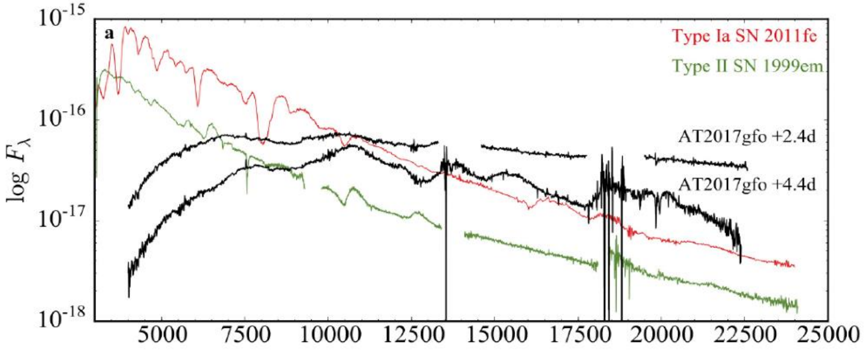
Smartt et al. 2017 Nature



Arcavi et al. 2017 Nature



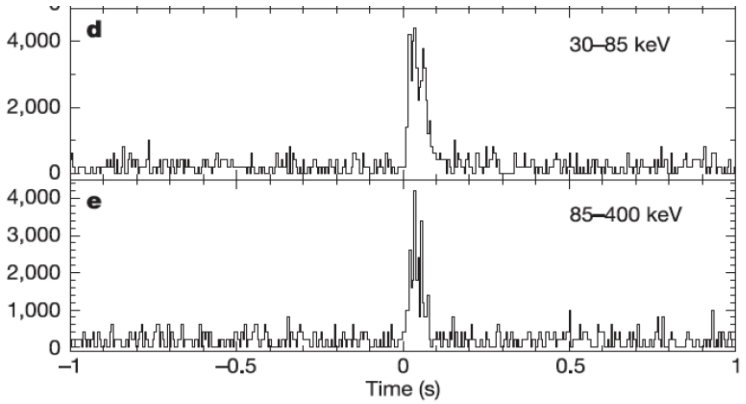
Jin et al. 2016 EPJWC (OMEG 2015)



Smartt et al. 2017 Nature

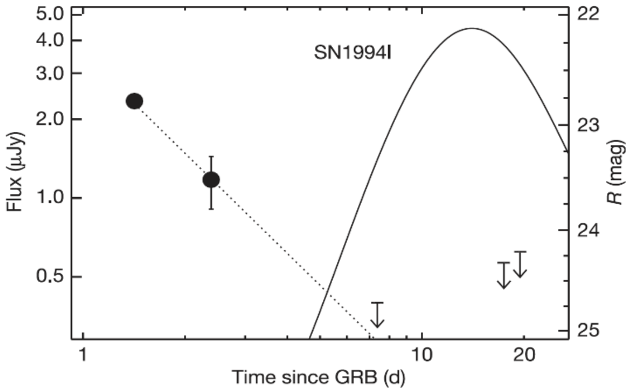
GRB 050709 : first sGRB with optical afterglow

HETE 2



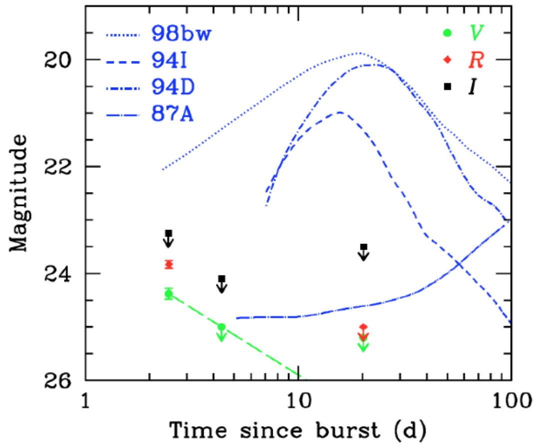
Villasenor et al. 2005

Danish 1.5m



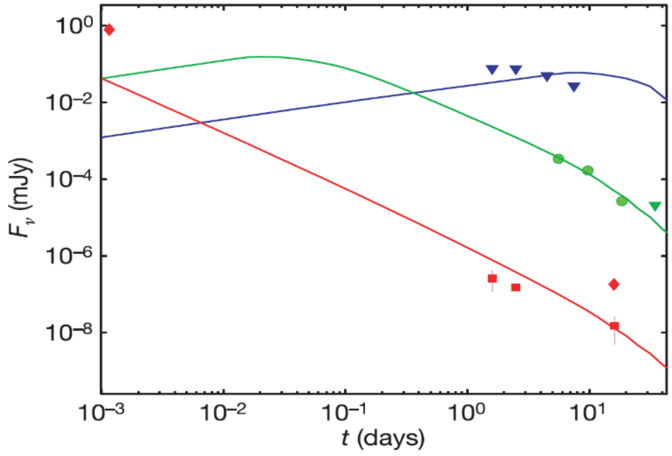
Hjorth et al. 2005

VLT



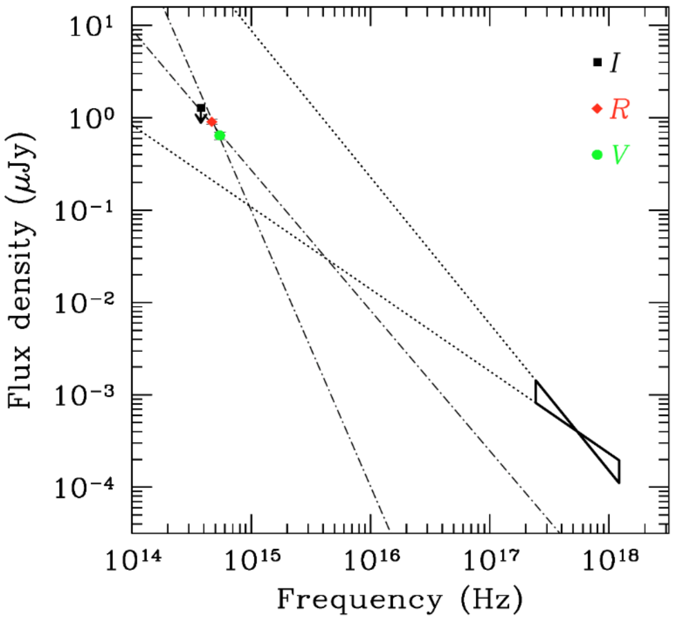
Covino et al 2006

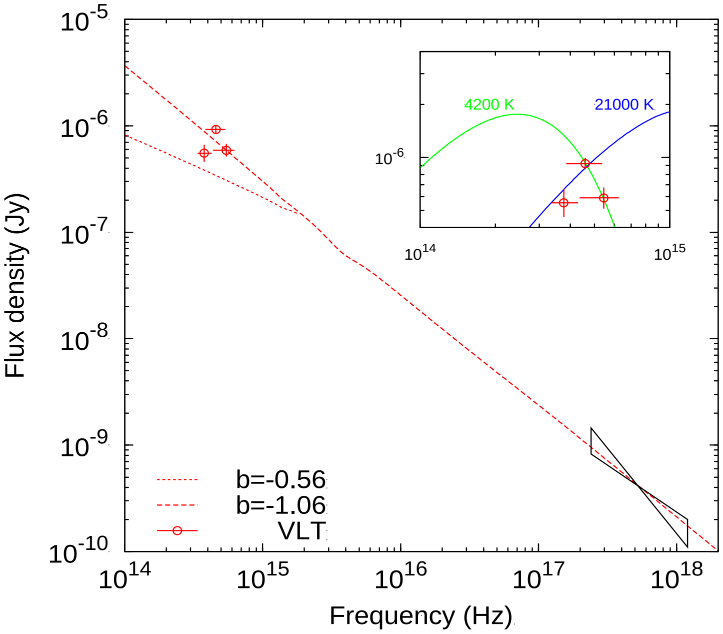
HST

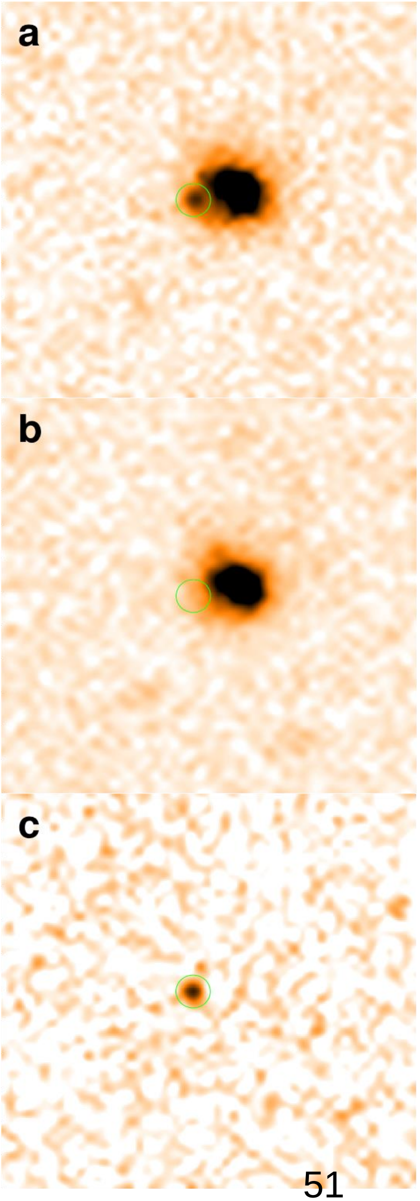


Fox et al. 2005

GRB 050709: new detection in the re-analysis



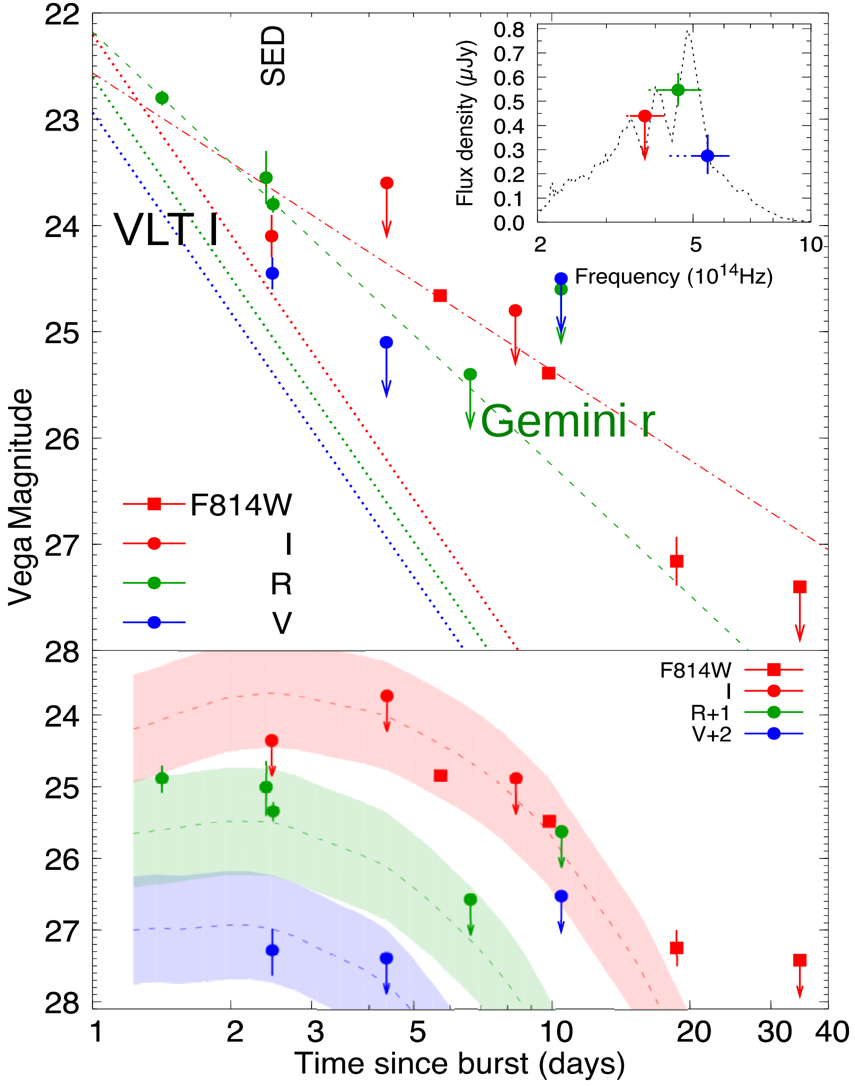


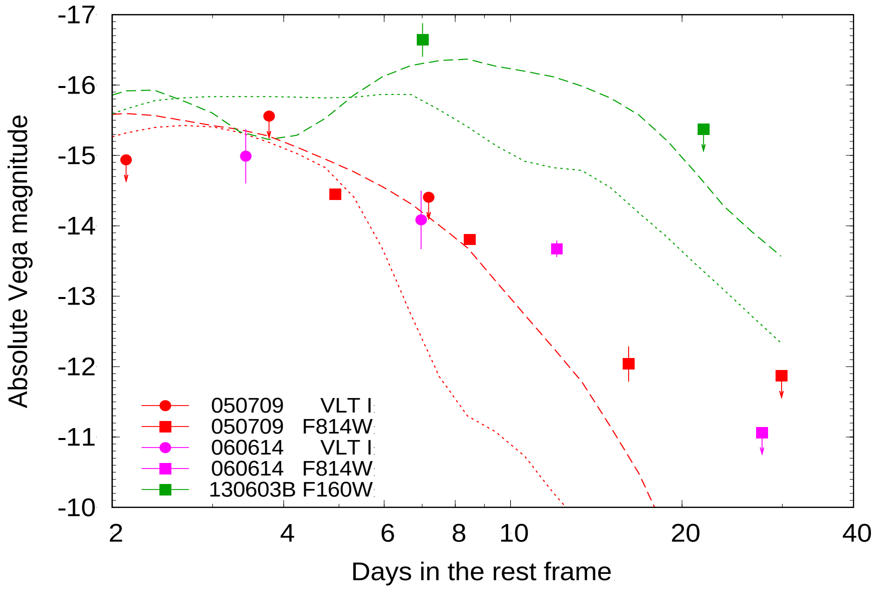


Jin et al. 2016 Nat. Commun.

- The I-band observation at t=2.5 days yields a detection rather than an upper limit
- The VLT I/R/V SED@t=2.5days is quite strange, likely line-like

GRB050709: kilonova signal

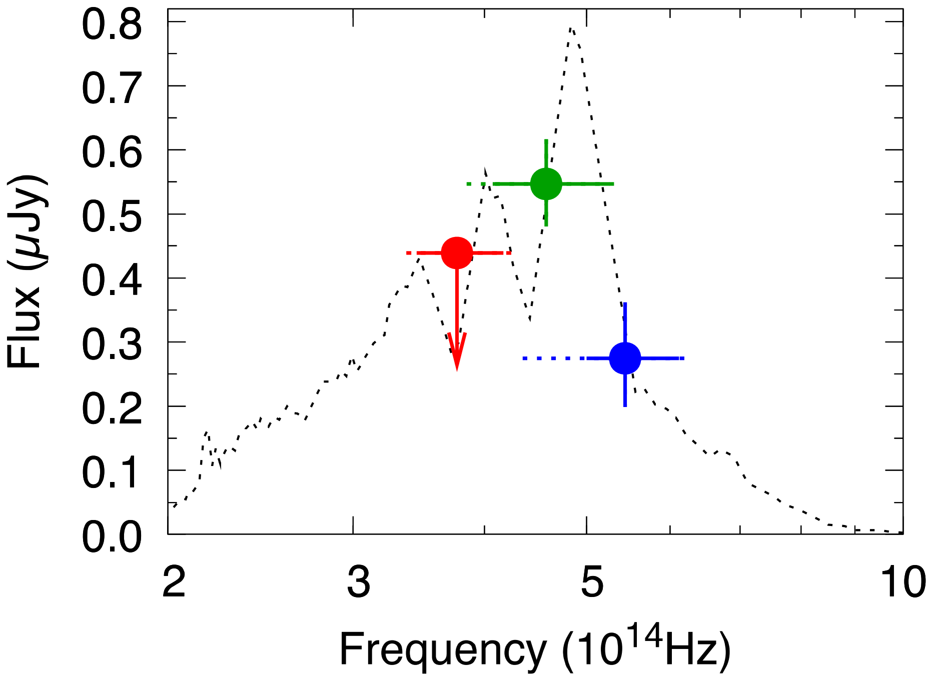




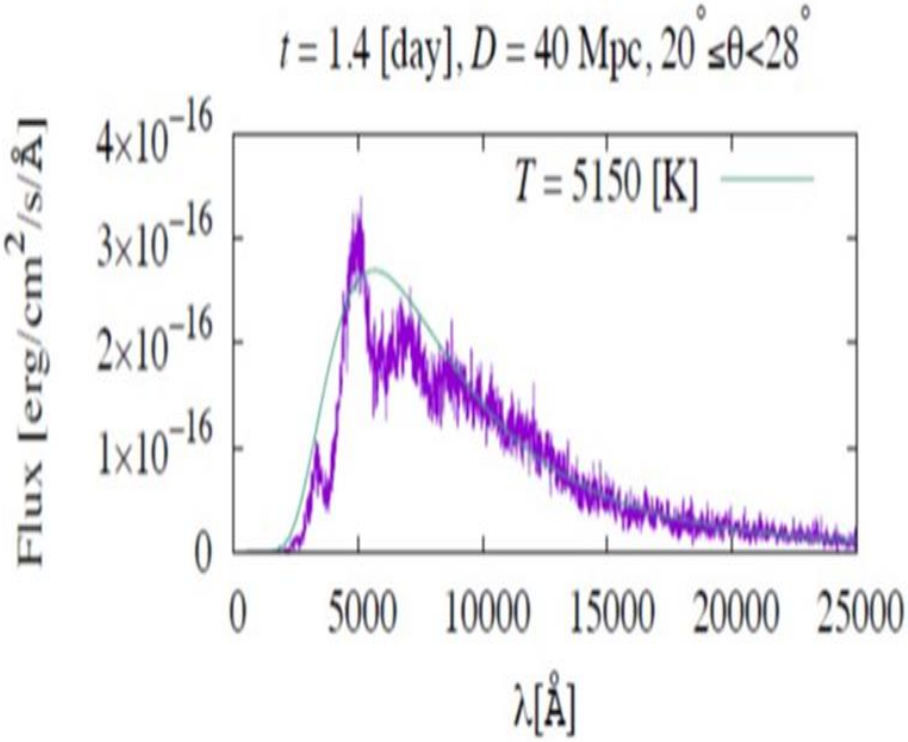
Left: The decline behaviors of I/F814W and R are significantly different!
Right: GRB 050709 I/F814W band lightcurve is similar to the macronova in GRB 060614.

Jin et al. 2016 Nat. Commun.

GRB 050709: first line-like signal of kilonova?



VLT SED @ 2.5 days: unique so far

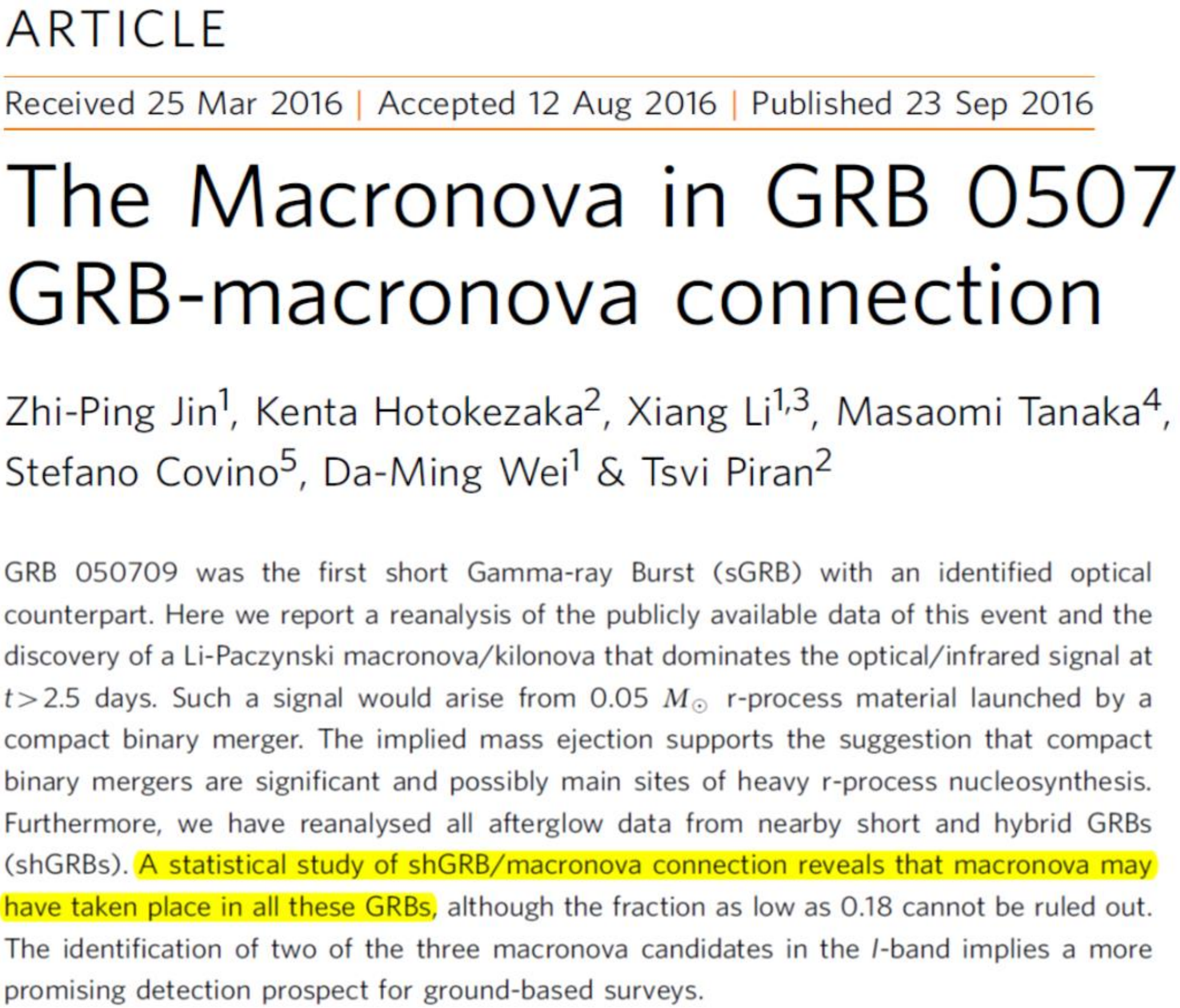


An early time kilonova SED found in the numerical simulation.

Jin et al. 2016

Tanaka et al. 2017

GRB-kilonova connection



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OPEN

The Macronova in GRB 050709 and the GRB-macronova connection

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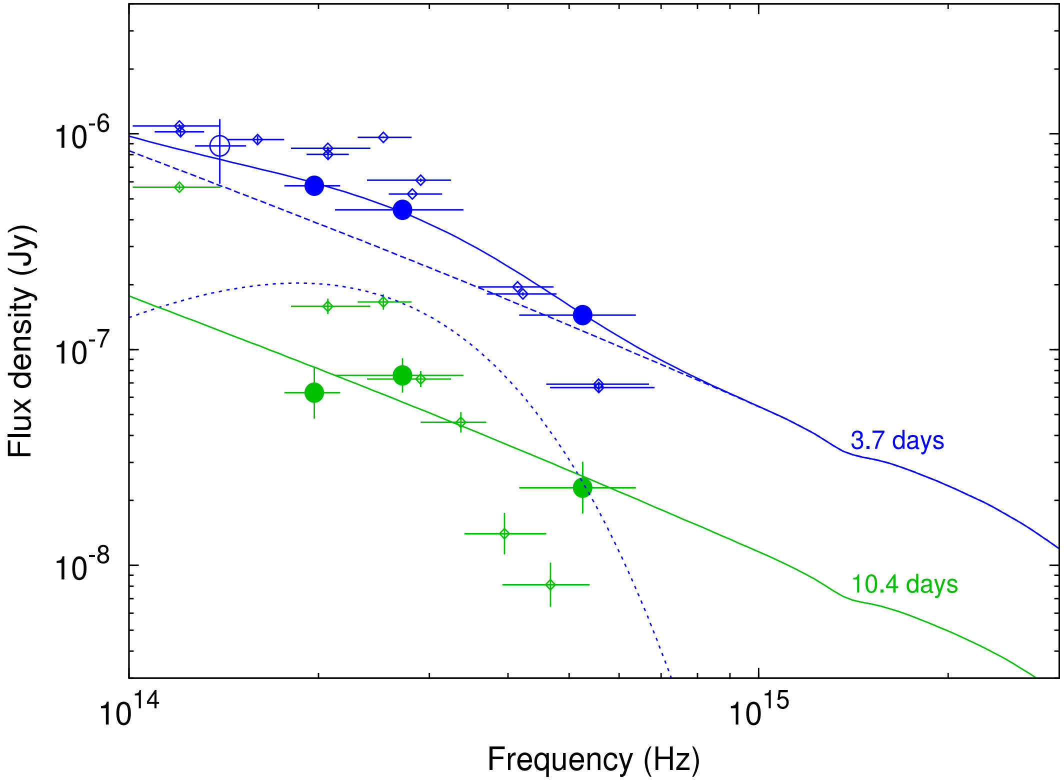
GRB 050709 was the first short Gamma-ray Burst (sGRB) with an identified optical counterpart. Here we report a reanalysis of the publicly available data of this event and the discovery of a Li-Paczynski macronova/kilonova that dominates the optical/infrared signal at $t>2.5$ days. Such a signal would arise from 0.05 $M_{\odot}$ r-process material launched by a compact binary merger. The implied mass ejection supports the suggestion that compact binary mergers are significant and possibly main sites of heavy r-process nucleosynthesis. Furthermore, we have reanalysed all afterglow data from nearby short and hybrid GRBs (shGRBs). A statistical study of shGRB/macronova connection reveals that macronova may have taken place in all these GRBs, although the fraction as low as 0.18 cannot be ruled out. The identification of two of the three macronova candidates in the *I*-band implies a more promising detection prospect for ground-based surveys.

- A statistical study of the sGRB/macronova connection suggests that the macronovae may be ubiquitous
- The non-identification of the signal in most events is likely due to the lack of enough data

GRB 160821B: evidence for kilonova in Aug. 2017

(HST proposal ID: 14237, PI: Nial Tanvir)



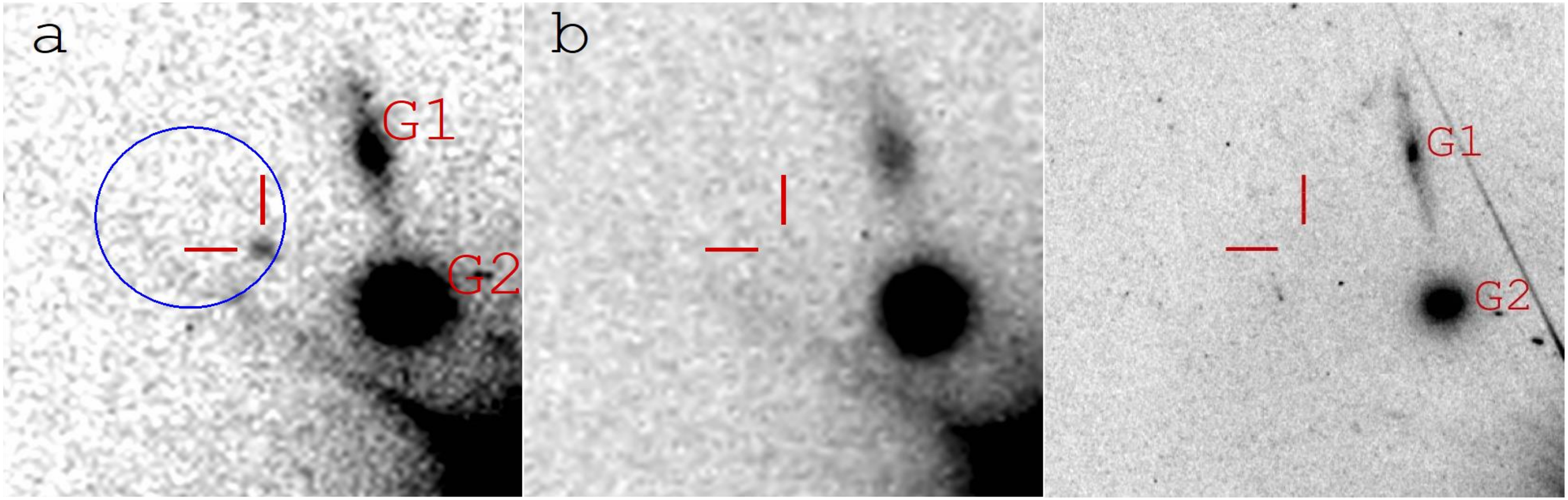
We searched for the kilonova signal well before the data release of AT2017gfo.

The HST measurement data at t~3.6 days after the trigger can be interpreted as the superposition of a power-law afterglow component and a thermal-like component at the temperature of ~ 3000 K (https://arxiv.org/pdf/1708.07008v1.pdf).

Jin et al. (2018; a comparison to AT2017gfo added later);

see Troja et al. (2019) and Lamb et al. (2019) for new evidence with more data

GRB 070809: limited but useful data



Keck R 0.5 day

Keck R 1.5 days

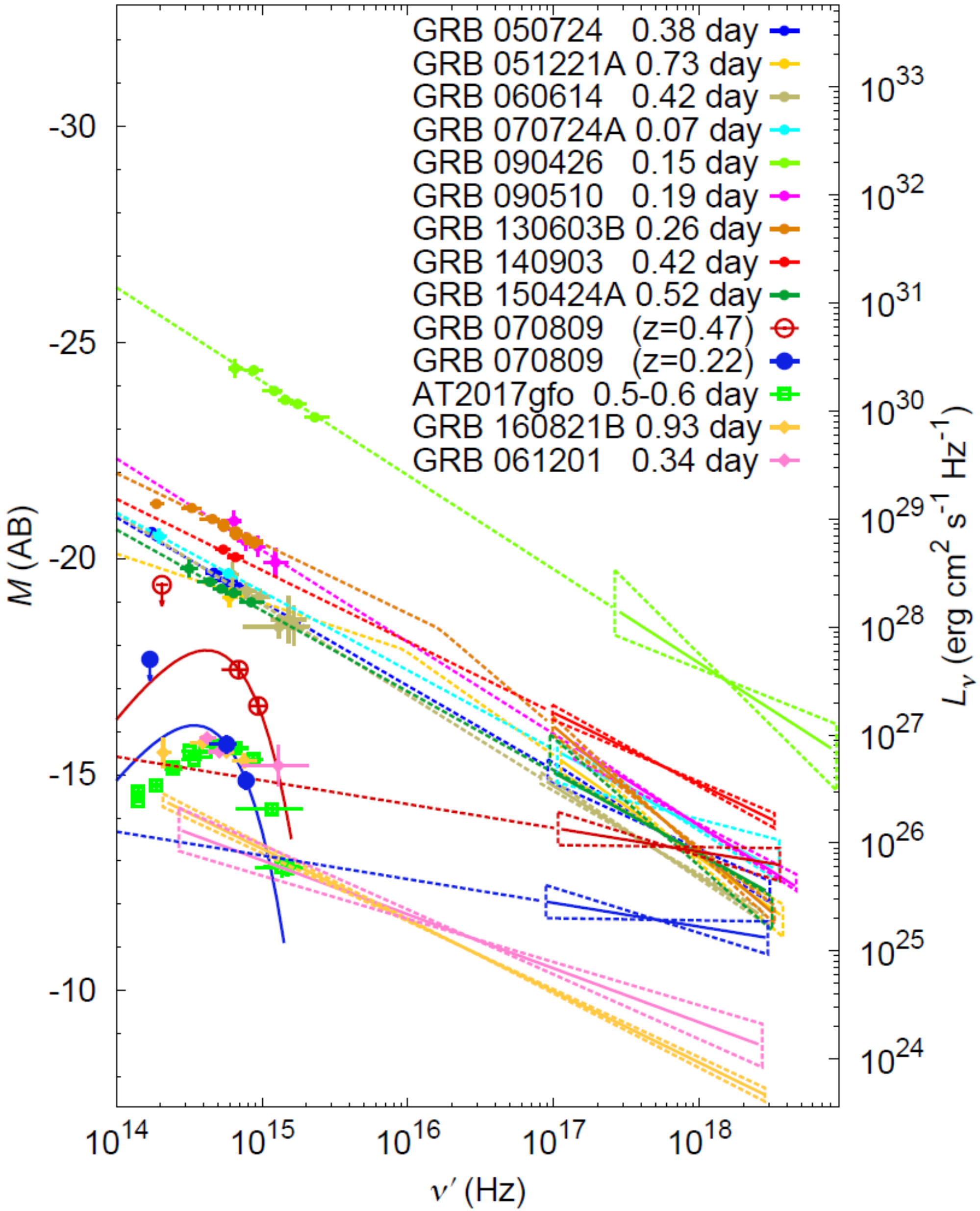
HST F606W 731 days

G1: z=0.218, offset 5.9 seconds (Perley 2008)

G2: z=0.473, offset 6.0 seconds (Berger 2010)

GRB site: m(F606W)>28.0 AB mag; Limited optical data without serious attention until this year

GRB 070809: the kilonova signal

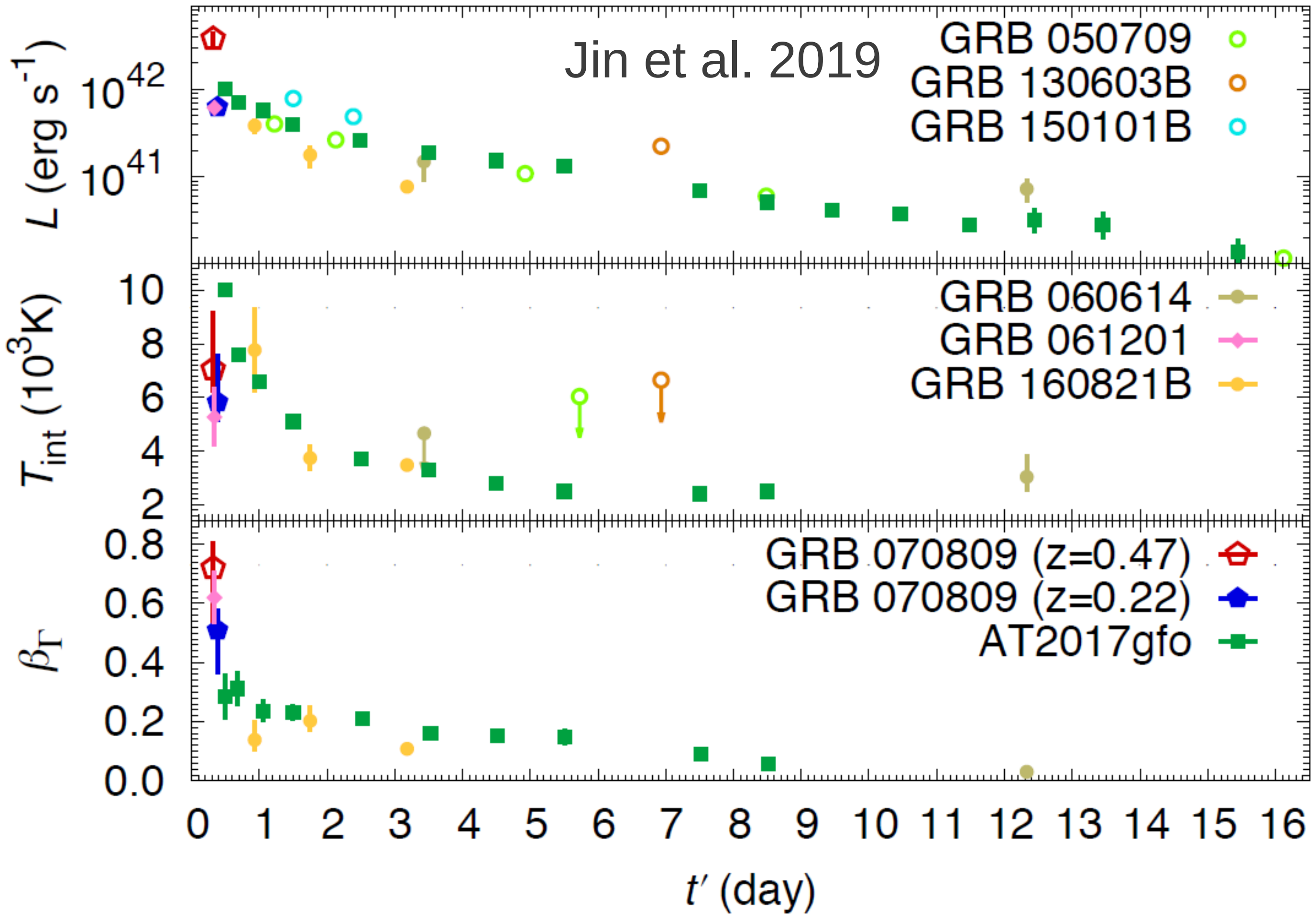


Jin et al. (2019 Nat. Astron.): GRB 070809 has the hardest X-ray spectrum and the softest optical spectrum.

The thermal-like optical emission is well in excess of the extrapolation of the X-ray spectrum!

AT2017gfo, GRB 070809, GRB 160821B and possibly GRB 061201 likely form a kilonova group.

Statistical properties of kilonovae



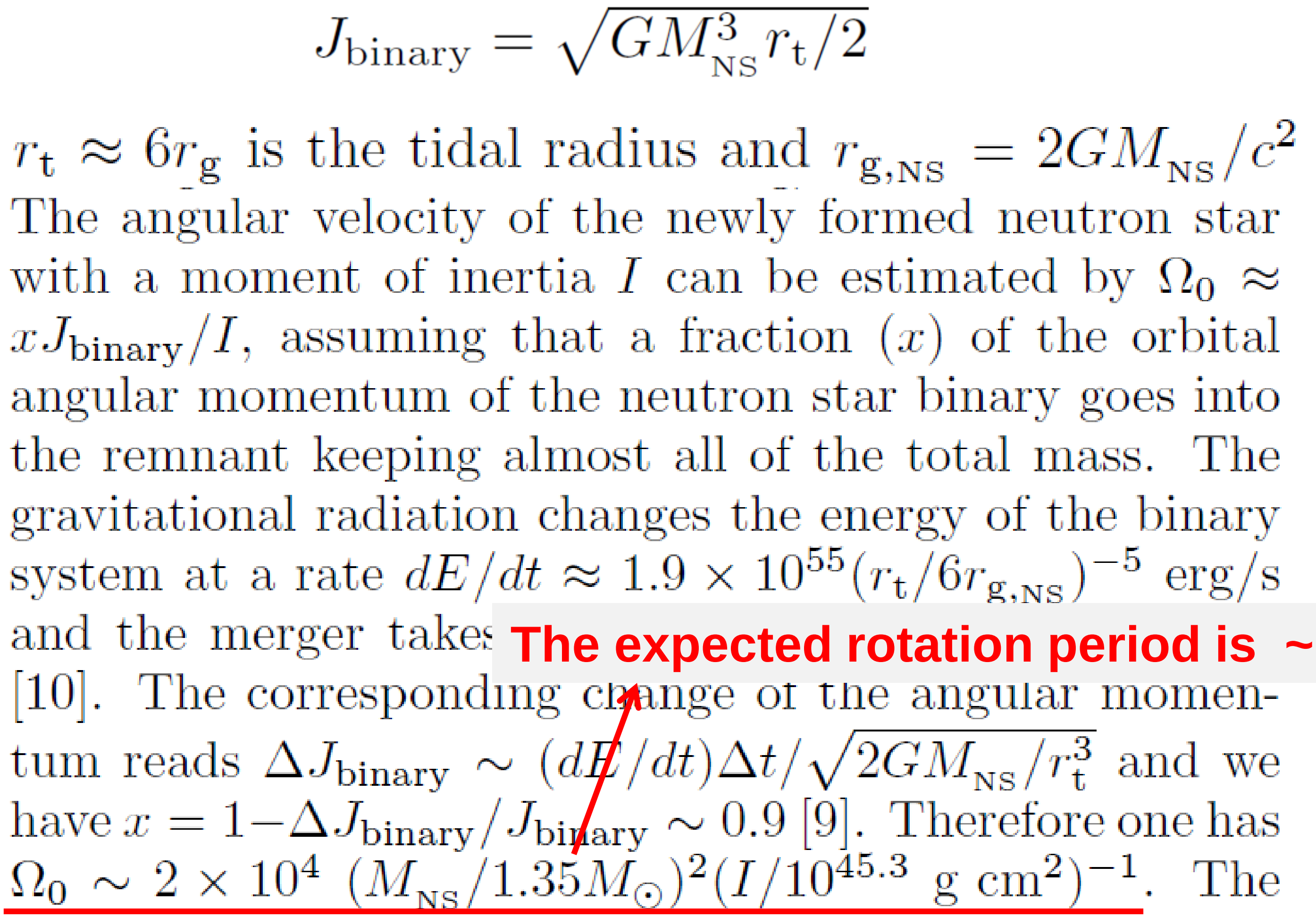
- **The kilonova of GRB 070809 is the earliest one identified in "typical"/bright sGRBs.**
- **The early kilonova emission: diverse $T_{\rm int}$, β_Γ and then diverse physical origins?**

Summary: kilonova candidates and implications

- The mysterious long-short/hybrid GRB 060614 is intrinsically "short"
- The late-time temperatures of the macronova/kilonova signal of GRB 060614 and AT2017gfo are ~2500 K, supporting the production of Lanthanides
- The macronovae/kilonovae may have line-like features (e.g., GRB 050709)
- The macronovae/kilonovae are likely ubiquitous and hence ideal EM counterparts of most NS merger events

Thank you!

Signature of gravitational wave radiation in the X-ray afterglow lightcurve?



$$J_{\rm binary} = \sqrt{G M_{\rm NS}^3 r_{\rm t}/2}$$

$r_{\rm t} \approx 6 r_{\rm g}$ is the tidal radius and $r_{\rm g,NS} = 2GM_{\rm NS}/c^2$ The angular velocity of the newly formed neutron star with a moment of inertia I can be estimated by $\Omega_0 \approx x J_{\rm binary}/I$, assuming that a fraction (x) of the orbital angular momentum of the neutron star binary goes into the remnant keeping almost all of the total mass. The gravitational radiation changes the energy of the binary system at a rate $dE/dt \approx 1.9 \times 10^{55} (r_{\rm t}/6 r_{\rm g,NS})^{-5}$ erg/s and the merger takes [10]. The corresponding change of the angular momentum reads $\Delta J_{\rm binary} \sim (dE/dt)\Delta t/\sqrt{2GM_{\rm NS}/r_{\rm t}^3}$ and we have $x = 1 - \Delta J_{\rm binary}/J_{\rm binary} \sim 0.9$ [9]. Therefore one has $\Omega_0 \sim 2 \times 10^4\ (M_{\rm NS}/1.35 M_{\odot})^2 (I/10^{45.3}\ {\rm g\ cm^2})^{-1}$. The

The expected rotation period is ~1 ms!